INFLUENCE OF THE ENHANCED MIXING WITHIN THE SOUTHERN OCEAN FRONTS ON THE OVERTURNING CIRCULATION

Oleg A. Saenko*
Canadian Centre for Climate Modelling and Analysis, Victoria, B.C., Canada

1. MOTIVATION

Climate models typically do not resolve oceanic mesoscale variability (Fig. 1). The associated effects on large scale circulation are commonly parameterized using the Gent and McWilliams (1990; GM90) scheme. It is an adiabatic scheme which, implicitly, assumes viscous dissipation of the available potential energy removed by eddies from baroclinically unstable flows. If one were to assume that much of this energy dissipates locally (e.g., by breaking of internal waves), then it could be related to diapycnal mixing in the interior (Tandon and Garrett, 1996). The associated diapycnal diffusivity should be expected to be enhanced in frontal regions, and recent observational estimates do indicate that vertical mixing is enhanced along the major fronts of the Antarctic Circumpolar Current (ACC) (Sloyan, 2005; Naveira Garabato et al., 2004), with relatively large diffusivity values observed through much of the water column. The purpose here is to evaluate the potential impacts of the enhanced vertical mixing along the major fronts of the ACC. An attempt is made to ensure that the parameterization employed in a climate model to represent the effects of small-scale mixing is energetically consistent with that representing mesoscale mixing.

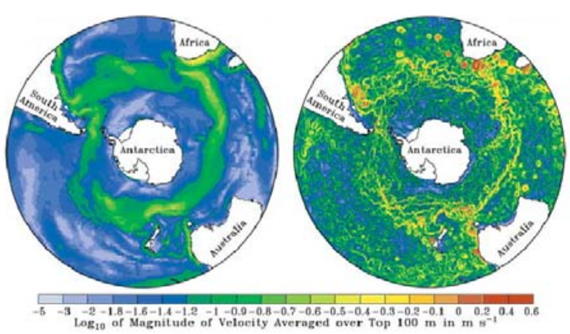

Fig. 1: Snapshots of near-surface velocity in the same model at resolutions of (left) 1 and (right) 1/6 degrees (from Hallberg and Gnanadesikan, 2006).

* *Corresponding author address:* Oleg A. Saenko, CCCma, Ocean, Earth and Atmospheric Sciences Building, Rm A217, University of Victoria, 3800 Finnerty Road, Victoria, B.C., V8P 5C2, Canada;
e-mail: oleg.saenko@ec.gc.ca

2. THEORETICAL FRAMEWORK

Consider the time mean buoyancy budget (in 2D for simplicity) wherein small scale mixing and buoyancy fluxes due to mesoscale eddies balance the advection of buoyancy by the mean circulation:

$$J(\overline{\psi},\overline{b}) = \underbrace{(K\overline{b_z})_z}_{\text{small-scale mixing}} + \underbrace{[-(\overline{v'b'})_y - (\overline{w'b'})_z]}_{\text{mesoscale eddies}} \quad (1)$$

Assuming that mesoscale eddies are adiabatic, i.e.

$$(\overline{v'b'})\,\overline{b_y} + (\overline{w'b'})\,\overline{b_z} = 0 \quad (2)$$

eq. (1) becomes

$$J(\psi_{res},\overline{b}) = (K\overline{b_z})_z \quad (3)$$

which simply means that the so-called residual circulation ("res") , i.e. the sum of the mean and eddy-induced circulations, would tend to follow mean buoyancy surfaces in the interior unless there are sizable effects due to small-scale turbulence.

