New Data on Deep Sea Turbulence Shed Light on Vertical Mixing

Rough Seafloor Topography Has Far-Reaching Effect

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The global thermohaline circulation is basically a wholesale vertical overturning of the sea, driven by heating and cooling, precipitation and evaporation. (Changes in temperature=thermo, changes in salinity=haline.) Bottom waters move equatorward from their high-latitude regions of formation (the cold limb of the circulation), upwell, and return poleward at intermediate depth and/or the surface (the warm limb). As the bottom waters are colder than the overlying waters, this circulation is responsible for a large fraction of the ocean's poleward heat transport. In addition, these flows often redistribute fresh water, as the northward and southward moving waters generally have different salinities.

These oceanic heat and water transports play a significant role in Earth's climate. The earth gains heat from the sun at low latitude, and radiates heat back to space about the poles. To maintain a quasi-steady state, the ocean–atmosphere system must carry heat from low to high latitude. At mid-latitudes, where the poleward heat flux is maximum, the oceanic and atmospheric contributions are about equal. One component of the atmospheric heat transport involves evaporation, water vapor transport, and its subsequent condensation. Net north/south water vapor transport in the atmosphere is balanced by liquid water transport by rivers and ocean currents.

For almost 200 years, since the writing of Count Rumford in 1797, there has been a basic understanding of the cold limb of the thermohaline circulation. The combination of atmospheric cooling, evaporation, and, in some cases, salt rejection during the formation of sea ice causes surface waters at high latitudes to become sufficiently dense that they sink to the ocean bottom. These newly formed deep waters subsequently spread horizontally within the constraints of the seafloor's bathymetry to renew the deep waters found in the interiors of the world's oceans. There are two principal formation sites for dense bottom water: the Greenland and Norwegian Seas of the northern North Atlantic Ocean, and around the Antarctic continent, particularly within the Weddell Sea. Together, these source regions export some 20 to 30 million cubic meters per second of bottom water to the other ocean basins. (For comparison, the chiefly wind-driven Gulf Stream, Kuroshio, and Agulhas Currents carry in excess of 100 million cubic meters per second within horizontal circulations.)

The processes involved with the return limb of the thermohaline circulation—the transformation of these bottom waters to lower density, and their

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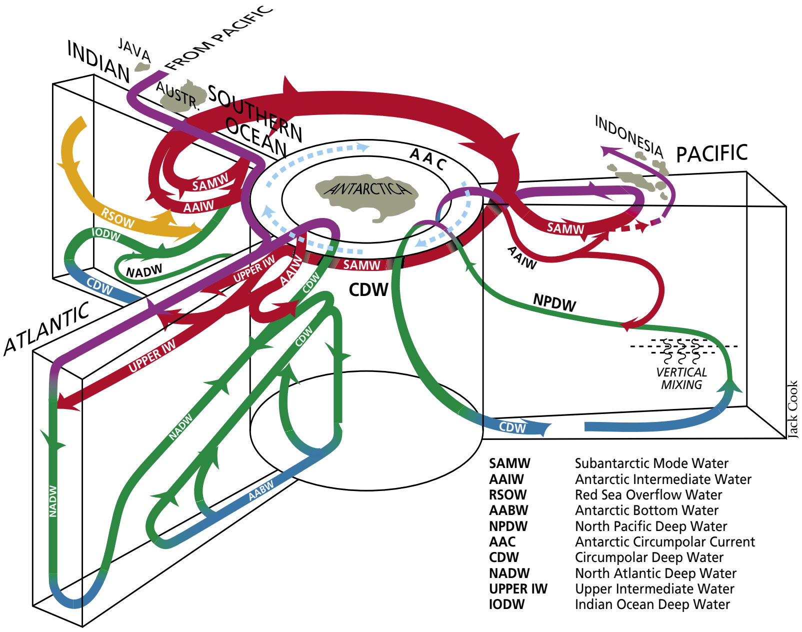
The principal tool for work described in this article is the high resolution profiler. It records temperature, salinity, pressure, and horizontal velocity 10 times per second on descent to the ocean floor, then returns to the surface. For a detailed discussion of the instrument's development, see the Spring/Summer 1995 issue of Oceanus.



SAMW	Subantarctic Mode Water
AAIW	Antarctic Intermediate Water
RSOW	Red Sea Overflow Water
AABW	Antarctic Bottom Water
NPDW	North Pacific Deep Water
AAC	Antarctic Circumpolar Current
CDW	Circumpolar Deep Water
NADW	North Atlantic Deep Water
UPPER IW	Upper Intermediate Water
IODW	Indian Ocean Deep Water

Circulation schematic of the world's major water masses (also see inside front cover). Of concern here are the mixing processes that modify the bottom and deep waters within the cold-to-warm limbs of the overturning circulation.

upwelling and eventual return to the high-latitude cooling zones—are less well understood. An upwelling of deep and bottom waters is believed to be fed by the continual supply of new bottom water: Dense new waters intrude below older waters and force them upwards. The bottom water source strength of 20 to 30 million cubic meters per second translates into a globally averaged upwelling rate at mid-ocean depth of about 3 meters per year. This upwelling has both dynamical and thermodynamical implications.

