DIFFUSION

See **DISPERSION AND DIFFUSION IN THE DEEP OCEAN**

DISPERSION AND DIFFUSION IN THE DEEP OCEAN

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Introduction

One of the very consistent results of oceanic microstructure measurements over the past two decades is that the rate of turbulent mixing is quite weak below the well-stirred surface layer. With few exceptions, the interior ocean seemed remarkably nonturbulent, indeed, almost laminar. A major puzzle arose, as the rate of renewal of deep waters seemed well in excess of what could be absorbed by turbulent vertical mixing in most of the oceanic gyres. Without mixing to warm the deep water, the large-scale meridional overturning circulation would cease, as this mixing is, in a very fundamental way, its driving mechanism. New observations in the abyssal ocean have shown that there are, in fact, sites of greatly enhanced turbulence, which appear to be sufficiently strong and extensive to provide the necessary mixing. The new observations, the basic physics involved, and the apparent energy sources for this turbulence are reviewed below.

The Thermohaline Circulation

A major feature of the ocean circulation is the sinking of cold, dense water at high latitudes, its spread to low latitudes, and eventual upwelling. During this upwelling the water must be warmed and made less dense; this is accomplished by interior vertical mixing. This is a key step in the process, indeed it can be considered its driving agent, if the meridional temperature gradient is accepted as a given. The interior mixing can be thought of as a 'suction' which pulls cold water into the various basins; without this suction, the deep circulation would stagnate. Numerous modeling studies have now shown that it is the mixing rate that sets the strength of the thermohaline circulation. One of the long-standing puzzles in oceanography has been the apparent lack of sufficient mixing to accommodate the estimated production of cold bottom waters. Given the strength of bottom-water sources and the area and stratification of the ocean basins, the required eddy diffusivity of turbulent vertical diffusion can be readily estimated; this turns out to be about $1 \times 10^{-4}\,\mathrm{m^2\,s^{-1}}$. However, numerous measurements by sensitive temperature and velocity probes of the microstructure of the ocean yield a typical midgyre value of diffusivity that is at least an order of magnitude smaller. This body of work has been confirmed by tracer release studies in the upper thermocline of the North Atlantic. Thus, the apparent lack of mixing cannot be ascribed to statistical sampling issues or the models used for the interpretation of microstructure data. Rather, it is now apparent that the main problem was one of lack of observations, since the majority of turbulence measurements were confined to the upper few hundred meters. This shows the vital importance of exploratory observations in the vast and undersampled oceans.

Deep-sea Observations of Mixing

The clear importance of mixing to the thermohaline circulation has inspired recent attempts to sample the turbulent mixing rate in the deep sea. The variables of interest for estimating mixing rates are the dissipation rates of temperature variance and turbulent kinetic energy. These require measurements of centimeter-scale gradients of temperature and velocity with very sensitive instruments. There were a number of technical difficulties to overcome; sensors capable of detecting the subtle signatures of oceanic turbulence in the weakly stratified abyss can have difficulties withstanding the immense pressure at the bottom of the sea. Also, untethered instruments must be used, in order to reach 5–6 km depth and to avoid the vibrations introduced by trailing cables. This leads to a requirement for significant redundancy in tracking and weight-release mechanisms, to minimize the risk of losing a sophisticated instrument. The 'High Resolution Profiler' was developed at the Woods Hole Oceanographic Institution for studies of deep-ocean mixing.

Profiles of dissipation below 3000 m depth began to be acquired in the early 1990s. The first were from the area around a submerged seamount in the eastern North Pacific. These showed substantial elevation of turbulence levels in the deep ocean near the seamount but there was no detectable enhancement of dissipation beyond 10 km away from the base of the seamount. Similar patterns were found in the Atlantic in a few deep dissipation measurements made in association with the North Atlantic Tracer Release Experiment. Profiles showed a rather uniform value of the vertical eddy diffusivity with depth except very near the bottom. These dissipation profiles were also the first to show that the models used to interpret turbulence measurements yielded mixing rates in good agreement with tracer dispersion in the upper thermocline (*see* **Double-diffusive Convection**).

