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The residual circulation of the Southern Ocean: Which spatio-temporal scales are needed?

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ABSTRACT

The Southern Ocean circulation consists of a complicated mixture of processes and phenomena that arise at different time and spatial scales which need to be parametrized in the state-of-the-art climate models. The temporal and spatial scales that give rise to the present-day residual mean circulation are here investigated by calculating the Meridional Overturning Circulation (MOC) in density coordinates from an eddy-permitting global model. The region sensitive to the temporal decomposition is located between 38°S and 63°S, associated with the eddy-induced transport. The "*Bolus*" component of the residual circulation corresponds to the eddy-induced transport. It is dominated by timescales between 1 month and 1 year. The temporal behavior of the transient eddies is examined in splitting the "*Bolus*" component into a "*Seasonal*", an "*Eddy*" and an "*Inter-monthly*" component, respectively representing the correlation between density and velocity fluctuations due to the average seasonal cycle, due to mesoscale eddies and due to large-scale motion on timescales longer than one month that is not due to the seasonal cycle. The "*Seasonal*" bolus cell is important at all latitudes near the surface. The "*Eddy*" bolus cell is dominant in the thermocline between 50°S and 35°S and over the whole ocean depth at the latitude of the Drake Passage. The "*Inter-monthly*" bolus cell is important in all density classes and is maximal in the Brazil–Malvinas Confluence and the Agulhas Return Current. The spatial decomposition indicates that a large part of the Eulerian mean circulation is recovered for spatial scales larger than 11.25°, implying that small-scale meanders in the Antarctic Circumpolar Current (ACC), near the Subantarctic and Polar Fronts, and near the Subtropical Front are important in the compensation of the Eulerian mean flow.

1. Introduction

The meridional overturning stream function gives an integrated view of the circulation in the meridional-vertical plane. It captures a large part of the thermohaline and wind-driven overturning circulations and for this reason it has been used an innumerable amount of times to characterize these circulations. However, it should be stressed that there are many areas where the three-dimensional structure of the circulation is essential, in particular in the Southern Ocean (Sloyan and Rintoul, 2001; Drijfhout et al., 2003). The overturning stream function is defined as a vertical indefinite integration of the meridional velocity, followed by a zonal integration over an entire basin or, as in the atmosphere, all around the world. It was introduced in the 1960s as a way to analyze numerical simulations of the atmospheric circulation (Smagorinsky, 1963; Wallace and Holton, 1968), making it possible to study the meridional-vertical circulation like the Hadley, Ferrel and Polar cells.

With the first coupled ocean–atmosphere models (Wetherald and Manabe, 1972) similar meridional-vertical cells were discovered in the oceans. One of these cells was the Deacon Cell in the Southern Ocean. It was first mentioned by Bryan (1991) and England (1992) and named by Bryan (personal communication) after the studies made by George Deacon in the Southern Ocean during the 1930s (Deacon, 1937). Associated with the Deacon Cell, about 20 Sverdrups ($1Sv = 10^6$ m^{3}s^{-1}) appears to downwell near 40°S down to a depth of several thousand meters. This water upwells further south towards Antarctica (Fig. 1). It was argued that most of this cell was due to a geometrical effect of the east–west slope of the isopycnals (Döös and Webb, 1994; Döös, 1994), that is associated with standing eddies (*i.e*, the meridional excursions from the zonal mean overturning circulation) and more importantly, basin-scale gyres, and that no cross-isopycnal flow was associated with it. It is however accepted that this Cell do not represent the "real" Southern Ocean overturning circulation, which must be evaluated in density space.

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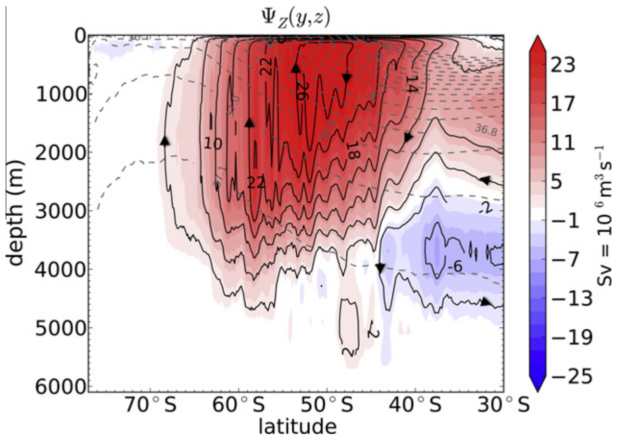

Fig. 1. Meridional overturning stream function as a function of latitude and depth. Color interval is 2 Sv. Black solid lines have a 4 Sv interval. Positive stream lines correspond to clockwise circulation and negative stream lines to anti-clockwise circulation. Dashed line are the zonally averaged isopycnal σ_2 between 35.5 kg m^{-3} and 37 kg m^{-3} (contour intervals 0.1 kg m^{-3}).

A much better description of the Southern Ocean overturning circulation in geometrical coordinates arises when the residual circulation is considered, i.e., the transport by transient eddies is also accounted for (Marshall and Radko, 2003). To account for a complete description of the net along and cross-isopycnal flow, the circulation must be evaluated in density space as well. When the zonal integration is performed along isopycnals, only a few Sv are left that locally recirculate in the meridional-isopycnal frame. This "residual" cell is either due to model drift, or to a real diabatic water mass transformation. Drijfhout (2005) pointed out that the cancelation obtained by Döös and Webb (1994) was due to both transient eddies (i.e, the deviation of the overturning circulation from the mean Eulerian circulation) and the choice of an isopycnal framework; Döös and Webb (1994) used 73 five-day snapshots for the isopycnal calculation, thereby sampling the mesoscale eddy field. In the OCCAM model later analyzed by Drijfhout (2005) the role of transient eddies in the cancelation was about 30%, while the geometrical effect (tilting gyres and standing eddies) accounted for 70%. This partition was made possible by comparing an isopycnal calculation of the time-mean flow with a sum of a long series of five-day averages. A similar decomposition was also performed in Lee and Coward (2003).

The role of transient versus standing eddies and even larger-scale geometric effects becomes particularly intriguing when one considers the Southern Ocean. This ocean partly consists of an open channel with the Antarctic Circumpolar Current (ACC) flowing around the globe, and of subtropical gyres, which are blocked by continents. For the ACC, an along and cross-stream coordinate system can be defined, and for the along-stream averaged flow all cross-stream transport must be due to transient eddies (Marshall and Radko, 2003; Olbers and Visbeck, 2005). A description of the Southern Ocean overturning circulation using this decomposition has recently been applied (Treguier et al., 2007; Viebahn and Eden, 2012). It was shown that using along-streamline integration removes the standing-eddy part of the circulation and therefore allows for a better physical representation of the Southern Ocean overturning. However, the integration path is model-dependent and might be different between the eddy-permitting and the coarse resolution models (due to the smoothness of the contour of integration). Also, the method breaks down when the ACC is not strictly equivalent barotropic.

