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Localized Acceleration of the Antarctic Circumpolar Current

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ABSTRACT

The influence of wind forcing on the strength of the Antarctic Circumpolar Current (ACC) is explored using realistic eddy simulations. The ACC transport is found to be set by both the zonal wind stress, at latitudes of Drake Passage, and by the curl of the wind stress, localized in the western South Atlantic. As such, for certain wind stress patterns, the ACC transport is dramatically increased, without any increase in the mean zonal wind stress.

The mechanism by which local wind curl variations effect the strength of the ACC is as follows: In the western South Atlantic the ACC meanders over the shallowest topographic features of its circumpolar path. In this region a positive wind curl induces vortex compression. This compression helps the ACC to move equator-ward and over the shallow topography. This interaction reduces the momentum transfer to the bottom for a given ACC transport. The total ACC transport then increases so that the momentum imparted at the sea surface is transferred to the sea floor.

Local wind curl variations in the western South Atlantic are found to be far more effective at driving year to year fluctuations in ACC transport than the zonal wind stress. In addition, changes both in the pattern and in the magnitude of the Southern Hemisphere westerlies, concurrent with observed climate change, are likely to have *both* had an accelerating influence on the ACC of equivalent magnitude.

1. Introduction: The ACC

The Antarctic Circumpolar Current, the ACC, is the largest current in the world ocean. The ACC links the three major Ocean basins along its path around Antarctica. Its consequent steeply sloping isopycnals connect a huge fraction of the deep ocean to the Atmosphere. Turbulent processes, themselves intimately linked to the ACC, play a major role in exchanges between near surface waters and the ocean interior. Knowledge of what drives the ACC is thus critical to our understanding of ocean circulation and climate (See Rintoul et al. 2001).

Simple models of the ACC present a linear relationship between its transport and the strength of the winds in the Southern Hemisphere (e.g. Marshall 2003). Although realistic ocean models show some relationship between the winds and the ACC transport, the story is far more complex (Gnanadesikan and Hallberg 2000; Gent et al. 2001; Tansley and Marshall 2001).

In addition to wind strength, modeled ACC transport is known to be influenced by thermodynamics (Gnanadesikan and Hallberg 2000; Gent et al. 2001), the parameterization of mixing processes (Gent et al. 2001), the explicit resolution of eddies (Hallberg and Gnanadesikan 2006) and intrinsic processes (Hogg and Blundell 2006; Hughes et al. 1999). Each of these, affecting the variability of the ACC on different time scales (Olbers and Lettmann 2007; Webb and De Cuevas 2007).

Promisingly however, it is likely that on inter-annual to decadal timescales, the forcing, and in particular the wind forcing, is dominant in controlling the ACC transport (Treguier et al. 2010). The control of the ACC by wind forcing, both its magnitude and spatial pattern, is the topic of the present study.

Variability in Southern Hemisphere winds is dominated by the Southern Annular Mode (SAM, Thompson and Wallace 2000). A positive SAM involves a southward shift and strengthening of the westerly winds. In recent years, an increase in the SAM has been observed and attributed to anthropogenic climate change (Marshall 2003). That is, the winds in the Southern Hemisphere have tended to both increase and shift southward, and this is expected to continue under climate change scenarios.

Disagreement has arisen as to the effect of a changing SAM on the ACC. Observational studies suggest, on the one hand, that inter-annual fluctuations in ACC transport are driven by changes in the SAM (Meredith et al. 2004) while on the other hand, that no long term trend in ACC transport is evident (Boning et al. 2008). Sophisticated, yet coarse resolution coupled climate models suggest an increase in ACC transport with increasing SAM (Hall and Visbeck 2002; Fyfe and Saenko 2006; Sen Gupta and England 2006). Simplified experiments with high resolution ocean models suggest that the ACC strength is less sensitive to increasing Southern Hemisphere winds (Meredith and Hogg 2006; Hallberg and Gnanadesikan 2006).

A companion study to this one explores the sensitivity of Southern Ocean dynamics with both realistic forcing changes and permitted eddies (Dufour et al. submitted). Using a $0.5^\circ \cos(\text{Latitude})$ resolution model, Dufour et al. (submitted) assess the response of the ACC to both a homogeneous increase in the wind stress and an increase in the wind stress consistent with an increase in the SAM. Dufour et al. (submitted) find that, despite having weaker zonal winds at all latitudes, the SAM experiments have far greater ACC transports than their Homogeneous counterparts. How the spatial pattern of the SAM is able to accelerate the ACC is the topic of this study.