These hints of enhanced mixing near topography helped to motivate a study of mixing in an abyssal fracture zone. Fracture zones are valleys that cut across midocean ridges, thus providing a passage for flow of cold bottom water from one ocean basin to another. The Romanche Fracture Zone on the Atlantic equator was suspected of harboring strong mixing because of the rapid change in water temperatures along the valley. That is, cold water entering the valley was observed to warm significantly as it flowed through. Turbulence observations confirmed that this was a site of intense mixing. The flow over the rough topography was strongly turbulent, though the mixing rates dropped dramatically above the layer of fast moving water. Though these observations provided the first solid evidence for strong mixing in the deep ocean, they were obtained in a rather specialized site, so that generalizations of mixing rates for an entire basin were not feasible. Thus, an effort was mounted to examine mixing over a more typical region of deep ocean bathymetry.

The region next examined was in the Brazil Basin of the western South Atlantic. The Mid-Atlantic Ridge (MAR) poses a barrier to eastward movement of the coldest, densest bottom waters in the basin. Confined between the continental rise to the west and the MAR to the east, the Antarctic Bottom Water (AABW) enters the Brazil Basin through passages in the south and exits through the Romanche fracture zone and across the equator to the North Atlantic. Just as in the Romanche, the bottom waters are seen to warm as they progress through the basin. An estimate of the rate of input of cold water, and knowledge of the surface area of isotherms and vertical temperature gradients within the basin allow the required mixing intensity to be calculated. A number of investigators have made such estimates for the Brazil Basin, since the southern source flows and northern outflows were reasonably well measured. Similar to the earlier global estimates of deep water-formation rates, the required mixing coefficient is $\sim 1\text{–}4 \times 10^{-4}\,\mathrm{m^2\,s^{-1}}$.

Measurements of the turbulent dissipation rate made using the High Resolution Profiler revealed that the mixing was weak and insignificant in the western part of the basin. However, to the east approaching the MAR, there was a dramatic increase in turbulence. The bottom topography also changed character from smooth to rough from west to east, as can be seen in **Figure 1**. This basic picture of the localization of mixing over rough topography had been suggested by previous work but never before demonstrated.

The pattern of turbulent dissipation suggested that a tracer release experiment near the MAR would be of greater interest than elsewhere in the basin. Accordingly, 110 kg of the tracer sulfur hexafluoride (SF_6) were released at 4000 m depth at a point about 500 m above the ridge tops of the fracture zones that trend westward from the ridge crest. When sampled 14 and 26 months after the release, a dramatic spread of the tracer was observed both laterally (**Figure 2**) and vertically (**Figure 3**). The lateral dispersion is characterized by two features: the bulk of the tracer which drifts and spreads to the southwest, and a secondary maximum which propagates eastward toward the MAR. These two tracer lobes are especially apparent after 26 months. The rate of lateral spread is rather modest compared to similar experiments in the upper ocean, since the mesoscale eddies are weak at these depths. The east–west trending fracture-zone valleys, extending perpendicularly from the main north–south axis of the Ridge, are prominent features of **Figure 2**. These valleys play an important role in establishing the bimodal structure of the tracer plume. That is, the valleys seem to serve as conducts for the tracer that is carried to the east, a feature easily seen in the sections of **Figure 3**. It appears that the tracer mixed downward from the injection plume has been carried eastward toward the ridge, and tracer-free water has been advected in below the core of the plume. Propagation both along and across density surfaces is apparent. These sections were obtained in one of the fracture zones, where the tops of the confining ridges are at a depth of 4500 m in the vicinity of the main tracer plume. The diapycnal mixing coefficient estimates from the

