Linking Earth, Ocean, and Air at the AGU

December's annual fall meeting of the American Geophysical Union presented another opportunity for specialists in everything from air pollution to the origin of Earth to immerse themselves in their narrow disciplines as well as cross into related areas. Overlap between disciplines can be peripheral but interesting, as in the examples below. The amount of salt in surface water can influence ocean circulation and thus climate, and water passing from the crust through sediments into the ocean can help control the concentration and composition of seawater salts.

Is a Climate Jump in Store for Earth?

Wallace Broecker is worried about the future of Earth and how little he understands about it. A prominent geochemist at the Lamont-Doherty Geological Observatory, Broecker looks at how the ocean and atmosphere have interacted in the past as climate has swung from one extreme to another, sometimes with stunning abruptness, and wonders why we are not more concerned about that happening in the future, our immediate future. At a Union session of the AGU meeting, he warned that, as the greenhouse warming pushes the climate system to temperatures unheard of for millions of years, things might happen all too quickly. "One might not be surprised," he said, "if the buildup of carbon dioxide provokes the system into another mode of operation," one not at all to the liking of humans and other living things.

Broecker sees several past examples of abrupt climate change. It used to be that the most familiar abrupt change was the one at the end of the most recent ice age. Eighteen thousand years ago, the ice age was at its peak. Between 14,000 and 6,000 years ago, 50 million cubic kilometers of ice melted and Earth was soon enjoying one of its warmest climates in millions of years.

But the end of an ice age is no longer seen as all that abrupt. Climate records deciphered from Greenland ice cores show 6°C leaps of temperature accompanied by 20% increases of carbon dioxide, all of which took as little as a few hundred years. Western Europe experienced an even more abrupt climate jump, called the Younger Dryas period, about 11,000 years ago after the ice had begun receding. Forests that had dominated parts of northern Europe for 2000 years after the ice's withdrawal succumbed during a few decades to renewed cold. The glacial-era shrubs that replaced the trees persisted for less than 1000 years before the climate just as abruptly jumped back to the relative warmth that favored forests.

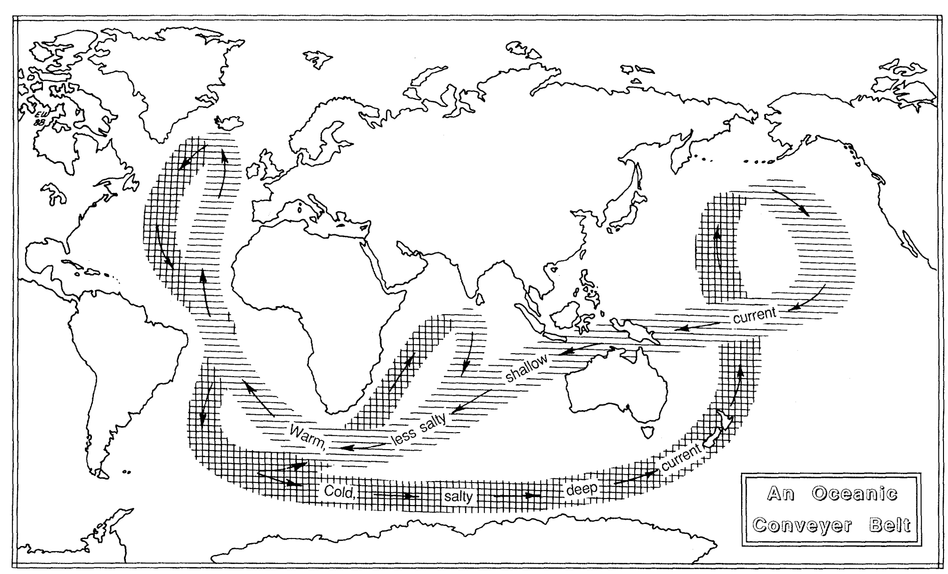
Broecker does not claim that the causes of these climate jumps are completely understood, but he and others do see a central role for major reorganizations of the ocean-atmosphere system. Such reorganizations are common today, at least on a regional scale, he notes. Every summer the sun warms the Tibetan Plateau to the point that the winds of chilled, dry air falling southward across the Indian subcontinent are replaced by warm, moist air drawn northward by the rising of warm air over the plateau. That marks the arrival of the monsoon and its rains. "That is a response to the sinusoidal seasonal cycle that is abrupt, a matter of a day," Broecker observed. "The glacial-interglacial change was of this type."

The major reorganization at the end of the ice age, about 13,500 years ago, seems to have involved the turning on of a transport system that to this day carries water and heat nearly around the girth of the globe. It can be visualized as a conveyor belt of ocean currents carrying heat and freshwater. One end is in the North Atlantic near Iceland, where the cold air blowing across the water from Canada removes heat and by evaporation water vapor. Downwind, that heat moderates the climate of Europe.

Now colder and more saline, the surface waters of the far north are dense enough to sink and form a deep-sea current called the North Atlantic Deep Water (NADW), a subsurface ocean river whose flow is 20 times the flow of all the world's rivers. While out of touch with the surface, NADW heads south, rounds the tip of Africa, and eventually reaches the other end of the conveyor belt, the North Pacific.

There the reverse operation occurs. Water rising near the surface takes on heat and freshwater as it heads south. Broecker suspects that the water that freshens the North Pacific is the same water that was distilled from the North Atlantic, which would require that it cross from sea to sea in the atmosphere. Eventually, the freshened Pacific water makes its way back to the South Atlantic and heads north by a circuitous route, picking up heat as it goes.