By way of introduction, various proposed driving mechanisms of the ACC are discussed in Section 2. Following this discussion we arrive at the hypothesis that local wind curl variations in the western South Atlantic may strongly influence the strength of the ACC (Section 3). The eddy permitting ocean model employed in this study and the series of experiments undertaken are described in Section 4. In Section 5 we show that the ACC transport can be strongly influenced by the wind curl in the western South Atlantic. We demonstrate, in Section 6a, that local variations in wind curl largely control the inter-annual variability of the ACC in our simulations, while in Section 6b we show that the Southern Annular Mode accelerates the ACC, both through an increase in zonal wind stress, and through changes in wind curl in the western South Atlantic. The major conclusions of this study and perspectives for future work are summarized in Section 7.

2. Driving Mechanisms of the ACC

Here we discuss various theories of the driving mechanisms of the ACC.

a. Zonal momentum balance

In this section we describe the role of the zonal momentum balance, in controlling the ACC transport. Consider an ocean with a free surface elevation η , depth H , depth integrated velocity \mathbf{U} , pressure p , surface wind stress τ_0 and bottom stress τ_b . In a (statistically) steady state the depth integrated momentum equation may be written (following Hughes and de Cuevas 2001)

$$f\mathbf{k} \times \mathbf{U} = - \int_{-H}^{\eta} \nabla p dz + \tau_{\mathbf{0}} + \tau_{\mathbf{b}} + \mathbf{A} + \mathbf{B} \quad (1)$$

In (1), f is the coriolis frequency, \mathbf{k} is the unit vector in the vertical (z), \mathbf{A} is the depth integral of the viscous stress divergence and \mathbf{B} represents nonlinear (and fluctuating) terms in \mathbf{U} . Zonally integrating (1) in realistic ocean models (Hughes and de Cuevas 2001, and this study) one finds the dominant balance in (1) to be between the pressure gradient term and the surface wind stress term

$$\oint \int_{-H}^{\eta} \frac{\partial p}{\partial x} dz dx \approx \oint \tau_{\mathbf{0}} d\mathbf{x}. \quad (2)$$

The left hand side of (2) represents *form stress* and can be interpreted as the stress placed on the solid earth by the ocean. In this interpretation the zonal momentum imparted by the wind stress (right hand side) is removed at the sea floor by form stress (left hand side). One arrives at an alternative, volumetric, interpretation of (2) by dividing by f and some reference density ρ_0 . Hence, the left hand side of (2) is the geostrophic flow and the right hand side is the Ekman transport. If the winds drive an Ekman transport northward, this is balanced by a southward geostrophic flow.

One may ask: *what does the zonal momentum balance tell us about the transport of the ACC?* The answer relates to the fact that in the Southern Ocean at latitudes of Drake Passage (approximately -60° to -54°) there exist an zonally unbounded channel. This means that the momentum imparted by the wind stress can only be extracted (assuming 2 is correct) below the sill depth (approximately 2000m). As Munk and Palmén (1951) point out, this stress is achieved by a strong zonal flow, the ACC. Zonal momentum is imparted into the

ocean by the winds. This momentum sets up a zonal current. The zonal current imparts momentum into the ocean floor. From the volumetric viewpoint, the northward Ekman transport draws dense water from the south, tilting isopycnals. The isopycnal slope causes a strong zonal circulation. Dense water is then replenished by the deep geostrophic return flow. This process continues, ever accelerating the ACC (Fig.1b).

The total transport depends both on both the magnitude of the wind stress (tilting isopycnals) and the rate at which momentum is transported downward (flattening isopycnals). Although vertical mixing and thermodynamics may play a role, the dominant mechanism for this downward transfer, is thought to come from both standing and transient eddies (Rintoul et al. 2001). From both the ‘stress’ and ‘volumetric’ viewpoints the strength of the ACC depends on the accelerating effect of the wind stress and the effectiveness of eddies (both standing and transient) in transferring momentum vertically (Fig. 1).

The idea that the zonal wind stress is an effective driver of the ACC has been supported qualitatively using coarse resolution and eddy permitting ocean models (Gnanadesikan and Hallberg 2000; Tansley and Marshall 2001). Following the use of eddying ocean models and recent improved observations (Boning et al. 2008; Meredith and Hogg 2006), debate has emerged as to the effectiveness of the wind stress as a driver of the ACC. This debate has generally revolved around ‘eddy saturation’. If the ACC is ‘eddy saturated’, additional wind stress, generates increased eddy activity. This eddy activity transfers any additional momentum to the sea floor with little effect on the mean flow.

