Numerical Study of the Meridional Overturning Circulation with “Mixing Hotspots” in the Pacific Ocean

Takahiro Endoh* and Toshiyuki Hibiya

Department of Earth and Planetary Science, Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan

(Received 27 September 2005; in revised form 14 December 2005; accepted 16 December 2005)

Using an idealized ocean general circulation model, we examine the effect of “mixing hotspots” (localized regions of intense diapycnal mixing) predicted based on internal wave-wave interaction theory (Hibiya et al., 2006) on the meridional overturning circulation of the Pacific Ocean. Although the assumed diapycnal diffusivity in the mixing hotspots is a little larger than the predicted value, the upwelling in the mixing hotspots is not sufficient to balance the deep-water production; out of 17 Sv of the downwelled water along the southern boundary, only 9.2 Sv is found to upwell in the mixing hotspots. The imbalance as much as 7.8 Sv is compensated by entrainment into the surface mixed layer in the vicinity of the downwelling region. As a result, the northward transport of the deep water crossing the equator is limited to 5.5 Sv, much less than estimated from previous current meter moorings and hydrographic surveys. One plausible explanation for this is that the magnitude of the meridional overturning circulation of the Pacific Ocean has been overestimated by these observations. We raise doubts about the validity of the previous ocean general circulation models where diapycnal diffusivity is assigned ad hoc to attain the current magnitude suggested from current meter moorings and hydrographic surveys.

1. Introduction

Diapycnal mixing is an integral factor in the global meridional overturning circulation (MOC) of the ocean because the slow upwelling in the pycnocline requires counteacting diapycnal diffusion. In a number of ocean general circulation models (OGCMs) (e.g. Bryan, 1987; Cummins et al., 1990; Marotzke, 1997; Hasumi and Suginoara, 1999a; Zhang et al., 1999; Tsujino et al., 2000; Park and Bryan, 2000; Scott and Marotzke, 2002), the MOC was shown to be sensitive to the value of diapycnal diffusivity. The intensity and distribution of diapycnal diffusivity in the pycnocline are therefore crucial parameters for accurate modeling of the global MOC.

Diapycnal diffusion in a stably stratified fluid requires mechanical energy, which is originally supplied from tide-topography interactions as well as wind stress fluctuations (Munk and Wunsch, 1998). The energy supplied is then transferred across the local internal wave spectrum down to small dissipation scales by nonlinear interactions among internal waves. In a series of numerical experiments by Hibiya et al. (1996, 1998, 2002), this energy cascade was shown to be dominated by parametric subharmonic instability (PSI) that transfers energy from the low vertical wave number, double-inertial frequency band to a high vertical wave number, near-inertial frequency band. They suggested that the resulting enhanced, high vertical wave number, near-inertial current shear plays a crucial role in controlling the intensity of diapycnal mixing in the pycnocline.

The dominant role of PSI in the real ocean was confirmed by Nagasawa et al. (2002) who found that the distribution of the finescale vertical shear measured by expendable current profilers (XCPs) correlates very well with that of the low vertical wave number, double-inertial frequency internal wave energy numerically predicted by Nagasawa et al. (2000) and Niwa and Hibiya (2001a, b). By incorporating the observed finescale vertical shear into the empirical formula proposed by Gregg (1989), Nagasawa et al. (2002) and Hibiya and Nagasawa (2004) showed that diapycnal diffusivity is strongly latitude-dependent. Furthermore, Hibiya et al. (2006) related the estimated diapycnal diffusivity to the numerically predicted semidiurnal internal tide energy at each location to find an empirical relationship between them. Then,
incorporating the numerically predicted semidiurnal internal tide energy at each longitude and latitude into the resulting empirical relationship, they found that strong diapycnal mixing ("mixing hotspot" in the pycnocline) is limited to prominent topographic features at latitudes 20°–30° where the available semidiurnal internal tide energy can be efficiently transferred to dissipation scales by PSI.

