STEPHEN BURT

THE WEATHER OBSERVER'S HANDBOOK

CAMBRIDGE

THE WEATHER OBSERVER'S HANDBOOK

The Weather Observer's Handbook provides a comprehensive, practical, and independent guide to all aspects of making weather observations. Automatic weather stations today form the mainstay of both amateur and professional weather observing networks around the world, and yet – prior to this book – there existed no independent guide to their selection and use. Traditional and modern weather instruments are covered, including how best to choose and to site a weather station, how to get the best out of your equipment, how to store and analyze your records, and how to share your observations with other people and across the Internet. From amateur observers looking for help in choosing their first weather instruments on a tight budget to professional observers looking for a comprehensive and up-to-date guide covering World Meteorological Organization recommendations on observing methods and practices, all will welcome this handbook.

Stephen Burt has a professional background in physics, meteorology and climatology, information technology, and marketing. He is a Fellow of the UK's Royal Meteorological Society and is also a member of both the American Meteorological Society and the Irish Meteorological Society. He has run his own meteorological observatory for more than 40 years. After almost 10 years with the UK Met Office he took up a business career within the computer industry, successfully managing international marketing roles for several of the world's largest high-technology firms. During this time he was also elected to the UK's Chartered Institute of Marketing.

Stephen is a regular contributor to the Royal Meteorological Society's monthly magazine *Weather*, with more than 100 published papers or articles and several hundred published photographs to date. He is a recent member of the Royal Meteorological Society's Council governing body, Chairman of the Society's South-east Centre and a long-standing committee member of the Society's Special Interest Group on Weather Observing Systems. Stephen was awarded the Royal Meteorological Society's Gordon Manley Prize in 2006. He is also a Trustee of the Chilterns Observatory Trust and Chairman of the Climatological Observers Link. He lives in southern England with his wife and two daughters.

‘This is a very impressive work! Stephen has done a great job of addressing many issues that I have personally wondered about. At last there is a comprehensive book on the tricky issue of accurately measuring the weather. This timely publication is a must for anyone in the market for a weather station, libraries, and weather observers of all stripes, both amateur and professional.’

– Christopher C. Burt (no relation to Stephen), Weather Historian, Wunderground, Inc., and author of *Extreme Weather: A Guide and Record Book*

‘Sophisticated equipment for weather observing is now within reach of more people than ever. Yet a poorly sited station or a wrongly interpreted report can do more harm than good. With this marvelous book, Stephen Burt has given us a very practical and helpful guide to installing and using one’s own reporting station, enhanced with perspective drawn from the centuries-long history of meteorological instrumentation. *The Weather Observer’s Handbook* is an ideal companion to the practice of monitoring the atmosphere.’

– Robert Henson, author of *The Rough Guide to Weather* and *The Rough Guide to Climate Change*

‘People have been making observations of the weather for thousands of years, and observations remain central to our capabilities to forecast the weather and predict the changing climate. But it’s not just professional meteorologists who make weather observations; there are literally millions of amateur observers across the world making observations every minute of every day. In meteorology, as well as in other science disciplines, amateur observers (I include all non-professional meteorologists in this) have always played a crucial part in supporting well-established national observation programmes and in making a very valued contribution to our scientific understanding.

‘We have many amateur members and schools in our Society and I’m often asked if I can recommend a good book to help them in their observing exploits. Well, now I can. This is the first comprehensive book of its type that I know of that offers a practical guide to anyone with an interest in making observations of the weather. It’s not only an essential practical handbook, but it showcases the wide range of observations that can now be made with relative ease, and, importantly I think, it helps to enthuse others to follow their interest. If you have an interest in observing the weather, then this book is as essential as your observing equipment.’

– Paul Hardaker, Chief Executive of the Royal Meteorological Society

The Weather Observer's Handbook

Stephen Burt

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For Helen

Mr Hook[e] produced a part of his new weather Clock which he had been preparing which was to keep an Account of all the Changes of weather which should happen, namely the Quarters and points in which the wind should blow. 2ly the strength of the Wind in that Quarter. 3ly The heat and cold of the Air. 4ly The Gravity and Levity of the Air. 5ly The Dryness and moisture of the Air. 6ly The Quantity of Rain that should fall. 7ly The Quantity of Snow or Hail that shall fall in the winter. 8ly The times of the shining of the Sun. This he was desired to proceed with all to finish he hoped to doe within a month or six weeks.

From Royal Society Journal Book (JBO/6), dated 5 December 1678. Reproduced by kind permission of the Royal Society Archives

Contents

Acknowledgements

It has often been said that the exercise of writing a book both tests and expands the knowledge of the writer, and that has certainly been my experience in researching and writing this book. I have been fortunate in being able to draw upon on the willing help and assistance of many people around the world in helping to answer my questions, some simply seeking a photograph or a reference to published work, others much more detailed or technical in nature. Sure enough, the process of having to set it all down on a blank sheet of (virtual) paper has immeasurably broadened and deepened my own understanding of the topics covered. I hope that this has, in turn, found its way onto the pages that follow.

Of course, the nature of weather itself knows no international boundaries. The credit for suggesting the expansion of my original book proposal into a global weather observer's manual goes to my Editor Dr Matt Lloyd, of Cambridge University Press in New York: I am very grateful to Matt and to Amanda O'Connor, Editorial Assistant, for their help and support throughout the process from proposal to launch; to Lindsey Anderson from Cambridge University Press's production agency Integra in Chicago, and to Fran Robinson and Joy Mizan for their help in pulling together the book's launch marketing plans in the UK and U.S. markets, respectively. Many individuals around the world willingly provided their expertise in the preparation of this volume, took the trouble to read and comment on draft chapters and offered helpful suggestions; I hope you will recognise your input in the pages following. I would particularly like to thank the following for their contributions and support: Dr Hans Bergström (University of Uppsala, Sweden), Richard 'Heatwave' Berler (Chief Meteorologist, KGNS TV, Laredo, Texas), Christopher C. Burt (Weather Historian for Weather Underground, Inc.), Professor Dario Camuffo (Istituto di Scienze dell' Atmosfera e del Clima, Bologna, Italy), WL Chang and SW Chow (Hong Kong Observatory, China), Professor Claudio Cocheo (Centro di Ricerche Ambientali, Padua, Italy), Steve Colwell (British Antarctic Survey, Cambridge), Joanna Corden and Emma Davidson (Royal Society, London), Nolan Doesken (Colorado State University, and co-founder of CocoRaHS), Dr Wolfgang Fritze and Dr Stefan Gilge (Deutscher Wetterdienst, Hohenpeissenberg Observatory, Germany), Dr Emily Gleeson (Irish Meteorological Society, Dublin), Grant Goodge (formerly of NOAA's National Climatic Data Center, Asheville, North Carolina), Aidan Green (Surface Networks Manager, UK Met Office, Exeter), Richard Griffith (Climatological Observers Link/COL, Horsham), Professor Paul Hardaker (Royal Meteorological Society, Reading, UK), Professor Giles Harrison and Dr Keri Nicoll (Department of Meteorology, University of Reading, UK), Bob Henson (UCAR, Colorado), Rob Hughes (Fredericton, NB, Canada), Dr Gert König-Langlo (World Radiation Monitoring Center, Alfred Wegener Institute, Bremerhaven, Germany), Melody Magnus (NOAA/NWS webmaster, Silver Spring, Maryland), Maurizio Maugeri (University of Milan, Italy), Dr Joe Michalsky (NOAA), David Myers (ex-IBM and ex-Dell), Charles T. Orloff and Mike Iacono (Blue Hill Observatory, Massachusetts), Isabel Plana (Meteoswiss, Zürich), John Prior (National Climate Information Centre, UK Met Office, Exeter), Henry Reges (CoCoRaHS, Colorado), Francesca Steffanoni (Ev-K2-CNR Committee, Bergamo, Italy), Dr Ian Strangeways (Terradata, Wallingford, UK), Phil Thomas (COL, Alvechurch), Professor Frank Vignola (Department of Physics, University of Oregon), Julia Wessels (Swiss Institute for Snow and Avalanche Research, Davos), Gary Wicklund (NOAA/ National Weather Service, Pocatello, Idaho), and James Zdrojewski (National Weather Service HQ, Silver Spring, Maryland). As ever, Steve Jebson and Mark Beswick in the National Meteorological Library, Exeter, UK, provided exemplary support in the tracking down of references and other source materials. Other individuals and organisations preferred or requested not to be mentioned by name; my thanks are there all the same.

This book is deliberately independent of any instrument manufacturer or supplier, but it would be incomplete without the willing help and assistance of many individuals within those companies who went the extra mile (or should it be 1609 metres?) to help out with sourcing product specs, photography and a thousand other details for me. Particular thanks go to Dick Saffell, Iain Thornton and Mike Brettle from Campbell Scientific Ltd (Loughborough, UK); Dr John Dann from Prodata (Ely, UK); and Dan Anderson and James Thoreson from RM Young USA (Traverse City, Michigan).

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Finally, a special thank-you to my family – to my wife Helen and my two daughters, Fiona and Jennifer. Without your support, love and understanding I could not have started, far less completed, this seven-year project.

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Abbreviations, footnotes and references

Abbreviations are defined within the text when first used; they are listed below only if used more than once.

Footnotes (indicated by superscripted symbols*† and so on) are given at the foot of the page.

References and further reading are indicated within the text by bracketed numerals as [9]. They indicate sources of material or further reading for those who require more detail on the topic. References are numbered within each chapter and listed at the end of that chapter.

ASOS	Automated Surface Observing System
AWS	Automatic weather station
DWD	Deutsche Wetterdienst – the German state weather service
KNMI	Koninklijk Nederlands Meteorologisch Instituut – the Dutch state weather service
LAT	Local Apparent Time
MMTS	Maximum-Minimum Temperature System
MSL	Mean sea level
NOAA	National Oceanic and Atmospheric Administration
PC	Personal computer
PRT	Platinum resistance thermometer
RTD	Resistance Temperature Device
SRG	Standard Raingauge (US)
TBR	Tipping-bucket raingauge
USB	Universal Serial Bus (a communications port on computers)
USCRN	U.S. Climate Reference Network
USRCRN	U.S. Regional Climate Reference Network
USWB	United States Weather Bureau (now the National Weather Service)
WMO	World Meteorological Organization

Important note

Throughout this book, suggestions and recommendations are completely independent of manufacturer or supplier influence. No sponsorship or incentives were requested or offered by any of the companies whose products are referred to in this book. Although it is not possible to be fully conversant with every instrument or system described in this book, wherever possible usage details are from firsthand experience. System specifications and performances have been taken from published manufacturer literature or websites, except where specifically stated otherwise. Because product specifications change over time, it is suggested that potential purchasers always check manufacturer literature or websites for the latest information.

If you use this book to help choose an automatic weather station, or the components of one, please mention this to your reseller or dealer when you make your purchase.

For the latest product information, occasional equipment reviews, useful references and downloadable material related to this book, please visit www.cambridge.org/9781107662285 and the author's website www.measuringtheweather.com.

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PART ONE

THE BASICS

1 Why measure the weather?

Of all the physical sciences, meteorology depends more than any other on frequent, accurate and worldwide measurements. Every day, millions of weather measurements are made by thousands of people across the globe, on land, over the oceans, in the upper air and from space, providing the raw data essential to supercomputer-based weather forecasting models that are vital to modern economies. Meteorology (and its statistical cousin, climatology) is one of the few sciences where both amateurs and professionals make significant contributions.

'Measuring the weather' is undertaken for many different reasons: as well as input to weather and climate forecasts, it is a vital part of aviation safety, critical in detecting and quantifying climate change, keeping tabs on typhoons and hurricanes, monitoring the ebb and flow of pollutants and arctic ice, and hundreds of other applications of enormous benefit to society. Weather records are made in every country and region in the world – from the hottest deserts to the coldest polar regions, from densely populated city centres to the most remote mountaintops. There is even a permanent automatic weather station at 8,000 metres above sea level just below the summit of Mt Everest (**Figure 1.1**), whose observations are updated to the Internet hourly.

For many, professionals and amateurs alike, measuring the weather is also an absorbing long-term interest, guaranteed to deliver something different every day of every year. Well-kept records by individuals and organizations alike assist in the scientific analysis of all types of weather phenomena, and can become a permanent part of a nation's weather record.

About this book

This book has been written with four main audiences in mind:

- Weather enthusiasts and amateur meteorologists
- Professional users, including local authorities and other statutory bodies
- Schools, colleges and universities
- Weather-dependent outdoor activity professions and organizations.

The aim of this book is to provide useful and practical guidance on most aspects of weather observing, with emphasis on observations using instruments. Particular attention is paid to the selection and use of modern electronic instruments and 'automatic weather stations' (AWSs), while not forgetting the long and interesting history of 'traditional' instruments.

Figure 1.1. Installing the world's highest weather station at 8000 m above sea level on the south col of Mt Everest, May 2011. The summit is 8850 m. Observations are updated hourly on the web – http://share-everest.it/SHAREEverest2011MeteoData/SouthCol/sensorSouthCol.html (Photograph courtesy of the Ev-K2-CNR Committee archive)

Weather enthusiasts and amateur meteorologists

For individuals who are new to the fascinating science of measuring the weather, this book is intended to help guide your choice of what may be your first item or items of weather-measuring equipment. It explains the important things to look out for, what can be measured within particular budgets, how best to site your instruments, and how to start collecting and sharing data. Whether your site and equipment is basic and sheltered, or extensive and well exposed, this book provides help to improve the quality and comparability of your observations to attain, or even surpass, the standards established by the World Meteorological Organization (WMO).

For those who already have experience of weather observing and who perhaps are looking to add an AWS to complement their existing 'traditional' instrumentation, or who already own a basic AWS and are looking to upgrade to a more capable system, this book provides assistance and suggestions on choosing and siting appropriate equipment. It is also a practical day-to-day observing reference handbook to help get the most out of your instruments and your interest.

Professional users

There are many ‘professional’ users who need reliable and accurate weather information, for one or more sites, whose needs can be served by a properly sited AWS. Typical users include local or state authorities managing road maintenance (including winter gritting or snow clearance), landfill management, environmental monitoring as part of civil engineering projects, and airport weather systems. For professional users requiring environmental records, perhaps as part of new statutory requirements, this handbook provides independent guidance on choice of systems, siting of sensors, and suggestions on data collection and handling processes. The information gathered needs to be both manageable and relevant, while meeting the appropriate standards of measurement and exposure. It also includes advice on how to document the site and instruments in use (and any changes over time), to minimize possible future downstream technical or legal challenges relating to the data obtained.

Schools, colleges and universities

The installation of automated weather-monitoring equipment offers the chance to include weather observations at all levels within the educational curriculum, from early schooldays to post-doctoral levels. Weather measurements are often made more relevant and interesting to the student by virtue of the readings being made at the school or college site, particularly where both real-time and long-term archived records are available for study purposes. From junior school to university, the observations can be used immediately (especially so in an interesting spell of weather, such as a heatwave or flood event) or in a variety of curricular activities such as numeracy, IT, telecommunications, severe weather awareness training and alarms, office software packages (particularly spreadsheets), statistics and website design, in addition to conventional geography, science and mathematics courses [1]. This book provides assistance on choosing and siting suitable systems and making best use of the data collected.

Many of those who have gone on to study meteorology further and who become professional meteorologists picked up the ‘weather observing’ bug at school (including the author). The importance of encouraging curious young minds to observe and take an active and enquiring interest in their physical environment, and its changes on a day-to-day basis, cannot be underestimated.

Weather-dependent outdoor activity professions and organizations

Many organizations or clubs need site-specific weather information; for example, yacht clubs, gliding clubs, private aviation airfields, as well as windsurfers and microlight pilots. In some cases, particularly microlight and gliding clubs, members may live a considerable distance from the main club operations and value the opportunity to be able to view live weather conditions at the site on a club website before making a decision whether to travel to the club that day. Farmers and other professions largely at the mercy of the weather also need accurate and timely weather information, perhaps from more than one site within a local area. Many such organizations or businesses may not have previously considered their own weather station or monitoring network as being affordable. Today, respectable quality weather data in real time is available from inexpensive, easily maintained and robust systems. Modern electronic weather stations connected to the Internet can provide local or distant-reading output facilities quickly, cheaply and reliably; this book outlines what is available and where to site the instruments for best results.

Topics covered

Current 'traditional' weather instruments – largely non-digital – and their development are also covered in this handbook. They still have a very important part to play, not just in providing continuity with existing and historical records, but because they are likely to remain the reference or benchmark system for at least the next decade or two. For those seeking to automate an existing manual climatological station, suggestions are provided on how to minimize the discontinuity of record that often occurs when new observing systems are brought into use, although in all cases the network administrator (such as NOAA in the United States or the Met Office in the United Kingdom) should also be consulted at the earliest opportunity.

This book covers a wide range of weather station systems, sensors and associated technology, from $100 (U.S.) to upwards of $1,500 (at 2012 pricing). It does not cover homemade instruments or remote-reading sensors without any means of logging (such as wireless temperature and humidity displays), nor does it cover in detail professional systems costing many thousands of dollars (for which more specific pre-sales advice should be sought from the manufacturer). It covers land- and surface-based systems only. Sensors and logging equipment for aircraft or buoys have very different characteristics and are not covered in this book.

Geographical coverage

This book covers equipment, standards and measurement methods as set out by the World Meteorological Organization (WMO), based in Geneva, Switzerland [2]. The details of some measurements and methods differ slightly from country to country, and where applicable this book provides specifics relevant particularly within the United States, the United Kingdom and the Republic of Ireland. The majority of the book is also relevant outside these geographies, but readers in other regions should check the availability of products and the detail of country-specific equipment, specifications and siting recommendations with their national meteorological service prior to implementation [3].

Abbreviations, references, footnotes and further reading

Abbreviations and technical terms are kept to a minimum: where used, they are defined at first use and indexed. The most frequently used abbreviations are listed at the front of the book for easy reference. References and suggestions for further reading are included for readers who may wish to delve further into these topics. Specific references are indicated within the text by a number within square brackets, thus [9]. References and further reading are listed in numerical order at the end of each chapter. Footnotes are indicated by symbols thus * † with the appropriate text appearing at the foot of the page on which the footnote appears.

A number of sample and template spreadsheets are available online at www.cambridge.org/9781107662285 and at www.measuringtheweather.com. These are referenced at the appropriate point in the text and are available for free download. They can then be customized to your specific requirements.

Units

Meteorology is necessarily an international science and consistent units are required for information exchange and understanding. In this book WMO recommendations for units are used in preference, with bracketed alternatives where necessary; for instance, wind speeds can be expressed in metres per second (m/s), knots (kn) or miles per hour (mph), depending upon the requirement. Conversions between the different units involved are given in **Appendix 3**.

Automatic weather stations

In this book an automatic weather station (AWS) is defined as any system which creates and archives a digital (computer-readable) record of one or more weather 'elements', such as air temperature, precipitation, sunshine, wind speed or other parameters.

In its simplest form, an AWS can be a single sensor integrated with a small, inexpensive electronic data recorder (a 'datalogger' or simply 'logger'). Loggers that can record only one input signal, or 'channel', are therefore 'single-channel loggers'; those that can handle two or more are 'multi-channel'. Most such systems can be left exposed as a whole unit including the logger, perhaps for several months in a remote location, before the recorded data are retrieved. The most advanced AWSs (**Figure 1.2**) are completely automated remote multi-element single-site observing systems, requiring only the minimum of human attention and maintenance, self-powered by a solar cell array or wind turbine and communicating observations at regular intervals over a telecommunications system to a collecting centre. Telecommunications may be direct to satellite in the most remote areas.

Most of the world's meteorological services are moving towards such devices as replacements for costly human observers. But even with today's most sophisticated technology and sensors, human observers are still required for many weather observing tasks; for example, AWSs are still very poor at telling the difference between rain and wet snow, nor can they report shallow fog just starting to form across the low-lying parts of an airfield or see distant lightning flashes on the horizon which warn of an approaching thunderstorm. Human weather observers will continue to be required for a long while to come!

The makers of the observations

Fascination with the changes in day-to-day weather is nothing new, although weather records were by necessity purely descriptive until the invention of meteorological instruments in the 17th century [4]. Probably the oldest known weather diary in the Western world is that of Englishman William Merle, who kept notes on the weather in Oxford and in north Lincolnshire from 1337 to 1344 [5]. In North America, the earliest surviving systematic weather records are those made by John Campanius Holm, a Lutheran minister originally from Sweden, who made observations at Fort

Figure 1.2. The U.S. National Weather Service Automated Surface Observing System (ASOS) sensor package located at Pocatello, Idaho (42° 55’ N, 112° 34’ W, 1356 m above MSL, WMO station no. 72578), October 2011. From left to right, the instruments shown are – heated tipping-bucket raingauge within wind shield: aspirated temperature and humidity sensors: present weather sensor: 10 m wind mast with heated ultrasonic wind sensor: data collection panel (big box): laser ceilometers: freezing precipitation sensor (little tilted box), and finally the visibility sensor. (Photograph by Gary Wicklund)

Christina in New Sweden (near present-day Wilmington, Delaware) in 1644–5. (Today, the annual National Oceanic and Atmospheric Administration NOAA John Campanius Holm Award is given for outstanding accomplishments in the field of cooperative meteorological observations.)

During the Renaissance, the invention of instruments to measure the temperature and pressure of the atmosphere, and later other elements, made it possible to track the changes in weather conditions more accurately, and more consistently, between different observers and locations. Galileo invented the air thermoscope around 1600; Santorio added a scale to make it a thermometer in 1612. The first liquid-in-glass thermometer (in a form we would recognize today) was invented by Ferdinand II, the Grand Duke of Tuscany, in 1646, while Evangelista Torricelli invented the mercury barometer in 1644.

Surprisingly perhaps, what we would now call multi-element automatic weather stations began to appear very early in the history of weather instruments. Sir Christopher Wren (1632–1723) is best known today as the architect of London’s St Paul’s Cathedral, but in his early career he was a noted astronomer [6], a founding member of the Royal Society in London [7] in 1660, and a prolific instrument designer. Together with Robert Hooke (1635–1703) he designed and built many weather instruments, including Hooke's sophisticated mechanical 'weather clock' in the 1670s [8] (see Box, *Wren and Hooke: a fertile partnership*). The earliest surviving rainfall records in the British Isles were made by Richard Towneley at Towneley Hall near Burnley, Lancashire, in northern England from January 1677 [9]; the raingauge used was based upon Wren's design. It was Wren who first described the tipping-bucket form of raingauge, modern varieties of which are still in use at tens of thousands of locations across the globe today (see Chapter 6).

Wren and Hooke: a fertile partnership

Wren's long friendship and professional collaboration with Robert Hooke spawned many designs for instruments to 'measure the weather'. Wren is acknowledged as the inventor – around 1662/3 [10] – of the tipping-bucket mechanism for measuring rainfall, the principle of which is still used in today's instruments. Hooke was a polymath with a superb ability for translating ideas into practical working devices [11], and he built many weather instruments, as the following extract from the Royal Society Journal Book (JBO/6), dated 5 December 1678, shows:

> "Mr Hook[e] produced a part of his new weather Clock which he had been preparing which was to keep an Account of all the Changes of weather which should happen, namely the Quarters and points in which the wind should blow 2ly the strength of the Wind in that Quarter. 3ly The heat and cold of the Air. 4ly The Gravity and Levity of the Air. 5ly the Dryness and moisture of the Air. 6ly The Quantity of Rain that should fall. 7ly The Quantity of Snow or Hail that shall fall in the winter. 8ly the times of the shining of the Sun. This he was desired to proceed with all to finish he hoped to doe within a month or six weeks."

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As materials and methods evolved, meteorological instruments became more practical, robust, reliable and cheaper, and thus were used more widely, carried to the New World on the ships of the European superpowers of the day. The once-ubiquitous Six's maximum-minimum thermometer was invented by James Six in 1782, and although they ceased to be used for accurate climate recording more than 100 years ago, these instruments can still be found today in many a gardener's greenhouse (**Figure 1.3**). In the early 19th century one of the first amateur meteorologists, apothecary Luke Howard of London, more popularly known as 'the inventor of clouds', [12] owned a magnificent – and very expensive – 'clock-barometer', or mercury barograph [13]. Records from this instrument survive today; a very similar instrument, made for Great Britain's George III in 1763–5 by Alexander Cumming (c. 1732–1814), remains in the Royal Collection [14].

Weather instruments benefited from the enormous technological and manufacturing advances made between the late 18th and late 19th centuries. Many of today's instruments date from this period (see timescale in **Figure 1.4**) [15] including the Stevenson screen (see Box, *The lighthouse Stevensons*). A meteorological observer from the late 19th century would today have little difficulty in making a weather observation at many of today's standard climatological stations in North America or in the United Kingdom and Ireland. Many of these instruments are being rapidly

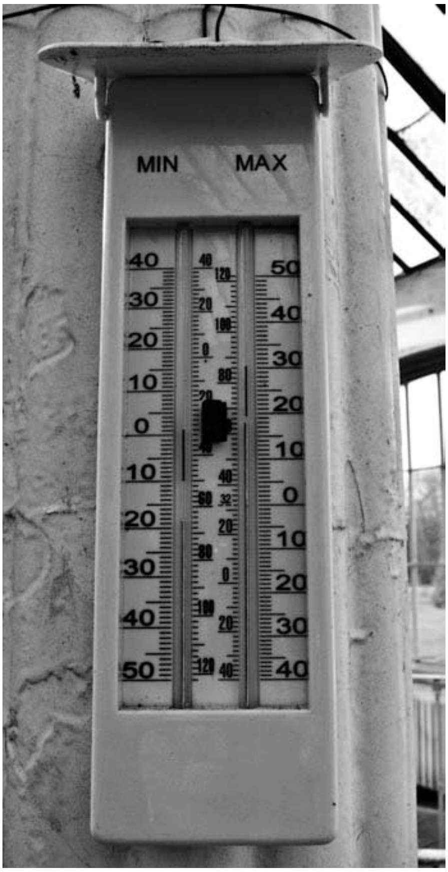


Figure 1.3. A Six's maximum-minimum thermometer; this in the Temperate House at Kew Gardens in west London. (Photograph by the author)

superseded by newer electronic equipment, the subject of later chapters, and our Victorian-era observer will have much greater difficulty in making sense of the instruments in a few years time.

Recording meteorological instruments continued to be developed and improved during the 18th and 19th centuries, but while many ingenious designs were invented, almost all relied upon mechanical components and thus were, to a greater or lesser degree, subject to friction, often hugely expensive (many were made to order or in very small numbers), and difficult to maintain in good working order when exposed to the elements. For these reasons few were made – and even fewer have survived, even in museums.

The lighthouse Stevensons

Thomas Stevenson (1818–87) was a marine engineer; a member of the famous Stevenson engineering dynasty which built most of Scotland's lighthouses [16]; and the father of Robert Louis Stevenson (1850–94), author of *Treasure Island* (1881), *Kidnapped* (1886) and *The Strange Case of Dr Jekyll and Mr Hyde* (1886).

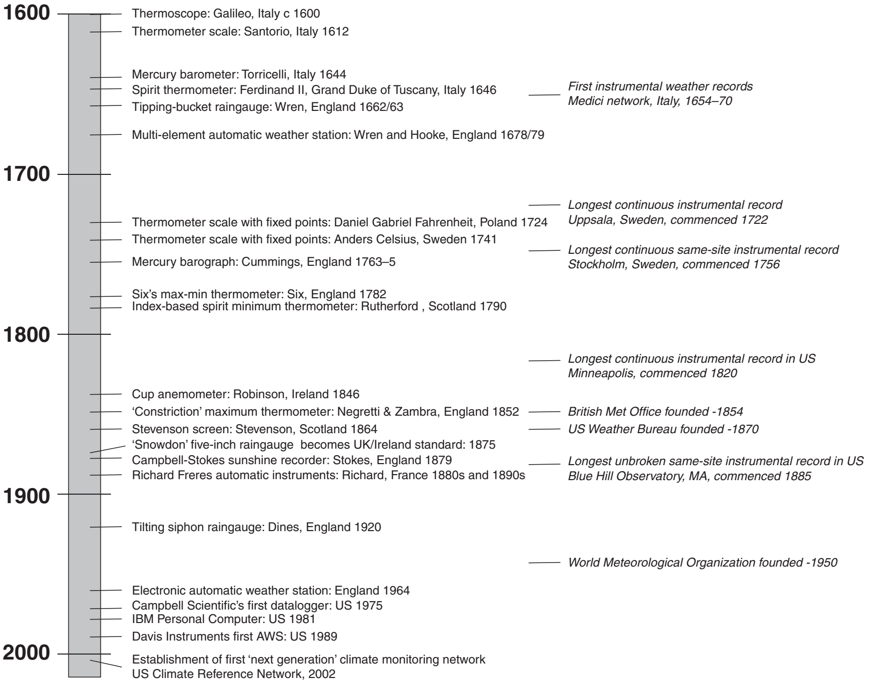


Figure 1.4. Four hundred year timeline showing key dates in the development of meteorological instruments and weather recording. For sources see references in the text.

In a brief note in the *Journal of the Scottish Meteorological Society* in 1866 [17] he described the form of thermometer shelter which still bears his name – a white-painted double-louvred box which protected the thermometers inside from rainfall, sunshine and infrared radiation from Earth and sky. At the time there were dozens of proposed designs for thermometer screens, some of which had been in use for a decade or more [4]. It was only a series of painstaking trials undertaken by the Reverend Charles Griffith at Strathfield Turgiss rectory in Hampshire, England, in the late 1860s and early 1870s comparing air temperatures measured in Stevenson's screen with other models (**Figure 1.5a**), that eventually led to its adoption (with minor amendments to the original design) as the preferred method for taking air temperature measurements by the Royal Meteorological Society in 1884 [18]. The de facto British standard spread rapidly to the rest of Britain's empire and then to the rest of the world (**Figure 1.5b**) as the enclosure was simple, easy to make locally, robust and gave good protection from the tropics to the poles. The basic principles – a white, louvred, roofed enclosure – remain common to many thousands of thermometer screens in daily use throughout the world today (**Figure 1.6**).

The end of the 19th century saw the advent of relatively inexpensive, mass-produced single-element mechanical recording instruments using clock-driven paper charts, such as the barograph and thermograph (**Figure 1.7**), and later various

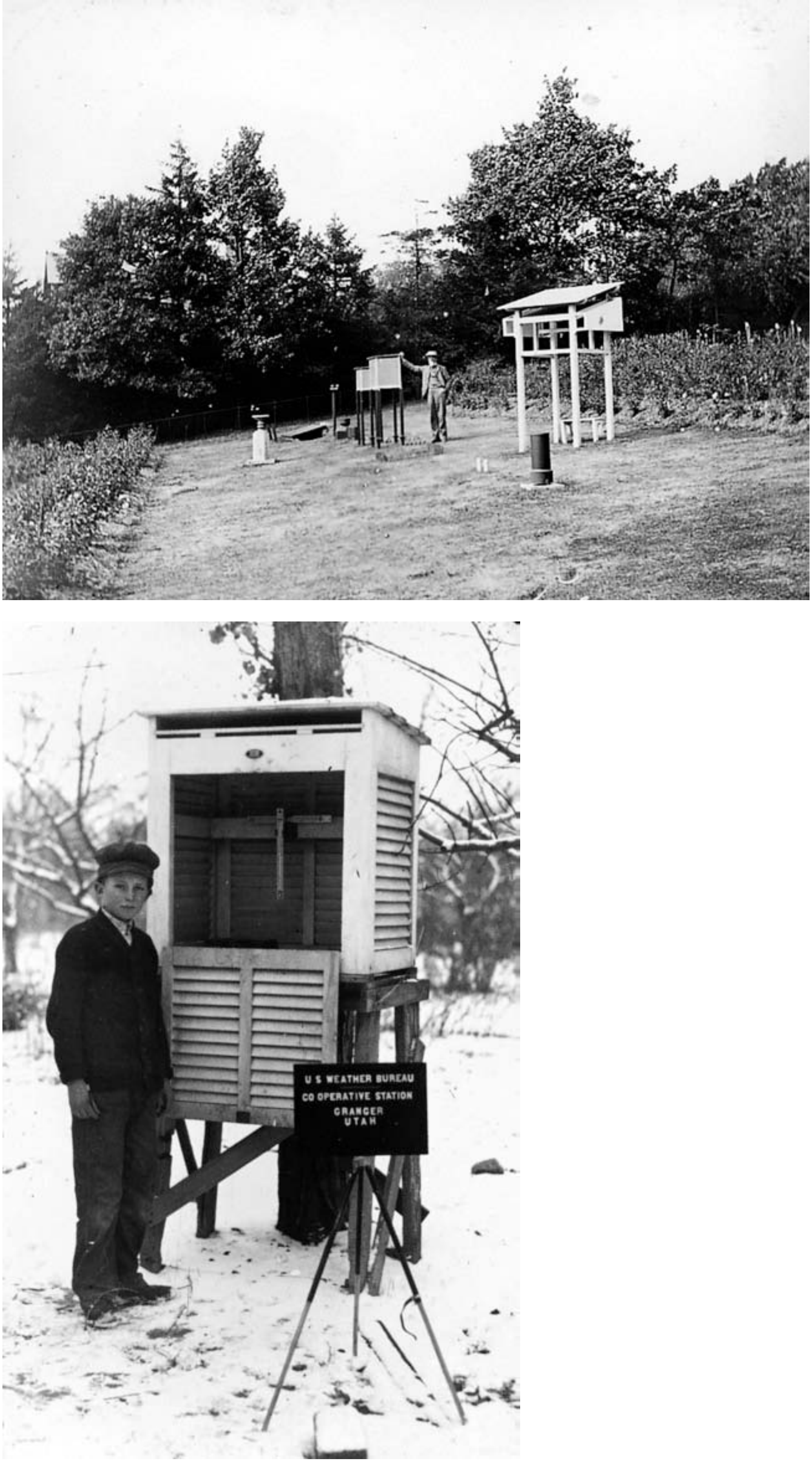


Figure 1.5. Early models of thermometer screen.

(a) This photograph was taken at Berkhamsted, Hertfordshire, England, on 29 July 1896, and shows two Stevenson screens (centre of picture) adjacent to a much larger modified Glaisher stand (an earlier and more open pattern of thermometer screen). The observer is Edward Mawley. (© Royal Meteorological Society)

(b) Cotton Region Shelter (see Chapter 5) and young observer at U.S. Weather Bureau observing site at Granger, Utah, c. 1930. (Courtesy NOAA/Department of Commerce National Weather Service Collection wea00903)

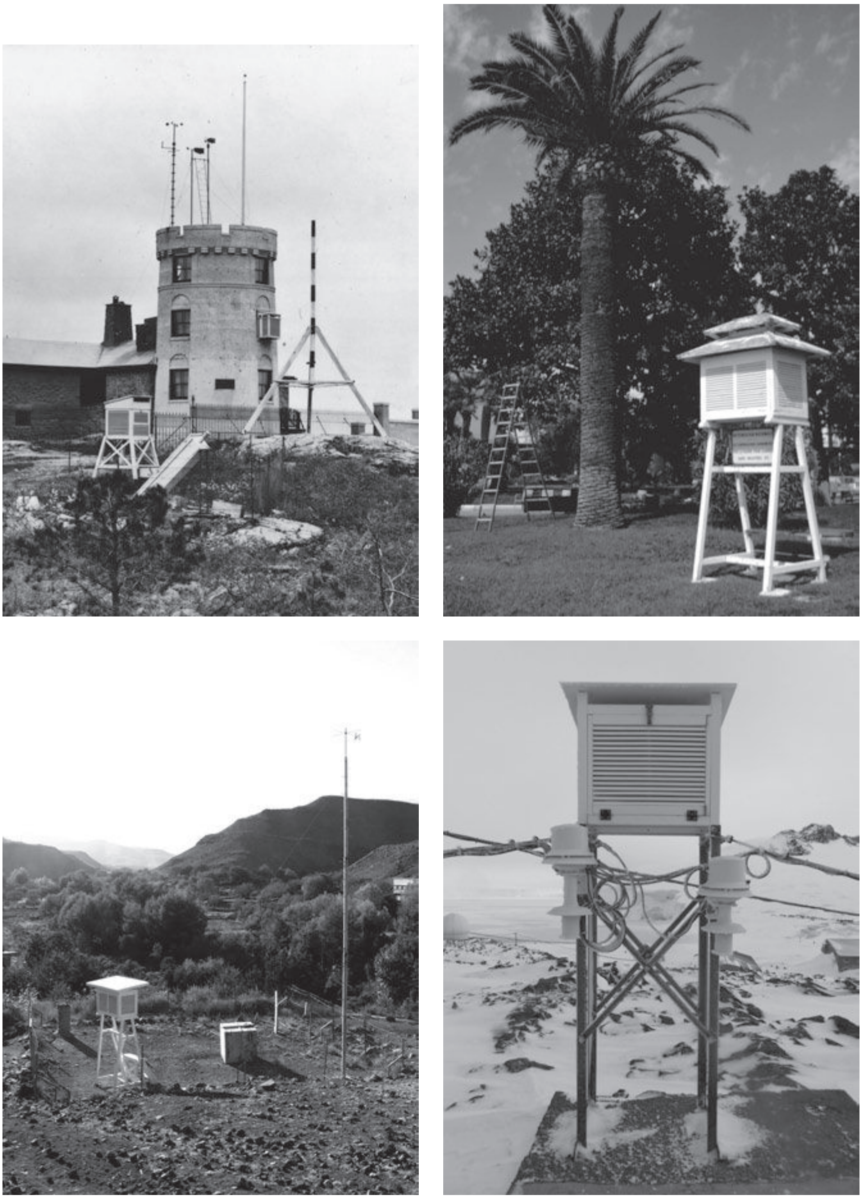


Figure 1.6. Stevenson-type thermometer screens in use on three continents and in the south polar regions. (Top, left) U.S. 'cotton region shelter' thermometer screen at Blue Hill Observatory, Massachusetts, USA (Courtesy of Blue Hill Observatory). (Top, right) Stevenson-type thermometer screen on the seafront at Cannes in the south of France. (Photograph by the author). (Bottom, left) Stevenson-type thermometer screen on the edge of the Sahara desert at Agoium, Morocco (approx 30.5 °N, 7.5°W, 1800 m AMSL). (Photograph by the author). (Bottom, right) Aluminium-and-plastic Stevenson screen in use at Rothera research station in the Antarctic, January 2010. (Photograph by Tamsin Gray, British Antarctic Survey)

forms of automatic rainfall recorders. These instruments revolutionized automated weather recording [19]. As a result, for over a century 'automatic' weather records were obtained by time-consuming manual analysis of paper-based records from these single-element instruments. Some can still be found in regular use today, although

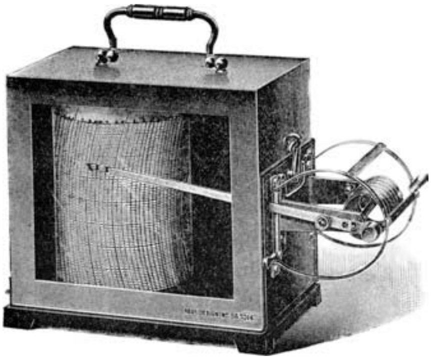


Figure 1.7. A thermograph from the London makers Short & Mason, 1913.

many have already been superseded by electronic systems much closer to Wren and Hooke's original concept of the 'weather clock' – namely, a single mechanism which recorded multiple elements – one which was 350 years ahead of its time.

The modern AWS, consisting of a datalogger connected to a variety of electrical sensors, began to take form in the early 1960s (**Figure 1.8** [20]). It was the advent of cheap computing power, advances in data storage and telecommunications allied with the enormous reduction in size of electronic components that resulted from the personal computer revolution during the 1980s that enabled the economies of scale needed for prices to fall sharply. A system with a mid-range budget capability today would have cost tens of thousands of dollars in the mid-1980s. Today, high-quality, multi-element, remote wireless data display and logging are available for less than the price of a new clock-driven thermograph.

The longest-running weather observations in the world

The earliest versions of many 'traditional' meteorological instruments were invented in Europe in the 17th or 18th century – the mercury barometer, mercury thermometer and various instruments to measure rainfall all appeared during this time, and people began to keep instrumental weather records. At first these were experimental and sporadic, rarely lasting for more than a few years in any one place, and of course with widely differing standards of exposure, accuracy and (not least) units. The earliest surviving instrumental weather records are from the Medici network, based in Florence, Italy, covering the period 1654 to 1670. Thanks to tremendous historical detective work, these early records have recently been recovered and analyzed [21]. We also have daily observations of a mercury barometer in Pisa, Italy, in 1657–8 [22], and for 1694 there are sufficient surviving barometric pressure records across Europe for outline daily synoptic weather maps to be prepared. An almost complete daily pressure record has been assembled for locations in Paris back to 1670, and in London since 1692 [23].

In the early 18th century regular and systematic weather records commenced in various places in Europe, often initially as part of the observational routine at astronomical observatories. Many of these observatories are still in existence, and at a few locations continuous weather observations have been made in much the

Figure 1.8. An early prototype automatic weather station at the then Institute of Hydrology in Wallingford, England in the late 1960s. (Photograph by Ian Strangeways)

same location for more than 200 years. Although most long-period records have been made in large towns or cities, and as a result individual temperature records have been affected by urban warming to a greater or lesser extent, the observations are still the most detailed and comprehensive records we have for changes in climate since the 17th century.

The longest temperature record in the world: 1659 to date

In 1953, the British climatologist Gordon Manley (1902–80) published his first paper on what became known as the Central England Temperature (CET) series in the Royal Meteorological Society's *Quarterly Journal* [24]. Manley's extensive and painstaking research assembled scattered early instrumental temperature records and descriptive weather diaries to produce a chronology of mean monthly temperatures representative of a roughly triangular area of England enclosed by Lancashire, London and Bristol covering the period 1698 to 1952. A second, longer paper in 1974 [25] extended the series back to 1659 – about the time the earliest thermometers appeared in England – and brought it up-to-date. Other records that had come to light in the intervening 20 years also allowed for corrections or improved estimates to the existing series. Since Manley's death the series has been kept up-to-date by the Hadley Centre, part of the UK Met Office, and today the series forms the longest instrumental record of temperature in the world. A similar monthly rainfall record, the 'England and Wales Precipitation' series, extends back to 1766 [26].

Early English temperature records are sufficiently numerous that an expanded daily temperature series back to 1778 was published in 1992 by David Parker and colleagues at the Hadley Centre [27]. Daily 'maximum' and 'minimum' CET are also available back to 1878. Since 1974 the data have been adjusted slightly to allow for urban warming.

Manley's work pieced together many disparate records to produce a figure representative of a region rather than a single site. There are other long composite series of temperature, rainfall and/or pressure records representative of other cities or regions in Europe extending back to the 18th century. At a few places instrumental weather records are still made today in the *same* location, or very nearly so, where continuous observations began in the 18th century (**Figure 1.9**).

Uppsala, Sweden – 1722 to date

59.847°N, 17.635°E, 25 m above sea level

The oldest mostly continuous records in Europe are those from Uppsala, Sweden, about 65 km (40 miles) north of Stockholm, where records commenced in 1722 [28]. The earliest organized meteorological observations in Sweden were initiated around

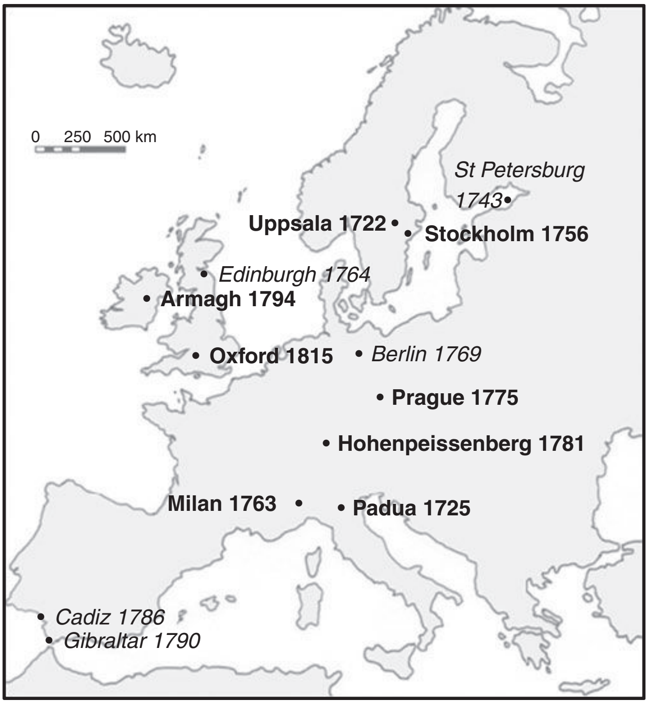


Figure 1.9. The locations of some of the longest-running meteorological records in Europe – see text for details.

1720 by the Society of Science in Uppsala, when Professor Erik Burman started the observations there. These were made at the old astronomical observatory in the centre of Uppsala ('Celsiushuset'), which was then a small town. He was assisted by the young Anders Celsius, who took over responsibility in 1729. The oldest surviving observatory journal dates from the year 1722, although there are some gaps in the Uppsala record until 1773. Before 1751 a variety of thermometer scales were used, among them of course Celsius's own thermometer with the first Celsius scale.

In September 1853, the observation site was moved to a then newly built astronomical observatory situated in open fields outside the town, about 1 km north-west of the original site (**Figure 1.10**, top). Further changes of site took place in October 1865, June 1952 and August 1959, all within a few hundred metres of each other, but the original rural site had become increasingly urbanized as Uppsala expanded over the years (its population today is around 150,000). In August 1959 the observing site moved to the Department of Meteorology at Uppsala University, and in January 1998 a further move took place 1.4 km further south to 'Geocentrum' at the new Department of Earth Sciences at the university. Today the observations are made hourly using a Campbell Scientific AWS (**Figure 1.10**, bottom).

Padova (Padua), Italy – 1725 to date

45.402°N, 11.869°E, 20 m above sea level

Meteorological observations commenced as part of the astronomical observational routine in Padova (Padua) in northern Italy in 1725 [29]. Until 1767, observations were made by the individual observers in their own dwellings within the town, but from 1768 to 1962 the records were kept at the *Specola* complex in the centre of Padua (**Figure 1.11**). Today, the records are maintained at the nearby Botanical Gardens.

The temperature record has been carefully reconstructed, taking account of multiple instruments, calibrations, observers, observing sites and practices, making this the oldest record in southern Europe.

Stockholm, Sweden – 1756 to date

59.342°N, 18.055°E, 38 m above sea level

Weather observations began at the old astronomical observatory in Stockholm in 1754. Complete daily mean series of air temperature and barometric pressure have been reconstructed from the original observational data for the period 1756 to date [30]. In 2006 the observatory completed 250 years of records, the longest unbroken same-site observation series in the world.

The first observer was the secretary of the Royal Swedish Academy of Sciences, the astronomer and statistician Pehr Wilhelm Wargentin (1717–83) [31]. He lived on the second floor in the then newly built observatory, and placed his thermometer outside one of his windows. Wargentin is a well-known figure in Swedish scientific history as the father of Swedish population statistics, and also for his studies of Jupiter's moons. When the observatory was renovated and extended in 1875 the thermometer was moved to a metal cage outside a window on the first floor. The current observation site, dating from 1960, is only about 10 metres away.

Figure 1.10. Weather records have been made in Uppsala, Sweden, since 1722. Top – the instruments in Observatory Park, where measurements were made 1853–1952. Bottom – the current site at Uppsala University Geocentre. (Courtesy of Dr Hans Bergstrom, Uppsala University)

Figure 1.11. The Specola complex in Padua, Italy, where weather observations commenced in 1768. (Photograph courtesy of Professor Dario Camuffo, Institute of Atmospheric Sciences and Climate, Padua)

Since 1901, the highest temperature observed has been 35.4 °C (on 6 August 1975), the lowest –28.2 °C (on 25 January 1942). Less rigorous early records show 36 °C on 3 July 1811 and –32 °C on 20 January 1814.

Milan, Italy – 1763 to date

45.471°N, 9.189°E, 121 m above sea level

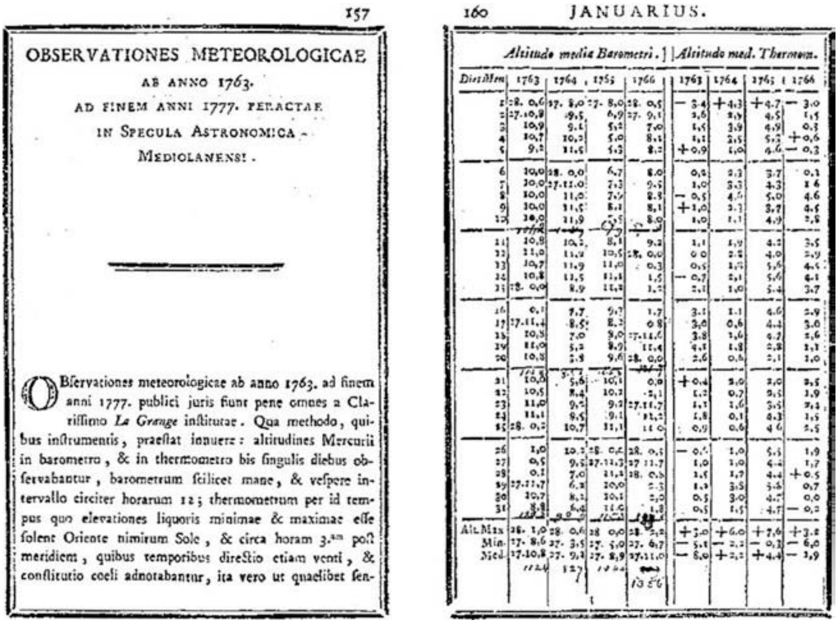
The Astronomical Observatory of Brera (OAB) in Milan was founded in 1762, and daily meteorological observations have been made here since 1763. It is the oldest scientific institution in Milan, and remains one of the top astronomical research institutes in the world today.

Although observations have always been made at the observatory, many changes of instruments, station location and observation methods over the years render the original observations series far from consistent. Fortunately, detailed metadata (records of the instruments and their exposure) were kept. A meticulous research programme conducted at the University of Milan, published in 2002 [32], reexamined all of the original records to produce a complete and homogeneous daily series of maximum, mean, and minimum temperature, and daily mean barometric pressures, covering the period from 1763 to date (**Figure 1.12**).

Prague, Czech Republic – 1775 to date

50.086°N, 14.416°E, 191 m above sea level

Regular meteorological observations commenced in the vast Baroque complex of the former Jesuit College in Prague's Old Town, the Klementinum, in 1752, although there



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OBSERVATIONES METEOROLOGICAE
AB ANNO 1763.
AD FINEM ANNI 1777. PERACTAE
IN SPECULA ASTRONOMICA
MEDIOLANENSI.

OBſervationes meteorologicae ab anno 1763. ad finem anni 1777. publici juris fiunt pene omnes a Clariſſimo *La Grange* inſtitutae. Qua methodo, quibus inſtrumentis, praeſtat innuere: altitudines Mercurii in barometro, & in thermometro bis ſingulis diebus obſervabantur, barometrum ſcilicet mane, & veſpere intervallo circiter horarum 12; thermometrum per id tempus quo elevationes liquoris minimae & maximae eſſe ſolent Oriente nimirum Sole, & circa horam 3.am poſt meridiem, quibus temporibus directio etiam venti, & conſtitutio coeli adnotabantur, ita vero ut quaelibet ſen-

160 JANUARIUS.

Figure 1.12. Barometer and thermometer records from the Brera Observatory in Milan, Italy, for the Januarys of 1763, 1764 and 1765. From Maugeri, M et al (2002) Daily Milan Temperature and Pressure Series (1763–1998): Completing and Homogenising the Data. *Climatic Change*, **53**, pp. 119–149. Reproduced by kind permission of Springer/RightsLink

are breaks in the record until 1775 [33]. Observations continue at the same site today, in much the same surroundings as they were at the end of the 18th century, with observations made at the 'Mannheim hours' of 7 A.M., 7 P.M. and 9 P.M. (see below).

Two thermometer screens are in use, similar to the original 18th century models rather than today's standards – a louvred screen located on the first floor of the north side of the south annex and another on the flat roof of the east annex. Rainfall amounts and sunshine duration are also measured here.

Since 1775, the temperature extremes at the site have been 37.8 °C (on 27 July 1983) and –27.6 °C (on 1 March 1785).

Hohenpeissenberg, Germany – 1781 to date

47.801°N, 11.010°E, 977 m above sea level

Hohenpeissenberg is the oldest mountain observatory in the world, and possesses one of the longest reliable observational records of any location [34, 35]. It is located about 80 km south-west of Munich at an altitude of just under 1000 m (**Figure 1.13**).

Meteorological observations were first made here in 1758/59, but regular and uninterrupted records started on 1 January 1781 as one of the stations in the Societas Meteorologica Palatina observation network, established by the Meteorological Society of the Palatinate with the support and funding of Karl Theodor, Elector of the Palatinate. This was the world's second international climate observation network (Florence's Medici Network in 1654–70 was the first): it consisted of 39 stations extending from eastern America to the Ural Mountains, and from Greenland to the Mediterranean. The Societas Meteorologica Palatina established standardized

Figure 1.13. (Top) Hohenpeissenberg observatory in southern Germany: meteorological observations have been made here without significant interruption since January 1781. (Bottom) the current meteorological instrument site at the Observatory. (Photographs courtesy of Dr Stefan Gilge, Deutscher Wetterdienst)

instruments, observing procedures and observation times (the so-called Mannheim hours of 7 A.M., 2 P.M. and 9 P.M.) for the first time. (Observations made at the Mannheim hours are still used for today's climatological records at Hohenpeissenberg.) Augustinian monks from the nearby Rottenbuch monastery made the observations; Hoher Peissenberg was a place of pilgrimage and a subsidiary convent.

The Palatinate came under occupation in 1792, during the Austrian-French war. This brought an end to the Societas Meteorologica Palatina, although fortunately the Augustinian Canons decided to continue the meteorological observations. Following secularization in 1803, the Bavarian Academy of Sciences assumed responsibility for the station and appointed the parish priest of Hohenpeissenberg as the responsible observer. In 1838, the observatory came under the responsibility of the Royal Observatory of Munich, and in 1878 part of the Bavarian State Weather Service. In 1934, the Meteorological Service of the Third Reich assumed responsibility for the site, which was expanded into a main weather observation location in late 1937, commencing synoptic observations. In 1940, the station was relocated a short distance from the existing monastery buildings into newly built premises on the western side of the mountain. In the closing days of the Second World War, southern Bavaria came under attack from the Allied armies. Observations at Hohenpeissenberg were interrupted by artillery fire on 28 April 1945, and had to cease altogether on 2 May because of the danger to the observers, but were restarted on 14 May. On 1 April 1946, the station was incorporated into the network of the newly founded West German state weather service, the Deutscher Wetterdienst (DWD), and in March 1950 the site was formally upgraded to that of a meteorological observatory.

The range of instrumentation and observing routines has expanded considerably since. Records of atmospheric ozone commenced in 1967, a weather radar was installed in 1968, later upgraded to Doppler capabilities, and observations of trace atmospheric gases commenced. In 1994, the observatory became a part of WMO's Global Atmosphere Watch (GAW) programme.

The annual mean air temperature at the observatory over the period 1781–2000 was 6.3 °C. Since records of maximum and minimum air temperature commenced in 1879, the highest temperature observed has been 33.8 °C (on 29 July 1947) and the lowest –29.1 °C (on 11 February 1929).

Armagh Observatory, Northern Ireland – 1794 to date

54.353°N, 6.648°W, 64 m above sea level

The astronomical observatory at Armagh, built in 1790, is the oldest scientific institution in Northern Ireland. Intermittent observations of the weather have been made on this site since 1784, prior to the building of the observatory: more systematic daily observations of temperature and barometric pressure commenced in December 1794. Although there are some gaps in the early years, and numerous changes of instrument and site around the observatory, the records are largely complete from 1833 to the present day. They represent the longest series of continuous weather records in Ireland. All of the records, including scanned copies of the original manuscript records, are available on the observatory website (http://climate.arm.ac.uk/main.html).

The site lies approximately 1 km north-east of the centre of the ancient city of Armagh, at the top of a small drumlin (hill) in an estate of natural woodland and parkland of some 7 ha. The observatory is still largely surrounded by countryside similar to that which has existed since its foundation. The population of Armagh has increased relatively little in 200 years (1991: 14,625) and so the observatory suffers from little or no urban micro-climatic effects [36].

The third director of the observatory, Thomas Romney Robinson, appointed in 1832, made many experiments in other fields of science. One of his most enduring

Figure 1.14. The Radcliffe Meteorological Station, Oxford, England. Meteorological observations have been made here since 1767; unbroken monthly temperature and rainfall records exist back to 1815. (Photograph by the author)

interests was the study of meteorology and in particular the measurement of wind speed. He invented the cup-anemometer (see Chapter 9), a device that is still widely used throughout the world.

The Radcliffe Meteorological Station, Oxford, England – 1815 to date

51.761°N, 1.264°W, 63 m above sea level

The University of Oxford is the oldest university in the English-speaking world, founded in 1249: the Radcliffe Observatory was established as part of the university in 1772. The observatory site, situated in the walled garden of Green-Templeton College in Woodstock Road adjacent to the old observatory building, possesses the longest same-site series of temperature and rainfall records in Britain (**Figure 1.14**). Irregular observations of rainfall, cloud and air temperature exist from 1767; temperature and rainfall records are unbroken from January 1815.

Dr Thomas Hornsby, then Savilian Professor of Astronomy at the university, approached the Radcliffe Trustees[*] with a request for funds for the erection and equipping of an astronomical observatory in 1768. Building began in 1772, although it was not completed until 1794. The central feature of the building is the octagonal tower, 33 metres high, an adaptation of the Tower of the Winds at Athens.

Initially, observations of air temperature (from thermometers mounted on the north wall of the observatory) were made three times daily to determine astronomical refraction. From 1849, meteorological observations were being made in their

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[*] John Radcliffe (1652–1714) was a British physician who bequeathed property to various charitable causes, including St Bartholomew's Hospital in London and University College, Oxford. A number of landmark buildings in Oxford, including the Radcliffe Camera, the Radcliffe Infirmary (now the John Radcliffe Hospital) and the Radcliffe Observatory, were named after him.

own right; thermometers were exposed in a thermometer screen at ground level on the north lawn within the observatory's walled garden [37].

Air temperatures, rainfall and sunshine records are measured today at the same place, and in very much the same way, as they have been since 1881, although an automatic weather station was installed in May 1994 to provide a continuous record of air temperature, relative humidity, wind speed and direction, solar irradiance and rainfall. Since July 1935 the station has been known as 'The Radcliffe Meteorological Station, Oxford'. In 1978 the site became part of what is today Green-Templeton College, with the university's School of Geography and the Environment responsible for the daily observations. A university decree guarantees the continuation of the observations 'as long as they are deemed to be of scientific value' [38].

Since daily maximum and minimum temperatures were first recorded in 1881, the extremes at the Radcliffe Meteorological Station, Oxford, have been 35.6 °C on 10 August 2003 and −16.6 °C on 14 January 1982.

The oldest weather records in North America

The earliest known instrumental weather record within today's United States was that made by Dr Cadwallader Colden, then of Philadelphia, who employed a combined thermometer-barometer in the winter of 1717–18. The instrument was apparently brought to New England – then still a British colony, of course – by Colden when he returned from England in late 1715 or early 1716. Colden had studied medicine in London and science in Edinburgh before first coming to America in 1710 [39]. The earliest record on the National Climate Data Center (NCDC) database is that for Nottingham in Prince George's County, Maryland, with records from August 1753 to December 1757; Morrisville in Pennsylvania has records from January 1790 to December 1859.

It was not until after the surgeon general of the United States issued an order in 1818 for each Army post surgeon to "keep a diary of the weather . . . noting everything of importance relating to the medical topography of his station" that any form of systematic observations began to be made in America. The Smithsonian Institution ran its own network of weather reporting sites between 1849 and 1874. Many additional weather observing sites were established at or shortly after the foundation of the U.S. Weather Bureau in 1870, but it was not until the adoption of a uniform plan of observations in 1895 and the printing of monthly climate reports which began in 1896 that standardization across the different networks was finally secured.

Probably the longest continuous current records for any U.S. city are those for Chapel Hill in North Carolina and for Minneapolis, Minnesota, both of which extend back to 1820. In Minneapolis, records commenced at Fort Snelling in 1820 [40] and continue today at Minneapolis-St Paul International Airport (since 1938). There are many hundreds of records extending back to 1872 or earlier (although many have moved from one site to another within the city/town within the period of record), including those for San Francisco (1850 for precipitation and 1870 for temperature) and Des Moines, Iowa (1865). The record for Central Park, New York, extends back to 1868, while the longest single-site record in the United States is that of the Blue Hill Observatory in Massachusetts.

Central Park, New York – 1869 to date

40.779°N, 73.969°W, 40 m above sea level

The longest records made on almost the same site are those for Central Park in New York, where Dr Daniel Draper began keeping records in December 1868. Originally observations were made at the Arsenal Building on 5th Avenue (between 63rd and 64th Streets), but since January 1920 they have been made at Belvedere Castle, Transverse Road (near 79th and 81st Streets) [41]. The distance between the two sites is just less than 1500 metres (0.9 miles), although the record is generally regarded as being fairly homogeneous. The equipment has been automated since the late 1980s.

Blue Hill Meteorological Observatory, Massachusetts – 1885 to date

42.212°N, 71.114°W, 193 m above sea level

The Blue Hill Meteorological Observatory is located at the top of a scenic range of hills 15 km (10 miles) south-south-west of Boston, Massachusetts (**Figure 1.15**), and describes itself as the 'home of the longest climate record in the nation' [42]. The observatory was founded in 1885 by Abbott Lawrence Rotch as a private scientific

Figure 1.15. The Blue Hill Meteorological Observatory, Massachusetts. Observations commenced here on 1 February 1885 and continue to this day. (Photograph by Mike Iacono, Blue Hill Observatory)

centre for the study and measurement of the atmosphere, and was the site of many pioneering weather experiments and discoveries: the earliest kite soundings of the atmosphere in North America (1890s) and the development of the radiosonde (1930s) both took place here. The first weather observations were made here on 1 February 1885. They have remained unbroken, and on the same plot, ever since, the most homogeneous climate record in North America.

Construction of the observatory was started by Rotch in 1884 using his own private funds [43]. The original structure consisted of a two-storey circular tower and an adjoining housing unit; extensions were added in 1889 and 1902. Native stone, gathered from the summit of the Great Blue Hill, was used for the buildings, while copper sheathing was used for roofing. The original stone tower was demolished in 1908 and a new reinforced three-storey late Gothic Revival concrete tower, 6 m wide and 10 m high and with a crenellated top, was constructed in its place. The site was declared a National Historic Landmark in 1989.

The observatory retains barometers and other instrumentation dating from the late 19th century – these instruments remain in use to calibrate modern instrumentation, preserving the accuracy and integrity of the long record period. Blue Hill is also unique in North America in possessing a long sunshine record made with the Campbell-Stokes sunshine recorder (see Chapter 11). The National Weather Service also operates automated remote-reading equipment at the site.

Since records commenced in February 1885, the highest recorded temperature has been 38.3 °C (101 °F) on 10 August 1949 and 2 August 1975, and the lowest –29.4 °C (–21 °F) on 9 February 1934. During the Great New England Hurricane of 1938, the observatory recorded one of the highest wind gusts yet recorded by surface instruments anywhere in the world – 186 mph (83 m/s, 162 knots).

Subiaco Abbey, Logan County, Arkansas – 1897 to date

35.303°N, 93.637°W, 152 m above sea level

Subiaco Abbey is a Benedictine monastery located in Logan County, Arkansas. The abbey – which is named after the original Subiaco Abbey in Italy – and its associated academy are major features of the town of Subiaco, Arkansas. Benedictine monks at the abbey began making weather observations there in September 1897, and the abbey now possesses one of the longest unbroken climatological records in the United States. In 2009 one of the observers at Subiaco Abbey was awarded the National Weather Service Thomas Jefferson Award (see page 388) for 45 years of unbroken high-quality observations [44].

Times of change . . .

The way we measure weather is changing rapidly. As with any change, both opportunities and threats present themselves. The last generation of meteorological observers brought up on mercury-in-glass thermometers and clock-driven autographic instruments with paper charts is already approaching retirement. (Alas, the thrill of experiencing first-hand the inky beauty of a well-maintained Dines pressure-tube anemograph ‘in full cry during a gale’, as so poetically described by Gordon Manley in his classic *Climate and the British Scene* [45], has gone forever . . .[*]) New sensors and measurement methods have evolved and are still evolving, some completely novel, and all offering improved ease of use, accuracy and cost-efficiency – although not always longevity – when compared with 'traditional' methods. So should we not just quickly move to these new methods as soon as they become available, ditching the old methods? Not necessarily, and for good reason . . .

Traditional methods of measuring the weather have evolved to their present form in brutal Darwinian fashion over many years. The mercury thermometer and the mercury barometer have both been refined in constant use over the course of almost 400 years, but the first AWS appeared barely one-tenth of that lifetime ago. Many traditional instruments still have their place, at least until we have a good overlap period using both 'old and new' methods of measurement, to avoid destroying the homogeneity of the few genuinely long-period weather records we possess. Reliable and consistent long-period records are essential to provide an accurate assessment of the 'global warming' trend that has become a major political and scientific topic since the late 1980s. A record of 25 years is useful; one of 250 years many times more so. Only consistent long records can help answer questions such as 'How is our climate changing?' and 'Are extremes of climate becoming more frequent?'

Why are instrumental and observing standards necessary?

Standards are needed in order to be able to compare observations between sites. Only by minimizing or eliminating measurement differences owing to varying exposures, instrumentation or observing methods can your own observations be directly comparable with those from the next village, or the next continent.

So-called traditional methods of measuring weather elements have evolved in Europe and North America during the last 100 to 150 years by careful intercomparisons between instruments, exposures and observation methods to determine which provided the best combinations of ease of use, cost, accuracy and suitability for the climatic regime. Sweeping away overnight the groundwork of previous generations of meteorologists who established sound reasons for standardizing measurements the way they are made today would be foolish in the extreme, until and unless we have something that we can clearly show to be an improvement and can quantify any differences between the two methods.

Such comparisons have already taken place for several weather elements. Barometric (air) pressure is today measured by solid-state pressure sensors, for example, and only rarely using mercury barometers, because comparative trials established that modern pressure sensors can provide data to the same or better levels of accuracy more cheaply, easily and without requiring a human observer (see Chapter 7). More problematic has been the replacement of other sensors, particularly sunshine (Chapter 11), where new electronic sensors sometimes give very different results from traditional instruments. Ill-thought-out replacement schemes have irreparably damaged the climatological continuity of many long sunshine records.

As a result of the need to maintain some form of practical standardization for purposes of comparison with other observations, each of Chapters 5–11 in this book,

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[*] Although, as one reviewer commented upon an early draft of this chapter, '. . . it surely compares with the thrill of first seeing real-time weather data on my PC, or even better on a web page when I'm half a world away . . .'

describing how to measure a particular element of the weather, starts with a short description of the currently accepted standard method or methods of making observations of that element, based upon the World Meteorological Organization rulebook [2]. The instruments, siting and observing practices involved in doing so are described, followed by methods of siting AWS sensors and adopting measurement and observing methods to obtain as nearly as possible 'standard' results. For most elements, 'perfect' sites are hard to come by, and where necessary compromises in exposure or instrumentation may be required. Some compromises are permissible where effects on the readings obtained will be relatively small, and where these are known allowances can often be made. Other compromises will render the records made largely meaningless, and they should therefore be avoided. Each chapter attempts to outline the permissible and the impossible in this regard.

This approach will benefit both first-time purchasers of such systems, who may have little or no prior knowledge of where, why or how to site their instruments to provide observations that can become genuinely useful beyond purely local record-keeping, as well as those looking to expand existing weather measurements. Those looking to establish a new professional weather monitoring site from scratch will also find useful guidance on current best practices.

The future

It is highly likely that many, if not most, of today's standard methods of measuring weather will change over the next decade or two, as improved technology and lower-cost measurement methods continue to be introduced. We have already begun to see the introduction of 'fresh start' weather measuring sites, equipped from the outset with modern electronic instruments, on good sites that offer both excellent exposures and a reasonable expectation of record continuity for decades or even centuries to come [46, 47]. Careful consideration today in choice and exposure of sensors, loggers and data archiving – all subjects covered in more detail in this book – will go a long way towards both 'future-proofing' and maximizing the practical benefits of a well-sited AWS.

The first step is to list your specific requirements for 'measuring the weather', then decide the best balance of budget and equipment to meet those requirements. How best to do this is set out in the following chapter.

Further Reading

Knowles Middleton's three excellent and very readable books on the history of meteorological instruments cover the entire spectrum of invention from the wildly impractical to the brilliantly simple:

Middleton, WEK
Invention of the meteorological instruments (1969)
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Ian Strangeways' *Measuring the natural environment* (Cambridge University Press, Second Edition, 2003) provides an excellent and readable account of most meteorological instruments, both 'traditional' and digital types, and very usefully picks up roughly where Middleton leaves off.

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2 Choosing a weather station

There are many different varieties of automatic weather stations (AWSs) available, and a huge range of different applications for them. To ensure any specific system satisfies any particular requirement, it is essential to consider carefully, in advance of purchase, what it needs to accomplish, and then to prioritize the features and benefits of suitable systems to choose the best solution from those available. The choices can be complex and a number of important factors may not be immediately obvious to the first-time purchaser. Deciding a few months down the line that the unit purchased is unsuitable and difficult to use (or simply does not do what you want it to) is likely to prove an expensive mistake, as very few entry-level and budget systems can be upgraded or expanded.

This chapter suggests a structured way to do this:

- Decide what the primary use of the system will be;
- Review relevant decision-making factors as outlined in this chapter, and prioritize accordingly;
- Balance requirements against budget, identify potential suppliers and models, and purchase the most appropriate system.

Armed with a list of key requirements from this chapter, Chapter 3 provides a short guide to AWS products and services available in both North America and Europe.

Throughout this and the next chapter, the following loose definition of AWS systems by budget level are suggested (see **Table 2.1**). Most systems fit comfortably within one of these price/performance bands: note that prices quoted are indicative only (at 2012 levels) and exclude local sales taxes, value added tax, delivery costs and optional sensors or fittings. Brand names in brackets are rebadged equivalents from the manufacturer or supplier shown.

Note, however, that an AWS doesn't have to be the first rung on the weather measurement ladder. Short of funds? Not sure whether you'll keep the records going and don't want to spend a lot until you have given it a few months? Not sure where to start? See Box, *Limited budget? Sheltered site?* on page 38.

Important note

Throughout this book, suggestions and recommendations are completely independent of manufacturer or supplier influence. No sponsorship, incentives or special treatment were requested or offered by any of the companies whose products are referred to in this book.

If you use this book to help choose an automatic weather station or other weather-related equipment, please mention this to your reseller or dealer when you make your purchase.

Step 1: What will the system be used for?

All AWSs maintain a digital record of one or more weather elements (air temperature, rainfall, sunshine, wind speed, and so on). Being clear from the outset what the essential system requirements are, and whether they can be expected to change over time, will quickly help narrow the search for suitable products.

Many first-time purchasers rush into buying the first system that appears to satisfy their immediate requirements (and the available budget) without adequately considering future needs, only to regret the decision some weeks or months later when limited functionality, expandability or build quality results in frustration. It is better, of course, to be sure of what is needed – and what is not – at the outset to avoid subsequent disappointment. Writing off the initial system after only a short time to buy a more capable system will clearly be more expensive (in both financial terms and installation time) than if the desired system characteristics had been clearly identified beforehand.

It is also important to regard money spent on the chosen system as a medium- to long-term investment. With careful consideration given to the robustness and longevity of system components and supplier reputation, with appropriate maintenance (and occasional sensor replacements) a lifetime of 10 or even 20 years is not unreasonable. Take this into account when making your decisions.

Table 2.1. *Categories and main brands of automatic weather stations. Prices are very approximate, in U.S. dollars, at 2012 levels, and* exclude *local sales taxes and shipping costs.*

	Entry-level single-element	Entry-level AWS	Budget AWS	Mid-range AWS	Advanced and professional systems
Typical price range	$100 or less	$200 or less	$200 to about $500	About $500 to $1,500	$1,500 upwards
Typical brands	TechnoLine Oregon Scientific	Fine Offset (Watson, Maplins) TechnoLine La Crosse Oregon Scientific	Oregon Scientific Davis Instruments Irox Ventus ***Specialist products*** Nielsen Kellerman/Kestrel Gemini/Tinytag	Davis Instruments	Campbell Scientific Davis Instruments Environmental Measurements Met One Instruments Vaisala

Typical uses for AWSs

AWSs are used for many different purposes; some of the main reasons for using them are given below. These are not mutually exclusive – requirements for any particular application may include several of the points below – and neither is it an exhaustive list.

- Home/hobby weather interest – either starting from scratch, or to expand an existing set of manual instruments
- Remote weather monitoring with distant-reading or website display facilities
- Absence and backup cover – unattended and/or more frequent observational records
- Statutory requirement to maintain records of certain weather elements
- Replacement of human observer/s to reduce costs
- Augmentation or automation of existing weather monitoring equipment
- Long-term climatological monitoring to ‘official standards’*
- Replacement of paper-based autographic recording instruments
- Significant weather event logging

Consider which of these are most relevant to your requirements, and then review the decision criteria in Step 2 below. The relative priority of each factor will differ for each requirement, and of course you may wish to add others of your own.

Advantages of AWSs

Most modern AWSs will measure and log a number of weather elements reasonably well with minimum user intervention. Even low-budget entry-level systems can provide worthwhile results, provided care and attention is paid to siting the instruments. All such systems provide a number of clear advantages, as follows.

Cost-effective deployment

The huge decrease in cost and improvements in accuracy in AWSs during the last 20 years means that such systems can be relied upon to provide both more frequent observations and better spatial coverage.

These advantages are combined when AWS are located in remote or inaccessible locations (such as hilltops or mountain sites) where making manned observations is impractical or impossible owing to distance from settlements, difficulty of access or frequent severe weather conditions. Similar advantages also apply to suburban gardens or backyards: the reduced cost and reasonable accuracy of most modern systems not only enables many more interested individuals to take part in the fascinating and ever-changing study that is observing and measuring the weather, but for those systems to form networks enabling us to map the distribution of (for example) urban climates or severe storms in unprecedented detail and, increasingly, in real time. There is more on this aspect in Chapter 19, *Sharing your observations*.

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* If the intention is to establish an official-standard site providing data to a state weather service network, the views of the relevant network authority should be sought prior to purchasing equipment or establishing the site.

Lower resource costs

The lower costs of AWSs, and their ability to run for long periods with little or no human intervention, also means that a valuable observation record can be obtained from sites where the cost of human observers would otherwise rule this out.

There are many civil and military airfields, for example, where automated weather observation systems run by the state weather service or the airport itself provide 24x7 instrument-based weather observations, even though the site may not be manned during weekends and on public holidays. Although automatic systems cannot (yet!) provide the full range of observations possible with a human observer, the presence of such systems does enable many of these sites to offer a complete (365 days per year) climatological record of at least the major elements. The same is true for amateur meteorologists and for school sites, where the deployment of an AWS can eliminate gaps in cover caused by vacation periods during the year, removing perhaps the largest single obstacle to maintaining an unbroken annual observational record.

Improved sensors

The development of modern systems has led to a vast expansion in the range, accuracy and sensitivity of sensors. Many of these are completely novel, being based upon very different physical measurement characteristics than the instruments they replace.

One example is the development of electronic sensors to measure sunshine, outmoding the traditional Campbell-Stokes recorder which has already been referred to (see also Chapter 11). Modern sunshine sensors are small, light and need little or no regular maintenance, so they can be more easily exposed on masts and on roofs where access and safety considerations may rule out the once-daily human access required to change the sunshine card on the iconic but bulky Campbell-Stokes instrument.

Objective digital data

The provision of objective, accurate and computer-ready digital data is a major advantage of AWSs, and of course observations are available as frequently as required. Manual observations can suffer from conscious or unconscious bias; some people subconsciously avoid certain decimal places when reading thermometers, for example, whilst some instruments show considerable 'interpretation' variations between observers.

A notorious example of the latter is the measurement and tabulation of sunshine cards from the Campbell-Stokes sunshine recorder, where the variation between human analysts can amount to 10 or 15 per cent, particularly on days of broken sunshine. With such variability, it can be difficult to be sure whether observed differences in sunshine duration between sites or over varying time periods are due to genuine climatic effects or simply observer/analysis variations. The introduction of new electronic sunshine sensors, whilst providing a clearly different determination of sunshine from 'traditional' instruments, offers objective, consistent and repeatable measurements between sites (more in Chapter 11, *Measuring sunshine and solar radiation*).

The sheer torrent of data that can result from AWSs can present problems of its own, of course: Chapter 17 *Collecting and storing data* offers suggestions and methods to optimize, analyze and archive the 'data avalanche' to ensure maximum benefit from the information generated. The investment of a little forethought in a data management strategy enables useful long-term climatological databases to be built quickly with little or no additional effort.

'As good or better' record quality

All of the above would be for nothing if the observational output from such systems were inferior to measurements made using 'conventional' or 'traditional' instruments and methods, and here the quality of record varies significantly by weather element. Some modern sensors, such as the new sunshine detectors, offer an improved (more objective and repeatable) record than traditional instruments and are already replacing traditional instruments in the field. For other elements, observing standards are still tied to those traditional instrument benchmarks and methods, although as outlined previously it seems likely that the next decade or two will see more of these replaced as the 'standard' by AWS observation/logging methods. However, careful long-term planning is needed to minimize the impact on existing long-period records when major changes of instruments take place, such as replacing manual observations with automated data capture.

Disadvantages of AWSs

AWSs clearly offer many advantages, but intending or current users should bear in mind two major disadvantages, both of which involve the potential for significant and irretrievable data loss.

Data loss owing to system failures

In the case of conventional instruments, damaging or breaking one instrument will not lead to loss of the entire record; for instance, accidentally breaking a thermometer may lead to the loss of a couple of weeks of record until a replacement can be obtained (best to keep a spare on hand to minimize this risk, of course), but it will not affect the readings of the other thermometers, or the raingauge, for example. With AWSs, however, a fault in a critical component, particularly the datalogger, may lead to total data loss – not just for the period of the fault, or a single element, but possibly the entire record stored in the system memory. Sometimes the very occasions when the records are most useful – during an exceptional cold spell, or in a violent thunderstorm, for example – are when the systems and the sensors are operating at or beyond their design specifications, and are more likely to fail.

Such problems can also arise from the most mundane of causes. The author's experience to date has included the failure of internal batteries, electrical shorting caused by moles nibbling cable insulation, close lightning strikes and numerous other similarly unpredictable events. For remote or unattended sites, even a 'back garden' weather station during a short period away from home, this can be a serious drawback as often the loss may not be obvious until the next data download – by which time it is too late, of course. A frequent (at least daily) download interval, wherever possible, should quickly highlight any actual or imminent problems and thereby minimize any loss of record.

Data loss owing to sensor failure

Electronic systems involve physical components that still require checking and maintenance. Sensor failures on a well-specified system which has been carefully installed and regularly maintained should be infrequent, but obviously any permanent sensor failures will result in data loss. Regular sensor replacement has been reported as necessary on some low-build-quality entry-level and budget systems. Particular attention needs to be paid to exterior connections on cabled systems to avoid ongoing data loss problems, which can be very difficult to trace, particularly where damaged or erratic connections may affect more than one sensor. A sensible precaution is to keep a small stock of key spare parts and sensor/s – this will eliminate record loss whilst waiting for replacement parts to arrive, for example, and will also extend the system life should a critical component fail after the manufacturer has discontinued the model. It is also a good idea to keep older equipment in place where it is feasible to do so – perhaps manual instruments that the AWS has replaced – as a backup in case of system failure.

More typical and insidious temporary failures include the blockage of the tipping-bucket raingauge funnel, often from bird droppings, or the jamming of the tipping-bucket mechanism by insects. Either can cause inaccurate or missing rainfall data for days or weeks, depending upon download and maintenance intervals. Best practice is to specify and log two tipping-bucket raingauges alongside a standard manual raingauge (more in Chapter 6, *Measuring precipitation*). The chance of both being blocked simultaneously is very slight – except during snowfalls – and the value closest to the manual raingauge total is more likely to be correct.

Step 2: Decision factors for AWSs

The extent to which any specific requirement is met will depend on a number of factors, the most common of which are listed below. Each of these factors is briefly outlined within the following sections.

As each system will have its own requirements, they are not arranged in any particular priority order. Which are most important to you?

- How good is the exposure where the instruments will be located?
- How many weather elements are to be measured using the system?
- Will all the sensors be exposed in one place, or will they be sited separately?
- Is there a requirement for backup system/s and conventional instruments?
- Does the system need to be capable of being expanded over time?
- What sensors are required – ‘standard’ (built-in) or specialist sensors?
- Will it be cabled or wireless?
- Will it be PC-based or have a separate logger?
- What degree of automation is sought?
- What degree of accuracy and precision is sought?
- How often is the information updated?
- How robust does the system need to be? What is its desired or expected lifetime?
- Is the system ‘mission-critical’?
- Is climatological continuity/compatibility/parallel running to ‘official standards’ a requirement?

- How important is ease of setup?
- What computing facilities and expertise are available?
- Will the system be mains-powered or solar-powered?

Finally, of course, there is the question of budget. Although this may well be the deciding factor, to avoid the risk of potentially frustrating and expensive under-specification it is better to consider each of the decision factors in turn before making the final budget decision. More detail on the capabilities that can be expected from different budget ranges is given in the following chapter.

How good is the exposure where the AWS will be located?

Careful consideration should also be given to the suitability of site where the measurements will be made. It is pointless spending hundreds or even thousands of dollars on a sophisticated and flexible AWS if the location where it will be used is poorly exposed to the weather it is attempting to measure.

In general a budget AWS exposed in a good location will give more representative results than a poorly exposed top-of-the-range system. Worthwhile observations *can* be made with budget instruments in limited exposures, but a very sheltered site may not justify a significant investment in precision instruments, as the site characteristics may limit the accuracy and representativeness of the readings obtained. More information on siting instruments is given in subsequent chapters.

Limited budget? Sheltered site?

Measuring the weather does not involve a minimum spend of thousands of dollars on instruments, and neither does it require a plot the size of a small airport to expose them properly. Observations made with robust, accurate and well-exposed weather instruments are of course an ideal to aim for, but if funds are short and a perfect spot in which to deploy them is simply not available, the records obtained can still be useful and interesting to make.

Most amateur meteorologists started out with one or two simple instruments (usually measuring air temperature and/or rainfall) and added more over time as budget and space allowed. Many started making their own weather records at school, sometimes influenced by a school ‘weather club’ or a memorable weather event – a heavy thunderstorm, a gale or a severe winter, perhaps. (The author started making his own observations at the age of 12, with a home-made raingauge, a Six’s thermometer and a unique design of thermometer screen made in school woodwork classes.) Moving from an apartment with a balcony to a house with a garden, perhaps eventually to one with a larger or less sheltered garden, often permits an improved exposure over time. The records made may not be fully comparable throughout, but they will be your own and they quickly build up as the years roll by.

There are numerous instruments available at lower price points than AWSs. These days, electronic temperature sensors, widely available for just a few dollars, will give passably accurate results when shielded from sunshine and precipitation, and making a raingauge is no more difficult than it was 40 years ago. Wind vanes are not expensive (and with a little mechanical ability are easy enough to make).

Logging wind speed is a little more complicated and thus expensive, so leave that until funds permit and estimate wind speed using the Beaufort scale or use an inexpensive handheld anemometer for now. It costs nothing to observe and record clouds. The important thing is to give measuring the weather a try and start keeping your own records.

How many weather elements are to be measured using the system?

Entry-level systems will typically include sensors for air temperature, perhaps humidity too, barometric pressure, rainfall, and occasionally wind speed and direction. More advanced systems tend to offer both higher-quality sensors (improved accuracy, build quality and robustness) and an expanded set of sensors. Typically these might include additional temperature sensors for grass and earth temperatures, a solar radiation or sunshine sensor or a higher-quality radiation shield for measuring air temperatures (see Chapter 5), but at a higher price. Advanced systems permit a fully customized system to be built with a wide range of additional sensors, to measure almost anything from cloud base height to snow depth.

A comprehensive weather monitoring system will include sensors for air, grass and earth temperatures, barometric pressure, rainfall, relative humidity (from which dew point can be derived), wind speed and direction, sunshine duration and solar radiation intensity. For any particular budget, a choice has to be made between the number of sensors and their quality, accuracy and robustness. Depending upon requirements and budget, it may be better to specify a few, high-quality sensors covering the key elements, at least to start with, rather than a wider range of cheaper sensors that may be of limited accuracy or poor build quality.

Will all the sensors be exposed in one place, or will they be sited separately?

For best results, the various sensors need to be sited separately – anemometers and sunshine recorders are best exposed well above ground level, while most national guidelines involve the raingauge being mounted at or close to ground level, for example. Take into account whether the various sensors can be separated in this way when choosing your system.

Many entry-level and budget systems include all or most of the sensors in one integrated instrument package, inevitably forcing compromises on instrument exposure. There are situations where a single integrated unit may be preferable or easier to install, of course, and where the sensor accuracy is ‘good enough’, in which case this design of system may be perfectly matched to the requirements placed upon it.

Is there a requirement for backup system/s and conventional instruments?

Although this book focuses on the increasing capability and use of automated electronic weather-logging systems, there are two areas where conventional instruments are likely to retain their place for some time to come. These are so-called ‘standard measurements’ and others that could be termed ‘backup measurements’.

For many weather elements, today’s current ‘standard measurement’ is still most often defined in terms of ‘conventional instruments’ (more details are given in the chapters following, by element). If it is a requirement to provide truly standards-based or standards-traceable measurements, then for most elements conventional instruments **must** be deployed alongside the AWS system to provide these, even if the conventional instruments are read only occasionally (for example, at a weekly 'maintenance visit' observation) and used only to provide record continuity and backup, calibration checking or to identify any gross errors. This is particularly so for rainfall; tipping-bucket raingauges (TBRs) are poor at providing climatologically accurate rainfall totals, and a co-located standard raingauge (see Chapter 6, *Measuring precipitation*) is essential where accurate data are required.

IS THERE A NEED FOR A BACKUP SYSTEM? The risk of total data loss from AWSs arising from the failure of a vital component or interruption of power supply is small, but when it does happen the risk of losing the lot is considerable. Where high data availability is required some form of 'backup' measurement system should be deployed alongside the AWS. Today, conventional instruments can usefully combine this role alongside that of providing 'standard system' calibration and error checks. A standard raingauge should *always* be deployed as a 'checkgauge' alongside an AWS, even at remote sites where the gauge may be read only occasionally. Period accumulations should be compared with the total from the same period derived from the TBR and any significant (> 5 per cent) discrepancies identified. Where the period rainfall accumulation is known, a total failure of the TBR will not result in a break in the climatological record, although obviously daily or sub-daily records may not be available for some or all of the period of defective record.

How reliable is 'reliable'?

Although modern systems are highly reliable when correctly installed, no system, datalogger or sensor is ever 100 per cent reliable. An availability of 99 per cent sounds impressive, but in reality this corresponds to around 88 hours per year (or nearly 4 days) 'missing or defective record'. If the periods of missing record were randomly distributed, this would be enough to spoil but not to ruin a year's records: but if the breaks were not randomly distributed, for example records were lost every time heavy rain fell or when the temperature fell below a certain level, then this would introduce a statistical bias into the remaining records, which would invalidate any climatological analyses based on that station's data.

A realistic availability target is 99.9 per cent or better, or 9 hours or less 'missing or defective record' in a year. To attain or exceed this, a backup system, perhaps a smaller or lesser-specified system or one based on conventional instruments, should be considered to 'shadow' the main system and to provide records in the periods when the main system is out of order or undergoing maintenance or calibration. The second system should be completely independent from the main system and ideally should not share sensors, logger, cable runs or power supplies so that the failure of one component will not degrade or bring down both systems. Any periods of missing or defective record from the main system should then be backfilled using the shadowed record. Periods of substitution should be indicated in the station metadata (see Chapter 16, *Metadata – what is it, and why is it important?*).

BATTERY BACKUP An essential requirement for all systems is the ability to operate all vital components (specifically the datalogger and sensors, not necessarily the data display) on battery power in the event of interruption to the primary power supply – whether from the mains or renewable sources. Battery backup must provide for at least 24 hours operation without needing to be recharged or replaced, and for remote or unattended sites perhaps a week or more – it may not be feasible to reach a hilltop or remote upland site for several days after a heavy snowstorm, for example. Even professional users are occasionally caught out – during south-east England's 'Great Storm' of October 1987, for example, many wind recording instruments located in south-east England failed to record the peak storm wind speeds owing to the widespread failure of mains power resulting from the storm itself. The good news is that the power consumption of modern electronic systems is so small that most entry-level and budget AWSs can be kept running for up to 24 hours with a small 9 v battery. Ensure, therefore, that battery backup is included in the manufacturer's specifications – and replace the backup battery/batteries at least every 12 months even if they have not been used in that period.

More sophisticated systems are likely to be battery-powered in any case, with a mains- or renewable-powered recharging system used for regular battery top-ups. It does, however, pay to monitor battery condition regularly (the datalogger itself can usually do this), and replace it before it dies. Battery failures can be sudden and unpredictable. Sealed lead-acid batteries have a lifetime of 2–3 years with a daily recharge cycle, for example, and should be replaced at the first signs of reduced charge capacity as this may be an indicator of imminent failure. Most systems also include a small button-cell lithium battery, to retain memory for short periods when the main battery is disconnected; they also need to be checked regularly and replaced as soon as they begin to run down. Keep a spare handy.

Does the system need to be capable of being expanded over time?

To get the best out of any AWS investment, think carefully before purchase about how the system may need to change or grow within the next 5–10 years. The initial requirement may be simply to log air temperature and rainfall once per hour, for example: most budget systems will provide basic capabilities of this nature with ease, and low-frequency monitoring of this type may meet many needs perfectly satisfactorily. It is important to be aware, however, that most budget AWSs come with a fixed range of sensors which cannot be added to, nor in most cases can the sensors themselves be replaced with alternative devices. If, some time after installation, the initial specification expands to add more elements to those measured, or the replacement of an existing sensor with an improved one is required (for instance, a more accurate temperature sensor), it may be impossible to upgrade the system.

Under such circumstances, it may be necessary to replace the system completely. Not only is this expensive, but the de-installation of the original system and re-installation of the higher-specification system may require considerable additional investment in time and resources.

For first-time AWS purchasers or those with very sheltered sites, a basic system to help decide what to measure, or to assess the site's suitability for weather measurements, may represent a sound investment, and future expansion may not be a prime consideration.

What sensors are required – 'standard' (built-in) or specialist sensors?

For most entry-level, budget and mid-range AWSs, the choice and selection of sensors is dictated by the manufacturer and little or no choice in specific instruments is possible.

To use more sophisticated, accurate or robust sensors, monitor more elements than are offered in a pre-configured package, or perhaps integrate existing instruments into a new AWS setup, the best advice is to consider first specifying a suitable datalogger, one that will handle the required number and type of sensor inputs (more on dataloggers in Chapter 13). Sensors appropriate to each required element can be identified, checking of course whether the logger and logger software will support them, and the configuration then built up item by item. Pre-sales support available from the manufacturers or resellers of more advanced systems can often provide details or recommendations on supported configurations.

A 'datalogger + sensors' approach may also be appropriate where there is a requirement for the sensors to be located in two or more locations (air temperature and rainfall at ground level, say, with wind and sunshine sensors on a rooftop or mast some way distant), to avoid the siting compromises necessary with entry-level and budget systems featuring 'all-in-one' instrument packages.

Upgrade the raingauge!

Upgrading sensors to higher accuracy or specification is impossible on most 'packaged' systems, with one exception – the tipping-bucket raingauge (TBR) unit. Most entry- and budget-level systems include as standard a 1.0 mm capacity TBR, which is much too coarse for accurate weather monitoring (see Chapter 6, *Measuring precipitation*).

Almost all TBRs generate a simple 'pulse' output, requiring only a straight forward two wire connection. It is therefore very easy to connect in a higher-spec unit – 0.2 mm or 0.01 inch capacity is ideal – to replace the supplied model. The calibration setting in the logger software should be adjusted as required to reflect the higher resolution sensor.

Will it be cabled or wireless?

Wireless systems are without doubt quicker and easier to set up, avoiding the need for trailing cables, wiring connectors and the like. For most systems of this type, exterior setup is merely a matter of siting the sensors appropriately and establishing low-power, high-frequency radio communication with the 'base station', usually located indoors. The range and reliability of wireless systems have improved enormously in the few years that they have been available, and although some budget systems are limited to 25–30 m line-of-sight reception, some manufacturers claim 300 m or more. Wireless repeaters are available for some AWS models, and these can extend the range to a kilometre or more.

Wireless: U.S. versus European specifications

It is important to note that different wireless frequencies are used within U.S. and European markets. North American specification wireless AWS products transmit at 915 MHz, whereas most European models use 433 MHz (some, such as the Davis Instruments Vantage Vue, use 868 MHz). In Europe, 915 MHz is reserved for mobile telephony, for various defence and national security applications and for the emergency services. Be warned – importing a U.S. model AWS into Europe and thereby generating unauthorized transmissions or interference on this frequency may not be treated very sympathetically by the relevant authorities!

Quoted reception capabilities are usually those available under ideal conditions and without intervening obstructions between transmitter and receiver. Where conditions are less than ideal (multiple line-of-sight obstructions, very thick exterior walls or foil-backed cavity wall insulation panels, for example, interference from other wireless systems on the same frequency, or sometimes the weather itself) the signal may become scrambled or drop out altogether, resulting in erroneous or missing data. Data from wireless systems can become unreliable in certain conditions, particularly where the transmitter and receiver are operating close to their maximum operating distance. For some systems this can be as little as 25 metres at best: a minimum wireless specification of 100 m or so is advisable, even in a domestic or suburban setting. Reductions in range, or more frequent data drop-outs, can also occur when the battery of the transmitter is running down, and if not changed quickly total data loss may occur for an extended period. This will become a problem on a domestic system if it occurs during a two-week period away from home, for example, or during cold weather when battery life may be reduced significantly. (The best solution is always to check thoroughly all connections and batteries well before an expected absence of more than a few days; however, don't do this the day before departure, just in case the new battery fails very soon after it is brought into use.)

Some AWSs are available in either cabled or wireless configurations. In some of these the wireless models update sensor readings less frequently than the equivalent cabled system, to preserve battery life; one wireless system on the market updates only every 90 seconds or so compared with about 10 times that frequency for its cabled equivalent. A high data rate is essential for some elements (particularly the accurate recording of wind gusts) but less so for others: see also the relevant chapter covering each parameter in turn for more on this point.

Cabled systems are a little more complicated to set up, in that the cable run needs to be securely and safely laid out, and robust weatherproof connections made. The number of connections should be kept to the absolute minimum to reduce the potential for wiring problems, but where the sensors are some distance from the logger a length of extension cable will normally be required over and above the length of cable supplied with the sensor or sensor package. The maximum cabling distance may be as little as 30 m for some systems, although more normally up to 100 m is supported. Check supported configurations with your supplier carefully

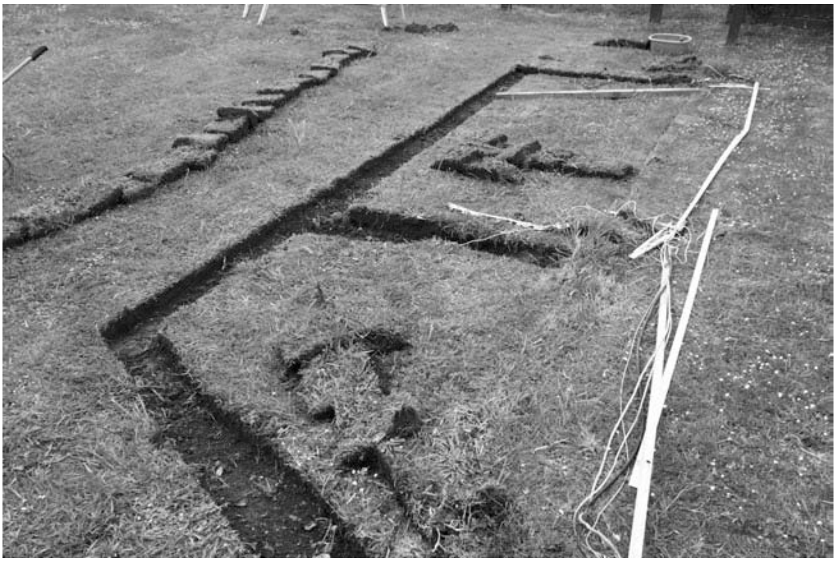

Figure 2.1. Installing a cabled AWS can involve considerable preparation work in digging trenches for cable runs . . . (Photograph by the author)

before purchase if the distance between sensors and logger is more than a few tens of metres. Remember when measuring this to factor in the actual length of the cable run, which will probably be greater than the line-of-sight distance.

Establishing a cabled system is likely to involve most, if not all, of the following activities:

- Setting up reliable and weatherproof cable connections and/or a suitable weatherproof exterior junction box
- Preparing a weatherproofed exit gland for the cable itself from the nearest building
- Securing external cable runs against wind and weather (particularly instruments in exposed locations, such as anemometers and sunshine sensors)
- Preparing trenches for burying cables where they run across grass or soil (**Figure 2.1**), or arranging suitable conduit to prevent trip hazards or accidental damage from strimmers, lawnmowers, children, and so on.

In some cases, it may be necessary to enclose all external cable in tough plastic or even metal conduit to avoid risk from insect or vermin attack (squirrels and moles appear rather partial to cable insulation), from vandalism, ground settlement or vehicular access, or to satisfy health and safety requirements, particularly in schools or public-access areas.

Installing a cabled AWS certainly involves more setup work than wireless units, but has two advantages. The first is that, once done carefully, the installation work should not need to be repeated (where possible, use wiring conduits to preserve access to the cable and any connections in the event of maintenance or replacement being required, or to allow the installation of additional cables should the system be expanded subsequently). The second is that a cabled system with sound connections is both weather-independent (not liable to potential signal disruption in severe conditions) and powered directly from the logger/PC, thus avoiding the risk of data loss associated with battery failure on wireless transmitters. In addition, data sampling rates on cabled systems can be substantially higher than on wireless equivalents. Finally, some elements cannot be measured using wireless sensors (earth temperatures, for example) and some form of cabled connection will be required in these circumstances. Note also that some manufacturers offer both cabled and wireless versions of the same system; the cabled versions are usually slightly less expensive.

In all cases, *screened* cable should be used, particularly for long runs or where electrical or radio-frequency interference may be a problem to the milliamp or even microamp currents involved. Screened cable, as the name suggests, screens or shields the current-carrying cables with an outer sheath of braided wire mesh, which is then earthed at both termination points. Electrical interference will manifest itself as 'noise' on the signal – a temperature sensor may change by a few tenths of a degree Celsius every few seconds, for example, or a raingauge may show spurious tip counts. Screened cable will normally eliminate such problems. The source of the electrical interference may be difficult to determine – close proximity to electrical mains wiring, domestic heating or air-conditioning installations and wireless computer networking or mobile phone femtocells can be troublesome in domestic situations – and may also be weather-dependent. Long runs of above-ground unscreened cable are particularly vulnerable to induced transient spikes caused by lightning, and these can play merry havoc with observations during severe electrical storms, sometimes introducing entirely spurious signals and throwing the reality of sections of the logged data into doubt. Screened cable is more expensive than standard cable, but it is essential for most installations – and certainly cheaper and easier than repeating an existing installation with screened cable at a later date[*].

It is also advisable to use a minimum size of cable strand. The cores in some multicore cable systems comprise cables consisting of just a few strands of very fine wire, little more than a human hair in diameter. These are very difficult to work with, to take solder and to guarantee secure connections. Wider cables are more expensive but much easier to work with and ensure much more reliable connections. A sensible minimum is a cable strand diameter of 0.8 mm and cross-sectional area of 0.5 mm^2 or more, corresponding to American Wire Gauge (AWG) of 20 or less. Davis Instruments sell small 'crimp connectors' from 3M (Davis part no. 7960) which are ideal for permanent and waterproof connection of fine wires or data cables, and very easy to fit (at the cost of a rather bulky junction bundle). These connectors are also available direct from 3M and their distribution partners as Scotchlok™ UY2 IDC connectors.

Will it be PC-based or have a separate logger?

Most weather monitoring requires 24 hours per day, 365 days per year availability. A dedicated datalogger provides standalone logging capability, a computer connection being required only occasionally for downloading data. With suitable battery backup a datalogger provides independence both from mains power and from reliance on a dedicated computer connection. A dedicated datalogger, capable of being connected to and swiftly downloaded from a desktop or laptop computer, or

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[*] The wire mesh jacket of screened cable also provides some degree of armouring for the cable, although where there is danger from lawnmowers, strimmers and the like it is wise to enclose the cable in tough conduit to provide protection.

sometimes from a handheld device, is much the easiest and most reliable method to ensure unbroken records from an AWS.

Most entry-level and budget AWSs do *not* include a dedicated battery-powered or battery-backed datalogger as part of the system, and will require a permanently connected computer (desktop, laptop or netbook-type device) to ‘record’ the data flowing from the sensors. Because the PC has to remain powered up at all times (and cannot be allowed to drop into a ‘sleep’ state at any time, to avoid missing downloads), this can entail considerable power consumption. A true 24x7 capability may require additional investment in backup power supplies to cover mains power failures, and of course failure of the PC will result in immediate cessation of records. Small, low-power consumption PCs or netbooks are cheap enough to consider their use as a ‘dedicated’ AWS PC, although their processing power may be insufficient for more advanced graphics or wireless Internet updates.

A standalone datalogging capability with battery backup, capable of being connected to and downloaded from a computer, is the preferred option on all modern systems.

What degree of automation is sought?

All but the most basic systems are capable of being left to run and record without attention for at least a few days, and for most ‘back garden’ installations where the logger is connected to, and downloaded regularly by, a directly connected computer (cabled or wireless connection) this degree of automation is adequate. For more remote locations such as isolated mountains or deserts, or even a city-centre rooftop site, where the site is not visited at least every few days, a greater degree of automation and a remote telecommunications capability may be required to allow recorded data to be downloaded and transmitted automatically at regular intervals to another location.

Transmission by telephone landline, via a mobile telephone network or by satellite are all options depending upon the equipment being used and your supplier, site access and availability of services – and of course budgets.

What degree of accuracy and precision is sought?

The terms ‘accuracy’ and ‘precision’ (sometimes ‘resolution’ in place of ‘precision’) are often used interchangeably, yet they do not mean the same thing (see Box, *Precision versus accuracy*).

The treatment of calibration and instrumental errors is considered later (Chapter 15) but for now it is sufficient to consider how accurate and how precise the AWS observations need to be. Many users will be content with being able to measure air temperatures within 2 degrees Celsius, or rainfall within 20 per cent of the ‘standard’ measurement methods, for example. This may be perfectly adequate for many purposes, particularly for new users, or if the exposure of the instruments is far from ideal and cannot be improved upon.

Where the requirement is to provide measurements conforming to standard practices, thereby enabling accurate comparisons to be made with other sites or historical records, then tighter tolerances are called for. For such applications the correct exposure and siting of the instruments become as important as the absolute accuracy of the sensors themselves, and typical standards will be ±0.2 degC for air temperature sensors and ±2 per cent for rainfall, for example.

The choice of system involves making decisions on the level of accuracy required. As might be expected, higher accuracy generally comes at a price. This is not to say that entry-level systems cannot produce consistent results to a high level of accuracy, particularly if elementary calibration tests can be carried out at installation and at least annually thereafter (see Chapter 15), but where high accuracy is a mandatory requirement it is more likely to be achievable from an AWS within the medium or higher price ranges.

Precision versus accuracy

It is a very frequent mistake in our digital world: just because a number is specified very *precisely* does not necessarily mean the value quoted is *accurate*. This applies to all measurements, of course, but is particularly important in weather measurements.

As an example: let us say I have two digital clocks in front of me. One says the time is 10:23:46, the other says it is 10:19. The first is very *precise*, but is it *accurate*? Both clocks show different times and clearly one must be wrong.

If I were to check the time using a third source of known accuracy, perhaps a radio-controlled clock, and found that at the time I observed the clocks, the exact time was 10:18:46, then it is apparent that although the first measurement is *precise*, it is not *accurate*. The second measurement is less *precise*, but it is more *accurate*.

Every measurement has an associated error. An AWS may display or log an air temperature of (say) 16.34 °C, but if the sensor is accurate only to ± 2 degC, then we can only say the temperature is somewhere between 14 and 18 °C. Quoting the value even to a single decimal place is clearly unjustified. If the sensor was a more accurate one, with an error at that temperature of ± 0.2 degC (more typical of professional-quality sensors), then we can say with greater confidence that the temperature lies between 16.1 and 16.5 °C.

With careful sensor calibration, it is possible to reduce errors further. Observations of air temperature are most often quoted to 0.1 degC, although this precision is not always justified by the accuracy of the sensor itself.

Similar arguments apply to raingauges. The accuracy of tipping-bucket raingauges can vary enormously in heavy rainfall, yet one popular brand of AWS specifies the maximum rate of rainfall to a precision of 0.1 millimetres per hour in its display (an implied precision of better than 0.1 per cent above 100 mm/h): this for a system that probably cannot deliver realistic accuracy of better than 20–30 per cent in such circumstances.

When comparing the errors of two sensors, unless one or both are accurately calibrated, observed differences between the two may be entirely spurious. Consider two temperature sensors similarly exposed in different parts of a nursery garden, for example: one regularly reads 2 degC higher than the other. Does that mean the sensor that reads higher is located in a warmer part of the garden? Maybe – or perhaps the sensor simply reads 2 degC high. Perhaps both of the sensors are accurate only to ± 1 degC, in which case any difference up to 2 degC may simply be due to a combination of instrumental errors.

Much the same applies to all weather measurements, although in professional work the errors are assumed to be small (normally because the instruments have been regularly calibrated, see Chapter 15), and so the errors are not usually quoted. Just because they are not quoted does not mean they do not exist, however, and quoting any particular uncorrected reading to a higher precision than its calibrated accuracy is unjustified.

How often is the information updated?

For many weather elements, an update interval of a minute or even two is sufficient on most occasions (see Box, *What is the difference between 'sampling interval' and 'logging interval'?*). For some elements, such as earth temperatures, once an hour (perhaps even once a day) is normally sufficient to record significant changes. For elements that change rapidly, particularly wind speed, a fast sampling interval is essential for comprehensive monitoring. Wind gusts, for instance, are defined by the World Meteorological Organization (WMO) as the 'highest 3 second running mean wind speed' [1]. It is clear that any system that updates on a time scale considerably longer than this – and some systems update only every 2–3 minutes – will not pick up the fine detail of the wind structure on a windy day, and as a consequence reported gusts will be much lower than those from faster-response systems. If monitoring of changes in wind speed and direction in particular is an important consideration, then the sampling time of the system must be no more than a few seconds.

What is the difference between 'sampling interval' and 'logging interval'?

The *sampling interval* (sometimes called the update interval) is the length of time between readings of that particular sensor. It can vary from element to element – wind speed needs to be sampled much more frequently than earth temperatures, for example – but typically is between 1 second and 1 minute on most AWSs.

The *logging interval* is the frequency with which means or extremes of the sampled values are archived – not every individual sample will be archived. The logging interval can be the same as the sampling interval, or a large multiple of it, but never less. For example, an AWS logging hourly means of wind speed might sample the anemometer every second: the hourly mean would therefore be the average of the 3,600 1 second samples. The same AWS might sample an earth thermometer just once per hour, and store that single sample. In this case the logging interval is the same but the sampling intervals are very different.

Entry-level AWSs may have a single, fixed logging interval: budget and mid-range systems will normally permit selection from a range from minutes to hours, depending upon the requirement (5–15 minutes being typical). More advanced dataloggers can log at more than one logging interval – perhaps storing data for some elements every 5 minutes, others every hour, and for all elements providing a once-daily summary of means and extremes, for example.

How robust does the system need to be? What is its desired or expected lifetime?

It is obvious that the weather instruments themselves, and the means by which they are exposed, need to be robust enough to stand up to (literally) the worst the weather can throw at them. There are few things in observational meteorology more frustrating than losing records of what may be a once-in-a-lifetime gale because the anemometer mast has blown down, for example.

Choose the monitoring system with both the intended usage and expected lifetime in mind, together with the expected climatic conditions at the site. An AWS monitoring conditions in the south of Florida will clearly be exposed to very different conditions to one on a clifftop in the west of Ireland, or in northern Manitoba: less obviously an anemometer mounted at roof level even in a suburban environment will receive a much greater degree of 'weather stress' than a similar instrument mounted lower down in a sheltered garden setting.

The robustness of the system in the expected climatic conditions should be carefully considered prior to purchase. Comparing notes with existing users on Internet newsgroups is often a good way to do this – see Chapter 19, *Sharing your observations* for sources – as very few manufacturers give any useful measure of reliability (such as the 'mean time between failure'). The most exposed sensors, usually the anemometer and wind vane, are most likely to fail early; even more expensive/professional sensors require replacement every 10 years or so – more frequently in windier locations. Other parts of the instrumentation and mechanics are also vulnerable. Plastic mountings and cable ties can become brittle and snap easily after just a few months exposure to the ultraviolet radiation in sunshine, bearings can freeze up, seize or jam, connectors can admit water and short out – the list is almost endless. One thing is certain – the weather *will* eventually win the corrosion battle!

A failure in one sensor over time may not be catastrophic in modular systems, where a replacement can be plugged in quite easily, but if replacements become required regularly the costs – and lost data – will soon mount up. It is also likely that replacement parts on entry-level systems will become difficult or impossible to obtain after only a few years, as new systems are introduced regularly and older models (and their spares) are withdrawn from sale. Careful siting helps – avoid mounting instruments on a fence if that is the most likely structure to blow down in a gale, for example – but the more robust the sensor and its mountings, the longer the expected lifetime and the fewer corrosion-related incidents to be expected. Regular inspections and proactive maintenance will keep corrosion-related problems to a minimum and will often provide early warning of potential failure points.

Over the longer term, experience to date strongly suggests that the useful working lifetime of electronic AWSs is less than that of most conventional 'manual' instruments such as thermometers and raingauges. Liquid-in-glass thermometers need re-calibrating every few years, but with care there is no reason why they should not give reliable service for 50 years or more: standard copper or steel raingauges will last at least as long with a little care and maintenance. Even wooden Stevenson screens should give 20–30 years service provided the woodwork is kept in good order. In contrast, the expected lifetime of current AWSs varies between no more than 12 months for some entry-level units, to 15 or 20 years, perhaps more, for well-built mid-range and professional units (although some sensor replacements should be allowed for within this timeframe). It is therefore more likely than not that 'manual' instruments would outlast an AWS. Against this objection can be set the much greater useful volume of data from an AWS, as **Table 2.2** makes clear. The calculations assume a fairly basic AWS

Table 2.2. *A comparison of data volumes over 10 years from conventional once-daily read manual instruments versus an automatic weather station (leap years ignored)*

Element	Instrument	Frequency of observations	Number of observations per year	Number of observations in 10 years
Conventional instruments				
Precipitation (*Chapter 6*)	Manual raingauge	Once per day	365	3,650
Air temperature and humidity (*Chapters 5* and *8*)	Temperature in screen	Once per day	365	3,650
	Relative humidity in screen	Once per day	365	3,650
	Dew point	Once per day	365	3,650
	Maximum thermometer in screen	Once per day	365	3,650
	Minimum thermometer in screen	Once per day	365	3,650
Barometer (*Chapter 7*)	Mercury or aneroid barometer	Once per day	365	3,650
			Total manual observations	**25,550**
Automatic weather station				
Precipitation (*Chapter 6*)	Tipping-bucket raingauge	Every 5 minutes	12 x 24 x 365 = 105,120	1,051,200
Air temperature and humidity (*Chapters 5* and *8*)	Screen temperature	Every 5 minutes	12 × 24 × 365 = 105,120	1,051,200
	Relative humidity in screen	Every 5 minutes	12 × 24 × 365 = 105,120	1,051,200
	Dew point	Every 5 minutes	12 × 24 × 365 = 105,120	1,051,200
	Maximum temperature	Once per day	365	3,650
	Minimum temperature	Once per day	365	3,650
Barometer (*Chapter 7*)	Electronic pressure sensor	Every 5 minutes	12 × 24 × 365 = 105,120	1,051,200
			Total AWS observations	**5,263,300**

(without wind speed and direction sensors), a 5 minute logging interval and a conservative 10 year lifetime. Over this period, the AWS generates more than 200 times as much information. (There is more on making the best use of the 'data avalanche' in Chapters 17 and 18.)

Not surprisingly, there is a relationship between build quality, longevity and price. Trying a budget package for a couple of years before deciding whether to move on to a more advanced system is a sensible approach: robustness may not then be the most important element in such a decision, but purchasing an inexpensive AWS and expecting it to last for many years, particularly in an exposed location or one subject to wide climatic extremes, is merely wishful thinking.

Is the system 'mission-critical'?

Many AWSs provide weather inputs to other systems – catchment flash-flood warning systems perhaps, or to provide continuous monitoring and display of wind direction and speed at an airfield as part of the air traffic control system. For mission-critical applications such as these, particularly where lives may be at risk, the availability of the weather-monitoring system itself is paramount. Robust measures to ensure availability may be mandated as part of the system specification, particularly in severe weather. In these situations a remote, duplicate and independently powered failsafe/backup capability may be necessary.

Is climatological continuity/compatibility/parallel running to 'official standards' a requirement?

Where compliance to current WMO or state weather service is mandatory then the choice of both instruments and exposure must be made with this in mind. More details on how this is achieved are given in the following chapters.

Where an AWS is to be used to augment, automate or eventually replace traditional measurement methods, it is essential carefully to overlap and compare both sets of instrumentation, for at least a full seasonal cycle (12 months) and preferably longer, to identify any systematic instrumentation differences which could otherwise damage or destroy the continuity of the record.

Where differences identified as a result of the overlap are climatologically small/insignificant (expert advice should be sought on this), a 12 month overlap period is likely to be sufficient. Where differences are large or highly variable, the overlap period for these elements should be extended. For long-period sites, those with a record of say 50 years or more, an overlap period of 10 per cent of the record length should be allowed for. Where a site move is being considered in addition to an instrumentation change, the overlap should ideally cover both 'new' and 'old' instruments at the 'old' site together with the 'new' instruments at the 'new' site. The overlap period should again be at least 10 per cent of the existing record, and a minimum of 12 months.

How important is ease of setup?

Ease of setup and deployment is a powerful deciding factor for many purchasers, and here the pre-packaged hardware and software components of budget-level and mid-range systems have many advantages. One of the most obvious considerations is whether to specify 'wireless' or 'cabled' systems: both have their own advantages and disadvantages, as reviewed above.

The majority of software accompanying basic systems is easy to use and icon- or menu-driven. More advanced or customizable systems may require some programming ability, although most suppliers can provide customized/built-to-order packages covering installation, setup and programming. The extra costs can easily double the basic system price, however. More details are given in Chapter 13.

What computing facilities and expertise are available?

Most systems can operate entirely standalone, but all have a finite memory capacity: once the memory is full, the earliest data stored will be overwritten in turn by later data. To make maximum use of the collected data it normally has to be downloaded into a permanent storage medium before the memory becomes full. This can be undertaken with a direct computer connection (cabled or wireless), with a portable data collection unit (laptop, netbook or tablet computer, even some smartphones) or via a telecom connection (dedicated landline, mobile telephone transmitter or even direct to satellite in remote areas).

Most systems are easy to install and configure, but the more advanced systems may require some knowledge of datalogger programming, telecommunications protocols, and so on. The suppliers of such systems normally offer an optional installation service covering sensors, logger and software installation, but as previously mentioned the extra costs can be substantial, and the learning curve for self-teach is often very steep. In schools or colleges and universities in-house student or computing resource may be available, and may indeed make an attractive student project.

To display the output of any system in real-time (or near real-time) on the Internet, a dedicated weather station web page can be set up, or an auto-download of the logged data can be sent to a site which accepts inputs from many AWSs (see Chapter 19, *Sharing your observations*). For the non-technical user without a background in website programming, these operations are greatly simplified if a largely ‘pre-configured’ system is selected, because most of the required software is included in the package and little else is required beyond installing the sensors, hooking up to a suitable computer and running through a menu-driven configuration utility.

Will the system be mains-powered or solar-powered?

Most ‘domestic’ AWS systems are mains-powered, usually a low-voltage supply via a transformer, with battery backup sufficient to allow sensor input and logging to continue for at least 24 hours – the longer the better, to allow for possible extended power outages in severe weather conditions. Snowstorms, windstorms and big electrical storms can result in power spikes or lengthy power outages, even in urban or suburban areas, and must be allowed for even if they are very infrequent.

More sophisticated systems will normally be entirely battery-powered, usually from rechargeable high-capacity long-life sealed lead-acid batteries recharged either by mains power, where this is available, or from solar cells or a small wind turbine. Sites remote from mains power need to be completely self-powered, usually using a combination of solar cells and wind power combined with lead-acid batteries, the battery capacity being sufficient to keep the system working for long periods in the event of prolonged periods of low solar radiation (or when snow covers the solar cells . . .) Where power requirements are substantial, for telecommunications or sensor heating/de-icing for example, the manufacturer’s advice on suitable power supplies should be sought prior to installation.

Step 3: Balance requirements against budget

The last item to consider is possibly the most important – namely, what is the available budget?

There are a few excellent basic systems for less than $100 which will measure, display and log just one or two elements to tolerable accuracy. One of these may be perfectly adequate for a first-time purchasers, or for a present for a friend or relation to ‘dip a toe in the water’ of measuring the weather. Other users require more sophisticated, capable, expandable and robust systems, which depending on requirements may cost ten or a hundred times that of an entry-level system. Not surprisingly, the more accurate, expandable, robust and flexible systems (with good post-sales support, should it be needed) tend to be more expensive.

For private individuals, the money spent on a system is best viewed as a multi-year investment. Provided care is taken in exposure and siting, and with occasional maintenance, a mid-range system should last 10 or 20 years or more with little further outlay required beyond the initial purchase price. For professional users, budgeting for a capable and robust system which should give many years trouble-free service will reduce future service costs and minimize downtime.

One-minute summary – *Choosing a weather station*

- There are many different varieties of automatic weather stations (AWSs) available, and a huge range of different applications for them. To ensure any specific system satisfies any particular requirement, consider carefully, in advance of purchase, what are the main purposes for which it will be used, then consider and prioritize the features and benefits of suitable systems to choose the best solution from those available.
- The choices can be complex and a number of important factors may not be immediately obvious to the first-time purchaser. Deciding a few months down the line that the unit purchased is unsuitable and difficult to use (or simply does not do what you want it to) is likely to prove an expensive mistake, as very few entry-level and budget systems can be upgraded or expanded.
- Decide firstly what the AWS will mainly be used for: some potential uses may not be immediately obvious. Once that is clear, review the relevant decision-making factors as outlined in this chapter, then prioritize them against your requirements.
- An AWS does *not* have to be the first rung on the weather measurement ladder. Short of funds? Not sure whether you'll keep the records going and don't want to spend a lot until you have given it a few months? Not sure where to start? Different options are covered in this and subsequent chapters.
- Consider firstly whether the site where the instruments will be used is suitable. There is little value in spending hundreds or even thousands of dollars on a sophisticated and flexible AWS if the location where it will be used is poorly exposed to the weather it seeks to measure. In general a budget AWS exposed in a good location will give more representative results than a poorly exposed top-of-the-range system. Worthwhile observations *can* be made with budget instruments in limited exposures, but a very sheltered site may not justify a significant investment in precision instruments, as the site characteristics may limit the accuracy and representativeness of the readings obtained.
- Carefully consider the key decision areas. Should the system be cabled, or wireless? Is it easy to set up and use? How many sensors are offered, and how accurate and reliable will they be? Are all the sensors mounted in one 'integrated' system, or can they be positioned separately for the optimum exposure in each case? Do the records obtained need to conform to 'official standards'? Examples and suggestions are given in this chapter.
- Finally – and this should be the last step – match the available budget against the requirements and specifications outlined in previous steps. Consider that a reasonable mid-range or advanced system, when used with care and maintained, should last for 10 or even 20 years, and budget accordingly. There are many 'cheap and cheerful' systems available, but will they last longer than their warranty period?

Reference

[1] World Meteorological Organization, WMO (2008) *Guide to Meteorological Instruments and Methods of Observation*. WMO No. 8 (7th edition, 2008). Available online from: http://www.wmo.int/pages/prog/www/IMOP/publications/CIMO-Guide/CIMO%20Guide%207th%20Edition,%202008/CIMO_Guide-7th_Edition-2008.pdf

3 Buying a weather station

To this point, this book has largely treated AWSs as a single unit category. Of course, that is not the case and there are enormous differences in functionality and capability between basic and advanced models. The general rule that 'you get what you pay for' holds true for AWSs as well as for most other products, but in any price category some systems *are* better than others and it pays to check available products carefully against the requirements outlined in the previous chapter to ensure the best fit.

