CHAPTER

S1

Brief History of Physical Oceanography

Supplementary Web Site Materials for Chapter 1

This supplementary chapter contains an eclectic and necessarily truncated treatment of the history of physical oceanography. Numerous books, journal issues, and memoirs provide diverse resources. Among these, the Scripps Institution of Oceanography's library archive provides a webpage that is an excellent place to begin searching for original materials, biographies, and institutional histories (SIO, 2011).

While the ocean has been the object of many ancient science applications, the science of oceanography is fairly young. Its origins are in a great variety of earlier studies including some of the earliest applications of physics and mathematics to Earth processes. Archimedes, the Greek physicist and mathematician, can also be considered one of the earliest physical oceanographers. The familiar Archimedes principle describes the displacement of water by a body placed in the water. Archimedes also made extensive studies of harbors to fortify them against enemy attack. Pytheas was another early physical oceanographer; he correctly hypothesized that the moon causes the tides.

Many early mathematicians used their skills to study the ocean. Sir Isaac Newton did not directly work on problems of the ocean, but his principle of universal gravitation was an essential building block in understanding the tides. Both Laplace and Legendre, who were mathematicians, advanced the formal theory of the tides (Laplace, 1790); Laplace's equation is a fundamental element in a description of the tides. English mathematicians worked on a mathematical description of the ocean waves that surrounded their homeland. All of these studies are clearly part of what we now know as physical oceanography.

Early charting of the ocean's surface currents came hand in hand with exploration of coastlines and ocean basins and was performed by the earliest seafaring nations. Peterson, Stramma, and Kortum (1996) provided an excellent review of the history of ocean circulation mapping, from the earliest Greek times, through the middle ages and rise of the Arabian empire, through the Renaissance and into the eighteenth and nineteenth centuries. In the late eighteenth century, John Harrison's development of the chronometer to measure longitude was a watershed, making more accurate mapping possible. By the nineteenth century, descriptions of subsurface and even deep circulation were becoming possible.

S1.1. SCIENTISTS ON SHIPS

Early charts of the ocean circulation were produced by mariners. Benjamin Franklin, among his many different accomplishments, was also a scientist, was one of the first to make measurements at sea specifically to chart its features (Figure 1.1b in the textbook). His goal was to decrease the time required for mail packets to cross the Atlantic from Europe to the United States. Another source of sea-going physical studies of the ocean came from studies made by "naturalists" who went along on British exploring expeditions. One example was Charles Darwin, who went along as the ship's naturalist of the *HMS Beagle* on a voyage to chart the southeast shore of South America. This journey included many long visits to the South American continent where Darwin formulated many of his ideas about the origin of species. During the cruise he took measurements of physical ocean parameters such as surface temperature and surface salinity.

There were so many naturalists traveling on British vessels in the early 1800s that the Royal Society in London decided to design a set of uniform measurements. Then Royal Society secretary, Robert Hooke, was commissioned to develop the suite of instruments that would be carried by all British government ships. One noteworthy device was a system to measure the bottom depth of the deep ocean. It consisted of a wooden ball float attached to an iron weight. The pair was to be dropped from the ship to descend to the ocean floor where the weight would be dropped; the wooden ball would then ascend to the surface where it would be spotted and collected by the ship.

S1.2. ORGANIZED EXPEDITIONS PRIOR TO THE TWENTIETH CENTURY

In the eighteenth century, organized ocean expeditions contributed valuable knowledge of the oceans. One of the most successful ocean explorers was Captain James Cook who made three major exploring voyages between 1768 and 1780. On these cruises, British naturalists observed winds, currents, and subsurface temperatures; among other discoveries they found the temperature inversion in the Antarctic, with cold surface water lying over a warmer subsurface layer.

In 1838 the U.S. Congress had the Navy organize and execute the United States Exploring Expedition to collect oceanographic information from all over the world (see Chapman, 2004). Many of the backers of this expedition saw it as a potential economic boon, but others were more concerned with the scientific promise of the expedition. In 1836, $150,000 had been appropriated for this expedition. As originally conceived, the expedition was to benefit natural history, including geology, mineralogy, botany, vegetable chemistry, zoology, ichthyology, ornithology, and ethnology. Some practical studies such as meteorology and astronomy were also included in the program. Most of the science was to be done by a civilian science complement; the Navy was to provide the transportation and some help with the sampling. The Navy did not like this arrangement and insisted that a naval officer lead the entire expedition. This responsibility was given to Lieutenant Charles Wilkes who had earned the reputation of being interested in and able to work on scientific problems. At the same time it was widely known that Wilkes was proud and overbearing, with his own ideas on how this expedition should be executed. Most of the scientific positions were filled with naval personnel. Only nine positions were offered to civilians who were subject to all the rules and conditions of behavior applying to the naval staff.

Unlike other later and more significant single-ship expeditions, five naval vessels carried out the United States Exploring Expedition. Starting in Norfolk, Virginia, the expedition sailed across the Atlantic to Madeira, re-crossed to Rio de Janeiro, then south around Cape Horn and into the Pacific Ocean. By the time the ships had sailed up the west coast of South America to Callao, Peru, storms had put three ships out of commission. What remained of the expedition crossed the Pacific and while the "scientific gentlemen" were busy making collections in New Holland and New Zealand, two ships, the *Vincennes* and the *Porpoise*, sailed south into the Antarctic region where Wilkes believed that there was a large land mass behind a barrier of ice. In the austral summer of 1839–1840, Wilkes sailed his ships south until blocked by the northern edge of the pack ice. He then sailed west along the ice barrier and was able to get close enough to see the land. At one point he came within a nautical mile of the coast of "Termination Land" as Wilkes named it. This was the most interesting part of the expedition as far as Wilkes was concerned. His alleged discovery of Antarctica was strongly contested by the British explorer Sir James Clark Ross, but it remains as the only well-known benefit of this mission. Other possible claimants to having discovered Antarctica were Captain Nathaniel Palmer, an American sealing captain who claimed to have sighted it in 1820, and the Russian Fabian von Bellingshausen who circumnavigated the Antarctic continent from 1819 to 1821 as part of a Russian Navy expedition.

