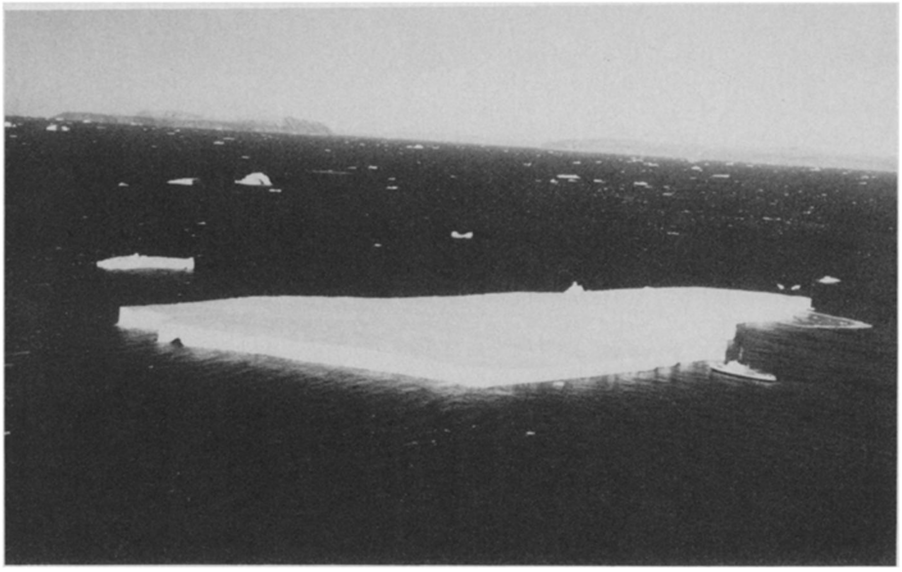
Salt Fingers, Icebergs and Stars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Molecular diffusion can establish surprisingly complex circulation patterns within the fluids that make up oceans and stars

By IVARS PETERSON

At first glance, the melting of icebergs seems to have little to do with the layering of molten rock within chambers beneath volcanoes and even less to do with currents inside stars. But a new branch of fluid mechanics that deals with complex circulation patterns is emerging to link these phenomena. The theory's most important application may be to the mixing of large masses of ocean water when, for example, warm, salty water from the Mediterranean Sea slips into the cooler, less salty depths of the Atlantic Ocean.

The process that links all these examples is called "multicomponent convection." Single-component convection is familiar to anyone who has watched shimmering air currents above a heater or felt the draft of air being drawn up a chimney or simply noted that hot air rises. In these cases, temperature differences, which alter the air's density, drive the air's motion. In the ocean, two components—heat and salt — govern the flow of liquid from one place to another. Inside a star, four components may be responsible for fluid motion: angular momentum, heat, magnetic field and the ratio of hydrogen to helium. Complicated convective patterns can arise whenever any of these components differ from place to place within a fluid.

Only 25 years ago, two-component (or "double-diffusive") convection was considered "an oceanographical curiosity." It first came up when a team of oceanographers speculated that a "perpetual salt fountain" could be set up in the ocean. They imagined vertically suspending a mile-long copper pipe in water that was warmer and saltier at the pipe's upper end than it was at its bottom. A pump starts the process by drawing water up the pipe. As the water rises, it warms but picks up no additional salt. This makes it less dense than the surrounding water at the upper end of the pipe, so the water continues to rise, pulling more water into the lower end of the pipe. Once the process begins, the pump is no longer necessary, and the fountain's upward flow continues until the sea's salt is evenly spread throughout the water.

Researchers soon realized that the pipe wasn't necessary for the process to occur naturally within the ocean. Because heat diffuses about 100 times faster than salt, miniature salt fountains or salt fingers could form at the interface between a layer of warm, salty water sitting on top of colder, fresher water. On the basis of temperature alone, the warm water should remain on top of the colder layer. Nevertheless, once an instability sets off the process, a nest of convective cells — sets of descending fingers and ascending fountains — forms, and mixing occurs because the salt concentration doesn't change as rapidly as the water's temperature.

Salt fingers remained merely an interesting theoretical and laboratory curiosity until 1973, when salt fingers were detected at the edges of a tongue of warm, salty water flowing through the Straits of Gibraltar into the Atlantic. There, innumerable salt fingers, each only a centimeter wide and a meter tall, played their role in efficiently mingling the different waters. Raymond W. Schmitt of the Woods Hole Oceanographic Institution in Massachusetts says, "They form a nest of heat exchangers." Warm, salty fluid flowing down is continually exchanging heat and salt with cold, fresh fluid coming up.