The number, range and rate at which new models are introduced make it impossible for any printed work to provide up-to-date details or reviews of every AWS currently available on the market. This chapter outlines typical system specifications within various budget categories. When used with the prioritized assessments of functionality from the previous chapter, it should provide pointers to the main brands, products and suppliers.

What products are available?

The five product and budget categories shown in **Table 3.1** were introduced in the previous chapter. Most systems fit comfortably within one of these price /performance bands: note that prices quoted are indicative only (at 2012 levels) and exclude local sales taxes, value added tax, delivery costs and optional fittings.

Brand names and typical specifications of products within each category are outlined in **Table 3.2** and in more detail in the remainder of this chapter. (Brand names in brackets are rebadged equivalents from the manufacturer or supplier shown.)

The cut-off feature for inclusion is a means of logging data from one or more sensors over a cabled (USB) or wireless connection to a personal computer. Display-only systems are not included in this review.

Table 3.2 compares weather stations by category. AWS models change frequently, particularly in the entry-level and budget categories, and for this reason this table is intended as a general overview rather than a guide to specific branded products[*]. Where shown, specific products are detailed as representative of that category as at the time of writing, but these can be expected to change every year or two. Some of the specifications will differ between U.S. and European markets – for instance, tipping-bucket raingauge capacities of 0.01 inch and 0.2 mm, respectively.

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[*] A useful feature comparison for U.S.-specification products also appears on the Ambient Weather website http://ambientweather.wikispaces.com/Weather+Station+Comparison+Guide

Table 3.1. *Categories and main brands of automatic weather stations. Prices are very approximate, in U.S. dollars, at 2012 levels, and* exclude *local sales taxes and shipping costs. (This table is identical to* Table 2.1.*)*

	Entry-level single-element	Entry-level AWS	Budget AWS	Mid-range AWS	Advanced and professional systems
Typical price range	$100 or less	$200 or less	$200 to about $500	About $500 to $1,500	$1,500 upwards
Typical brands	TechnoLine Oregon Scientific	Fine Offset (Watson, Maplins) TechnoLine La Crosse Oregon Scientific	Oregon Scientific Davis Instruments Irox Ventus ***Specialist products*** Nielsen Kellerman /Kestrel Gemini/Tinytag	Davis Instruments	Campbell Scientific Davis Instruments Environmental Measurements Met One Instruments Vaisala

Best prices? Or best support?

Shopping around will often lead to keener prices, but the lowest price may not represent the best value. For relatively complex and long-lasting products such as these, pre-sales and particularly post-sales support should be an important part of the purchasing decision. Is the reseller a registered dealer for that manufacturer, or are they selling 'grey' stock imported cheaply from fire-damaged stock in Asia? How long have they sold products from this manufacturer? Do they have access to the manufacturer's dealer support and technical helpdesks? Can they help with setup, installation and software questions? Do they stock spare parts and accessories? Most importantly, will they still be around if there's a problem under warranty?

In most cases, it is better to pay a little more for a product from a legitimate dealer who offers post-sales support, spares and warranty cover than to risk becoming stuck with a dead system and no support.

Which product/s best suit my needs?

Table 3.3 suggests specifications for AWSs within four very loose 'user profiles'. These are intended only as a pragmatic starting point to what is practical and affordable within various budget and site restraints rather than being overly prescriptive – for instance, with a limited budget it is probably better to concentrate on air temperature and rainfall observations, as wind speed and direction are more expensive to measure, and the site requirements are more complex: these can probably follow at a later stage as budgets (and perhaps an improved site) allow. Entry-level systems can be ideal for those looking to make a start in weather measurement, with the option of 'trading up' to more capable and accurate systems over time. (See also Box, *Weather instruments as gifts*.)

Table 3.2. *AWS specification table.*

Feature comparisons – weather stations											
x – not specified in manufacturer or reseller literature/website			Entry-level	Entry-level	Entry-level	Budget	Budget	Budget	Budget	Mid-range	Advanced
			Fine Offset	TechnoLine	Maplins	Oregon Scientific	La Crosse	Oregon Scientific	Davis Instruments	Davis Instruments	Campbell Scientific
			WS 1080	WS2350	USB WWF	WMR180X	WS 2801	WMR200X	Vantage Vue	Vantage Pro2	Modular
	Typical price ($US) 2012		$100	$150	$175	$275	$325	$450	$500	$800	> $1500
Elements logged	Air temperature		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Outside humidity (RH)		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Barometric pressure		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Rainfall		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Wind speed		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Wind direction		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Solar radiation		No	No	No	No	No	No	Optional	Optional	Yes
	Earth temperatures		No	No	No	No	No	No	No	Optional	Yes
Resolution	Temperature resolution	*deg C*	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Temperature accuracy	*deg C*	x	x	x	± 1–2	x	± 1–2	± 0.5	± 0.5	± 0.2
	RH resolution	%	x	1%	1%	1%	1%	1%	1%	1%	1%
	RH accuracy	%	x	x	x	± 5–7%	x	± 5–7%	± 3–4%	± 3–4%	± 2–3%
	Pressure resolution	*hPa*	0.1	0.1	1	1	x	1	0.1	0.1	0.1
	Pressure accuracy	*hPa*	± 1.5	x	x	± 10	x	± 10	± 1	± 1	± 0.5
	Rainfall resolution	*mm*	1	0.5	1	1	0.5	1	0.2	0.2	0.2
	Rainfall accuracy	%	x	x	x	± 7%	x	± 7%	± 4%	± 4%	± 2%
	Wind speed resolution	*unit*	x	0.1 unit	1 unit	0.1 unit	0.1 unit	0.1 unit	1 unit	1 unit	0.01 unit
	Wind speed accuracy	%	x	x	x	± 3 m/s	x	± 3 m/s	± 5%	± 5%	± 2%

Table 3.2. (*cont.*)

Feature comparisons – weather stations

x – not specified in manufacturer or reseller literature/website			Entry-level	Entry-level	Entry-level	Budget	Budget	Budget	Budget	Mid-range	Advanced
			Fine Offset	TechnoLine	Maplins	Oregon Scientific	La Crosse	Oregon Scientific	Davis Instruments	Davis Instruments	Campbell Scientific
			WS 1080	WS2350	USB WWF	WMR180X	WS 2801	WMR200X	Vantage Vue	Vantage Pro2	Modular
	Typical price ($US) 2012		$100	$150	$175	$275	$325	$450	$500	$800	> $1500
Features	Radiation shield included?		No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Update interval wireless wind/other	*sec*	48	128	48	56 / 102	17 / 13	14 / 60	2.5 / 60	2.5 / 60	< 1
	Stated wireless range	*m*	100 m	25 m	60 m	100 m	50–100 m	100 m	300 m	300 m	> 1 km / Cabled
	Console included?		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
	Logger included		No	Yes, serial	No	No	Yes	Yes	Yes	Yes	Yes
	Logger capacity (5 min resolution)		x	15 h	N/A	N/A	6 days	x	9 days	9 days	28 days
	Software included		x	HeavyWeather	Easyweather	Virtual	Weather	Proprietary	Weather OS	WeatherLink	
	Weatherlink		LoggerNet								
	Sensors separate		Yes	Yes	Yes	Yes	x	Yes	No	Yes	Yes

Typical prices exclude sales tax, delivery and optional extras
All specifications from manufacturer's literature via internet searches, January 2012.
Errors and omissions excepted. Product specifications subject to change. Check latest specifications and prices for yourself before making purchase decisions.

Table 3.3. *Suggested minimum specification levels for weather measuring equipment within various 'user profiles'; see text for detail*

	Starter	Hobbyist	Amateur	Professional
Suggested AWS category	*Entry-level*	*Budget*	*Mid-range*	*Advanced*
Air temperature	± 2 degC	± 1 degC	± 0.5 degC	± 0.2 degC
Rainfall	± 20%	± 10%	± 2%	± 2%
Wind speed	Estimate using Beaufort scale	Estimate using Beaufort scale, or use handheld instrument	± 10%	± 5%
Wind direction	Estimate using wind vane	Estimate using wind vane	± 10 degrees	± 5 degrees
Air pressure	± 2 mbar	± 1 mbar	± 0.5 mbar	± 0.2 mbar
Sunshine	–	–	± 10%	± 5%

Non-instrumental weather observing is also a useful supplement to all categories and budget level (see Chapter 14), and does not depend upon budget.

'Starter' – suitable for budget-conscious buyers and first-time buyers, for those with a limited, non-standard or very sheltered site, or those for whom accuracy and comparability with other observations is not the highest priority

'Hobbyist' – recommendations for those with a slightly higher budget, or with sheltered sites

'Amateur' – mid-range systems, suitable for sites that range from slightly sheltered to well-exposed, and for those looking to make medium- or long-term records which will be comparable with other sites

'Professional' – systems suitable for serious amateur or professional long-term weather monitoring applications

Weather instruments as gifts

Weather instruments make ideal gifts for those who are interested in making their own observations – whether for a teenage child or grandchild, for a special anniversary, or as a retirement gift for a work colleague: there are many different possibilities. Traditionally such gifts might have included an aneroid barometer, or a barograph: modern weather stations offer a much wider range of options and interest for a similar outlay. There are very few gifts that offer something different every day and provide sustained interest – perhaps even stimulate a career in meteorology or start a new retirement hobby. But what is the best choice when it comes to deciding what to buy?

When it comes to gifts, budget is probably the single most important criterion, followed by intended lifetime. A gift to stimulate or encourage interest in observations in a grandchild may serve its purpose (or not!) in a matter of months; a retirement gift should ideally last for many years.

For gifts up to about $100, a single-element system would be most appropriate – a small wireless raingauge or a logging wireless temperature sensor with display, perhaps (the latter will also need some form of shading from the Sun, and to protect delicate electronics from the elements). Where the budget available is more substantial, a multi-element AWS would be an ideal choice. Generally, the larger the budget, the higher the quality, accuracy and lifetime of the system. This chapter provides more details on the capability of products within each budget category, advice on what to look for when choosing a system, and outlines some of the most popular products available.

Most popular systems today

Reliable information on the relative popularity or sales of AWS hardware and software components is very difficult to obtain: the major manufacturers are understandably reluctant to divulge such commercially sensitive information, which is in any case constantly changing. To obtain a 'snapshot' view of the most popular installed systems, information on AWS hardware and software currently in use was extracted manually from site information provided at 150 randomly-chosen sites[*] with observations displayed on WeatherUnderground (www.wunderground.com/wundermap) within (i) the continental United States and (ii) the UK and Ireland [1]. The results by hardware brand are shown in **Table 3.4**. (Those for system software are given in Table 13.2 in Chapter 13, *Dataloggers and AWS software*.)

On both sides of the Atlantic Ocean, systems from Davis Instruments and Oregon Scientific accounted for the majority of the AWSs surveyed – Davis Instruments being the brand leader in both geographies, although with a lower share in UK/Ireland (39 per cent) than in the United States (61 per cent). Oregon Scientific models accounted for around 20 per cent of the units in use in both geographies, and La Crosse about 10 per cent. The most popular single model was the Davis Instruments Vantage Pro2, which accounted for just less than 70 per cent of the Davis Instruments units in both surveys. Earlier models of the Vantage Pro AWS were in use at about 20 per cent of the Davis Instruments sites. The next most popular models were the Oregon Scientific WM928 in the UK and Ireland, in use at 12 locations (8 per cent of the total), and the WMR968 in the United States (12 per cent of all sites). In the UK and Ireland, Fine Offset and Watson saw just less than 20 per cent share between them, mainly through electronics resellers such as Maplin

Table 3.4. *AWS hardware survey*

	U.S. survey		UK/Ireland survey	
Product brand	*n*	%	*n*	%
Davis Instruments	92	61	59	39
Oregon Scientific	25	17	33	22
La Crosse	20	13	13	9
Fine Offset	1	1	16	11
Watson	0	0	11	7
Others	12	8	18	12
Total	**150**	**100**	**150**	**100**

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[*] In the absence of any other readily-available information on installed systems, it is impossible to say whether or not the population of 'AWS observing sites reporting into Weather Underground' is a representative sample of 'all AWS observing sites'.

Electronics, although they have very little presence within the American market. Their products are sold 'rebadged' by other companies, so they may also be known by other brand names.

Entry-level systems

There are two different types of AWSs in the entry-level category: those that display and log only a single weather element, and those that measure two or more.

Single-element AWSs

Although there are a few 'digital barograph' devices, offering display and logging of barometric pressure, most of the products in this sub-category log temperature or rainfall only. They usually consist of an exterior wireless sensor and an interior display unit with integrated logger.

Rainfall-only units usually consist of a small, 1 mm (0.04 inch) capacity tipping-bucket raingauge connected wirelessly to an interior display console. Most of these devices will store only a few readings, typically daily totals for the last 7–10 days: within this period, values stored on the device can be recalled on the display for manual tabulation.

Given a reasonable exposure (see Chapter 6, *Measuring precipitation*), these little devices can provide a fair indication of rainfall totals: tests by the author on one model (**Figure 3.1**) showed that over a 2 year period the gauge caught a fairly consistent 10 per cent less than an adjacent standard raingauge. The 1 mm resolution precludes accurate recording of small daily amounts, mostly because small falls are more likely to evaporate from the tipping-bucket mechanism than to be recorded, but given a reasonable exposure these units can provide a *rough* indication of the rainfall amount, and thus offer reasonable value for money. They are simple but robust – the author's unit has been in place for 6 years at the time of writing – but like all tipping-bucket raingauges, they are useless in snowfall. Choose a unit with an open round funnel, not a square or rectangular opening, as distorted airflow over non-circular gauges leads to unpredictable results. Avoid any that have any obstructions or grids within the funnel opening (other than insect barriers) as these can obstruct airflow and rainfall ingress; they can also catch 'fogdrip' in windborne fog and generate spurious precipitation records.

Figure 3.1. Entry-level wireless raingauge. (Photograph by the author)

Temperature-only units consist of an exterior temperature sensor connected wirelessly to an interior display unit with integrated logger: sometimes a humidity sensor is also included. Provided the exterior sensor is adequately protected from sunshine and rainfall with an appropriate radiation shield (see Chapter 5), such devices can provide surprisingly good results. The author has had a TechnoLine unit exposed within a Stevenson screen for several years: its indication is almost always within half a degree Celsius of an adjacent (and much more expensive) calibrated, professional-standard platinum resistance temperature sensor. Calibration should be checked carefully prior to use, however, as not all units may be as accurate 'out of the box' (see Chapter 15 for details). The sensor unit is rather bulky, and its bulk does render it rather slow to react when the temperature changes rapidly (an effect known as 'thermal inertia'), but the unit has been found to be accurate and reliable enough to use as a backup device. The logger stores slightly more than 3,000 readings, one logged every 5 minutes (the logging interval is fixed), and thus the unit needs downloading at least every 11 days to avoid the internal memory becoming full and older values being over-written. The Windows-based software provided, although basic, is easy to use and does its job well. Check the required PC connectivity, however – many of these devices require a serial port on the host computer, rather than USB (and some will not work with a serial-to-USB connector), and many modern laptops no longer include a serial port as standard.

For those who seek only temperature logging, and who can provide suitable exterior protection for the sensor, with a basic calibration check such devices can be very cost-effective and offer excellent value for money.

Entry-level multi-element AWSs

Entry-level AWSs are typically priced at or below $150 to $200, and are often 'cheap and cheerful' consumer-boxed products offered by branded electronics stores, online resellers or other retailers. Most include some element of weather forecast options (algorithms normally based upon current values and trends in air pressure and wind direction), but these are not considered further here. Such systems do provide a good starting point for weather monitoring (and some offer good value-for-money), although limited accuracy, functionality, wireless range and durability are more likely to feature at this price point. Almost all include some form of display console, and some will include display/logging software in the base system price, but at this level very few include even the most basic of inbuilt dataloggers (see Box, *What does 'PC Connection' mean?*). Software included with the system may be the manufacturer's own or a limited-functionality version of a more fully featured third-party package. Software is often very basic: however, higher-quality third-party software is available for most popular AWS models, and upgrading the supplied software may make these products more suitable (or indeed usable). More details on system software and a survey of system software in use today are given in Chapter 13.

What does 'PC connection' mean?

Check the manufacturer's specifications carefully before purchasing as many are, perhaps deliberately, rather vague on exactly what 'PC connection', 'PC link' or 'data recording' actually means.

If ‘PC connection’ or a similar term is used, it almost certainly means that there is no separate logger (see *PC-based or separate logger*? in Chapter 2) and therefore a PC or low-cost netbook must remain permanently connected to the AWS, and powered up, to receive and store data. Check also whether the connection is via a USB or serial port. If the latter, note that most laptops and many desktop systems no longer include serial ports as standard. Even if a serial port is available, getting the PC to talk to the AWS will likely provide unwelcome re-acquaintance with fiddly serial settings for parity, baud rates and stop bits, out-of-date drivers, and the dusty recesses of Windows’ Device Manager setup menus. USB systems are usually considerably easier to set up, and all modern PCs include USB ports as standard.

Entry-level systems typically offer the basic set of sensors (usually air temperature, rainfall, barometric pressure, sometimes humidity, wind speed and/or wind direction). Usually the anemometer/wind vane component – at least – can be separated from the other sensors to enable it to be sited more appropriately. It is rare to find manufacturer specifications for sensor accuracy in this price range, but experience shows these are often rather poor – typically ± 2 degC / ± 4 degF for temperature and ± 2–5 mbar for pressure. The supplied raingauge is normally a 1 mm / 0.04 inch tipping-bucket unit (i.e., too coarse for reliable rainfall measurements). Normally only the manufacturer’s sensors can be used with these systems, and no expansion or customization is possible. The sensors themselves should be replaceable in the event of malfunction, although this is not always the case: reports of frequent sensor failure on entry-level systems are quite common. Update intervals are also lengthy – typically 1–2 minutes: this severely limits the high-frequency resolution of the records obtainable (particularly gust wind speeds), although depending upon requirements such relatively coarse resolutions may be quite acceptable for other parameters.

Is it possible, therefore, for products within this category to provide any worthwhile weather measurements? The answer is definitely *yes* – at least for some parameters – provided a few basic principles are followed from the outset.

Firstly, site and exposure. It has already been stated that a basic AWS with a good exposure will often provide more representative results than a top-of-the-range model in a very sheltered position. There is more on site and exposure in the following chapters: paying careful attention to the detail of where the sensors will be located makes an enormous difference both to the quality of the records and, at least as important, how comparable they are with other records, whether they be observations made in the next city or records made 100 years ago. For sites where the exposure is very restricted, the accuracy of the temperature and rainfall records in particular may be limited more by the degree of shelter than by the sensors themselves. It is often difficult to find an ideal exposure for truly representative wind measurements, particularly in urban or suburban areas.

Secondly, it is vital to ensure that the temperature sensor is properly shielded from sunshine and rainfall. Very few entry-level systems include adequate protection for the temperature sensor – some provide none at all. Without such protection from both solar and terrestrial (infrared) radiation, indicated temperatures will be much too high on sunny days and too low on clear nights. Contrary to popular belief, exposing temperature sensors on a shaded north wall will also give rise to significant errors. If the supplied radiation shield is poor (or non-existent), allow additional budget for adding one to the system, taking care to ensure that the temperature sensor will fit into the option chosen. (Note that it may be less expensive to specify a higher-spec system which includes a better radiation shield.) Chapter 5 gives additional details on the requirements for measuring air temperatures.

Thirdly – it is essential to check accuracy by carrying out a calibration check of at least the temperature and rainfall sensors prior to installation, and every 6 months thereafter. Basic calibration checks are not difficult to do: more details in Chapter 15. With a little attention to detail in this regard, it should be possible to reduce the likely 'out-of-the-box' errors significantly.

One of the biggest shortfalls in performance in entry-level wireless systems is in wireless range. A typical quoted wireless range spec for entry-level systems is 25–50 m, but based upon feedback from existing users these rarely seem attainable in practice. The transmission range of one entry-level system, user-reviewed on an online site, was described as 'very poor, typically 5 m or less' despite a specification of ten times that figure. Wireless range will decrease in poor weather, in cold spells and when the transmitter batteries are running down, and loss of record will inevitably follow – sometimes for long periods.

A final factor to consider is longevity. Clearly all AWSs need to be capable of withstanding prolonged exposure to all types of weather. Entry-level systems built to a price cannot be expected to be as robust as higher-specification units, and regular replacements of sensors should be expected. It is unrealistic at this price point to expect spares to remain available for many years after purchase, and accordingly the availability of spare parts to keep the system working may become a problem quite soon after the manufacturer has replaced it with a newer model. Even with regular replacement of sensors, some exterior system components may not last more a couple of years. Online reviews abound of cheaper systems lasting no longer than the basic warranty period, sometimes even less.

Entry-level systems – summary

There are many situations where an entry-level system may perfectly meet the requirements. Provided their limitations in terms of accuracy, capability and lifetime are understood and accepted at the outset, and careful attention is paid to siting and exposure, such systems can represent reasonable value for money for a 'starter' weather monitoring system, or those with limited budgets. (I wish they had been available when I was a cash-strapped teenager . . .)

Budget systems

Budget systems are typically priced between about $200 and $500 (at 2012 prices, excluding local sales taxes, shipping and options). Taking the budget to this level begins to ensure a more capable, functional, accurate and robust system* which will meet many user requirements for a basic weather monitoring system.

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* Many of these devices are euphemistically referred to by their manufacturers as 'professional' systems, but don't be misled by puffery – none of these can be considered professional weather monitoring systems.

Systems in this price range offer a similar range of sensors to entry-level products, typically comprising exterior temperature and humidity, rainfall, wind speed and wind direction and barometric pressure. Most will also display 'derived' measurements, calculated from the readings from two or more sensors, such as windchill (derived from temperature and wind speed readings).

Compared with entry-level systems, sensors are generally of a slightly higher standard and with improved accuracy. Quoted specifications are typically ± 1–2 degC / ± 2–4 degF for temperature, ± 5–7% for humidity, ± 10% for wind speed and ± 5 mbar for pressure (although the quoted pressure specification for Oregon Scientific's units is no better than ± 10 mbar). As with all other AWSs, local calibration checks are advisable prior to installation and at six-monthly intervals thereafter. Only towards the higher price points of this category is anything other than a 1 mm / 0.04 inch capacity tipping-bucket raingauge included as standard; as previously suggested, a 0.2 mm / 0.01 inch unit is preferable for climatological monitoring purposes and is a worthwhile add-on if budget permits.

Most budget-level systems also include some form of radiation shield for the temperature sensor, although to judge by their visual appearance many of these are unlikely to be particularly effective (some are not even white). If air temperature measurements with any claim to accuracy are sought, it is worth budgeting for a higher-quality radiation shield, or consider higher-spec systems which have more effective units included as standard. All models in this category are still limited to the manufacturer's own sensors, with little or no upgrade/expansion/customization potential. Most systems permit separation of wind and other sensors for better siting of the anemometer and wind vane, but some users may prefer the 'all-in-one' instrument package model used in the Davis Vantage Vue AWS, which is also included in this price band [2].

Systems in this price range typically include a display console as standard, while a basic standalone datalogger as standard can be expected from roughly the mid-point of this price category (see *PC-based or separate logger?* in Chapter 2). It pays to check specifications very carefully as some systems imply datalogging capability, which close reading reveals is PC-based rather than logger-based. A standalone logger removes the necessity for a permanently connected, always-on PC to collect data from the system; depending upon logging interval and memory, a separate datalogger will allow unattended operation for days or weeks.

As with entry-level systems, software included with budget units may be the manufacturer's own basic package, or a limited-functionality version of a more fully featured third-party component: higher-quality third-party software is available for most popular AWS models. Intended purchasers may wish to take note and allow budget to cover the upgrade costs, or choose an alternative system. More details on system software and a survey of system software in use today are given in Chapter 13.

Sampling intervals on budget systems are better than on entry-level systems, typically 1 minute or less. More frequent updates are essential to provide a good record of high-frequency elements, particularly gust wind speeds: Chapter 9 includes more details on the importance of high-frequency measurements when measuring wind gusts. Oregon Scientific's AWSs in this price category specify 14 second update intervals for wind speed and 60 seconds for other elements: better still is the Davis Instruments Vantage Vue unit, which updates wind data every 2.5 seconds.

Check what fittings are included

Check system specifications for what fixtures and fittings are included, as most AWS packaged systems will include only the basic bolts and brackets for fixing sensors to a 25–35 mm (1–1½ inch) diameter mast. Suitable lengths of sturdy steel tubing suitable for mounting anemometers can be obtained from most hardware stores, disguised as tubular TV aerial supports. Builders merchants can source heavier-duty lengths of galvanized scaffolding pole for more substantial installations, rooftop or gable-end masts or particularly exposed sites.

More details on siting anemometers are given in Chapter 9, *Measuring wind speed and direction*.

The higher price point of this category also results in a worthwhile improvement in wireless transmission range. Typical quoted specifications are around 100 m, although as has been noted in the previous chapter these are maximum rather than typical ranges, and they will drop sharply where there are obstructions, in heavy rainfall, or when the battery is near exhaustion. However, loss of record owing to wireless transmission dropouts tend to be much lower with budget systems than those at entry level. System longevity, too, is much improved compared with entry-level systems. Although some sensor failures can be expected during the system lifetime, given typical exposure and occasional maintenance a useful working life of 5 years or more can be anticipated. Availability of spares and replacements often remains problematic for older systems, however.

Site and exposure remain essential ingredients to successful weather measurements, and the importance of both factors stressed earlier in this chapter applies to budget systems as well as entry level. A good radiation shield is also essential for representative and comparable temperature measurements. As with cheaper systems, it is also essential to check the calibration of at least the temperature and rainfall sensors prior to installation, and every 6 months thereafter. Methods of doing this are set out in Chapter 15. With a little attention to detail in this regard, it is possible to reduce the likely ‘out-of-the-box’ errors considerably.

Budget systems – summary

Budget AWSs will meet the needs of many users looking for a system that has tolerable accuracy and covers a reasonably wide range of weather parameters. As with entry-level systems, provided careful attention is paid to siting/exposure and calibration, such systems can provide reasonably accurate weather records over a number of years. Some represent very good value for money.

Mid-range systems

The mid-range portion of the AWS marketplace is dominated by Davis Instruments. At the time of writing the Davis Vantage Pro2 AWS was (by some margin) the best-selling system in any price range.

At this level, products are generally reasonably accurate and robust, and offer some expansion options. A dedicated standalone logger and high-quality reliable software are normally included as standard. One of this class of AWSs will meet many user requirements for a mid-range weather monitoring system: provided the sensors are reasonably well-exposed, and the system given occasional maintenance (including the odd sensor replacement as necessary), there is every reason to expect high-quality reliable and comparable observations for a decade or more.

The range of measurements offered on mid-range systems is similar to budget systems (typically – exterior temperature and humidity, rainfall, wind speed and direction and barometric pressure, together with ‘derived’ measurements such as windchill), but with more accurate and robust sensors. Sensor accuracy approaches professional standards: typically ± 0.5 degC / ± 1 degF or better for temperature, ± 3–4% for relative humidity, ± 0.5 mbar or better for barometric pressure and ± 5% for wind speed: a 0.2 mm / 0.01 inch increment tipping-bucket raingauge is normally included as standard. The radiation shield included as standard on the Davis Instruments Vantage Pro2 model (**Figure 3.2**) is of reasonable quality and efficiency, and consequently temperature measurements from it are broadly comparable to those obtained in Stevenson screens (see Chapter 5 and reference [3] for more details). Some expandability is available – the Davis Vantage Pro2 unit can be expanded to include earth temperature and solar radiation measurements, for example – although apart from support for one third-party anemometer, at the

Figure 3.2. Exterior sensors of a Davis Instruments Vantage Pro2 AWS. (Photograph by the author)

Figure 3.3. The interior display unit of a Davis Instruments Vantage Pro2 AWS. The logger fits into the back of this unit. (Photograph by the author)

time of writing the choice of sensors remains restricted to the manufacturer's units. On the Davis Vantage Pro2 system, the radiation shield and raingauge are combined into one unit, which is far from ideal from an exposure perspective*, but the anemometer/wind vane unit can be separated to optimize exposure, if necessary using an optional separate wireless transmitter to site the wind sensors some distance from the main unit.

All systems in this price range include a display console as standard (**Figure 3.3**), together with a well-specified standalone datalogger, removing the necessity for a permanently connected, always-on PC to collect data from the system. Depending upon logging interval, a separate datalogger permits unattended operation for days or weeks. Software included is of a considerably higher standard than budget-level systems. Davis systems are also supported by most third-party software options (see Chapter 13).

Sampling intervals are a step up from budget systems, and come much closer to that required to provide a good record of high-frequency elements, particularly gust wind speeds: the Davis Instruments Vantage Pro2 model updates wind data every 2.5 seconds, for example.

The higher price point brings a substantial improvement in wireless transmission range. Typical quoted specifications are around 300 m, although as has been noted in the previous chapter these are maximum rather than typical ranges, and they will reduce sharply where there are obstructions, or in poor weather conditions. Except where such systems operate at or close to the maximum supported wireless range, accurate measurements show less than 0.25 per cent loss of record owing to wireless transmission dropouts. System longevity, too, shows a marked improvement on systems at lower price points. Of course, some sensor failures can be expected during the system lifetime, but given typical exposure and occasional maintenance a useful working life of at least a decade can be anticipated, and probably longer. (The author's first Davis Instruments AWS lasted 17 years before being retired.) Long-term

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* Some AWS resellers will supply the radiation shield and raingauge separately, to special order.

availability of spares and replacements, particularly for older systems, can still be an issue. Purchasing spares for key components and sensors, even if not immediately needed, can extend system life well beyond the time when the system is withdrawn from sale by the manufacturer as new models are introduced.

Site and exposure remain essential ingredients to successful weather measurements, and the importance of both factors stressed earlier in this chapter applies to every system. As with other models, it is essential to check calibration of at least the temperature and rainfall sensors prior to installation, and every 6 months thereafter. Methods of doing this are set out in Chapter 15. With a little attention to detail in this regard, it should be possible to reduce most 'out-of-the-box' errors to near-professional levels.

Mid-range systems – summary

Mid-range AWSs will meet the needs of many users looking for a system that has generally good accuracy and covers a wide range of weather parameters. Provided careful attention is paid to siting/exposure and calibration, such systems can be expected to provide reliable and accurate weather records over a decade or more. A typical mid-range AWS costing three times as much as a budget-level system is likely to provide higher-quality records and probably last four or five times longer: viewed over a typical 10 year period, mid-range systems therefore represent much better value for money.

Portable weather stations

Before moving on to the 'advanced' AWS category, it is worth briefly covering portable instruments. These are less often used for 'routine' measurements but invaluable for particular applications, specifically *portable calibration reference units* and *portable AWSs*. Both are within the 'budget' price category. Handheld anemometers are widely and cheaply available, reasonably accurate (site limitations are usually the larger source of error in wind speeds) and are ideal for spot wind measurements where budget or site considerations do not permit permanent installations.

Portable calibration reference units

A portable reference unit is one which can be accurately and professionally calibrated in a laboratory, and then used on-site to check the calibration of other instruments. This is most frequently undertaken with temperature sensors, and a process for doing this is given in Chapter 15.

A suitable product is one of the Tinytag logger range from Gemini Instruments (Chichester, West Sussex, UK – www.geminidataloggers.com). Tinytag dataloggers are self-contained, rugged and reliable battery-operated electronic devices for monitoring environmental parameters. Records are quickly and easily transferred to a PC with a USB or serial cable: a range of wireless data loggers is also available. Tinytag temperature (and humidity) loggers can be supplied with a three-point calibration certificate, making them ideal for checking other sensors. (Members of the UK's Climatological Observers Link – see Appendix 4 for contact details – can borrow one of these units to check the temperature calibration of their own equipment for a nominal fee, plus postage and packing).

Figure 3.4. Tinytag TH-2500 logger (left of centre), here monitoring air temperatures inside a Stevenson screen alongside a platinum resistance sensor and conventional thermometry. (Photograph by the author)

Temperature and/or humidity can be easily and accurately monitored using one of these units, with or without a display (**Figures 3.4**, **3.5**). They are small, light, weatherproof, battery powered, easy to use and very reliable. Tinytag loggers are available with various thermistor options: a thermistor on a short lead will give better results than a logger with a built-in sensor, because the thermal inertia of the logger body makes their response too sluggish. Logging times are software-selectable from seconds to days, and their memory capacity is sufficient to run for typically 4–6 weeks between downloads. Temperature sensors will of course require protection from solar radiation and rainfall in order to provide accurate air temperature measurements. If a screen/radiation shelter is available, the Tinytag sensor should be placed in the screen close to the temperature sensor whose calibration is being checked.

If accurate and high-quality air temperature measurements are required, without the need for a remote display or other weather elements, an ideal combination is the small Tinytag TGP-4020 logger together with a fast-response thermistor on 60 cm / 2 ft lead, plus download cable and logger software, exposed in a small AWS-type radiation shield such as the Campbell Scientific Met21 model shown in **Figure 3.5**. The author's tests of such a combination over 12 months showed a performance almost indistinguishable from that of a professional-quality platinum resistance sensor in an adjacent Stevenson screen. (For more details, see Chapter 5.)

Portable AWSs

Portable AWSs are small, light and entirely self-contained. They are therefore particularly useful for field research, for walkers, for outdoor sports enthusiasts including rowers, glider pilots and the like and any others who require current on-the-spot wind and weather conditions in a handheld unit.

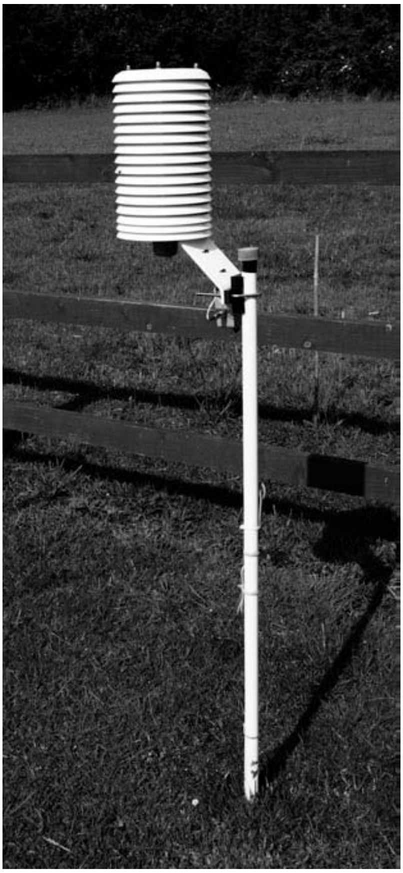

Figure 3.5. Tinytag Plus 2 TGP-4020 logger, here monitoring air temperatures inside a Campbell Scientific Met21 AWS screen. (Photograph by the author)

The Kestrel range of handheld weather meters, manufactured and sold by Nielsen-Kellerman (http://www.nkhome.com/kestrel) of Boothwyn, Pennsylvania provide a surprising number of AWS features in a small device. The top-of-the-range model Kestrel 4000 (**Figure 3.6**) is about the size of a mobile phone, and two AAA batteries will run one for months. It will even float if dropped into water. The Kestrel 4000 measures and logs air temperature, barometric pressure, relative humidity and wind speed (current, average and gusts). Derived values are available for pressure trend, altitude, heat stress index, dew point, wet bulb temperature, density altitude and wind chill (other models are available to support different user requirements). A built-in datalogger records up to 4,000 data points. Logged data can be inspected or graphed on-screen or downloaded to PC using the optional optical coupler, or wirelessly via Bluetooth on more recent models. Logging intervals from 2 seconds to 12 hours are available. Sensor responsiveness, accuracy and repeatability are reasonably good, particularly where local calibration checks against fixed instruments can be made beforehand: temperature within 0.5 degC / 1 degF and pressure within 0.5 mbar is easily attainable. Thermal inertia can be a problem, however – when taken from a warm room to a cold outside environment, the unit can take 10–20 minutes to settle to the ambient temperature, and this must be allowed for in use.

Figure 3.6. The Nielsen-Kellerman Kestrel 4000 portable AWS. (Photograph by the author)

Portable AWSs are particularly useful for field or portable work: with a suitable choice of logging interval they can be used for short-term logging at permanent sites. They are, however, unsuitable for permanent installation.

Advanced systems

Above the price point of approximately $1,500 are the advanced systems. In reality, very few pre-packaged systems exist at this level, the vast majority being combinations of datalogger, software and sensors built to a specification, whether assembled individually to a specific requirement or as part of an ongoing customer contract for hundreds of units. An example of the latter is the UK Met Office's national roll-out of updated monitoring equipment, which commenced in 2010/11 [4]. Pre- and post-sales technical support for configuration options and installation and maintenance services are also part of most contracts.

As might be expected from professional-quality products, systems in this price range are accurate, robust and highly customized, and such AWSs from companies such as Campbell Scientific, Environmental Measurements, Met One Instruments and Vaisala can be found at observatories, universities, airports and wind energy sites throughout the world. Provided site and exposure requirements are satisfied, and regular calibration checks undertaken, such systems can be relied upon to provide accurate, reliable and high-quality weather measurements over many years, for almost all applications, whether in remote or inaccessible locations or in city centres, even in the most hostile of climates (**Figure 3.7** and **Figure 9.6**, page 200).

Professional sensors need to be of a high standard, not only in terms of accuracy but robust enough to withstand extreme operational environments and climates in remote locations where site visits are infrequent. Typical professional-level accuracy levels include ± 0.2 degC / ± 0.5 degF or better for temperature, ± 2–3 % for relative humidity, ± 0.2 mbar or better for barometric pressure and ± 1 % for wind speed, while sensor calibrations traceable to national or international standards are available on request. Air temperature measurements are made within Stevenson-type screens, smaller multi-element AWS screens or, increasingly, aspirated screens (see Chapter 5 for details).

Figure 3.7. Campbell Scientific AWS at the Chota Sikri Glacier, Himachal Pradesh, a remote and high-altitude site in the Himalayas, October 2009. (Photograph courtesy of Campbell Scientific)

The range of measurements possible is limited only by the availability of sensors: if there is a suitable sensor for that parameter that can be hooked up to the datalogger at the heart of the system, then measurements can be made. Such systems can therefore measure a wide variety of additional meteorological parameters beyond the capability of 'packaged' AWSs – visibility, cloud base, CO_2 concentrations, snow depths, atmospheric pollution, lightning detection and warning, rainfall acidity, atmospheric electric fields and present weather are just a few examples. When specifying multi-element systems, care should be taken to ensure the datalogger has both the physical capacity (number of available inputs) and the on-board processing power to manage all of the required sensor channels, together with sufficient onboard memory to store days or weeks of data between downloads if necessary. Dataloggers are covered in more detail in Chapter 13.

System software is of a high professional standard, and such systems offer almost infinite flexibility for customization (although sometimes at a cost of a very steep learning curve). Sampling and logging intervals can be separately specified, and sampling rates as high as 200 kHz are supported. Although no meteorological variables would require a sampling rate anywhere near this figure, sub-second sampling is advantageous in wind and microclimate studies. Some systems are mains powered (with battery backup), but most are run from batteries charged by solar cells and/or wind turbines. Communications can be wireless (with a typical range of 1 km or so), via mobile telecommunications networks or even directly to satellite in remote areas or at sea.

As with every other class of weather measurement, the importance of adequate site and exposure remain unchanged. It is worth repeating that a budget-level system in a well-exposed location will normally provide superior measurements to a more expensive AWS which has been poorly sited. No amount of expenditure on advanced or professional systems will bring the required results without paying careful attention to site and exposure requirements: these are considered in more detail in the following chapter.

Advanced systems – summary

Advanced AWSs tend to be custom-built to a specific requirement, whether for the serious amateur or professional installation, and are capable of almost unlimited expansion. Systems in this price range are accurate, robust and capable of measuring a very wide range of elements, but at a price to match. Provided site and exposure requirements are satisfied, and regular calibration checks undertaken, such systems can be relied upon to provide accurate, reliable and high-quality weather measurements over many years, for almost all applications and locations, even in the most remote areas or hostile climates.

One-minute summary – *Buying a weather station*

- There are enormous differences in functionality and capability between basic and advanced models. The general rule that 'you get what you pay for' holds true for AWSs as well as most other products, but some systems *are* better than others and it pays to check available products carefully against your requirements to ensure the best fit.
- To simplify selection, this chapter suggests five product and budget categories. Most systems fit comfortably within one of these price/performance bands – entry-level systems (single-element, or AWS): budget AWS: mid-range AWS: portable systems: and advanced or professional systems.
- *Entry-level systems.* There are many situations where an entry-level system may perfectly meet the requirements. Provided their limitations in terms of accuracy, capability and lifetime are understood and accepted at the outset, and careful attention is paid to siting and exposure, such systems can represent reasonable value for money for 'starter' weather monitoring system, or those with limited budgets.
- *Budget AWSs* will meet the needs of many users looking for a system that has tolerable accuracy and covers a reasonably wide range of weather parameters. As with entry-level systems, provided careful attention is paid to siting/exposure and calibration, such systems can provide reasonably accurate weather records over a number of years. Some represent very good value for money.
- *Mid-range AWSs* will meet the needs of many users looking for a system that has generally good accuracy and covers a wide range of weather parameters. Provided careful attention is paid to siting/exposure and calibration, such systems can be expected to provide reliable and accurate weather records over a decade or more. A typical mid-range AWS costing three times as much as a budget-level system is likely to provide higher-quality records and probably last four or five times longer: viewed over a typical 10 year period, mid-range systems therefore represent excellent value for money.
- *Portable AWSs* are particularly useful for field or portable work: with a suitable choice of logging interval they can be used for short-term logging at permanent sites. They are, however, unsuitable for permanent installation.
- *Advanced AWSs* tend to be custom-built to a specific requirement, whether for the serious amateur or professional installation, and are capable of almost unlimited expansion. Systems in this price range are accurate, robust and capable of measuring a very wide range of elements, but at a price to match. Provided site and exposure requirements are satisfied, and regular calibration checks

undertaken, such systems can be relied upon to provide accurate, reliable and high-quality weather measurements over many years, for almost all applications and locations, even in the most remote areas or hostile climates.

- AWS specifications are suggested within four very loose 'user profiles' – Starter, Hobbyist, Amateur and Professional – intended as a pragmatic starting point to what is practical and affordable within various budget and site restraints. As an example, with a limited budget it is probably better to concentrate on air temperature and rainfall observations: wind speed and direction (for instance) are more expensive to measure, and the site requirements are more complex. These and other elements can probably follow at a later stage as budgets (and perhaps an improved site) allow.

References

[1] Surveys undertaken by the author in December 2010 (UK/Ireland) and September 2011 (U.S.). Sites were chosen randomly across UK and Ireland, and on a quota basis by state population for the United States. Synoptic reporting sites, and sites where no information on hardware or software was listed, were excluded from the analysis. Survey size was 150 complete sites (hardware and software details) in each geography. As the survey represented a 'snapshot' of an existing body of users with a variety of purchase dates, some of the models listed will no longer be on sale, having been replaced by more recent product introductions.

[2] Online Accuweather review of Davis Instruments Vantage Vue can be found at http://www.accuweather.com/blogs/weathermatrix/story/23115/gadget-blog-the-davis-vantage-vue-station.asp.

[3] Burt, Stephen (2009) *The Davis Instruments Vantage Pro2 wireless AWS – an independent evaluation against UK-standard meteorological instruments*. PDF available at http://www.weatherstations.co.uk/expert_reports.htm and at www.measuringtheweather.com.

[4] Green, Aidan (2010) From observations to forecasts – Part 7. A new meteorological monitoring system for the United Kingdom's Met Office. *Weather*, **65**, pp. 272–277.

4 Site and exposure – the basics

There's an oft-repeated saying that real-estate agents will tell you of the three important factors when it comes to property: *location, location, location*. When it comes to setting up instruments to measure the weather, the refrain could be similar: *exposure, exposure, exposure*.

It is certainly true that a well-exposed budget AWS will give more representative and reliable statistics than a poorly exposed top-of-the-range AWS costing as much as a small car. However, a garden the size of New York's Central Park is not a prerequisite to making worthwhile weather observations, because by taking some care in siting your sensors and following the advice in this chapter, good results can be obtained from all but the most sheltered locations.

Firstly, what is meant by **site** and **exposure**? The two terms are often used synonymously, but in this book *site* is normally used to refer to 'the area or enclosure where the instruments are exposed', while *exposure* refers to 'the manner in which the sensor or sensor housing is exposed to the weather element it is measuring'.

Exposure to what?

Self-evidently, sensors to 'measure the weather' need to be located where they are exposed to the elements. It is not immediately obvious to those venturing into weather measurement for the first time that a perfect exposure for one sensor can be very far from ideal for another. For example, a first-class anemometer exposure would be one where the sensor is mounted on a 10 m (33 ft) mast, without any significant obstructions (ideally nothing more than a couple of metres high, and certainly nothing higher than the height of the anemometer) for at least 300 metres around. Put a raingauge on the mast next to that anemometer, however, and it will catch a lot less than a standard gauge mounted near ground level. Exactly the same applies to raingauges mounted in rooftop locations. This is because the stronger winds and resulting increased aerodynamic turbulence at height act to blow more of the rain over and around the raingauge, rather than allow it to fall into the funnel. The effects are more pronounced with stronger winds, and so are more apparent in windier locations, in winter compared to summer, and on wet days that are also windy.

The following chapters set out preferred site and exposure characteristics for each of the major weather elements in turn, based upon World Meteorological Organization (WMO) published guidance [1], and provide details on the siting of sensors to achieve results that will be comparable to other locations. The overriding reason for setting out standard methods, sensors and observing practices in weather measurement is to minimize or eliminate instrumental or process differences that are not due to real climatic variations. By doing this, the chances are much higher that observations made at one site will be comparable to those made at another – regardless of whether that site is located 10 or 10,000 kilometres away, or whether the records were made an hour ago or a century ago.

Before considering the needs of each element in turn, however, some general remarks about the siting of instruments can be established.

The ideal location for sensors to measure **air temperature** and **rainfall** is a ground-level position on flat ground, or no more than gently sloping terrain, well away from hedges, buildings, trees and other obstructions.

The instruments should be mounted above short grass (in areas where grass grows: the natural terrain of the locality where grass does not grow) and well clear of buildings, areas of tarmac, concrete paving and other artificial surfaces. As far as possible, the site chosen should be typical of its locality (whether city-centre, suburban, rural, coastal, mountaintop or whatever). That way the readings obtained are most likely to be representative of the area in which the instruments are located, and as a result they will be more useful and comparable to other sites, than those which exhibit local effects. Many 'official' weather observing sites are today located at airfields which are often a long way from the centre of the nearest town or city whence they derive their nominal location. But which provides the more representative picture of the city's climate – the windswept airfield outside the built-up area, or a carefully sited AWS in a suburban garden?

For **sunshine**, generally the higher the sensor is located, the better, because horizon obstructions reduce the amount of sunshine recorded by the instrument and therefore make comparison of records with other locations difficult or impossible. (More exposed instruments also tend to suffer less from dew or frost deposits, which can block low-angle sunshine.) **Wind** instruments also benefit from being exposed at height, to reduce the frictional effects of houses, trees and other surface obstructions which will affect wind measurements (both speed and direction) very considerably. Wind speed is probably the most difficult of all elements to measure reliably in a sheltered suburban, 'domestic' or back-garden environment. Rooftop sites are generally not ideal for wind measurements as they can be affected by considerable turbulence, which will itself result in some distortion to measurements, but often such sites may represent the only viable opportunity to obtain wind readings.

Particularly with mast- or rooftop-based measurements, **safety considerations for installation and maintenance are paramount** (see Box, *Important safety considerations for installing and maintaining weather instruments*).

If *wireless sensors* are planned, ensure the distance to the receiver is no more than about half of the manufacturer's maximum separation distance (reception conditions often deteriorate in poor weather). There should not be any significant 'line of sight' obstructions, such as thick brick walls, that will block the signal. For *cabled sensors*, ensure the entire cable length required is supported by the logger and interfacing software: some systems, and some sensor types, do not allow long cable runs. Check also that the cabling can be safely installed without incurring safety risks. For example, unsecured cabling should not obstruct a walkway, be strung close to head height in an area where it may not be visible in darkness, or become entangled with other wiring. This applies particularly in public areas and in schools.

An hour's careful site survey will be time well spent, and may avoid the laborious task of relocating instruments to a better site at a later date. Get a good compass, tape measure and preferably a clinometer (some compasses include a clinometer needle). Note the areas which have best exposure to sunshine, wind and rain. The prevailing wind direction in temperate latitudes is between south and west, and in these climate zones a location open to winds from this quarter, but not too windy, is a good start. (The second-most common wind direction in temperate latitudes is generally between north and east, so if possible try to optimize exposure in those directions too.) Other climate zones should optimize exposure with a view to prevailing winds. Avoid positions close to buildings, close to or under trees, or near solid fences or dense or tall hedging. Avoid locations that might be suitable now, but may become seriously oversheltered owing to tree growth in only a few years – rapidly growing trees or hedges to the south will interrupt a sunshine record, reduce wind speeds, affect maximum temperatures and very substantially reduce measured rainfall totals. If the proposed site may be subject to unwelcome visitors, whether curious small children, domestic pets, wild animals or vandals, you may need to consider some form of site access restriction (see Box, *Access restrictions?*).

Table 4.1 summarizes the main site and exposure requirements by element. More details are given in the following chapters.

Important safety considerations for installing and maintaining weather instruments

Installing and running ground-based weather instrumentation should present few health and safety concerns, provided trailing cables and the like are carefully secured. The risks become much greater, however, when rooftop sites are used. Modern electronic instruments offer many advantages over conventional instruments, not least that small, low-power sensors (such as those used to measure sunshine, wind speed and direction and solar radiation) can more easily be exposed on a mast or rooftop to provide a better exposure. With little or no maintenance required, they can be left here for months or even years. Predecessor instruments which required manual chart records to be changed daily (the Campbell-Stokes sunshine recorder, for example) required safe working access on a daily basis, and this limited the number of sites where the instrument could be deployed.

Rooftops or masts may provide much better exposure for sunshine and wind sensors, amongst others (although they should be used only as a last resort for measurements of temperature and rainfall), but carefully consider the accessibility of the site before attempting to install the sensors. If you have no head for heights, are not comfortable on long ladders, or are in any way unsure whether your do-it-yourself (DIY) skills are up to the job, **DON'T TAKE RISKS**. TV aerial fitting contractors or local builders will often be happy to quote to undertake the work required. With appropriate equipment and experience, a job that would be a major undertaking (and possibly very risky) for a DIY installation will probably be 'all in a day's work' to a specialist.

Installing equipment in a position where it is difficult to gain safe and easy regular access makes it absolutely essential to ensure the equipment and all its connections are set up and tested thoroughly (including logging requirements) over a period of at least a couple of days prior to installation. Finding out that your new wireless anemometer needs a dipswitch setting changed the day after a builder has installed it on your roof is likely to be expensive. Many instruments require regular maintenance – wireless transmitters need batteries replacing from time to time, for example – and unless risk-free access is available these instruments should not be mounted in difficult-to-reach locations.

Exposure to the weather will eventually cause most instruments to fail, but if the expected lifetime is measured in years rather than months then balancing a good exposure against a builder's bill for hire of a scaffolding tower once every 10 years or so may be a fair compromise. Some things remain unpredictable, however. Anemometer bearings may seize up and need lubrication: birds may build a nest around your sunshine recorder: cable clips may snap and leave cables whipping about in strong winds – unfortunately a large bill may result if you are unable or unwilling personally to attend to what is required. The Golden Rule is – **don't take any risks you are uncomfortable with taking**. The DIY installation and maintenance of sensors exposed at considerable heights falls considerably outside the gamut of most domestic or small-office DIY tasks.

Rooftop or mast installations may increase the risk from lightning strikes. Full lightning protection, such as that afforded to church steeples, rooftop satellite dishes and the like is commercially available from specialist contractors, but the costs of doing so will dwarf expenditure on the instruments themselves. Except in the areas most prone to severe electrical storms, the risks of being struck in any one year are quite small unless the building, mast or tower is particularly tall or very exposed, but even a close strike stands a good chance of writing off both sensors and logger (and quite possibly any connected PC and mains electricity circuits too). Some form of commercial lightning protection or grounding kit should be considered in vulnerable areas. When possible, isolate equipment from other components during thunderstorms by using a surge protector or physically unplugging it, and take care not to stand near tall instrument masts during electrical storms.

Access restrictions?

Physical access and site security will not normally be concerns in domestic garden or backyard sites, but they must be carefully considered for sites with public access such as federal or local authority parks, schools and similar environments where vandalism may be a problem. Erecting dense high fencing around the instruments may keep the vandals out, but it will probably keep most of the weather out too. The records of many a long-established regional climatological station have become essentially worthless due to the resultant deterioration in exposure caused by the erection of vandal-proof fencing.

Especially in domestic locations or schools, observation sites may have to share space with other activities. It is not a good idea to site the raingauge where children may use it as a proxy goalpost, for example, and neither is it a good move to shield the instruments from sight by small trees – because in a very few

Table 4.1. *Summary of the main site and exposure requirements by element*

Element	Preferred siting	Access required	More details
Air temperature and humidity	Representative ground-level position, on flat ground well away from obstructions. Instruments should be mounted in a radiation screen (see Chapter 5 for details) around 1.25 m / 4 ft above short grass and well away from areas of tarmac etc. Rooftop sites should be avoided.	Maintenance including cleaning of thermometer shelter, regular grass cutting etc. Hedges and trees should be cut back if growth encroaches. Securely fenced if vandalism may be a problem.	*Temperature*, Chapter 5 *Humidity*, Chapter 8
Precipitation	Representative ground-level position, on flat ground well away from obstructions. Raingauges should be mounted on the ground, preferably above short grass, with their rim at the national standard height. They should be sited well away from areas of hardstanding, concrete or tarmac (which may cause insplash in heavy rain). Rooftop sites are not suitable.	Maintenance including cleaning of raingauge funnel, regular grass cutting etc. Hedges and trees should be cut back if growth encroaches. Securely fenced if vandalism may be a problem.	*Precipitation*, Chapter 6
Wind speed and direction	Ideal is a 10 m (33 ft) mast in open country. Failing this, rooftop sites will probably provide better records than sheltered ground-level sites, but representative records can be difficult to obtain. In some countries, building or planning permission may be needed for masts etc.	Some instruments or wireless transmitters require regular maintenance; where this is so, safe access is essential.	*Wind speed and direction*, Chapter 9
Sunshine and solar radiation	Clear horizon from north-east through south to north-west (in northern hemisphere, temperate latitudes); a rooftop or mast may be ideal for electronic sensors.	Some instruments or wireless transmitters require regular maintenance; where this is so, safe access is essential.	*Sunshine and solar radiation*, Chapter 11
Atmospheric pressure	Sensors can be mounted indoors, provided the building is not sealed. They should not be mounted where they are subject to significant vibration or changes in temperature or airflow (not in direct sunshine, for example, or near heating, ventilation or air conditioning outlets).	Little access or maintenance is normally required.	*Atmospheric pressure*, Chapter 7
Grass and earth temperatures	Open ground-level site freely exposed to sunshine, wind and precipitation - similar to temperature and rainfall instruments – probably co-located with those instruments.	Maintenance including regular grass cutting etc. Hedges and trees should be cut back if growth encroaches.	*Grass and earth temperatures*, Chapter 10

years time those trees will grow enough to overshadow your raingauge, and you will wonder why your rainfall records seem to show a steady (but very local) tendency towards a climate more typical of Morocco than Manchester or Minneapolis. Small children, domestic animals, wild animals or birds and thermometers exposed on the grass simply don't mix – for their safety and the continuity of your records plan appropriate fencing when setting out an observing location. Crows, foxes and squirrels tend to be particularly persistent and creative offenders.

Carefully consider ease of access for maintenance when laying out the site – can the grass be kept tidy around and between the instruments without risk to the instruments or cabling, for example? If the maintenance is being undertaken by an external contractor, in schools, for example, can the required work be undertaken by the contractor without risk of damage to the instruments? Are there any automatic garden sprinklers which may 'water' the raingauge? Think ahead to consider whether a well-exposed site today will become very sheltered in just a few years time as that new conifer hedge planted around it becomes established.

Assessing and grading site and exposure

The UK's Climatological Observers Link (COL)[*] instituted a standard scheme for assessing the relative exposure of its members' observing sites in 1986. This was revised and expanded in 2008 to cater for the increasing adoption of AWSs. The system provides a quick and easy means of assessing the comparability of data between sites with different levels of site, exposure and equipment level, and has since been adopted for use by the UK Met Office on its Weather Observations Website [2].

The COL grading scheme [3] is based around four key site and instrument characteristics, as follows:

- Exposure, standard and calibration of instruments
- Observing practices
- Site, exposure and 'urban profile' information
- Contribution to standard climatological or rainfall networks run by official bodies (such as NOAA in the United States, the Met Office or Environment Agency in the UK, Met Éireann in the Republic of Ireland)

The station grade is summarized by a combination of letters/numbers (**Table 4.2**).

Site, exposure and 'urban profile' information in the COL grading scheme

Because every site is different, objective methods are needed to assess relative exposures. One simple measure, introduced almost 150 years ago by the then British Rainfall Organization, is based upon the ratio of the distance of obstructions from the instrument in question to their height above the sensor. As an example, a building 8 m tall located 25 m away from a raingauge whose rim was at the UK-standard 30 cm height above ground would be said to have a 'shelter

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[*] For details of all organizations referred to, see Appendix 4.

Table 4.2. *The UK Climatological Observers Link station grading scheme*

COL station grading	Characteristics
A	**Standard site**. Records likely to be indistinguishable from those made at other standard sites. Inspected or verified site, with up-to-date site/instrumental metadata.
B	**Sheltered site**. Records made with standard instruments; sheltered exposure may result in some differences from standard site readings.
C1	**Very sheltered site**. Records made with standard instruments; very sheltered exposure may result in significant differences from standard site readings.
C2	**Non-standard instruments or exposure**. Records may exhibit significant differences from standard site owing to instrumentation or exposure limitations.
U	**Exposure and instruments unstated or unknown**. Includes new sites not yet graded.

ratio' of 3.2 h (i.e., 25 / 7.7). For most instruments, the larger the ratio the better the exposure.

Over the years, a minimum ratio of 2 h (i.e., obstructions are at least twice their height away from the instrument) has been found to be a reasonable rule-of-thumb threshold for a degree of shelter likely to result in some effects on the observations made. (Although the measure was defined originally for rainfall measurements in the UK, it has been found over the years to have useful relevance to other measurements and other countries too, and is included in many WMO guidelines.) The nature, extent and compass bearing of all obstructions should be carefully considered – a dense hedge extending 20 m in either direction at a distance equivalent to twice its height to the south of a raingauge or thermometer screen will have much more effect on measurements than a tall, slender anemometer mast to the north, for example. For this reason it is advisable to take ground measurements at the planned site (distance, bearing, heights and/or angles using a clinometer) and, plotting the results, carefully evaluate the best position for instruments (one which will be least affected by obstructions) bearing in mind climatic factors – prevailing winds and the wind direction which provides most rainfall, for example.

Shelter is assessed under the COL grading scheme in a simple numerical code from 0 to 5, where 5 is the most exposed (**Table 4.3**): *h* represents the ratio of the distance of the obstruction to its height above the sensor.

In a survey of UK COL stations in 2008 [4], the distribution of shelter gradings was as shown in **Figure 4.1**. About 40 per cent of the published sites rated as 'very open', 'open' or 'standard' exposures; the majority were somewhat restricted in exposure. As stated previously, a restricted or sheltered exposure should not be seen as an insuperable barrier to making worthwhile weather measurements, provided careful consideration is given to choosing the best possible site under the circumstances. After all, many 'restricted' or 'sheltered' sites may be much more representative of their suburban locations within a town or city than a distant airfield. They are often more typical (and certainly exist with a greater spatial density) than observations made in inner-city parkland sites such as the state weather service reporting site at St James's Park in central London (**Figure 4.2**).

Table 4.3. *The UK Climatological Observers Link shelter assessment scheme*

5	**Very open exposure;** no obstructions within 10h or more of temperature or rainfall instruments
4	**Open exposure;** most obstructions/heated buildings ≥ 5h from temperature or rainfall instruments, none within 2h
3	**Standard exposure;** no significant obstructions or heated buildings within 2h of temperature or rainfall instruments
2	**Restricted exposure;** most obstructions/heated buildings ≥2h from temperature or rainfall instruments, none within 1h
1	**Sheltered exposure;** significant obstructions or heated buildings within 1h of temperature or rainfall instruments
0	**Very sheltered exposure;** site obstructions or sensor exposure severely limit exposure to sunshine, wind, rainfall
R	**Rooftop site**

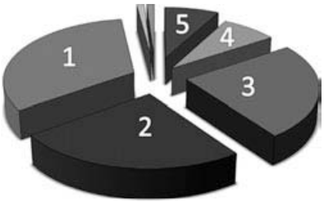

Figure 4.1. Shelter gradings at COL stations in UK and Ireland in 2008; see text for details. The two smallest segments refer to exposure 0 and rooftop sites.

Figure 4.2. The weather station at St James's Park in London in 2009. Observations have been made at this inner-city site, located only 400 m south-west of Trafalgar Square in central London, since 1903, although the record is not continuous and there have been several minor site moves in that time. (Photograph by the author)

Urban profile

The COL station grading scheme adopts work by the Canadian climatologist Professor Timothy Oke [5, 6] of the University of British Columbia in Vancouver in attempting to provide a broad-brush categorization of the wider urban or rural environment surrounding the site (**Figure 4.3**). A combination of the shelter coding

Urban Climate Zone, UCZ[1]	***Image***	***Rough-ness class***[2]	***Aspect ratio***[3]	***% Built (imperm-erable)***[4]
1. *Intensely developed urban with detached close-set high-rise buildings with cladding, e.g. downtown towers*		8	>2	>90
2. *Intensely developed high density urban with 2–5 storey, attached or very close-set buildings often of brick or stone, e.g. old city core*		7	1.0–2.5	>85
3. *Highly developed, medium density urban with row or detached but close-set houses, stores & apartments e.g. urban housing*		7	0.5–1.5	70–85
4. *Highly developed, low or medium density urban with large low buildings & paved parking, e.g. shopping mall, warehouses*		5	0.05–0.2	70–95
5. *Medium development, low density suburban with 1 or 2 storey houses, e.g. suburban housing*		6	0.5–0.6, up to >1 with trees	35–65
6. *Mixed use with large buildings in open landscape, e.g. institutions such as hospital, university, airport*		5	0.1–0.5, depends on trees	<40
7. *Semi-rural development, scattered houses in natural or agricultural area, e.g. farms, estates*		4	>0.05, depends on trees	<10

Keys to image symbols. ▯ buildings; ♠ vegetation; ▬ impervious ground; ┄ pervious ground

Figure 4.3. Oke Urban Climate Zones. Reproduced from *WMO Instruments and Observing Methods Report No. 81, Initial guidance to obtain representative meteorological measurements at urban sites,* by Tim R. Oke (2006): by kind permission of the World Meteorological Organization, Geneva.

Notes to original Figure: [1] A simplified set of classes that includes aspects of the schemes of Auer and Ellefsen plus physical measures relating to wind, thermal and moisture controls (columns at right). [2] Effective terrain roughness according to the Davenport classification. [3] Aspect ratio = z_H/W is average height of the main roughness elements (buildings, trees) divided by their average spacing, in the city centre this is the street canyon height/width. This measure is known to be related to flow regime types and thermal controls (solar shading and longwave screening). Tall trees increase this measure significantly. [4] Average proportion of ground plan covered by built features (buildings, roads, paved and other impervious areas) the rest of the area is occupied by pervious cover (green space, water and other natural surfaces). Permeability affects the moisture status of the ground and hence humidification and evaporative cooling potential.

For full details and references, the original document should be consulted.

and the urban profile coding provides a first approximation of the site characteristics, and enables better comparisons to be made between sites. For example, a site graded as 'open exposure, rural' might be expected to experience lower night minimum temperatures and higher wind speeds than a nearby site assessed as 'restricted exposure, suburban'. Differences in observed night minima between the two sites might provide an indication of the intensity of the urban heat island in and around the town or city where the sites are located. A recent Dutch study has used both amateur and professional weather stations to map urban heat island effects [7].

The following chapters now consider the detail of weather measurements by element.

One-minute summary – *Site and exposure – the basics*

- *Site* refers to 'the area or enclosure where the instruments are exposed', while *exposure* refers to 'the manner in which the sensor or sensor housing is exposed to the weather element it is measuring'.
- Satisfactory site and sensor exposure are fundamental to obtaining representative weather observations. An open well-exposed site is the ideal, of course, but with planning and careful positioning of the instruments, good results can often be obtained from all but the most sheltered locations.
- A good exposure for one sensor can be the exact opposite for another. For representative wind speed and direction readings, for example, an anemometer mounted on top of a tall mast is ideal, but this would be a poor exposure for a raingauge owing to wind effects (more on this in Chapter 6).
- Based upon World Meteorological Organization (WMO) published guidance, this chapter outlines preferred site and exposure characteristics for the most common sensor types. No single exposure will provide a perfect fit for the requirements of all sensors. A simple and objective grading scheme to assess and report site, exposure and instrumentation is outlined.
- Rooftops or masts may provide much better exposure for some sensors, but carefully consider the accessibility of the site before attempting to install the sensors. If the proposed site cannot be reached safely, fit appropriate safety measures or find another site. **Do not take personal risks, or encourage others to do so, when attempting to install weather station sensors, particularly at height**.

References

[1] World Meteorological Organization, WMO (2008) *Guide to Meteorological Instruments and Methods of Observation*. WMO No. 8 (7th edition, 2008). Available online from: http://www.wmo.int/pages/prog/www/IMOP/publications/CIMO-Guide/CIMO%20Guide%207th%20Edition,%202008/CIMO_Guide-7th_Edition-2008.pdf.

[2] UK Met Office Weather Observations Website (WOW): http://www.metoffice.gov.uk/climate/uk/wow.html.

[3] Burt, Stephen (2008) *The 2008 COL station grading system: Progress review and proposed amendments*. Presentation by the author to COL Annual General Meeting, York, England, October 2008; full details at http://www.met.rdg.ac.uk/~brugge/col/grade.html

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[7] Wolters, Dirk and Brandsma, Theo (2012) Estimating the Urban Heat Island in residential areas in the Netherlands using observations by weather amateurs. *Journal of Applied Meteorology and Climatology*, doi: http://dx.doi.org/10.1175/JAMC-D-11-0135.1.

PART TWO

MEASURING THE WEATHER

This and the following chapters provide brief descriptions of both 'traditional' and 'modern' methods of measuring each weather element. The format is identical for each variable in turn – international recommendations on siting and instruments from the World Meteorological Organization are given first, followed where appropriate by country-specific details for the United States, the United Kingdom and the Republic of Ireland. A book of this size cannot hope to include detailed observational practice for every observed element covering every country in the world, but by setting out the appropriate WMO recommendations followed by references to individual national or state weather services it is hoped that information regarding any variations in observing practice for other countries or regions can be quickly and easily identified.

Guidelines for choosing a representative exposure for each instrument type are given in turn, and methods to ensure compatibility with existing national or international standards and sensors are also suggested. Of course, it is not always possible to follow WMO guidance in every detail, particularly where site and/or exposure may be limited, and tips for obtaining optimum results under such circumstances are given.

A brief summary of each chapter is given at the end of that chapter; for those looking for a quick overview of each element, this short section ('One-minute summary') summarizes briefly the main points covered. For convenience, these short summaries are collected together in Chapter 20, Summary and getting started.

An understanding of how mechanical and electrical instruments function and respond is very helpful in getting the most out of any measurement system. More technical details on instrumental theory and methods are given in Appendix 1 and more specialized material listed in its reference list.

5 Measuring the temperature of the air

Air temperature is the first element reviewed in this section of the book, as for many this will be the first or highest measurement priority. This chapter describes how the temperature of the air is measured, and the main difficulties involved in obtaining accurate and representative measurements. Recommendations on siting and instruments from the World Meteorological Organization (WMO) are included [1], followed by country-specific details most relevant to the United States, the United Kingdom and the Republic of Ireland. Recommendations on observing practices in other countries can generally be found on that country or region's state weather services web pages [2]. A brief summary is given at the end of the chapter.

Methods for making grass and earth temperature measurements are covered in Chapter 10.

What is meant by 'air temperature'?

The 'temperature' of a body is a measure of the heat energy of that object, itself a measure of the kinetic energy of the atoms or molecules of which the object is composed. Temperatures are measured with reference to defined fixed scales set out in terms of physical changes in state of various substances, such as ice and water for temperatures within normal meteorological ranges [3]. In international meteorological and climatological use, temperatures are normally expressed in degrees Celsius (°C), although the older Fahrenheit scale (°F) is still in general public use within the United States. Temperature *intervals* are expressed in Celsius degrees (degC) or Fahrenheit degrees (degF): 1 degC is also identical to 1 Kelvin, a measure of absolute temperature, where absolute zero = 0 K (= – 273.15 °C). A conversion table from °C to °F is given in Appendix 3.

Temperature is one of the most important meteorological quantities; it is also one most influenced by the exposure of the thermometer[*]. Take great care in exposing air temperature sensors to ensure that, as far as possible, the instrument reading is both accurate and representative, and not unduly influenced by the instrument housing, surrounding vegetation or ground cover, the presence of buildings or other objects. The establishment of standards by bodies such as WMO goes a long way to ensuring

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[*] The term 'thermometer' is used in this chapter as convenient shorthand for 'a device capable of measuring temperatures', rather than in the conventional sense of a graduated liquid-in-glass sensor. Unless a specific context is given, it should be taken as covering all sensor types used to measure temperatures. Where the narrower sense is meant, this is made clear in the text.

that temperature records from one locality, or a particular time period, can be confidently compared with those made in another locality or in previous decades, for studying phenomena as varied in timescale as decades-long climate change or hour-by-hour urban heat-island intensity.

Measuring the temperature of the air is therefore not as straightforward as it may seem. There are numerous factors which can influence the reading of a thermometer exposed to the air [4]:

- During daylight hours, it must be adequately protected from both incoming and reflected short-wave solar radiation (sunshine) at all incident angles, and from re-emitted long-wave (infrared) radiation from the Earth's surface and atmosphere. Without adequate shielding the sensor will absorb this radiation, and as a result the temperature indicated will be higher, perhaps much higher, than the true air temperature.
- At night, the sensor must be shielded against terrestrial radiation, from both sky and ground, because exposure to infrared radiation from the sky will cause it to read lower than the true air temperature, particularly under clear skies.
- Air is a very effective insulator, and to ensure changes in air temperature are reflected in the sensor reading the instrument should be in good contact with the air – and therefore well-ventilated, so that it quickly takes up and indicates the temperature of the air passing over it and responds quickly to changes. In most conventional thermometer housings, however, this requirement has to be balanced against the need for protection against solar and terrestrial radiation, not always successfully.
- The sensor requires protection from precipitation, for a device that is wet will cool below the true air temperature in dry air, owing to evaporative cooling (this is the principle of the wet-bulb thermometer, used to determine water vapour content of the air – see Chapter 8).
- The thermometer housing should also provide a uniform internal temperature environment which is the same as the true external air temperature. Its response time to take up changes in air temperature should be as small as possible, preferably no more than about a minute (see Appendix 1).
- The sensing device used must be sensitive enough to respond quickly to changes in air temperature on timescales of a minute or less, but not so sensitive as to respond to minor second-by-second fluctuations which are largely irrelevant for most meteorological purposes.
- The sensor itself should be robust, stable in calibration, easy to use and capable of deployment and use by non-specialists in different operational environments, some of which may be in challenging climatic conditions or in remote locations. An operational life of a decade or more is preferable, to provide consistency in measurements and minimize sensor changes in the station's climate record.
- As far as is commensurate with other requirements above, the sensor must also be protected from the corrosive effects of air pollution or the weather itself, from the risks of accidental damage, and all too frequently from the attention and destructive influences of thieves or vandals.

Many of these requirements mandate a physical thermometer shelter, often referred to generically as a 'thermometer screen'. Many different types and designs of thermometer screen have been used over the years, and numerous descriptive and comparative analyses have been documented [5]. WMO's recommendations [1] state "In order to achieve representative results . . . a standardized exposure of the screen and, hence, of the thermometer itself is . . . indispensable."

For most weather measurements, the requirement is to measure air temperatures which are representative of conditions over a wide area. The height above ground at which the temperature measurements are made is important, because the surface of the ground can become very much warmer in sunny conditions, and very much colder on clear nights, than the air just a metre or two above the surface. Large vertical temperature gradients can come and go very quickly. For this reason air temperatures are typically measured at a height between 1.2 m and 2.0 m above ground level, with some variation from country to country. The type of ground surface will also influence air temperatures – readings made above black tarmac will be higher in sunny weather than those measured above short grass, for instance – and measurements made over or near such artificial surfaces will be unrepresentative.

These requirements are covered within this chapter, starting with site and exposure.

Finally, in order to ensure compatibility with other observing locations, the time period/s within the day to which measurements relate (such as mean, maximum and minimum daily temperatures) must be consistent between sites. This is covered in more detail in Chapter 12, *Observing hours and time standards.*

Site and exposure requirements for measuring air temperatures

WMO's guidance [1, paragraph 2.1.3.4] is clear and concise:

> "The best site for [temperature] measurements is, therefore, over level ground, freely exposed to sunshine and wind and not shielded by, or close to, trees, buildings and other obstructions."

Significant obstructions such as buildings, walls, hedges and so on should preferably be located at least twice their height, and preferably five times or more, distant from the planned observation location. More sheltered locations can still provide worthwhile measurements provided the instruments are sited carefully (see previous chapter). Certain locations are best avoided, however, as readings obtained in these situations may bear little comparison to observations made elsewhere under standard conditions:

- Very sheltered positions, with little free airflow or exposure to sunshine, including north-facing walls: obstructions or buildings which will lead to significant local sheltering – such as a tall thick hedge located upwind in the direction of the prevailing wind – or other locations surrounded by buildings or tall fencing/hedging;
- Locations which may result in significant additional reflected radiation, such as a large expanse of south-facing wall or windows located north of the instruments, should be avoided because the additional reflected radiation will result in warming by day. Stored heat released during the night will also affect nocturnal temperatures;
- Rooftop or chimneypot sites, house eaves and shed roofs should be avoided because of the complex effects of the building itself on the observed temperature;

- Sites with significant topographic shelter – on steep slopes, in narrow valleys or in hollows, where such shelter may induce or enhance stable stratification and enhanced radiational cooling leading to the generation, draining and trapping of cold air. Such sites can be subject to exceptional conditions and may not be representative of the wider area;
- Masts or towers where the screen is significantly sheltered by the mast structure, or where the sensor/screen combination is higher than about 2 m above the ground, may give misleading results, as will locations under overhanging trees or near exhaust gases (for example, close to air conditioning outlets);
- Areas of tarmac or concrete near the site should be avoided, as these can become very warm in sunny conditions, and may lead to artificially high readings. The UK Met Office has recently added the specific stipulation to its requirements that 'less than 50% of the area within 100 m of the site should be hardstanding or buildings'. Many airport or airfield sites are very close to extensive areas of tarmac; where there is little choice of site for operational reasons, if possible ensure the thermometer screen is located *upwind* of the prevailing wind direction of such surfaces.

If a site open in all directions cannot be found, one allowing the best available exposure to sunshine and wind (particularly the prevailing wind) should be chosen. Any site shelter should not be so dominant in any direction as to make readings difficult to compare with other sites under varying wind conditions.

Shelter effects – daytime and night-time

Unfortunately, 'ideal WMO site' conditions are not always available, and many sites necessarily have to compromise in one area or another, most often in the degree of shelter.

The effects of site shelter will vary with time of day, time of year and with weather conditions, and are most pronounced under conditions of little or no cloud and light winds. Under sunny skies and light winds, a sheltered site will usually show higher air temperatures than a nearby 'open' location, as a result of the reduction in heat transport by the wind (advection/forced convection) away from objects warmed by sunshine – including of course the screen structure itself. All else being equal, maximum temperatures in sheltered locations under such conditions during the summer months in temperate latitudes are often 1–3 degC / 2–5 degF above those measured in more open locations nearby. Even under cloudy and windy conditions, differences can remain substantial – during the summer months a difference of 1 degC / 2 degF is not unusual even under unbroken cloud cover. In subtropical or tropical latitudes, these differences can be expected to be larger, given higher solar radiation receipts.

During the night, effects due to direct solar radiation are obviously eliminated, but other factors come into play. Wind speeds are normally lower at night, and a sheltered location may experience little or no air movement at screen height for several hours, whereas a more exposed site may experience a persistent breeze throughout. This continual stirring of the air may act to keep the temperature at the more open site significantly different (higher *or* lower) from that in a sheltered location.

A sheltered urban or suburban site which is surrounded by buildings often experiences higher night-time minima (typically by 0.5–2 degC / 1–4 degF) under clear-sky conditions in both winter and summer, the effects being a combination of delayed heat release from the urban infrastructure and a reduction in both outgoing radiation and ventilation affecting the screen/radiation shelter itself. In fine, settled, hot spells in summer these urban heat-island effects can quickly become substantial, and differences of 5–7 degC (9–13 degF) between suburbs and nearby rural districts just a few kilometres away are not uncommon, particularly early in the night. On the other hand, cloudy, windy, dry nights can be a good time to check calibrations across different types of screens and sensors, because differences should be small – less than 0.1 degC / 0.2 degF – and any significant calibration errors can be identified quite easily, provided the readings of at least one sensor are known accurately. (See Chapter 15 on calibration techniques for details.)

How representative are urban and suburban sites?

How best to measure and represent urban climates is a subject that has generated debate amongst the professional climatological community for decades, for a well-exposed open site in a city centre is, almost by definition, not likely to be typical of the built-up area. Although the biases likely to result from sheltered sites can be comparable with, or even greater than, sensor calibration errors, a sheltered location in itself need not rule out useful weather measurements. Indeed, many a back-garden or backyard site, with carefully located instruments, may be more typical of the location and provide a more representative picture of the 'true' climate of the town or suburb. It is, however, more difficult to distinguish between purely site- or instrument-specific effects, and those that are truly representative of the urban or suburban character of the area.

Thermometer screens

We have already seen that thermometers need to be protected from the elements, while at the same time ensuring adequate ventilation is provided. Such protection is most often provided by a suitable instrument shelter, usually referred to generically as a 'thermometer screen' (*not* a 'temperature screen') or 'radiation shield'. Because the means of exposure of air temperature sensors has a much greater impact on the observed readings than all but the least accurate sensors, the type and choice of thermometer screen is the most important factor when it comes to making accurate and comparable measurements of air temperature. It is therefore considered first.

There are many different types and designs of thermometer screens in use worldwide [5, 6], but three types dominate – the louvred or *Stevenson screen* type, still the standard shelter in many countries; smaller plastic *AWS radiation screens* ideally suited for deploying smaller electronic sensors, such as those used at Maximum Minimum Temperature System (MMTS) sites in the United States; and *aspirated screens*, which use a fan to provide a constant flow of air drawn from the immediate surroundings over the sensors. Aspirated sensors are used in the Automated Surface Observing System (ASOS) and the U.S. Climate Reference Network (USCRN) (see *Acronym soup* below). All three main types are described here, together with their advantages and disadvantages.

Less expensive alternatives, including home-made shelters, can suffice where high accuracy or comparability with other sites is not required, or for those on a tight budget, and these are also covered briefly. It should be noted at this point that *almost any form of radiation shield will give better results than a bare sensor*.

Louvred screens

Louvred wooden or plastic thermometer screens are as close to a worldwide standard as currently exists, and are a familiar sight around the world (**Figure 1.6**). The wooden, double-louvred shelter now known as the *Stevenson screen* (**Figure 5.1**) was first described by Thomas Stevenson in Scotland in 1866 [7] (see Chapter 1). It was subsequently refined slightly in various experimental trials in England in the 1870s before it was adopted as the standard thermometer shelter by the Royal Meteorological Society in Britain in 1884 [8], and quickly adopted in many parts of the then British Empire during the late 19th century. Various iterations of the original design remain the standard screen to this day in Great Britain, Ireland, Canada, Australia, New Zealand and many other countries within the British Commonwealth. The *Cotton Region Shelter*, introduced by the U.S. Weather Bureau towards the end of the 19th century and still widely used throughout the Americas (**Figure 5.2**), is slightly larger than the Stevenson screen but is otherwise similar in design, materials, and construction (some are single-louvred, rather than double). Broadly similar designs of louvred screen remain in use in many other countries.

Comparative dimensions of the U.S. Cotton Region Shelter and the UK-pattern Stevenson screen

Approximate external dimensions W x D x H, in millimetres; slight variations in size and pattern exist.

Cotton Region Shelter (**Figure 5.2**)	760 × 510 × 810 mm	Volume 0.31 m^3
UK Stevenson screen – large pattern (**Figure 5.1**)	1100 × 400 × 600 mm	Volume 0.26 m^3
UK Stevenson screen – standard size (**Figure 5.3**)	570 × 390 × 580 mm	Volume 0.13 m^3

The basic elements of the louvred screen design are similar – a four-sided single- or double-louvred enclosure with overlapping floorboards, topped off with a ventilated rain-proof roof. The ventilated roof, louvres and the overlapping bottom boards allow natural ventilation of the interior of the screen, while preventing the ingress of direct or reflected solar or terrestrial radiation or rainfall (fine snow does, however, tend to be blown into such screens). One side is hinged as a door to allow access to and observation of the thermometers – normally on the north side in the northern hemisphere, to prevent the Sun shining on the instruments at any time of day while the door is opened. The screen is usually mounted on a metal stand. WMO guidance is that the thermometers be located between 1.2 m and 2 m above ground level

Figure 5.1. Large Stevenson screen from the UK showing the enclosed thermometers and two autographic recording instruments. The two vertically mounted units are the dry-bulb (left) and the wet-bulb: the horizontal thermometers are the maximum (top) and minimum. The two autographic paper-based instruments are a thermograph (left) and hygrograph (right). Sandhurst, Berkshire, UK. (Photograph by the author)

Figure 5.2. A Cotton Region Shelter, near Asheville, North Carolina. (Photograph by Grant Goodge)

(the standard height in the UK and Ireland is 1.25 m ± 0.1 m; in the United States between 4 and 6 feet), although in areas where significant accumulations of snow occur the screen can be mounted on an adjustable stand to keep the thermometer height at roughly the same level above the snow surface as the snow depth varies. The whole structure is painted gloss white to reflect as much solar radiation as possible. All surfaces should be kept clean by regular washing, particularly in areas with significant levels of airborne pollution or high windborne salt loading.

Louvred thermometer screens of this type and size were usually built to accommodate more than one type of thermometer, most often maximum and minimum thermometers together with a dry- and wet-bulb hygrometer, used to determine humidity (see Chapter 8). Some models accommodate clock-driven automatic instruments recording on paper charts (**Figure 5.1**). Modern electronic sensors, and even loggers, are so much smaller than traditional paper-based autographic instruments that large Stevenson-type thermometer screens are no longer *de rigeur*, except for the purpose of maintaining consistency and homogeneity with long-period records, and smaller radiation screens are steadily replacing them. Smaller screens, with reduced bulk/mass and thus lower thermal inertia, are probably preferable to bulkier 'traditional' screens where continuity or overlap of record is not a prime consideration.

Plastic Stevenson-type screens

Stevenson screens were originally made of wood (and many still are), but more recently aluminium and plastic or fibreglass models (**Figure 5.3**) have become available. Careful side-by-side trials conducted in several locations – by the UK Met Office in particular, who adopted the 'Metspec' plastic screen as standard in 2006 – have shown that differences between plastic and wooden screens are small, typically < 0.1 degC, and so mostly insignificant for operational and climatological purposes [9,10]. Accordingly, traditional wooden screens are being progressively replaced by the Metspec variety at both UK Met Office synoptic and climatological stations and an increasing number of privately maintained sites. A similar replacement policy is in place for Met Éireann sites within the Republic of Ireland.

Plastic Stevenson-type screens – more expensive than the wooden variety – possess the enormous advantage of being almost maintenance-free, requiring little more than an occasional wipe-down with a wet cloth (although a regular thorough wash, inside and out, also helps to keep the inevitable resident insect population in check). When new, these screens are bright, shiny white, but over time exposure to the elements, particularly ultraviolet radiation, tends to dull the surface to a pale grey matte finish. The plastic can also become brittle, particularly at low temperatures. Plastic Stevenson screens have been in widespread use for less than 20 years and the extent and significance of any long-term deterioration in radiative properties have yet to be determined.

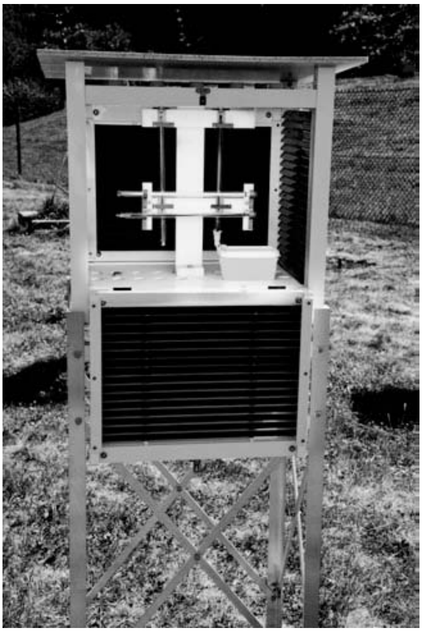

Figure 5.3. Modern plastic and aluminium 'standard size' UK Stevenson screen by Metspec showing the thermometers/sensors located inside the unit, and the black interior finish. Whipsnade Observatory, Bedfordshire, England, July 2010. (Photograph by the author)

In the United States, many Cotton Region Shelters containing conventional thermometers have been replaced by electronic sensors housed within small plastic radiation shields as part of the MMTS programme [11].

Acronym soup: a brief overview of today's U.S. and UK observing systems

ASOS – Automated Surface Observing System (U.S.)

ASOS sites (**Figure 1.2**) are operated in the United States jointly by the National Weather Service (NWS), the Federal Aviation Administration (FAA) and the Department of Defense (DOD) [12]. As at late 2011, there were 938 ASOS sites within the United States (**Table 5.1,** page 103). Deployment of ASOS units began in 1991 and was completed in 2004, and followed on from an earlier program, the Automated Weather Observing System, AWOS. Some AWOS sites remain in use.

ASOS is primarily a multi-element observing system to meet the requirements for meteorological information for aviation, but also serves as the primary climatological observing network in the United States. Because of this, not every ASOS is located at an airport; for example, one is located at Central Park in New York City to continue the long weather record there (see Chapter 1).

ASOS systems normally report at hourly intervals, but also report special aviation observations if weather conditions change rapidly. Standard reports include wind speed and direction, visibility, automated present weather (falling precipitation), cloud extent and base/ceiling, air temperature (aspirated platinum resistance sensor) and dew point (humidity sensor), barometric pressure, precipitation accumulation and icing (freezing rain); some also report nearby lightning strike activity.

MMTS – Maximum-Minimum Temperatures System (U.S.)

The U.S. National Weather Service (NWS) began to update its second-order climatological observing network in the mid 1980s, with a programme to replace traditional liquid-in-glass thermometers and Cotton Region Shelters at thousands of cooperative observer sites across the country [13]. The wooden shelters had become increasingly expensive and difficult to maintain, while NWS was also experiencing difficulties in sourcing high-quality self-registering thermometers at an acceptable price. An ageing corps of volunteer observers was also finding these thermometers difficult to read. Over a period of a few years, about half of the network was migrated to a remote-reading (cabled) temperature measurement system, the imaginatively titled maximum-minimum temperatures system (MMTS), comprising an electrical resistance sensor (thermistor) housed in a specially designed radiation shield (**Figure 5.4, top**) mounted at about 1.5 m / 5 feet above ground level. As at mid 2011, there were more than 2,000 MMTS sites across the United States.

MMTS is a manual system – no logger is included. Daily maximum and minimum are recalled from the remote display unit's memory (**Figure 5.4, bottom**) and noted manually, and the memory then reset, thus directly replicating the observation routine of conventional thermometry. Observations are then transcribed to an electronic or manuscript form and then sent monthly to a regional National Weather Service office, where they are digitized and added to the regional and national weather archives.

Figure 5.4. (Top) MMTS radiation shield (right of picture). The large shelter is a ‘Hazen’ louvred screen, fitted with an aspiration fan. Fort Collins, Colorado. (Photograph by Grant Goodge). (Bottom) MMTS interior display unit. (Photograph courtesy of National Weather Service)

The MMTS system is simple and inexpensive: however, its rapid introduction has been criticized as giving rise to major discontinuities in many long-term U.S. climatological records [11], although independent temperature measurements using precision aspirated thermometers ‘suggested that MMTS measurements were likely closer to truth ... than those from the traditional wooden weather shelters’ [13]. However, one sustained criticism has been its use of cabling between sensor location and display, and relatively short cable runs at that, the cabling providing both power and data transmission. Where obstacles or lack of resource have made burying the cable impossible, some sensor locations have had to be relocated, and some badly compromised in doing so. Many previously satisfactory observing sites were moved to highly unsuitable positions, being relocated only 2–3 m from buildings, in parking lots, too close to air conditioning outlets, and so on [14]. A multi-year volunteer survey [15] found that the exposure of only a small minority of the MMTS sites could be regarded as ‘satisfactory’. Other researchers have suggested that the introduction of MMTS created a strong cooling bias in maximum temperatures and a moderate warming bias in minimum temperatures, resulting in an overall cooling bias in mean temperatures. A suitable remedy would seem to be to replace existing cabled systems with wireless units in more suitable exposures, but clearly significant damage has already been done to many long-term temperature records.

Lightning-induced currents in the cables also resulted in frequent damage to electronics modules, and even started a few fires. More difficult to spot was the change in resistance in the thermistor circuit that accompanied less severe electrical surges, some producing permanent temperature changes of 1–2 degC (2–4 degF). Damage to cables also occurred from rodents and burrowing animals, while (particularly in the southern states of the U.S.) various unpleasant insects found MMTS units to be ideal residences [16]! The early years of the MMTS program also saw the 'white' paint of the louvred plates deteriorate to pale yellow within a few years, although more recent models have improved paint formulations that are more resistant to yellowing.

MMS – Meteorological Monitoring System (UK)

The UK Met Office owns and operates a network of more than 200 AWSs. In 2003, a project to deliver a modern, value-for-money and sustainable replacement surface observing system was established, known as the Meteorological Monitoring System (MMS) [17]. This replaced and updated a number of older discrete systems run by the UK's national weather service.

MMS offers the availability of observations at time resolutions down to 1 minute, improved central control and monitoring capabilities, and greater overall flexibility to add new sites and sensors. At manned sites the capability to include various 'manual' or 'eye observations' (such as cloud amounts and types) within the coded messages is also included. MMS is run from a highly resilient central system located at the UK Met Office headquarters in Exeter in south-west England.

MMS units are primarily deployed in support of operational forecasting, aviation and defence requirements, but some units automate existing long-term climatological sites.

Whilst offering the advantages of an improved real-time synoptic reporting network, the withdrawal of daily observer presence often leads to a decrease in record quality and reliability. Minor faults – such as a blocked tipping-bucket raingauge or instruments becoming buried by snowfall – can remain unnoticed and uncorrected for days or weeks at a time, and maintenance is often reduced or withdrawn altogether by the host authority. Enclosure and instruments can quickly become unkempt or overgrown (**Figure 5.5**). Unfortunately, the cumulative effect is often damage to the continuity, reliability and quality of the observational record.

USCRN and USRCRN – NOAA's new Climate Reference Networks

The U.S. Climate Reference Network (USCRN) consists of 126 stations (at the time of writing) developed, deployed, managed, and maintained by NOAA in the continental United States for the express purpose of detecting the national signal of climate change [18]. Such a system is rightly distinct from the less stringent requirements of day-to-day operational meteorology required for aviation and forecasting purposes.

The USCRN program adheres as closely as possible to Climate Principles endorsed by the U.S. National Academy of Sciences (NAS) and the Global Climate Observing System (GCOS). The vision of the USCRN program is to maintain a sustainable high-quality climate observation network that, 50 years from now, can with the highest degree of confidence, answer the question: *How has the climate of the nation changed over the past 50 years?*

Figure 5.5. The climatological station at Kew Gardens in west London. This is a well-exposed and representative site, established in 1981 following the closure of the nearby Kew Observatory. At the time of writing, it holds the record for the highest air temperature yet reliably measured in the British Isles, namely 38.1 °C on 10 August 2003. Manual observations ceased when the site was automated in 2007, and since then the site maintenance has deteriorated, as evident from these two photographs, taken in July 2007 (top) and July 2011 (bottom). (Photographs by the author)

Three independent measurements of temperature and precipitation are made at each site (**Figure 5.6**), ensuring continuity of record and maintenance of well-calibrated and highly accurate observations. The stations are placed in pristine environments expected to remain free of development for many decades (**Figure 5.7**). Stations are monitored and maintained to high standards, and are

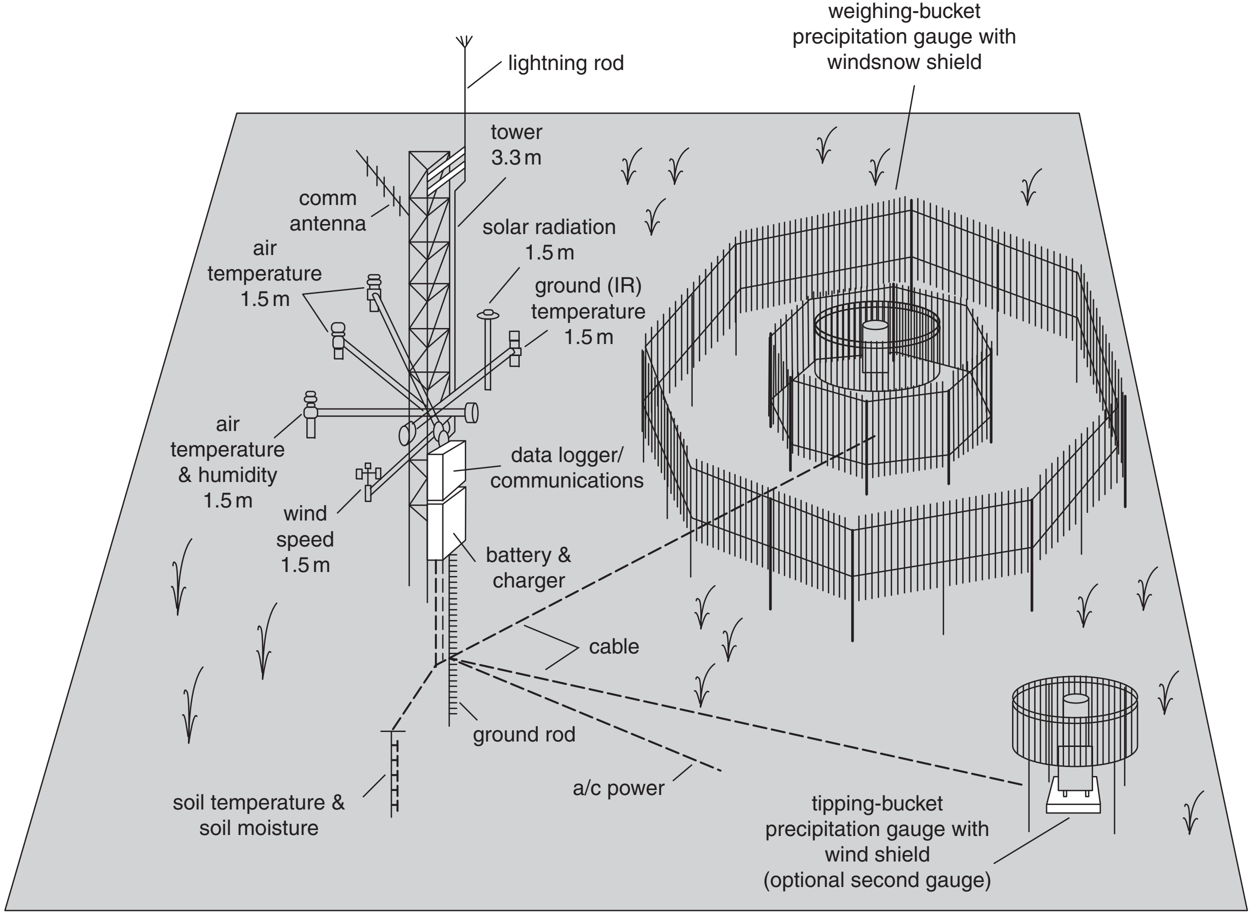

Figure 5.6. The site layout of a typical U.S. Climate Reference Network (USCRN) location. (National Oceanic and Atmospheric Administration/ National Climate Data Center)

Figure 5.7. A site in the USCRN network (Santa Margarita Ecological Reserve, San Diego, California – 33.4°N, 117.2°W, 343 m / 1127 ft AMSL, 30 April 2008) showing the three aspirated screens which are used at over 100 sites across the United States to obtain parallel and fail-safe air temperature data. (Photograph courtesy of the National Oceanic and Atmospheric Administration/National Climate Data Center)

calibrated on an annual basis. In addition to temperature and precipitation, these stations also measure solar radiation, surface skin temperature and surface winds, and are being expanded to include triplicate measurements of soil moisture and soil temperature at five depths, as well as atmospheric relative humidity. Experimental stations have been located in Alaska since 2002 and Hawaii since 2005, providing network experience in polar and tropical regions.

A new network of stations, the U.S. Regional Climate Reference Network (USRCRN) is also being deployed by NOAA. These stations maintain the same level of climate science quality measurements as the national-scale USCRN, but are spaced more closely, and focus solely on temperature and precipitation. Beginning with a pilot project in the south-west, USRCRN stations will be deployed at a 130 km spatial resolution to monitor regional climate change. Following completion of the pilot project, the long-term plan is for systems to be deployed in each of the nine NOAA climate regions of the United States. USRCRN stations also feature triple redundancy, although to a slightly lower level, and are also sited in pristine environments. By the time the project is complete, about 538 locations in the United States will have either a USRCRN or USCRN station in place. The project is managed by NOAA's National Climatic Data Center in partnership with the Office of Science and Technology in NOAA's National Weather Service and NOAA's Atmospheric Turbulence and Diffusion Division.

More information on these state-of-the-art climate monitoring networks, including details of the instruments used, real-time measurements and many site photographs, can be found at www.ncdc.noaa.gov/crn/#

The total number of observing sites in the United States has declined only slightly in 30 years; there are currently about 10,400 operational sites (**Table 5.1**), which

Table 5.1. *U.S. weather observing network population (October 2011)*

All figures are approximate.	
NOAA cooperating sites	
Rainfall-only sites – plastic 4 in raingauge	140
Rainfall-only sites – manual 8 in raingauge (SRG)	1872
Rainfall-only sites – automated gauges	1047
Temperature and rainfall sites – MMTS	2227
Temperature and rainfall sites – non MMTS	3643
Other (mostly river stations, various others)	349
	9278
Climate Reference sites	
US Climate Reference Network (USCRN)	126
US Regional Climate Reference Network (USRCRN)	64
NWS, FAA and DoD sites	
ASOS sites	938
U.S. weather observing network total sites	**10 406**

Source: NCDC

compares with 11,615 observing sites in December 1981. Many more are now automated, of course.

Installing and maintaining thermometer screens

Louvred screens All Stevenson and Cotton Region Shelter models require a suitable stand, usually made of metal, and with four legs for stability and wind resistance (**Figure 5.2**). The base of the stand should be buried at least 30–50 cm (12 to 18 in) below ground level, depending upon the model, and oriented so that the door of the screen when mounted on the stand will face due north in northern temperate latitudes, to prevent the Sun being able to shine on the sensors except at low angles near dawn and dusk at midsummer. In the southern hemisphere the door should face south, and in the tropics the screen should either be rotated according to season, or fitted with doors to both north and south, used according to season. The screen height should be adjusted so that the air temperature sensor within the screen – not the base of the screen – is at the correct height for the country (WMO recommend between 1.2 and 2 m: the standard height in the UK and Ireland is 1.25 metres above ground level, 4 to 6 feet in the United States, higher in other countries or regions, particularly where there is a high annual snowfall). The soil removed should then be replaced and packed down firmly to ensure the stand cannot move, and the grass cover reinstated.

The screen should be firmly secured to the stand (this requires two people to lift into place) using appropriate fixing brackets and bolts. It is important to ensure it is immovable once fixed to the stand, because it is not unknown for screens to be blown off stands in severe gales with resulting damage to the contents. In very exposed sites, some additional guying of the screen may be required.

Cheaper self-assembly screens The same principles apply – the screen should be firmly secured to a post or small mast, such that it will not be blown over in strong winds. The door should open to the north in the northern hemisphere, and the thermometer bulb/s or sensor unit should be fixed so that readings are made at or close to 1.25 m / 4–5 feet above ground, preferably above short grass. Fixing to walls, even north walls, is not recommended as the different infrared response and thermal inertia of the building to which it is attached will significantly affect the readings obtained. The screen should consist of white exterior-quality (UV-resistant) plastic or gloss white painted wood, to minimize any solar heating effects on the sensors within the shelter.

Radiation screen Most are lighter and can be easily affixed to a vertical pole or similar, using the supplied brackets or other fixings (see **Figures 5.4**, **5.8**). The pole should be firmly secured or concreted into the ground, to avoid the risks of accidental damage or strong wind upset. Direct fixing to (for example) an existing fence or post is not recommended except as a last resort, as the fence will warm in sunshine and thus affect the readings obtained. The construction should be of white exterior-quality (UV-resistant) plastic to minimize any solar heating effects on the sensors within the shelter. Where possible, the screen should be mounted in a grassed area and fixed so that the temperature sensor it contains is located at the correct height above ground level.

Ready-made standard-pattern wooden Stevenson-type screens or Cotton Region Shelters are expensive (typically $1,000 or more, at 2012 prices), and becoming more so as demand for wooden screens steadily diminishes. It is perfectly possible to make one, as plans and designs are still available [19]: note however that reasonable carpentry skills are required! Given occasional maintenance, a new well-constructed wooden thermometer screen should last 20 or 30 years. Regular care is essential, however: they should be thoroughly washed, inside and out, at least twice per year (more often in areas of high atmospheric pollution loading) and external surfaces repainted at least every 3 years (internal surfaces in good condition need repainting less frequently). As with any exterior woodwork, high-quality gloss paint should be used and the appropriate base coats carefully applied to previously well-prepared surfaces. Wooden screens with deteriorating exterior paintwork will warm

Figure 5.8. (Right of centre) Davis Instruments small plastic AWS screen, model 7714 (eight ‘stacked plates’, 18 × 18 cm, 14 cm high) shown alongside a smaller plastic AWS screen (left of centre – six ‘stacked plates’, 8 cm diameter, 9 cm high). Under comparative tests, the Davis unit performed well, but the smaller unit proved too small to provide adequate shielding against solar radiation and overheated badly in sunshine. (Photograph by the author)

more than well-maintained gloss-white models in sunshine, and this will gradually affect the temperature readings obtained. Differences of 1 degC between newly painted screens and those in need of repainting have been reported (as have differences between screens coated with whitewash compared with those painted using modern oxide-based paints [20]). Minor repairs should be attended to promptly, well before decay becomes established, because if the major structural members start to rot there is often little that can be done to save the rest of the structure. Sanding-down and repainting a wooden Stevenson screen is a major task, and will likely involve the loss of one or two days' record, so a parallel 'backup' temperature measurement system should be readied in advance to avoid any loss of readings while the work is carried out and the paint allowed to dry thoroughly.

AWS radiation screens

AWS radiation screens come in a wide variety of shapes and sizes: all are physically much smaller than traditional louvred screens. Most are made of moulded plastic with a gloss white exterior, but some are black inside[*]. (For no very obvious reason, a few of the low-end models are grey rather than white on the outside.) Almost all are varieties of the 'multiple inverted saucer' design school – examples are illustrated in **Figures 3.2**, **3.5**, **5.4**, and **5.8**. Where weatherproof/ultraviolet resistant materials are used, they should prove both durable and maintenance-free for many years, and require little more than the occasional wipe down with a damp cloth.

Electrical temperature sensors themselves are smaller and less bulky than standard liquid-in-glass thermometers, and as the sensors are remotely displayed and/or logged the radiation shield does not have to open to permit access for an observer to read the instruments. Both factors combine to reduce the size of the units, bringing benefits in reduced thermal inertia (which can be significant with louvred screens, particularly in light winds) and thus improved response times. Smaller screens are also cheaper and easier to deploy – usually a single well-fixed pole will suffice in place of a substantial metal stand. However, a minimum size of screen is required to provide sufficient shielding: the very small units included with some entry-level and budget AWSs simply do *not* provide adequate protection against solar radiation (**Figure 5.8**).

Just as with louvred thermometer screens, a well-designed radiation shield must provide protection against solar and terrestrial radiation and precipitation whilst permitting good natural ventilation throughput. Some are very much better at doing this than others, and some are frankly useless. Unfortunately, it is not always obvious at first glance which is which. The only way to be sure is to run comparative side-by-side trials over a period of at least several months using, as far as is possible or affordable, identical calibrated sensors in each type of screen tested. The Campbell Scientific 'Met21' screen (**Figure 3.5**), which will accommodate a wide variety of sensor types, provides a temperature record very similar to the larger and more expensive Stevenson screen [21]. Some less expensive units also do an excellent job, the Davis Instruments passive radiation screen (**Figure 5.8**)

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[*] The black interior apparently reduces solar radiation penetration, although whether this results from the black finish or merely the use of plastic with better infrared opacity has not been convincingly demonstrated.

being one such example, performing much better than units costing several times as much in the author's tests [22].

'Mixing and matching' sensors and screens is perfectly possible, and it is worth spending a little more on a screen which has been shown to perform well, but pay careful attention to interior screen dimensions and sensor sizes to ensure the chosen sensor will fit comfortably and benefit from unrestricted airflow.

Aspirated screens

Stevenson screens and AWS radiation shields are naturally ventilated units (also known as 'passive' radiation screens), in that air transport through the screen is accomplished solely by means of the surface wind. The construction of any type of shelter offers some resistance to natural ventilation, and when the surface wind speed is low it is likely there will be little or no air movement through the screen. In sunny weather, exposed surfaces of thermometer screens will warm up as they absorb solar radiation. The effect is slight in a moderate breeze, but in light winds the excess heat is less easily carried away and as a result all passive screens tend to overheat in conditions of strong sunshine and low wind speeds. They are also likely to respond sluggishly under low wind conditions, this being particularly marked with the larger louvred screens, where the indicated temperature can lag changes in true air temperature by anything up to an hour [23] (see also Appendix 1). Temperature records in passively ventilated screens tend to be smoothed compared with more responsive screen/sensor combinations (**Figure 5. 9**), which can also result in the under-recording of daily maximum or minimum temperatures. Sheltered sites, with lower mean wind speeds, are still more vulnerable to such effects.

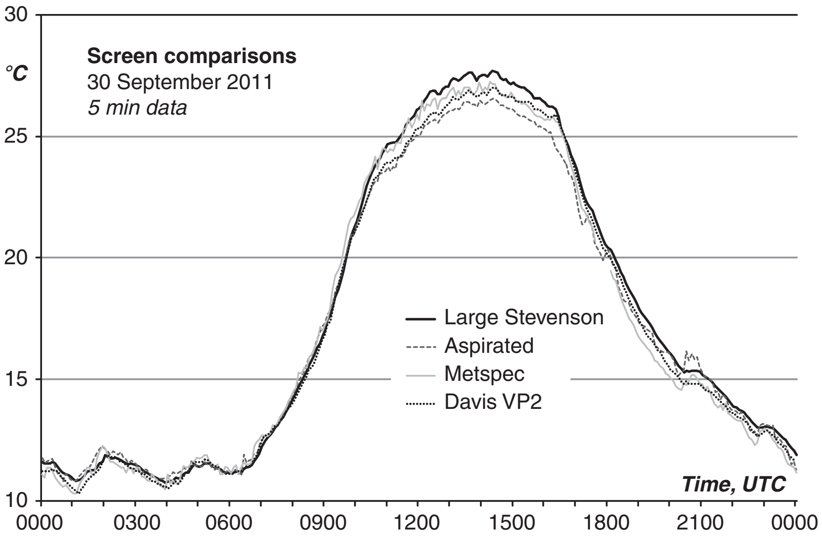

Figure 5.9. Comparison of temperature records from a large-pattern Stevenson screen, a smaller Metspec plastic Stevenson screen, an aspirated sensor (RM Young model 43502) and a Davis Instruments Vantage Pro2 sensor, showing the more responsive temperature record from the aspirated screen and the 15–30 minute lag of the larger screen. From the author's trial site in southern England, on a day of unbroken sunshine and light winds – 30 September 2011.

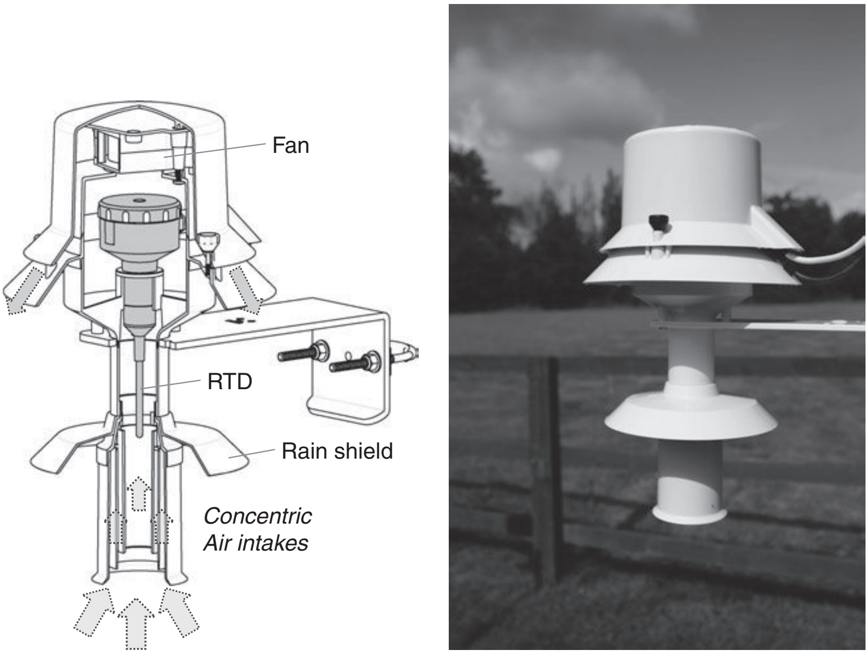

Figure 5.10. (Left) Sectional view of RM Young Model 43502 Aspirated Radiation Shield (33 cm high x 20 cm diameter). Air is drawn through the unit using the top-mounted fan; the temperature sensor is protected from solar radiation and precipitation by coaxial PVC tubes, thermally insulated from each other, shielding the sensor from external thermal radiation and minimising any heating effects within the body of the unit. Depending upon the sensor size, the airflow past the sensor is between 5 and 11 metres per second – equivalent to winds between Force 3 and Force 6 on the Beaufort Scale. (Courtesy of RM Young Company, Traverse City Michigan USA) (Right) RM Young Model 43502 Aspirated Radiation Shield in use. (Photograph by the author)

Aspirated screens (**Figures 5.10**, **5.11**) overcome this source of error, which is more pronounced in subtropical and tropical climates, by using a built-in fan to drive (pull) a continuously moving stream of air over the sensor, regardless of surface wind speed[*]. The heating effects of direct or indirect solar or long-wave radiation are therefore largely eliminated, the reasonable assumption being made that the sensor is measuring the temperature of free air that was external to the screen less than a second previously. A Stevenson-type screen can warm by 1–2 degC (2–4 degF) above ambient temperature in conditions of strong sunshine and light winds even in mid-latitudes, but typical performance specifications for aspirated screens under such conditions are for a heating effect of 0.2 degC or less even under very intense insolation (1000 W/m^2 – a value rarely attained for more than a few minutes in temperate latitudes, even at midsummer). The benefits are not restricted to sunny days with light winds, however, for the forced ventilation greatly improves contact between sensor and the ambient air, largely eliminating thermal inertia and lag on temperature records, resulting in very fast-reacting and

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[*] A few Stevenson screens have fans retrofitted to provide aspiration – the large Hazen screen in Figure 5.4 has been fitted with an aspiration fan, as can be seen on the side of the screen nearest the camera.

Figure 5.11. ASOS aspirated temperature shield (foreground) and MMTS (background) at New York's Central Park ASOS site, May 2010. (Photograph courtesy of Anthony Watts, www.surfacestations.org and Evan Jones)

highly responsive temperature measurement by both day and night (see **Figure 5.9**)*. But see also Box, *Screens in hot, dry climates*.

WMO recommend the use of aspirated systems, as these are most likely to provide a temperature measurement that is a very good approximation to the 'true air temperature'. So why are they not universally used?

The main reason is because the records obtained, while more representative of the 'true air temperature', are not consistent with existing long-period records and 'standard methods'. (Perhaps it is more accurate to say that, while existing methods have known errors, climatologists are rightly reluctant to introduce a step change in existing historical records without a good period of overlap, and overlaps are currently short in length and few in number.) Replacing a long-period Stevenson-type screen temperature record with one from an aspirated system requires a substantial period of overlap, using both sensors and screens, to preserve the value of existing records. Aspirated methods and instruments have been around for more than a century [24], but until the advent of small AWS sensors and remote dataloggers they were rather impractical, expensive and operationally difficult. Wooden louvred screens were cheaper, better suited to widespread adoption and required no power.

Now that the combination of aspirated screens, small sensors and dataloggers and low-power units that can be run from solar or wind generators have made the technology practical, they are finding increasing favour. NOAA's U.S. Climate

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* It seems logical to assume that aspirated screens will provide more representative temperature measurements at sheltered sites, where existing natural ventilation (and thus screen throughput) is already more limited than at more open sites, although more work is needed to test this assumption.

Reference programmes (**Figures 5.6**, **5.7**) are exemplary examples of 'new generation' climatological monitoring networks designed from the outset to adopt modern technologies, capable of updating as technologies and measurement systems advance over time, maintaining excellent site metadata (see Chapter 16). Aspirated temperature sensors are also used in the U.S. Automated Surface Observing System programme, ASOS (**Figures 1.2** and **5.11**).

Another significant reason for the slow adoption is because aspirated systems require power. For sites with access to mains power this is not an issue, but for remote sites the power drain from one or more 'always-on' ventilation fans can be many times the power required for all other sensors and datalogger combined. During the day this power need can be met from solar cells or wind turbines, but to maintain ventilation during the night, for long periods of dull or calm weather, or in the polar regions during the winter months, a substantial (and thus expensive) battery-based storage system is required. The fan mechanism on aspirated screens also requires regular maintenance or replacement owing to its continuous operation, and as a result such units may be less suitable for exposed or remote sites. During periods of power failure (or fan failure) air temperature readings from aspirated screens quickly become unreliable, particularly under light wind conditions and/or strong sunshine, as natural ventilation for the sensor is often very constricted. The USCRN network has overcome this by adopting a triple-redundancy approach, while industry research and development efforts to design and manufacture a highly reliable single-unit, low-power and low-cost aspirated screen, which can also function as a passive screen for limited periods if necessary, will eventually bear fruit and eliminate this implementation roadblock.

Other types of thermometer screen

In some parts of the world, many 19th or early 20th century temperature records were made in 'thatched screens', particularly where wood was scarce. These were large, open-plan shelters with roofs and sides made from local materials, often palm fronds (a good insulator). There are very few of these left in operation. **Figure 5.12** shows the one still in use today at the Hong Kong Observatory, continuing a daily record which started in January 1884. Records from a more conventional Stevenson screen have also been maintained in nearby King's Park since the 1950s.

Do different types of thermometer screen give different results?

Yes. Differences are greatest in strong sunshine and light winds. In most cases the readings differ only slightly, but even a few tenths of a degree is more than enough to damage the continuity of a long-term temperature record, for example, or when comparing records across a limited geographical area, as in urban heat island studies.

Numerous side-by-side measurements made in different climatic regimes around the world using sensors exposed in louvred screens, small plastic AWS radiation shelters and aspirated screens show that the results obtained can differ wildly in some conditions: such trials and comparative analyses have been documented by WMO [5, 25], within the International Standards Organization [6], in the United States [11, 13], UK [9, 10, 21, 22], Australia [26], The Netherlands [27] and Sweden [28], amongst others.

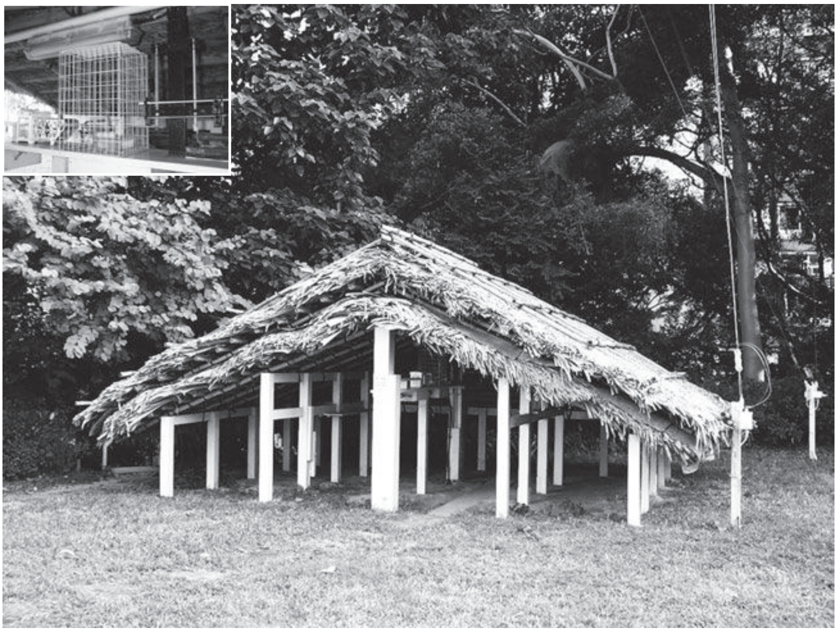

Figure 5.12. The thatched screen in the grounds of the Hong Kong Observatory, October 2001. *Inset:* screen interior. (Photographs by the author)

Screens in hot, dry climates

In 2011 WMO reported upon a comparison of 18 different types of thermometer screens (11 'passive', 7 aspirated) undertaken at Ghardaïa, Algeria (32°24' N, 3° 48' E, 468 m above sea level) in the northern Sahara desert during 2008/09 [25]. It might be expected that aspirated screens would provide the most representative temperature readings in these hot, dry desert conditions, but in fact their results were 'disappointing', partly because airborne dust and sand reduced the ventilation efficiency of the units in the trial. Most small passive multi-plate plastic radiation shields performed well. The large Stevenson screens provided 'very good results', although with significant lag.

There is a great deal of variability in the effectiveness of small AWS radiation shields, particularly on entry-level consumer products. Some models perform very poorly, in that under conditions of strong sunshine and light winds measured air temperatures rise well above those measured in an adjacent Stevenson-type screen, thus rendering the measurements largely worthless. Other designs show much less heating in sunshine, with air temperature measurements similar to or slightly below those measured in nearby louvred screens. At the time of writing the closest approach to 'true air temperature' from any screen-based measurement system seems most likely to come from accurately calibrated aspirated sensors, and it is for this reason that WMO recommends adoption of this method. The U.S. Climate Reference Network already does so with its multiple-redundancy aspirated temperature measurements. Although, as yet, no one model or manufacturer has been endorsed by WMO or clearly adopted by several of the world's major state weather services, it seems more likely than not that aspirated methods of measuring air temperature will become the norm in more and more national meteorological observing networks within the next decade or so. Forward-thinking installations might therefore wish to augment (rather than replace) existing louvred screen records with an aspirated method of measuring temperature, thereby commencing a record overlap at the earliest opportunity.

Table 5.2 summarizes the results from the many and diverse screen trials held around the world. More detail is given in the original references at the end of this chapter.

Suppliers of thermometer screens

Some suppliers of thermometer screens, including wooden and plastic Stevenson screens and Cotton Region Shelters, are listed in Appendix 4. Most 'off-the-shelf' AWS systems manufacturers offer their own model of passive radiation screen designed to fit proprietary sensor units; Davis Instruments offer optional aspirated units which can be fitted in place of their standard passive model if required [*].

New Stevenson-type louvred screens, whether wooden or plastic, are expensive. With care, they should last for decades and should be viewed as an investment. For those looking for a less expensive way to get started, cheaper alternatives are available where compatibility with existing standard methods is less important – a home-made shelter made from white-painted flower-pot bases is better than nothing, and various self-build 'recipes' can be found on the Internet – for example www.loganvillageweather.com/station/stevenson.html.

A reasonable option is the 'simple screen'. **Figure 5.13** shows one example, available to order from UK resellers in assemble-yourself and ready-made versions; other types exist. Although records from these screens will not be fully comparable with those made in a Stevenson-type louvred screen, they are a fraction of the price and will provide reasonable protection from the effects of short-wave and long-wave radiation and from rainfall. They are large enough (270 x 200 x 90 mm) to contain a couple of conventional thermometers, for those who are already making, or who may wish to make, traditional weather records, or they can accommodate one or more electronic sensors.

