Giant Ocean Cataracts

Undersea cataracts that descend farther than any waterfall and carry more water than any river play a crucial role in maintaining the chemistry and climate of the deep ocean

by John A. Whitehead

Trivia enthusiasts know that Angel Falls in Venezuela, with a height just short of a kilometer, is the world's tallest waterfall, and that the Guaíra Falls along the Brazil-Paraguay border has the largest average flow rate: about 13,000 cubic meters per second. Trivia enthusiasts have not peered below the Denmark Strait. There an immense cascade of water—a giant ocean cataract—carries five million cubic meters of water per second through a descent of 3.5 kilometers, dwarfing Angel Falls in height and Guaíra Falls in flow rate. Even the mighty Amazon River, which dumps 200,000 cubic meters of water into the Atlantic every second, pales beside the Denmark Strait cataract. And although even the largest waterfalls on land are trivial components of the earth's climatic balance, giant cataracts play a vital role in determining the temperature and salinity of the deep ocean.

Ocean cataracts have been seriously investigated by oceanographers only within the past 20 years. They are a direct result of the process of convection: the transfer of heat by the bulk motion of a fluid. One can imagine the ocean to be a shallow pan of water that is exposed to the sun at one end (the Tropics) and not at the other (the high latitudes) [*see illustration on page 52*]. The cold water near the pole is the densest and therefore sinks in convective currents to the bottom of the pan. From there it spreads toward the temperate latitudes, displacing the warmer water above it. The warmer water therefore begins to rise in a gentle upwelling that is thought to take place almost everywhere in the ocean. Because warmer layers prevent bulk upward motion of the colder bottom layers—just as a Los Angeles temperature inversion traps cold air under warm—the upwelling is extremely slow. At the same time the cold water is heated by contact with the warmer layers above.

The ocean is in thermal equilibrium, and so the heat flowing upward in this process must equal the heat flowing downward. But because convection is an extremely efficient mechanism for transferring heat, the downward convective currents do not have to be very large in cross-sectional area to balance the heat transferred by the oceanwide warming of the deep water. The narrow currents of sinking cold water are in fact the precursors to the ocean cataracts proper.

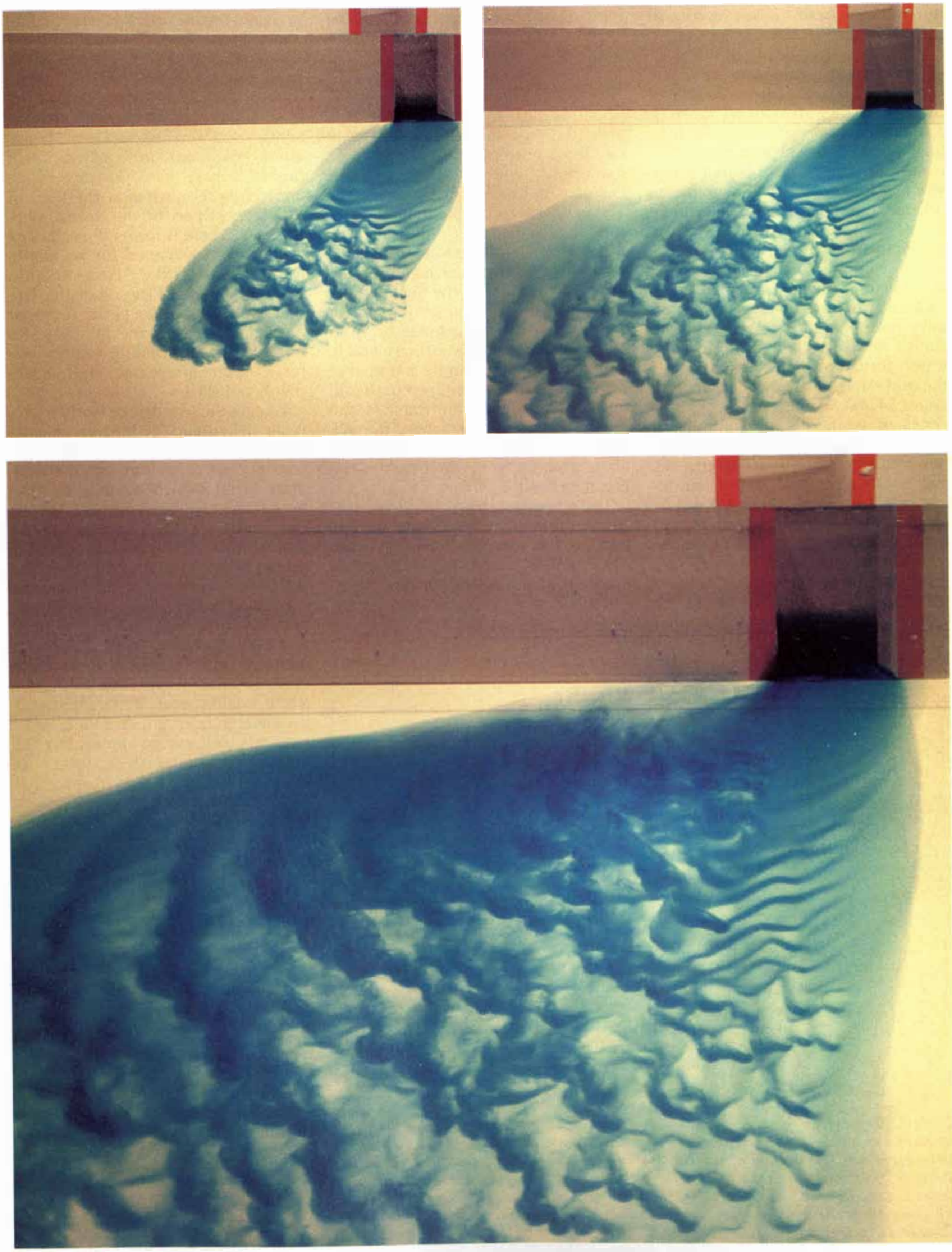
It is easy to estimate the amount of time over which the upwelling takes place. If the ocean pan has a volume of roughly 3×10^{17} cubic meters and is being fed by a stream of cold water at five million cubic meters per second, then to fill the pan with cold water would take about 2,000 years. If the pan is five kilometers deep, and no heat is transferred from the warm upper layers to the cold lower layers, the cold-water level would rise at a rate of from two to three meters per year. Although this is a crude estimate, it corresponds roughly to the rate of upwelling thought to take place in the real ocean.

