The Ocean's Salt Fingers

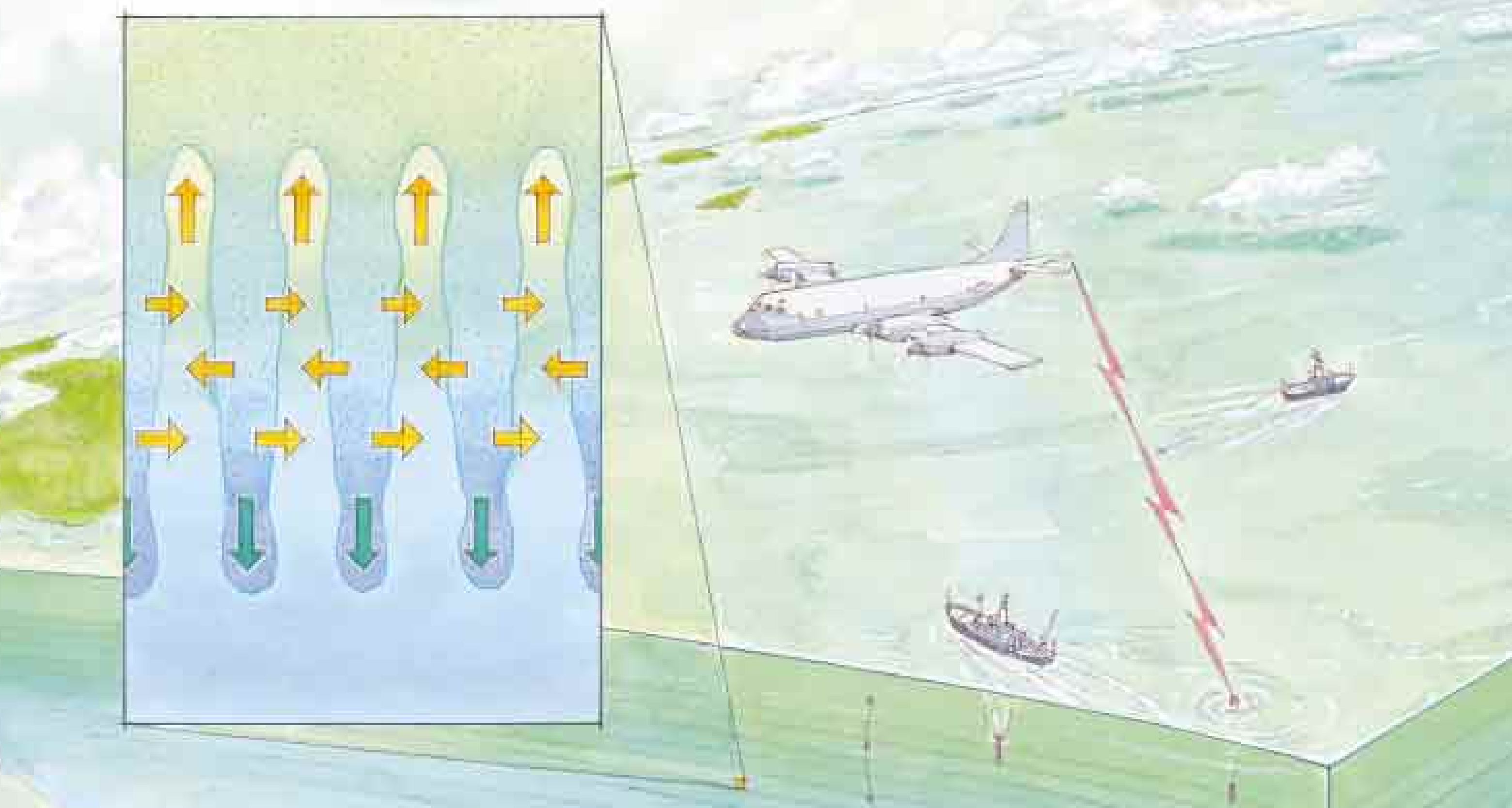
A small-scale oddity in the way seawater mixes can have large-scale consequences for the structure of the ocean

by Raymond W. Schmitt, Jr.