During this same period there was an important development in the United States. A Navy lieutenant, Matthew Fontaine Maury, was seriously injured in a carriage accident and was not able to go to sea for many years. Instead he was put in charge of a fairly obscure Navy office called the Depot of Charts and Instruments (1842–1861). This later became the U.S. Naval Observatory. This depot was responsible for the care of the navigation equipment in use at that time. In addition it received and sent out logs to be filled out by the bridge crew ships. Maury soon realized that the growing number of ship logs in his keeping was an important resource that could be used to benefit many. His first idea was to make use of the estimates of winds and currents from the ships to develop a climatology of the currents and winds along major shipping routes. At first most people were skeptical about the utility of such maps. Luckily one of the clipper ship captains plying the route between the east and west coasts of the United States decided to see if he could use these charts to select the best course of travel for his next voyage. He found that this new information made it possible to cut many days off of his regular travel. As word got around, other clipper ship captains wanted the same information to help to improve their travel times. Soon other route captains were doing the same and Maury's information became a publication known as "sailing directions." Even today the U.S. Coast Guard continues to publish "Sailing Directions," although the publication has little to do with sailing and more to do with harbor approaches and changes in coastal conditions.

This publication was so successful that many European nations decided to adopt similar practices. Maury was invited to advise the European nations on how to develop and implement similar systems. In the United States he expanded his use of these archived data and also expanded his "depot" to include other oceanographic measurements. It was under his guidance that a Lieutenant Baker developed one of the first deep-sea sounding devices. Baker stuck with the age-old concept of measuring the ocean depth by dropping a line from the surface. The problem had been that in 4000 m of water the line became too heavy to retrieve from the surface, so he designed a new metal line whose cross section varied from a very narrow gauge wire at the bottom to a much thicker wire nearer the surface. In addition, Baker followed one aspect of Hooke's design and dropped the weight at the bottom, again making the system much lighter for retrieval. A later addition was a small corer added to the end of the line to collect a short (a few centimeters) core of the top layer of sediment. This device led to the first comprehensive map of bottom topography of the North Atlantic. Unfortunately for Maury, when the civil war broke out he returned to his

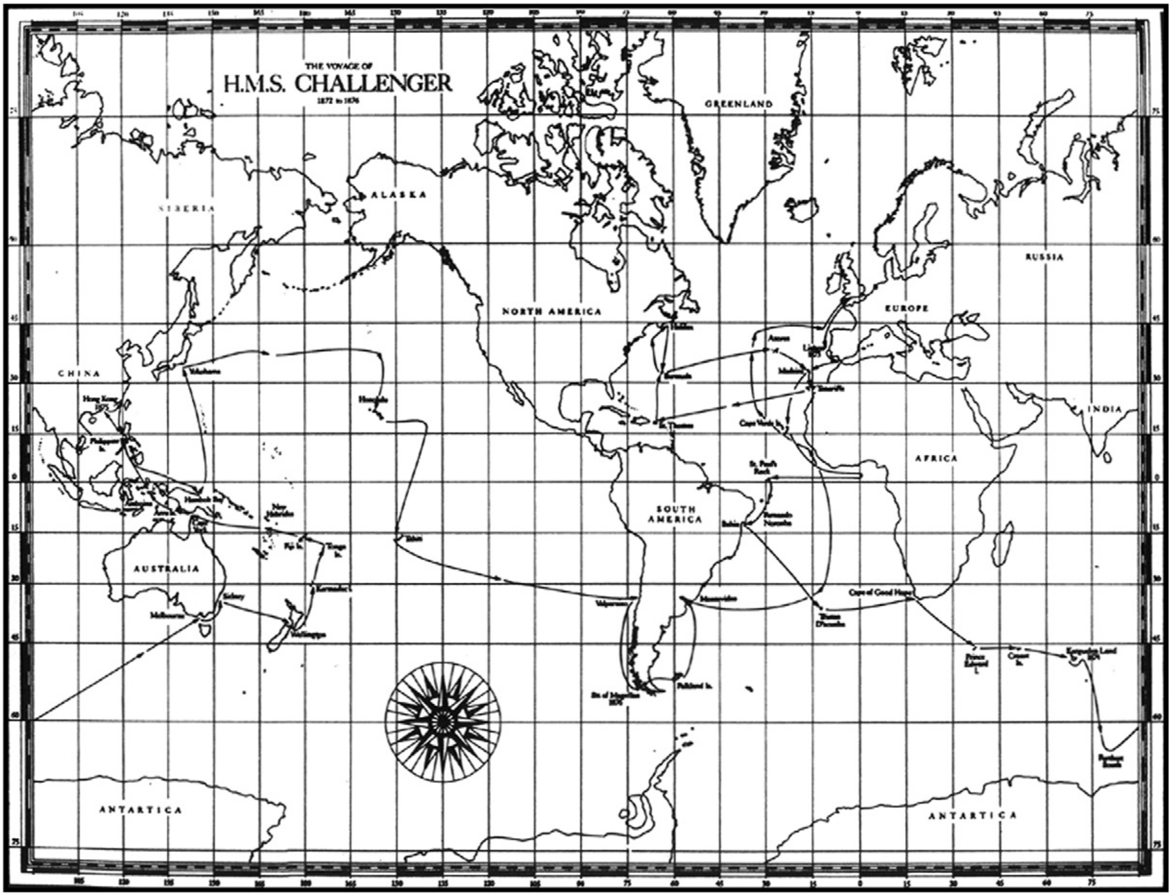

FIGURE S1.1 Track of the HMS *Challenger* Expedition 1872–1876.

native south and spent most of the war developing explosive devices to destroy enemy ships and to barricade harbors. An important part of Maury's legacy is a book, the *Physical Geography of the Sea,* which remarkably is still in print (Maury, 1855).

