14.3 THE ROLE OF EDDY FLUXES IN THE DYNAMICS OF THE ANTARCTIC CIRCUMPOLAR CURRENT

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1. INTRODUCTION

The Antarctic Circumpolar Current (ACC) dominates the dynamics of the Southern Ocean and plays a critical role in the global meridional overturning circulation (MOC) and the formation of intermediate and deep waters, particularly Antarctic Intermediate Water (AAIW). The ACC is driven primarily by the strong zonal winds of the Southern Hemisphere. As a result of the circumpolar nature of the ACC, eddy fluxes must play an leading role in balancing the surface wind forcing. On the other hand, the MOC is tied to the thermohaline forcing of the ocean, heat loss and gain at ocean surface and strong surface salinity fluxes associated with evaporation and precipitation in the north and ice formation and melt in the south.

Here, we illustrate how our recent work has created a framework to discuss the details of these balances. We describe the MOC as a residual circulation—the imbalance between the eddies and the winds—to emphasize the subtleties involved in modeling it.

2. THE FRAMEWORK

Following Karsten et al. (2002) and Karsten and Marshall (2002a), we rewrite the conservation of buoyancy, b, using the transformed Eulerian mean (TEM). For the ACC, the mean cross-stream advection is determined by the Ekman transport streamfunction, $\overline{\Psi} = -\tau/\rho_0 f$, where τ is the averaged wind stress, ρ_0 is the mean density, and f is the Coriolis parameter. The eddy fluxes can be described by introducing the eddy-induced streamfunction given by $\Psi^* = \overline{v'b'}/\overline{b}_z$, where $\overline{v'b'}$ is the cross-stream eddy flux of buoyancy. The sum of these two streamfunctions gives the residual streamfunction, $\Psi_{res} = \overline{\Psi} + \Psi^*$.

Having introduced the residual circulation, buoyancy conservation can be written as:

$$J(\Psi_{res}, \overline{b}) = \frac{\partial B}{\partial z}, \qquad (1)$$

where $J(A, C) = A_y C_z - A_z C_y$, B is the surface buoyancy fluxes, and, we have ignored diffusion and assumed that the eddy fluxes are adiabatic below the mixed layer. Equation (1) gives a very simple description of the MOC: the residual overturning circulation is forced by the thermohaline surface fluxes.

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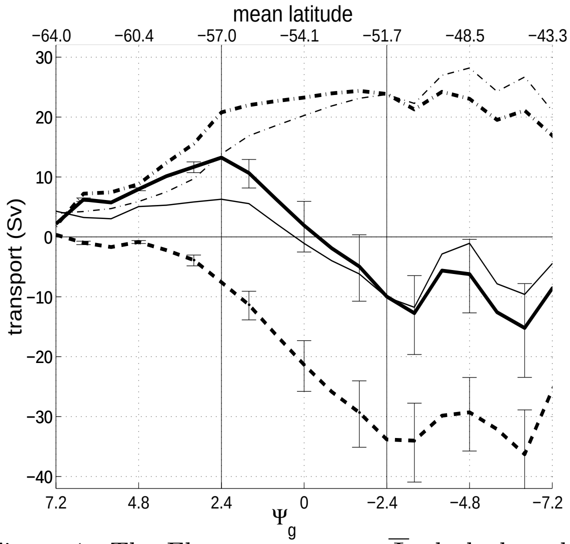

Figure 1: The Ekman transport, $\overline{\Psi}$, dash dot, the eddy induced transport, Ψ^*, dashed, and the residual transport, Ψ_{res}, solid. The thin lines are based on the HR winds; the thick on SOC winds. The error bars are calculated from the errors in the eddy diffusivity.

3. THE OBSERVED CIRCULATION

In Karsten and Marshall (2002) we use observational data to examine the ACC dynamics in the framework given above. To map the Ekman transport we use two wind stress data sets: the Southhampton Oceanography Centre (SOC) winds and the Hellerman and Rosenstein (HR) winds. We calculate the eddy-induced transport by estimating eddy diffusivity using altimetry data following Keffer and Holloway (1988). We then combine the two to form Ψ_{res}. The results are shown in Fig. 1, where we plot Ψ_{res} as well as its two components, $\overline{\Psi}$ and Ψ^*. Our residual circulation estimate suggests that there is a convergence of flow in the ACC—the Antarctic Convergence—and thus, implied subduction—the formation of AAIW.

