Cancellation of the Deacon Cell by Vertical Eddy Fluxes

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The Overturning Circulation of the Southern Ocean has been investigated using a state of the art, eddy resolving ocean-sea ice model. The overturning circulation at constant depth and latitude reveals a 'Deacon Cell', a wind-driven meridional cell which acts to flux light surface waters Northward and downward and dense deep waters Southward and upward. The overturning has been further analysed in density-latitude space. Northward transport of light water and Southward transport of dense water by the Deacon Cell are compensated by the standing meanders of the Antarctic Circumpolar Current and other stationary features. The overturning has been finally analysed in depth-density space. Here, the Deacon Cell is compensated by transient eddy fluxes. We thus propose a new paradigm to conceptualize the Southern Ocean Overturning Circulation: the ACC's standing meanders transport light water Southward and dense water Northward with little vertical excursion; transient eddies then act on the resulting zonal gradients of isopycnals, transporting light water upward and dense water downward. Although transient eddies have previously been shown to play a minor role in meridional exchanges in the Southern Ocean, here they are found to play a crucial role in vertical exchanges.

1. Introduction

The Southern Ocean is a critical juncture in the global oceanic circulation. The Southern Ocean Overturning, in particular, exposes a substantial fraction of the deep ocean's water masses to the atmosphere and has contributed to around 40% of the oceanic uptake of anthropogenic CO_2 [Sabine et al., 2004]. The precise dynamics of the Southern Ocean overturning are thus critical to our understanding of the climate system and its sensitivity [see Rintoul et al., 2001, for a review of Southern Ocean dynamics].

Vigorous zonal winds over the Southern Ocean drive a Northward Ekman transport of up to 30 Sv (Sv = 10^6 m^3 s^{-1}). At latitudes of Drake Passage, the Southern Ocean is zonally unbounded. The Northward Ekman transport can not be balanced by a Southward mean geostrophic flow, except below topography (around 2000 m). Thus, light surface waters are driven Northward and downward and dense deep waters are driven Southward and upward south of Drake Passage. This overturning circulation is known as the 'Deacon Cell'.

It has been recognised that the Deacon Cell does not represent the true pathway of water parcels in the Southern Ocean. This was most clearly demonstrated by Döös and Webb [1994]. Using an eddy permitting model, Döös and Webb [1994] diagnose the Southern Ocean Overturning in density-latitude space. They see no closed Deacon Cell but rather a net Northward transport of light water and Southward transport of dense water on isopycnal layers.

Disagreement has arisen as to processes by which the Deacon Cell is compensated. Döös and Webb [1994] argue that the wind driven Deacon Cell is compensated by the meanders of the Antarctic Circumpolar Current (ACC). The ACC, they argue, transports light water Southward in the open ocean and dense water Northward along the coast of Argentina. Motivated by idealised channel simulations and the atmospheric literature, others argue that the Deacon Cell is compensated by transient eddy fluxes, which flatten isopycnal slopes [Johnson and Bryden, 1989]. In theoretical descriptions of the ACC, it is assumed that transient eddies act to flatten isopycnals in the meridional direction, transporting light water Southward and upward and dense water Northward and downward [Marshall and Radko, 2003].

Here we analyse the Southern Ocean Overturning in a state of the art, eddy resolving model of the Southern Ocean. We reveal that the standing meanders and transient eddies play complimentary, rather than independent roles in the compensation of the Deacon Cell.

2. Eddy-Resolving Coupled Ocean-Sea Ice Simulations

We use a 1/8° version of the coupled Ocean-Sea Ice model NEMO [Madec, 2008, version 3.2], here after PERIANT8. The domain of PERIANT8 is the entire ocean South of 30°S. Grid spacing scales with the cosine of latitude giving a refined grid with increasing latitude (approximately 6km x 6km at 60°S). At the Northern Boundary, temperature and salinity are restored to the output of the global Drakkar simulation ORCA025-G70 [Drakkar-Group, 2007]. The model is forced at the sea surface using the Drakkar Forcing Set 4 [Brodeau et al., 2010, a composite of ERA40 and ECMWF reanalysis products] over the period 1969–2007.