The first global oceanographic cruise was made on the British ship the HMS *Challenger*. This three-year (1872–1876) expedition (Figure S1.1) was driven primarily by the interest of a pair of biologists (William B. Carpenter and Charles Wyville Thomson) in determining whether or not there is marine life in the great depths of the open ocean. Thomson was a Scot educated as a botanist at the University of Edinburgh, and in the late 1860s he was a professor of natural history at Belfast, Ireland. He had been working with his friend Carpenter, a medical doctor, to discover if the contention by another British naturalist (Edward Forbes) that there was no life below 600 m (called the azoic zone) was true. Even in the early phase of the *Challenger* expedition dredges of bottom material from as much as 2000 m had demonstrated the great variety of life that exists at the ocean bottom. In addition to biological samples, this expedition collected a great number of physical measurements of the sea such as sea-surface temperature and samples of the min-max temperatures at various depths.

Along with Thomson and Carpenter, the *Challenger* scientific staff consisted of a naturalist, John Murray, and a young chemist, John Young Buchanan, both from the University of Edinburgh. The youngest scientist on the staff was 25-year-old German naturalist Rudolf von Willemoës-Suhm who gave up a position at the University of Munich to join the expedition. Henry Nottidge Moseley, another British naturalist who had also studied both medicine and science, joined the expedition after returning from a Government Expedition to Ceylon. Completing the staff was the expedition's artist and secretary, James John Wild. Much of the visual documentation that we have from the *Challenger* expedition came from the able pen of James Wild. The addition of John Murray was fortuitous in that he later saw to the publication of the scientific results of the expedition. Upon return, it was soon found that the *Challenger* expedition had exhausted the funds available for the publication of the results. Fortunately Murray, who was really a student from the University of Edinburgh, recognized the value of the phosphate formations that dominated Christmas Island. Claiming the island for England, Murray later set up mining operations on the island. The income from this operation was later used to publish the *Challenger* reports.

S1.3. SCANDINAVIAN CONTRIBUTIONS AND THE DYNAMIC METHOD

In the last quarter of the nineteenth century a group of Scandinavian scientists began to investigate the theoretical complexities of the sea in motion. In the late 1870s, a Swedish chemist, Gustav Ekman, began studying the physical conditions of the Skagerrak, part of the waterway connecting the Baltic and the North Sea. Motivated by fisheries problems, Ekman wanted to explain shoals of herring that had suddenly reappeared in the Skagerrak after an absence of 70 years. He discovered that in the Skagerrak there are layers of less-saline water from the Baltic "floating" over the deeper, more saline North Sea water. At the same time he found that herring preferred a particular water layer of intermediate salinity. This shelf, or bank water, as it was called, moved in and out of the Inland Sea and with it went the fish. Ekman knew that his results would not be of any use to the fishermen unless the shelf water and the other layers could be mapped. He joined forces with another Swedish chemist, Otto Pettersson, and together they organized a very thorough series of hydrographic investigations. Pettersson was to emerge from this experience as one of the first physical oceanographers. It should be noted that in Swedish "hydrography" translates as "physical oceanography.

Pettersson and Ekman both understood that to obtain a useful picture of the circulation a series of expeditions involving several vessels that could work together at many times throughout each year would have to be organized. This was a new approach to the study of the sea. In the name of fisheries research such a series of research cruises was begun in the early 1890s. These were some of the first cruises that emphasized the physical parameters of the ocean. For the vertical profiling of the ocean temperature a new device was available. Since 1874, the English firm Negretti and Zambra had manufactured a reversing thermometer that recorded accurate temperatures at depth.

During this time, another Scandinavian broke new ground in the rush to reach the North Pole. As a young man of 16, Norwegian Fridtjof Nansen was the first person to walk across Greenland. This exploring spirit led Nansen to propose a Norwegian effort to reach the North Pole. After studying evidence, Nansen decided that there was a northwestward circulation of ice in the Arctic. Instead of mounting a large attack on the Arctic, Nansen wanted to build a special ship that could withstand the pressures of the sea ice when the ship was frozen into the Arctic pack ice (Figure 12.7 in the textbook). He believed that if he could sail as far east as possible in summer he could then freeze his ship into the pack ice and be carried to the northwest. His plan was to get as close as possible to the North Pole at which time he and a companion would use dog sleds to reach the pole and then return to the ship. Named the *Fram* ("forward" in Norwegian), this unique ship was too small to carry a large crew. Instead Nansen gathered a group of nine men who would be able to adapt to this unique experience. Always a scientist, Nansen planned a large number of measurements to be made during the *Fram*'s time in the ice pack.

On March 1895 the *Fram* reached 84°N, about 360 miles from the pole (Figure 12.7). Nansen believed that this was about as far north as the *Fram* was likely to get. In the company of Frederik Hjalmar Johansen and a large number of dogs, Nansen left the relative comfort of the *Fram* and set off to drive the dog sleds to the North Pole. They drove slowly north over drifting ice until they were within 225 miles of their goal, farther north than any person had been before. For three months they had traveled over extremely rough ice, crossing what Nansen referred to as "congealed breakers" and they had lost their way. From their farthest north point they turned south eventually reaching Franz Josef Land where they hoped to encounter a fishing boat in the short summer season. Surviving by eating their dogs, Nansen and Johansen were very fortunate to meet a British expedition led by Frederick Jackson. In the summer of 1896 they sailed home to Oslo aboard the *Windward*. Meanwhile the *Fram* drifted further west and south and emerged from the ice pack just north of Spitsbergen. She sailed back to Oslo and arrived just a week after Nansen and Johansen.