Assuming that the eddy buoyancy flux is related to the mean buoyancy gradient, the eddy-induced circulation can be related to the mean slope of the isopycnals (GM90; Gent et al., 1995)

$$\psi^* = (\overline{v'b'})/\overline{b_z} \sim -k\overline{b_y}/\overline{b_z} = k\cdot slope \quad (4)$$

The corresponding term is typically introduced in tracer budget equations of ocean climate models. Alternatively, this can be shown (e.g., Gent et al., 1995; Olbers et at., 1985) to be (almost) equivalent to enhancing vertical transfer of momentum by the so-called interfacial form stress, or adding the following term to momentum budget equations

$$f\psi_z^* \sim f(k\cdot slope)_z \approx \left(k\frac{f^2}{N^2}\overline{u}_z\right)_z \quad (5)$$

with the corresponding energy dissipation given by

$$E = k\frac{f^2}{N^2}(u_z)^2 \quad (6)$$

Then, adopting the Osborn (1980) relation between dissipation rate and buoyancy flux

$$K = \Gamma\frac{E}{N^2} \quad (7)$$

where Γ is mixing efficiency (≈0.2), one can relate the diapycnal diffusivity K to the GM90 layer thickness diffusivity k (Tandon and Garrett, 1996):

$$K = \Gamma\, k \cdot slope^2 \qquad (8)$$

The latter relation implies enhanced values of diapycnal diffusivity in frontal regions. If one assumes that the layer thickness diffusivity is itself proportional to the isopycnal slope (e.g., Marshall and Radko, 2003; Visbeck et al., 1997), then the dependence of diapycnal diffusivity on the slope of isopycnals would become even stronger.

3. OBSERVATIONAL ESTIMATES

Observational estimates (Fig. 2, left) indicate that in the Southern Ocean, vertical mixing is enhanced in the abyss, and also along the Antarctic Polar Front (APF) and Subantarctic Front (SAF), penetrating through much of the water column.

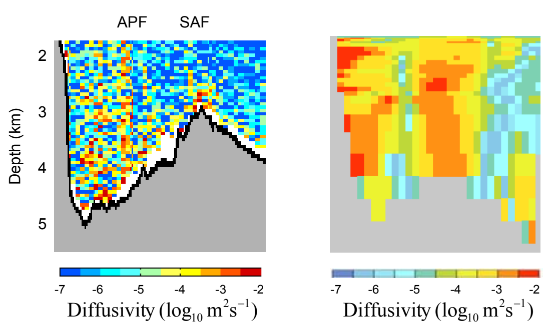

Fig. 2: Sections of vertical diffusivity across the ACC in the Indian Ocean: (left) observational estimates (from Sloyan, 2005) and (right) estimated from eq. (8) using Levitus data to calculate isopycnal slopes and using a representative value for the layer thickness diffusivity, $k = 10^3 \mathrm{m^2 s^{-1}}$.

Using Levitus data and eq. (8) one arrives at essentially the same conclusion (Fig. 2, right): vertical diffusivity can be of the order of $10^{-3}\mathrm{m^2 s^{-1}}$ in the regions of strong baroclinicity, reaching values as large as $10^{-2}\mathrm{m^2 s^{-1}}$, with the regions of elevated diffusivity being broader than those observed. (Note that in the right panel of Fig. 2 the diffusivity is enhanced in a vast area off the Antarctic continent, presumably due to a rather weak stratification in this region as represented in the Levitus data. In the left panel, a similar tendency for enhanced values of diffusivity is more confined near the continent and also to the sea floor.)

4. MODEL RESULTS

To give a sense of what kind of effects might be expected, two numerical examples are briefly presented. Both are based on the GFDL ocean model (coarse resolution) coupled to simple atmosphere and sea ice models. The first example is based on an idealized basin configuration, whereas the second example employs a realistic continental configuration (see Saenko, 2008).

