Chapter 2

The Historical Setting

Our knowledge of oceanic currents, winds, waves, and tides goes back thousands of years. Polynesian navigators traded over long distances in the Pacific as early as 4000 BC (Service, 1996); Pytheas explored the Atlantic from Italy to Norway in 325 BC; Arabic traders used their knowledge of the reversing winds and currents in the Indian Ocean to establish trade routes to China in the Middle Ages and later to Zanzibar on the African coast; and the connection between tides and the sun and moon was described in the Samaveda of the Indian Vedic period extending from 2000 to 1400 BC (Pugh, 1987). Those oceanographers who tend to accept as true only that which has been measured by instruments, have much to learn from those who earned their living on the ocean.

Modern European knowledge of the ocean began with voyages of discovery by Bartholomew Dias (1487–1488), Christopher Columbus (1492–1494), Vasco da Gama (1497–1499), Ferdinand Magellan (1519–1522), and many others. They laid the foundation for global trade routes stretching from Spain to the Philippines in the early 16th century. The routes were based on a good working knowledge of trade winds, the westerlies, and western boundary currents in the Atlantic and Pacific (Couper, 1983: 192–193).

The modern explorers were soon followed by scientific voyages of discovery led by (among many others) James Cook (1728–1779) on the *Endeavour*, *Resolution*, and *Adventure*, Charles Darwin (1809–1882) on the *Beagle*, Sir James Clark Ross and Sir John Ross who surveyed the Arctic and Antarctic regions from the *Victory*, the *Isabella*, and the *Erebus*, and Edward Forbes (1815–1854) who studied the vertical distribution of life in the oceans. Others collected oceanic observations and produced useful charts, including Edmond Halley who charted the trade winds and monsoons and Benjamin Franklin who charted the Gulf Stream.

2.1 Definitions

The long history of the study of the ocean has led to the development of various, specialized disciplines each with its own interests and vocabulary. The more important disciplines include:
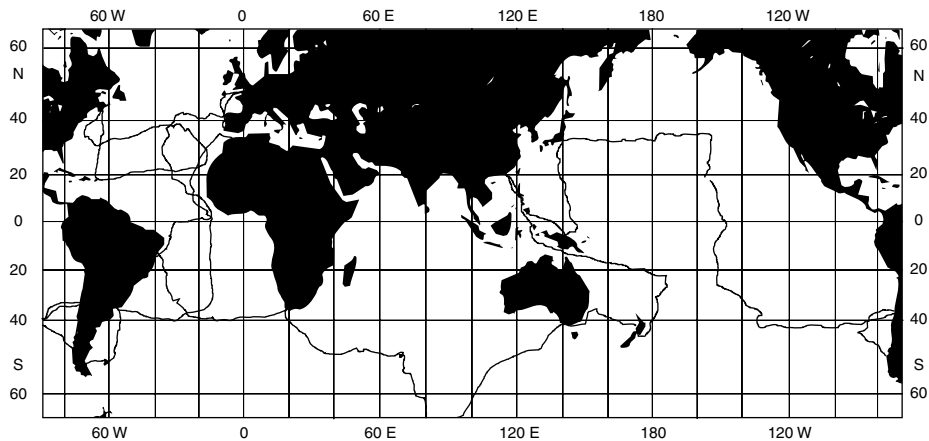
Figure 2.1 Example from the era of deep-sea exploration: Track of H.M.S. *Challanger* during the British Challanger Expedition (From Wust, 1964).

Oceanography is the study of the ocean, with emphasis on its character as an environment. The goal is to obtain a description sufficiently quantitative to be used for predicting the future with some certainty.

Geophysics is the study of the physics of the Earth.

Physical Oceanography is the study of physical properties and dynamics of the oceans. The primary interests are the interaction of the ocean with the atmosphere, the oceanic heat budget, water mass formation, currents, and coastal dynamics. Physical Oceanography is considered by many to be a subdiscipline of geophysics.

Geophysical Fluid Dynamics is the study of the dynamics of fluid motion on scales influenced by the rotation of the Earth. Meteorology and oceanography use geophysical fluid dynamics to calculate planetary flow fields.

Hydrography is the preparation of nautical charts, including charts of ocean depths, currents, internal density field of the ocean, and tides.

2.2 Eras of Oceanographic Exploration

The exploration of the sea can be divided, somewhat arbitrarily, into various eras (Wust, 1964). I have extended his divisions through the end of the 20th century.

1. Era of Surface Oceanography: Earliest times to 1873. The era is characterized by systematic collection of mariners' observations of winds, currents, waves, temperature, and other phenomena observable from the deck of sailing ships. Notable examples include Halley's charts of the trade winds, Franklin's map of the Gulf Stream, and Matthew Fontaine Maury's *Physical Geography for the Sea*.