One of Nansen's primary objectives in the *Fram* expedition was to form a more complete idea of the circulations of the northern seas. This was achieved by taking systematic measurements of the temperatures and salinities of the Arctic water. Using one of Pettersson's insulated water bottles, Nansen had attached a reversing thermometer to sample the temperature and salinity profiles. This arrangement, known as a "Nansen bottle," is still in use. Working in the Geophysical Institute of the University of Bergen, Norway, Nansen tried to explain the measurements made by the *Fram*. The hydrographic measurements suggested a very complex connection between the Norwegian and Arctic Seas. The daily position information from the *Fram* was also of great interest for this study. As a young student, Ekman worked on this problem with Nansen. Both were interested to note that the *Fram* did not drift in the same direction as the prevailing wind, instead it differed from the wind by about 20 to 40 degrees to the right.

Using the measurements made by the *Fram* along with simple tank models of the *Fram*, Ekman developed his theory of the wind-driven circulation of the ocean. Published as part of the *Fram* report, Ekman (1905) postulated the response of the ocean to a steady wind in a uniform direction. Making some simple assumptions about the turbulent viscosity of the ocean, Ekman could show how the ocean current response to a steady wind must have a surface current 45 degrees to the right of the wind in the Northern Hemisphere. Below that there is a clockwise (Northern Hemisphere) spiral of currents (called the Ekman spiral) down to a depth where the current vanishes.

In spite of these successes with the *Fram* data, Nansen realized that he could have done much more. This was motivated by the development of the "dynamic method" for estimating geostrophic ocean currents (see Chapter 7 in the textbook). Developed also in Bergen, this method made it possible to map currents at every level from a detailed knowledge of the vertical density structure. The *Fram's* measurements were not detailed enough to take advantage of this technique. This theory was furthered developed by Wilhelm Bjerknes, a professor of meteorology at the University of Oslo, who coined the term "geostrophy" from the Greek *geo* for earth and *strophe* meaning turning.

Two other Scandinavian physical oceanographers of this period were Johan Sandström and Bjorn Helland-Hansen, both of whom were interested in the ocean circulation and its measurement. The Norwegian Board of Sea Fisheries had invited Helland-Hansen, Nansen, and Johan Hjort to participate in the first cruise of their new research vessel. They were responsible for the collection of hydrographic measurements. A new problem surfaced while they were collecting their measurements. In their process of measuring salinity it was necessary to have a "reference sea water" to make the measurement precise, since slightly different methods and procedures were being used. At this time a Danish physicist, Martin Knudsen, was working on a set of hydrographical tables that would clearly define the relationship between temperature, salinity, and density. At the 1899 meeting of the International Council for the Exploration of the Sea (ICES), Knudsen had proposed that such tables be published to facilitate the standardization of hydrographic work (Knudsen, 1901). For this same reason Knudsen suggested that a standard or normal water be created and distributed to oceanographic laboratories throughout the world as a standard against which all salinity measurements could be compared. Knudsen then proceeded to set up the Hydrographical Laboratory for ICES in Copenhagen and the standard seawater later became known as "Copenhagen Water." He also published standard tables called "Knudsen Tables," which displayed the relationships between chlorinity, salinity, densities, and temperature.

Nansen and Helland-Hansen's careful study of the Norwegian Sea made it the most thoroughly studied and best-known body of water in the world. The new method of computing geostrophic currents had played a large role in defining the circulation of the Norwegian Sea. This "dynamic method," as it was called, was slow to spread to other regions. Then, around 1924, a German oceanographer named Georg Wüst applied the dynamic method to the flows at different levels through the Straits of Florida. He compared the results to the current profiles collected in the 1880s by a Lieutenant Pillsbury in the same area with a current meter. The patterns of the currents were essentially the same and confidence in the dynamic method increased. Another test of the dynamic method arose when the International Ice Patrol (IIP) began to compute the circulation of the northwest Atlantic to track the drift of icebergs. Created after the tragic sinking of the Titanic, the IIP was charged with mapping the positions and drifts of icebergs released into Baffin Bay from the glaciers on Ellesmere Island.

S1.4. THE *METEOR* EXPEDITION

German scientists performed the real test of the dynamic method on the *Meteor* expedition in the Atlantic from 1925 to 1927 (Spiess, 1928). This expedition was conceived by a German naval officer, Captain Fritz Spiess, to create an opportunity for a German navy vessel to visit foreign ports (prohibited by the treaty at the end of World War I) in the capacity of an ocean research vessel. Captain Spiess had served both prior to and during the war as a hydrographer in the German navy. He realized that to be successful he must find a recognized German scientist to be the "father" of the expedition.

Spiess presented his idea to Professor Alfred Merz, then the head of the Oceanographic Institute in Berlin. Merz had been educated as a physical geographer, but had always worked on the physics of the ocean. He was happy to accept