If considering the purchase of an entry-level or budget AWS where no radiation shield is included with the unit, one of these little screens, properly exposed, will significantly improve the measurement of ambient air temperatures. An appropriate pole or stand is also required to expose the screen at the correct height above the ground surface. Avoid mounting on a north wall.

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[*] Davis Instruments sell a 'hybrid' aspirated system for their Vantage Pro2 AWS, the Fan Assisted Radiation Shield (FARS, model 7755), in which a solar cell-powered fan provides aspiration during daylight hours only, and the system reverts to natural aspiration during the hours of darkness when no solar power is available. Such hybrid systems are not fully-aspirated but neither are they 100% passively ventilated. The resulting measurements are also not clearly of one type or another, which can make accurate comparisons with other sites complex and unreliable.

Table 5.2. *Thermometer screen types compared. See text for details and references*

	Advantages	Disadvantages
Wooden louvred screens *Examples: Stevenson screen, Cotton Region Shelter*	Still the current standard measurement benchmark in many countries Ideal housing for manually read conventional thermometry	Relatively expensive Require regular maintenance Overheat in sunshine, particularly in light winds, owing to low ventilation throughput Less responsive than smaller or aspirated screens, owing to considerable thermal inertia (due to bulk) and reduced ventilation Manual instruments require screen to be open for duration of the observation Requires substantial stand
Plastic Stevenson-type screens *Examples: UK Met Office standard*	Results almost indistinguishable from wooden models and thus valid substitute Low maintenance Ideal housing for manually-read conventional thermometry, where still in use	Relatively expensive Overheat in sunshine, particularly in light winds, owing to low ventilation throughput Less responsive than smaller or aspirated screens, owing to considerable thermal inertia (due to bulk) and reduced ventilation Manual instruments require screen to be open for duration of the observation Requires substantial stand Materials may age and become light grey or yellow over time Long-term characteristics unknown (but certainly more stable than wooden screens)
Small plastic AWS radiation shields *Example: NOAA MMTS, Davis Instruments Vantage Pro2*	Much cheaper Lighter – less thermal inertia, more responsive Ideal for small sensors Remote-reading sensors mean screen can be sited away from buildings, etc. No need to open housing to make observation Low maintenance Easy mounting on small mast or tripod	Results differ from conventional louvred screens Wide variations in performance – some are dreadful No clear leading design or model to consolidate standards More responsive than records from louvred screens and so not fully homogeneous Cannot house conventional thermometers
Aspirated screens *Examples: ASOS and USCRN*	Probably closest to 'true air temperature' Highly responsive Ideal for small sensors Low maintenance Easy mounting on small mast or tripod No need to open housing to make observation	Results differ from both conventional louvred screens and radiation screens Requires mains power or substantial solar power/battery combination Readings quickly become invalid if power fails More responsive – thus records not fully homogeneous with other screen measurements Most cannot house conventional thermometers May become unreliable in hot, dusty climates

Figure 5.13. Simple thermometer screen. (Photograph courtesy of Russell Scientific Instruments Ltd)

Choosing a thermometer screen – the best and the worst

'Off-the-shelf' consumer AWSs will generally not provide any choice of radiation screens (most entry-level and some budget units will not provide one at all). Relatively inexpensive self-assembly wooden screens (**Figure 5.13**) can provide reasonable protection, and are a worthwhile alternative if budget is limited. Third party plastic AWS screens are available from Campbell Scientific (**Figure 3.5**) and Davis Instruments (**Figures 3.2** and **5.8**) amongst others, but check beforehand whether the AWS sensors can fit (and be securely affixed into) the unit chosen.

Budget and mid-range AWS systems will usually include a radiation screen of some description. Very few have been evaluated alongside conventional 'standard' screens to assess their effectiveness; one exception is the Davis Vantage Pro2 unit where the author has previously published the results of a year-long evaluation [22]. Despite a substantial black plastic raingauge being sited atop the radiation screen itself, rather surprisingly this had little or no effect on air temperature measurements even on days with strong sunshine and light winds. Temperatures compared closely to those from an adjacent Stevenson screen. In general terms, however, it is better to choose a radiation screen that is built for the purpose and not combined with other instruments.

Where compatibility with existing standards and/or existing records is required, seek guidance from the state weather service or climatological network operator. The drawbacks of existing benchmarks (such as the Stevenson screen, whether wooden or plastic, and the Cotton Region Shelter) have been known for decades, but where continuity of record is important then a dual-record overlap period is essential. Louvred screens can also usually contain one or more conventional thermometers, useful for those who maintain records using existing instrumentation and who wish to run an AWS alongside conventional thermometry, or to use liquid-in-glass thermometers as a backup or calibration check on electronic sensors.

That said, however, the best patterns of small radiation screen probably provide a better representation of 'true air temperature', and a faster response, than traditional louvred screens, owing to their lower thermal inertia and better natural ventilation. Mere build and appearance are little help in determining the real-world performance characteristics of different types of screen or radiation shelter. Very small screens, such as the miniature screen illustrated in **Figure 5.8**, have good ventilation and almost no thermal inertia and thus offer a fast response, but also offer very little resistance to direct or reflected solar radiation. They therefore tend to overheat significantly in sunshine and cannot be recommended. Larger plastic models constructed of a minimum of six or seven 'inverted saucers' have a greater thermal inertia and reduced through ventilation, and are thus slightly less responsive, but in winds of 5 knots or more can provide results reasonable enough for most climatological purposes. Larger louvred screens are generally slower to respond, and in light winds can take tens of minutes to respond to a sudden change in temperature (**Figure 5.9**) – see Box, *Measuring responsiveness*.

Measuring responsiveness

Enhanced responsiveness is desirable, up to a point (unlike wind speeds, for example, there is little benefit in sampling air temperature every second), but too sensitive a system will simply generate slightly higher maximum and slightly lower minimum air temperatures than those recorded by conventional instruments in a louvred screen, for no reason other than differences in instrumental responsiveness. It is for this reason that it is good practice, where supported by the logger functionality, to sample the air temperature every few seconds but to take a running average over a short period, and to take the highest and lowest (respectively) of the running average samples as the day's maximum and minimum air temperature. This also helps to iron out minor stray electrical noise or sensor/logger resolution artefacts.

The recommendation from WMO [1, Annex 1.B] is for 1 minute mean temperatures to be adopted. The UK has adopted this (running average of 60 x 1 second samples) in its new MMS system [17]. To provide some measure of compatibility with older mercury thermometers, however, the U.S. preference is for a 5 minute running average in the ASOS system, and fixed 5 minute periods in USCRN [18], although both systems have a much lower time constant (see Appendix 1) of about 20 seconds [29].This is not just an academic concern, as it affects the acceptance – or not – of weather extremes. A good example is accorded by the maximum temperature recorded at Dodge City, Kansas during the heatwave which affected the southern and eastern states of America in summer 2011. Dodge City has one of the longest continuous temperature records in the United States, commencing in 1875. The hottest day on its long record stood at 110 °F (43.3 °C). On 26 June 2011 the highest 1 minute temperature observed was 111 °F (43.9 °C). However, the value (logged on an ASOS system) was not accepted as a new record because ASOS takes the maximum temperature as the highest 5 minute running mean, which was 110°F. Thus, the official high by the U.S. method was 110°F, tying rather than exceeding the previous record: by the WMO recommended method the maximum was 111 °F, which would have set a new record*.

Measurement responsiveness is quantified using a measure known as the *time constant*, which is the length of time an instrument (or screen, in this case) takes to respond to a certain fraction of a step change in a variable (see also Appendix 1). For air temperature, the sensor and the screen each have their own time constant, the latter normally being the larger. Both are very dependent upon ventilation, so

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* I am indebted to Christopher C. Burt, U.S. weather historian, for drawing my attention to this event.

temperature time constants are expressed in terms of the time taken to show a response to a fraction of an instantaneous change in temperature – usually 63 per cent – at a given ventilation speed.

The 63 per cent time constant for a small temperature sensor in a 5 m/s (10 knots) breeze is typically around 20 seconds, for mercury thermometers about a minute. For a Stevenson screen, the time constant in a 10 m/s breeze (about 20 knots) is 4 minutes, increasing to 17 minutes in a wind of 0.5 m/s (1 knot) [23, 30]. The ideal response time for a meteorological temperature measurement system is between about 30 and 60 seconds. This is achievable with an aspirated system, and with small AWS screens in moderate wind speeds and higher, but as can be seen above even in a fresh breeze the time constant of a Stevenson screen is likely to be considerably greater than ideal.

Many wireless-display in/out temperature displays and AWSs use sensors which are encased in a much larger block containing batteries, electronics and the like. Owing to their relatively bulky nature, these systems can be quite slow to respond to sudden changes in air temperature. Any two sensors, no matter how well-calibrated, which differ in time constant will display or log different readings when the temperature changes – as it does almost continuously. This will be shown as a lag in indicated temperature of the less responsive unit, particularly when the temperature is changing rapidly. Lag can result in under-recording extremes – the maximum temperature being under-recorded and the minimum over-recorded – the magnitude of the effect depending upon the rate of change of temperature at the time of the extreme. Days with short but intense spells of sunshine often see an under-recording of maximum temperatures by ‘slow’ sensors. Although **Figure 5.9** has been prepared using fast-response sensors, it can be appreciated that a sensor with a larger lag time would be even less likely to record peaks and troughs accurately.

Temperature sensors

Almost any physical property of a substance which is a function of temperature can be used as the basis for indicating temperature. Over the years, many different methods of measuring temperatures have been devised, but today three sensor types dominate in meteorological applications – namely, the traditional liquid-in-glass thermometer, electrical temperature sensors or resistance temperature devices (RTDs), and mechanical sensors.

Liquid-in-glass thermometers

Conventional thermometers use the thermal expansion of a liquid in a graduated and calibrated narrow-bore glass tube to provide a temperature reading. The liquid most often used is mercury, but alcohol is normally used for minimum thermometers or for those used in cold climates because it has a lower freezing point (–115 °C / –175 °F) than mercury (–38 °C / –36 °F).

Liquid-in-glass thermometers, recognizably similar to those still in widespread use today, have been used to make weather measurements since their invention in Italy almost 400 years ago. Long use and familiarity have produced reliable, accurate and reasonably robust instruments – there have been few significant changes in the last 150 years. With a little practice, they can be read quickly and accurately by eye to 0.1 degC.

In construction, there are two main patterns of meteorological thermometer – the *sheathed* and the *unsheathed*. Sheathed thermometers are encased in an outer glass sheath, hence the name: the thermometer scale is normally engraved on the thermometer stem, and is thus protected from weathering. Unsheathed thermometers usually have the graduations marked on the thermometer stem or on a separate plastic, metal or wooden scale attached to the thermometer. Because the scale is exposed to the elements, it can be subject to wear, expansion and contraction in varying temperature and humidity, and fading over time. 'Attached' scales inevitably move slightly over time, rendering the thermometer calibration less certain.

The main types of meteorological thermometer in use are the so-called 'dry bulb' thermometer (**Figures 5.1**, **5.14, top**), which indicates the current temperature: the 'wet bulb' (**Figure 5.1**), identical in form to the dry bulb except that its bulb is kept permanently moist, the difference between the two readings being a measure of the water content of the air (see Chapter 8): the maximum thermometer (**Figure 5.14, middle**), which by virtue of a small constriction near the bulb will show the current temperature as the temperature rises, but which will leave the column of mercury at the highest point as the temperature begins to fall: and the minimum thermometer (**Figure 5.14, bottom**), which indicates the lowest temperature reached as the alcohol meniscus carries a small glass index in the thermometer stem down with it. Both maximum and minimum thermometers are exposed almost horizontally within

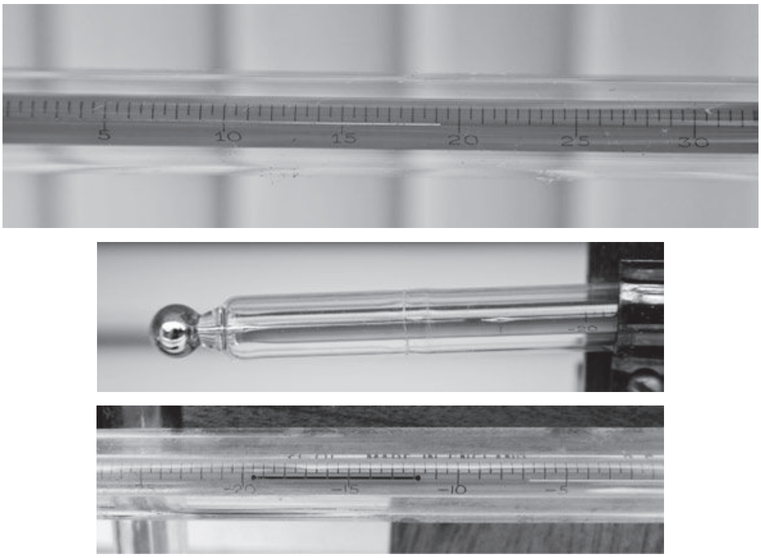

Figure 5.14. Liquid-in-glass thermometers.

Top Sheathed dry-bulb thermometer. The thermometer is reading 19.2 °C

Middle Sheathed maximum thermometer showing the constriction in the stem

Bottom Sheathed minimum thermometer index. The minimum temperature is reading –11.8 °C, and the current temperature is –6.8 °. (Photographs by the author) a suitable thermometer screen, the dry- and wet-bulb thermometers vertically (**Figures 5.1**, **5.3**).

Opening the screen door to make the readings, and the proximity of the observer, can very quickly affect the readings of liquid-in-glass thermometers (by 0.5–1 degC / 1–2 degF), and care should be taken to read (in the order dry-wet-max-min), and if necessary reset, the thermometers, and close the screen door, as quickly as possible.

In humid weather, all four thermometers can become covered with a thin film of moisture, particularly when the observation time is close to the normal time of minimum temperature. To avoid unwanted wet-bulb effects until the thermometers dry off naturally, it is good practice in such conditions to wipe down the thermometer bulbs and stems at the observation. This must be performed quickly, so as not to affect the readings by doing so, particularly the maximum thermometer.

The maximum thermometer is reset by grasping the end of the thermometer furthest from the bulb and shaking the mercury column back down past the constriction towards the bulb in the manner of a clinical thermometer. The minimum thermometer is reset by gently tilting the thermometer bulb-end upwards until the index rests once more on the end of the alcohol meniscus or ‘bubble’. Both screen thermometers are most vulnerable to breakage while being reset.

For use in meteorological or climatological applications, the calibration of liquid-in-glass thermometers should be checked at least every 5 years. Expected accuracy over the normal range of temperatures at the observing location should be ± 0.2 degC [1, section 2.1.3.2, Annex 1.B]. Because of their size, liquid-in-glass thermometers must be exposed in Stevenson-type screens. They also require manual observation, rendering them unsuitable for regular observations from remote or largely unmanned observation sites. Wherever possible, maximum and minimum thermometers should remain within a screen after AWS installation, as they provide a useful calibration check on electronic sensors.

Resistance Temperature Devices (RTDs)

Many materials exhibit variations in their properties with changing temperature. Metals or semiconductors that show variation in electrical resistance are particularly useful as temperature sensors, because Ohm’s law can be used to determine resistance given accurate measures of voltage and current in an electrical circuit; the measurements and calculations lend themselves well to remote logging applications. The sensors themselves can also be made very small, much smaller than a conventional liquid-in-glass thermometer, for example, and this improves response times (for many meteorological applications they can even become too sensitive, responding to minor random temperature fluctuations which are of little climatological benefit or interest). Because of their small size, they can be exposed in smaller screens (see section above) which also helps to increase responsiveness, although for consistency and homogeneity of record many countries continue to expose electrical sensors within Stevenson screens.

There are two types of electrical sensor in common meteorological usage – *the platinum resistance thermometer*, and the thermally sensitive resistor or *thermistor*.

For more detailed technical information on these – and other – sensor types, see the references [31] for this chapter.

Platinum resistance thermometers (PRTs)

The resistance of platinum varies significantly with temperature in an almost linear fashion (at least over typical meteorological ranges), and this property makes it a popular choice for electrical temperature sensors. Professional-quality AWS systems use PRTs, which can be manufactured to repeatability tolerances better than liquid-in-glass thermometers, within ± 0.1 degC over a typical range of temperatures (see Box, *PRT classes*). Calibration is easier for PRT probes than for other sensors, usually requiring only one fixed point (see Chapter 15), and calibration stability is usually good. (This should not be used as an excuse to forego regular calibration checking.)

PRT classes

The ISO PRT standard, DIN/IEC 60751, requires the RTD to have an electrical resistance of 100.00 Ω at 0.0 °C and a temperature coefficient of resistance of 0.00385 Ω/°C between 0 and 100°C. Many dataloggers are set up by default to accept such 'standard' PRTs, which are known as 'Pt100' sensors.

There are three resistance tolerances for PRT RTDs specified in IEC60751, essentially defining the confidence in the resistance versus temperature characteristics for the sensor type – Class B, Class A and Class AA (also known as '1/3 DIN'). The larger the element tolerance, the more the sensor may deviate from the 'standard' resistance characteristic curve, and the more variation possible between sensors. Within high-accuracy meteorology applications, it is important to be sure one sensor can be swapped out for another without introducing significant calibration errors (although the calibration should always be checked when sensors are swapped). A fourth class, 1/10 DIN, is not formally defined within the IEC60751 standard, but has the least variation between type sensors – within 0.05 degC between any two units at normal air temperatures. Meteorological sensors are normally Class A PRTs, or better.

PRT class	Repeatability at 0 °C	Repeatability at 50 °C
Class B	0.30	0.55
Class A	0.15	0.25
Class AA or 1/3 DIN	0.10	0.18
1/10 DIN	0.03	0.05

When logged using a datalogger, the maximum and minimum temperatures can normally be extracted using software – usually with the time of occurrence – obviating the need for three separate instruments. PRTs can also be set up as wet bulbs for accurate determinations of atmospheric humidity (see Chapter 8, *Measuring humidity*).

Semiconductor resistance thermometers (thermistors)

A thermistor is a semiconductor device whose resistance varies significantly with temperature. Their resistance, and the variation of resistance with temperature, is considerably higher than PRTs. They are somewhat smaller than PRTs, and considerably cheaper, and as a result are used as the temperature sensor in almost all AWS systems below advanced and professional standard. They offer almost all of the advantages of PRTs given above, but are slightly less accurate (a typical error for a high-quality thermistor being ± 0.5 degC / 1 degF over the –10 °C to +35 °C / 15 °F to 95 °F range) and less stable in their calibration, although both can be improved with regular calibration checks every couple of years.

Not surprisingly, less expensive thermistors tend to have larger errors and/or less stable calibrations, but again regular calibration checks can reduce this to manageable levels. Because of the variability between units, there is no 'standard thermistor' in the same sense as the 100 Ω PRT, and because of this calibration is less repeatable between devices. It may not hold outside narrow limits, and additional corrections may be required at extremes of temperature.

Mechanical Sensors

The differential rate of expansion with temperature of two metals has previously been applied in the bimetallic thermograph (**Figure 1.7**: one can also be seen in the screen in **Figure 5.1**). In this instrument, one end of the bimetallic strip is fixed to the case of the instrument, and the other attached (via a magnifying lever mechanism) to a pen arm rotating on a weekly clock-driven paper chart. The slight changes in curvature of the strip resulting from temperature changes are thus recorded as a trace on the paper chart.

The instrument includes a calibration adjustment screw; with care, the instrument can indicate changes in temperature to within 0.5 degC / 1 degF, although without regular adjustment and maintenance the errors will grow. Accurate scaling across the expected annual range of temperatures is difficult to achieve, but with regular adjustments reasonably accurate records can be obtained. The small scale of the paper charts (typically 1.6 mm/h horizontally and 1.6 mm per degC vertically), and uncertainties in the timing accuracy of 10–20 minutes owing to backlash in the clock gearing, limit the resolution of the analysis obtainable from paper thermograph charts. As a result these instruments are rapidly being superseded by cheaper and more flexible electronic logging systems, which can be left unattended for much longer than the normal weekly cycle of clock-driven instruments. Digital devices also eliminate the ongoing consumables costs, archive storage requirements and manual chart analysis necessitated by paper-based instruments. Digital records are of course also immediately available for powerful computer analysis (see Chapters 17 and 18) without requiring the labour-intensive and error-prone manual transcription of paper chart records.

Logging requirements

Air temperature does not change as quickly as other weather elements (wind speed and solar radiation, for example): very rapid changes, of more than a few degrees

Celsius within a minute or so, are uncommon. In any case, as noted above, time constants and response times of the screen/sensor combination are likely to be measured in minutes rather than seconds for all except aspirated screens when mean surface wind speeds are below about 5 m/s (10 knots, Beaufort Force 3 or so). A very frequent sample rate is therefore unnecessary. Sampling air temperature at 10 second intervals, and logging 60 second running averages every minute (the average of 6 x 10 second samples), meets all WMO recommendations. Even 5 minute averages are sufficient for many climatological requirements.

Where supported by the logger and software, short-period running averages can be very useful to remove minor electrical noise or smooth out high-frequency natural random fluctuations (which are almost certainly faster than the sensor's ability to respond fully in any case).

Observation times

For observations to be comparable between different locations, it is preferable for the sampling and logging intervals, the times at which observations are made, and the time period covered by the daily maximum and minimum temperatures, to be as nearly identical as possible. This latter topic is covered more fully in Chapter 12.

One-minute summary – *Measuring the temperature of the air*

- Temperature is one of the most important meteorological quantities, but it is also one most easily influenced by the exposure of the thermometer. Great care needs to be taken in exposing air temperature sensors to ensure that, as far as possible, the instrument measures a true and representative value, which is not unduly influenced by the instrument housing, surrounding vegetation or ground cover, the presence of buildings or other objects.
- The WMO recommendation is for a site over level ground, freely exposed to sunshine and wind and not shielded by, or close to, trees, buildings and other obstructions. Of course, it is not always possible to follow WMO guidance in every detail, particularly where site and/or exposure may be limited, and suggestions on the best methods for obtaining optimum results under such circumstances are presented. Certain locations, such as hollows or rooftop sites, are best avoided, as readings obtained in these situations may bear little comparison to observations made elsewhere under standard conditions.
- Some form of thermometer screen is essential to provide protection from direct sunshine, infrared radiation from Earth and sky, and from precipitation. The main screen types – louvred (Stevenson screen, Cotton Region Shelter), radiation screens (MMTS, other AWS screens) and aspirated screens (such as ASOS and USCRN) – are covered in some detail, because the thermometer housing (or lack of it) is likely to have the largest impact upon the observed temperature. Almost any form of radiation shelter will provide better results than a bare sensor. If the AWS model chosen does not include an effective radiation screen, allow budget to purchase a suitable third-party one and use that.
- Traditional louvred screens can accommodate both traditional liquid-in-glass thermometers and small electronic sensors, but small AWS radiation shields can be used only with electronic sensors. Aspirated units currently provide the best estimate of true air temperature (they are highly responsive and largely free

of influence from the screen itself), but they provide a slightly different temperature record from other standard methods. Next-generation climate monitoring networks are increasingly using aspirated methods of measuring air temperature.

- To avoid the significant vertical temperature gradients near the Earth's surface, thermometer/s to measure air temperature should be exposed at 1.2 – 2 m above ground level. In the UK and Ireland, the standard height is 1.25 m above ground; in the United States, between 4 and 6 feet.
- Sites that have long current records of temperature made in traditional thermometer screens (Stevenson, Cotton Region Shelter) should not substitute an alternative method of measuring temperature (for example, an aspirated screen) without a substantial overlap period, because doing so risks destroying the homogeneity of the long record. The overlap period should be a minimum of 12 months, or one-tenth of the station record length, whichever is the longer.
- Most air temperature measurements are now made using resistance temperature devices (RTDs), which are steadily replacing liquid-in-glass thermometers. The main types of sensor in use today are the *platinum resistance thermometer* and the *thermistor*. The former is more accurate and more repeatable, but more expensive. Both can be made very small and thus highly responsive.
- Logging intervals of 1 to 5 minutes, with shorter sampling intervals (typically 5 to 15 seconds), are sufficient for most air temperature measurement applications. Running means can be used to smooth out very short-period temperature fluctuations, which are of little significance in climatological measurements, and any stray electrical noise.
- Sheltered sites can introduce significant measurement errors, but with some care given to siting the screen and sensor/s reasonable air temperature measurements can be made in all but the most restricted locations. Temperature records from suburban sites, even those with limited exposures, can often provide more numerous and more representative climate records for a town or city than those from more distant sites with near-perfect exposures.

Further Reading

Knowles Middleton's *A history of the thermometer and its uses in meteorology* (Johns Hopkins, Baltimore, 1969– now more widely available in a new print-on-demand edition) provides absorbing background reading of the development of thermometry over 300 years.

Ian Strangeways' *Measuring global temperatures: Their analysis and interpretation* (Cambridge University Press, 2010) gives a comprehensive and up-to-date summary of the various methods of measuring temperature, on land, over the sea and in the upper air, including a useful analysis of historical methods and their limitations. This is essential (and well-referenced) background material for all who wish to understand more about the methods involved in assessing long-term climate change records.

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[3] More information on the fixed points of temperature scales can be found on the website of the International Bureau of Weights and Measures www.bipm.org, and on the International Temperature Scale 1990 site www.its-90.com.

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6 Measuring precipitation

Determining some measure of the amount of precipitation (the term includes rain, drizzle, snow, sleet, hail and so on as well as – occasionally – smaller contributions from dew, frost or fog) is not difficult: almost any bucket left out in the rain will suffice. Obtaining accurate, consistent and comparable measurements does, however, require a little more care and sophistication in technique. This chapter outlines methods for doing so, based upon World Meteorological Organization (WMO) recommendations on siting and instruments [1], and discusses some of the pitfalls involved. Making precipitation measurements in snowfall is also covered. A brief 'One minute summary' completes the chapter.

Precipitation is one of the most variable of all weather elements, in both space and time. For this reason most countries have a greater density of precipitation measurement locations than other meteorological variables, such as air temperature or solar radiation. More recently, the spatial coverage of precipitation measurements has been considerably improved by radar and satellite remote sensing techniques, but these still rely upon accurate 'ground truth' observations for calibration and quality control. However, precipitation measurements are very sensitive to exposure – particularly to the wind – and it can be difficult to derive measurements representative of an area from the spot values provided by a ground-based sensor, particularly in urban areas or those with complex topography. Precipitation measurement networks tend to be densest in well-populated areas of gentle terrain rather than in remote mountainous areas with complex topography and harsher weather. Unfortunately, the latter are often the areas with highest annual average precipitation and/or snowfall, and may well be the prime source of a city or region's water resources, requiring careful and consistent long-term measurements.

Precipitation gauges are often referred to simply as 'raingauges', although some also do a passable job at collecting solid precipitation. In this chapter, the term 'raingauge' is used as a general-purpose term to refer to precipitation monitoring devices. For reasons of history and politics as much as differences in climate, there remain many different types of raingauge in use around the world, and as a result the measurements are not strictly comparable between countries. The analysis of precipitation data is greatly simplified where common standards of equipment, siting and observation times, such as those promulgated by WMO, are adopted by the appropriate national network authority, often the state weather service or similar body. Most countries have published guidelines to enable measurements to be made in line with national standards. As in the previous chapter, country-specific details are included for the United States, the United Kingdom and the Republic of Ireland.

Reference to the websites of individual national or state weather services [2] will provide detail on current precipitation measurement practices and policies for other countries.

What is being measured?

'Precipitation' is defined by WMO as 'the liquid or solid products of the condensation of water vapour falling from clouds or deposited from the air onto the ground', and includes rain, hail, snow, dew, frost and rime, and wet fog. A raingauge measures the depth of precipitation accumulating over a horizontal unit area. The measurement is normally expressed in millimetres of liquid water equivalent, although inches are still the preferred unit for public communication in the United States. A rainfall depth of 1 mm is dimensionally equivalent to 1 litre of water per square metre, and rainfall values are sometimes expressed in these units*. Daily precipitation measurements are normally made to a precision of 0.1 or 0.2 mm, or 0.01 inches.

WMO guidelines suggest an accuracy of 5 per cent is attainable in precipitation measurements, but to achieve representative and comparable measurements which are consistent over time a number of important factors need to be considered, the most important of which are as follows:

- *Shelter* Clearly, the gauge must not be unduly sheltered from the precipitation it is intended to measure. The site chosen should therefore, as far as possible, be clear of buildings, trees and other obstructions (including other meteorological instruments) for some distance around the raingauge. Counter-intuitively, slight over-shelter can sometimes slightly *increase* the catch of a raingauge, but significant shelter will inevitably reduce it. The effects of shelter can vary with wind direction and speed, and over time (as trees or hedges grow in the vicinity of the raingauge, for example, or if new buildings are erected nearby). Shelter can affect gauge catch from perhaps 10 per cent above to as much as 80 per cent below the 'true' value [3].
- *Over-exposure to wind* Very exposed sites are equally problematic, for here the physical presence of the gauge causes the wind to accelerate over the top of it, carrying away drops that should have been caught. Loss of catch by wind is the greatest single factor in precipitation measurement inaccuracy, particularly in snow. Average losses have been estimated at 20 per cent for U.S. rainfall measurements in a mean daily wind speed of 8 metres per second (roughly Beaufort Force 4–5), increasing to 70 per cent in snowfall [4]. Where snow normally contributes a significant fraction of the total precipitation in the year, such errors can result in very significant under-estimation of mean annual precipitation values [5], but it is likely that almost all precipitation gauges under-read by some amount owing to wind losses. In an attempt to reduce these, the fitting of wind shields is standard practice in some countries, particularly where annual

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[*] For non-specialist audiences, the measurement of rainfall as a depth in millimetres can be difficult to grasp, and the concept of litres per square metre can sometimes be more readily appreciated. During the writing of this book, a fall of 66 mm of rain in a few hours at the author's site was more readily understood by a lay audience as 'a similar volume of water to that of a full tank of petrol (gasoline) for an average car, falling over every square metre'. Unfortunately the numerical coincidence is rather less convenient for rainfall measurements expressed in inches and the other quantities in U.S. gallons and square feet …

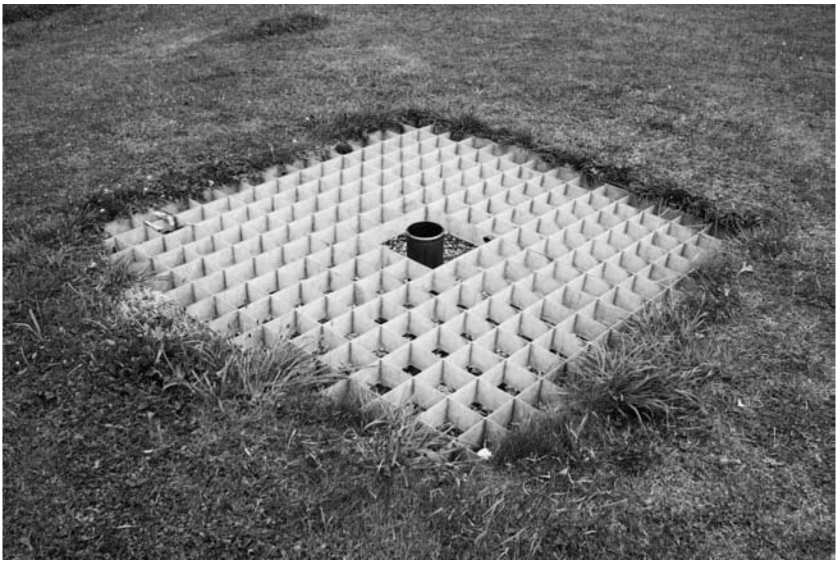

Figure 6.1. Ground-level or 'pit' raingauge; the gauge is exposed at ground level within a strong metal mesh which reduces turbulence and prevents insplash. Wallingford, Oxfordshire, England. (Photograph by the author)

snowfall is significant. These are described in more detail later in the chapter. More aerodynamic raingauges can also improve catch in windy locations.

- *Height above ground* Wind speed increases with height, so raingauges exposed well above the ground (whether mounted on the ground with a high rim height, or exposed on rooftops or masts, for example) will almost invariably catch less precipitation than an identical gauge nearer the ground. This was first described by William Heberden in 1769, although the true cause was not identified for another 100 years. The reduction is caused by the distortion of the wind field owing to the presence of the gauge itself, as described above, combined with increased wind velocity at height. Differences increase with height and with wind speed (the latter, of course, is highly variable on all timescales), and possibly also with wind direction. Theoretically at least, the ideal height for a raingauge is flush with the ground surface (**Figure 6.1**), but such exposures are often difficult and impractical to establish and maintain, and they quickly become useless in snowfall. In a 1989 WMO survey across more than 100 countries [6] the most common height of the raingauge rim was between 50 cm and 150 cm (18 inches to 5 feet) above ground level, being generally higher in countries where substantial snowfall occurs (gauges at lower heights can quickly become buried by heavy or drifting snow, and in such districts the standard raingauge height is normally set well above the mean annual maximum expected snow depth). Unless some form of splash-proof surround is provided, such as illustrated in **Figure 6.1**, raingauges exposed at or close to ground level are vulnerable to insplash or surface water ingress in heavy rain[*].

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[*] Research summarised in the American Society of Civil Engineers *Hydrology Handbook* (ASCE Publications, 1996 – Chapter 2, *Precipitation*, page 32) suggests that 'splash height' in heavy rain can reach 1 m above smooth, rigid surfaces, although splash heights are much less over grass and bare soil.

- *Level* The raingauge collecting surface must be set, and maintained, absolutely level. Slight errors in the level of the funnel rim can result in significant under- or over-catch, the reduction averaging about 1 per cent for each degree of tilt [7]. Unless firmly fixed in the ground and regularly checked, it is very easy for slight errors of level to occur – movement of the gauge in dry soil, even minor knocks from a lawnmower, can affect the gauge and are easily overlooked. Raingauges located on masts are not only subject to greatly increased wind effects, but can prove almost impossible to keep level.
- *Observation times* To ensure that rainfall measurements from differing sites are comparable, a common period within the day to which the measurement refers must be specified. Many synoptic or automatic weather stations will provide real-time rainfall measurements at hourly, three-hourly or six-hourly intervals, but most manual raingauges are still read once daily, usually at a convenient morning observation time. The standard rainfall observing time in the United States is 7 A.M. local time; in the UK and Republic of Ireland, 0900 UTC (9 A.M. clock time in winter, 10 A.M. summer time); in Spain and Portugal 0900 UTC; and in Australia 9 A.M.
- Finally, the *design, construction and materials* of the raingauge itself can influence the amount of precipitation measured. A deep round funnel is important, to avoid outsplash in heavy rain, and to help retain solid precipitation (particularly snow) in windy conditions. Shallow funnels are liable to lose precipitation catch due to outsplash, and are completely ineffective in snowfall. Square or rectangular funnels can create turbulent eddies over the gauge, the effects of which will vary with wind direction, and are not recommended. The material of the gauge itself can affect the catch, particularly where amounts are small. Different materials have differing wetting characteristics – droplets react differently to well-weathered metals, such as copper, and shiny plastic surfaces, for example. Where a particular surface favours the formation of near-spherical droplets which do not quickly run off, those droplets may evaporate and thus be lost to the record. The surface characteristics of the catching surface can also change over time, affecting runoff and thus gauge catch. Where the gauge is designed to store liquid water for subsequent measurement, it is vital to ensure that the design of the unit minimizes evaporation from the storage container to avoid losses between the time of precipitation and the time of measurement, particularly if the gauge is not read daily.

For all these reasons, the measurement of precipitation is, perhaps more than any other element, closely defined by standards.

A global habit

The measurement of surface precipitation is the most common form of meteorological measurement made globally – a WMO survey in the 1980s [6] identified more than 150,000 manually read raingauges then in use. Although rationalization of rainfall networks, usually for financial reasons, has certainly led to some reductions within recent decades, the increase in automated recording systems, both professional and consumer models, has also resulted in a significant net increase in gauge density. Today there may well be a million or more raingauges in use worldwide, although the degree of standardization has also reduced. The majority of these gauges are read only once daily, but an increasing proportion of the global network consists of automatic instruments which can provide a record of rainfall against time. Some are connected over landline, mobile telephone or even direct-to-satellite circuits and can be interrogated remotely, either on demand or at preset intervals, such as hourly or three-hourly polling slots.

In the United States, around 10,000 sites report rainfall into the NOAA network (**Table 5.1**), the vast majority through NOAA/NWS's voluntary cooperating observer programme, while at the time of writing the CoCoRaHS network [8] had grown to more than 15,000 observation locations across 50 U.S. states (see also Chapter 19), and was expanding into Canada. In Australia, the raingauge network operated by the Australian Bureau of Meteorology consisted of 6,047 sites in mid 2011. Most are run by volunteers, who provide daily rainfall totals for the impressive Bureau of Meteorology weather and climate website [9]. In the United Kingdom, there were 3,214 sites reporting rainfall measurements to the UK Met Office, the Environment Agency or its equivalents in Scotland and Ireland in 2010 (**Figure 6.2**) [10]: almost 30 per cent of these were automatic sites. At the time of writing there were 475 rainfall-recording sites in the Republic of Ireland reporting to Met Éireann [11], around 90 per cent of which are run on a voluntary basis.

The United Kingdom has probably the densest rainfall network in the world (**Table 6.1**), with an average of one gauge per 76 km^2 (for England alone, the figure is one per 60 km^2), although perhaps surprisingly the more challenging terrain of Switzerland is close behind at one gauge per 101 km^2. In the wide open spaces of Australia, the figure rises to one gauge per 1272 km^2, although Australia has five times the number of raingauges per head of population as the UK or the United States.

Many sites have long and homogenous rainfall records, which are extremely valuable for long-term climate change studies. Probably the oldest current rainfall record in the United States is that for Charleston, South Carolina, which has precipitation records dating back to 1738 [12], although with missing data 1766–84, 1792–1806 and 1812–30. Surprisingly, continuous records were kept there throughout the American Civil War. In 2011 there were 1,474 raingauge sites in Australia with more than 100 years record (compared with just 59 in the UK). One rainfall site in Melbourne has a near-complete record commencing in April 1855, while another on Observatory Hill in Sydney has records from July 1858. The oldest same-site rainfall record in the British Isles is that continued today at the Radcliffe Observatory in Oxford, where rainfall records have been made without a break since January 1815 (see Chapter 1).

Standard methods of measuring precipitation

There are two basic types of raingauge. Both types of instrument are described in this chapter.

- *Manual gauges*, often known as 'storage' or 'accumulation' gauges, simply collect liquid precipitation using a funnel, for subsequent manual measurement in a measuring cylinder or similar. Most are read daily (sometimes more than once daily); in remote locations high-capacity versions are read weekly or monthly. These are the simplest in design and construction, and with no moving parts and

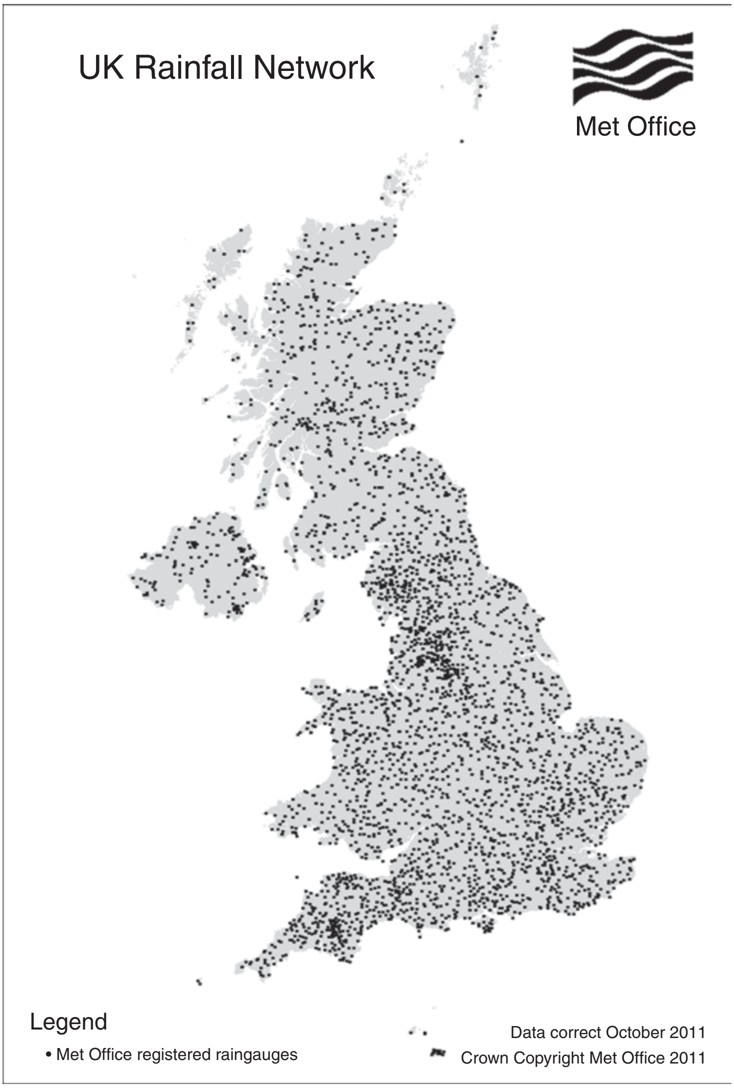

Figure 6.2. The rainfall network in the UK in 2011. (© Crown copyright 2011, the Met Office)

needing no power supply they comprise the backbone of both current and historical rainfall networks in most countries.

- *Recording gauges*, which provide a record of the amount of rainfall with time, using a variety of mechanical, electronic or optical sensors. Recording raingauges are often co-located with a manual storage gauge. Because of losses inherent in mechanical recording gauges, the 'standard' rainfall measurement is normally taken from the manual raingauge. In the UK and Republic of Ireland the standard gauge is usually referred to as the 'checkgauge' for this reason. Sub-daily measurements from the recording gauge or gauges, such as hourly totals, should always be adjusted to agree with the period total from the manual gauge using a simple linear adjustment factor.

Site and exposure requirements are common to both types and are described first.

Table 6.1. *Raingauge coverage around the world*

Country	Network	Land area (km^2)	Population 2011 (millions)	No of sites	km^2 per raingauge	Raingauges per million people
USA	NOAA network	9,629,091	312.1	10 406	925	33
	CoCoRaHS	9,629,091	312.1	15 000	642	48
Australia	Bureau of Meteorology	7,692,024	22.7	6 047	1272	266
United Kingdom	Met Office/ EA/ SEPA/NIW	242,900	62.4	3 214	76	52
Republic of Ireland	Met Éireann	70,273	4.6	475	148	104
Switzerland	MeteoSwiss	41,277	7.9	407	101	52
France	Météo France	640,294	65.8	5 520	116	84
Netherlands	KNMI	37,354	16.7	287	130	17
Germany	DWD	357,114	81.8	4 058	88	50
India	Indian Met Office	3,287,263	1 210	4 161	790	3

Land areas and population (2010/2011 estimates) from online sources. U.S., Australia, Switzerland, UK and Republic of Ireland raingauge data are from primary sources outlined in the text: data for the other countries from reference [10]; for these countries the number of gauges has been calculated from the gauge density and land area given in the reference. More countries are given in reference [6], although the information in that 1989 WMO report is now more than 20 years out of date.

Site and exposure requirements

As with observations of air temperature, the requirement for precipitation measurements is to obtain a sample representative of the area where the raingauge is located. The choice (and documentation) of site is therefore of particular importance. To achieve a representative precipitation measurement, the ideal site should be open to the weather – not too exposed to the wind, nor too sheltered from it. As most other meteorological instruments are best exposed in sites that are as open as possible to the elements, it is sometimes necessary to site the raingauge or raingauges in a more sheltered place, perhaps even in a different location, from the other instruments, particularly the wind sensors. Very exposed sites are rarely ideal for making rainfall observations, because wind-related errors will be high, for the reasons explained earlier. Sites on headlands or cliffs, on windy moorlands, exposed lighthouses and even some airfields are particularly troublesome. Locations on a slope, and particularly rooftop locations, should also be avoided.

WMO guidelines [1] suggest that an ideal site for measuring rainfall or snowfall is one where vegetation (such as a forest clearing, or an orchard) or other objects can provide an effective windbreak, while avoiding close obstacles which may unduly shelter the instruments. The guidance is that ‘in general, objects should not be closer to the gauge than a distance of twice their height above the gauge rim’ (see Box, *Determining ‘safe’ distances for objects around a raingauge*). Where there is little alternative to a very exposed site, much more representative rainfall and snowfall observations can sometimes be obtained by using a suitable wind shield, an aerodynamic raingauge or even a ground level (pit) exposure (**Figure 6.1**).

The gauge should be set firmly into the ground, or bolted to a suitable surface, with its rim level and at the correct height above ground level, which varies by country (see below). Mounting the gauge within an area of short grass or a surround of gravel or shingle will reduce the risk of insplash in heavy rain, particularly if the gauge rim is quite close to ground level. Hard surfaces such as concrete or tarmac should be avoided as this will greatly increase the risk of insplash. If using a CoCoRaHS-type four-inch plastic raingauge (or similar) mounted on a post, avoid mounting them on fence posts within a fence line, as the turbulence caused by the fence itself will affect the raingauge catch.

How far away should obstacles be from the raingauge?

WMO's recommendation that 'no object should be within twice its height above the rim of the gauge' has been adopted by most state weather services around the world. The easiest way to determine whether the condition is satisfied is by making a site plan. Measure the distance to all significant obstructions – buildings (including outbuildings), fences, trees and other nearby meteorological instruments – and draw up a site map to scale. Next, using a clinometer, take accurate elevation bearings on each significant object*. The height of the object H is given by

$$H = \text{Tan}\theta \times D$$

where θ is the observed clinometer angle (in degrees) and D is the distance to the object. Values of tangents can be obtained from standard tables, on the web (for instance, at www.science-projects.com/TangentTable.htm) or from the function within Excel.

Determining 'safe' distances for objects around a raingauge

Example: the top of a tree 17 m away subtends an angle of 12 degrees when measured at eye height (**Figure 6.3**). How high is the tree? Is it far enough away to satisfy WMO raingauge exposure criteria?

- Tan 17° is 0.3057; the tree is therefore 0.3057 × 17 m tall = 5.2 m above eye height. Assuming the clinometer is read ± 1 degree, the error is therefore ± 0.3 m, and the tree height 5.2 m ± 0.3 m.
- If eye height is 1.7 m, then the tree is 6.9 m tall, ± 0.3 m.
- If the raingauge rim is at 30 cm above ground, then the tree is 6.6 m above its rim; as the tree is 17 m distant, the height multiple is (17 / 6.6) = 2.6 ± 0.1
- This exceeds the minimum recommendation of twice its height above gauge rim, therefore **the tree is not unduly sheltering the raingauge**.

Working the equation backwards will show the minimum distances that objects of a certain height need to be above the raingauge rim – for example:

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* The elevation measurement should be made from the height of the raingauge rim, although this is easier said than done from gauges which are close to ground level, as in the United Kingdom. It is of course easier to take the measurement from normal eye height, and adjust accordingly, as in the example on this page.

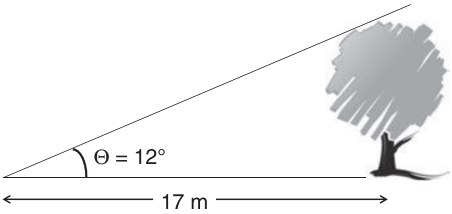

Figure 6.3. Determining raingauge site exposure.

- For a U.S. standard raingauge with rim at 4 feet, an outbuilding 11 feet high should be at least 2 x (11–4) ft = 14 ft distant: a building or tree 52 feet high should be at least 2 x (52–4) ft = 96 feet distant
- For a UK standard raingauge with rim at 30 cm, an outbuilding 2.5 m high should be at least 2 x (2.5–0.3) m = 4.4 m distant: a building or tree 12 m high should be at least 2 x (12–0.3) m = 23.4 m away.

These are minimum distances, and usually the greater the separation the better, up to a height/distance multiple of about 10 (see Table 6.2).

Simple trigonometry will show that the WMO recommended minimum height multiple of 2 corresponds to an elevation angle of 27 degrees, and thus a quicker method is simply to check with a clinometer whether any objects in the vicinity subtend an angle of 27 degrees or more from the raingauge rim. (Making a site plan is good practice, however, and is useful for documenting the site details and location of other instruments, if any – see Chapter 16, *Metadata – what is it, and why is it important?*) For ease of reference, **Table 6.2** calculates the height/distance ratio for elevation angles from 3 to 40 degrees. (Remember that the elevations refer to the height of the rim of the gauge, and not eye height.) This table also gives the WMO site description, based upon the *average* elevation angle through the full 360° around the site or within four or eight compass segments around the compass.

Objects closer than a ratio of about 1.5 are likely to result in increasing loss of natural precipitation, particularly in windy conditions, while rain or droplets of wet fog from very close objects may also drip or be blown into the raingauge (even when it is not raining).

However, I have seen rainfall sites so sheltered as to make finding the raingauge itself quite difficult but which produced results indistinguishable from neighbouring gauges, and other apparently perfect sites for which the observed rainfall simply did not fit in with the local pattern. The only real test is to set up the equipment and make observations over a period of at least several months, and compare results with local stations whose observations and equipment are known to meet appropriate national standards for equipment and exposure – see also Chapter 19, *Sharing your observations*. It is important that sites used for comparisons are (as far as possible) reasonably close, in similar terrain and at a similar altitude above sea level, because (particularly in hilly areas) large differences in rainfall can result from sometimes seemingly minor changes in topography or aspect. Results should be compared over a period of at least several months rather than days or even weeks, as rainfall patterns can vary substantially over short periods. The inclusion or otherwise of a single heavy rainfall event at a single site can distort conclusions.

Table 6.2. *Height-distance ratios for given elevation angles above raingauge rim, as determined by clinometer*

Clinometer angle, degrees	Ratio *h*	Exposure category	WMO exposure description [1]
3	19.1	*Probably over-exposed*	Average 0–5 degrees: **Exposed site**. Only a few small obstacles such as bushes, group of trees, a house
5	11.4		
6	9.5		Average 6–12 degrees: **Mainly exposed site**. Small groups of trees or bushes or one or two houses
8	7.1		
10	5.7		
12	4.7		
14	4.0		Average 13–19 degrees: **Mainly protected site**. Parks, forest edges, village centres, farms, group of houses, yards village centres, farms, groups of houses, yards
16	3.5	**Optimum exposure**	
18	3.1		
20	2.7		Average 20–26 degrees: **Protected site**. Young forest, small forest clearing, park with big trees, city centres, closed deep valleys, strongly rugged terrain, leeward of big hills
22	2.5		
24	2.2		
26	2.1		
27	2.0		
28	1.9	*Over-sheltered exposure*	
30	1.7		
32	1.6		
34	1.5		
36	1.4	*Very sheltered exposure*	
38	1.3		
40	1.2		

The character of the obstruction is also important – trees and hedges have a very significant sheltering effect (particularly when in leaf), open structures such as a widely spaced fence less so. Tall but thin obstructions, such as a small anemometer mast, probably have little impact on precipitation measurements provided they are located at least a few metres away. It is always best to site a raingauge with its most open exposure to the prevailing rain-bearing winds. In temperate latitudes in the northern hemisphere, this will normally be between south and west, but often with a significant secondary maximum on north or north-easterly winds which is easy to overlook. Local topography (particularly hills or mountains upwind) can also introduce significant regional differences. Determining the wind directions which produce the majority of rain in your location is itself an interesting project – see Chapter 18, *Making sense of the data avalanche* for how to do this.

How high should the raingauge be?

The standard *height of the raingauge rim* varies by country. Rim height is an inevitable compromise between several factors – low rim heights reduce wind errors but increase the risk of insplash in heavy rain, while higher rims increase wind losses significantly but are less likely to be buried by snowfall. In addition, the physical size of raingauges renders near-ground level exposure impractical except in research facilities (**Figure 6.1**), although pit gauges are preferable where practical. However, pit gauges are not necessary in the average garden, park or university campus; only at exposed sites will there be any benefit. Nor are wind shields worthwhile at most domestic sites. The national standard for raingauge rim height will normally be defined by the state weather service, and for observations to be comparable instrument type/s, exposure and rim height should follow national standards as closely as possible. Most countries specify a gauge height between 50 cm and 150 cm (18 inches to 5 feet) above ground level. Varying climatic factors, together with the need to maintain consistency and homogeneity in a country's long-term precipitation records, the expense of re-equipping or re-siting significant networks and the inevitable politics of international diplomacy, probably make a fixed worldwide common standard impossible to enforce.

In the UK and Ireland the standard height of the raingauge rim was established at 30 cm (1 foot) above ground level following a number of comparative trials in the 1860s and 1870s (**Figures 4.2**, **6.4**, **6.5**): in the United States, the standard height is usually between 3 and 4 feet (90 to 120 cm) (**Figure 6.6**).

Particularly in domestic or school situations, ideal sites will not always be available and the exposure of a raingauge is often a compromise. Even if the site is sheltered, and the exposure less than perfect, careful consideration of the available options may allow a rainfall record that is sufficiently close to standard neighbouring gauges to permit useful comparisons to be made.

A raingauge exposed to meet defined national standards of instrument type, exposure, observing time, site and rim height can be regarded as providing a

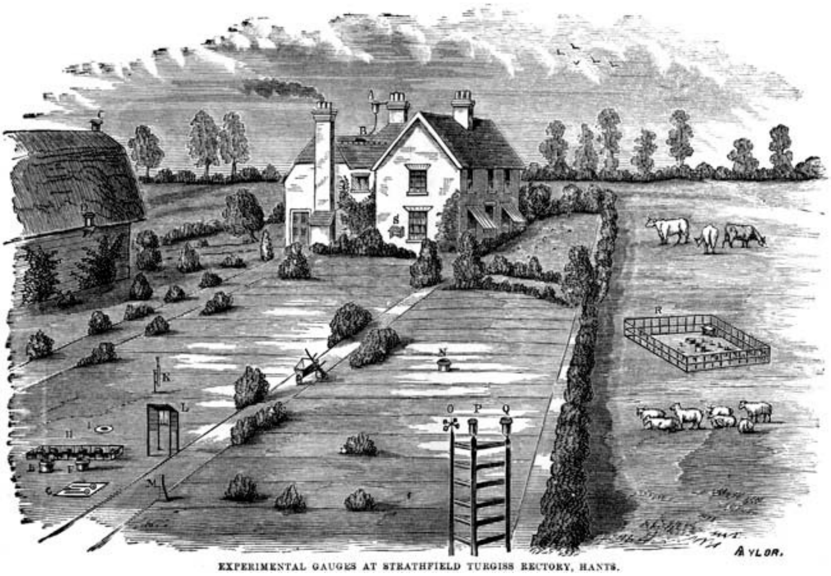

Figure 6.4. The Frontispiece from *British Rainfall 1868,* showing 42 experimental raingauges in the grounds of Strathfield Turgiss (now Stratfield Turgis) rectory in north Hampshire, England. Detailed comparisons of the different types and exposures were published in *British Rainfall* by the observer, the Rev. Charles Griffith. These tests were largely responsible for establishing the UK's standard raingauge type, height and exposure, which remains in place today.

Figure 6.5. Standard UK raingauge with rim at 30 cm above ground. See also Figure 6.8. Inset: shallow-funnel rain gauge. These are liable to under-read in heavy rain, owing to outsplash, and are not recommended. (Photographs by the author)

Figure 6.6. Standard U.S. National Weather Service raingauges – standard manual eight-inch gauge (left), Fischer & Porter automatic gauge (right), being serviced by Gary Wicklund at Malta, Idaho, July 2010. (Photograph courtesy of Gary Wicklund and Vernon Preston)

'standard' rainfall record, fully comparable both with other records made under similar conditions, and with the historical rainfall record.

As with all external meteorological instruments, security and access to the site should also be considered carefully: in public areas pay particular attention to site security to reduce the risk of vandalism, theft or sometimes unwanted 'additional contributions'.

Types and choice of raingauges

As outlined earlier, there are two basic types of raingauge: manual gauges that simply store the water from liquid precipitation (melted in the case of solid precipitation) for subsequent measurement, and those that provide a record of the amount of rainfall with time. Many sites will have both a manual gauge (which provides the 'standard' rainfall total for the period) and a co-located recording gauge.

Manual raingauges

The first known measurements of precipitation were made in India in the fourth century B.C. [13]: the basic principle has changed little over time. Most manual raingauges are very simple, consisting of a funnel of known surface area which collects rainwater. This is stored in a suitable container, and subsequently measured in a calibrated vessel. The measuring vessel is typically a glass measuring cylinder, or similar graduated container, whose surface area is considerably smaller than that of the collecting funnel. The ratio of the two surface areas provides scale magnification, making small amounts easy enough to read to a precision of 0.1 mm or 0.005 inches. It is essential to ensure that the measuring cylinder is correctly paired with the gauge funnel diameter, as even slight differences in funnel size will make substantial differences in the measurements made. Chapter 15, *Calibration*, shows how to calculate the volume or weight of water for a given depth of rainfall and a specified funnel diameter, and thereby check the calibration is accurate.

There are many and varied types and designs of manual raingauge in use around the world: the 1989 WMO report [6] illustrated 54 main types. No doubt many more have appeared since then.

Measuring small amounts of precipitation

A rainfall amount below the lowest graduation on the measuring cylinder – usually 0.05 mm or 0.005 inches – is, by long convention, entered in the records as 'trace'. Where it is known from personal observation that precipitation has fallen, but there is none in the gauge, it is also acceptable to enter 'trace' (personally I use '< trace' to distinguish such events).

When the measured amount results from condensation from dew, fog or frost, the entry can be made as 'trace – dew', 'trace – fog' or 'trace – frost', as appropriate. Occasionally fog or dew can result in as much as 0.1 or 0.2 mm / 0.01 inches in the gauge, in which case the entry should read 'Dew 0.2' ('Dew 0.01' for inch measurements), or similar. 'Dew – trace' and similar terms should be entered only where there is some water in the gauge, and not merely when dew is seen on the grass, for example. Where there is a trace in the gauge resulting from precipitation, and a further trace subsequently results from (say) dew or fog, only 'trace' should be entered.

The U.S. standard raingauge

The most common pattern of manual raingauge in use in the United States, known simply as the Standard Rain Gauge, or SRG, consists of an aluminium (aluminum) metal cylinder with a copper, aluminium or plastic funnel on top and a plastic measuring tube in the middle. The standard funnel diameter is eight inches (203 mm), and includes an accurately turned knife-edged rim. The body of the gauge itself is typically about 2 feet (600 mm) long, and the gauge is normally fixed to a small metal stand or tripod, itself bolted into the ground or a suitable heavy object such as a block of concrete, to bring the rim height normally to between 3 and 4 feet (90 to 120 cm) above ground level, as shown on the left of **Figure 6.6**. In areas subject to heavy snowfalls, gauges can be mounted on supports at greater heights to remain well above normal snow accumulation levels. Wind shields may also be fitted to gauges in such districts.

The collected water from the deep funnel is measured by eye in a measuring cylinder located inside the gauge unit, readable to a precision of 0.01 inches. This can hold up to 2 inches or 50 mm of rain before it overflows into the larger outer cylinder. If rainfall overfills the tube, the excess is caught in the outer overflow can. If this occurs, the overflow from the outer can is poured back into the measuring cylinder after the 2 in measurement is noted, and incremental overflow measurements added to this to obtain a daily total.

This type of gauge has been in use for more than 100 years, and most are read daily. The majority of long-term U.S. precipitation records are derived from gauges of this type.

The U.S. plastic raingauge

There are more plastic raingauges in the United States than SRGs – currently more than 15,000 in the CoCoRaHS network alone (see Chapter 19) – although only about 140 of these provide records for NOAA's standard rainfall network (**Table 5.1**). The most common model is shown in **Figure 6.7**. This pattern is about one-tenth of the

Figure 6.7. Four-inch plastic raingauge, as used in the U.S. CoCoRaHS network. (Photograph by Henry Reges, Colorado State University)

price of its eight-inch metal equivalent. The gauge is made of clear, tough butyrate and has a capacity of 11 inches (275 mm) of precipitation. The internal measuring tube is graduated to 0.01 inch, and has a capacity of 1 inch. Precipitation greater than 1 inch overflows into the outer cylinder and is measured by pouring into the measuring tube. Versions with metric calibration are also available.

As with the larger SRG, the receiving funnel and measuring tube are removed for collection of snow (see below).

The UK and Ireland standard raingauge

The British Rainfall Organization encouraged a number of comparative raingauge tests in the 1860s and 1870s (**Figure 6.4**), and from these tests emerged the standard deep funnel copper 'Snowdon' storage raingauge, still the UK and Ireland standard almost 150 years later. (The WMO analysis in 1989 also showed that the Snowdon gauge was in use at around 18,000 sites around the world, being adopted as the standard model in 29 countries – [6].) This simple, inexpensive and robust instrument is also known as the 'five-inch' raingauge, as the diameter of the funnel is exactly 5 inches (127 mm). The 'Met Office Mk II' or 'splayed base' raingauge (**Figures 6.5**, **6.8**) is identical to the Snowdon pattern with the inclusion of the outer splayed base, which makes the raingauge more stable when dug into the ground – a Snowdon gauge tends to become loose over time, particularly in sandy soils or dry weather, and requires regular checking to ensure it stays upright and level. The splayed base also provides additional overflow capacity in the event of exceptional rainfall.

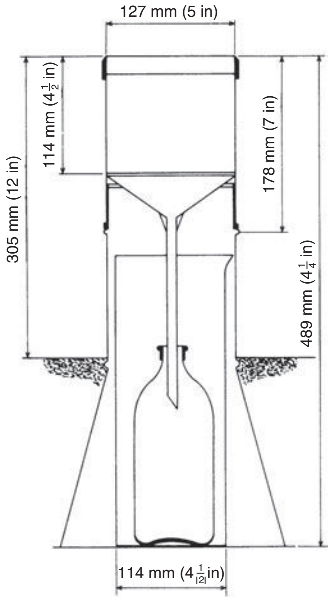

Figure 6.8. UK splayed base five-inch 'Mark II' raingauge. (© Crown copyright 1982, the Met Office)

Changing the UK classic raingauge?

Starting in 2006, the UK Met Office began introducing a stainless steel variant of the classic copper Snowdon raingauge. Stainless steel had not been invented at the time of the British Rainfall Organization raingauge trials in the 1860s and 1870s and was therefore not one of the materials tested. But does changing the material from which the standard gauge is made affect the results in any way? Even a small change – such as changing from a glass bottle to a plastic one – may damage the consistency of the 150 years of rainfall records already secured, so the question is important. Ongoing side-by-side trials of two gauges, one copper and the other stainless steel, are under way at the Chilterns Observatory at Whipsnade, Bedfordshire in south-east England, to determine whether records from the two gauge types really are fully interchangeable.

The basic principle is the same in both models – water collected in the deep funnel, rimmed with a brass knife-edge which precisely define the catchment area, falls through the connecting tube into the collecting bottle. The deep funnel largely eliminates insplash and outsplash in heavy rain and hail and is an essential feature*. The connecting tube has a narrow cross-sectional area and fits the neck of the collecting bottle fairly tightly; this together with the fact that the bottle is mostly underground and largely unaffected by extremes of surface temperature both minimizes evaporation and almost eliminates the chance of the contents freezing in cold weather. The collecting bottle is surrounded by an outer container or can which serves as an overflow in extremely heavy rainfall. In the Mk II gauge the splayed base acts as a second-level overflow container.

At the nominated daily observation time, the collected water is carefully poured into a 10 mm capacity measuring cylinder and read by eye, to the bottom of the water meniscus, to a precision of 0.1 mm. Amounts of more than 10 mm are summed from successive fillings of the measuring cylinder (taking care not to drop or spill the raingauge bottle while doing so, of course). The measuring cylinder is tapered at the bottom to facilitate the measurements of small amounts.

Other types of manual raingauge

The many different types of manual raingauge in use around the world all use a similar principle, but funnel diameters, rim heights and measurement details vary considerably from country to country (sometimes within a country). It is difficult to be sure that rainfall statistics are comparable between different gauge types or countries, or are consistent in time where instruments or methods have changed. As a modern follow-on to the raingauge trials of almost 150 years ago depicted in **Figure 6.4**, WMO continue to set out international intercomparison field trials of meteorological instruments, including raingauges. **Figure 6.9** shows part of the test

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[*] Some UK weather-equipment resellers sell copper five-inch gauges with shallow funnels (Figure 6.5 inset). Whatever the description quoted, these are *not* standard raingauges and should be avoided at all costs. Gauges with deep funnels are only slightly more expensive, but offer greatly superior performance in conditions of heavy rain, hail or snow.

Figure 6.9. International raingauge intercomparison field trial at Vigna di Valle, Italy, in 2009. (Photograph courtesy of the World Meteorological Organization, Geneva, from reference 14)

array at a recent intercomparison of 31 rainfall intensity gauges, hosted at the Centre of Meteorological Experimentations of the Italian Meteorological Service in 2009. Detailed results of this trial were published by WMO [14]. The results of other international raingauge intercomparisons trials have also been published [15], covering both manual and recording instruments and the measurement of snowfall in precipitation gauges.

Manual raingauge capacity

Reliable raingauge records of extreme rainfall events are of enormous scientific and civil engineering value. The capacity of a manual raingauge should be sufficient to capture (at least) a ‘once in 100 years’ daily rainfall event, and preferably a 1,000 year occurrence. For gauges which are read less frequently than daily, the gauge capacity should be in proportion. While the chances of exceptional short-period rainfall events are very remote at any one point, it would be frustrating in the extreme to lose the record of a once-in-many-lifetimes event simply because the raingauge had overflowed!

How much should a raingauge hold?

Within the UK and Ireland, a manual gauge should hold at least 150 mm of rain, particularly if the site is not visited daily (and this may include amateur observers’ gauges whilst absent on holiday, or schools over holiday periods, for example). A Snowdon gauge will hold 150 mm, a MkII gauge about 250 mm. Falls in excess of 100 mm in a few hours have been recorded in almost all parts of the British Isles, and are not particularly uncommon in the wetter mountainous districts. The highest 24 hour rainfall total yet reliably recorded in the British Isles occurred at Seathwaite Farm in Cumbria on 19 November 2009: in the 24 hours ending at midnight on 20 November 316 mm was recorded by a logged tipping-bucket raingauge [16]. Great difficulties attend the measurement of very intense short-period rainfall events, not least enormous volumes of floodwater, but a raingauge record of 193 mm in about 2 hours at Walshaw Dean Reservoir near Halifax, West Yorkshire on 19 May 1989 has now been generally accepted [17]. More recently, up to 300 mm may have fallen in 4 hours near the centre of the storm responsible for the Boscastle flood in Cornwall on 16 August 2004 [18].

Within the United States, the expected maximum daily 24 hour fall varies from below 18 inches (450 mm) in Montana to in excess of 38 inches (close to 1,000 mm) in Texas and Louisiana [19]. A standard U.S. raingauge will hold 20 in (500 mm). The highest daily falls on record within the United States are 43.0 in (1092 mm) at Alvin, Texas on 25–26 July 1979 and 38.7 in (983 mm) at Yankeetown, Florida on 5 September 1950. Whilst it would be unrealistic to implement as standard a raingauge network that could cope with such extreme falls without difficulty – the fall at Alvin would amount to a little over 35 litres, or 9 U.S. gallons, of collected water in a standard eight-inch gauge – a minimum raingauge capacity of 20 in / 500 mm is advisable. Note that daily falls in excess of 600 mm have been recorded as far north as New Jersey and Iowa.

Reliably calibrated and maintained recording gauges are capable of recording such extreme events (provided, of course, that they remain unaffected by surface flooding or storm debris), thus avoiding the requirement for a physically very large storage container as part of the gauge itself. In February 2007, a 400 cm^2 tipping-bucket raingauge near the summit of Cratère Commerson on La Réunion island in the Indian Ocean (21° 12′ S, 55°39′ E, elevation 2,310 m / 7,579 ft) successfully recorded new world record three- and four-day falls of 3,929 mm (154.7 inches) and 4,869 mm (191.7 inches), respectively, during the passage of Tropical Cyclone *Gamede* [20].

Raingauge sites which are themselves susceptible to flooding – either the site of the gauge itself, or access to the gauge – should be avoided, as the gauge may not be reachable after a heavy rainfall event. Worse still, the gauge itself may have been flooded above its rim, or even swept away in floodwater.

Recording raingauges

Most recording raingauges can be assigned to one of four categories:

- Tipping-bucket raingauges;
- Float gauges;
- Weighing gauges; and
- Drop-counter optical instruments.

All four are discussed briefly in the remainder of this chapter. Each has its advantages and disadvantages.

Tipping-bucket raingauges (TBRs)

By far the most common type of recording raingauge used in modern AWSs is the tipping-bucket type. Ironically this is one of the oldest of today's meteorological instruments, first described by Christopher Wren, the architect of London's St Paul's cathedral, around 1663 [13]. This sensor has become very much more popular with the advent of digital loggers – Sir Christopher was clearly around 350 years ahead of his time.

The principle of the tipping-bucket raingauge is simple and robust (**Figure 6.10**). Rainwater from the collecting funnel is fed into one of two 'buckets' mounted on a pivot. One bucket fills with water until its weight exceeds that of a counterbalancing weight, at which point it 'tips' forward, out of the path of the incoming flow of water from the funnel, emptying as it does so and bringing the other bucket quickly into place underneath the collecting tube. As the bucket tips forward, a magnet attached to the bucket mechanism swipes over a reed switch, making and breaking a brief electrical contact. The pulse thus generated represents one increment of rainfall. The second bucket then fills until it also tips, generating another pulse, at which point the original bucket takes its place under the funnel once more. The cycle repeats itself as long as water continues to flow into and through the funnel. The instrument is sensitive to level, and un-balanced buckets or an off-level gauge will lead to irregular tip behaviour.

Figure 6.10. Tipping-bucket raingauge, showing details of the tipping-bucket mechanism. (Photograph by Ian Strangeways)

Bucket and funnel capacities are paired to achieve a specific increment of rainfall, usually 0.1, 0.2, 0.5 or 1 mm, or 0.01 to 0.10 inches of rainfall. Some manufacturers offer 'mix and match' tipping-bucket raingauge funnel diameter and bucket capacities, reducing unit costs. An increment of 0.2 mm is ideal for most climate monitoring needs, including remote AWSs, although a 1 mm tip may be preferable for remote areas with a high annual average rainfall and/or a frequent high-intensity rainfall regime. Note, however, that the 1 mm units typically found on entry-level and some budget AWS models are simply too coarse for accurate daily or sub-daily rainfall records (see below).

Although TBRs previously generated paper chart records, using a ratcheted mechanical cog mechanism, nowadays most are connected to a datalogger of some description. The logger counts the pulses on a regular basis, and the accumulated rainfall over time is simply derived from total tips *x* bucket capacity. Short-period estimates of rainfall *intensity* can be obtained if the number of tips in a given period is known, or if the tip times are also logged (see Box, *Event-based rainfall logging*). However, TBRs are poorly suited to the measurement of the *duration* of rainfall, particularly persistent light rain or drizzle, owing to the incremental nature of their record. A count of the frequency of hours with 0.2 mm or more is a useful climatological statistic in itself which is more objective than manual methods of determining rainfall duration from paper chart records: it is also much more easily derived from digital summaries, and is becoming more widely adopted.

Tipping-bucket raingauges are very widely used, but they are not as accurate nor as repeatable as manual gauges. Calibration can fluctuate quite widely, sometimes for no very apparent reason, while a wide variety of external factors ranging from insects to snowfall can partially or completely spoil the record. *For these reasons it is not recommended that TBRs be used as the sole precipitation measurement device.* It is always advisable to site a manual 'checkgauge' close by, even if this is read only occasionally – perhaps weekly or monthly at unmanned or remote sites. Exact agreement with the manual gauge is unlikely (see Box, *Should my raingauges agree exactly?*), but significant or increasing differences should be investigated promptly as it is more likely that the TBR mechanism or calibration is at fault. Some TBRs used in the United States retain the rainfall passing through the buckets for subsequent manual measurement, as a double-check on the instrument's record.

Should my raingauges agree exactly?

Probably not. For a number of reasons, outlined in the text, similarly exposed manual and automatic gauges will normally give slightly different rainfall totals. Larger differences can be expected with solid precipitation, if the gauges are exposed some distance apart or if one of the gauges is exposed differently (mounted considerably higher above the ground, on a mast or rooftop, for example).

The key word here is *slightly*. A correctly calibrated and well-exposed tipping-bucket raingauge can be expected to agree with a standard manual gauge to within about 2 per cent. A difference of up to 5 per cent in total rainfall over a period of a month or so is acceptable (although daily totals may vary more than this): normally the automatic raingauge will be the lower. Where period totals differ by more than about 5 per cent, the reasons for the discrepancy should be investigated – it may be that the tipping-bucket raingauge calibration is adrift (see Chapter 15 for ways to check and correct this), that the tipping-bucket raingauge funnel has become blocked, that the gauge is no longer level, or that the magnetic reed switch mechanism is defective (easily checked by shorting the two contacts together). Field trials suggest that the accuracy of some tipping-bucket raingauges with small funnels (and thus bucket capacity), such as the unit included as standard with the Davis Instruments Vantage Pro2 AWS, may also vary significantly with temperature [21].

Sometimes it is simply not possible to identify the reasons for significant discrepancies, or the discrepancy may be irregular in nature. Assuming both gauges are level and the TBR calibration has been checked and adjusted as necessary (and this should be repeated every year or so), continual slight tweaking of the TBR calibration simply to force agreement with the checkgauge should be avoided. The two gauges can be expected to differ slightly and the pursuit of absolute agreement is both frustrating and ultimately unnecessary.

Like most instruments, tipping-bucket raingauges benefit from occasional maintenance. To increase the chances of obtaining an uninterrupted record of rainfall, two units should be used alongside a standard raingauge, so that in the event of one becoming defective the record from the second unit should still be available.

Common problems to watch out for include the following:

BLOCKED FUNNEL, OR BUCKET MECHANISM OBSTRUCTIONS. Most tipping-bucket raingauges include a mesh filter on the funnel exit pipe, but these can easily become blocked by bird droppings (small birds seem to find a raingauge rim an excellent toilet perch), insects, leaves and the like. It is not always obvious at a glance, however, whether the funnel is obstructed. Often the first evidence will be a period of no record during a known period of rainfall, or (more likely) a period of very steady even ‘rainfall’ accumulation, which may also continue long after the rain has ceased, as the water held up by the blockage slowly seeps through into the buckets. If this happens, there is no remedy – the record is irrecoverable unless there is a backup gauge providing a parallel data source. It is thus good practice to check the funnel and filter visually for blockages every day or two, and thoroughly flush out the funnel and the collector pipe every month, whether or not obvious obstructions are present. Some types of insects also find tipping-bucket raingauges irresistible; no record from the TBR after a dry spell may mean that spiders or earwigs have taken up residence and obstructed the pivot mechanism.

Unattended period totals from tipping-bucket raingauges should present few difficulties (other than the finite memory capacity of the attached logger), although in practice the likelihood of loss of record owing to mechanical blockages or obstructions places an operational limit on the maximum ‘safe’ period they can be left between visits – typically, 3–4 weeks is about the limit.

SNOWFALL. Unfortunately, running two parallel tipping-bucket raingauges will not guarantee a record in snowfall, because TBRs – like most raingauges – are largely

Figure 6.11. Manual and tipping-bucket raingauges gauges following heavy snowfall, January 2010. (Photograph by the author)

useless in such conditions (**Figure 6.11**). In climates where significant falls of snow are a regular feature of the winter months, models with internal heaters are available which will melt snow falling into the funnel as it falls. These are controlled by thermostats to minimize electrical power usage and evaporative losses, but they need a substantial power supply to keep pace with a heavy snowfall, one rarely feasible in remote locations or with solar-powered or battery-driven systems. See also *Measuring snowfall*, below.

EVAPORATION FROM PARTIALLY-FILLED BUCKETS. One reason why tipping-bucket raingauges under-record compared with standard raingauges is that the receiving bucket is likely to remain partially filled at the end of a period of rainfall. If more rain falls soon afterwards and the humidity remains high, little water will evaporate, but on occasions when small amounts of rainfall are separated by spells of dry weather, the contents can evaporate entirely and thus be lost to the record. The total rainfall indicated will therefore be too low.

Errors increase with bucket capacity, particularly where small amounts of rain (1 mm or less) are much more frequent than larger falls. **Table 6.3** shows an example. The values here are in millimetres, but the principle applies equally to inch measurements.

Here the hypothetical ‘actual fall’ is shown to 0.05 mm for the sake of example. All the gauges are assumed to be accurately calibrated (i.e., tip at the nominal capacity shown), while an evaporation rate of 0.2 mm/day is assumed for the tipping-bucket gauges.

Table 6.3. *Example comparison of a daily rainfall sequence between various raingauges; see text for the assumptions made. Values in millimetres*

			Tipping bucket capacity		
Day number	Actual fall	Manual gauge total	0.1 mm	0.2 mm	1.0 mm
1	0.15	0.2	0.1	*Nil*	*Nil*
2	*Nil*	*Nil*	*Nil*	*Nil*	*Nil*
3	0.30	0.3	0.3	0.2	*Nil*
4	*Nil*	*Nil*	*Nil*	*Nil*	*Nil*
5	0.70	0.7	0.7	0.6	*Nil*
6	0.10	0.1	0.1	*Nil*	*Nil*
7	1.90	1.9	1.9	1.8	2
8	0.50	0.5	0.5	0.6	1
9	0.90	0.9	0.9	0.8	*Nil*
10	*Nil*	*Nil*	*Nil*	*Nil*	*Nil*
PERIOD TOTAL	**4.55 mm**	**4.6 mm**	**4.5 mm**	**4.2 mm**	**3 mm**
		100%	*98%*	*91%*	*65%*

The 0.1 mm tipping-bucket raingauge closely follows the 'actual' and the manual gauge closely, recording the correct number of days with 0.1 mm or more of precipitation (7)[*]. The 0.2 mm tipping-bucket raingauge shows only 5 days with rain, missing out the slight falls on day 1 and day 6 but under-recording several of the falls by 0.1 mm. These then evaporate, leaving the period total 4.2 mm (9 per cent below the manual gauge value). The 1 mm capacity bucket is simply too coarse a resolution to record small amounts accurately, and it records rainfall only on 2 days. Because some rainwater remains in the bucket from previous days, both days are slightly higher than the total from the manual gauge. However, the period total is only 3 mm, only two-thirds of the manual gauge total. Clearly this sensor would hardly present a good climatological account of this spell of weather.

LOSS IN HIGH-INTENSITY RAINFALL EVENTS. Tipping-bucket raingauges perform best at rainfall rates between about 0.6 mm and 30 mm (0.02 and 1.2 inches) per hour. During periods of very heavy rainfall, a tipping-bucket gauge can under-read by far more than normal compared to a standard raingauge. This is often the result of two factors – losses in the tipping process or so-called 'continuous tipping' or 'bucket bounce', both of which become much more likely above a particular threshold, typically 100–150 mm/hr (4–6 inches/hr). At these rainfall rates, the inflow of water from the raingauge funnel is so rapid that the smooth mechanical operation of the tip mechanism is disrupted or even ceases, as a result of which the bucket tip rate slows down or stops altogether. At a rainfall rate of 500 mm/hr (20 in/hr), for example, it takes only 1.4 seconds to fill a 0.2 mm capacity tipping bucket, compared with about 0.5 seconds for the tipping process to complete. The bucket may empty

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[*] This is perhaps too generous to a 0.1 mm unit, as small amounts such as 0.1 mm are easily lost in wetting the sides of the funnel, and in evaporation thereafter, particularly where the funnel has previously been heated in sunshine – immediately before a light shower, for example.

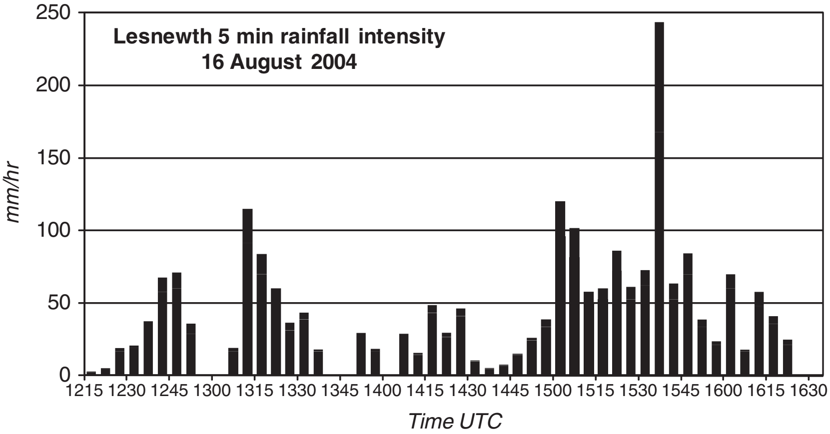

Figure 6.12. Rainfall record from Lesnewth in Cornwall, south-west England, during the 'Boscastle storm' of 16 August 2004 (from reference 18).

and bounce back almost immediately, or the empty bucket may not be able to move into position because of the rapid flow of incoming rainwater, and the full bucket therefore remains in position (no further tips) until the rain rate eases off. The effects are probably non-linear with rainfall rate (and the threshold will obviously be lower with smaller bucket capacity), and can be very difficult to assess retrospectively in exceptional storms. Field trials such as those operated by WMO [14] suggest that, as long as the tipping mechanism continues to function, empirical calibration at high rainfall rates in addition to more usual levels offers useful guidance. Chapter 15 suggests how to do this.

Making accurate records of very intense short-period rainfall records is one of the most useful areas in which relatively dense networks of 'personal' weather stations can contribute to the understanding of severe convective storms, but without an adjacent manual gauge to give a good estimate of 'ground truth' TBR records always remain subject to doubt over their accuracy. A good example occurred in the series of severe thunderstorms which caused catastrophic flooding in Boscastle, Cornwall in south-west England on 16 August 2004. The nearest tipping-bucket raingauge to the centre of the storm, at Lesnewth, recorded 155.2 mm, 19 per cent below the adjacent manual raingauge total of 184.9 mm [18]. With the manual gauge reading known (from a well-maintained gauge, read by a conscientious observer), it was possible to make assumptions of the likely losses sustained by the TBR and thus estimate the peak rainfall intensity during the storm – which approached 500 mm/hr at this site. The adjusted record from the Lesnewth tipping-bucket raingauge at the height of the Boscastle storm is shown here (**Figure 6.12**). This remains the highest resolution record yet obtained of any major rainfall event in the British Isles.

In extremis, however, all TBRs will fail in very intense rainstorms, the ultimate limit being the flow rate through the pipe leading from the funnel (including a particle filter, where fitted). Too narrow a pipe will start to 'back up' at unacceptably low rainfall rates, smoothing out the true intensity profile (this also happens in hailfalls), while in dry conditions too generous a diameter may permit the passage of insects or leaves into the gauge mechanism, and increase evaporation losses from the buckets.

A realistic upper limit for a well-designed 0.2 mm TBR is probably around 1,000 mm/hr (40 in/hr).

Raingauge suppliers

Manual gauges In the United States, standard and plastic raingauges are available from the suppliers listed in Appendix 4. It may be worth a call to your local National Weather Service office, because if you live in a gap in the existing rainfall network they may loan you equipment free of charge. In the UK, standard 'five-inch' copper Snowdon or MkII gauges are available from several suppliers (see Appendix 4). (Remember to include a 10 mm measuring cylinder with your order.) A well-made copper raingauge is not expensive, and can be expected to last a lifetime. The author's manual gauge was purchased with the proceeds of a Saturday job in 1975, and is still in daily use. The Chilterns Observatory Trust (see Appendix 4) may also consider long-term loans of standard Snowdon raingauges at a nominal fee to applicants residing in the UK or Ireland, subject only to meeting basic criteria.

Tipping-bucket raingauges can be purchased as standalone instruments, with or without a simple single-channel logger, or as part of multi-element AWSs. In most cases, a sub-standard AWS system 'bundled' TBR can be easily replaced by a higher-quality or higher-resolution unit, as the connection is a simple two-wire one (ensure the logger calibration can be adjusted to reflect the upgraded unit). High-quality 0.2 mm tipping-bucket raingauges are expensive (with prices starting at a similar level to a mid-range AWS system), although secondhand units do occasionally become available. With care, however, they can be expected to provide reliable records for 20 years or more.

STRAY PULSES. TBR+logger records can be very susceptible to stray pulses. These can be mechanical in origin (the gauge being rocked by high winds, perhaps, or accidentally bumped while the grass is trimmed around it – both resulting in one or more spurious tips), or as a result of stray electrical impulses. The latter are most likely where long runs of unscreened cable connect sensor and logger, particularly following close lightning strikes and especially if the cable is coiled anywhere along its run. The use of screened cable throughout (see *Will it be cabled or wireless?* in Chapter 2) is therefore strongly recommended. All such spurious tips known not to result from genuine precipitation, including those from calibration or maintenance tests, should be removed from the archived record, and the station metadata file annotated accordingly.

Float raingauges

The basic principle of float gauges is readily understood: rainwater collected using a funnel falls into a chamber containing a float, which is attached to an indicating mechanism, usually a pen arm, which marks a clock-driven chart. As rainwater accumulates in the float chamber, the float rises and the pen with it, the slope of the trace being directly proportional to rainfall intensity. The design of such instruments factors-in a suitable ratio of the surface area of the catchment funnel versus

Figure 6.13. The Dines tilting siphon raingauge (TSR). (Photograph by the author)

float chamber to achieve sufficient scale magnification, and a very sensitive and responsive instrument is possible.

Because the record would otherwise be limited by the capacity of the float chamber, a reliable mechanism for automatically emptying the float chamber (and returning the pen to zero) must be included in any practical instrument. The float chamber must also be relatively small, both to maximize instrument sensitivity and minimize physical size.

Designing and building working instruments that successfully and reliably emptied the float chamber proved extremely difficult, however. Although the first surviving design of a float gauge dates from 1782, it was not until 1920 that a practical and reliable instrument was developed – the tilting-siphon rain recorder (TSR), invented by W H Dines [13] (**Figure 6.13**). This quickly became the instrument of choice for recording rainfall intensity and duration within the UK and Ireland: by the 1970s several hundred were in use.

The instrument uses an ingenious siphoning mechanism. As the float nears the top of the float chamber, a catch is unhooked that causes the chamber, mounted on two knife-edge pivots, to become unbalanced and tilt over to one side. The abrupt tilting causes siphoning of the water from the float chamber. The float chamber quickly empties and is pulled back to its original position by a counterbalancing weight, while the pen arm drops back to the zero line. For instruments intended for use within the British Isles, the float chamber capacity is 5 mm of rainfall (higher-capacity ‘tropical’ models are available), and the chart record consist of a series of ascending lines of varying slope (**Figure 6.14**).

Although many have now been replaced by TBR/logger combinations, a considerable number of Dines TSRs remain in use. Records from the instrument are superb for providing an immediate visual impression of continuously varying rates of rainfall, although it can be very difficult to distinguish successive near-vertical pen traces in very intense precipitation. The duration of rainfall can also be assessed from the chart records (at least from daily charts) with a little practice, although the treatment

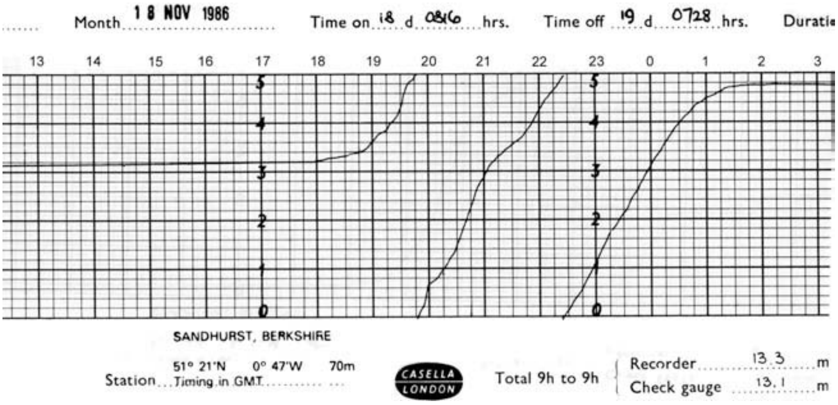

Figure 6.14. An example of a paper chart record from a Dines TSR. Sandhurst, Berkshire, southern England, 18 November 1986.

of very light precipitation tends to be rather subjective and subject to large variations between analysts. The biggest disadvantages of the TSR are the requirement for daily chart changes and the need for regular maintenance to keep it in good working order. The siphoning mechanism can also fail when the water table is very close to the surface, and this has resulted in a frustrating early cessation of record in several notable storm events. Manual analysis of the resulting chart records is also very labour-intensive, automated chart digitization initiatives meeting with little success.

Float gauges are almost unknown within the United States and Canada, probably because the float or float chamber are liable to burst if allowed to freeze in cold weather, putting the instrument out of operation.

As a result of its manual nature, the Dines TSR is quickly becoming much less common, but for those instruments still in use there is currently a good supply of spares from unwanted instruments becoming obsolete as they are replaced with tipping-bucket raingauge/logger combinations.

Weighing raingauges

The basic principle of weighing raingauges is equally straightforward. Rainwater collected using a funnel falls into a collecting chamber, the weight of which is measured. After allowing for the weight of the collection container, changes in weight are directly proportional to rain entering the chamber. (Some allowance can be made for slow evaporation, or for wind eddies causing vibration of the weighed chamber.) The receiving chamber is emptied manually, usually on a weekly or monthly basis.

In the pre-electronic era, weight was measured using mechanical levers similar to a kitchen scale, but today's weighing raingauges use exquisitely sensitive strain gauges, load cells or a vibrating wire (whose frequency is a function of the applied weight) hooked up to a logger to provide a continuous record of accumulated precipitation. Because they have no moving parts and do not depend upon liquid water for successful operation, and provided that they are adequately protected from loss due to wind effects, they can provide high-accuracy precipitation records in snow as easily as in rain (particularly where antifreeze is added to the container) when the funnel has been removed to allow snow to fall directly into the container.

Weighing gauges are all but unknown within the UK and Ireland, but form the vast majority of the recording raingauge network in the United States. The most common type of recording precipitation gauge in the United States is the Fischer & Porter gauge (**Figure 6.6**, right), first introduced into service in 1963 and subsequently manufactured by the Belfort Instrument Company.

In the original instruments the accumulated amount of precipitation was recorded at 15 minute intervals by means of paper holes punched on paper tape, to a precision of 0.1 inches of rainfall (2.5 mm). The tape was changed monthly and analyzed by computer, with records subsequently archived at the National Climatic Data Center (NCDC) in Asheville, North Carolina. A major NWS program commencing in 2009 saw the progressive refitting of the old punched-tape mechanism in these gauges – of which there are almost 2,000 in use – by a new electronics module [22]. Although there are few external differences, an electronic load cell, coupled with a simple data logger, replaces nearly all of the internal mechanical components, including the punch-tape assembly. The records are available to a improved precision (0.1 mm or better) and are downloaded monthly from the unit using a USB memory stick, instead of bulky and fragile punched tapes.

The USCRN station network (see Chapter 5) and many sites in Environment Canada use Geonor weighing-bucket gauges. Oil and antifreeze in the container are weighed with a sensor which provides a frequency output: the frequency is a function of the tension applied to the vibrating wire. Simply put, the frequency increases as tension on the wire increases as the bucket becomes heavier due to accumulated precipitation. Multiple redundancy and real-time error checking is afforded by making simultaneous measurements on three vibrating wires. This method is well suited for remote locations requiring reliable and long-lasting instruments: see also *Measuring snowfall*, below.

Combination tipping-bucket – weighing raingauges

The biggest disadvantage of a tipping-bucket raingauge is its incremental nature. To overcome this, several instrument manufacturers are developing combination 'weighing tipping-bucket raingauges', which continuously weigh a tipping-bucket (or single-sided 'tipping-spoon') collection unit to fill in the 'between tips' detail[*]. The great sensitivity and relatively low cost offered by commercial load cells or strain gauges, combined with the small size and mechanical reliability of a tipping-bucket raingauge and a dual-channel logger, offers the possibility of a new type of small, reliable and very precise recording raingauge. Such a sensor would combine the best features of tried and tested weighing and tipping-bucket raingauges, and would be capable of accurate measurements of both intensity and total fall across a very wide range of rainfall rates. Although still undergoing field trials at the prototype stage, it is likely that if such instruments prove robust, reliable and

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[*] The desirability of both measures was recognized very early on. Robert Hooke's weather clock, in 1679, recorded both the number of tips and 'shewed what part of the bucket is fill'd', according to William Derham (*Philosophical Experiments and Observations of Dr Robert Hooke*, London, 1726).

accurate they will start to appear in precipitation measurement networks sooner rather than later.

Optical raingauges

The principles of optical raingauges are easy enough to grasp, although the implementation requires sophisticated state-of-the-art electronics and software to obtain and process the measurements. Such systems, although very expensive and confined to the professional sector (where they often double as 'present weather sensors'), nonetheless offer another method for identifying the type and amount of precipitation, one which can cope as easily with frozen precipitation as with rain, drizzle or even wet fog. They are mainly intended for use at remote sites where no manual observations are available, but are also starting to appear at manned sites to cover out-of-hours operations.

There are two main types – *forward scatter* and *occlusion*. *Forward scatter sensors* use a beam of light (usually near-infrared) and detect the light forward-scattered from it at an acute angle. The magnitude and frequency of the scatter signal provides a means of identifying precipitation, usually aided by a measurement of air temperature and a detector of surface wetness. The *occlusion type present weather sensors*, or disdrometers, use a horizontal light sheet, usually a laser, passing directly from a transmitter to a detector. They measure the amplitude and duration of the light blocked or occluded from the sheet as hydrometeors (droplets of rain or drizzle) pass through. Since the size and terminal velocity of drops are closely related, at least in light winds, it is possible to estimate the size of each drop. Solid precipitation (hail or snow) has different characteristics to raindrops and can be distinguished using sophisticated onboard software. These sensors are better suited to measuring particle size distributions than the conventional forward-scatter type sensors.

A newer design combines some of the properties of both. In this sensor (**Figure 6.15**) a laser beam is split into four horizontal layers about a millimetre

Figure 6.15. The Campbell Scientific PWS100 present weather sensor and optical raingauge. (Photograph courtesy of Campbell Scientific)

apart. A drop of rain falling through these layers scatters light forwards from each layer in turn. This is picked up by two detectors, one picking up light scattered vertically upwards by 20 degrees, and one light scattered horizontally by 20 degrees [23]. The detected signal takes the form of a series of spikes as the drop passes each layer. The time between each layer picking up the drop gives a direct measurement of the speed it is falling, while the time taken by the drop to fall through a layer gives its diameter. In this way the sensor measures the size and speed of each drop falling through the sample area. Small droplets, less than about 2 mm in diameter, tend to be nearly spherical in shape, but as the drops grow larger they tend to become oblate (flattened at the base): an empirical correction is included to allow for this. Combining droplet size and fall rate gives both the type of precipitation and an accumulation rate, and integrating accumulation rate over time gives a conventional rainfall depth measurement. The sensor can measure rates up to 120 drops per second and drop diameters from 0.1 mm upwards. Fog and solid precipitation are identified and measured as with a conventional forward scatter sensor.

The advantages of an optical raingauge/present weather sensor are its ability to sample precipitation in the free air, rather than relying on varying collection efficiencies of a raingauge funnel, and to provide very short-period rainfall intensity profiles. Such instruments have the potential to provide 'ground truth' precipitation measurements from first principles, although their cost and complexity will restrict them to research or professional, operational meteorological monitoring (such as detecting the onset of freezing precipitation at airports) for many years to come. Operational field trials are required to assess how well their results compare with conventional precipitation measurement techniques – if at all.

Reducing the effects of wind on raingauges

As outlined earlier in this chapter, the distortion of the wind-flow due to the presence of the raingauge is the largest source of error in precipitation measurements, particularly in snowfall. Because the raingauge is out of the wind and so does not interfere with the air flow, WMO defines a ground-level or 'pit' raingauge (**Figure 6.1**) as its standard reference instrument for measuring liquid precipitation [1]. Such gauges are mounted flush with the ground surface within a strong plastic or metal anti-splash grid. Although the catch varies with the exposure and surroundings of the gauge, they generally record 5–10 per cent more precipitation than 'above ground' gauges. However, as has already been referred to, they are large, often impractical to install and maintain, ill-suited to widespread adoption, and perform poorly in snowfall. As a result, a number of methods have been tried over the years in an attempt to reduce wind-related errors in precipitation measurements, particularly in snowy climates or in very exposed locations. The most widely used approaches are the wind shield, the turf wall and more aerodynamic gauge designs.

Raingauge wind shields

The Nipher wind shield (**Figure 6.16**, **left**), first described in the United States in 1878, consists of an inverted trumpet-shaped cone surrounding the gauge, which deflects the wind downwards. Although used with some success in mountainous areas of the western U.S. for many years, they are prone to fill with snow and can block the gauge completely when this happens.

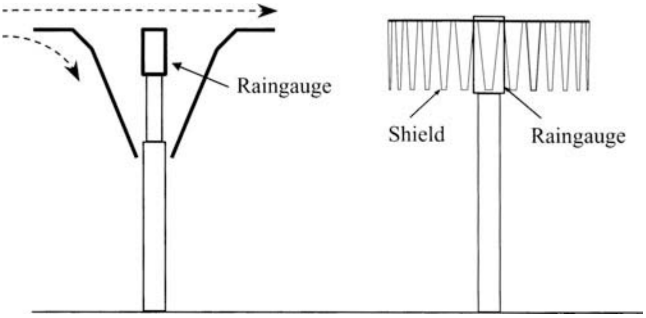

Figure 6.16. (Left) Nipher wind shield (right) Alter wind shield. (Courtesy of Ian Strangeways)

Figure 6.17. Alter wind shields (right of image) around ASOS raingauges at Cheyenne Airport, Wyoming 41.16°N, 104.81°W, 1876 m AMSL, October 2011. (Photograph by Henry Reges, Colorado State University)

The Alter shield (Figure 6.16, **right,** and Figure 6.17), invented in 1937 also in the States, consists of a ring of metal strips which hang loosely around the gauge. The deflection of these by the wind results in a less turbulent airflow over the gauge, improving its performance particularly in strong winds and snowfall.

Table 6.4 *Precipitation totals (rain and snow) measured by different gauges at Valdai, Russia, November 1991 to March 1992, from the WMO solid precipitation intercomparisons trials [24]*

Gauge type	Total precipitation (mm)	% of reference
Tretyakov in bushes	367	100
DFIR (Tretyakov)	339	92
DFIR (Canadian Nipher)	342	93
Canadian Nipher shielded	314	86
Tretyakov	258	70
U.S. 8 inch Alter shielded	273	75
U.S. 8 inch unshielded	208	57

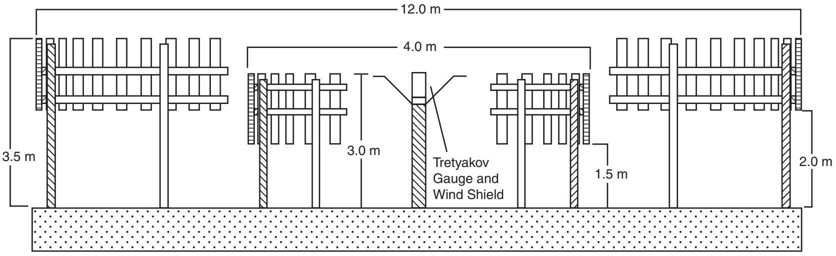

Figure 6.18. The Russian Tretyakov wind shield (centre) showing the WMO Double Fence Intercomparison Reference outer shielding arrangement. (Courtesy of World Meteorological Organization, Geneva: from reference 24)

The Russian Tretyakov wind shield (**Figure 6.18**) resembles a combination of the two, with fixed plates. This wind shield, based on a pattern of raingauge used as the Russian standard for many decades, forms part of the WMO reference gauge for solid precipitation, known rather snappily as the WMO Double Fence Intercomparison Reference (DFIR). It has octagonal vertical double fences surrounding a gauge fitted with a Tretyakov wind-deflecting shield [24]. Including the surrounding fences, the equipment measures 12 metres in diameter.

There is no perfect solution to this problem, as **Table 6.4** shows – in this gauge intercomparison trial, conducted in Russia over one winter, precipitation catches were found to vary by 25 per cent depending upon the type of wind shield used. However, the results do at least agree in showing that all the shielded gauges caught considerably more than the unshielded model.

The standard wind shield structure used by the U.S. Climate Reference Network is the Small Double Fence Intercomparison Reference (SDFIR) – see **Figures 5.6** and **5.7**. At about 8 metres in outside diameter it is smaller than the DFIR and thus more practical to use at many sites, yet it achieves collection efficiencies in high-wind snow events that are within 10 per cent of the much larger WMO standard DFIR system. When combined with an Alter shield internal to the wooden inner shield it can improve overall collection efficiency close to the stand-alone standard DFIR shields [25].

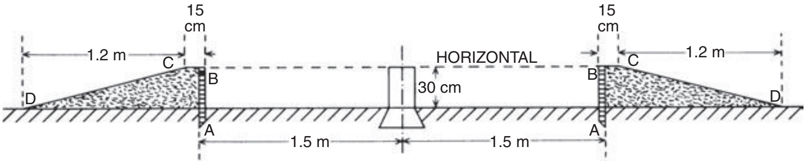

Figure 6.19. A ‘turf wall’ as used in the British Isles to provide shelter for raingauges on exposed sites. A-B represents the vertical retaining structure, B-C the level portion of the turf wall and C-D the sloping portion of the wall (gradient 1 in 4). (© Crown copyright 1982, the Met Office)

The ‘turf wall’

Wind shields are only practical for raingauges exposed as standard at 1 m or more above ground level; the size of the shields renders them unsuitable for gauges with a lower standard rim height, as used in the UK and Ireland. For this reason, very few raingauges are fitted with an Alter wind shield in the UK. Instead, the recommended method of reducing wind eddies around a standard raingauge in exposed locations in the British Isles is the ‘turf wall’ (**Figure 6.19**).

The turf wall method was first described in 1933 following a multi-year series of trials conducted at an exposed moorland location in northern England [26]. The design of the shallow turf wall surrounding the gauge reduces the effects of turbulence over the gauge structure in a similar way to the taller wind shields described above. The method is not perfect, however, as the gauge itself (and sometimes the turf wall) may be buried under snowdrifts; in areas where the gauge is visited only infrequently such effects may still lead to serious undercatch in the winter months. The inundation and filling of turf wall enclosures by floodwater or flood-borne debris has occasionally been reported during spells of intense rainfall. The turf wall structure also requires regular maintenance, while in remote areas its very existence can unwittingly highlight the presence of the gauge to casual passers-by, sometimes resulting in vandalism or theft.

Aerodynamic raingauges

A third approach to precipitation being lost through wind effects is to redesign the gauge to minimize disruption to the wind flow around it (**Figure 6.10**). Some success has been reported with different shapes of gauge [27, 28].

Accessories required

The only accessories required with a manual raingauge are a standard, calibrated measuring cylinder suitable for the funnel diameter. Check the calibration of new measuring cylinders before use by carefully pouring a known amount of water into it (see Chapter 15, *Calibration*). A spare raingauge bottle or outer collecting can is also useful as a spare in case of accidents, and for swapping over quickly when melting snowfall.

Where the measuring cylinder is not built-in to the gauge structure, a Stevenson-type thermometer screen provides a convenient storage location. If the measuring cylinder is stored outside, it should be stored upside down to allow any remaining rainwater to drain fully, and stored securely with clips to minimize the risk of breakage or movement due to accidental damage or to strong winds.

Logging requirements

Raingauges combined with loggers (and sometimes real-time communications links) are now widely used for measuring precipitation. They are a boon both for remote sites where automated gauges can be left to record hourly or daily climatological measurements for up to a month or so, and for providing real-time high-resolution precipitation records invaluable in the study and forecasting and of severe storms, for tracking active fronts or squall lines, or for flood warning systems.

Loggers normally record at fixed intervals. For many climatological purposes, hourly rainfall totals are sufficient, but for the analysis of severe storms, frontal passages and the like a logging interval of 5 minutes, preferably 1 minute, is essential. Even higher resolution, down to seconds, can be obtained from optical raingauges or from a tipping-bucket raingauge using an event-based logger (see Box, *Event-based rainfall logging*). Depending on the type of recording gauge, a logger can be set to record the pulses generated by a tipping-bucket raingauge, or to log a continuous weight value for weighing gauges. For all types of sensor, calibrations must be carefully checked, and adjusted if necessary, before bringing the unit into use – it is astonishing how many tipping-bucket raingauges are used ‘out of the box’ without any calibration checks being undertaken. Details on how to do this are given in Chapter 15.

Event-based rainfall logging

Most dataloggers used in weather measurements log at a user-defined time interval – typically 5–15 minutes for modern AWSs. This is fine for period rainfall totals, but it is very likely that the rate of rainfall will vary considerably within this period, and accordingly time-based rainfall logging will underestimate peak rainfall intensities. For high-resolution analysis of rainfall events, a tipping-bucket raingauge/logger combination with a resolution of 1–10 seconds would be ideal, but storing every element from an AWS at such resolution would quickly generate a vast and unmanageable quantity of data. Generating and storing an enormous number of nil entries, with just a few rare intense events buried within the dataset, is a very inefficient storage and archival method.

One inexpensive solution is to connect a tipping-bucket raingauge to an *event-based logger* (where the tipping-bucket raingauge includes a double-pole reed switch, the same unit can be simultaneously connected to a conventional logger). As the name implies, an event-based logger will log an event time only when that event occurs (a tip from the tipping-bucket raingauge in this case) – whether these are one second or several weeks apart. Logger memory and battery life is thus used very efficiently, and yet very high-resolution (sub-minute) rainfall intensity analyses can be obtained (**Figure 6.20**, **Table 6.5**) in addition to the more conventional hourly and daily totals. The event in **Figure 6.20** was logged at the author’s site in southern England (51.4°N, 1.0°W), and shows a very narrow, intense pulse of rain accompanying a marked frontal passage. The event lasted only 2 minutes, yet peaked at 120 mm/h, the most intense short-period fall at the site in 2 years. The method was first described more than 20 years ago [29], but it is only recently that small, self-contained, battery-operated loggers such as those available from Onset and Omega (see Appendix 4) have made the proposition both practical and economic.

The rainfall intensity is determined very easily from the interval between the two tips. For example, where the TBR has a 0.2 mm bucket capacity, two tips 50 seconds apart indicate a rainfall intensity of 14 mm/h (0.2 mm in 50 seconds = 0.2 mm x 60/50 per minute = 0.2 mm x 1.2 x 60 per hour). This is also the basis on which the Davis Instruments VantagePro2 AWS evaluates peak rainfall intensity. Note, however, that instrument measurement errors increase rapidly with high rainfall intensities, and a precision of 0.1 or even 1 mm/h is certainly not justified. It is advisable to pre-calibrate the TBR at a range of intensities, up to perhaps 500 mm/h, to quantify the errors involved and adjust the intensities derived. The method for doing so is described in Chapter 15.

It is surprising how often even a 'normal' heavy shower can produce short bursts of intense rainfall, often lasting well under a minute. Only an event-based logger approach can extract the maximum available information from the output of a conventional tipping-bucket raingauge.

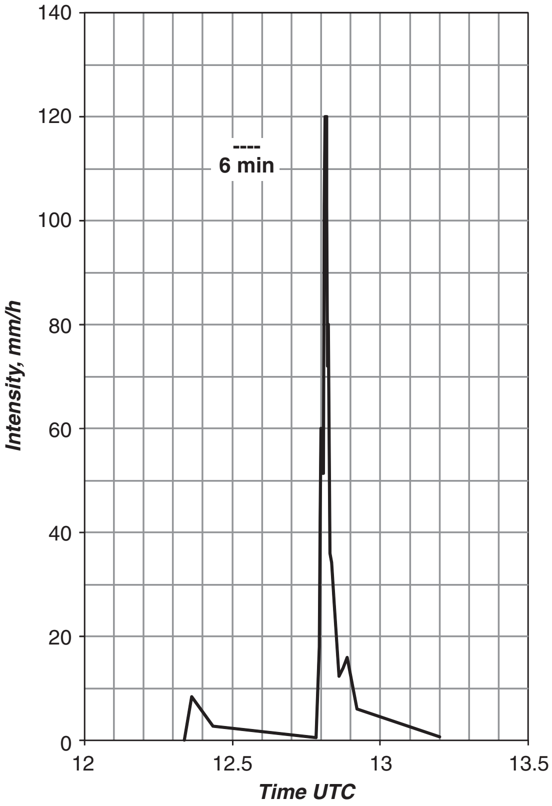

Figure 6.20. High-resolution rainfall intensity record from a tipping-bucket raingauge with event logger; Berkshire, southern England, 11 November 2010. Time is in decimal hours – 12.5 is 1230 UTC.

Table 6.5. *Output from an event-based rainfall logger using a 0.2 mm TBR, for the event shown in Figure 6.20: central southern England, 11 November 2010*

Date	Time UTC	TBR total	Seconds since last tip	Intensity mm/h
11 Nov 2010	10:13:34	41.8		
11 Nov 2010	12:20:19	42.0	7605	0
11 Nov 2010	12:21:44	42.2	85	8
11 Nov 2010	12:26:06	42.4	262	3
11 Nov 2010	12:46:55	42.6	1249	1
11 Nov 2010	12:47:35	42.8	40	18
11 Nov 2010	12:47:52	43.0	17	42
11 Nov 2010	12:48:04	43.2	12	60
11 Nov 2010	12:48:18	43.4	14	51
11 Nov 2010	12:48:32	43.6	14	51
11 Nov 2010	12:48:39	43.8	7	103
11 Nov 2010	12:48:45	44.0	6	120
11 Nov 2010	12:48:52	44.2	7	103
11 Nov 2010	12:49:00	44.4	8	90
11 Nov 2010	12:49:06	44.6	6	120
11 Nov 2010	12:49:13	44.8	7	103
11 Nov 2010	12:49:23	45.0	10	72
11 Nov 2010	12:49:32	45.2	9	80
11 Nov 2010	12:49:52	45.4	20	36
11 Nov 2010	12:50:13	45.6	21	34
11 Nov 2010	12:50:40	45.8	27	27
11 Nov 2010	12:51:38	46.0	58	12
11 Nov 2010	12:52:30	46.2	52	14
11 Nov 2010	12:53:15	46.4	45	16
11 Nov 2010	12:55:14	46.6	119	6
11 Nov 2010	13:11:58	46.8	1004	1
11 Nov 2010	13:13:56	47.0	118	6
11 Nov 2010	15:12:49	47.2	7133	0

Measuring snowfall

Four hundred years of invention and evolution has produced many fine, accurate, precise, robust, reliable and easy-to-use meteorological instruments. But in one area, namely the accurate and representative measurements of precipitation in snowfall, technology has made few advances indeed – a graduated stick is still much the best method of obtaining a record of snow depth, as indeed it would have been in Galileo's time.

Methods to improve accuracy and consistency of snow depth measurements, and the determination of precipitation amounts, have been published by WMO [1] and by many national meteorological services. This section provides a summary of these, although the detail varies somewhat from country to country – places where snowfalls are rare have different processes to countries where metres may accumulate in a few days – and individual country guidance should be consulted for details as appropriate.

Measuring the depth of snow

Measure the total depth of snowfall using a graduated rule held vertically. Choose a location free from drifting or scouring by wind. Take several measurements at different places (about 10 will suffice) and note them down; disregard the highest and lowest readings of the set, then take the average of the rest as the snow depth. (If using a short 30 cm / 1 foot rule to make the measurements, don't forget to allow for the short gap between the end of the ruler and the zero mark when you make your measurement, and ensure the ruler does not pierce the grass or other ground surface beneath the snow: either will give a false reading.)

Note also the maximum and minimum depths within an area representative of the observing site – between drifted areas and parts scoured of snow by strong winds, for example. Measurements should be made in appropriate units – centimetres (record anything less than 0.5 cm as '< 0.5 cm') or inches, according to national standards. The U.S. standard is to report the depth to the nearest inch.

As far as possible, routine measurements of snow depth should be made at or close to the same time as the raingauge is read – typically between 7 and 9 A.M. If it is snowing heavily at the time, precipitation measurements may be impossible or even dangerous to undertake; in such circumstances, the snow depth should be measured and the precipitation measurement delayed until a more opportune time as soon as possible thereafter.

Note that an increase in depth on successive days may not fully reflect the depth of a new snowfall, owing to underlying compaction of the previous snowpack. The best method of measuring 'fresh snow' is by placing a wooden 'snowboard' (typically a white-painted board some 600 mm square) level on the snow surface at each observation, and measuring 'fresh snow depths' using that as the base level. It should obviously be re-set level on the snow surface at each observation once the measurement has been made. Measurements are normally made at 6 hour intervals.

Automatic snow depth measurements

Some AWSs are fitted with snow depth sensors, which work on the same principle as radar – a short ultrasound pulse is fired from the sensor, the time of return of the pulse from the underlying surface is measured by onboard electronics and converted into a height. These are sensitive enough to measure grass growth (indeed, all such sensors at UK Met Office AWSs are routinely deactivated during the summer months to prevent false readings) but they suffer from a very limited field of view; if the snow is drifting around the AWS, or being blown away from it, the measurement will be unrepresentative. At remote sites the errors may not be obvious to data users, and several such sensors in different locations may be required to obtain multiple samples, particularly where the accurate measurement of snowpack is vital for hydrological balance research.

Measuring snowfall equivalents of precipitation

The relationship between snow depth and water equivalent is very variable for fresh snow, between about 5 and 20 (sometimes even higher). In general a ratio of 10 or 12 to 1 (i.e., 10 cm of snowfall will produce about 10 mm rainfall equivalent / 1 inch of snow to 0.1 inch rainfall equivalent) is typical for many snowfalls in temperate latitudes [30]. However, this 10-to-1 snow to liquid ratio is certainly not infallible. Where the snow falls at temperatures well below freezing, giving very 'fluffy' dry snow, the ratio can be much higher – 20-to-1 or more (i.e., 20 cm of snow would melt to provide 10 mm of equivalent rainwater). At the other extreme, heavy wet snow falling at or just above 0 °C, particularly if it turns to rain at times, can produce a snow-to-liquid ratio of 5-to-1 or less (i.e., 5 cm of snow would melt to provide 10 mm of water).

Wherever possible, a more objective measure of water equivalent precipitation should be attempted: the procedures for doing so vary somewhat by country.

USING A STANDARD U.S. EIGHT-INCH RAINGAUGE. During the winter, the observer should remove the funnel and inner measuring cylinder and allow snow to collect in the outer tube. The snow should then be melted using a known (measured) amount of warm water, and the meltwater measured in the same manner as for liquid precipitation, remembering to subtract the amount of warm water added to melt the snow. Measurements of liquid and solid precipitation are normally identified separately on U.S. precipitation returns.

FOR OBSERVERS IN THE BRITISH ISLES. *Light to moderate snowfalls, light winds* On such occasions, the funnel of a standard raingauge will be partially filled with snow. Before the observation, prepare approximately 500 ml of warm water (not hot – about 30–40°C) in a suitable container. At the raingauge site, fill the 10 mm measuring cylinder almost full with the warm water, and note the amount using the measuring cylinder graduations. Then carefully pour the warm water onto the snow in the raingauge funnel, taking care to melt as much of the snow as possible. This may need to be repeated several times to melt all the snow: note down the amount of warm water added each time. Then carefully remove the funnel and measure the water content in the raingauge bottle. The rainfall equivalent is the measured amount of water in the bottle less the amount of warm water added. If a spare raingauge funnel and bottle is available, it may be easier to swap both over and bring the snow-filled units inside to melt.

Heavy snowfalls, or snowfalls accompanied by strong winds On these occasions, a raingauge at the standard rim height of 30 cm may become partially or completely buried by drifted snow, strong winds may sweep most or all of the snow out of the gauge, or the snow may simply exceed the funnel capacity: any of these will result in the funnel contents being unrepresentative of the general precipitation level. Provided the gauge is not completely buried, it is worth first attempting the method described above. A more reliable method in such cases is the 'snow core' approach, which gives best results in fine, dry snow (heavy wet snow, or snow followed by rain followed by further snowfall, may produce misleading results).

Assuming it is not snowing at the time of the observation, after measuring any snowfall contained in the funnel, insert the inverted funnel (or a spare) vertically into a representative area of lying snow (avoiding drifts or areas where snow has been removed by strong winds) to obtain a 'snow core' sample down to ground level. As far as possible, ensure all of the snow in the area enclosed by the raingauge funnel is collected in the funnel, then melt and measure the snow sample using the warm water method as described above. Repeat this three times in locations several metres apart, and take an average. (This method will obviously include any existing lying snow in the total, but when used for successive snowfalls the previous day's snowfall equivalent measure should be subtracted from the total to obtain the incremental amount.)

In spells of severe weather, or where significant additional snowfall is expected before the next observation, the process can be simplified by 'snow coring' down to the surface of a snowboard at subsequent observations, as described above. A thin cane inserted next to the board will assist in finding it after a snowfall event. Measuring the water content of snow cores daily provides essential information on the hydrology of the snowpack [30].

PROCEDURE WITH RECORDING GAUGES. With the exception of a few weighing gauges, unless the instrument is fitted with heating elements to melt falling snow as it falls, most instrumental records will be unreliable at best, and probably useless. *Weighing gauges* can provide a good record of snowfall accumulation where fitted with a suitable wind shield and gauge neck heater (an interesting account of the performance of several of the USCRN weighing-bucket gauge sites in a heavy snowstorm in New England, where up to 60 cm snow fell, is given in reference [31]). Snow melting in a *tipping-bucket raingauge* funnel will produce a series of tips as the snow melts, but unless the snow is melting as quickly as it falls or the gauge has a substantial heater attachment, the record will bear little resemblance to the actual rate of fall. After a heavy snowfall, the melting of snow in the funnel may not take place for some time (days, possibly weeks) after the snowfall event, and to avoid uncertainties in subsequent records it is best to scoop out the snow from the funnel soon after the snow has stopped falling.

If sub-daily totals are required (hourly rainfall equivalent estimates, for example) but the record is unavailable owing to heavy snowfall, often the only method will be to apportion the rainfall-equivalent total for the snowfall period (from melted snowfall in the gauge) using eye observations and/or intermediate observations of snow depth, where these are available. If no observations are available, rainfall radar evidence may provide indications of precipitation timing and intensity.

In all cases where records have been lost owing to snowfall, a note should be made in the station records to indicate this. Where the records have been completed using estimates, the source and basis for estimate should be clearly stated. Estimates are not ideal, but reasonable 'best efforts' estimates are always better than gaps or 'nil entry due to snowfall' in the record.

Accuracy versus precision in precipitation measurements

Two well-maintained and reliably calibrated standard raingauges exposed adjacent to each other should agree to within 2 per cent or so (see Box, *Should my raingauges agree exactly?* on p. 143). Errors due to shelter (too much or too little), incorrect exposure, poor levelling and so on can easily double or treble these differences. Small differences are next to impossible to spot without regular comparisons with another well-exposed gauge, and yet over the medium- to long-term they are more than enough to destroy the homogeneity of any long-period rainfall record.

While a quoted precision of 0.1 mm for daily falls makes sense, quoting monthly or annual totals to this precision is certainly unjustified in terms of their accuracy. The greatest mismatch of precision and accuracy comes from one leading brand of AWS, who quote 'highest rainfall intensity' rates to 0.1 mm/hr – even when that rate is over 100 mm/hr – the rate quoted is probably no better than ± 20% at best under such circumstances.

Access and security

The guidelines given in the previous chapter with regard to site security apply equally to rainfall; in many cases both temperature and rainfall instruments will be co-located on the same site. Any security fencing should not be of a size or nature itself to shelter the raingauge, but even in a domestic or school situation some protection should be considered to avoid unwanted attention by young children, young children's curious friends, or pets (for obvious reasons in the case of the family dog). Consider carefully the operation of any automatic garden sprinklers, and avoid planting fast-growing vegetables, crops, flowering plants or hedges anywhere near raingauges. Remember to allow sufficient clearance around the gauge and any associated cabling to permit easy grass cutting. Copper is widely used for raingauges – it is a soft metal, easily formed and soldered, but sheet copper dents very easily. If the maintenance is being undertaken by an external contractor, in schools for example, can the required work be undertaken by the contractor without risk of damage to the instruments or cabling? More than one shiny new raingauge on a golf course has been turned into mangled copper strips by a gang mower whose driver didn't know it was there! Stainless steel gauges are increasingly common, and are more resistant to bumps and knocks, but care is still needed to avoid accidental damage or deflection of the gauge level.

Measurement and observing standards

Keeping daily records with a standard raingauge, and perhaps one or more recording raingauges to indicate the timing, duration and intensity of precipitation, should present few difficulties to most observers, provided the raingauges are kept in good condition and the funnels checked regularly for blockages. Snowfalls can make observations more difficult, however, and special measures are required to obtain accurate precipitation measurements (see *Measuring snowfall* above).