In PERIANT8 vertical mixing is represented with the TKE scheme with a background vertical mixing coefficient

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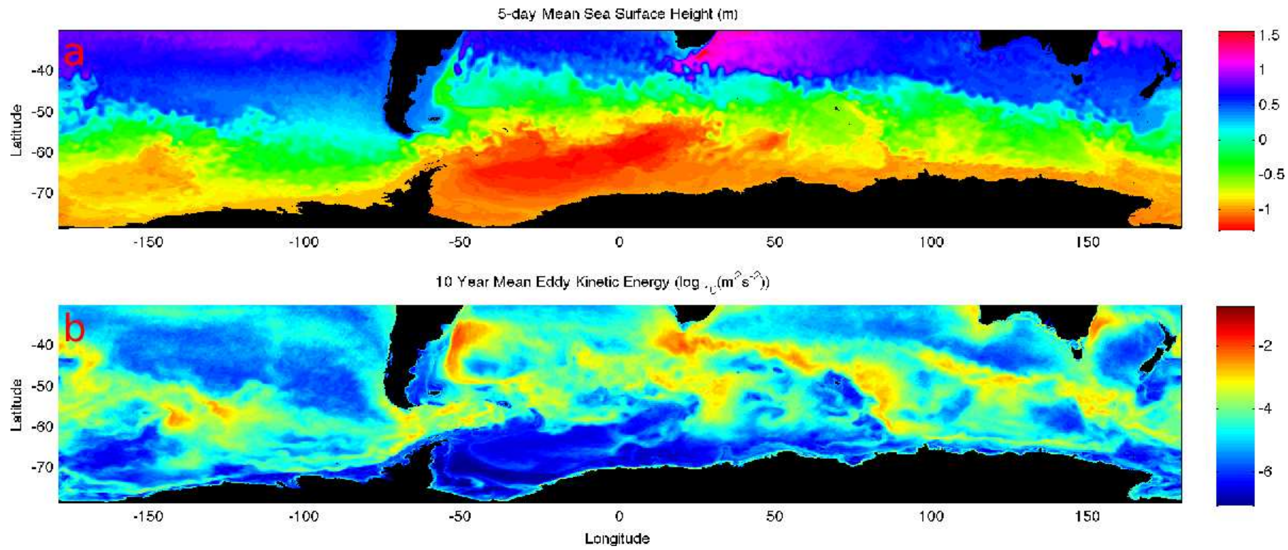

Figure 1. Surface properties of PERIANT8: a) Sea surface height for the final 5-days of simulation (27th – 31st of December 2007). b) Log_{10} of mean eddy kinetic energy for the final 10 years (1998–2007)

of 10^{-5} m^2 s^{-1}. Tracers are mixed along isopycnals with a coefficient of 130 m^2 s^{-1} . There is no parameterisation for eddy induced advection. To avoid the effects of the misrepresentation of dense water formation, temperature and salinity are restored to climatological values where $\sigma_2 < 37.11$ kg m^{-3} (well below the sill depth at Drake passage; σ_2 is potential density referenced to 2000 m depth) with a restoring timescale of 2 years. Experiments with coarser resolution versions of PERIANT8 have demonstrated that this restoring does not effect variability of the flow but simply prevents spurious trends in bottom water content and shoaling of the shallower isopycnals [Treguier et al., 2010]. Surface salinity is also restored to climatological values with a piston velocity of 50 m / 300 days [an intermediate value compared to those used by Ocean Climate Models; Griffies et al., 2009].

The ACC transport, as measured at Drake Passage, rapidly adjusts during the first 5 –10 years of the model run from 150 Sv to around 125 Sv with interannual variability of +/- 5 Sv. There is a small apparent trend of 2 – 3 Sv per decade. The remainder of this letter discusses only the final 10 years (1998 – 2007) of the simulation.