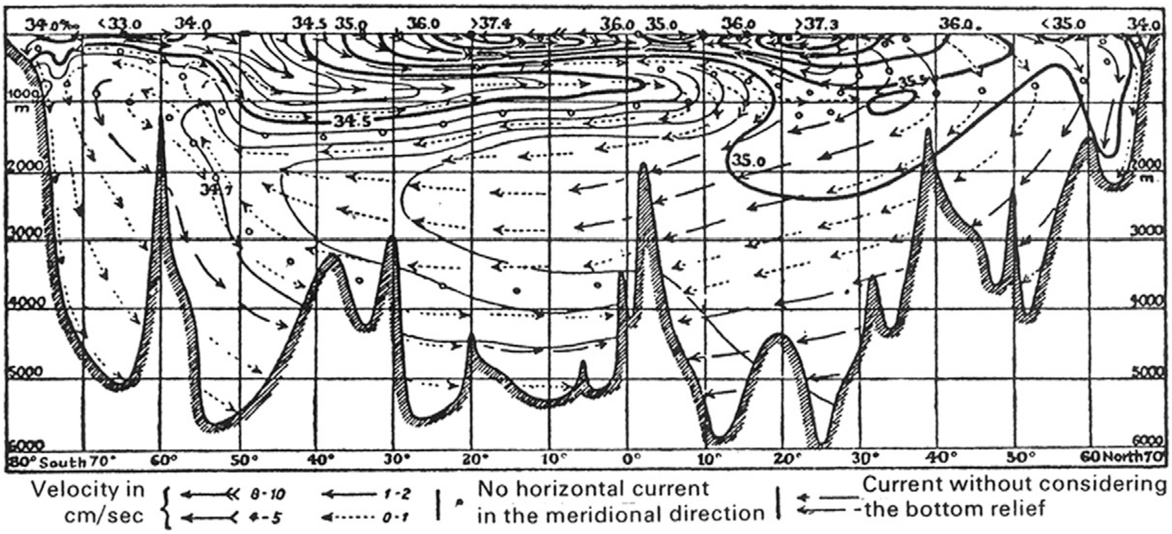

FIGURE S1.2 Overturning circulation of the Atlantic Ocean according to Merz and Wüst (1923).

the role of scientific leader of the future ocean expedition. This interest included the participation of his son-in-law and former student Georg Wüst, who was previously mentioned with respect to his use of the dynamic method.

Prior to the *Meteor* expedition, Merz and Wüst collected all of the German and British hydrographic observations and presented a new vision of the horizontal and vertical circulation in the Atlantic with different water masses in thick layers (Figure S1.2). Our present view of the Atlantic's "overturning circulation" is not very different from their concept. Richardson (2008) provided an excellent overview of the history of charting the overturning circulation from these early attempts to the present.

The verification and improved resolution of this proposed circulation became the focus for the expedition. Because the *Meteor* was not a very large ship, it was decided that the crew would have to help out in many measurement programs. Consequently, many crewmembers were sent to school at the Oceanography Institute in Berlin. In addition it was decided to execute a "test or shakedown cruise" to determine if all the equipment was working properly. This cruise went from Wilhelmshaven on the North Sea to the Azores and back. This pre-cruise turned out to be a very wise move, resulting in a number of very basic changes. The smokestack was lengthened in an effort to get the heat of the engines higher off the deck. In the tropics the lack of good ventilation on the ship became a serious problem and a lot of work had to be done on the deck. The unique system developed for the *Meteor* to anchor in the deep ocean had to be corrected. In addition, the forward mast was set up to carry more sail to save coal on some of the longer sections (Figure S1.3).

There were also some interesting personnel changes that were arranged after the pre-expedition. Most important was the fact that a chemist who was to be in charge of the salinity titrations was found to be colorblind. (The titration has a color change at the end point.) It was then necessary to find someone who could do the salinity titrations. The solution was that Wüst, although not originally slated to participate in the expedition, was taken along to titrate the salinity samples. This later became very important since the expedition leader, Dr. Merz, passed away in Montevideo after the

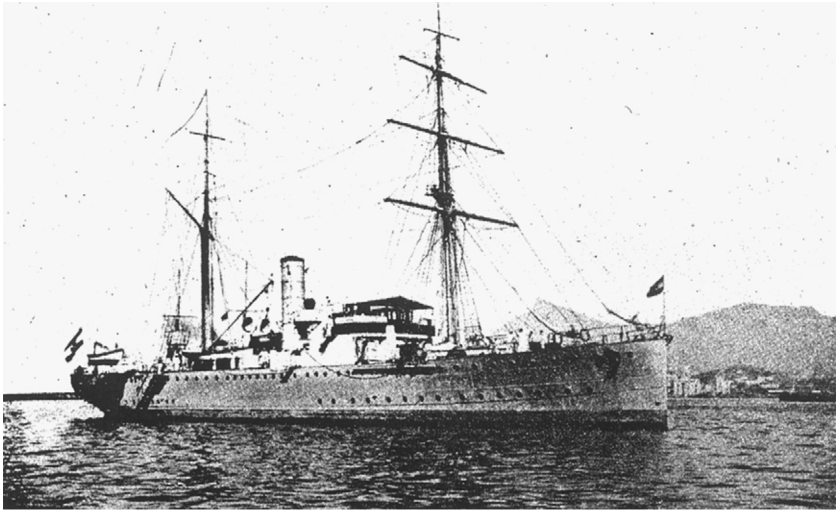

FIGURE S1.3 *Meteor* after refit. *Source: From Spiess (1928).*

first of the *Meteor's* east-west sections had been completed. This left the ship without a science leader. Although Wüst was the most knowledgeable, he was considered too junior to take over as expedition leader. Instead Captain Spiess officially took over both as scientific leader and naval captain. In practice, however, it was Wüst who guided the execution of the many measurements in physical oceanography. He was committed to testing the scheme that he and Merz had developed for the circulation of the Atlantic. He was also a careful and painstaking collector of new measurements, making sure that no "shortcuts" were taken in collecting or processing the measurements.

On April 16, 1925, the *Meteor* left Wilhelmshaven on her way to Buenos Aires, Argentina, which was to be the starting point of the expedition. Outfitted with every new instrument possible, the *Meteor* was the first ocean research cruise to concentrate primarily on the physical aspects of the ocean. She carried not one but two new echo-sounding systems, which were to accurately measure the depth of the ocean beneath the ship. With no computer or even analog storage machines it was necessary for someone to "listen" continually to the "pings" of the unit. Crewmen were enlisted in this operation and two sailors had to be in the room 24 hours a day listening to pings and writing down the travel times.

In addition the *Meteor* had a new system that enabled it to anchor in the deep ocean. Because the *Meteor* was able to moor itself in the deep ocean, Ekman developed a current meter that could be used multiple times when suspended from the main hydrographic wire (Figure S1.4). Ekman had gone on the pre-expedition trip to the Azores, but did not go along on the main cruise. His current meter was used repeatedly during the deep-sea anchor stations.