In the mid-1950s Henry M. Stommel and Arnold B. Arons, researchers at the Woods Hole Oceanographic Institution, stood staring at a chalkboard, groping for a way to measure the pressure at the bottom of the sea. In desperation they were considering constructing a three-mile-long tube from the surface to the bottom and drawing the ocean's deepest water up into the pipe. Because water is less salty near the seafloor than at the surface, the column of water within the tube would, after coming to thermal equilibrium, be lighter and so stand higher than the ocean surface around it.

Stommel and Arons imagined that they could then easily measure changes in pressure at the base of this ungainly instrument by watching the water level in the tube go up and down. As they gazed at their sketch, focused entirely on the problem of pressure measurement, Arons suddenly got a strange idea. He added a spigot to the top of the pipe in the diagram and said, "Hank, if we open the faucet, it will run forever."

Stommel dubbed this astonishing mental construction "the perpetual salt fountain." He and his colleagues immediately convinced themselves of the veracity of their idea by setting up a model salt fountain in the laboratory. Sub-



SALT FINGERS FORM because heat conducts through seawater (*horizontal arrows*) much more rapidly than dissolved salts diffuse. At places in the ocean where warmer, saltier water overlies colder, fresher water, an instability can result. Narrow streams of saltier water that cool and descend alternate with slender filaments of fresher water that warm and rise. This process can produce a distinctive pattern of stratification in which thick layers of uniform properties are separated by thin interfaces undergoing vigorous salt fingering.

sequently, they attempted to fabricate an actual salt fountain at sea, although their modest efforts toward a full-scale demonstration of the concept gave ambiguous results.

Stommel and Arons's salt fountain might have remained a mere oceanographic curiosity had not their theoretically minded colleague Melvin E. Stern realized a few years later that the ocean was fully capable of producing salt fountains on its own. He pointed out that seawater conducts heat about 100 times faster than it allows the diffusion of dissolved salts. As a result, a "parcel" of water in the ocean can reach thermal equilibrium with its surroundings far sooner than it can achieve chemical equilibrium by sharing dissolved salts. Thus, adjacent water parcels can differ significantly in salinity even in the absence of a physical barrier (like the wall of a pipe), and those differences can drive motion in the fluid. Because this phenomenon occurs only at scales of a few centimeters (the range of effective heat conduction), the small, elongate streams that form by this process have come to be known to oceanographers as salt fingers.