2. Era of Deep-Sea Exploration: 1873–1914. Characterized by wide ranging oceanographic expeditions to survey surface and subsurface conditions near colonial claims. The major example is the *Challenger* Expedition (Figure 2.1), but also the *Gazelle* and *Fram* Expeditions.
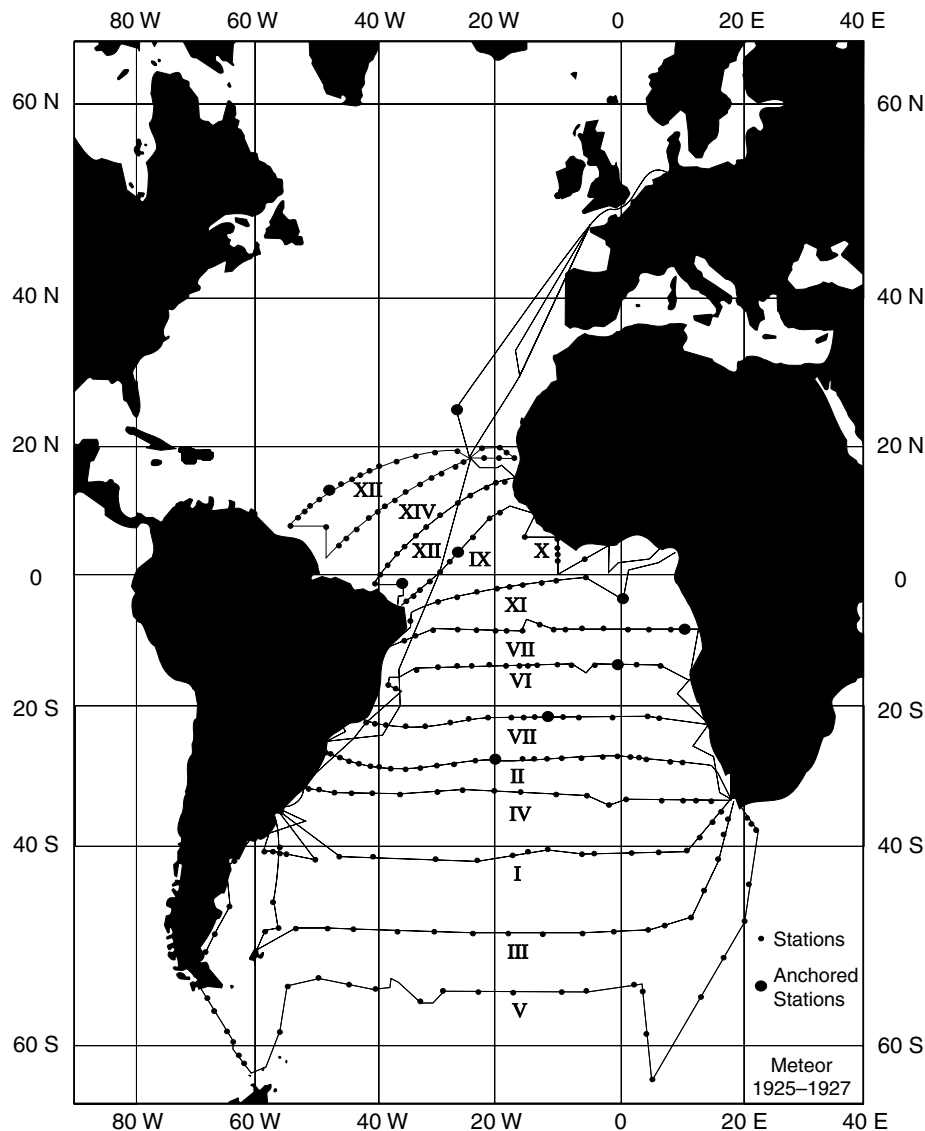
Figure 2.2 Example of a survey from the era of national systematic surveys. Track of the R/V *Meteor* during the German Meteor Expedition (Redrawn from Wust, 1964).

3. Era of National Systematic and National Surveys: 1925–1940. Characterized by detailed surveys of colonial areas. Examples include *Meteor* surveys of Atlantic (Figure 2.2), and and the *Discovery* Expeditions.