Of course, the real ocean is not as simple as a pan of water; it contains topographical features that divide it into a series of large basins. Suppose that the ocean pan is divided into a polar and an equatorial basin by a hump, or sill. Cold water sinking at the pole can now fall into only the polar basin. To reach the lower latitudes the dense water must first rise above the sill; it does this by the gradual upwelling discussed above. During the process the water is heated by contact with the warmer layers above, but because the conductivity of water is very low, the heat transfer is minimal and the temperature change is not large.

Consequently the water temperature at sill depth in the polar basin is less than the temperature at sill depth in the equatorial basin. The polar water is therefore denser than the equatorial water, and so it spills over the sill, displacing the warmer water. I shall refer to the resulting current across the sill as an ocean cataract. As it flows from the polar basin into the equatorial basin, the cataract skims off warmer water encountered at or above sill depth and carries it downward to the bottom of the second basin. Moreover, as the cataract flows downward it often mixes turbulently with the surrounding downstream water. The net result of the skimming and mixing is that the water temperature at the bottom of the equatorial basin equals—or even exceeds—the water temperature at sill depth in the polar basin.

The study of real-world cataracts must take into account the fact that oceans contain many basins. Certain complicating factors that I shall discuss below, such as the Coriolis force and friction, also enter the picture, with the result that the paths of some cataracts are not oriented from north to south and do not end at the Equator. Nevertheless, the simple model accounts for most of the observations: cataracts of cold, dense water flow from the polar basins into the temperate-latitude basins. At each stage the water is warmed through skimming and mixing. Thus the bottom tempera-

JOHN A. WHITEHEAD is a senior scientist in the department of physical oceanography at the Woods Hole Oceanographic Institution. He received a B.S. at Tufts University and an M.S. and a Ph.D. from Yale University, the last in 1968. In addition he is a past holder of a Guggenheim fellowship and is a fellow of the American Physical Society. His research interests center on analytical and laboratory studies of fluid mechanics in oceans, atmospheres and planetary interiors. For relaxation Whitehead plays the trombone in the Falmouth, Mass., town band, which is conducted by his wife, Linda.



LABORATORY CATARACT is created by introducing a stream of salt water into a rotating tank of fresh water. The denser salt water, here colored blue, begins to sink. As it descends along the sloping bottom of the tank it develops waves and mixes turbulently with the surrounding water. The Coriolis force arising from the tank's rotation causes the cataract to veer to its right. A difference in salinity also drives the cataract that flows out of the Strait of Gibraltar into the North Atlantic.

ture of ocean basins increases toward the Equator.

Because the giant ocean cataracts occur at great depths in limited areas, they are not easy to study. Although oceanographers alluded to their presence as early as the 1870's, it was not until the 1960's that extensive investigation of the phenomenon became possible. The breakthrough came when vacuum tubes were replaced by transistors—leading to electronic equipment that could withstand being thrown overboard.

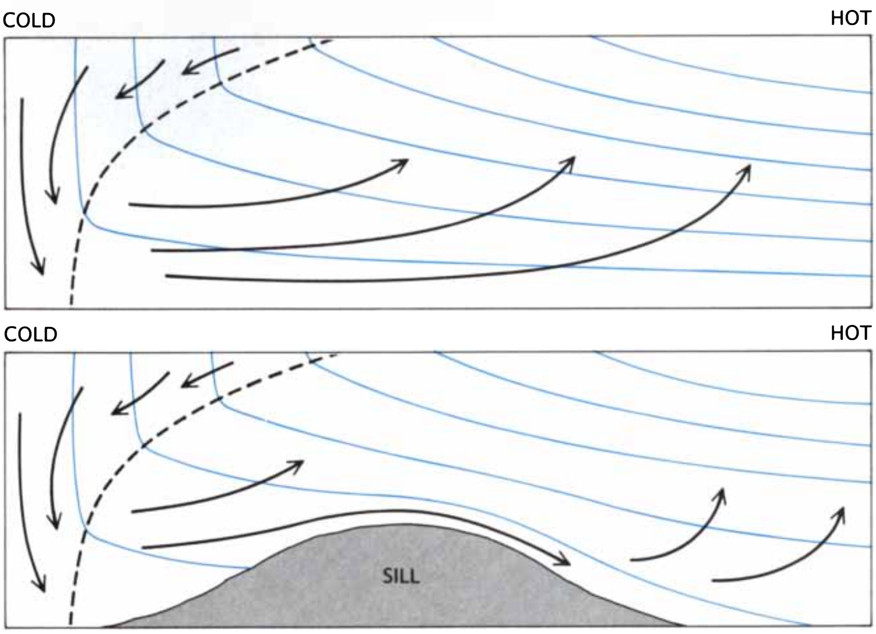
One way to find cataracts is to examine a north-south ocean slice that includes the suspected region of cold-water formation—the region where the cold water sinks [*see illustration on pages 54 and 55*]. One can then plot a series of isotherms, or contours of constant temperature. A cataract carries cold water downward over a sill, and so if a cataract is present, an isotherm just above sill depth will be roughly level on the upstream side of the sill but will descend sharply on the downstream side. Colder water, lying just below sill depth, will not flow over the sill; consequently the isotherms representing its temperature will be found in the upstream basin but not in the downstream one.