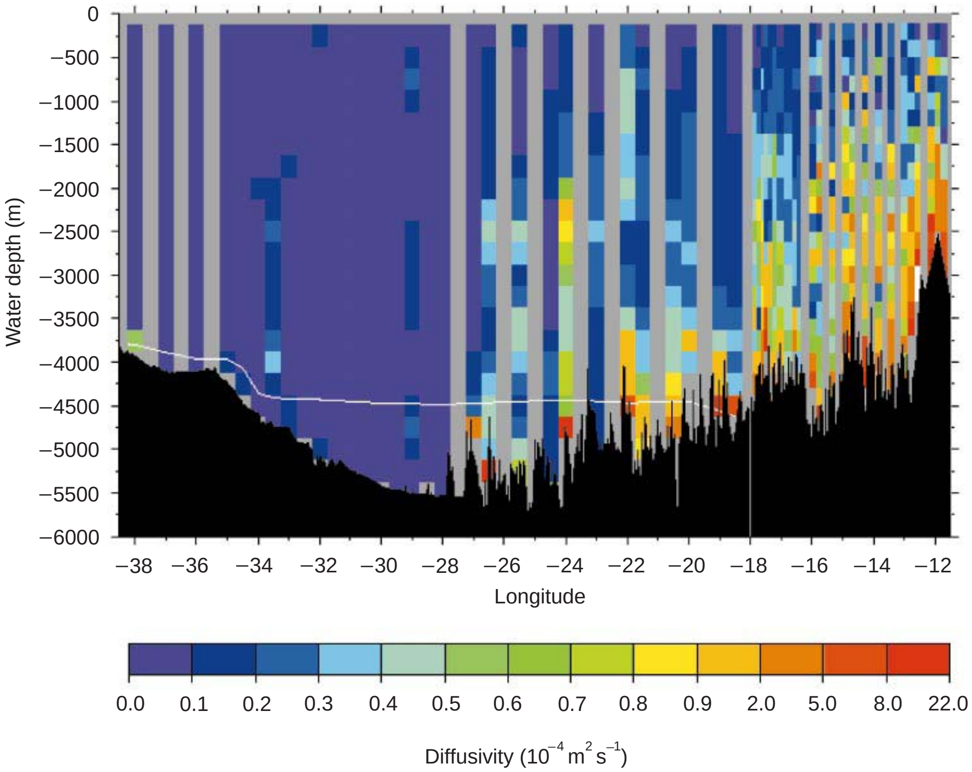

Figure 1 A composite section of the vertical eddy diffusivity in the Brazil Basin, as estimated from direct turbulence measurements in the deep ocean. The rough bottom topography approaching the mid-Atlantic Ridge has a clear influence on mixing rates well into the water column above, whereas little mixing is observed above the smooth bottom region in the west.

tracer dispersion is $\sim 3\times10^{-4}\,\mathrm{m}^2\,\mathrm{s}^{-1}$ at the level of the injection and increases greatly toward the bottom, a pattern also displayed by the turbulence measurements.

The separation of the plume into two main clouds by 26 months after injection suggests two mixing regimes are active at this site. The upper, interior, cloud seems to be spreading vertically, advecting southwestward, and sinking deeper across density surfaces. The downward motion is expected for a mixing rate that increases toward the bottom, though most oceanic models assume that upward flow is the rule. This finding means that the tracer experiment has added unique new knowledge to our understanding of the deep ocean. The flow of the lower tracer plume to the east is also exciting, as it shows how the deepest water is warmed in the course of eastward flow in the canyon. That is, the downward trend of the isopycnals requires a flow to the east in response to the pressure gradient; in steady state, the density gradient must be maintained by mixing (a steady state is a reasonable assumption, as the same density structure appears in surveys over 3 years.) Thus, the fracture zones radiating from the ridge axis act as conduits which draw the bottom water toward the ridge, warming it and effectively upwelling it to lighter density strata. This is a secondary flow driven by the enhancement of mixing within the fracture zone valleys and toward the ridge. Such secondary flows just affect the stratification and circulation in the vicinity of rough bottom topography.

These insights into the patterns of deep-ocean mixing are complemented by new information on the mechanisms causing the mixing. The overall pattern of spatial variation on the basin scale showed an enhancement of mixing over rough topography. There was also an enhancement in the vertical shear in horizontal velocity on scales of $\sim$ 20–200 m in patterns that are indicative of internal waves. The variations in mixing can be further defined by examining the dissipation profiles above a variety of topographic types in the rough area. A simple classification of bottom types into crest, slope or valley profiles, and averaging of the data in a 'height above bottom' coordinate system, shows distinct differences between the average mixing rates (**Figure 4**). The 'slope' profiles show the greatest vertical extent of strong mixing above the bottom. This is to be expected if the bottom is a source of low-frequency internal waves or serves to reflect and amplify ambient internal waves. Internal waves propagate horizontally as well as vertically, with the lower frequency waves having a more horizontal propagation direction. Thus, the waves at a ‘slope’ station are likely to have come laterally from up-slope topographic features. The overall pattern of mixing variation has important consequences for estimating the net rate of mixing in the region.