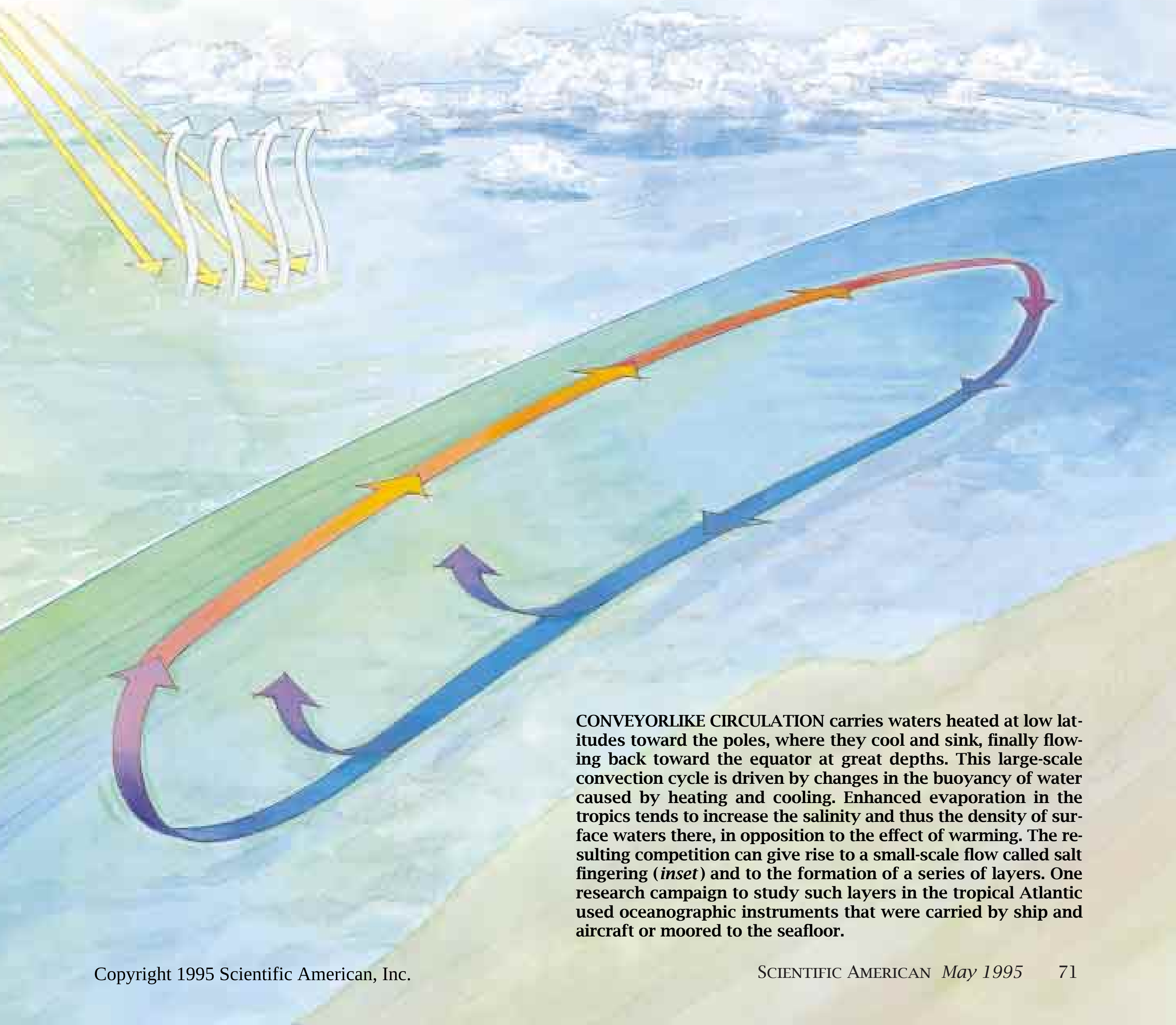
My interest in studying salt fingers was sparked by fascination, but it has been maintained over many years by a growing appreciation that these miniature oddities can exert considerable control on the large-scale structure of the upper ocean. Oceanographers now realize that a fundamental understanding of salt fingers and the extent of their global influence is needed to model the ocean's temperature and salinity accurately. Such advances should help determine many critical but as yet poorly known quantities, such as the rate at which the mixing in the ocean can redistribute carbon dioxide, pollutants and heat.

Nature's Salt Fountains

The sun warms the earth more intensely near the equator than at the poles, but the ocean works vigorously to correct the uneven distribution of heat. Warm waters flow poleward from the tropics along the surface of the ocean while frigid waters at high latitudes sink and flow back toward the equator at great depths.

This immense convective system arises because cold water is denser than warm water, but in the ocean a complicating factor—the presence of dissolved salt—can produce similarly important density changes. The salinity of the sea varies from place to place because of

BARRY ROSS



CONVEYORLIKE CIRCULATION carries waters heated at low latitudes toward the poles, where they cool and sink, finally flowing back toward the equator at great depths. This large-scale convection cycle is driven by changes in the buoyancy of water caused by heating and cooling. Enhanced evaporation in the tropics tends to increase the salinity and thus the density of surface waters there, in opposition to the effect of warming. The resulting competition can give rise to a small-scale flow called salt fingering (*inset*) and to the formation of a series of layers. One research campaign to study such layers in the tropical Atlantic used oceanographic instruments that were carried by ship and aircraft or moored to the seafloor.

Missed Opportunity for Discovery during the 19th Century

I have lately become fascinated by two researchers who came close to understanding the physics of salt fingers well before their discovery by Melvin E. Stern of Woods Hole in the late 1950s. First to approach the problem was English economist W. Stanley Jevons. During his youth, Jevons spent five years in Australia, where he pursued a number of scientific topics, including meteorology.

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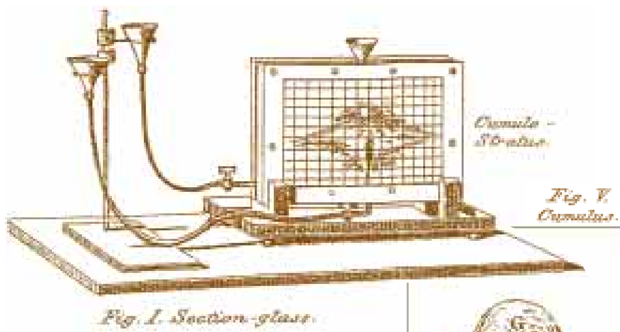
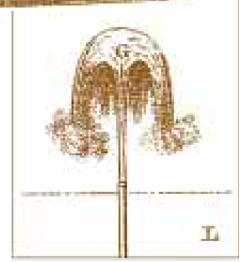
W. STANLEY JEVONS in Australia at the age of 22.