"Now a number of us are quite excited," says Schmitt. "We feel that [salt fingers] are a very important oceanographic phenomenon. It's one of the areas of oceanography that is ripe for a lot of progress."

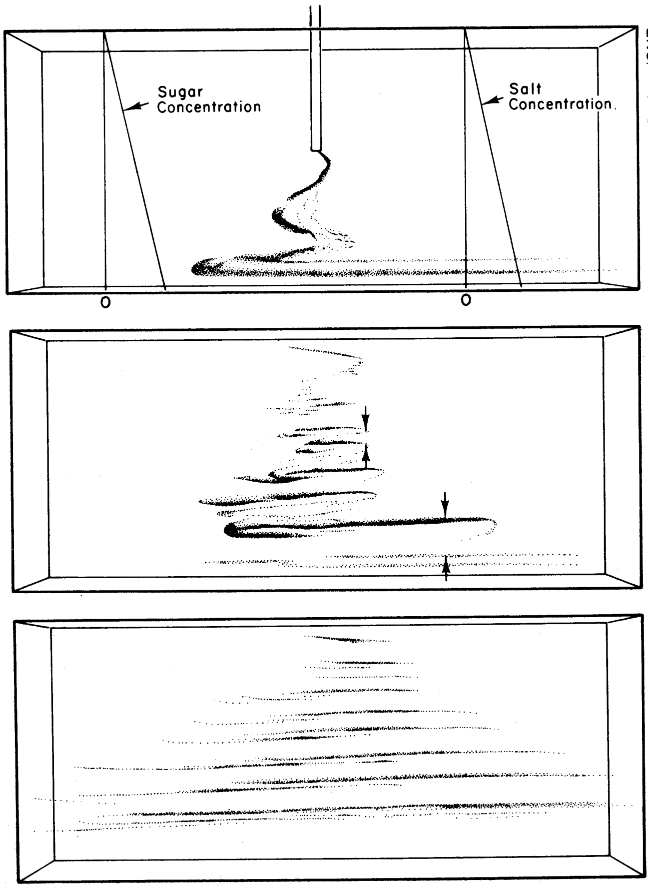
Most oceanographers now concede that double-diffusive convection is a significant mixing mechanism wherever water masses having very different salt and heat contents meet to form fronts, particularly in polar waters. This conclusion comes as a surprise to those who never expected a process that occurs essentially at the molecular level to be as important in stirring up the ocean as larger-scale processes like turbulence and internal waves. In the last few years, salt-finger "signatures," steplike temperature-depth profiles, have also shown up in tropical oceans. Now, researchers are beginning to study salt-finger "fields" more systematically to determine their extent and how they change over time.

David H. Johnson of the Solar Energy Research Institute (SERI) in Golden, Colo., says, "The excitement in the field comes from the fact that strong convective motions can result even when a dense fluid underlies a less dense fluid, where naive arguments would predict stability."

Complicated currents and systems of layers also arise, for example, when warm, salty water lies underneath colder, fresher and less dense water. Diffusion of heat and salt across the boundary can set up oscillations within the liquid, which gradually break the interface up into a set of layers. Johnson describes the process as "almost like a molecular tug-of-war" in which the opponents — heat and salt — weaken and strengthen at different rates. Compared with salt fingers, which directly transfer volumes of fluid across a boundary, mixing is slower in this case because it depends only on the motion of individual molecules.

This process has been identified in Antarctic lakes and at the bottom of the Red Sea. Currently, it's a significant concern for solar-pond designers, who are interested in preventing layering and consequent mixing from occurring.

A solar pond, typically 10 acres in area



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In this laboratory demonstration, interleaving tongues of water form along a vertical front between concentrated salt and sugar solutions after removal of a barrier separating the two fluids. The fluids have the same density profile but different diffusion rates.

and about 12 feet deep, traps heat from the sun within a very salty storage region at the bottom of the pond. An intermediate zone, which gradually gets saltier as the depth increases, separates the salty storage region from the fresher top layer. The pond's salt concentration gradient allows sunlight to pass through but prevents heat from being convected back out. This provides efficient, yet transparent, heat insulation against the atmosphere. SERI's Federica Zangrando says, "If the gradient becomes unstable, that is, convective layers form in the interior of the gradient, or the boundaries are eroded, thus decreasing the effective thickness of the gradient zone, then the pond will lose some of its 'insulation' and the thermal performance will drop."