Observation times – and 'throwing back'

For observations to be comparable between different locations, it is important that the times at which observations are made, are as similar as possible: this particularly applies to the time period covered by daily rainfall totals.

For rainfall measurements made once daily during the morning, the convention is to 'throw back' the reading to the previous day, since the majority of the 24 hour period since the previous measurement occurred on the day prior to the measurement being made. This applies even if it is known from personal observation that all of the rain in the gauge fell in a shower 2 minutes before the measurement was made. When observations are made at other times, the date applied should also be the one in which the majority of the observing period falls. This important topic is covered more fully in Chapter 12.

One-minute summary – *Measuring precipitation*

- The term 'precipitation' includes rain, drizzle, snow, sleet, hail and the like as well as the occasional minor contribution from dew, frost or fog. Precipitation is highly variable in both space and time, and precipitation measurement networks are usually denser than for other elements to improve spatial coverage. There may be as many as 1 million raingauges operating globally, although standards vary from country to country.
- Precipitation measurements are very sensitive to exposure – particularly to the wind – and the choice of site is very important to ensure comparable and consistent records are obtained. Choose an unsheltered (but not too exposed) spot for the raingauge/s – loss of catch through wind effects is the greatest single error in precipitation measurements, particularly in snow. A site on short grass or gravel is preferable. Wherever possible, obstructions (particularly upwind obstructions in the direction of the prevailing rain-bearing winds) should be at least twice their height away from the raingauge. Rooftop sites are particularly vulnerable to wind effects and should be avoided. The site should also be secure, but accessible for maintenance (grass cutting, etc.) as required.
- The gauge should be exposed with its rim at the national standard height above ground – in the UK and Ireland, this is 30 cm; in the United States, between 3 and 4 feet (90 to 120 cm). Most countries define a 'standard rim height' as between 50 cm and 150 cm above ground. Take care to set the gauge rim level, and to maintain it accurately so.
- Manual raingauges should have a round, deep funnel to minimize outsplash in heavy rain (shallow funnel gauges are not recommended) and should have a capacity sufficient to cope with at least a '1-in-100 year' rainfall event – a minimum of 150 mm in the UK and 500 mm (20 inches) in most parts of the United States. The gauge must be paired with an appropriately calibrated glass measuring cylinder.
- Most manual raingauges are read once daily, usually at a standard morning observation time, typically between 7 A.M. and 9 A.M. local time. The morning reading should be 'thrown back' to the previous day's date.
- To obtain records of the timing and intensity of rainfall, one or more recording raingauges are often sited alongside the manual raingauge. The record from the manual gauge should be taken as the standard period total and sub-daily records (hourly totals, for instance) taken from the recording gauge adjusted to agree with the daily total taken from the manual gauge. The use of standalone recording gauges is not recommended when accurate or comparable rainfall totals are required.
- The preferred resolution of a recording raingauge is 0.1 or 0.2 mm; 1 mm tipping-bucket raingauges are too coarse for accurate measurements of small daily amounts. Recording raingauges should be logged at 1 minute or 5 minute resolution (higher frequencies are possible using an event-based logger). They should be regularly inspected for funnel blockage or any obstruction to the operating mechanism, which will result in the complete loss of useful record if not quickly corrected.
- Snowfall is difficult to measure accurately with most types of raingauge, and without some form of wind shield most raingauges will lose 50 per cent or more of the 'true' catch through wind errors introduced by the presence of the gauge, which interferes with the flow of the wind over it, causing a loss of some of the catch.
- Procedures for measuring snow depth and the water equivalent of snowfall are given.

Further Reading

Ian Strangeways' *Precipitation: theory, measurement and distribution* (Cambridge University Press, 2007) comprehensively covers all aspects of precipitation, from the physics of cloud droplets to future ground- and satellite-based measurements of rainfall, in a comprehensive but readable text.

The Snow booklet: A guide to the science, climatology and measurement of snow in the United States by Nolan Doesken and Arthur Judson (Colorado Climate Center, Colorado State University, 1996) provides a more in-depth treatment of the subject, and is particularly relevant to U.S. readers.

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7 Measuring atmospheric pressure

This chapter covers the measurement of atmospheric or barometric pressure (often abbreviated to 'air pressure' or simply 'pressure'), and its importance.

Air pressure is one of the most important of all meteorological elements. Fortunately, it is also the easiest of all to measure, particularly with modern sensors, and even basic AWSs or household aneroid barometers can provide reasonably accurate readings. It is also the only instrumental weather element that can be observed indoors, making a barometer or barograph – analogue or digital – an ideal instrument for weather watchers living in apartments, or those who for whatever reason are unable to site weather instruments outside. It is important, however, to ensure that pressure sensors are correctly exposed to ensure consistent and reliable readings: WMO recommendations on exposure and instrument accuracy [1] are included.

Great accuracy is not required for casual day-to-day observations, as very often the trend of the barometer in temperate latitudes, whether it is rising or falling, and how rapidly, provides the best single-instrument guide to the weather to be expected over the next 12–24 hours.

Where accurate air pressure records are required, the observed barometer reading needs to be adjusted to a standard level, usually mean sea level (MSL), because of the rapid decrease in air pressure with altitude. Uncorrected readings simply reflect the height of the instrument above sea level, rather than the true variations of pressure shown by isobars (lines of equal pressure) on a weather map. This chapter explains how to correct or 'set' a barometer to mean sea level. Accurate records also require the calibration of the pressure sensor to be checked regularly to avoid calibration drift, which can become substantial if not corrected. Methods for doing this are explained, with examples.

What is being measured?

Barometric pressure refers to the force per unit area exerted by a column of air extending from the Earth's surface out to (at least in theory) the outer limits of the atmosphere. Air is a compressible fluid acted upon by the gravitational attraction of the Earth, and so the mass of the atmospheric column (and thus the air pressure) decreases upwards above any point on the surface. The atmosphere is therefore densest at the Earth's surface. The outer limit of the atmosphere is rather arbitrary, but if we take it as a point where the pressure has fallen to one thousandth of that at sea level, then it is about 50 km above the Earth's surface. About half of the mass of the atmospheric column lies below about 5 km.

Figure 7.1. Household barometer legends. (Photograph by the author)

We often refer to something as being ‘as light as air’, and yet the weight of the air all around us is very substantial. At sea level and at typical atmospheric pressure and temperature, the weight of the column of air above a 1 metre square surface is around 11 tonnes. We do not notice this great weight or pressure because the pressure within our bodies is the same, but very few humans adapted to life at sea level are able to function without prolonged acclimatization at altitudes above 3000 or 4000 metres where the pressure is 30 per cent or more lower than at sea level. Our bodies cannot sense barometric pressure directly, nor anything but the most rapid changes in pressure (such as ‘ear popping’ experienced by aircraft passengers in the first few moments of a flight, for example), yet it has been known since the 17th century that relatively small fluctuations in atmospheric pressure are often closely linked to significant changes in the weather in temperate latitudes – hence the familiar legends adorning many household aneroid barometers (**Figure 7.1**).

Standard methods of measuring pressure

The earliest form of the barometer was invented by Evangelista Torricelli in 1644 [2], and consisted simply of an inverted glass tube in a bowl of mercury. Torricelli correctly reasoned that the weight of the mercury column in the inverted tube exactly counterbalanced the weight of the atmospheric column of air on the mercury reservoir. As the weight of the mercury column was directly proportional to its height, so the earliest units of barometric pressure were expressed as the height of a column of mercury, measured in millimetres or inches of mercury (mmHg or inHg, respectively), or often simply mm or inches (‘… of mercury’ being assumed). The earliest surviving records of barometric pressure were those made by Vincenzo Viviani and Alfonso Borelli in Pisa in northern Italy, covering the period November 1657 to May

1658 [3], barely a decade after Torricelli's invention of the barometer. Daily barometric pressure records exist, with only a few short gaps, for Paris from 1670, and for London from 1692 [4].

In 1914, the standard unit of pressure became the millibar (mbar). This is numerically identical to the preferred unit in the international SI system of units, the hectopascal (hPa): thus 1 mbar = 1 hPa = 100 Pa (1 Pa = 1 Newton per square metre): 1 hPa = 0.75 millimetres of mercury (mmHg)[*]. 'Inches of mercury' are still used on some household barometers and in some public weather communications within the US: 1 inHg = 33.86 hPa. For the remainder of this chapter, the hPa unit is used.

Mercury barometers

Mercury is used in traditional barometers for three reasons. Firstly, its high density (about 13.5 times that of water) makes for an instrument of practical size. The height of a column of mercury at average atmospheric pressure is about 760 mm (0.76 m); if the measuring fluid was water, the column would be about 10 metres high, the height of a two-storey building. Secondly, under normal atmospheric conditions mercury is an opaque silvery liquid, which makes it easy to read the height of the liquid column. Finally, mercury has a vanishingly small vapour pressure at room temperature, which means that in properly constructed instruments the vacuum at the top of the barometer does not deteriorate over time owing to the evaporation of the barometric fluid into it, which would be the case with (say) water or alcohol.

Although mercury barometers are delicate, the method remains one of the most accurate and stable methods of determining barometric pressure. Some are still in operational use today, but in recent years stringent health and safety restrictions on the use of liquid mercury have severely restricted its use and mercury barometers are now more likely to be seen in museum collections of scientific instruments. Mercury is highly poisonous, and while mercury barometers are perfectly safe in normal use – contrary to popular opinion, existing mercury barometers have *not* been outlawed by the EU, although the sale of new mercury barometers was banned in October 2009 [5] – mercury spillages or fires are a major health concern [6] and specialist assistance should be sought immediately in such circumstances. Health concerns have rightly hastened mercury's replacement in modern scientific instruments – mercury barometers have already largely been replaced by electronic sensors, and mercury thermometers can be expected to follow the same path over the next decade or so.

Aneroid barometers and barographs

The 'aneroid barometer' (from the Greek, 'without fluid') consists of a partially evacuated closed metal capsule, prevented from collapsing under the influence of atmospheric pressure by an internal spring. Constant fluctuations in atmospheric pressure cause the distance between the two faces of the capsule to vary slightly. This movement can be amplified using a system of levers (as in a household aneroid barometer or barograph – see **Figure 7.2**), with a direct-reading micrometer (as in a portable precision aneroid barometer, often used as a travelling calibration standard), or electronically. Electronic pressure sensors use a variety of sensor types – typically

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[*] Equivalents valid strictly only at 'standard conditions', normally defined as 1000 hPa pressure at a temperature of 0 °C and gravitational constant 9.806 65 m/s^2.

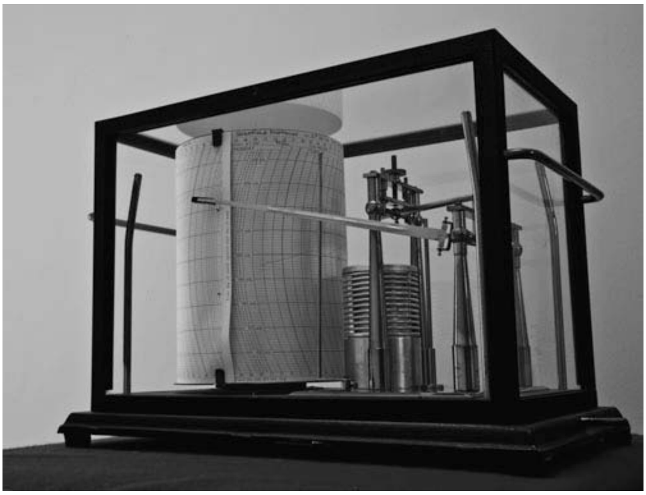

Figure 7.2. Aneroid barograph. This consists of a stack of aneroid pressure capsules (visible to the right of centre) connected via a lever mechanism to a pen arm. The lever mechanism magnifies the small changes in size of the aneroid capsules with changes in atmospheric pressure. The pen marks a chart which rotates using a clock-driven drum. The charts are usually changed weekly. (Photograph by the author)

Figure 7.3. Modern electronic barometric pressure sensor; this unit is about 60 mm square. (Photograph by the author)

variable capacitance circuits or piezo-electric substances – to generate an electrical output as the aneroid capsule flexes in response to changes in atmospheric pressure.

Modern electronic pressure sensors (Figure 7.3) are, when correctly calibrated, almost as accurate as mercury barometers and have the great advantages of being small, robust (mercury barometers are very vulnerable to damage in transport or with careless handling) and can be made relatively insensitive to ambient temperature variations. Their electrical output signal also makes such sensors easy to include in computerized logger-based data acquisition systems such as AWSs. All such sensors are, however, prone to calibration drift and they require regular checking against a reference instrument or the local synoptic pressure field over at least a few days. How to do this is described later in this chapter.

Siting air pressure instruments

Barometric pressure sensors, whether mercury, aneroid or electronic, are easy to expose, because they are normally sited indoors (some electronic sensors can be sited outdoors). Care must be taken to avoid placing them in a position subject to significant variations in temperature, such as near a heating or air conditioning system, away from draughts or vibration, and especially out of direct sunlight. Electrical noise (whether from the sensor power supply, or nearby electromagnetic sources such as computers or wireless computer/telephone equipment), can also be a problem and the equipment should be sited appropriately to reduce or eliminate these effects. Most budget and mid-grade AWS systems have the barometric pressure sensor located internally within the interior display console. Professional systems often have little choice but to locate the pressure sensor in the external logger enclosure, although this is not ideal – transient 'spikes' caused by wind eddies, the greater risk of condensation on sensor components and large temperature ranges affecting the instrument calibration can all reduce the accuracy and reliability of pressure data under such circumstances.

It may be difficult to obtain reliable pressure readings inside an air-conditioned building, owing to the differential pressure created by such equipment, and an external connection is sometimes required to obtain satisfactory readings. Barometric pressure sensors can usually be fitted with a length of flexible tubing connected to a static port on an outside wall to achieve such an external connection. In windy locations it can be difficult finding a suitable location for a static port that is reliable in all wind directions, and several alternatives may need to be tried before a satisfactory position is found [7].

Types and choice of sensors

Most budget and mid-range AWS systems include the barometric pressure sensor within the interior display console. Standalone sensors are available for advanced systems, with simple electrical connection to a datalogger (**Figure 7.3**). Considering the considerable difference in cost, there is surprisingly little difference in day-to-day performance between 'budget' and 'professional' pressure sensors. A modern electronic pressure sensor, once correctly calibrated, should provide barometric pressure readings of comparable accuracy to a good mercury barometer, without the disadvantages of the traditional instrument. Calibration drift remains one of the biggest potential sources of error with electronic sensors (particularly with budget systems). Drift results from long-term changes in sensor sensitivity, or settling-in of the sensor components: it therefore tends to be more pronounced with new sensors, reducing somewhat with time. Despite this, step jumps in calibration can occur – often for no obvious reason – and it is best to check outputs frequently (ideally on a weekly basis) against another co-located sensor where there is one (perhaps a mercury barometer), or other local observations on days of light winds, to spot these. Frequent checks will not eliminate calibration errors, but will reduce their duration and impact on the records when they are spotted and corrected quickly. Ways to do this are covered later in this chapter.

Electrical sensors can be logged remotely, and as frequently as required, enabling a continuous record of barometric pressure to be made without the necessity for frequent manual observations or for the tedious manual analysis of weekly paper barograph charts. Traditional barographs – aneroid barometers making a record on a paper chart, normally changed weekly (see **Figure 7.2**) – remain popular for display and aesthetic purposes. Most electronic sensors will provide more stable and more accurate records of barometric pressure than those from a barograph: most systems will display current and recent records in graphical formats, enabling pressure trends to be monitored as easily as with the more traditional instrument. Barograph charts can be expensive, particularly for those with an expanded scale such as the model illustrated in Figure 7.2, while pens, charts and supplies for older instruments can be difficult to obtain.

Logging requirements

Barometric pressure changes continuously, although not often very rapidly. Hourly readings are sufficient for many purposes, although to examine the fine detail of pressure changes accompanying individual showers or thunderstorms, or marked frontal passages, more frequent sampling and logging intervals are preferable. WMO recommend 1 minute logging when using electronic sensors and dataloggers, while obtaining accurate daily or monthly maximum and minimum pressure values requires logging at 5 minute intervals (or less).

Even within buildings, wind effects can cause significant short-period fluctuations in pressure. To avoid 'noise', whether arising from power supply, electromagnetic induction or wind gusts, a suitable solution is to log running means of sampled pressures – perhaps taking the mean of 12 *x* 5 second samples every minute, as with outside air temperature.

Figure 7.4 shows the barometric pressure detail during a period of disturbed conditions, logged at 1 minute resolution. Hourly observations would clearly be insufficient to resolve such detail, which can provide valuable evidence on storm dynamics, atmospheric gravity waves and frontal structure, particularly when combined with high-resolution wind, temperature and rainfall records.

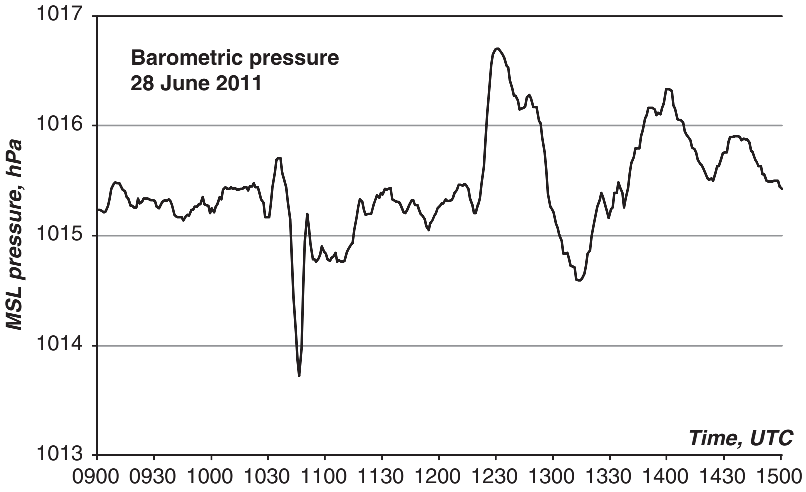

Figure 7.4. Disturbed barometric pressure record during a 6 hour period – 1 minute observations, MSL pressure, 0900 to 1500 UTC on 28 June 2011, central southern England. Hourly observations would clearly have been insufficient to document the rapid variations in atmospheric pressure on this occasion.

Correcting barometer readings for altitude

Atmospheric pressure decreases rapidly with height, much more rapidly than with horizontal distance. Because of this, where barometric pressures from different places are to be compared (for instance, in compiling national or international weather charts, or for setting aircraft altimeters) the observed barometric pressure at each point needs to be corrected to a standard reference height. In the meteorological context, this is normally mean sea level (MSL) – hence the two terms ‘station level pressure’ or SLP, and ‘mean sea level pressure’, or MSLP:

$$\begin{aligned}\text{Mean sea level pressure MSLP} = {} & \text{station level pressure SLP} \\ & + \text{height correction } \Delta p\end{aligned}$$

The height correction Δ p

The correction to be applied depends upon a number of factors, of which the two largest are the height of the barometer above mean sea level, and the external air temperature. (For mercury barometers there are several smaller additional terms, including those to correct the observed temperature of the mercury column to a standard temperature, and for variations in gravity on a non-spherical Earth.) The output from electronic sensors is normally well-compensated across a fairly wide range in ambient temperatures. As a result, corrections arising from changes in sensor temperature are normally tiny and can be safely ignored, particularly where the range of temperatures will be small, as is typical of an interior installation.

Four methods of deriving a height correction for a pressure sensor are described*. Which one is used depends not only upon the accuracy sought, but also upon the accuracy of the sensor in use – there is little benefit in using a high-precision method with a sensor whose accuracy is no better than 1 hPa, for example, as will be the case with most entry- or budget-level AWS systems (see **Table 3.3** on page 59). Methods 1, 2 and 3 are suitable for use at low elevations; stations above about 200 m above sea level, or where accurate readings are required for safety reasons (such as aviation requirements) should refer to method 4.

Aviation pressure reporting – Q codes

For aviation purposes, barometric pressure is reported slightly differently. There are three main ‘Q codes’ denoting various aviation standards for reported barometric pressure, as follows:

QFE

Pressure at airfield level; set on an aircraft (pressure) altimeter when height above local aerodrome level (strictly the official threshold elevation) is required.

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* Note that WMO does not prescribe which particular method of correction is used within a country or region [reference 1 this chapter, section 3.11], although the state meteorological service will generally do so for its region of influence. This is slightly odd, as for all but the lowest elevations differences in the method used to derive MSL corrections will be larger than the error of the barometric pressure itself.

QFF

Pressure at mean sea level (reduced according to actual/mean temperature). The same as MSLP in the meteorological context.

QNH

Pressure at mean sea level (reduced according to ISA profile); set on an aircraft (pressure) altimeter when height above local mean sea level is required.

MSL pressure corrections – method 1

This is a quick and easy method, which does not require knowledge of the height of the site above mean sea level. It is accurate to only about 1 hPa at low elevations, and greater errors will occur at greater heights and at the extremes of pressure. This level of accuracy will suffice for many purposes (or for inexpensive sensors, where measurement errors will probably be greater than this).

Most state weather services publish hourly weather observations for a selection of stations on their websites, and these will normally include MSL pressures given to 1 hPa – for example, NOAA's national and international weather site at http://www.weather.gov/, the UK Met Office site at www.metoffice.gov.uk > weather > UK observations, Met Éireann www.met.ie > latest weather > latest reports.

Note the reading of your barometer each hour on the hour for 2–3 hours, and write down the readings. Then, from the Internet, check the current weather observations at the site or sites nearest to your location (you may be lucky and have an observation point quite close, or you may be between two or more listed locations) and note down the pressures at those sites. It is best to do this on a day when the pressure is fairly steady and winds light, as pressure gradients (the horizontal variation of atmospheric pressure) are larger on windy days. Days with a nearby anticyclone (high pressure area) dominating the weather situation are ideal, although comparisons should be made at both low and high pressures.

If there is an observing location quite close (within say 15 miles/25 km or so) then use the pressure given for that site. If you are between two or three locations with available observations, then take the average of the pressures at those sites, being sure to include observations north as well as south, east as well as west, to avoid biasing the average towards one direction. Compare your barometer readings with the MSL pressures from the official reporting stations, averaging or weighting inversely by distance as necessary. Ensure you compare the observations at the same time as your own readings (allowing for summer time if necessary). Your MSL pressure correction will be the amount you need to add to or subtract from your barometer reading to give approximately the same reading as the website observations. Most AWS systems will allow you to enter either a 'MSL pressure' or a fixed correction to ensure that your barometer readings are thereafter always approximately corrected to MSL by this amount.

Repeat this exercise over several days, at different times within the day, particularly with different wind directions (avoiding windy or very showery days), and at different pressures too. Average the corrections. Check and repeat every 6 months or so to identify and correct for any calibration drift in the sensor. The correction obtained should be reliable to within about 1 hPa.

MSL pressure corrections – method 2

This simple calculation is the WMO recommended method for sites below about 50 m above mean sea level. A knowledge of the height of the site above mean sea level is required (see below for how to obtain this), together with an estimate of the mean annual air temperature (to within 1 degC or so is sufficient).

Correct the observed station-level pressure reading p to MSL by adding the value C, where

$$C = p \times \frac{h}{29.27 \times T_v}$$

p is the station level pressure (in millibars or hectopascals), h is the height of the barometer above MSL (in metres) and T_v is the mean annual virtual temperature at the site (in Kelvins). The virtual temperature of damp air is the temperature at which dry air at the same pressure would have the same density as the damp air. To a reasonable approximation, and at a wide range of mean annual air temperature and humidity values, T_v will be about 1 degC above mean air temperature T (the exact value does not affect the result significantly).

Example: for a site at 35 m above mean sea level with a station level pressure of 1005 hPa and a mean annual temperature of 10 °C (283 K), the correction C will be:

$$C = 1005 \times (35/(29.27 \times 284)) = 4.2 \text{ hPa}$$

This correction should be added to the station level pressure, either manually or automatically using the sensor/logger software. The MSL pressure is therefore 1005 + 4.2 = **1009.2 hPa**.

This calculation is easily set up in a spreadsheet to produce a small barometer correction table (**Table 7.1**) – this spreadsheet can be downloaded from www.measuringtheweather.com and customized as required.

Table 7.1. *An example of a simple barometer correction table, for sites at or below 50 m above MSL*

Station height h	35	*m above MSL*	*(Valid only for sites 50 m or less above mean sea level)*
Mean annual air temperature	10	*°C*	
Station level pressure (hPa)		Correction to be added (hPa)	
960		4.0	
970		4.1	
980		4.1	
990		4.2	
1000		4.2	
1010		4.3	
1020		4.3	
1030		4.3	
1040		4.4	
1050		4.4	

The correction does of course vary a little with the observed station level pressure, but below 20 m above MSL the variation across a typical range of pressures (970 to 1030 hPa) is only ± 0.1 hPa – within the error range of all but the most accurate of pressure sensors. Even at 50 m the correction varies by only ± 0.25 hPa across this pressure range. Unless great accuracy is required, a single value of C for the MSL correction will suffice for all but the most extreme values of station level pressure at heights below 50 m or so above MSL.

MSL pressure corrections – method 3

This is an extension of method 2 above, which applies up to about 150 m above sea level. It can be used at greater altitudes, but the errors increase rapidly with height thereafter.

The first step requires an accurate determination of the height above MSL of your barometer. This is best obtained from local detailed topographical maps (in the United States, the U.S. Geological Survey local maps: in the British Isles, the Ordnance Survey/Ordnance Survey Ireland maps – online or hardcopy – at 1:25,000 scale, which include contour lines at 5 m vertical intervals). Google Earth can also provide a height measure digitized to a GPS overlay, although this may not be accurate enough for this purpose. (As barometric pressure at low levels decreases by roughly 1 hPa for every 10 m increase above sea level, a 5 m error in height will result in roughly 0.5 hPa error in barometric pressure, so an accurate determination of height is essential for precise work.) Remember also to allow for the height of the barometer within the building, or datalogger enclosure if outside – if it is in a first-floor room, for example, it is likely to be an additional 6 metres or so above ground level, and that needs to be added to the ground height given from the base map. (A good barometer will easily show the difference in pressure between ground and first floors in a building.)

The method also makes the initial assumption that the pressure sensor has no calibration errors across the normal pressure range (say 950 to 1050 hPa). As this is extremely unlikely, if the calibration errors are known these should be applied to the observed reading before the MSL correction is added[*], or added to the calculated MSL correction as described below.

For most purposes **Table 7.2** will be sufficiently accurate to correct an electronic sensor to within 1 hPa for locations below about 150 m above sea level [8]. Note that this simplified correction table is *not* valid for mercury barometers, which require several additional corrections to be included. Above about 150 m above sea level the table can still be used, but corrections become substantial (20 hPa or more), and the accuracy of the MSL correction less reliable as a result, particularly at low

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[*] Few pressure sensors other than those intended for advanced-class AWSs will come with a calibration certificate. To determine any calibration errors, obtain the MSL pressure correction as outlined in the rest of the chapter and use that to derive a 'first-pass' corrected MSL pressure. To determine sensor error, compare the 'first pass' readings over a couple of weeks with neighbouring synoptic network observations as described in the section *Checking calibration drift on barometers* in Chapter 15; any calibration error greater than a few tenths of a hectopascal should become apparent. Note that the error may vary with barometric pressure, so determine sensor errors over as wide a range of pressure as possible – in temperate latitudes, the winter months have the largest range in pressure. Repeat every 6 months or so. Keep a note of corrections applied – this will indicate whether there is continued sensor drift over time.

Table 7.2. *Barometric correction to mean sea level for various heights and external temperatures, for station-level pressure (SLP) 1000 hPa. From* Handbook of Meteorological Instruments*, reference 8, Table LVI, page 446–7*

	External air temperature				
Height (m)	−10°C	0 °C	10 °C	20 °C	30 °C
10	1.3	1.3	1.2	1.2	1.1
20	2.6	2.5	2.4	2.3	2.3
30	3.9	3.8	3.6	3.5	3.4
40	5.2	5.0	4.8	4.7	4.5
50	6.5	6.3	6.0	5.8	5.6
60	7.8	7.5	7.3	7.0	6.8
70	9.1	8.8	8.5	8.2	7.9
80	10.4	10.0	9.7	9.4	9.0
90	11.7	11.3	10.9	10.5	10.2
100	13.1	12.6	12.1	11.7	11.3
110	14.4	13.8	13.3	12.9	12.5
120	15.7	15.1	14.6	14.1	13.6
130	17.0	16.4	15.8	15.2	14.7
140	18.3	17.6	17.0	16.4	15.9
150	19.6	18.9	18.2	17.6	17.0
160	21.0	20.2	19.5	18.8	18.2
170	22.3	21.5	20.7	20.0	19.3
180	23.6	22.7	21.9	21.2	20.5
190	24.9	24.0	23.2	22.4	21.6
200	26.3	25.3	24.4	23.6	22.8
250	33.0	31.7	30.6	29.5	28.5
300	39.7	38.2	36.8	35.5	34.3
350	46.4	44.7	43.1	41.6	40.2
400	53.2	51.2	49.4	47.7	46.1

temperatures. Corrected MSL pressure readings from high-altitude sites are inherently rather less accurate than those from low-level sites because the assumptions and approximations involved in the corrections rapidly become substantial, and are very dependent upon the treatment of the external air temperature.

All corrections to mean sea level are positive (add them to the observed barometer reading) for locations above sea level. An observed pressure of 1000 hPa is assumed: other corrections are in proportion – that is, the value for 980 hPa will be 0.98 × 1000 hPa value shown. Interpolations between the cells shown are in proportion, thus the correction for a site at 83 m above sea level would be the value at 80 m plus 3/10 of the difference between the values for 80 m and 90 m.

Correcting a barometer to mean sea level: example using average values

Using **Table 7.2**, for an observing site at 65 metres above sea level, barometric pressure 1020 hPa, external air temperature 15 °C, the correction would be obtained from the table as follows:

— Height correction for 10 °C and 1000 hPa would be + 7.9 hPa (midway between the values for 60 m and 70 m above sea level)

— Height correction for 20 °C and 1000 hPa would be + 7.6 hPa (midway between the values for 60 m and 70 m above sea level)

Thus at 15 °C and 1000 hPa, the correction is +7.75 hPa (interpolating between the values for 10 °C and 20 °C derived above)

Finally, as the observed pressure is 1020 hPa, the correction to be applied is (1020/1000 × 7.75) hPa = 7.9 hPa

Thus the corrected MSL pressure for this site given the observed temperature and pressure is 1020 + 7.9 hPa = **1027.9 hPa**

Method 2 and **Table 7.2** shows that, to within a reasonable margin of error (1 hPa or so), and close to sea level, a single, average sea level correction value is 'close enough' for many purposes. At 100 m above sea level, for example, the average correction at an outside air temperature of 10 °C (a reasonable figure for temperate mid-latitudes) is 12.1 hPa; this varies by less than 1 hPa on either side between –10 °C and +30 °C, so for a barometer accurate only to ± 1 hPa an average correction will be sufficient. Most budget and mid-range AWS software use this 'average' MSL correction method. Note though that at very high or very low temperatures, particularly at altitudes greater than about 100 m above sea level, this assumption departs somewhat from the truth (calculated MSL pressures will be too low in winter, too high in summer – at 200 m above sea level ranging about 2 hPa between winter and summer). Different 'average' corrections for summer, winter and the equinoxes should be used at greater altitudes.

For electronic sensors with an accuracy better than about 0.5 hPa, a more accurate site-specific barometer correction table can easily be prepared*, see **Table 7.3**. This simple Excel spreadsheet can be downloaded from www.measuringtheweather.com and customized as required. Enter the height of the sensor above sea level (in metres – remember to include the height of the barometer above ground level if necessary) and, if known, any sensor calibration errors at specific pressures. The spreadsheet will then generate a site-specific sea level correction table, to 0.1 hPa precision, for a range of external air temperatures and observed pressures. The table can then be printed and used as required. This needs to be done only once, and the table will remain valid unless any changes in calibration become apparent (see *Checking calibration drift on pressure sensors* in Chapter 15), or if the station height changes (the barometer is moved). Advanced loggers can be programmed to use the same calculation method to correct station-level pressures to MSL to data as it is logged, using actual sampled air temperature.

MSL pressure corrections – method 4

Accurate corrections of barometric pressure to MSL are required for many purposes, particularly aviation briefings and climatological averages, where precision and accuracy to 0.1 hPa are essential. The process and method is not trivial, and it is outside the scope of this book to go into the detail. Readers who have requirements outside the scope of methods 1 to 3 above are referred to the WMO *Guide to*

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* Note that this simplified correction table is *not* valid for mercury barometers, which require several additional corrections to be included.

Table 7.3. *Example of a site-specific barometer correction table. This spreadsheet can be downloaded from www.measuringtheweather.com and customized as required. Small cell intervals minimize interpolation required which makes the table easier to use.*

(Name of site) *From The Weather Observer's Handbook* by Stephen Burt

Barometric pressure correction table

Altitude above MSL 65.0 metres Add the hPa correction below to the 'as read' barometer reading

Station-level pressure	Outside air temperature, °C																										
hPa	–15	–10	–8	–6	–4	–2	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
950	7.6	7.4	7.4	7.3	7.3	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8	6.8	6.7	6.7	6.6	6.6	6.5	6.5	6.4	6.4	6.4	6.3	6.3	6.2
955	7.6	7.5	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8	6.7	6.7	6.6	6.6	6.6	6.5	6.5	6.4	6.4	6.3	6.3	6.3
960	7.6	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8	6.7	6.7	6.6	6.6	6.5	6.5	6.5	6.4	6.4	6.3	6.3
965	7.7	7.5	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8	6.7	6.7	6.6	6.6	6.5	6.5	6.5	6.4	6.4	6.3
970	7.7	7.7	6.5	7.5	7.4	7.4	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8	6.8	6.7	6.7	6.6	6.6	6.5	6.5	6.4	6.4	6.4
975	7.8	7.6	7.6	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8	6.7	6.7	6.7	6.6	6.6	6.5	6.5	6.4	6.4
980	7.8	7.7	7.6	7.5	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8	6.7	6.7	6.6	6.6	6.6	6.5	6.5	6.4
985	7.8	7.7	7.6	7.6	7.5	7.5	7.4	7.4	7.3	7.3	7.2	7.1	7.1	7.0	7.0	7.0	6.9	6.9	6.8	6.8	6.7	6.7	6.6	6.6	6.5	6.5	6.5
990	7.9	7.7	7.7	7.6	7.6	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8	6.8	6.7	6.7	6.6	6.6	6.5	6.5
995	7.9	7.8	7.7	7.7	7.6	7.5	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8	6.7	6.7	6.7	6.6	6.6	6.5
1000	8.0	7.8	7.8	7.7	7.6	7.6	7.5	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8	6.7	6.7	6.6	6.6	6.6
1005	8.0	7.9	7.8	7.7	7.7	7.6	7.6	7.5	7.5	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.9	6.8	6.8	6.7	6.7	6.6	6.6
1010	8.0	7.9	7.8	7.8	7.7	7.7	7.6	7.5	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8	6.8	6.7	6.7	6.6
1015	8.1	7.9	7.9	7.8	7.8	7.7	7.6	7.6	7.5	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8	6.7	6.7	6.7
1020	8.1	8.0	7.9	7.8	7.8	7.7	7.7	7.6	7.6	7.5	7.5	7.4	7.4	7.3	7.2	7.2	7.1	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8	6.7	6.7
1025	8.2	8.0	7.9	7.9	7.8	7.8	7.7	7.7	7.6	7.5	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.9	6.8	6.8	6.7
1030	8.2	8.0	8.0	7.9	7.9	7.8	7.8	7.7	7.6	7.6	7.5	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8	6.8
1035	8.2	8.1	8.0	8.0	7.9	7.8	7.8	7.7	7.7	7.6	7.6	7.5	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.8	6.8
1040	8.3	8.1	8.1	8.0	7.9	7.9	7.8	7.8	7.7	7.7	7.6	7.5	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	7.0	6.9	6.9	6.8
1045	8.3	8.2	8.1	8.0	8.0	7.9	7.9	7.8	7.7	7.7	7.6	7.6	7.5	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9	6.9
1050	8.4	8.2	8.1	8.1	8.0	8.0	7.9	7.8	7.8	7.7	7.7	7.6	7.6	7.5	7.5	7.4	7.4	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	6.9	6.9

Meteorological Instruments and Methods of Observation [reference 1 to this chapter, Annex 3.A], which contains an up-to-date summary of the methods to be used for both mercury and digital pressure sensors.

Synoptic observing locations in mountainous areas above about 1,500 m usually report pressure readings corrected to a different level, such as the 850 hPa surface, because of the very large corrections that would otherwise be needed to correct to sea level. Because of the requirements of aviation forecasts, these methods are defined by international agreement, and can be found in the various WMO publications already referred to.

Calibration

Unless access to a 'travelling standard' portable reference barometer is available, a comparison with neighbouring synoptic stations using the method outlined in Method 1 above, but working to a precision of 0.1 mbar, offers the best method of checking the calibration of barometric pressure sensors and evaluating calibration drift over time. The method is described more fully in Chapter 15, *Calibration*.

Precision versus accuracy

For operational, aviation or climatological purposes, precision to 0.1 hPa and accuracy to within 0.3 mbar are mandated by WMO. For many other purposes, accuracy to within 0.5 hPa will be sufficient. However, regular checks for calibration drift should be made to ensure the accuracy of the sensor remains within this range. For stations above about 150 m above sea level, instrumental errors of 0.5 mbar will be eclipsed by variations in the methods used to derive the correction to mean sea level, which vary from country to country.

Hours of observation

When the weather is settled and the pressure fairly constant, the *diurnal cycle* of barometric pressure (or more accurately, the *semi-diurnal cycle*) will be evident on a pressure graph or barograph trace – a twice-daily peak and trough caused by tidal movements within the atmosphere. In tropical latitudes, the amplitude can be as much as 5 hPa, although in temperate latitudes more often 1–2 hPa. In mid-latitudes they are often obscured by much larger changes in pressure resulting from the day-to-day movement and change in intensity of large-scale weather systems. The diurnal cycle is very marked when examining hourly pressure means over a period of even a few days (**Figure 7.5**).

Because of the known variation from hour-to-hour, it is therefore important to state the hour or hours at which barometric pressure observations are made regularly, or for which averages are quoted. Long-term pressure means are often quoted for one or more fixed hours of the day, often 9 A.M. and 3 P.M. local time. Sometimes 24 hour means are stated, calculated from hourly or three-hourly observations made throughout the 24 hour civil day and thus averaging out the diurnal cycle. In the UK and Ireland pressure means are most commonly quoted for 0900 UTC, largely for reasons of historical consistency. AWSs can easily provide a true 24 hour mean, and it seems likely over time that 24 hour means will replace published averages for specific observation hours.

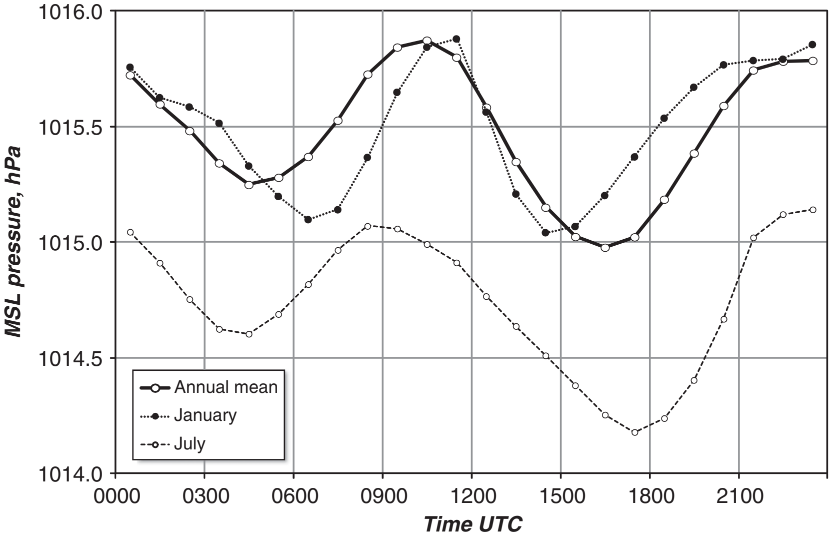

Figure 7.5. Hourly means of barometric pressure show the diurnal cycle of pressure very clearly. The curves here are for January, July and the year as a whole, and are from the author's own records in central southern England, covering the 10 year period 2001–2010.

Extremes of barometric pressure, where quoted, should always refer to the full 24 hour civil day (i.e., midnight to midnight local time, excluding any summer time adjustments), as any particular day or month's maximum or minimum pressure will only fortuitously coincide exactly with any particular observation time. Maximum and minimum pressures over any time periods based upon a single daily observation – usually a morning reading – will therefore significantly under-represent the true range of barometric pressure in any given time period.

One-minute summary – *Measuring atmospheric pressure*

- Pressure is the easiest of all of the weather elements to measure, and even basic AWSs or household aneroid barometers can provide reasonably accurate readings. It is also the only instrumental weather element that can be observed indoors, making a barometer or barograph – analogue or digital – an ideal instrument for apartment dwellers.
- The units of atmospheric pressure are hectopascals (hPa) – a hectopascal is numerically identical to the more familiar millibar. Inches of mercury are still used for some public weather communications within the United States – one inch of mercury is 33.86 hPa.
- Pressure sensors must be located away from places that may experience sudden changes in temperature (direct sunshine, heating appliances or air conditioning outlets) or draughts, which will cause erroneous readings.
- Great accuracy is not required for casual day-to-day observations, as very often the trend of the barometer in temperate latitudes, whether it is rising or falling, and how rapidly, provides the best single-instrument guide to the weather to be expected over the next 12–24 hours.

- Where accurate air pressure records are required, the observed barometer reading needs to be adjusted to a standard level, usually mean sea level (MSL), because air pressure decreases rapidly with altitude. A variety of approaches exist to correct or 'set' a barometer to mean sea level: four are described in this chapter. The choice of method depends upon accuracy sought (and the accuracy of the sensor) and height above sea level. Downloadable Excel spreadsheets are available to simplify the production of site-specific sea level correction tables where desired.
- The calibration of all barometric pressure sensors, particularly electronic units, should be checked regularly to avoid calibration drift. More details are given in Chapter 15.
- Because of the twice-daily diurnal cycle of barometric pressure, the hour of observation should always be stated when presenting averages. AWSs can easily provide 24 hour means, which eliminate the effects of the diurnal cycle in atmospheric pressure.

References

[1] World Meteorological Organization, WMO (2008) *Guide to Meteorological Instruments and Methods of Observation*. WMO No. **8** (7th edition, 2008). Chapter 3, *Measurement of atmospheric pressure*. Available online from: http://www.wmo.int/pages/prog/www/IMOP/publications/CIMO-Guide/CIMO%20Guide%207th%20Edition,%202008/CIMO_Guide-7th_Edition-2008.pdf.

[2] Middleton, WEK (1964) *The history of the barometer*. The Johns Hopkins Press, Baltimore.

[3] Camuffo, D et al (2010) The earliest daily barometric pressure readings in Italy: Pisa AD 1657–1658 and Modena AD 1694, and the weather over Europe. *The Holocene*, **20**, pp. 337–349.

[4] Cornes, Richard (2010) *Early Meteorological Data from London and Paris*. PhD thesis – University of East Anglia: also Cornes, RC, Jones, PD, Briffa, KR and Osborn, TJ (2011) A daily series of mean sea-level pressure for London, 1692–2007. *International Journal of Climatology*. Online: doi: 10.1002/joc.2301, and Cornes, RC, Jones, PD, Briffa, KR and Osborn, TJ (2011) A daily series of mean sea-level pressure for Paris, 1670–2007. *International Journal of Climatology*. Online: doi: 10.1002/joc.

[5] For an up-to-date review on EU legislation concerning the sale and restoration of mercury barometers, consult Philip Collins' *Barometer World* blog at http://www.barometerworld.co.uk/news.htm.

[6] More details and safety measures to be observed when handling mercury are given in WMO, reference 1 above, section 3.2.7. For detailed information, consult your statutory health and safety agency.

[7] Brock, FV and Richardson, SJ (2001) *Meteorological measurement systems*. Oxford University Press, New York. Information regarding the exposure of static ports is given in section 2.5.

[8] HMSO (1981) *Handbook of meteorological instruments*: Volume 1, Measurement of atmospheric pressure: Section 1.5. London, Her Majesty's Stationery Office.

8 Measuring humidity

This chapter describes the various methods for measuring humidity, defines what the various humidity terms mean, and explains how they are related to each other. It describes the instruments and sensors used to measure atmospheric water vapour concentrations, and outlines the advantages and disadvantages of each. World Meteorological Organization guidelines on humidity instruments, siting and standard measurement techniques [1] are also included.

What is being measured?

The term ‘humidity’ refers to the amount of water vapour in the air. The fascinating physics of water vapour is one of the main components of the atmospheric heat engine which produces our weather. As a result, humidity measurements are an essential requirement for operational meteorological analysis and forecasting, for climate studies, hydrology, agriculture and many other areas of human activity and comfort. In the meteorological context, the terms *relative humidity* (RH) and *dew point* (T_d) are most often used in specifying atmospheric water vapour content, but other terms are also used.

Humidity terminology

Under normal atmospheric conditions, the amount of water vapour any sample of air can hold depends mainly upon its temperature – warm air can hold much more water vapour than cold air. There are various terms used for expressing the amount of water vapour in the air – each can be converted to any of the others (see the example below), so knowing any one together with the air temperature (the ‘**dry bulb**’) enables the others to be found.

Wet bulb temperature – the temperature indicated by a thermometer covered by a thin muslin cap which is kept permanently moistened with distilled water. The difference between the readings of the paired wet-bulb and dry-bulb thermometers (known as a ‘psychrometer’) increases as the humidity decreases: when the air is saturated, two correctly calibrated thermometers will read the same temperature.

Vapour pressure e – in meteorology, this refers to the partial pressure of water vapour in air: units hectopascals (hPa), numerically identical to millibars (mbar). The **saturation vapour pressure** is the vapour pressure at the temperature at which a sample of air just becomes saturated – that sample of air is then holding as much water vapour as it can at that temperature (and its Relative Humidity, or RH, is

Table 8.1. *The variation of saturated vapour pressure, mixing ratio, specific humidity and absolute humidity with air temperature. Data taken from the Vaisala online humidity calculator [2]. From this it can be seen that saturated air at 20 °C holds almost four times the amount of water vapour as saturated air at 0 °C.*

Variations of various humidity parameters with temperature

Air temperature *°C*	Saturated vapour pressure *mbar*	Mixing ratio r *g/kg*	Specific humidity q *g/kg*	Absolute humidity *g/m³*
–15	1.9	1.18	0.54	1.61
–10	2.9	1.77	0.64	2.37
–5	4.2	2.61	0.72	3.42
0	6.1	3.79	0.79	4.87
5	8.7	5.42	0.84	6.82
10	12.3	7.66	0.88	9.43
15	17.1	10.68	0.91	12.87
20	23.5	14.74	0.94	17.34
25	31.8	20.14	0.95	23.10
30	42.6	27.28	0.96	30.43
35	56.4	36.68	0.97	39.68

therefore 100%). Any cooling will lead to condensation, that is, removal of water vapour from the air sample. Its variation with temperature is shown in standard meteorological tables, in online calculators [2] and in simplified form in **Table 8.1**. Vapour pressure varies by more than an order of magnitude across the normal range of observed air temperatures. There are two forms – the saturation vapour pressure with respect to water, e_w, and with respect to ice, e_i. The difference between the two is small, but crucial to many atmospheric processes.

Relative Humidity or RH – is defined as the observed vapour pressure expressed as a percentage of the saturation vapour pressure at that temperature (and pressure); that is, e / e_w x 100% (or e / e_i x 100%, depending upon temperature). Where the two are the same, the RH is 100% and the air is said to be *saturated*.

Dew point temperature T_d – the temperature at which the amount of water vapour in the air just equals the maximum amount of water vapour that the air can hold at that temperature (i.e., the RH is 100%). Any cooling of the air below this temperature will lead to condensation. An alternative definition is 'the temperature to which the air must be cooled to become saturated, without removing water vapour'. The **dew point depression** is the difference between the air temperature and the dew point – the larger the difference, the lower the humidity.

Vapour pressure is directly related to the **specific humidity** q (the amount of water vapour in a sample of moist air, in grams of water vapour per kilogram of air, g/kg) and to the **humidity mixing ratio** r (the amount of water vapour in a sample of dry air, in grams of water vapour per kilogram of dry air, g/kg): $q = r / (1 + r)$. The **absolute humidity** refers to the amount of water vapour per cubic metre of dry air, in grams (g/m^3).

Several humidity parameters are given for a range of temperatures in **Table 8.1**.

Example: using humidity parameters

An observation shows that the air temperature (dry-bulb temperature) is 25 °C and the RH is 39%. What is the vapour pressure and the dew point temperature?

Using psychrometric tables or an online calculator [2], the vapour pressure is found to be to be 12.3 mbar[*]. From tables (such as **Table 8.1**) or an online calculator, this corresponds to the saturation vapour pressure at 10 °C – therefore the dew point is 10 °C.

Alternatively, the observation parameters could have been stated as – air temperature 25 °C and dew point 10 °C. What is the RH and vapour pressure?

Using **Table 8.1** or an online calculator, we can see that the saturation vapour pressure at the dew point temperature of 10 °C is 12.3 mbar. From **Table 8.1**, or the online calculator, we find the saturation vapour pressure at the air temperature of 25 °C is 31.8 mbar. The RH is then 12.3 / 31.8 = 39%.

For this example with the air temperature at 25 °C, we could therefore quote the observed humidity as any or all of the following parameters:

RH	39%
Wet-bulb	14.6 °C
Wet-bulb depression	10.4 degrees Celsius (degC)
Vapour pressure	12.3 mbar
Dew point	10 °C
Dew point depression	15 degrees Celsius (degC)
Mixing ratio	7.7 g/kg
Absolute humidity	9.4 g/m^3

In surface operational meteorology, the dew point is the most quoted measure; in upper-air measurements, specific humidity or mixing ratio: in climatology, RH.

Standard methods of measuring relative humidity

The traditional method of measuring humidity is with a pair of matched mercury-in-glass thermometers, known individually as dry-bulb and wet-bulb thermometers and in combination as a dry- and wet-bulb psychrometer (**Figure 5.1**, page 95).

As the name implies, one thermometer has its bulb kept permanently wet using a thin close-fitting cotton cap or sleeve attached to a wick, which draws water from an adjacent container by capillary action. The cap or sleeve should extend at least 2 cm up the stem of the thermometer or electrical sensor probe to minimize errors due to conduction. The wet-bulb is cooled by evaporation, and the difference between the dry-bulb and wet-bulb temperatures is a measure of the humidity of the air. The lower the water vapour content of the air, the greater the difference – at saturation, both will read the same temperature[†]. Both thermometers should be read (or logged)

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[*] The calculation varies somewhat depending upon the airflow over the sensors, and for accurate work this needs to be taken into account. For this reason there are different psychrometric formulae and tables for sensors exposed in a passively ventilated shelter such as a Stevenson screen and for those in a forced airflow, such as an aspirated or whirling psychrometer (Chapter 5). There are also slight differences in the method of calculation for temperatures below 0 °C, owing to differences in the saturation vapour pressure over liquid water and ice surfaces: for details, see references [1, 8 and 9].

[†] When the temperature is falling rapidly, it is possible for a wet-bulb to read slightly higher than a dry-bulb for a short period, owing solely to differences in response time. If, in saturated air and when temperatures are changing only slowly, the two thermometers do not read the same temperature, then the calibration of both sensors should be checked.

simultaneously, to a precision of 0.1 degC: then, using tables, an online calculator or formulae, the relative humidity (or any of the other humidity measures) can be quickly and easily determined.

For accurate readings, the wet bulb must be carefully maintained using only pure water (distilled or de-ionised, not tap water). It is also essential that the covering of the wet-bulb be as thin as possible commensurate with maintaining an adequate supply of water, and it must be kept clean – a dirty wet-bulb will read higher than it should, and thus the indicated RH will be higher than the true value. It is difficult to maintain a good wet-bulb at temperatures below freezing (an ‘ice-bulb’), particularly if the air is dry, and humidity measurements at low temperatures are more difficult using the dry- and wet-bulb method. On occasions of very low humidity, heat transfer from the dry stem of the wet-bulb can be significant, and the true difference between the wet-bulb and the dry-bulb (the ‘wet-bulb depression’) reduced as a result, in which case the indicated humidity will again be higher than the true value.

The traditional dry- and wet-bulb psychrometer is easily replicated using two matched resistance temperature devices (thermistors or platinum resistance thermometers): both are then continuously logged using a datalogger. This approach is often used where accurate measures of humidity are required, where strict continuity with existing measurement methods is preferred or simply to provide a calibration check on adjacent electronic sensors. Keeping the long tubular wicks on the wet-bulb sensor clean and consistently moist can be difficult, however, and the same difficulties occur as with mercury-in-glass thermometers when the temperature falls below freezing. In addition, the covering on the wet-bulb sensor acts to make the thermometer less responsive. When the temperature and/or humidity is changing quickly it can take some time to settle, particularly if the airflow over the sensing elements is fairly limited, as is often the case when the sensors are exposed in a Stevenson screen or similar shelter.

It has been known since the 17th century that human hair responds to changes in humidity, and as a result (carefully washed) hair has long been used as the sensing element in older humidity instruments, such as the hair hygrograph (**Figure 5.1**, page 95). In this instrument, changes in the length of a bundle of hair strands are magnified and linearised by a complex system of levers and cams to give a mechanical indication on a scale or to move a pen on a paper chart. However, the instrument’s response tends to be sluggish, and the hair elements themselves are sensitive to airborne salt, pollution or deposition of condensation in damp conditions. According to WMO, the bundle of hair elements on a hygrograph should be washed at frequent intervals with distilled water, although this seems rarely (if ever) done in practice. Such instruments, when well-adjusted, do provide an indication of changes of RH over time, but they are not particularly accurate, especially at high or low humidities, or at low temperatures.

Humidity, comfort and tracking airmasses

Humans are sensitive to humid air because the human body uses evaporative cooling as its primary mechanism of regulating temperature. When the humidity is high, the rate at which perspiration evaporates on the skin is less than it would be if the air were less humid. Because humans perceive the rate of *heat transfer* from the body, rather than *temperature* itself, we feel cooler when the air is dry rather than when it is humid.

But what is it that gives the best comfort measure? The percentage relative humidity alone is a poor indicator, as a cold winter fog (100% RH at 2 °C) is certainly a lot colder than a humid summer's day (75% RH at 25 °C). The dew point temperature is a much better indicator of comfort levels, although the level of sensitivity depends upon acclimatization. In general, however, a dew point temperature above 17 °C (63 °F) in southern England will start to see people feeling uncomfortable with 'the humidity', while at 20 °C (68 °F) the majority will be so. For citizens of New York or Washington, D.C., with acclimatization the comfort thresholds are shifted upwards a few degrees. The highest dew points in the world occur near very warm bodies of water such as the Red Sea and the Persian Gulf. Assab in Eritrea, on the coast of the Red Sea, boasts an unenviable average dew point of 29 °C (84 °F), while dew points as high as 35 °C have been recorded in the Persian Gulf[*].

Various 'heat index' formulae have been devised to reflect the combined cooling effect (or lack of it) of differing temperature and humidity levels – for example the U.S. Heat Index (www.nsis.org/weather/heatindex.html) and the Canadian Humidex index (www.csgnetwork.com/canhumidexcalc.html). Such indices are useful in weather forecasting models to predict occasions when heat stress is likely to affect vulnerable sections of the population. Some AWS models can be configured to calculate and display current humidity index values, or even to sound an alarm when particular thresholds are reached.

The dew point value is also invaluable in operational meteorology as a means of identifying and tracking airmasses. Unless the water vapour of a sample of air changes (by water vapour evaporating into it, or by cloud droplets condensing out into precipitation), the dew point value does not change, even if the air is warmed. It is therefore a good conservative indicator of the properties of a sample of air, even when that sample of air has travelled thousands of kilometres horizontally from its source, or has been raised vertically by forced ascent over a mountain range. The passage of fronts in the cyclonic systems of temperate latitudes are often more easily identified by changes in dew point temperature than air temperature, particularly during the summer half-year.

Arising primarily from the requirements of balloon-borne temperature and water vapour sensors for routine upper-air measurements, small and reliable electrical sensors have been developed which provide an output signal proportional to relative humidity. One device consists of a polymer foil sandwiched between two gold foil electrodes to form a capacitor, whose electrical impedance varies with relative humidity. Once calibrated and logged, these give a direct measurement of RH. Such sensors are small, fast-reacting, reasonably stable in calibration, work reliably at temperatures well below 0 °C and in very low humidities [3] and consume little power: they are therefore ideal for use in AWSs. They are not perfect, however. Their response is slow when the humidity changes only slowly, particularly near saturation,

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[*] One consequence of warmer air holding much larger amounts of water vapour is that, contrary to popular perception, fogs are densest at higher temperatures rather than at lower. Visibility in a mountain fog at 20 °C, particularly when it is sustained by a strong breeze, can be very poor, and the fog very 'wet' indeed, with copious condensation on any surfaces even slightly below the dew point. (Fog at 35 °C does not bear thinking about, however.)

and once they have reached saturation they can take some time to 'dry out', particularly if they have been in very wet air for long periods, such as after a foggy night or in persistent hill fog[*]. Such sensors require a protective micropore filter, as direct contact with water can damage the sensitive element. The presence of the filter significantly increases sensor lag, particularly where ventilation is limited (below about 2 m/s, as it often is inside a Stevenson screen). Response time is often slow as a result. Such sensors are also prone to calibration drift, of which more below, and tend to have a fairly limited working life. Useful lifetime is quite variable and not easily predictable, but is rarely more than a few years, occasionally just a few months, particularly on entry-level and budget systems or in areas with high air pollution (particularly sulphur dioxide, which degrades the polymer used in many sensors) or plentiful airborne salt particles. The sensor should be replaced if its readings become erratic or the calibration becomes unstable. The readings from a failing sensor will quickly bear little resemblance to changes in atmospheric humidity, and to avoid loss of record the sensor should be replaced at the first signs of trouble.

For very accurate work, dew point sensors can be used. These use the optical response of a light sensor to the misting of a mirrored sensor cooled progressively to the dew point, measured using an integral temperature sensor. Although this device is straightforward enough in theory, in practice they are difficult to maintain especially in remote or unmanned environments (requiring frequent maintenance for optimum results, particularly in keeping the mirror surface polished). They tend to exhibit a slow response, require a significant power supply and can be unreliable when ambient conditions change quickly. Co-locating the assembly used to warm and chill the mirror with sensors used to determine air temperature can also result in errors to the latter. The U.S. ASOS systems originally used a chilled-mirror sensor for dew point determination, but most if not all have since been replaced with simpler but more reliable capacitative sensors [4].

Site and exposure requirements

Humidity sensors are normally exposed alongside temperature sensors in a thermometer screen (see **Figure 5.1**), either as a dry- and wet-bulb combination or as a combined temperature/humidity probe for an AWS. Exposure requirements are the same as those for thermometers. Direct solar radiation will not directly affect the humidity value obtained from the sensor, but if the sensor or the radiation screen in which the sensor is exposed becomes warmer than the ambient air temperature (for example, if it becomes unduly warm in sunshine) then the indicated humidity will be lower than the true value. Restricted airflow through the screen or shelter can lead to a very sluggish response from the humidity sensor, particularly if saturated or near-saturated air persists for many hours. The problem is more acute in sheltered locations, where surface winds speeds are low anyway, and at night, when wind speeds tend to be lower than during the day.

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[*] They can also spuriously indicate RH values slightly in excess of 100%, although that is easily taken care of with suitable code in a programmable logger. Less easily managed is the tendency in some instruments for readings to 'plateau' at typically 97–98%, never actually attaining 100% even in saturated air. The non-linear response just below 100%, especially when combined with sensor hysteresis (see Appendix 1) and possible wetting of the sensor, often makes it difficult to be confident of 2% accuracy readings from electrical sensors in the 95–100% RH range.

In coastal locations, and even occasionally some distance inland after gales, airborne salt can be deposited on temperature and humidity sensors. As salt is hygroscopic it will absorb moisture from the air, resulting in erroneously high humidity readings. Regular checking and the occasional wipe-over with a damp cloth will normally reduce the problem. Some RH sensors include a micropore filter to keep out dust and salt, but at the expense of increased response times. Aspirated screens (Chapter 5) are ideal for accurate temperature measurements, and when fitted with RH sensors will generally give more representative RH values too, but the greater volume of air movement over humidity sensors tends to exacerbate dust and salt ingress problems and probably ultimately shortens their working life.

Calibration and calibration drift

Most requirements will be satisfactorily met by an electronic humidity sensor, whether a standalone unit, one combined with a temperature sensor[*] or as an integral part of an AWS system. Calibration drift is a problem with humidity sensors, particularly in less expensive systems where it can exceed 5% per year. Whatever type of equipment is used, regular checking over a range in humidities is essential if reasonably accurate long-period humidity measurements are sought. Calibration checking is best carried out annually, or more frequently if spot checks indicate the sensor is regularly more than about 5% different from independent instruments.

To check and monitor calibration, place a second, independent and calibrated humidity sensor, such as a portable Tinytag TH2500 unit (see Chapter 5) or a well-maintained dry- and wet-bulb psychrometer, alongside the sensor being checked, and allow at least an hour to settle. At high humidities, response is slow and both sensors may take some time to respond once the humidity does begin to fall. Calibration overlaps should take account of differing instrument sensitivities, response rates and hysteresis (see Appendix 1) to avoid biasing results. The best conditions for comparisons are when the RH is steady or changing only slowly (not when it is just beginning to fall after a long period of saturation or near-saturation) and with good ventilation – a breezy day or night. It is unrealistic to expect perfect agreement between any two sensors, even of the same type, at all times.

Logging requirements

Logging requirements for humidity are the same as for air temperature, although sampling intervals can be less frequent (once per minute is ample; indeed, WMO [1] recommend an averaging time of 3 minutes for climatological applications). Depending upon sensor and logger combinations, the output is most often given as RH and dew point, although if required other humidity parameters can be easily looked up from tables, calculated directly using a programmable logger [5] or

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[*] In general, dedicated humidity sensors are to be preferred over combined temperature/humidity units, for although a combined probe simplifies exposure and wiring, takes up less space and is less expensive than separate instruments, replacing the humidity sensor mandates replacing the temperature sensor too, which may have a different calibration from the one it replaces. The presence of an RH sensor on a combination temperature/RH unit also makes ice bath temperature calibration checks (see Chapter 15) impossible, because immersion in water will damage or destroy the RH sensor.

determined from post-processing formulae [6, 7] in a suitable spreadsheet or data processing routine.

Accuracy versus precision

The errors inherent in the measurement of humidity – whether by dry- and wet-bulb or by electronic sensor – mean that the RH is at best accurate only to about 2–3% in its mid-range. This level of accuracy is also about what can be expected from the individual calibration errors of two thermometers used as a paired dry- and wet-bulb, and meets WMO 'working standard' requirements [1, Table 4.4 and Annex 1.B therein]. Quoting RH to one or more decimal places is therefore unjustified except possibly under strictly controlled laboratory conditions. At high humidities response will be slow, while at low humidities and low temperatures, errors increase and the accuracy falls off further. The same goes for dew point – although often quoted to a precision of 0.1 degC, in reality the measurement is probably no better than ± 0.5–1 degC when derived from humidity measurements, with still wider error ranges at low temperatures and humidities. Such accuracies are permissible for most climatological applications, provided calibration drift is watched for and corrected promptly.

One-minute summary – *Measuring humidity*

- 'Humidity' refers to the amount of water vapour in the air, a vital component of the weather machine.
- Various measures are used to quantify the amount of water vapour in the air – relative humidity and dew point being the two most commonly used. Knowledge of any two values can derive other humidity parameters. The amount of water vapour that the air can hold varies significantly with temperature – saturated air at 0 °C holds only a quarter of the amount that saturated air at 20 °C can hold.
- The traditional method of measuring humidity is by using a pair of matched mercury-in-glass thermometers, known individually as dry-bulb and wet-bulb thermometers and in combination as a dry- and wet-bulb psychrometer. The wet-bulb is a thermometer whose bulb is kept permanently wet using a thin close-fitting cotton cap or sleeve. The wet-bulb is cooled by evaporation, and the difference in temperature between dry-bulb and wet-bulb thermometers is a measure of the humidity of the air. Using tables, an online calculator or formulae, the relative humidity (or any of the other humidity measures) can be quickly and easily determined from simultaneous readings of the two thermometers.
- Dry- and wet-bulb thermometers can easily be replicated using electrical sensors, although small capacitative humidity sensors have largely replaced the traditional dry- and wet-bulb psychrometer. Modern sensors are small, economical on power, more reliable at temperatures below freezing and datalogger-friendly.
- Establishing and maintaining reasonably accurate calibration can be difficult; even the best humidity sensors are no better than ± 2–3%. Calibration drift is a problem (regular calibration checks are essential) and working lifetimes can be limited. Combined temperature/RH sensors are popular, but can become expensive and inconvenient if the relatively short working lifetime of the humidity component mandates replacement (and recalibration) of the temperature sensor too. The combination of the two sensors will also preclude ice-bath calibration checks being made on the temperature sensor (see Chapter 15).

- Humidity sensors are normally exposed alongside temperature sensors in a thermometer screen (Stevenson screens or similar, AWS radiation screens or aspirated units).
- Logging intervals should be the same as those for temperature observations, although sampling intervals can be reduced (once per minute is ample).

References

[1] *WMO Guide to Meteorological Instruments and Methods of Observation* (Seventh edition, 2008), Part I – Measurement of meteorological variables: **Chapter 4**, Measurement of humidity. Available at www.wmo.int/pages/prog/www/IMOP/publications/CIMO-Guide/CIMO_Guide-7th_Edition-2008.html.
[2] See, for example, www.vaisala.com/humiditycalculator.
[3] Burt, Stephen (2011) Exceptionally low relative humidity in northern England, 2–3 March 2011. *Weather*, **66** (7), pp. 197–199.
[4] NOAA/National Weather Service (2002) *ASOS Product Improvement Implementation Plan, for Dew Point Sensor Upgrade*. Available online from www.nws.noaa.gov/ops2/Surface/documents/DewPoint0816.pdf.
[5] Campbell Scientific (2000) *Calculating dew point from RH and air temperature*. Campbell Scientific technical note 16, available online from www.campbellsci.co.uk/index.cfm?id=352
[6] There are a number of sources for humidity computation formulae: the methods and coefficients in the equations used can vary significantly from one to another. The WMO Guide, *op cit*, Annex 4.B lists the methods adopted by WMO in 1990. Older tables or programmable routines may give different results, particularly at low temperatures and humidities. Current WMO formulae and coefficients should be used unless there are good reasons for doing otherwise.
[7] Brock, FV and Richardson, SJ (2001) *Meteorological measurement systems*. Oxford University Press, New York: Chapter 5, *Hygrometry*.

9 Measuring wind speed and direction

The wind is the most variable of all weather elements. The speed of the wind can double, or halve, within a few seconds. Its direction can, and occasionally does, change by 180 degrees within a minute, and can make several turns right around the compass within an hour or two. Wind direction and speed both vary continuously with a time-period measured in seconds, about a mean value which itself changes on a minute-by-minute, hour-by-hour, day-to-day and month-to-month basis (**Figure 9.1**) in fractal-like fashion. The wind can blow with barely perceptible force, or with sufficient strength to cause complete destruction of forests and buildings. It is also one of the most important measurements in operational meteorology and in aviation forecasting.

Measuring and summarizing such a fickle element poses considerable challenges, not least in requiring rapid-response sensors (coupled with high sampling and logging rates) that are also physically robust. They must respond accurately in the lightest of breezes, yet also be capable of surviving winds in excess of hurricane force.

The exposure of the instruments themselves is also vital for accurate, reliable and comparable results. The recommendations of the World Meteorological Organization [1] are that wind instruments should be sited on level terrain with no significant obstacles within 100 metres, but even WMO accept that ‘in practice, it is often difficult to find a good or even acceptable location’. For this reason, high-quality wind records can be the most difficult to obtain of all of the more common weather elements, especially in a domestic or sheltered suburban environment where a ‘perfect’ exposure is almost impossible to realize. The necessarily elevated nature of the sensors can pose significant safety issues for access, installation and maintenance, while continual exposure to the elements at height (rain and snow, ice and frost, sunshine and solar radiation and possibly lightning, in addition to buffeting by the wind itself) takes its toll on sensor reliability, longevity and electrical connections. In a windy location, even the best sensors may last only a few years before replacement is necessary.

Despite these significant obstacles and requirements, it is possible to make useful automated observations of wind speed and direction even without a handy airfield-sized plot of land, although they may be rather more site-specific than is the case with other measured parameters. This chapter describes methods to ‘measure the wind’, suggests suitable instruments and how best to expose them, and outlines some common pitfalls.

Those new to weather measurement, or on a tight budget, may find it easier to concentrate on temperature, rainfall and pressure records, as covered in the preceding chapters, at least initially, before tackling the altogether more difficult territory of automated wind measurements at a later date. Manual estimates of wind speed (using

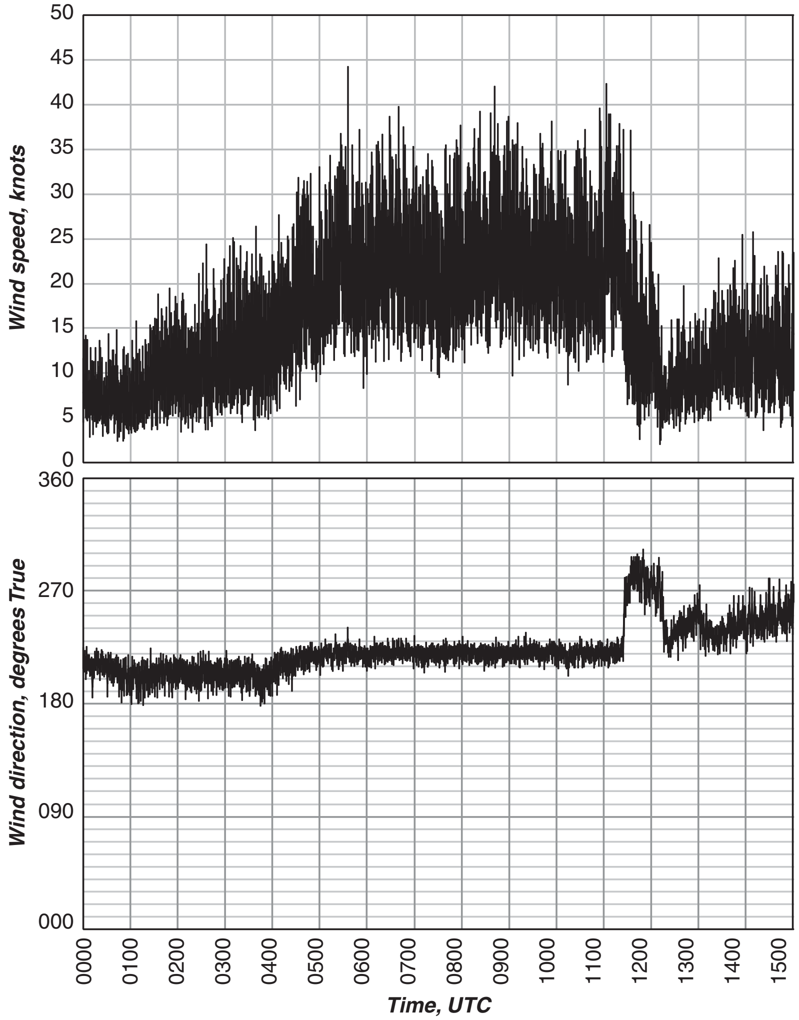

Figure 9.1. A 15 hour record of wind speed (upper graph, knots) and wind direction (lower graph, degrees True) at the author's site in central southern England on 3 January 2012, showing typical rapid variations in both wind speed and direction with time, both on a minute-by-minute and hour-by-hour basis.

the Beaufort Scale – see below) and wind direction, or 'spot' wind speeds obtained from inexpensive handheld anemometers, will be sufficient for many purposes.

What is being measured?

'Wind' is the continual movement of air over the surface of the Earth – air currents resulting from differential heating of the planet by the Sun. The Earth's wind systems are vast three-dimensional heat-exchange engines distributing heat around the planet. We are familiar with surface gusts and lulls – turbulent effects caused by friction in the so-called boundary layer, the lowest layer of the atmosphere in contact with the Earth's surface – but we are probably less familiar with the intricate and continually changing structures of the winds above our heads. Wind speeds are normally lowest, and most variable, close to the Earth's surface; the greater the height of surface obstacles, the greater the short-period variations in wind speed and direction (which we experience as gustiness). Winds at sea are generally stronger but steadier (in both speed and direction) than on land because frictional effects are much lower: winds in built-up city-centre environments, with many, high and varied surface obstacles, are notoriously variable. Winds are much stronger in the upper atmosphere, where at 10 km or so above the Earth's surface they sometimes blow for days at speeds in excess of 100 metres per second (200 knots, 230 mph) in jet streams.

Mathematically, wind is expressed as a vector quantity – one which has both direction and speed. In this context, *wind speed* and *wind velocity* have different meanings – 'wind speed' (more correctly, 'scalar wind speed') refers to distance travelled in a specified time ('a 10 metres per second wind'), whereas 'wind velocity' includes both speed and direction ('a 10 metres per second northerly wind')[*]. The 'vector mean wind' is a useful way to combine wind speed and direction records to come up with a 'resultant', or 'averaged', wind direction and speed, and is covered in more detail later in this chapter.

It is normal practice to measure wind speed and wind direction using separate instruments, although some newer instruments, such as sonic anemometers, measure wind as a true vector and resolve it into direction and speed components. Operational meteorology often uses 'raw' wind vector information, but for ease of handling wind speed and wind direction are most often treated as separate quantities in climatological summaries.

Units of wind speed and wind direction

Wind speed is dimensionally expressed in terms of distance and time – for example, the wind speed could be stated as so many metres per second (m/s) or miles per hour (mph). In meteorology, the knot (nautical miles per hour, or kn, but not the tautological 'knots per hour': 1 kn = 1.15 mph) is still the preferred unit in many countries and for aviation purposes. This reflects the preferences of the earliest users of wind speed observations, Britain's Royal Navy in the 17th and 18th centuries, where commonality with the units of measure of sailing ship speed was essential. Depending upon preference, miles per hour or kilometres per hour are also sometimes used. Conveniently, 1 m/s is very nearly 2 knots; the exact conversions are given in Appendix 3.

Whichever units are chosen, it is important to ensure that they are noted in the site metadata, as this will not be obvious from the record itself (a visual inspection of tabular temperature data from an AWS would quickly reveal whether it was in °C or °F, for example, but the difference between knots and miles per hour would be impossible to determine).

Two measures of scalar **wind speed** are important – the *mean wind speed* (usually expressed over a defined period of time, most often 10 minutes) and the *gust speed*. Because wind speeds can vary enormously within a few seconds, gusts are defined by

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[*] Strictly, wind vectors are three-dimensional in nature (x, y and z components), rather than just two, but since the vertical component of wind speed z is usually small near the Earth's surface, at least in comparison with the horizontal component, it is usually ignored in conventional meteorological measurements.

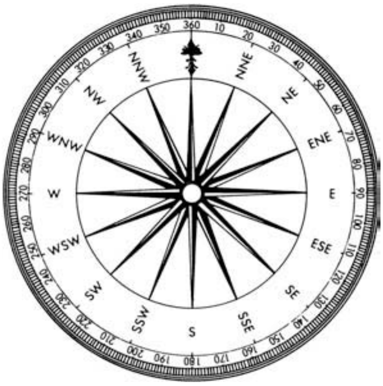

Figure 9.2. Compass points on the 360 degree compass. (© Crown copyright 1982, the Met Office)

WMO as 'the highest mean wind speed over a 3 second period' – see also Box, *Measuring wind gusts* on p. 198. There are many and varied effects which influence recorded gust speeds, amongst them being the anemometer type and sensor height, sampling interval frequency and the processing applied to the samples. Regardless of site or shelter, for wind gust records to be in any way comparable and meaningful, the sampling interval has to be short enough to 'catch' transient gusts (see *How often is the information updated?* in Chapter 2). If accurate records of wind speed – both means and gusts – are an important requirement, as clearly they will be at an airport, or monitoring crosswinds on an exposed railway viaduct, for example, then a short sampling period – no more than a second or so – is needed. For applications where only the mean wind speed is required, a short sampling period is less important. More details on logging and sampling intervals are given later in the chapter.

By convention, in meteorology **wind direction** is defined as the direction *from which the wind is blowing*, relative to true north, not magnetic north. Thus a south-westerly wind blows *from* the south-west *to* the north-east.

Compass points have been used to define wind directions for hundreds of years, but for more precise weather measurements the direction is specified using the 360 degrees of the compass, starting from north and working clockwise (technically 'the veer from north'), so that 90° represents an easterly wind, 180° a southerly wind, 270° a westerly wind, and so on (**Figure 9.2**). By convention, north is represented as 360° rather than 0°, as '0' is reserved to indicate calm (the absence or near absence of wind – see Box, *How calm is calm?* on p. 202) in both wind direction and speed. In meteorological reporting, wind directions are often given to the nearest 10 degrees, with the final digit omitted, thus wind direction '23' would be understood to mean '230 degrees', or south-westerly. To avoid misinterpretation, leading zeroes are usually quoted, so that '09' refers to '090 degrees' (easterly) and not '009 degrees' (just east of north).

Standard methods for measuring wind speed and direction

The World Meteorological Organization's specifications for wind measurement sites specify that they should be made at 10 m above ground level, in an open, level location 'where the distance between the anemometer and any obstruction is at least 10 times the height of the obstruction' [1]. Wind sensors are located above ground level, usually on an open mast or tower (**Figure 9.3**), to minimize frictional effects

Figure 9.3. Anemometer and wind vane on 10 m masts in an exposed, open location; Valentia Observatory in south-west Ireland, October 2010. (Photograph by the author)

near the ground. Turbulent effects from obstructions such as trees, buildings or other obstacles can extend downwind to 12 or 15 times the height of the obstacle, and their presence will clearly make it difficult to measure 'undisturbed' wind flow.

However, such 'standard' sites are very difficult to find, particularly in urban or suburban areas, a limitation acknowledged by WMO. Some degree of site compromise and/or empirical correction to measured winds may become necessary to obtain wind measurements that conform more closely to the WMO standards, and these are briefly outlined.

The following sections describe the various types of instruments used to measure wind direction and speed, and provide more detail on the exposure, installation and logging of wind sensors.

Measuring wind speed

Wind speed records are very sensitive to the type and response of the sensors and logger components making the measurement. The response of the system determines whether the wind record accurately records short-period gusts (**Figure 9.1**): measurements made using slow-response instruments will give different values for both peak gusts and gust ratios, as explained subsequently.

The cup anemometer

There are a number of different ways to measure wind speed, the most familiar being the cup anemometer invented by Thomas Romney Robinson, an astronomer at

Figure 9.4. Vector Instruments cup anemometer, model A100, and wind vane, model W200P. (Photograph by the author)

Armagh Observatory in Northern Ireland, in 1846 [2] – see also Chapter 1. Current instruments use three cups located 120 degrees apart mounted on a vertical shaft with low-friction bearings. The drag coefficient of the open face of the cup is greater than that of the smooth conical or hemispherical opposite face, and this difference causes the shaft to rotate as the cups spin in a breeze (**Figure 9.4**). The speed of revolution of the shaft is (very nearly) proportional to the speed of the wind, although cup anemometers tend to speed up (in a gust) faster than they slow down, and so slightly overestimate true wind speeds. Modern low-power digital cup anemometers convert the shaft revolutions into a distance measurement by breaking a beam of light, the 'breaks' then being counted by a pulse counter logger. Older analogue instruments used a small dynamo to generate a voltage, measured by a recording voltmeter, or mechanical gearing to rotate a distance-measurement counter, similar in mechanical principle to a car odometer. Both suffered larger frictional losses than the modern 'light chopper' designs, and so tended to have a higher starting speed (see below). Pulses are also more reliably transmitted over long cable lengths than the relatively small analogue voltages generated by the small generators used in anemometers.

The design of the instrument is simple and has been refined over the years, and with modern materials and electronics the sensors are both very sensitive (low starting speed) and robust (low maintenance, high maximum wind speed).

The Vector Instruments A100 cup anemometer illustrated in **Figure 9.4** – also known as the 'Porton anemometer', after Porton Down in Wiltshire, England where it was developed in the 1970s – is widely used in professional weather monitoring around the world. It has a starting speed around 0.2 m/s (0.4 knots) – a barely perceptible flow of air – and a stopping speed of half that, yet is rated up to 75 m/s (over 150 knots), twice hurricane force, with a stated accuracy of 1% ±0.1 m/s up to 56 m/s (108 knots).

Measuring wind gusts

A wind 'gust' is defined by WMO as 'the maximum observed wind speed over a specified time interval', usually over a 3 second period; the 'highest gust' is defined as the maximum 3 second mean in any given period. To obtain accurate gust measurements, wind speed samples must therefore be made at or less than 3 seconds apart. Where samples are taken at longer intervals, the gust speed will be averaged over a longer time period and individual gusts will be 'smeared out' into a longer duration, lower speed value.

Why 3 seconds? The WMO recommendation for a 3 second gust period originated from an analysis [3] published in 1987, which reasoned that, in strong wind conditions, a 3 second gust would possess dimensions typically 50 to 100 m (25 m/s wind × 3 seconds = 75 m), sufficient to engulf typical urban or suburban structures and expose them to the full wind loading of a potentially damaging gust. Gusts of shorter duration are of insufficient scale to engulf complete structures in this way.

AWSs and loggers differ in their sampling intervals, from 1 second or less to a minute or more. **Figure 9.5** and **Table 9.1** illustrate how wind gusts averaged over different sampling periods from 1 second to 60 seconds (open circles) vary in comparison with the standard 3 second mean (solid circle)[*]. 'Gust' speeds from an anemometer sampling at different intervals from the standard 3 second running mean will vary from an average of 21 per cent above the 3 second value for a sampling time of 0.25 seconds, to 30 per cent below for a 60 second sampling interval. Where wind speeds are sampled at shorter intervals than 3 seconds, the logger should be programmed to calculate 3 second running means from the shorter-period samples. So if the samples were at ¼ second intervals, then a running mean of 12 samples would become the 3 second value: the highest gust would be the highest of the 3 second means, not the highest individual ¼ second sample.

The fine-scale structure of individual gusts, particularly in windy conditions, is such that exact minute-by-minute agreement on wind speeds, particularly gust speeds, is simply not achievable on adjacent instruments where these are more than a few metres apart.

The **gust ratio** is the ratio of the gust speed to the mean speed over any given interval: for example, an hour with a mean wind speed of 14 knots and a highest gust of 21 knots would have a gust ratio of 1.5. Gust ratios are higher over land than over sea or at coastal sites, higher by day and in turbulent or unstable airmasses, and higher in 'cluttered' anemometer exposures more typical of urban sites. Very open exposures – such as a standard 10 m mast site on an open airfield – generally record lower gust ratios. Analysis of gust ratios can be useful in airmass stability modelling, while comparisons of gust ratios from a relatively dense network of anemometers across cities or complex topography can provide useful indications of relative turbulence of benefit to pollution dispersal modelling or the architectural design of city buildings.

The reduction in *average* wind speeds as a result of friction is greater than for gust speeds, for a variety of physical reasons. An anemometer at 2 m above

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[*] The figures presented here are based upon observations from a single site, and will vary somewhat according to terrain, land use, anemometer height, and so on.

ground typically records mean wind speeds about 30 per cent less than those of one at the standard 10 m above ground, but gust speeds might be only 10 per cent lower on average – occasionally they may even exceed that of the higher instrument. For this reason gust speeds are *not* corrected for height.

Table 9.1. *Variation of wind gusts with sampling time, as a fraction of the standard 3 second running mean. 'Observed' – based upon the author's own observational data for calendar year 2010, central southern England (51.4°N, 1.0°W): 'Modelled' – based upon the logarithmic profile shown in the dashed line in Figure 9.5.*

Sampling time (sec)	0.25	0.5	1	2	3	5	10	20	30	60
Observed			1.05	1.03	**1.00**	0.96	0.90	0.82	0.78	0.70
Modelled	1.21	1.15	1.08	1.02	**1.00**	0.94	0.88	0.82	0.78	0.72

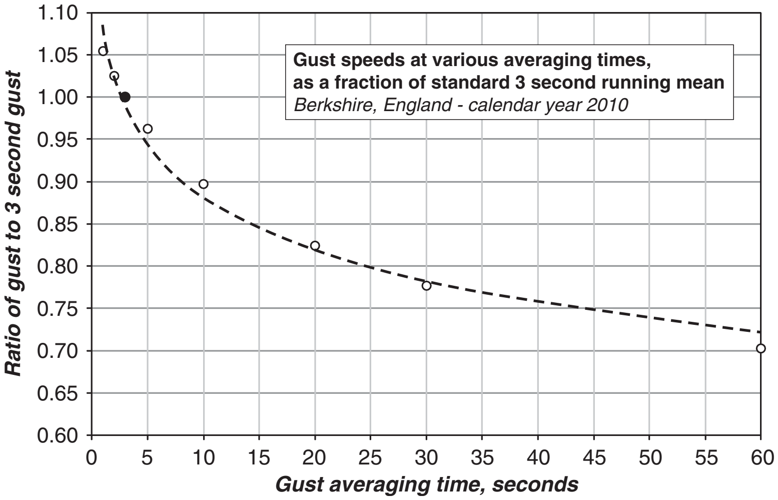

Figure 9.5. Sampling intervals: gust speeds, as a fraction of the standard 3 second gust speeds, for sampling intervals from 1 second to 1 minute. Plotted points are actual observations, and the dashed line is a logarithmic curve fitted to the observations. Based upon the author's observations at his site in central southern England, calendar year 2010.

Propeller or 'windmill' anemometers

The second most common form of anemometer is the propeller or windmill variant (**Figure 9.6**). In this design of instrument, the propeller element is kept facing into the wind by being mounted on a wind vane. This makes the sensing head directionally sensitive. As the wind blows through the rotor, differential drag forces across the blades, together with lift from the blade aerofoil itself, causes the blades to spin. In low wind speeds the wind vane may not turn into the wind and the propeller blades may therefore be at an angle to the wind, rendering the instrument unresponsive. A propeller anemometer needs a wind that is strong enough to turn the wind vane into

Figure 9.6. Automated snow, wind and weather AWS in the Swiss Alps, run by the Swiss Institute for Snow and Avalanche Research. The location is Vallée de la Sionne Windstation 'Crêta Besse' (4VDS1), in the Swiss Canton of Valais, at 2696 m above MSL. (Photograph courtesy of WSL-Institut für Schnee- und Lawinenforschung SLF, Davos, Switzerland)

the wind – in contrast to the cup anemometer, which is insensitive to direction and therefore has a lower starting speed.

At higher wind speeds, particularly in sites with less than ideal exposures such as those typical of urban or suburban areas, turbulence often results in large, rapid and erratic changes in wind direction, resulting in the sensing head again being more often than not at an angle to the wind, reducing the wind speed measured by the instrument. Propeller anemometers perform best in medium to strong winds where the direction does not vary rapidly, and are somewhat less prone to ice or rime build-up than cup anemometers.

Sonic anemometers

Although the principle of the sonic anemometer was first outlined as far back as the 1960s [4], until relatively recently they have remained largely confined to research establishments. The increasing capability and processing power of modern dataloggers has broadened their suitability and appeal, and although still relatively expensive they are now much more frequently used for routine weather monitoring applications, particularly at remote sites. They offer a number of significant advantages, the main one being that they have no moving parts. It is likely that as prices come down they will start to find their way into mid-range systems.

Figure 9.7. Sonic anemometer – Gill Windsonic. (Photograph courtesy of Gill Instruments)

The principle of the 2D sonic anemometer (**Figure 9.7**) is simple[*]. The speed of sound in air is equal to the speed of sound in still air, plus the speed of the air. Using two small sound emitter/receiver pairs at 90 degrees to each other, the difference in the speed of an ultrasonic sound pulse across the unit is measured very accurately (the temperature is also measured, as the speed of sound is temperature-dependent). Using sophisticated onboard electronics, the instrument derives both wind speed and direction readings, wind direction being calculated as a vector from the measurement of the air speed across two axes at right angles to each other.

Starting speeds

One of the most important specifications for wind instruments, particularly in areas with low mean wind speeds, is the 'starting speed' (sometimes referred to as 'threshold speed'). As the term implies, this is the speed at which either the anemometer cups just begin to rotate (and therefore at which wind speed measurement commences), or (for wind vanes) the speed at which the vane just turns into the wind.

Almost all modern wind sensors have a starting speed of 1 m/s (2 knots) or less, a big improvement on older, heavier cup anemometers, some of which had a starting speed of 3 m/s (6 kn) or more [5]. Any anemometer with a starting speed that is a significant fraction of the true mean wind speed will inevitably produce a very distorted wind climatology, particularly an unrealistic frequency of 'calm'. (See Box, *How calm is calm?* below.)

A selection of starting speeds for various common anemometers and wind vanes is given in **Table 9.2**. The starting speeds on some anemometers increase as the instruments age, presumably owing to mechanical wear on the bearings. Sonic anemometers, with no moving parts, are of course immune to mechanical ageing: indeed, the manufacturer's specification for the unit shown in **Figure 9.7** is for a mean time between failure (MTBF) in excess of 15 years.

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[*] Commercial sonic anemometer units are available for both two-dimensional (2D) and three-dimensional (3D) monitoring of wind speed and direction, 3D units being particularly useful in turbulence, flux and dispersion boundary layer research projects because of their rapid response times.

Table 9.2. *Starting speed specifications for various common anemometers and wind vanes. Sources are as indicated.*

Anemometers	Gill Windsonic sonic anemometer	0.01 m/s (0.02 kn)	*Manufacturer specification*
	Vector Instruments A100 cup anemometer	0.2 m/s (0.4 kn)	*Manufacturer specification*
	Davis Instruments Vantage Pro2 AWS cup anemometer	0.7 m/s (1.4 kn)	*Author's tests* [*15*]
	RM Young four blade helicoid propeller combined anemometer/wind vane	1.0 m/s (2 kn)	*Manufacturer specification*
	Met Office Mk 4A cup anemometer	3 m/s (6 kn)	*Reference 5*
Wind vanes	Gill Windsonic sonic anemometer	0.01 m/s (0.02 kn)	*Manufacturer specification*
	Vector Instruments W200P wind vane	0.6 m/s (1.2 kn)	*Manufacturer specification*
	Davis Instruments Vantage Pro2 AWS wind vane	1.0 m/s (2 kn)	*Author's tests* [*15*]
	RM Young four blade helicoid propeller combined anemometer/wind vane	1.0 m/s (2 kn)	*Manufacturer specification*

The Gill Windsonic 2D unit has a wide speed range (the manufacturers quote 0–60 m/s, with a lower threshold of just 0.01 m/s) and high accuracy (±2%) [6]. The sensor consists of a tough corrosion-free polycarbonate body, and having no moving parts it is ideally suited to harsh environmental conditions or exposure in 'awkward to reach' locations. Heavy rain, hail and accumulating snow or ice can cause erroneous readings, although the 'roof' on current models presumably counters this to some extent. This type of sensor does require a small power supply.

How calm is calm?

Reliable statistics on the true incidence of very light winds are hard to come by, and can be distorted by changes of anemometer type, site and exposure over the years (see *Starting speeds* above). Until the relatively recent advent of lightweight electronic sensors and loggers, standard anemometers had starting speeds of 2–3 m/s (4–6 kn) or higher: winds lighter than this were often estimated when the chart record was subsequently analyzed, based upon the degree of 'mobility' of the wind vane record (although often even the wind vane was insensitive below about 2 kn). For this reason, statistics of 'calm' tended to be the catch-all for anything below about 2–3 kn and were, as a result, higher than reality by varying degrees.

True 'flat calm' – wind speed 0.0 kn at 10 m, 'smoke rising vertically' on the Beaufort scale – is distinctly uncommon in most temperate latitudes. Tests by the author using a sensitive anemometer and wind vane combination (Vector Instruments A100L2 and W200P, respectively), mounted on a mast at 11 m above ground level in a relatively unobstructed rural exposure in central southern England, showed that over a 10 year period the wind fell below 0.05 m/s (0.1 kn) for an average of only 122 hours per year, just 1.4 per cent of all observations (based on 5 minute data intervals). Monthly averages ranged from 0.7 per cent in January to 2.4 per cent in September.

Raising the threshold to 0.25 m/s (0.5 kn) increased the average duration of ‘calms’ more than threefold to a little more than 400 hours annually (4.6 per cent), while raising it to 2.5 m/s (5 kn), thereby simulating an anemometer with a higher starting speed, raises the annual average enormously, to almost 5,600 hours per year, a little over 63 per cent of all observations (based on hourly data).

WMO’s definition of ‘calm’ [1, section 5.1.2] is ‘an average wind speed below 0.5 m/s or 1 kn’. Perhaps a more sensible definition for modern wind sensors would be ‘a mean wind speed less than or equal to 0.25 m/s (0.5 kn) over the logging period’, because below this threshold most anemometers and wind vanes become unresponsive (see *Starting speeds* above). A wind speed of 0.25 m/s is a barely perceptible drift of air. The less sensitive the anemometer, the higher the starting speed and the greater the frequency of calms. Gradual wear on anemometer bearings will also result in a slow increase in starting and stopping speeds, and thus a gradual year-on-year increase in the frequency of calms as the instrument ages.

Handheld anemometers

Within the last few years a great many handheld anemometers have appeared on the market. Some offer just a single measurement (instantaneous display of wind speed): more sophisticated models (such as the Kestrel 4000 unit, **Figure 3.6**, page 72) can provide means and highest gusts over specified time periods (typically 2 minutes), often together with other measurements such as temperature and humidity. One Kestrel model can even be fitted with a tripod and wind vane to monitor wind direction. Such instruments are now very inexpensive and reasonably accurate (the greatest source of error is more likely to result from exposure at ground level or in a relatively sheltered location). They can often provide ‘good enough’ indications of wind speed when budget or site limitations preclude more sophisticated automated wind logging equipment, or for temporary or portable field use, although wherever possible calibration should be carefully checked against a calibrated instrument before use.

The Beaufort wind scale

Reasonably accurate estimates of mean wind speeds can also be made using the Beaufort Scale. Devised by Admiral Sir Francis Beaufort in 1806 (his original manuscript outlining the scale can still be seen in the UK Met Office Archives), the Beaufort wind scale has been adapted somewhat over the years, but is still the most frequently used guide when making eye estimates of mean wind speed. Admiral Beaufort’s original scale referred only to the effects on sailing ships at sea, but descriptions were later extended to land-based observations. **Table 9.3** is the current version, with equivalent wind speeds at 10 m shown*. Consistent estimates of wind speeds can be produced with only a little practice. It is important to remember that the scale reflects *mean* wind speeds, and not gusts; twigs may be removed from trees

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* The derived empirical relationship between Beaufort Force B and 10 m wind speed V is $V = f\sqrt{B^3}$, where the factor f is 1.625 when V is in knots, 0.836 for m/s and 1.87 for mph.

Table 9.3. *The Beaufort wind scale, for use on land*

		Wind speed				
Beaufort Force	Description	knots mean	knots range	mph mean	m/s mean	Effects on land
0	Calm	0	< 1	0	0	Calm; smoke rises vertically
1	Light air	2	1–3	2	0.8	Direction of wind shown only by smoke drift
2	Light breeze	5	4–6	5	2.4	Wind felt on face, leaves rustle
3	Gentle breeze	9	7–10	10	4.3	Leaves and small twigs in motion; light flag extended
4	Moderate breeze	13	11–16	15	6.7	Dust, leaves and paper raised by the wind, small branches move
5	Fresh breeze	19	17–21	21	9.3	Small trees in leaf begin to sway; crested wavelets (whitecaps) form on inland waters
6	Strong breeze	24	22–27	28	12.3	Large tree branches in motion, telephone wires begin to 'whistle', umbrellas used with difficulty
7	Near gale	30	28–33	35	15.5	Large trees sway, difficult to walk against the wind
8	Gale	37	34–40	42	18.9	Twigs and small branches are broken from trees, walking is difficult
9	Strong gale	44	41–47	50	22.6	Some slight damage occurs to buildings, slates and shingles may be blown off roofs
10	Storm	52	48–55	59	26.4	Trees are broken or uprooted, considerable structural damage results
11	Violent storm	60	56–63	68	30.5	Extensive and widespread damage
12	Hurricane	64+	64+	73+	33+	

with *gusts* to Beaufort Force 8 ('Gale'), but this does not necessarily mean that the *mean* speed has attained gale force. Simultaneous estimates of *wind direction* should be made, preferably using a wind vane, but failing that on the direction shown by chimney smoke or dropped leaves, grass stems and the like. The direction of low-level clouds should *not* be used, as this may differ significantly from the surface wind direction.

Measuring wind direction

The principle of a wind vane is identical to that of any church spire 'weather vane' – the force exerted by the wind on a vane causes a counterbalanced arrow or pointer to swing into the wind. The two most important characteristics of a wind vane are that it should turn on its bearings with the minimum of friction, and that it must be balanced. If the unit is not balanced, or is mounted slightly off vertical, it will come to rest in a preferred neutral position, thus biasing wind direction frequencies.

A common sensing element on modern wind vanes is a potentiometer grid located underneath the vane – the position of the pointer is sensed using a grid of magnetically operated reed switches linked to a small bank of resistors, the measured resistance then being converted into a digital signal, sampled and displayed/logged as required. Other vanes use an array of infrared light emitting diodes (LEDs) and photodetectors ranged around the wind vane shaft to encode a binary direction code.

As with anemometers, modern materials and electronics have driven the development of very sensitive and accurate sensors which consume very little power, ideal for digital logging applications. Almost all budget and mid-range AWSs will include a wind vane of reasonable accuracy, although starting speeds can be rather high. The Vector Instruments W200P Potentiometer wind vane illustrated in **Figure 9.4** is widely paired in advanced systems with the A100 cup anemometer it is illustrated with. The starting speed of this unit is nominally 0.6 m/s (1.2 knots) – the author's experience with this instrument is that it will reliably react down to one-third of this speed – yet like its sibling anemometer it is rated up to 75 m/s (over 150 knots). Typical accuracy is ±2° obtainable in steady winds over 5 m/s, with a resolution of ±0.2°. The variability of wind direction is normally far greater than these specifications. Its stated lifetime is around 50 million revolutions (equivalent to 10 years' typical exposure).

Choosing wind sensors

Most 'packaged' AWSs include the manufacturer's proprietary wind speed and direction sensors – most often a cup anemometer and potentiometer or LED-based wind vane. On such systems it is rarely possible to substitute more accurate, more reliable or more robust sensors, although Davis Instruments do offer support for one third-party anemometer on their Vantage Pro2 range. As the wind sensors are the most exposed and are therefore likely to receive the greatest pounding from the weather, failures are most likely here. It may be worth considering at the outset whether to purchase a more expensive AWS to avoid the higher risk of premature sensor failure and related replacement/reinstallation costs: see also *How robust does the system need to be?* in Chapter 2.

Severe weather performance

The operation of all the wind sensors described above suffers in severe wintry weather, and they may cease to operate altogether. Heavy wet snow can build up on anemometers and wind vanes; repeated melting and refreezing cycles can result in the instruments becoming literally frozen solid for long periods unless access is possible to clear the snow and ice away (this may itself be difficult or dangerous in severe weather, of course). Riming (the build-up of frozen windborne water or ice particles in sub-zero conditions, particularly in cloud) is also a problem for many wind instruments; as well as affecting the measurements themselves, the weight of the accumulated rime can damage or even destroy the sensors and supporting mast or tower (**Figure 9.8**).

Winter riming is a particular problem on many exposed mountain sites in temperate and polar latitudes around the world, particularly in maritime regions such as the mountains of the British Isles. Two early AWS models were established by Heriot-Watt University and the then Institute of Hydrology on the summit of Cairn Gorm in Scotland (1245 m, 57°N, 3°W) in 1976 [7], recording wind speed, wind direction and temperature (**Figure 9.9**). To combat the effects of heavy riming, the Heriot-Watt instruments are housed in a heated cylinder, which is exposed to sample the weather for only 3 minutes every half hour, 48 observations per day. The station built up over the years a unique set of observations in the UK's

Figure 9.8. Severe riming on a tower at the summit of Mt Washington, New Hampshire (1917 m / 6288 ft) in May 1991. The small building on the left was the original Mt Washington Observatory, which held the record for the world's highest measured wind speed until 1996. (Photograph by the author)

Figure 9.9. An early model automatic weather station on Cairn Gorm summit in Scotland (1245 m, 57°N, 3°W) in the 1980s, showing the problems of rime icing. (Photograph by Ian Strangeways)

most severe climate, including the highest surface wind speed yet recorded in the British Isles (a gust of 79 m/s, 153 kn or 176 mph, on 3 January 1993) [8]. The mean wind speed on the summit is 15 m/s, and the average annual temperature +0.5 °C. Unfortunately, while the Heriot-Watt weather station and webcam were set up by funded research projects, funding to support these facilities finished a number of years ago and at the time of writing the AWS remains out of action for long periods.

Life at the top: a challenge for any anemometer

The high-altitude manned observatory at the summit of Mount Washington in New Hampshire (1917 m / 6288 ft) describes its climate as 'The worst weather on Earth' [9] – the observatory has even trademarked the phrase 'Home of the world's worst weather'. The observatory is supported by NOAA, the National Science Foundation and the University of New Hampshire alongside commercial partners and tourist income, and records have been taken here continuously since 1932. Instruments (and observers) at the observatory are tested well beyond normal extremes in its cold and windy climate. Since early in its history, the observatory has operated and maintained equipment for research, testing and environmental monitoring purposes at its facility on the summit and in Bartlett, New Hampshire in the Mount Washington Valley. Anemometers in particular need to be tough – both to cope with riming (which occurs here even in the summer months – see **Figure 9.8**) and because of the very high wind speeds at this site. Gusts in excess of 130 kn (67 m/s, 150 mph) have been recorded in every month but June and August. Until 1996, Mount Washington also held the world record for the highest surface wind speed measurement, 103 m/s (201 kn, 231 mph), recorded on 12 April 1934.

The figures support the observatory's tagline – the mean annual wind speed (1971–2000 normal) is 15.8 m/s (30.6 kn or 35.3 mph), the mean annual temperature –2.7 °C (27.2 °F) and the average annual rainfall 2589 mm (102 inches) [10]. If you're ever in New Hampshire, the site is easily accessible during the summer months by the Cog Railway or the auto road and the observatory is well worth a visit – but don't forget to take appropriate clothing, because conditions on the top are often very different from those in the valley!

Extreme wind speeds present a challenge for most wind measuring instruments, whether or not accompanied by riming. When hurricane *Andrew* hit Florida in August 1992, a Davis Instruments AWS anemometer in Miami registered a gust of 184 kn (212 mph / 95 m/s) [11] shortly before part of the owner's house was destroyed, along with the anemometer itself. Subsequent wind-tunnel tests on similar instruments indicated that the peak gust was probably closer to 154 kn (177 mph, 79 m/s) rather than the 184 kn originally logged, but the performance for this class of instrument in such severe conditions is noteworthy.

The strongest surface wind speeds occur in strong tornadoes, but the forces involved are much too great for anemometers to survive. The highest recognized surface wind speed yet reliably recorded by an anemometer, namely 113 m/s (253 mph, 220 kn) occurred on 4 April 1996 at Barrow Island, Australia (20°40′ S, 115° 23′ E, elevation 64 m / 210 ft), during the passage of Tropical Cyclone *Olivia* [12].

The instrument was a heavy duty three-cup anemometer mounted on a mast 10 m above ground level, sited towards the centre of the island about 4 km from the coast to the south-east and about 7 km inland from the south-south-west, the direction of the strongest wind gusts. The instrument was well exposed in all directions, in good working order and was regularly inspected with comparisons made against a handheld anemometer.

The peak wind gust measurement was one of five extreme gusts during a series of 5 minute time periods. Gusts of 199, 220 and 202 knots were followed by a series of four lower values which were then followed by two more extreme gusts of 187 and 161 knots in the subsequent 5 minute periods. The maximum 5 minute mean wind was 95 knots.

Calibration, accuracy and precision

In all but the very best-exposed of sites, the accuracy of the wind speed measurements obtained will depend more upon the limitations of instrument exposure than upon the absolute accuracy of the anemometer itself. Very few anemometers at or below those included in advanced-level AWSs will come with a calibration certificate, but the quoted accuracy of mid-range AWS anemometers is around ± 5% (**Table 3.2**, page 57), considerably less than the reduction in wind speed that can be expected from an imperfect exposure. With entry-level and budget system anemometers, reliability, longevity, high starting speeds and slow sampling intervals are likely to result in greater uncertainties in record quality than the absolute accuracy of the sensor itself.

Mean wind speeds are usually quoted only to 1 kn (0.5 m/s) in synoptic or operational environments. For climatological applications, greater precision (to 0.1 kn or 0.1 m/s) is desirable, although this may not be fully justified by the likely errors resulting from imperfect siting or instrument calibration.

The main source of error in wind vanes is likely to be alignment (see below for details on how to align wind vane sensors), although high starting speeds and high-friction bearings will also result in slow or damped responses in light winds. The fixings holding the sensor in place should be checked occasionally, as they may work loose over time, causing changes in vane alignment.

Exposure of wind sensors

The ‘ideal site’

Because wind *speed* increases quickly with height as a result of frictional effects near the ground, the standard exposure for wind instruments is at 10 m above ground level: the sensors are normally mounted at the top of an open mast or tower (**Figure 9.3**)*. In open terrain, the change of wind *direction* within 10 m is so small as to be disregarded for most purposes. The ideal site for wind measurements is a level, open area with no obstructions or obstacles closer to the anemometer than 10 times their

* Other instruments benefiting from an elevated exposure, such as sunshine or solar radiation sensors, may sometimes also be mounted on the mast, although care needs to be taken in doing so to ensure that no instrument shields another.

height (in practice, this requires no obstacles higher than about 2–3 m within a radius of 300 metres in all directions). This should provide wind measurements representative of an area of at least a few kilometres around the site.

More typical urban or suburban wind sites

It is, of course, almost impossible to find such a 'standard' site in an inner-city park or typical university or college campus, far less in a suburban or domestic setting. WMO guidelines recognize this, and admit 'surface wind measurements without exposure problems hardly exist' [1, section 5.94].

Urban and suburban sites usually contain many unevenly distributed obstacles to free wind flow, the frictional impact of which is to reduce average wind speeds and increase turbulent eddies (and thus gustiness). Some compromise is therefore almost always necessary in finding the best available site for wind observations, and because of this the records obtained may be rather more site-specific than is the case with other measurements. It is therefore very important that site metadata (see Chapter 16) provides details on the type and exposure of the wind sensors, particularly the height of the anemometer and full details of all surrounding objects such as buildings and trees (a scale drawing is best to show this information), the units in use and whether any corrections have been applied to the readings. Without this it is difficult to make meaningful comparisons with records from other locations, or to attempt any meaningful correction of mean wind speeds to *approximate* those made under standard exposure conditions.

Generally speaking, the best exposure to the wind will be obtained by exposing both anemometer and wind vane in as open a position as possible, as high as possible, commensurate with both safety and accessibility for installation and maintenance (see Box, *Safety aspects of installing and maintaining weather instruments*). Where location permits, the mast should be well above the level of surrounding obstructions to the wind flow. For a typical suburban or urban area with buildings 10–15 m in height, the mast should ideally be around twice as high as the surrounding obstructions – rarely feasible, of course.

Safety aspects of installing and maintaining weather instruments

Never take risks with personal safety when installing any weather sensors at height.
If the proposed location for the instruments cannot be reached safely, take appropriate safety precautions – or choose another site.

Remember also that all instruments will need occasional maintenance – wireless transmitters need batteries replaced occasionally (use a solar-powered unit if possible), anemometer bearings can seize up and may need an occasional squirt of penetrating oil to free them, birds may build nests in the most inconvenient places, the mast fittings or cable run may need checking or tightening after a gale – so make sure they can be reached safely if and when needed.

In domestic or suburban locations, the best available position may be on a short mast attached to a chimneystack or on a mast projecting above the roofline. Try to locate the instruments at least 2 m above the roofline or any other obstructions to the free wind flow, to reduce turbulence and eddying in strong winds (**Figure 9.10**). If mounting near a chimneystack, ensure that hot flue gases will not affect the instruments. If a rooftop site is not possible, find the best exposure available – perhaps mounting the instruments on a tall pole or mast in a garden (see Box, *Do I need zoning or planning permission?*). Lightweight and weatherproof aluminium masts or towers in various heights are available from instrument suppliers. Some are hinged to allow the mast to be tilted over to near ground level to permit maintenance access to the instruments. Towers or masts must be firmly installed (concreted in) to avoid damage in strong winds, and guying may also be required in windy areas or sandy soils.

Ensure the exposure of the instruments is optimized to the direction of the prevailing wind – usually between south and west in temperate latitudes. Don't forget that winds between north and east are the second-most common directions here, so try to ensure a good fetch from those directions too. In subtropical latitudes, north-easterly or easterly surface winds will dominate.

Figure 9.10. Anemometer, wind vane and Instromet sunshine recorder on mast attached to the gable end of a house; the anemometer is 11 m above ground level and 2.7 m above the apex of the roof-line. This photograph was taken from the south-west (the prevailing wind direction). (Photograph by the author)

If, like me, you are not comfortable with tall ladders and crawling about on rooftops, TV aerial (antenna) installation companies will often undertake the work. Explain clearly what is required (mounting an anemometer/wind vane set on a mast attached to a chimney stack, with a cable run into a loft, is very similar to the installation procedure for a TV antenna), and ask for a quote. Local builders can often provide similar services – a builder may be a better choice if there is any doubt about the ability of the structure to which the mast is affixed to take the weight and additional windborne stress of the instrument package involved, or if a more substantial mast is required (such as the one shown in **Figure 9.10**). If in any doubt, ask for a pre-installation site inspection and quote, and of course allow sufficient budget to cover the installation costs.

Do I need zoning or planning permission?

Most countries operate some form of planning law, the extent of which varies from country to country. Planning law may impose legal constraints on what can or cannot be built within a region of a town or city or within a building's footprint, and these may include restrictions on the erection of masts or towers to support weather instruments. If your property is rented or leased, then of course the permission of the landlord must also be obtained before commencing installation work.

Within the UK, unless you live in a conservation area, a listed building or restrictive covenants covering your property forbid TV aerials and the like, and with few exceptions, planning permission is not normally required for roof-mounted wind sensors or 'weather vanes', and the erection of an unobtrusive anemometer/wind vane sensor package should not result in a letter from your local authority's planning department – TV aerials, satellite dishes, solar panels and wind turbines all represent more visually obtrusive extensions to a roofline. Planning permission is also not required if the installation replaces or reinstates existing equipment that has been in place for 7 years or more.

A 2008 planning application in Leicestershire for a typical 'domestic' anemometer installation was granted unconditionally by the local authority [13]. Knowledge of this application (there are probably many others) may be useful in the event that local planning authorities are unaware of precedents to unconditional permission being granted for siting exterior weather instruments.

Within the United States, zoning laws vary by state and city, and local planning authorities should be consulted in advance of any planned installation work.

Unless you happen to live on a remote farmstead, it is of course always advisable to discuss any proposals informally with neighbours and landowners well before any planned installation. Building a 10 m tower in your backyard, even putting up a tall pole, may prompt complaints or contravene local planning regulations. Policies do vary widely, however. Where there is any doubt, seek professional local advice prior to installation.

Exposed and elevated locations make wind instruments much more vulnerable to weather-related failure than sensors mounted at ground level. Weather-related exposure problems can include the accumulation of snow, ice or rime[*] (see *Severe*

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[*] Heated units are available, although the substantial power requirements generally rule out their use at locations without access to a nearby permanent mains power supply.

weather performance, above), large temperature ranges, component deterioration owing to ultraviolet exposure, wind-driven rain penetration of connectors or electronic circuitry, and of course damage due to wind loading – whether due to a single strong wind event, or resulting from long-term component fatigue of the instrument or its mountings due to repeated wind vibration.

Lightning can also pose risks to exposed, elevated sensors. For all but the tallest masts in high-risk, open sites such as open moorland or exposed airfields, or in areas with a high frequency of electrical storms, the chances of an instrument being directly struck by lightning are small, although an electrical surge from a nearby lightning strike (even one several hundred metres distant) can damage electronic sensors and loggers. A good earth connection for the mast or tower is essential to reduce the build-up of static electricity in thundery conditions. However, the cost of full lightning protection may be higher than the cost of the equipment being protected, and a 'self-insure' policy may be more cost-effective where domestic or property insurance specifically excludes exterior equipment such as TV aerials or anemometer masts. At the very least, where the sensors are connected to the datalogger using cables, ensure the datalogger-PC connection is via an optical link rather than an electrical connection. That way a direct lightning strike may fry your sensors and the logger, but hopefully the damage will be contained there. It is good practice of course to switch off and unplug vulnerable electrical equipment during close lightning storms.

Things to avoid

Growing trees and hedges will gradually (and often significantly) reduce recorded wind speeds over time. The erection of new buildings nearby often has a more immediate impact. Keep hedges or trees cut back (not always possible if it is a neighbour's tree that is becoming overgrown, of course). Take a set of site photographs throughout the full 360 degrees around the instrument every 2 years to assess or document slow changes in the exposure of wind instruments. The technique is covered in more detail in Chapter 11, *Measuring sunshine and solar radiation*.

Installation and maintenance of wind sensors

Wind sensors are most easily installed when both anemometer and wind vane are either combined in one unit, as in the Davis Instruments weather stations, or where separate anemometer and wind vane sensors are mounted on one cross-piece which holds both and is then itself fixed to a mast (**Figure 9.10**). Mounting a single frame to a mast is easier than handling two separate instruments, and will also ensure that one sensor does not shelter the other. Ensure that the wind sensors are located at the top of the pole or mast used, a minimum of 500 mm / 18 in apart, so that the body of the pole or mast itself does not shelter the instruments from the free wind flow – any sheltering effects can be minimized by mounting the cross-frame perpendicular to the prevailing wind direction. Ensure that the sensors are in a secure position, and one where they cannot easily be vandalized.

It is vital to ensure that both anemometer and wind vane are mounted absolutely vertically, and firmly secured in place. If the anemometer is not vertical, its rotation will be lopsided at low speeds, and the starting speed will be higher as a result – affecting the quality of the wind records obtained. If the wind vane is not vertical, it will settle into a preferred neutral position, which will bias wind direction statistics.

On cabled systems, always leave some slack in cables, as it may be necessary to move or adjust the sensor position for optimum exposure at some later date. Ensure any slack cable is firmly secured to prevent fraying or movement in strong winds.

Before installing wind sensors in their intended location, particularly if access is difficult or if installation is to be undertaken by a contractor, it is advisable to install the sensors at ground level, making sure everything works for at least a few days. Better to find out a wireless anemometer transmitter is not working at ground level than on the end of a ladder. Pay particular attention to connectors for cabled systems, as wind-driven rain is much more penetrating in exposed locations.

Correcting wind speed readings made at a non-standard height

The correction of observed mean wind speeds to emulate those observed under ‘standard’ conditions is a complex area. Guidance, based on the so-called roughness length z_0, is given in the WMO guidelines in reference 1 to this chapter (section 5.9.4). It should be noted that it simply may not be possible to obtain satisfactory and consistent corrections in a location with multiple and unevenly distributed obstacles, such as a typical urban site. However, some general principles regarding the variation of wind speed and direction with height can be stated.

Mean wind speeds increase with height. An approximate correction factor for *mean* wind speeds observed at heights other than 10 m is given in **Table 9.4**. This is derived from the reciprocal of the expression [5, pages 4–15]:

$$V_h/V_{10} = 0.233 + 0.656 \log_{10}(h + 4.75)$$

Where V_h/V_{10} are wind speeds at height h and at 10 m respectively and h is the height of the anemometer, in metres.

The table shows that, for example, the mean wind speeds at 3 m above ground need to be *increased* by about 22 per cent to approximate those at 10 m above ground; at 20 m, they would need to be *reduced* by 13 per cent.

It must be stressed that these factors apply only to *mean* speeds in an open location over relatively long periods (days or months), and that the variation of wind speed with height will vary with atmospheric conditions minute-by-minute, hour-by-hour and day-by-day. Individual spot readings over short periods, and observations made in obstructed or sheltered sites, may depart significantly from these averages. The correction factors *do not apply to gust speeds*, which vary much less with height. Gust speeds should be reported *without* applying any corrections.

Where corrections are made to any wind speed reading, archive both uncorrected and corrected values so that the original data are always available for subsequent analysis if required.

Table 9.4. The variation of mean wind speeds with height

Anemometer height h, metres	1	2	3	4	5	6	7	8	9	10	15	20
Correction factor to 10 m equivalent	1.37	1.29	1.22	1.18	1.13	1.10	1.07	1.04	1.02	1.00	0.92	0.87

Table 9.4 can also be used to estimate the so-called *effective height* of the anemometer, which is defined as 'the height above open level terrain in the vicinity of which mean wind speeds would be the same as those actually recorded by the anemometer' [14]. Compare mean wind speeds over an extended period – several months at least – with a neighbouring site having an unobstructed exposure and similar weather types (comparing a hilltop site with a valley site, for example, would be unrealistic) and note the mean differences: the 'effective height' of the anemometer can be estimated by comparison with the factors given in this table. (Differing levels of obstruction around the compass may provide different values of effective height by compass bearing, which greatly complicates any possible applied corrections.)

Example: compare Station A, where the anemometer is located 6.5 m above ground level in a high-clutter suburban location, with Station B a few kilometres distant in a rural area of otherwise similar terrain, where the anemometer is located at 10 m above ground in an unobstructed site. Over a period of 2 years, Station A's mean wind speeds were 19 per cent below Station B. Table 9.4 shows that a 19 per cent difference corresponds to an effective height of about 3.75 m. So although the anemometer is actually located at 6.5 m above the ground, the sheltered surroundings and local urban infrastructure are reducing wind speeds at the actual anemometer height to what might be expected to be found at about 3.75 m above ground in 'open level terrain in the vicinity'. In this case, to approximate the 'open level terrain' wind speeds observed in the vicinity, the mean wind speeds from Station A's anemometer should be increased by 1.19 (the correction for an 'effective height' of 3.75 m) rather than the 1.08 that would be suggested from the actual anemometer height of 6.5 m.

For best results, the determination of 'effective height' should be performed from several different comparison sites, at different compass points. The main difficulty here will be scarcity of unobstructed anemometer records (and the difficulty in getting hold of data from those instruments).

In practice, it is much better to locate the anemometer and wind vane as high as possible at the outset, than to locate them in a sheltered exposure at only a metre or two off the ground and rely on correction factors which may not be appropriate for your site. In any case, no correction factor can provide a representative wind speed if the low-level anemometer shows calm when the wind speed at 10 m is not zero. Particularly with 'budget' systems, operational factors related to anemometer reliability and high starting/stopping speeds may prove more troublesome than height corrections.

Correcting wind directions made at a non-standard height

The variation of wind *direction* with height is insignificant in the lowest few metres of the atmosphere. Assuming that there are no gross obstructions to the flow, the mean direction at lower levels will not be significantly different from that observed at 10 m, although the variability will almost certainly be greater, owing to greater turbulent effects nearer the surface.

In sites with significant obstructions, the variability of the wind may be such that some time-averaging or frequency-counting algorithms may be required to pick out the true wind direction from 'noisy' rapid second-by-second fluctuations. AWSs with infrequent spot value sampling of speed and direction may show large fluctuations in displayed and logged wind direction and speed – such results are unlikely to be very representative of true wind conditions.

Aligning the wind vane

Setting up a wind vane correctly is one of the more fiddly aspects of installing an AWS. It is very important that it be accurately aligned not only to the compass points, but as stated previously the rotational axis of the sensor must be mounted as close to the true vertical as possible to avoid a preferred neutral position.

To obtain an accurate display and record of wind direction, the wind vane must be correctly oriented to true north (see Box, *Finding true north*). There are various ways to do this, and the recommended methods differ slightly from manufacturer to manufacturer, but essentially the process is as follows:

- Before installation, and from the intended site of the wind vane (or as close to it as possible), use a sighting compass to determine true north (or another cardinal point if this is easier)[*]. Digital compasses which can be pre-adjusted to take magnetic declination into account in their readout, or some GPS units, which will display a bearing to 5° or even 1°, may be easier to use than a small magnetic compass.
- If this has not already been taken into account, adjust the alignment to take account of magnetic declination (see Box, *Finding true north*).
- Take a sighting along the compass to a distant object or group of objects, preferably on the horizon, or as far away as possible if not, and align the compass point to this reference. It may be easier to take a photograph and mark the alignment of the chosen compass point on the photograph for reference.
- Set up the wind vane in the desired location, and fix firmly into position, allowing for any minor adjustments that may still be needed. Ensure that there is a little slack in the wiring to permit final adjustments to be made without imposing strain on the cables and connectors, but not so much that cables will ‘flap’ in strong winds.
- Two people are needed for this next step – one next to the wind vane, the other by the display and able to call out the display reading. Align the wind vane to the designated cardinal point on the horizon (pointing as close TO that point as possible), allow the display to settle for a few seconds then ensure the display reading coincides with the compass point chosen. If not, loosen the wind vane fixings and adjust as necessary until good agreement is attained, then re-tighten securely.