Curiosity about the formation of clouds led Jevons to carry out an experiment in which he introduced a layer of warm sugar water above cold freshwater. In one of his first publications, an 1857 report in *Philosophical Magazine,* he stated that he had observed an "infiltration of minute, thread-like streams." Jevons had created sugar fingers, and he came close to realizing how they formed. He wrote, "The parts of these strata, however, which are immediately in contact, soon communicate their heat and tend to assume a mean temperature; and it is evident that whenever this is the case, the portions of liquid containing sugar must always be slightly denser than those that are pure, and must consequently sink below and displace the latter." This statement, with its implicit understanding that heat diffuses faster than dissolved substances, is a reasonable description of salt fingers. He then went off course, however, by oversimplifying the physics involved and assuming





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SECTION GLASS APPARATUS that was constructed by Jevons to simulate the formation of clouds in the laboratory.

two closely related phenomena. Evaporation removes freshwater from the surface of the ocean and leaves a higher concentration of salts, which increases the density of the remaining water. Conversely, precipitation dilutes the seawater and decreases its density.

Typically the changes in local seawater density arising from evaporation and precipitation tend to oppose those from the global pattern of heating or cooling. That is, greater evaporation at low latitudes increases near-surface salinity and density, whereas enhanced precipitation at high latitudes decreases both these properties.

This common pattern leads to something of a competition between the effects of temperature and salinity in the upper ocean. At most locations, the ocean is gravitationally stable, with lighter, warm water overlying heavier, cool water. But the ocean's salt gradient (considered in isolation from its temperature gradient) is decidedly top-heavy. The precarious salinity distribution survives in most places in the ocean by virtue of the stabilizing influence of temperature.

Nevertheless, according to Stern's theory, at those places where the differences in salinity between shallow and deep layers become large enough, fountain-like flow between adjacent levels should begin spontaneously. Calculations and laboratory experiments show that these flows, when fully developed, form a regular pattern of long, thin vertical filaments that appear as small square cells in horizontal cross section.

With theory making this clear prediction, seagoing oceanographers began searching in the mid-1970s for direct evidence of these salt fingers. One site studied for this purpose was in the eastern North Atlantic Ocean, where the salty outflow of the Mediterranean Sea can be detected to depths of more than one kilometer. (These waters are highly saline because the Mediterranean experiences a large excess of evaporation over precipitation.) As this water flows westward from the Strait of Gibraltar, it sinks and spreads into the Atlantic.

On an expedition in the 1970s to detect salt fingers, Bruce A. Magnell, then a graduate student at the Massachusetts Institute of Technology, towed a special instrument through the Mediterranean outflow in the Atlantic. The device contained unique, rapid-response sensors that could track small-scale temperature and salinity changes across salt fingers. From the same ship, Albert J. Williams of Woods Hole deployed a free-falling optical apparatus that could image the variation in refractive index caused by fingers. Both methods produced evidence that the expected centimeter-scale fluctuations occurred at the transition between Mediterranean and Atlantic waters. Salt fountains, albeit tiny ones, did in fact exist in nature.

The success of the initial fieldwork provided impetus for many further studies of salt fingers. For example, Thomas R. Osborn of Johns Hopkins University recently observed from a submarine that an asymmetrical form of salt fingering could take place: he found narrow, downward-falling plumes of warm, salty water that were surrounded by broad, upward flow. I have been able to show that such fingers are al-

RAYMOND W. SCHMITT, JR., after earning a B.S. in physics from Carnegie Mellon University, left his landlocked home state of Pennsylvania and went on to the University of Rhode Island. There he completed a Ph.D. in physical oceanography on the shores of Narragansett Bay. In 1978 he began a postdoctoral fellowship at the Woods Hole Oceanographic Institution overlooking Vineyard Sound in Massachusetts. He has remained there since and is currently a senior scientist. Schmitt's research interests include small-scale mixing in the ocean from both salt fingering and mechanical turbulence. He has published numerous articles on salt-finger mixing and the history of its scientific investigation. He also studies the role of the ocean in the global water cycle.

that all convection should occur as "minute streamlets."

