DEEP OCEAN CURRENTS

Deep ocean currents, the dynamics of which are not yet well understood, involve significant vertical and horizontal movements of seawater. They distribute oxygen- and nutrient-rich waters throughout the world's oceans, thereby enhancing biological productivity.

PRINCIPAL TERMS

- **bathymetric contour:** a line on a map of the ocean floor that connects points of equal depth
- **bottom current:** a deep-sea current that flows parallel to bathymetric contours
- **bottom-water mass:** a body of water at the deepest part of the ocean identified by similar patterns of salinity and temperature
- **continental margin:** the part of Earth's surface that separates the emergent continents from the deep-sea floor
- **Coriolis effect:** an apparent force, acting on a body in motion, caused by the rotation of Earth
- **salinity:** a measure of the quantity of dissolved salts in water
- **surface water:** relatively warm seawater between the ocean surface and that depth marked by a rapid reduction in temperature
- **thermohaline circulation:** vertical circulation of seawater caused by density variations related to changes in salinity and temperature
- **turbidity current:** a turbid, relatively dense mixture of seawater and sediment that flows downslope under the influence of gravity through less dense water
- **upwelling:** the process by which bottom water rich in nutrients rises to the surface of the ocean

Evidence for Existence

Deep-sea currents—ocean currents that involve vertical as well as horizontal movements of seawater—are generated by density differences in water masses that result in the sinking of colder, denser water to the bottom of the ocean. For many years, however, most oceanographers refused to accept the presence of these currents. Even when the Deep Sea Drilling Project, an international effort to drill numerous holes into the ocean floor, was initiated, most researchers envisioned the deep sea as a tranquil environment characterized by sluggish, even stationary, water. More recently, however, oceanographers and marine geologists have accumulated abundant evidence to suggest the opposite: that the deep sea can be a very active area in which currents sweep parts of the ocean floor to the extent that they affect the indigenous marine life and even physically modify the sea floor.

In the 1930's, Georg Wust argued for the likelihood that the ocean floor is swept by currents. Furthermore, he suggested that these currents play an important role in the transport of deep-sea sediment. Wust's ideas were not widely accepted; in the 1960's, however, strong evidence for the existence of deep-sea currents began to accumulate. In 1961, for example, oceanographers detected deep-sea currents moving from 5 to 10 centimeters per second in the western North Atlantic Ocean. These researchers also determined that the currents changed direction over a period of one month.

In 1962, Charles Hollister, while examining cores of deep-sea sediment drilled from the continental margin off Greenland and Labrador, noted numerous sand beds that showed evidence of transport by currents. The nature of these deposits suggested to Hollister that they did not accumulate from turbidity currents, dense sediment-water clouds that periodically flow downslope from nearshore areas. Moreover, it appeared to Hollister that the sand was transported parallel to the continental margin rather than perpendicular to it, as might be expected of sediment transported by a turbidity current. He argued that the sand beds in the cores were transported by, and deposited from, deep-sea currents moving along the bottom of the ocean parallel to the continental margin. Since then, extensive photography of the ocean floor has provided direct evidence for the existence of deep-sea currents. Such evidence includes smoothing of the sea floor; gentle deflection, or bending, of marine organisms attached to the sea floor, as though they were standing in the wind; sediment piled into small ripples by saltation; and local scouring of the sea floor.

Thermohaline Circulation

Essentially all earth scientists now agree that the deep-sea floor is swept by rather slow-moving (less than 2 centimeters per second) currents. The driving force behind these currents, and all oceanic currents for that matter, is energy derived from the sun. Differential heating of the air drives global wind circulation, which ultimately induces surface ocean currents. The vertical circulation of seawater, and thus the generation of deep-sea currents, is controlled by the amount of solar radiation received at a point on Earth's surface. This value is greatest in equatorial regions; there, the radiation heats the surface water, the seawater that lies within the upper 300 to 1,000 meters of the ocean. As this water is heated, it begins to move toward the poles along paths of wind-generated surface circulation, such as the Gulf Stream current of the northwestern Atlantic Ocean.

The cold waters that compose the deep-sea currents originate in polar regions. There, minimal solar radiation levels produce cold, dense surface waters. The density of this water may also be increased by the seasonal formation of sea ice, ice formed by the freezing of surface water in polar regions. When sea ice forms, only about 30 percent of the salt in the freezing water becomes incorporated into the ice. The salinity and density of the nearly freezing water beneath the ice are therefore elevated. This cold, saline seawater eventually sinks under the influence of gravity to the bottom of the ocean, where it moves slowly toward the equator. Deep-sea circulation driven by temperature and salinity variations in seawater is termed "thermohaline circulation" and is much slower than surface circulation; the cold, dense water generated at the poles moves only a few kilometers per year. After moving along the bottom of the ocean for anywhere from 750 to 1,500 years, the cold seawater rises to the surface in low-latitude regions to replace the warm surface water, which, as noted above, moves as part of the global surface circulation system back to the polar regions.