To maintain a steady-state temperature distribution in the face of this upwelling of cold water, a compensating warming is required. This warming may be accomplished by internal mixing of the deep ocean. Models exploring the thermodynamic balance between the downward diffusion of heat associated with mixing by turbulent eddies and the upwelling of cold water were published by Klaus Wyrtki (University of Hawaii) and Walter Munk (Scripps Institution of Oceanography) in the mid 1960s. At about the same time Wyrtki's and Munk's papers appeared, Henry Stommel, considering the dynamical effects of deep upwelling, proposed the existence of abyssal gyre circulations involving poleward deep flow in the ocean interiors fed by a series of western boundary currents. These boundary flows ultimately connect to the high-latitude bottom water formation sites. Twenty years later Frank Bryan (National Center for Atmospheric Research) published a study of an idealized, three-dimensional ocean model showing a direct relationship between the intensity of the vertical mixing and the strength of the thermohaline overturning circulation. These theoretical ideas linking diffusion, upwelling, and the deep current systems have guided research on abyssal circulation for the past three decades.

But how much vertical diffusion is there in the oceans, and what processes sustain it? Munk's application of his model to data from the North Pacific Ocean required a downward diffusive heat flux about 1,000 times larger than that caused by molecular diffusion (the process whereby differences in temperature or concentration of a dissolved substance are removed by the random motion of molecules). More recent studies concerning vertical diffusive heat fluxes in semi-enclosed basins also required downward diffusive heat fluxes thousands of times greater than those due directly to molecular diffusion. All of the researchers involved invoke turbulent mixing as the mechanism supporting these large diffusive heat fluxes.

Ocean turbulence is the focus of a subgroup of physical oceanographers specializing in microstructure, that is, temperature and velocity structures occurring at spatial scales directly influenced by seawater's molecular viscosity and thermal diffusivity—typically around one centimeter. These scientists have extensively sampled the upper ocean in recent years. Apart from the surface layer (which is actively mixed by wind and waves), the shallow ocean margins, and highly sheared flows like the equatorial undercurrent, the microstructure data suggest turbulent diffusive fluxes some ten times smaller than the studies mentioned above. This seeming discrepancy caused some to question the models used to deduce the intensity of vertical diffusion from microstructure data, and whether sufficient data had been gathered to adequately describe ocean microstructure. Relatively weak mixing in the upper ocean away from boundaries was, however, recently confirmed by a nontoxic chemical tracer release experiment in the Northeast Atlantic led by Jim Ledwell.