A few years later Jevons returned to England and went on to become quite distinguished in the fields of economics and logic. His career was cut short by his untimely death by drowning at age 47.

Another opportunity to uncover the physical basis of salt fingers came around the time of Jevons's death, in 1882. In the following year the renowned English physicist Lord Rayleigh (John William Strutt) published a theoretical analysis of Jevons's experiments in a paper entitled "Investigation of the Character of the Equilibrium of an Incompressible Heavy Fluid of Variable Density." In it he provided a mathematical treatment of motion in stratified fluids. Rayleigh did not, however, consider the role of diffusion and so missed the opportunity to understand how salt fingers operate. He did formulate the conditions for the simpler Rayleigh-Taylor instability, now known to be important in plasma dynamics and supernova explosions.

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JOHN W. STRUTT at age 28, three years before succeeding his father as the third Baron Rayleigh.

Rayleigh's published acknowledgment of Jevons's earlier work is limited to a brief footnote in his 1883 paper, in which he also states that he had arrived at his theory in 1880. Intrigued about the timing and motivation of Rayleigh's work, I recently examined his original notebooks, which are archived at Hanscom Air Force Base in Massachusetts. A laboratory notebook in the hand of Rayleigh's assistant, his sister-in-law Eleanor Sidgwick, reveals that they, too, performed a sugar-finger experiment, at the Cavendish Laboratory in Cambridge, England, in April 1880. She wrote: "We repeated several times the experiment of W. S. Jevons [see Phil. Mag. for July 1857] on the formation of cirrous clouds.... The effects obtained resembled those described by him.... In all cases moreover the extremities of the filaments were expanded in a mushroom like form." Strangely, no mention of these experiments is made in Rayleigh's 1883 paper.

Rayleigh, who later received a Nobel Prize for the discovery of argon, was an astute theoretician and talented experimentalist. Yet despite having read Jevons's hint and duplicated his experiments, Rayleigh failed to recognize the role of heat conduction in the formation of salt fingers. Perhaps he could have reached this understanding through discussions with Jevons (both were Fellows of the Royal Society) had Jevons not died prematurely. We can only speculate that he delayed publication in order to have such discussions but never got the chance. Discovery of the physics of salt fingers had to wait for almost a century. *—R.W.S.*

lowed by theory; however, no one has yet identified the specific mechanism that causes the asymmetrical geometry to form.

Undersea Staircases

My own experience with salt fingers has come from laboratory and theoretical work as well as a number of oceanographic expeditions. The most ambitious of these voyages took place thousands of miles away from Gibraltar, on the other side of the Atlantic near the Caribbean Sea. The vertical salt gradient in that region is especially favorable to salt fingers, and like the Mediterranean outflow in the eastern Atlantic, the ocean there displays a very curious structure in the way in which temperature and salinity change with depth. Ordinarily, the upper ocean displays a continuous variation in temperature, linking the warm, sun-drenched surface layer to the cold, dark water of the abyss. Oceanographers call this gradual temperature transition the main thermocline.

Yet for at least as long as oceanographers have been able to make detailed measurements in this part of the North Atlantic (the past 25 years), the thermocline has been far from smooth. Instead temperature declines with increasing depths through a series of distinct steps, each between five and 40 meters thick. Oceanographers have come to refer to such structures as thermohaline staircases, a name that reflects the steplike changes in both temperature and the concentration of halide salts. Like vast geologic strata, individual layers of uniform temperature and salinity can be traced for hundreds of kilometers. It is difficult to imagine how such regular features can survive in a continually churning ocean. Should not the ever present internal waves and eddies (the ocean's turbulent "weather") quickly destroy the staircase pattern? What strange process can maintain such a subsea ziggurat?

The answer to this oceanographic puzzle lies in salt fingers. The motion of water in the fingers transports salt downward. Heat, too, travels downward with the salty filaments, even as it conducts sideways into the surrounding water. The motion thereby reduces the normal vertical gradient in the temperature and salinity. But remarkably enough, the overall density of seawater is affected oppositely: the ocean develops *greater* density differences when it forms salt fingers. This is because fingers transport more salt than heat; this action further reduces the density of the already lighter water on top and increases the density of the heavier water below. The result appears counterintuitive: ordinary mixing caused by turbulence would act to decrease the density gradient, not to increase it.

