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Temperature steps in salty seas

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With the right combination of temperature and salinity, the water column of a lake or ocean exhibits a layered, staircase structure. Such aquatic staircases have been observed throughout the world, from tropical Africa to the Arctic Ocean.

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As the summer heats up, many people will head to local lakes to refresh themselves. In a temperate climate, the surface layer of a lake often warms to above 20 °C. However, if you were to dive down into the lake, you would soon be in water with a temperature close to a frigid 4 °C. That cooler water settles in the deep, partially isolating itself from the warmer, sunlit upper layer that you enjoy. You can thank the physics of the water molecule for that—pure, salt-free water is at its most dense at 4 °C.

Bodies of water tend to settle into a state in which the fluid density increases with depth. That tendency, called density stratification, is often a dominating influence on the physics of lakes and oceans. The phenomenon, however, is more complicated when the water contains dissolved salts. Along with heat, salts act to change the density of water—the higher the salinity, or concentration of dissolved salts, the denser the water. If salinity increases with depth, then a water body can maintain density stratification even as its temperature increases with depth. Likewise, density stratification is possible for the reverse situation in which temperature and salinity decrease with depth. But because salt and heat diffuse at different rates, those density-stratified states can become unstable.

The perpetual salt fountain

Physicists Arnold Arons and Henry Stommel had an epiphany in the mid 1950s while brainstorming about measuring pressure changes in the subtropical Atlantic Ocean. As part of their musings, they envisioned a long pipe extending from the surface to great depths. Arons then realized that the decrease of salinity and temperature with depth in the subtropical Atlantic leads to a remarkable result: If seawater is initially pumped up the pipe, it will continue to flow without any additional energy input. That is because heat can be transferred through the pipe wall, but salt cannot. Once the water in the pipe is raised, its temperature rises to that of its surroundings, but the low salinity remains unchanged. Thus the water density will always be less than that of its surroundings, and it will continue to rise indefinitely in what Stommel and Arons called a perpetual salt fountain.

The fountain was a surprising discovery, but researchers were uncertain whether it represented an important process

in natural water bodies (which don't include long pipes). However, oceanographer Melvin Stern, a close colleague of Arons and Stommel, soon recognized that since salinity diffuses much more slowly than temperature, the impermeable pipe was not necessary: The slow diffusion of salt effectively provides a natural pipe wall.

The mechanism behind the perpetual salt fountain applies when warm, salty water overlies cooler, fresher water. For the reverse situation, in which warm, salty water lies beneath cooler, fresher surface water, the instability mechanism is a bit different. You can understand it by imagining a water parcel that is raised slightly from its normal resting level. In its new cooler and fresher environment, it loses heat much faster than it loses salt, thus becoming denser than it was to begin with. It therefore sinks deeper than its initial level and finds itself in warmer surroundings. It absorbs heat and rises again, now above the point to which it was first displaced. In that way the water packet oscillates with ever-growing amplitude.

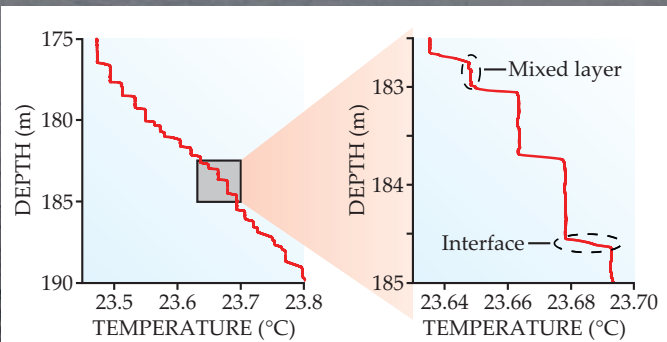
The processes described above have come to be known as double diffusion because they require at least two components that affect water density (usually temperature and salinity) and because the components must have different molecular diffusion speeds. Double diffusion occurs over vast areas of the world's oceans and in several salt-containing lakes. Although the double-diffusive mechanism is different depending on whether temperature increases or decreases with depth, in either case the outcome is a staircase structure of the water column, as shown in the figure. The steps exist because vertical fluid motions are constrained by the stable density gradient. But neither how the staircases form nor what determines the thickness of the layers is entirely clear, and both constitute active areas of research.

Poles apart

In this Quick Study, we focus on two double-diffusive water bodies that exhibit increasing temperature and salinity with depth. Although Africa's equatorial Lake Kivu and the Arctic Ocean would, at a glance, appear to be as opposite as can be, both have double-diffusive staircases that rank among the world's most remarkable.