A good example of this pattern is provided by the Rio Grande cataract, which begins at about 20 degrees south latitude in the Atlantic Ocean and flows north. The Rio Grande Rise itself is the sill for this cataract; it lies at 4,000 meters below sea level. The isotherm for a potential temperature of zero degrees Celsius is slightly deeper (potential temperature is the actual temperature corrected for the effect of pressure in the deep ocean). Therefore the sill blocks this water, which originates in the Antarctic, from spilling into the more northern Brazilian Basin. Slightly warmer water, at .2 degree C, lies above the crest of the sill and is denser than the water to the north; this water flows over the sill, and the .2-degree isotherm descends about a kilometer to the bottom of the Brazilian Basin.

The one-degree and 1.4-degree isotherms reveal a second cataract farther to the north, where the Ceara Abyssal Plain separates the Brazilian Basin from the North Atlantic Basin. The plain, lying close to the Equator, prevents one-degree water in the Brazilian Basin from flowing into the North Atlantic Basin. On the other hand, the 1.4-degree water lies above the sill, which is thought to be at about four degrees north latitude. To the south the 1.4-degree isotherm is relatively level, but north of the sill it descends more than 2,000 meters and apparently terminates at the floor of the deepest part of the North Atlantic Basin. There it forms the Antarctic bottom water—named for its southern origins—of the North Atlantic. The termination of the 1.4-degree isotherm probably reflects the fact that during its descent the falling water mixes with surrounding warmer water; its temperature rises and the isotherm vanishes.

Tracing the two-degree isotherm reveals the Atlantic's third great cataract, the Denmark Strait overflow. The current that flows through the Denmark Strait (which actually lies between Greenland and Iceland) travels from north to south, opposite to the flow of Antarctic bottom water in the cataracts I have discussed above. Once the current crosses the sill, called the Greenland-Iceland Rise, it descends as a cataract some 200 meters deep and 200 kilometers wide; 1,000 kilometers downstream it reaches a depth of about 3,500 meters and forms the North Atlantic deep water. During its 3.5-kilometer descent the falling water may mix with warmer water, increasing its temperature above that of the Antarctic bottom water. In any case, the North Atlantic deep water is not as dense as the Antarctic bottom water and consequently forms a distinct layer above it.

Thermometers are not the only means by which oceanographers can probe cataracts. Radioactive isotopes dissolved in seawater also provide an effective way to trace the paths of these underwater currents. Tritium, a radioactive isotope of hydrogen with a half-life of 12.5 years, was produced at levels far above natural background levels by the atmospheric nuclear-bomb tests in the 1950's and early 1960's. Most of the tritium was released in the Northern Hemisphere and entered the ocean in the form of tritiated, or heavy, water. With the termination of aboveground testing in 1963 that source of tritium disappeared, and atmospheric levels of the isotope have declined steadily since. Thus a large volume of water that lay at the surface during the years of atmospheric testing was labeled with tritium.



CONVECTION drives most ocean cataracts, as is demonstrated in a pan of water when one end is heated and the other is cooled (*top*). The cold water at the "pole" sinks rapidly to the bottom of the pan (*arrows*) and spreads toward the "equator." There it encounters warmer water layers above. This temperature inversion prevents the cold water from rising rapidly; instead it is gradually heated by contact with the warmer layers and rises at a rate of about a meter per year in the ocean. A cataract is formed when a hump, or sill, is introduced into the pan (*bottom*). Water in the polar basin is colder and hence denser at the sill depth than water in the equatorial basin; the effect is manifested by the raising of the isotherms, or lines of constant temperature (*solid lines*), on the left-hand side. The polar water therefore flows over the sill to the bottom of the equatorial basin. This rapid descent, accompanied in some cases by turbulent mixing, is a model for a giant ocean cataract.

In 1972 the Geochemical Ocean Sections Study (GEOSECS) Operations Group measured tritium levels at various depths along a north-south slice of the Atlantic. The data showed that tritium from the atmospheric tests had been transported by the Denmark Strait cataract to a depth of roughly 3,500 meters, into the base of the North Atlantic deep water. The GEOSECS project found no tritium in the deeper layer of Antarctic bottom water, however. This indicates that the tritium deposited in the Southern Hemisphere has not had time to reach the Northern Hemisphere by way of the deep currents. At the ocean turnover rate estimated above, hundreds more years will elapse before tritium will appear in the Antarctic bottom water of the North Atlantic.

Tritium is generally difficult to detect in the Southern Hemisphere because the bomb tests were held primarily in the Northern Hemisphere. In contrast, chlorofluorocarbons—freons and other gases now thought to be depleting the ozone layer—produce a greater Southern Hemisphere signal. The concentrations of these manmade compounds in the atmosphere have been increasing rapidly in the past several decades. They dissolve in the surface layer of the ocean and mix downward slowly. John L. Bullister of the Woods Hole Oceanographic Institution has recently discovered a form of freon called freon 11 in a prime source of the Antarctic bottom water: the Filchner Ice Shelf cataract. The Filchner Ice Shelf lies in the Weddell Sea directly south of the Atlantic Ocean and off the coast of Antarctica. Cold, dense water spills off the Filchner Ice Shelf into the deep Weddell Sea. The fact that Bullister measured high concentrations of freon 11 at a depth of 1,500 meters in the Antarctic is a clear indication that manmade compounds are beginning to enter the Antarctic bottom water.