4. Era of New Methods: 1947–1956. Characterized by long surveys using new instruments (Figure 2.3). Examples include seismic surveys of the Atlantic by *Vema* leading to Heezen's physiographic diagram of the sea floor.
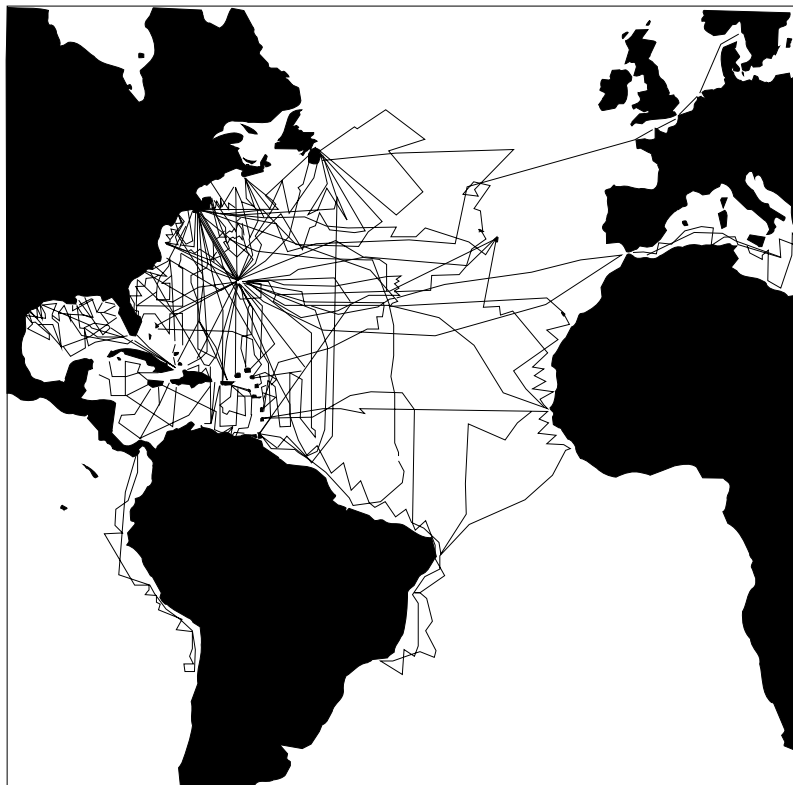
Figure 2.3 Example from the era of new methods. The cruises of the R/V *Atlantis* out of
Woods Hole Oceanographic Institution (From Wust, 1964).

5. Era of International Cooperation: 1957–1970. Characterized by multi-national surveys of oceans. Examples include the Atlantic Polar Front Program, the NORPAC cruises, and the International Geophysical Year cruises (Figure 2.4).

6. Era of Large Experiments: 1970–1978 Characterized by multiship studies of oceanic processes. Examples include MODE, POLYMODE, and NORPAX, and the JASIN experiment; plus the International Decade of Ocean Exploration.

7. Era of Satellites: 1978–1995. Characterized by global surveys of oceanic processes from space. Examples include Seasat, NOAA 6–10, NIMBUS–7, Geosat, Topex/Poseidon, and ERS–1 & 2.

