NOTES AND CORRESPONDENCE

Effects of Strait Mixing on Ocean Stratification

HARRY L. BRYDEN AND A. J. GEORGE NURSER

Southampton Oceanography Centre, Empress Dock, Southampton, United Kingdom

27 June 2002 and 20 March 2003

ABSTRACT

The density distribution in the abyssal Atlantic Ocean suggests that mixing associated with overflows across deep sills may account for substantial amounts of deep mixing. Estimates of the strait mixing are made from published estimates of the overflows and the difference between Antarctic Bottom Water densities across the Vema Channel and the Romanche Fracture Zone to demonstrate that the strait mixing is an order of magnitude larger than the abyssal mixing estimated for a standard diffusivity of 1×10^{-4} m^2 s^{-1}.

1. Introduction

Recent discussions on the size of deep ocean mixing and whether it is done by boundary mixing over rough topography or by slow vertical diffusion appear to have neglected mixing in strait and sill regions and associated descending outflow plumes (Munk and Wunsch 1998). Measurements of turbulent mixing in the ocean indicate mixing coefficients of order 0.1×10^{-4} m^2 s^{-1} in interior regions away from topography, 10×10^{-4} m^2 s^{-1} above rough bottom topography, and 1000×10^{-4} m^2 s^{-1} in straits (Polzin et al. 1996, 1997). The widely accepted global average diffusivity of 1×10^{-4} m^2 s^{-1} is then thought to be due to boundary mixing over 10% of the ocean underlain by rough topography. This work asks whether the global mixing in the deep ocean might actually be accomplished by intense mixing over 0.1% of the ocean representing straits and sills and descending outflows.

2. Model

We consider here an ocean consisting of a series of deep basins separated by sills. The basins have smooth bottom topography and the entire ocean is initially filled with water of a single density, ρ. We begin to fill the ocean with a cold, dense deep water from the south, perhaps being formed in the Antarctic at a rate Q_1 with a density ρ_1. For simplicity we assume initially that there is no interior mixing (Fig. 1). The dense water fills up the basin behind the first sill until it reaches the crest of the sill when it begins to spill into the next basin. We expect that the height of the ρ_1 reservoir above sill depth will achieve a level sufficient that the flux Q_1 can flow over the sill in some kind of hydraulically controlled process and then there is ''strait'' mixing as the dense water plunges down into the next basin so that the dense water filling the next basin has density ρ_2, less dense than ρ_1 but more dense than ρ. The amount of water filling this second basin is proportionally larger than the original source of dense water, Q_1, by a factor of $(\rho_1 - \rho)/(\rho_2 - \rho)$ because of the mixing in of less dense water.

The second basin fills with dense water until the ρ_2 reservoir height reaches the height of the second sill and ρ_2 water begins to spill into the third basin, mixing as it descends as a density current to fill the third basin with slightly lesser density ρ_3 waters. When the reservoir in the third basin fills to the height of the third sill, water begins to spill over the sill and mix as it fills the fourth basin with again slightly less dense ρ_4 waters. At the end of the process we have stratification that varies from basin to basin depending on the configuration and number of sills. Narrower sills would have stronger currents and more mixing in the descending outflow. Bottom waters become progressively less dense as they spill over successive sills, and so the stratification between the bottom water and the deep water above is weaker as one gets farther from the source.

The motivation for this model comes from the observed distribution of density in the deep waters of the Atlantic Ocean (Fig. 2). At the southern end of the A16 section, Antarctic Bottom Water (AABW) piles up in the Argentine Basin behind the sill in Vema Channel at

---

Corresponding author address: Dr. Harry L. Bryden, Southampton Oceanography Centre, Empress Dock, Southampton SO14 3ZH, United Kingdom.
E-mail: h.bryden@soc.soton.ac.uk