In the state-of-the-art climate models, the oceanic component usually includes a coarse resolution grid of discretization. Consequently, the effect of the sub-grid scale processes (effect of the eddies) needs to be parametrized. The Gent and McWilliams (1990) parameterization (hereafter, denoted GM) is often applied in depth-coordinate models for representing the contribution of unresolved motions to the large-scale flow (eddy-induced transport). The residual mean flow in that case is described as the sum of the zonally-averaged Eulerian mean flow plus an eddy-induced component (GM transport). Sometimes, the GM-coefficient is chosen to cancel the Deacon Cell associated with the zonally averaged Eulerian-mean flow in depth coordinates (Olbers and Visbeck, 2005). If the residual circulation partly arises through standing eddies, the chosen GM-coefficient is then too large. If on the other hand, the Deacon Cell is a purely geometrical effect, as suggested by Döös and Webb (1994), transient eddies do not play a role at all, and even without GM the Eulerian mean flow should equal the residual mean flow in density space. The GM coefficient should then be small. Averaging the Eulerian mean flow along streamlines should already give the residual mean flow. Additionally, if the standing-eddy component is dominated by small-scale topographic effects and small-scale standing eddies in the ACC, the interpretation of GM becomes different because it should also include the effect of these small-scale standing eddies. It is thus important to know the dominant time and spatial scale of the Southern Ocean overturning circulation.

Here, we investigate the temporal and spatial scales that give rise to the present-day residual mean circulation, by calculating the Meridional Overturning Circulation (MOC) in density coordinates from an eddy-permitting global model. The calculation consists of time-averages over increasing periods, effectively decreasing the time resolution of the model output, and spatial-averages over increasing zonal lengths, effectively decreasing the spatial resolution of the model output. The time-scale decomposition has an extra dimension because the seasonal cycle of the large-scale flow may have a rectifying effect on the circulation, which we call the "*Seasonal*" bolus transport. This diagnostic is also is relevant for (1) understanding the details of the overturning circulation in the Southern Ocean, e.g. the eddy-induced heat transport, and (2) evaluating the variability of the different components of the overturning cells. The length-scale decomposition is performed along constant latitude to elucidate the role of standing eddies with varying length scales in counteracting the Eulerian mean flow. For this reason we have refrained from choosing the along and cross-streamline coordinate system, as this would have obscured the impact of the standing eddy component on the overturning circulation. The present paper is structured as follows. A short description of the model and data used in this study is introduced in Section 2. Section 3 deals with the definition and mathematical formulation of the meridional overturning stream function in the depth-level and density coordinates, their decomposition and the characterization of the eddy-induced transport ("*Bolus*") component. The results are presented and discussed in Section 4.

2. Models & data descriptions

In the present study, we analyze output from the Ocean General Circulation Model (OGCM) NEMO (Madec, 2006) in the ORCA025 configuration, which corresponds to an horizontal spatial resolution of about 0.25°. The vertical dimension is discretized into 64 depth-levels increasing from 6 m near the surface to 200 m in the deepest cells. At the sea surface, the ocean model is coupled to the sea ice model LIM (Fichefet and Maqueda, 1997). The parameterization of the sub-grid scale turbulence physics (GM, Gent and McWilliams, 1990) is not used. The ORCA025-N112 run that we analyze is a 44 year run forced by atmospheric reanalysis fields (Brodeau et al., 2010). The model integration is available as 5-day means from the last 12 years of the ORCA025-N112 integration.

McDougall (1987) argued that a fluid parcel tends to follow local neutral density surfaces and Hirst et al. (1996) discussed the MOC stream function in depth-levels as well as potential and neutral density coordinates. As in Lee and Coward (2003) they concluded that the MOC calculated on potential density classes for σ_2 or deeper reference levels is able to capture similar patterns and transports as a MOC calculated on neutral density classes. Therefore, in the present study, the potential density referenced to the intermediate depth of 2000 m is used as "vertical coordinate". However, using a σ_2 projection requires that the model is in steady state, in other words, that the isopycnals should not drift. The model drift is discussed and analyzed in Appendix A. For the analysis of isopycnal transports, density needs to be interpolated to velocity grid points and to remove static instabilities, we applied pairwise averaging of grid boxes.

3. Meridional overturning stream functions

3.1. Total, mean and bolus

If the depth is chosen as a vertical coordinate the meridional overturning stream function is defined as:

$$\Psi_Z(y,z) \equiv \frac{1}{t_1 - t_0}\int_{t_0}^{t_1}\int_{x_W}^{x_E}\int_{z(x,y,t)}^{\eta(x,y,t)} v(x,y,z',t)dz'\,dx\,dt \quad (1)$$

where $v(x,y,z',t)$ is the meridional velocity; x,y,z',t the zonal, meridional, vertical and time coordinates; x_E and x_W are the longitudes of the eastern and western coasts, and t_0 and t_1 are the initial and final times.

The overturning stream function can also be derived as a function of density (Döös and Webb, 1994). When calculating the time-averaged overturning stream function with density as a vertical coordinate it is important to take into account that the depths of the isopycnals vary in time. Therefore, the velocity field has to be integrated vertically first, then zonally and thereafter over time. This "***Total***" overturning stream function is defined as:

$$\Psi_T(y,\sigma) = \frac{1}{t_1 - t_0}\int_{t_0}^{t_1}\int_{x_W}^{x_E}\int_{z(x,y,\sigma,t)}^{\eta(x,y,t)} v(x,y,z',t)dz'\,dx\,dt \quad (2)$$

where $z(x,y,\sigma,t)$ is the depth of the isopycnal with σ-density.

If the time average is instead first performed on the meridional velocity and then integrated zonally along the time averaged isopycnals, a "***Mean***" stream function on mean density levels can be formulated as:

$$\Psi_M(y,\sigma) \equiv \int_{x_W}^{x_E}\int_{z_M(x,y,\sigma)}^{\eta} v_M(x,y,z')dz'\,dx \quad (3)$$

where v_M is the time-mean meridional velocity:

$$v_M(x,y,z') \equiv \frac{1}{t_1 - t_0}\int_{t_0}^{t_1} v(x,y,z',t)dt$$

and the time-mean depth of the isopycnal is:

$$z_M(x,y,\sigma) \equiv \frac{1}{t_1 - t_0}\int_{t_0}^{t_1} z(x,y,\sigma,t)dt$$

This "*Mean*" stream function Ψ_M will include the standing eddies but will miss the contribution of the correlation between the time fluctuating meridional velocity and isopycnals since the zonal integration is not strictly along the isopycnals for Ψ_M for every time sample. This missing term is hence

$$\Psi_B \equiv \Psi_T - \Psi_M \quad (4)$$

and can be referred to as the "***Bolus***" stream function or eddy-induced stream function. This component of the overturning is made of the transient eddies.

3.2. Temporal decompositions of the stream function

By varying $\Delta t = t_1 - t_0$ in v_M and z_M and averaging over several such periods, it is possible to estimate at what period the bolus effect is most important. To this end Ψ_M is calculated for a chosen sub-time period Δt and then averaged over the total period (L_t). The "*Bolus*" component is in this way included for a particular time period Δt where $N_t\Delta t = L_t$ so that

$$\Psi_{DT}(y,\sigma,\Delta t) \equiv \frac{1}{N_t}\sum_{n=0}^{N_t-1}\int_{x_W}^{x_E}\int_{z_M^{\Delta t}(x,y,\sigma,t)}^{\eta} v_M^{\Delta t}(x,y,z,t)dz\,dx \quad (5)$$

with

$$v_M^{\Delta t}(x,y,z,t) \equiv \frac{1}{\Delta t}\int_{t_0+n\Delta t}^{t_0+(n+1)\Delta t} v(x,y,z,t)dt$$

$$z_M^{\Delta t}(x,y,\sigma) \equiv \frac{1}{\Delta t}\int_{t_0+n\Delta t}^{t_0+(n+1)\Delta t} z(x,y,\sigma,t)dt$$

This method is equivalent to decreasing the temporal resolution of the output data.