For topography to be a source of internal waves, there must be flow over the rough bottom. This could be a mean flow, such as in the Romanche Fracture Zone, or a time-varying flow, due to eddies or the tides. Since the deep eddy field was not found to be particularly strong in this region, we suspect the tides are the main source of energy for the enhanced internal waves. A simple comparison of the 3-day averaged vertically integrated dissipation rate (in mW m^{-2}) with the tidal velocities estimated

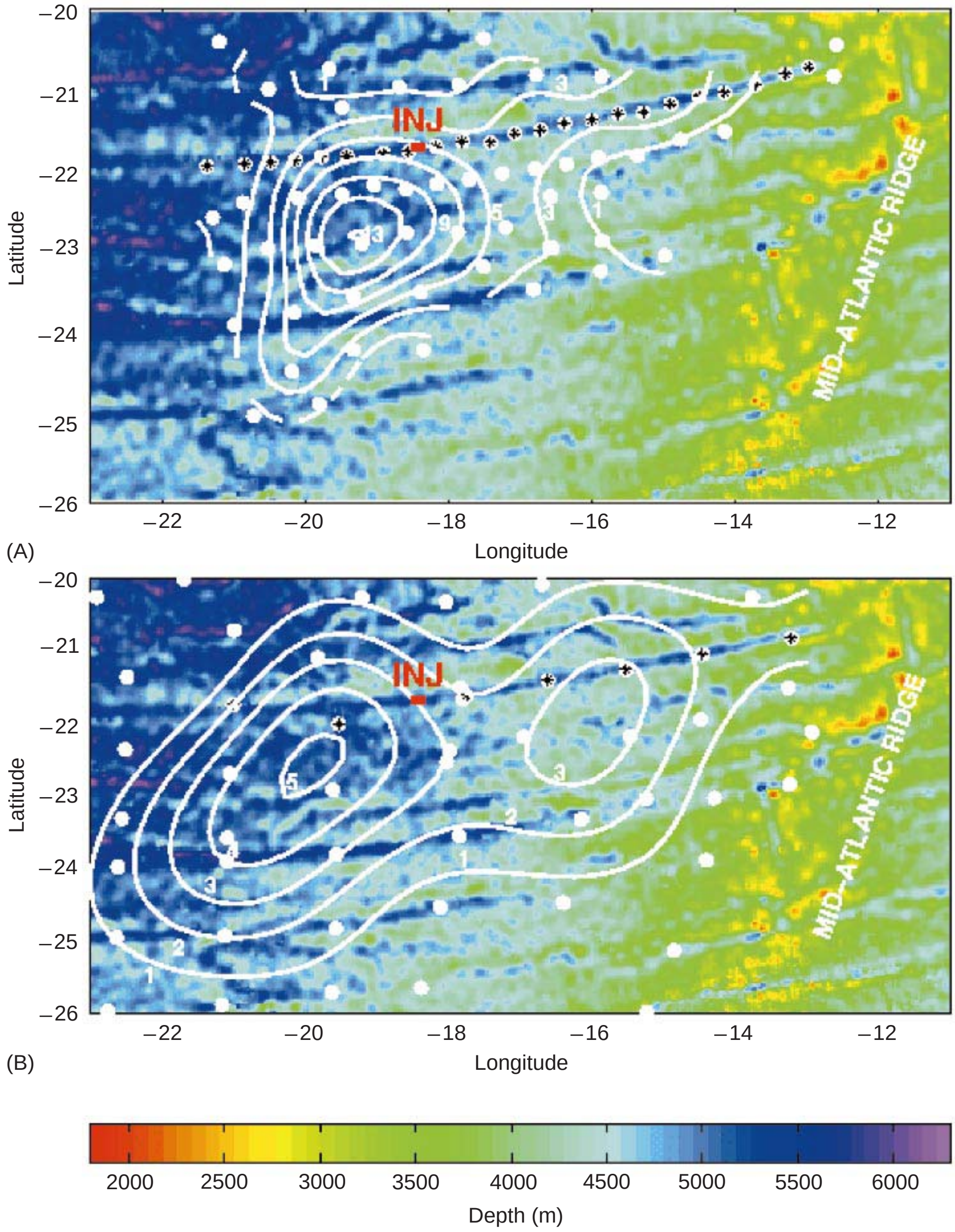

Figure 2 Tracer distribution at 14 months (A) and 26 months (B) after injection. The red bars labeled ‘INJ’ mark the release site of the tracer. The contours denote the column integral of SF$_6$ (in nmol m^{-2}) and colors denote bottom depth. The station positions are shown as white dots; those with stars are used for the sections in the fracture zone valley of **Figure 3**. Southerly latitude and westerly longitude are shown as negative numbers.

from a global model is very suggestive of a dynamical link with the tides (**Figure 5**). The record reflects the conditions at the geographical position of the dissipation profiles during the survey, and the tidal speed shows the amplitude of the estimated semidiurnal (12.42 hour period) tidal velocity over the spring–neap cycle during the cruise. The net dissipation is well correlated with the tides and appears to lag the forcing by about a day or two, a reasonable time scale for the vertical propagation of internal waves into the water column above.