Thermohaline circulation and related deep-sea currents are commonly affected by the shape of the ocean floor. Although sinking cold seawater seeks the deepest route along the sea floor, deep-sea currents may be blocked by barriers. The Mid-Atlantic Ridge, the large volcanic ridge effectively bisecting the Atlantic Ocean basin, may prevent the movement of water from the bottom of the western Atlantic to the eastern Atlantic. Conversely, the funneling of deep-sea currents through narrow passages or gaps in seafloor barriers will lead to an increase in the velocity of the current. Once beyond the passage, however, the current spreads and velocity is reduced. Because both air and water act like a fluid, these effects and behaviors are entirely analogous to those of winds produced in the atmosphere by air density differences resulting from the uneven distribution of solar energy over Earth's surface.

Coriolis Effect

The circulation pattern of deep-sea currents is controlled to a large extent by Earth's rotation. The Coriolis effect—the frictional force achieved by Earth's rotation that causes particles in motion to be deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere—induces deep-sea currents to trend along the western margins of the major oceans. Thus, water sinking from sources in the North Atlantic Ocean and moving south toward the equator will be deflected to the right, causing it to run along the western side of the North Atlantic. Similarly, north-directed deep-sea currents generated by the sinking of cold water from the Antarctic region will also be deflected to the western margin of the Atlantic.

The Coriolis effect guides deep-sea currents along bathymetric contour lines, lines on a map of the ocean floor that connect points of equal depth. Deep-sea currents that have a tendency to move parallel to the bathymetric contours are known as bottom currents. Barriers to flow may locally deflect deep-sea currents from the bathymetric contours; nevertheless, bottom currents are most conspicuous along the western margins of the major oceans.

Short- and Long-Term Controls

The formation of the cold seawater required to set deep-sea currents in motion can itself be considered in terms of short- and long-term controls. Seasonal sea ice formation is probably the most important process in the production of the north-flowing water generated at the south polar region, or the Antarctic bottom water (AABW). Velocities of the AABW are highest in March and April, that period of the year when sea ice production in the ocean surrounding Antarctica is greatest. During Southern Hemisphere summers, however, the sea ice melts and there is an increase in the freshwater flux to the ocean from the continent, both of which reduce the salinity and therefore the density of the seawater, thereby decreasing AABW production.

Many oceanographers and marine geologists have argued that long-term variations in the production of the cold, dense bottom water required to generate deep-sea currents may be related to global climatic changes. More specifically, deep-sea currents appear to be most vigorous during glacial periods, when sea ice production is enhanced and the sea ice remains on the ocean surface for a greater proportion of the year. Nevertheless, there is also evidence to suggest that the velocities of deep-sea currents in the North Atlantic Ocean were much lower during the most recent glacial periods than they were during the times between glacial phases. Much more work is required to gain a more complete understanding of long-term controls on deep-sea currents.

Measurement Tools and Techniques

The most common methods for the study of deep-sea currents include direct measurement of current velocities, bottom photography, echo sounding, and the sampling of ocean-floor sediment. The speed and direction of deep-sea currents have been determined by the use of free-fall instruments, such as the free-instrument Savonics rotor current meter. This device, dropped unattached into the ocean, is capable of recording current velocities and directions over a period of several days. It returns automatically to the surface of the ocean, at which time a radio transmitter directs a ship to its position. Other current-measuring devices can be suspended at various depths in the ocean from fixed objects, such as buoys or light ships, to monitor currents for long periods. One such anchored meter measures the flow of water past a fixed point. Flowing water causes impeller blades, similar to the blades of a fan, to rotate at a rate proportional to the current's speed. In addition, the blades cause the meter to align with the current's direction. Electrical signals indicating the direction and speed of the current are transmitted by radio or cable to a recording vessel. Current velocities of less than 1 centimeter per second can be detected by this meter.

To get the most complete picture of the variability of the ocean, a combination of various measurement techniques with remote sensing may be employed. Such a multidimensional approach may involve the measurement of current velocity, pressure (a measure of depth), water temperature, and water conductivity (a measure of salinity). These data can be transmitted via satellite to a land station or even directly to a computer.