We define the averaged "*Seasonal*" stream function Ψ_S as:

$$\Psi_S(y,\sigma) \equiv \frac{1}{\Delta t_S}\int_0^{\Delta t_S}\int_{x_W}^{x_E}\int_{z_S(x,y,\sigma,t_S)}^{\eta} v_S(x,y,z',t_S)dz'\,dx\,dt_S \quad (6)$$

such that v_S is the seasonal meridional velocity:

$$v_S(x,y,z',t_S) \equiv \frac{1}{N_t}\sum_{n=1}^{N_t} v(x,y,z',t_S + n\cdot\Delta t_S)$$

and the seasonal depth of the isopycnal is:

$$z_S(x,y,\sigma,t_S) \equiv \frac{1}{N_t}\sum_{n=1}^{N_t} z(x,y,z',t_S + n\cdot\Delta t_S)$$

with N_t the number of years, Δt_S the total number of snapshots during 1 year. v_S and z_S are averages over the same time span in each year of the model run. For example, if the data come in monthly means, v_S and z_S are averages over all Januaries, all Februaries etc.

In addition, we decompose the "*Bolus*" component as the sum of three terms: the "*Eddy*" bolus Ψ_{EB}, the "*Inter-monthly*" bolus Ψ_{IB} and the "*Seasonal*" bolus Ψ_{SB} component. The "*Eddy*" bolus is the correlation between density and velocity fluctuations due to mesoscale eddies (Eq. (7)). The "*Inter-monthly*" bolus is the correlation between velocity and density fluctuations by large-scale motion on timescales longer than one month that is not due to the seasonal cycle (Eq. (8)). The "*Seasonal*" bolus is the correlation between density and velocity fluctuations due to the average seasonal cycle (Eq. (9)).

$$\Psi_{EB}(y,\sigma) = \Psi_T(y,\sigma) - \Psi_{DT}(y,\sigma,\Delta t = 1\text{ month}) \quad (7)$$

$$\Psi_{IB}(y,\sigma) = \Psi_{DT}(y,\sigma,\Delta t = 1\text{ month}) - \Psi_S(y,\sigma) \quad (8)$$

$$\Psi_{SB}(y,\sigma) = \Psi_S(y,\sigma) - \Psi_M(y,\sigma) \quad (9)$$

3.3. Spatial decompositions of the stream function

Considering a zonal length $[L_x]$ for the entire globe, a decomposition can be adapted to the spatial dimensions too. By varying the zonal integration $\Delta x = x_{i+1} - x_i$ in Ψ_T (Eq. (2)), it is possible to estimate at which length scale the bolus effect is most important. A stream function on zonal-mean density levels is therefore calculated for a chosen sub-spatial scale Δx, and then an average is

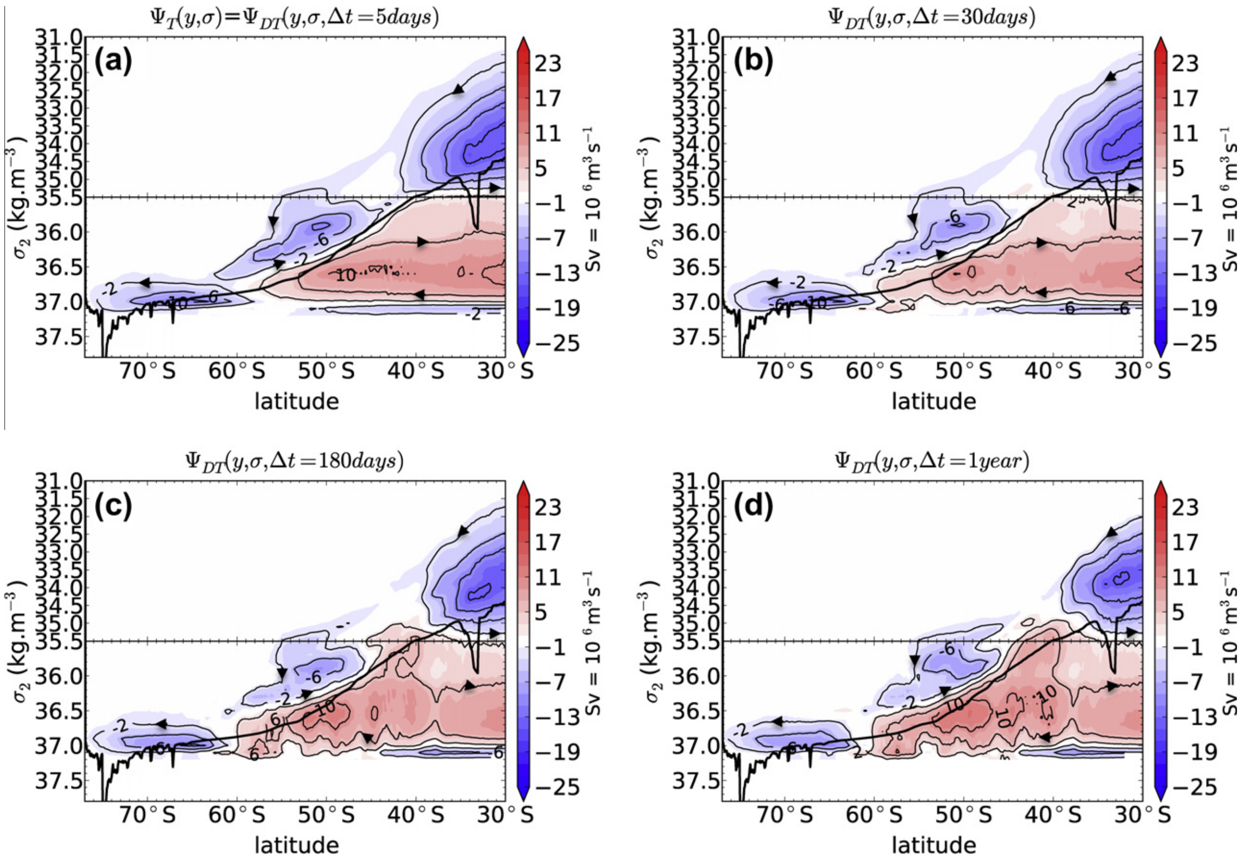

Fig. 2. Temporal decomposition (a) 5 days, (b) 30 days, (c) 180 days, (d) 1 year of the meridional overturning stream function in the Southern Ocean as a function of latitude and potential density σ_2. The color shading has intervals of 2 Sv and the solid contours have an interval of 4 Sv. Here and in following Figures, the thick solid line corresponds to the averaged maximum potential density at the sea surface for each latitude.

calculated over the total domain. A spatial bolus component is in this way included for a particular sub-spatial scale Δx where $N_x\Delta x = L_x$ so that

$$\Psi_{DX}(y,\sigma,\Delta x) \equiv \frac{1}{t_1-t_0}\int_{t_0}^{t_1}\int_0^{N_x-1}\int_{z_M^{\Delta x}(n,y,\sigma,t)}^{\eta} v_M^{\Delta x}(n,y,z,t)\,dz\,dn\,dt \tag{10}$$

with (for $n = 0, N_x - 1$)

$$v_M^{\Delta x}(n,y,z,t) \equiv \frac{1}{\Delta x}\int_{x_W+n\Delta x}^{x_W+(n+1)\Delta x} v(x,y,z,t)\,dx \tag{11}$$

$$z_M^{\Delta x}(n,y,\sigma,t) \equiv \frac{1}{\Delta x}\int_{x_W+n\Delta x}^{x_W+(n+1)\Delta x} z(x,y,\sigma,t)\,dx \tag{12}$$

where $v_M^{\Delta x}$ is the velocity averaged on the sub-space Δx and $z_M^{\Delta x}$ is the isopycnal depth averaged on the sub space.