MAJOR OCEAN CATARACTS are indicated on a map of the Atlantic. The Denmark Strait, which lies between Greenland and Iceland, produces what is probably the world's largest cataract, with a flow rate of about five million cubic meters per second. The Iceland-Faroes cataract supplies the eastern North Atlantic with cold, dense water. The Ceara Abyssal Plain cataract, flowing from south to north, supplies the North Atlantic with its coldest and deepest water—the Antarctic bottom water. Through Discovery Gap water flows at a rate of 210,000 cubic meters per second from the eastern equatorial Atlantic to the eastern North Atlantic. The Filchner Ice Shelf cataract produces some of the world's densest bottom water. The South Shetland Islands cataract may be important in maintaining krill breeding grounds. Unlike these cataracts, which are due to temperature differences, the Strait of Gibraltar cataract is driven by differences in salinity. The red line traces the part of the 1972–73 GEOSECS expedition that resulted in the slice shown on the next two pages.

The most spectacular manifestation of giant ocean cataracts is of course their enormous flow rates. The Denmark Strait cataract once again provides the prime illustration. In 1967 L. Val Worthington of Woods Hole attempted to measure its flow rate by deploying an array of 30 current meters at various depths in the sill region. The currents were so severe that 20 of the meters were never recovered. Those that were recovered had recorded currents of up to 1.4 meters per second, which is sizable compared with the rates—from .1 to .5 meter per second—at which surface currents usually flow. It was on the basis of this peak current that the volume flux of the Denmark Strait cataract was estimated at five million cubic meters per second, the figure I gave above.

Unfortunately since Worthington's initial studies few flux measurements have been made. In 1973 workers of the Bedford Institute of Oceanography in Dartmouth, Nova Scotia, arrived at an estimate of 2.5 million cubic meters per second. The threat posed to moored current meters by the deep-sea trawlers in the Denmark Strait may preclude any future surveys.

In 1978 Worthington and I began measurements of the flow rate into the Ceara cataract, which delivers Antarctic bottom water to the North Atlantic Basin. Current meters deployed on the sill at four degrees north latitude yielded an estimated flow rate of from one to two million cubic meters per second—or some five to 10 times the flow rate of the Amazon. By this time buoy technology had advanced, so that we were able to deploy the moorings for a full year without any losses. This enabled us to measure the flux at tenth-of-a-degree intervals between 1.0 and 1.9 degrees C.

At about the same time Nelson G. Hogg and William J. Schmitz, Jr., of Woods Hole, in conjunction with Wilford D. Gardner and Pierre E. Biscay of the Lamont-Doherty Geological Observatory, measured the flux into the Rio Grande cataract. After two years of observations they estimated the flow rate into this cataract to be four million cubic meters per second, perhaps as large as the Denmark Strait cataract.

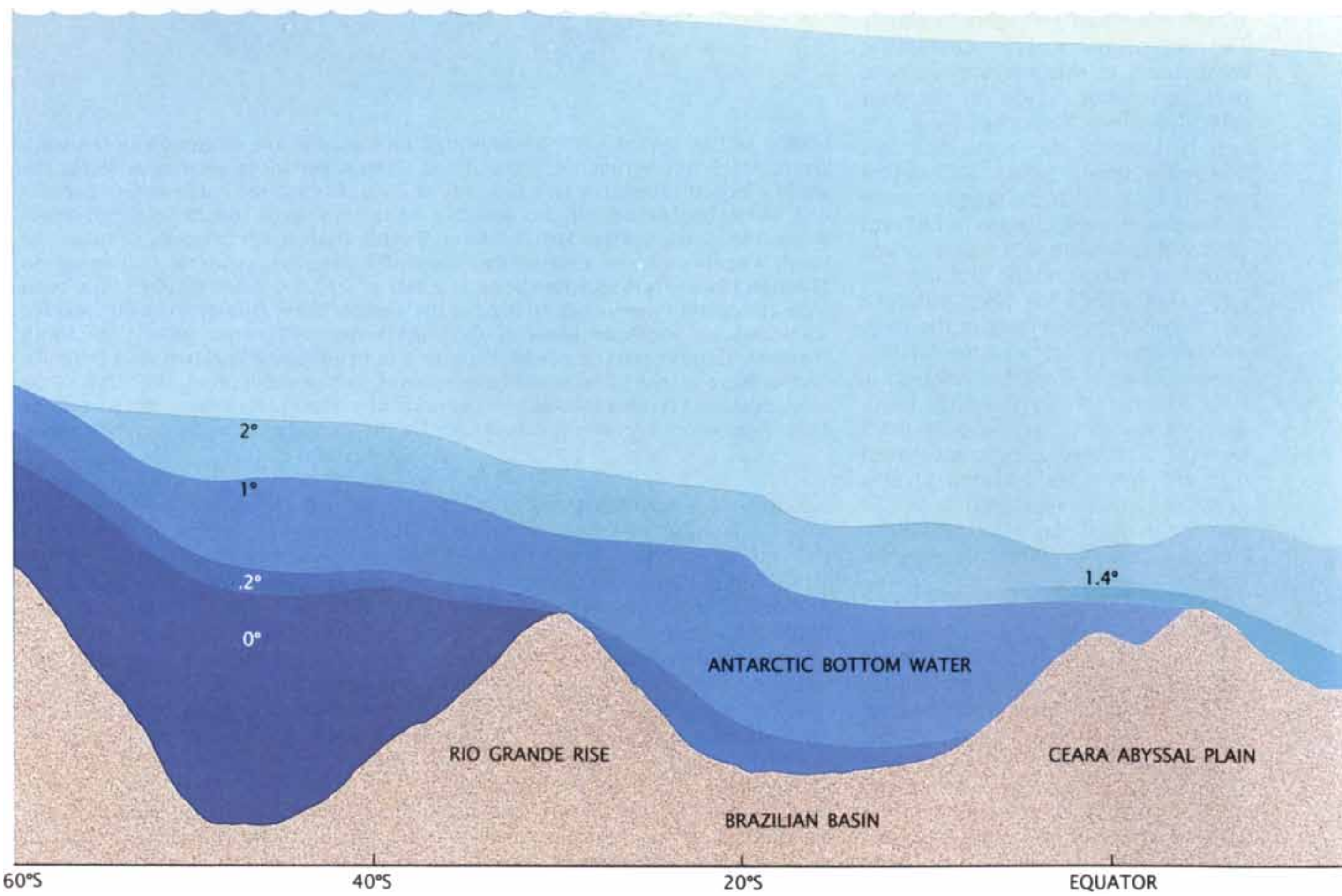
These enormous fluxes are generally driven by temperature differences between two basins, but not always. For example, owing to evaporation, water in the Mediterranean is much saltier—and therefore much denser—than even the deepest water in the Atlantic, even though it is warmer. Water flowing out of the Mediterranean through the Strait of Gibraltar therefore tends to sink into the Atlantic as a cataract.