Zangrando says little research has been done to understand the physics of systems, like solar ponds, with strong concentration and temperature gradients. Recent solar-pond studies show that the breaking up of the gradient into distinct layers is generally confined to small regions of this zone rather than spread across the pond's entire profile. This suggests that a pond's stability depends on small, local variations in the properties of the gradient within the pond. Enough is now known to evaluate solar-pond stability in general and to come up with the most stable salt gradients for a successful solar pond, Zangrando says.

Other situations in which engineers must watch for double-diffusive effects like salt fountains and layering are sewage disposal in the sea and the disposal of effluent from desalination plants. Normally, the effluent is ejected from a pipe laid along the bottom of the ocean. Engineers must ensure that the effluent stays at the bottom and doesn't rise to the surface because of complex convection processes. Potentially dangerous situations can arise for similar reasons during the transport and storage of liquefied natural gas or when liquefied natural gas spills on the sea surface.

Layering and diffusive mixing also occur at the melting, below-water faces of an iceberg or a glacier. The meltwater spreads out in a series of layers all along the depth of a vertical wall of melting ice instead of convecting right to the surface and collecting in a pool at the top. This makes the collection of fresh meltwater from icebergs technically more difficult than many people expected.

Some geologists now speculate that similar layering may occur when new molten rock flows into the base of a magma chamber beneath a volcano. These liquids, which may consist of two or more chemical components that diffuse at markedly different rates, would then cool and crystallize into distinctive patterns. One obvious place to apply and test these new concepts, says Herbert E. Huppert of the University of Cambridge in England, is the Skaergaard intrusion, a large geologic formation in Greenland. The complex patterns seen in the intrusion look like double-diffusive layers. The exposed, solidified cores of some volcanoes show similar rock layers.

Multicomponent convection may also be responsible for a variety of crystallization patterns seen in the laboratory or in industrial processes. Metallurgists suspect that diffusive-convection effects may be responsible for "freckling," the appearance, within solidified castings, of long, narrow regions in which impurities tend to segregate. Similar processes may be at work creating unwanted dendrites (branched crystals) that possibly slow down the growth of crystals from molten material.

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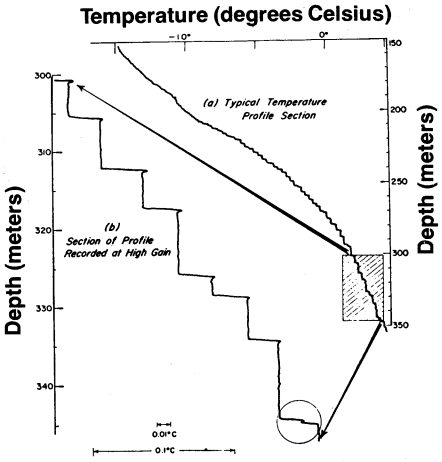

Salt fingers produce a characteristic "signature" consisting of a sequence of steps that sometimes show up in oceanic temperature-depth profiles. This example was taken in the Arctic Ocean.

One of the most intriguing possibilities for multicomponent-convection theory involves the complex motions that occur within the fluid interiors of stars. For example, if a star's core rotates faster than its surface, then the angular momentum will depend on the radius. One can imagine "angular momentum" fingers interacting with local variations in the star's magnetic field and its elemental composition to set up extensive currents that help redistribute the star's energy.

In a 1981 review article in the JOURNAL OF FLUID MECHANICS, Huppert and J. Stewart Turner of the Australian National University in Canberra wrote, "... the phenomena described are widespread and probably occur in contexts which have not yet been recognized." The problem is that transfer of this understanding from one field to another, they noted, depends mainly on the accidental communication between scientists whose interests appear at first sight very different. Huppert asks, "Could igneous geologists be expected to read papers on melting icebergs?" One attempt to bridge the gap was a conference devoted to double-diffusive convection, held last year in Santa Barbara, Calif., that attracted astrophysicists, chemists, fluid dynamicists, geologists, geophysicists, metallurgists and solar-pond engineers.

Nevertheless, Johnson, who chaired the conference, says, "The extent to which double-diffusive phenomena occur in nature, and their importance, is still a controversial topic." ☐