8. Era of Global Synthesis: 1995– Characterized by global determination of oceanic processes using ship and space data in numerical models. Examples include the World Ocean Circulation Experiment (WOCE) (Figure 2.5) and Topex/ Poseidon (Fig 2.6), SeaWiFS and Joint Global Ocean Flux Study (JGOFS).
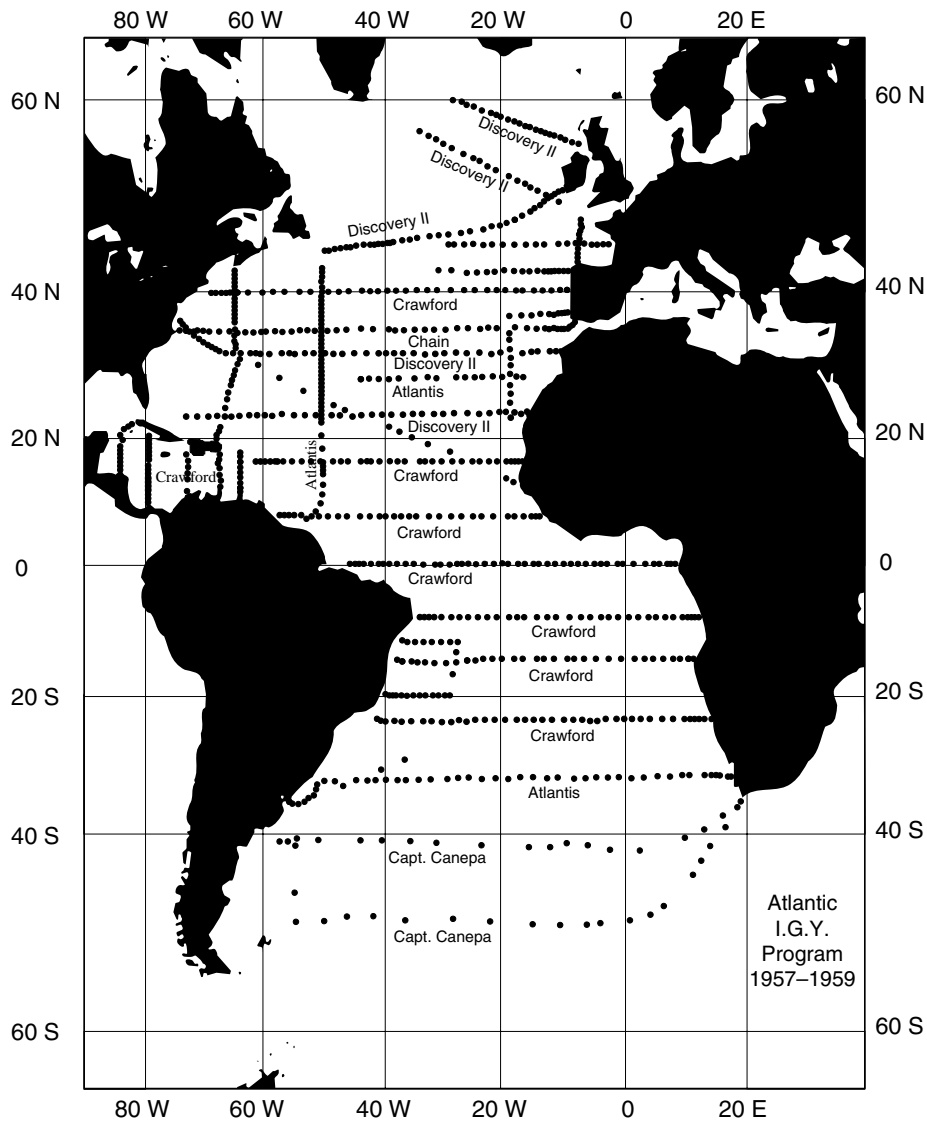
Figure 2.4 Example from the era of international cooperation . Sections measured by the International Geophysical Year Atlantic Program 1957-1959 (From Wust, 1964).

2.3 Milestones in the Understanding of the Ocean

Before describing our present understanding of the ocean, it is useful to look back at the ever increasing knowledge beginning with the first scientific investigations of the 17th century. Note that progress was slow. First came very simple observations of far reaching importance, by scientists who probably did not consider themselves oceanographers, if the term even existed. Later came more detailed descriptions and oceanographic experiments by scientists who specialized in the study of the ocean.
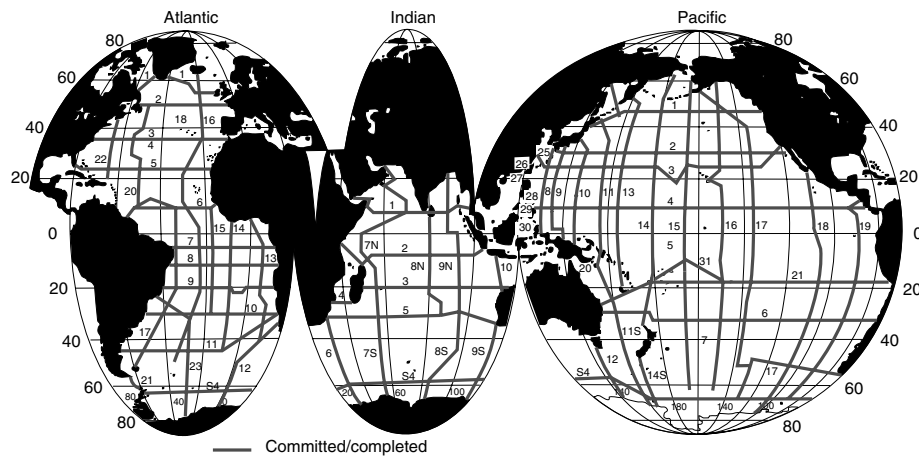
Figure 2.5 World Ocean Circulation Experiment: Tracks of research ships making a one-time global survey of the oceans of the world.

1685 Edmond Halley investigated the oceanic wind systems and currents, publishing "An Historical Account of the Trade Winds, and Monsoons, observable in the Seas between and near the Tropicks, with an attempt to assign the Physical cause of the said Winds" *Philosophical Transactions*, 16: 153-168.