A 5-day average of sea surface height from PERIANT8 shows an abrupt Northward meander of the ACC at Drake passage and along the coast of Argentina (Fig.1 a). The 5-day average also shows the rich eddy field achieved. The signature of these eddies is evident in eddy kinetic energy averaged over a the final 10 years (Fig.1 a; $EKE = \overline{u'^2 + v'^2}/2$, u' and v' being the deviations from the time mean zonal and meridional velocities).

3. Overturning Streamfunction Diagnosis

Here we describe three alternative overturning diagnostics used to interpret PERIANT8.

We define the depth-latitude overturning streamfunction, Ψ_{z-y}, as the zonal and vertical integral of the meridional velocity.

$$\Psi_{z-y} = -\oint \int_0^z v dz^* dx^* \tag{1}$$

where z is depth, y is latitude and x is longitude. In PERIANT8, Ψ_{z-y} reveals the wind driven Deacon Cell (clockwise cell in Fig.2a).

The density-latitude overturning streamfunction, $\Psi_{\sigma-y}$, is here defined as the vertical integral of v from the surface to the depth of the σ isopycnal.

$$\Psi_{\sigma-y} = -\oint \int_0^{z(\sigma_2^*=\sigma_2)} v dz^* dx^*. \tag{2}$$

For readers unfamiliar with isopycnal averaging, Fig.3d is a useful aid. Here, a cross section at constant latitude is taken. The meridional transport is integrated in isopycnal ranges (light grey being light water and dark grey dense). A net meridional transport can be present at a given density, without any zonal-mean meridional transport at nearby depths.

Computing $\Psi_{\sigma-y}$ for every 5-day average of PERIANT8 and averaging over the period 1998 – 2007, we determine a mean of $\Psi_{\sigma-y}$. As in Döös and Webb [1994], we re-project the density-latitude overturning into pseudo-depth-latitude space, where the pseudo-depth is given by the average depth of the density surface (Fig.2 b showing the zonal mean of σ_2). Indeed, the Deacon Cell, which is evident in the depth-latitude overturning (Fig. 2 a), is no longer present in density-depth overturning (Fig.2 c).

In order to determine whether it is the standing meanders of the ACC or transient eddy processes that cause the cancellation of the Deacon Cell in density-latitude space, we decompose the transport into a eulerian mean and transient component.

$$\Psi'_{\sigma-y} = \Psi_{\sigma-y} - \overline{\Psi}_{\sigma-y}. \tag{3}$$

The eulerian mean $\overline{\Psi}_{\sigma-y}$ is determined from the eulerian mean meridional velocity $\overline{v}$ (i.e. v averaged in time on the model grid rather than at constant density).

The transient eddy overturning $\Psi'_{\sigma-y}$ only partially works against the Deacon Cell (Fig.2d). At some latitudes the eddy overturning can reach 10 Sv but this is simply in response to spatial variations in the mean vertical velocity at constant latitude at scales of around 50 km. At the scale of the Deacon cell the transient eddy contribution to the density-latitude overturning is approximately 5 Sv. Clearly the standing meanders of the ACC are what counters the Deacon Cell in density-latitude space and not transient eddies. The standing features of the ACC flux light water Southward and dense water Northward.