4.1 Idealized basin geometry

The model domain is shown in the upper panel of Figure 3. It has a circumpolar gap in the south. Zonal winds are prescribed from climatology. Two equilibrium model solutions are compared. The first corresponds to a weak and uniform vertical diffusivity everywhere in the domain. In this case, the only sizable overturning circulation that reaches the abyss (i.e., below 2-3 km) is that due to the northward Ekman flux across the circumpolar flow compensated at depth. There is essentially no basin-scale overturning below 3 km (Fig. 3, bottom left). Increasing vertical diffusivity locally in the south within the circumpolar gap to the value representative of those observed in the Southern Ocean fronts (i.e., $10^{-3}\mathrm{m^2 s^{-1}}$) and suggested by theory (Tandon and Garrett, 1996) results in development of basin-scale overturning in the abyss. This is composed of localized upwelling in the south, supplied by a broad sinking outside of the "Southern Ocean" (Fig. 3, bottom right). The rate of this overturning is roughly consistent with what might be expected based on the advective-diffusive balance, given the value of diffusivity and the area over which it was imposed in the model.

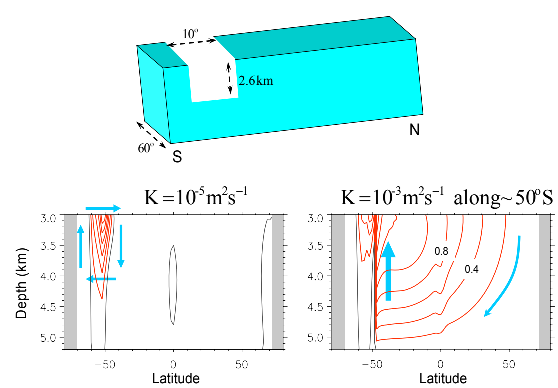

Fig. 3: (Upper) Model domain. (Lower) Meridional overturning circulation in the abyssal ocean: (left) in the case of relatively weak and uniform vertical mixing and (right) when the mixing in enhanced locally in the "Southern Ocean" to mimic the observations. Contour interval is 0.2 Sv; the arrows indicate the direction of the circulation.

4.1 Realistic configuration

Here a similar experimental design is adopted, using the same model but with realistic continental configuration. As in the case of idealized configuration, two model solutions are compared. One corresponds to the case where vertical diffusivity is enhanced only in the regions of strong tidal energy dissipation (such as in Simmons et al., 2004). The structure of the corresponding vertical diffusivity at mid-depths in the Southern Ocean is shown in the upper panel of Fig. 4. In the second case, the diffusivity is enhanced in regions that roughly correspond to the position of APF and SAF (Fig. 4, lower panel) (this case is represented by two sensitivity runs – see the caption to Figure 5).

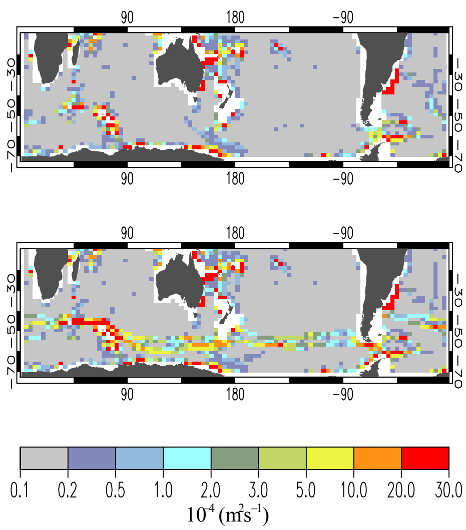

Fig. 4: Vertical diffusivity at about 1670 m: (top) due to the tidal dissipation only and (bottom) due, in addition, to the enhanced mixing along the APF and SAF (from Saenko, 2008).

An expectation, based on the idealized configuration results, is that the rate of global overturning circulation associated with the northward flux of Antarctic Bottom Water (AABW) is to weaken when vertical mixing is enhanced within the Southern Ocean fronts. This is illustrated in Fig. 5. Due to the frontally-intensified vertical mixing along the ACC, a sizable fraction of AABW and Lower Circumpolar Deep Water (LCDW) is converted locally to the Upper Circumpolar Deep Water (UCDW). While not necessarily related to the frontal mixing, it should perhaps be noted that observational evidence for an enhanced conversion of AABW/LCDW to UCDW in the Scotia Sea is presented in Naveira Garabato et al. (2007).