Davis Instruments Vantage Pro2 anemometers make this step straightforward, in that the mounting arm of the anemometer needs merely to be accurately sighted to true north for the vane to be correctly aligned. (This can be changed if north is not a convenient alignment.)

If it is not possible to sight along and adjust the wind vane by eye (perhaps if the sensor package is to be fixed in place on a tall mast as one unit), then an alternative is to pre-fix the wind vane onto a cross-piece with north at 90 degrees to the long axis of the arm, then ensure the bearing of the cross-piece is exactly aligned (say) west-east by sighting along it from ground level using a digital compass, adjusting the angle of the cross-piece until exact alignment required has been achieved, then locking it in place.

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[*] If the mast or tower includes any ferrous components, the structure itself may affect the compass needle, and all bearings should be checked some distance away from the support if this is suspected.

Finally, firmly clamp all sensors into position (taking great care not to disturb the alignment of the wind vane when doing so) and then secure all cabling. Use ultraviolet-resistant plastic cable ties to secure cabling – do not use staples or a staple gun, because these may cut through the wiring. Any exterior connectors and building entry points for cables must be thoroughly weatherproofed to avoid water ingress.

If, after installation, it becomes apparent from comparison with neighbouring sites that the alignment is slightly incorrect, most weather station software will allow a fixed adjustment or offset to be made to the observed readings. (If the wind vane has been accidentally set up to indicate where the wind is going TO, rather than where it is coming FROM, simply set an offset of 180° into your software to correct this.) As with all adjustments, make a note in your site metadata of the correction applied, and the date it was introduced.

It is good practice, wherever possible, to compare recorded wind directions with other reliable local observations on a regular basis, as a gradually increasing or variable discrepancy may indicate that the wind vane fixings have worked loose. The alignment then needs to be reset and the mounting re-secured.

Finding true north

Because the north pole and the north magnetic pole are not in the same place on the Earth (the north magnetic pole currently lies near Ellesmere Island in northern Canada, at about 83°N, 114°W, and is moving toward Russia at 55–60 km per year), a magnetic compass points to magnetic north, not true north. Wind directions are referenced to true north, not magnetic north; therefore for accurate alignment of a wind vane, the difference between the two must be corrected for when setting up a wind vane. The current value of the correction to magnetic north can be found from http://www.magnetic-declination.com/ – simply enter the latitude and longitude of the site.

In the British Isles, the compass needle currently (2012) points a little west of true north. Although in some parts of the world the compass needle deviation from true north is large – 20° or more – across the British Isles it is currently very small, roughly 2° west in south-east England increasing to 5° west in the west of Ireland and north-west Scotland. Without specialist equipment it is difficult to align a wind vane to better than 5° by eye – but in any case only the most exacting applications will require the vane to be aligned to better than 5° accuracy.

Wind accessories and fixtures

The anemometer and wind vane sensors are often combined into a single unit in pre-built AWSs, but if not a mounting frame or cross-frame to secure them to a mast will be helpful, as described above (see **Figure 9.10**). Aluminium tubular masts suitable for mounting lightweight wind sensors are readily available (as TV antenna supports) in 2 m or 3 m lengths from most DIY stockists; don't forget the fixing brackets too. Instrument suppliers (Appendix 4) can supply more substantial masts or lightweight towers, or local builders merchants can supply suitable scaffolding fixtures to construct a purpose-built unit.

Logging requirements

Chapter 2 emphasized the importance of a rapid sampling time – no more than about 3 seconds – for an AWS if accurate depiction of gust speeds is required. Lower sampling intervals will not capture the detail of the high-frequency gusts. WMO's recommendation is for a sampling interval of 0.25 sec (4 Hz) where the logger can support this, although a non-overlapping interval down to 3 sec is 'quite acceptable'. If the requirement is only to measure mean wind speeds rather than gusts, a site investigation for a wind turbine site, for example, then such frequent sampling periods may not be necessary.

Where sampling and logging intervals can be separately specified, a sampling time of 0.25 to 1 second and a logging time from 1 minute to 1 hour will be suitable for almost all requirements.

Wind run

The term 'wind run' is still used in some applications. 'Wind run' is a measure of mean wind speed, expressed in terms of 'distance covered over a given period'. A mean wind speed of 10 kn over one hour would generate a 'wind run' of 10 nautical miles; over 24 hours, 240 nautical miles. A 10 m/s mean wind over 24 hours would result in a wind run of 864,000 m (864 km) = 10 m/s x 86,400 seconds in 24 hours. Many older anemometers generated a 'wind run' distance display by mechanical gearing from the rotation of a cup anemometer in a similar manner to that of a car odometer. Subtracting successive daily readings made at the morning observation provided mean wind speed, usually at 2 m above ground level, for the period between observations. The reduction in size and cost of dataloggers has increasingly made such 'cup counter' anemometers redundant, although 'wind run' is still included in some AWS outputs.

Wind direction reporting

There are two methods of reporting wind directions over the logging interval – the 'modal' method, and the 'vector mean wind' approach.

The *modal method* counts the frequencies of observed wind directions within each sampling interval within pre-determined ranges or classes, and reports the class with the highest frequency as the logged wind direction. This method is used on all Davis Instruments AWSs: the classes are the 16 compass points (N, NNE, NE, ENE, etc.) and the wind direction is therefore available only to a precision of 22.5 degrees (360/16).

A more accurate method is the *vector mean wind* calculation, which is described in the text box *Vector mean winds*. The arithmetic required can be carried out by a programmable logger as it processes the wind samples, or it can be calculated retrospectively using a spreadsheet. The accuracy of the logged wind direction is limited only by the accuracy of alignment and the sensor specification, and ± 2 degrees is attainable, although ± 5 degrees is sufficient for most weather measurements.

Vector mean winds

A vector mean wind calculation provides a means of generating a *resultant wind flow* from a series of differing wind velocities over time – wind velocity here denoting both wind direction and scalar wind speed. The calculation resolves individual samples of wind velocity into east-west and north-south components using trigonometry, which can then be averaged numerically in the normal manner. The averaged value of the two components is then converted back into the resultant (think 'average') wind direction and speed.

This method of calculation is necessary because the use of polar co-ordinates (compass bearings) means they cannot be simply averaged numerically – the 'mean' of a north-westerly wind (315°) and a north-easterly wind (045°) is clearly not a southerly wind, as would be indicated by the numerical average of the two wind directions ((315+45)/2 = 180).

The expression is tedious to undertake by hand, but very easily automated in a spreadsheet: an Excel template and macro are listed in Appendix 2 and available for download on www.measuringtheweather.com. The calculations can be performed over a minute, a day, a year or for any other time period.

Appendix 2 gives more details of the calculation method, but a simple example will suffice here.

Suppose that, in one hour, the wind blows from the south-west (225°) for the first 30 minutes at 20 knots, and for the next 30 minutes from the north-west (315°) at 10 knots (see **Figure 9.11**). To keep it simple, we assume that the wind direction and speed remain unchanged within these 30 minute periods.

The *scalar mean wind speed* for the hour is **15 knots** *(the average of 10 and 20)*

The *vector mean wind* for the hour is **252°, 11.2 knots**

It is perhaps easier to envisage this by drawing out the two vectors:

The output can be viewed as representing the end point of a parcel of air – say, a hot-air balloon at a constant height – at the close of the time period (1 hour, in this example) had the observed wind speeds and directions been replaced by a constant wind of that speed and direction. Note that of course the vector mean wind speed can only be the same as, or more often less than, the scalar mean speed: the difference between the two will increase with the variability of the wind. Also, the calculations are necessarily only two-dimensional in nature.

Advanced loggers include a vector mean wind option to summarize sampled wind speeds and directions in logged output. Where AWS software output is given as compass points rather than as degrees, a simple Excel function (also listed in Appendix 2 and downloadable from www.measuringtheweather.com) can be used within an Excel spreadsheet to convert compass bearings into equivalent degrees (so that, for example, all southerly winds will be converted to 180 degrees, SSW to 202.5°, and so on). The vector mean wind calculation can then be run as above.

Wind data tabulations

Statistical summaries of wind speed and direction normally consist of hourly, daily, monthly and annual tabulations. For hourly summaries, the modal or vector mean direction, scalar mean speed and the highest gust, usually with the time and direction of the highest gust, are usually quoted. For daily, monthly or annual summaries, the vector mean wind (direction and speed) along with the scalar mean speed, the highest hourly scalar mean wind speed and its direction with date and hour of occurrence, the highest gust and the date/time and direction of the highest gust are the norm,

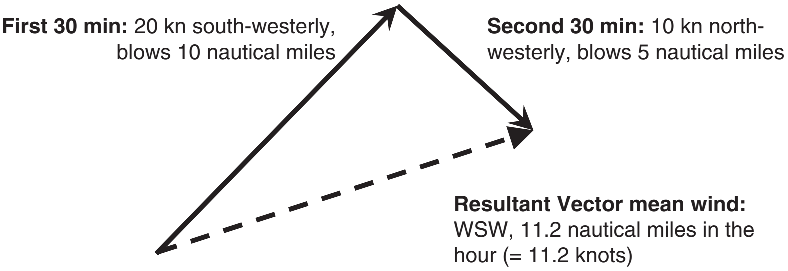

Figure 9.11. Vector mean wind visualisation; see text for details.

alongside statistical summaries of wind direction frequencies. A useful table is one of 12 x 30 degree sectors starting at north (350–010°, 020–040°, and so on).

Wind roses present a more graphical means of expressing the frequency of various wind direction and speed combinations over time. Appropriate software is suggested in Chapter 18, *Making sense of the data avalanche*.

Terminal hours

Daily wind speed and direction summaries normally refer to the civil day period midnight to midnight, disregarding any corrections for Summer or Daylight Savings time. Most AWS software will generate the appropriate daily summaries for this period without adjustment, unless the logger is set to Summer Time. For more on time standards, see Chapter 12.

One-minute summary – *Measuring wind speed and direction*

- The wind is highly variable in both speed and direction, and obtaining good measurements of the wind poses particular challenges for instruments, logging equipment and site requirements.
- Wind is a *vector* quantity – it has both direction and speed. Wind direction refers to where the wind is coming from. A wind vane needs to be accurately aligned to true north, which is slightly different to the magnetic north shown by a magnetic compass.
- Mean wind speeds normally refer to 10 minute periods, gust speeds to 3 seconds. For accurate determination of gust speeds, a high sampling interval (no more than a few seconds) is essential, although the logging interval can be much longer than this.
- Wind direction and speed are normally measured using separate instruments, most often a cup anemometer and a potentiometer-based wind vane. The absolute accuracy of wind speed measurements is more likely to be limited by the height and exposure of the anemometer, rather than the accuracy of the sensor. The accuracy of wind direction measurements depends more upon careful alignment at installation.
- The ideal site for wind instruments is atop a 10 m mast in open, level terrain, well away from any obstacles. However, such ideal sites are hard to come by, particularly in urban or suburban areas, and wind records are therefore necessarily

more site-specific than most other weather measurements. Some corrections for the variation of mean wind speed with height are possible, and these are described in this chapter. Gust speeds should not be corrected.

- Generally speaking, the best exposure to the wind will be obtained by exposing both anemometer and wind vane in as open a position as possible, as high as possible, commensurate with both safety and accessibility for installation and maintenance. The necessarily elevated exposure will increase the vulnerability of the instruments to extreme weather conditions, particularly snow or ice, lightning and of course high winds. Great care should be taken in installation and cabling to minimize the potential for subsequent weather-related reliability issues.
- Planning permission or zoning approval is not normally required for domestic rooftop-mounted anemometers or wind vanes, and local authority case precedents exist within the UK. Specialist legal advice should be taken if in doubt.
- **Never take risks with personal safety when installing any weather sensors at height**.

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10 Measuring grass and earth temperatures

After air temperature, grass and earth temperatures are the most commonly observed surface climatological parameters. This chapter describes the methods used to measure temperatures other than those of the air, and includes reference to the relevant WMO guidance [1].

The grass minimum

Why measure grass temperature? Assuming there are no obstructions to outgoing radiation to space, the lowest temperatures on a clear night will be recorded at or close to ground level, where stirring and mixing of the cooling air by wind is at its minimum. The nature of the surface, primarily whether it is a good or bad conductor of heat upwards from the earth, then determines its temperature under such conditions. Where the surface is covered by short grass, the lowest temperatures are attained just above the tips of the grass blades, because air trapped between the grass blades acts as a partial insulator to the upward heat transfer ('heat flux') from the warmer earth beneath.

In many countries, the so-called 'grass minimum temperature' (or 'grass min') is measured using a thermometer or electrical sensor freely exposed at the tip of the grass blades (**Figure 10.1**). In the UK, grass minimum temperatures have been measured in this fashion since the 1850s. Recently, some AWSs have begun to monitor surface temperatures using a downward-pointing infrared sensor mounted about 2 m above ground level. Grass or surface minimum temperatures are sometimes referred to as the 'radiation minimum' or 'skin temperature'.

Grass minimum temperatures and 'ground frosts'

In many countries around the world, when the grass minimum falls below 0 °C this is termed a 'ground frost' (as opposed to the minimum in a thermometer screen falling below 0 °C, which is called an 'air frost')*. Because minimum temperatures over grass

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* The term 'ground frost' is so defined in the *Oxford Dictionary of Weather* (Oxford University Press, 2001), but in the UK until 1971 the threshold grass minimum temperature for a ground frost was -0.9° C (see, for example, *Meteorological Glossary*, UK Met Office, 1961 edition). Older UK statistical summaries may therefore refer to the lower threshold. Where there is no danger of confusion with pre-1971 records, the term 'ground frost' is an acceptable term referring to 'grass minimum temperature below 0°C'.

Figure 10.1. Grass temperature sensor. (Photograph by the author)

are generally lower than air temperatures, the number of ground frosts in a year at any location may be considerably higher than the number of air frosts.

Exposing the grass minimum thermometer

At its simplest, the grass minimum sensor (an alcohol-based minimum thermometer, or more often today an electrical temperature sensor[*]) is laid on the surface of short grass. More usually, a pair of small pegs fashioned from wooden dowelling or similar is constructed to support the sensor. Alcohol-based thermometers should be placed with the bulb end slightly lower than the top of the thermometer, to allow any alcohol evaporated during the heat of the day to find its way back down to the bulb without 'bubbling' in the thermometer stem. The supports are gradually raised in height as the underlying grass grows. Where the thermometer is frequently dislodged by animals or birds – foxes, crows and magpies can be particularly troublesome – a

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[*] A robust 'bare' sensor is essential for a grass minimum thermometer – either an alcohol-based minimum thermometer or an electrical sensor probe. The larger thermal mass and reduced emissivity of bulky thermometers with outer casings, digital sensors combined with LCD displays or battery housings, or battery-powered wireless for example, will result in a more sluggish response and higher readings than the true minimum temperature. In addition, being exposed to the full force of the elements – hot sunshine as well as cold wet rain – will quickly take its toll on battery life and electrical connections for instruments that are not completely weatherproof. The slight differences in radiative emission and response times between glass thermometers and metal probes can result in slightly different temperatures being recorded, although even identical thermometers exposed close to each other in an identical exposure will usually differ slightly in any case. If close consistency with glass thermometers is sought, WMO [1, section 2.4.3] recommend enclosing the electrical sensor probe within a glass sheath. This may also provide additional resistance to water penetration into the sensor body, which will eventually cause faulty readings and damage the sensor.

loop or closed peg enclosing the thermometer stem in two places will generally solve the problem.

Place the sensor in a position permitting maximum exposure to the sky (not underneath a tree or close to a wall, for example). It is essential that there be no obstructions – either natural or artificial, such as a protective cover – above the thermometer or sensor once it is placed on the grass surface, because any obstruction will reduce outgoing terrestrial radiation and result in higher grass temperatures than the true value, perhaps by several degrees.

The grass needs to be kept mown fairly short, but not bowling-green short as the radiative and insulating properties of very short grass are closer to those of bare earth than true short grass cover. Similarly, grass should not be allowed to grow over the sensor itself, for if the sensor becomes ‘buried’ within grass, observed temperatures will again be higher than the true ‘grass minimum’, owing to the obstruction of outgoing radiation by the grass, together with heat retention from the ground surface by insulating air pockets trapped within the grass. Under no circumstances should artificial surfaces, such as ‘astroturf’, be substituted for natural grass cover under a grass minimum sensor, as the physical properties of such materials differ substantially from natural vegetation.

It is advisable to mark out the location of the grass temperature sensor using white-painted pegs or a low barrier fence, no closer than at least 50 cm or so to the thermometer, to avoid accidental damage to sensors, particularly very fragile glass thermometers. The author can vouch for the fact that they are very easy (and very expensive) to step on by mistake, particularly in darkness or poor weather and especially when exposed in the middle of a large grassed area. A short post, 30–50 cm in height and painted other than white, will also make it easier to locate the instrument after a snowfall. In a domestic environment, children, pets, ball games and lawnmowers need to be kept away from the sensor for the same reason. However, the fencing must be movable to allow easy access for cutting the grass (remember to move the thermometer/sensor to a place of safety FIRST!). If the grass minimum thermometer is a cabled thermistor or platinum resistance thermometer (PRT), ensure also that the cable will not be damaged by the lawnmower, strimmer or garden shears used to maintain the area where the instruments are located. Shears and strimmers will slice through AWS cables in an instant, even screened cable, where the screening otherwise provides some armouring. Minimize the risk of accidental damage from lawn tools by enclosing all but the business end of the cable in tough plastic conduit. This applies particularly on government or school sites where maintenance is carried out by external contractors. Personnel may change on a regular basis, and not know to look out for the sensor until – oops, too late.

The ‘grass minimum depression’

The difference between the air temperature and the grass temperature is known as the ‘depression of the grass minimum’. This varies significantly during the hours of darkness (**Figure 10.2**), being on average greatest early in the night and least nearer dawn, because the air cools less rapidly than the ground surface after dusk. Of course, **Figure 10.2** ignores readings from the sunshine-affected sensor during daylight.

The grass minimum will typically lie 2–4 degC (4–7 degF) below the air minimum after a clear night, but values vary significantly from minute to minute, day-to-day

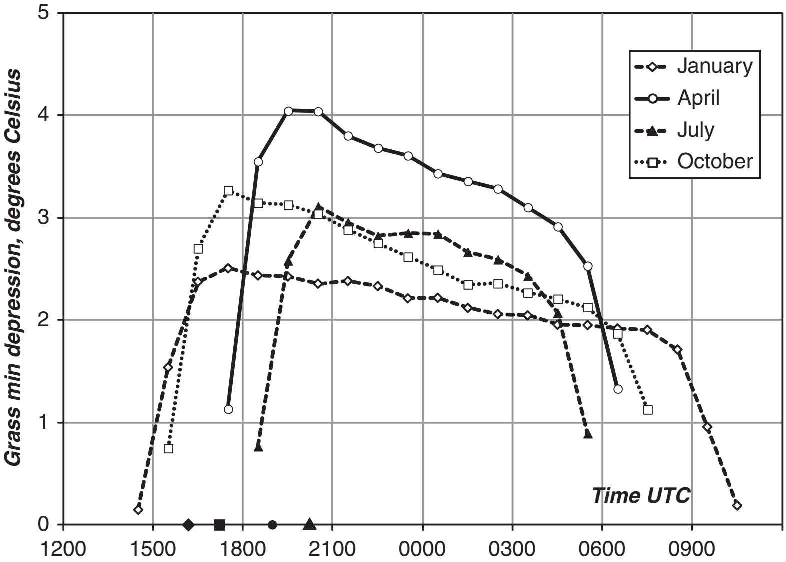

Figure 10.2. Hourly averages of the grass minimum depression (the difference between screen and grass temperatures), showing how the greatest difference from screen temperatures (at 1.25 m) tends to occur within an hour or two of sunset. Sunset times (UTC) are indicated by filled symbols on the baseline – 15 January, 1624 UTC: 15 April, 1859 UTC: 15 July, 2015 UTC: 15 October, 1712 UTC. From the author's records in central southern England (51.4°N, 1.0°W), averages over 8 years 2004 to 2011.

and location to location. Some sites regularly see very large grass minimum depressions (occasionally 10 degC / 18 degF or more), others the opposite. More sheltered sites tend to have smaller grass minimum depressions, because partial obstruction of the sky limits outgoing terrestrial radiation. Frost hollow sites also tend to have reduced grass minimum depressions, whereas exposed sites that shed cold air more easily can experience very large air-grass temperature differences. In fog, low cloud and after a period of warm weather the grass minimum can occasionally be slightly higher than the air minimum, but usually by no more than a few tenths of a degree Celsius. Anything more than this should prompt a calibration check of one or both thermometers.

The grass minimum, by virtue of its being exposed as a bare sensor, is more often than not covered in moisture, particularly at night, and thus is more accurately considered as a wet bulb. The errors introduced are not significant, however, as the air at grass-tip height quickly attains saturation on any clear night.

Snowfall and grass-tip thermometers

Snowfall of more than 1–2 cm will normally bury a grass minimum sensor. If the sensor is buried in snow, it will give a misleading reading, which should be discarded*.

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* Being buried in snow can provide a very useful natural 'ice-point' calibration check, because in these conditions the sensor will normally be held at exactly 0.0°C for some time, owing to loss or gain of latent heat (see also Chapter 15, *Calibration*). Sometimes this condition will persist for several hours, until all the snow has either melted or frozen. If a logged electrical sensor is in use, the temperature observed during such long steady periods in snow can be easily determined, even if a fall or rise

Once the snow has stopped falling, the grass temperature sensor should be carefully removed from its covering of snow and placed carefully and level on fresh and undisturbed snow cover at the earliest opportunity. If snow is still falling, this process should be repeated at the next observation or when the snow stops falling. Fresh snow, particularly deep fresh snow, is a very effective insulator as it contains so much trapped air, and the temperature on a snow surface can fall very rapidly indeed under clear skies. Very low surface temperatures can be reached under such circumstances.

In areas with frequent winter snowfalls, or in remote areas, some AWSs use downward-pointing infrared emission sensors to determine 'skin' or snow surface temperature. This avoids surface sensors becoming buried, and provided the sensor remains well above the snow surface, a variable depth of snow will not affect readings.

Minimum temperatures above other types of ground surface

The need to monitor and model concrete or tarmac temperatures to aid road surface temperature forecasting (particularly to aid winter gritting 'freeze/no freeze' decisions by highway authorities) has led to a requirement to measure minimum temperatures above other surfaces. Some sites monitor 'concrete minimum' or 'tarmac minimum' temperatures, the measurements made in a similar fashion to grass minimum measurements as described above. As the name implies, the 'concrete slab minimum' refers to the reading of a minimum thermometer, or electrical sensor, mounted just above a concrete slab. In the UK the standard size of slab is 100 × 60 × 5 cm, and pale grey in colour. Some roadside AWSs report actual road surface (or just sub-surface) temperatures using sensors buried in the road surface.

A 'bare soil minimum' is measured in a similar fashion, the sensor exposed just above the surface of a patch of bare soil, typically about 1 m^2 in area, kept free of weed growth.

Terminal hours and daytime exposure considerations

WMO guidance is that the grass minimum temperature (and, by extension, other surface minimum temperature observations) should refer to the period from just before sunset to the normal morning observation hour (often 7 A.M. to 9 A.M., nominally 0900 UTC in the UK and Ireland). If a minimum thermometer is in use, it should be kept within the thermometer screen (if one is available) during the day to avoid 'bubbling' (see below). The WMO terminal hour recommendation on surface minimum temperatures differs from the standard 'climatological day', where measurements normally refer to a full 24 hour period. However, this convention is becoming blurred at unmanned sites where there is no-one to stow the grass minimum sensor by day and replace it before sunset, or where temperatures are measured by a permanently-exposed electrical sensor. This topic is covered more fully in Chapter 12, *Observing hours and time standards.*

Alcohol-based minimum thermometers can suffer 'bubbling' when left out in the Sun all day, arising from evaporation and distillation of the alcohol within the

subsequently takes place. If, for example, during such an episode the thermometer stayed steady at (say) −0.4°C for an hour or so, more likely than not the sensor calibration is 0.4 degC too low. While this does provide a calibration check at just a single point, and calibration may differ at higher or lower temperatures, 0°C is the single most useful calibration point for a grass minimum thermometer.

thermometer stem caused by solar heating[*]. Subsequent condensation back into the alcohol column can result in the breaking-up of the spirit column (hence the term ‘bubbling’), resulting in the observed minimum temperatures being too high *or* too low, depending on the position of the index. To minimize the effects of solar radiation on thermometers left out all day, a short black shield is normally placed on the end of the thermometer furthest from the bulb – in sunshine this becomes warmer than the glass body of the thermometer, reducing the risk of alcohol condensation in the expansion reservoir at the top of the thermometer. Bubbling can be rectified by *very gently* heating the thermometer in warm water (not hot) or over a heat source to drive the alcohol column close to the upper reservoir, at which point the ‘bubbles’ will safely fold back into the upper chamber. This should be followed by *slow* cooling back to ambient room temperatures. Too rapid cooling will simply reintroduce bubbles in the thermometer stem.

No such problems affect electrical temperature sensors, which can normally be left in position throughout the 24 hours. It is perfectly acceptable to remove or relocate a grass minimum sensor of any type from its normal exposure during the day, particularly if this minimizes the risk of damage or theft, but it is important it be replaced before sunset as grass temperatures fall more quickly than air temperatures during the early evening, and occasionally the night’s grass minimum temperature will be reached at dusk.

Very occasionally – perhaps a couple of days in every winter in temperate latitudes – the lowest ‘morning to morning’ grass temperature will be reached during daylight hours. This usually results from an abrupt rise in temperatures overnight following afternoon rain or hail showers. In these circumstances, the ‘daytime’ grass minimum should be noted if the sensor has been left exposed, but the ‘climatological’ grass minimum temperature entered for the day should be the ‘sunset to next morning observation’ value, per WMO guidelines.

Logging intervals

For ease of comparison, it is best to sample and log grass temperature at the same intervals as air temperature. Ensure that the *minimum* temperature reached in each logging interval is logged, and not merely the spot value at that time. Grass temperatures can fluctuate very rapidly, particularly on nights with variable cloud cover (indeed, overnight records from an electrical grass temperature sensor often provide good proxy evidence for the presence or absence of cloud cover). The true minimum may be missed even with 5 minute logging intervals, if spot temperatures are logged instead of interval minima.

Earth or soil temperatures

Earth temperatures[†] are measured at a variety of depths, such measurements being particularly useful in agricultural applications as being more representative of the

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[*] ‘Bubbling’ can also affect the air minimum thermometers exposed in a thermometer screen, although usually much less frequently. If any spirit minimum bubbles frequently, it should be replaced.

[†] The term ‘soil temperature’ is sometimes used to refer rather narrowly to shallow depths (less than 30 cm), and ‘earth temperatures’ to 30 cm or greater, but to all intents and purposes the terms ‘earth’ or ‘soil’ are interchangeable in this context. For consistency, ‘earth’ is used throughout this book.

conditions experienced by growing plants. They are also useful in comparative climatology, where they can provide a clearer understanding of heat flow and retention within different soil types – sandy soils gain and lose heat more quickly than a heavy clay soil, for example.

Earth temperature depths and measurement methods

WMO recommendations for 'standard depths' at which earth temperature measurements should be taken are at 5, 10, 20, 50 and 100 cm below the surface, although unless the records are required for agricultural or research purposes, few sites record earth temperatures at all of these depths. A few locations maintain records at depths greater than 100 cm. In the UK and Ireland, many sites measure earth temperatures at 30 cm (1 foot) depth for continuity with historical records (earth temperatures at 30 cm have been measured since the mid 1870s in the United Kingdom – records at 100 cm began only in 1971 when the previous standard depth of 4 feet / 122 cm was abandoned in favour of the metric 100 cm depth).

Historically, shallow earth temperatures (depth 20 cm or less) have been measured using mercury-in-glass thermometers with an elongated bent stem, the bulb being located at the desired depth with the stem of the thermometer lying flat within a small plot of bare earth, kept free of weeds and lying snow. To ensure representative results, the plot should be level rather than inclined, and the land surface use around the plot should be typical of the area.

Temperatures at depths of 30–50 cm and deeper were measured in thermometers exposed in steel tubes of the appropriate depth, the thermometer being attached to a length of chain to allow it to be raised to the surface to be removed for reading. The thermometer bulb was also heavily lagged with paraffin wax, to ensure its indication did not change appreciably whilst being read (**Figure 10.3**).

Figure 10.3. 30 cm depth earth thermometer (with wax-covered bulb), shown next to earth thermometer tube. (Photograph by the author)

More recently, significant errors associated with using conducting steel tubes have been recognized [2] and the methods are changing slightly as a result. Increasingly, black-painted steel earth temperature tubes are being replaced by white or grey plastic tubes which have much lower thermal conductivity. (Although such a change is likely to lead to more accurate earth temperature readings, changing the method can damage the homogeneity of existing records as the new plastic tubes will likely result in a slight increase in winter temperatures and a slightly greater decrease in summer temperatures. If a change in method is planned, a minimum 12 month overlap period with daily sensor readings from both tubes is advisable.)

In theory at least, the most accurate earth temperature readings are likely to be those from electrical sensors buried at the appropriate depth. Care needs to be taken in ensuring minimum disruption to the existing soil profile when installing the sensors. The best method is to prepare a trench to the depth required, then insert the sensors at the appropriate depth into the undisturbed vertical face of the trench. The trench should then be carefully refilled with earth, taking care as far as possible to preserve the original strata and drainage characteristics. Once the ground has settled, buried sensors should provide a good measure of the earth temperature at that depth, without the largely unknown effects resulting from heat conductivity (up or down) by a foreign body (i.e., the metal thermometer tube, whose properties differ from the surrounding soil).

The situation is slightly complicated by the need for occasional access for sensor checking/recalibration and, eventually, replacement. Buried sensors will need replacing every few years, particularly those in the permanently wet soils typical of many temperate and polar latitudes. However, replacement is impossible to achieve without considerable disturbance to the location where measurements are being made. A pragmatic approach is probably to place the electrical sensors in narrow-bore plastic tubes whose (sealed) bases are located at the required depth but whose top (and cable exit) remains not far under the surface, where it can be reached relatively easily but where it is not exposed to high diurnal temperature ranges arising from daily solar radiation input (or to danger from lawnmowers, etc.). Using this method, conduction and convection errors resulting from the presence of the tube will be hugely reduced compared to the steel tube method, whilst access for sensor calibration or replacement remains manageable (always assuming a record has been made of the location of the buried tube, of course . . .). Alternatively, duplicate measurements can be made at the site from two locations some metres apart, and planned sensor replacements undertaken at one position in different years from the other.

Whether tubes or electrical probes, or a combination of both, are used, representative earth temperatures are best obtained from underneath an area which is fully exposed to sunshine, wind and rainfall – an area of bare soil for shallow earth temperature measurements, one beneath short grass for sensors at 30 cm or deeper. Earth temperature records made in very sheltered sites, in areas of heavy shade, or amongst growing plants, are likely to be representative of only the immediate surroundings. Where records of such environments are required, for agricultural crop trials and the like, the records may not be comparable with those made within a standard climatological enclosure.

As with grass temperature sensors, most entry-level and budget AWSs do not offer ‘trailing lead’ thermistor options required to measure earth temperatures. Some mid-range and advanced systems do so, however, whether with manufacturer-specific sensors (such as those offered by Davis Instruments as an option to their Vantage

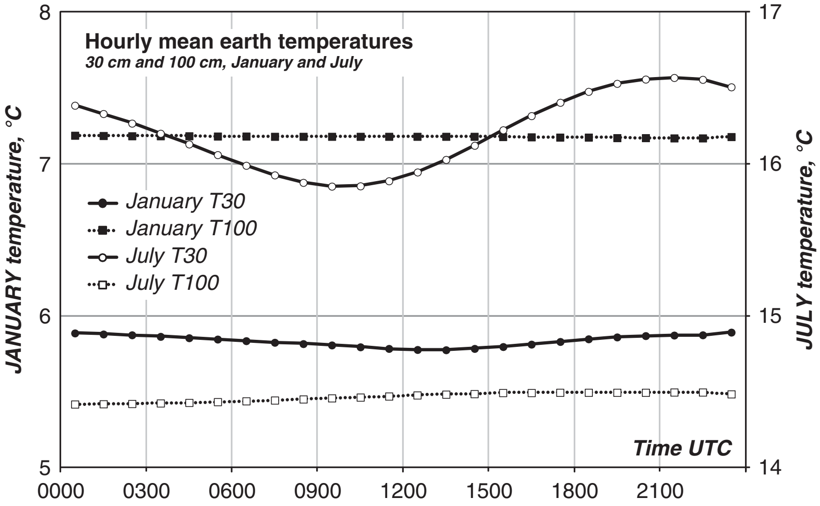

Figure 10.4. Hourly mean earth temperatures – 30 cm and 100 cm, January (left scale) and July (right scale), °C. The vertical scale interval is the same on both. From the author's records in central southern England (51.4°N, 1.0°W), averages over 8 years 2004 to 2011.

Pro2 AWS) or with standard thermistors or PRTs read by a programmable datalogger. Standalone single-channel loggers with trailing leads (such as Gemini Dataloggers' Tinytag models) can also be permanently dedicated to one earth temperature depth measurement. Time stamped records are easily consolidated with the other AWS outputs in a spreadsheet or database package.

Logging intervals

Where mercury thermometers are used, clearly a manual observation is necessary, and for this reason most earth temperatures have been measured once per day, usually at the morning observation. Most historical records refer to this once-daily observation. The use of logged electrical temperature sensors enables more frequent observations of earth temperatures to be made (**Figure 10.4**). While the shallow thermometers respond to the diurnal cycle of solar heating, the time lag from the screen maximum and minimum increases, and the daily range decreases, with depth. At 30 cm the daily maximum and minimum will be 6–12 hours behind their screen equivalents, while at 100 cm the daily variation is negligible. Exact relationships will vary from location to location and with soil type, soil moisture content and other factors. Even at 5 cm depth, hourly sampling and logging intervals are likely to be ample; at 100 cm depth and greater, the very small daily range of temperature at this depth means that once-daily logging is probably sufficient.

One-minute summary – *Measuring grass and earth temperatures*

- Grass and earth temperatures are the most commonly observed temperature measurements, after air temperature.
- The lowest temperatures on a clear night will be recorded at or close to ground level. Where the surface is covered by short grass, the lowest temperatures are

attained just above the tips of the grass blades. The so-called 'grass minimum temperature' (or 'grass min') is measured using a thermometer or electrical sensor freely exposed in this position. A 'ground frost' occurs when the grass minimum falls below 0°C.

- Temperatures are occasionally measured above concrete or tarmac surfaces, or using sensors buried in road surfaces at roadside AWSs, to provide information on road surface temperatures to aid road forecasting models.
- To measure grass temperatures, a spirit-based minimum thermometer or an AWS or dedicated logger with inputs for a trailing-lead electrical sensor (thermistor or platinum resistance thermometer, PRT) is required. Entry-level and budget AWSs generally do not include suitable additional sensors or 'spare' sensor ports. A sensitive yet robust sensor is required to measure grass minimum temperatures, as it will be exposed to all extremes of weather.
- WMO guidelines indicate that grass and surface minimum temperatures should relate to the period 'sunset to the morning observation on the following day', although the greater prevalence of unmanned sites is leading more locations to adopt the conventional 'morning to morning' 24 hour period.
- Earth temperatures are most frequently measured at depths of 5, 10, 20, 30, 50 and 100 cm below ground level. Measurements at 30 cm or deeper are normally made under a grass surface, while the shallower depths are measured under a bare soil plot. Both should remain fully exposed to sunshine, wind and rainfall.
- Earth temperatures at 30 cm or deeper are measured using specially lagged thermometers hung on chains in steel tubes at the required depth, or using electrical sensors. Cabled sensors are ideally suited to measuring grass or earth temperatures, although care needs to be taken in how earth temperature sensors are exposed, as locating them in tubes with higher conductivity than the surrounding soil will introduce significant errors.
- Earth temperatures are normally quoted for a morning observation hour, although hourly values can easily be derived from logged electrical sensors. Hourly values provide useful insights into diurnal temperature variations below the earth's surface.
- Grass temperatures should be sampled and logged at the same interval as used for air temperatures; for earth temperatures, particularly at depth, an hourly or even once-daily logging interval may be sufficient.

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11 Measuring sunshine and solar radiation

> “*The number of hours the Sun is visible each day . . . is of interest to the meteorologist, the climatologist, the horticulturalist, the biologist, and even the local Chamber of Commerce.*”

So began Norman Foster and Laurence Foskett’s description of their new photoelectric sunshine recorder in May 1953 [1]. Today, the climatologist and biologist might prefer a global solar radiation value instead of sunshine hours, but it is likely that few non-specialist members of the public would be immediately familiar with the detail and units of solar radiation records. It is certain, however, that most would recognize ‘11 hours of sunshine’ as being a sunny day.

This chapter covers the instruments and methods used to measure both sunshine and solar radiation. Broadly, measurements of ‘solar radiation’ refer to the interception of radiant electromagnetic energy emanating from the Sun (which can be measured at the top of the atmosphere by satellites, or at the Earth’s surface). Our eyes are sensitive to only a part of this stream of radiation, some of which is absorbed and reflected in its passage through the Earth’s atmosphere. Measurements of ‘sunshine’ refer more specifically to the appearance or otherwise of the solar disk, and more particularly shadows cast by the Sun, when viewed from the surface of the Earth. ‘Sunshine’ can therefore be considered as a binary (yes/no) condition, occurring only when visible solar radiation exceeds a particular threshold. Solar radiation measurements are therefore the more complete, and provide more useful and precise values for solar energy input, whether that be to a domestic solar panel or a supercomputer-based global climate model. However, presence or absence of sunshine is often the more significant in terms of human perception and health.

Records of the duration and intensity of sunlight are important aspects of the description of any climate, yet the number of sites which maintain records of these elements is still a long way behind temperature or rainfall. Perhaps that is because solar radiation is, after wind speed and direction, the most variable of all weather elements, and obtaining accurate measurements poses a number of unique challenges. The subject, and its instrumentation needs, can be daunting – there are more varieties, classes and sub-classes of specialized sensors in this field than in any other category of weather measurements. Some are research-grade precision sensors with world-class accuracy (with prices to match), found only in national observatories or international research institutions; others are rather more affordable instruments suitable for mid-range AWSs. This chapter describes the most common types of instruments in use, together with their advantages and disadvantages. Different instruments can give different results, sometimes significantly so.

Accurate measurements of solar radiation and sunshine require as open an exposure as possible, and the relevant WMO recommendations [2] regarding instrument siting are covered. Very few locations can offer a 'perfect' site, however, and methods of estimating the potential losses resulting from nearby obstructions are also discussed. Further reading recommendations are given for those who wish to explore this diverse, complex and fascinating field in more detail, followed finally by the 'One minute summary'.

What is being measured?

Our nearest star, the body we call the Sun, is the source of (almost) all the energy redistributed around the globe by the global weather machine, and thus of all life on our planet. (A small amount of energy originates from the radioactive decay of elements in the Earth's crust, but the amount is insignificant compared to radiant solar energy receipts.) Measurements of the radiant energy we receive from the solar disk are thus amongst the most important in climatology and climate change studies, if perhaps less so in day-to-day operational or synoptic meteorology. Particularly in mid-latitude climates, the presence or lack of sunshine has probably a greater impact on public perception of day-to-day weather than any other single element, while too much or too little solar radiation are known to have serious effects upon human health and well-being.

Solar radiation, the term covering the electromagnetic output from the Sun, covers a wide range of wavelengths [3]. **Figure 11.1** summarizes the distribution by wavelength of solar radiation received at the top of the atmosphere (bold line). The peak intensity lies in the visible wavelengths (i.e., the narrow part of the electromagnetic spectrum that we perceive as colour), with a wide spread into the (more energetic) ultraviolet part of the spectrum, and a longer and flatter tail in the (less energetic) infrared.

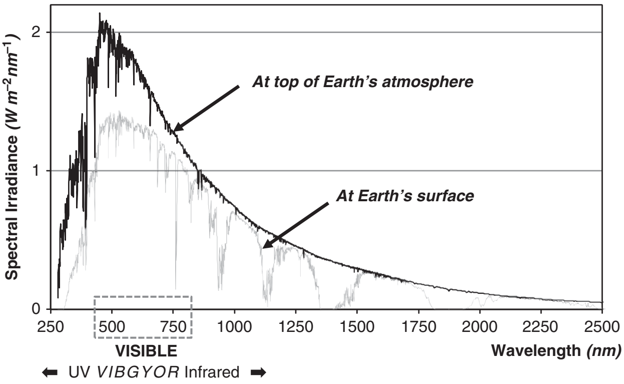

Figure 11.1. The Earth's atmosphere absorbs solar radiation. The upper dark line shows the spectral irradiance (W/m^2/nm) by wavelength at the top of the atmosphere: the lower grey trace shows the typical irradiance by wavelength near sea-level at the Earth's surface, based on the ASTM G-173–03 standard (also known as ISO 9845–1). Visible region denoted by the colours VIBGYOR (Violet, Indigo, etc). For sources, see Reference 3 for this chapter.

Table 11.1. *The main wavelengths of solar and terrestrial (or atmospheric) radiation used in meteorological measurements. Adapted from WMO [2] and Kipp & Zonen table at www.kippzonen.com*

Radiation category	Category name	Wavelength range	Sources
Short-wave solar radiation (ultraviolet)	UV-C	100–280 nm	Emitted from the Sun *Completely absorbed by the Earth's atmosphere before reaching the ground*
	UV-B	280–315 nm	Emitted from the Sun *Around 90% absorbed by the Earth's atmosphere before reaching the ground, but what gets through is biologically very active – main cause of sunburn and skin cancer*
	UV-A	315–400 nm	Emitted from the Sun *Most reaches the ground, but less biologically active than higher-energy UV-B rays*
Visible light	Visible light spectrum	400–780 nm	Emitted from the Sun *The visible spectrum of colours from violet (400 nm) to red (780 nm)*
Long-wave radiation (infrared)	Near infrared	780–3000 nm (3 μm)	Heat radiation from the Sun
	Far infrared	3 μm – 50 μm	Emitted from the Earth and atmosphere *Heat radiation from the atmosphere, clouds, Earth and surroundings*

All bodies above absolute zero emit thermal radiation, the peak wavelength of which depends upon the absolute temperature of the body (Wien's law): the higher the temperature of the body, the greater the emission of radiation (Stefan's law). The Earth and its atmosphere also emit radiation, but as both are much cooler than the Sun, the peak wavelength is much lower (in the infrared rather than the visible part of the spectrum), and the total emitted radiation is also much lower. Table 11.1 summarizes the wavelengths most relevant in meteorological measurements. Only solar radiation is considered further in this chapter.

Units of measurement

The measurement unit of solar radiation intensity or *irradiance* is the Watt per square metre (W/m^2). When integrated over time, as is usual to express daily totals of solar radiation, the unit becomes the Joule per square metre (J/m^2) – 1 Joule is 1 Watt per second. This is a very small unit, and daily totals are more conveniently expressed as megajoules per square metre, or MJ/m^2 (1 MJ = 10^6 Joules). Divide the values by 3.6 to convert from megajoules per square metre (MJ/m^2) to kilowatt-hours per square metre (kWh/m^2).

Sunshine measurements are most often expressed as a total duration ('hours of sunshine'), whether for a day, a month or a year, although sometimes as a 'percentage of maximum possible'. The latter is obtained by expressing the actual sunshine duration as a percentage of the time the Sun is above the horizon (see Box, *Determining 'percentage of maximum possible sunshine'* on page 245).

Absorption by the atmosphere

Solar radiation is the only meteorological element where it makes sense directly to compare measurements made at the top of the atmosphere with those made at the Earth's surface. The average intensity of solar radiation just outside the Earth's atmosphere, perpendicular to the incoming solar beam, is about 1366 W/m^2 (the so-called *solar constant*) [4]. This varies seasonally by about ± 3% owing to the elliptical nature of the Earth's orbit around the Sun, being at its maximum in January when the Earth is closest to the sun, and at its minimum in July when the Earth is furthest away. Averaging across day and night, the seasons and all latitudes, about 342 W/m^2 arrives at the *top* of the Earth's atmosphere. Of course, the amount of solar radiation received at the Earth's *surface* varies enormously: from day to night, between winter and summer, from poles to tropics, and under thick cloud or clear skies. Averaged over the year and across the globe, a little over half of that received at the top of the atmosphere reaches the Earth's surface, the rest being absorbed by the atmosphere or scattered and reflected back to space from the air, clouds and particles of dust or other atmospheric aerosols. Absorption by the atmosphere largely shields us from the most energetic sections of the solar spectrum, particularly the far ultraviolet, most of which is absorbed by the stratospheric ozone layer 25–45 km above our heads (**Figure 11.1**). This is fortunate for all life on Earth as ultraviolet radiation is known to result in genetic damage, including a clear causative link with skin cancer.

Instruments on satellites and at the Earth's surface routinely measure incoming solar radiation across the wavelength ranges shown in **Table 11.1**, but most surface-based instruments make their measurements only between the near ultraviolet and the near infrared, including the visible spectrum.

Standard methods of measuring sunshine and solar radiation

At the bottom of the Earth's atmosphere, after some of the solar beam has been scattered and reflected on its passage through the depth of the atmosphere, there are two main components[*] to solar radiation – *direct* and *diffuse*. As the name implies, *direct* solar radiation is that received directly from the solar disk alone, while *diffuse* is that received from the rest of the sky as a result of atmospheric scattering and reflection. By definition[†]:

Total (or global) solar radiation I = direct solar radiation D + diffuse solar radiation G

On a very clear day, or at high altitudes, the direct component can account for 85 per cent or more of the global solar radiation; on a cloudy day, the direct contribution is zero. Measurements of diffuse radiation are useful in determining the scattering of inbound solar energy (essential for planetary radiation balance studies), and for monitoring the transparency (or otherwise) of the atmosphere

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[*] For simplicity, this ignores some smaller terms, such as the reflected short-wave (reflex) element.

[†] This applies only to equal-area measurements (all-sky or hemispheric values), and not to the readings from separate direct and global radiation sensors, which cannot simply be summed arithmetically. Direct radiation measurements apply only to a small area of the sky, while global radiation measurements require a cosine correction term to allow for solar angle.

and its constituents. Instruments are available to measure both direct and global solar radiation, although measurements of the latter greatly outnumber the former.

Sunshine recorders can be considered as a subset of the wider category of solar radiation instruments. The principle of these instruments is simple enough – to provide an unambiguous binary (on/off) trace or electrical output when the Sun is shining – and there are several methods of achieving this.

What is the difference between radiometric terms and units (irradiance, W/m^2) and photometric terms (illuminance, lux)?

Radiometric quantities refer to measurements of radiation, of any wavelength, from any physical body – in this case, the Sun or the Earth. *Photometric* quantities describe how the human eye senses optical radiation, and therefore such measurements refer only to the visible part of the spectrum.

Irradiance is a radiometric term which refers to electromagnetic radiation incident upon a unit surface area; it is measured in Watts per square metre (W/m^2).

Illuminance is a photometric term, referring to the incident flux of radiant energy emanating from a source within the visible spectrum and weighted by the response of the human eye to energy in visible wavelengths. It therefore simulates how bright the source appears to the human eye. A light-adapted eye generally has its maximum sensitivity at around 555 nm, which lies in the green region of the optical spectrum. Illuminance is measured in units of lux (lx).

Ultraviolet or infrared radiation from the Sun (or any other suitable source) will register on a suitable solar radiation detector, but will not register on a photometer (or lux meter) because it lies outside the visible spectrum, and therefore (by definition) has no illuminance.

Measuring direct solar radiation

Instruments to measure direct solar radiation are called *pyrheliometers*. A pyrheliometer consists essentially of a suitable electrical sensor – sensitive to a wide range of solar radiation, typically between 200 nm and 4000 nm – exposed at the end of a narrow internally blackened tube, which is pointed directly at the Sun to make a measurement (**Figure 11.2**). The detector has a field of view of about 5 degrees (approximately 10 times the apparent diameter of the solar disk) and thus excludes nearly all of the scattered radiation from the sky. The intensity of solar radiation from this narrow angle, perpendicular to the solar beam, is known more formally as the *normal incidence direct irradiance*.

Measurements from manual pyrheliometers have been made for over a century, now largely replaced by automatic versions kept pointing at the Sun by accurate tracking mechanisms and so providing continuous unattended records. Not surprisingly, such equipment is very expensive, and usually found at only a few research observatories within any given country. However, the principle of measuring direct solar radiation using a direct incidence pyrheliometer is important to grasp, because it forms the basis for the WMO definition of sunshine, as we shall see shortly.

Figure 11.2. Solar radiation sensors at Neumayer station, Antarctica. The platform tracks the sun, and the two black spheres continuously shade one pyranometer measuring diffuse solar radiation and one pyrgeometer measuring long-wave downward radiation. One direct-incidence pyrheliometer (an Eppley Normal Incidence Pyrheliometer) is mounted above a four-quadrant sensor to the right of the platform in the photograph, directly above the observer's glove. (Photograph courtesy of Dr Gert König-Langlo of the World Radiation Monitoring Center at AWI)

Measuring global solar radiation

By far the most commonly seen solar radiation instrument is the *pyranometer* (occasionally referred to as a *solarimeter*) (**Figure 11.3**). A pyranometer is normally used to measure global solar radiation (i.e., the combined direct and indirect components) on a plane horizontal surface*, as opposed to pyrheliometer measurements which are made perpendicular to the solar beam. The global solar radiation measurements obtained are more formally defined as *global solar radiation on a horizontal surface*.

Measurements of diffuse radiation can be made using a pyranometer fitted with a shadowing disk or shading ring which blocks radiation from the immediate area of the solar disk. A shading ring requires seasonal adjustments to follow the path of the Sun in the sky, or (as with the pyrheliometer) an accurate tracking mechanism can be used in which a small metal disk or sphere permanently eclipses the solar beam (as can be seen in **Figure 11.2**). Where both global and diffuse radiation measurements are made at the same site, two matched sensors are commonly mounted adjacent to each other, ensuring of course that neither instrument shadows or casts reflections upon the other. Where simultaneous measurements are made, the direct component can be inferred by subtracting the cosine-corrected diffuse component from the global. Alternatively, where both direct and global

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* Measurements are sometimes made with pyranometers at an angle, or pointing only in one direction (such as 'facing east, angled at 45°'). These are most often made for solar energy research purposes and the like, but for weather measurements global radiation sensors must be accurately horizontal.

Figure 11.3. Banks of pyranometers at the UK Met Office test site in Exeter, England. (Photograph by the author)

radiation are measured simultaneously, the diffuse solar radiation can be determined by subtracting the direct component from the cosine-corrected global value.

As with many other meteorological instruments, there are a variety of instruments and suppliers to meet differing budgets and accuracy requirements (**Table 11.2**).

Davis Instruments solar radiation sensor

Davis Instruments offer an optional solar radiation sensor for their mid-range Vantage Pro2 AWS (**Figure 11.4**). The instrument consists of a silicon photodiode detector with a spectral response across the wavelength range 300 to 1100 nm (near ultraviolet, through the visible spectrum and into the near infrared). Reasonably priced, the instrument offers acceptable accuracy, the manufacturer quoting ±5%. It is difficult to obtain accurate calibration for these instruments, however, without which the absolute accuracy of the readings obtained is difficult to verify. Some indication of calibration accuracy (or otherwise) can be gathered from a comparison of results with neighbouring stations, particularly where comparisons can be made against calibrated instruments, although the number of sites measuring solar radiation is much less than for temperature and rainfall, for example, and reliable statistics are more difficult to find. The photodiode sensor is fairly insensitive to rapid changes in solar radiation, however (the time constant of this sensor is 60 seconds), and even 1 minute logging intervals will fail to reproduce completely the rapid swings in solar radiation on a day of broken cloud (see **Figure 11.6** on page 243). A brief summary of the Davis sensor performance is also included in reference [5].

Table 11.2. *Key specifications for various categories of pyranometer, comparing WMO recommendations for the various classes of instrument with the Davis Instruments 6450 solar radiation sensor and the Kipp & Zonen CMP3 unit. WMO specifications are from reference [2] (Table 7.5 therein), Davis Instruments and Kipp & Zonen sensors are from manufacturer literature/websites. In WMO terms, 'High quality' refers to 'near state of the art', international observatory reference instruments: 'Good quality' refers to national observatory network standards, 'Moderate quality' to national solar radiation monitoring networks. N/A means 'not available' or not supplied by manufacturer.*

Characteristic	High quality	Good quality	Moderate quality	Davis Instruments 6450 sensor	Kipp & Zonen CMP3 sensor
Spectral range (nm)				400–1100	310–2800
Response time (seconds) *95 per cent response*	< 15	< 30	< 60	60	18
Resolution (W/m^2) *Smallest detectable change*	1	5	10	1	1
Calibration stability (% full scale) *Change per year*	0.8	1.5	3.0	2	< 1
Temperature response (%) *Maximum error due to 50 K change in ambient temperature*	2	4	8	6	< 5
Non-linearity (%) *Percentage deviation from sensor response at 500 W/m^2 due to a change of irradiance within the range 100 to 1000 W/m^2*	0.5	1	3	N/A	< 2.5
Directional response (W/m^2) *Directional error at 1000 W/m^2 assuming beam from any direction*	10	20	30	N/A	< 20
Achievable uncertainty in daily totals *95 per cent confidence level*	2%	5%	10%	5%	10%

Figure 11.4. Davis Instruments solar radiation sensor, model 6450. (Photograph courtesy of Davis Instruments)

Kipp & Zonen solar radiation sensors

Kipp & Zonen, based in Delft, The Netherlands, are the leading global manufacturer of solar radiation instruments and they produce a range of high-quality sensors for all budget levels, differing in capability, accuracy and time constant (response time). Their beautifully engineered top-of-the-range instruments offer traceability to national and international calibration standards, at a price to match.

Most Kipp & Zonen pyranometers are thermopile instruments. A thermopile consists of an electrical circuit composed of two different metals, with one junction designated as ‘hot’ and the other as ‘cold’. When there is a temperature difference between the hot and cold junctions, a small electrical potential is generated. In a pyranometer, the ‘hot’ junction (in reality, very many fine junctions) is painted matt black and exposed under a glass dome in the centre of the instrument, while the ‘cold’ junction is bonded to the instrument chassis (shaded from direct solar radiation) and thus at or close to the ambient air temperature. (The glass dome is essential to prevent ambient wind affecting the heat gain or loss of the sensor, while it also protects the delicate sensor elements from precipitation and dust. The dome is normally made of quartz glass, which is transparent to radiation over the wavelength range 250–2800 nm approximately – it is opaque in the far infrared. Some instruments include a double dome, to reduce solar heating and long-wave radiation errors still further.)

When solar radiation falls on the instrument, the blackened hot junction becomes warmer than the ambient temperature, the difference in electrical potential being proportional to the intensity of the solar radiation. The instrument requires no power and is very responsive to rapid changes in solar radiation – a typical instrument has a time constant of only a few seconds to respond to 63 per cent of a step change in solar radiation (see Appendix 1 for more on instrument performance measures). Because the output signal is very small – typically only around 10 μV per W/m^2 – shielded cables and high-quality connections are essential for this class of instrument.

The Kipp & Zonen CMP3 pyranometer (**Figure 11.5**) is a small, light instrument ideal for use with AWSs. It covers the spectral range 300 to 2800 nm. Each

Figure 11.5. Kipp & Zonen CMP3 pyranometer. (Photograph by the author)

instrument is supplied with an individual calibration certificate; year-to-year stability is quoted as within 1 per cent. Once installed (see below for exposure requirements) the instrument is maintenance-free apart from an occasional visual check and clean of the quartz glass dome and the shading disk covering the instrument chassis. It is best to clean the glass dome daily, during the morning wherever possible, as deposits of dust, frost, dew and particularly snowfall can significantly impact output. At low solar angles, for example, a thin cap of frost or dew can reflect solar radiation back onto the sensor and greatly increase the apparent output for up to 30 minutes. During snowfall, anything more than a centimetre or two of snow on the dome will result in near-zero solar radiation being recorded while the snow remains in place on the instrument, so the snow should be cleared off as soon as practicable to do so.

Pyranometer performance in darkness

During the hours of darkness, the output from most pyranometers will normally fall slightly below zero. There are two reasons for these negative night-time values. Firstly, sudden changes in temperature can produce short-lasting negative or positive values, as the sensor element and the body of the pyranometer adjust to the change at different rates. Such sudden changes in temperature can be caused by weather conditions – a sudden increase in cloud, a shower of rain – or even by nocturnal birds perching on the sensor. The second, more significant and present on most nights, results from the normal situation whereby the Earth is warmer than sky. The sensor will thus 'see' the sky temperature, similar to the grass minimum sensor, whereas the sensor body will be at or close to ambient air temperature. The temperature differential will produce a slight negative value. The output can fall close to -10 W/m^2 on clear nights, particularly when the temperature is falling quickly.

Reference-standard pyranometers can compensate for these effects to a certain extent, and units which include ventilation and heating fixtures almost eliminate them. Any persistent offsets under cloudy night-time skies at night may indicate a small zero error in the sensor, and adding the mean 'cloudy' offset can help compensate for a drifting zero point.

Although negative values can easily be suppressed by a simple line in the logger programme, night-time records from a pyranometer can also be a useful, if rather qualitative, indicator of changes in overnight low and medium-level cloud cover. However, when calculating daily totals of solar radiation, all negative values should be treated as zero.

Measuring solar radiation from satellites

Some countries use geostationary satellite cloud data to provide estimates of surface solar radiation receipts. Cloud types, breaks and thicknesses at grid points are categorized from satellite imagery, and surface-level solar radiation levels estimated from these categories. In Australia, the Bureau of Meteorology uses this method to estimate daily solar radiation totals for thousands of locations across the country, the estimates being tied to ground truth using a much smaller network of surface solar radiation measurement sites [6]. Accuracies are better in clear-sky conditions (typically within 7 per cent of ground measurements) than under cloudy skies (± 20 per cent). Within the UK, a similar experimental approach to estimating daily *sunshine* totals has been described [7], although results were mixed.

Measuring ultraviolet (UV) radiation

The UV region (**Table 11.1**) covers the wavelength ranges from 100 to 400 nm. The spectral distribution of atmospheric UV irradiance is very variable, depending mainly on the elevation of the Sun and stratospheric ozone levels. Almost all of the higher-energy UV is absorbed by the Earth's atmosphere, but limited UV exposure has beneficial effects for human biology.

For all but the most specialized applications it is only necessary to monitor 'total UV' irradiance, which represents the combined UV-A and UV-B components: UV-A radiation at the Earth's surface is normally 15–20 times greater than UV-B. (UV-C is completely absorbed by the Earth's atmosphere.) UV radiation measured with a similar response to the human skin is termed *Erythemally active UV irradiance* (UVE) and is normally communicated as a Solar UV Index (UVI) on weather forecasts. Some budget and mid-range AWSs offer an optional 'ultraviolet sensor', providing an approximate indication of ultraviolet radiation in terms of the UVI index scale, although they should not be regarded as precision instruments in this regard.

More detailed information on measuring ultraviolet radiation is given by the World Meteorological Organization [2, section 7.6]. Where accurate measurements of UV radiation are required, application advice should be sought from specialist instrument manufacturers such as Kipp & Zonen (see Appendix 4).

Measuring sunshine

Sunshine recorders are a specialist subset of solar radiation sensors, in that they provide a record only of the times within a day when the intensity of the visible radiation from the solar disk at the surface of the Earth exceeds a particular threshold. To the human eye, this is more easily perceived as the appearance or disappearance of shadows in daylight, and for this reason 'sunshine' measurements relate to the visible spectrum only.

The WMO definition of sunshine [2] is 'the duration of the period for which the direct solar irradiance exceeds 120 W/m^2. (Prior to 1981, the threshold was set at 210 W/m^2, and some older reference material still contains this figure.) Note that this threshold refers to the measurement of *direct* solar radiation using a narrow-aperture pyrheliometer located perpendicular to the incoming beam as previously described, not to the *global* solar radiation on a horizontal surface measured from a pyranometer. The latter usually exceeds 120 W/m^2 at local noon even in mid-latitudes for most months of the year, even under cloudy skies. A simple tally of the duration of *global* solar radiation exceeding 120 W/m^2 will give a huge overestimate of the true duration of sunshine. **Figure 11.6** illustrates the highly variable relationships between global solar radiation and sunshine on three very different types of day.

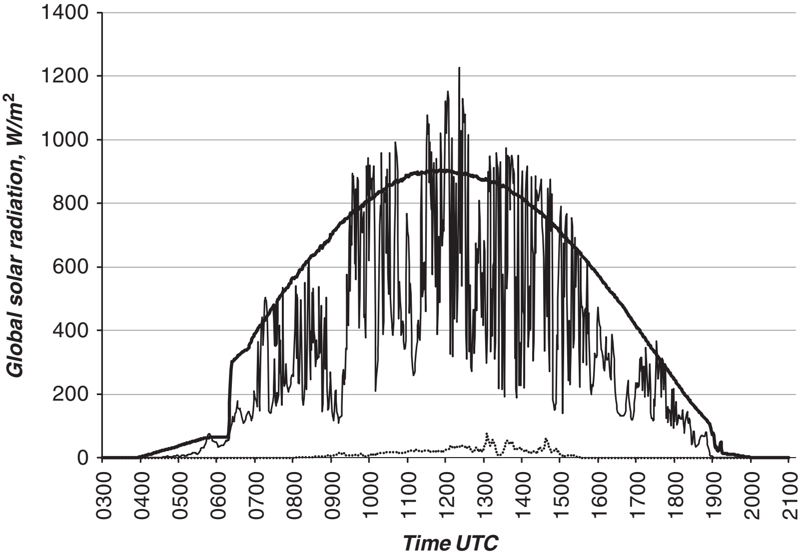

Figure 11.6. Global solar radiation measurements on three very different days. Thick line – 3 June 2010, a day with clear skies almost throughout (the beginning and end of the record is affected by horizon obstructions): thin line – 8 May 2011, brisk south-westerly breeze with extensive cumulus development: dashed line – 16 December 2010, a heavily overcast midwinter's day without any sunshine. All records are from the author's own site in central southern England. The values graphed are 1 minute mean values, which themselves downplay the rapidity of changes in solar radiation on days with broken cloud.

Absolute versus relative measurements: solar radiation and sunshine duration

The total amount of solar radiation in any given period is an absolute measure of energy receipt. Daily solar radiation totals made at any one site throughout the year, or at different locations around the world, are directly comparable with each other.

In western European mid-latitudes, the mean daily solar radiation on a horizontal surface in June is typically 10 times that of the average day in December, whereas the mean daily duration of sunshine between the two months varies by a factor of just three or four. Daily sunshine durations can provide only an approximate relative measure of solar radiation inputs – a mid-latitude December day with 6 hours sunshine receives less than a fifth of that of a day in June with the same sunshine duration (**Figure 11.7**), because in midsummer the solar elevation is higher and the hours of daylight almost three times as long as in midwinter. These seasonal differences are greatest nearer the poles. It is for this reason that global solar radiation measurements are preferred to sunshine duration or 'percentage sunshine' in energy and agricultural modelling and similar applications.

In theory at least, the existence and duration of sunshine is best determined from minute-by-minute records made by a tracking pyrheliometer (this is of course the

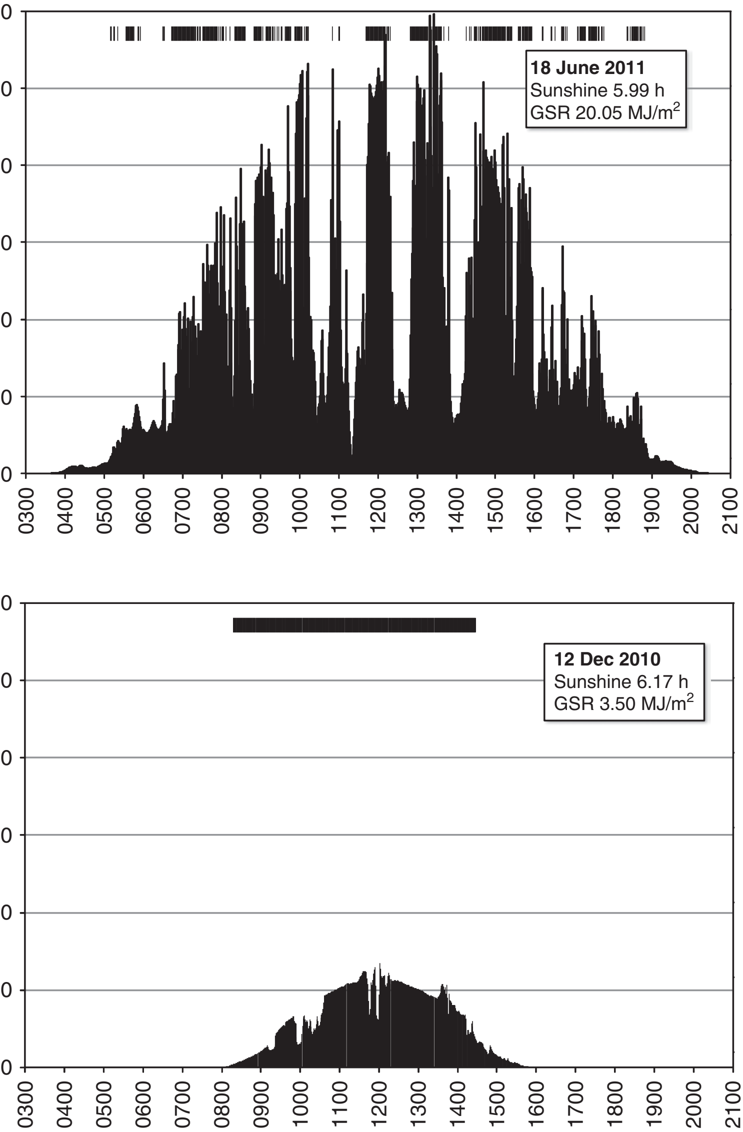

Figure 11.7. One-minute values of global solar radiation (column chart, left scale in W/m^2) and spells of sunshine (vertical bars, at top of radiation plot). (*Top*) A day near the midsummer solstice (18 June 2011) with 6 hours of sunshine, compared with (*bottom, same scale*) a day with a similar sunshine duration near the midwinter solstice (12 December 2010). Although the daily sunshine totals were almost identical, the global solar radiation (GSR) receipt was almost six times higher in June (20.05 vs 3.50 MJ/m^2). From the author's site in central southern England, latitude 51.4°N.

implementation of the WMO definition of sunshine[*]). However, the expense of such instruments renders widespread adoption impractical. Instead, less expensive and

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[*] Even here, there remains some uncertainty relating to the definition of sunshine, as according to WMO [2, section 8.1] direct pyrheliometer measurements can vary somewhat according to the angle of view of the instrument: a tolerance of ± 20% is permitted. The presence of rain or snow on the

more practical instruments are used, their response and performance being carefully assessed against standard ‘reference’ instruments at regular WMO and World Radiation Center intercomparison events [8].

Leaving aside direct radiation measurements made by a tracking pyrheliometer, there are two main types of sunshine recorder in widespread use today:

- The first uses solar rays to change the properties of a recording medium – this is the principle of the Jordan photographic sunshine recorder [9], first described about 1886, which produces a record on photographic paper, and of the iconic Campbell-Stokes sunshine recorder, described in more detail below.
- The second uses an electronic circuit to infer the existence of shadows by comparing the difference in output between two photosensitive devices in the sensor body, one of which is exposed to direct solar radiation, the other kept shaded. When the difference between the two exceeds a given threshold, as it will in sunshine bright enough to cause hard-edged shadows, the instrument’s electrical output changes in a step fashion, which can be detected by a suitable logger and/or associated timing circuit. The first type of electronic ‘differential’ or ‘contrast’ sunshine recorder was the Foster-Foskett sunshine switch, widely used in the United States between 1953 and 2009 (and described in more detail below). The same basic principle is used in other electronic sensors.
- The threshold intensity sufficient to trigger a sunshine recorder is typically that which will just cast a *distinct*, hard-edged shadow, so very weak or hazy sunshine will normally not be recorded, nor will sunshine be registered when the solar disk is close to the horizon. Typically the Sun will need to be at least 2–3 degrees above the horizon before the intensity of sunshine is strong enough to register, and of course this necessarily assumes a clear horizon, without obstructions from mountains, trees, buildings and the like. In mid-latitudes, this means that sunshine during the first and last 20–30 minutes or so of daylight will not normally be recorded, even if the sky is clear and (to the eye) the Sun looks to be shining[*]. See Box, *Determining ‘Percentage of maximum possible sunshine’*.
- Another method for deriving sunshine duration is directly from global solar radiation records, using an appropriate threshold to determine the ‘sunshine/no sunshine’ cutoff point. More details on the methodology are given below.

Determining ‘Percentage of maximum possible sunshine’

The maximum possible period of daylight for any particular date is taken as the length of the period between sunrise and sunset. (For astronomical purposes precision to within a second or better is required, but for meteorological purposes tables accurate to a minute are perfectly adequate.) The ‘percentage of maximum possible sunshine’ is the daily duration of sunshine expressed as a percentage of the maximum possible period of daylight for that date.

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pyrheliometer viewing window can also produce erroneous results, whereas raindrops on a pyranometer dome usually have little significant effect.

[*] See also the ‘Exposure’ section following. Very occasionally, reflections from cloud layers just above the horizon at sunrise can result in sunshine being registered by electronic sensors only a few minutes after dawn, but such events are due more to a fluke of atmospheric conditions than to the performance characteristics of the sensor involved.

A very useful calculator providing precise sunrise and sunset times and hours of daylight for any location (enter latitude, longitude and time zone, and year) can be downloaded from http://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html – choose 'NOAA_Solar_Calculations_Year' in the spreadsheet format preferred.

Because sunshine recorders are insensitive to low solar angles, sunshine will generally not be registered until the Sun rises to about 3° above the horizon after dawn, or when it sets below 3° near sunset. The length of time taken for the Sun to reach 3° after dawn, or to sink from 3° to the horizon at sunset, varies with latitude and season; on the equator it is as little as 13 minutes, but at 60°N it varies between 44 minutes near the summer solstice and 53 minutes at the winter solstice. (At higher latitudes the Sun does not reach 3° elevation in midwinter.) In mid-latitudes, 20–30 minutes is typical. A 20 minute cutoff after sunrise and before sunset equates to roughly 7 per cent of the maximum possible daily duration averaged over the year. It is therefore unlikely that even the sunniest days will exceed about 95 per cent of the 'maximum possible duration' – the limits of current sensor sensitivity dictate that 100 per cent cannot *quite* be attained.

Weekly or monthly 'percentage of maximum possible sunshine' statistics are obtaining by summing the observed daily sunshine durations and expressing that as a percentage of the sum of the daily 'maximum possible daylight' values for the period.

As there are only a small number of sunshine instruments in widespread use, each is described in a little more detail than is feasible for some of the other sensor types covered in this book.

The Campbell-Stokes sunshine recorder

The idea of using the sun's rays to burn a record of sunshine duration was first described as far back as 1646 [10], although it was not until John Campbell described a method of mounting a spherical glass lens in a wooden bowl in 1857 that the method became practical. Campbell's design was improved upon by the famous physicist and mathematician Professor Sir George Stokes in the late 1870s [11]: the instrument he described quickly became known as the Campbell-Stokes sunshine recorder, and has remained essentially unchanged since (**Figure 11.8**). With only slight modifications, it was adopted as the WMO Interim Reference Sunshine Recorder in 1962, until this designation was withdrawn in favour of direct pyrheliometer measurements in 1981. Although the Campbell-Stokes recorder forms the basis for most of the historical record of sunshine in many countries, including the United Kingdom (where it has been in use since 1879) and the Republic of Ireland, it was less widely used in some countries, including the United States, because of its lack of an electrical output to facilitate remote or automatic monitoring.

This simple and iconic instrument consists of a precisely machined spherical glass lens mounted in a larger metal frame, shaped to reflect the path of the Sun through the sky throughout the year. Accurately cut grooves in the frame hold strips of blue-green ('Prussian Blue') coloured cardboard, graduated in hours. Because the path of the Sun in the sky varies during the year, the length and shape of the cards varies according to season. Models for both temperate and tropical latitudes are available.

Figure 11.8. The Campbell-Stokes sunshine recorder at Braemar, Scotland. (Photograph by the author)

When the Sun is shining, solar rays are focused onto the card, charring it (**Figure 11.9**). (The card is blue-green rather than black so that it chars rather than ignites: the burns are also easier to distinguish against the background.) After sunset[*], the card is changed and the length of the burns on the card summed to determine the sunshine duration. Analysis of the width of the burn can also provide useful information on the intensity of the solar radiation [12].

The Campbell-Stokes sunshine recorder suffers from several key disadvantages, as a result of which it is steadily being supplanted by newer electronic sensors (see below):

- The performance of the instrument is very variable because of the effect of weather conditions on the state of the card and of the glass sphere, but chiefly

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[*] At some sites, where no observer is available after sunset, the card is changed at the morning observation. Provided the cards are changed at exactly the same time every day, this approach works almost as well. However, if the time of observation on the second day differs by more than a few minutes from that of the previous day, and the Sun is shining on both mornings, the second day's burn may become indistinguishable from the previous day's, with resulting uncertainty in the duration for both days.

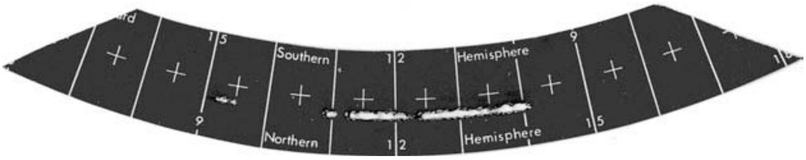

Figure 11.9. Campbell-Stokes sunshine recorder card (winter variant), showing the burn produced by a day's sunshine. The daily sunshine duration was 3.6 hours. (Photograph by the author)

because of the overburning of the card in conditions of intermittent sunshine [13]. In broken sunshine, individual burns tend to overlap, leading to an exaggerated sunshine duration – an hour's burn might actually represent only 35–40 minutes sunshine under some conditions.

- The measurement of burn length is quite subjective, particularly on days with broken sunshine and near sunrise and sunset, and the measured duration of sunshine can differ by 10–20 per cent between different analysts. (It is not unknown for locations vying for the position of 'sunniest place in . . .' to be 'generous' in their interpretation of Campbell-Stokes sunshine recorder cards.) Detailed instructions on evaluating burns are given by WMO [2], although these are often only incompletely followed, if at all. Whenever feasible to do so, it is best to have all cards independently analyzed by two people.
- The actual threshold for burning the card varies considerably according to whether the card is wet or dry (less sunshine might be recorded after a shower than before it, for example) and whether or not the light-gathering efficiency of the glass sphere has been reduced by frost, dew or snowfall deposited on its surface. Various tests [13, 14] have shown that the 'sunshine burn threshold' averages about 170 W/m^2, but that this can vary by a factor of four or more (between 70 and 301 W/m^2, depending on time of day and weather conditions). With dew or rain on the sphere, the burn threshold can exceed 400 W/m^2.
- Even the type and exact colour of the sunshine cards in use can make a significant difference. The WMO implementation of the Interim Reference Sunshine Recorder, IRSR (1962–81) specified the pattern of instrument as used in the UK Met Office, but fitted with cards to the specification of the French state weather service, Météo France. Tests at Kew Observatory in London in 1979/80 [13] showed that an IRSR instrument using the 'French' card specifications recorded 6 per cent less sunshine than one using the 'British' cards. The conclusion drawn was that the 'French' cards had a slightly higher burn threshold.
- For complete records, the instrument requires a clear (or almost clear) horizon. It is insensitive to low solar angles however, 3 degrees elevation being a typical minimum for a burn to commence or cease, somewhat higher if the sphere is coated with dew or frost. As a result, all else being equal, sunshine is far more likely to be recorded near sunset, when the air tends to be warmer and drier than just after dawn, when it is often at its coldest and dampest. WMO [2, section 8.2.3.3] quote the average error from this cause in northern European climates (ascertained from comparative trials of adjacent heated and unheated instruments) as ranging from 1 per cent of the monthly mean in summer to 5–10 per cent of the monthly mean in winter. Of course, the

preference for an unobstructed horizon is no different for electronic sensors, although the latter (being smaller and requiring only a cable for remote reading) can be more easily mounted on a mast or tall structure some way above the ground without the requirement for safe daily access to the instrument. Instruments mounted well above ground level also tend to suffer less dewfall than those exposed at lower levels.

- The cards from a Campbell-Stokes recorder need to be changed daily, requiring the physical attendance of the observer, preferably at or just after dusk. (If the card is not changed daily, each subsequent day's burns will simply 'over-burn' previous traces, and the records from individual days quickly become indistinguishable one from another.) The instrument is therefore unsuitable for use at sites where manual observations are not made 365 days per year, locations which are not manned outside normal working hours (including weekends), or at remote sites. The price of the sunshine cards is also a significant ongoing running expense (in 2012, a year's supply cost about $125).
- At high latitudes, two instruments are required to cover the full range of solar azimuths at midsummer.
- The instrument does not provide an electrical output and therefore cannot easily be integrated into an automated datalogging system.

Even in geographies where the Campbell-Stokes has been the standard instrument for decades, it is steadily becoming obsolete in favour of smaller, remote-logging-friendly unattended electronic sensors. In the UK, the *coup de grâce* came in 2003 when the Met Office dropped the instrument in favour of the Kipp & Zonen CSD sunshine sensor. Although they are still – just – the most common sunshine instrument within the UK at the time of writing[*], the number of sunshine records made with Campbell-Stokes recorders looks set to continue to decline to where it becomes a minority instrument, retained only for overlap or continuity with historical records made at long-period sites. It is surprising, therefore, that the UK Met Office still references its sunshine records to the Campbell-Stokes benchmark (see Box, *Are today's sunshine measurements compatible with those made last year or last century?).*

Electronic sunshine sensors

Sunshine is detected by electronic sunshine sensors as a difference in output between two photosensitive devices, one of which is exposed to direct solar radiation, the other being shaded. When the difference between the two exceeds a given threshold, closely comparable to shadows being cast, the instrument output changes in a step fashion, an electrical signal which can easily be logged. The duration of sunshine is then simply the length of time the 'sunshine = yes' output is indicated (usually measured in minutes or hundredths of an hour, but to the nearest second if required). Such sensors provide a more objective and generally less weather-dependent output, but few detailed tests of relative performance have yet been published to quantify

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[*] As at February 2012, 111 sites in the UK Met Office network recorded sunshine, of which 42 (38%) used Kipp & Zonen sensors, the remaining 69 (62%) continuing to use manual Campbell-Stokes sunshine recorders. For the amateur sites featured in the UK Climatological Observers Link bulletin for January 2012, 60 sites measured sunshine using an electronic sunshine recorder, the vast majority of which were Instromet sensors.

differences between different sensors, or even between same-model sensors on the same site. A few uncertainties remain with regard to the spectral response of different instruments, some of which may lie partly in the near infrared rather than in the visual range.

The Foster-Foskett sunshine switch

The Foster-Foskett sunshine switch (**Figure 11.10**) was first described in 1953 [1]. Over the next decade or so, it quickly supplanted the then-standard Maring-Marvin thermoelectric sunshine sensor as the standard sunshine sensor within the United States. In 1990, around 150 locations measured sunshine using this instrument, although the number of sites had declined to about 100 by 2009, and more rapidly since.

The instrument consists of a pair of selenium photoelectric cells inside a translucent tube; one cell is shaded. When the Sun is not shining, output across both cells is equal and no current flows in the comparator circuit connecting them. During periods of sunshine, the increased output of the unshaded cell results in an unbalanced output, and a current flows in the circuit, activating a chart recorder or timing circuit, which is analyzed manually to determine the duration of sunshine. According to the original description by its inventors, the sensor responds only to direct solar radiation.

The threshold sensitivity of the instrument can be adjusted manually as required using an internal potentiometer (by all accounts the instrument required frequent

Figure 11.10. Foster-Foskett sunshine switch at Weather Forecast Office Pocatello, Idaho, October 2011. (Photograph by Gary Wicklund)

adjustment to maintain a consistent voltage threshold for detecting sunshine [15]). Comparative tests carried out as far back as the late 1960s [16] indicated that the average threshold for sunshine detection using this instrument was just 87 W/m^2, almost 30 per cent below the WMO recommended threshold of 120 W/m^2. Clearly, a lower threshold for sunshine detection would result in a much higher indicated duration of sunshine compared with instruments set at the WMO recommended level. It seems likely, therefore, that records made using the Foster-Foskett sunshine switch are not directly comparable with records made using different sunshine recorders, within the United States or elsewhere.

In late 2009, the U.S. National Weather Service quite suddenly discontinued the use of the Foster-Foskett sunshine switch at many of its observing locations [17]. The reasons given included the large difference in its detection threshold from the WMO standard, and increasing difficulties in maintaining the instrument's calibration and in obtaining spare parts.

Since the cessation of records from the Foster-Foskett network, the publication of sunshine durations (which were usually expressed as a percentage of maximum possible, rather than a duration in hours) has largely been discontinued in the United States.

The Instromet sunshine recorder

Instromet are a supplier of weather instruments based in Norfolk, England. Over the past decade or so this simple, reliable, consistent and reasonably priced sensor (**Figure 11.11**) has deservedly become the sunshine sensor of choice for most of the amateur and hobbyist weather observing community within the UK and Ireland. The sensor unit is small and light, easy to fix to a mast or rooftop, and relatively undemanding in alignment requirements, needing only to be aligned level and pointing approximately south (in the northern hemisphere). Once in place, it needs little or no maintenance, although if the unit is safely accessible it is advisable occasionally to check the glass dome for bird droppings and the like, and give it a wipe from time-to-time.

It is suitable for either standalone recording (it comes as standard with a digital display recording to 0.01 h), or can easily be interfaced to a suitable datalogger (both voltage and square-wave pulsed outputs are available). Note however that most pre-built consumer AWSs do not include a 'spare' pulse counter input, and therefore a programmable logger will normally be required to log output from one of these units[*]. Given due care in installation and attention to connections, one of these instruments should provide many years of reliable records. The author's unit has worked faultlessly for over a decade at the time of writing.

This instrument has its peculiarities (including spelling – see **Figure 11.11b**). The electronics control box includes a small LED, which is lit when the Sun is shining; unfortunately this is hidden underneath the front panel of the control box. It would be more useful if this LED was mounted on the digital display, although it is easy enough to connect an external LED to the 5 v voltage output provided if required. Another

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[*] As the pulsed output is similar to the 'tip' from a tipping-bucket raingauge, it is possible to substitute the output from an Instromet recorder for the tipping-bucket raingauge connection on some AWSs. Setting the 'calibration' of the input from (say) 0.2 (mm, tipping-bucket raingauge) to 0.01 (h, sunshine recorder) will allow logging of sunshine duration in the field previously occupied by rainfall data. Alternatively, a separate time- or event-based logger can be used.

Figure 11.11. The Instromet electronic sunshine recorder. (*Top*) Sensor; (*bottom*) Display unit. Note the spelling of 'Accumulated'! (Photographs by the author)

quirk of some of these instruments is that they will indicate between 101 and 102 pulses per hour in unbroken sunshine (i.e., it will indicate a sunshine duration of 1.01 or 1.02 h). Whilst the absolute error is small in climatological and sensor terms, it does lead to sunshine durations in excess of the maximum possible on days of unbroken sunshine. If the instrument output is logged hourly, it is advisable to reduce all hourly totals greater than 1.00 h to 1.00 h exactly using the 'search and replace' function in a spreadsheet to eliminate this glitch. The daily sunshine total should then be taken as the sum of the hourly durations, rather than the 24 hour logged value or the reading from the digital display, both of which will include the 'overcounts'. If only the digital display value is used for daily totals, be aware that on days with long spells of unbroken sunshine the displayed value may exceed the maximum possible sunshine duration.

A more serious drawback to this instrument is its dependence on a 12 v AC supply (through a mains transformer). Power outages result in loss of record, although this is not obvious because even when logged the gap is shown only as 'nil sunshine' rather than 'missing data' (and of course there is no way to determine whether a gap in record has occurred solely from the digital display unit). Supplementary records (eye observations or logged solar radiation data) are therefore required to assess whether the Sun was shining while the power was off and thus complete any short gap in the record.

Perhaps the biggest objection to this instrument is its vague threshold calibration. The control unit includes a potentiometer which can be adjusted to vary the detection threshold of sunshine. This is not difficult to do, requiring only a minor adjustment with a screwdriver on a day when borderline hard-edged shadows are cast through thick cirrus or similar (best to set this once, check it a couple of times on suitable occasions, then leave it alone rather than constantly fiddle with it), but clearly the threshold setting is partially subjective. At the time of writing, a comparison is under way to compare two identical instruments with the potentiometers adjusted in the opposite direction, to assess the impact over several months on logged daily and monthly sunshine totals. Better still, of course, would be for the manufacturers to offer a laboratory-based calibrated threshold traceable to the WMO definition of sunshine, perhaps for a small additional fee above the standard instrument pricing.

The Kipp & Zonen CSD sunshine recorder

This sensor (**Figure 11.12**) replaced the Campbell-Stokes recorder as the ‘standard sunshine sensor’ of the UK Met Office in 2003. It has now almost entirely displaced the Campbell-Stokes instrument at Met Office-staffed sites, although most of the Met Office’s co-operating climatological stations which measure sunshine still use the traditional instrument. The Kipp & Zonen instrument has also been adopted as a standard instrument by the German weather service, Deutsche Wetterdienst. With increasing automation, and the continuing rise in the price of sunshine recorder cards, it seems likely that more and more sites will adopt one or other of the electronic sensors over time.

Its operating principles are similar to the Instromet sunshine sensor, but it is considerably larger (and very much more expensive – in 2012 it was almost eight times the price of the smaller instrument). It is also the fastest-reacting of the sensors

Figure 11.12. Kipp and Zonen CSD electronic sunshine recorder; UK Met Office, Exeter. (Photograph by the author)

covered here, with a time constant of less than a millisecond, enabling it to record short bursts of sunshine only a second or two in duration. Unlike the Instromet sensor, which needs only to be mounted level and aligned roughly due south, the Kipp & Zonen requires latitude setting at installation. It also requires regular replacements of a desiccant cartridge to avoid internal misting, ruling out installation in sites where the unit cannot be safely reached relatively frequently.

The Blake-Larsen sunshine recorder

A very recent addition to the genre, the Blake-Larsen sunshine recorder (**Figure 11.13**) was announced in 2011. The device uses a relatively simple solar irradiance measurement similar to the global radiation measurement from a pyranometer coupled with sophisticated software to determine 'sunshine/no sunshine' output, the duration of 'sunshine' then being summed using an attached PC. As a newcomer to the field, there are as yet few comparative tests with which to assess its performance against other sensors: some preliminary results are available online at www.sunrecorder.net.

Other types of sunshine recorder

The Haenni sunshine sensor uses a rapidly-rotating metal shutter briefly to obscure the direct solar beam from an array of photocells. If the Sun is shining, the passage of the shutter causes a brief drop in the cell output, whereas in cloudy conditions the output drop is very small. With suitable adjustments to the trigger threshold, the sensor provides an electrical 'sunshine/no sunshine' output with a small time constant. A drawback is that the instrument requires continuous power to drive the shutter mechanism, and it is therefore less well suited to remote AWS sites. Results of a comparison of sunshine recorders including this instrument run by WMO in

Figure 11.13. Blake-Larsen sunshine recorder. (Photograph by Ole Jul Larsen)

Budapest in 1984 [18] show that the Haenni sensor had a threshold of 200 W/m^2 rather than the WMO standard of 120, and it therefore under-recorded sunshine. One of the first electronic sunshine sensors, the instrument is less often encountered today.

Comparisons between different models of sunshine recorder

The various models of sunshine recorder each measure ‘sunshine’ slightly differently. Experience from within the UK and The Netherlands has shown that electronic sunshine sensors tend to record slightly more sunshine than the traditional Campbell-Stokes model during the winter months, about the same on days with long spells of unbroken sunshine, and considerably less during spells of broken sunshine, particularly in summer. A short series of comparative trials of five sunshine sensors (including a Campbell-Stokes unit) were undertaken by the UK Met Office during 1998/99 [19], and it was as a result of these trials that the Kipp & Zonen CSD1 electronic sensor (now the CSD3 model) was eventually adopted by the UK Met Office as its standard.

While several comparisons between (loosely) ‘traditional’ and ‘electronic’ sensors have been carried out [for example, 8, 20], results show that there is no simple ‘conversion factor’ to give an ‘equivalent value’ for one instrument based upon readings from the other. Based upon these side-by-side trials, empirical monthly mean ‘conversion factors’ between some models have been published, but hourly and daily relationships are highly variable and derived daily values simply unreliable. Indeed, because different instruments operate on very different principles, attempts to merge two or more sets of records in a seamless fashion seem doomed to failure (see also Box, *Are today’s sunshine measurements compatible with those made last year or last century?).* Any sites considering changing from one instrument to another should plan on a substantial overlap period – at least 2–3 years – to avoid irreparable damage to existing record homogeneity.

It does seem feasible that the results obtained from different models of electronic sensor based upon similar principles, such as the Kipp & Zonen and the Instromet units, might be expected to be closer to each other than the output from the older Campbell-Stokes recorder. At the time of writing, side-by-side trials are under way to understand how closely records from the main types of sunshine recorder in use within the UK and Ireland compare with one another. The trials are being undertaken jointly by the Chilterns Observatory Trust and the UK Met Office, and are taking place at three sites in England (one coastal, two inland) over a 2 year period.

Estimating sunshine duration from pyranometer data

In theory at least, it should be possible to provide a measure of the duration of sunshine directly from logged global solar radiation records obtained from a pyranometer, using an appropriate threshold to determine the ‘sunshine/no sunshine’ cutoff point. The threshold varies with solar elevation (and thus season) and the elevation response of the pyranometer sensor (the cosine of the solar elevation). Various algorithms have been devised in an attempt to do this [21, 22]. Most involve a comparison of the current or logged value of solar radiation with the calculated maximum for that date, time and place, using astronomical tables. When the value of incident solar radiation exceeds a threshold, usually a fraction of the calculated maximum possible global solar radiation at that location and time, then that interval is counted as ‘sunshine’. The arithmetic involved is rather laborious, although modern programmable loggers with powerful on-board processing capabilities can undertake the threshold calculations ‘on the fly’, comparing pyranometer readings minute-by-minute to produce a real-time binary (yes/no) sunshine output. These minute-by-minute markers are then summed by the logger to generate hourly and daily sunshine durations or percentage sunshine values, as required. Alternatively, the logged output from a pyranometer, or a network of sites, can be retrospectively processed by computer to determine hourly and daily sunshine durations. As ever, the devil is in the detail, and different methods can sometimes produce very divergent estimates[*].

The Dutch state meteorological service, KNMI, pioneered algorithm-based estimates to derive estimates of sunshine duration from pyranometers in 1992 [22], replacing its network of Campbell-Stokes recorders, and this method is outlined in current WMO publications [2]. An alternative method has also been published by Campbell Scientific [23]. A useful recent summary and comparison of several methods is given in reference 24.

But how do such estimates compare against measurements from dedicated sunshine recorders exposed at the same site? None of the various methods in use have yet been shown in independent evaluations to provide good and consistent agreement with the records from any particular type of sunshine recorder, particularly at hourly and daily timescales, although some methods do claim a reasonable statistical agreement when comparing totals over monthly or annual timescales. This clearly poses numerous difficulties with regard to the continuity of existing historical records of sunshine (see Box, *Are today’s sunshine measurements compatible with those made last year or last century?*). More work is urgently needed to verify and standardize the approaches taken.

The main difficulty is undoubtedly in establishing the threshold from ‘no sunshine’ to ‘sunshine’, which varies with cloud conditions, often on a minute-by-minute basis. Clearing fog can give rise to very high levels of diffuse radiation which can easily be interpreted as sunshine, even though it is unlikely that clear shadows would be cast under such circumstances. Days with thick high cloud cover, where the level of solar radiation may be very close to the ‘sunshine/no sunshine’ threshold, or a day with broken cumulus, give very different results for only small changes in the assumptions made in the program. Variations in solar elevation, seasonal factors and site characteristics (coastal, inland or mountain sites may all react differently) further complicate the picture. Until agreement on a common threshold algorithm methodology can be reached within WMO’s membership, true comparability of pyranometer-based sunshine estimates from country to country and year to year will remain elusive. If a WMO standard method can be agreed and communicated, it may yet lead to a global standard measure of ‘daily sunshine duration’.

For the time being at least, it is advisable to regard sunshine durations derived solely from global solar radiation instruments as ‘rough estimates’ which are likely to

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[*] Owners of a Davis Instruments Vantage Pro2 AWS will notice that the system shows estimates of ‘sunshine duration’ when fitted with an optional solar radiation sensor. Unfortunately, these are obtained simply by summing the duration of *global* solar radiation exceeding 100 W/m^2 rather than by adopting one of the more sophisticated methods outlined in this chapter. As the solar radiation graphs in **Figures 11.6** clearly show, this quantity bears little relation to the true duration of sunshine, and leads to a huge over-estimation of the true duration of sunshine. The method, and its results, cannot be recommended.

differ – often by large amounts – from measurements made with dedicated sunshine recorders. For this reason, the source of any 'sunshine' measurements – instrumental or calculated, together with any changes – should be clearly identified in the station metadata (Chapter 16).

Are today's sunshine measurements compatible with those made last year or last century?

The answer depends upon which country's records are being referred to, but the answer is almost certainly 'no'. As an example, let us look at the situation in three different countries – The Netherlands, the United States and the United Kingdom.

In **The Netherlands**, sunshine records were made using Campbell-Stokes recorders until 1992; records using this instrument commenced at De Bilt, near Utrecht, in 1901. In 1992 a new method of determining sunshine from records of global solar radiation was adopted throughout the country's climatological network [22]. Comparisons between old and new methods [25] from overlap observations made at De Bilt 1993–2000 showed that the new method gave an average of 16 per cent greater sunshine duration than the Campbell-Stokes during the combined winter months (December, January and February) but 7 per cent lower during the summer period (June, July and August combined). As summer months are sunnier than winter, average differences almost cancelled out over the year as a whole, although considerable variations remained from year-to-year depending upon the character of the weather in that year. It is clear, however, that the two periods of record (1901–1992, and since 1992) are not homogeneous. The new approach used by KNMI in Holland does produce an estimate of sunshine duration that is consistent from location to location across the country, together with a consistent dataset of 'sunshine' records from 1992, but at the cost of losing compatibility with those made in any other country. The KNMI method is included in the current (2008) WMO guidelines [2], although to the best of my knowledge it has not yet been implemented by any other country.

In the **United States**, the historical sunshine record has been based upon three 'standard' instruments in use at different periods [26] – the Jordan photographic sunshine recorder (in use between 1888 and 1907), the Maring-Marvin thermoelectric sunshine sensor (1893 to the mid 1960s), and the Foster-Foskett sunshine switch, progressively introduced from 1953, retired in 2009/10[*]. All three instruments differed in their method of recording and their sensitivity and responsiveness to solar radiation. For example, the 'sunshine' threshold of the Maring-Marvin thermoelectric sunshine recorder averaged 255 W/m^2, while its response time to the appearance or disappearance of the Sun was stated as '5 to 10 minutes' [16]. In contrast, the threshold of the Foster-Foskett sensor averaged just 87 W/m^2 – one-third of the previous device in use, and subject to frequent and subjective manual adjustments. Although some analysts assert the basic homogeneity of the U.S. historical sunshine record remains intact [27], such

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[*] Very few American sites used the Campbell-Stokes recorder; one notable exception was the Blue Hill Observatory in Massachusetts (see Chapter 1), where records commenced in 1885, and continue today.

conclusions appear to be optimistic at best given the enormous disparities in instrument performance. When considered alongside the long-standing documented policy to include manual 'guesstimations' of sunshine duration for low solar angles and missing data due to obstructions or defective record [1, 15, 26], which clearly introduce an additional variable subjective component into the records from each individual site, it is difficult to understand how the U.S. historical sunshine record can be regarded as anything other than seriously flawed – doubts first raised in print as far back as 1985 [28]. The decision to drop the Foster-Foskett sunshine switch in 2009 was perhaps partly brought about by the realization that records from this instrument lacked the consistent and repeatable performance necessary to be able to compare records between different sites and within long single-site records. It remains to be seen whether any attempt to 'homogenise' U.S. historical sunshine records can be attempted, based upon any overlaps that exist between sites with pyranometer, pyrheliometer and Foster-Foskett datasets. Perhaps 'sunshine duration' will cease to be published in U.S. climatological reports.

In the **United Kingdom**, the earliest records made with a prototype Campbell-Stokes recorder date back to 1875/76. A handful of sites have sunshine records made at the same site with the same type of instrument – although almost certainly not the *same* instrument – extending back 100 years or more. Campbell-Stokes sunshine recorder records commenced at the Radcliffe Observatory in Oxford, England in February 1880 [29] and continue to this day[*]. The introduction of electronic sunshine sensors was led by the UK Met Office following comparative trials in 1998/99 [19], following which the Kipp & Zonen CSD sunshine recorder was finally adopted as the standard or reference instrument in 2003. Overlap measurements were made at several sites, for a limited period, and the results published [20]. Although no break in record homogeneity is welcome, not to embrace the benefits of the more accurate and consistent records available from modern electronic sensors, as described elsewhere in this chapter, is surely unwise. The detrimental effects of any major change of instrument can be minimized by ensuring two or more representative series of overlapping records using both instruments are carried out prior to any change. (The overlap should be at least several years in length for sites with long records made using the older instrument.) Where records from the old and new instruments are unlikely to be truly seamless, as is the case here, it makes sense to adopt the new instrument across all other sites as quickly as possible, ensuring a degree of record overlap wherever feasible, to minimize the resulting period of ambiguity.

The policy of the UK Met Office in this regard is puzzling, however, in that sunshine durations reckoned from the newer instrument are adjusted to 'emulate' the older model, despite its known deficiencies, rather than vice versa. As the substitution of Campbell-Stokes recorders with automatic electronic sensors

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[*] Astonishingly, the original unit remained in daily use for 96 years! It was finally replaced in September 1976, when a new instrument was installed on a more open rooftop site a few hundred metres distant. According to Gerald Stanhill [10], the Campbell-Stokes recorder currently in use at the Royal Observatory in Cadiz, Spain has been in operation since 1871. As this would predate prototype trials at Kew Observatory in 1875/76, a start date in the early to mid-1880s seems the more likely.

continues to gather pace, for the reasons outlined elsewhere in this chapter, a point will be reached within a very few years where the *majority* of records are being adjusted simply to retain consistency with a fast-disappearing *minority*, with all sorts of downstream statistical fudges and confusion. In this case, surely it would be better to accept that the two types of instrument are essentially incompatible, and to move forward on the basis of overlap comparisons at as many sites as possible. The lack of clarity in the current situation is increasingly damaging to the historical sunshine records of the United Kingdom.

Calibration of solar radiation and sunshine sensors

Pyrheliometers

Checking and calibration of national and international-standard reference pyrheliometers takes place at intercomparisons organized by WMO, which take place every 5 years at the World Radiation Center (WRC) at Davos in Switzerland [30]. The WRC ensures worldwide homogeneity of meteorological radiation measurements by maintaining reference instruments which are used to establish the World Radiometric Reference and transferable calibrations.

Pyranometers

WMO [2] recommend pyranometer calibrations be undertaken using side-by-side comparisons between the records of an instrument of known calibration (pyrheliometer or pyranometer) and the sensor requiring calibration. This can be done externally (by comparing logged records over a period of time and under various weather conditions and solar elevations), or using standard light sources in a laboratory. National meteorological services have instruments of known calibration, themselves calibrated against national or international standard instruments, which can be used as travelling standards for this purpose. Alternatively the instrument manufacturer may be able to provide, or refer to, a calibration facility which can undertake the instrument calibration or recalibration. Recalibrations are advised at 2 year intervals.

Where no side-by-side calibration facilities are available, approximate calibrations can be obtained by comparing records with a nearby site using an instrument of known calibration, although the errors in doing so obviously increase with distance. Summarized records of solar radiation are published in most countries, an increasing number online and in real-time or nearly so. Daily and monthly solar radiation totals vary less than the equivalent statistics for sunshine duration, and interpolations between sites are often possible, even over considerable distances, provided there are no significant exposure or climate differences between the two regions (a valley site subject to persistent winter fogs would not be a good comparison for an upland location, for example).

Sunshine recorders

WMO guidelines [2] state unambiguously that ‘no standard methods of calibrating sunshine recorders are available’ – indeed, this is part of the difficulty in obtaining a 'standard sensor'. Side-by-side comparisons with direct pyrheliometers are feasible only at well-equipped national or international observatories. Probably the best ongoing method of checking output is observing the threshold of detection, or loss of signal, at times when the sunshine is borderline – when shadows are becoming distinct or hard-edged. If the recorder is 'on' when no shadows are visible, or when indistinct shadows are evident, or 'off' when distinct shadows are present, the threshold may be incorrectly adjusted. Frequent threshold adjustments introduce a subjective element into the record, however, and should be avoided.

Site and exposure requirements

An unobstructed horizon

The ideal exposure for any sunshine or solar radiation sensor is a clear horizon below the level of the instrument, as any obstructions will reduce sunshine duration or solar radiation receipts. A flat roof will often provide a suitable location to locate solar radiation or sunshine sensors, provided safe and secure access is available. Exposing the sensor or sensors on masts may also be acceptable, once again providing safe access can be ensured (see below). Failing this, the instruments should be mounted on a secure and rigid stand 1–2 m above ground level in the most open and unobstructed position available.

Obstructions just above the instrument's horizon (up to about 3 degrees elevation[*]) will have negligible impact on the record, as discussed earlier in this chapter. Obstructions greater than about 3 degrees (corresponding to an object 3 metres above the level of the instrument located 50 metres away) will result in some reduction in record, the effect varying with azimuth (compass bearing) and solar elevation (time of day and time of year)[†]. Obstructions to the north of the instrument[‡] will have much less effect than those from the south, providing they do not reflect solar radiation back onto the sensor/s, while shading from deciduous trees will be less in the winter months.

In particular, a *sunshine recorder* requires (as far as is possible) an unobstructed horizon above 3° elevation for the range of azimuths where the Sun rises or sets during the course of the year – in mid-latitudes, roughly between north-east and south-east, and between south-west and north-west. Some obstruction to the south is permissible provided it does not extend above the elevation of the Sun at noon on the winter solstice (which at 50°N is about 17 degrees, and at 60°N 7 degrees). An obstruction in the path of the Sun around the sky will appear simply as a period of 'no sunshine' for the period where the Sun is obstructed. (See *Assessing the impact of shade*, below.)

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[*] Information on how to determine azimuth angles and elevations and making a site plan is given in Chapter 6, *Precipitation*.

[†] It is notable that the 'pyranometer/threshold' method adopted by KNMI in The Netherlands [22, and WMO reference 2, Annex therein] ignores all pyranometer readings below 5.7 degrees solar elevation. In Washington, D.C. (38.9°N) on 21 December, this would disqualify the first 40 minutes of record after sunrise, and the same period before sunset; in Amsterdam (52.4°N), the first and last hour; whereas in Reykjavik, Iceland (64.1°N) the Sun does not reach this elevation at any time between 23 November and 20 January. Although midwinter days are very short there, Iceland's capital does experience *some* midwinter sunshine!

[‡] All azimuths, compass bearings and references to obstructions referred to in this chapter refer to the northern hemisphere unless stated otherwise.

For *pyranometers*, obstructions will block most or all of the direct radiation but only some of the diffuse radiation from that part of the sky, and the effects of shadowing on the record are therefore generally less pronounced. Provided that there is reasonable exposure between east and west through south, that there are few significant obstructions in or around the Sun's path in the sky within about 3 hours on either side of local noon, and assuming that the instrument is not badly oversheltered by obstructions in other parts of the sky, daily solar radiation receipts should not be reduced by more than about 10 per cent compared with an unobstructed site – and this is the order of magnitude of the instrumental error in any case. Sites subject to reflections from windows, light-coloured buildings or even a white thermometer screen poleward of the instrument should be avoided for obvious reasons.

The exercise below is particularly valuable to identify in advance whether or not a particular site is suitable for solar radiation or sunshine instruments. If the site is unsuitable, the expense of the instruments can be avoided.

Assessing the impact of shade

The likely extent of obstruction to a sunshine or solar radiation record can be judged accurately by measuring local site obstructions and plotting them on to onto a *solar elevation diagram* (**Figure 11.14**). These are available as custom-drawn PDFs at http://solardat.uoregon.edu/SunChartProgram.html. Enter the site latitude and longitude and specify time zone to produce two site-specific diagrams, one for December to June, the other June to December. Each diagram shows the azimuth and elevation of the Sun at monthly intervals throughout the year; the curved lines crossing the date curves show the time in UTC or other chosen time zone. Thus, from **Figure 11.14**, top it can easily be seen that at this site at 1100 UTC on 20 April, the Sun will be 48 degrees above the horizon, and its azimuth 157° True.

Next, take a series of digital photographs from the instrument site (or planned site), and assemble these into two panoramas (there are a number of freeware photographic 'stitch' utilities available on the Internet which will do this). One should cover north-east to north-west through south, the other west to east through north. Use a good sighting compass to obtain accurate bearings, and mark azimuths at 10 degree intervals on to a printed version of the panorama photograph. Remember to allow for any variation between magnetic (compass) north and true north – http://www.magnetic-declination.com/ will provide this information. (Azimuth bearings should always be relative to true north.)

Then, with a clinometer (some compasses include a built-in clinometer), measure the elevation of obstructions above the horizon every 10 degrees around the compass, and mark the readings directly on the photograph. Remember to do this from as near as possible to the site where observations will be made, to ensure the elevations relate to the site and height above ground of the instrument, and not to a nearby ground level.

Next, mark in the 'skyline' of obstructions on one of the solar elevation diagrams using the elevations measured at each 10 degree point. Use the detail of the photograph to fill in a realistic skyline between the plotted 10 degree points (**Figure 11.14,** bottom). Indicate whether trees are deciduous or evergreen as appropriate – as the extent of obstruction may vary considerably between winter and summer.

When this is complete, copy the 'skyline' to the other solar diagram (the months are symmetrical about the solstices, only the hour curves differ between the first half and second half of the year).

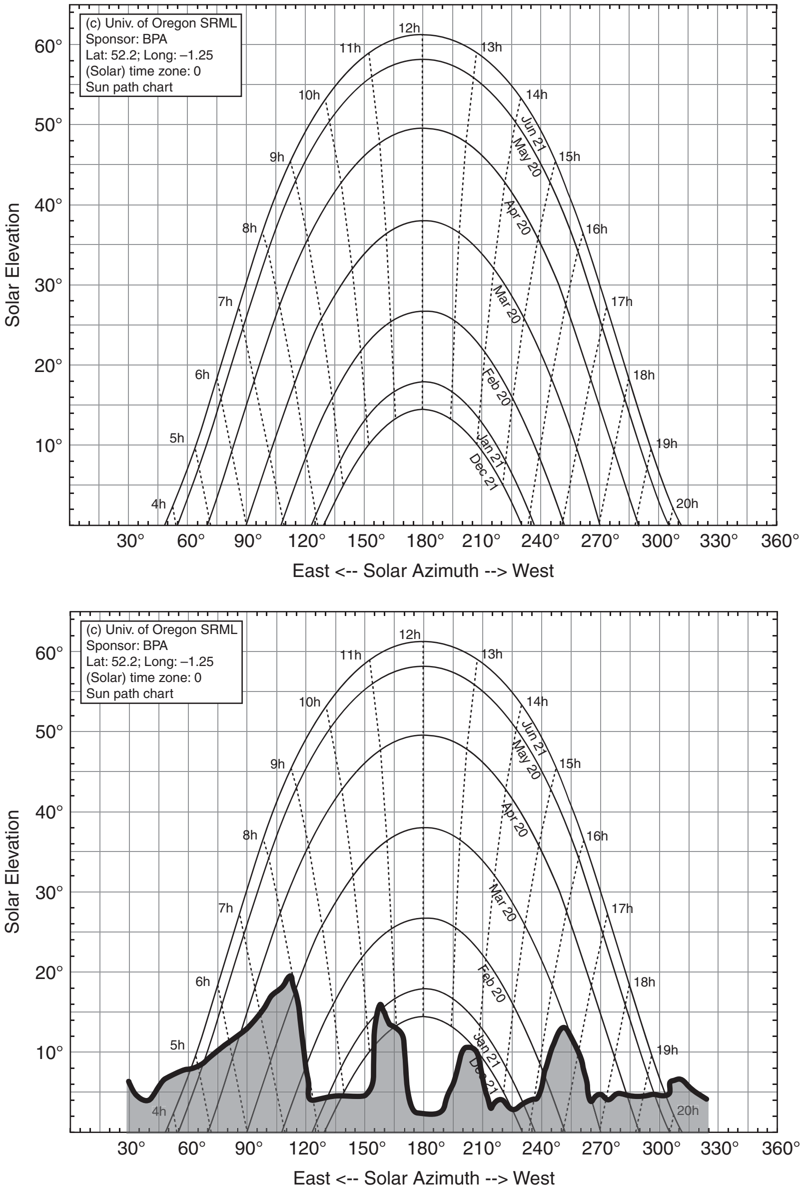

Figure 11.14. *Top* Solar elevation diagram; this is the December to June diagram. (Courtesy of University of Oregon Solar Radiation Monitoring Laboratory). *Bottom* Solar elevation diagram with measured elevations of obstructions plotted and obstruction path shaded. From this it can be seen that the greatest obstruction to sunshine records at this site will be around 20 March, with about 3.5 hours shadowing to be expected; however, about 45 minutes of this is below the 3° threshold in any case.

Using the two diagrams, carefully estimate the potential duration of obstruction for each date curve throughout the year, to the nearest 0.1 hour. Compare these to the ‘realistic maximum possible’ sunshine duration for these dates (in this context, the ‘realistic maximum possible’ duration is the length of time the Sun is above 3 degrees elevation on that date curve, as obstructions below about 3 degrees have little effect). Evaluate the potential loss of record on that date (obstructed hours / realistic maximum possible duration, as a percentage). The actual loss will be less than this – to a fair approximation, it will be proportional to the climatological percentage of maximum possible sunshine in any month, because not every hour will be sunny. In mid-latitudes, the actual reduction in sunshine records will be *very roughly* one-third of the possible obstruction percentage, and about half that figure for pyranometer records. In middle and high latitudes, or other regions where the monthly mean cloud cover or daylight hours vary significantly during the year, the average annual loss will be weighted towards the sunnier months, which normally experience lower obstruction losses owing to higher solar elevations.

The exercise should be repeated every 2 years to check on the growth of trees, or if a significant obstruction (a new building, perhaps) appears likely to affect the exposure. The slow growth of trees can insidiously wreck the exposure of solar instruments. Regular sets of panorama photographs taken at the same time in the year, 2 years apart, are useful to assess these slow skyline changes. Reductions in solar radiation or sunshine duration at the site due to tree growth may otherwise become apparent only after several years comparison with one or more unobstructed nearby sites – by which time the damage has been done, of course.

Other useful solar geometry sites

Jonathan Sachs ephemeris: http://home.comcast.net/~jonsachs/Ephemeris.htm
Sunrise/sunset times: http://www.esrl.noaa.gov/gmd/grad/solcalc/
Solar calculator: www.esrl.noaa.gov/gmd/grad/neubrew/SolarCalc.jsp

Perfect sites are hard to come by – what about obstructions to the record?

It is almost impossible to make accurate estimates of any sunshine 'lost' owing to obstructions unless they are very short, and first-hand observations or unobstructed solar radiation records are available. Doing so risks introducing a subjective variable element into the record, which should be avoided: sunshine or solar radiation measurements are best tabulated 'as recorded'. A metadata note (see Chapter 16) combined with site and solar diagrams should be used to describe all significant obstructions which may affect the record, and this should be updated – with photographs wherever possible – every 2 years, as detailed above.

Having said this – **very few sites are perfect**. 'Calculated' obstructions of 15 per cent or less in any month or over the course of a year (in mid-latitudes, typically resulting in about 5 per cent actual reduction in sunshine records) are generally acceptable. More significant obstructions (15–25 per cent) can be expected to result in greater losses of recorded sunshine, perhaps 10–15 per cent when compared with nearby 'standard' sites. Locations where the measured obstructions amount to 25 per cent or more are likely to be too obstructed for meaningful sunshine or solar radiation measurements in any normal meteorological sense, although of course this objection may not apply to natural obstructions in mountainous regions or to (for example) site-specific agricultural or microclimate studies.

Levelling, azimuth and latitude adjustments

It is very important that solar radiation or sunshine instruments be mounted securely and accurately level. Particularly with solar radiation sensors, a tilt of even a few degrees towards or away from the Sun is likely to result in large errors in output measurements. Once installed, the level should be checked at least twice per year and adjusted as necessary. Most instruments have one or more small built-in spirit levels to facilitate regular level checks.

Almost all instruments require accurate azimuth alignments, usually to face due true south. Some require very precise alignment, and for this an accurate compass is essential (compensation from magnetic north must also be taken into account). Pyranometers have a 360 degree field of view, and although in theory they are azimuth-independent, in some instruments the sensitive elements of the thermopile will have been calibrated assuming a particular alignment. If in doubt, or if no azimuth alignment is specified, orient the device so that the output cable emerges on the poleward side of the unit away from the noonday Sun.

Campbell-Stokes and Kipp & Zonen sunshine recorders also need to be adjusted for latitude at installation (this needs to be done once only). Ensure the latitude adjustment screw is firmly tightened after setup to avoid later slippage.

Exposure at height

The preferred exposure for solar radiation sensors or sunshine recorders is, much like wind instruments, ‘as open as possible’ – which often means ‘as high as possible’. If the location chosen for the instruments cannot be accessed safely for installation or maintenance, with appropriate equipment such as a ladder or scaffolding tower, then choose another site. **Do not put yourself or others in danger when installing or maintaining meteorological instruments at height**. See also Box, *Important safety considerations for installing and maintaining weather instruments* in Chapter 4, on page 78.

Site security is a particular issue with solar radiation and sunshine instruments, particularly the glass sphere which is an integral part of the Campbell-Stokes recorder. Some sites within the British Isles suffer repeated thefts of these attractive objects.

Specialist contractors (TV and satellite aerial fitting companies, or a local builders) will often be able to quote for installing meteorological sensors on roofs, disused chimneystacks and the like provided the requirements are made clear to them in advance. Because alignment and level are critical on solar sensors, check beforehand – perhaps by temporary installation at ground level – that the fittings to be used will hold the instruments accurately and securely in position, and that they are robust enough to survive strong winds, snowfall, UV exposure and other weather hazards, most of which will have greater impact at height. If arranging for a contractor to fit or maintain instruments which require accurate level or azimuth adjustments, ensure the operator is clear what is required *before* commencing operations – perhaps with a short prior demonstration at ground level. It is much easier to do this than when he or she is at the top of a ladder and cannot easily hear instructions! If the location chosen for the instrument/s is not readily accessible, it is vital to ensure during installation that cabling is secured and all risk of chafing eliminated. All connections must be made secure and fully weatherproof, and all cables shielded as voltages are very small. Frequent contractor visits to fix minor issues (cables flapping in strong winds, battery replacements on wireless sensors or water ingress into connectors) will quickly become very expensive.

It is advisable to wipe over the dome of a pyranometer or sunshine sensor occasionally, but this may not be possible if the instruments are difficult to access, and in dusty locations dust accumulations on the sensor may affect readings. On the plus side, sensors located at height often experience much less condensation-related obstruction as a result of dewfall than sensors at ground level. It may be difficult to maintain level when instruments such as pyranometers are mounted on tall masts, particularly if the mast sways a little in the wind. Clearly, where the site is inaccessible some records may be lost owing to obstructions which cannot easily be cleared (particularly the accumulation of ice or snow), but **on no account should personal safety risks be taken to reach the instruments in difficult or dangerous weather conditions**.

Logging requirements

Logging requirements for solar radiation and sunshine sensors vary with both instrument type and the application.

Solar radiation sensors: solar radiation intensity can and does vary very rapidly (**Figures 11.6** and **11.7**). If the requirement is to capture variations in daily solar radiation in fine detail, a high sampling and logging rate (1–5 seconds and 1 minute, or even less, respectively) will be required, assuming the time constant of the instrument is fast enough to justify doing so. For many climatological purposes, hourly and daily means and extremes (perhaps the highest 60 second mean within the hour) are quite adequate for most purposes. The logging interval can be much less frequent than the sampling interval if only hourly or daily means are required.

Electronic sunshine recorders: for instruments such as the Instromet sunshine recorder, which provides a square-wave pulse count every 0.01 h, an hourly logging interval (pulse counting) is sufficient for most climatological purposes, although for comparison with other elements a 1 minute logging interval can be useful (**Figures 11.6** and **11.7** were drawn from 1 minute data). For other sensors which output a binary 'sunshine yes/no' signal, logging needs to be at least at 1 minute resolution to provide daily sunshine totals to an acceptable precision. If the logger sampling time is 1 second (or less), and the instrument's response time is fast enough, it is easy enough to obtain period sunshine totals to a precision of 1 second, although this level of precision is unnecessary for normal climatological purposes.

Daily solar radiation measurements

The intensity of solar radiation is expressed in units of Watts per square metre (W/m^2). These units are used for *instantaneous* values of solar radiation, or averages over short periods (up to about an hour). For periods longer than about an hour, *total solar radiation* inputs are integrated over time using the unit Joules per square metre (or, more usually, Megajoules per square metre) – one Joule is one Watt per second. The daily total solar radiation measure is the integral with time of the day's instantaneous values – easiest to envisage as the area under the curve of sampled solar radiation intensity shown in **Figures 11.6** and **11.7**.

To obtain the daily total solar radiation from sub-daily records (best performed in a spreadsheet):

		Example
Derive the 24 hour mean solar radiation intensity in W/m^2 from logged output *The number of readings does not affect the calculation, although obviously the sampling and logging frequency must be high enough to be representative of the day's conditions, especially on days where it changes rapidly: 1 minute is preferable, 15 minutes the maximum*	Ensure the full 24 hours are included, not just positive readings in daylight. Note that most pyranometers will show a slight negative value during darkness owing to outgoing terrestrial radiation, particularly under clear skies, and for accurate work it is best to set all negative readings to zero in the calculation of daily means	224.6 W/m^2
Multiply by 86,400	The number of seconds in the day	19,405,440
Divide by 1,000,000	1 W = 1 J/s, so this factor scales from Joules to Megajoules to attain a more manageable number	19.405 440
	Total daily global solar radiation on a horizontal surface	**19.41 MJ/m^2**

Time standards and terminal hours

Daily solar radiation totals and sunshine durations are normally quoted for the time zone's civil day, that is, midnight to midnight, excluding any summer time adjustments. More specialized solar radiation applications may require the use of Local Apparent Time (LAT), sometimes known as 'true solar time'. Noon in LAT is, by definition, when the Sun reaches its highest elevation over the observing position. Astronomical tables or Internet-based calculators show LAT, which can vary by almost 20 minutes on 'local mean time'. A very useful downloadable calculator providing LAT, sunrise and sunset times and hours of daylight (useful for 'percentage of maximum possible' sunshine calculations) for any location (enter latitude, longitude and time zone, and year) can be downloaded from http://www.esrl.noaa.gov /gmd/grad/solcalc/calcdetails.html – choose 'NOAA_Solar_Calculations_Year' in the spreadsheet format preferred.

It is more difficult to set up a standard datalogger to log using LAT than standard clock hours, and it may be easier to log at 1 minute intervals and adjust hourly solar radiation means and extremes to LAT retrospectively by software if required

More information on terminal hours is given in Chapter 12.

Accuracy versus precision

Barring gross errors owing to excess shadowing, particularly obstructions in the southern half of the sky or those resulting from incorrect levelling or poor calibration, global solar radiation measurements from sites in similar terrain which are reasonably close to each other are more generally comparable than their sunshine durations (see *Calibration of solar radiation and sunshine sensors* above). Davis Instruments quote an expected accuracy of ±5% for their optional add-on solar radiation sensor for the Vantage Pro2 AWSs, although this may be optimistic. The more expensive Kipp & Zonen instruments quote ±10% on total daily radiation accuracies for their CMP3 instrument and 1 per cent for top-of-the-range sensors, in each case with a linearity drift expected of less than 1 per cent per year.