This is equivalent to decreasing the zonal resolution. It is important to take into account the variation of the bathymetry in each sub space when doing the spatial decomposition, and a cell volume weight has to be applied in each grid cell. In each decomposition, the zonal averaging starts from the longitude 70°W (Drake Passage).

4. Results & discussion

In this part, the total overturning in the latitudinal-depth space and in the latitudinal-density space are first discussed to highlight the difference in the Southern Ocean circulation between the two frameworks. The temporal decomposition of the overturning and the bolus component in density coordinates are then analyzed to identify the temporal compensation of the Eulerian mean overturning. Finally, the spatial decomposition of the Southern Ocean overturning is proposed to determine its dominant length scale.

4.1. Total overturning

The Deacon Cell is, in the present study, quantitatively defined as the sum of all the stream lines that recirculate in the Southern Ocean with a northward transport near the surface and a southward return flow in the deep ocean (Fig. 1). This results in a maximum amplitude of the Deacon Cell of 28.8 Sv near 52°S. The dashed lines in Fig. 1 represent the zonally averaged isopycnals between 35.4 and 37.1 kg m^{-3}. It is clearly seen that this fictitious circulation occurs where the zonally averaged meridional tilting of the isopycnal is largest, that is, where the largest impact of eddies is expected. Also, the vertical streamlines associated with the upwelling and downwelling branches of the Deacon Cell occur in an area of the global ocean which is highly stratified (between 40°S and 60°S).

To account for the effect of transient and standing eddies we calculate the "*Total*" overturning stream function Ψ_T (Eq. (2)), with $\Delta t = t_1 - t_0 = 12$, being an average over 12 years (Fig. 2(a)). In this calculation, volume fluxes were projected on 100 equally spaced potential density layers extending from 28 to 38 kg m^{-3}. The thick solid line represents for each latitude the average maximum potential density at the ocean surface, *i.e.*, an average over the deepest density classes that have been

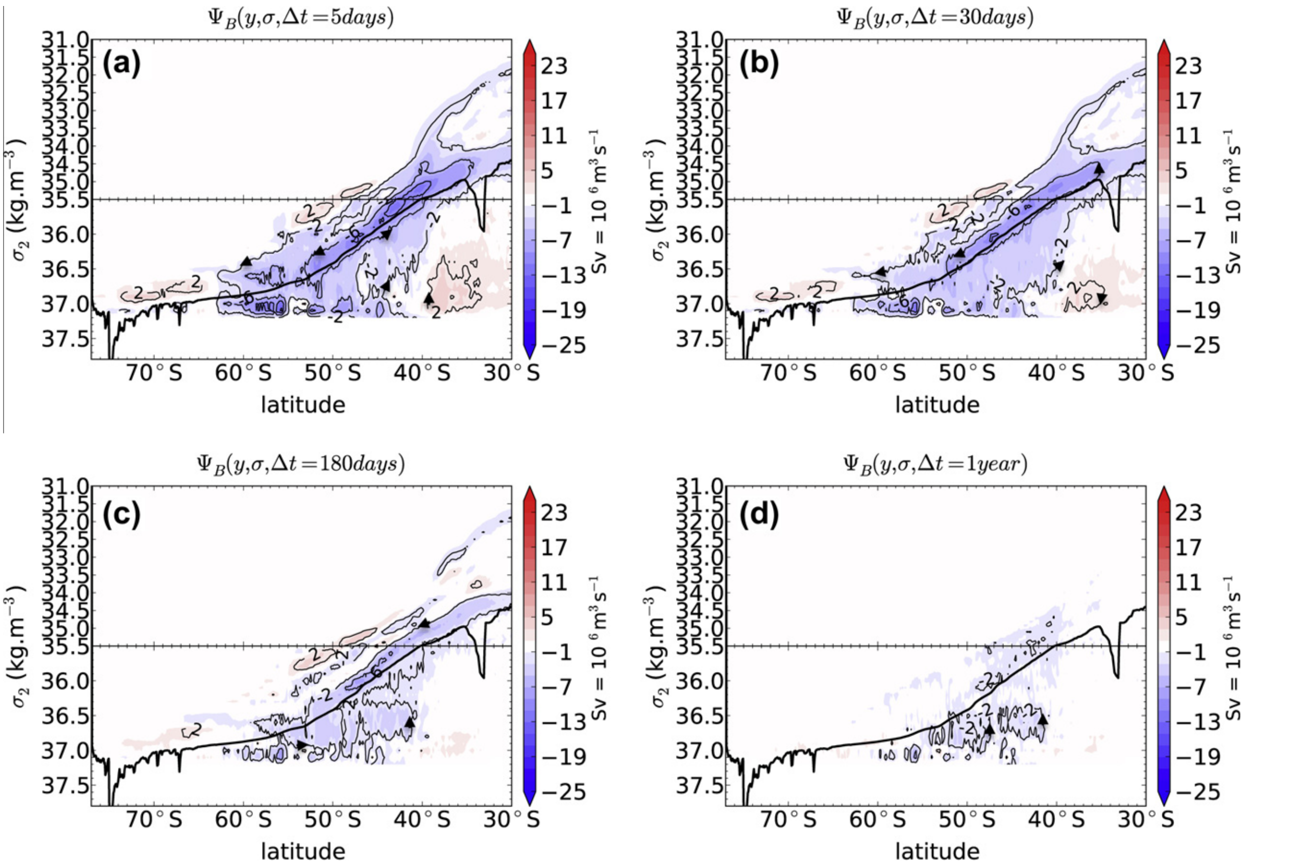

Fig. 3. Temporal decomposition of the "*Bolus*" component of the meridional overturning stream function in the Southern Ocean as a function of latitude and potential density σ_2, (a) 5 days, (b) 30 days, (c) 180 days, (d) 1 year. Color interval is 4 Sv. Filled contour interval 2 Sv.