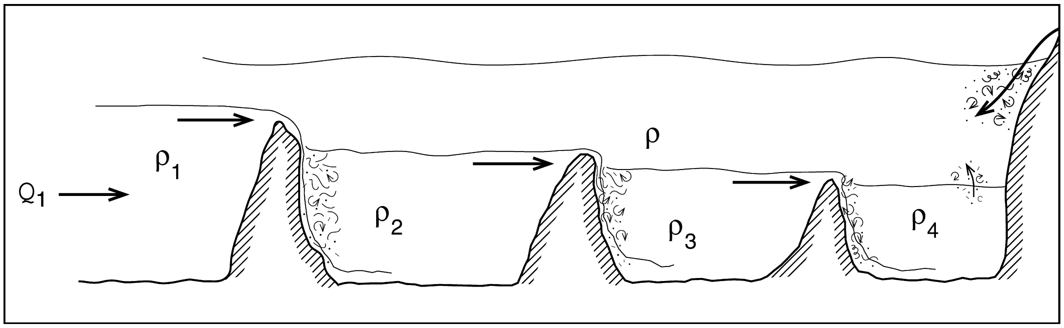

FIG. 1. Schematic model for the effects of strait mixing on the properties of bottom water.

about 31°S. There is then a discontinuity in bottom-water density between the Argentine Basin and the Brazil Basin as the AABW flowing through Vema Channel mixes as it descends and fills the Brazil Basin (Hogg et al. 1982). Similarly, at the equator, the modified AABW in the Brazil Basin piles up behind the sill in the Romanche Fracture Zone and then mixes as it flows over the sill and down into the eastern North Atlantic (Ferron et al. 1998). As a result, there is again a discontinuity in bottom-water density between the Brazil Basin and the eastern North Atlantic. Last, there appears to be a small discontinuity in bottom-water density at 37.5°N where there is a sill at Discovery Gap (Saunders 1987).

3. Amount of strait mixing

If Q is the flow over the sill and $\Delta\rho$ the difference in density between the overflow (ρ_1) and the deep water filling the next basin (ρ_2), then the overall amount of mixing in the strait, sill, and descending outflow regions, or, more precisely, the turbulent density flux across the ρ_2 isopycnal, can be estimated as $Q\Delta\rho$. A turbulent density flux across the ρ isopycnal of strength $Q\Delta\rho$ is needed if the flow Q is to change its density by $\Delta\rho$ [see the discussion of entrainment fluxes at the base of the surface mixed layer in Nurser et al. (1999)].

In the case of the Vema Channel, we can estimate $\Delta\rho$ to be 0.05 kg m^{-3} from Fig. 4 in Tsuchiya et al. (1994) and Q to be 6.9 Sv (Sv $\equiv 10^6\ \mathrm{m}^3\ \mathrm{s}^{-1}$) from Hogg (2001). Thus, the amount of mixing in the Vema Channel overflow amounts to about 3×10^5 kg s^{-1}. For comparison, interior mixing using an average diffusivity of 1×10^{-4} $\mathrm{m}^2\ \mathrm{s}^{-1}$ over the abyssal Brazil Basin with an area of 3×10^6 km^2 where the vertical density gradient in the bottom water is 0.3 to 1×10^{-4} kg m^{-4} amounts to only 1–3 ($\times 10^4$ kg s^{-1}), an order of magnitude less than our estimate for the Vema Channel mixing.

For the flow through the Romanche Fracture Zone, we can estimate $\Delta\rho$ to be 0.12 kg m^{-3} from Fig. 4 in Tsuchiya et al. (1992) and Q to be 1.22 Sv from Mercier and Speer (1998), so the amount of mixing, $Q\Delta\rho$, associated with the flow of AABW from the Brazil Basin to the eastern North Atlantic over the sill in the Romanche Fracture Zone is about 1.5×10^5 kg s^{-1}. The vertical density gradient in the abyssal eastern North Atlantic is 2 to 5 ($\times 10^{-5}$ kg m^{-4}), so for a surface area of 8×10^6 km^2 from the equator to 30°N and a standard diffusivity of 1×10^{-4} $\mathrm{m}^2\ \mathrm{s}^{-1}$, the interior mixing in the abyssal eastern North Atlantic would amount to 1.6 to 4 ($\times 10^4$ kg s^{-1}), again an order of magnitude less than the mixing in the Romanche Fracture Zone overflow.