1735 George Hadley published his theory for the trade winds based on conservation of angular momentum in "Concerning the Cause of the General Trade-Winds" *Philosophical Transactions*, 39: 58-62.
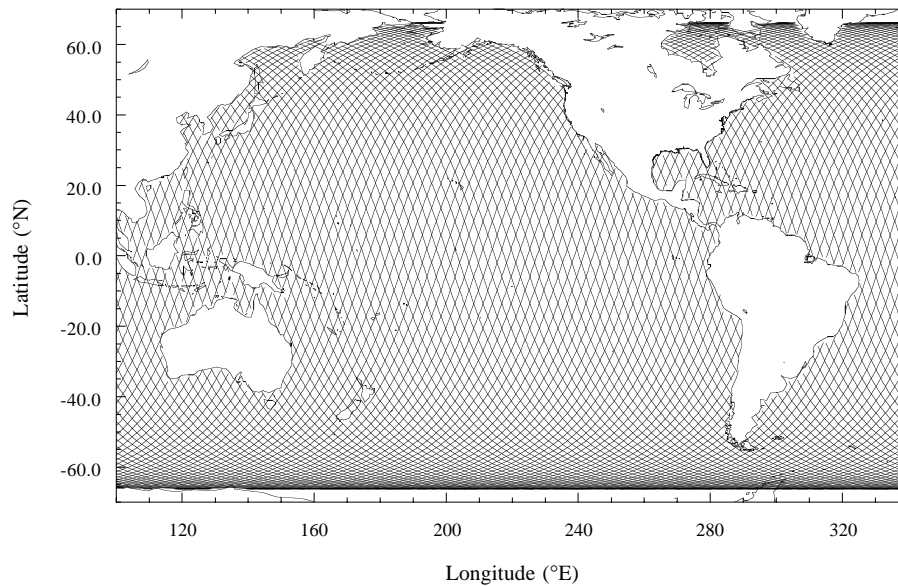

Figure 2.6 Example from the era of satellites. Topex/Poseidon tracks in the Pacific Ocean.
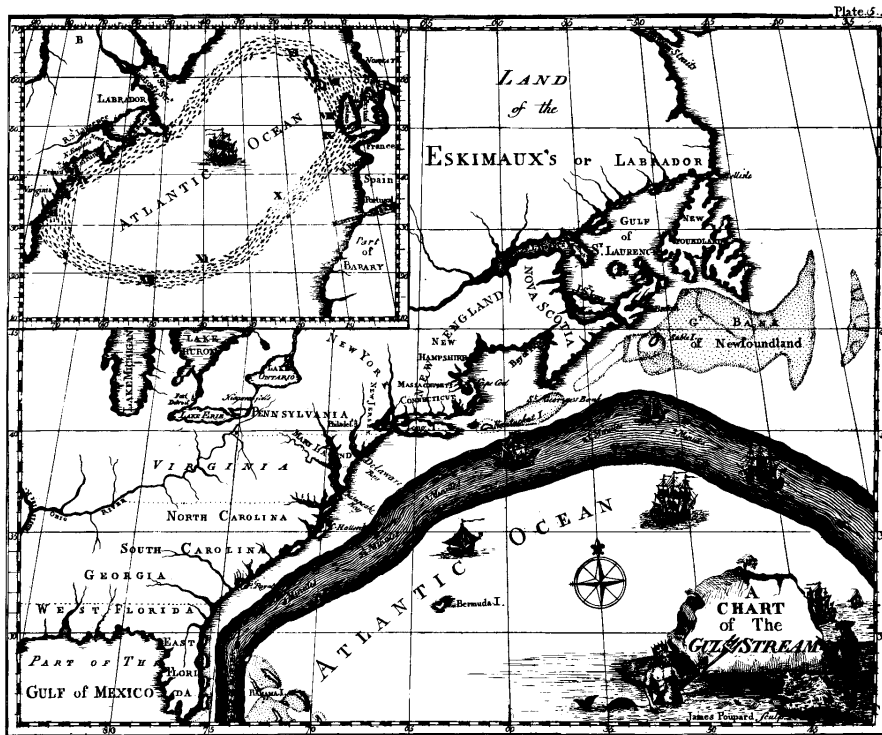
Figure 2.7 The Franklin-Folger map of the Gulf Stream published in 1769.

1751 Henri Ellis made the first deep soundings of temperature in the tropics, finding cold water below a warm surface layer, indicating the water came from the polar regions.

1770 Benjamin Franklin, as postmaster, collected information about ships sailing between New England and England, and made the first map of the Gulf Stream (Figure 2.7).

1775 Laplace's published his theory of tides.

1800 Count Rumford proposed a meridional circulation sinking near the poles and rising near the Equator.

1847 Matthew Fontain Maury published his first chart of winds and currents based on ships logs. Maury established the practice of international exchange of environmental data, trading logbooks for maps and charts derived from the data.

1855 *Physical Geography of the Sea* published by Maury.

1872–1876 Challenger Expedition began the first systematic study of the biology, chemistry, and physics of the oceans of the world.