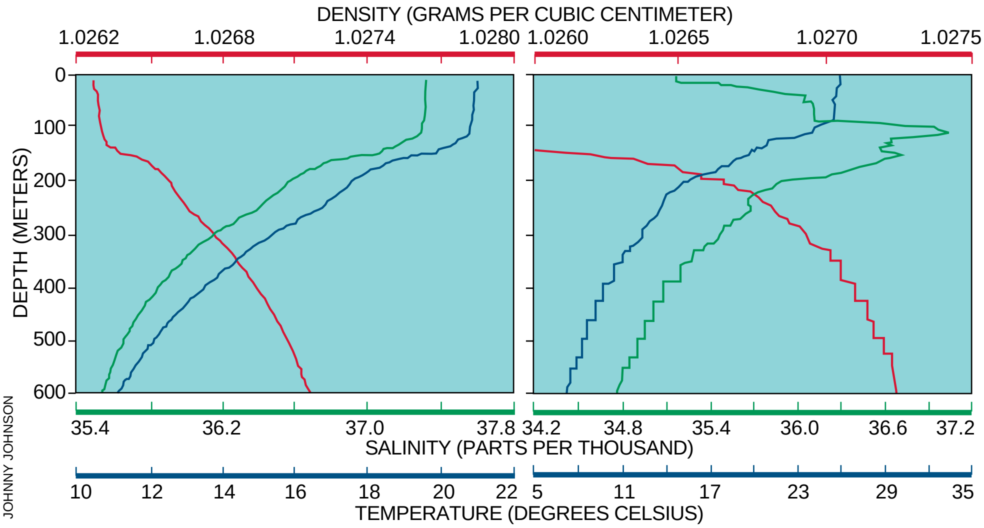
The peculiar density flux of salt fingering has a surprising consequence that neatly explains the staircase structure observed in the tropical Atlantic and other areas. Whereas ordinary mixing through random turbulence would be expected to smooth out any initial irregularities in a density profile, mixing by salt fingers serves to enhance them. In zones where the density gradient already changes sharply, the shift can become even more extreme. These places experience the highest density flux, which becomes large enough to reduce the density variation in adjacent regions. As a result, the upper ocean organizes itself into layers of fairly uniform temperature and salinity, bounded by "sheets," or interfaces, of high gradients. The layers contain large-scale convective flows; the interfaces are laced with salt fingers.

Thermohaline staircases were first observed in the laboratory at Woods Hole by Stern and J. Stewart Turner of the University of Cambridge in the late 1960s. At about the same time, other researchers began finding staircases in the ocean with electronic instruments that could register temperature and salinity continuously as they were lowered into the sea. Only recently have oceanographers developed a detailed picture of the internal workings of such remarkable structures.

Operation "C-SALT"

In 1985 my colleagues and I had the opportunity to study a large area where staircases form in the vicinity of the Caribbean. Our program was funded by the National Science Foundation and the Office of Naval Research, and good navy style demanded that we develop a suitable acronym. We adopted C-SALT, which stands for "Caribbean Sheets and Layers Transects."

Prior to our fieldwork, Janice D. Boyd of the Naval Research Laboratory determined from existing collections of oceanographic data that staircaselike temperature and salinity structures were commonly observed over a large area just east of Barbados. To probe this region, we assembled an observational armada that included aircraft and ships as well as stationary instruments moored to the sea bottom. The first rather pleasant surprise was that the system we sought covered a vast expanse. An area of over one million square kilometers—approximately equal to the extent of California and Texas combined—showed staircase-shaped profiles in our measurements. Typically 10 distinct layers could be seen. That such relatively thin features (each about 30 meters thick) could stretch for hundreds of kilometers over a large area of the ocean was entirely unexpected.



JOHNNY JOHNSON

OCEANOGRAPHIC PROFILES typically reveal a gradual change between the warm, saltier surface layer and cold, fresher waters below (*left*). In the transition zone salt fingering can create steplike changes in temperature and salinity that appear remarkably regular (*right*).