For reasons stated earlier, it will be apparent that measurements of sunshine duration are less consistent from instrument to instrument and site to site than for many other meteorological variables. Agreement to within 5 per cent (i.e., within 30 minutes on a summer's day with 10 hours sunshine) is probably about as good as can be expected. Although electronic sunshine recorders can generate daily totals to a precision of 1 second, in reality inter-instrument variation means that this level of precision is difficult to justify except in instrument comparison or calibration tests. The WMO recommended resolution for daily sunshine duration is 0.1 h (6 minutes). Monthly totals are best quoted to 1 h.

Further Reading

Solar radiation is a complex and fascinating subject with a vast but often highly technical literature. The Kipp & Zonen website www.kippzonen.com contains much useful background reading and definitions of the various terms involved, while Reinhold Rösemann's updated *Guide to solar radiation measurements* (Gengenbach Messtechnik, September 2011) provides an accessible and up-to-date technical account of the topic. A wealth of useful and practical information on radiation measurements is given in the *World Climate Research Programme Baseline Surface Radiation Network (BSRN) Operations Manual* (2004), which is available online at http://www.bsrn.awi.de/fileadmin/user_upload/Home/Publications/McArthur.pdf

One-minute summary – *Measuring sunshine and solar radiation*

- Radiation from the Sun consists of a wide range of wavelengths, from extreme ultraviolet to the far infrared, peaking in the visible region. Solar radiation is amongst the most variable of all weather elements, and consists of two main components – *direct solar radiation* from the solar disk, and *diffuse solar radiation* from the rest of the sky, the latter as a result of the scattering and reflection of the direct beam in its passage through the atmosphere.
- The most common measurements made are of *sunshine duration*, using a sunshine recorder, and *global solar radiation on a horizontal surface*, using a pyranometer. 'Sunshine' is defined in terms of the intensity of a perpendicular beam of visible wavelength solar radiation from the solar disk. The intensity of solar radiation is measured in Watts per square metre (W/m^2), and daily totals in Megajoules per square metre (MJ/m^2). Sunshine durations are measured in hours, or quoted as a percentage of the maximum possible duration.
- There are different models of sunshine recorder. The iconic Campbell-Stokes sunshine recorder has been in use since the late 1870s, although it is being replaced by datalogger-friendly electronic sensors, which give slightly different measurements – the Campbell-Stokes unit tending to over-record in broken

sunshine. Estimates of sunshine can be derived from pyranometer data, although no method for doing this has yet been shown to provide consistent agreement with dedicated sunshine recorders. Changes in recorder types over time (for instance, the transition from the Campbell-Stokes unit to electronic sensors) mean that today's measurements are not directly comparable with measurements made using different instruments in previous years.

- All solar radiation instruments require an open exposure, one with as clear a horizon as possible: a flat rooftop or a mast are often suitable locations. The effects of obstructions can be assessed using a solar elevation diagram in conjunction with a site survey, although obstructions within about 3 degrees of the horizon have little effect on the record. The instruments must also be accurately levelled, and most also require some form of azimuth alignment and/or latitude setting. **Never put yourself or others in danger when installing or maintaining meteorological instruments at height**.
- Calibrations for solar radiation instruments tend to be based upon comparisons with reference instruments. WMO organizes instrument intercomparisons amongst national meteorological services every 5 years to ensure consistent and transferable measurement standards.
- A high sampling interval is advisable for electronic sensors as solar radiation is amongst the most variable of all weather elements. The logging interval can be much less frequent than the sampling interval, and hourly means will be sufficient for many applications.
- Sunshine and solar radiation instruments tend to be slightly more variable in their outputs than many meteorological sensors, and even adjacent instruments can be expected to vary somewhat in their readings. For this reason, all but the highest-specification sunshine and solar radiation measurements should be regarded as prone to errors of up to a few per cent.

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12 Observing hours and time standards

For weather measurements to be comparable between different locations, the time (or times) at which observations are made, and the period covered by the measurements, should be common as far as possible. WMO provides guidance on observation times for the main international synoptic observing networks, while ‘climatological’ observing practice tends to be defined at a country or regional level. It is outside the scope of this book to provide detailed guidance on all aspects of standard climatological observing practice for every country in the world, so this chapter outlines common observing routines, based around a once-daily morning observation. Examples based upon current practice within the United States, UK and Ireland are given where these illustrate generally applicable principles. The importance of common time standards and common time period/s for once-daily values, such as maximum temperature or total rainfall, are stated, and the meaning, relevance and importance of ‘terminal hours’ is introduced.

Country-specific details on observing practices, including standard observing hours and ‘terminal hours’, can be found in the websites or publications of the world’s state meteorological services listed on the WMO website [1].

Time standards – Local Time and Coordinated Universal Time (UTC)

By convention, operational weather measurements throughout the world are made to a common time standard – Coordinated Universal Time (UTC). Greenwich Mean Time (GMT) and UTC are effectively one and the same – the differences are insignificant (less than 1 second) – and for the purposes of this book they are regarded as equivalent.

‘Local time’ differs from UTC depending upon longitude, and whether or not clock adjustments for ‘summer time’ or ‘daylight savings time’ are in force – for example, Pacific Time in the western U.S. is UTC minus 8 hours. During the period of summer time – in the northern hemisphere, typically late-March to late-October – clocks are advanced 1 hour on local regional time. With few exceptions, standard observing hours are based on local regional time without ‘summer time’ adjustments, so that an observation made at 8 A.M. in the winter months would be made at 9 A.M. during the period of summer time[*].

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[*] In the UK, this statement assumes that no changes are made to the long-established practice of adopting GMT (UTC) during the winter months, and adding an hour during the period of Summer Time / Daylight Savings Time. In 2011 a proposal was laid before the British Parliament to change the basis of British clock time to Central European Time (CET = UTC +1) in winter, and CET+1 in summer. The proposal was defeated, but if it were to be adopted at some future date, 0900 UTC would become 10 A.M. in winter and 11 A.M. in summer.

Maintaining consistent observations is greatly simplified where one time standard is used throughout the year. For AWSs on automatic download, using clock time will result in the apparent loss of an hour's data when the clocks are put forward in spring, followed by the greater confusion of two sets of data apparently for the same hour when the clocks are put back in autumn. Most AWS software can be set to 'ignore Daylight Savings Time' clock changes, regardless of whether or not the PC's system clock is so updated, and thus maintain the observation database in a common time standard throughout. The station metadata (see Chapter 16) should make clear which time standard has been used.

Observing hours

Many countries around the world implement a once-daily morning observation routine, the time of the morning observation typically between 7 A.M. and 9 A.M., with some degree of flexibility and variation permissible. Many observers will find it more convenient to make the observation at the same 'clock time' throughout the year regardless of summer time clock changes – some will be unable to make a 9 A.M. observation at 10 A.M. because of working hours, at least on weekdays, for instance. For many a regular once-daily manual morning observation time around 8 A.M. or a little earlier is the norm.

AWSs will of course perform observations throughout the 24 hours, and for instrumental data it is very easy to use AWS records to maintain an adjusted observation record conforming closely to the 'nominal' standard morning observation time (for example, 0900 UTC in the UK and Ireland), even if it is rarely possible to make manual observations at that time. Adopting the national or regional standard observing hour (or close to it) greatly simplifies comparisons of weather observations with other sites – particularly daily rainfall records. For this reason, a daily morning observation time within an hour or so of 8 A.M. to 9 A.M. wherever possible is greatly preferable to one made at other times of day.

Terminal hours

The once-daily morning observation hour has, in turn, defined the standard 24 hour period over which many 'daily' values, such as maximum temperature and total rainfall, are tabulated. Some other elements, such as sunshine, fall more naturally within the 'civil day', midnight to midnight local regional time. The start and end time of these recording periods are known as the 'terminal hours' of that measurement. The term 'terminal hour' refers to the time of day at which the extremes are reset – whether this is the maximum and minimum thermometers being manually reset, or to the datalogger clearing its memory of the highest and lowest temperatures observed in the previous 24 hours and starting again at the time deemed to be the first minute of the new climatological day.

Elements whose terminal hours are based upon different time spans can (and do) cause occasional confusion and inconsistency, because the date upon which the value was recorded can differ from the one to which it is assigned by convention. Historical convention has, rather confusingly, left us with four different

Table 12.1. *Typical terminal hours, by element*

	Terminal hours	Elements
These periods and terminal hours are normally defined by the state weather service for standard climatological observations	**Civil Day** 0000 to 0000 local regional time	Wind speed (means and extremes) Sunshine (daily totals) Global solar radiation (daily totals) Air pressure (daily means and extremes) Mean daily temperatures (derived from sub-daily data) Most 'days with . . .' element counts (see Chapter 14)
	Climatological Day Morning to morning, typically 9 A.M. to 9 A.M. local regional time	Maximum and minimum air temperatures Mean daily temperatures (derived from averaging maximum and minimum temperatures) Daily rainfall totals
	Sunset to 0900 regional	Grass minimum temperatures only
These periods and terminal hours are defined by WMO for the exchange of international observations	**Synoptic Day** Terminated at 0600 and 1800 UTC	Maximum and minimum air temperatures and 12 hour rainfall totals over the periods 0600–1800 / 1800–0600 UTC Within the UK, maximum and minimum air temperatures over the periods 0900–2100 UTC and 2100–0900 UTC are also reported

terminal hour groups, as shown in **Table 12.1**. (These may vary slightly from country to country.) Each is covered in more detail below.

'Civil day' terminal hours

There is no doubt that the civil day (midnight to midnight local regional time) is the obvious and logical choice for terminal hours – here there can be no doubt as to the date of the occurrence. It is also the default for most AWS software. However, as long as the majority of rainfall and temperature measurements are read manually, once daily, it is clearly unrealistic to mandate that such once-daily manual observations be made by thousands of volunteer observers at midnight (1 A.M. in summer time) instead of 8 or 9 A.M.

Many elements are most conveniently assigned to a civil day – daily sunshine and solar radiation totals, for example. For others, the choice of terminal hours makes no systematic difference to monthly means – wind speed and barometric pressure are examples here. For others, particularly temperature and rainfall, long historical convention and the need to retain homogeneity with existing records mandates that existing 'morning to morning' conventions be retained, at least for the time being. It does make good sense, however, to maintain parallel 'morning to morning' and civil day records for temperature and rainfall where AWS records permit doing so. The logic of the civil day is inescapable, and this together with the increasing number of automatic stations, which can provide civil day data as easily as any other 24 hour period, make it probable that it will eventually replace the 'morning to morning' convention for all but rainfall observations.

'Climatological Day' terminal hours

Air temperature

The standard period for 'once daily' extreme temperature records is normally 'morning to morning', as close to the national 'standard morning observation time' as is possible. In the UK and Ireland, this is 0900–0900 UTC, or as near as possible to 0900 UTC for sites that cannot observe at that hour; in the United States, typically 7 or 7.30 A.M. regional time.

By convention, the maximum temperature – which is most likely to have occurred the previous afternoon – is entered to the day prior to the observation, or 'thrown back', while the minimum temperature – most likely to have occurred on the morning of the observation – is entered to the day of reading. Unfortunately, the weather does not always co-operate with these tidy record-keeping conventions, and maximum and minimum temperatures can occur at any time of day. Particularly in temperate latitudes, this quite often results in maximum or minimum temperatures being credited to a different day to the one on which they actually occurred. The problem is most acute and frequent during the winter months.

The following example is not untypical (**Figure 12.1**):

- Thursday morning was cold, with a heavy frost. The temperature at the 9 A.M. observation was –5.7 °C and still falling, and this was entered as the minimum for Thursday. The temperature continued falling slowly for another 45 minutes,

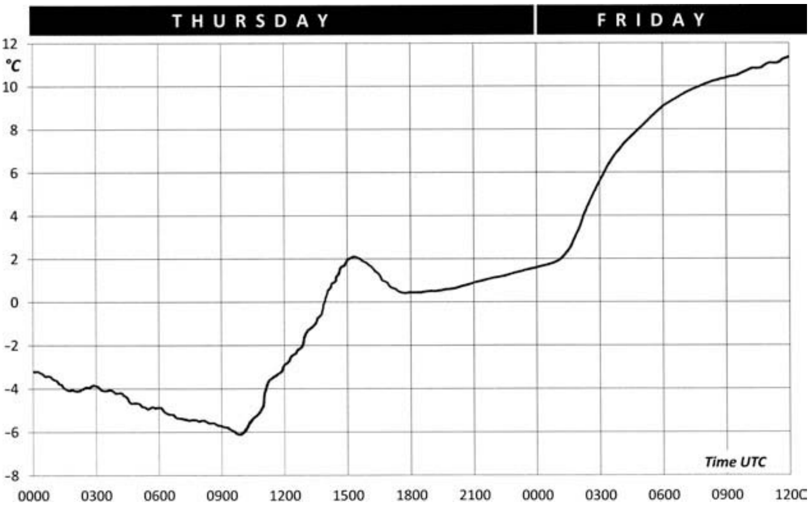

Figure 12.1. An example of the 'day minimum/night maximum' phenomena that occasionally provides bizarre climatological statistics – see text for details.

reaching –6.2 °C at 9.45 A.M. before rising once more. Thursday was cold all day, the highest temperature attained during daylight hours being only +2.1 °C, but after an initial fall the temperature began to rise during the late evening and continued to rise all night. At the 9 A.M. observation on Friday the temperature had risen to 10.5 °C.

- The minimum entered to Friday, –6.2 °C, actually occurred at 9.45 A.M. on Thursday. Friday morning was mild, and the night was frost-free, despite the severe frost indicated by the minimum temperature.
- The maximum entered to Thursday, 10.5 °C, actually occurred at 9 A.M. on Friday. Thursday was a cold day (barely 2 °C), yet the recorded maximum temperature would indicate the opposite.
- Another peculiarity of the method of assigning extremes using the 'morning to morning' convention can happen when the temperature is falling at the morning observation, and continues to fall thereafter. In this case, as on the Thursday example above, the *minimum* temperature for the date is the temperature at the 9 A.M. observation. However, if the temperature continues falling and does not subsequently reach the 9 A.M. value again, the 9 A.M. temperature also becomes the *maximum* for the day. In this case the daily range (the difference between the maximum and minimum) will be zero, despite indications from electronic or mechanical recording instruments that this was clearly not so.

During the winter months in temperate maritime latitudes, airmass and wind direction have far more effect on the air temperature than the Sun, and the 'morning to morning' convention can lead to bizarre results, as above. Particularly in unsettled conditions, maximum and minimum temperatures can be recorded at any time of the day or night.

Synoptic terminal hours

WMO operational guidance is for synoptic reporting stations report maximum and minimum temperatures, and 12 hour rainfall totals, daily at the 0600 and 1800 UTC observations, simply because they are able to do so and have done so for decades. Depending upon longitude and season, however, these may or may not coincide with 'day' or 'night' periods.

Day maximum / night minimum

Within the UK and Ireland, synoptic sites usually report maximum and minimum temperatures at 0900 and 2100 UTC. The 0900–2100 maximum corresponds more neatly to perceptions of the 'day maximum' near the Greenwich Meridian, and similarly the 2100–0900 minimum to 'night minimum'. (Although the time zones are specific, the problem is applicable to other time zones too.) It is tempting to regard these 12 hour periods as somehow more 'truthful' than the 24 hour 0900–0900 values, which (because the air minimum is often reached close to 0900 UTC in the winter months) can easily result in one cold morning showing up twice in the records.

This is flawed reasoning, however, because extremes reached in the other 12 hour period of the day are then lost to the record – and this may well include the highest or lowest temperature in any given month, especially in the winter half-year[*]. Any climatological analysis that knowingly discards such events from the archive clearly cannot be regarded as presenting a complete and accurate picture. The phenomenon occurs so frequently in temperate latitudes that its effects are clearly seen in climatological averages and extremes. Observations from locations using 'day/night' terminal hours cannot be directly compared with those using the full 24 hour span[†].

Table 12.2 shows that at the author's site in central southern England (51.4°N, 1.0°W) during the 10 years 2001–10, an average 28 days per year – 8 per cent of all observations – recorded the day's maximum outside the period 0900–2100 UTC. Whilst these results are obviously specific to a single site, and variations can be expected between different locations and over different periods, they serve to illustrate this important issue.

Although occurrences were most frequent during the winter months (an average 7 days in December, almost twice a week), they did happen in every month of the year. On these occasions the average difference between the 0900–2100 and 0900–0900 UTC *maximum temperature* was a little over 1 degree Celsius: the largest difference was 7.6 degrees. The cumulative effect was to reduce the 0900–2100 UTC mean maximum slightly compared to the 0900–0900 UTC value, by around 0.1 degrees Celsius over the year as a whole, but by more than 0.3 degC in December.

The differences are much greater for *minimum temperatures*: on average, 54 nights per year over the 10 year period (15 per cent of all observations) recorded a 24 hour minimum during the 'daytime' period 0900–2100 UTC. On these occasions the average difference between the 2100–0900 and 0900–0900 minimum temperature was 1.8 degrees Celsius, the largest difference being 9.6 degrees. In December and January, on average around one night in three did not record the minimum temperature during the 'night' period of 2100–0900 UTC. The cumulative effect over the year was to increase the 2100–0900 UTC mean minimum slightly compared to the 0900–0900 UTC value, by almost 0.3 degrees Celsius over the year as a whole, and by nearly a degree in December and January.

Although differences in monthly means of only a few tenths of a degree may sound insignificant, these are of course comparable to sensor calibration error, record biases resulting from sheltered exposure and urban heat island effects. The bottom line is simple – *air temperature records from sites using different terminal hours are not directly comparable.*

It is, however, very easy to adjust AWS data to tabulate daily extremes to a standard 'morning to morning' period using a spreadsheet template, even where manual observations cannot be made at (or close to) the 'preferred' time of the morning terminal hour. See also the section in Chapter 14 on *Observing at set times.*

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[*] Where sites report 'day' maxima and 'night' minima, the corresponding extremes in the 'other' 12 hour period (i.e., the 'day' minimum and the 'night' maximum) should also be reported. Only the full 24 hour span should be used when preparing climatological averages and extremes.

[†] In western Europe, the practice of quoting the '0600 minimum' – the 1800–0600 UTC minimum reported as part of the 0600 UTC synoptic observation – is particularly prone to mislead, simply because for 6 or 7 months of the year the air temperature is still falling at 0600 UTC and the minimum air temperature is not likely to be reached until 2–3 hours afterwards. The '0600 minimum' will therefore almost certainly not be the true minimum for the day. (If the next reported minimum temperature is not until the 1800–0600 UTC period the following day and the temperature continues to fall after the 0600 UTC observation – as it very often does during the winter half-year – the true minimum for the day will not be reported at all.)

Table 12.2 ***Differences in daily maximum and minimum temperatures arising from various terminal hours***
Data for the author's observing site in central southern England, 10 years 2001–2010.
+ indicates warmer than standard 0900–0900 UTC period. Values in degrees Celsius.

		J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Annual**
Mean max	09–21 vs 09–09	–0.20	–0.09	–0.04	–0.03	–0.08	–0.03	–0.02	–0.01	–0.01	–0.09	–0.17	–0.33	–0.09
	00–00 vs 09–09	–0.06	–0.03	–0.01	–0.03	–0.06	–0.02	–0.03	–0.01	–0.01	–0.04	–0.01	–0.11	–0.04
Mean min	21–09 vs 09–09	+0.81	+0.51	+0.21	+0.04	+0.03	+0.01	+0.01	+0.02	+0.05	+0.26	+0.54	+0.94	+0.29
	00–00 vs 09–09	–0.02	–0.21	–0.40	–0.37	–0.42	–0.47	–0.35	–0.44	–0.60	–0.66	–0.35	+0.05	–0.35
Average number of ***days*** *in each month when the temperature extremes differed from the 0900–0900 values:*														
Max attained outside 09–21h		4.8	2.8	0.9	0.8	2.0	1.3	0.6	0.6	0.9	2.6	4.1	6.7	28.1
Min attained outside 21–09h		10.2	6.7	5.0	1.3	1.3	0.8	0.2	1.2	2.1	5.4	8.7	11.2	54.1
Max 00–00h differs from 09–09h		6.4	4.0	1.4	0.9	2.6	1.3	0.8	0.9	1.1	3.2	5.4	8.6	36.6
Min 00–00h differs from 09–09h		20.9	16.9	15.7	10.5	11.5	9.3	8.9	12.0	11.0	16.6	19.1	19.4	171.8

Comparisons between 0900–0900 UTC and 0000–0000 UTC terminal periods are even more difficult to generalize. Over the same 10 year period at the author's site (51.4°N, 1.0°W), the 0000–0000 UTC maximum differed from the 0900–0900 value on an average of 36 days annually (10 per cent of all observations), while the 0000–0000 UTC minimum differed from the 0900–0900 UTC value on very nearly one day in two (average 172 days per year). The effects on the mean maximum and minimum compared with 0900–0900 are much more variable, the largest effects on mean minimum occurring during the summer half of the year.

The logic for an eventual adoption of the civil day as the reckoning period for extremes appears inescapable, particularly as the balance of the observing network shifts rapidly from primarily manual-observation based to automatic. Automated systems can quickly and easily provide extremes tabulated to either period, but 'morning to morning' values will continue to be required for comparison with historical records for the immediate future, and for sites where manual instruments are read only once daily at the nominal morning observation time. Going forward, it seems likely that there will be a move away from historical practices of 'morning to morning' reckoning, towards a standard based upon the civil day. This will avoid any ambiguities regarding the dates of extremes, and will improve consistency with other elements already tabulated in this fashion.

For now, AWS users might be best advised to 'parallel log' daily maximum and minimum temperatures under both 'morning to morning' national standards and the midnight to midnight civil day conventions. That way, should national policies change, both sets of records will already exist for at least a few years. An overlap will enable average differences between the two methods to be determined (similar to **Table 12.2**) and thus any required adjustments to existing site-specific long-term records or averages allowed for.

Effects on mean temperature

By convention, the 'mean temperature' for any period (whether a day or a year) is usually defined as the mean of the daily maximum and minimum temperatures. Of course, the true daily mean temperature can be more reliably calculated from the average of the much greater number of hourly (or more frequent) observations available from an AWS. Over time it seems likely that the 'civil day mean temperature' derived from higher-frequency automatic observations will replace the 'mean of the morning-to-morning maximum and minimum temperatures' as the preferred measure. However, where daily mean temperatures for any site are quoted or compared, the derivation should be clearly stated in the station metadata (Chapter 16) to avoid possible confusion.

Grass minimum terminal hours

WMO guidance is that the grass minimum temperature (and, by extension, other surface minimum temperature observations) should refer to the period from just before sunset to the following morning observation terminal hour. This differs from the normal 'climatological day' standard described above. However, this guidance is becoming blurred at unmanned sites where there is no-one to stow the grass minimum sensor by day and replace it before sunset, or where temperatures are measured by a permanently exposed electrical sensor. Two slightly different observing regimes exist – the 'morning-to-morning' stations and the 'sunset to morning' sites, the former recording a significantly greater frequency of ground frosts.

Grass temperatures fall more quickly than air temperatures during the early evening, and occasionally the night's grass minimum temperature is reached at dusk*. Very occasionally – perhaps a couple of days in every year – the lowest 'morning to morning' grass temperature will be attained during daylight hours (often as a result of rain or hail showers, followed by an overnight rise in temperature).

In these circumstances, the 'daytime' grass minimum should be noted if the sensor has been left exposed, but the 'climatological' grass minimum temperature entered for the day should be the 'sunset to next morning observation' value, per WMO guidelines.

Precipitation

As with other elements, in most countries once-daily rainfall observations are made at a morning observation between 7 A.M. and 9 A.M. In the United Kingdom and Republic of Ireland the standard is 0900 UTC, the practice of reading the instruments at 9 A.M. first established in the 1860s.

As with once-daily thermometer readings, there is considerable variation in the time of the morning observation – the same reasons applying in both cases. There are very sound reasons here for retaining a morning observation time. Midnight is undoubtedly a more logical choice for AWS sites, avoiding any possible ambiguity about the date on which the rain actually fell, but the majority of the manually read daily raingauges in the world's observational networks are still read at a morning observation. A change in reading time to midnight (1 A.M. in summer time) would also meet with a less than enthusiastic response from thousands of rainfall observers, at least until the majority of the raingauge network is automated, or almost all manual gauges run alongside automatic loggers.

The standard period for daily rainfall measurements in the United Kingdom and Republic of Ireland is 0900–0900 UTC, a period known as the 'rainfall day'. By convention, the rainfall measured at 0900 UTC is 'thrown back' (credited) to the *previous day* – the rationale being that 15 of the 24 hours lay in the previous day, compared with nine on the day of measurement. This applies even if one knows from personal observation that all the rainfall measured at 0900 fell in the 5 minutes preceding the observation. This convention is widely observed in other countries too.

Daily rainfall observations between different sites become increasingly divergent the further apart the observing hours, and to compare like-with-like a morning (rather than evening) observation time is much to be preferred. Daily and perhaps monthly rainfall totals from two sites using different terminal hours are unlikely to show close agreement, even if the site and instruments are both standard in all other respects. An AWS which includes recording raingauge data does enable this problem to be overcome very easily – simply use AWS period rainfall totals to adjust

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* The UK Met Office has adopted the convention of tabulating grass minimum temperatures over the period 1800–0900 UTC at all their automatic sites. As the Sun sets earlier than 1800 UTC for half of the year, this convention means that true grass minimum readings will be missed when temperatures are lowest at or shortly after dusk (see **Figure 10.2**, page 225). As this happens quite frequently, a safer start time would be 1600 UTC.

checkgauge readings made at other times to conform to the national standard morning observation time.

UK terminal hours survey – who uses what?

A recent survey of observers in the UK Climatological Observers Link [2] showed that the vast majority use 24 hour extremes, based upon a 'morning to morning' terminal hour policy:

Morning terminal hours – 24 hour extremes	84%
Midnight terminal hours – 24 hour extremes	9%
Other terminal hours – not 24 hour extremes	5%
Terminal hours unstated	2%

For many amateur observers, the 'morning observation' is necessarily earlier than the UK standard 0900 UTC (a typical morning observation time might be 8 A.M. clock time rather than 0900 UTC). Of course, using logged AWS data to adjust manual observations made at other than 0900 UTC makes greatly simplifies adherence to the 0900 UTC standard.

One-minute summary – *Observing hours and time standards*

- By convention, weather measurements throughout the world are made to a common time standard – Coordinated Universal Time (UTC). For all practical purposes, UTC is identical to Greenwich Mean Time (GMT).
- For weather measurements to be comparable between different locations, the time/s at which observations are made, and the period covered by the measurements, should be common. WMO provides guidance on observation times for the main international synoptic observing networks, while the main 'climatological' observing practice tends to be defined at a country or regional level.
- Many countries around the world have adopted a once-daily morning observation as standard practice, the time typically between 7 A.M. and 9 A.M. Where AWS data are available, it is straightforward to adjust records to conform more closely to the 'nominal' standard morning observation time, even if it is rarely possible to make manual observations at that hour. Adopting the standard observing time (or close to it) greatly simplifies comparisons of weather observations with other sites – particularly daily rainfall records.
- The once-daily morning observation naturally establishes a standard 24 hour period over which many 'once-daily' values are tabulated, such as the daily maximum and minimum air temperatures. Some other elements, such as sunshine, fall more naturally within the 'civil day' (midnight to midnight local regional time), whilst synoptic reporting sites may use different, globally-defined, observing times.
- The start and end time of these recording periods are known as the 'terminal hours' of that measurement. The term 'terminal hour' refers to the time of day at which the extremes are reset.
- By convention, 24 hour minimum temperatures read at the morning observation are entered to the day on which they were read, whereas 24 hour maximum temperature and total rainfall are entered to the day *prior* to the observation

(they are said to be 'thrown back'). Although this occasionally leads to some bizarre anomalies, a midnight-to-midnight record period would be difficult to introduce at sites where only manual instruments are in use (particularly at rainfall-only locations).

- Terminal hours based around 'day maximum' and 'night minimum' temperatures (where the extremes span only 12 hour periods) will generally give results which are incompatible with '24 hour' sites, particularly in temperate latitudes in the winter months.
- WMO guidance is that the grass minimum temperature should refer to the period from just before sunset to the following morning observation terminal hour.

References

[1] A list of, and links to, the world's national weather services is available on the WMO website: http://www.wmo.int/pages/members/members_en.html.

[2] The Climatological Observers Link survey was based on details from 269 member sites, and took place in late 2008.

13 Dataloggers and AWS software

The datalogger, and its associated software, is the heart of any AWS. It is very often an electronic ‘black box’, hidden from view inside a display unit, but its specification defines both the capabilities and limitations of the AWS.

This chapter provides a non-technical guide to the various logger types, outlines their capabilities and limitations, and briefly covers a selection of popular AWS software. There are many different types of datalogger and software that can be used in meteorological measuring systems, ranging from basic pre-programmed fixed-sensor units to highly flexible, programmable devices which can link to a huge range of professional-quality sensors.

As with other components, it is advisable to match capabilities with requirements (and budget) carefully before purchasing any system. One of the biggest mistakes when purchasing a new AWS is under-specification. Very few budget systems can be expanded or upgraded, and therefore any required expansion – additional sensors, more detailed logging and so on – may necessitate the complete replacement of the original system. This has obvious implications for cost, inconvenience and temporary loss of record.

Datalogger basics

All dataloggers are essentially dedicated computers which perform a short basic set of tasks. At a predefined interval they interface with one or more sensors, ‘poll’ the sensor reading and convert the electrical value into a measurement in the appropriate units, and then store the reading in non-volatile memory[*]. A useful history of the development of this branch of electronics, which made AWSs possible, is given in reference 1 to this chapter [1], while more details on the system processes involved are covered in Appendix 1.

Dataloggers have only a certain amount of memory capacity, and the records stored need to be copied or moved to a permanent storage medium before the memory becomes full, because at that point the oldest records will begin to be over-written with current observations. Dedicated logger software manages the downloading of the datalogger memory contents to a host system, normally a personal computer, carrying out tasks related to data display (sometimes in real-time) and permanent data storage on computer media as appropriate.

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[*] Non-volatile memory is electronic memory which retains the stored value when the datalogger is switched off, usually by means of a small lithium battery cell.

Dataloggers are normally self-contained and most do not have to be permanently connected to a PC. Where the connection is permanent, as in a domestic AWS for example, the PC does not have to be kept switched on at all times for the datalogger to function, and downloading can be automatic (say, every hour, or twice every day), or instigated manually as required.

There are different types of datalogger – most are time-based, but event-based loggers have interesting new applications in rainfall studies (see Box, *Types of datalogger*).

The datalogger is the heart of any system, and its capability defines the capability of the AWS. It is therefore important to consider what functions the datalogger needs to perform, or does not need to perform, with the same care and attention given to the choice of sensors. The sections below outline some of the main decision criteria.

Power supply

Very few entry-level AWSs include a dedicated datalogger, and rely upon the connected personal computer to manage interfacing and communication with the system sensors. Nothing wrong in that, of course, aside from needing the PC to remain permanently powered up and connected to the AWS. Any power outage or software glitch will result in the connection being dropped with cessation of record for the duration. It will also be more expensive in electricity, as the PC cannot be allowed to drop into a power-saving 'sleep' mode[*].

Higher budget systems usually include some form of dedicated datalogger, although this may be an optional component, priced separately to the main system. In most budget systems, the datalogger draws power from the AC mains display power supply, usually via a low-voltage transformer connection. Most are fitted with a battery-operated backup power supply in the event of mains failure (otherwise even a short power cut would result in the entire datalogger memory being lost). It is essential to ensure the backup battery or batteries are replaced regularly with fresh units (annually should suffice) to ensure that the datalogger continues to operate even during lengthy power outages. Power supply interruptions are most likely during spells of severe weather, occasionally for 24 hours or longer particularly in rural areas, and battery backup should be capable of providing at least 24 hours cover. There are few things more frustrating than to lose the AWS record during a period of severe weather, but provided the batteries continue to provide power to the datalogger, the records should be safe until the download can be undertaken when power is restored. (It is a good idea, however, to replace the system batteries immediately after any prolonged power outage, as they may not then be sufficiently charged to survive another one.)

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[*] More recently, some users use a netbook PC as a dedicated logging device. Netbooks are low-cost PCs, cheap enough to allow them to be dedicated to a logging role. They have very low power requirements (some just 10 W or so), and their built-in battery provides power for several hours should the AC mains supply fail. Whilst underpowered in processing and memory terms compared to more sophisticated laptops or desktop PCs, the computing power available is more than sufficient to run most AWS software. Developments in stripped-down 'bare bones' PCs such as the UK's Raspberry Pi (running a version of Linux on a credit-card sized system unit, with solid-state memory, SD card slot storage and standard input/outport ports such as USB and HDMI) are also likely to provide economical, low-power dedicated logging units as the devices gain market foothold.

More advanced dataloggers normally operate from 12 v rechargeable sealed lead-acid batteries, the batteries being recharged either from mains or from a solar or wind turbine power source. Similarly, the unit should be capable of operating for long periods without mains power or solar recharge, particularly if it is located at a remote site.

Memory

Every datalogger has a finite amount of memory, and once the memory becomes full, the logger will normally overwrite the oldest data first. The memory capacity of a system is more usefully thought of in terms of 'days of record' rather than megabytes of physical memory, as the amount of memory used will depend upon the number of elements and the logging interval – clearly, a large number of sensors logged at 1 minute intervals will require more storage space than a single sensor logged once per hour.

Types of datalogger

There are many types of datalogger on the market, but for meteorological purposes there are two main categories, **time-based** and **event-based** loggers. The first is by far the most commonly used in meteorological monitoring systems, while the second type opens an entirely new class of measurement possibilities, particularly for rainfall measurements.

Time-based loggers, as the name implies, sample or 'poll' one or more sensors at a specified sampling interval, then log data at a particular logging interval (the 'archive interval' on Davis Instruments AWSs). (See Chapter 2 for more on sampling and logging intervals.) Most loggers allow user choice of the *logging* interval (typical values are between 1 minute and 1 hour), although generally only the more advanced programmable loggers will allow user selection of *sampling* intervals.

Within this category, there is a range from pre-configured to fully programmable loggers. Not surprisingly, functionality and expandability increase alongside price. Budget AWSs offer a limited sensor set (usually non-expandable and non-interchangeable) built around a small datalogger combined with some form of display software. More elaborate AWS systems, such as the Davis Instruments Vantage Pro2 range, support a greater range of sensors, but the loggers themselves are largely pre-configured and configurable only within quite narrow limits. Sophisticated professional-quality loggers, such as those available from Campbell Scientific, offer a huge range of bespoke programming and sensor interfacing capabilities, but at a price well above even the high end of the budget AWS market (and with a steep learning curve). They do offer excellent expansion and configurability, are extremely reliable and robust and backed by first-class support. With care, they can be expected to provide consistent measurements for many years, and any budget decision should take stability, longevity and manufacturer technical support into account.

Event-based loggers, as the name suggests, log only when a trigger event occurs. They are particularly suited to rainfall measurement, where a short sampling interval – measured in seconds – is desirable to provide information on high-intensity rainfall events. Consider a fixed time-based datalogger logging (say) every second: this would quickly generate unmanageable record sizes (more than

30 million one-second data points *per element* in a year). At a site with an annual rainfall of 1000 mm, that is, 5,000 tips measured with a 0.2 mm tipping-bucket raingauge, 99.98 per cent of the record would be zero. Contrast this with the event logger, requiring only 5,000 data points over the same period. Event loggers therefore provide a way to capture very high-intensity rainfall events (logging down to the minimum time resolution of the device, typically 1 second: 0.2 mm in 1 sec = 720 mm/hr, a rate at or beyond the capability of most tipping-bucket raingauges) while also being capable of coping with lengthy dry spells. They provide a scale extension impossible to achieve with ink-and-paper chart-based devices. The logger software may also be configurable to generate hourly and daily rainfall totals for standard climatological analyses, or this can be undertaken by exporting data to a spreadsheet as required.

One such device is the Pendant event logger by Onset Computer Corporation: an example of the analyzed record from one of these loggers is given in Chapter 6.

Where a connection (cabled or wireless) is available to a host PC, most datalogger software can be configured to download at specified intervals. To avoid loss of record through memory being overwritten, it is important to ensure that the download interval is less (preferably much less) than the memory capacity. On the Davis Instruments Vantage Pro2 system, memory period (in days) is numerically roughly twice the logging interval (in minutes) of the base system – a 5 minute logging interval equates to about 10 days data retention. (As the data are stored in fixed-length records, the inclusion or otherwise of additional optional sensors makes no difference to the memory capacity.) If the system is not downloaded for two weeks at 5 minute logging interval, about 4 days data will be lost as the logger will begin to overwrite after about 10 days. If the PC used to connect to the datalogger is left running 24x7, set the download interval to hourly. If the PC is switched on only occasionally, it is best to download at least once per day. For domestic AWS users, when a spell of more than a few days away from home is expected, either leave the PC running with a once or twice daily auto-download set up[*], or reduce the logging period to suit. Lengthening the logging period to 15 min from 5 min on a Davis Vantage Pro2 would permit about 4 weeks records to be retained in the datalogger memory, sufficient to cover an extended holiday, for example. At a school site, a 30 min logging interval should be sufficient to cover a 6 week summer break (ensuring, of course, that the logging PC's power supply will not be switched off by the caretaker as soon as the last pupil has left the premises . . .). Inevitably, the record resolution is impaired a little by reducing the logging interval, but better some data than none, and of course daily totals and extremes will be preserved.

Tinytag loggers

Gemini dataloggers manufacture and sell a range of small, weatherproof temperature and humidity loggers which are ideal for offline meteorological monitoring

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[*] Ensure the logging PC is not configured for 'deep sleep' mode; in particular, to avoid download time-out problems, the hard disk to which the records are to be written must not be allowed to power-down (although it makes no difference whether most other system components, such as the monitor, do so). It is advisable to test all the arrangements for a prolonged absence well beforehand, so that any unforeseen problems arising out of 'system hibernation' can be identified and corrected in good time.

(see also **Figures 3.4** and **3.5**). Most can be supplied with a sensor calibration certificate on request. Whilst they make ideal temperature and RH loggers in their own right, or as a backup to a larger system, they are perhaps most useful as portable calibration benchmarks to check the accuracy of other sensors (see also Chapter 15). Their robust packaging makes them suitable to check calibration of grass and earth thermometers as well as those within a screen, for example, but it should be noted that they are 'offline' loggers in that most require physical downloading using a USB PC connection at regular intervals; they do not provide a display of current values.

When choosing sensors for use with Tinytag loggers, it is essential to select a 'plug-in' sensor, as the response time for 'internal' sensor models is very slow owing to the thermal inertia of the logger itself. A slow response will mean that the range of measured air temperatures will be reduced, and rapid changes may be missed altogether – see Appendix 1 for more on time constants and response times.

Input options

Dataloggers vary in complexity, from a single dedicated channel for one sensor, to complex programmable units which will accept a wide variety of sensor input types (**Table 13.1**). Most meteorological sensors provide one of the following types of input (a few can provide two). When planning an AWS with a range of sensors, it is important to ensure that the required number of available inputs, and their types, are physically available on the datalogger.

Table 13.1. *Datalogger input types*

Sensor input type	Method of operation	Typical measurements
Analogue	The datalogger reads a voltage generated by the sensor, or the capacitance or voltage drop across a sensor whose properties vary with the element being measured, and then internally converts this into a digital value. This is then converted into meteorological units using an appropriate internal conversion/calibration algorithm.	Most continuous output variables – temperature, humidity, barometric pressure, wind direction and solar radiation sensors are analogue.
Digital or pulse	The sensor generates a pulse output, which is detected and counted by the datalogger. The count is then converted into meteorological units using appropriate internal algorithms or conversion factors.	Wind speed, sunshine and tipping-bucket raingauge sensors are usually pulsed outputs.
Binary code	The position of a sensor, such as a wind vane, is defined by a binary code (the 'Gray code') driven by a contactless optical coding mechanism.	Some wind vanes.

Alternative data acquisition architectures

Traditionally, a datalogger connects directly to the sensor or sensors, whether by cabled or wireless communications path. As AWSs evolve, slightly different architectures are evolving. In the Davis Instruments Vantage Pro2 system, for example, the components are:

Sensor → Integrated Sensor Suite (ISS) → console → logger

Much of the sensor interfacing (analogue to digital conversion, pulse counting and so on) is undertaken by the ISS, which then passes a complete packet of raw data from all attached sensors to the console every 2.5 seconds. At the console it is processed further and then made available in 'digested' form for logging by the logger, if required. The logger also provides the PC interface, but the PC does not have to remain permanently connected.

Professional-standard dataloggers can be interfaced to almost any type of meteorological sensor. This is not true of pre-configured budget systems, however, which are usually very restricted in their choice and expandability of sensors, with expansion options likely to be limited or even non-existent. It is advisable to define system requirements carefully before purchase (see Chapters 2 and 3), to ensure any future expansion can be allowed for without the necessity of stripping out and replacing one system in its entirety with another possessing the desired expansion capability. Not only is this expensive in purchase costs, installation and cabling or recabling time and additional programming, it may result in a break in record during the de-installation/re-installation process.

Programming capability

As covered in the previous section, most AWS systems from budget-level upwards will include some form of pre-programmed datalogger. Configuration options on such devices are usually very limited, although this makes them easy to use, being essentially 'plug-and-play'. In contrast, programmable loggers are highly configurable – with different sampling and logging intervals for different sensors, for instance, and the ability to calculate sensor calibrations or corrections 'on the fly' (such as the reduction of barometric pressure to mean sea level, or the calculation of vector mean winds). Averages (including running means and other functions) and extremes over specified periods can also be derived or calculated by the logger from data held in memory, and output in almost any format required. Such programmable loggers offer almost infinite flexibility in recording and storing data, and offer excellent expandability, but the capability is at the cost of a steep learning curve. For flexible, customized and highly expandable measurement systems they are without equal. Although the purchase price of a programmable datalogger plus a variety of professional-quality sensors is about the same as a small car, build quality is usually far superior to budget packages, and little further investment should be required for many years.

Communication options

Last but certainly not least are the communication options available on the datalogger. Most modern dataloggers will connect to a PC using a USB port, although some still require older (and slower) serial or even parallel port connections. Most serial output dataloggers will operate satisfactorily with serial-to-USB adaptors, but check with the manufacturer as some models are quite fussy as to the adaptors and driver software they will work with. Dedicated communications software supplied with the logger enables manual or automatic (set interval) downloads to be configured as required. USB connections are more likely to 'drop out' when long cables or USB hubs are used, and it is best if possible to plug the logger into a port on the PC itself rather than via an intermediate hub[*].

Connections and downloads can be made using a permanent PC connection, or as required by connecting directly to a mobile device such as a laptop or tablet PC – the latter particularly useful for a remote or multi-site station network, where the regular download visit (perhaps weekly or fortnightly) should also be an opportunity to check the physical condition of the instruments and site, check the raingauge funnel for obstructions, and perform any required maintenance of the enclosure, such as cutting the grass.

Most loggers can also be configured to communicate via a telephone network, whether landline (modem or broadband) or mobile, and can therefore be accessed remotely – particularly useful whether the AWS is in the field next door or on top of a mountain half a continent away. Sophisticated fault-tolerant systems designed for very remote areas, and for ocean-going ships, can also transmit directly via satellite.

Dataloggers – the risks

Dataloggers are very reliable electronic components, and should work for many years without any problems. However, they are the core of any AWS, and as such failure of the datalogger is likely to result in partial or complete loss of data. Some basic steps can be taken to minimize the risk of catastrophic data loss:

- Check and test out the entire data acquisition chain thoroughly, over a period of at least a few days, before permanent hardware installation or embarking on any long-term data collection. This applies particularly at remote sites. It is surprising how often this reveals a flaw in the initial configuration or a poor connection, either of which are much easier to resolve 'on site' prior to final installation.
- Ensure the mains power supply to the logger/display unit (if there is one) is protected via a surge protector. This will reduce, but not entirely eliminate, the risk of potentially damaging power surges from close lightning strikes, other electrical components on the same circuit and similar hazards.
- Ensure battery backup is fully charged, and has the capacity to survive an extended power outage. (But be careful the battery is also not over-charged – a

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[*] USB dropouts can be a frustrating and recurring problem. Radio frequency interference (RFI) around the logger cable is the most likely cause, although mains power spikes can also have the same effect. Use top-quality cables and connectors, and keep them as far as possible from other RFI sources on and around the PC. Applying an RFI choke or ferrite ring around the logger cable close to the USB cable connection may also help.

permanently-connected charger may over time increase the voltage across the logger to a level beyond its operating specification.)

- Ensure the datalogger is not exposed to extremes of heat or cold, and remains well-ventilated so that component heat cannot build up and condensation does not occur. Desiccant cartridges should be used to prevent condensation where loggers are housed externally.
- Set up a frequent data download schedule – hourly if the host PC remains on 24x7, at least daily otherwise. Frequent downloads will reduce the risk of memory overflow and any period of data loss in event of logger failure.

AWS software

AWS software has just three main functions:

- System setup and configuration
- Communication with and downloading of data from the datalogger, and
- Data display – of current conditions, or historical data from the downloaded records – to a dedicated display console, to a host computer or (with appropriate software) to the Internet.

All AWS software packages should be capable of displaying both tabular and graphical data from multiple elements, and for exporting downloaded data to a spreadsheet. Sophisticated analysis, presentation graphics and long-term archiving are best left to spreadsheets (see Chapter 17, *Collecting and storing data*).

Chapter 3 gave details of AWS hardware surveys conducted within the UK/Ireland and the United States. AWS software was also surveyed, with the results given by geography in **Table 13.2**.

There is a much greater variety of AWS software in use than hardware, although five packages accounted for around 80 per cent of all software. The same five dominated both geographies, although the order was slightly different. In the United States, Ambient Weather's Virtual Weather Software (VWS) was the most popular, accounting for 38 per cent of all sites, compared with 15 per cent in the UK/Ireland survey.

Within the UK and Ireland, Sandaysoft's Cumulus was the most popular, accounting for 29 per cent of all users, although just 7 per cent in the U.S. poll.

Table 13.2. *Most popular AWS software – United States and UK/Ireland*

	United States			**UK and Ireland**		
Rank	*Package*	*n*	%	*Package*	*n*	%
1	Virtual Weather	57	38	Cumulus	43	29
2	Weather Display	25	17	Weather Display	39	26
3	WeatherUnderground	15	10	Virtual Weather	23	15
4	Cumulus	10	7	WeatherUnderground	13	9
5	WeatherLink	7	5	WeatherLink	11	7
	Others	36	24	Others	21	14
	Total survey	150	100		150	100

The survey was conducted from WeatherUnderground sites detailing both hardware and software in use. UK/Ireland survey conducted in December 2010, U.S. survey in September 2011.

Brian Hamilton's Weather Display was the second-most popular choice in both geographies. The highest-rated 'manufacturer' software was Davis Instruments' WeatherLink, although this was used by only 5–7 per cent of the sample. This is much lower than Davis Instruments' hardware usage, which was 61 per cent in the U.S. survey and 39 per cent in the UK and Ireland.

AWS software compared

The five highest-ranking AWS software packages in the survey are briefly compared below, in alphabetical order, together with contact details for the software publisher. The details have been taken from the websites referenced and, while correct at the time of writing, potential users are strongly advised to make their own checks regarding compatibility and support levels. There are a wide variety of types of AWS software, and because updates occur even more frequently than AWS hardware, detailed reviews, screen shots and features tables are not included in this book as they would quickly date. It is best to check online for updated manufacturer specifications, display examples and reviews from other users. Most offer some form of free downloadable software to allow the software to be installed and evaluated for a period before purchase.

Which application best meets any particular requirement is largely a personal choice – there is no clear-cut winner, as there are pros and cons to all of the available software packages. The simpler ones tend to be more robust – not surprisingly, because they have fewer features – and so are easier to configure and to use. Some people cannot have too many features – for others 'less is more'. A high feature-count inevitably correlates with more complex configuration and 'screen clutter'.

Note that by far the majority of AWS systems and their associated dataloggers, both budget and professional, are designed to operate within a Microsoft Windows computer environment. Software and support for other devices, such as Apple and Linux operating systems, is available but more limited – see, for example, links at www.wunderground.com/weatherstation/index.asp. With the increasing adoption of 'bare-bones' PCs based around Linux and open source components, however, this may change quickly.

What's the date? 11 February – or 2 November?

One important but often overlooked software consideration is that of date format. Date conventions differ between European style (day-month-year, d-m-y) and North American (month-day-year, m-d-y); so that 2 November 2015, for example, would be written as 2.11.15 within Europe but 11.2.15 in the United States and Canada. Within AWS software it is important to check which date convention is in use, and whether display and output modes can be altered to suit regional preferences. Without checking, 'American' 2 November will be transposed to 11 February in 'European', with entirely predictable downstream results!

Cumulus – http://sandaysoft.com/products/cumulus

Cumulus was written by Steve Loft of Sandaysoft, based at Sanday in Orkney, a group of windswept islands off the north coast of Scotland. The software is free (the author asks for a donation should you continue using it beyond a trial period). It will store downloaded data from the AWS and upload/display to a web server if required: templated web pages are included to simplify this process. Cumulus also supports automatic uploads to Weather Underground, CWOP/APRS and the UK Met Office WOW site (see Chapter 19, *Sharing your observations*).

Most popular AWSs are supported. The web display shows current conditions, near real-time/most recent upload instrument readings, maximum and minimum readings for various elements for current and previous days and their all-time records, and graphed trends from the sensors over periods of 24 hours and 1 month.

The web interface is clean and informative, and easily customized to suit most requirements. Configuration options usefully support a choice of meteorological day (midnight to midnight or 0900–0900 morning to morning, for example). Free support is provided in a support forum, via Frequently Asked Questions (FAQs) file and a wiki application. The Sandaysoft website also includes an impressive interactive map of Cumulus users, which at the time of writing showed almost 800 locations from Austria to Venezuela.

Virtual Weather Software (VWS) – www.ambientweather.com/virtualstation.html

VWS from Ambient Weather (Chandler, Arizona) offers similar functionality to Cumulus and Weather Display, covering the display, plotting and storing of AWS data and (if required) uploading to a website. The interface is completely customizable, and the software supports all Davis Instruments and Oregon Scientific models as well as some La Crosse units. The software is priced at $100 (U.S.) for the 'Internet edition', and a free trial version is available for download. Prices exclude delivery costs to European addresses. Links to a VWS online community are included on the home page, although at the time of writing many of the links were broken or out-of-date.

Weather Display – www.weather-display.com/index.php

Brian Hamilton, from Waiuku in New Zealand's North Island, is the creator of Weather Display. Weather Display supports a very wide range of AWS models from all major manufacturers, and includes near real-time auto-scaled display functions, easy data upload to a web page, e-mail notifications of extreme conditions, auto-generated METAR or SYNOP coded messages, averages and extremes, webcam support and animated webcam images, 'weather dial' displays and a weather 'answerphone', together with numerous other functions and features including automatic uploads to consolidation sites such as WeatherUnderground, UK Met Office WOW site, CWOP, etc.

The software costs $70 (U.S.) for a lifetime license, and support is provided by software forum. The website includes links to the 'Weathermap live' site, which at the time of writing displayed data from almost 1,500 sites worldwide using Weather Display, including some additional synoptic and METAR reports. (Note that there is an additional subscription for this facility.)

Weather Display can also be used to provide near real-time viewing of weather data on the Internet using the Weather Display Live add-on, a separate item of software written by Julian Best, priced at an additional $40 (U.S.). Both packages are available on a trial basis – the Weather Display trial version is fully functional but will expire after 30 days, the Weather Display Live trial version is fully functional with no time limit but displays an ‘Evaluation Version’ watermark when viewed in a web browser.

Weather Underground – http://www.wunderground.com/weatherstation/index.asp

Rather than software to download, display and communicate AWS data, Weather Underground is a website which displays near real-time and archived weather station data from thousands of sites around the world. Free interfacing software is available for a wide range of weather station hardware and software options, allowing data to be uploaded to regional maps. More on Weather Underground is included in Chapter 19, *Sharing your observations.*

WeatherLink – http://www.davisnet.com/weather/products/software.asp

Davis Instruments WeatherLink software is a very reliable package which provides good (if now rather dated-looking) display and download facilities. The software can be configured to display data to a weather website – detailed instructions are available from Davis or through their resellers. Connections via USB or serial port (for older computers) are available, and the software is available in both Windows and Macintosh versions.

A related Davis product, **WeatherLinkIP**, is a different logger with an output interface that plugs directly into a network connection (no PC necessary). WeatherLinkIP sends a small burst of data up to the Davis WeatherLink.com server every minute, which then automatically generates web pages that can be viewed by anyone. No website building experience is required, and so WeatherLinkIP is probably the simplest way for anyone to put their data online. At the time of writing, there were some 7,000 WeatherLinkIP devices worldwide, all visible on the WeatherLinkIP map http://www.weatherlink.com/map.php (be patient – the whole map takes a few moments to load because of the sheer number of sites included).

WeatherLink and WeatherLink IP are the most expensive packages listed here, and no ‘trial’ option is offered.

Davis Instruments also offer Vantage Connect™, a new addition to the Davis Vantage family that allows weather data to be uploaded automatically from a remote field site to a website via the mobile (cellular) phone network. Using Vantage Connect in conjunction with a Davis Vantage Pro2 AWS, weather observations can be made at a remote site (with no facilities required other than cellphone reception) and then viewed from a central website via smartphone or computer from anywhere in the world. Readings can be updated every few minutes, including the option to download data to a PC for detailed analysis, archiving and reporting.

One-minute summary – *Dataloggers and AWS software*

- The choice of datalogger is critical to the effective operation of any AWS. Together with the AWS software, its specification fully defines the capabilities (or limitations) of the AWS, and the choice of unit should be given at least as much consideration as the choice of sensors.
- Most budget AWS packages will include a pre-programmed datalogger with display software, although flexibility and expandability may be limited. Sophisticated programmable multi-sensor loggers and software are highly

expandable, but are considerably more expensive and complex to programme and use.

- The critical decision criteria for dataloggers are – choice of power supply, and battery backup capability: amount of memory: number and type of input options (‘ports’): and programmable capabilities, if any.
- AWS software provides three key functions – system setup and configuration, communication with and downloading of data from the datalogger, and the display of current and logged data. Most offer some form of data upload to Internet/website.
- The majority of AWS owners opt for a third-party AWS software package over the manufacturer’s offering. At the time of writing, five leading packages accounted for more than four in five of AWSs surveyed in the United States, the United Kingdom and Ireland, although there are also others available. There is no ‘best’ solution, all packages have pros and cons, and the choice is largely one of personal preference. Most of the leading software is available on a ‘try before you buy’ basis, and it is best to ‘try before you buy’.
- It is advisable to check and test all sensor / datalogger / software and communications thoroughly, over a period of at least a few days, before permanent hardware installation or embarking on any long-term data collection.
- As with any major expenditure, carefully match capabilities with requirements (and budget) before purchasing a system.

References

[1] Strangeways, Ian (2004) Back to basics: The ‘met enclosure’, Part 10 – Dataloggers. *Weather*, **59**, pp. 185–189.

14 Non-instrumental weather observing

Instrumental readings are of course vital in making weather observations, but for a complete picture non-instrumental and 'narrative' weather observations are as important. This chapter sets out how to make non-instrumental observations, usually performed at a set time, how to document the frequency of various occurrences such as snowfall, thunderstorms, hail and the like, and how best to maintain a useful weather diary.

Observations at set times

The conventions regarding observing hours were set out in Chapter 12. Many weather stations make one 'morning observation' daily, typically between 7 and 9 A.M. (nominally 0900 UTC in the UK and Ireland). At this 'morning ob' instruments are read and reset for the coming 24 hours, and various eye observations made, as detailed below.

As described in more detail in Chapter 12, the importance of a once-daily observation at a set time has declined as AWSs have made it easier to adjust instrumental observations made at other times, or variable times, to the national or regional standard 'climatological day' and so greatly simplifying the comparison of observations between sites. Even with an AWS, it is preferable wherever possible to make at least one 'manual' observation every day at approximately the same time, as home and work schedules permit.

I have an AWS – why do I need to do a manual observation?

Many new weather observers, particularly those whose first experience is with a domestic AWS rather than with 'traditional' instruments, ask this very logical question. The answer is, of course, *you don't*, but there are many good reasons for doing so nonetheless. As well as reading and resetting any manual instruments, such as the standard raingauge (see Chapter 6) or liquid-in-glass screen, earth or grass thermometers (see Chapters 5 and 10), a manual observation provides the opportunity to note various important non-instrumental elements such as cloud amounts and types, visibility, the depth and extent of any snow cover, and so on. After all, weather observing should certainly not be limited to sitting in front of a computer screen! When made in a consistent manner, these observations will quickly build into a valuable supplementary weather record.

A daily manual observation is also the ideal time to make a quick visual check that all instruments are functioning correctly, that the tipping-bucket raingauge funnel is clear of debris, and that no temporary obstacles, obstructions, damaged cabling or instrument defects are affecting readings. When combined with inspection of the logged/displayed AWS record, regular visual checks reduce the risk of a long period of lost or defective record owing to undiagnosed instrument or signal failure. Above all, the 'ob' should take only a couple of minutes to do.

I work irregular hours and can't observe at a fixed time . . .

An AWS will, of course, provide 24x7 observational cover, regardless of whether regular manual observations are or can be made. As outlined in Chapter 12, there are many advantages to maintaining an observational routine built around standard 'terminal hours', whether or not these actually coincide with regular manual observations. Even those with irregular working patterns may also find noting the occurrence of snowfall, thunderstorms, hail and the like to be useful in building a more complete picture of local weather conditions than can be provided solely with the digital output from an AWS. Occasional visual checks on the integrity of both instruments and data are probably even more important for those with irregular routines, as a minor problem may take longer to become apparent and put right.

The daily observation

The best time to do a once-daily observation is in the morning. In most countries the standard morning observation time is between 7 and 9 A.M. (in the UK and Ireland 0900 UTC, 9 A.M. clock time in winter and 10 A.M. clock time during summer time). If this is not possible, make the observation at a more convenient time for you, and use AWS records to adjust the readings to the country standard 'daily climatological day', as described more fully in Chapter 12. No observation time is perfect, but a consistent slot is usually easier to fit into a daily routine.

Observational routine

After reading and resetting any manual instruments as required, note non-instrumental observations as detailed below using a small notepad or similar[*]. (It is assumed here that observations of temperature, humidity, barometric pressure and perhaps other elements will be logged by the AWS, although it is good practice to make manual assessments of wind direction and speed and check the accuracy of your estimates against AWS readings.) Inspect all instruments daily, particularly to check the raingauge funnel/s is/are clear of obstructions, for example, as blockages may not become apparent until the next spell of rainfall.

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[*] Weather observing logbooks are available from the Royal Meteorological Society in the UK, or can be drawn up individually and pages photocopied to suit. It is advisable to use a notepad and pencil for the outside observation and copy up the observation into the logbook immediately afterwards to avoid the pages and previous manuscript observations being damaged if rain should fall during the observation.

Cloud amount and type/s

Cloud amount is estimated by eye, in eighths of the sky (or *oktas*)[*]. The easiest way to do this is to mentally divide the sky into quarters and assess whether each quarter is clear of cloud, partially covered by cloud, or completely covered by cloud. A clear sky will obviously be 0 oktas (0/8), and a complete cloud cover 8 oktas (8/8). A trace of cloud will be 1, and a chink of blue sky in an otherwise cloudy sky rates 7. It is important to rate cloud cover without regard to the thickness or density of the cloud – it is quite possible to have unbroken sunshine with 8/8 cloud cover of cirrus or cirrostratus, for example. When the sky is obscured (usually by fog, occasionally by falling snow), code it as 8/8 or X (not '9'). Aircraft contrails should be counted as cloud cover, unless they last for only a short period before evaporating completely – less than about 30 seconds, say. Cloud amounts can be quickly and accurately estimated by eye with only a little practice, and after a time it becomes automatic.

A full tutorial on *cloud types* is beyond the scope of this book (and its illustration budget . . .). The interested reader is referred to two excellent and well-illustrated recent books on this subject – Richard Hamblyn's *The Cloud Book* [1] and Gavin Pretor-Pinney's *The Cloudspotter's Guide* [2]. With a little practice, and a good 'spotter's guide' to work from, the major cloud types can be identified quickly and easily. There are also many excellent cloud photographs on the Cloud Appreciation Society website at cloudappreciationsociety.org.

Visibility

Visibility is defined as 'the greatest distance at which an object . . . is visible to the naked eye' [3]. Visibility is an important element in operational meteorology, especially for aviation: poor visibility in bad weather is a major cause of aircraft accidents. In climatological applications the main application of visibility observations is to define the frequency of fog. In the meteorological sense, fog is said to occur when the horizontal visibility falls below 1000 m (1100 yards), and thick fog when the visibility is below 200 m (220 yards). Poor visibility – between about 1000 and 4000 m visibility – is referred to as 'mist' when the relative humidity is above about 95 per cent, and 'haze' when below 95 per cent.

Eye observations of visibility, and thus the determination of fog frequency, are easily made with a little preparation. Look around the horizon from your observing site and note clearly identifiable objects or distinct landmarks at various distances. Nearby, these could be buildings – a church steeple, for example: at greater distances, a prominent hilltop or skyline. Note their azimuth (compass bearing) and then, using maps of the area – Google Earth is particularly useful – determine their straight-line

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[*] The term *okta* is attributed to Ernest Gold, DSO, FRS (1881–1976), one-time Deputy Director of the UK Met Office, and came into general use when meteorological reporting codes were revised in 1948 (EG Bilham, Washington codes, *Meteorological Magazine*, 77, pp. 217–220). Why eighths in a decimal world? Because when observations are coded for international distribution on the meteorological communications networks, reporting cloud cover N in eighths requires only a single character. Prior to 1948, cloud amounts were reported in tenths, which required two characters. $N = 9$ in coded synoptic reports is used to indicate 'sky obscured' (due to fog, dust or sand or snow, for example), although for statistical purposes $N = 9$ is counted as 8 oktas cloud cover (if the $N=9$ coding is used, be sure to count all such observations as $N = 8$ to avoid distorting average cloud cover calculations). Synoptic AWSs cannot report cloud extent, and therefore always report N as /.

distance from your observation site. To determine the occurrence of fog and thick fog accurately, you should ideally have objects both a little below and a little above 200 m and 1000 m distance, respectively, but if there is no suitable object or landmark close to those distances, careful interpolation from other objects will be necessary. Visibility in fog is very rarely less than about 20 m, but you should define a selection of 'visibility objects' (as they are known) from 10 m to the most distant points visible on a clear day – ideally 30 km (20 miles) or more. Where possible, it is best to choose objects close to the boundary of the category – for example, the visibility or otherwise of an object close to 4000 m distant would establish clearly whether the meteorological visibility was 'poor' or 'moderate'. Visibility objects do not all have to be in the same direction (see Box, *Visibility objects*).

Visibility objects

A typical list of visibility objects might look something like the following:

Visibility objects at Slapton-in-the-Slush. Objects are viewed from the thermometer screen.

Visibility category	Object	Bearing	Distance
Very dense fog (< 20 m)	Sunshine recorder pillar	ESE	9 m
Dense fog (< 50 m)	School clock tower	NW	45 m
Thick fog (< 200 m)	Poplar tree	SSW	185 m
	White-fronted building	E	220 m
Fog limit (< 1000 m)	Pylon	SW	1050 m
Poor visibility (1000–4000 m)	Church spire	N	2.1 km
	TV mast	ESE	3.7 km
Moderate visibility (4–10 km)	Trees on skyline	SE	6.5 km
Good visibility (10 km or more)	Cluster of tall buildings	NE	9.7 km
	Gap in scarp slope	ENE	28 km
Excellent visibility (> 40 km)	Distant hills	WNW	42 km

At the observation, note which is the furthest object to be clearly visible. If the visibility varies by direction, patchy fog for example, the lowest visibility should be noted, together with the direction. Note 'fog at observation' if the visibility is below the fog limit (1000 m) for whatever reason; it may be heavy snow, or even a dust storm, rather than fog.

Present weather

Note the occurrence of any significant weather (rainfall, fog, snowfall, etc.) at the time of the observation, together with its intensity and persistence – using unambiguous terms such as 'continuous light rainfall' or 'heavy snowfall ceased within the past hour'. Operational reporting observing sites use the 'present weather code', a two-digit code [4] which covers almost all weather types; a short written description is perfectly adequate for most purposes.

Note any other observations as required, for example the extent and depth of snow cover at the time of the observation (see also *Days with* section below).

Away from home?

An AWS is ideal for providing unbroken instrumental records during observer absences – whether due to family holidays, lack of weekend observational cover at, for example, local authority observing sites, or gaps due to school breaks, but non-instrumental observations can be more difficult to cover. Short periods of absence can often be filled in by asking a family member, neighbour or another local observer either to make observations in your absence, or at least 'keep a weather eye open' so that occurrences of thunderstorms and the like are not lost from the observational record. Ensure the AWS will record for the intended period of absence, if necessary by setting up an automatic download in good time (see Chapter 13).

Photographic records

Some weather observation sites feature webcams, providing a permanent record of cloud and weather conditions. Perhaps more useful is the simple expedient of keeping a camera handy at all times, to record notable weather events photographically – significant flooding, large hail, tree damage after severe gales . . . Over time, such images build into a valuable visual record of noteworthy events, and can help document environmental changes as a result of individual events, or a prolonged sequence of unusual weather.

Occurrence frequencies or 'Days with . . .'

Climatological statistics often include the frequency of various meteorological phenomena at a particular location. Some of these (such as counts of air or ground frosts) are derived from thresholds applied to instrumental observations, but most are derived from eye observations of particular weather types, such as the occurrence of snow or thunderstorms. For accurate reporting a 24x7x365 weather watch is required (at least in theory), something that very few operational meteorological sites manage these days but one which many amateur observers pride themselves on covering as fully as possible. An amateur observer with a home-based weather station can very often provide a more complete 'weather watch', particularly at weekends, public holidays or in severe weather, than the operational meteorological networks can provide (and at much lower cost). For this reason eye observations are of enormous value provided standard definitions and terms are used.

'Days with' frequencies most often refer to the civil day (midnight to midnight local regional time, excluding summer time adjustments). Some refer to a specific time, usually the morning observation. Definitions of the most common 'days with' elements are listed in **Table 14.1**: those derived from instrumental observations are also included for convenient reference.

Table 14.1. *Definitions of the most commonly used 'days with' climatological elements. Most feature the current definitions in use within the UK and Ireland, with U.S. differences shown where appropriate. Definitions and terms do vary slightly from country to country – check these by referring to your state weather service publications or website [6].*

The definitions in the following section refer to occurrences within the civil day, midnight to midnight local regional time, excluding any summer time adjustments	
Thunder heard	*Definition:* The audible sound produced by a lightning discharge, arising from the intense heating and expansion of the air by the electrical current [3]. A day with 'thunder heard' is logged whenever thunder is heard. There is no minimum duration or intensity, even a single weak rumble of thunder counts as a 'day with thunder heard', although great care should be taken to distinguish genuine thunder from other noises such as aircraft. 'Thunder heard' does *not* have to be accompanied by visible lightning, although it is helpful to note whether lightning was also seen. A thunderstorm which starts at 2350 h and finishes at 0005 h counts as 2 'days with thunder'. 'Lightning seen' (only) does not count as a 'day of thunder' as it can sometimes be seen from a great distance: thunder is not normally audible beyond about 15–20 km from the parent storm, whereas lightning at night can sometime be visible more than 100 km distant.
Gale	*Definition:* A surface wind of mean speed 34 knots (17 m/s) or more, averaged over a period of at least 10 minutes [7]. Note that the surface wind refers to that measured at 10 m above ground, and thus the mean speed threshold will be lower nearer ground level (see Chapter 9). Where instrumental wind speed records are available, these should be used to assess whether the threshold has been attained. If instrumental records are not available, estimates using the Beaufort Scale (see Table 9.3, Chapter 9) should be made. The source should be stated in the site metadata.
Snow or sleet observed to fall	*Definition of snow:* Solid precipitation in the form of individual tiny ice crystals when temperatures are low, or larger snowflakes when the air temperature is near 0 °C [3]. *Definition of sleet in UK/Ireland*: A mixture of rain or drizzle and melting snow. *Definition of sleet in the United States*: Frozen precipitation that results when raindrops freeze while falling, before hitting the ground. A day with 'snow or sleet observed to fall' is logged whenever snow or sleet is seen to fall. There is no minimum duration or intensity – even a single flake of snow counts, at least in theory. Slight snow showers, overnight snowfall or blowing snow after a snowfall can be difficult to include or exclude from counts, and considerable alertness is needed in marginal situations. Snow showers from shallow convective clouds can occasionally reach the ground after the parent cloud has evaporated, or be blown some way from the parent cloud, leading to the apparent fall of snow from a largely clear sky. Particular care should be taken to distinguish genuine sleet from cold rain at temperatures between about 1 and 3 °C. Snow (or sleet) which starts at 2350 h and finishes at 0005 h counts as 2 'days with snow (or sleet)'. For statistical purposes, it is helpful to distinguish 'days with snow' from 'days with sleet only'. A day when both occur is counted as 'snow'. Within the UK and Ireland, the following types of wintry precipitation also count as 'snow' for statistical purposes - **Snow** – definition above **Snow pellets** – opaque, white ice particles, which can be spherical or conical in shape, with a diameter generally 2–3 mm or less **Snow grains** – very small, opaque white particles which appear flat or elongated, and normally 1 mm or less in diameter; the wintry equivalent of drizzle **Ice pellets** – transparent ice particles, spherical or irregular in shape, and typically 1–5 mm in diameter, rarely more. This type of precipitation is known as 'sleet' in the United States – see above.

Table 14.1. (*cont.*)

	At low temperatures, small **ice crystals, ice prisms** or **ice needles** may fall from freezing fog or occasionally, below about −10 °C, from a clear or almost clear sky (sometimes very appropriately referred to as 'diamond dust'). These should not be counted as 'snow' in statistical summaries.
Hail observed to fall	*Definition:* Solid precipitation in the form of balls or pellets of ice [3]. For statistical purposes, falls of hail are usually classified as 'small hail' (where the ice particles are less than 5 mm in diameter), and 'hail' (5 mm or more in diameter). When large hailstones occur (10 mm or more in diameter), it is useful to note measurements of the mean and maximum stone size, and (where possible), photographs should be taken and samples of the stones collected for preservation in a freezer. A simple hailgauge can assist considerably in the accurate reporting of hail, as hail often occurs for very short periods and/or mixed with other forms of precipitation and can easily be missed (see Box, *A simple hailgauge*).
The definitions in the following section refer to occurrences within the standard 'climatological day' (morning to morning) – in the UK and Ireland, 0900 to 0900 UTC	
Air frost	*Definition:* A minimum air temperature below 0.0 °C. The temperature refers to measurements made in a standard thermometer screen or equivalent (see Chapter 5), unless clearly stated otherwise ('Aspirated thermometer air frost', for example).
Ground frost*	*Definition:* A minimum temperature below 0.0 °C observed by a thermometer exposed above short grass. Grass temperatures on a clear night are typically 2–5 degrees Celsius below air temperature, although the values vary depending upon exposure, soil type, intermittent cloud cover and wind speed. More details on instruments, measurement methods and sensor exposure are given in Chapter 10.
Rain day	*Definition:* A day on which 0.2 mm or more of precipitation is recorded during the 'rainfall day', the 24 hour period commencing at the time of the morning observation (within the UK and Ireland, conventionally 0900 to 0900 UTC). First set out by George Symons, founder of the British Rainfall Organization, in *British Rainfall 1865* [8]. Where the inch is the unit of measurement, the rain day is usually 0.01 inches (0.25 mm) or more within the rainfall day. Occasionally, thick wet fog or a heavy dewfall can deposit 0.2 mm or more in the raingauge. This should be measured and recorded as 'Fog 0.2' in the register, and counted as a 'rain day'.
Wet day	*Definition:* A day on which 1.0 mm or more of precipitation is recorded during the 'rainfall day', the 24 hour period commencing at the time of the morning observation (within the UK and Ireland, conventionally 0900 to 0900 UTC). This definition first appeared in *British Rainfall 1920* and was the result of a UK Met Office metrication push at the time. However, it was not until 1971 that all UK rainfall records were finally made in millimetres. [8]
The following definitions refer to observations made at the morning observation	
Snow lying at morning observation	*Definition:* Snow lying occurs when snow covers one half or more of the ground of an open area representative of the site at the morning climatological observation [7]. Within the UK and Ireland there is no minimum depth for 'snow lying' – sometimes just a fine dusting can count as a 'snow cover', as it is the coverage rather than the depth that is the criterion for the event. In the United States, the minimum depth for 'snow lying' is 'a measureable depth' – which usually means 0.5 inch (1.3 cm) or more. 'Representative of the site' excludes rivers and lakes, cleared paths or roads, areas of tarmac, house roofs, cars and the like as well as areas with significantly different altitude, such as nearby hills or mountains. The remains of snow drifts, whether natural or artificial (such as those from snow clearing operations) should not be included in the assessment. If the

Table 14.1. (*cont.*)

	observation is not made at the normal time, the time should be included – for example, ‘snow lying at 0630 h, depth 2 cm, melted by 0900 h’. On occasions when snow is lying, the snow *depth* at the observation should also be carefully measured and noted – see Chapter 6 for details on how to do this.
Fog at morning observation	*Definition:* A visible suspension of water droplets in the atmosphere near the surface, and defined by international agreement as reducing visibility to less than 1000 metres / 1100 yards [3]. When the surface visibility is below 1000 metres at the morning observation, a ‘day with fog’ should be noted – even if the obscuration is not due to fog itself (smoke, blowing dust or sand, heavy snow or torrential rain can also reduce visibility below 1000 m). If the time of observation is significantly different from the standard morning observation time, the time of the observation should be stated. In most areas fog frequencies are much higher at dawn than later in the morning, and where the morning observation is made earlier than at other sites (say at 7 A.M. rather than 9 A.M.) the observed frequency of fog will be greater. To avoid possible confusion, the normal time of observation should be clearly stated in the site metadata (Chapter 16).
Thick fog at morning observation	As above, but when the visibility is below 200 m (220 yards).

[*] WMO guidance on observation period is ‘sunset to the subsequent morning observation’, but at unmanned sites where the grass minimum thermometer cannot be exposed shortly before sunset the ‘morning to morning’ period necessarily becomes the default. See the notes on this topic in Chapter 10, *Measuring grass and earth temperatures*, and in Chapter 12, *Observing hours and time standards.*

A simple hailgauge

The determination of the number of days on which hail falls is an important climatological statistic, but the transient nature of such events is such that all but the heaviest falls are easy to miss for even the most conscientious observer. The reported frequency is therefore more dependent upon the alertness of the observer than any other single factor.

One way to improve matters is to use a simple hailgauge [5]. This simple instrument is easy to make and is underused. In its simplest form, a hailgauge can be made from a small sheet of thin metal foil (aluminium/aluminum foil as sold in supermarkets is ideal). The foil is simply stretched across a small open frame such that an area of perhaps 200 cm^2 is left unsupported, or alternatively the foil can be lightly supported on a backing material such as a block of polystyrene foam (**Figure 14.1**). Fix the instrument firmly in a position where it is well-exposed to precipitation (and where it will not blow away in strong winds), one where it is also convenient to examine the surface of the foil on a daily basis.

When hail falls, the surface of the foil quickly becomes pitted, the extent depending upon the intensity of the hail. Minor hailfalls may be marked by only a few small dents, whereas heavy hail or large stones may shred the foil. Hailgauges with an area of unsupported foil tend to be a little more sensitive, but are more easily punctured by a few stones: supported variants are more robust but less sensitive. The raw materials are, of course, easily obtainable and inexpensive, and a combination of both types gives good results. Different shapes and sizes can be used to augment results (for instance, an upright cylinder or cone can be used to estimate the direction of hailfall and precipitation angle).

Figure 14.1. A simple hailgauge, constructed from a small sheet of aluminium foil stretched over a block of polystyrene and freely exposed to the weather. Dimensions are approximately 95 x 135 mm. (Photograph by the author)

Keeping a weather diary

The 'narrative element' of weather observation is frequently overlooked, and yet it can often serve as a more meaningful and easily recalled description of a day's weather than a raw table of instrumental statistics. Keeping a simple daily weather diary takes very little time, typically just a couple of minutes per day, and over time it builds into a useful reference document.

The exact form of the document is largely a matter of personal choice, whether that be a daily manuscript entry in a bound annual desk diary, or a daily paragraph added to a document on a laptop computer or smartphone (but don't forget to back it up daily – see Chapter 17). Some people use a voice recorder, although subsequently searching for a day's event is more difficult with audio files. The advantage of computer-based records are that they can be easily searched ("How many times have I seen rainbows in the last 5 years?"), copies or extracts can be easily provided to others (for example, observations of a severe thunderstorm), and if necessary photographs or tables/graphical output of AWS data can easily be pasted in alongside descriptive text. They are also easy to store alongside other computer records – bound volumes of desk diaries can take up a lot of bookshelf space over time, and manuscript records are of course irreplaceable in event of theft or fire or water damage.

The amount of detail included is also largely a personal decision. Obviously, the more detail included the longer the entries will take to complete each day. My personal preference is to write around 100–150 words per day's weather – although that varies from only a line or two on a day with 8/8 unbroken overcast and no significant weather, to a longer entry for a major weather event such as a prolonged and heavy snowfall. It is best to write down the detail of such events as soon as possible, preferably on the day itself, while the details are still fresh in the memory. I find it next to impossible to recall the detail of most days' weather even a few days afterwards without a 'prompt' from instrumental data. Having a written description prepared immediately after the event does help to recall the day's weather, even months or years later.

One-minute summary – *Non-instrumental weather observing*

- Instrumental readings are of course vital in making observations of the weather, but for a complete picture non-instrumental and 'narrative' weather observations are equally important, especially for the analysis of severe weather events.

- A once-daily 'morning observation' is the best time to read/reset any manual instruments in use, as well as perform visual checks on the operation of the sensors for an AWS, particularly raingauge funnels which are likely to become blocked if left unchecked. A manual observation also provides a convenient opportunity to note current weather details such as the amount and types of cloud, the surface visibility, present weather, the occurrence of lying snow, and so on. Weather observing should not be restricted to viewing graphical or tabular output on a computer screen!
- With a little practice, maintaining a near 24 hour weather watch becomes second nature, and with some assistance from friends, family or neighbours a 365 day, 24 hour coverage of significant weather is not difficult. When combined with the instrumental observations from an AWS and a brief daily descriptive weather diary, a high-quality combined weather record quickly builds up.

References

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[2] Pretor-Pinney, Gavin (2006) *The Cloudspotter's Guide.* Sceptre/Hodder & Stoughton: also by the same author, *The cloud collector's handbook*, published by Sceptre/Hodder & Stoughton in 2009.
[3] Dunlop, Storm (2001) *The Oxford Dictionary of Weather*. Oxford University Press.
[4] Full details of all WMO codes can be obtained at http://www.wmo.int/pages/prog/www/WMOCodes/Manual/Volume-I-selection/Sel10.pdf. the present weather code is 4677. 'Beaufort Letters' (see http://weatherfaqs.org.uk/node/158) are easy and intuitive to use, and can provide a standard abbreviated shorthand description for weather diary entries.
[5] Meaden, G T (1976) Practical hail gauges for climatological stations. *J. Meteorology*, **1**, pp. 313–319.
[6] A list of, and links to, the world's national weather services is available on the WMO website: http://www.wmo.int/pages/members/members_fn.html.
[7] Met Office (1982) *Observers Handbook*. HMSO, London, p. 81.
[8] Burt, Stephen (2010) *British Rainfall 1860–1993. Weather*, **65**, pp. 121–128.

15 Calibration

> *"The person who has only one watch knows what time it is, but the person who has two is . . . not sure."*
>
> *A favourite saying of professional metrologists, quoted by Richard Davis, formerly head of the Bureau International des Poids et Mesures (BIPM) mass division, at the Royal Society in London, 24 January 2011*

Instrument calibrations are both one of the most important, and yet also one of the most neglected, areas of weather measurement. We have already seen in Chapter 2 that precision is not the same as accuracy. To make *accurate* weather measurements the instruments themselves need to be accurately calibrated, or at least regularly compared against instruments of known calibration to quantify any differences, or error (which should then be added to, or subtracted from, the observed reading to give the true value). As calibrations can drift over time, the calibration should be checked regularly, and adjusted if necessary. An error of 1 degree Celsius in temperature, or 20 per cent in rainfall, may not seem very significant on a day-to-day basis, but if monthly or annual values are adrift by even half this amount, the readings obtained will not be comparable with other locations, or with historical records. A 1 degree Celsius difference in mean air temperature corresponds on average to about 150 metres difference in altitude, or to the difference in annual mean temperature between London and Paris, or between Boston and New York.

One difficulty that applies to calibrating weather instruments is that, without a duplicate set of instruments, removing the sensor (and sometimes the logger too) for offsite calibration means that the record from that instrument is lost while it is away, which may be for several weeks. Therefore, methods which allow *in situ* calibration of the instruments are preferable. Depending on the instrument type, this can be achieved using an 'absolute' or 'fixed point' method, or by comparing readings over a period with a portable reference instrument whose calibration is accurately known.

This chapter describes straightforward methods to check and adjust calibrations for the most common weather instruments – precipitation, temperature, humidity, and air pressure sensors.

Calibrating a recording raingauge

For the reasons outlined in Chapter 6, *Measuring precipitation*, it is always advisable to ensure that the 'reference' precipitation measurement is made using a standard 'manual' raingauge (a five-inch gauge in the UK and Ireland, eight-inch pattern in the United States). Recording gauges (such as tipping-bucket or weighing raingauges) will almost always read a little lower than the standard gauge, owing to both instrumental and evaporative losses and different exposure. By definition, a standard manual raingauge, when correctly exposed, gives the 'reference' rainfall total. Minor differences between the standard gauge and a recording raingauge are therefore to be expected: rarely will two raingauges record exactly the same amount of rainfall. An automatic raingauge should *not* be adjusted merely to attempt exact agreement or near-agreement with the standard gauge – instead, carry out the method below to derive an absolute calibration for the unit by passing a known volume of water through the unit and comparing its measured output.

The method below assumes a tipping-bucket raingauge, but the principle is the same for almost any type of recording gauge.

For the test, the recording raingauge should be connected either to its normal display or logging system, or to a pulse counter, whichever is easier. If a tipping-bucket raingauge is in use, the calibration check can be performed *in situ* on a dry day (remember to delete the calibration test tips from the record afterwards). Ensure the gauge is absolutely level before and during the test.

First, carefully measure out 500 ml of water[*] at room temperature. This should be measured as accurately as possible, preferably with a laboratory balance, but with digital scales if not. At room temperature, 1 ml (= 1 cm^3 or 1 c.c.) of water weighs 1 g [†], so measure 500 g of water, netting off the weight of the container of course.

This needs to be carefully poured through the tipping-bucket raingauge. Pouring it in too rapidly will simply overload the buckets (they will stick in the 'tipped' position and the resulting calibration will therefore be inaccurate), so the rate of inflow needs to be reduced to a steady trickle. A large plastic funnel with sufficient capacity to hold at least 500 ml water, obtainable from hardware stores, can be adapted to do this. Push a blob of Blu-Tack, putty or similar material well down into the spout of the funnel so that it blocks it. Using a small screwdriver, carefully make a small hole in the Blu-Tack. Fix the plastic funnel securely in place above the raingauge funnel and tipping-bucket unit (make sure the gauge is perfectly level, and in a position where the water from the emptying buckets can safely drain away). Pour a cupful of water (not the measured 500 ml sample yet) into the funnel and allow it to drip into the raingauge funnel, at a rate to ensure the buckets tip no more often than once per minute or so – simple arithmetic will show that this corresponds to a rainfall rate of 12 mm/h for a 0.2 mm tipping-bucket unit. Adjust the hole size as necessary. (This also serves to pre-wet the surfaces of the funnel and the tipping buckets.) Too rapid a rate of flow risks the buckets overflowing – too slow a rate will simply mean that the test takes hours to complete[‡].

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[*] 500 ml is sufficient for most raingauges with funnels of diameter 100–200 mm (4 to 8 inches) or so; larger or smaller funnels may need more or less than this. The exact amount is not critical (although of course it must be accurately known), but it must be sufficient to generate at least 100 tips (of a 0.2 mm tipping-bucket unit) to minimise random counting errors.

[†] Strictly, this applies at a water temperature of 4 °C, but at 20 °C the difference in specific gravity is less than 0.2% (1.000 g/cm^3 at 4 °C, 0.9982 g/cm^3 at 20 °C). The error in the weighing device is likely to be larger than this.

[‡] It is worthwhile to repeat similar calibration 'runs' at different flow rates to assess the variation of calibration with rainfall intensity. The resulting matrix of calibration factors versus rainfall intensity becomes a useful aid in the accurate analysis of intense rainstorms. For a 0.2 mm capacity bucket, a

Once the water has completely drained through, remove the raingauge funnel and empty (tip) any partially filled buckets by hand. Replace the raingauge funnel. Note the rainfall reading or pulse count at this point; this is the zero point of the calibration test.

Re-fix the plastic funnel in position and *very carefully* pour the measured 500 ml into it, ensuring that none is spilt and that as little as possible remains in the original vessel. Allow it to flow slowly through the partially obstructed funnel into the tipping-bucket raingauge – this will take an hour or so.

After all the water has passed through – check both the plastic funnel and the raingauge funnel to ensure none remains – note the logged rainfall reading or pulse counter value.

The volume of water v collected by a cylindrical raingauge funnel is given by the formula

$$v = \pi r^2 h$$

. . . where r is the *radius* of the funnel (half the *diameter*) and h the height of the cylinder (= the measured depth of rainfall). Rearranging in terms of h:

$$h = \frac{v}{\pi r^2}$$

Measure the radius of the raingauge funnel opening, in millimetres, as accurately as possible.

Using the above equation, and knowing the radius of the raingauge funnel, it is straightforward to calculate the depth of water (= amount of rainfall) that passing through 500 cm^3 of water – or any other amount – should cause the gauge to indicate[*].

Example: using a Davis Instruments Vantage Pro2 tipping-bucket raingauge (funnel diameter 165 mm, radius 82.5 mm = 8.25 cm), and working in *centimetres* throughout:

$$h = \frac{500}{3.14 \times 8.25 \times 8.25}$$

$$= 2.34 \text{ cm} = 23.4 \text{ mm of rainfall}$$

Calculate the calibration from the comparison with the measured amount during the test. For example, if the indicated amount shown by the display was 19.8 mm[†] then the calibration is 19.8 / 23.4 = 85 per cent and the tipping-bucket unit reads

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simulated 5 mm/h rainfall rate will generate one tip every 2.4 minutes; at 60 mm/h the tip time is 12 sec; at 200 mm/h 3.6 sec; at 500 mm/h 1.4 sec. (Note that the tip rate will slow over time as the hydrostatic pressure of the water head is progressively reduced.) Even assuming the inflow pipe diameter can handle such intensities, above this level splashing, 'continuous tipping' or multiple bounce-tips become increasingly significant and repeated calibration runs may generate different results. Where high-intensity rainfall is a regular occurrence, higher capacity tipping buckets matched with wider inflow pipes will yield more reliable intensity profiles, at the cost of decreased resolution for low-intensity rainfall events.

[*] This method also applies to checking the calibration of a measuring cylinder for a standard raingauge, for example. For a UK-standard five-inch gauge, 1 mm of rainfall corresponds to 12.7 cm^3 of water; for a U.S.-standard eight-inch gauge, 0.1 inches of rainfall is 82.4 cm^3.

[†] If using a pulse counter, multiply the number of tips by the nominal bucket capacity: so, for example, 99 tips of a 0.2 mm unit would give 99 × 0.2 = 19.8 mm.

15 per cent low (a not atypical value 'out-of-the box'). The nominal 0.2 mm tip capacity in this case is therefore actually 0.17 mm (85 per cent of 0.2 mm).

It is advisable to repeat the test at least once more and compare results. If the two derived calibrations differ by more than 5 per cent, repeat a third time and average the two closest results.

If the derived calibration is more than 5 per cent different from the nominal 0.2 mm (i.e., outside the range 0.19 to 0.21 mm), the tipping capacity of the buckets themselves should be adjusted. The manufacturer's manual should be checked for the recommended way to do this, but usually this is achieved by adjusting the base-plate upon which the buckets rest in the empty position, by means of an adjusting screw or nut. Lowering the plate increases the bucket capacity (more water required to tip the bucket) and vice versa; the objective should be to adjust the tip capacity to as close to 0.2 mm as possible. It is very important that both buckets are adjusted evenly, and it may be helpful to mark the screw heads or nuts to ensure the same amount of adjustment is made to both sides[*].

Once any adjustments have been made, repeat the calibration process and check results. Calibration within 5 per cent of 0.20 mm is satisfactory: with care, 2 per cent may be achievable on some units.

The calibration test should be repeated at least once every 12 months. The derived calibration may show seasonal variations, particularly with tipping-bucket raingauges using small buckets (the Davis Instruments Vantage Pro2 0.2 mm capacity bucket holds only 4.3 cm^3, for example)[†] and therefore it is best to perform the calibration test at an air temperature close to the annual mean. Most AWS software will permit the actual bucket calibration, where known, to be substituted for the nominal (and default) 0.2 mm capacity.

Calibrating temperature sensors

One way to obtain accurate temperature calibrations is to send off the sensors (for electronic sensors, probably the logger too), to a professional calibration facility. As well as being expensive, it is also quite impractical because (except in the case of mercury thermometers) the sensors, wiring and logger will have to be de-installed then re-installed on their return. Unless duplicate equipment is available as a backup, this may mean the loss of several weeks' records.

For temperature sensors, there are two calibration methods which are easy enough to perform *in situ*: the *absolute* method, using the melting point of ice as a fixed point, and the *comparative* method, comparing results over time against a

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[*] Particularly on new units, the initial setting of the buckets may be unbalanced. If this is the case, the calibration of the gauge will vary according to which bucket is in use. This can be checked by carefully timing the intervals for 10 or so tip times on each side as the water drips through. If the average tip time for one side is noticeably different from the other, then the bucket tipping capacities differ. If so, both buckets should be adjusted to one end or other of their adjustment and then 'wound back' evenly so that they are at the same adjustment position. The calibration test, and the tip timing measures, should then be performed again until the discrepancy between the two has been eliminated and both tip at the equivalent of 0.2 mm ± 5%.

[†] The density of water varies little over normal air temperature ranges, but its viscosity (and thus surface tension) reduces significantly with rising temperature (http://hyperphysics.phy-astr.gsu.edu/hbase/surten.html#c3) : this may lead to incomplete emptying of small buckets at lower temperatures, an effect which has been observed on Davis Instruments AWSs (see reference [22] in Chapter 5 for details).

sensor of known calibration. Of the two, the absolute method is to be preferred, but as it involves immersing the sensor or sensors to be calibrated in an ice/water mixture, the method is not suitable for some devices. In addition, the design of many consumer AWS models makes it difficult or impossible to access or remove the temperature sensor/s for an immersion calibration test, and the comparative method may be the only option available.

Absolute temperature calibration using an ice/water mixture

This method uses a fixed point, namely the melting point of ice at 0.01 °C, to establish an accurate calibration point. Using a similar approach, calibrations from −5 °C to +40 °C are easy enough to obtain.

This method is easiest to undertake with electrical sensors in steel probes, and with many types of direct-reading mercury thermometer. Unfortunately, this approach cannot be used for many budget or mid-range consumer AWSs, because it requires that the temperature sensors be immersed in the ice/water mixture (as described below). Where access to the temperature sensors is difficult, or they cannot easily be detached from their housing, the method is impractical. It should also **not** be undertaken with combined temperature/humidity sensors, because immersing the humidity element in water will irreparably damage it. It is also unsuitable for certain types of thermometers, such as maximum and minimum thermometers. For these sensor types, the comparative method described below is a better option.

The method is very straightforward. It requires a small, insulated container (a small Thermos-type flask is perfect) and a supply of ice – ice cubes from the freezer are fine (preferably made with distilled water). Partially crush the ice cubes to fit them into the flask, and fill it almost full with crushed ice. Add a little cold water, just sufficient to allow the ice to 'float' almost to the brim of the flask, and shake vigorously for a minute or two before carefully inserting the sensors.

Electrical temperature sensors should be connected to a logger (preferably the logger that will be used with the sensor when operational) and logged during the test. Mercury thermometers should be inserted as fully as possible into the flask, although some stem needs to protrude in order to hold and remove them. When inserting mercury thermometers into the ice/water mixture, be very careful not to fracture the bulb or stem by excessive force, or by subsequent stirring. Where two or more devices are being checked at the same time, carefully secure the probes or thermometer stems together with an elastic band so that they can be inserted and removed from the flask as one unit. The temperature sensitive areas (bulbs of mercury thermometers, probe ends on electrical sensors) should be as close to each other as possible.

Carefully insert the sensor or sensors into the flask. Ensure the probe sensors are fully immersed into the ice/water mixture, and as much of the thermometer stem/s as possible is also immersed (make sure the thermometer does not fall into the flask, or it may break).

Gently and continuously shake or stir the flask for several minutes, to ensure an even temperature distribution within the ice/water mixture. Avoid over-energetic shaking or stirring, which may fracture thermometer stems or bulbs. Allow the sensors a few minutes to adjust to the flask temperature and settle to a steady reading.

Over a period of at least 15 minutes, take several readings of each sensor, stirring or gently shaking throughout. The reading from electrical probes should be logged every 30–60 seconds, or read off the displayed output as frequently. If thermometers are being tested, carefully withdraw the stem by the least amount possible to enable a rapid thermometer reading (to 0.1 degC precision) every couple of minutes.

Note and average the 'steady state' temperatures, ignoring the highest and lowest values. If the sensor is correctly calibrated, the average should be 0.0 °C. An average of, say, –0.3 °C would indicate that the sensor was reading 0.3 degC too low, and thus the correction to be applied at this temperature would be +0.3 degC.

Ice point calibration for platinum resistance thermometers (PRTs)

This method is very suitable for checking the calibration of PRTs. If the sensor is an ISO standard unit, its change of resistance with temperature is accurately defined (the world-wide standard for 'Pt100' platinum RTDs, DIN/IEC 60751, requires the unit to have an electrical resistance of 100.00 Ω at 0 °C and a temperature coefficient of resistance of 0.00385 Ω/degC between 0 and 100 °C). So once the sensor error (if any) at 0.0 °C has been determined, and provided of course the correct temperature coefficient of resistance is used in the logger, then this simple offset correction can be applied to all other temperatures measured by the sensor.

Establishing other calibration points using this method

The method can easily be extended to establish calibrations at other temperature points. A mixture of crushed ice and salt in the flask can be used to obtain temperatures down to –5 °C, or a little lower. Removing the ice and salt and adding warmer water allows flask temperatures to be obtained at various points up to about +40 °C. An insulated flask and continuous gentle stirring is essential to maintain a steady temperature, particularly where the flask temperature differs considerably from the ambient air temperature.

The method is the same as for the ice-point test, but for all points above 0 °C, an accurate temperature reference is required. If one of the sensors is a PRT, applying the offset determined from the ice point test should give a temperature accurate to 0.1 degC. If no PRT is available, a calibration thermometer (a thermometer with an expanded scale, enabling it to be read to 0.05 degC) or another electrical sensor should be used. Obviously, either must themselves be accurately calibrated before the test. A pre-calibrated Tinytag logger with a flying lead (see Chapter 3) is ideal for this purpose.

Once the ice point and extended point tests have been completed, prepare a calibration table for the sensor similar to that shown in **Table 15.1**. Points between calibration points can be obtained by interpolation. If the calibration is of a manually-read mercury thermometer, calibrations (to 0.1 degC precision only) should be added to the observed reading at every observation prior to recording the value in the observation register. If an electrical sensor is being used, the calibration algorithm should be incorporated into the logger programming or setup configuration.

Note the test date, results and calibrations applied in the site metadata, particularly whether or not corrections have already been included in observations from the site (to avoid mistakenly including them again when the observations are archived). Calibrations on electrical sensors should be checked at least every

Table 15.1. *Simple calibration and correction table, derived from the fixed-point calibration method described in this chapter*

Dry-bulb thermometer *Serial no. 12345/12*
Corrections to be applied at various temperatures
Based on fixed-point calibration tests, October 2012. Calibration introduced 1 Jan 2013

At observed °C	Add correction to observed reading, degrees C
–15.0	**+0.3**
–10.0	**+0.3**
–5.0	**+0.2**
0.0	**+0.2**
5.0	**+0.1**
10.0	**+0.1**
15.0	**0**
20.0	**0**
25.0	**–0.1**
30.0	**–0.1**

2 years, or immediately if any sudden change in calibration is suspected. Mercury thermometers should be checked every 5 years.

Comparative temperature calibration using a sensor of known calibration

The second method is cross-calibration alongside a sensor of known accuracy. For temperature sensor calibrations, this can be done quite easily and accurately (with care, to 0.1 degC) with a calibrated portable reference [1]. The Tinytag loggers made by Gemini Dataloggers (see Chapters 2 and 3, also Appendix 4 for supplier details) are perfect for this purpose; similar units are available from other suppliers. These small, rugged, accurate units can be calibrated to a traceable national standard by the manufacturer, and then exposed alongside existing equipment for an extended comparison period (days to weeks).

There are two types of Tinytag logger – a larger unit which has a built-in sensor package and a digital display of current temperature and humidity (**Figure 3.4**) and a smaller logger which is temperature-only and has no display (**Figure 3.5**). The larger unit is ideally suited to being left in a thermometer screen, but is not weatherproof: the smaller loggers are weatherproof, so can easily be used to check the calibration of exterior sensors, such as grass minimum or earth temperature units (see Chapter 10), as well as sensors exposed in a thermometer screen or a small radiation screen.

This section provides a step-by-step guide to doing this, assuming the smaller logger with a flying lead is being used. Tinytag loggers with built-in sensors are not suitable for this method, as the thermal inertia of the relatively bulky logger unit means response times are too slow – see Appendix 1.

1. Obtain a calibrated datalogger

Required – a temperature logger with a sensitive thermistor on a flying lead, a calibration table from the supplier (specify three calibration points at –10 °C, +10 °C and +30 °C when ordering the logger), logger software and USB cable to connect the logger unit to a PC[*]. The calibration process is undertaken within spreadsheets (it helps to be reasonably spreadsheet-literate, as doing it by hand would be a very tedious task). Sample spreadsheets are available from www.measuringtheweather.com. In the examples below, Microsoft Excel has been used but most spreadsheet packages should be able to duplicate the functions described easily enough.

2. Set up the logger

Connect the thermistor to the logger, install the software if not already installed, then launch the datalogger. Check that the battery is fully charged, and that the logger is working satisfactorily by leaving it to log for an hour or two with a short logging interval (say, 1 minute). After this period, check logged data can be downloaded satisfactorily to the PC.

Once everything has been tested and is working satisfactorily, reset the logging interval to be the same as the logging interval on the AWS for the element being monitored (which may be 5 minutes for air temperatures, for example, or perhaps hourly for earth temperatures or for comparing against maximum and minimum thermometers in a Stevenson screen – see Chapter 3 for more on logging intervals). Choose to log either temperature only at the set interval, or maximum and minimum temperatures attained during the logging interval – the latter provides a closer calibration against maximum and minimum observed temperatures logged by the AWS sensor under test, or conventional thermometry. Relaunch the logger. Make a diary note of the date when the logger memory will become full and require downloading.

Choosing more parameters and shorter logging intervals will of course use memory more quickly and so shorten the interval between logger downloads. On current models, selecting 5 minute resolution with spot temperature, maximum and minimum recording permits 4–6 weeks record before the memory becomes full and starts over-writing once more. A few minutes' data will inevitably be lost when the logger is temporarily removed for downloading, so try not to change the logger near a time of maximum or minimum temperature – the morning observation is often a suitable time to do this.

3. Expose the temperature sensor adjacent to the equipment to be checked

Expose the small flying-lead thermistor adjacent to the sensor whose calibration is being checked. The sensor comes with 60 cm of lead, so it should be easy enough to locate it exactly where it is required. In a Stevenson screen (or similar), expose the thermistor close to (but not touching) the main air temperature sensor (**Figure 3.4**). Things are a little more complicated with smaller plastic AWS radiation shields as it is more difficult to see where the sensors are, but try to fix the thermistor in place as close as possible to the AWS temperature sensing element without actually touching it. Check that it is not exposed to direct or indirect solar radiation through the

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[*] The Tinytag units are quite expensive, but within the UK the Climatological Observers Link (COL) operates a loan scheme for members. For a nominal fee plus postage, one of the units can be borrowed for up to a month to conduct cross-calibration tests on your own equipment. Contact details for COL are given in Appendix 4.

'saucers' of the radiation screen (try shining a small torch through them at dusk). Whether in an AWS screen or Stevenson screen, secure the thermistor and its lead with cable clips or weatherproof tape to ensure it cannot work loose. (When removing the unit, ensure you do not accidentally snip through the thermistor lead as well as the cable clips.)

When checking other sensors, for example a grass minimum or earth temperature sensor, locate the unit as close to the sensor to be checked as possible. For the grass minimum sensor, ensure the calibration sensor is not located on top of the unit being checked as this will itself affect outgoing radiation and thus the indicated temperatures.

Finally, connect the calibration thermistor to the Tinytag logger. Minimize any thermal inertia effects from the body of the logger itself by locating it some distance from the sensor/s in use. In small radiation screens, there is unlikely to be sufficient internal space to house the logger, so trail the lead carefully outside the screen and secure the logger to a convenient external mounting point (**Figure 3.5**). Ensure the cable connecting logger to thermistor is not snagged or stretched, as it is easily damaged: the cable connector plug must also be screwed tight into the logger port to avoid moisture ingress. The logger should not be located where it will itself affect the temperature record within the radiation screen (by warming up in sunshine, or blocking ventilation, for example). The logger itself is weatherproof and can safely be left exposed to the elements, provided the risk of theft or vandalism is small.

Allow the sensor and logger to settle to the outside temperature before commencing logging (a delay-start option is available for this purpose), or ignore the first 30 minutes or so of readings to allow for settling. If the logger has been in a centrally heated room and is then taken outside in winter it may be 20 degrees or more warmer than the ambient air temperature, and while cooling down it will affect the readings obtained to a decreasing extent.

4. Log comparison data

Leave the calibration logger to record alongside your existing sensors for as long as possible (at least 2–3 weeks). The logger itself will require removal for downloading to the PC at regular intervals as its memory becomes full, but this need involve only a few minutes loss of record (disconnect the sensor from the logger, and leave the sensor in place). The larger the range of temperature covered during the period, the better, because this provides a better estimate of the calibration curve (see below).

5. Download logger data and apply calibration to logged temperatures

At the end of the logging period, remove the logger, connect to the PC and download the data using the logger software. Export it into a suitable spreadsheet.

The manufacturer's calibration certificate provided with the instrument will give the logger calibration: this is normally linear across the range of calibration temperatures. Plot these on a graph and determine the slope of the calibration curve (a few mouse clicks in Excel will do this). For example, if the calibration values were as follows:

At –10 °C	*Subtract 0.25 degC*
At +10 °C	*Subtract 0.15 degC*
At +30 °C	*Subtract 0.05 degC*

. . . then the calibration offset at any logged value would be given by:

$$\text{Calibration offset} = (\text{Observed temperature } ^\circ\text{C} - 40) \times 0.005$$

The calibrated temperature is then observed temperature + calibration offset

Lay out a spreadsheet something like this (sample calibration spreadsheets in Excel format, including one to determine the slope of the calibration curve with temperature, are available for free download at www.measuringtheweather.com):

Logger record	Date/time	Logger observed temperature	Calibration offset	Calibrated logger temperature
1	23.2.2014 18:15	10.00 °C	–0.15	**9.85 °C**
2	23.2.2014 18:20	9.62 °C	–0.15	**9.47 °C**
3				

6. Compare the results to check calibration

The next step depends on whether the requirement is to check the calibration of liquid-in-glass thermometers in a screen, such as maximum and minimum thermometers, or to check sensors on an AWS. Note that for thermometers in a screen it is best to do this check against the readings of self-registering thermometers (i.e., maximum and minimum) rather than an ordinary (dry-bulb) thermometer, because opening the screen door and the proximity of the observer while reading the thermometer is likely to change the observed reading slightly. With self-registering thermometers 'observer proximity' effects are less of a problem, unless the maximum or minimum occurs at the time of the observation – if that happens it may be advisable to exclude such observations from the comparison.

To check the calibration on once-daily results (maximum and minimum thermometers in a screen, for example) – go to step 7 below. To check the calibration of logged temperature sensors (air temperature from an AWS, for example) – go to step 8.

7. To check maximum and minimum thermometers in a screen

Determine which period your maximum and minimum temperatures refer to (the 'terminal hours'– see Chapter 12). For the purposes of this calibration comparison it could be any period, say 0700 to 0700, so long as 'test' and 'reference' instruments use the same one. Note that the default time period for most AWS extremes is midnight to midnight, so unless screen thermometers are normally read and reset at midnight some adjustment of the period to which the AWS extremes relate will be needed in order to be able to make direct comparisons with the once-daily reading given by the thermometers. Note also that if hourly logging has been selected, then terminal hours will need to be 'exact hours' (perhaps 0700 or 0800) rather than fractional hours (such as 0730).

Table 15.2. *Sample calibration results for daily maximum and minimum thermometers*

	Maximum temperature °C			Minimum temperature °C		
Date	Calibrated logger	Observed thermometer	Difference degC	Calibrated logger	Observed thermometer	Difference degC
23 Feb 14	11.65	11.7	−0.05	2.85	3.1	−0.25
24 Feb 14	8.72	8.9	−0.18	−3.36	−3.2	+0.16
. . .						

Using the spreadsheet, evaluate the logger-observed daily maximum and minimum temperatures (using the values with manufacturer calibration included, as shown in the table in step 5) over the same time period as the thermometers. Enter these in a second tab on your spreadsheet, looking something like **Table 15.2**.

The 'difference' column is (calibrated logger value minus thermometer) – this is the correction to be applied to the thermometer reading to indicate the same temperature shown by the calibrated logger. Don't worry that logger values are more precise (more than one decimal place), because the thermometers are read only to one decimal place.

It is always best to undertake side-by-side comparisons for as long as possible in order to obtain a wide range of temperatures to derive a good calibration curve. This particularly applies to cross-calibrations where only a single data point per thermometer per day is noted, as is the case with maximum and minimum temperatures. Try to achieve a range of (say) 10 degC or 20 degF on either side of the mean annual maximum and minimum temperature, but even a few days worth of data will quickly identify any gross calibration errors. Note that some results which appear out of line with others may need to be manually excluded. This can happen for various reasons, the most likely of which is due to the differing time constants (response times) of the two sensors (for instance, one day the maximum temperature may occur during a very short spell of sunshine: the response of the mercury thermometer will lag slightly behind that of the smaller, more responsive thermistor, and a relatively lower maximum temperature reading will result: including this in the calibration curve may result in a biased calibration).

Next, for each thermometer separately (as they will probably have differing calibration curves), plot an Excel scatter plot of the observed thermometer value (horizontal x axis) versus the calibrated logger values (vertical y axis) – a suitable template is included on the downloadable spreadsheet. Using Excel, evaluate the equation of this line, which may be linear (varies in a straight line with the thermometer reading) or polynomial (a curve which includes more than one term) – see example in **Figure 15.1**.

With a good spread of data points, this trendline equation should provide a robust calibration comparison over a reasonable range of temperatures. These calibrations should then be manually applied to the observed readings of the maximum and minimum thermometers. It is easiest to do this by reading off the ranges for corrections in 0.1 degC increments from the graph – resulting in the small correction table given in **Table 15.3**.

Make a note in the station metadata (see Chapter 16) of the calibrations applied, and the date they were introduced – better still, keep a copy of the calibration tables

Table 15.3. Sample thermometer calibration/correction table

Minimum thermometer *Serial no. 23456/11*

Corrections to be applied at various temperatures

Based on calibration against calibrated Tinytag sensor October 2012. Calibration introduced 1 Jan 2013

At observed °C	True temperature is °C	**Add correction to observed**
–15.0	–14.2	**+0.8**
–10.0	–9.2	**+0.8**
–5.0	–4.3	**+0.7**
0.0	0.7	**+0.7**
5.0	5.6	**+0.6**
10.0	10.5	**+0.5**
15.0	15.5	**+0.5**
20.0	20.4	**+0.4**
25.0	25.4	**+0.4**
30.0	30.3	**+0.3**

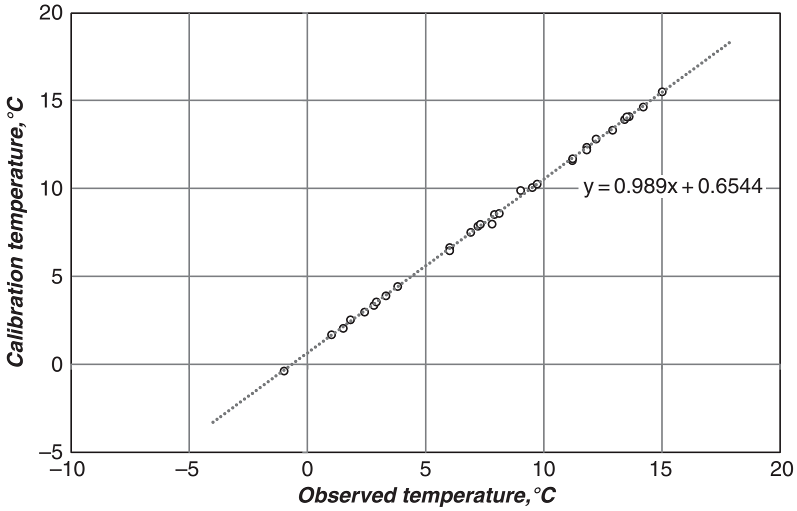

Figure 15.1. Sample scatterplot for a minimum thermometer obtained in a cross-calibration exercise (real data). The plot shows both observed and calibrated temperatures. The dashed line shows the trendline derived using Excel, together with the equation of the line.

within the metadata document. Strictly speaking, the derived calibration is valid only over the observed range of temperatures examined (this is the reason why it is a good idea to undertake one cross-calibration run in winter and another in summer, and combine the results), but when the fit is good (as in **Figure 15.1**) the results can normally be extrapolated using the derived calibration equation for at least a few degrees Celsius above and below the upper and lower observed value. The trendline and the correction table should not be extrapolated too far beyond the observed range of temperatures if the scatter is wide, or the trendline non-linear.

Keep a link to the calibration comparison test results, as these will be useful to refine calibrations if a wider range of temperature data becomes available (if perhaps the initial calibration run in a winter month can be followed up some months later by a summer comparison).

If the comparison undertaken was against thermometers only, go now to step 9 below.

8. To check logged temperature sensors

Ensure the logged values from the calibration logger and the sensor being checked are at the same time interval (5 minutes is ideal) and that both observations are made approximately simultaneously (for example, at 0900, 0905, 0910 and so on).

Check the system documentation as to whether the temperature sensor being cross-calibrated outputs a 'spot' or 'sample' value at the logging interval, or whether all samples are averaged over the logging interval (some AWSs allow toggling between these two options).

If the values are 'spot' values, then these can be compared directly with the 'spot' calibrated logger values as described in section 5 above.

If they are averaged over the logging interval, it is best to compare them with a pseudo-average derived from the calibrated logger data. For short data intervals, the average of (spot value at beginning of logging period + spot value at end of logging period + observed maximum during logging period + observed minimum during logging period) will be very close to the sampled average – and this is very easy to calculate in the Excel table.

Paste into the existing logger spreadsheet the appropriate data from the sensor being checked, taking care to ensure that all data values are coincident in time*. So the comparison table will now look like this:

Logger record	Date/time	Logger observed temperature	Calibration to be applied	**Calibrated logger temperature °C** (*from Step 5*)	**Temperature of sensor being checked °C**	**Difference**
1	23.2.2014 18:15	10.00 °C	–0.15	**9.85**	**9.82**	**+0.03**
2	23.2.2014 18:20	9.62 °C	–0.15	**9.47**	**9.45**	**+0.02**
3						

The 'difference' column is (calibrated logger value minus sensor to be checked) and this is the correction to be applied to the sensor being checked to indicate the same temperature shown by the (calibrated) logger.

With logged data at frequent intervals over a period of several weeks, many more observations are available to provide a good comparison and the optimum times to

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* During summer time, ensure both loggers are operating to the same time standard – UTC, local regional time or summer time. If the transition from summer to winter time, or vice versa, happens during the comparison period, check both loggers have handled the transition correctly. (It is much simpler to use one time standard throughout the year, of course.)

check cross-calibrations can be extracted from the record. These are cloudy, windy, dry conditions at night (no solar radiation), when the temperature is stable (from the author's experience, a rate of temperature change less than 1 degC per hour is preferable). Occasions to avoid include times when the temperature is changing rapidly, because relatively large transient differences may arise due to response time/lag effects rather than genuine calibration differences (see Appendix 1). Excluding these occasions enables the construction of a more consistent and thus accurate calibration curve. Here is how to extend the spreadsheet to filter out these specifics:

Temperature change In a new column, define a variable that is 1 when the temperature has changed less than 0.25 degC (in either direction) in the previous 15 minutes (i.e., a rate of 1 degC/hour). This value is not critical, and it may be increased a little if too many cells are being excluded from the analysis to obtain representative results.

Day/Night Set out a new column that has Day = 1 and Night = 0. Defining day/night periods is easy if pyranometer data are available (day = pyranometer output positive: make the threshold slightly above zero to allow for the slight zero offset of these instruments). If no pyranometer record is available, a table of sunrise/sunset times will provide these (see Chapter 11 for sources); enter 0 or 1 in the column for each observation time.

Wind speed If wind speed data are available, set out a third column to indicate 1 if the wind speed at the observation time is above a pre-set value, say 5 knots to start with, else leave it zero. Remember that if the anemometer is located well above screen height, the anemometer-indicated wind speed may not be representative of screen-level wind speeds and a higher threshold may need to be chosen. Again, adjust the value if there remain too few cells in the analysis when the filter is included.

If wind speed data are not available, use only the temperature change and day/night splits. Rainfall is another factor that can make a difference when comparing between screen types (louvred screens tend to stay wetter for longer than the smaller plastic AWS radiation screens, and can therefore appear cooler for a time owing to evaporative cooling effects), but it is difficult to define from recording raingauge data alone how long a surface will remain wet once the rain has stopped.

Next draw a scatter plot of the observed sensor value (horizontal x axis) versus the difference from the calibrated logger values (vertical y axis), as in the previous example. Using Excel, evaluate the equation of this line, which may be linear (varies in a straight line with the thermometer reading) or polynomial (a curve which includes more than one term). The better the spread of data points, the better the calibration result. Using the Excel Filter function, evaluate the curves for (a) all observations and (b) cloudy, windy nights only with steady temperature – the latter will have far fewer observations (and temperature range) but a smaller range of variance and thus a more accurate derived calibration.

The calibration curve obtained should then be applied to all future logged values – some systems will allow programmed calibrations to be applied as the values are logged, with others it will have to be done in a spreadsheet post-download. Make a note in the station metadata (see Chapter 16) of the calibrations applied, and the date they were introduced. If possible retain a link to the calibration comparison test results, as these will be useful to refine calibrations if a wider range of temperature data becomes available (if perhaps the initial calibration run in a winter month can be followed up some months later by a summer comparison).

Strictly speaking, the derived calibration curve is valid only over the observed range of temperatures examined (this is the reason why it is a good idea to undertake one cross-calibration run in winter and another in summer and pool the results), but in practice the results can normally be extrapolated using the derived calibration equation for at least a few degrees Celsius above and below the upper and lower observed value.

9. Check regularly for calibration drift or sensor malfunction

The calibration of any temperature sensors, whether platinum resistance/thermistor or liquid-in-glass thermometers, can change over time: liquid-in-glass thermometers are susceptible to slow chemical and physical changes in the glass from which they are made, while electrical sensors occasionally go awry for no obvious reason. Whichever type of instrument is in use, it is therefore advisable to repeat this calibration test every 2 years, immediately if the sensor is suspected of malfunctioning.

Calibrating humidity sensors

Humidity sensors can be calibrated in a laboratory environment using a variety of chemicals which will produce a known relative humidity in an enclosed environment. However, this approach is rarely practical for *in situ* calibration, and a cross-calibration process is more applicable for operational sensors. The process is essentially identical to that for cross-calibrating temperature sensors, with the following provisos:

- No two humidity sensors will agree exactly for very long; agreement to within 2–3 per cent is perfectly satisfactory.
- Avoid using observations where one sensor remains close to saturated while the other begins to fall. These circumstances can give rise to large transient differences owing to time constant/lag effects and hysteresis (see Appendix 1) rather than true differences in calibration. Including them in the calibration curve will bias the results obtained.
- The sensor ‘ceiling’ (maximum indicated humidity) in saturated air may be as low as 94–95% on some sensors. Calibration comparisons at high humidities should be treated with care.
- Best results will be obtained for readings in the range of 50 to 90 per cent humidity, with reasonable sensor ventilation (= screen-level breeze), and when the humidity is not changing too quickly. Afternoon humidity values can vary rapidly by several per cent, and it may be best to smooth both compared and calibrated values by averaging over, say, 15 minute periods, and comparing these results, rather than 5 minute ‘spot’ values.
- Humidity sensors tend to have a shorter lifetime than temperature sensors, and calibration checks should be carried out every 12 months, or if readings become erratic.
- The raw readings should be adjusted in line with the revised calibration as appropriate.

As with other sensors, note any calibrations derived and applied in the site metadata, with the date they were applied.

Checking calibration drift on pressure sensors, including barographs

Chapter 7 gave details of setting or correcting barometric pressure sensors to mean sea level. Entry-level systems usually provide barometric pressure readings to a precision of only 1 hPa or mbar (although the accuracy may only be ± 5–10 mbar), but for accurate meteorological and climatological purposes a precision of 0.1 mbar is required. However, sensor *precision* to 0.1 mbar does not imply *accuracy* to 0.1 mbar, and the calibration should be checked – and regularly rechecked, at least every 6 months – to guard against calibration drift. Drift is inevitable, even in the best sensors: a good electronic sensor should drift by 0.1 mbar per year or less, but a household aneroid barometer or small-scale barograph may drift by much more, perhaps several millibars over a year.

Calibration of pressure sensors in a pressure chamber is expensive, but sensor accuracy (after MSL correction) can be quite easily benchmarked against the synoptic pressure field using essentially a more detailed version of the method given in Chapter 7 (section *MSL pressure corrections – approximate method* page 174). This more accurate method uses more stations, and requires original readings to 0.1 mbar. Unfortunately many state weather service websites list pressure observations only to 1 mbar precision, which is not precise enough for accurately determining calibration drift.

Unless your site is very close to a main reporting synoptic station (within about 10–15 km / 10 miles or so, and at a similar height – in which case a single station is sufficient), select at least four synoptic stations, preferably at similar distances to the north, east, south and west. Locations and maps of observing sites are usually available on state weather service websites. Plot them on a sketch map with your observing location at the centre. On an overlay, plot their reported MSL pressures[*], then draw isobars (lines of equal pressure) at 0.5 mbar intervals. Estimate the pressure at your location from the isobars, and compare this with your own observations made at the same times. (Remember that the synoptic station observations will always be in UTC – see Chapter 12 for more on time standards – so if your observations are in local clock time, or summer time, remember to correct for the difference.) Repeat this at different times of day over a couple of weeks, and keep track of the results in a small spreadsheet. If possible, do the exercise in a period with significant pressure changes as the calibration error may vary with pressure.

Include as many observations as possible to minimize outlier errors – occasional large stray differences may result from showery activity, rapid pressure changes at frontal passages, slight timing differences or even observational error. Check every data point and discard any that are obviously outside the normal range to avoid

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[*] MSL pressures from synoptic reporting stations to the required 0.1 mbar accuracy, decoded from transmitted observations, can be obtained from several locations on the web – for example, UK and Ireland observations from www.met.reading.ac.uk/~brugge/latest_weather.html. Numerous synoptic reporting websites, such as **ogimet.com**, provide coded observations from reporting stations worldwide – the pressure observation is contained within the coded observations (details of the synoptic codes and how to decode the coded pressure value can be obtained from various meteorological reference sites on the web). The existing method of distributing coded observations using the so-called SYNOP code will be withdrawn at some stage before 2014; at the time of writing it is unclear whether Internet access to coded synoptic observations, including accurate barometer readings, will continue to be available once this code is phased out.

biasing the results obtained. Analyze the results to ascertain how close your barometer readings are to the background field, then adjust future observations accordingly.

When done carefully, this method can easily pick out calibration drift errors down to 0.1 mbar. Once set up in a spreadsheet, it becomes easy to repeat every few months as required.

Calibrating other sensors

It is possible to cross-calibrate other sensors *in situ* using similar methods to those for temperature, but the relatively high cost of additional sensors for other elements (such as solar radiation) makes this an expensive exercise unless a spare calibrated unit can be borrowed for the duration of the test. Of course, unless the calibration of the 'reference' unit is reliably known, using another instrument to adjust calibrations on existing sensors will almost certainly make matters worse.