1881 Samuel Langley invented the bolometer for measuring radiant heat. Later, he published "Researches on Solar Heat" *Prof. Pap. Signal Service* 15: 242 pp.

1885 Pillsbury's made direct measurements of currents in the Florida Current using current meters deployed from a ship moored in the stream.

1910–1913 Vilhelm Bjerknes published *Dynamic Meteorology and Hydrography* which laid the foundation of geophysical fluid dynamics. In it he developed the idea of fronts, the dynamic meter, geostrophic flow, air-sea interaction, and cyclones.

1912 Founding of the Marine Biological Laboratory of the University of California which became the Scripps Institution of Oceanography.

1930 Founding of the Woods Hole Oceanographic Institution.

1942 Publication of *The Oceans* by Sverdrup, Johnson, and Fleming, the first comprehensive survey of oceanographic knowledge.

Post WW 2 Founding of oceanography departments at state universities, including Oregon State, Texas A&M University, University of Miami, and University of Rhode Island, and the founding of national ocean laboratories such as the various Institutes of Oceanographic Science.

1947–1950 Sverdrup, Stommel, and Munk publish their theories of the wind-driven circulation of the ocean. Together the three papers lay the foundation for our understanding of the ocean's circulation.

1949 Start of California Cooperative Fisheries Investigation of the California Current.

1952 Cromwell and Montgomery rediscover the Equatorial Undercurrent in the Pacific.

1955 Bruce Hamon and Neil Brown develop the CTD for measuring conductivity and temperature as a function of depth in the ocean.

196x Sippican Corporation invents the Expendable BathyThermograph XBT now perhaps the most widely used oceanographic instrument.

1969 Kirk Bryan and Michael Cox develop the first numerical model of the oceanic circulation.

1978 NASA launches the first oceanographic satellite, Seasat. The satellite was used to developed techniques used by a generation of remotes sensing satellites.

1979–1981 Terry Joyce, Rob Pinkel, Lloyd Regier, F. Rowe and J. W. Young develop techniques leading to the acoustic-doppler current profiler for measuring ocean-surface currents from moving ships, an instrument widely used in oceanography.

1992 Russ Davis and Doug Webb invent the autonomous drifter that continuously measures currents at depths to 2 km.

1992 NASA and CNES develop and launch Topex/Poseidon, a satellite that maps ocean surface currents, waves, and tides every ten days.
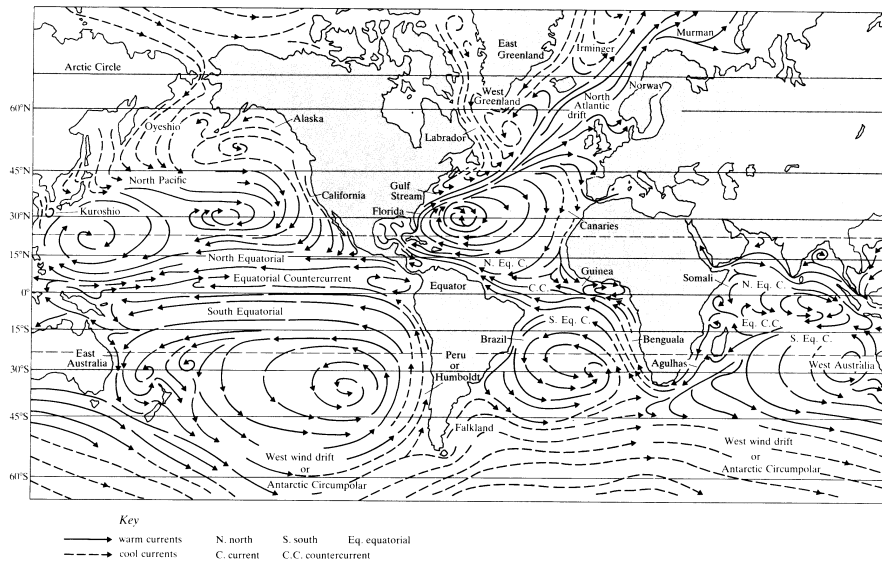
Figure 2.8 The time-averaged, surface circulation of the ocean deduced from nearly a century of oceanographic expeditions (From Tolmazin, 1985).

More information on the history of physical oceanography can be found in Appendix A of W.S. von Arx's *An Introduction to Physical Oceanography.*

Data collected from the centuries of oceanic expeditions have been used to describe the ocean. Most of the work went toward describing the steady state of the ocean, its currents from top to bottom, and its interaction with the atmosphere. The basic description was mostly complete by the early 1970s. Figure 2.8 shows an example from that time, the surface circulation of the ocean. More recent work has sought to document the variability of oceanic processes, and to provide a description of the ocean sufficient to predict annual and interannual variability.