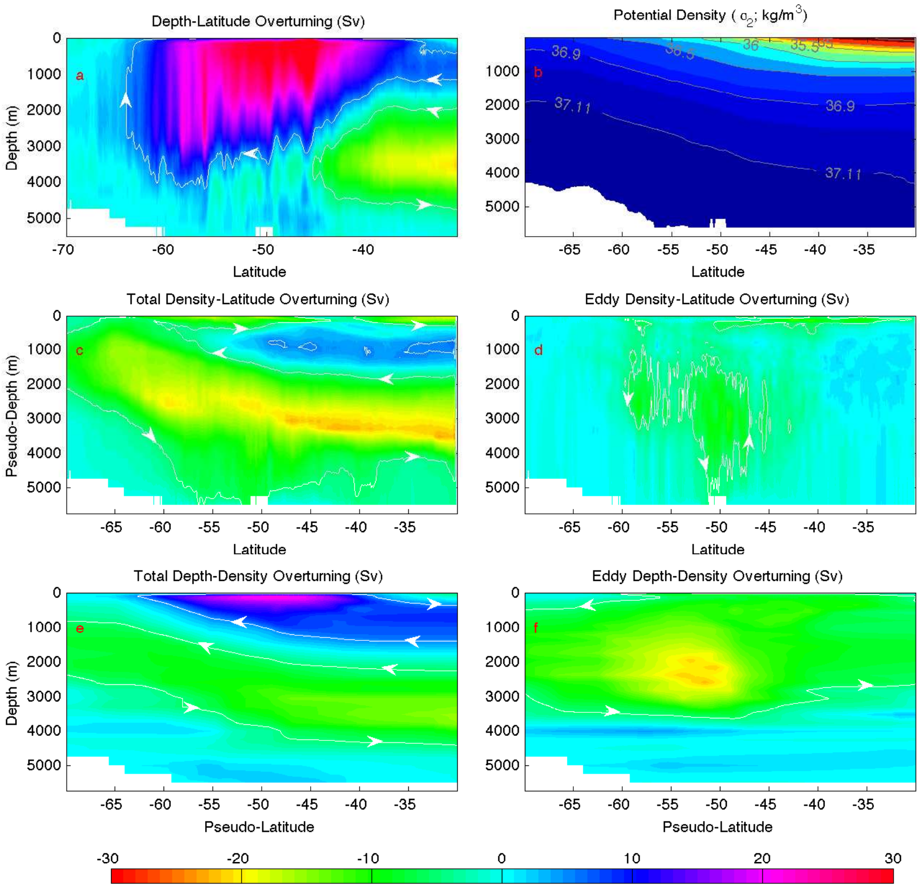

Figure 2. Overturning diagnostics of PERIANT8. a) Overturning averaged in depth-latitude coordinates (Ψ_{z-y}; Sv) comprising a large, 25 – 30 Sv clockwise cell (purple to dark blue) known as the Deacon Cell. The +5 and -5 Sv streamlines are shown in white with arrows indicating the flow direction. b) Zonally averaged potential density (σ_2; kg m^{-3}). c) Overturning circulation averaged in density-latitude coordinates ($\Psi_{\sigma-y}$; Sv). $\Psi_{\sigma-y}$ has been reprojected to pseudo-depths corresponding to the depths of densities in b. d) Transient eddy contribution ($\Psi'_{\sigma-y}$; Sv). e) Overturning circulation averaged in depth-latitude coordinates ($\Psi_{z-\sigma}$; Sv), reprojected to pseudo-latitudes corresponding to the latitudes of densities in b. f) Transient contribution ($\Psi'_{z-\sigma}$; Sv).

In order to gain further insight into the anatomy of the Southern Ocean Overturning we average the overturning in depth-density space. Nurser and Lee [2004] and Nycander et al. [2007] argue for the averaging of flows in isopycnal ranges and at constant depth. Such a diagnostic represents the actual vertical transport of water masses, and can be interpreted as the potential energy input into the ocean by the circulation. To date, such an averaging approach has only been applied in idealised cases and in a global ocean model. In the latter case, downwelling in one hemisphere can be compensated in another.

Here we apply depth-density averaging in the Southern Ocean only. We argue that depth-density averaging has the additional advantage of being naturally 'streamwise'. That is, density contours at constant depth follow the path of the ACC in time and space.

We define the depth-density streamfunction $\Psi_{z-\sigma}$ as

$$\Psi_{z-\sigma} = \int\int_{R(z,\sigma_2)} w dx dy \quad (4)$$

where w is the vertical velocity and $R(z, \sigma_2^*)$ is the area of a constant depth surface where $\sigma_2^* > \sigma_2 > \infty$.