Away from the effect of surface buoyancy fluxes, (1) implies that the residual circulation is constant along isopycnals and we can simply map the surface circulation down to depth. In Fig. 2, we plot the mean residual circulation versus depth and a cross-stream coordinate. The circulation two meridional overturning cells. The

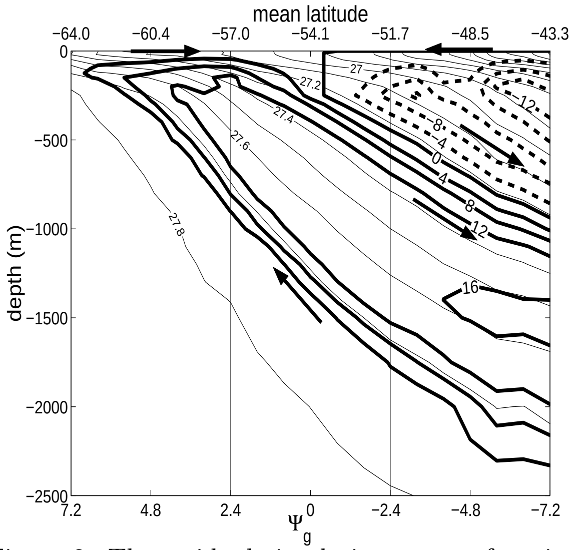

Figure 2: The residual circulation stream function. The contour interval is 4 Sv with solid (dashed) contours indicating positive (negative) values. The faint lines are contours of neutral density.

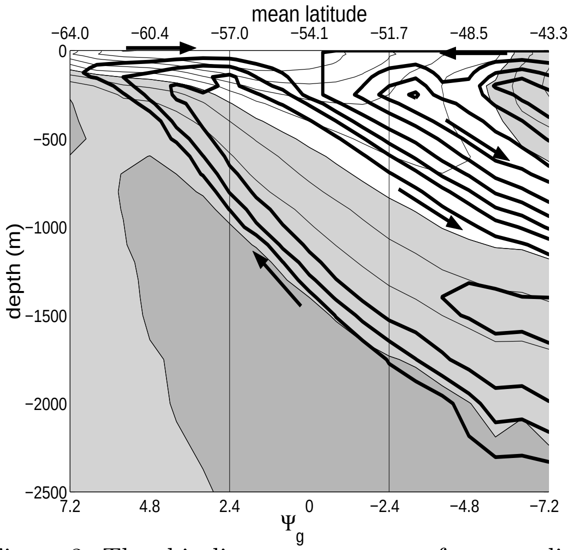

Figure 3: The thin lines are contours of mean salinity. The region of no shading marks fresh waters, salinity < 34.4. The dark solid lines are contours of the residual circulation.

lower cell has Circumpolar Deep water upwelling to the surface south of the ACC, gaining buoyancy and then subducting to form AAIW. The upper, weaker cell has Subantarctic Mode Water moving southward, losing buoyancy, and subducting to form AAIW. While these Diabatic Deacon cells have been discussed before we believe we are the first to diagnose them from observations and estimates of eddy fluxes.

The residual circulation can be used to explain many things, for example the distribution of fresh water in the Southern Ocean. In Fig. 3 the salinity field is presented using a grey scale. The light region at the surface poleward of the ACC marks fresh water form by precipitation and ice melt. A tongue of low salinity clearly marks the subduction of surface water to form relatively fresh AAIW. Superimposed in the figure are the streamlines of the residual circulation with arrows indicating the direction of flow. The path of the flow suggested by the residual circulation agrees remarkably well with the observed salinity tongue. We believe this is clear evidence that the large-scale pattern of the residual circulation calculated here is plausible.

4. CONCLUSIONS

We conclude from our analysis that reframing the dynamics of the ACC in terms of the TEM is extremely useful. It clearly demonstrates the leading order balance between winds and eddies and the secondary balance between the MOC and the thermohaline forcing. In doing so it allows us to concentrate on the important details of the ACC dynamics.

The framework stresses the balance of the winds and eddies and their connection through the stratification (see Karsten and Marshall 2002b) and thus, it is essential that eddy fluxes are correctly included in any model. This balance can also be described as the balance between the input of momentum at the surface and the downward transfer of momentum by interfacial form drag. Such a description highlights the role of topographic form drag.

Finally, the framework stresses the importance of accurate surface buoyancy fluxes, since they drive the MOC. For example, if the ocean surface is relaxed to a steady atmosphere on a relatively fast scale, surface buoyancy fluxes will be quickly reduces and the MOC will vanish.

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