During its descent the salty Mediterranean water mixes with Atlantic water. This mixing reduces the Mediterranean water's density until at a depth of only 1,000 meters it equals that of the surrounding Atlantic water. At this depth the water ceases its descent and spreads out in a plume over a sizable part of the northeastern Atlantic, where it is responsible for a pronounced maximum in ocean salinity.

The turbulent mixing of the Gibraltar cataract with Atlantic waters explains the depth of the plume but is itself a puzzle. No one yet knows why the Gibraltar cataract mixes more strongly with its surroundings than the Denmark Strait cataract does. Four potential explanations are (1) the steepness of the continental slope off Spain, (2) rougher geologic features there than in the Denmark Strait, (3) the fact that the Mediterranean cataract is driven by a difference in salinity whereas the Denmark Strait is a thermal cataract, and (4) the large surges in the flow through the Strait of Gibraltar as a result of tides and storms. To determine which if any of these explanations is correct will require fundamental studies in geophysical fluid dynamics in conjunction with much more observation.

Even though the factors determining the degree of mixing are highly uncertain, investigators agree that mixing is extremely important in determining the heat budgets of cataracts and their surroundings. The Ceara cataract protrudes into the North Atlantic as a tongue of cold water. Because the tongue has been observed to be stationary over many years, the northward-flowing water must be warming and hence rising through the isotherms. That is possible only if warmer water from above is mixing into the cataract water and heating it. Fluid dynamicists call this process turbulent-eddy mixing.

Indeed, the sharp boundaries of cataracts make them a good place to study turbulent-eddy mixing in the ocean. The degree of mixing and so the thermal-energy budgets (the degree to which heat can be transferred in and out of a cataract) are relatively easy to obtain. Studies of cataracts' thermal-energy budgets by Hogg, Schmitz, Gardner and Biscay, by Worthington and me and by Peter Saunders of the Institute of Oceanographic Sciences in England all in-



NORTH-SOUTH SLICE of the Atlantic from Greenland to Antarctica reveals several cataracts. The Rio Grande Rise at about 30 degrees south latitude blocks the northward flow of Antarctic bottom water with a temperature below zero degrees Celsius. Water at .2 degree, however, spills over the rise into the Brazilian Basin, forming the Rio Grande cataract. The Ceara Abyssal Plain near the Equator prevents water colder than one degree from flowing farther north. Water at 1.4 degrees spills