Proponents of the zonal momentum balance theory tend to assume the ACC can be understood as a zonally, or streamwise, averaged current. Changes in the pattern of the wind stress, like those expected with a changing SAM, have generally not been considered using

eddy simulations. In this study we demonstrate that local forcing effects can enhance the vertical transfer of momentum and thus strongly control the ACC transport.

b. Sverdrup Theory

Here we describe attempts to use the depth integrated vorticity equation to explain the transport of the ACC. Taking the curl ($\nabla \times$) of the depth integrated momentum equation (1), one arrives at the depth integrated vorticity equation

$$\nabla \cdot (f\mathbf{U}) = \nabla \times (\mathbf{p}_b \nabla H) + \nabla \times (\tau_0 + \tau_b) + \nabla \times (\mathbf{A} + \mathbf{B}) \quad (3)$$

In the above, p_b is the pressure at the sea floor. It has been broadly demonstrated that the dominant terms in the vorticity balance along the ACC, are the meridional flow (βV , β being the meridional gradient of f and V the depth integrated meridional transport), the curl of the wind stress ($\nabla \times \tau_0$) and bottom pressure torque (Wells and De Cuevas 1995; Grezio et al. 2006) such that

$$\beta V \approx \nabla \times \tau_0 + \nabla \times (p_b \nabla H). \quad (4)$$

The above has become known as Topographic Sverdrup Balance (Holland 1967). Classical Sverdrup balance is between the left hand side and the first term on the right hand side of (4).

If one applies classical Sverdrup theory to the ACC, wind curl at latitudes at and around Drake Passage induces Ekman pumping. This Ekman pumping drives a southward flow (i.e. as the Ocean interior is in Sverdrup balance). The southward flow is then returned within

a boundary layer along the coast of Argentina. Within this boundary layer large bottom pressure torques remove the vorticity originally imparted by the winds (see Hughes 2002, for the details of the various ‘Sverdrup-like’ theories of the ACC).

Budgets of the depth integrated vorticity along the ACC in realistic models tend to confirm this balance on large scales (Wells and De Cuevas 1995; Grezio et al. 2006). The ACC gradually migrates southward in the eastern South Atlantic, Indian and South Pacific Ocean basins consistent with the curl there. It then abruptly moves northward in Drake Passage and in the western South Atlantic.

Although the balance in (4) holds, Sverdrup balance has been largely ruled out as the process that sets the ACC transport (Gnanadesikan and Hallberg 2000; Tansley and Marshall 2001). That is, increased wind curl in the Atlantic, Indian and Pacific Oceans at latitudes of Drake Passage does not lead to increased ACC transport in coarse and eddy permitting ocean models.

In the following sections, we demonstrate that the ACC transport is not controlled by classical basin-scale flat-bottom Sverdrup balance in our simulations. However, vorticity dynamics do play a role in setting the ACC transport. We show that localized wind curl variations in the western South Atlantic, where the ACC veers northward, can strongly influence the strength of the ACC.

c. Other ACC control mechanisms

Thermodynamics are also thought to play a role in setting the transport of the ACC with strong density contrasts between north and south setting up a zonal circulation (see for

example Gent et al. (2001) and Gnanadesikan and Hallberg (2000)). Although thermodynamics may be a major driver of the ACC, its description in eddy permitting models requires long integrations and an improved description of overflows (namely Antarctic bottom water formation in the case of the ACC; Lee et al. 2002). In this study we do not examine the role of thermodynamics in controlling the ACC.

Hughes et al. (1999) have proposed that on 5-day to annual timescales, the ACC may act as a ‘free mode’. A free mode being a solution to the depth integrated potential vorticity equation closely following contours of constant f/H (the depth integrated vorticity equation is derived by dividing (1) by H , then taking its curl) . Once accelerated, a free mode may travel unhindered until dissipated by bottom friction.

However, the time mean ACC does not follow f/H contours. This lead Hughes et al. (1999) to propose that on longer timescales the ACC is a kind of ‘forced-free mode’. A forced free mode largely follows f/H contours except in regions where it must be ‘forced’ across f/H contours. It is unclear whether this forcing must come from the wind or other terms in the depth integrated potential vorticity equation.

The concept of a forced free mode is as close a theory in the literature as that proposed in this study. We choose, however, to rationalize the ACC in terms of the zonal momentum and integrated vorticity balances, rather than potential vorticity, although it is possible that the same conclusions could be reached.

3. Control of the ACC by wind curl in the western South Atlantic

In this section we propose that the vertical transfer of momentum may be increased or reduced due to wind curl variations in the western South Atlantic.

a. Vertical transfer of Zonal Momentum

Zonal momentum in the ACC can be transferred vertically by the zonal and temporal average interfacial form stress, $f\rho_0 \langle \bar{v}\bar{\rho} \rangle / \langle \bar{\rho} \rangle_z$ ($\langle a \rangle$ being the zonal average and \bar{a} the temporal average of some variable a ; Stevens and Ivchenko 1997). Taking the ‘volumetric’ view discussed in Section 2a, positive form stress constitutes a equator-ward transport of light water and pole-ward transport of dense water, acting against the tilt of isopycnals due to a northward Ekman transport and deep geostrophic transport (Fig 1).