Again, Fig.3d is a useful aid in understanding the meaning of depth-density averaging. Here, a cross section is taken at constant depth and the vertical transport is integrated in isopycnal ranges (light grey being light water and dark grey dense). A net vertical transport can be present in depth-density space, without any zonal-mean vertical velocity.

A mean of $\Psi_{z-\sigma}$ is developed from five day averages of PERIANT8. In the Southern Ocean, the meridional density gradient is, at large scales, monotonic. Thus $\Psi_{z-\sigma}$ can be reprojected into pseudo-latitude in the same way $\Psi_{z-\sigma}$ is projected into pseudo-depth (Fig. 2 e). In practice we re-sort the zonal mean density on each depth level so that it is exactly monotonic for the whole Southern Ocean, before ascribing a pseudo-latitude. Such re-sorting of density as a function of latitude only becomes important around the coast of Antarctica and near the northern boundary, but not at latitudes of Drake Passage.

The large scale features of the depth-density overturning are much the same as the density-latitude overturning (Fig. 2 c and Fig. 2 e respectively). The Deacon Cell is again cancelled. A notable differences between the density-latitude and depth-density streamfunction is the loss of a counter-clockwise cell in the upper 500 m, centred at 55°S, in the density-latitude case. This verifies the assertion of Treguier et al. [2007] that this counter-clockwise cell is a barotropic feature that disappears in a streamwise coordinate, such as the density-depth coordinate used here. In addition, the bottom water cell is stronger in the density-latitude case than in the depth-density case. This is because the density-latitude overturning includes waters that are transported Southward, transformed into denser waters and then transported Northward at the same depth. The depth-density overturning, however, shows only waters that are transported upward and downward in different isopycnal ranges.

As was done for the density-latitude streamfunction we separate the depth-density streamfunction into a mean and transient eddy component, such that

$$\Psi'_{z-\sigma} = \Psi_{z-\sigma} - \overline{\Psi}_{z-\sigma}. \tag{5}$$

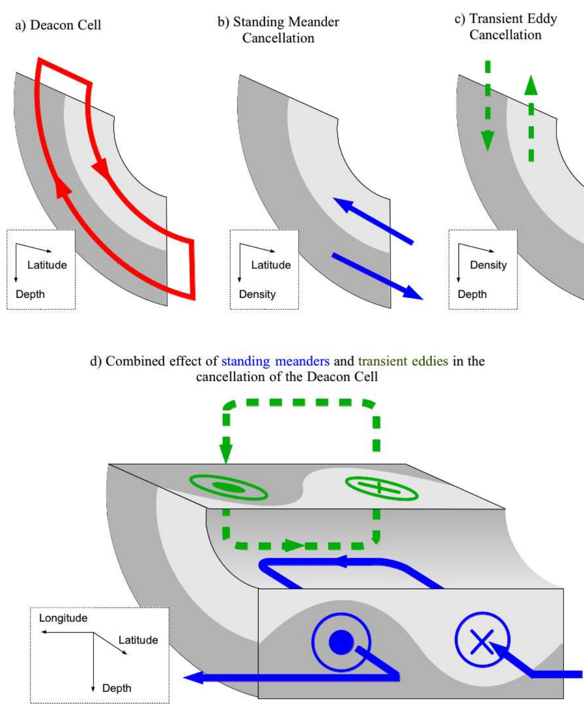

Figure 3. Schematic diagram explaining isopycnal averaging and the key results of this study. a) Flow at constant depth and density reveals a closed 'Deacon Cell' (red) transporting light water (light grey) downward and Northward and dense water (dark grey) Southward and upward. b) Averaging at constant latitude and depth shows a cancellation of the Deacon Cell by the mean flow (blue). c) Averaging at constant depth and density shows a cancellation by transient eddy transport (green). d) Standing meanders of the ACC transport light water Southward through a cross-section at constant latitude while transient eddies transport the same light water upward through a horizontal cross-section. Together, the standing meanders and transient eddies, cancel the Deacon Cell.

where $\overline{\Psi}_{z-\sigma}$ is derived only from the eulerian mean vertical velocity, $\overline{w}$. Plotting the transient eddy contribution, $\Psi'_{z-\sigma}$, in depth-pseudo-latitude space, reveals the enormous role of transient eddies (Fig. 2 f). Transient eddies contribute 15–25 Sv of depth-density space overturning at latitudes of Drake Passage and between 1000–3000 m depth. The transient eddy overturning is counterclockwise. Clearly transient eddies, more so than the standing meanders of the ACC, work against the Deacon cell in the vertical plane. Here transient eddies flux light water upward and dense water downward.