Before returning to Germany in the spring of 1927, the *Meteor* made 14 sections across the Atlantic, traveled 67,000 miles, made 9 deep-sea anchor stations, and occupied a total of 310 hydrographic stations. In addition over 33,000 depth soundings had been made in an area where only about 3000 depth soundings already existed. During this voyage she encountered more than one hurricane that greatly challenged her seaworthiness. She had also suffered due to the problem of storing sufficient coal for the crossings.

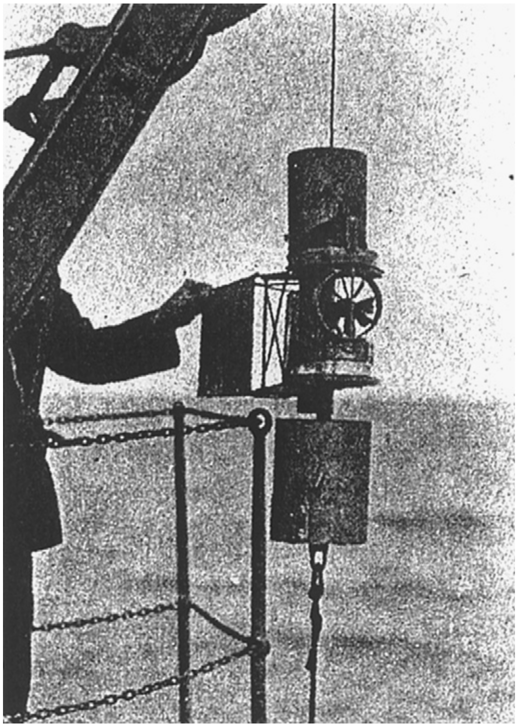

FIGURE S1.4 Ekman repeating current meter. *Source: From Spiess (1928).*

It was indeed fortunate that Wüst was present on the cruise to take over the scientific leadership. He worked on later analyses of the *Meteor* results with Albert Defant of the Oceanographic Institute in Berlin (Wüst, 1935; Defant, 1936). Defant joined the *Meteor* for the last section across the Atlantic.

S1.5. WORLD WAR II AND MID-TWENTIETH CENTURY PHYSICAL OCEANOGRAPHY

Before World War II a number of oceanographic institutions were founded in various parts of the world. In the United States two very notable institutions were created. In California, the San Diego Marine Biological Association was founded in 1903, becoming the Scripps Institution for Biological Research in 1912 and renamed Scripps Institution of Oceanography (SIO) in 1925 (Shor, Day, Hardy, & Dalton, 2003), while in Massachusetts the Marine Biological Laboratory (MBL) located in Woods Hole spun off the Woods Hole Oceanographic Institution (WHOI) in January of 1930. Both organizations became and continue to be leading American institutions for the study of the ocean. At WHOI Henry Bigelow was made the first director in spite of his genuine distaste for administrative duties. Originally WHOI was only to be operated in the summer leaving Bigelow the rest of the year for his scientific research and hobbies (fishing). Bigelow was so convinced of the importance of having a fine, seaworthy vessel capable of making long voyages in the stormy North Atlantic that he dodged the efforts of many to donate old pleasure yachts or tired fishing vessels. Instead he agreed to spend $175,000 on the largest steel-hulled ketch in the world. A sailing ship with a powerful auxiliary engine was chosen over a steamship because of the inability to carry sufficient coal for long distance cruising. The contract was awarded to a Danish shipbuilding company and included two laboratories, two winches, and quarters for 6 scientists and 17 crewmembers. After delivery in the summer of 1931 Bigelow hired his former student, Columbus O'Donnel Iselin, as master of the research vessel named *Atlantis*. Iselin later became the director of WHOI and left a legacy of important developments in the study of the water masses of the ocean.

At SIO, Harald Sverdrup was hired as the new director in 1936, bringing from the Bergen school an emphasis on physical oceanography. Within a year of his arrival, SIO purchased a movie star's pleasure yacht and converted her into the research vessel *E.W. Scripps*. Sverdrup had earlier been involved with an international effort to sail a submarine under the North Polar ice cap. During a test it was discovered that the submarine, named the

Nautilus, had lost a diving rudder and would not be able to cruise beneath the ice. (It was not until 1957 that another submarine named *Nautilus* cruised beneath the North polar ice cap and surfaced in one of the larger leads in the ice pack.)

As is usually the case, war prompted some new developments in physical oceanography. At WHOI, a naval Lieutenant William Pryor came looking for an explanation as to why the destroyer he was working on as a soundman could not find the "target" submarine in the afternoon after being able to do it well in the morning. At WHOI, Bigelow and Iselin were happy to collaborate with the navy and an experiment was set up in the Atlantic and in Guantanamo Bay where for two weeks two ships "pinged" on each other. From the *Atlantis*, closely spaced water bottles and thermometers were let down into the water. As Iselin expected, the results showed that Pryor's assumption that bubbles created by plankton were not the cause of the acoustic problems; instead the vertical temperature profile was found to alter dramatically during the day. The change of the vertical temperature distribution caused the sound pulses to be refracted away from the target location making it impossible to detect the submarine. What was needed was a detailed knowledge of the vertical temperature profile in the shallow upper layers of the ocean.

Detailed studies of the generation and propagation of ocean waves led by Harald Sverdrup and his student Walter Munk at SIO began during World War II, driven by the importance of forecasting wave conditions for military operations, including beachhead assaults (Sverdrup & Munk, 1947; Nierenberg, 1996; Inman, 2003).

In the 1940s and 1950s, Sverdrup and Munk at SIO were also studying the dynamics of wind-driven currents. At WHOI, Henry Stommel was also involved in these studies. Basic models of the wind-driven circulation emerged from these studies starting with Sverdrup's model, which explained the basic balance between the major currents and the pressure gradients, followed by Stommel's model and its explanation of the westward intensification that closed the major ocean gyres at the western end (Section 7.8 in the textbook). Munk's model, with a slightly different explanation for the westward intensification, put it all together, presenting a realistic circulation in response to a simplification of the meridional wind profile. These models were the basis for future more complex and eventually numerical models of the ocean circulation.