Additional Study Methods

Perhaps the most persuasive evidence for the existence of deep-sea currents and their influence on the ocean bottom has been gained through bottom photography. Sediment waves, or ripples, apparently formed by the saltation of sediment carried by deep-sea currents, along with evidence of current-induced scour of the ocean floor, were first photographed in the Atlantic Ocean in the late 1940's. Since then, the technology of bottom photography has advanced greatly. Bottom photography permits detailed study of some of the smaller features on the ocean floor apparently formed by deep-sea currents. Benthonic, or benthic, organisms, marine organisms that live attached to the ocean floor, bending in the flow of the current, are a particularly intriguing example of the phenomena recorded by this technique.

Echo-sounding studies of the sea floor have yielded abundant information on ocean-floor features that are either formed or modified by deep-sea currents. Notable among these are very long ridges in the North Atlantic evidently constructed from sediment carried by deep-sea currents. In echo sounding, a narrow sound beam is directed from a ship vertically to the sea bottom, where it is reflected back to a recorder on the ship. The depth to the sea floor is determined by multiplying the velocity of the sound pulse by one-half the amount of time it takes for the sound to return to the ship. The depths to the ocean floor are recorded on a chart by a precision depth recorder, which produces a continuous profile of the shape of the sea floor as the ship moves across the ocean.

Sediment transported by and deposited from deep-sea currents can be studied directly by actually sampling the ocean floor. Sampling of these deposits is best accomplished by the use of various coring devices capable of recovering long vertical sections, or cores, of seafloor sediment. Sediment recovery is achieved by forcing the corer, a long pipe usually with an inner plastic liner, vertically into the sediment. The simplest coring device, the gravity corer, consists of a pipe with a heavy weight at one end. This type of corer will penetrate only 2 to 3 meters into the sea floor. The piston corer, used to obtain longer cores, is fitted with a piston inside the core tube that reduces friction during coring, thereby permitting the recovery of 18-meter or longer cores. Analysis of the sediment recovered from the ocean floor by these and other coring devices reveals much information about small-scale features formed by deep-sea currents.

Importance to Life on Earth

Because cold bottom-water masses often are nutrient-rich and contain elevated abundances of dissolved oxygen, deep-sea currents are extremely important to biological productivity. There are areas of Earth's surface where nutrient-rich cold bottom waters rise to the ocean surface. These locations, known as areas of upwelling, are generally biologically productive and therefore are important food sources. Especially pronounced upwelling occurs around Antarctica. Bottom waters from the North Atlantic upwell near Antarctica and replace the cold, dense, sinking waters of the Antarctic.

The great amount of time required for seawater to circulate from the surface of the ocean to the bottom and back again to the surface has become an important practical matter. If pollutants are introduced into high-latitude surface waters, they will not resurface in the low latitudes for hundreds of years. This delay is particularly important if the material is rapidly decaying radioactive waste that may lose much of its dangerous radiation by the time it resurfaces with the current. The introduction of toxic pollutants into a system as sluggish as the deep-sea circulation system, however, means that they will remain in that system for prolonged periods. Nations must, therefore, be concerned with the rate at which material is added to this system relative to that at which it might be redistributed at the surface of the ocean by wind-induced surface circulation. The multinational Geochemical Ocean Sections (GEOSECS) program, introduced as part of the International Decade of Ocean Exploration, attempted to better assess the problem of how natural and synthetic chemical substances are distributed throughout the world's oceans. The GEOSECS program, carried out from 1970 to 1980, yielded abundant information regarding the movement of various water masses and, among other things, the distribution of radioactive material in the oceans. For example, GEOSECS demonstrated that tritium produced in the late 1950's and early 1960's by atmospheric testing of nuclear weapons had been carried to depths approaching 5 kilometers in the North Atlantic Ocean by 1973.

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Further Reading

Baker, D. J. "Models of Oceanic Circulation." *Scientific American* 222 (January, 1970): 114. A somewhat complex discussion of surface circulation in the world's oceans. Generally suitable for college-level readers.

Broecker, Wally. *The Great Ocean Conveyor*. Princeton, N.J.: Princeton University Press, 2010. Discusses ocean currents, focusing specifically on the great conveyor belt. Written by the great ocean conveyor's discoverer; explains the conception of this theory and the resulting impact on oceanography. Written in an easy-to-follow manner, yet still relevant to graduate students and scientists.

Colling, Angela. *Ocean Circulation*. 2d ed. Oxford: Butterworth-Heinemann, 2001. Discusses the effects of ocean circulation as reflected in various phenomena.