5. RELEVANT PROJECTED CHANGES

Climate models project an increase in the wind energy flux to the ocean (Fig. 6, left), mostly due to projected strengthening of zonal wind stress in the ACC region. If this projection were realized, it could have implications for mixing in the Southern Ocean, both at mesoscales and at small scales. For example, some recent numerical experiments with eddy-resolving models suggest enhanced mesoscale eddy activity in response to imposed strengthening of wind stress in the Southern Ocean.

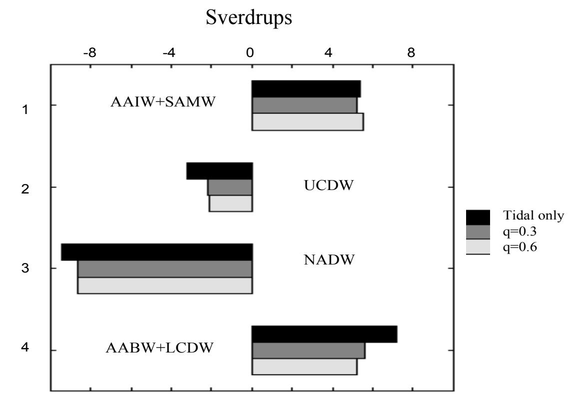

Fig. 5: The global mass exchange across 35°S within four potential temperature classes which represent some of the major global-scale water masses. The black bars correspond to the model experiment wherein the interior diffusivity is given only by the tidally-driven mixing, plus small background diffusivity. The grey bars correspond to the model experiments where, in addition, the diffusivity is enhanced along the APF and SAF using different values for the fraction of the energy (*q*) that dissipates locally (from Saenko, 2008).

However, winds do not change on their own. Rather, their changes are associated with changes in climate. Perhaps the most relevant to this discussion is increasing ocean stratification in a warmer climate, including in the Southern Ocean (Fig. 6, right; see also Saenko, 2006). For example, the condition for baroclinic instability, which in 2-layer QG approximation is (in conventional notation)

$$u_1 - u_2 > \beta \frac{g' H_2}{f^2} \qquad (9)$$

depends on stratification (g').

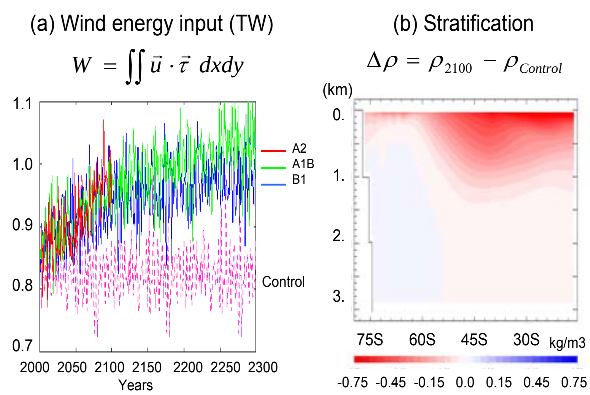

Fig. 6: (Left) Projected changes in the wind energy input to the ocean corresponding to three different scenarios for the increase of concentration of greenhouse gases in the atmosphere by year 2100, followed by its stabilization at the 2100 level (from Saenko, 2007). (Right) Zonally-averaged projected changes in the annual-mean potential density corresponding to scenario A1B.

6. CONCLUSIONS

1. Observational estimates indicate that vertical mixing is enhanced along the major fronts of ACC.
2. Models indicate that this can have a sizable effect on the overturning circulation and water mass transformation in the Southern Ocean interior.
3. The schemes employed in climate models to parameterize different subgrid-scale processes (e.g., those arising due to mesoscale eddies and small scale turbulence) should perhaps be energetically consistent with each other.
4. Wind energy input to the ocean and oceanic stratification are both expected to increase in a warmer climate, which may affect mixing in the ocean at a variety of scales.

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