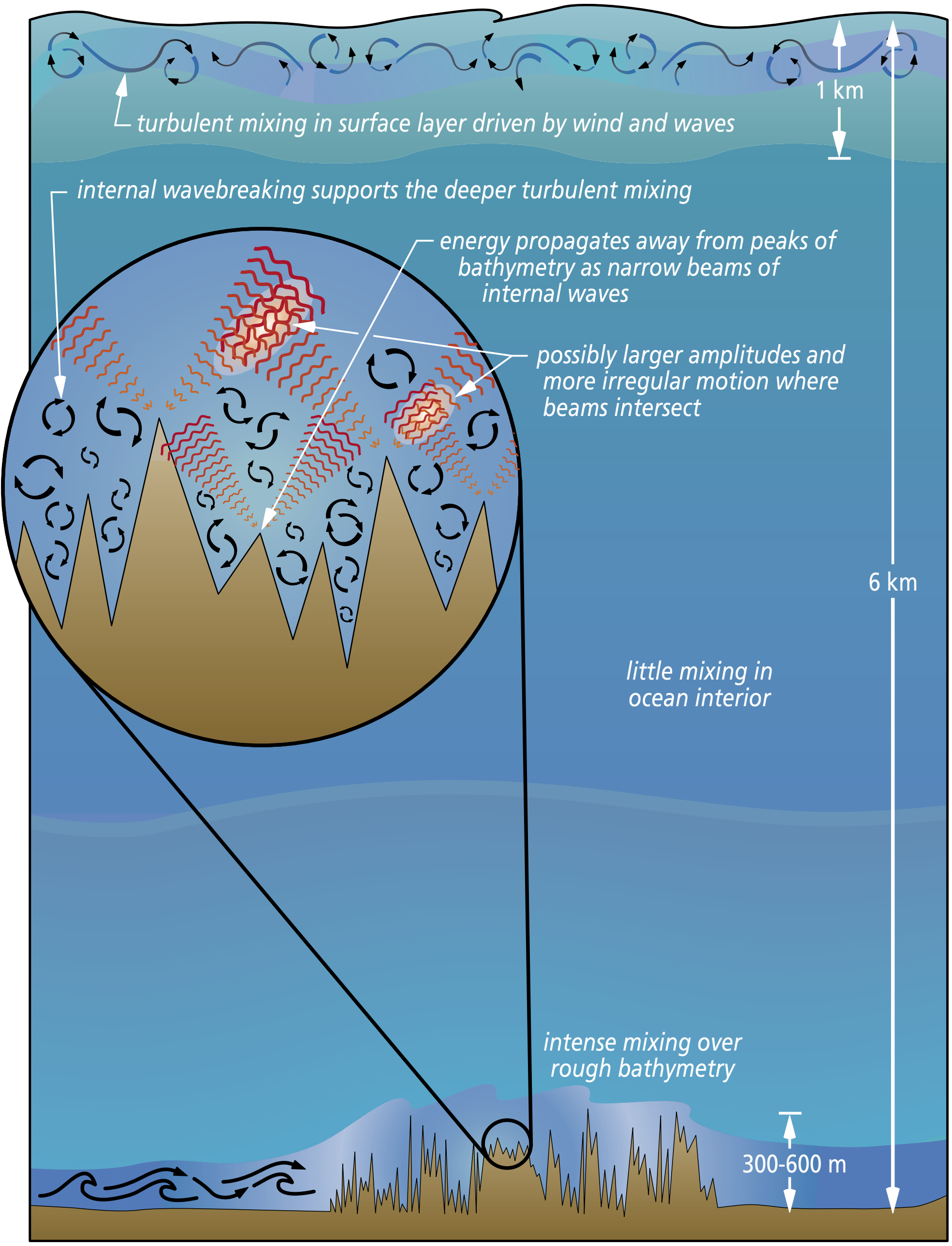
The apparent contradiction between microstructure-based and indirectly determined estimates of vertical diffusion might actually reflect a real difference with depth in the ocean. Part of the problem is that the indirect estimates of vertical mixing have been derived for the deep ocean, while the bulk of the microstructure observations are from the top 1 kilometer of the ocean. Ray Schmitt, Kurt Polzin, and I have recently addressed this issue with a series of cruises on which we acquired full-ocean-depth profiles of temperature and velocity microstructure. We find evidence of enhanced turbulent mixing in the deep ocean near the bottom, particularly in regions where the bottom is rough. The zone of enhanced mixing extends upward to several hundred meters above the bottom, a span much greater than that of the traditional bottom boundary layer, a roughly 10-meter-thick, vertically homogenized layer that is maintained by bottom-generated turbulence. Our data also show strong internal waves at these sites, and we believe the enhanced mixing is sustained by the breaking of these internal waves, which are both generated at and reflected from the rough bottom.

These observations also document striking horizontal patterns in the turbulent mixing at depth. Our current study (a joint microstructure-tracer experiment in collaboration with Jim Ledwell) is now underway in the Brazil Basin, the region where Nelson Hogg and colleagues inferred significant vertical diffusion from a heat budget for the bottom waters. In the interior of the basin where the bottom is smooth, the microstructure data imply turbulent fluxes less than a tenth of Hogg and colleagues' basin-averaged value. In contrast, above the rough flanks of the Mid-Atlantic Ridge in the eastern third of the basin, we deduce turbulent fluxes greater than their figure.

We find that the horizontally averaged turbulent heat flux for our study region, based on the microstructure data now in hand, is in near accord with that derived from the bottom water heat budget. Our results suggest that vertical diffusion in the deep ocean is dominated by turbulent mixing near rough bathymetric structures, a refinement of Munk's hypothesis that it occurs generally near the bottom. Greater average turbulent fluxes may be achieved at depth than in the upper ocean because a larger fraction of the deep ocean is in close proximity to the bottom. Spatially variable mixing in turn implies existence of horizontal circulations to distribute modified waters from these mixing zones throughout deep basins. Moreover, given the dynamical links between mixing, upwelling, and circulation, our findings hint that the deep gyres predicted by Stommel might be highly distorted in the real ocean.

The scientific community is just beginning to document the intensity and patterns of mixing in the ocean abyss. It is not surprising that mixing in ocean climate models has so far been generally taken as spatially uniform. Much work remains to be done, both observational and theoretical, to fully understand the role of turbulent mixing in the ocean's thermohaline circulation.

The research discussed in this article was supported by the National Science Foundation. Initial development of the High Resolution Profiler was supported by the Department of Defense and the Office of Naval Research.



A schematic drawing of turbulent processes at work in the ocean.

Attraction to the sea and ocean science began for John Toole with a keen interest in sailing. He maintains an eclectic research program at WHOI that includes study of basin-scale circulations and the processes of ocean mixing. Developing understanding of the cold-to-warm limb of the thermohaline circulation represents a synthesis of research supported by grants from the National Science Foundation and the Office of Naval Research. With WHOI colleagues and his wife (and chief foredeck crew), he also continues to campaign sailing race courses through the summer, as research cruises and meetings permit.