For anemometers, the exposure of the instrument is likely to have a greater effect on the readings obtained than any relatively small deficiencies in calibration. Accurate calibration of wind instruments is important, but less important than getting the best possible exposure – see Chapter 9 for details.

One-minute summary – *Calibration*

- Instrument calibrations are one of the most important, yet also one of the most neglected, areas of weather measurement. Making accurate weather measurements requires accurately calibrated instruments.
- Recording raingauges can be easily and accurately calibrated by passing a known volume of water through the gauge, and comparing with the indicated measurement. 'Out of the box' errors for some AWS tipping-bucket raingauges of this type can exceed 20 per cent, so this is a vital test for all new instruments at first installation. Recording raingauges should not be adjusted merely to attempt exact agreement, or near-agreement, with a standard raingauge, because instrumental and exposure differences will always lead to slight variations in the amount of rainfall recorded.
- Two calibration methods are described for temperature sensors, whether liquid-in-glass thermometers or electrical units. The first is a quick and easy method based on the fixed point of melting ice at 0.0 °C. An extension of the approach can extend the range of calibration points from –5 °C to +40 °C when used with an accurately calibrated reference thermometer. However, this method is not suitable for certain types of sensor, and on some AWS models the temperature elements may not be accessible to allow this test to be undertaken.
- The second temperature calibration method involves careful comparison over a period with a portable reference unit of known calibration. Both sensors (calibrated reference and test) are exposed in identical adjacent surroundings exposures for a period (days to weeks). Careful comparison of readings can derive an accurate calibration curve, which is then used to apply the corrections obtained to the sensor readings going forward.
- Calibration checks, and checks for calibration drift, on pressure sensors can be made using pressure reports from synoptic sites over a period of a few days or weeks.

- Make a note in the site metadata of all calibrations applied, and the date. Keep a copy of the calibration table or algorithms used in the metadata file. Retain the calibration test results.
- Calibrations can drift over time, so calibrations should be checked (and adjusted if necessary) regularly – at least once every 6 months for pressure sensors, every 2 years for electronic temperature probes and every 5 years for liquid-in-glass thermometers.

Reference

[1] Burt, Stephen (2008) Calibration of air temperature sensors. *Climatological Observers Link Bulletin* No. **460**, August 2008, pp. 30–32.

16 Metadata – what is it, and why is it important?

Metadata is literally ‘data about data’. In the context of weather records, it is a description of the site and its surroundings, the instruments in use and any changes over time, information about observational databases and units used, where the site’s records are archived, and any other details about the measurements that may be relevant.

Why is it important? Because it provides the essential information for any other user of the records to understand more about the location and characteristics of the data, and therefore enables more informed use of the data. For example, your metadata could make it clear that the anemometer in use was at a different height for the first few years of the record, and that records before and after the change are not homogeneous. Such details may be known to the observer but may not be immediately obvious from the records themselves. Metadata are especially important for elements which are particularly sensitive to exposure, such as precipitation, wind and temperature. A comprehensive site and instruments description also allows you and other observers to compare records with a degree of confidence, and to be sure that you are ‘comparing apples with apples’.

For professional sites, a good account of the site, instruments and their calibration (and any changes) together with details of observing practices, is particularly important for long-period records, or where the records themselves may be required for legal evidence – at a local authority pollution monitoring site, for example. Most ‘amateur observer’ weather station owners will have this information in their head rather than written down, but it is good practice to write it down and keep it with the station records (and on your website, if you have one), updating it occasionally as things change. Why? Because observers do not live for ever, and good site metadata may enable others to make use of your carefully collected data in the future, perhaps long after you have passed away.

This chapter deals with what should be recorded about records made at the site, including reference to WMO guidelines and template forms [1] and good example documentation [2].

More detail on collecting and storing the measurements themselves, particularly digital files, is given in the following chapter.

Metadata – what should it include?

There are no hard and fast rules or standard formats – a short written or tabular description is normally sufficient. Site metadata should include whatever is relevant. The following topics are suggested:

- Station name, location, geographical co-ordinates (latitude, longitude) and height above mean sea level
- Geographical context including local topographical map
- Site description and sketch map of site and instruments
- Date records began (and ended, if the site is no longer current)
- Observing hours
- Instruments in use, calibration details, exposure information, record length and changes over time
- Site and instrument photographs
- Station records – location, format, units, and so on
- Any other relevant information

Two examples of metadata files are given at the end of this section, but any format giving the same information will suffice. A sample form in Microsoft Word format is given on www.measuringtheweather.com website, or alternatively the WMO form can be used [1]. Use either, and the examples presented here, as a starting point and adapt as required to document your own site information.

Metadata information can be in manuscript or computer file format. It is suggested that a hard copy be retained with printed station records, and soft copy (word processor file or PDF document) be kept with other digital station observational records, including links on websites[*]. The computer file should be included in the same directory as the site data files, and clearly identifiable with the word 'Metadata' in the file name. It is good practice to review the file annually, and update it as necessary.

Station name, location and geographical co-ordinates

Include the city, town or village name in the station name, together with an identifier to distinguish it from other sites in the area (perhaps other observing sites you have previously maintained in the same locality). The station name 'White House' is not too specific; better would be 'Washington, D.C. – White House, 1600 Pennsylvania Avenue'.

The location statement should provide brief detail on the area around the observing site, while the geographical co-ordinates (latitude, longitude and – in the UK – National Grid Reference or NGR) define the site precisely. The co-ordinates should include the station altitude above mean sea level.

Latitude and longitude can be obtained most easily from Google Earth (many online mapping sites can also provide reasonably accurate latitude and longitude from an address or postal code), or from a handheld GPS device. When stating latitude and longitude be clear whether decimal notation (e.g. 51.564°N) or degree notation (51° 33′ 50″N) are being used. (Showing latitude and longitude to three decimal places is accurate to about 108 m in latitude and 76 m in longitude at 45°N.) Altitude is best obtained from detailed local topographic maps, such as the USGS 1:50 000 or 1:24 000 maps or UK Ordnance Survey 1:25 000 series. Altitudes can be read off from Google Earth and some GPS units, but are much less reliable than from local topographical maps (an accurate altitude is essential for reliable barometric pressure corrections to mean sea level, as described in Chapter 7).

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[*] For privacy reasons, and to minimize the risks of vandalism or theft, you may wish to remove some details, such as private postal or e-mail addresses, postal codes, phone numbers and the like, and 'round' positional information slightly, before placing it online.

Geographical context

Give a short description of the area surrounding the observing site – is it a ‘city canyon’, a high-density suburb, an open university campus, or rural moorland? Is it a hilltop or valley site? If the former, is the site open and windswept, or does it have local shelter? If the latter, does it tend to collect or dam cold air? What about soil types – is the site in an area of light, sandy soils (which would tend to amplify the observed range in air and grass temperatures), or on heavy clay (which tends to suppress temperature ranges)? How close is the site to the coast, inland lakes and rivers or other significant bodies of water? Proximity to open water may affect many observed weather elements, particularly air temperatures, humidity, and wind speed and direction, while the daily temperature regime at coastal sites may be heavily influenced by the state of the tide.

Include an extract from a local topographical map showing the surroundings for 3 km / 2 miles or so or so around the site, marking the location of the instruments. If the instruments are split across two or more sites, or the site has moved from a nearby location, indicate all relevant locations.

Site description

Narrow down the description to the observing location. Is it a suburban back garden site, a city park, or an exposed hilltop? Is it well-exposed to sunshine, wind and rainfall from all directions, or is it partially sheltered by hills, houses or forest? If so, from which direction/s? Are there buildings or trees nearby – how far away are they? Are they likely to affect the readings?

Include a sketch plan, to scale, of the observing location, the instruments and the immediate surroundings, identifying the nature and height of all obstructions within 5–10 times their height from the screen or raingauge. For hedges and trees, give their heights (with a date) and indicate whether they are deciduous or evergreen. Suggested methods are given in Chapter 6.

Date records began

Include the date records commenced – if this is different for various elements, include the start dates for each. If the site has since closed, include the last date of records too, and whether the record recommenced elsewhere. If the instruments and records at this site were moved from a nearby site, give details, together with the overlapping period of records, if any.

Observing hours

Include details on the observing hour/s and the terminal hours used for each element. Examples might include:

> “The observing hour is 8 A.M. clock time throughout the year: maximum and minimum temperatures and rainfall totals for the previous 24 hours are read and reset at this time.”
> “No manual observations are made at this site: max, min and rainfall are logged by the AWS and refer to the period 00–00h Pacific Time.”

If maximum and rainfall observations read at the morning observation are thrown back to the previous day (see Chapter 12), then that should be clearly stated.

Instruments in use, calibration details, exposure information, record length and changes over time

This is necessarily the most detailed section of the metadata summary. List here sufficient detail of the instruments in use to give any future user of the data a clear idea of the exposure, length, quality and reliability of the records obtained, and any significant changes in instruments or exposure over time (for example, the introduction of an AWS replacing thermometers exposed in a Stevenson screen, with the date of the changeover). It is particularly important to note the details of the thermometer screen, if one is in use, and any changes over time.

Where more than one instrument is used to record the same element (for example, where both a manual and recording raingauge are in use), state which measurement is regarded as the site standard. Include brief details of the instrument manufacturer and any instrumental calibrations applied, where known, and the date/s when any changes in calibrations were introduced (see Chapter 15). Serial numbers and details of calibrations can be referenced or hyperlinked as necessary. For anemometers, note particularly the height of the anemometer and any changes over time, and any obstructions within the immediate area. In the case of AWS, note the logging interval (and, if known, the sampling interval), by element.

For ease of preparation and subsequent reference, it is best to divide the description by element – air temperature, grass and earth temperature/s, rainfall, sunshine, wind speed and direction, and so on: see the examples at the end of this section. Where no measurements are made of any particular element, the section can be annotated ‘no records of [sunshine] made at this location’, or simply omitted altogether.

Site photographs

Include a link in the metadata document (and on any related weather website) to a selection of site photographs, preferably one taken showing the site and instruments from each cardinal compass point (facing north, east, south and west). Take a set in both winter and summer, as the presence or absence of leaves on deciduous trees may make a significant difference to site shelter. Take a series of photographs every year or two, from the same viewpoints if possible, to document any changes in exposure caused by growing trees or the cutting-back of vegetation. Take a hard copy (and your own soft copy) of anything created outside your control, as Google Earth imagery (for example) changes from time-to-time and may not show how your site looked before that new housing development was built across the road. If an aerial photograph of the area is available, include that too.

For posterity, why not include a photograph of the observer as well?

Station records – location, format, units and so on

Summarize in this section information about what records are available (elements measured), date of start and perhaps end of records, the time frequency of observations (one record daily, or 1 minute resolution AWS data?) and where the station records can be found (for example, in the local library or county or state archives). State also what format the records are in – hard copy and/or computer files (more details on storing computerized records are given in the following chapter). If computer files, state the application that was used to create them (such as Microsoft Excel), and include duplicate records in standard, portable formats such as Portable Document Format (PDF).

State the units used for each measured element – the difference between temperature records in Fahrenheit and Celsius will be obvious on inspection, but are wind speeds in miles per hour or knots? Have any units changed during the period of record? It is good practice also to include units details in the metadata header for each computerized record dataset – more on storing the measurements themselves in the following chapter.

Any other relevant information

It might be appropriate here, for example, to include details of previous or local sites which have been used to extend the record length or to estimate long-period averages and extremes.

Examples of metadata files

Tables 16.1 and 16.2 are examples of metadata statements (the sites are fictional). Both files are available on the www.measuringtheweather.com website and can easily be downloaded and adapted to suit.

The metadata record should be only as long, or as short, as required. Where appropriate, additional details (instrument serial numbers, photographs, site plans and the like) should be referenced in this document, or linked on a website, rather than included in the text, to simplify preparation and maintenance. A document that is easy to maintain is more likely to be updated than one which is not.

One-minute summary – *Metadata – what is it, and why is it important?*

- Metadata is literally ‘data about data’. In the context of weather records, it is a description of the site and its surroundings, the instruments in use and any changes over time, information about observational databases and units used, and any other details about the measurements that may be relevant.
- Metadata statements are important because they provide the essential information for any other user of the records to understand more about the location and characteristics of weather records made at any site, thereby enabling more informed use of the data to be made.
- A metadata statement is best prepared as a short structured text document, and retained alongside data files in soft copy or hard copy. A copy or link should also be included on the site weather website, if there is one. Links should also be provided to site photographs, instrument calibration certificates and other related documents.
- Review the metadata statement whenever instrument or site details change, and at least annually. Update as required. Retain previous site descriptions and photographs, which will assist in documenting site, instrument and exposure changes over the years.

Table 16.1. *Example site metadata*

Site metadata for **Slapton-on-the-Hill, Devon, England**
Compiled on 1 January 2014

Station name, location and geographical co-ordinates	**Slapton-on-the-Hill** This site is located near Hilltop Farm, Slapton-in-the-Slush Site authority – University of Slapton Latitude 50.727°N, Longitude 3.474°W National Grid Reference SX (20) 960 930 Altitude 225 metres above MSL Latitude and Longitude have been obtained from GPS, NGR and altitude from Ordnance Survey 1:10 000 map
Geographical context	Open and well-drained moorland site, near the summit of a low hill; nearest buildings are 2 km to the north
Site description	Exposed site. Raingauge exposed within a turf wall to minimize over-exposure. Site enclosure approx 12 m x 12 m, protected from sheep and passers-by with open-link fencing, no closer than 5 m from gauge. Plan of site is given at (*location or hard copy*) and photographs from cardinal points at (*location of images*). The exposed hill climate results in some over-exposure of the gauge, and snow falling in strong winds is probably under-represented in the records.
Date records began at this site	Rainfall – 1 May 1984 No other measurements are made at this site
Date records ended	Records continue at the date of writing
Observing hours	Raingauge is read manually once monthly, normally on the first of the month, although the date and time are weather-dependent. Details of the observation date and time are noted with each monthly total.
Instruments in use	
Rainfall	Standard five-inch monthly raingauge, measured with standard 10 mm measuring cylinder. Daily rainfall totals are not available for this site.
Site photographs	A selection of site photographs taken on 2 September 2013 are available at *location*.
Station records	Records from this site are held at the University of Slapton Geography Department; copies are sent to the Environment Agency and the Met Office.

Table 16.2 *Example site metadata*

Site metadata for **Cypress City, Idaho, USA**
Compiled on 23 March 2014

Station name, location and geographical co-ordinates	Cypress City (Washington Avenue) The site is located at 1600 Pennsylvania Avenue, Cypress City, Idaho 83205 Observer – John Doe Latitude 42.87°N, Longitude 112.34°W Altitude 1925 m (6316 ft) above MSL Latitude, Longitude and altitude have been obtained from USGS 1:24 000 map
Geographical context	Suburban site, located in medium-density housing area towards western edge of the city. Edge of urban area lies about 400 m west and south of site. Cypress City (population 15,000) is located in a valley: western suburbs are higher than the town centre, on gentle well-drained southeast-facing slope. Underlying soil is sandy loam, drains freely to the McKay river, approx 1500 metres SSW at closest point.

Table 16.2 (*cont.*)

Site metadata for **Cypress City, Idaho, USA**
Compiled on 23 March 2014

Site description	Suburban backyard, approx 28 m x 39 m, longer axis running roughly ENE-WSW. Reasonably well-exposed between south-east and west, rather sheltered by buildings and trees especially to north and north-east. Nearest buildings are the observer's house, 10 m tall at apex and approximately 22 m N of raingauge, and deciduous tree 9 m tall 18 m NE of raingauge. Plot is bordered by open fence 1.8 m tall to south and on all other sides by conifer hedging 1.2–1.5 metres high. Plan of site centered on the standard eight-inch rain gauge is given at (*location or hard copy) and* photographs from cardinal points also centered on the rain gauge at (*location of images*). The sheltered nature of the plot, together with southeast-facing valley aspect and light sandy soil, results in maximum temperatures on sunny days with light winds being a little higher than other sites in the area.
Date records began at this site	Barometric pressure – 6 August 1999 Rainfall – 1 October 2002 Air temperature – 10 March 2004 Wind speed and direction – 14 May 2006 Solar radiation – 4 March 2010. For instrumental details, see below.
Date records ended	Records continue at the date of writing.
Observing hours	Raingauge is read manually once daily at the morning observation, normally at 8 A.M. clock time throughout the year. The AWS, installed May 2006, maintains continuous records (5 minute resolution) of air temperature, relative humidity, wind speed (mean and gust) and wind direction, rainfall and barometric pressure. AWS and all records are maintained on Mountain Time throughout the year. For instrumental details, see below.
Instruments in use *Rainfall*	A 1 mm (0.04 inch) wireless tipping-bucket raingauge was installed on 1 October 2002. Records from this instrument continued until July 2006. A standard eight-inch NWS raingauge was installed on 17 August 2005. Daily rainfall totals have been taken from this instrument since that date (a 12 month overlap with the wireless unit showed the latter to read approximately 18% low). The gauge is mounted above short grass with its rim approx 1.07 m (3 ft 6 in) above ground, and is read once daily (using standard measuring tube) at 8 A.M. Daily rainfall totals adjusted to 8 A.M. manual observation using AWS data during absence from home. Units: inches. Resolution: 0.04 in to August 2005, thence 0.01 in. A Davis Instruments Vantage Pro2 AWS was installed on 14 May 2006, and is located 3 m east of the raingauge: 5 minute rainfall totals are available from the AWS 0.2 mm tipping-bucket raingauge (TBR). TBR calibration checked and adjusted annually (last checked on 11 August 2013). Standard daily rainfall totals taken from the eight-inch gauge, AWS sub-daily totals being adjusted to agree with daily gauge totals as required.
Air temperature	Temperature records commenced from a digital wireless max-min sensor/display unit on 10 March 2004, and continued until September 2006. The unit was mounted on a north-facing wall. An NWS standard Max-Min Temperature Sensor (MMTS) was installed on 20 April 2009, and is located 5 m east of the rain gauge. This uses a thermistor contained within a baffled shelter ('bee-hive' type) mounted 1.5 m / 5 feet above short grass. This transmits a resistance

Table 16.2 (*cont.*)

Site metadata for **Cypress City, Idaho, USA**
Compiled on 23 March 2014

	value, via buried cable, to an electronic NIMBUS readout within the observer's residence. The readout displays current ambient temperature and stores the 24 hour maximum and minimum temperature values for up to 35 days. Units: °F. Resolution: 0.1 degF. Since its installation on 14 May 2006, temperature records have also been taken from the Davis Instruments Vantage Pro2 AWS, located 3 m east of the rain gauge. The temperature and humidity sensor is mounted within the AWS passive radiation shield at 5 ft (1.5 m) above short grass, logged at 5 minute resolution. Maximum and minimum temperatures from AWS are logged by default over 00–00h Mountain Time. Calibration of temperature sensor checked and adjusted over 6 week period March-April 2012 using a portable calibrated reference logger (see *location* for calibration test results). Calibration adjustments included in real time by means of software offset. Units: °F. Resolution: 0.1 degF.
Relative humidity and dew point	Humidity measurements made at 5 min resolution using the Davis AWS. Manufacturer's sensor calibration used without adjustment (not checked). Humidity units: % RH. Resolution: 1%. Dew point calculated by AWS software from observed temperature and relative humidity. Units: °F. Resolution: 1 degF.
Barometric pressure	Once-daily pressure observations, usually about 8 A.M. clock time, commenced in August 1999 using a small household aneroid barometer, 'set' to mean sea level. This was read to 1 millibar, although accuracy likely ± 2–3 mbar. Aneroid barograph installed 24 April 2001, recording on weekly charts: sea level pressure at 8 A.M. daily read off charts. Records from this instrument continue. Since its installation on 14 May 2006, pressure records have been taken from Davis Instruments Vantage Pro2 AWS. Pressure sensor mounted within the AWS display unit located in a second-storey room of observer's residence, logged at 5 minute resolution, 'set' to mean sea level. Calibration checked and adjusted twice-annually by comparison with hourly pressure readings from Norze Brighton airport (22 km west) and Flag City USAF (12 km south of the site); most recent check in April 2012. Units: millibars. Resolution: 0.1 mbar.
Wind speed and direction	Wind speed and direction records commenced with installation of the Davis AWS on 14 May 2006. When first installed, anemometer and wind vane were mounted on 4 m mast located in south-west corner of the plot. The location was sheltered by buildings and trees, particularly to the north and north-east. Instruments re-located on 22 August 2008 to a 2 m mast affixed to a chimneystack located 2 m above the building roofline, at 12 m above ground level, to improve exposure. Post-move wind speeds are about twice those before the move, with reduced frequency of calms (< 0.5 knots). Both wind speed (mean speeds and highest gust) and wind direction (16 point compass) logged at 5 minute resolution. Manufacturer's calibration of anemometer sensor has been used. Wind direction is in degrees true: units of wind speed are knots (miles per hour before 22 August 2008), resolution 1 knot.

Table 16.2 (*cont.*)

Site metadata for **Cypress City, Idaho, USA** Compiled on 23 March 2014	
Sunshine and solar radiation	Solar radiation records are made using a Davis Instruments solar radiation sensor, mounted on anemometer mast 12 m above ground level. Records commenced on 4 March 2010. Exposure is partially obstructed to south-east by deciduous trees (exposure diagram is available at servicing Weather Forecast Office *location)*. Instrument is a silicon photodiode, logged at 5 min intervals by Vantage Pro2 AWS. Units: W/m^2. No sunshine records are available for this site.
Site photographs	A selection of site photographs taken on various dates between 2002 and 2013 are available at *location*. The most recent set of photographs, taken on 20 June 2013, show the site from each of the four cardinal points. A Google Earth aerial photograph of the immediate area is also available at the servicing Weather Forecast Office *location*.
Station records	Records from this site are held by the observer, John Doe, at 1600 Pennsylvania Avenue, Cypress City, Idaho 83205. Official temperature, rainfall, snowfall, and snow depth records for National Weather Service are retained on Weather Service (WS) Form B-91. This station uses the Weather Coder (WxCoder) web page to enter daily readings. The recorded Davis AWS data consist of spreadsheets of once-daily observations of maximum and minimum temperature, rainfall, mean wind speed and highest gust, together with counts of days with thunder heard, snow or sleet observed to fall, and (where relevant) snow depth at the morning observation. All temperature, wind, solar radiation and 'days with' observations refer to the period midnight to midnight Mountain Time daily (no adjustments made for summer time); all rainfall observations refer to 8 A.M. to 8 A.M. Mountain Time daily. Records from the AWS at 5 minute resolution, covering all major elements, are also available in annual Excel spreadsheets and Davis Instruments WeatherLink software native AWS file format. Copies of both the daily and AWS records, as Microsoft Excel spreadsheets, are sent on CDs annually in January to the Idaho Archives Office in Idaho Falls.
Averages and extremes	A daily rainfall record is available for Cypress Heights Farm, located 2.2 km south-east of the site at a slightly lower altitude (6195 ft). Records here commenced in 1974. Over the 5 year period 2006–2010 this site recorded on average 2.6% less rainfall than the current location. The estimated 1981–2010 average annual rainfall for this site, 526 mm, has been derived by applying this factor to the observed monthly averages for 1981–2010 from the Cypress Heights Farm rainfall record.

References

[1] World Meteorological Organization (2008) *WMO Guide to Meteorological Instruments and Methods of Observation* (Seventh edition, 2008), Part I – Measurement of meteorological variables, Chapter 1 – General (basic metadata form at Annex 1.C). Available at www

.wmo.int/pages/prog/www/IMOP/publications/CIMO-Guide/CIMO_Guide-7th_Edition-2008.html.

[2] Much useful information on assembling site metadata is given in the World Climate Research Programme *Baseline Surface Radiation Network (BSRN) Operations Manual* (2004), section 3.1.3, available online at http://www.bsrn.awi.de/fileadmin/user_upload/Home/Publications/McArthur.pdf.

PART THREE

MAKING THE MOST OF YOUR OBSERVATIONS

Having described in turn each of the elements in a typical weather observation, the remaining chapters focus on managing and using the observations obtained.

17 Collecting and storing data

To make the best use of collected weather observations, thought needs to be given to how records are kept: collecting more and more observations is normally a means to an end, rather than an end in itself. Traditional once-daily observations of just a few elements pose few data storage concerns, as they can easily be written up in manuscript in an observations logbook and/or typed up into a small spreadsheet for archiving and analysis purposes. With an AWS in place, however, give careful consideration to managing and storing the avalanche of digital data, which otherwise can quickly become unmanageable and difficult to use. Even a few months of observations can provide useful insights about the climate of a particular location: the longer the record, the better, of course, and implementing an effective record-keeping strategy from the outset will greatly simplify data collection and management as the record length grows. The more effectively records are stored, the easier it is to analyze and use them productively – the subject of the next chapter. This statement applies equally to both professional and amateur observers.

This chapter provides tried and tested suggestions on methods for collecting, storing and archiving data from both manual observations and AWSs. The next chapter outlines techniques for analysing data, building upon the foundations set out in this section. Together they should assist in making best use of collected observations, now and in the future.

Familiarity with the use of spreadsheet software is assumed, as detailed instructions are beyond the scope of this book. Many good 'teach yourself' guides are available for the major packages in both hardcopy and online formats.

Sampling and logging intervals

The concepts of sampling and logging intervals were introduced in Chapters 2 and 3 (see box, page 48, *What is the difference between 'sampling interval' and 'logging interval'?*). The sampling interval is how often the instrument or sensor is read ('polled' in the case of dataloggers), while the logging interval (the 'archive interval' in Davis Instruments terminology), as its name suggests, refers to how often the element is logged – this may consist of many individual samples.

For efficiency, consistency and simplification in record-keeping, it is advisable to define a logging interval that meets your particular requirements, and then stick to it*. Management and analysis of an AWS record over several years becomes more

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* Many 'advanced' AWS software allows more than one logging interval to be set, providing a more flexible approach to data capture – for example, a system could be configured to log a few elements at

complicated if the dataset comprises a mixture of records made at several different logging intervals.

Collecting data

Storing manual observations

Traditional once-daily manual observations can easily be written up in manuscript in an observations logbook (the Royal Meteorological Society in the UK publish a logbook [1] for just this purpose) and/or typed up into a small spreadsheet for archiving and analysis purposes (more on spreadsheet formats below). Over the years the completed logbooks will build into a useful hardcopy record of the weather, but of course records in this format do not permit easy computer analysis. Storing records on computer also facilitates making backup copies of the observations in the event of loss or damage to the manuscript records. Unfortunately, all too often observational records held only in manuscript registers are lost forever in house clearances after the death of the observer. Maintaining digital records as well as hardcopy reduces the risk of total loss, particularly where the records are regularly copied to a dedicated archive site for such records, as provided in the UK by the Climatological Observers Link Archive [2] or the Chilterns Observatory Trust [3]. The latter will also accept legacy donations of observational records in manuscript form.

Storing AWS observations

There are three good reasons for archiving AWS records in spreadsheet format – usually in addition to the 'native' AWS file format used within the AWS software package. Exporting the data into a spreadsheet allows for the creation of much larger datasets (longer record lengths), much improved analysis, graphing and presentation capabilities and (where required) the inclusion of calibration adjustments and automated error checking/quality control methods. Each of these is considered in turn below.

Fortunately it is very straightforward to generate spreadsheet files from AWS software. Every AWS software package includes an '*Export* . . .' function, whereby records for a specified date or time period can be exported into different file formats. Supported and near-universal formats are normally text or ASCII format (.txt files) and/or Comma Separated Variable (.csv) files: these file types can be read and opened by all popular spreadsheet packages on both Windows and Apple-based computers. Once imported, the file is then saved in the normal spreadsheet format ('*Save as* . . .'). Additional records can simply be added onto the end of existing files at a later stage using standard cut-and-paste methods.

Data volumes

Without some thought given to record management, data volumes can rapidly become overwhelming, as **Table 17.1** illustrates. For a typical system, logging 30 elements

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1 minute and 5 minute resolution, others at hourly intervals, and daily extremes just once daily at a predefined time, say 9 A.M. The records from such systems capture both high-resolution data, which is very useful for studying particular events, whilst simultaneously generating useful climatological datasets, such as hourly and daily averages and extremes.

Table 17.1. *Number of unique data points, and consequent approximate file sizes, for various combinations of logging interval and element count*

Logging interval	Records per element per day	Records per element per year	10 years x 30 elements	Approximate file size (MB) 10 years data
1 min	1440	525,600	157,680,000	1,224
5 min	288	105,120	31,536,000	245
15 min	96	35,040	10,512,000	82
1 h	24	8,760	2,628,000	20
2 h	12	4,380	1,314,000	10
24 h	1	365	109,500	1

File size depends upon element type and is given as an approximation only (Microsoft Excel 2007 for Windows). Excel 32 bit version can support a maximum of slightly more than 1 million rows of data, sufficient to hold about 5 years of 1 minute data.

at hourly resolution for 10 years will accumulate some 2.6 million data points. (As a very rough approximation, a Microsoft Excel 2007 file with 2.6 million data points will be a little over 20 MB in size[*].) Most AWS software becomes rather unwieldy as databases become large. Davis Instruments' WeatherLink software largely avoids the problem by creating a new data file monthly (each about 750 KB in size), although this does lead over time to an enormous number of small files which need to be retained in the working directory and backed up regularly to avoid catastrophic data loss[†].

Analysis and presentation

The second main reason to use a spreadsheet to store long-term records is that most AWS software lacks sophisticated data analysis and graphics capabilities, written as it is primarily to poll sensors, to copy short-term data to a logger database and to present fairly basic graphical representations of current real-time or stored data on request. Most spreadsheet packages will include a much richer set of data analysis and graphical output functions, greatly simplifying statistical analysis and presentation of stored historical data. (Almost all of the examples in this book have been created using standard spreadsheet software; there are more details in the next chapter.)

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[*] If 30 elements seems over-specified, bear in mind that the dataset will need to hold both date (date-month-year format) and date, month and year as separate fields: that air temperatures need to be stored as 'spot' hourly values, maximum and minimum readings, quite possibly with times of occurrence of the extremes: that wind speeds need to include both mean and gusts, with time of the maximum gust: and so on. These items alone account for 12 elements over just three parameters (date/time, air temperature, wind speed).

[†] Most AWS software runs quietly in the background, using minimum system resources except when (for example) a sensor poll is running. This can create problems for backup systems, because to avoid the risk of file corruption, most backup software will bypass any working files that are in use when the backup runs. As the AWS software is always running, this can mean that AWS files in use never get backed up. If the system crashes on the last day of the month, the whole month's data could be lost. To be on the safe side, if the AWS files are being bypassed (check the date and timestamp of your backups), it is a good idea once a week or so to stop the AWS software for a few minutes to create a backup, even if that consists of a simple manual copy of the directory contents to another location.

Inclusion of calibration and error checking

Some AWS software will allow editing of the stored records (for example, removing spurious tips from a tipping-bucket raingauge when the instrument was moved to mow the grass around it), although the line-by-line editing process is very manually intensive and thus suitable for only very limited corrections to be incorporated in the record. Storing records in a spreadsheet allows for more extensive edits to be made more quickly and easily – perhaps to delete several days of logged tipping-bucket raingauge records if the funnel became blocked, for example, or to amend observed air temperatures whilst the screen was being washed. Simple routines can also be set up to provide basic quality control (to check for sensor readings falling outside normal limits owing to intermittent faulty connections, for instance), flagging appropriate corrections or deletions as a result.

More sophisticated dataloggers will allow calibration corrections to be applied directly to the sensor reading as it is logged, but most budget AWS software has little or no calibration capability. Where required, calibration corrections or offsets can be quickly and easily applied to 'raw' AWS data using a spreadsheet. Both 'as read' and 'corrected' values should be archived, so that any changes can be undone or amended at a later stage if necessary.

Missing data

It is usual practice to indicate missing data in climatological datasheets by an entry such as –999 or similar, but in Excel spreadsheets missing data cells are best left blank to avoid corrupting the analysis of means and extremes. Blank cells are simply ignored in calculations. However, if records are to be exported from Excel for use in other software or to be included in other datasets, it is best to check whether there is any preferred import specification to mark such 'missing data' cells.

Legality of altering records

Where amendments are made to an AWS record, whether they be amendments, estimated data or deletions, the change should be recorded in a metadata entry detailing both 'as recorded' and 'corrected' entry or entries, with a brief explanation for the deletions or amendments. No changes should be made to the logged record without good reason, but of course it is valid to make corrections or deletions to maintain record accuracy or completeness. (One example would be deleting or estimating screen temperatures while the thermometer screen was being painted.) Note that if a corrected AWS record is produced in support of a legal case then both 'as read' and 'corrected' records should be presented, along with the explanation for the amendment, to avoid raising any possible questions regarding data integrity.

Managing the data avalanche

Climatological observations tend to fall naturally into three types of dataset, namely hourly, daily and monthly observations. Where data are available for each timescale, a good way of managing the record is to set up a separate spreadsheet for each (as the elements covered will be different – for example, the hourly datasheet would include 'spot' temperatures at each hour, the daily dataset 24 hour maximum and minimum temperatures, and the monthly dataset monthly and annual means and extremes of daily maximum and minimum temperatures). It is perhaps easiest to think of each spreadsheet table as a logbook page (albeit a page of almost infinite length).

Using Microsoft Excel's 'tabbed worksheets' feature, data for each timescale can be held in separate tabs within a single spreadsheet file, although as the tabbed worksheets grow over time the file size will become rather unwieldy and separate files, rather than separate tabs within one file, become easier to manage. Once-daily manual observations can be easily accommodated by a single spreadsheet containing two tabbed worksheets, one for daily values and the other summarizing monthly totals or means.

Content, format and layout suggestions for each of the three types of spreadsheet are given below.

Hourly spreadsheet

Data for this worksheet comes from an AWS – either directly, for logged intervals of 1 hour, or by 'distillation' from higher-frequency logged data (such as 5 minute observations), most easily pre-processed using another small template spreadsheet and then cut-and-paste into the hourly table.

Distilling observations

Elements logged at 5 minute intervals can always be 'distilled' to derive hourly records, although of course the reverse is not the case. 'Distilling' sub-hourly records into hourly, hourly into daily and daily into monthly records greatly simplifies data handling and is easily accomplished using Microsoft Excel's Pivot Table function (see Chapter 18, *Making sense of the data avalanche*) or with template spreadsheets. For the latter (sample templates for 5 minute data to hourly, hourly to daily and daily to monthly are provided on www.measuringtheweather.com, and these can be easily adapted to suit) simply cut-and-paste blocks of exported AWS data into the 'data' tab, then copy and paste the required distillation from the 'output' tab. The arithmetic is straightforward (for example, the 'hourly to daily' spreadsheet simply sums all the hourly rainfall values to give a 24 hour total).

Note that the sample templates assume identical numbers of observations per interval (for example, 12 x 5 minute observations in every hour), and that if one or more rows of observations are missing, duplicated or replaced by observations at a different logging interval then the pre-programmed functions will produce erroneous results. In such cases, use the Excel Pivot Table feature in preference.

Content obviously depends upon instrumentation and archiving requirements, but typical elements in a basic dataset might include the elements listed below. If possible, ensure the order of elements in the spreadsheet is the same as in the exported AWS file, as this will simplify the cut-and-paste operation.

It is a good idea to include a tabbed metadata worksheet detailing the origin of each of the measurements (sensors, brief exposure details, height of anemometer, etc.), and the units used. It may be obvious from inspection whether air temperatures are in degrees Celsius or degrees Fahrenheit, but not so obvious whether wind speeds are in knots, miles per hour, kilometres per hour or metres per second. Note also that some elements will be 'spot' values (such as air temperature 'on the hour') while others will be period means (such as hourly mean wind speed) – the exact derivation should be stated in the metadata sheet as again it may not be obvious, or it may change over time.

This fairly basic hourly spreadsheet layout (**Table 17.2**) includes 15 elements and is suitable for archiving the output from a Davis Instruments Vantage Pro2 AWS with little amendment. (Sample Excel templates, with metadata tab included, can be found on www.measuringtheweather.com.)

Table 17.2. *Example of hourly dataset layout and format*

Date	Include date in standard numerical form (d.mm.yyyy – example 20.06.2011). *Within most spreadsheet software the actual date can be entered in one way and output formatted another – so the dates might come from the AWS logger as '20.12.10', but they can easily be output as '20 December 2010' (or almost any other combination) if required. This is useful when European (d m y) and American (m d y) date conventions differ. To avoid transposition errors between date and month, check which date convention is in use within the AWS/logger software, and whether it can be altered to suit*	As will be seen in the next chapter, there are analysis advantages to holding the date in separate dd, mm and yyyy parameters in addition to the date in standard form. *Note that if dates are held in yyyymmdd format, they will be automatically sorted into date order in file structures held on computer – this is especially useful when creating file names (for example '2013–05 observations' and '2013–06 observations' will by default be filed in the correct order, whereas 'May 2013 observations' and 'June 2013 observations' will not (they will appear adjacent to the May and June observations for other years)*
dd	Numerical day number from date	In Microsoft Excel, this is the =DAY(*) function.
mm	Numerical month number from date	In Microsoft Excel, this is the =MONTH (*) function.
yyyy	Numerical year number from date	In Microsoft Excel, this is the =YEAR(*) function.
HH	Hour – use one time standard (UTC, or local regional time) throughout	Specify in metadata whether the averages and extremes refer to the hour *ending* at this time (most AWS default to this), or the hour *commencing* at this time. The spot values should refer to the logging interval ending 'on the hour'.
TT Tx Tx	Air temperature – hourly spot value 'on the hour', maximum and minimum temperatures within the hour (three variables)	State in metadata whether the sensor is in a screen, with type and height, etc., units of measurement, and any calibration applied.
RH	Relative Humidity – normally a spot value 'on the hour'	Give instrument details in metadata. Units can be assumed to be %.
Td	Dew point temperature 'on the hour'	Normally an AWS derivation from air temperature and RH readings rather than a measurement. State units.

Table 17.2. (*cont.*)

ff mean ff gust	Wind speed	Normally the (scalar) mean wind speed and the highest wind gust in the preceding hour. State in metadata anemometer height and type, any calibration applied and particularly units of measurement.
dd	Wind direction	Normally the value 'on the hour', although a macro can be set up to calculate the more accurate vector mean wind (speed and direction) over the hour from higher-frequency measurements (see Chapter 9 and Appendix 2). Note however that Davis Instruments systems log 'modal wind direction': using spreadsheet macros, compass points can be easily converted into bearings (i.e., SW becomes 225 deg) which simplifies numerical analyses. An Excel macro to do this is available from www.measuringtheweather.com. State in metadata wind vane height (if different from anemometer) and derivation of measurement (vector mean wind or modal wind direction).
MSLP	Barometric pressure 'on the hour'	State in metadata whether the pressure is corrected to mean sea level, and if so what method is used: also units of measurement.
Rain	Hourly rainfall total	State in metadata raingauge type, height, tipping-bucket capacity and units of measurement.
Optional parameters		For analysis and summary purposes, it can be useful to derive certain parameters by reference to the logged value – for instance, if a parameter 'RainHour' is set = 1 when 'rainfall in the hour > 0' and 0 otherwise, then hours with rainfall can be flagged for analysis using Excel's 'filter' functions (see next chapter). The template spreadsheet includes a few examples; others can easily be added over time as required.

Depending upon sensor availability, hourly sunshine, hourly mean and maximum solar radiation, earth temperatures and other elements can easily be included. If it is planned to add other sensors at a later date, setting out a spreadsheet format which accommodates current observations yet is flexible enough to expand as required in the future will avoid duplication of effort at a later date.

Daily spreadsheet

In most cases, data for this worksheet will consist of a mix of AWS and manual observations. AWS data can be distilled down to daily totals/averages/extremes from hourly records as required.

Specific content is again dependent upon instrumentation and archiving requirements, but typical elements in a basic dataset might include the items in **Table 17.3**. As there is likely to be a mixture of terminal hours (some will be morning to morning, some will be midnight to midnight, others will be spot observations – see Chapter 12), brief metadata descriptions are essential to describe content (some of the metadata will be identical to the hourly spreadsheet, and can be cut and pasted).

Many observers also use the daily dataset to record the elements from one or more manual observations during the day (see Chapter 14 for details). It would be easy enough to include columns to include, say, cloud cover and types, wind direction and speed, barometric pressure, air temperature and humidity from a daily 8 A.M.

Table 17.3. *Example of daily dataset layout and format*

Date	Include date in standard numerical form (d.mm.yyyy – example 20.06.2011) or yyyymmdd, according to preference	As will be seen in the next chapter, there are analysis advantages to holding the date in separate dd, mm and yyyy parameters in addition to the date in standard form.
dd	Numerical day number from date	In Microsoft Excel, this is the =DAY(*) function.
mm	Numerical month number from date	In Microsoft Excel, this is the =MONTH(*) function.
yyyy	Numerical year number from date	In Microsoft Excel, this is the =YEAR(*) function. Hold as four digits rather than two, to ensure dates on either side of year 2000 are sorted into correct order, and to ensure correct calculation of period lengths.
TT	Mean air temperature	Derive the midnight to midnight mean temperature from the mean of the 24 hourly observations. State in metadata whether the sensor is in a screen, with type and height etc., units of measurement, terminal hour, and any calibrations that have been applied.
TTmax	Maximum air temperature during the day	State period covered in terminal hours metadata – is it morning to morning or midnight to midnight? If the former, is the maximum temperature 'thrown back' to the day preceding the date of morning observation?
TTmin	Minimum air temperature during the day	State period covered in terminal hours metadata – is it morning to morning or midnight to midnight?
Rain	Total rainfall during the 24 hours	State period covered in terminal hours metadata – is it morning to morning or midnight to midnight? If the former, is the rainfall 'thrown back' to the day preceding the date of morning observation?

Table 17.3. (*cont.*)

Rain - continued		Is this from a manual checkgauge, or the sum of hourly tipping-bucket raingauge data? (Both can be held, of course.) State in metadata raingauge type/s, height, tipping-bucket capacity and units of measurement.
ff	Mean daily wind speed	Normally a daily mean (scalar) wind speed, midnight to midnight. State in metadata anemometer height and type, units of measurement, and any calibration applied.
ff-gust	Highest wind gust	Normally refers to the same period as the mean daily wind speed. Instrument and units can be assumed same as for wind speed.
dd	Wind direction	Use either the AWS 'daily' output (Davis Instruments AWSs output a daily 'modal wind direction') or vector mean wind from sub-daily observations – see Appendix 2 for calculation details. State in metadata wind vane height (if different from anemometer) and derivation of measurement (vector mean wind or modal wind direction).
MSLP	Daily mean barometric pressure	Normally a daily mean midnight to midnight. State in metadata whether the pressure is corrected to mean sea level, and if so what method is used: also units of measurement.

morning observation if required, alongside AWS-generated fields. Obviously, the manual observation records will need to be entered using the keyboard, rather than imported from the AWS.

This basic daily spreadsheet example in **Table 17.3** includes 12 elements: a template can be downloaded from www.measuringtheweather.com

As well as details from non-instrumental 'eye' observations, the daily spreadsheet can also include counts of 'days with' elements – include columns for snow or sleet observed to fall, snow lying at the morning observation and the like. (Prepopulate them all with 0, and when one of these events occurs within the relevant time period, amend the 0 to 1. This will enable both automatic summing and filtering/analysis of such events*.)

It is also good practice to include a free text column to note 'significant weather' such as the time of thunderstorms, snow depths and any other 'significant weather'.

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* Many observers make a coding distinction between some elements, such as differentiating between different sizes of hail. Clearly, using such a method will invalidate simple sum-based frequency counts, but can easily be accommodated by creating an additional 'binary' flag which is 1 if the figure in the 'hail falling' column is > 0, else it is zero. Similar coding methods could be used to note thunderstorm intensity on a scale from 1 to 9, intensity of snow events, and so on. The coding convention is up to you, but note it in your metadata.

You may also wish to include also ‘derived’ or calculated binary flags (0 = no, 1 = yes) for the following parameters, as these will simplify later analyses:

- Air frost (minimum temperature < 0 °C)
- Ground frost (grass minimum temperature < 0 °C)
- Ice days (maximum temperature < 0 °C)
- Hot days (maximum temperature ≥ 25 °C) – or any other applicable threshold
- Rain days (daily rainfall 0.2 mm or more), wet days (daily rainfall 1.0 mm or more), or other rainfall thresholds as required
- Nil sunshine (daily sunshine = 0)

The sample spreadsheet includes some of these as examples, but others can easily be added as required, or included at a later date.

Monthly spreadsheet

The monthly spreadsheet is normally derived from the daily datasheet, and will normally include monthly summaries (totals, means and/or extremes, with dates) of the elements in the daily observational record. An example spreadsheet is available at www.measuringtheweather.com.

Preserving your observations

Weather measurements are more interesting and useful when analyzed and shared, either in real-time on weather websites or forums, or perhaps via monthly observation-exchange agreements with other sites in the area, or by joining enthusiast organizations such as the UK’s Climatological Observers Link or one of the other national amateur observer organizations (more on *sharing observations* in Chapter 19). Professional weather observers can probably assume that their observations are transmitted and stored on reliable computer systems, regularly backed up, and that the data will eventually be securely archived in a purpose-built data storage facility. Unfortunately amateur observers cannot rely on this happening unless they take those steps themselves: the rest of this section is intended primarily for such observers.

You may wish to ensure that your observations are preserved for future researchers, perhaps many years after your death. But what would happen to your records if you were to drop dead tomorrow? The sad fact is that many amateur observers’ records (and often their instruments, too) are simply thrown away in post-funeral house clearances – very often, today this applies just as much to PC or laptop records as well as manuscript logbooks. It is tempting to think that computerized records are ‘future proof’, but in fact the opposite is true – frequent changes in hardware, software, storage media and operating systems make computerized records the *least likely to survive* for any length of time without careful record management. (If you feel this is unnecessarily pessimistic, consider whether your records stored in VisiCalc, written under MS-DOS on an 8088-based PC and stored since 1984 on an eight-inch floppy disk, would now be readable by anyone else.) Will anyone still be able to read Excel 2010 files on a USB memory stick in 50 years, or will they be just as dead as LocoScript files on three-inch floppy disks created on your old Amstrad PCW8256?

Many people have a hugely over-optimistic opinion of the lifetime of various computer media. Consider the following examples:

- The expected lifetime of an external USB hard drive is typically only 2–3 years, less if subject to knocks and vibration, and a catastrophic failure (all data lost) becomes more likely than not after that time.
- The magnetic media which memory sticks are made of has a limited number of read/write cycles, typically only a few thousand, and cannot be relied upon to retain data for more than a few years, sometimes only months.
- The surface of optical media such as CD-ROMs can be expected to decay sufficiently to introduce data errors within 10–15 years. While there are numerous 'archive-quality' media options available at higher prices, consider whether an expensive gold-coated CD or DVD 'guaranteed' to last 100 years (will you still be around to claim if it doesn't?) is of benefit if, firstly, there are no longer any CD readers to read the disk and, secondly, whether the file formats themselves will still be readable more than a decade or two in the future?

The history of the personal computer industry over the last 30 years or so does not give grounds for optimism regarding future compatibility!

Even hard copy (printed) output is not future-proof. Laser-printed hard copy output may deteriorate beyond readability, or facing pages adhere to each other, in 10 years or less, 20 at the most. And if you keep all your observations in a manuscript book, what happens if your house is struck by lightning, flooded, burgled or has a disastrous fire? The answer is, of course, you will probably lose the lot.

However, taking some basic record management/archiving decisions now can significantly increase the chances that your records will survive more than a decade or two. Here are a few suggestions:

- Sharing observations with other observers or groups which publish their records, such as one of the various national amateur observer organizations, will increase the chances of copies of your observations surviving.
- Back up all key files (hourly, daily and monthly spreadsheets, AWS files[*], weather diary files, metadata, station photographs) to an external USB disk – daily. Backup software is not expensive and will automate the process – if your PC remains permanently on, the software can be set up to run at off-peak times, perhaps during the early hours of the morning. Keeping copies of key files on an external USB disk reduces the chance of losing everything if your main system disk crashes.
- Better still, back up your key files weekly to another external USB hard drive and keep it in a separate location, perhaps at the office or with a neighbour or relative. That way, if anything happens to your house or PC (fire, flooding, storm, burglary . . .) your records are safe, at least up to the most recent backup.
- Open old files (including those written using previous versions of the software currently in use) and periodically 'Save as' into current version file formats.
- For manageability, keep a minimum number of files – one large Excel file containing 20 years records is much easier to maintain and use than 20 separate annual data files.
- Holding multiple copies of your records, in different places and in different formats (hard copy, computer records), will significantly increase the chances

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[*] If backing up AWS native file formats (such as Davis Instruments WeatherLink .WLK files) separately from the AWS software that generated them, keep a duplicate copy of the AWS software on the remote media, to increase the chances that the files can be read in the future.

of your records surviving a catastrophe. Keep multiple copies – computer files, hard copy printed material of the key documents and optical disk/memory stick – and ensure digital files are rewritten regularly in the current version of a popular format, such as Adobe PDF or Microsoft Office (Word, Excel) for documents or JPEG/TIFF for image files. Make sure the file naming convention and backup management process avoids any risk of overwriting newer files with older ones of the same name (by including the date or a version number in the file name, for example, and by always backing up only from one specific disk to another backup volume – never the other way around, unless of course a damaged file is being restored from the backup medium).

- At least once per year, write all important data, metadata and site photograph files to a CD-ROM/DVD-ROM or memory stick and keep it offsite – perhaps at the office, or give a copy to the local library or public records office. Optical media do not have an infinite lifetime (assume a decade, no more), and memory sticks much less, so replace or update the media at least every few years.
- It is becoming feasible to keep copies of electronic records online in 'cloud storage' – this could include site photographs, metadata, and so on, as well as the records themselves – to avoid total loss in a household catastrophe. There are several free ways to achieve this; online backup services such as www.iDrive.com and www.dropbox.com can be used to backup all but the largest collections of weather records (both provide 2 GB free at the time of writing, and charge for more).
- A simpler but more manual approach is to e-mail the records to your (free) Hotmail or Gmail account. Both have unlimited storage, and of course are also readily accessible from any Internet-connected computer. E-mailing key files monthly to the Hotmail or Gmail servers is as good a way as any, and costs nothing.
- Laser-printed material may begin to deteriorate within a decade or two (unless printed on archive-quality paper and stored in archive conditions), and may need reprinting. If your files are in a current format that should not be a problem, but if the original software to read/write/print the files becomes obsolete, then the file content may not be recoverable.
- If your records are kept in manuscript form in a hard copy logbook, photocopy recent pages every so often and keep copies safe in a second location.

Keep all your records organized, so that if you should drop dead tomorrow someone knows where your records are and what to do with them. Include a codicil to your will specifying what should happen to your instruments and records. With such prior agreements in place, the UK's Chilterns Observatory Trust (details in Appendix 4) can often provide a home for station records and unwanted instruments. Wherever possible, instruments will be found other owners to ensure they remain useful for longer, while softcopy or hardcopy observations will be archived and made available to future generations through the Trust's library.

One-minute summary – *Collecting and storing data*

- Making weather measurements, particularly using an AWS, can quickly generate vast amounts of data and these can become unmanageable without some thought being given to how records are to be kept and used.
- Spreadsheets are ideal for archiving weather records, and provide more comprehensive analysis tools than the AWS software used to log the sensors.

Holding and archiving data in hourly, daily and monthly spreadsheets is easy to do, simplifies record-keeping and makes subsequent analysis much more straightforward.

- Each spreadsheet should include an integral metadata sheet or 'tab' detailing the instruments used, their exposure, units of measurement, record length and any other essential information.
- Months or years of data can be lost in an instant if held in a single file on one hard disk. An entire lifetime's manuscript record could just as easily be lost forever in a house fire or burglary. Taking simple steps, including putting in place a multiple backup strategy, can hugely improve the chances that records (and instruments) will survive to be used by future researchers.

References

[1] The Royal Meteorological Society *Weather Watchers Log Book* is available from http://www.shop.rmets.org/ or from Amazon.

[2] In the UK, the Climatological Observers Link (www.colweather.org.uk) archives all monthly and annual summaries submitted by members, together with numerous long runs of monthly station data added specially. In 2011, this was used to create and publish 10 and 30 year averages for all sites with sufficiently long records.

[3] The UK Chilterns Observatory Trust was set up in 2009 to:

A. Establish a climatological observatory at Whipsnade, Bedfordshire, and publish records from it
B. Establish a meteorological/climatological library which can be visited by researchers, students and members of the public by appointment
C. Provide advice and assistance for weather observers, including the availability of some meteorological instruments on a long-term loan basis.

Contact details are given in Appendix 4.

18 Making sense of the data avalanche

For the majority of observers collecting weather measurements is a means to an end, rather than an end in itself, because making good use of the records obtained is ultimately more rewarding still. Records build rapidly into useful datasets, particularly from AWSs, and even a few months worth of data can provide fascinating and sometimes unexpected insights into local weather patterns. Current records can be combined or compared with historical and local digital climate information from national records, which are freely available online in many countries. Modern spreadsheet software provides a wide variety of sophisticated, yet easy-to use, graphical and statistical analysis tools which allow the potential of the records to be much more quickly and easily realized than when held in manuscript form.

This chapter builds upon the suggested ways of collecting and storing data outlined in the previous chapter, to show how quickly and easily presentation-quality graphics and sophisticated statistical analyses of meteorological records can be generated using everyday software. (A reasonable working knowledge of spreadsheets has been assumed, as it is beyond the scope of this book to attempt to provide detailed software tuition.) Numerous examples are presented to aid understanding and provide a starting point for those with more limited spreadsheet literacy: there are also many excellent book and video-based tutorials available for all software literacy levels. Readers are encouraged to use these ideas and concepts to develop their own projects using their own observational records. Practice quickly builds into expertise.

Most examples use Microsoft Excel 2007 or 2010, the industry standard spreadsheet, and the examples given here relate to the PC/Windows commands. While the detailed functions may be different in other packages, the principles outlined in this chapter remain broadly similar whichever software is in use.

Managing and analysing the data avalanche

The previous chapter suggested ways to store weather records, both manual observations and those exported directly from an AWS. Three separate dataset formats, namely a spreadsheet each for hourly, daily and monthly observations, were suggested. You may not need all of these, and of course you can define your own format to meet your specific requirements (or start off with one of the template examples on www.measuringtheweather.com and edit to suit), then grow your dataset(s) over time. Don't forget to include a 'metadata' worksheet tab to provide essential details regarding site, instruments, observing practices, data content and units (see Chapter 16).

Separating hourly, daily and monthly record types makes good sense because of the different timescales and nature of the elements observed. For instance, the amount of rain that falls by wind direction can be quickly and easily analyzed within an hourly dataset, because normally the wind direction does not vary much within an hour, but clearly to do this for a day, or even a month, with just one figure for rainfall amount and another single data point for a prevailing wind direction would not provide the granularity essential for a comprehensive analysis. Similarly, analysing 30 years of hourly rainfall data to derive long-period monthly and annual average rainfall amounts would involve a huge number of records – much simpler to use just the 30 monthly and annual totals.

Updating the datasets with recent observations is best done regularly, every month or two. Once hourly, daily and monthly records have been 'distilled' from the high-frequency AWS record, augmented where necessary by manually entered observations such as cloud amounts, snow depths and the like, updates can be reduced to a series of regular and straightforward cut-and-paste operations.

Where to start? Ask the question!

Examining, selecting, graphing, analysing and sorting weather records is made much easier with records held on computer, whether these are manually entered (such as daily maximum, minimum and rainfall values), higher-frequency digital records exported from an AWS, or local long-period records from a national climate archive. Basic graphing, averages and extremes can be performed in a few clicks: beyond that almost anything is possible, when allied with a keen curiosity. The best way to get started is to think of questions waiting to be asked:

- Which is wetter (or sunnier, or warmer . . .) – a westerly wind, or an easterly?
- When is the snowiest time of the year? And the most thundery?
- Which is the wettest day of the week?
- Is it windier when it is raining? Is it warmer when the Sun is shining, or not?

Some of these will be presented as examples in this chapter, but there are an infinite number of other possibilities. The real interest is in asking, and answering, other questions of your own collected data. You may sometimes be very surprised by the answers!

Microsoft Excel basics

Microsoft Excel offers an excellent – even bewildering – range of presentation-quality graphical output facilities. At the basic level, it takes only a few clicks of the mouse to generate simple line or bar graphs (**Figure 18.1** shows graphed daily maximum and minimum temperatures and daily rainfall for one month), scatter plots (**Figure 18.2** – daily sunshine totals versus daily solar radiation amounts for 5 years in June), and many other combinations. Copies of the illustrations, example worksheets and templates are given on www.measuringtheweather.com, including those in Figures **18.1** and **18.2**. The illustrations presented in this book are necessarily in monochrome only, and can only give a hint of what is possible – colour illustrations are given on the website. Correctly applied, colour can make even the largest or most complex table or diagram instantly understandable.

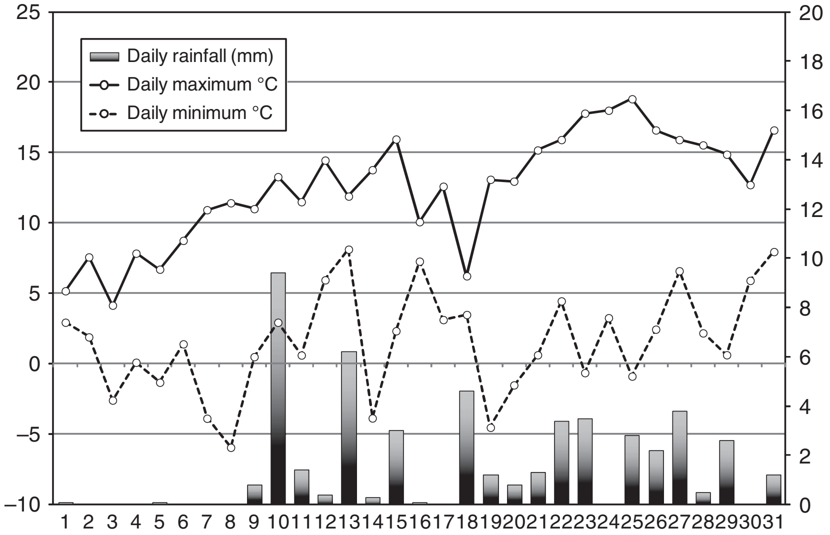

Figure 18.1. A basic Microsoft Excel graph plot, showing graphed daily maximum and minimum temperatures (left scale, °C) and daily rainfall totals (right scale, mm) for 1 month.

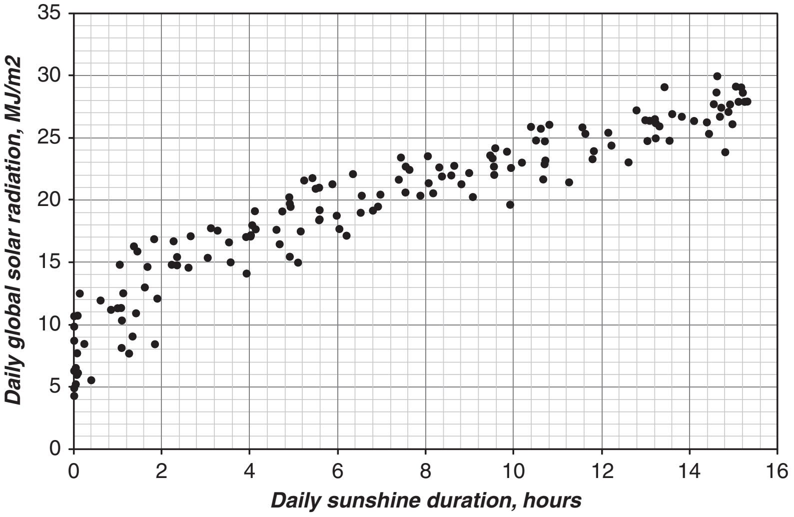

Figure 18.2. Microsoft Excel scatterplot showing the relationship between daily sunshine duration and daily global solar radiation totals during 5 years in June. Records from the author's observing site in southern England at 51.4°N, 1.0°W.

Try out the basic graphical capabilities to gain experience, then experiment with some of the more sophisticated analysis and plotting techniques.

Using Microsoft Excel to graph a month's observations

It is very easy to produce a graph of several elements for one month (**Figure 18.1**).

1. Create a simple two-dimensional table of daily values arranged by date in a vertical column. The dates should be included as the left-most column, followed by one or more sets of daily values in successive columns to the right of the date (**Table 18.1**). The first row should give the column headings, such as Date, 'Tmax', 'Rain09–09' and so on as appropriate.
2. Using a mouse, select the Tmax, Tmin and Rain09–09 columns of data (including the column headings). When all the columns are highlighted, click on the 'Insert' toolbar (immediately to the right of the 'Home' toolbar at the top of the page), then 'Line' (for line chart). Excel will then create a simple line chart similar to **Figure 18.1**.
3. Click on the maximum and minimum chart lines, then right-click and select 'Format Data Series'. The options on this menu will allow setting of line colours and styles, widths, markers and various other formatting tools – try it and see.
4. Click on the rainfall graph generated. Right-click on the line, select 'Format Data Series', then 'Series Options', then 'Plot on Secondary Axis'. The rainfall graph will now have its own axis (on the right). To change it from a line graph to a histogram, select it again, go to 'Chart tools', 'Change Chart Type', and select one of the column options. The columns can then be formatted to suit. The graph is now a histogram of rainfall amounts by day of the month.
5. Formatting, layout, colours and titling can all be changed as required. Experiment with the various styles and types of graphs and graphical presentations to gain familiarity with the capability of the software.

Averages and extremes

Spreadsheets are ideal for handling and analysing rows and columns of numerical data, and generating statistical outputs from a set of meteorological records is very straightforward. In most spreadsheets, the command takes the form of a **function name** (such as *average*) and the spreadsheet *cell range* over which that function is to be applied. In Excel, for example, averaging a month's daily maximum temperatures contained in columns B2 to B32 in the spreadsheet illustrated in **Table 18.1** (the file can also be downloaded from www.measuringtheweather.com) would take the form:

=**average(b2:b32)** –for the mean daily maximum

– the calculation result being placed in the cell which contains the function. (It does not matter whether the function and cell references are in upper-case or lower-case.) Note that the last cell reference will need to be changed if there are less than 31 days in the month (or simply leave those cells blank).

If the month's daily minimum temperatures are in column C, as here, copying and pasting the cell that calculated the average daily maximum in column B *to the*

Table 18.1. *A very basic data table in Microsoft Excel, similar to that used to generate Figure 18.1*

	A	B	C	D
1	**Date**	**Tmax**	**Tmin**	**Rain 09–09**
2	1 May 2011	20.3	9.7	0
3	2 May 2011	17.7	7.6	0
4	3 May 2011	15.8	4.3	0
5	4 May 2011	18.6	0.1	0
6	5 May 2011	20.2	8.0	0
7	6 May 2011	23.9	6.7	5.7
8	7 May 2011	21.1	13.0	15.7
9	8 May 2011	18.2	13.4	0.2
10	9 May 2011	18.8	5.8	trace
11	10 May 2011	19.2	4.3	0
12	11 May 2011	17.1	5.8	0
13	12 May 2011	18.2	5.0	0
14	13 May 2011	16.8	1.6	0
15	14 May 2011	17.2	4.8	0
16	15 May 2011	15.9	6.2	trace
17	16 May 2011	18.9	10.1	0
18	17 May 2011	16.9	10.3	0.2
19	18 May 2011	19.4	12.2	0.7
20	19 May 2011	19.2	3.2	0
21	20 May 2011	18.0	5.4	0
22	21 May 2011	19.4	1.9	0.3
23	22 May 2011	18.2	9.4	0
24	23 May 2011	16.9	5.2	trace
25	24 May 2011	18.0	3.7	0
26	25 May 2011	19.8	0.7	trace
27	26 May 2011	17.1	8.9	2.7
28	27 May 2011	15.8	9.7	trace
29	28 May 2011	16.3	7.1	0.1
30	29 May 2011	18.4	11.7	trace
31	30 May 2011	15.7	12.4	2.9
32	31 May 2011	18.3	4.3	0

same relative position in column C will repeat the calculation for the data in column C, without the formula needing to be retyped.

Similar syntax goes for the highest and lowest in the range of cells, and here the Excel functions are ***max*** and ***min***. So to place the highest and lowest daily maximum temperatures of the month's data contained in columns B2 to B32 in columns B37 and B38, enter the instructions:

(In cell B37) **=max(b2:b32)** – for the highest daily maximum, and
(In cell B38) **=min(b2:b32)** – for the lowest daily maximum

Similarly, copying and pasting these two cells to the equivalent position in the 'Tmin' column C will repeat the result for that element.

Daily rainfall totals are given in column D. Copying the average, max and min functions from columns B and C into the equivalent cells in column D will calculate the same functions for the daily rainfall totals. However, neither the mean daily rainfall or the minimum daily rainfall within a month are particularly helpful statistics, so better to replace the **=average** function with **=total (d2:d32)** to sum total rainfall, a more useful figure, while also deleting the cell deriving the minimum daily rainfall value.

This simple example illustrates basic cell selection and handling of statistical functions. The process is identical for, say, 10 years of monthly rainfall observations used to derive a decadal site average together with the highest and lowest monthly totals during that period (**Table 18.2**). This table is also given on www.measuringtheweather.com.

The most useful Excel functions are listed in **Table 18.3**.

Sorting

It is very easy to sort any selection of data into a defined order – for numerical data such as the observations in **Table 18.1**, an ascending or descending rank order is very useful.

Sorting and its related function, filtering, are extremely powerful tools when working with large volumes of data, such as 10 years of hourly records or 100 years of monthly rainfall totals.

Useful Excel tips

Wrong totals?

If Excel does not seem to be calculating results properly, check 'automatic calculation' is turned on – From the Office button > Excel options > Formulas > Calculation options

Backup copies, Autosave and Undo

Make a backup of all data before you commence any spreadsheet operations – particularly if the data table you are working with is fresh from logger memory and no other copy exists. Excel can do this for you automatically using **Autosave**.

Data copied from a paper observation sheet will not be lost should the software crash, or if a section of the table is corrupted owing to a mistake in entering Excel commands, but it is possible to lose or corrupt data by entering a wrong command. The 'undo' function is very useful here, but if the error is not spotted for several steps it may not be possible to 'undo' all the intervening steps without causing additional damage. I usually set Excel's Autosave to 2 minutes (Office button > Excel options > Save > Autorecover options), and this normally restricts the maximum loss of work from system or software crashes to 2 minutes or less. Autosave creates and works on a backup copy of the file, which is only saved when the 'Save' or 'Save as' button is pressed. Once a save has been made, however, Autosave and Undo start from scratch once more, so if you have any doubts about the accuracy or reliability of the entries you have just made, 'Save as' into a new but related file name – perhaps 'Averages table v2 (date)' rather than the original file 'Averages table'. To avoid creating confusion with many multiple versions of similar files, however, it is important to clear out all 'version' variants as soon as they are no longer needed. If all important files are backed up daily to separate disks (see Chapter 17) then even a major crash should not lose more than a few hours' work.

Table 18.2. *Monthly and annual rainfall totals at the author's observing site in central southern England (51.4°N, 1.0°W), 2001–10, in millimetres*

Year	Jan	Feb	Mch	Apl	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2001	77.2	81.3	106.0	62.9	38.5	18.5	55.5	88.7	65.8	102.8	30.7	20.9	748.8
2002	71.1	87.3	43.4	35.6	67.6	55.6	84.9	68.9	28.7	85.2	160.9	123.2	912.4
2003	74.7	26.3	22.5	44.7	34.1	49.5	45.9	16.4	5.5	32.4	135.1	64.8	551.9
2004	88.4	22.1	47.4	77.9	51.0	22.5	53.2	125.8	29.4	131.1	29.4	45.4	723.6
2005	26.6	15.9	41.5	65.8	17.0	24.8	39.7	34.0	31.7	70.2	36.3	60.8	464.3
2006	22.0	56.7	50.9	34.3	80.6	11.5	18.3	44.7	54.8	108.8	122.0	88.5	693.1
2007	84.6	88.3	46.6	0.7	131.0	86.3	142.4	41.1	34.7	35.6	74.8	48.8	814.9
2008	101.4	19.8	86.3	64.1	65.9	57.0	91.3	75.9	53.1	59.4	75.5	30.7	780.4
2009	69.4	61.7	28.6	31.1	27.0	22.1	96.6	25.9	14.9	44.3	151.2	112.1	684.9
2010	71.4	74.7	45.9	25.9	21.8	14.7	22.3	81.7	36.3	53.7	62.3	25.8	536.5
Average	**68.7**	**53.4**	**51.9**	**44.3**	**53.5**	**36.3**	**65.0**	**60.3**	**35.5**	**72.4**	**87.8**	**62.1**	**691.1**
Maximum	101.4	88.3	106.0	77.9	131.0	86.3	142.4	125.8	65.8	131.1	160.9	123.2	912.4
Minimum	22.0	15.9	22.5	0.7	17.0	11.5	18.3	16.4	5.5	32.4	29.4	20.9	464.3

Table 18.3. *Common Excel functions useful in climatological analyses.*

Function	Purpose	Excel command
Maximum and minimum	Evaluating the highest and lowest values within a selection of data; for example, the highest and lowest maximum temperatures within a month	=MAX(cell1: cell2) =MIN(cell1: cell2)
Average	Taking the mean of a selection of values; for example, calculating average monthly rainfall over a number of years	=AVERAGE(cell1: cell2)
Summation	Summing a selection of values, usually of one element; for instance, the number of days with snow falling in March during the previous 10 years	=SUM(cell1: cell2)
Round	Useful for rounding data values to a lower precision, perhaps to decrease the number of class sizes. Note that 'number' formatting will change the precision of *displayed* numbers, but 'round' will **permanently** change the precision of the *stored* values and should therefore be used with extreme caution	=ROUND(cell reference, number of decimal places required)
Sort	Ranking one or more elements from largest to smallest, or vice versa: useful for finding the extremes of any element, and for performing quality control (for example, checking for spurious barometric pressures outside 950–1050 hPa/mbar range)	On Data tab: sort button. Select the cells to be ranked. Excel will ask whether to include other columns. Respond 'yes' to ensure that the values remain linked to the date and the other values on that date. Ensure the row is kept as one unit to avoid mis-references to other elements on the row such as the date of occurrence, etc.
Match	Use to find a specified item in a range of cells, then return the relative position of that item in the range. For example, if the range A1:A3 contains the values 15, 62, and 9, then the formula =MATCH(62,A1:A3,0) returns the number 2, because 62 is the second item in the range. Use Match instead of one of the LOOKUP functions when the position of an item in a range instead of the item itself is required – such as the date in a month when the highest or lowest value occurred	=MATCH(lookup_value, lookup_array, [match_type]) The value in match_type controls whether the value MATCHed is higher, lower or the same as the value being checked – in the example on theleft, 0 indicates the value being looked for must be an exact match
Filter	Picking out all records satisfying one or more criteria; for example, all air temperatures above 16 °C in November, from hourly, daily or monthly datasets	On Data tab: filter button. Select the cells to be filtered, and enter the filter criteria (values less than *x*, or more than *y*, as required)
Conditional formatting	Applies highlighting (variable colour, highlighted borders, icons and the like) to cells meeting certain criteria: for example, highlighting all monthly rainfall totals below 5 mm in a long-period dataset. Can be used in conjunction with other functions.	On Home tab: Conditional formatting button. Select the cells to be highlighted, and enter the criteria for display, or simply rank the cells and apply a colour range from highest to lowest

Table 18.3. (*cont.*)

Function	Purpose	Excel command
IF	The IF function permits another operation to take place only when the value is within the range specified by the IF statement; for example, a column could be set to mark all days with wind gusts over 10 m/s by checking the highest gust, and setting the column entry from 0 to 1 if this value was exceeded	Examples are given under 'dependent variables' below. Another variant, useful for monthly or annual frequency counts, is the =COUNTIF function, which for a given cell range will count all values above, below or equal to a specified value, and return that number in the cell: for example, to count the number of days in a month with air frost. If that is the only requirement, COUNTIF avoids the requirement for a separate column of 0s and 1s on a spreadsheet.
Undo	Most functions can be 'undone'	If in doubt, save regularly, or work from a copy of the 'master' spreadsheet.

Filtering

As datasets become larger, it is very useful to be able to pick out observations that meet only certain criteria, and then either display those records or perform statistical analyses on that subset alone. For example, in a 10 year record it would take only a few mouse clicks to pick out the last time the minimum fell below −10 °C, for example, or to calculate the average July maximum temperature on all days with (say) more than 10 hours sunshine duration.

Filtering can also be undertaken with two or more parameters: the second example above could be extended to filter for days with more than 10 hours sunshine duration AND a mean daily wind speed of less than 5 knots. It is very easy to sort and/or filter selected events or combinations of events.

It is perfectly acceptable to derive averages for subset conditions (for example, the mean daily maximum temperature on all days in July with 10 hours or more sunshine duration) provided that sample sizes remain large enough to be meaningful.

After filtering, the table can be restored to its original layout by removing the Filter commands – de-select by reversing the way in which the filter was set up. If using multiple filters, be sure to de-select all the filters applied.

Within Excel, there is a much easier and more powerful way of deriving averages, extremes and frequency counts of data tables using sorting and filtering – namely, the **pivot table** function, which is outlined later in this chapter.

Dataset sizes

Datasets obviously expand as more records are added. The hourly dataset will be the largest – after about 10 years data, a typical hourly dataset, containing 30 measurements each hour, will be around 20 MB. Almost 90,000 rows of hourly records will be held in this file, far too many to check or analyze by eye. With a reasonably powerful computer it is very easy to analyze, average, display entire datasets tens of megabytes in size, to sort and/or filter selected events or combinations of events, or to produce sophisticated statistical tables, all in just a few mouse clicks.

Dependent variables

A useful way to filter and analyze meteorological datasets is to assign *dependent variables*. As the name implies, these are tabular elements whose value is dependent upon another element. These can be assigned automatically using an Excel function, or they can be entered manually. Examples are given below, and are included in **Table 18.1** on the website www.measuringtheweather.com:

(Automatic) Set a cell value to 1 if the daily rainfall is greater than a certain value, otherwise assign 0
(Manual) Insert a cell value of 1 if thunder is heard on that day, else leave it as default 0
(Automatic) Use an Excel function to specify a numerical value corresponding to the day of the week
(Automatic) For any particular day's data, define an arithmetical expression to calculate the week number within the year

Example – to mark rain days and wet days:

In **Table 18.1**, create two new columns headed 'RainDays' and 'WetDays'.
In cell E2 (rain days) enter
=if(d2> 0.19,1,0) . . . and then copy-paste to all the other entries for the month
In cell F2 (wet days) enter
=if(d2> 0.99,1,0) . . . and then copy-paste to all the other entries for the month

Excel will assign a value of 1 to these cells if the daily rainfall is greater than a certain value, here 0.19 mm or 0.99 mm[*], otherwise 0 will be entered into the cell.

The count of rain days or wet days is then simply the sum of the monthly column of 0s and 1s. Similar working goes for air and ground frosts, days with/without sunshine or other daily data elements as required.

To differentiate between data imported or manually entered and that calculated automatically in this fashion, it can be useful to show the latter in a different colour on the spreadsheet – perhaps dark blue rather than black. This also helps prevent accidental over-writing of cells containing formulae.

Lookup tables

Sometimes it can be helpful to reduce the number of class sizes to avoid generating an unwieldy number of classes, each containing low sample counts. One way of doing this is to use the =ROUND command, which will (permanently) round any given

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[*] The values 0.19 and 0.99 have been used as the function is strictly 'greater than' rather than 'equal to or greater than': setting the threshold to 0.20 and 1.00 mm would not count records equal to these values. This function will count any text entries, such as 'trace', as fulfilling the inequality, so to avoid spurious counts of rain days, for example, ensure the column being checked contains only numerical data. For period counts, =COUNTIF may be more useful.

Table 18.4. *VLOOKUP table entries for sorting wind speed into Beaufort Force classes values in knots*

ff	Beaufort Force
0	0
1	1
3.5	2
6.5	3
10.5	4
16.5	5
21.5	6
27.5	7
33.5	8
40.5	9
47.5	10
100	100

value or values to a given number of decimal places. For elements where the class size may be variable, the LOOKUP function is the more useful. When analysing wind speed records, for example, it can be useful to sift observed hourly or daily mean speeds into the equivalent Beaufort Force: here the class sizes increase with wind speed (see 'The Beaufort Scale', Table 9.3, page 204). This can be quickly and easily achieved using an Excel 'lookup table' with its associated =VLOOKUP function. Essentially a lookup table provides upper limits for classes, so the lookup table to convert mean wind speeds into Beaufort Force would be as shown in **Table 18.4**.

In this table, an hourly mean wind speed of 6.3 kn would be categorized as '2' (i.e., Beaufort Force 2), while one of 6.6 kn would be '3'. Similar lookup tables can be used to convert wind directions in degrees into compass points, or other similar functions as required. Full syntax details are given in the Excel online help function.

Conditional formatting

Conditional formatting provides a quick and easy way to highlight cells which meet specified selection criteria. It differs from the filter command in that the highlighted cells remain visible within the complete table of data, rather than displayed as a reduced subset. It is very useful to pick out (for example) the highest or lowest values in a set of data, to colour-code values to provide easier visual assessment of the displayed information, or to apply rule-based quality control to a set of records, perhaps to identify erroneous or missing values.

Table 18.5 is based upon **Table 18.2**. Here the basic table of 10 years of monthly rainfall totals has had conditional formatting applied, so that all monthly totals in excess of 120 mm have been highlighted in bold with a solid cell border. Similarly, monthly totals below 20 mm have been outlined with a dashed border. On a computer monitor, colour shaded cells, or other distinguishing formatting, could have been used just as easily. (Note of course that the conditional formatting applied to the monthly cells has *not* been applied to the annual totals, otherwise all would show > 120 mm; separate conditional formatting rules could be applied here in the same way as for the monthly totals.)

Table 18.5. *Monthly and annual rainfall totals at the author's observing site in central southern England (51.4°N, 1.0°W), 2001–10, in millimetres. Conditional formatting applied to pick out the driest months (< 20 mm), and the wettest (> 120 mm)*

Year	Jan	Feb	Mch	Apl	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2001	77.2	81.3	106.0	62.9	38.5	18.5	55.5	88.7	65.8	102.8	30.7	20.9	748.8
2002	71.1	87.3	43.4	35.6	67.6	55.6	84.9	68.9	28.7	85.2	**160.9**	**123.2**	912.4
2003	74.7	26.3	22.5	44.7	34.1	49.5	45.9	16.4	5.5	32.4	**135.1**	64.8	551.9
2004	88.4	22.1	47.4	77.9	51.0	22.5	53.2	**125.8**	29.4	**131.1**	29.4	45.4	723.6
2005	26.6	15.9	41.5	65.8	17.0	24.8	39.7	34.0	31.7	70.2	36.3	60.8	464.3
2006	22.0	56.7	50.9	34.3	80.6	11.5	18.3	44.7	54.8	108.8	**122.0**	88.5	693.1
2007	84.6	88.3	46.6	0.7	**131.0**	86.3	**142.4**	41.1	34.7	35.6	74.8	48.8	814.9
2008	101.4	19.8	86.3	64.1	65.9	57.0	91.3	75.9	53.1	59.4	75.5	30.7	780.4
2009	69.4	61.7	28.6	31.1	27.0	22.1	96.6	25.9	14.9	44.3	**151.2**	112.1	684.9
2010	71.4	74.7	45.9	25.9	21.8	14.7	22.3	81.7	36.3	53.7	62.3	25.8	536.5
Average	**68.7**	**53.4**	**51.9**	**44.3**	**53.5**	**36.3**	**65.0**	**60.3**	**35.5**	**72.4**	**87.8**	**62.1**	**691.1**
Maximum	101.4	88.3	106.0	77.9	131.0	86.3	142.4	125.8	65.8	131.1	160.9	123.2	912.4
Minimum	22.0	15.9	22.5	0.7	17.0	11.5	18.3	16.4	5.5	32.4	29.4	20.9	464.3

Conditional formatting is quick and easy to apply and is useful for quickly picking out the key features in complex numerical tables such as this. To apply conditional formatting: using the mouse, select the cell range to which the conditional formatting is to be applied, then select ‘Conditional formatting’ on the ‘Home’ toolbar; then select the formatting and threshold/s required. Try it and see for yourself.

Excel analysis and processing tips

Storing dates. There are many analysis advantages to holding the date in separate date, month and year parameters (i.e., dd, mm and yyyy), as well as the complete date as dd-mmm-yyyy. To create these additional numerical date parameters within Excel, =DAY(date cell reference) function will split out the date (dd, 01–31), =MONTH(date cell reference) the month (mm, 01–12) and =YEAR (date cell reference) will do the same for year. Example: 4-Sep-14 would be held as dd = 04, mm = 09, yyyy = 2014. These can then be formatted as required in Excel (for instance, the month could be formatted on output as *9*, *09*, *Sep* or *September*, even in different languages, depending upon requirements and preference). Some of the subsequent analyses in this chapter show the benefits of splitting dates in this fashion.

Continuous data. Separate continuous data into discrete classes for ease of analysis. For example, to analyze rainfall totals by wind speed, the range of hourly mean wind speeds could be from 0.0 to 40 knots or more, at 0.1 knot intervals, giving 400 x 0.1 kn classes, maybe more in windy locations, many of which will be empty and most of which will contain only a few observations. Defining a smaller number of classes, perhaps grouping into Beaufort forces using the LOOKUP function, gives a more manageable number of classes and thus a larger number of points in each sample, reducing table sizes and improving both legibility and statistical reliability.

Defined events. Include ‘binaries’ (1 or 0) for ‘defined events’, for example ‘hours with rain’ or ‘air frost’. For the latter the Excel function would be

=IF(*cell containing temperature record*< 0,1,0)

Note that in this case a blank cell (missing data) will give the same result as a negative entry, so check that no blanks are included in the selected cell range/s.

Beware of small class sizes. Too many classes or too small a sample will result in some classes having very few observations: averages or extremes from these small cell sizes will be unreliable. This can be a problem with some wind directions (in the south of England, for example, winds from the east-south-east occur on only a handful of days every year) and of course some observations will in any case fall into the statistical ‘tail’ of the distribution. For obvious reasons, not many entries from events with a ‘1 in 100 year’ recurrence can be expected in a 5 year climate record. For such analyses it may be better to increase the class size to generate more reliable averages. Ideally, each cell should have 30 or more data points. This is not always possible, of course, and provided the small class size is appropriately qualified smaller class sizes may be acceptable.

Pivot tables

The concept of Excel's pivot table function is easily understood, although at first glance it can appear somewhat daunting: once again, starting with simple analyses will quickly build familiarity. Pivot tables have an easy 'drag and drop' metaphor but take a little practice to become proficient. They are well worth taking the trouble to get to know as they are enormously powerful analysis tools, simplifying even highly complex statistical analyses, as the following examples will demonstrate.

A pivot table essentially provides the means to summarize a larger body of data, perhaps many years of weather observations, into one or more subset tables. A wide range of statistical functions are available, of which the most useful in meteorology are totals and averages, maximum, minimum and frequency counts. Providing the original dataset permits splitting the data into a manageable number of classes, pivot table analyses are quick and easy to generate. They are ideal for both quick 'what if . . .' or 'how often . . .' questions, as well as for more formal structured analyses such as constructing tables of long-period averages.

All of the following examples used pivot tables to generate the data, which was then graphed in Excel. The pivot tables took typically less than a minute to set up, provide output, and graph. The results illustrated here all use the author's own hourly, daily and monthly observation spreadsheets. All use real data throughout.

Setting up a Pivot table

Click on any cell within the spreadsheet. The data must be contiguous – individual cells can be blank, but there must be no blank rows or columns, and all columns must include a heading in Row 1 with a suitable abbreviated title such as 'Tmax', 'RH', and so on, as in **Table 18.1**.

On 'Insert' ribbon, select 'Pivot table' (on far left)

- Select data range (contiguous cells, no gaps)
- Choose layout – drag/drop experiment for best results
- For each value, select operation required (averages, max or min, totals etc)
- To filter (e.g. by year, month or other value within the dataset), drag field (year) into 'filter' box, then use drop-down tick boxes at top left of table to select
- Choose options to define row/column totals, and so on
- Experiment with data layouts to suit
- Format or use conditional formatting for optimum display readability

Example 1: when is the sunniest time of the year?

This example uses 10 years of hourly sunshine totals (2001–10) from the author's own hourly database, 87,650 observations in all. The table is very simple – hour of day (column) by month of year (row), with the mean sunshine (hours) for each cell calculated using the pivot table function. All available records are included (it would be just one more mouse click to include the number of observations in each cell, if required). On-screen conditional formatting could instead colour-code the entries from blue to red ('heatmapping'), but in for the sake of example in monochrome it is easy enough to pick out only the Top 5 values automatically (heavy border).

From opening the dataset to producing the fully formatted table (**Figure 18.3**) took just 73 seconds. It can be very quickly seen that the sunniest time of the year at my observing location (over the last 10 years at least) is mornings in April, June and September, each averaging a little over 50 per cent of the possible duration.

This layout is also suitable for hourly mean temperatures, pressures, humidity, wind speed – most elements. Try it (or something similar) based upon your own records – your conclusions may be very different.

Example 2: the variation of rainfall amount by wind direction

It is also very easy to produce analyses based upon cell totals, rather than means, and to analyze one element in terms of another. This two-dimensional table (**Figure 18.4**) shows the total rainfall by wind direction over the 17 year period 1994–2010. Depending on the format of the observational records, this can be done by compass point (SW, WSW, W etc), or by azimuth degrees.

If analyzed by compass point, Excel will by default lay the column headings out in alphabetical order, so to obtain the correct order around the compass some cut-and-pasting into a separate table will be required.

If analyzed by degrees, to avoid an unmanageable number of column headings (and the problem of small cell counts), it is best to aggregate the original observations into 10 degree segments. In Excel this is best done using a dependent variable, rounding to the nearest 10 degrees (using Excel's =ROUND command). Some care is needed to allow for wind directions going through north; here it is best to assign wind directions between 355.1 deg and 004.9 degrees to '360' rather than '000' to avoid confusion with 'calm'. In the dataset used, hours with a mean speed of less than 0.5 knots have the wind direction assigned as -1 by an =IF statement in Excel.

Here the pivot table is constructed from hourly observations using 10 degree wind direction classes: the total rainfall within each class is summed.

This table took only 43 seconds to generate from 17 years of hourly observations (almost 150,000 records). It has been formatted using a variant of conditional formatting, 'data bars', which give a good visual indication of the dominance of rainfall from between 180 and 230 degrees (south to south-west) in central southern England – more than 40 per cent of all rain falls with winds in this sector. For simplicity, the table has been generated using all observations, but it would have been only one additional mouse click to provide a split by month, for example (or by temperature, wind speed, barometric pressure . . .)

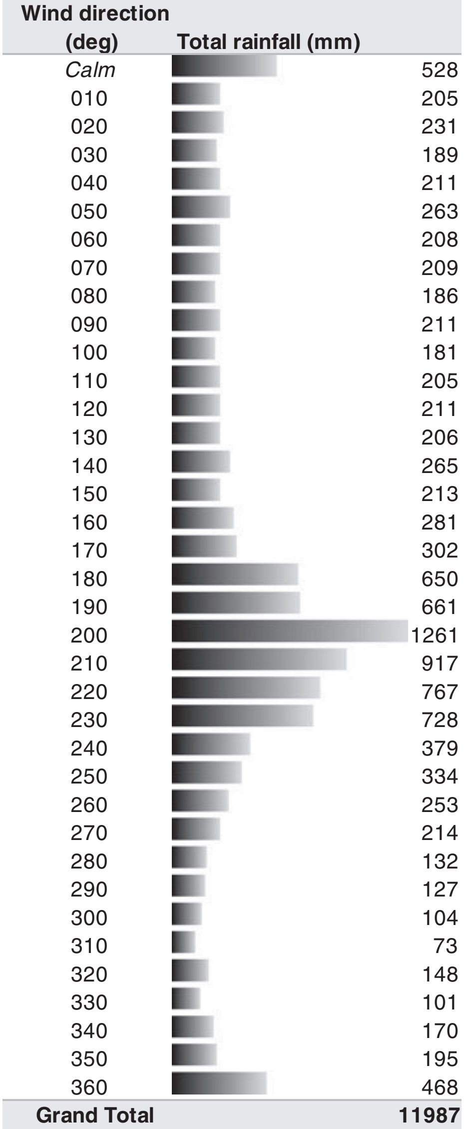
A more visually striking display method is to plot the data within Excel using polar co-ordinates, omitting the calm segment. **Figure 18.5** clearly shows both the dominance of rain-bearing winds from between south and south-west in central southern England, and the lack of rain on north-westerly winds.

Clearly the shape of this plot can be expected to vary significantly with geography – New Orleans or New Hampshire would look very different, for example. Try this with your own hourly observations – even a year or two of data should be sufficient to provide a good indication. Is it what you expected? Is it different from the appearance of the data presented here? Why?

Year (Multiple Items)

Average of Sunshine hr	**Column Labels**																								
Row Labels	**0000**	**0100**	**0200**	**0300**	**0400**	**0500**	**0600**	**0700**	**0800**	**0900**	**1000**	**1100**	**1200**	**1300**	**1400**	**1500**	**1600**	**1700**	**1800**	**1900**	**2000**	**2100**	**2200**	**2300**	**Grand Total**
1	0	0	0	0	0	0	0	0.00	0.17	0.30	0.34	0.36	0.38	0.35	0.30	0.24	0.03	0	0	0	0	0	0	0	0.10
2	0	0	0	0	0	0	0	0.10	0.26	0.34	0.35	0.33	0.34	0.33	0.33	0.32	0.23	0.02	0	0	0	0	0	0	0.12
3	0	0	0	0	0	0	0.09	0.33	0.38	0.44	0.45	0.42	0.40	0.40	0.40	0.39	0.37	0.21	0.00	0	0	0	0	0	0.18
4	0	0	0	0	0	0.16	0.43	0.48	0.50	0.49	0.49	0.46	0.45	0.45	0.47	0.48	0.49	0.43	0.17	0	0	0	0	0	0.25
5	0	0	0	0	0.12	0.38	0.43	0.45	0.44	0.42	0.39	0.35	0.35	0.37	0.37	0.38	0.42	0.43	0.40	0.11	0	0	0	0	0.24
6	0	0	0	0	0.21	0.43	0.47	0.51	0.52	0.48	0.46	0.42	0.41	0.39	0.42	0.44	0.47	0.47	0.47	0.29	0	0	0	0	0.29
7	0	0	0	0	0.13	0.36	0.42	0.45	0.43	0.40	0.37	0.36	0.36	0.36	0.42	0.43	0.41	0.44	0.41	0.25	0	0	0	0	0.25
8	0	0	0	0	0.01	0.25	0.43	0.45	0.45	0.44	0.42	0.40	0.41	0.40	0.40	0.41	0.45	0.43	0.29	0.03	0	0	0	0	0.24
9	0	0	0	0	0	0.02	0.33	0.43	0.47	0.52	0.48	0.47	0.47	0.46	0.45	0.43	0.46	0.32	0.02	0	0	0	0	0	0.22
10	0	0	0	0	0	0	0.06	0.28	0.38	0.42	0.40	0.40	0.41	0.40	0.40	0.38	0.25	0.01	0	0	0	0	0	0	0.16
11	0	0	0	0	0	0	0	0.09	0.30	0.35	0.38	0.38	0.40	0.37	0.33	0.23	0.02	0	0	0	0	0	0	0	0.12
12	0	0	0	0	0	0	0	0	0.17	0.27	0.33	0.34	0.33	0.32	0.29	0.14	0	0	0	0	0	0	0	0	0.09
Grand Total	**0.00**	**0**	**0**	**0**	**0.04**	**0.13**	**0.22**	**0.29**	**0.37**	**0.40**	**0.40**	**0.39**	**0.39**	**0.38**	**0.38**	**0.35**	**0.29**	**0.22**	**0.14**	**0.06**	**0**	**0.00**	**0.00**	**0**	**0.19**

Figure 18.3. Microsoft Excel pivot table analysis showing hourly mean sunshine (in hours) for every hour of the year over 10 years 2001–10, using automatic conditional formatting to highlight the top five values using bordered cells. The columns are time UTC, hour commencing: the rows are month number (1 = January, 2 = February, and so on). Records from the author's observing site in southern England at 51.4°N, 1.0°W.



Wind direction (deg)	Total rainfall (mm)
Calm	528
010	205
020	231
030	189
040	211
050	263
060	208
070	209
080	186
090	211
100	181
110	205
120	211
130	206
140	265
150	213
160	281
170	302
180	650
190	661
200	1261
210	917
220	767
230	728
240	379
250	334
260	253
270	214
280	132
290	127
300	104
310	73
320	148
330	101
340	170
350	195
360	468
Grand Total	**11987**

Figure 18.4. Pivot table analysis showing rainfall totals (mm) by 10 degree wind direction classes in central southern England, 17 years 1994–2010 – tabular presentation using Excel's conditional formatting 'databars' tool.

Example 3: the variation of rainfall intensity by wind direction

If we simply repeat the pivot table above, using instead *mean* hourly rainfall by wind direction rather than *total*, then a very different picture is obtained (**Figures 18.6** and **18.7**). Note the values are now in millimetres per hour.

Contrasting analyses such as these are amongst the most interesting uses of accumulated weather records, and can quickly lead to real insights. In this case, we can quickly see that while winds from between south and south-west produce the *majority* of the rainfall at this site, the *heaviest* rain tends to occur with winds between east-south-east and south-south-east or south. These directions are often associated

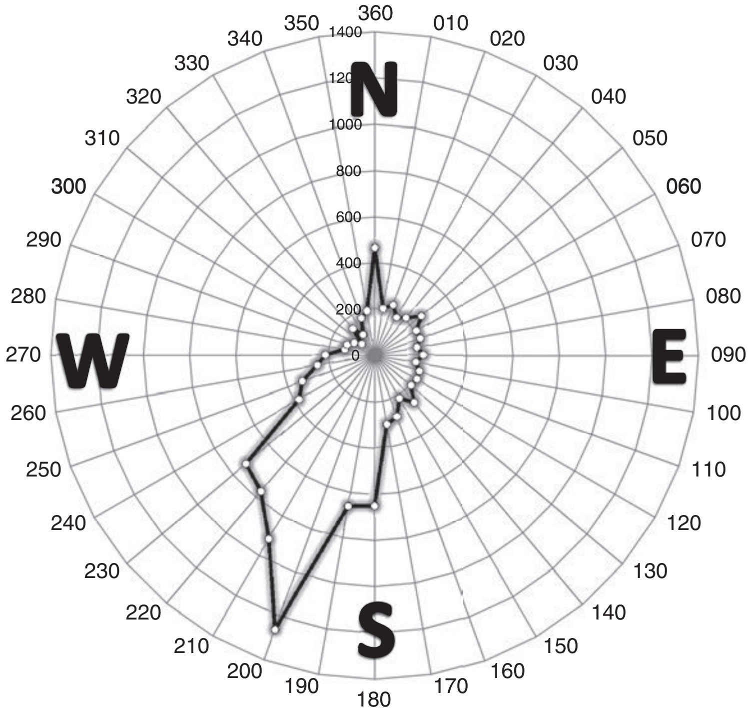


Figure 18.5. As Figure 18.4 but plotted on polar axes.

with cyclonic and warm frontal rainfall events in temperate latitudes. Note also the above-average intensities of rainfall from the north-west at this site – although the quantity of rainfall is small on a north-westerly surface wind, when it does rain the rain can be quite heavy. These are often showers at or immediately after a cold front, or sometimes showers originating from the Irish Sea through the 'Cheshire Gap' and passing across the English Midlands. Again, repeat this with your own observations. What conclusions do you draw?

Similar analyses are quickly and easily generated for temperature, sunshine or the other elements. The benefit of such analyses is not merely providing quantitative confirmation of what we may know or suspect already, but sometimes in throwing out very surprising results – the reader may care to consider that a similar analysis for sunshine showed that winds from east-south-east are also the sunniest, for example. Why should one wind direction experience both the heaviest rainfall and the sunniest conditions? Compare and contrast with your own observations.

Example 4: when is the snowiest/most thundery period of the year?

There are many advantages in weekly analyses – they provide improved granularity over monthly statistics, and reduce the statistical variability associated with low class sizes when using daily data, particularly with relatively short periods of record. This example examines the annual variation of the frequency of snowfall ('snow or sleet observed to fall 00–24 h') and 'thunder heard' by week. Definitions of these elements were given in Chapter 14.

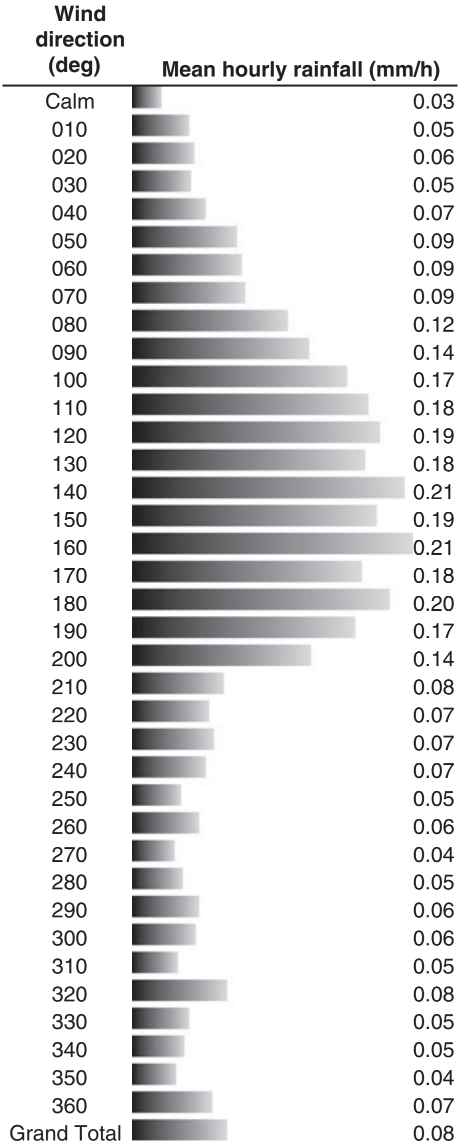


Figure 18.6. As Figure 18.4 but for rainfall intensity (mm/h).

To do this, a new variable needs to be assigned in the data table, to provide the week number. There are two ways to calculate this:

- Excel provides a =WEEKNUM function. However, this function numbers the weeks starting on Sunday, which means that the first and last weeks of the year will include a variable number of days. If, for example, 1 January falls on a Saturday, then 1 January will be week 1, Sunday and the rest of that week will be week 2, and so on. Week 1 therefore consists of a single day's entry. This renders any statistical analysis of week 1 data highly unreliable, as the number of days will vary from year to year.
- A better method is to ensure that, every year, week 1 consists of the observations from 1 to 7 January, week 2 is 8–14 January, and so on, regardless of the weekday

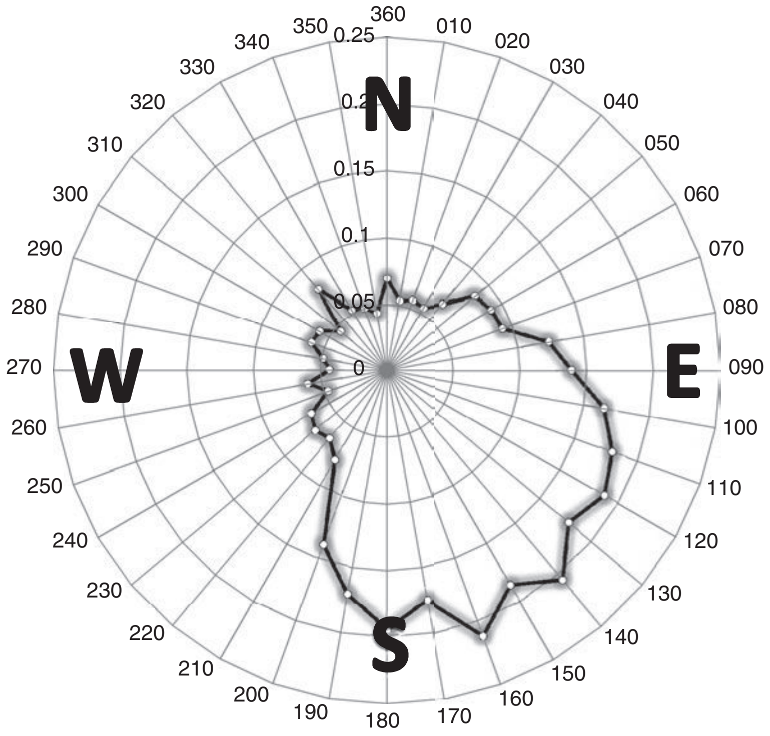


Figure 18.7. As Figure 18.5 but for rainfall intensity (mm/h).

upon which the week starts. To do this work from the yearday, where 1 January = yearday 1, 2 January = yearday 2 and so on. This is easy to do in Excel simply by setting a yearday value in a separate column: 1 January is 1, then every subsequent day increments this value by 1 (thus yearday for 3 January = yearday for 2 January +1). The week number is then simply (yearday + 3) / 52, rounded to an integer. (Remember to start again with 1 next 1 January.) The Excel function is as follows:

=ROUND((yearday+3)/7,0)

Of course, as the number of weeks in a year is not an exact multiple of 365 (365 x 52 = 364), then this leaves week 53 with only one or two days; but this is easier to allow for than a variable number of days in week 1. Including this function in the daily data spreadsheet permits easy analysis of variables by week in the year, due allowance being made of course for week 53 always being 'short'. This also has the advantage of including 29 February in its rightful place within the year in leap years.

Applying a pivot table analysis to 30 years (1981–2010) of days with snowfall and days with thunder data (manual spreadsheet data entry: 0 = none, 1 = observed), it takes only a few mouse clicks to derive **Figure 18.8**. Note that in the pivot table *sum* should be used to give the total number of days, not *count* which counts all days with data ('0' being a valid data point). Applying conditional formatting in the form of 'data bars' enables a rapid visual analysis of the data. (This table took less than 90 seconds to specify, output and format as shown here.)

Week No	Wk Comm	Freq snow/sleet	Freq thunder
1	1 Jan	28	2
2	8 Jan	27	1
3	15 Jan	10	2
4	22 Jan	14	2
5	29 Jan	20	3
6	5 Feb	36	2
7	12 Feb	26	1
8	19 Feb	41	1
9	26 Feb	33	3
10	5 Mar	12	1
11	12 Mar	14	4
12	19 Mar	14	5
13	26 Mar	14	6
14	2 Apr	11	8
15	9 Apr	13	7
16	16 Apr	5	4
17	23 Apr	5	13
18	30 Apr	1	6
19	7 May	0	15
20	14 May	0	16
21	21 May	0	12
22	28 May	0	13
23	4 Jun	0	13
24	11 Jun	0	8
25	18 Jun	0	16
26	25 Jun	0	7
27	2 Jul	0	30
28	9 Jul	0	13
29	16 Jul	0	11
30	23 Jul	0	14
31	30 Jul	0	21
32	6 Aug	0	17
33	13 Aug	0	15
34	20 Aug	0	11
35	27 Aug	0	10
36	3 Sep	0	6
37	10 Sep	0	13
38	17 Sep	0	8
39	24 Sep	0	5
40	1 Oct	0	3
41	8 Oct	0	4
42	15 Oct	0	5
43	22 Oct	0	1
44	29 Oct	2	0
45	5 Nov	1	1
46	12 Nov	1	0
47	19 Nov	11	4
48	26 Nov	1	1
49	3 Dec	8	1
50	10 Dec	8	0
51	17 Dec	24	3
52	24 Dec	20	0
53	31 Dec	2	0
	Grand Total	402	368

Figure 18.8. Weekly frequencies in 30 years of the number of days with (first column) snow or sleet observed to fall and (second column) thunder heard, by week number: central southern England (51.4°N, 1.0°W), 1981–2010.

It can be quickly seen that during these 30 years, the snowiest week of the year was week 8, starting on 19 February. In the 30 years it snowed on 41 days, so on average more than one day in that week could be expected to see a snowfall.

Thunder has almost the opposite distribution throughout the year in southern England: only at the beginning of April is there both a reasonable and approximately even chance of either occurring. The majority of thundery activity occurs between weeks 17 and 38 (23 April to 17 September). Between them these 22 weeks accounted for 288 days of the 368 days with thunder in 30 years, or 78 per cent of all occurrences. The most thundery week of all was the week commencing 2 July, which saw 30 occurrences in 30 years – an even chance of thunder on at least one day in that week.

The risk of thunder, or snow, or the variations of any other element by week can be very quickly analyzed this way. This form of analysis can be very useful for shortlisting possible dates for weddings, holidays, sporting events, school fêtes and the like. It is very important to remember, however, that the outcome is a statistical probability based on previous observations, and *not* a weather forecast as such!

Example 5: which is the sunniest / driest day of the week?

Excel offers a simple function to derive a numerical value for the day of the week, making statistical analyses by weekday very easy to set up.

Example – days of the week:

> In a daily data table, create a new column headed 'DayOfWeek'. In the first row, enter in the cell
>
> =**weekday**(*cell containing full date dd-mmm-yyyy*)
> and then simply copy-paste to all the other entries by date.

Excel will assign a weekday numerical value to these cells based on the date: Sunday = 1, Monday = 2, and so on to Saturday = 7 (the numerical values and start day can be changed if required, using an optional second parameter: for more details and syntax see Excel's help function).

Applying a pivot table analysis and conditional formatting to 30 years (1981–2010) of daily values of rainfall (mm) and sunshine (hours), we can quickly derive **Figure 18.9** and **Table 18.6**[*].

It is interesting (if perhaps not very statistically significant) to know that at this site during the 30 years analyzed:

- Tuesday was the *wettest* day of the week, and Thursday the *driest*: the difference in mean daily rainfall between the wettest and driest days of the week was 17 per cent.
- Saturday was the *sunniest* day of the week – and Friday the least sunny: the difference in means is 9 per cent. Contrary to popular opinion, the weekends are the sunniest days, and slightly drier, than the days of the working week . . .

The reader is left to draw his or her own conclusions!

Example 6: is it windier when it's raining?

To answer this question requires a slightly more complicated pivot table analysis of hourly data over a number of years, as follows:

---

[*] The obligatory statistical health warning: while many of these differences may look real, it is most likely that the differences in the means are merely coincidental and without statistical significance – different periods of data may give different results. Such analyses are always popular for non-specialist audience presentations, however, and here provide a good example of pivot tables using a dependent variable, and the possibilities of more creative output formatting options.

Table 18.6. *Mean daily values of 0900–0900 UTC rainfall (mm) and daily sunshine duration (hours) by day of the week at the author's observing site in central southern England, 30 years composite record 1981–2010*

	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Week
Mean daily rainfall (mm)	1.85	1.92	2.04	1.91	1.75	1.98	1.88	1.90
Mean daily sunshine (h)	4.41	4.32	4.32	4.27	4.31	4.20	4.59	4.35

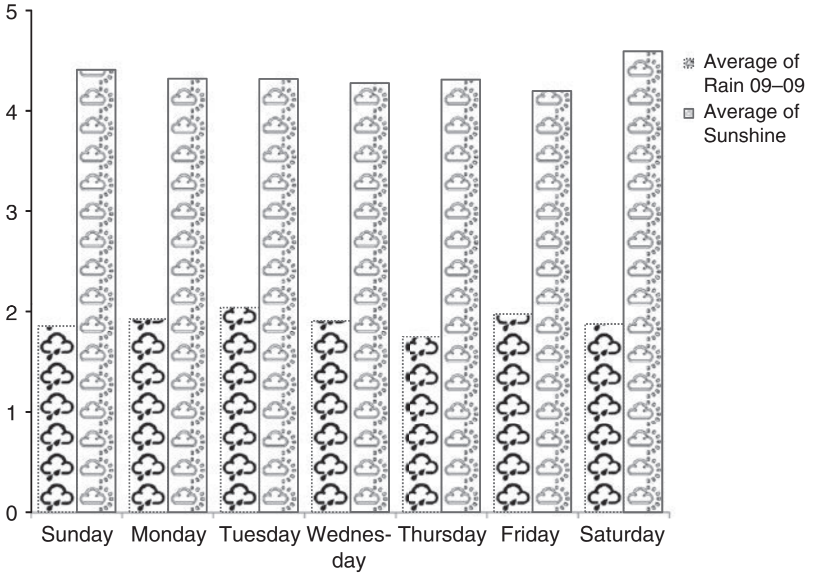


Figure 18.9. Mean weekday values of daily rainfall (mm) and daily sunshine duration (hours) for the author's observing location in central southern England (51.4°N, 1.0°W), 30 years 1981–2010.

To categorize all occasions with 'rain', define a parameter which is 1 when the hourly rainfall total is not 0, and 0 otherwise (it could be a higher threshold if required). The cell entry will be:

=IF(*hourly rainfall total*> 0,1,0)

Then, using the pivot table function, produce means of hourly wind speeds for all occasions with rain and those without rain. Graph and compare (**Figure 18.10**).

It can be seen that, in central southern England at least, mean wind speeds *are* higher when it is raining than when it is dry. This is true throughout the year, although the difference is insignificant during the summer months.

Of course, this analysis can quickly be expanded by the interested reader. Do the findings hold true for all wind directions? Are winds stronger when rain falls on winds from the main rain-bearing wind directions (see Example 2, above)? What about gust speeds? Gusts (and thus the gust ratio, see page 198) might be expected to be higher in showery rain rather than frontal rain situations. Is this borne out by the observations?

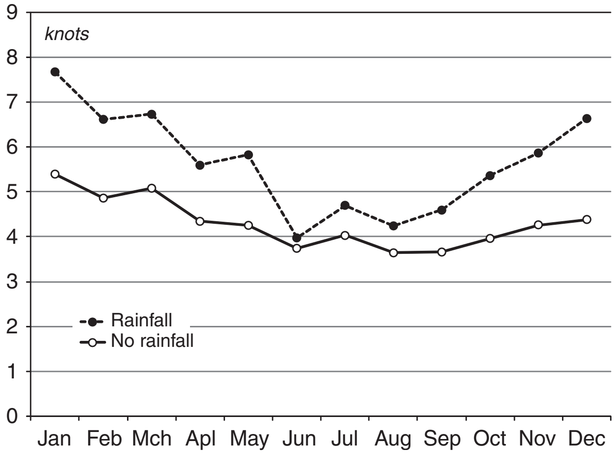


Figure 18.10. Hourly mean wind speeds (knots) for hours with and without recorded rainfall: 10 years 2001–10, central southern England (51.4°N, 1.0°W).

Be careful of introducing unintentional statistical bias. Why would repeating the above analysis for sunshine instead of rainfall introduce a very significant bias?

Example 7: different ways of looking at observational records

There are many different ways of looking at, analysing and presenting weather data. Some are familiar, while the analysis and graphical facilities within Excel make it easy to experiment with different, more creative methods of displaying information. One example is given in **Figure 18.11**, which shows 5 minute sunshine data from a whole year (2010) at the author's observing site. A similar diagram appeared in Edward Tufte's inspiring book *The visual display of quantitative information* [1] many years ago (page 165). Preparing this manually would take days. I puzzled how best this could be generated quickly within Excel. Using conditional formatting, it took only a few minutes, as follows.

The starting point is a table of 5 minute logged AWS sunshine data across the full 24 hours x 365 days. In any 5 minute period, the maximum amount of sunshine is 0.083 hours. Using conditional formatting, all values were assigned different shades, from black (nil sunshine) through light grey (0.01 or 0.02 h sunshine in the 5 minute period) to white (0.07 h or more). The visual metaphor thus corresponds clearly to the data, namely the lightest areas being the times when the Sun shone for longest. Colour could be used just as easily.

There is no easy way to suppress the cell values, so the font size was set to the minimum possible. The height and width of the grid were reduced so that individual cells are represented by tiny squares. Individual dates or times will not then of course be visible (if required, hour markers at 6 hour intervals, 0600, 1200 and so on, can be added to the plot, as here).

The final result consists of slightly more than 105,000 separate data points. The graphical output resembles how the burns from a year's worth of Campbell-Stokes sunshine recorder cards would look if they could all be neatly assembled into one annual array. It illustrates the variation of sunshine both throughout the day (longer

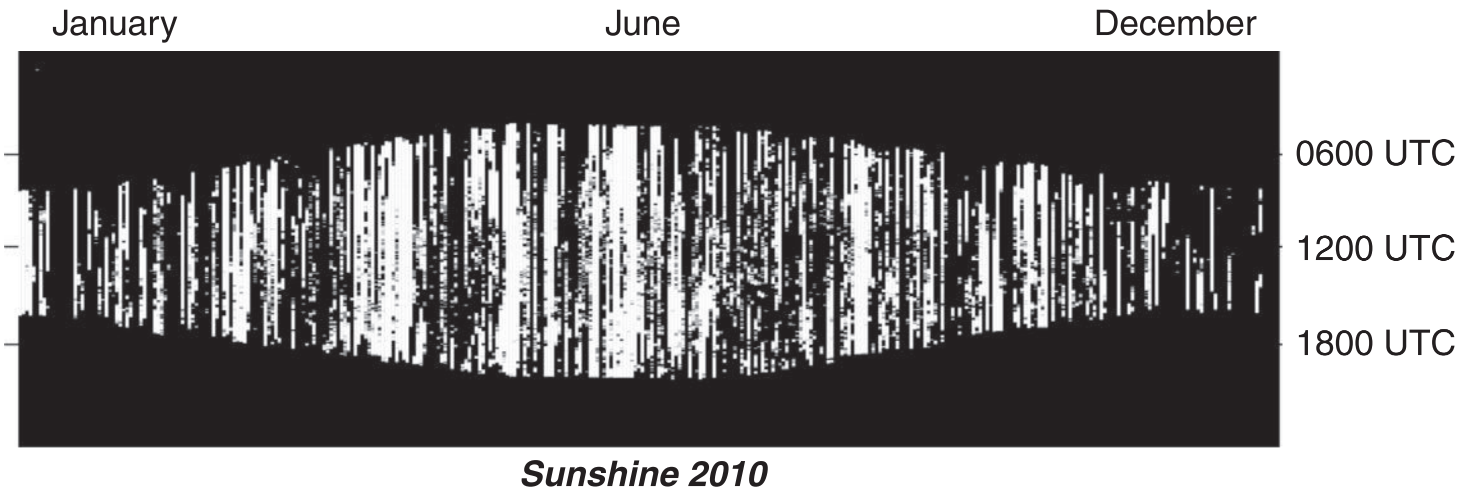


Figure 18.11. Graphical 5 minute sunshine data for the year 2010 at the author's observing site in central southern England. See text for details.

days in the summer months) and throughout the year, in a diagram that is both striking and quite easy to produce.

Tufte's extraordinary books [1, 2, 3], which pre-date modern data analysis and graphics software, will suggest many other inspiring examples of striking data presentation formats to the interested reader. There are many other examples to delight and inspire in David McCandless's *Information is beautiful* (Collins, 2009), and its associated website InformationIsBeautiful.net which gives many interactive examples. With a little imagination, meteorological statistics need be anything but dull!

Wind roses

A wind rose is a polar area plot, used to show the relative frequency of combinations of wind speed and direction. Microsoft Excel cannot prepare wind roses directly, although it is helpful to use it to prepare the input files for software packages that can do so. There are a few Windows-based wind rose packages: the examples shown here have been prepared using the WindRose PRO3 package from Enviroware s.r.l. (enviroware.com/windrose.htm – see also suppliers list in Appendix 4 for details). The diagrams here are in black and white, although the originals are in colour.

To prepare the wind rose, the software reads a pre-prepared datafile of wind direction and speed, typically hourly data from an Excel file or from an AWS. Depending upon the needs of the analysis, the data could represent all observations within that period, or a filtered subset — for example, all hours with more than 5 mm of rainfall within a given period, or all sunny hours, or any other subset – provided class sizes do not become too small. The options (class intervals, colours, titling and other presentation aspects) can be varied as required, and the analysis can be as detailed as 360 one-degree segments. The software produces standard-format graphics file output which can be pasted into other applications.

Figure 18.12 compares the wind roses between the warm year of 2006 and the cold year of 2010, from observations made at the author's site (51.4°N, 1.0°W). (Note that the scales differ on the two plots.) The difference in the frequency of northwesterly, northerly and north-easterly winds is striking – all colder directions, of course.

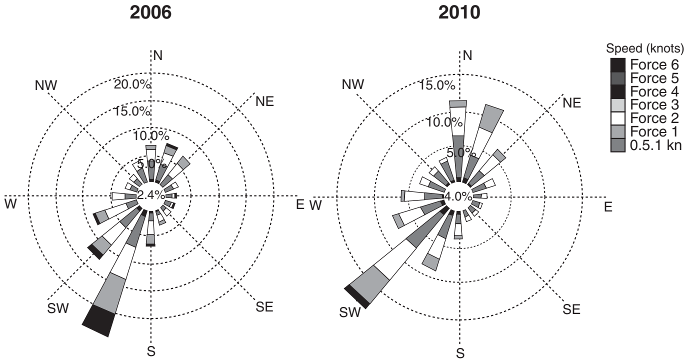


Figure 18.12. Wind roses for 2006 (a warm year) and 2010 (a cold year) at the author's observing site in central southern England, 51.4°N, 1.0°W. Wind speeds are in Beaufort Force: the figure in the centre of the plot is the frequency of calms (< 0.5 kn). Prepared using WindRose PRO software from Enviroware.

Putting current records into perspective: averages and extremes

It is often useful to compare or extend records with long-period climate data from local sites, whether this is raw hourly/daily/monthly data, or summarized in 30 year averages. (The WMO standard period for climatological averages is 30 years, the most recent period being 1981–2010.)

In many countries, weather records obtained and archived at public expense are free, or attract only nominal data preparation charges. Many provide for free access, inspection and download over the Internet. A few examples are given below: if your country is not listed here, check the WMO list of national weather services websites, and search for ‘climate records’.

Australia

The Australian Bureau of Meteorology provides an exemplary climate website. Access to the nation’s weather records, many extending back over 100 years, is free and very easy using a well laid out search facility. For most sites, even rainfall-only locations, online records are updated daily. There is an impressive wealth of information on all aspects of Australia’s weather and climate readily available in tabular, graphed or mapped form. I have used the site extensively in preparing this book.

Australian climate data: http://www.bom.gov.au/climate/data/

Canada

Environment Canada’s online climate data site provides a similar impressive level of data accessibility and functionality to Australia’s site. Easy drop-down menus permit direct access to a vast range of historical hourly, daily and monthly climate data by province and location, average and extreme temperature and precipitation values for particular sites, and whole-country summaries of averages and extremes for particular months and years. More specialized records such as upper-air information, precipitation radar records, short-period rainfall intensity-duration-frequency statistics and many others are also available for inspection or download as required, together with a wide range of Historical Environment Canada publications available in digital form. Full information on dataset layout, content and definitions of measurement units is also available online. Data not available on the website can be obtained on application to Environment Canada for a basic charge.

Canada climate information: http://climate.weatheroffice.gc.ca/Welcome_e.html

The Netherlands

KNMI (Koninklijk Nederlands Meteorologisch Instituut, the Royal Netherlands Meteorological Institute) climate website provides free online access to daily records of temperature, sunshine, cloud cover and visibility, air pressure, wind and precipitation from 36 weather stations across The Netherlands. Some have more than 100 years of records. Information is updated daily for all current sites.

The Netherlands: http://www.knmi.nl/climatology/daily_data/selection.cgi

New Zealand

Access to New Zealand's climate database has been free since April 2007, when data charging was scrapped to permit and promote more widespread use of New Zealand's national climate database. The database holds data from about 6,500 locations (including rainfall-only sites) which have been operating for various periods since the earliest observations were made in 1850. The database continues to receive data from more than 600 stations that are currently operating.

The operation is run by NIWA, the National Institute of Water and Atmospheric Research (a Crown Research Institute established in 1992), and web access is through the CliFlo system (link below). CliFlo returns raw data and statistical summaries. Raw data include 10 minute, hourly and daily records: statistical data include about 80 different types of monthly and annual statistics and six types of 30 year normals. CliFlo Data is free: access is via an online, biennial registration. Some restrictions to climate data apply, such as Pacific Island sites.

New Zealand national climate database: http://cliflo.niwa.co.nz/

United States

NOAA's National Climatic Data Center (NCDC) offers a huge range of online climate data, averages, reports and publications, for both the United States and many other countries. All raw physical climate data available from NOAA's various climate observing systems as well as the output data from state-of-the-science climate models are openly available in as timely a manner as possible. Much is free, although charges are levied for long runs of station records – for example, 10 years of daily maximum and minimum temperatures, daily precipitation and snow depth from Chicago's O'Hare International Airport was charged at $20 at the time of writing, while downloading the entire record from the Central Park site in New York, available online from July 1876 to date (probably the longest and most detailed U.S. climate record – see also Chapter 1), was $200. Access and selection are easy enough, although navigation through the bewildering number of sites offering similar information could be improved. The sites below are good places to start:

NOAA's National Climate Data Center pages: http://www.ncdc.noaa.gov/climate-monitoring/#cirs

NCDC's Multi-data network system access: https://mi3.ncdc.noaa.gov/mi3qry/search.cfm

GCOS Surface Network (GSN) worldwide data: http://www.ncdc.noaa.gov/hofngsn/HOFNGsnStn

United Kingdom

Part of the UK Met Office public service remit is to "provide public access to historic weather information via our Library and Archive and climatological records", and yet in contrast with many other countries only a tiny fraction of the available information is actually available to the public without incurring very large data charges.