If one accounts for the variation in mixing rate due to the observed differences in slope and time of sampling relative to the tides, it is possible to estimate the net amount of mixing over the surveyed area, and make reasonable extrapolations for the rest of the Brazil Basin. When this is done, the mixing induced by tides and topography appears to

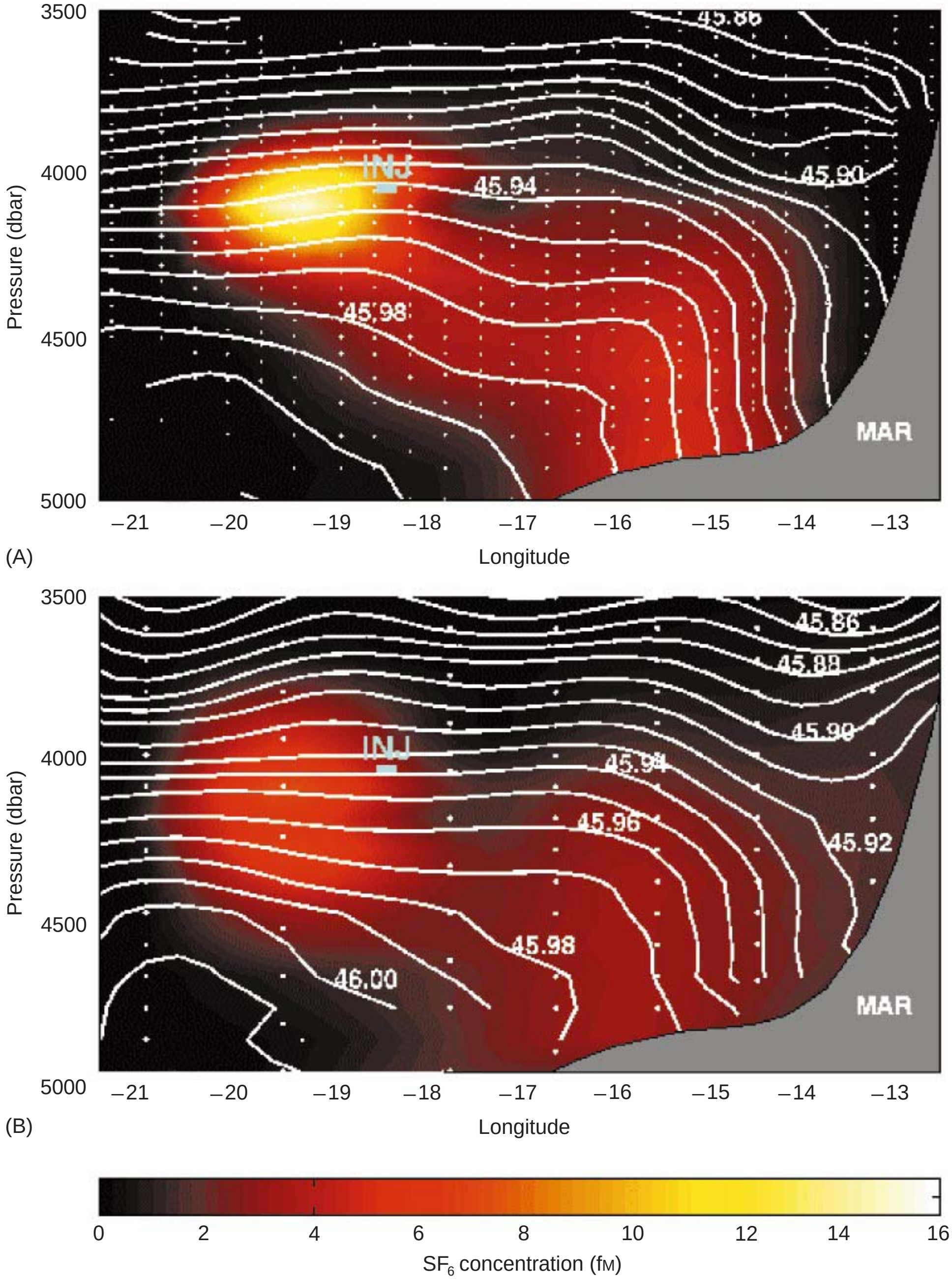

Figure 3 Sections of tracer concentration at 14 months (A) and 26 months (B) after release in an east–west oriented fracture zone of the Mid-Atlantic Ridge (MAR). The blue bar marks the injection site (INJ) and the white dots represent sample bottles. The white contours represent the potential density anomaly (kg m^{-3}) referenced to 4000 dbar.

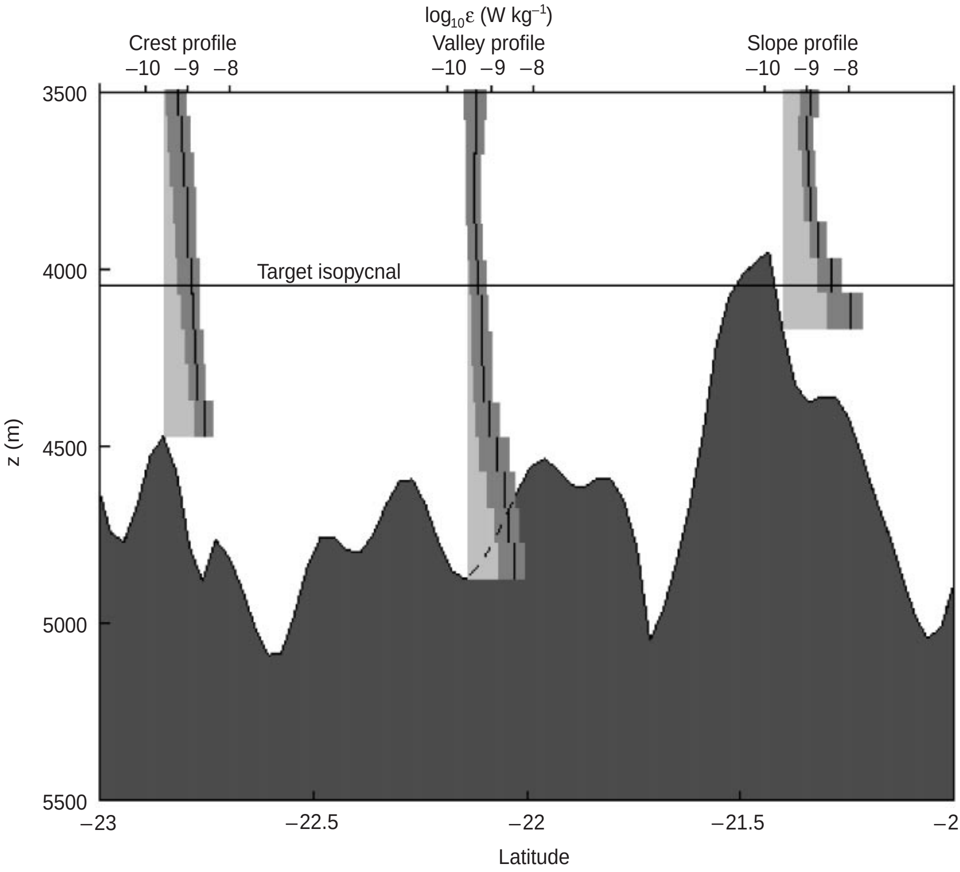

Figure 4 Average profiles of turbulent kinetic energy dissipation rate above different types of topography. Profiles in a 'height above bottom' coordinate system are shown along a section of meridional topography at 18.5°W, the longitude of tracer injection at the depth marked with a horizontal line. The dissipation is greater at the tracer level for sites above crests and slopes than over valleys.