2.4   Evolution of some Theoretical Ideas

A theoretical understanding of oceanic processes is based on classical physics coupled with an evolving understanding of choatic systems in mathematics and the application to the theory of turbulence. The dates given below are approximate.

19th Century Development of analytic hydrodynamics with friction. Bjerkness develops geostrophic method widely used in meteorology and oceanography. (1898).

1925–40 Development of theories for turbulence based on aerodynamics and mixing-length ideas. Work of Prandtl and von Karmen.

1940–1970 Refinement of theories for turbulence based on statistical correlations and the idea of isotropic homogeneous turbulence. Books by Batchelor (1967), Hinze (1975), and others.

1970– Numerical investigations of turbulent geophysical fluid dynamics based on high-speed digital computers.

1985– Mechanics of chaotic processes. The application to hydrodynamics is just beginning. Most motion in the atmosphere and ocean may be inherently unpredictable.

2.5 The Role of Observations in Oceanography

The brief tour of theoretical ideas suggests that observations are essential for understanding the oceans. The theory of flow of a convecting, wind-forced, turbulent fluid in a rotating coordinate system has never been sufficiently well known that important features of the oceanic circulation could be predicted before they were observed. In almost all cases, oceanographers resort to observations to understand oceanic processes.

At first glance, we might think that the numerous expeditions mounted since 1873 would give a good description of the oceans. The results are indeed impressive. Hundreds of expeditions have extended into all oceans. Yet, much of the ocean is poorly explored.

By the year 2000, most areas of the ocean will have been sampled from top to bottom only once. Some areas, such as the Atlantic, will have been sampled three times: during the International Geophysical Year in 1959, during the Geochemical Sections cruises in the early 1970s, and during the World Ocean Circulation Experiment from 1991 to 1996. All areas will be undersampled. This is the sampling problem (See Box). Our samples of the ocean are insufficient to describe the ocean well enough to predict its variability and its response to changing forcing. *Lack of sufficient samples is the largest source of error in our understanding of the ocean.*

2.6 Selecting Oceanic Data Sets

Much existing oceanic data have been organized into large data sets. For example, satellite data are processed and distributed by groups working with NASA. Data from ships have been collected and organized by other groups. Oceanographers now rely more and more such collections of data produced by others.

The use of others data produced by others introduces problems: i) How accurate are the data in the set? ii) What are the limitations of the data set? And, iii) How does the set compare with other similar sets? Anyone who uses public or private data sets is wise to obtain answers such questions.

If you plan to use data from others, here are some guidelines.

1. *Use well documented data sets.* Does the documentation completely describe the sources of the original measurements, all steps used to process the data, and all criteria used to exclude data? Does the data set include version numbers to identify changes to the set?

2. *Use validated data.* Has accuracy of data been well documented? Was accuracy determined by comparing with different measurements of the same variable? Was validation global or regional?

3. *Use sets that have been used by others and referenced in scientific papers.* Some data sets are widely used for good reason. Those who produced the sets used them in their own published work and others trust the data.

4. *Conversely, don't use a data set just because it is handy.* Can you document the source of the set? For example, many versions of the 5-minute bathymetric data set are widely available. Some date back to the first sets produced by the U.S. Defense Mapping Agency, others are from the ETOPO-5 set. Don't rely on a colleague's statement about the source. Find the documentation. If it is missing, find another data set.

2.7 Design of Oceanographic Experiments

Observations are essential for oceanography, yet observations are expensive because ship time and satellites are expensive. As a result, oceanographic experiments must be carefully planned. While the design of experiments may not fit well within an historical chapter, perhaps the topic merits a few brief comments because it is seldom mentioned in oceanographic textbooks, although it is prominently described in texts for other scientific fields. The design of experiments is particularly important because poorly planned experiments lead to ambiguous results, they may measure the wrong variables, or they may produce completely useless data.

The first and most important aspect of the design of any experiment is to determine *why* you wish to make a measurement before deciding how you will make the measurement or what you will measure.

1. What is the purpose of the observations? Do you wish to test hypotheses or describe processes?

2. What accuracy is required of the observation?

3. What temporal and spatial resolution is required? What is the duration of measurements?

Consider, for example, how the purpose of the measurement changes how you might measure salinity or temperature as a function of depth:

1. If the purpose is to describe water masses in an ocean basin, then measurements with 20–50 m vertical spacing and 50–300 km horizontal spacing, repeated once per 20–50 years in deep water are required.

2. If the purpose is to describe vertical mixing in the ocean, then 0.5–1.0 mm vertical spacing and 50–1000 km spacing between locations repeated once per hour for many days may be required.