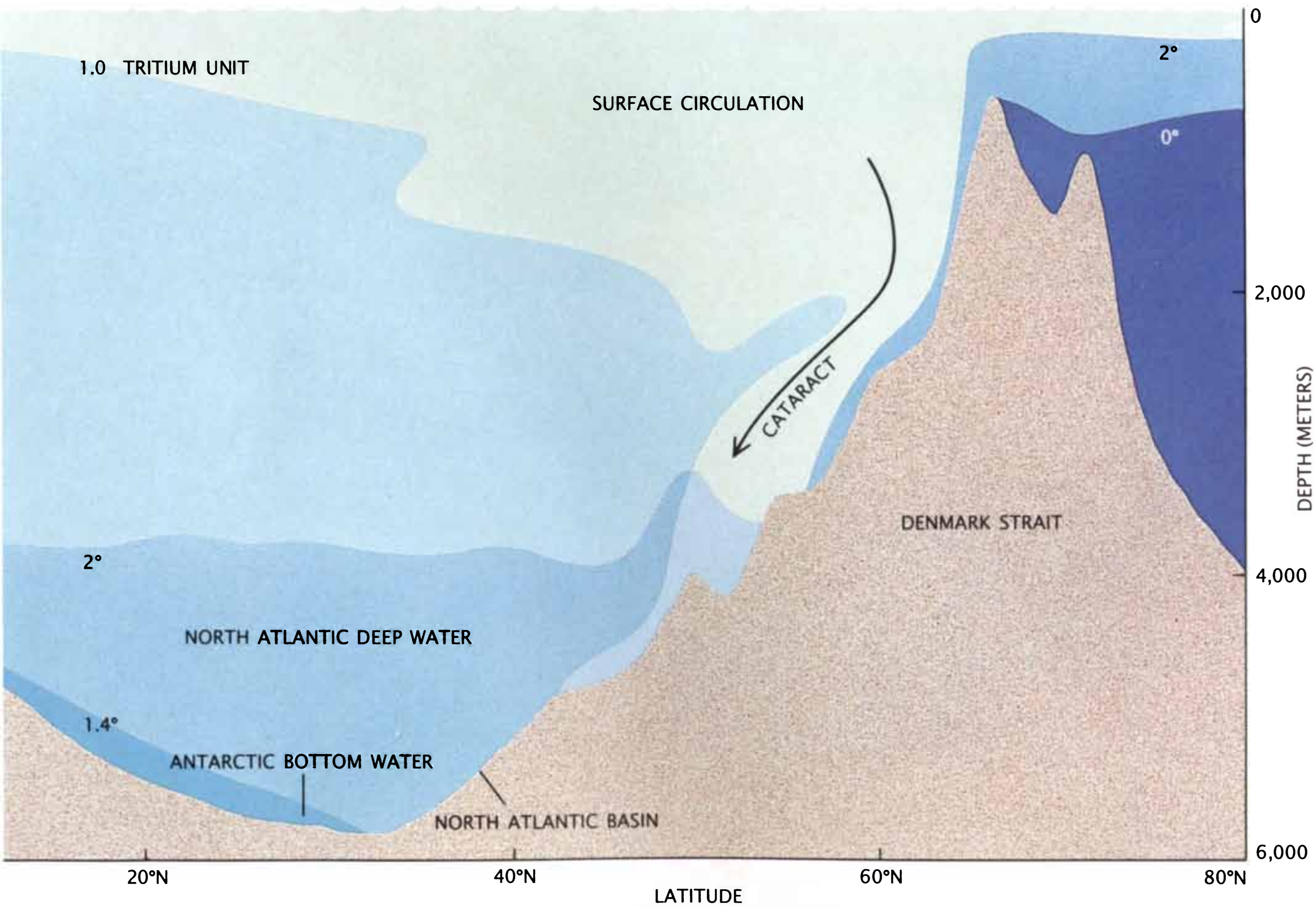
dicate that turbulent mixing is approximately 1,000 times as efficient in transferring heat as ordinary molecular conduction. Eventually we hope to determine thermal-energy budgets for other cataracts and ultimately for the ocean as a whole.

Since to some extent a cataract can be viewed as a system isolated from the rest of the ocean, it lends itself to laboratory study. In 1959 Thomas H. Ellison and J. Stewart Turner, then at the University of Manchester, constructed a simple experiment: they released salty water at the top of an incline that was itself at the bottom of a tank filled with fresh water. The denser salt water sank to the bottom of the tank, and the change in salinity as a function of the incline's slope and the flow rate was measured.

The slope and flow rate determine the Froude number, which essentially measures the ratio of inertial forces to buoyancy forces (the ratio of the actual velocity of an object to the velocity it would acquire if it were subjected only to gravitational acceleration). Ellison and Turner found that when the Froude number of such a laboratory cataract was much greater than 1, the flow became turbulent; the resultant mixing in turn drove the Froude number toward 1. This suggested, then, that the flow of cataracts tends to balance inertial and buoyancy forces.

The Ellison and Turner experiment was only a crude model of an ocean cataract and ignores a number of complicating factors that must be included for a more realistic description. Principal among these are the Coriolis force and friction. The Coriolis force is due to the rotation of the earth; it tends to deflect a moving object at a right angle to the object's trajectory. If the object is moving along a north-south path, it will be deflected to its right in the Northern Hemisphere and to the left in the Southern Hemisphere. In the Denmark Strait cataract, Coriolis forces cause the water to rise about a kilometer higher on the right-hand wall of the channel than on the left-hand wall. Also because of Coriolis forces, the salty Mediterranean current bends to the right after leaving the Strait of Gibraltar; the cataract it forms actually flows parallel to the Spanish coast.

An attempt to take certain of the complicating factors into account in analyzing the dynamics of ocean cataracts was made by Peter C. Smith of the Massachusetts Institute of Technology in 1973. Smith constructed a laboratory model that produced the Coriolis force by means of a rotating turntable, and that also included bottom friction (friction between the water and the channel bottom). Then, in a theoretical model, he added friction between the cataract and overlying layers of water, which was taken into account in the form of entrainment, or the mixing of different fluid layers. From the theoretical