Continuations of basin-scale measurements of temperature, salinity, and other properties from research ships continued in the 1950s with the International Geophysical Year (IGY). In the 1960s, the international Indian Ocean Experiment completed the global scale observations begun in the IGY. In the 1970s, the International Southern Ocean Study (ISOS) concentrated on more restricted regions and involved many different countries.

Meanwhile, understanding of the shorter time and space scales in the ocean began to emerge thanks to development of reliable moored current meters, with studies of eddies in the 1970s beginning with a Russian experiment, Polygon 70, which established the importance of large-scale "synoptic" eddies in the ocean. Considered the "weather" of the ocean, these mesoscale features carry heat, momentum, and other properties as they move about the ocean. The work was definitively expanded by the U.S. Mid Ocean Dynamics Experiment of the early 1970s and the subsequent joint U.S.-Russian Polymode Experiment, which began to reveal the rich variability that occupies much of the ocean (Munk, 2000). In the 1970s in the North Pacific, an ambitious program of temperature profiling from merchant ships began to define the time and space variability of a large swath of ocean.

There has been a dramatic shift in emphasis of research in physical oceanography near the end of the twentieth century. A global survey of ocean circulation (WOCE), whose main purpose was to assist through careful observations; the development of numerical ocean circulation models used for climate modeling; and an intensive ocean-atmosphere study of processes governing El Niño in the tropical Pacific (Tropical Ocean Global Atmosphere; TOGA) were completed. Many of the programs that have continued beyond these studies focus on the relationship between ocean physics and the climate. At the same time the practical importance of ocean physics in the coastal ocean is emerging. The need for military operations in the ocean has shifted to the coasts largely in support of other land operations. Oil operations are primarily restricted to the shallow water of the coastal regions where tension with the local environment requires even greater study of the coastal ocean.

The most dramatic shifts in physical oceanographic methods at the turn of the twenty-first century are to extensive remote sensing, in the form of both satellite and more automated in situ observations, and to ever-growing reliance on complex computer models. Satellites measuring sea-surface height, surface temperature, and most of the components of forcing for the oceans are now in place. Broad observational networks measuring tides and sea level and upper ocean temperatures in the mid-to-late twentieth century have been greatly expanded. These networks now include continuous current and temperature monitoring in regions where the ocean's conditions strongly affect climate, such as the tropical Pacific and Atlantic, and growing monitoring of coastal regions. Global arrays of drifters measuring surface currents and temperature, and subsurface floats measuring deeper currents and ocean properties between the surface and about 2000 m depth are now expanding. Meanwhile the enormous growth in available computational power and numbers of scientists engaged in ocean modeling is expanding our modeling capability and ability to simulate ocean conditions and study particular ocean processes. With increasing amounts of globally distributed data available in near real time, numerical ocean modelers are now beginning to combine data and models to improve ocean analysis and possibly prediction of ocean circulation changes in a development similar to that for numerical weather prediction in the twentieth century. Full climate modeling includes ocean modeling, and many oceanographers are beginning to focus on the ocean component of climate modeling. These trends are likely to continue for some time.

S1.6. A BRIEF HISTORY OF NUMERICAL MODELING IN PHYSICAL OCEANOGRAPHY

Numerical modeling is a major component of contemporary ocean science, along with theory and observation. Models are quantitative expressions of our understanding of the ocean and its interactions with the atmosphere, solid earth, and biosphere. They provide a virtual laboratory that allows us to test hypotheses about particular processes, predict future changes in the ocean, and to estimate the response of the ocean to perturbations in external conditions. The complexity and nonlinearity of the physical laws governing the system preclude solution by analytical methods in all but the most idealized models. The most comprehensive models, known as ocean general circulation models, are solved by numerical methods, often on the most powerful computers available. Blending of models and observations to provide comprehensive descriptions of the actual state of the ocean, through a process of data assimilation similar to that used in numerical weather forecasting, has become a reality in the past decade, due to advances in observing systems, increases in computer power, and dedication of scientific effort.

The growth and evolution of ocean modeling is paced, to a certain degree, by the growth in computing power over time. The computational cost of a model is determined by its resolution, that is, the range of scales represented; the size of the domain (basin or global, upper ocean or full depth); and the comprehensiveness and complexity of the processes, both resolved and parameterized, that are to be represented. An ocean model is typically first formulated in terms of the differential equations of fluid mechanics, often applying approximations that eliminate processes that are of no interest to the study at hand. For example, in the study of large-scale ocean dynamics, sound wave propagation through the ocean is not of great importance, so seawater is approximated as an incompressible fluid filtering sound waves out of the equations.

The continuous differential equations must then be discretized, that is, approximated by a finite set of algebraic equations that can be solved on a computer. In ocean models this step is most often done with finite-difference or finite-volume methods, although finite-element methods have also been employed. In addition to the choice of numerical method, a major point of diversity among ocean general circulation models is the choice of vertical coordinate. In the upper ocean, where vertical mixing is strong, a discretization based on surfaces of constant geopotential or depth is the most natural. In the ocean interior, where transport and mixing occur primarily along neutral density surfaces, a vertical discretization based on layers of constant density, or isopycnal coordinates, is the most natural. Near the ocean bottom, a terrain-following coordinate provides a natural and accurate framework for representing topography and applying the boundary conditions for the flow.

The earliest three-dimensional ocean general circulation models, originally developed in the 1960s by Kirk Bryan and colleagues at the NOAA Geophysical Fluid Dynamics Laboratory, were based on finite-difference methods using depth as the vertical coordinate (Bryan & Cox, 1968; Bryan, 1969). Models descended from this formulation still comprise the most widely used class of ocean general circulation models, particularly in the climate system modeling community. The first global ocean simulations carried out with this type of model were limited by the then available computational resources to resolutions of several hundred kilometers, insufficient to represent the hydrodynamic instability processes responsible for generating mesoscale eddies.