2.8 Accuracy, Precision, and Linearity

While we are on the topic of experiments, now is a good time to introduce three concepts needed throughout the book when we discuss experiments: precision, accuracy, and linearity of a measurement.

Accuracy is the difference between the measured value and the true value.

Precision is the difference among repeated measurements.

Sampling Error

Sampling error is caused by a set of samples not representing the population of the variable being measured. A population is the set of all possible measurements; and a sample is the sampled subset of the population. We assume each measurement is perfectly accurate.

To determine if a measurement has a sampling error, it is necessary i) to specify the population, and ii) to determine if the samples represent the population. Both conditions are necessary.

Consider a program to measure the annual-mean sea-surface temperature of the ocean to determine if global warming is occuring. In this example, the population is the set of all possible measurements of surface temperature, in all regions in all months. If the sample mean is to equal the true mean, the samples must be uniformly distributed throughout the year and over all the area of the ocean, and sufficiently dense to include all important variability in time and space. This is difficult. Ships avoid stormy regions such as high latitudes in winter, so ship sample tend not to represent the population of surface temperatures. Satellites may not sample uniformly throughout the daily cycle, and they may not observe temperature at high latitudes in winter because of persistent clouds, although they tend to sample uniformly in space and throughout the year in most regions. If daily variability is small, the satellite samples will be more representative of the population than the ship samples.

From the above, it should be clear that the accuracy of a sample depends on the space-time distribution of the signal to be measured. In addition, sampling aliases the signal. Sampled data cannot be used to estimate the variability between samples.

Because sampling errors dominate most oceanic measurements, many instruments may be over designed for climate studies. For example, the required accuracy for scatterometer measurements of wind is smaller than the uncertainty in monthly mean values of wind at a point in the ocean.

In defining sampling error, we must clearly distinguish between instrument errors and sampling errors. Instrument errors are due to the inaccuracy of the instrument. Sampling errors are due to a failure to make a measurement. Consider the example above: the determination of mean sea-surface temperature. If the measurements are made by thermometers on ships, each measurement has a small error because thermometers are not perfect. This is an instrument error. If the ships avoids high latitudes in winter, the absence of measurements at high latitude in winter is a sampling error.

Meteorologists designing the Tropical Rainfall Mapping Mission have been investigating the sampling error in measurements of rain. Their results are general and may be applied to other variables. For a general description of the problem see North & Nakamoto (1989). For an application to scatterometer measurements of winds see Zeng and Levy (1995).

The distinction between accuracy and precision is usually illustrated by the simple example of firing a rifle at a target. Accuracy is the average distance from the center of the target to the hits on the target; precision is the average distance between the hits. Thus, ten rifle shots could be clustered within a circle 10 cm in diameter with the center of the cluster located 20 cm from the center of the target. The accuracy is then 20 cm, and the precision is roughly 5 cm.

Linearity requires that the output of an instrument be a linear function of the input. Nonlinear devices rectify variability to a constant value; so a nonlinear response leads to wrong mean values. Non-linearity can be as important as accuracy. For example, let

$$Output = Input + 0.1(Input)^2$$
$$Input = a \sin \omega t$$

then

$$Output = a \sin \omega t + 0.1 \left(a \sin \omega t \right)^2$$
$$Output = Input + \frac{0.1}{2} a^2 - \frac{0.1}{2} a^2 \cos 2\omega t$$

Note that the mean value of the input is zero, yet the output of this non-linear instrument has a mean value of $0.05a^2$ plus a small term at twice the input frequency. In general, if *input* has frequencies ω_1 and ω_2, then *output* of a non-linear instrument has frequencies $\omega_1 \pm \omega_2$. Linearity of an instrument is especially important when the instrument must measure the mean value of a turbulent variable. For example, we require linear current meters when measuring currents near the sea surface where wind and waves produce a large variability in the current.

Sensitivity to other variables of interest. Errors may be correlated with other variables of the problem. For example, measurements of conductivity are sensitive to temperature; and errors in the measurement of temperature in salinometers leads to errors in the measured values of conductivity or salinity.

2.9 Important Concepts

From the above, I hope you have learned:

1. The ocean is not well known. What we know is based on data collected from only a little more than a century of oceanographic expeditions supplemented with satellite data collected since 1978.

2. The basic description of the ocean is sufficient for describing the time-averaged mean circulation of the ocean, and recent work is beginning to describe the variability.

3. Observations are essential for understanding the ocean. Few processes have been predicted from theory before they were observed.

4. Oceanographers rely more and more on large data sets produced by others. The sets have errors and limitations which you must understand before using the them.

5. The planning of experiments is at least as important as conducting the experiment.

6. Sampling errors arise when the observations, the samples, are not representative of the process being studied. Sampling errors are the largest source of error in oceanography.