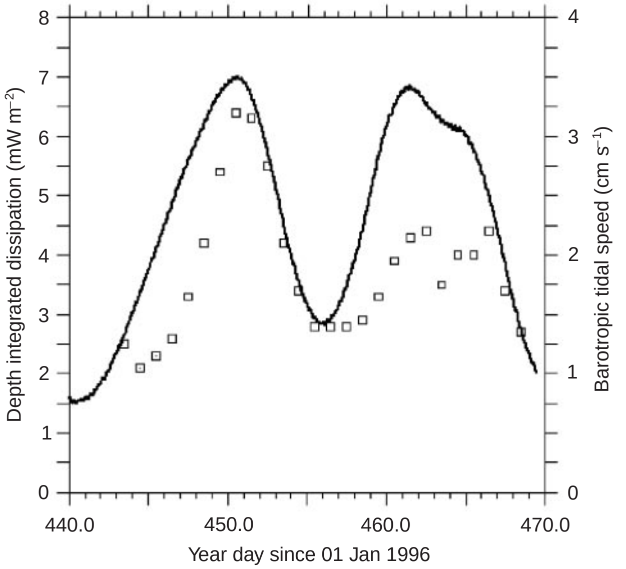

Figure 5 Comparison of the vertically integrated turbulent dissipation rate and tidal speeds at the time and location of the profiles for the 1997 Brazil Basin cruise. A three-day running boxcar average has been applied to both variables.

account for the warming of Antarctic Bottom Water that is observed in the Brazil Basin. This apparent balance is an important advance in our understanding of the deep flows in the ocean and the maintenance of the thermohaline circulation.

However, it is too early to say whether tidally induced internal waves arising over rough topography generate enough mixing in the global ocean to absorb all the deep water production. Only a tiny fraction of the deep ocean has been surveyed with microstructure instruments. Models of how the tides interact with topography are only now being developed. Detailed bathymetric data and improved tidal models will be necessary to develop an estimate of the global mixing rate due to the tides. Consideration of the energetics of mixing for the thermohaline circulation suggests that the tides may cause about half the required mixing globally, making available about $3\,\mathrm{mW\,m^{-2}}$ on average. This is the minimum value of the column integrated dissipation rates observed in the rough regions of the Brazil Basin during the spring–neap cycle, though much lower values are obtained in smooth-bottom regions.

The other potential source of enhanced turbulence in the deep ocean may be the flow of the Antarctic Circumpolar current over rough topography. This current receives a great deal of energy from its constant driving 'tailwind' and is a flow that extends to the bottom. The main dissipation mechanism is likely to be internal lee wave generation as the currents interact with complex topographic features. These waves can deliver energy to small vertical scales well up into the water column. Preliminary data suggest that internal waves are indeed enhanced in rough areas of the Antarctic Circumpolar current, with an energy distribution suggestive of more uniform mixing in the vertical. This would provide a more conventional upwelling pattern than the complex circulations found in and around the valleys of the MAR. Estimates of the energetics involved suggest that it may be as important globally as the tides. However, no deep ocean turbulence measurements have been made in these remote areas, so the rates of mixing remain speculative. We must await the results of future scientific expeditions to explore this mechanism. Indeed, much also remains to be done on the tidal mixing issue, since the currently available data amount to little more than a glimpse into a complex problem.

Summary

Whereas a decade ago, the mechanisms for mixing the ocean seemed quite mysterious, and the 'missing mixing' seemed to undermine our theories of the thermohaline circulation, we now have some leading candidates for how this mixing occurs. Bottom topography is key to these mixing mechanisms. They are as follows:

1. Flows through passages: fracture zones and other deep-sea passages serve to connect topographic deeps. Dense bottom waters can spill through these valleys at high velocity and experience strong mixing as they cascade over sills and rough topography. The change in deep-water properties has long been noted but now we know that the turbulence levels are indeed enhanced in such areas.
2. Tidal flows over rough topography: though midocean tidal velocities are weak, and thus generate negligible turbulence on their own, they readily interact with bottom topography to produce internal waves. These waves propagate into the water column above and produce enhanced turbulence to 1000–2000 m above the bottom. This mechanism predicts that interior mixing will be concentrated above rough bathymetry in areas with the strongest tides. It is not 'boundary mixing' in the traditional sense, since rough topography tends to be in association with midocean ridges and more heavily sedimented continental margins tend to have smooth bathymetry. The bottom source of energy for the waves leads to a decay of turbulence rates with height which leads to a general cross isopycnal flow 'downward'. A diapycnal flow 'upward' is found in canyons, which serves to provide the requisite mixing and upwelling for the bottom waters. This mechanism may be the leading mixing process serving to convert bottom waters into lighter density classes above midocean ridges throughout the world ocean. Antarctic Bottom Water in particular may be warmed largely by this process.
3. Mean flows over rough topography: this is a candidate mechanism about which little has been documented, but seems likely to play a role in key regions. The leading area of importance is the Southern Ocean, where the deep reaching Antarctic Circumpolar Current flows over significant bottom topography. Preliminary indications are that the vertical distribution of internal wave energy is more uniform, suggesting less variability in turbulent mixing rate, and thus a more uniform upwelling profile. This mixing may be key for converting the deep and intermediate waters into thermocline waters. The North Atlantic Deep Water is the primary candidate for warming in the region of the Antarctic Circumpolar Current.