In the present study, using an idealized OGCM, we examine how the MOC of the Pacific Ocean is affected by the widely distributed mixing hotspots. In addition to the tidally driven mixing hotspots predicted by Hibiya et al. (2006), the wind-driven mixing hotspot as well as the boundary mixing area are incorporated into the model, following Nagasawa et al. (2000) and Niwa and Hibiya (2001a), respectively. Based on the result that the MOC with these mixing hotspots is significantly weaker than that estimated from previous current meter moorings and hydrographic surveys, we suggest the possibility that the magnitude of the MOC of the Pacific Ocean has been overestimated by these observations.

2. Model

The OGCM used in the present study is the Miami Isopycnic Coordinate Ocean Model (MICOM) described in detail by Bleck et al. (1992). MICOM combines a bulk mixed-layer model parameterized following the formulation of Gaspar (1988) and an isopycnic coordinate model of the stratified ocean interior. Interior diapycnal mixing is calculated using a scheme developed by McDougall and Dewar (1998). An isopycnic coordinate model is better suited to this study than widely used level models that inevitably suffer the problem associated with a projection of numerical truncation errors onto diapycnal mixing (Griffies et al., 2000). The equation of state is an approximation of the United Nations Educational, Scientific and Cultural Organization equation of state (UNESCO; Jacket and McDougall, 1995) expressed in the form of a polynomial that is cubic in potential temperature, quadratic in pressure, and linear in salinity (Brydon et al., 1999). The modulation of seawater compressibility by potential temperature anomaly is taken into account following the formulation of Sun et al. (1999). Isopycnic mixing is parameterized in the form of a Laplacian diffusion for tracer and a biharmonic diffusion for momentum and layer thickness. Vertical viscosity is omitted in MICOM.

The model domain is an idealized basin of the Pacific Ocean, ranging 100° in longitude and extending from 70°S to 56°N, with a constant depth of 5000 m (Fig. 1). The horizontal grid is on a Mercator projection with a resolution of 3° in longitude. In total, 18 layers are assumed in the vertical, namely, a surface mixed layer (index 1) and 17 isopycnic layers beneath (indices 2–18). The values of potential density assigned to layers 2–18 are listed in Table 1. At the side boundaries of the domain, no-slip and impermeability conditions are applied for the momentum equations and insulating conditions are applied for the heat and salt conservation equations. The coefficients for the isopycnal viscosity, the layer thickness diffusivity, and the isopycnal tracer diffusivity are assumed to be about $9 \times 10^{10}$ m²s⁻¹, $9 \times 10^6$ m²s⁻¹, and $3 \times 10^3$ m²s⁻¹ at the equator, respectively, and linearly proportional to the horizontal grid size. Although the values of these parameters are somewhat arbitrarily determined, the MOC does not change appreciably, even when the layer thickness diffusivity, for example, is increased by two orders of magnitude. A quadratic ocean bottom stress is applied with a dimensionless drag coefficient of 0.003.

Figure 1 shows the horizontal distribution of diapycnal diffusivity incorporated into the model. A background diapycnal diffusivity is assumed to be $0.2 \times 10^{-4}$ m²s⁻¹, the typical value inferred from previous microstructure measurements (e.g. Gregg, 1987) as well as tracer-release experiments (e.g. Ledwell et al., 1993) in the pycnocline. Supersposed on this, the tidally driven mixing hotspots are assumed, which correspond to prominent topographic features at latitudes 20°–30°, namely, the Izu-Ogawasara Ridge (143°E–164°E), the Hawaiian Ridge (157°W–178°W), and the Tuamotu Archipelago (136°W–157°W), where the diapycnal diffusivity is assumed to be $1 \times 10^{-4}$ m²s⁻¹ (Hibiya et al., 2006). We also prescribe the wind-driven mixing hotspot with diapycnal diffusivity of $1 \times 10^{-4}$ m²s⁻¹ south of 20°N in the western

![Fig. 1. Model geometry and horizontal distribution of diapycnal mixing incorporated into the model. Dark shaded regions denoted by T, W, and B indicate the tidally- and wind-driven mixing hotspots, and the boundary mixing area, respectively.](image-url)