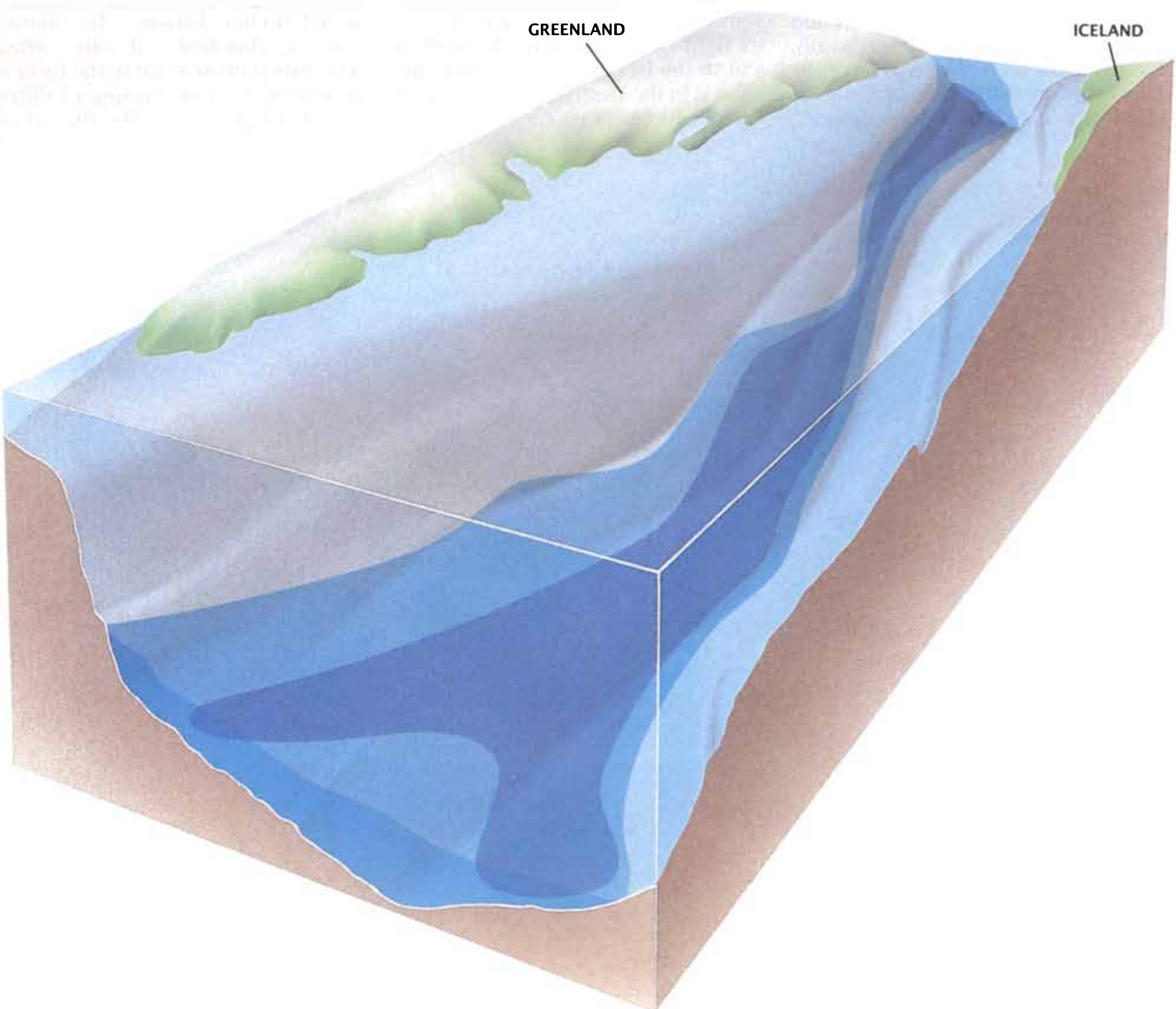
over the rise into the North Atlantic Basin as the Ceara cataract, supplying the North Atlantic with Antarctic bottom water. The Denmark Strait cataract, flowing southward, carries water at two degrees from the Norwegian Sea down to roughly 3,500 meters; it forms the North Atlantic deep water, which lies just above the Antarctic bottom water. In addition to temperature, tritium, a radioactive isotope of hydrogen produced in atmospheric nuclear-weapons tests, also traces this cataract.

model he concluded that the mixing rates found in the Denmark Strait are the result of bottom friction rather than drag between neighboring water layers. He also concluded that bottom friction dominated near the top of the cataract, whereas entrainment became important farther downstream.

In the past few years James F. Price and Martha T. O'Neil of Woods Hole have refined Smith's model; their formula for entrainment is based on high-resolution studies of mixing in the upper ocean. Working with Thomas B. Sanford of the University of Washington and Rolf G. Lueck of Johns Hopkins University, they have made measurements of the velocity, temperature and salinity within the Gibraltar Strait cataract. Comparison of the observations with the model indicates that it gives a realistic picture of the density change along an ocean cataract. Their findings also suggest (lending confirmation to Smith's results) that drag is caused mainly by bottom friction unless a certain critical velocity is exceeded, at which point the water mixes strongly with its surroundings. In contrast to Smith's result, however, the workers find that entrainment is important near the top of the cataract, whereas bottom friction is important farther downstream.

There is still a question, however, about whether the results of theoretical models and laboratory experiments—which are limited by the size of the turntables—can be scaled up to the real ocean, where turbulence is likely to be much greater and where the topography of the bottom introduces a largely unknown amount of drag and mixing. Indeed, the degree of drag and mixing at the ocean bottom has only recently begun to be measured. Consequently it is still not clear that the amount of friction assumed by investigators is appropriate to the real ocean; new data will help to decide whether the assumptions that are built into the models are reasonable or need to be discarded.