in contact with the atmosphere at any point of the integration. The maximum of the Southern Ocean overturning cell is reduced from 28.8 Sv to 10.5 Sv. So, the combined effect of transient and standing eddies compensate the Eulerian mean overturning with 18.3 Sv. The maximum overturning cell is embedded in a clockwise cell that is bounded by the isopycnals 35.5 kg m^{-3} and 37 kg m^{-3} and is characterized by water flowing southward to 60°S, upwelling from 37 kg m^{-3} to lighter density classes and then moving northward. This cell represents the transformation of inflowing North Atlantic Deep Water (NADW) into Antarctic Intermediate Water (AAIW). In addition, three anti-clockwise cells recirculate surface water above the maximum surface density. The first one is a portion of the wind-driven Subtropical cell between 30°S–40°S and 31 kg m^{-3}–35.5 kg m^{-3}, with a maximum meridional flux of 18 Sv. A second surface cell lies above the residual circulation, between 50°S and 60°S, having a maximum intensity of 10 Sv. This circulation at the surface in the ACC region is known to be associated with the contribution of time-mean and transient eddies in latitudinal averaging (Hallberg and Gnanadesikan, 2006) or streamlines averaging (Treguier et al., 2007). The third surface cell is a sub-polar cell between 60°S and 77°S including the contribution of the sub-polar gyres in the Weddell and Ross Seas. A fourth anti-clockwise cell, associated with Antarctic Bottom Water (AABW), is located between the bottom and the clockwise NADW/Circumpolar Deep Water (CDW) cell. Similar to Spence et al. (2009) we find that the upwelling branch of the NADW cell is situated farther north in Ψ_T compared to Ψ_Z. The southern boundary of the upwelling branch moves from 68°S to about 58°S. This shift is related to the large-scale tilt of the isopycnals that is not captured by Ψ_Z.

4.2. Temporal decomposition

Fig. 2(b)–(d) show the temporal decomposition of the meridional overturning circulation Ψ_{DT} respectively for Δt = 30 days, 180 days and 1 year (Eq. (5)). The stream function in Fig. 2(d) is similar to the "*Mean*" stream function Ψ_M (Eq. (3), where Ψ_M = $\Psi_{DT}(\Delta t$ = 12 years)). From Ψ_T to Ψ_M the maximum meridional transport in the NADW cell increases from 10.5 Sv to 15.2 Sv. In Fig. 2(d) the NADW cell is about 13.2 Sv. This indicates that the compensation of the Eulerian mean overturning through the transition in vertical coordinate from z to σ_2 is not a purely geometric effect due to standing eddies and tilting gyres; it only becomes complete when transient eddies are accounted for. The region most sensitive to the temporal decomposition is located between the southern and the northern branch of the Deacon Cell (38°S–63°S). The deep AABW cell and subpolar surface cell are disconnected in the model. This is due to the model drift (cf. Fig. A.8), indicating that AABW formation is weakening. Also, it might be that downwelling of AABW and upwelling of NADW partly overlap in the zonal average between 52°S and 58°S. Interestingly, the disconnection between the two cells becomes more pronounced when the averaging time scale increases, indicating that transient eddies are important in AABW formation. Because of the large drift in the AABW cell we refrain from discussing this aspect of the Southern Ocean overturning in more detail. South of 63°S and north of 38°S, the meridional transport is almost unchanged. Around 50°S, the effect of standing eddies is larger and the maximum of the NADW cell is almost reduced with a factor of two (compared with Ψ_Z), but this is still not enough to completely compensate an apparent wind-driven recirculation of a few Sv in the

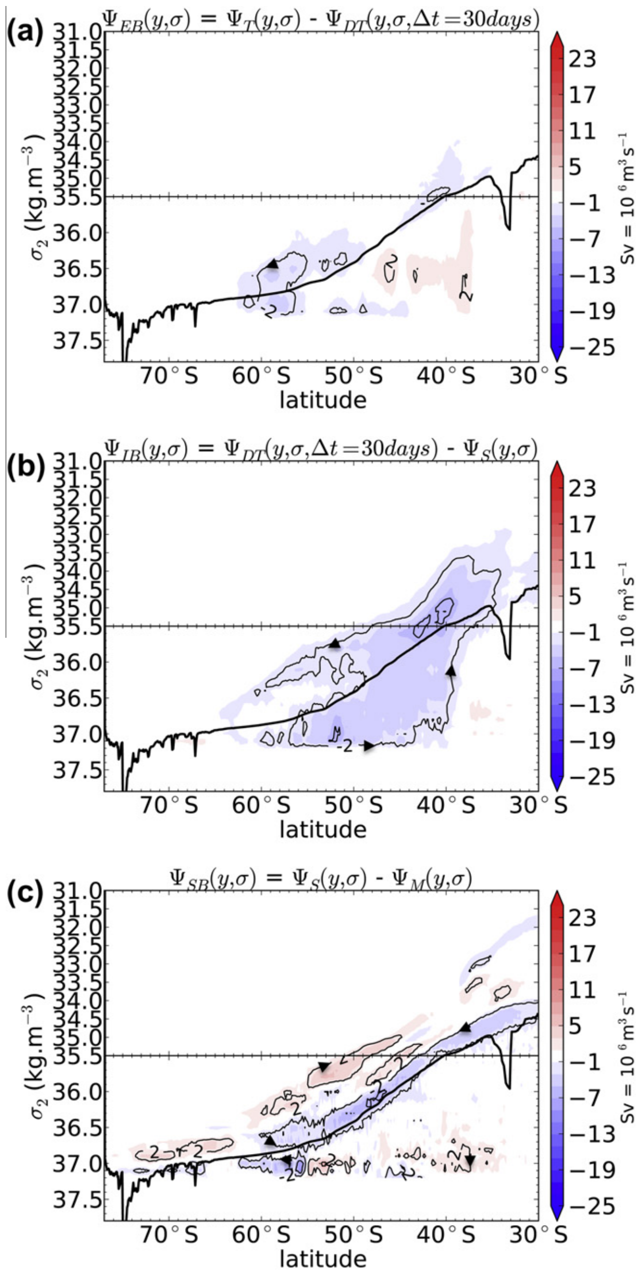

Fig. 4. Comparison between (a) *Eddy* Bolus, (b) *Inter-monthly* bolus and (c) *Seasonal* bolus components of the meridional overturning stream function in the Southern Ocean as a function of latitude and potential density σ_2 in the eddy-permitting integration. Color interval is 2 Sv. Solid contour interval is 4 Sv.

Southern Ocean mid-latitudes. The surface cell in the ACC region does not disappear for averaging over longer time scales. This confirms that the ACC surface cell is weakly associated with transient eddies (Treguier et al., 2007).

Fig. 3 represents the temporal decomposition of Ψ_B, the "*Bolus*" component (Eq. (4)) of the meridional overturning circulation in the Southern Ocean for 5, 30, 180 days and 1 year. The "*Bolus*" stream function in Fig. 3(a) is dominated by a large anti-clockwise cell spreading from 40°S to 64°S, which flows against the NADW/CDW cell. In addition, three clockwise circulations appear: one is situated between 40°S and 30°S and between the 35.5 and 37.0 kg m^{-3} density classes, probably related to the fact that some isopycnals have a slight upward slope northwards in this region (cf. Fig. 1). The other two are surface cells, one is centered around 50°S and the other lies in the sub-polar region. Two intense (4–6 Sv) anti-clockwise "*Bolus*" circulations are present in the Southern Ocean. The first one lies between 35°S and 52°S (above the maximum surface density at the sea surface) and is directly in contact with the atmosphere. The second bolus cell is a much deeper circulation, near the density class of 37 kg m^{-3}. It lies between 55°S and 60°S, covering the latitudes of Drake Passage. The "*Bolus*" component (Fig. 3(a)) is comparable to the remapped bolus stream function in Fig. 6(b) in Lee et al. (2007). In diagnosing the meridional transport in an eddy-resolving OGCM, Lee et al. (2007) highlighted two intense eddy transport regions associated with the Subantarctic/ Polar Front and the Subtropical Front. The same two cells appear in Fig. 3(a). The temporal decomposition shows that the "*Bolus*" component almost vanishes when the temporal averaging is done for a period of 1 year (Fig. 3(d)) or greater. Most of the deeper part seems to be dominated by timescales of a few months, while the surface part of the bolus stream function is substantially changed on intra-monthly timescales (cf. Fig. 3(b) and (c)).