Garrison, Tom S. *Oceanography: An Invitation to Marine Science*. Belmont, Calif.: Brooks/Cole, Cengage Learning, 2010. Discusses the circulation of the oceans, including deep-water and surface currents. Describes various aspects of waves and the physics of tides. Provides abundant diagrams to aid readers from the layperson to advanced undergraduates.

Goni, G. J., and Paola Malanotte-Rizzoli. *Interhemispheric Water Exchange in the Atlantic Ocean*. Amsterdam: Elsevier B.V., 2003. While the focus of this book is the dynamics of the tropical Atlantic Ocean, the overall goal is to relate those dynamics to the ocean globally through the operation of deep ocean currents. Written for ocean science specialists.

Hollister, C. D., A. Nowell, and P. A. Jumar. "The Dynamic Abyss." *Scientific American* 250 (March, 1984): 42. Addresses the formation of bottom waters that flow away from the polar regions toward the equator. Suitable for high school students.

Ittekko, Venugopalan, et al., eds. *Particle Flux in the Ocean*. New York: John Wiley and Sons, 1996. Contains descriptions of the chemical and geobiochemical cycles of the ocean, as well as the ocean currents and movement. Suitable for the high school reader and beyond. Illustrations, index, bibliography.

Jeleff, Sophie, ed. *Oceans*. Strasburg: Council of Europe, 1999. This collection of debates and lectures is a detailed account of oceanography and ocean ecology. Discusses ocean circulation, marine chemistry, and the ocean's structure. Illustrations and bibliography.

Kennett, James P. *Marine Geology*. Englewood Cliffs, N.J.: Prentice-Hall, 1982. Contains an excellent discussion of deep-sea currents and thermohaline circulation. Discusses the major methods of study of deep-sea currents, including bottom photography (there are two pages of black-and-white bottom photographs). Best suited to the college student.

Oceanography Course Team. *Ocean Circulation*. 2d ed. Oxford: Butterworth-Heinemann, 2001. Discusses surface currents and deep water currents, with a focus on the North Atlantic Gyre, Gulf Stream, and equatorial currents. Describes the El Niño phenomenon and the great salinity anomaly. Offers a good introduction to oceanography.

Ross, David A. *Introduction to Oceanography*. 5th ed. New York: HarperCollins College Publishers, 1995. A fine introductory oceanography textbook with an informative discussion of deep-sea currents and their mechanisms of generation. Includes a section on oceanographic instrumentation. Suitable for high school students.

Siedler, Gerold, John Church, and John Gould. *Ocean Circulation and Climate: Observing and Modelling the Global Ocean*. London: Academic Press, 2001. Written to guide the reader consistently through the broad range of world ocean circulation experiment science, with cross-referenced contributors' list, a comprehensive index, and unified reference list. Easily readable at the undergraduate level.

Smith, F. G. "Measuring Ocean Currents." *Sea Frontiers* 18 (May, 1972): 166. Discusses methods used to determine the speed and direction of ocean currents.

Teramoto, Toshihiko. *Deep Ocean Circulation: Physical and Chemical Aspects*. New York: Elsevier, 1993. Provides a detailed look at ocean circulation and currents. Offers much information on the chemical processes that occur in the deep ocean. Illustrations, maps, and bibliographical references.

Trujillo, Alan P., and Harold V. Thurman. *Essentials of Oceanography*. 10th ed. Upper Saddle River, N.J.: Prentice-Hall, 2010. Describes deep ocean currents in the broader context of the whole ocean and oceanography. Uses a systems approach that is useful to all earth science students.

Vallis, Geoffrey K. *Atmospheric and Oceanic Fluid Dynamics: Fundamentals and Large-Scale Circulation*. New York: Cambridge University Press, 2006. Begins with an overview of the physics of fluid dynamics to provide foundational material on stratification, vorticity, oceanic and atmospheric models. Discusses topics such as turbulence, baroclinic instabilities, wave-mean flow interactions, and large-scale atmospheric and oceanic circulation. Best suited for graduate students studying meteorology or oceanography.

See also: Carbonate Compensation Depths; Deep-Sea Sedimentation; Gulf Stream; Hydrothermal Vents; Observational Data of the Atmosphere and Oceans; Ocean-Atmosphere Interactions; Ocean Pollution and Oil Spills; Oceans' Origin; Oceans' Structure; Ocean Tides; Ocean Waves; Remote Sensing of the Oceans; Sea Level; Seamounts; Seawater Composition; Surface Ocean Currents; Tsunamis; Turbidity Currents and Submarine Fans; World Ocean Circulation Experiment