The Met Office began digitizing the UK's climatological and rainfall records in the early 1960s, and continues to do so today. The information – originating largely from a voluntary observing network – is collected, quality-controlled and archived in computer format entirely at the public expense, yet almost nothing of these computerized archives are readily available. Until the early 1990s, summary information was published in monthly and annual hard copy publications (the *Monthly Weather Report*, first published in 1884, and *British Rainfall*, first published in 1860). In 1993, the Met Office terminated both publications. Since that date, only a tiny fraction of the climatological and rainfall data in the Met Office archive has been published.

A standard response to complaints regarding the high charges levied by the Met Office is that 'the original paper records are available for transcription or photocopying within its Archives'. This is simply no longer the case with current information, most of which originates in digital format over computer links rather than via handwritten paper forms.

Unfortunately, at the time of writing the Met Office shows little inclination to make its digital climatological archives, and data catalogues, available online free or at nominal charges. Very little site-specific data is freely available online. At the time of writing, the policy is under scrutiny from a Parliamentary Select Committee.

The Met Office Archives and National Meteorological Library, in Exeter, Devon (and a similar repository for Scotland in Edinburgh), do possess an enormous amount of manuscript climate data, some extending back to the 17th century. The collections include the entire archives of the British Rainfall Organization (founded in 1860, eventually taken over by the Met Office in 1919). The BRO 'ten year books' neatly list monthly and annual rainfall totals at literally thousands of locations throughout the UK back to the 18th century (there are very few places within UK that have not had at least one rainfall record within 5 km within the last 150 years). In the absence of the free downloadable climate database access offered by other countries, a day's visit to the Met Office Archives (and some cash to pay for photocopies) is the most cost- and time-effective method of researching a long-period local rainfall record. The Met Office Archives, and some public libraries, also hold copies of the UK's main climatological publications, particularly the long-running *British Rainfall* and *Monthly Weather Report* series, from which local or regional climatological observations can be extracted. Unfortunately almost no climatological information has been published by the Met Office since both ceased publication.

The UK Climatological Observers Link holds a database of monthly records from several hundred member stations, some extending back to the 1940s, and updated monthly. Members can request copies of station records from sites within their area at no charge. Averages and extremes for several hundred stations have been produced, most recently the 1981–2010 normals in a bound hardcopy publication in 2011 [4].

One-minute summary – *Making sense of the data avalanche*

- Spreadsheets are ideal for archiving weather records, and provide more comprehensive analysis and presentation tools than the AWS software used to store sensor output. Holding and archiving data in hourly, daily and monthly spreadsheets is easy to do, simplifies record-keeping and makes subsequent analysis much more straightforward.
- If you don't already . . . store your data in spreadsheets. Develop a format and structure that works for you – and stick with it. The files will build rapidly into useful datasets, and even a few months observations can reveal interesting local

weather patterns and peculiarities. Don't forget a 'metadata' sheet giving details of the records in the spreadsheet contents.

- Current local records can often be augmented and compared with historical records from the national climate archives. In many countries, online access and downloads are free or available at a nominal charge.
- The examples in this chapter and on www.measuringtheweather.com suggest a few ideas for analysis and how to perform them using Microsoft Excel spreadsheet software. Excel's Pivot Table function is particularly useful for analysing weather records.
- Other specialist graphics plotting software is also relevant for certain types of analysis, such as the preparation of wind roses.
- As with any software, practice builds experience. Experiment with simple graphing and analysis to become familiar with the spreadsheet functions, then experiment with question-based analysis along the lines of the examples given in this chapter. Potential topics and questions are infinite.

References

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19 Sharing your observations

Up to this point, all the previous topics relate to a single weather station with one or more sets of instruments at one site. Of course, weather knows no boundaries. Interest in 'measuring the weather' at any particular location improves with the exchange and comparison of observations with others – locally, nationally or internationally. This chapter suggests ways to exchange information with other sites and other observers, under three main headings – online or real-time sharing using the Internet, online or offline reporting to informal or voluntary networks, and co-operation with national weather services and other official bodies.

Real-time information exchange

There are two main ways to share real-time (or near real-time) weather information via the web: using a site-specific website, one or more data consolidation/aggregation sites or newsgroups which accept data feeds from a number of locations, or both. With a relatively dense network of reporting locations in populated areas, together with a fast update/refresh rate, highly detailed mesoscale displays of current weather conditions are instantly available on the web, even on portable devices such as smartphones (**Figure 19.1**).

Site-specific websites

All of the popular AWS packages include software and connection details sufficient to enable users with a minimum level of computer expertise to produce their own basic 'weather website' using design templates, using web space from their existing Internet Service Provider (ISP). Some of the wide variety of software has been covered earlier in Chapter 13, *Dataloggers and AWS software*. Once configured, the data feed runs in the background and regularly refreshes current weather conditions such as air temperature, humidity, wind speed and direction, barometric pressure and tendency, and so on. Davis Instruments produce a useful guide to 'going online' (Application Note 26), available from their website at www.davisnet.com. Details can change rapidly, though, so for the latest information, contact the various suppliers using the details given in Appendix 4.

A permanently-on PC using a broadband line and logging AWS data can update frequently – every few seconds if required, although a 5–15 minute update interval is sufficient for most purposes. The various software packages available permit a wide choice of communication options. Most offer some form of free trial download

Figure 19.1. Smartphone weather. "It's amazing – my smartphone can tell me exactly what the weather is doing, right here, right now . . ." (Copyright © Katie Abramson, reproduced with permission)

option, and choosing between them becomes a matter of personal choice. Users possessing higher technical or programming skills may even wish to write their own applications.

Include essential details of your site on your webpage

It is good practice to include basic site/exposure, instrument details (metadata) and the length of record, together with site photographs (from different directions) and contact details if necessary, on all 'weather websites' fed by real-time or near real-time AWS data. Without this information it is impossible to judge how representative the station records are of the locality. Are temperature records taken from a sensor protected from sunshine? Does the raingauge sit at ground level or on a roof? Is the anemometer sited at 1 m or 10 m above ground? See Chapter 16 for a more comprehensive site information template.

Weather station software suppliers – why not include a metadata section on your web page design to encourage users to provide site, exposure, and instrument information?

Unwanted visitors

Sometimes, weather stations can attract unwelcome attention from certain members of the community. If this happens, the user may wish to consider whether the site location details or photographs are sufficiently accurate on, say, a Google Earth map that a potential vandal or thief could find the site with little difficulty. A location reference accurate to 100 m or so is good enough to locate the observations on almost all mapping scales. More accurate site location references, including the site address, should perhaps be made available only to genuine enquirers upon request.

Data aggregation websites

Data aggregation sites usually accept inputs from many sources, including different models of weather stations and brands of software. Larger websites support a very wide range of popular AWS models. These sites provide display facilities, often plotting all recent observations within a specific area of interest on a scalable map background such as Google Earth. Such websites also include updated reports from 'official' observation sites such as airports. The combination of many different data feeds can provide high-density observation coverage in some areas, particularly useful when monitoring fast-moving frontal systems or severe local storms. Some offer download access to stored observations, a selection of graphical outputs, averages, extremes, and similarly useful functions. Some now offer historical data, usually in map form, for a specific area and time, which is very useful for the retrospective analysis of specific past weather events – for example, a map of 'temperatures at 1500 yesterday afternoon' or a snapshot of conditions around the time of a marked frontal passage or convective storm.

Lack of information on data quality remains the biggest limitation with data aggregation sites. In most cases, there is no easy way to assess instrument accuracy, reliability, or exposure. For most 'electronic' sensors, apart perhaps from barometric pressure, variations in instrument exposure are likely to dwarf instrumental calibration errors. Knowing whether thermometers are exposed in a good radiation shelter or mounted on a south-facing patio, or whether anemometers are in a sheltered urban garden or in a standard exposure on a windy hilltop, is clearly essential for almost any purpose.

Most data aggregation sites receive funding partly or completely by advertising, and pop-up ads can not only take a long time to load, they are often highly distracting.

Should you decide to submit your personal weather station data to the website, be aware of the site's Terms and Conditions, which generally permit site owners to use your data without restriction, or notification, for any purpose, and often without one's knowledge.

An excellent guide on 'broadcasting a backyard weather station', the example using the Davis Instruments Vantage Vue AWS, is given on the Accuweather website at http://www.accuweather.com/blogs/weathermatrix/story/51548/how-to-broadcast-a-backyard-weather-station.asp.

The following notes and pointers to the leading sites are deliberately brief, as the detail of all such sites changes frequently.

The Citizen Weather Observer Program – CWOP: http://wxqa.com/

CWOP (sometimes seen by its original name of APRSWXNET) is the oldest and largest online data aggregation site. This organization began U.S. operations in the 1990s, and, at the time of writing, has more than 20,000 members in 149 countries (363 UK and 14 Republic of Ireland sites were listed), with upwards of 10,000 observation sites currently reporting hourly or more frequently.

CWOP collects surface observations from a wide variety of AWSs, most privately owned. Data are sent from either a PC with Internet connectivity or via ham radio protocols, and follow simple setup steps within the display/logging software. Following temporal and spatial consistency quality control checks, information from U.S. sites are fed into NOAA's Meteorological Assimilation Data Ingest System (MADIS), for direct use in NOAA's short-term forecast models.

The CWOP home page contains details on how to register and submit observations. There are a range of options for viewing observations, either as data plots on a map background (only a few available outside North America) or as tabular observations from individual sites. Sites submitting observations can request automatic quality control reports on their data, using a near-neighbour comparison method to correct systematic sensor errors, in barometric pressure for example. For U.S. sites, units default to Fahrenheit for temperature and inches for rainfall. Few pages include a 'metric units' option, which limits usefulness outside North America.

Weather Underground: www.wunderground.com

The Weather Underground, a creation of the University of Michigan in 1995, currently claims more than 21,000 weather observation locations around the world (a significant proportion originate from CWOP or MADIS feeds). Weather Underground focuses on North America, although with good coverage of amateur AWSs in many other countries including the UK and Ireland. Synoptic observations and METAR reports (aviation weather observations from airfields) are also plotted.

Users can customize the default 'start-up page' to a location and scale of their choice. Adding your own AWS data is easy enough for any PC with a broadband connection, as a wide range of AWS software is supported.

The site display uses a Google Earth background map and displays current observations using a 'station circle' model, with a limited set of elements. Multivariate plots outside the rather narrow menu options are not supported (for instance, both air and dew point temperatures cannot be displayed simultaneously). The default units are Fahrenheit for temperature, miles per hour for wind speed, and inches for rainfall and barometric pressure. Although these default units can be converted to metric equivalents on the display, the values are held on the dataset in imperial units, introducing rounding errors to the original observational record. Archived data from individual stations can be viewed and even downloaded (very useful when researching significant local weather events), although the time standard in use is often unclear, particularly during 'summer time' operation. Archived observations can be plotted for any particular date and time, not just 'current weather', which is useful for looking back at past weather events. Unfortunately, some stations continually appear in the wrong locations, which also limits the usefulness of the site, although in fairness to Weather Underground positional errors may be due to the 'feed' from other networks. Some AWS hardware and software metadata is included (the hardware and software surveys in Chapters 3 and 13 were based on Weather Underground site information), although no metadata information is provided regarding thermometer exposure, the height of the anemometer and other important components. This would be a useful addition to the site.

AWEKAS: www.awekas.at

An Austrian site, AWEKAS (the acronym stands for Automatisches WEtterKArten System, or automatic weather map system) provides similar functionality to Weather Underground as it displays overview maps of weather data from participating private weather stations. There are various scales of maps covering regions of Europe, the United States and Canada, and other regions of the world. Metric or imperial units are available. Data displays are of the 'coloured symbol' variety, rather than more useful numerics, but individual sites can be selected either for current observations, or an observer's own website, with just a couple of clicks. There are also facilities for members to provide details of site and instruments. At the time of writing AWEKAS listed almost 6,000 members, making it the largest European data aggregation site.

PWSweather: www.pwsweather.com

Another U.S. data aggregation site, headquartered in Georgia, PWSweather (PWS stands for Personal Weather Stations), has a similar strong North American focus to its content and displays. It also has global coverage, although with a much lower station density than Weather Underground. The same concerns regarding site information and record quality apply. By default, units are Fahrenheit for temperature and inches for rainfall, with no metric conversion available on most pages, which clearly limits usability outside North America.

London Grid for Learning: http://weather.lgfl.org.uk

The London Grid for Learning (LGfL) site began operations in June 2000 as a resource-sharing site between the 33 local authorities in the Greater London area, combining some IT facilities and e-learning tools within London's schools. The site includes weather information, claiming 'the densest real-time urban network of weather stations in the world.' AWSs outside greater London are also shown at a density sufficient to delineate London's urban heat island in reasonable detail during favourable weather situations. However, this site is badly let down by its lack of effective quality control, and glaring errors appear widely. This mars the usefulness of the information, especially in a teaching environment, in addition to which LGfL does not provide any hardware, site or exposure information for reporting stations. The site also limits access to all but the most basic of information to registered users within the participating educational authorities, which is a pity for a facility that could easily become a valuable city-wide resource.

Weather Observations Website WOW: http://www.metoffice.gov.uk/climate/uk/wow.html

The much newer UK WOW website with supporting infrastructure (a joint initiative of the Royal Meteorological Society, the UK Met Office, and the Department of

Education), was set up by the Met Office in 2011. The additional coverage offered by private weather stations benefits the resolution of the 'official' (but thinly spread) Met Office observing network, particularly in urban and suburban areas. In turn, this improves the detection and monitoring of small-scale weather phenomena such as severe local storms, which can otherwise slip through the relatively coarse network of reporting sites.

At the time of writing, functionality and data access on the site are quite limited. Support for automatic AWS data feeds was limited to only a few models, although this is slowly improving. UK WOW does include limited site, instrumentation and exposure information, adopting the Climatological Observers Link station grading scheme (see Chapter 4 for details), something other networks might do well to consider.

Other weather station data aggregation sites

A few weather station manufacturers and software suppliers maintain maps of current users of their equipment. Most appear long out-of-date with many broken links, but one of the best sites, Sandaysoft's map at http://sandaysoft.com/maps/cumulus-map.php, lists users of Cumulus software, with links to user websites. At the time of writing, 770 sites were included, mainly in Europe and North America, although with a good scatter across the globe: not surprisingly perhaps, only Cumulus software users are included, so synoptic and aviation reports are not shown. Inevitably, they have a lower station density than on the multi-platform sites, while the unknowns regarding site, exposure, and instruments remain the same.

Country-specific weather networks

Scotland – http://www.scottishweather.net/wxabout.php
Ireland – http://www.irelandsweather.com/
Other country websites are linked on these pages.

There are a few other sites, most with links to a few dozen AWSs at best. The various sites tend to appear and disappear quite regularly, and the coverage and quality of the information are highly variable. It seems likely that, over time, the multiplicity of such sites will diminish, while a smaller number of more professional supersites will expand (possibly with support from state weather services, as well as advertising funding from weather equipment resellers and other interested parties) with better organization, layout and navigation.

Weather newsgroups and blogs

There are numerous online newsgroups and blogs covering weather-related topics, and these can be a useful source of observations, information and comment, particularly at times of interesting weather. Some offer generalized weather 'chat', others (such as the U.S storm-chasing sites) are more specific in their topics. Unfortunately, most of the non-moderated interactive Internet newsgroups suffer from the aggressive activities of a few social misfits posting under pseudonyms to spoil the experience of the majority: some sites are best avoided altogether.

U.S. weather newsgroups and useful links:
http://www.wunderground.com/blog/
http://www.wxforum.net

http://www.weather.com/blog/ *(the Weather Channel blog)*
http://www.davisnet.com/weather/cool/other_sites.asp

UK and Ireland weather newsgroups:

The COL Forum – accessible via
http://www.colweather.org.uk/ or http://www.uktrail.com/colchat/intro.php
The online discussion board for the UK Climatological Observers Link (see below). Anyone on the Internet can read the forum, but only members can post. A wide variety of topics, ranging from current weather to observation protocols, and a good source of answers to observing or instrument questions.

uk.sci.weather – access via numerous newsgroup readers such as http://groups.google.com/group/uk.sci.weather/topics

UK Weatherworld – A moderated 'general weather' newsgroup, with the advantage of being able to include graphics within posts – useful for cloud photographs, weather charts, AWS graphical output and so on: http://www.ukweatherworld.co.uk

Information exchange via like-minded groups or organizations

Get to know other weather observers in your area: most are happy to exchange observations, upon request, usually on a monthly basis by post or an e-mail PDF, while some will have their own weather websites containing real-time data. Local comparisons are interesting, and highlight the variability of rainfall patterns, urban and elevation influences, the sites most prone to fog or frost, and the like. Making contact with local observers may also lead you to a source of long-period records for sites in your area, assistance with observational techniques or site guidance for new observers, a calibration check on your instruments, and numerous other benefits. A small local network consisting of a few local observers can prove useful to help fill gaps in observational records, particularly non-instrument observations such as the occurrence of snowfall, thunderstorms and so on, when a primary observer cannot make observations due to a business trip, family holiday, or other absence from home.

One of the largest networks of co-operating voluntary or amateur observers in the world is the UK's Climatological Observers Link, now more than 40 years old; similar organizations exist in some other countries. Contact details for some of these are given in Appendix 4. Some have the active support of their national weather services; in the United States, the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) is a notable example.

The Climatological Observers Link (COL)

The Climatological Observers Link (COL – www.colweather.org.uk) is one of the largest network of (mostly) amateur meteorologists in Europe. COL was founded by Tom Suttie in 1970 [1] and at the time of writing has around 450 members. COL publishes a comprehensive monthly weather review around the 20th of the month following, including monthly summary listings of observations made at approximately 350 sites (the majority within the UK and Ireland, but including some observations from other countries) together with observers' notes on the month, a synoptic summary, and an active letters section. The monthly COL bulletin is available in either softcopy (downloadable PDF) or hardcopy. The entire 40 year COL archive is also available as PDF files on CD-ROM.

Membership is open to everyone, from teenage to pensioners (the author joined COL when in the former category, now all too quickly approaching the latter . . .) COL has a surprisingly wide range of occupations, including a good number of professional meteorologists (Devon, home of the UK Met Office, has one of the highest station density of all the UK's counties). In addition to the monthly bulletin, the strengths of COL membership include access to other like-minded members' help and experience, access to local meetings, and an annual members meeting with an interesting range of presentations.

In September 2010 COL celebrated its 40th anniversary with a weekend meeting at the University of Reading, arranged jointly with the Royal Meteorological Society and the Tornado and Storm Research Organisation (**Figure 19.2**). In early 2011 COL became the first organization in Europe, and possibly the world, to introduce the new 30 year 1981–2010 averages within its monthly bulletin. During summer 2011, a full set of hard copy averages covering the new standard period 1981–2010, with decadal averages for 2001–10 for almost 250 sites, was published [2]. A member directory, containing details of several hundred past and present COL sites and contributing members, with station photographs, is published regularly. For those looking to make contact with like-minded weather observers within the UK or Ireland, COL is an excellent place to start. Contact details are given in Appendix 4.

The Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS)

CoCoRaHS is a community network of volunteers of all ages and backgrounds working together to measure and map precipitation across the United States (and expanding into Canada). Using low-cost plastic raingauges **Figure 6.7**) and a high-quality, high-content interactive website with online training and education resources, CoCoRaHS provides precipitation data to a high standard for natural resource, education and research applications throughout the United States. A prime objective of the program is increasing the density of precipitation data available by encouraging volunteer weather observing. CoCoRaHS also encourages citizens to have fun participating in meteorological science while heightening their weather awareness.

From a modest beginning within Colorado State University's Climate Center in 1998, today the network includes thousands of volunteers nationwide. Its major sponsors are the National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation (NSF). CoCoRaHS welcomes anyone with an enthusiasm for watching and reporting weather conditions, and encourages observers to enter their daily precipitation reports on the www.cocorahs.org website. Users range from national official bodies such as the National Weather Service to local farmers, teachers, and students.

The CocoRaHS web page provides information on the necessary type of instrumentation and how to join the network. Quality, easy-to-read training materials are available as a free download from the site, with links to Youtube and Facebook, and there is also *The Catch*, a chatty and informative bi-monthly e-mail letter to all participants.

Providing your observations to official bodies

Most national weather services welcome and encourage the contribution of weather observations made by individuals or bodies outside the professional

Figure 19.2. Delegates at the joint meeting of the Climatological Observers Link (COL), the Royal Meteorological Society and the Tornado and Storm Research Organisation, held to commemorate COL's 40th anniversary, at the University of Reading, England, in September 2010. (Photograph courtesy of Royal Meteorological Society)

synoptic or real-time observing networks (many of which focus on aviation reporting or forecasting requirements, rather than weather and climate monitoring). Such observers generally provide less frequent observations (usually once daily, reporting weekly or monthly in arrears) but at a higher spatial density than the sparse official networks. Some ‘co-operating observers’ go on to provide years or even decades of observations at little or no cost other than minor investments in training, encouragement, and equipment by the state meteorological agencies. Information from such ‘second tier’ climatological and rainfall networks is vital to ‘fill in the gaps’ in mapping weather patterns between the government agency-run ‘tier one’ sites, from both day-to-day and long-term climate perspectives. Detailed mapping of rainfall patterns, the tracks and impact of severe local storms, and research into city climates, particularly spatial variation and intensity of urban heat islands, all benefit enormously from relatively dense networks of weather observations run by volunteers. In Australia, for example, the Bureau of Meteorology maintains a voluntary network of more than 6,000 rainfall stations [3]. Providing information to the state meteorological services also provides one way of ensuring your observations are made to agreed standards; they will also become a permanent part of the national weather record.

To ensure compliance to common observing practices, site exposure and instruments at co-operating sites must conform to a set of standards set out by the relevant state meteorological authority. In some cases, the necessary equipment may be provided free of charge, or on a long-term loan basis. Observers are given training in observing and reporting. Most sites can expect an inspection visit every 2 to 5 years to ensure the equipment operates properly, verify instrument calibrations, and ensure the exposure remains satisfactory (sometimes with a recommendation to cut back trees, trim shrubs, etc.). Such visits, together with more frequent contact via newsletters or training events, also build a mutually beneficial relationship between the observer and the state meteorological service, contributing enormously to both observer motivation and data quality.

Some voluntary observers make weather observations for the majority of their lifetime. The U.S. cooperating network (see below) provides awards for observers who have contributed observations for more than 10 years [4]. The award range includes the Ruby Stufft Award, given to observers who complete 70 years of observations, and honours Ruby Stufft of Elsmere, Nebraska. In 1991 Ms Stufft became the first woman to achieve 70 years of cooperative service. The 75 year Earl Stewart Award honours the efforts of Mr Earl Stewart for 75 years of continuous observations at Cottage Grove, Oregon from 1917 to 1992.

The UK Met Office had a similar programme of awards to voluntary observers, including presentation barographs and nominations for national honours such as MBE and OBE for those contributing 30 or 40 years of records, or more. The longest known contributing observer in the UK was John Walker of Ruddington, near Nottingham. Like Mr Stewart in the States, Mr Walker contributed 75 years of observations (1873–1947) [5]. Mr Walker died shortly after completing his 1947 return, at the age of 91. Mary Rope, BEM, of Upper Abbey, Suffolk, began taking rainfall observations in 1909 and continued doing so for 72 years, until her death in 1981 [6]. Mary was awarded the British Empire Medal (BEM) for her dedication.

Unfortunately, the UK’s official recognition and thanks process for long-term voluntary weather observers has fallen into disuse in recent years, with little if any formal appreciation of the long-term contribution to the nation’s weather records for these volunteers. This stands in sharp contrast with the successful long-term voluntary co-operating weather observer programmes run within the United States, Australia and other countries.

The U.S. cooperating observers network

The U.S. National Weather Service's (NWS) Cooperative Observer Program (COOP) manages an observing network of approximately 11,000 volunteers who take weather observations on farms, in urban and suburban areas, National Parks, seashores, and mountaintops. The programme, which was set up in 1890 as part of the U.S. Weather Bureau (now the U.S. National Weather Service)[*], has two main objectives:

- Provide observational meteorological data, usually consisting of daily maximum and minimum temperatures, snowfall, and 24 hour precipitation totals, necessary to define the climate of the United States and help measure long-term climate changes.
- Provide observational meteorological data in near real-time to support forecast, warning and other public service programs of the NWS.

COOP observational data supports the NWS climate program and field operations. NWS has responsibility for selecting data sites, recruiting and training observers, installing and maintaining equipment, maintaining site documentation and metadata, collecting, quality-controlling and archiving the data, and delivering the information to users.

A cooperative station is a site where observations are taken by volunteers or contractors. Some of these stations include AWSs as part of their equipment, and some co-locate with other observing locations. Many observers record their daily temperature and precipitation and send the reports monthly to their supporting NWS office, which then sends the reports to the National Climatic Data Center (NCDC). Since 2009, an increasing number of observers enter their daily observations through a unique Internet web page (WxCoder). Many cooperative observers provide additional hydrological or meteorological data, such as evaporation. Data are sent either by telephone, computer or post. Equipment in use at NWS cooperative stations remain the property of the NWS, the observer, a company, or other government agency. Equipment must meet NWS equipment standards.

Some U.S. weather records began long before 1890, of course. John Campanius Holm's weather records from New Sweden, at Fort Christina, now in Wilmington, Delaware, taken without the benefit of instruments in 1644–5, were the earliest known observations in the United States. Subsequently many notable American citizens, including George Washington, Thomas Jefferson, and Benjamin Franklin, kept their own weather records. Thomas Jefferson maintained an almost unbroken record of weather observations between 1776 and 1816, and George Washington made his last weather observation just a few days before he died in 1799. The

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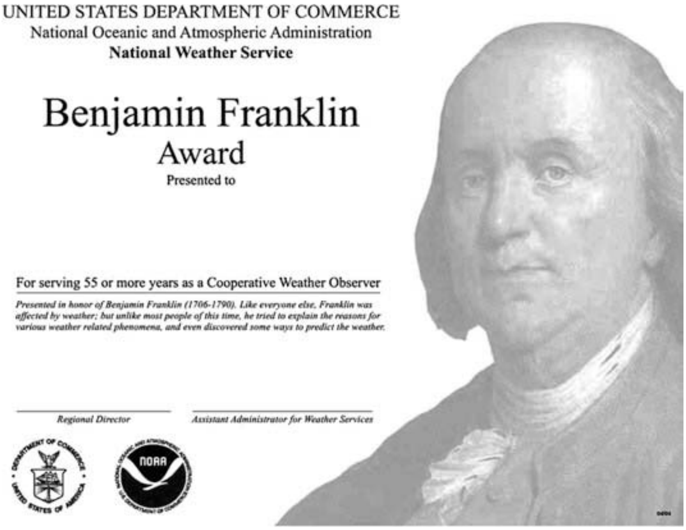
[*] The U.S. Weather Bureau was established in 1870 through a joint resolution of Congress signed by President Ulysses S. Grant with the mission "… to provide for taking meteorological observations at the military stations in the interior of the continent and at other points in the States and Territories … and for giving notice on the northern [Great] Lakes and on the seacoast by magnetic telegraph and marine signals, of the approach and force of storms."



UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service

Benjamin Franklin
Award
Presented to

For serving 55 or more years as a Cooperative Weather Observer

Presented in honor of Benjamin Franklin (1706-1790). Like everyone else, Franklin was affected by weather; but unlike most people of this time, he tried to explain the reasons for various weather related phenomena, and even discovered some ways to predict the weather.

Regional Director

Assistant Administrator for Weather Services

Figure 19.3. The NOAA / National Weather Service Benjamin Franklin Award. This award is granted to an observer for 55 years of service. It was established in honour of Benjamin Franklin (1706–1790), who variously served as ambassador and scientist, and was one of the signatories of the United States Declaration of Independence in 1776. As Postmaster General, he received weather reports from a network of observers along the coast, the first reference to hurricane tracking. (Courtesy of National Oceanic and Atmospheric Administration/National Weather Service Cooperating observer program)

NOAA/NWS Benjamin Franklin award (**Figure 19.3**) is given for 55 years of service as a cooperating observer: the Holm and Jefferson Cooperative Weather Observer awards are two of the most prestigious [4].

Because of its many decades of relatively stable operation, high station density, and high proportion of rural locations, the Cooperative Network remains the most definitive source of information on U.S. climate trends for temperature and precipitation and forms the core of the U.S. Historical Climate Network (HCN). Observations arriving at NCDC in Asheville, North Carolina, undergo a final quality control check, and (if necessary) electronic scanning into a digital format before becoming part of the U.S. climate archive.

In July 2011, NOAA's National Weather Service made a presentation of the agency's Family Heritage Award to Harold Thomson of Richmond, Utah, for his family's outstanding service in the Cooperative Weather Observer program, with a ceremony in the presence of his family and senior NWS officials (**Figure 19.4**). Joseph Thomson (Harold's grandfather) began operating the station in October 1911, with, then, U.S. Weather Bureau instruments. In 1956, after 45 years, Joseph transferred station responsibility to his son Verno, relocating the equipment 600 metres north of the original site. Harold took over responsibility for the observations in 1969 from his father, and continues to observe from the same location. This award remains unique as only a very small number of families have served for such a long period. "Volunteers like Harold Thomson and his family are crucial to National Weather Service operations," said Rick Dittmann, meteorologist-in-charge of the weather forecast office in Pocatello, Idaho, at the ceremony. "The National Weather Service

Figure 19.4. Recipients of the NOAA / National Weather Service Family Heritage Award in July 2011 for outstanding service in the Cooperative Weather Observer program, Harold Thomson and his wife Gloria, from Richmond, Utah. Left to right: Vickie Nadolski, NWS Western Region Director; Mr and Mrs Thomson; Rick Dittmann, Meteorologist-In-Charge of Weather Forecast Office, Pocatello, Idaho. (Photograph courtesy of National Oceanic and Atmospheric Administration/National Weather Service Cooperating observer program)

depends upon this network of cooperative weather observers, who provide a valuable service to the National Weather Service, the nation, and the people who rely on their observations. The Thomson family's unselfish and unrelenting service in weather observing and record-keeping for the community of Richmond and the National Weather Service provide valuable climatic information as part of the national network of around 11,000 volunteers."

More information on the U.S. programme, and how to contribute, is available from www.weather.gov/om/coop/.

The UK co-operating observers network

In 1978, the UK climatological network was described by the UK Met Office as '. . . a remarkable institution . . .' [7], and the contribution of the co-operating observer community was acknowledged as a vital and highly cost-effective part of the networks maintained by the state meteorological service. At that time, the network consisted of 624 climatological observing sites within the UK (only 20 per cent of which were directly administered or manned by Met Office personnel), and a little more than 6,000 rainfall sites, most of them reporting daily observations monthly in arrears. Today, only about 250 climatological stations remain (a reduction of more than 60 per cent since 1970, despite more than half becoming automated in recent years) and slightly more than 3,000 rainfall sites [8]. The proportion of voluntary co-operating sites has fallen significantly, and is now believed to be less than 10 per cent. In this respect the approach of the UK national weather service is very different from its U.S.-equivalent body, for it actively discourages the registration of 'private' voluntary co-operating climatological sites. Aside from its new Weather Observations portal referred to above, all references to 'making voluntary weather observations' have been withdrawn from its public website, despite advances in flexible and affordable technology and a higher than ever public interest in taking weather observations. Offering to provide observational data to the UK Met Office today will probably be met with nothing more than a standard letter communicating a polite refusal.

In 2001, the day-to-day administration of the remaining rainfall networks became part of the Environment Agency in England and Wales, the Scottish Environment Protection Agency (SEPA) in Scotland, and Northern Ireland Water in Northern Ireland. These agencies now maintain the majority of the voluntary rainfall observer network across the British Isles. Voluntary rainfall observers operate to set standards, after a short introductory training session, using agency equipment consisting of a standard five-inch raingauge (see Chapter 6, *Measuring precipitation*). Some sites have a tipping-bucket recording gauge, with data-logger or telemetering capability. Site inspections take place normally every 3 years.

New observers are sought where significant gaps exist in the rainfall monitoring network, or when existing observers withdraw from the activity. Recruiting efforts are made to obtain new observers to fill a reporting gap: regional hydrometry and telemetry teams manage and communicate with the observers [9].

The co-operating observers network in Ireland

At the time of writing, Met Éireann oversees 475 rainfall stations, of which 65 also provide additional climatological statistics [10]. The number of rainfall stations has seen a slight decline in recent years, although the number of climatological stations remains stable. Approximately 80 per cent of the sites (both rainfall and climatological) are voluntary, the balance made up from bodies such as the Irish Agriculture and Food Development Authority (Teagasc), Ireland's Electricity Supply Board (ESB), or various local authorities.

Offers of additional observation sites are welcome, subject to site requirements. However, voluntary offers may be declined if a particular area has good coverage. Efforts are made wherever possible to fill in any gaps occurring within a network, and from time to time Met Éireann actively seek new observers, usually by inviting existing observers to pass on requirements by word of mouth. Occasionally, a large gap might be filled following local visits to recruit a suitable voluntary observer in the area. Standard equipment and training is provided by Met Éireann in order to maintain WMO standards.

One-minute summary – *Sharing your observations*

- Weather knows no boundaries. The inherent interest and benefit of making weather observations is greatly enhanced by exchanging and comparing observations with others locally, nationally or internationally.
- There are three main methods of doing so: online or real-time sharing using the Internet, offline reporting to informal or voluntary networks, and more formal co-operation with national weather services and other official bodies.
- Sharing real-time weather information from a digital weather station over the Internet via a site-specific website, or submitting the output automatically to one or more data aggregation sites, the largest of which store and display observations from thousands of locations across the world, can help build a clearer picture of weather conditions within a town, city or country, help pin down the tracks of showers or thunderstorms, or map an urban heat island.

- With a relatively dense network of reporting locations in populated areas, together with a fast update/refresh rate, highly detailed mesoscale displays of current weather conditions are instantly available on the web, even on portable devices such as smartphones.
- National forums and publications to assist the exchange of data between those with an interest in 'measuring the weather' are available in several countries: the Climatological Observers Link (COL) in the UK and the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) network in the United States are good examples.
- Most national weather services welcome and encourage the contribution of weather observations made by private individuals or organizations, as these provide a richer network of observing points to supplement the wider spacing of professional observing networks. For more than 120 years in the United States, the Cooperative Observer Program has proven itself as a cost-effective method in weather data collection, and currently administers about 11,000 observing sites. The Australian Bureau of Meteorology oversees in excess of 6,000 rainfall stations across the continent.
- Agreeing to provide observations to a state meteorological service requires minimum standards of site, exposure and instrumentation, but the controlling agency may provide the instruments on a free loan basis where the observing site fills a gap in the network. For observers collecting data for a state meteorological agency, they also have the benefit of knowing their observations become a part of the nation's permanent weather archive.
- Voluntary observers provide the backbone of most countries observing networks, and tend to do so for many years. There are examples within the UK and the United States of a few individuals completing 70 years or more of high-quality weather records. Without doubt, the longer the record, the more interesting it becomes to look back upon notable events.

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[3] The Australian Bureau of Meteorology has an excellent website, very easy to navigate and with much useful information updated on a daily basis. For information on the station networks, see www.bom.gov.au/inside/org_structure.shtml.

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[10] This information was provided in an e-mail response from Met Éireann, dated 20 May 2011.

20 Summary and getting started

This final chapter summarizes all of the*'One minute summary'* sections of previous chapters in one location. Page numbers for the relevant chapters are also included, and together with the subject index permit rapid reference to any of the information contained within this book.

Choosing a weather station

Chapter 2 – page 32

- There are many different varieties of automatic weather stations (AWSs) available, and a huge range of different applications for them. To ensure any specific system satisfies any particular requirement, consider carefully, in advance of purchase, what are the main purposes for which it will be used, then consider and prioritize the features and benefits of suitable systems to choose the best solution from those available.
- The choices can be complex and a number of important factors may not be immediately obvious to the first-time purchaser. Deciding a few months down the line that the unit purchased is unsuitable and difficult to use (or simply does not do what you want it to) is likely to prove an expensive mistake, as very few entry-level and budget systems can be upgraded or expanded.
- Decide firstly what the AWS will mainly be used for: some potential uses may not be immediately obvious. Once that is clear, review the relevant decision-making factors as outlined in this chapter, then prioritize them against your requirements.
- An AWS does *not* have to be the first rung on the weather measurement ladder. Short of funds? Not sure whether you'll keep the records going and don't want to spend a lot until you have given it a few months? Not sure where to start? Different options are covered in this and subsequent chapters.
- Consider firstly whether the site where the instruments will be used is suitable. There is little value in spending hundreds or even thousands of dollars on a sophisticated and flexible AWS if the location where it will be used is poorly exposed to the weather it seeks to measure. In general a budget AWS exposed in a good location will give more representative results than a poorly exposed top-of-the-range system. Worthwhile observations *can* be made with budget instruments in limited exposures, but a very sheltered site may not justify a significant investment in precision instruments, as the site characteristics may limit the accuracy and representativeness of the readings obtained.

- Carefully consider the key decision areas. Should the system be cabled, or wireless? Is it easy to set up and use? How many sensors are offered, and how accurate and reliable will they be? Are all the sensors mounted in one 'integrated' system, or can they be positioned separately for the optimum exposure in each case? Do the records obtained need to conform to 'official standards'? Examples and suggestions are given in this chapter.
- Finally – and this should be the last step – match the available budget against the requirements and specifications outlined in previous steps. Consider that a reasonable mid-range or advanced system, when used with care and maintained, should last for 10 or even 20 years, and budget accordingly. There are many 'cheap and cheerful' systems available, but will they last longer than their warranty period?

Buying a weather station

Chapter 3 – page 55

- There are enormous differences in functionality and capability between basic and advanced models. The general rule that 'you get what you pay for' holds true for AWSs as well as for most other products, but some systems *are* better than others and it pays to check available products carefully against your requirements to ensure the best fit.
- To simplify selection, Chapter 3 suggests five product and budget categories. Most systems fit comfortably within one of these price/performance bands – entry-level systems (single-element, or AWS): budget AWS: mid-range AWS: portable systems: and advanced or professional systems.
- *Entry-level systems*. There are many situations where an entry-level system may perfectly meet the requirements. Provided their limitations in terms of accuracy, capability and lifetime are understood and accepted at the outset, and careful attention is paid to siting and exposure, such systems can represent reasonable value for money for 'starter' weather monitoring system, or those with limited budgets.
- *Budget AWSs* will meet the needs of many users looking for a system that has tolerable accuracy and covers a reasonably wide range of weather parameters. As with entry-level systems, provided careful attention is paid to siting/exposure and calibration, such systems can provide reasonably accurate weather records over a number of years. Some represent very good value for money.
- *Mid-range AWSs* will meet the needs of many users looking for a system that has generally good accuracy and covers a wide range of weather parameters. Provided careful attention is paid to siting/exposure and calibration, such systems can be expected to provide reliable and accurate weather records over a decade or more. A typical mid-range AWS costing three times as much as a budget-level system is likely to provide higher-quality records and probably last four or five times longer: viewed over a typical 10 year period, mid-range systems therefore represent excellent value for money.
- *Portable AWSs* are particularly useful for field or portable work: with a suitable choice of logging interval they can be used for short-term logging at permanent sites. They are, however, unsuitable for permanent installation.

- *Advanced AWSs* tend to be custom-built to a specific requirement, whether for the serious amateur or professional installation, and are capable of almost unlimited expansion. Systems in this price range are accurate, robust and capable of measuring a very wide range of elements, but at a price to match. Provided site and exposure requirements are satisfied, and regular calibration checks undertaken, such systems can be relied upon to provide accurate, reliable and high-quality weather measurements over many years, for almost all applications and locations, even in the most remote areas or hostile climates.
- AWS specifications are suggested within four very loose 'user profiles' – Starter, Hobbyist, Amateur and Professional – intended as a pragmatic starting point to what is practical and affordable within various budget and site restraints. As an example, with a limited budget it is probably better to concentrate on air temperature and rainfall observations: wind speed and direction (for instance) are more expensive to measure, and the site requirements are more complex. These and other elements can probably follow at a later stage as budgets (and perhaps an improved site) allow.

Site and exposure – the basics

Chapter 4 – page 76

- *Site* refers to 'the area or enclosure where the instruments are exposed', while *exposure* refers to 'the manner in which the sensor or sensor housing is exposed to the weather element it is measuring'.
- Satisfactory site and sensor exposure are fundamental to obtaining representative weather observations. An open well-exposed site is the ideal, of course, but with planning and careful positioning of the instruments, good results can often be obtained from all but the most sheltered locations.
- A good exposure for one sensor can be the exact opposite for another. For representative wind speed and direction readings, for example, an anemometer mounted on top of a tall mast is ideal, but this would be a poor exposure for a raingauge owing to wind effects (more on this in Chapter 6).
- Based upon World Meteorological Organization (WMO) published guidance, this chapter outlines preferred site and exposure characteristics for the most common sensor types. No single exposure will provide a perfect fit for the requirements of all sensors. A simple and objective grading scheme to assess and report site, exposure and instrumentation is outlined.
- Rooftops or masts may provide much better exposure for some sensors, but carefully consider the accessibility of the site before attempting to install the sensors. If the proposed site cannot be reached safely, fit appropriate safety measures or find another site. **Do not take personal risks, or encourage others to do so, when attempting to install weather station sensors, particularly at height**.

Measuring the temperature of the air

Chapter 5 – page 89

- Temperature is one of the most important meteorological quantities, but it is also one most easily influenced by the exposure of the thermometer. Great care needs to be taken in exposing air temperature sensors to ensure that, as far as possible, the instrument measures a true and representative value, which is not unduly influenced by the instrument housing, surrounding vegetation or ground cover, the presence of buildings or other objects.

- The WMO recommendation is for a site over level ground, freely exposed to sunshine and wind and not shielded by, or close to, trees, buildings and other obstructions. Of course, it is not always possible to follow WMO guidance in every detail, particularly where site and/or exposure may be limited, and suggestions on the best methods for obtaining optimum results under such circumstances are presented. Certain locations, such as hollows or rooftop sites, are best avoided, as readings obtained in these situations may bear little comparison to observations made elsewhere under standard conditions.
- Some form of thermometer screen is essential to provide protection from direct sunshine, infrared radiation from Earth and sky, and from precipitation. The main screen types – louvred (Stevenson screen, Cotton Region Shelter), AWS radiation screens and aspirated screens – are covered in some detail, because the thermometer housing (or lack of it) is likely to have the largest impact upon the observed temperature. Almost any form of radiation shelter will provide better results than a bare sensor. If the AWS model chosen does not include an effective radiation screen, allow budget to purchase a suitable third-party one and use that.
- Traditional louvred screens can accommodate both traditional liquid-in-glass thermometers and small electronic sensors, but small AWS radiation shields can be used only with electronic sensors. Aspirated units currently provide the best estimate of true air temperature (they are highly responsive and largely free of influence from the screen itself), but they provide a slightly different temperature record from other standard methods. Next-generation climate monitoring networks are increasingly using aspirated methods of measuring air temperature.
- To avoid the significant vertical temperature gradients near the Earth's surface, thermometer/s to measure air temperature should be exposed at 1.2–2 m above ground level. In the UK and Ireland, the standard height is 1.25 m above ground; in the United States, between 4 and 6 feet.
- Sites that have long current records of temperature made in traditional thermometer screens (Stevenson, Cotton Region Shelter) should not substitute an alternative method of measuring temperature (for example, an aspirated screen) without a substantial overlap period, because doing so risks destroying the homogeneity of the long record. The overlap period should be a minimum of 12 months, or one-tenth of the station record length, whichever is the longer.
- Most air temperature measurements are now made using resistance temperature devices (RTDs), which are steadily replacing liquid-in-glass thermometers. The main types of sensor in use today are the *platinum resistance thermometer* and the *thermistor*. The former is more accurate and more repeatable, but more expensive. Both can be made very small and thus highly responsive.
- Logging intervals of 1 to 5 minutes, with shorter sampling intervals (typically 5 to 15 seconds), are sufficient for most air temperature measurement applications. Running means can be used to smooth out very short-period temperature fluctuations, which are of little significance in climatological measurements, and any stray electrical noise.

- Sheltered sites can introduce significant measurement errors, but with some care given to siting the screen and sensor/s reasonable air temperature measurements can be made in all but the most restricted locations. Temperature records from suburban sites, even those with limited exposures, can often provide more numerous and more representative climate records for a town or city than those from more distant sites with near-perfect exposures.

Measuring precipitation

Chapter 6 – page 124

- The term 'precipitation' includes rain, drizzle, snow, sleet, hail and the like as well as the occasional minor contribution from dew, frost or fog. Precipitation is highly variable in both space and time, and precipitation measurement networks are usually denser than for other elements to improve spatial coverage. There may be as many as 1 million raingauges operating globally, although standards vary from country to country.
- Precipitation measurements are very sensitive to exposure – particularly to the wind – and the choice of site is very important to ensure comparable and consistent records are obtained. Choose an unsheltered (but not too exposed) spot for the raingauge/s – loss of catch through wind effects is the greatest single error in precipitation measurements, particularly in snow. A site on short grass or gravel is preferable. Wherever possible, obstructions (particularly upwind obstructions in the direction of the prevailing rain-bearing winds) should be at least twice their height away from the raingauge. Rooftop sites are particularly vulnerable to wind effects and should be avoided. The site should also be secure, but accessible for maintenance (grass cutting, etc.) as required.
- The gauge should be exposed with its rim at the national standard height above ground – in the UK and Ireland, this is 30 cm; in the United States, between 3 and 4 feet (90 to 120 cm). Most countries define a 'standard rim height' as between 50 cm and 150 cm above ground. Take care to set the gauge rim level, and to maintain it accurately so.
- Manual raingauges should have a round, deep funnel to minimize outsplash in heavy rain (shallow funnel gauges are not recommended) and should have a capacity sufficient to cope with at least a '1-in-100 year' rainfall event – a minimum of 150 mm in the UK and 500 mm (20 inches) in most parts of the United States. The gauge must be paired with an appropriately calibrated glass measuring cylinder.
- Most manual raingauges are read once daily, usually at a standard morning observation time, typically between 7 A.M. and 9 A.M. local time. The morning reading should be 'thrown back' to the previous day's date.
- To obtain records of the timing and intensity of rainfall, one or more recording raingauges are often sited alongside the manual raingauge. The record from the manual gauge should be taken as the standard period total and sub-daily records (hourly totals, for instance) taken from the recording gauge adjusted to agree with the daily total taken from the manual gauge. The use of stand-alone recording gauges is not recommended when accurate or comparable rainfall totals are required.

- The preferred resolution of a recording raingauge is 0.1 or 0.2 mm; 1 mm tipping-bucket raingauges are too coarse for accurate measurements of small daily amounts. Recording raingauges should be logged at 1 minute or 5 minute resolution (higher frequencies are possible using an event-based logger). They should be regularly inspected for funnel blockage or any obstruction to the operating mechanism, which will result in the complete loss of useful record if not quickly corrected.
- Snowfall is difficult to measure accurately with most types of raingauge, and without some form of wind shield most raingauges will lose 50 per cent or more of the ‘true’ catch through wind errors introduced by the presence of the gauge, which interferes with the flow of the wind over it, causing a loss of some of the catch.
- Procedures for measuring snow depth and the water equivalent of snowfall are included in this chapter.

Measuring atmospheric pressure

Chapter 7 – page 167

- Pressure is the easiest of all of the weather elements to measure, and even basic AWSs or household aneroid barometers can provide reasonably accurate readings. It is also the only weather element that can be observed indoors, making a barometer or barograph – analogue or digital – an ideal instrument for apartment dwellers.
- The units of atmospheric pressure are hectopascals (hPa) – a hectopascal is numerically identical to the more familiar millibar. Inches of mercury are still used for some public weather communications within the United States – one inch of mercury is 33.86 hPa.
- Pressure sensors must be located away from places that may experience sudden changes in temperature (direct sunshine, heating appliances or air conditioning outlets) or draughts, which will cause erroneous readings.
- Great accuracy is not required for casual day-to-day observations, as very often the trend of the barometer in temperate latitudes, whether it is rising or falling, and how rapidly, provides the best single-instrument guide to the weather to be expected over the next 12–24 hours.
- Where accurate air pressure records are required, the observed barometer reading needs to be adjusted to a standard level, usually mean sea level (MSL), because air pressure decreases rapidly with altitude. A variety of approaches exist to correct or ‘set’ a barometer to mean sea level: four are described in this chapter. The choice of method depends upon accuracy sought (and the accuracy of the sensor) and height above sea level. Downloadable Excel spreadsheets are available to simplify the production of site-specific sea level correction tables where desired.
- The calibration of all barometric pressure sensors, particularly electronic units, should be checked regularly to avoid calibration drift. More details are given in Chapter 15.
- Because of the twice-daily diurnal cycle of barometric pressure, the hour of observation should always be stated when presenting averages. AWSs can easily provide 24 hour means, which eliminate the effects of the diurnal cycle in atmospheric pressure.

Measuring humidity

Chapter 8 – page 183

- ‘Humidity’ refers to the amount of water vapour in the air, a vital component of the weather machine.
- Various measures are used to quantify the amount of water vapour in the air – relative humidity and dew point being the two most commonly used. Knowledge of any two values can derive other humidity parameters. The amount of water vapour that the air can hold varies significantly with temperature – saturated air at 0 °C holds only a quarter of the amount that saturated air at 20 °C can hold.
- The traditional method of measuring humidity is by using a pair of matched mercury-in-glass thermometers, known individually as dry-bulb and wet-bulb thermometers and in combination as a dry- and wet-bulb psychrometer. The wet-bulb is a thermometer whose bulb is kept permanently wet using a thin close-fitting cotton cap or sleeve. The wet-bulb is cooled by evaporation, and the difference in temperature between dry-bulb and wet-bulb thermometers is a measure of the humidity of the air. Using tables, an online calculator or formulae, the relative humidity (or any of the other humidity measures) can be quickly and easily determined from simultaneous readings of the two thermometers.
- Dry- and wet-bulb thermometers can easily be replicated using electrical sensors, although small capacitative humidity sensors have largely replaced the traditional dry- and wet-bulb psychrometer. Modern sensors are small, economical on power, more reliable at temperatures below freezing and datalogger-friendly.
- Establishing and maintaining reasonably accurate calibration can be difficult; even the best humidity sensors are no better than ± 2–3%. Calibration drift is a problem (regular calibration checks are essential) and working lifetimes can be limited. Combined temperature/RH sensors are popular, but can become expensive and inconvenient if the relatively short working lifetime of the humidity component mandates replacement (and recalibration) of the temperature sensor too.
- Humidity sensors are normally exposed alongside temperature sensors in a thermometer screen (Stevenson screens or similar, AWS radiation screens or aspirated units).
- Logging intervals should be the same as those for temperature observations, although sampling intervals can be reduced (once per minute is ample).

Measuring wind speed and direction

Chapter 9 – page 192

- The wind is highly variable in both speed and direction, and obtaining good measurements of the wind poses particular challenges for instruments, logging equipment and site requirements.
- Wind is a *vector* quantity – it has both direction and speed. Wind direction refers to where the wind is coming from. A wind vane needs to be accurately aligned to true north, which is slightly different to the magnetic north shown by a magnetic compass.

- Mean wind speeds normally refer to 10 minute periods, gust speeds to 3 seconds. For accurate determination of gust speeds, a high sampling interval (no more than a few seconds) is essential, although the logging interval can be much longer than this.
- Wind direction and speed are normally measured using separate instruments, most often a cup anemometer and a potentiometer-based wind vane. The absolute accuracy of wind speed measurements is more likely to be limited by the height and exposure of the anemometer, rather than the accuracy of the sensor. The accuracy of wind direction measurements depends more upon careful alignment at installation.
- The ideal site for wind instruments is atop a 10 m mast in open, level terrain, well away from any obstacles. However, such ideal sites are hard to come by, particularly in urban or suburban areas, and wind records are therefore necessarily more site-specific than most other weather measurements. Some corrections for the variation of mean wind speed with height are possible, and these are described in this chapter. Gust speeds should not be corrected.
- Generally speaking, the best exposure to the wind will be obtained by exposing both anemometer and wind vane in as open a position as possible, as high as possible, commensurate with both safety and accessibility for installation and maintenance. The necessarily elevated exposure will increase the vulnerability of the instruments to extreme weather conditions, particularly snow or ice, lightning and of course high winds. Great care should be taken in installation and cabling to minimize the potential for subsequent weather-related reliability issues.
- Planning permission or zoning approval is not normally required for domestic rooftop-mounted anemometers or wind vanes, and local authority case precedents exist within the UK. Specialist legal advice should be taken if in doubt.
- **Never take risks with personal safety when installing any weather sensors at height**.

Measuring grass and earth temperatures

Chapter 10 – page 222

- Grass and earth temperatures are the most commonly observed temperature measurements, after air temperature.
- The lowest temperatures on a clear night will be recorded at or close to ground level. Where the surface is covered by short grass, the lowest temperatures are attained just above the tips of the grass blades. The so-called ‘grass minimum temperature’ (or ‘grass min’) is measured using a thermometer or electrical sensor freely exposed in this position. A ‘ground frost’ occurs when the grass minimum falls below 0°C.
- Temperatures are occasionally measured above concrete or tarmac surfaces, or using sensors buried in road surfaces at roadside AWSs, to provide information on road surface temperatures to aid road forecasting models.
- To measure grass temperatures, a spirit-based minimum thermometer or an AWS or dedicated logger with inputs for a trailing-lead electrical sensor (thermistor or platinum resistance thermometer, PRT) is required. Entry-level and budget AWSs generally do not include suitable additional sensors or ‘spare’ sensor ports. A sensitive yet robust sensor is required to measure grass minimum temperatures, as it will be exposed to all extremes of weather.

- WMO guidelines indicate that grass and surface minimum temperatures should relate to the period 'sunset to the morning observation on the following day', although the greater prevalence of unmanned sites is leading more locations to adopt the conventional 'morning to morning' 24 hour period.
- Earth temperatures are most frequently measured at depths of 5, 10, 20, 30, 50 and 100 cm below ground level. Measurements at 30 cm or deeper are normally made under a grass surface, while the shallower depths are measured under a bare soil plot. Both should remain fully exposed to sunshine, wind and rainfall.
- Earth temperatures at 30 cm or deeper are measured using specially lagged thermometers hung on chains in steel tubes at the required depth, or using electrical sensors. Cabled sensors are ideally suited to measuring grass or earth temperatures, although care needs to be taken in how earth temperature sensors are exposed, as locating them in tubes with higher conductivity than the surrounding soil will introduce significant errors.
- Earth temperatures are normally quoted for a morning observation hour, although hourly values can easily be derived from logged electrical sensors. Hourly values provide useful insights into diurnal temperature variations below the earth's surface.
- Grass temperatures should be sampled and logged at the same interval as used for air temperatures; for earth temperatures, particularly at depth, an hourly or even once-daily logging interval may be sufficient.

Measuring sunshine and solar radiation

Chapter 11 – page 232

- Radiation from the Sun consists of a wide range of wavelengths, from extreme ultraviolet to the far infrared, peaking in the visible region. Solar radiation is amongst the most variable of all weather elements, and consists of two main components – *direct solar radiation* from the solar disk, and *diffuse solar radiation* from the rest of the sky, the latter as a result of the scattering and reflection of the direct beam in its passage through the atmosphere.
- The most common measurements made are of *sunshine duration*, using a sunshine recorder, and *global solar radiation on a horizontal surface*, using a pyranometer. 'Sunshine' is defined in terms of the intensity of a perpendicular beam of visible wavelength solar radiation from the solar disk. The intensity of solar radiation is measured in Watts per square metre (W/m^2), and daily totals in Megajoules per square metre (MJ/m^2). Sunshine durations are measured in hours, or quoted as a percentage of the maximum possible duration.
- There are different models of sunshine recorder. The iconic Campbell-Stokes sunshine recorder has been in use since the late 1870s, although it is being replaced by datalogger-friendly electronic sensors, which give slightly different measurements – the Campbell-Stokes unit tending to over-record in broken sunshine. Estimates of sunshine can be derived from pyranometer data, although no method for doing this has yet been shown to provide consistent agreement with dedicated sunshine recorders. Changes in recorder types over time (for instance, the transition from the Campbell-Stokes unit to electronic sensors) mean that today's measurements are not directly comparable with measurements made using different instruments in previous years.

- All solar radiation instruments require an open exposure, one with as clear a horizon as possible: a flat rooftop or a mast are often suitable locations. The effects of obstructions can be assessed using a solar elevation diagram in conjunction with a site survey, although obstructions within about 3 degrees of the horizon have little effect on the record. The instruments must also be accurately levelled, and most also require some form of azimuth alignment and/or latitude setting. **Never put yourself or others in danger when installing or maintaining meteorological instruments at height**.
- Calibrations for solar radiation instruments tend to be based upon comparisons with reference instruments. WMO organizes instrument intercomparisons amongst national meteorological services every 5 years to ensure consistent and transferable measurement standards.
- A high sampling interval is advisable for electronic sensors as solar radiation is amongst the most variable of all weather elements. The logging interval can be much less frequent than the sampling interval, and hourly means will be sufficient for many applications.
- Sunshine and solar radiation instruments tend to be slightly more variable in their outputs than many meteorological sensors, and even adjacent instruments can be expected to vary somewhat in their readings. For this reason, all sunshine and solar radiation measurements should be regarded as prone to errors of up to a few per cent.

Observing hours and time standards

Chapter 12 – page 271

- By convention, weather measurements throughout the world are made to a common time standard – Coordinated Universal Time (UTC). For all practical purposes, UTC is identical to Greenwich Mean Time (GMT).
- For weather measurements to be comparable between different locations, the time/s at which observations are made, and the period covered by the measurements, should be common. WMO provides guidance on observation times for the main international synoptic observing networks, while the main 'climatological' observing practice tends to be defined at a country or regional level.
- Many countries around the world have adopted a once-daily morning observation as standard practice, the time lying typically between 7 A.M. and 9 A.M. Where AWS data are available, it is straightforward to adjust records to conform more closely to the 'nominal' standard morning observation time, even if it is rarely possible to make manual observations at that hour. Adopting the standard observing time (or close to it) greatly simplifies comparisons of weather observations with other sites – particularly daily rainfall records.
- The once-daily morning observation naturally establishes a standard 24 hour period over which many 'once-daily' values are tabulated. Some other elements, such as sunshine, fall more naturally within the 'civil day' (midnight to midnight local regional time), whilst synoptic reporting sites may use different, globally-defined, observing times.
- The start and end time of these recording periods are known as the 'terminal hours' of that measurement. The term 'terminal hour' refers to the time of day at which the extremes are reset.

- By convention, 24 hour minimum temperatures read at the morning observation are entered to the day on which they were read, whereas 24 hour maximum temperature and total rainfall are entered to the day prior to the observation (they are said to be 'thrown back'). Although this occasionally leads to some bizarre anomalies, a midnight-to-midnight record period would be difficult to introduce at sites where only manual instruments are in use (particularly at rainfall-only locations).
- Terminal hours based around 'day maximum' and 'night minimum' temperatures (where the extremes span only 12 hour periods) will generally give results which are incompatible with '24 hour' sites, particularly in temperate latitudes in the winter months.
- WMO guidance is that the grass minimum temperature should refer to the period from just before sunset to the following morning observation terminal hour.

Dataloggers and AWS software

Chapter 13 – page 282

- The choice of datalogger and AWS software is crucial to the effective operation of any AWS. Its specification will define the capabilities (or limitations) of the AWS, and the choice of unit should be given at least as much consideration as the choice of sensors.
- Most budget AWS packages will include a pre-programmed datalogger with display software, although flexibility and expandability may be limited. Sophisticated programmable multi-sensor loggers and software are highly expandable, but are considerably more expensive and complex to programme and use.
- The critical decision criteria for dataloggers are – choice of power supply, and battery backup capability: amount of memory: number and type of input options ('ports'): and programmable capabilities, if any.
- AWS software provides three key functions – system setup and configuration, communication with and downloading of data from the datalogger, and the display of current and logged data. Most offer some form of data upload to Internet/website.
- The majority of AWS owners opt for a third-party AWS software package over the manufacturer's offering. At the time of writing, five leading packages accounted for more than four in five of AWSs surveyed in the United States, the United Kingdom and Ireland, although there are also others available. There is no 'best' solution, all packages have pros and cons, and the choice is largely one of personal preference. Most of the leading software is available on a 'try before you buy' basis, and it is best to 'try before you buy'.
- It is advisable to check and test all sensor / datalogger / software and communications thoroughly, over a period of at least a few days, before permanent hardware installation or embarking on any long-term data collection.
- As with any major expenditure, carefully match capabilities with requirements (and budget) before purchasing a system.

Non-instrumental weather observing

Chapter 14 – page 294

- Instrumental readings are of course vital in making observations of the weather, but for a complete picture non-instrumental and ‘narrative’ weather observations are equally important, especially for the analysis of severe weather events.
- A once-daily ‘morning observation’ is the best time to read/reset any manual instruments in use, as well as perform visual checks on the operation of the sensors for an AWS, particularly raingauge funnels which are likely to become blocked if left unchecked. A manual observation also provides a convenient opportunity to note current weather details such as the amount and types of cloud, the surface visibility, present weather, the occurrence and depth of snow cover and so on.
- With a little practice, maintaining a near 24 hour weather watch becomes second nature, and with some assistance from friends, family or neighbours a 365 day, 24 hour coverage of significant weather is not difficult. When combined with the instrumental observations from an AWS and a brief daily descriptive weather diary, a high-quality combined weather record quickly builds up.

Calibration

Chapter 15 – page 304

- Instrument calibrations are one of the most important, yet also one of the most neglected, areas of weather measurement. Making accurate weather measurements requires accurately calibrated instruments.
- Recording raingauges can be easily and accurately calibrated by passing a known volume of water through the gauge, and comparing with the indicated measurement. ‘Out of the box’ errors for some AWS tipping-bucket raingauges of this type can exceed 20 per cent, so this is a vital test for all new instruments at first installation. Recording raingauges should not be adjusted merely to attempt exact agreement, or near-agreement, with a standard raingauge, because instrumental and exposure differences inevitably lead to slight variations in the amount of rainfall recorded.
- Two calibration methods are described for temperature sensors, whether liquid-in-glass thermometers or electronic units. The first is a quick and easy method based on the fixed point of melting ice at 0.0 °C. An extension of the approach can extend the range of calibration points from –5 °C to +40 °C when used with an accurately calibrated reference thermometer. However, this method is not suitable for certain types of sensor, and on some AWS models the temperature elements may not be accessible to perform this test.
- The second temperature calibration method involves careful comparison over a period with a portable reference unit of known calibration. Both sensors (calibrated reference and test) are exposed in identical adjacent surroundings exposures for a period (days to weeks). Careful comparison of readings can derive an accurate calibration curve, which is then used to apply the corrections obtained to the sensor readings going forward.
- Calibration checks, and checks for calibration drift, on pressure sensors can be made using pressure reports from synoptic sites over a period of a few days or weeks.

- Make a note in the site metadata of all calibrations applied, and the date. Keep a copy of the calibration table or algorithms used in the metadata file. Retain the calibration test results.
- Calibrations can drift over time, so calibrations should be checked (and adjusted if necessary) regularly – at least once every 6 months for pressure sensors, every 2 years for electronic temperature probes and every 5 years for liquid-in-glass thermometers.

Metadata – what is it, and why is it important?

Chapter 16 – page 322

- Metadata is literally ‘data about data’. In the context of weather records, it is a description of the site and its surroundings, the instruments in use and any changes over time, information about observational databases and units used, and any other details about the measurements that may be relevant.
- Metadata statements are important because they provide the essential information for any other user of the records to understand more about the location and characteristics of weather records made at any site, thereby enabling more informed use of the data to be made.
- A metadata statement is best prepared as a short structured text document, and retained alongside data files in soft copy or hard copy. A copy or link should also be included on the site weather website, if there is one. Links should also be provided to site photographs, instrument calibration certificates and other related documents.
- Review the metadata statement whenever instrument or site details change, and at least annually. Update as required. Retain previous site descriptions and photographs, which will assist in documenting site, instrument and exposure changes over the years.

Collecting and storing data

Chapter 17 – page 335

- Making weather measurements, particularly using an AWS, can quickly generate vast amounts of data and these can become unmanageable without some thought being given to how records are to be kept and used.
- Spreadsheets are ideal for archiving weather records, and provide more comprehensive analysis tools than the AWS software used to log the sensors. Holding and archiving data in hourly, daily and monthly spreadsheets is easy to do, simplifies record-keeping and makes subsequent analysis much more straightforward.
- Each spreadsheet should include an integral metadata sheet or ‘tab’ detailing the instruments used, their exposure, units of measurement, record length and any other essential information.
- Months or years of data can be lost in an instant if held in a single file on one hard disk. An entire lifetime’s manuscript record could just as easily be lost forever in a house fire or burglary. Taking simple steps, including putting in place a multiple backup strategy, can hugely improve the chances that records (and instruments) will survive to be used by future researchers.

Making sense of the data avalanche

Chapter 18 – page 348

- Spreadsheets are ideal for archiving weather records, and provide more comprehensive analysis and presentation tools than the AWS software used to store sensor output. Holding and archiving data in hourly, daily and monthly spreadsheets is easy to do, simplifies record-keeping and makes subsequent analysis much more straightforward.
- If you don't already . . . store your data in spreadsheets. Develop a format and structure that works for you – and stick with it. The files will build rapidly into useful datasets and even a few months observations can reveal interesting local weather patterns and peculiarities. Don't forget a 'metadata' sheet giving details of the records in the spreadsheet contents.
- Current local records can often be augmented and compared with historical records from the national climate archives. In many countries, online access and downloads are free or available at a nominal charge.
- The examples in this chapter and on www.measuringtheweather.com suggest a few ideas for analysis and how to perform them using Microsoft Excel spreadsheet software. Excel's Pivot Table function is particularly useful for analysing weather records.
- Other specialist graphics plotting software is also relevant for certain types of analysis, such as the preparation of wind roses.
- As with any software, practice builds experience. Experiment with simple graphing and analysis to become familiar with the spreadsheet functions, then experiment with question-based analysis along the lines of the examples given in this chapter. The number of topics and questions are infinite.

Sharing your observations

Chapter 19 – page 378

- Weather knows no boundaries. The inherent interest in taking weather observations are greatly enhanced by exchanging and comparing observations with others locally, nationally or internationally.
- There are three main methods of doing so: online or real-time sharing using the Internet, offline reporting to informal or voluntary networks, and more formal co-operation with national weather services and other official bodies.
- Sharing real-time weather information from a digital weather station over the Internet via a site-specific website, or submitting the output automatically to one or more data aggregation sites, the largest of which store and display observations from thousands of locations across the world, can help build a clearer picture of weather conditions within a town, city or country, help pin down the tracks of showers or thunderstorms, or map an urban heat island.
- With a relatively dense network of reporting locations in populated areas, together with a fast update/refresh rate, highly detailed mesoscale displays of current weather conditions are instantly available on the web, even on portable devices such as smartphones.

- National forums and publications to assist the exchange of data between those with an interest in 'measuring the weather' are available in several countries: the Climatological Observers Link (COL) in the UK and the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) network in the United States are good examples.
- Most national weather services welcome and encourage the contribution of weather observations made by private individuals or organizations, as these provide a richer network of observing points to supplement the wider spacing of professional observing networks. For more than 120 years in the United States, the Cooperative Observer Program has proven itself as a cost-effective method in weather data collection, and currently administers about 11,000 observing sites. The Australian Bureau of Meteorology oversees in excess of 6,000 rainfall stations across the continent.
- Agreeing to provide observations to a state meteorological service requires minimum standards of site, exposure and instrumentation, but the controlling agency may provide the instruments on a free loan basis where the observing site fills a gap in the network. For observers collecting data for a state meteorological agency, they also have the benefit of knowing their observations become a part of the nation's permanent weather archive.
- Voluntary observers provide the backbone of most countries observing networks, and tend to do so for many years. There are examples within the UK and the United States of a few individuals completing 70 years or more of high-quality weather records. Without doubt, the longer the record, the more interesting it becomes to look back upon notable events.

APPENDIX 1

Metrology and meteorology: The basics of instrument theory

Metrology is the science of instruments and their behaviour. *Meteorology* is the science of the atmosphere and its phenomena. The two are intimately related by far more than having all but two letters in common, for meteorology depends upon instrumentation to provide quantitative measurements of the state of the atmosphere at any time or over a period of time.

For most users of meteorological instruments it is certainly not essential to possess a detailed knowledge of the mathematical and physical principles behind the theory and design of any particular sensor, but it can be helpful to understand a few basic concepts and terms as they apply to both the sensors themselves and the output of measurement systems. A knowledge of how sensors react to the elements they measure, what the outputs are and how they are interpreted into useful forms, what errors or limitations there may be on those outputs, and how key sensor characteristics can be compared, all help to create a clearer understanding of the way any measurement system performs and its applicability to the application in hand.

This appendix provides a very simplified overview of some of the basics of measurement as applied to meteorological sensors. An excellent single-volume reference source on the subject is *Meteorological measurement systems* by Fred Brock and Scott J. Richardson, published by Oxford University Press in 2001; some of the following material has been adapted and summarized from this standard work. Readers who seek more detailed information beyond the necessarily brief topics outlined here are recommended to consult this volume.

Components of a measurement system

Any measurement system, whether it be a simple mercury thermometer or a complex, multi-site instrumented AWS network, consists of some or all of the following components:

- Sensor or transducer
- Analogue output
- Signal processing
- Data transmission
- Data display
- Data storage

The *sensor* (or *transducer*) is the component which reacts to the element being measured. Most generate an *analogue output* which varies in a known manner with changes in the element being measured. This is often a change in physical properties –

the expansion of mercury in a liquid-in-glass thermometer with rising temperature, for example, or the expansion and contraction of an aneroid barometer capsule with changes in atmospheric pressure.

This output is given form by the *signal processing* component. In a mercury thermometer, the expansion or contraction of the mercury in the bulb of the thermometer is magnified by movement within the much smaller capillary tube which forms the stem of the thermometer. In the aneroid capsule, tiny expansions or contractions result in changes of electrical capacitance across a circuit, which is then converted into an oscillator frequency output by a second circuit. There may be several sequential signal processing stages, involving for example the eventual conversion of the oscillator frequency into units of atmospheric pressure, or the resistance of a thermistor into units of temperature. Often these are performed when the sensor output is connected to and processed by a datalogger.

The raw or processed signals may be *transmitted* elsewhere. This may be a simple cable connecting a sensor to the datalogger, or output from one or more loggers being sent over a communications system, whether a direct cabled connection to a host computer or a complex multi-stage network connection involving radio or satellite links. There may be several transmission links before the information arrives at its final destination.

At the end of this chain there will usually be some way of *displaying* and presenting the information from the sensor. In the mercury thermometer, this is the function of the scale adjacent to the mercury column in the capillary tube, the height of which is read off manually as ‘temperature’. Usually the scale will be expressed in terms of standard units, and will have been calibrated against known fixed points or reference instruments. In AWSs, this stage may combine display outputs from several sensors or even multiple observing locations.

Finally, there is usually a *data storage* step, whereby the processed output from the sensor or combination of sensors is stored in some form. For systems generating digital output directly, this will normally be storage on a computer system. Data storage may be in two or more stages – a temporary (real-time) store, and a long-term computer archive in the form of spreadsheet or database entries which facilitate subsequent data retrieval and analysis. In a well-designed archive system, the latter may take place as easily whether the measurement was made seconds or decades earlier.

Examples of meteorological measurement systems

Of course, not all of these steps apply to all types of instrument. The simple example above of the mercury thermometer is typical of many ‘traditional’ instruments. In this example there are no communications links, while the first data storage step results from the manual transcription of the observed reading of the thermometer by the observer in the manuscript observation register, which may subsequently be scanned or otherwise digitized into a computer archive.

A modern cup anemometer provides a more typical example of what may be referred to as a ‘digital’ instrument. Here the sensor converts changes in wind speed into variations in the rotation rate of a vertical shaft (see Chapter 9), which is approximately linear with wind speed. One class of anemometer uses a small, low-power light source and photodiode sensor mounted close to the shaft. As the shaft rotates, a suitable optical window alternately transmits or interrupts the light beam, thereby generating a pulsed or frequency output. These pulses are counted by the signal processing system, usually at the datalogger interface, and converted into appropriate units. If it is known from calibration tests that 10 pulses per second correspond to 1 metre of 'wind run', then a count of 223 pulses in a sampling interval of 1 second indicates a wind speed of 22.3 metres per second (m/s) over that sample. Storing every sample would generate an enormous and largely unnecessary volume of wind speed data, and usually a second stage of signal processing at the datalogger averages a number of samples to generate a mean wind speed over any programmed time interval. This value would then be displayed and stored as required. The data acquisition, processing, display and storage routines would then be repeated for each subsequent sampling interval, which may be every ¼ second.

One important facet of instrument performance to consider is that the sensor does not directly 'measure' the element being sampled. Instead, it is variations in some physical property of the sensor itself that are being measured. This property will have a known relationship with the element being sampled, and the output signal will be processed into appropriate units at some later stage in the chain. The relationship may be linear, or non-linear. In *linear systems* the output is directly proportional to changes in the sensed element. An example would be the variation of resistance of a standard 'Pt100' 100 Ω platinum resistance thermometer (PRT), which is accurately made to be 100.0 Ω at 0 °C and 138.5 Ω at 100 °C. Linear interpolation by datalogger software will deduce that a PRT showing a resistance of 107.7 Ω indicates a sensor temperature of 20.0 °C. In *non-linear systems* the signal processing routine must include suitable scaling to achieve the appropriate mathematical conversion of the output signal into relevant units as required. Thermistors (sensors whose resistance varies significantly with temperature) are an example of a type of non-linear sensor.

Not all sensors generate a continuous analogue output. The sensor output from a tipping-bucket raingauge, for example, is also a pulse. In the same fashion as the pulsed anemometer above, the output is then processed into useful units by the multiplication of sensor counts by the known capacity of the tipping bucket.

Sensor characteristics

Any particular sensor possesses a number of output characteristics, which Brock and Richardson subdivide into *static* and *dynamic performance*, *calibration drift* and *exposure effects*. Each is briefly considered below.

Static performance

As the term implies, the static performance of a sensor refers to the characteristics of a sensor – sometimes the combined performance of the sensor/signal processing/output components combined, if they are combined into one unit – under steady-state conditions. An example of a static performance metric would be the calibration of a temperature sensor, which could be stated as an error at a particular temperature ('calibration error at 20.0 °C is –0.19 degC'). Such calibration would normally be obtained by comparing the sensor output against a known reference under static conditions. For temperature sensors this would typically be obtained using a stirred water bath maintained at a particular temperature. At each calibration point, both sensors – reference and the one being calibrated – are allowed to reach equilibrium before comparisons are made. The ambient temperature is then adjusted to the next calibration point, and the process repeated.

Dynamic performance

When the input to a sensor changes, we expect the output to change too – after all, that is the function of a sensor. For many physical reasons, the change in sensor output may not exactly track changes in input under changing conditions. Of course, meteorological sensors would be of little use if they were not able to react quickly to changes in the element which they are measuring, and so one of the most important properties of any particular sensor sets out its response to changes in ambient conditions. How quickly can that particular sensor (or sensor type) be expected to react?

Consider the response of two temperature sensors to the sudden (instantaneous) 10 degrees Celsius drop in temperature shown in **Figure A.1**. (For simplicity, it is assumed that both are accurately calibrated at the outset.) It is clear that one responds much more rapidly to the change than the other. Further, it is apparent that the readings of the two sensors differ appreciably for a considerable time after the step change.

The response times of many meteorological sensors and systems can be evaluated and thus compared by using a parameter known as the *time constant*, τ. The response of a so-called 'first order' sensor[*] to a step change is exponential in form, and the time constant derived from the relationship

$$x = C\,e^{-t/\tau}$$

. . . where x is the transient value at time t and C is a constant.

Thus when $t = \tau$, x will be proportional to $1/e$, and so at t the sensor will show 63% of the step change (and 86% when $t = 2\tau$, 95% when $t = 3\tau$). The responsiveness of many meteorological sensors (and combined systems, such as a temperature sensor within a Stevenson screen) can thus be assessed and compared once their time constants are known, enabling better matching of sensors to the application. Manufacturers will usually quote the time constant in sensor specification literature, although care needs to be taken to distinguish whether performance is quoted to 63% (τ) or 95% levels (3τ).

Figure A.1 and **Table A1.1** have been prepared assuming sensor A has a time constant $\tau = 20$ seconds, and sensor B $\tau = 2.5$ minutes. The former is typical of fast-reacting temperature sensors which are in good contact with the surrounding medium (for example, an aspirated air temperature sensor), while the latter is more typical of a temperature sensor exposed within a Stevenson screen with surface winds of 2 m/s or more[†] [1]. (Where any system consists of two components with differing time constants, the time constant of the combined system will equal that of the slower component). The table and graph clearly show the well-known phenomenon of *sensor lag*; sensor B *lags* sensor A by an amount which increases with the difference in their time constants.

> *Sensor/system A* From Table A1.1, we can see that, 60 seconds (3τ) after the 10 degrees Celsius step change from 25 °C to 15 °C, sensor A has responded to 95% of the change (9.5 degC). The sensor display will therefore show 15.5 °C at that instant. It attains near-equilibrium (within 0.1 degC, a typical sensor accuracy specification) slightly more than 90 seconds after the step change.

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[*] In this context, 'first order' means that the rate of change of the measurement is proportional to the difference between the observed value and the ambient value.

[†] Response times for thermometer screen combinations in light winds can exceed 15 minutes – see reference [1] for more details.

Table A1.1. *Temperature response from sensor A ($\tau = 20\,s$) and sensor B ($\tau = 2.5\,min$) to a sudden temperature change from 25 °C to 15 °C*

Time (s)	Time (min)	*Sensor A reading °C*	*Sensor B reading °C*
0		25.0	25.0
10		21.1	24.4
20		18.7	23.8
30	0.5	17.2	23.2
40		16.4	22.7
50		15.8	22.2
60	1.0	15.5	21.7
70		15.3	21.3
80		15.2	20.9
90	1.5	15.1	20.5
	2.0	15.0	19.5
	3.0	15.0	18.0
	4.0	15.0	17.0
	5.0	15.0	16.4
	6.0	15.0	15.9
	7.0	15.0	15.6
	8.0	15.0	15.4
	9.0	15.0	15.3
	10.0	15.0	15.2
	11.0	15.0	15.1
	12.0	15.0	15.1
	13.0	15.0	15.1
	14.0	15.0	15.0
	15.0	15.0	15.0
	16.0	15.0	15.0
	17.0	15.0	15.0
	18.0	15.0	15.0
	19.0	15.0	15.0
	20.0	15.0	15.0

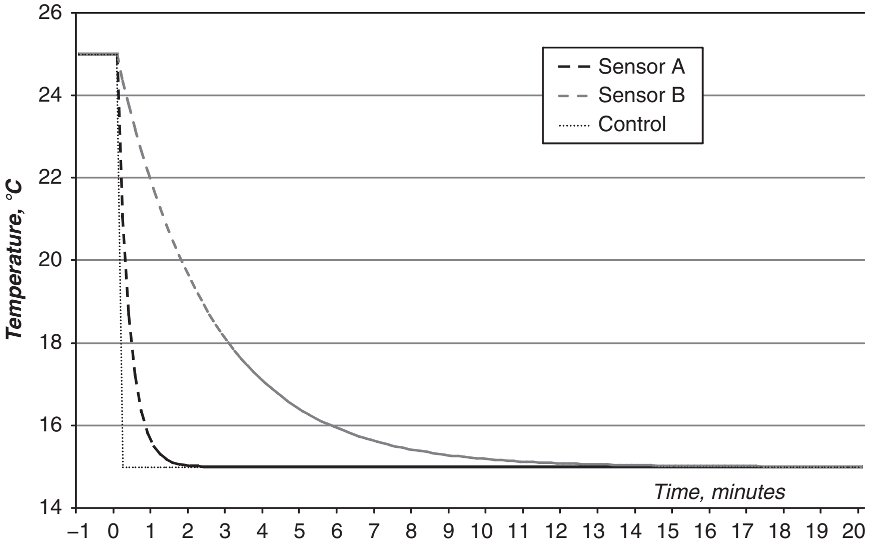

Figure A.1. Illustrating the response of two sensors, A and B, to an instantaneous temperature fall from 25 °C to 15 °C. Sensor A has a time constant τ of 20 s, B 2.5 min.

Sensor/system B With a slower time constant, after 60 seconds sensor B has responded to just 3.3 degrees Celsius of the sudden 10 degC change, and so will read 21.7 °C (remember that sensor A reads 15.5 °C at this instant). With the 2.5 minute time constant assumed here, sensor B does not attain 95% of the step change until 7½ minutes (3τ) has elapsed. It will not reach near-equilibrium with the new ambient temperature until almost 12 minutes after the drop.

Without being aware beforehand that the time constants (or lag) of the sensors involved differed appreciably, the details of a real-world step change could be interpreted very differently. Whilst instantaneous step changes in temperature of the magnitude such as the one used in this example do not occur in the real atmosphere, changes of similar magnitude do occur within time periods of considerably less than a minute as a result of frontal passages, gust fronts, mountain winds and other phenomena. It is clear that Sensor A would provide a much more realistic record of any such event. It is also evident that a casual examination of the records of the two sensors at, say, 9 minutes into the event would give the impression that Sensor B was incorrectly calibrated.

Of course, real world temperature changes do not take place in such clearly defined steps. A sudden temperature fall might be followed by a less rapid one, or a rise, or a period of rapidly varying temperatures, perhaps in a period of intermittent strong sunshine. In the latter case, the amplitude of the oscillations would be very much reduced by the slower response of Sensor B. Considering **Figure A.1**, it can be seen that if the temperature began to rise once more 5 minutes after the initial fall, that Sensor A would indicate a minimum temperature of 15.0 °C, whereas Sensor B would record a minimum of 16.4 °C.

In an ideal measurement system, the sensor response time should be similar to the timescale of the most rapid changes expected. Some elements, particularly wind speed and solar radiation, can experience changes of an order of magnitude within seconds, and the need for fast response is evident. The converse is also true, in that where a rapid response is not required – measuring earth temperatures at all but the shallowest of depths for example – there is no benefit in specifying a high-performance rapid-response sensor, which may also be considerably more expensive.

Hysteresis

Hysteresis is the term given when the response (output) of a sensor varies according to whether the input is increasing or decreasing. It arises in systems or sensors whose response depends not only on the current environment, but also on recent past state. The effects are most obvious on pressure and humidity sensors. At high humidity levels (close to saturation), a reduction in ambient humidity may not be immediately reflected in the sensor output.

When a sensor type is known to exhibit hysteresis, it is essential to ensure that any calibration comparisons are undertaken under steady-state conditions, both sensors being allowed to settle to at least 5τ of the slower unit.

A special case – the distance constant

In the special case of anemometers, the standard form of the time constant equation results in a decrease of time constant with wind speed – clearly a contradiction in terms and less helpful for defining system characteristics. For this reason, a related parameter known as the *response length* λ is normally quoted for anemometers: λ can be shown to depend upon the mass of the anemometer cups and their cross-sectional area (the lighter the cups and the larger they are, the smaller the distance constant). The response length can be considered as approximately the passage of a length of airflow (in metres) required for the output of a wind speed sensor to indicate 63 per cent of a step-function change of the input speed. Typical anemometer distance constants are between 1 m and 10 m.

In the same way as the more normal time constant parameter for other sensors, the distance constant is a measure of anemometer performance, and 95% of the response can be expected to occur within 3λ. While the lower the distance constant the better the response of the instrument, anemometer design is necessarily a compromise between response and robustness. Ensuring the instrument can withstand high wind speeds may introduce constraints on the 'large, lightweight cups' approach.

Calibration drift

Calibration drift is caused by changes in output caused by physical changes in the sensor itself, one example being the slow settling of components in an aneroid barometer capsule (see Chapter 7). Drift is usually considered separately from static and dynamic characteristics. It can become a problem with all sensors, although it tends to be more rapid (and thus more troublesome) on certain types. It is not always a slow process – the calibration of some RTDs can change quite suddenly for no very apparent reason, for example. It is usually unpredictable, and can generally only be identified by comparing the sensor against a known 'good' reference, either continuously in operational monitoring or in formal calibration tests. The U.S. Climate Reference Network (see Chapter 5) employs three aspirated temperature sensors, to provide a '2-against-1' checking method for all measurements. Where one sensor differs significantly from the others on a regular basis, its calibration will be checked and adjusted as necessary. Clearly, 'buddy checking' is not possible with single sensors, and in a comparison between two instruments it will not necessarily be clear which is at fault. However, care should be taken to distinguish calibration drift from dissimilar response times (see above). For this reason three identical sensors, in identical exposures, are preferable for any measurement, although clearly cost alone means that this ideal is rarely achievable in most meteorological measurement systems.

Exposure effects

Exposure errors can, and do, amplify or dwarf many sensor or system errors. The recommendations on sensor exposure given in the relevant chapters of this book should be adopted wherever possible to minimize exposure errors.

Reference

[1] Harrison, RG (2011) Lag-time effects on a naturally ventilated large thermometer screen. *Quarterly Journal of the Royal Meteorological Society*, **137**, pp. 402–408. See also Chapter 5.

APPENDIX 2

Useful functions

1. Vector mean winds
2. Sunshine records using a pyranometer

1. Vector mean winds

The ‘vector mean wind’ is a useful way to combine wind speed and direction records to come up with a *resultant wind flow* from a series of varying wind velocities over time. The calculation resolves individual samples of wind velocity into east-west and north-south components, which can then be averaged numerically in the normal manner. The averaged value of the two components is then converted back into the resultant (think ‘average’) wind direction and speed.

This method of calculation is necessary because the use of polar co-ordinates (compass bearings) means they cannot be simply averaged numerically – the ‘mean’ of a north-westerly wind (315°) and a north-easterly wind (045°) is clearly not a southerly wind, as would be indicated by the numerical average of the two wind directions ((315+45)/2 = 180). The calculations can be performed over a minute, a day, a year or for any other time period.

The details of the method are given below [1] together with a listing of an Excel macro (also downloadable from www.measuringtheweather.com). Advanced loggers include a vector mean wind option to summarize sampled wind speeds and directions in logged output.

Vector mean wind theory

Given a sequence of N observations of direction θ_i and velocity u_i, the mean east-west, V_e, and north-south, V_n, components of the wind are:

$$V_e = \frac{1}{N}\sum u_i \sin(\theta_i) \tag{1}$$

$$V_n - \frac{1}{N}\sum u_i \cos(\theta_i) \tag{2}$$

The resultant mean wind speed and direction are:

$$\overline{U}_{RV} = \sqrt{(V_e^2 + V_n^2)} \tag{3}$$

$$\overline{\theta}_{RV} = \mathrm{ArcTan}(V_e/V_n) + FLOW \tag{4}$$

$$\text{where} \quad FLOW \begin{array}{ll} = +180; & for\ \mathrm{ArcTan}(V_e/V_n) < 180 \\ = -180; & for\ \mathrm{ArcTan}(V_e/V_n) > 180 \end{array}$$

Equation 4 assumes the angle returned by the ArcTan function is in degrees.

Calculation using Excel

The listing below (**Table A2.1**) will return the two components, east and north, from two cells containing the scalar mean wind speed (in chosen units) and the wind direction in degrees (0° to 360°). This code is downloadable from www.measuringtheweather.com.

Conversion of compass point wind directions to degrees

Some brands of AWS output wind direction only as compass points, rather than as degrees of azimuth. The latter is required for a vector mean wind calculation. A small Excel script downloadable from measuringtheweather.com will convert a selection of cells from compass points to degrees so that, for example, all southerly winds will be converted to 180 degrees, SSW to 202.5°, and so on. (Note: this will permanently change the cell values; if you wish to retain the compass points, copy the column first and apply the macro to the copy.)

2. Sunshine records using a pyranometer

As outlined in Chapter 11, various algorithms have been devised in an attempt to derive sunshine duration from global solar radiation data alone. Most methods involve a comparison of the current or logged value of solar radiation with the calculated maximum for that date, time and place, using astronomical tables. When the value of incident solar radiation exceeds a threshold, a defined fraction of the calculated maximum possible at that location and time, then that interval is counted as ‘sunshine’.

While straightforward enough to understand, as ever the devil is in the detail, particularly the exact methods used to establish the ‘sunshine/no sunshine’ threshold. The method below was published by the UK Met Office in 1999 [2].

$$\text{Pyranometer ‘sunshine threshold’ (in W/m}^2\text{)} = (1030 \text{ x } A^{1.22}) \text{ x } (B - 0.16 \text{ x } \sin((C\text{-}5)/2))$$

Where

A = sin θ_s , where θ_s is the solar elevation angle (in degrees)
B = a site-specific value, found to be 0.88 for Berkshire and 0.95 for Shetland
C = Day number in year

The solar elevation angle θ_s is the angle between the centre of the sun’s disk and the (idealized) horizon. Neglecting the effects of atmospheric refraction, it can be calculated to a good approximation using the following formula:

Table A2.1. *Excel code to calculate a vector mean wind. Calculate the north and east components (cells A4 and A5) from every observation of scalar mean wind speed (cells A1 and A2). Average these components over the period required, then evaluate cells A6 to A14 from the period averages to derive the vector mean wind.*

Cell	Content or action	Excel code
	Evaluate for the range of observations required …	
A1	Scalar mean wind speed, in chosen units *From AWS*	
A2	Wind direction, in degrees *From AWS*	
A3	*Blank cell*	
A4	N component *Check first that wind is not calm, then evaluate cosine of wind direction*	=IF(A1>0,A1*COS(A2*(PI()/180)),A3)
A5	E component *Check first that wind is not calm, then evaluate sine of wind direction*	=IF(A1>0,A1*SIN(A2*(PI()/180)),A3)
	… ***then evaluate for the period chosen, using the average of the N and E components as derived above***	
A6	Sin/Cos ratio	=A4/A5
A7	Take modulus of sin/cos ratio	=SQRT(A6*A6)
A8	Take arctan of modulus	=ATAN(A7)*180/PI()
A9	Quadrant 1 *A value will fall in this sector if arctan modulus is between 0° and 90°*	=IF(AND(A4>0,A5>0),90-A8,0)
A10	Quadrant 2 *A value will fall in this sector if arctan modulus is between 90° and 180°*	=IF(AND(A4<0,A5>0),90+A8,0)
A11	Quadrant 3 *A value will fall in this sector if arctan modulus is between 180° and 270°*	=IF(AND(A4<0,A5<0),270-A8,0)
A12	Quadrant 4 *A value will fall in this sector if arctan modulus is between 270° and 360°*	=IF(AND(A4>0,A5<0),270+A8,0)
A13	Vector mean wind angle (degrees)	=MAX(A9:A13)
A14	Vector mean wind speed (original units)	=SQRT((A4*A4)+(A5*A5))

$$\sin\theta_s = \cos h \cos \delta \cos \Phi + \sin \delta \sin \Phi$$

where

θ_s is the solar elevation angle

h is the hour angle, where solar noon = 0 (morning negative values, afternoon positive)

δ is the current Sun declination –

$$\delta = -23.44 \times \cos\left[(360^\circ/365) \times (N + 10)\right]$$

- where N is the Day Number within the year

Φ is the latitude of the observation location

These terms can be calculated directly to a good approximation in real time by a programmable logger, and the result then compared every logging interval with the measured global solar radiation value. If the latter is above the calculated threshold, then that interval is counted as 'sunshine'. So, for example, if the logging interval was 1 minute, then the day's total duration would be the sum of the number of 'minutes with sunshine'. For this to be successful, the logging interval needs to be no longer than 5 minutes.

References

[1] Brooks, CEP and Carruthers, N (1953) *Handbook of statistical methods in meteorology*. HMSO, London, pp. 178–191. More details on the method can be obtained from Webmet.com: http://www.webmet.com/met_monitoring/62.html.

[2] Shearn, PD (1999) *Automatic sunshine sensor trial report*. UK Met Office, Observations, Logistics and Automation Branch. Unpublished report, copy available in National Meteorological Library, Exeter, Devon.

APPENDIX 3

Unit conversions

1. Temperature
2. Precipitation
3. Barometric pressure
4. Wind speed

Table A3.1. *Temperature conversions*

°C	°F	°F	°C
–40	–40	–40	–40.0
–35	–31	–30	–34.4
–30	–22	–20	–28.9
–25	–13	–10	–23.3
–20	–4	0	–17.8
–15	5	5	–15.0
–10	14	10	–12.2
–5	23	15	–9.4
0	32	20	–6.7
5	41	25	–3.9
10	50	30	–1.1
15	59	35	1.7
20	68	40	4.4
25	77	45	7.2
30	86	50	10.0
35	95	55	12.8
40	104	60	15.6
45	113	65	18.3
50	122	70	21.1
55	131	75	23.9
		80	26.7
		85	29.4
		90	32.2
		95	35.0
		100	37.8
		105	40.6
		110	43.3
		115	46.1
		120	48.9
		130	54.4

Table A3.2. *Precipitation conversions*

mm	inches	inches	mm
0.1	0.004	0.01	0.25
0.2	0.01	0.02	0.5
0.5	0.02	0.03	0.8
1	0.04	0.04	1.0
2	0.08	0.05	1.3
3	0.12	0.1	2.5
4	0.16	0.2	5.1
5	0.20	0.5	12.7
10	0.39	1	25.4
20	0.79	2	50.8
30	1.18	5	127
40	1.57	10	254
50	1.97	20	508
100	3.94	50	1 270
200	7.87	100	2 540
500	19.69	200	5 080
1 000	39.37	500	12 700
2 000	78.74		
5 000	196.85		
10 000	393.70		

Table A3.3. *Pressure conversions (at 0°C)*

hPa	inches	inches	hPa
950	28.05	28.00	948.2
960	28.35	28.25	956.7
970	28.64	28.50	965.1
975	28.79	28.75	973.6
980	28.94	29.00	982.1
985	29.09	29.10	985.4
990	29.23	29.20	988.8
995	29.38	29.30	992.2
1 000	29.53	29.40	995.6
1 005	29.68	29.50	999.0
1 010	29.83	29.60	1002.4
1 015	29.97	29.70	1005.8
1 020	30.12	29.80	1009.1
1 025	30.27	29.90	1012.5
1 030	30.42	30.00	1015.9
1 035	30.56	30.10	1019.3
1 040	30.71	30.20	1022.7
1 045	30.86	30.30	1026.1
1 050	31.01	30.40	1029.5
1 055	31.15	30.50	1032.8
		30.60	1036.2
		30.70	1039.6
		30.80	1043.0
		30.90	1046.4
		31.00	1049.8
		31.25	1058.2

Table A3.4. *Conversions between various units of wind speed*

Convert from	*Multiply by* knots (kn)	metres per second (m/s)	miles per hour (mph)	kilometres per hour (km/h)
knots (kn)	*1*	0.515	1.152	1.853
metres per second (m/s)	1.943	*1*	2.237	3.600
miles per hour (mph)	0.868	0.447	*1*	1.609
kilometres per hour (km/h)	0.540	0.278	0.621	*1*

APPENDIX 4

Useful sources

Contact details for meteorological societies and manufacturers and suppliers of meteorological instruments. All details are correct at the time of going to press.

Meteorological societies – by region and country

AFRICA		
AFRICA	**African Meteorological Society** *President: Soobasschandra Chacowry* Le Hochet, Rose Street, Terre Rouge, Mauritius P.O.Box 3056 *Secretary: Abdalah Mokssit* National Meteorological Service P.O. Box 8106, Casa-Oasis, 20103 Casablanca, Morocco	
NORTH AMERICA		
UNITED STATES OF AMERICA	**American Meteorological Society** 45 Beacon Street Boston, MA 02108-3693, USA Tel: (617) 227-2425 www.ametsoc.org	The American Meteorological Society (AMS) promotes the development and dissemination of information and education on the atmospheric and related oceanic and hydrologic sciences and the advancement of their professional applications. Founded in 1919, AMS has a membership of more than 14,000 professionals, students, and weather enthusiasts. AMS publishes nine atmospheric and related oceanic and hydrologic journals.
CANADA	**Canadian Meteorological and Oceanographic Society** P.O. Box 3211/ C.P. 3211 Station D / Succursale D Ottawa, ON, K1P 6H7, Canada Tel: 613-990-0300 www.cmos.ca	Founded in 1939 as the Canadian Branch of the Royal Meteorological Society, the Canadian Meteorological and Oceanographic Society (CMOS) is the national society of individuals and organizations dedicated to advancing atmospheric and oceanic sciences and related environmental disciplines in Canada. The Society runs 14 centres across Canada and comprises some 1,100 members and subscribers. Membership is open to all who share an interest in atmospheric and oceanic sciences, their related sciences and applications.

SOUTH AMERICA

SOUTH AMERICA	**Federation of Latin American and Iberian Meteorological Societies (FLISMET)** *President: Juan Manuel Horler* c/o National Meteorological Service 25 de Mayo 658, Capital Federal CP1002 ABN 1002 Buenos Aires Argentina

ASIA

There is a more complete list on WMO website at
http://www.wmo.int/pages/partners/nat_ met_soc_en.html

CHINA	**Chinese Meteorological Society** No.46, Zhongguancun Nandajie, Haidian District, Beijing, China	http://2011.cma.gov.cn/en/aboutcma/Institutions/200808/t20080802_13601.htm
	Hong Kong Meteorological Society c/o Hong Kong Observatory 134A Nathan Road Kowloon, Hong Kong Tel: +(852) 2926 8337	www.meteorology.org.hk
INDIA	**Indian Meteorological Society** c/o India Meteorological Department Lodi Road New Delhi 110003, India	http://www.indianmetsoc.com/
JAPAN	**Meteorological Society of Japan** c/o Japan Meteorological Agency 1-3-4, Ote-machi, Chiyoda-ku, Tokyo 100-0004 JAPAN Tel: +81-3-3212-8341 (ext.2546)	http://wwwsoc.nii.ac.jp/msj/index-e.html

AUSTRALASIA

AUSTRALIA	**Australian Meteorological and Oceanographic Society** GPO Box 1289 Melbourne VIC 3001 Australia www.amos.org.au	AMOS is an independent Australian society that supports and fosters interest in meteorology, oceanography and other related sciences. It provides support and fosters interest in meteorology and oceanography through its publications, meetings, courses, grants and prizes, and represents the views of its members to government, institutes and the public.

		The Society has regional centres in Sydney, Hobart, Perth, Melbourne, Canberra, Darwin, Adelaide and Brisbane to organize meetings and other activities in those locations.
NEW ZEALAND	**Meteorological Society of New Zealand** PO Box 6523, Te Aro, Wellington, NEW ZEALAND http://metsoc.rsnz.org	The Meteorological Society of New Zealand (incorporated 1979) is an independent group of weather enthusiasts who share an interest in the atmosphere, weather and climate, particularly as related to the New Zealand region. Anyone can join and membership currently consists of a broad spectrum of the community, both professional and non-professional.

EUROPE

EUROPEAN METEOROLOGICAL SOCIETY	**European Meteorological Society** c/o Freie Universität Berlin Carl-Heinrich-Becker-Weg 6–10 12165 Berlin, Germany Tel: +49 30 7970 8328 www.emetsoc.org	The EMS is an umbrella organization for the various national or regional meteorological societies in Europe. At the time of writing the Society has 35 Member Societies: contact details for all EMS members are given in this section and on the EMS website.
ANDORRA	**Asociació de Meteorología i Ciences de l′Atmosfera d′Andorra**	www.amaca.org
AUSTRIA	**Österreichische Gesellschaft für Meteorologie**	www.meteorologie.at
BELGIUM	**Société Royale Belge d′Astronomie, de Météorologie et de Physique du Globe**	www.srba.be
	Flemish Association for meteorology **Vlaamse Vereniging voor Weerkunde** (VVW) http://www.weerkunde.be/	Heat waves, piercing cold, hailstones, devastating summer storms, winter flooding, spring storms, fog, blizzards, a colourful sunset, a quiet autumn day or just a nice, warm summer day . . . some of the huge range of weather elements that nature dishes out. Many people are fascinated by this fascinating cocktail and they have united in the Flemish Association for meteorology. VVW is a very dynamic and rapidly growing organization that has a lot to offer those interested in the subject.
BULGARIA	**Aviometeorological Club of Bulgaria** **Bulgarian Meteorological Society**	Bulgarian Meteorological Society National Institute of Meteorology and Hydrology Blvd Tzarigradsko Chaussee, 66 1784 Sofia, Bulgaria

CROATIA	**Hrvatsko Meteorolosko Drustvo**	www.meteohmd.hr
CYPRUS	**Cyprus Meteorological Association**	www2.cs.ucy.ac.cy/~meteo/home.html
CZECH REPUBLIC	**Ceska Meteorologicka Spolecnost**	www.cmes.cz
DENMARK	**Dansk Meteorologisk Selskab**	www.dams.dk/en/
FINLAND	**Geofyysikkojen liitto** **Geofysiikan Seura**	www.dams.dk/en/ c/o Department of Physics P.O. Box 64 00014 University of Helsinki
FRANCE	**Société Météorologique de France** 73, avenue de Paris 94165 Saint-Mandé CEDEX, France Tel. +33 (0)1 77 94 73 64	www.smf.asso.fr
GERMANY	**Deutsche Meteorologische Gesellschaft** c/o Institut für Meteorologie Freie Universität Berlin C-H-Becker-Weg 6–10 12165 Berlin, Germany www.dmg-ev.de	DMG was established in 1883. It is a forum for communication and exchange, and acting in the interest of its members. There are six regional sections and four committees (biometeorology, history of meteorology, environmental meteorology and hydrometeorology).
	Ring europäischer Hobbymeteorologen e.V. (European amateur meteorologists ring) Senior editor – Hans-Martin Goede Leguanweg 4 D-70499 Stuttgart, Germany	www.wetterstationen-online.de/internationale-organisationen-und-vereine-fuer-wetterfreaks
GREECE	**Elliniki Meteorologiki Etaireia**	www.emte.gr/index.html
HUNGARY	**Magyar Meteorológiai Társaság** Fő utca 68, p.o. Box 433 1027 Budapest Adószám: 19815826-2-41 Tel: +36 1 346-4879	www.mettars.hu
ICELAND	**Félag Íslenskra Veðurfræðinga** Veðurstofu Íslands Bustadavegur 9 150 Reykjavik http://vedur.org/index.php/english	The Icelandic Meteorological Society is open to all with a genuine interest for weather and related disciplines. The purpose of the society is to improve and deepen the knowledge of meteorology and related fields in Iceland. There are no admittance fees. The society holds on average three national afternoon meetings each year. The meetings are open to all and have become a

		well-attended event where professional meteorologists and weather enthusiasts meet and share their interest in weather. Lectures on research in meteorology and related fields are given by both professionals and amateurs.
IRELAND	**Irish Meteorological Society** c/o Met Éireann Glasnevin Hill Dublin 9 Ireland www.irishmetsociety.org	The Irish Meteorological Society was founded in 1981. Its main aims are the promotion of an interest in meteorology and the dissemination of meteorological knowledge, pure and applied. The Society includes members not only from Ireland but from all over the world who are interested in weather and weather-related topics.
ISRAEL	**The Israeli Meteorological Society**	http://met-society.org.il/#
ITALY	**Associazione Italiana di AgroMeteorologia**	www.agrometeorologia.it/joomla/
	Associazione Geofisica Italiana	www.associazionegeofisica.it/
	Unione Meteorologica del Friuli Venezia Giulia	Via Silvio Pellico, 9 Cividale del Friuli (UD) 33043, Italy
NETHERLANDS	**Nederlandse Vereniging voor Beroeps Meteorologen**	www.nvbm.nl
	Vereniging voor Weerkunde en Klimatologie (Society for Weather and Climatology) www.vwkweb.nl	VWK was founded in 1974, now with several hundred members. Publishes a monthly magazine *Weerspiegel* ("Weather mirror"). Holds regular meetings, both centrally and regionally.
NORWAY	**Forskerforbundets meteorologiforening**	NMF Meteorologisk institutt P.O. Box 43, Blindern 0313 Oslo, Norway
POLAND	**Polskie Towarzystwo Geofizyczne** – Meteorological Section	http://nargeo.geo.uni.lodz.pl/~meteo/PTG_oL.html
PORTUGAL	**Associacão Portuguesa de Meteorologia e Geofisica**	www.apmg.pt/index.php
ROMANIA	**Societatea Meteorologica Romana**	Sos. Bucuresti-Ploiesti Nr. 97 013686 Bucuresti, sector 1, Romania Tel: 021 318 3240
SERBIA	**Meteorolosko drustvo Srbija**	www.meteo.org.rs
SLOVAKIA	**Slovenska Meteorologicka Spolocnost**	Jeseniova 17 83315 Bratislava, Slovakia
SLOVENIA	**Slovensko Meteorolosko Drustvo**	www.meteo-drustvo.si/domov/
SPAIN	**Asociación Meteorologica Española** Apartado de Correos, 285 28071 Madrid, Spain	www.ame-web.org/

	Asociación Española de Biometeología c/ Fortuny, 3–4°D 28010 Madrid, Spain	
SWEDEN	**Svenska Meteorologiska Sällskapet** C/O SMHI S- 601 76 Norrköping, Sweden	www.svemet.org
SWITZERLAND	**Schweizerische Gesellschaft für Meteorologie** MeteoSwiss Krähbühlstrasse 58 CH-8044 Zürich, Switzerland Tel. +41 44 256 92 32	www.sgm.scnatweb.ch
UNITED KINGDOM	**Royal Meteorological Society** 104 Oxford Road READING RG1 7LJ, UK www.rmets.org Tel. 0118 956 8500 (International: +44 118 956 8500)	Anyone with a genuine interest in the weather, its impact or the science behind it, or in the interface with related disciplines, such as hydrology and oceanography, can join the Society. The Society is made up of weather enthusiasts, practitioners, students and scientists from across the world, and was founded in 1850. There are numerous Special Interest Groups within the Society, and a thriving network of regional centres around the UK.
	Climatological Observers Link (COL) 16 Wootton Way MAIDENHEAD Berkshire SL6 4QU, UK www.colweather.org	The Climatological Observers Link is an organization of amateur meteorologists, founded in 1970. Its membership is mostly drawn from within the British Isles, although membership is open to anyone. COL publishes a monthly weather summary of British weather and an online weather forum, and organizes events and conferences for those interested in practical weather observing.
	Tornado and Storm Research Organisation (TORRO) www.torro.org.uk	Founded in 1974, TORRO is a privately supported research body which undertakes data-collection and research co-ordination of severe storm events, supported by some 300 to 400 voluntary observers, investigators and other contributors.
	Chilterns Observatory Trust Observatory Lodge The Green Whipsnade DUNSTABLE LU6 2LG, UK philip@weather-uk.com	The Chilterns Observatory Trust is a charitable trust which has established a meteorological/climatological library open to researchers, students and members of the public by appointment. Advice and assistance is offered for weather observers, including the availability of some meteorological instruments on a long-term loan basis. The Trust also runs the climatological observatory at Whipsnade.

Suppliers of meteorological instruments

This listing includes most of the instruments and sensors which are referenced in this book, but it is by no means a complete list of all manufacturers and suppliers worldwide. The website of the Association of Hydro-Meteorological Equipment Industry (HMEI) provides a more complete industry contact list – see www.hydrometeoindustry.org/catalogue/index.html for more information. Suppliers and manufacturers are listed below alphabetically by brand name. In most cases, products are available and supported internationally, but check with the supplier before placing an order.

Contact details shown are correct at the time of going to press.

CAMPBELL SCIENTIFIC	**Campbell Scientific, Inc.** 815 West 1800 North Logan, Utah 84321-1784 USA Tel: (435) 227 9000 www.campbellsci.com **Campbell Scientific Ltd** Campbell Park, 80 Hathern Road Shepshed, Loughborough LE12 9GX, UK Tel: +44(0)1509 601141 www.campbellsci.co.uk	Campbell Scientific manufactures dataloggers, data acquisition system and measurement/control systems used worldwide in research and industry. Campbell Scientific dataloggers form an integral part of many automatic weather station installations around the world, including the new UK Met Office Meteorological Monitoring System (MMS). They can also supply a wide range of third party professional sensors and accessories. Founded in Logan, Utah, USA in 1974, they have offices in Australia, Brazil, Canada, Costa Rica, France, Germany, South Africa, Spain and UK.
CASELLA	**Casella Measurement** Regent House Wolseley Road Kempston Bedford, MK42 7JY, UK Tel: +44 (0)1234 844 100 www.casellameasurement.com	One of the oldest names in meteorological instruments, originally established in Holborn, London in 1799, Casella's were one of the largest UK suppliers for many decades. In recent years Casella have diversified into other non-meteorological measurement areas, although they can still supply many 'UK standard' instruments such as Snowdon raingauges and sheathed thermometers. Casella is now a division of Ideal Industries Limited, based in Illinois, USA.
DAVIS INSTRUMENTS	**Davis Instruments Corporation** 3465 Diablo Ave. Hayward, California 94545 USA Tel. (510) 732–9229 www.davisnet.com	Davis Instruments, established in 1963, are a privately-held manufacturing company and developer based in Hayward, California. They have been a leader in the development and growth of the personal weather systems market since the launch of their first system in 1989, and today they have tens of thousands of users around the world, from far northern Alaska to Antarctica.
	Prodata Weather Systems Prodata Weather Systems	John Dann's Prodata Weather Systems is a leading supplier of Davis

	Unit 6, Espace North Building 181 Wisbech Road Littleport, Ely, Cambridgeshire CB6 1RA, UK Tel (UK): 03336 664 175 Tel (International): +44 1353 664 175 www.weatherstations.co.uk	Instruments equipment within the United Kingdom.
ENVIRONMENTAL MEASUREMENTS	**Environmental Measurements Ltd** Business and Innovation Centre Sunderland Enterprise Park (East) Wearfield, Sunderland SR5 2TA, UK Tel: +44 191 501 0064 www.emltd.net	Environmental Measurements Ltd (EML) designs and develops instrumentation for meteorological and environmental monitoring, including wind speed and wind direction sensors, aerodynamic raingauges, temperature humidity probes, radiation sensor shields, barometric pressure sensors, surface wetness probes, data loggers and automatic weather stations. EML is also a systems integrator, and supplies products worldwide.
EPPLEY	**The Eppley Laboratory, Inc**. 12 Sheffield Avenue, PO Box 419 Newport, Rhode Island 02840, USA Tel: 401-847-1020 http://www.eppleylab.com	Eppley, founded in 1917, are specialists in solar radiation measurement, manufacturing radiometers, pyranometers, pyrheliometers and pyrgeometers. Many national meteorological services use Eppley Instrumentation as their standard for radiometric measurements.
FAIRMOUNT	**Fairmount Weather Systems** Unit 4, Whitecroft Road Meldreth, Hertfordshire SG8 6NE, UK Tel. +44 (0) 1763 263415 www.fairmountweather.com	Fairmount manufacture meteorological instruments to standard specifications in their own production facilities; these include UK standard instruments such as splayed-base raingauges and Campbell-Stokes sunshine recorders. Fairmount supply worldwide.
FINE OFFSET	**Fine Offset Electronics Co., Ltd** 4/F, Block B3, East Industrial Park, Huaqiaocheng, Shenzhen City, Guangdong Province, China Tel: +86-755-86106171, 86106204 www.foshk.com/	Fine Offset Electronics Co., Ltd is a Chinese electronics company, founded in 2005 and based in Hong Kong. Fine Offset manufacture many of the entry-level weather station products sold by Maplin Electronics, Amazon and other retailers; their products are also sold under the Watson brand name.
GEMINI DATALOGGERS (TINYTAG)	**Gemini Data Loggers (UK) Ltd** Scientific House Terminus Road Chichester West Sussex PO19 8UJ, UK Tel: +44 (0)1243 813 000 www.geminidataloggers.com	Gemini Data Loggers (established in 1984) develop and sell the Tinytag range of dataloggers worldwide, offering loggers for a wide range of measurements in addition to those for weather applications. As well as manufacturing Tinytag data loggers, all Tinytag hardware, firmware and software is designed in-house, enabling

		tight quality control and the flexibility to respond to customer needs.
GEONOR	**Geonor AS** Grinidammen 10 P.O. Box 99 Røa N-0701 Oslo, Norway Tel: +47 6715 9280 www.geonor.no	Geonor AS manufactures and supplies all-weather precipitation gauges for accurate measurement of snow and rain. The company also manufactures and sells equipment and instruments for geotechnical and civil engineering applications. U.S. subsidiary office in Milford, PA.
GILL INSTRUMENTS	**Gill Instruments** Saltmarsh Park 67 Gosport Street Lymington, Hampshire SO41 9EG, UK Tel: +44 1590 613 500 www.gill.co.uk	Gill is the world leader in ultrasonic anemometers.
INSTROMET WEATHER SYSTEMS LTD	**Instromet Weather Systems Ltd** 10B, Lyngate Industrial Estate North Walsham Norfolk NR28 0AJ, UK Tel: +44 (0)1692 502 800 www.instromet.co.uk	Instromet manufacture and supply a range of weather monitoring equipment; they are best known for their sunshine recorder (see Chapter 11 for details).
KIPP & ZONEN	**Kipp & Zonen B.V.** Delftechpark 36 2628 XH Delft The Netherlands T: +31(0)15 2755 210 www.kippzonen.com	Founded in 1830, Kipp & Zonen provide class-leading instruments for measuring solar radiation and atmospheric properties particularly for weather and climate applications. Kipp & Zonen specialize in the measurement of solar and sky radiation, from the ultraviolet to the far infrared. Offices in France, USA and Singapore.
LA CROSSE	**La Crosse Technology** 2817 Losey Blvd South La Crosse, WI 54601, USA www.lacrossetechnology.com **La Crosse Technology France** 6A, rue du Commerce F-67118 Geispolsheim, France Tel: +33 38 85 55240	Founded in 1985, La Crosse manufactures and sells a range of electronic consumer products. A number of La Crosse's weather products are rebadged Technoline products. Technoline Ltd is a Macau based electronics company: their weather station products are sold through retailers both under their own brand name and rebadged as La Crosse.
METSPEC	**Metspec** W21/W25, Nottingham Business Centre Lenton Boulevard, Nottingham NG7 2BY, UK Tel. 0116 970 5308 www.metspec.net	Metspec manufacture and sell the UK Met Office-standard plastic and aluminium Stevenson screen and associated accessories. Metspec screens are also resold by UK Weathershop, Casella and other suppliers in UK and other countries.

NIELSEN-KELLERMAN	**Nielsen-Kellerman** 21 Creek Circle Boothwyn, PA 19061 Tel (US Toll Free): 800-784-4221 Tel: 610-447-1555 www.nkhome.com	Nielsen-Kellerman Company designs, manufactures and distributes rugged, waterproof environmental and sports performance instruments for active lifestyles and technical applications, including Kestrel Pocket Weather Meters.
NOVALYNX	**NovaLynx Corporation** 4055 Grass Valley Highway, Suite 102 Auburn, CA 95602–9156 U.S.A. Tel: (530) 823-7185 www.novalynx.com	Weather monitoring instruments and systems, including U.S.-standard Cotton Region Shelters and eight-inch raingauges.
OMEGA ENGINEERING	**OMEGA Engineering, Inc**. One Omega Drive P.O. Box 4047 Stamford, Connecticut 06907-0047, USA Tel. (800)-848-4286 or (203)-359-1660 www.omega.com www.omega.co.uk and other European sites	Omega Electronics offer an enormous range of electronics products. Particularly relevant to meteorological applications are resistance temperature devices (RTDs), both platinum resistance and thermistors, and a compact event logger ideal for high-resolution rainfall monitoring. Technical and presales support is first class. U.S.-based with subsidiaries in UK, France, Germany and The Netherlands.
ONSET	**Onset Computer Corporation** 470 MacArthur Blvd Bourne, MA 02532, USA Tel. 508-759-9500 www.onsetcomp.com *UK dealer:* Tempcon Instrumentation Ltd Unit 19 Ford Lane Business Park, Ford Lane, Ford Nr Arundel, West Sussex BN18 0UZ Tel: +44 (0) 1243 558270 www.tempcon.co.uk	Onset is the world's leading supplier of data loggers, used around the world in a broad range of applications including weather and climate monitoring. Onset's HOBO event-based loggers are ideal for combining with a tipping-bucket raingauge for high-resolution, low memory use rainfall logging (see Chapter 6).
OREGON SCIENTIFIC	**Oregon Scientific Inc**. 19861 SW 95th Avenue Tualatin, OR 97062, USA http://us.oregonscientific.com/ www.oregonscientific.co.uk	Oregon Scientific is a consumer electronics company, founded in Portland, Oregon, USA in 1989. Its product range includes time, health and sports products as well as weather stations. Oregon Scientific's parent company is IDT International Limited, an electronics company based in Hong Kong. Oregon Scientific's products are sold through resellers and retailers throughout the world.

R M YOUNG

R. M. Young Company
2801 Aero Park Drive
Traverse City, Michigan 49686
USA
Tel: (231) 946-3980
www.youngusa.com

Weather monitoring instruments and systems. Network of international resellers.

RS ONLINE

RS Components Ltd
Birchington Road
Corby
Northants
NN17 9RS, UK
Tel: **08457 201201**
http://uk.rs-online.com/web/

RS Components and Allied Electronics are the trading brands of Electrocomponents plc. RS Components is one of the world's largest distributors of electronics products, with operations in 32 countries selling 550,000 products from 2,500 leading suppliers. RS are a good source for many sensors relevant to meteorological measurement, particularly PRTs and thermistors.

RUSSELL SCIENTIFIC INSTRUMENTS

Russell Scientific Instruments Limited
Rash's Green Industrial Estate
Dereham, Norfolk NR19 1JG, UK
Tel: 01362 693 481
www.russell-scientific.co.uk

Russell Scientific Instruments manufactures precision thermometers, barometers and barographs, and scientific measuring instruments, and also stocks replacement charts, pens and inks for barographs and similar recording instruments.

The company has more than 100 years of experience in the design and manufacture of thermometers and is the sole UK manufacturer of Kew and Fortin precision barometers. They also supply UK-standard splayed-base copper raingauges, wooden Stevenson screens and smaller economy-model thermometer shelters.

TECHNOLINE

See La Crosse

UK WEATHERSHOP

Weather Front Ltd
Weather Shop
Unit 14 & 15, Westham Business Park
Eastbourne Road
Pevensey and Westham
East Sussex
BN24 5NP, UK
Tel: 01323 465 760
http://www.weathershop.co.uk/

A wide range of weather monitoring instruments and systems, including all the consumer brands (Davis Instruments, Oregon Scientific, Technoline etc); also Metspec screens (see *Metspec*)

VAISALA

Vaisala Oyj
Vanha Nurmijärventie 21, 01670 Vantaa
Helsinki, Finland
Tel: +358 9 894 91
www.vaisala.com

Vaisala is a leading global supplier of environmental and industrial measurement systems. Vaisala Oyj was founded in Helsinki, Finland in 1936, and today has offices in 15 countries. The company's worldwide customer base includes many national meteorological and hydrological

		institutes, aviation and road organisations, defence forces and wind parks.
VECTOR INSTRUMENTS	**Windspeed Limited (Vector Instruments)** 115 Marsh Road, RHYL Denbighshire, LL18 2AB, UK Tel: +44 (0)1745 350 700 www.windspeed.co.uk	Vector Instruments manufacture and sell wind sensors (anemometers and windvanes), including the class-leading low-power A100 series anemometer, widely used in professional AWS systems.
WATSON	*See* Fine Offset	
WEATHER-YOUR-WAY	**WeatherYourWay** 2966 Gateway Avenue Hartford, WI 53027, USA Tel. (262) 670 9697 www.weatheryourway.com	WeatherYourWay are a friendly and helpful US-based supplier of a wide range of consumer meteorological instruments, run by a qualified meteorologist (an ex-NWS forecaster). They are the official supplier to the CoCoRaHS network (see Chapter 19 for details) and supply (amongst many other products) the low-cost plastic raingauges used in the CoCoRaHS network.

Suppliers of meteorological software (see *Chapter 13*)

CUMULUS	http://sandaysoft.com/products/cumulus	AWS software
ENVIROWARE	**Enviroware srl** Via Dante, 142 20049 Concorezzo (MB) Italy Tel: +39 039 620 3636 www.enviroware.com	Wind rose software (Chapter 18)
VIRTUAL WEATHER (VWS)	Virtual Weather Software (VWS) www.ambientweather.com/virtualstation.html	AWS software
WEATHER DISPLAY (WD)	www.weather-display.com/index.php	AWS software
WEATHERLINK	http://www.davisnet.com/weather/products/software.asp	AWS software See also DAVIS INSTRUMENTS in instrument and sensor listings above
WEATHER UNDERGROUND	www.wunderground.com/weatherstation/index.asp	AWS software

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