Lake Kivu, on the border between Rwanda and the Democratic Republic of the Congo, is one in a chain of lakes that runs down East Africa's Great Rift Valley. From a vantage point on land or on a boat in the open water, the geologic origin of the lake is immediately apparent: The active Nyiragongo volcano stands ominously smoking on the northern shore. Centuries of eruptions of various volcanoes have produced a fractured volcanic soil that allows for the transport of warm, salty water into the lake through a series of deep springs. If you were to descend along the approximately 500-m depth of Lake Kivu's water column, you would feel a temperature increase of 3 °C and taste an increasing amount of salt. Those conditions are ripe for double diffusion, and indeed, the deep water features a staircase with hundreds of steps, a small section of which is shown in the figure.

Some 80° north from Lake Kivu, where the water temperature is about 25 °C cooler, is the Arctic Ocean. It is similar



An aquatic staircase in the tropics. The background image shows Lake Kivu and the smoking Nyiragongo volcano, located in tropical Africa. Deep springs inject warm, salty water below the lake surface and create the conditions needed for one of the double diffusion processes described in the text. As a result of that double diffusion, the temperature–depth profiles shown in the graphs exhibit a staircase structure. (Photograph by Jeff Carpenter; data courtesy of Tobias Sommer and Alfred Wüest.)

to a lake in that it has a limited connection to the bordering Pacific and Atlantic oceans. Relatively warm and salty Atlantic waters enter the Arctic through narrow channels close to Greenland. Being slightly denser than the surface waters of the Arctic, the Atlantic water descends to a depth of a few hundred meters as it circulates. The surface waters of the Arctic are extremely cold and fresh due to water flowing into the ocean from rivers in the surrounding continents and contact with the cold Arctic air, among other things. That cold, fresh surface water overlies the warm, salty Atlantic inflow; thus the conditions needed for double diffusion are in place. The resulting staircase has a similar geometry to that of Lake Kivu.

The strong salinity stratification of both Lake Kivu and the Arctic Ocean limits mixing and effectively isolates the deep waters from the surface. In Lake Kivu, the relative isolation of the deep water has led to the buildup of high concentrations of potentially hazardous dissolved methane and carbon dioxide gases. As the concentrations build, they will approach their saturation level and can erupt from the lake bottom. That sudden release of gases—called a limnic eruption—has already been documented in lakes Nyos and Monoun in Cameroon, with dire consequences (see *PHYSICS TODAY*, May 1996, page 20). The vertical transport of temperature, salinity, and gases by the relatively slow mixing across steps in the staircase affects the time scale over which the dissolved gases reach dangerous saturation levels.

The Arctic contains enough heat in the deep ocean to entirely melt the sea-ice pack. However, across much of the central Arctic Ocean, the staircase structure indicates that upward transport of deep heat is minimal. Density stratification acts as a cap on the transport of heat from the deep Arctic, and oceanographers are carefully watching the staircase for indications of changing heat transport.

A question of scale

Instruments tethered year-round to drifting sea-ice floes have enabled scientists to obtain a detailed picture of the double-diffusive Arctic staircase, even in the most remote and hostile regions of the ocean. The results of those intensive measurements show that each individual step of the staircase extends across almost the entire ocean basin. That means mixed layers on the scale of 1 m in the vertical have horizontal extents on the order of 1000 km, an aspect ratio of 10^6 ! A sheet of paper the size of a football field would have a similar aspect ratio.

In addition to discovering the immense horizontal scales of the staircases, scientists have made advances in resolving the tiniest scales of variability. So-called micro-structure profilers fall freely through the water column collecting measurements that can resolve turbulent fluctuations at a scale of just a couple of millimeters. Measurements in Lake Kivu and the Arctic Ocean have contributed to a growing body of evidence suggesting that the interfaces separating mixed layers are nonturbulent; transport across them is by molecular diffusion. Evidently, the individual staircase steps that stretch across vast regions of the Arctic Ocean are ultimately linked by the molecular collisions responsible for diffusion.

Additional resources

- ▶ H. E. Huppert, J. S. Turner, "Double-diffusive convection," *J. Fluid Mech.* **106**, 299 (1981).
- ▶ M. Schmid et al., "Weak mixing in Lake Kivu: New insights indicate increasing risk of uncontrolled gas eruption," *Geochem. Geophys. Geosyst.* **6**, Q07009 (2005).
- ▶ M.-L. Timmermans et al., "Ice-Tethered Profiler observations of the double-diffusive staircase in the Canada Basin thermocline," *J. Geophys. Res.* **113**, C00A02 (2008). ■