4. Discussion

Strait mixing can be considered to be a form of mixing over rough topography, but where the velocity is enhanced due to constriction by the strait.

The importance of strait mixing was emphasized by Ferron et al. (1998) in their study of the Romanche Fracture Zone. Their estimates of mixing in the region just downstream of the sill based on turbulence measurements, Thorpe scale analysis, and heat budgets from current meter measurements were one-half as large as the mixing over the Sierra Leone and Guinea abyssal plains in the eastern Atlantic. The estimates of mixing presented here for the Romanche Fracture Zone are larger because they are bulk estimates based on the flow over the sill and total density difference between the water at the sill and the deep water in the eastern Atlantic, so they are not restricted to just the region of very high mixing in the strait.

There are, of course, other sills that affect deep water properties in the Atlantic. Because of the orientation of the A16 hydrographic section (Fig. 2), the emphasis here has been on Vema Channel, Romanche Fracture Zone, and Discovery Gap. However, mixing in Hunter Channel (Zenk et al. 1999) may also help to determine deep water properties in the Brazil Basin, and mixing in Vema Fracture Zone (McCartney et al. 1991) may also help determine deep-water properties in the eastern North Atlantic.

Mixing may also be substantial for shallower straits such as the Strait of Gibraltar or Bab al Mandab. For the Strait of Gibraltar outflow of 0.7 Sv (Bryden et al. 1994) and a density difference between the ''Mediterranean Waters'' in the Mediterranean and in the North Atlantic of about 1.8 kg m^{-3}, the overall strait mixing

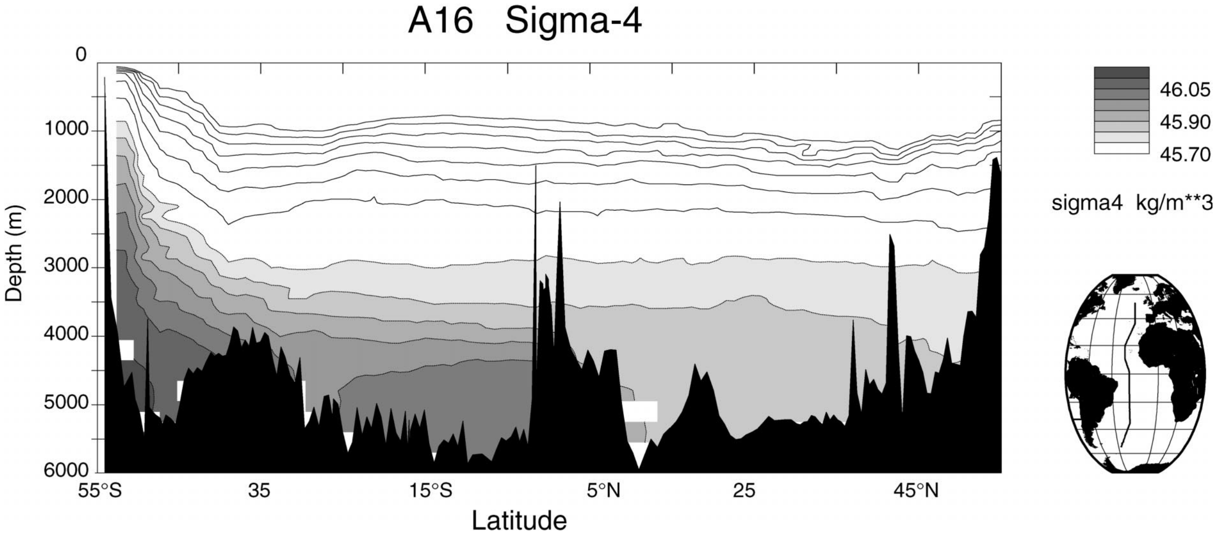

FIG. 2. Meridional density distribution in the Atlantic Ocean along WOCE section A16. Sigma-4, density referenced to a pressure of 4000 dbar, is used to focus on the deep density distribution. The location of the A16 section is shown on the insert chart.

can be estimated to be 1.3×10^5 kg s^{-1}, which again represents a substantial amount of mixing in the lower thermocline of the North Atlantic Ocean. In fact, in the Atlantic Ocean the lower thermocline and upper deep waters depicted by ρ in Fig. 1 are substantially made up of water masses that are the result of mixing in descending inflows that enter the interior ocean from shallow straits such as the Strait of Gibraltar, Denmark Strait, or Faroe Bank Channel.