Ocean sediment records show that the formation of NADW greatly slowed during glacial times, when Europe was iced over or covered with tundra. Broecker finds the most logical way to control the conveyor to be the conversion of the water vapor headed for the Pacific into precipitation while it



A great conveyor. *In this highly stylized diagram, freshwater and heat added at the Pacific end of the conveyor belt is carried into the Atlantic by shallow currents. At the other end of the belt, in the northern Atlantic, heat and freshwater are removed by cold air moving off Canada, causing the water to sink. That warms Europe when the belt is carrying a large load, as it does now, and leaves that area in the cold if the conveyor slows or stops.*

could still drain back to the Atlantic. This atmospheric alteration might be the sought-after link between the Milankovitch orbital cycles and climate change, Broecker says; an orbitally strengthened conveyor belt could have delivered enough heat to melt the great ice sheets, he notes.

Another type of control of the NADW conveyor belt may have been involved in the creation of the Younger Dryas cold snap. The most discussed mechanism involves the torrent of meltwater from the North American ice sheet that at first flowed down the Mississippi to the Gulf of Mexico. Once the ice sheet had retreated far enough, the St. Lawrence drew off much of that water to the Atlantic. There this much lighter freshwater could have floated on the surface of the northern Atlantic and formed a lid, reducing NADW formation as well as the supply of heat to Europe.

What this past behavior of the climate system means for our greenhouse future is anyone's guess, which is what bothers Broecker. On the bright side, since the ice melted, Earth seems to have been securely locked into the present mode of operation of its climate system. But the temperatures expected in the next century are unknown territory for paleoclimatologists. There is no clear record of how the climate behaves under those conditions. Attempts to create models that simulate the new climate are still hampered by simplistic renditions of the ocean.

JOIDES *Resolution*

Probing the sources of seawater.

Ocean Crust's Role in Making Seawater

Unlike a freshwater lake, the ocean is the end of the line for the salts dissolved in all natural waters. That is what makes the ocean salty. But, geochemists ask themselves, why that particular combination of salts? Why, for example, is there not more magnesium in the sea when so much is carried to it?

At the AGU meeting, Michael Mottl of the University of Hawaii and Marcus Langseth of the Lamont-Doherty Geological Observatory reported conclusive evidence that seawater whose composition has been altered by passing through warm crustal rock can leak through 300 hundred meters of mud to influence the composition of the ocean. The site that they studied, on the south flank of the Costa Rica Rift east of the Galápagos Islands, is one of the oldest sites yet found through which crustal seawater is leaking, and it is blanketed with the thickest sediments.

"It is an extreme case," says Mottl, "but sometimes the extreme cases can be most instructive because they set limits." Such limits are sorely needed if geochemists are to determine the roles of the competing processes controlling seawater composition, which include these low-temperature processes, the high-temperature processes evident in the hot springs spewing from the central rift, and the weathering of the land.

The first sign that something was unusual about the Costa Rica Rift site came in 1979 when the deep-sea drilling ship *Challenger* penetrated the sediment cover and punched into the crust. Curiously enough, the hole sucked a steady stream of seawater into the crust. Researchers concluded that they had penetrated a convection system. Heat lingering in the crust presumably was driving a rising arm of warmer water upward against the base of the sediment layer. Once that water cooled by conduction, it began sinking again and creating the 10 atmospheres of suction found in the hole. But is this circulation powerful enough to drive water through 300 meters of mud into the ocean, or is this crustal circulation completely sealed off by sediments?

To find out, Langseth, Mottl, Michael Hobart of Lamont-Doherty, and Andrew Fisher of the University of Miami surveyed a 100-square-kilometer area around the sucking hole. The average amount of heat flowing up through the sediment is typical for 6-million-year-old crust, they found, but there are small warm spots of heat flow twice as great as surrounding areas of reduced heat flow. These warm spots tend to lie over topographic high spots of the rocky crust.

Chemical analysis of the water squeezed from warm-spot sediments revealed that the concentration of dissolved calcium soared from the 10 millimoles per kilogram characteristic of the bottom water to 50 millimoles per kilogram 4 meters beneath the sea floor. Magnesium, on the other hand, tended to disappear about 10 meters down core over warm spots. Where heat flow was near average, bottom water concentrations prevailed throughout the shallow cores.

Langseth and his colleagues conclude that the circulation system within the crust does drive water, albeit a small amount, through the sediment. The sediment pore water 10 meters below the sea floor at warm spots seems to be altered seawater upwelling from crustal high spots. Reactions with the rocky crust remove magnesium and other elements from solution by forming new minerals and add calcium and other elements through leaching. To judge from the observed concentration gradients, water is upwelling at up to 6 millimeters per year. At those rates, the trip up takes tens to hundreds of thousands of years. The existence of a downward leg of the circulation system was confirmed recently when the pore water chemistry of a hole at site 677 drilled by the Ocean Drilling Program's ship JOIDES *Resolution* revealed clear signs of downwelling in one of the areas of lowest heat flow.

This site is one of the oldest shown to have a chemical connection between the crust and the sea. The younger, less thickly blanketed sites have higher flow rates but less extreme alterations of chemical content. As oceanographers get a more complete picture of the distribution of heat flow and chemical fluxes over the ocean floor, they should be able to estimate the role of such low-temperature processes on the amount and types of salt in the sea. ■

RICHARD A. KERR