In spite of the scarcity of good data, investigators continue to increase the sophistication of the models. Recent laboratory experiments have elucidat-

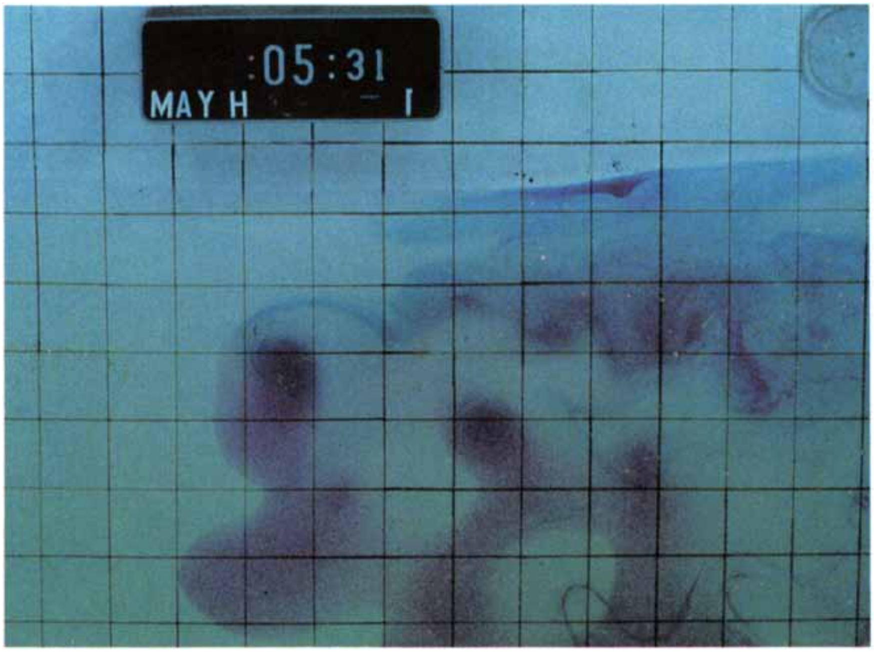


DENMARK STRAIT CATARACT is shown in perspective. The sill of this cataract is the Iceland-Greenland Rise, which lies 650 meters below sea level. Water from the Norwegian Sea flows over the rise at a rate that has been estimated to be 25 times that of the Amazon. The Coriolis force causes the water to rise about a kilometer higher on the right-hand wall (looking downstream) than on the left-hand wall. The dark blue contour is one-degree water, which fans out around the tip of Greenland. Above it lies 1.8-degree water, which protrudes into the North Atlantic as a tongue extending as far south as Newfoundland.

ed the effects of the Coriolis force in more detail. For instance, experiments done on a turntable by Ross W. Griffiths of the Australian National University and independently by Melvin E. Stern of Florida State University, Glenn R. Flierl and Barry A. Klinger of M.I.T. and me show that the Coriolis force results in the generation of isolated eddies, or small ocean whirlpools, directly above a cataract near the bottom of the ocean.

Two contrasting mechanisms of eddy generation have been proposed. Griffiths suggests the cataract produces an "inertial" wave in the ocean, that is, a vorticity wave that rotates first in one direction and then in another, like the water in a washing machine. The waves radiate upward and, according to Griffiths, they break and produce intense cyclones above the cataract. Such a process has indeed been observed in experiments in which a stirring grid produces inertial waves in a spinning fluid.

Stern, Flierl, Klinger and I propose a different mechanism. We think cyclonic circulation is a direct product of vertical mixing from small-scale turbulence in a rotating fluid when dense water lies under less dense water. According to this model, the turbulence mixes the less dense water above with the denser water below. The density of the former is effectively increased and it sinks, sucking water directly above it downward. The Coriolis force reorients the flow into a horizontal plane, turning it into a vortex, which lies between the cataract and the water's surface. Such eddies could be counterparts of the larger ocean eddies that can be several hundred kilometers across and persist for several years [see "Rings of the Gulf Stream," by Peter H. Wiebe; SCIENTIFIC AMERICAN, March, 1982], but to date the smaller vortexes have not been observed outside the laboratory.



LABORATORY EDDIES are created by introducing a blob of dense salt water, here dyed red, into a rotating tank of fresh water, some of which is dyed blue. The dense water descends, mixing turbulently with the surrounding water and drawing down the less dense water above. The Coriolis force makes the downward motion cyclonic, generating eddies. Three eddies can be seen here, each consisting of a lens of red fluid overlain by blue surface water. The same process, triggered by the descent of dense water in cataracts, may generate ocean eddies that can be kilometers across.

In addition to their effects on the climate and salinity of the deep ocean, cataracts might have important effects on marine biology. One such effect can be seen in the South Shetland Islands cataract. After leaving the Weddell Sea, which is south of the Atlantic Ocean, the South Shetland Islands cataract eventually descends westward toward the the Scotia Sea, south of the Pacific Ocean. Worth D. Nowlin, Jr., of Texas A&M University and Walter Zenk of the Institute of Marine Sciences at the University of Kiel in West Germany have suggested that the life cycle of krill in the Scotia Sea is shaped by the deep cataract.

Biologists know that the adult krill gather to spawn near the South Shetland Islands, forming extensive whale-feeding grounds. These spawning grounds lie near the immense Antarctic circumpolar current, a surface flow that sweeps eastward. Krill eggs are laid at depths of approximately 50 meters but sink to about 1,000 meters before hatching, and it has been a puzzle how the larvae, which cannot swim, can return to the spawning grounds as adults.

Curiously, it has been observed that the nursery grounds, where the larvae are found, are located hundreds of kilometers to the west, even though the Antarctic circumpolar current flows to the east. Nowlin and Zenk suggest that bottom cataracts are carrying the krill westward. If this scenario is correct, then the larvae rise after hatching and are carried eastward again to the spawning grounds by the Antarctic current. Thus ocean cataracts may provide the mechanism to close the circuit between the spawning area, the nursery and the feeding grounds.

Although much has been learned over the past 20 years about the extent of cataracts and their flow rates, temperature profiles and chemical contents, much more study needs to be done in order to determine the rates of mixing with surrounding water and the amount of drag at the ocean bottom. The result will be a clearer picture of the largest water cascades on the planet, which through their influence on the salinity, temperature and biology of the ocean have an effect on the climate and ecology of the entire earth.

FURTHER READING

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