4. Discussion

The three overturning diagnostics presented, reveal three different views of the one overturning. The depth-latitude overturning, Ψ_{z-y}, shows the wind driven Deacon Cell. The density-latitude overturning, $\Psi_{\sigma-y}$, shows how the Deacon Cell's meridional exchanges are compensated by a mean geostrophic flow due to mean standing features of the circulation. The depth-density overturning, $\Psi_{z-\sigma}$, however, demonstrates that the upward transport of dense water and downward transports of light water by the Deacon Cell, is compensated by transient eddy fluxes.

The schematic view of the overturning, according to Döös and Webb [1994], is one where water parcels follow the mean flow. These parcels are transported Northward at shallow depths along the coast of Argentina, then gradually downward and Southward across the South Atlantic, Indian and South Pacific Basins before being transported upward at and downstream of Drake Passage. The culmination of many of these meanders, each deviating by only a hundred meters or so, leads, they argue, cancel out the Deacon Cell.

The classical view of the role of transient eddies is that eddies flux light surface water both meridionally and vertically [Marshall and Radko, 2003]. Again, many small recirculations in many small transient eddies acts to compensate for the Deacon Cell.

Here we find that meanders of the ACC compensate for the Deacon Cell meridionally, but not vertically and that transient eddies do not compensate significantly for the Deacon Cell meridionally, but they do compensate vertically. We thus propose a new paradigm to describe the cancellation of the Deacon Cell, where both transient eddies and standing meanders play complementary roles: The standing meanders of the ACC, transport light water Southward, against the Deacon Cell; transient eddies then act zonally and thus flux light water up into the surface layers and dense water into the deep Ocean. The standing meanders act in the horizontal plane and transient eddies act in the vertical plane (Fig. 3).

5. Conclusions

A state of the art, eddy resolving model has been used to understand the dynamics of the Southern Ocean Overturning. We calculate overturning streamfunctions in both density-latitude and depth-density space. By doing so we elucidate the complimentary roles of both the ACCs standing meanders and transient eddies in responding to Deacon Cell.

This study implies that eddies may act much more efficiently in the zonal rather than meridional direction. Because isopycnal slopes are small, vertical isopycnal transport must also be associated with lateral isopycnal transport [McDougall and McIntosh, 1996]. And because eddy induced transport is small in the meridional direction (Fig2d) we conclude that eddy fluxes act vigorously in the zonal direction.

We posit that this zonal dominance is due to the β effect acting on the abrupt topographic meanders of the ACC. It is known that deep topography steers the near equivalent barotropic ACC [Hughes and Killworth, 1995]. It is also accepted that, due to planetary β effect, flows in the zonal direction are far more stable than in the meridional direction [Kang et al., 1982]. Thus topographically steered non-zonal flows are particularly unstable and turbulent processes act to align such flows with constant latitude circles. Results presented here suggest that, in an effort to align the flow with constant latitude circles, transient eddies act to flatten zonal density gradients. In doing so transient eddies, transport light water upward and dense water downward.

Finally, transient eddies play a key role in vertical exchange. This finding is likely to have broader implications. It has been established previously that transient eddies play a minor role in meridional heat and freshwaters transport [Jayne and Marotzke, 2002], even in the Southern Ocean [Meijers et al., 2007]. We propose a similar analysis to that carried out here, separating mean and transient components of vertical property transports. Such an analysis may further elucidate the key role that transient eddies play in the net vertical transport.

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