In this schematic circulation (Fig. 1), the bottom waters in the northern basin with density ρ_4 must ultimately mix upward into the overlying deep waters of density ρ in an interior mixing process, so interior mixing is still necessary. The point here is to emphasize that the interior mixing may be less important overall than the strait mixing in setting the stratification of the bottom waters. Strait mixing has converted abyssal source waters of density ρ_1 ultimately into less dense ρ_4 waters in the northernmost basin farthest from the Antarctic source of the bottom waters. Thus, the spatial distribution of the stratification between deep and bottom waters depends on the strait mixing: there is stronger stratification close to the source of abyssal waters, weaker stratification in basins farther from the abyssal source, with discrete changes in the stratification across the straits connecting the deep basins.

Acknowledgments. We thank Kate Davis who drafted Fig. 1 and Penny Holiday who created Fig. 2. This work has been supported by the Natural Environment Research Council as part of the ‘‘Large-Scale Long-Term Ocean Circulation’’ core strategic research program within the James Rennell Division.

REFERENCES

Bryden, H. L., J. Candela, and T. H. Kinder, 1994: Exchange through the Strait of Gibraltar. *Progress in Oceanography,* Vol. 33, Pergamon, 201–248.

Ferron, B., H. Mercier, K. Speer, A. Gargett, and K. Polzin, 1998: Mixing in the Romanche Fracture Zone. *J. Phys. Oceanogr.,* **28,** 1929–1945.

Hogg, N. G., 2001: Quantification of the deep circulation. *Ocean Circulation and Climate,* G. Siedler et al., Eds., Academic Press, 259–270.

——, P. Biscaye, W. Gardner, and W. J. Schmitz Jr., 1982: On the transport and modification of Antarctic Bottom Water in the Vema Channel. *J. Mar. Res.,* **40** (Suppl.), 231–263.

McCartney, M. S., S. L. Bennett, and M. E. Woodgate-Jones, 1991: Eastward flow through the Mid-Atlantic Ridge at 11°N and its influence on the abyss of the eastern basin. *J. Phys. Oceanogr.,* **21,** 1089–1121.

Mercier, H., and K. G. Speer, 1998: Transport of bottom water in the Romanche Fracture Zone and the Chain Fracture Zone. *J. Phys. Oceanogr.,* **28,** 779–790.

Munk, W., and C. Wunsch, 1998: Abyssal recipes II: Energetics of tidal and wind mixing. *Deep-Sea Res.,* **45A,** 1977–2010.

Nurser, A. J. G., R. Marsh, and R. G. Williams, 1999: Diagnosing water mass formation from air–sea fluxes and surface mixing. *J. Phys. Oceanogr.,* **29,** 1468–1487.

Polzin, K. L., K. G. Speer, J. M. Toole, and R. W. Schmitt, 1996: Intense mixing of Antarctic Bottom Water in the equatorial Atlantic Ocean. *Nature,* **380,** 54–57.

——, J. M. Toole, J. R., Ledwell, and R. W. Schmitt, 1997: Spatial variability of turbulent mixing in the abyssal ocean. *Science,* **276,** 93–96.

Saunders, P. M., 1987: Flow through Discovery Gap. *J. Phys. Oceanogr.,* **17,** 631–643.

Tsuchiya, M., L. D. Talley, and M. S. McCartney, 1992: An eastern Atlantic section from Iceland southward across the equator. *Deep-Sea Res.,* **39A,** 1885–1917.

——, ——, and ——, 1994: Water mass distributions in the western Atlantic: A section from South Georgia Island (54S) northward across the equator. *J. Mar. Res.,* **52,** 55–81.

Zenk, W., G. Siedler, B. Lenz, and N. G. Hogg, 1999: Antarctic Bottom Water flow through the Hunter Channel. *J. Phys. Oceanogr.,* **29,** 2785–2801.