Fig. 4 compares the "*Eddy*" bolus, "*Inter-monthly*" and the "*Seasonal*" bolus components (Eqs. (7)–(9)) of the meridional overturning circulations in the Southern Ocean. The "*Eddy*" bolus component is shown in Fig. 4(a). This bolus component indicates three anti-clockwise circulations: the first one is located at the surface near 41°S, a second cell is present at 50°S in the deep ocean and the third counter-clockwise circulation is located near 59°S and recirculates surface and deep waters. This cell is responsible for about 2–3 Sv of the compensation of the Eulerian mean circulation, while it tends to enhance the downwelling branch of the Eulerian mean circulation by 2 Sv between 37°S and 48°S. The "*Inter-monthly*" bolus cell stretches between 38°S and 63°S from the upper parts of the Southern Ocean to the deepest parts (Fig. 4(b)). This cell counteracts the Eulerian mean circulation by transporting deep water from the high to the lower latitudes with a 2–3 Sv intensity, then moving poleward the surface water. Note that the "*Inter-monthly*" bolus cell is weak between 55°S and 63°S where the "*Eddy*" bolus cell is dominant. The maximum ($\approx$4 Sv)"*Inter-monthly*" bolus cell is found between 40°S and 45°S, i.e. the latitude of the Agulhas leakage. The "*Seasonal*" bolus effect is mainly active above the maximum surface density line and deeper between 50°S and 60°S (Fig. 4(c)). At the sea surface, the seasonal bolus cell is dominated by clockwise circulations. These circulations counter with a 2 Sv intensity the ACC surface meandering and the sub-polar gyres in the Weddell and Ross Seas shown in Fig. 2(a). An anti-clockwise "*Seasonal*" bolus cell lies above the maximum surface density line between 30°S and 60°S and transports on a larger spatial scale the surface waters. Ignoring the deep cells, the "*Seasonal*" bolus stream functions are almost recovered in the 180-days averaging period (Fig. 3(c)). This seasonal decomposition also reveals that the positive bolus surface cells mainly take part in the "*Seasonal*" bolus component.

4.3. Spatial decomposition

The spatial decomposition of the meridional overturning circulation Ψ_{DX} is represented in Fig. 5(a)–(f), respectively for $\Delta x = 1.25^\circ, 3.75^\circ, 11.25^\circ, 22.5^\circ, 90^\circ$ and 360° (Eq. (10)). It is shown that the Southern Ocean cells have different spatial scales and that the dominant compensations occur between the southern and northern branch of the Deacon Cell. The three surface anti-clockwise circulations in the complete residual stream function Ψ_T have distinct spatial scales. The sub-polar cell has a spatial scale of about 90°, typical for the Weddell and Ross gyres. Additionally, the connection between the sub-polar gyre at the surface and the deep cell in the AABW density classes is lost already for the 3.75° averaging, suggesting that the AABW formation happens as a small-scale

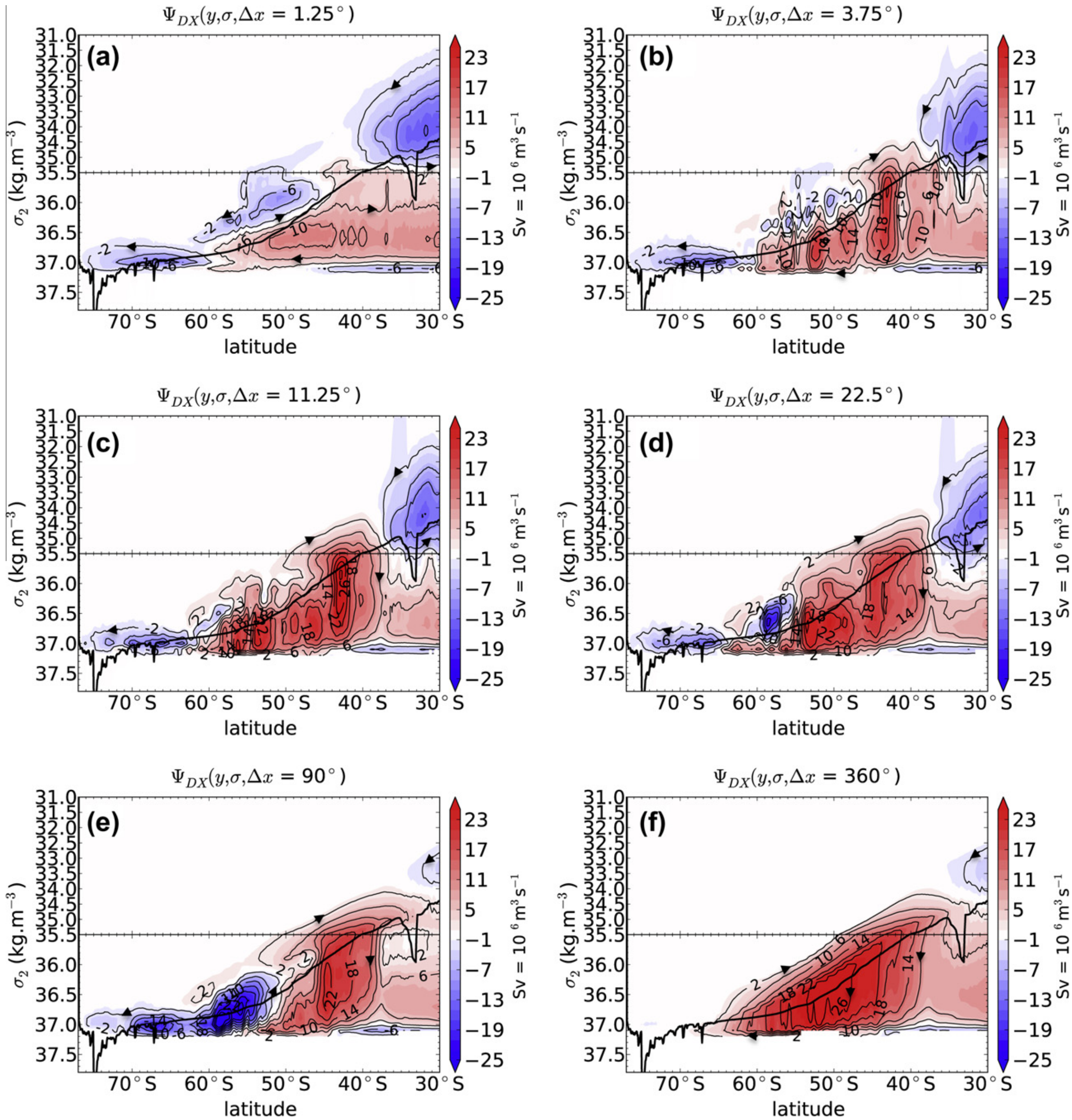

Fig. 5. Spatial decomposition (a) 1.25°, (b) 3.75°, (c) 11.25°, (d) 22.5°, (e) 90° and (f) 360° of the meridional overturning stream function in the Southern Ocean as a function of latitude and potential density σ_2. The color shading has intervals of 2 Sv and the solid contours have an interval of 4 Sv.