Another discovery about the staircase system was the manner in which temperature and salinity varied within individual layers. We found that these undersea strata became cooler and fresher to the south, warmer and saltier to the north. This pattern matches what can be observed in the laboratory when such layers are allowed to decay over time. From our measurements we concluded that the lateral changes in physical properties represent a balance between horizontal flow within the layers and differences in the vertical fluxes across the top and bottom interfaces.

Our documentation of the remarkably consistent way these properties varied with location provided an important clue that salt fingers were in fact maintaining the staircases. That is, we observed that within individual layers the changes in salinity were larger than those in temperature. No known mixing process apart from salt fingers could have caused such an imbalance. In fact, the measured ratio between salinity and temperature variations was very close to that expected from laboratory experiments and from theoretical predictions. Our study of staircase structures within the thermocline had confirmed that salt fingers were indeed the dominant form of mixing in the region, and we were quite excited by the discovery that the details of small-scale mixing had an observable effect on the large-scale temperature and salinity structure of the ocean.

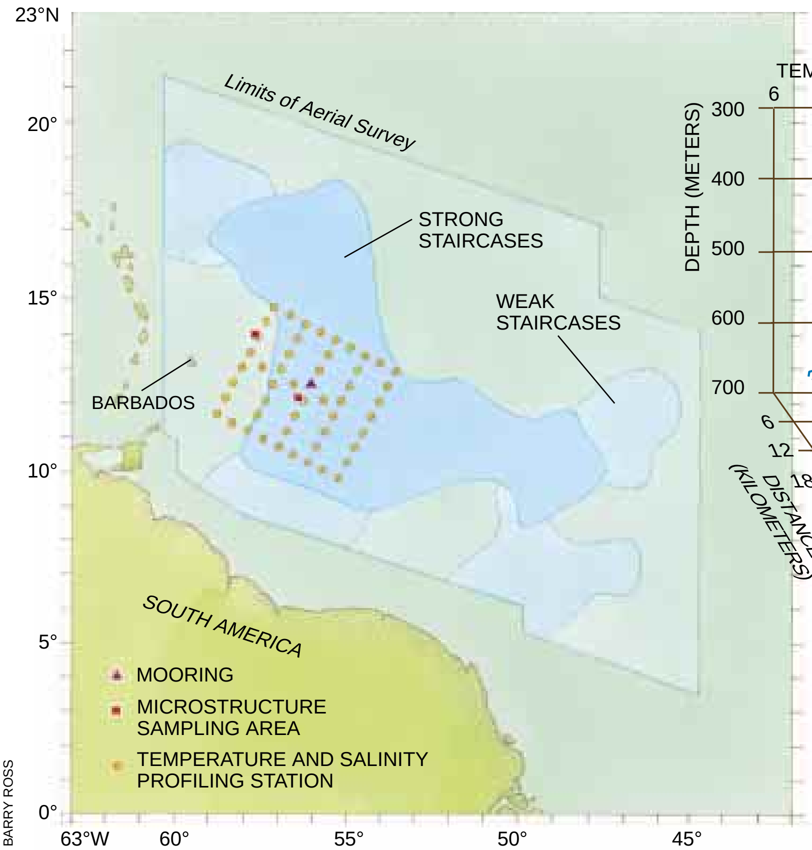
RICHARD MEGNA

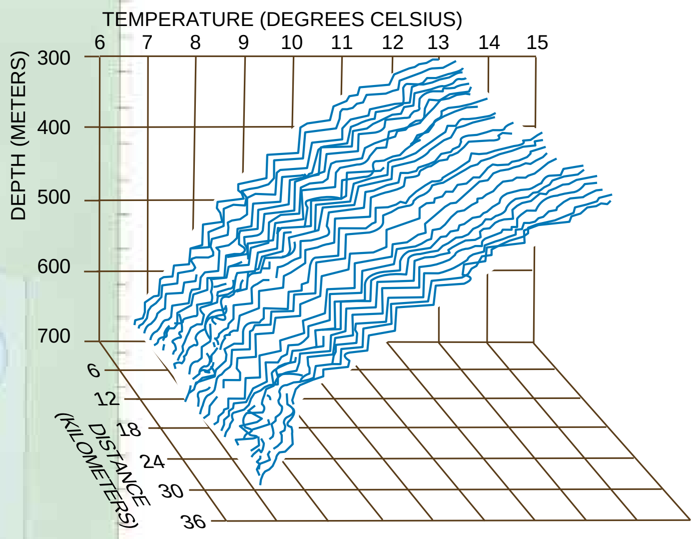
PURPLE FINGERS develop when warm, saline water containing potassium permanganate (which acts as dissolved salt and colorful tracer) floats on cold freshwater.