In the 1970s observational technology emerged that showed the predominance of mesoscale eddies in the ocean. A new class of numerical models with simplifications to the physics, such as using the quasi-geostrophic rather than the primitive equations and limited domain sizes with resolutions of a few tens of kilometers, was developed by Bill Holland, Jim McWilliams, and colleagues at the National Center for Atmospheric Research (NCAR). Models of this class have contributed greatly to the development of our understanding of the interaction of mesoscale eddies and the large-scale ocean circulation, and to the development of parameterizations of eddy-mixing processes for use in coarser resolution models, such as those used in climate simulations. Initially developed as a generalization to the quasi-geostrophic eddy-resolving models, isopycnal coordinate models such as that developed by Bleck and co-workers at the University of Miami (Bleck & Boudra, 1981) became increasingly popular for ocean simulation through the 1980s and 1990s. Today global eddy-resolving models have spatial resolution of less than 10 km, with regional models achieving much higher spatial resolution. A recent overview of progress was published in Hecht and Hasumi (2008) by many of the principal groups.

Terrain-following coordinate models, also known as “sigma coordinate” models initially developed primarily in the coastal ocean modeling community by Mellor and co-workers at Princeton University, were used in basin- to global-scale ocean studies throughout the 1980s and 1990s. A model of this type widely used at present in regional studies is the Regional Ocean Modeling System (ROMS).

Ocean general circulation models are important in coupled climate modeling, although they must be run in much coarser spatial configurations than the eddy-resolving versions to attain the many decades of integration required. Many of the major international modeling groups have participated in the Intergovernmental Panel on Climate Change assessments, which included more than 20 coupled models in its summaries (Meehl et al., 2007).

In the twenty-first century we are witnessing both a tighter integration of modeling with observational oceanography, for example, through the use of data assimilation techniques, and significant merging and cross-fertilization of the various approaches to ocean modeling described earlier. Computer power has reached a level where the ocean components of fully coupled climate system models have sufficient resolution to permit mesoscale eddies, blurring the distinction between ocean models used for climate applications and those used to study mesoscale processes. Several new models have emerged with hybrid vertical coordinates, bringing the best features of depth, isopycnal, and terrain-following coordinates into a single model framework.

References

Bleck, R., Boudra, D.B., 1981. Initial testing of a numerical ocean circulation model using a hybrid quasi-isopycnal vertical coordinate. J. Phys. Oceanogr 11, 755–770.

Bryan, K., 1969. A numerical method for the study of the circulation of the world ocean. J. Comp. Phys. 4, 347–376.

Bryan, K., Cox, M.D., 1968. A nonlinear model of an ocean driven by wind and differential heating. Part 1. J. Atmos. Sci. 25, 945–978.

Chapman, B., 2004. Initial visions of paradise: Antebellum U.S. government documents on the South Pacific. J. Gov. Inform. 30, 727–750.

Defant, A., 1936. Die Troposphäre des Atlantischen Ozeans. In Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition auf dem Forschungs- und Vermessungsschiff "Meteor" 1925–1927 6 (1), 289–411 (in German).

Ekman, V.W., 1905. On the influence of the Earth's rotation on ocean currents. Arch. Math. Astron. Phys. 2 (11), 1–53.

Hecht, M.W., Hasumi, H. (Eds.), 2008. Ocean Modeling in an Eddying Regime. AGU Geophysical Monograph Series, 177, 350 pp.

Inman, D.L., 2003. Scripps in the 1940s: the Sverdrup era. Oceanography 16, 20–28.

Knudsen, M. (Ed.), 1901. Hydrographical Tables. G.E.C. Goad, Copenhagen, 63 pp.

Laplace, P.S., 1790. Mémoire sur le flux et reflux de la mer. Mém. Acad. Sci Paris, 45–181 (in French).

Maury, M.F., 1855. The Physical Geography of the Sea. Harper and Brothers, New York, 304 pp.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., et al., 2007. Global climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Merz, A., Wüst, G., 1923. Die Atlantische Vertikal Zirkulation. 3 Beitrag. Zeitschr. D.G.F.E, Berlin (in German).

Munk, W.H., 2000. Achievements in physical oceanography. In 50 Years of Ocean Discovery: National Science Foundation 1950–2000. National Academy Press, Washington, D.C. 44–50.

Nierenberg, W.A., 1996. Harald Ulrik Sverdrup 1888–1957. Biographical Memoirs. National Academies Press, Washington, D.C. 69, 339–375.

Peterson, R.G., Stramma, L., Kortum, G., 1996. Early concepts and charts of ocean circulation. Progr. Oceanogr 37, 1–115.

Richardson, P.L., 2008. On the history of meridional overturning circulation schematic diagrams. Progr. Oceanogr 76, 466–486.

Shor, E., Day, D., Hardy, K., Dalton, D., 2003. Scripps time line. Oceanography 16, 109–119.

SIO, 2011. Scripps Institution of Oceanography Archives. UC San Diego. http://libraries.ucsd.edu/locations/sio/scripps-archives/index.html (accessed 3.25.11).

Spiess, F., 1928. Die Meteor Fahrt: Forschungen und Erlebnisse der Deutschen Atlantischen Expedition, 1925–1927. Verlag von Dietrich Reimer, Berlin, 376 pp. (in German — English translation Emery, W.J., Amerind Publishing Co. Pvt. Ltd., New Delhi, 1985).

Sverdrup, H.U., Munk, W.H., 1947. Wind, Sea, and Swell: Theory of Relations for Forecasting. U.S. Navy Dept., Hydrographic Office, H.O. Pub. No. 601, 44 pp.

Wüst, G., 1935. Schichtung und Zirkulation des Atlantischen Ozeans. Die Stratosphäre. In Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition auf dem Forschungs- und Vermessungsschiff "Meteor" 1925–1927, 6 1st Part, 2, 109–288 (in German).