process. The subtropical cell has a scale of about 20° and the surface cell near Drake Passage is dominated by spatial scales of 3° or less. Apparently this surface cell is driven by small-scale standing eddies but it is insensitive to the averaging time period (Fig. 2). The Eulerian mean cell is represented in the 360° averaging (Fig. 5(f)). For a spatial averaging of 3.75°, the circulations between 40°S and 60°S consist of cross-isopycnal transport with a meridional scale of about 3°. These structures likely correspond to small-scale standing meanders in the ACC. The differences between Fig. 5(b) and 2(a) reveal that small-scale meanders are important in the ACC, near the Subantarctic and Polar Fronts, and near the Subtropical Front. For a zonal averaging between 11.25° and 22.5° (Figs. 5(c) and (d)), most of the northern branch of the Eulerian mean cell is recovered. However, an additional near-surface cell is located in the southern branch of the Eulerian mean cell (centered near 58°S). This cell, which lies within the latitudes of the Drake Passage, appears for the spatial decompositions between 22.5° and 180° and might be associated with the northward deflection in the Atlantic sector of the ACC and with the global-scale meridional tilt of the core of the ACC between the Atlantic and Pacific Oceans.

Finally, to elucidate the zonal inhomogeneity of the bolus transports, the longitudinal integral of the bolus transport for four latitudes and the map of the "*Total*" bolus (i.e from the 5 days averaging decomposition), integrated from the surface down to the 37 kg m^{-3} isopycnal are shown in Fig. 6(a) and (b), respectively. At 39°S, the bolus component is quasi-inexistent in the Indo-Pacific basin, but reaches 4 Sv between the Greenwich Meridian and 24°W, i.e. in the Agulhas Retroflection region. At 56°S, the "*Total*" bolus is important near 169°W (South west of the New

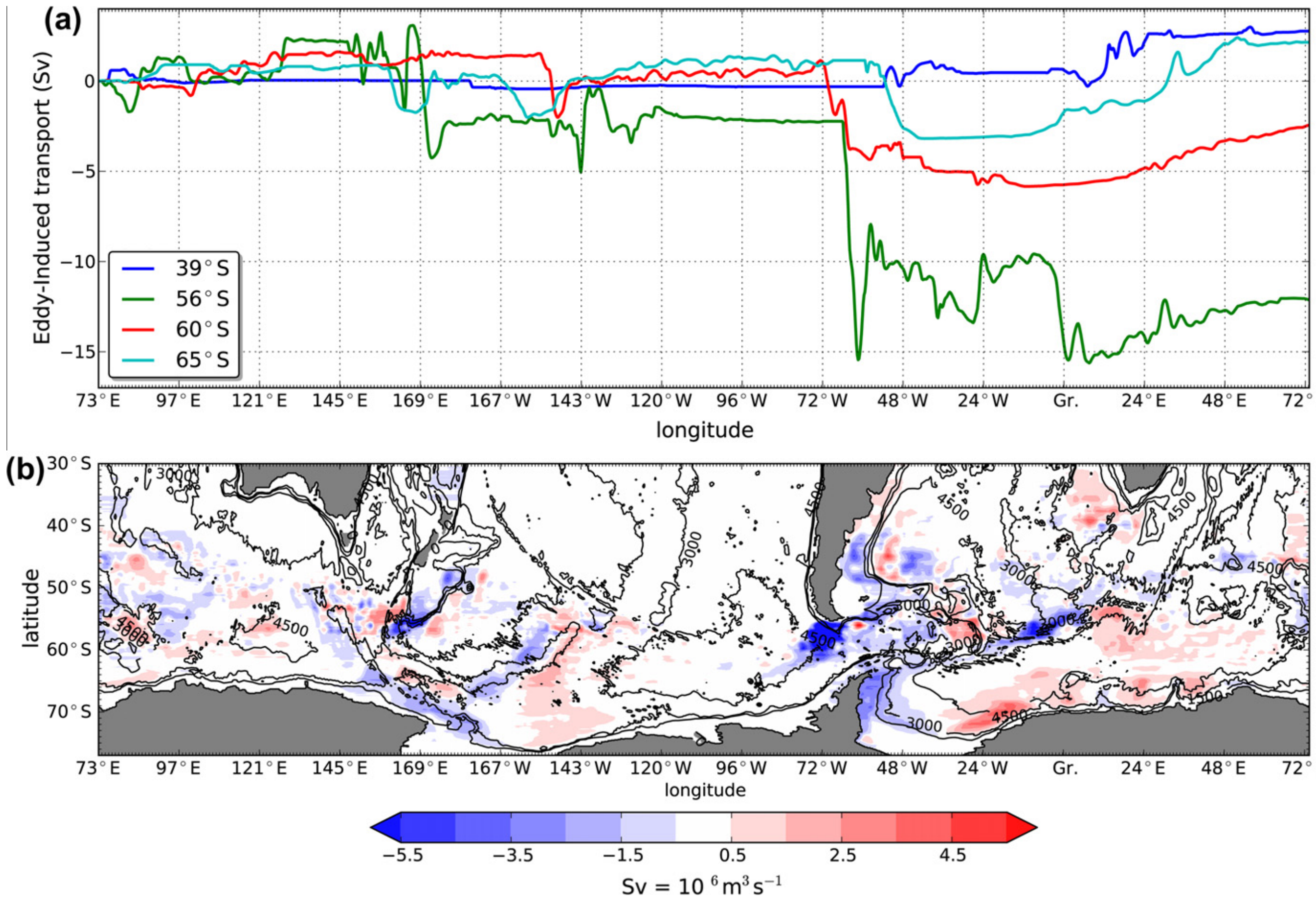

Fig. 6. Longitudinal integral of total bolus transports at 39°S, 56°S, 60°S and 65°S integrated from the surface down to the 37 kg.m^{-3} isopycnal and (b) maps of the total bolus transport integrated from the surface down to the 37 kg m^{-3} isopycnal (a 10° running mean is applied for in the zonal integral).

Zealand plateau), near 143°W (Pacific–Atlantic Ridge) but most of the bolus transport (up to 12 Sv) is generated in the Drake Passage and South Atlantic region. In the mid-to-high latitudes (60°S and 65°S), the bolus transport is mainly significant in the Weddell Gyre. From the map of the "*Total*" bolus, it seems that the bathymetry is playing a key role for the bolus activity. The oceanic plateaus, the ridges, as well as the straits which the flow in the ACC is encountering, participate in most of the bolus activities in the Southern Ocean channel.