Fingers at the Interfaces

During the final stages of C-SALT, we set out to measure mixing rates using two different ships. On one vessel, Michael C. Gregg and Thomas B. Sanford (both at the University of Washington), along with Williams and me, deployed instruments that could record temperature and salinity profiles as they fell freely through the water. Rolf G. Lueck of the Chesapeake Bay Institute towed a streamlined device that measured turbulence. From the other ship George O. Marmorino and his colleagues from the Naval Research Laboratory deployed a string of sensors capable of mapping the temperature structure of the staircase and also detecting the small-scale effects of salt fingers.

With each instrument we found a similar pattern of relatively regular temperature variations in the interfaces between layers that was quite distinct from the spiky signature of turbulence. The scale of the undulations that we observed corresponded to a three-centimeter cell size, in excellent agreement with salt-finger theory. The data obtained from the navy's towed tempera-





BARRY ROSS

THERMOHALINE STAIRCASES caused by salt fingering (*top*) have persisted for more than 25 years throughout a large area of the western tropical Atlantic (*left*). The extent of this structure shows that tiny salt fingers make an important contribution to the vertical mixing of water masses, a process that goes on only weakly in most other areas of the open ocean.

ture sensors further revealed convective plumes operating within the mixed layers. The ocean's workings seemed to be following the patterns we had observed in the laboratory.

Still, the overall vigor of salt fingering my colleagues and I encountered during C-SALT was somewhat lower than we had anticipated. Also surprising to us was that Williams's optical device showed the fingers to be tilted far from vertical by the changes in velocity (shear) between layers. The weaker mixing seems to have resulted because the interfaces proved to be a few meters thick rather than a few tens of centimeters, as we had expected from laboratory experiments. More sophisticated physical models recently developed by Eric Kunze of the University of Washington account for the thickness variations and the effects of the vertical shear on the ocean's salt fingers.

Measurements made during C-SALT also highlighted an important thermodynamic difference between salt fingers and ordinary ocean turbulence. When turbulence from waves and eddies mixes the upper ocean, it distorts the normal temperature distribution as it converts some of the kinetic energy of the surface movements into potential energy in the thermal structure (by lifting dense parcels of water and depressing light ones). Some of this kinetic energy is dissipated, however, as heat. Salt fingers also mix parcels of water upward and downward. But compared with turbulence, salt fingering causes relatively little heat dissipation and so may allow five to 20 times as much vertical mixing for the equivalent energy loss.

The staircases encountered during the C-SALT expeditions cover an enormous expanse (about 25 percent of the area of the Atlantic between 10 and 15 degrees north latitude). Our estimates suggest that the mixing rate for salt is 10 times larger in this region than outside it, where only weak mixing occurs. Thus, staircases like those encountered during the C-SALT expeditions may provide a critical path for the ocean's vertical transfer of salt, oxygen and nutrients, as well as for many recently introduced pollutants.

Fingering in Other Realms

Progress in understanding the mixing from salt fingers has application far beyond calculating the ocean's response to environmental change. It has been suggested that the tall, narrow structures found in basaltic rock formations (termed columnar jointing) result from a type of "basalt fingering" within the cooling magma. Recent experiments on molten glasses by Yan Liang and Frank M. Richter of the University of Chicago and E. Bruce Watson of Rensselaer Polytechnic Institute confirm that fingers can evolve in such viscous fluids. Fingers also occur in metal alloys, leading to speckling and strength defects in castings that are cooled from below.

Salt-finger mixing can in theory also arise within stars and in the atmospheres of gaseous planets. Will space probes of the next century discover extraterrestrial analogues to the C-SALT staircases when they explore the atmospheres of Jupiter and Saturn? The answer must await advances in planetary exploration, but further insight into this fascinating physical phenomenon can meanwhile be obtained from the continued study of the earth's own magnificent fluid laboratory, the ocean.

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