These mechanisms all involve bottom topography, and thus point to the importance of improved knowledge of bathymetry for progress in understanding the deep and intermediate circulation. The spatial variations in mixing rates must lead to greater complexity in deep flows than has been anticipated in the present generation of models. It should also be noted that these mechanisms are not 'boundary mixing' in the usual sense. That is, the mixing occurs well away from the thin benthic boundary layer and is more likely to be concentrated over a midocean ridge than near a lateral boundary. Indeed, no enhancement of mixing has been observed in western boundary currents where the bottom is smooth.

It is also important to note that numerous modeling studies have shown that the magnitude of the vertical mixing is limiting to the amplitude of the overall thermohaline circulation itself. Indeed, the role of interior mixing in the thermohaline circulation can be compared to the role of the wind stress in the wind-driven circulation; that is, turbulence provides the essential interior balance of vertical upwelling with downward mixing of heat, just as the wind stress pattern at the surface imparts circulation to the ocean's horizontal gyres. The high latitude sinking regions are then analogs of the western boundary currents that close the wind-driven flows. This view more clearly shows that it is the interior mixing acting on available density gradients, rather than the surface formation of dense water, that acts as the driving agent for the thermohaline circulation. Indeed, without mixing, the deep circulation would become cold and stagnant and oceanic warmth would be confined to a thin surface boundary layer. This issue is of major concern, since the substantial circulation of warm water poleward is responsible for much of the heat flux carried by the ocean. There is evidence that the North Atlantic limb of the thermohaline circulation was cut off at various times in the past, and some suggest that global warming could shut it off in future, due to surface water freshening by an enhanced hydrologic cycle. Recent modeling work shows that there is a delicate balance between the fresh water forcing and the rate of interior mixing that determines the stability of the thermohaline circulation. A better understanding of oceanic mixing is thus essential for prediction of the future evolution of the Earth's climate system.

See also

Double-diffusive Convection. Internal Tidal Mixing. Thermohaline Circulation. Tracer Release Experiments. Upper Ocean Mixing Processes.

Further Reading

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DISPERSION FROM HYDROTHERMAL VENTS

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Introduction

Among the most significant scientific events of the last century is the discovery of hydrothermal vent fields and their unusual ecological communities along the crests of the mid-ocean ridges. The venting consists of localized sources of very hot ($\sim 350°C$) water that rises 100–300 m above the vent before it spreads laterally, similar to the plume from a smokestack. Venting also occurs as less intense and relatively cool diffuse flow ($\sim 10°C$ above the ambient ocean temperature) spread out over a much broader area than the focused high-temperature vents. Diffuse flow rises only a few meters above the seafloor before it is mixed with the ambient sea water. While the diffuse flow carries about half of the total hydrothermal heat flux, its effect on the overlying water column is much less dramatic than the high-temperature vents.

The hydrothermal venting from diffuse and localized high-temperature venting is essentially continuous over periods of years to decades. On longer timescales the individual vent sites will dissipate and new sites will emerge at other locations along the ridge crest. This nearly continuous venting is also punctuated by intense short duration venting events. These intense events are produced by magma eruptions on the seafloor or tectonic activity that rapidly exposes large quantities of sea water to hot rock or releases large quantities of very hot water from the crust. The result is the creation of huge 'mega plumes' that can rise 500–1000 m above the ridge crest to form mesoscale eddies with diameters of $O(20\,\mathrm{km})$ and thickness of $O(500\,\mathrm{m})$.

Because of its large buoyancy and the dynamical control exerted by the Earth's rotation, vent fluid is not simply advected away by background flow. The venting is capable of forcing circulation on a variety of temporal and spatial scales and this may have important consequences on how the vent fluid is ultimately dispersed. This article focuses on the flow