5. Summary and conclusion

In the present study, we give a detailed picture of the total and eddy-induced transport in the Southern Ocean simulated in an eddy-permitting Ocean General Circulation Model. Transient and standing eddies counteract 64% of the Eulerian mean circulation canceling the Deacon Cell, and about 70% of this amount is purely associated with standing eddies. This result corroborates the finding of Drijfhout (2005). To investigate the time and spatial scales associated with the compensation due to the eddies, temporal and spatial filterings are performed on the Southern Ocean meridional overturning stream function as a function of latitude and potential density σ_2. The results indicate that the upwelling and downwelling branches of the Eulerian mean circulation are the main regions sensitive to the decompositions. The eddy-induced transport ("*Bolus*" cell) extends between 40°S and 64°S and mostly counteracts the Eulerian circulation with 2–3 Sv (i.e. ≈15%), except in two local maxima. These maxima are found at the surface near 41°S and in the deep ocean at 58°S. They counteract the Eulerian mean circulation with about 8 Sv transport. The temporal decomposition reveals that most of the "*Bolus*" transport is dominated by time scales of a few months to one year. The decomposition of the "*Bolus*" component into a "*Seasonal*", an "*Eddy*" and an "*Inter-monthly*" component indicates that the maximum surface bolus cell at 41°S is made up for 50% by the "*Inter-monthly*" bolus, for 25% by the "*Eddy*" bolus and for 25 % by the "*Seasonal*" bolus. The deep bolus cell at 58°S is made for 40% by the (≈3 Sv) "*Eddy*" bolus, for 20% by the "*Inter-monthly*" bolus (≈1–2 Sv) and for 40% by the "*Seasonal*" bolus (≈2–4 Sv).

To investigate the zonal scales associated with the compensation of the Eulerian mean circulation, spatial decompositions were performed on the Southern Ocean meridional overturning stream function. The Southern Ocean cells have distinct spatial scales. The AABW formation occurs on spatial scale less than 3° with time scales of less than one month. Similarly, the ACC surface cell is dominated by small scale processes (less than 3°), but is weakly associated with transient eddies. Small-scale standing eddies are important in the ACC, near the Subantarctic and Polar Fronts, and near the Subtropical Front. Transient eddies with time scales shorter than one month are important in the upper ocean between 58°S and 35°S and over the whole ocean depth at the latitude of Drake Passage. Moreover, a geolocation of the eddy-induced transports identifies the Drake Passage, the Agulhas Retroflection, the Falkland Basin and the Kerguelen Plateau as areas of intense bolus activity, where the bathymetry plays an important role on the currents.

To summarize our findings, the overturning metrics for different spatial and temporal filterings are illustrated in Fig. 7. From the residual circulation to the Eulerian mean cell, the maximum

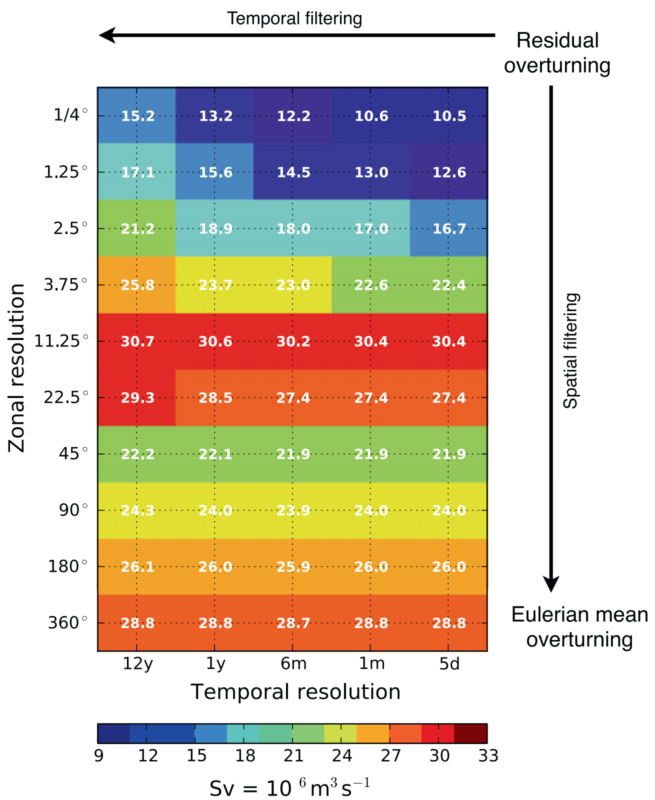

Fig. 7. Pixelated representation of the maximum meridional overturning (in Sv) in the Southern Ocean for various temporal and spatial filtering scales.

meridional overturning in the Southern Ocean varies between 10.5 Sv to 28.8 Sv. Two distinct regimes are noted: for the small scales processes with length scales less than 11.25°, significant changes in the maximum overturning associated with the temporal filtering occurs (transient eddies), indicating that transient eddies at these length scales are prominent, whereas for larger spatial decomposition (11.25°–360°) the overturning is unchanged for temporal filtering. In other words, the standing-eddy part of the circulation that counteracts the Eulerian mean flow occurs for scales less than 11.25°. The large-scale zonal tilt of the gyres is not the main factor in the geometrical effect that reduces the mean flow in density coordinates, as envisaged by Döös and Webb (1994). It still might be that the gyres are instrumental in creating a large part of this geometrical effect, but without resolving the tilt across the western boundary currents the geometrical effect is not captured. Finally, one can say that the temporal scales required for diagnosing the Southern Ocean overturning should not exceed 1 month, and to fully capture the residual overturning across Drake Passage smaller time scales of 5 days, or even less are required. The spatial scales needed to be taken into account must be smaller than 1°, preferably 1/4°; the decrease of the resolution from 1/4° to 1.25° filtering changes the overturning with an extra 2 Sv.

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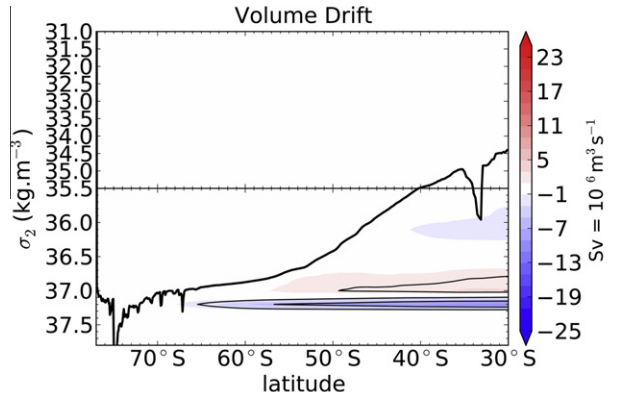

Fig. A.8. Stream function for the drift in volume, integrated from the bottom and from the south. Color interval is 2 Sv. Solid contour interval is 4 Sv.

Appendix A. The drift stream function

Following the derivation of Marsh et al. (2000), the meridional stream function can be decomposed into a steady state stream function (1) and a volume inflation rate (2):

$$\Psi(y,\rho,t) = \underbrace{\int_{C(\rho,\theta)} \int_{\rho}^{\rho_{max}} (hv) d\rho dx}_{Meridional\ \ Stream\ \ Function\ \ (1)} + \underbrace{\frac{\partial}{\partial t} \int_{C(\rho,\theta)} \int_{\rho}^{\rho_{max}} \int_{y}^{y+\partial y} h(x,\rho,t) dy d\rho dx}_{Volume\ \ Drift\ \ Stream\ \ Function(2)} \tag{A.1}$$

Fig. A.8 shows the drift in volume (rate of volume change) in the Southern Hemisphere for the ORCA025 integration. The main water mass subject the drift is the AABW mass. The drift in volume is of the order of $[-3; 3\ \mathrm{Sv}]$ between the 35.5 and 37.0 kg m^{-3} density classes and up to -9 Sv below 37.0 kg m^{-3}.

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