Separating the interfacial form stress into mean, standing and transient eddy components

$$\frac{f\rho_0}{\langle \bar{\rho} \rangle_z} \langle \bar{v}\bar{\rho} \rangle = \frac{f\rho_0}{\langle \bar{\rho} \rangle_z} [\langle \bar{v} \rangle \langle \bar{\rho} \rangle + \langle \bar{v} * \bar{\rho} * \rangle + \langle \overline{v'\rho'} \rangle]. \quad (5)$$

Above, the dash represents a deviation from the temporal and the star the deviation from the zonal mean. In (5), the first term on the right hand side is zero below the ekman layer and above the deepest topography, as no mean meridional transport ($\langle v \rangle = 0$). The second term is the standing eddy term, while the third term is the transient eddy term (See Fig.1 for a schematic representation of these two terms).

The standing eddy term, $\langle \bar{v} * \bar{\rho} * \rangle$, requires a meridional flow to be correlated with zonal density changes. For example, consider a quasi-zonal current as it flows over a topographic

feature (Fig 1). Over the feature the flow is equator-ward and away from the feature the flow is pole-ward. For there to be a net momentum transfer by interfacial form stress, there must be a difference between the density over the feature and away from the feature. For a downward momentum transfer, dense water must be moved equator-ward, and light water moved poleward. If the form stress is to change, there must either be an increase in the strength of the eddy (moving more dense water equator-ward and more light water poleward) and/or a change in the relative densities (moving denser water poleward and lighter water equator-ward).

In the following we will describe how a positive wind curl in the western South Atlantic is likely to enhance the standing eddy interfacial form stress of the ACC.

b. The ACC as a standing eddy

For flow in geostrophic balance, bottom pressure torque is simply a bottom vertical velocity w_b such that

$$-\frac{1}{f}\nabla \times (p_b \nabla H) = w_b. \tag{6}$$

An enhanced mean bottom pressure torque leads to an enhanced vertical velocity close to the bottom.

Downstream of Drake Passage, in the western South Atlantic, topography is shallow and the ACC meanders northward. The mean vertical transport due to bottom pressure torque draws dense water upward in this region. Hence, where v is strongly positive, ρ is also large, relative to its zonal average. When the ACC gradually returns southward, it brings with

it lighter water summing as a nonzero effect on the interfacial form stress (Fig.2). Bottom pressure torque can act as a brake on the ACC in this region. Increased torque there, causes an increased vertical velocity and hence increased interfacial form stress.

Consider now if the wind curl in the western South Atlantic were to become more positive. The wind curl in this region is then provides the balance in the vorticity equation (4) previously provided by bottom pressure torque. Assuming first that the ACC transport does not change (i.e. no change in βV), more positive wind curl would lead to reduced bottom pressure torque. This would in turn lead to less upwelling of dense water at the sill depth. The lack of dense water above the sill depth would reduce the contrast in density between the shallow topography and the remaining ocean. Hence the total interfacial form stress would be reduced. For the momentum balance to reach equilibrium, the same amount of interfacial form stress must exist. So, the strength of the ACC must increase.

The effectiveness of this process in the western South Atlantic is because the topography is shallowest there. At other points along the ACCs path the topography is much deeper. In these regions a strong bottom pressure torque may cause large bottom vertical velocities, but these velocities do not effect the stratification above the sill depth. Hence, changes in wind curl there, do not effect the interfacial form stress which transfers momentum from the surface to the shallowest topography.

c. Possible role of wind curl in reducing transient-eddy interfacial form stress

Recent studies have demonstrated a link between bottom pressure torque and interface height diffusion by transient eddies (Olbers et al. 2007; Eden and Olbers 2010). The authors

show that bottom pressure torque in (3) can be approximated by a term related interface height diffusion.

A local reduction in bottom pressure torque, i.e. due to a local change in wind curl, is likely to cause a reduction in interface height diffusion by transient eddies. This reduction in interface height diffusion would cause a reduction in the downward transfer of momentum. Additional downward transfer would then be required to balance the total wind stress. Hence accelerating the ACC.

This study does not quantify the effect of wind curl in changing the transient eddy interfacial form stress. We merely point out here that transient eddy processes and standing eddy processes are likely to respond to local changes in wind curl in similar ways.

4. Accelerating the ACC in an eddy-permitting ocean model

We explore the role of the wind in setting the ACC transport using a realistic ocean model. We choose a regional coupled ocean-sea ice configuration of NEMO (Nucleus for European Ocean Modelling, Madec 2008). The configuration used is a regional extraction based on ORCA05 (Mathiot et al. 2010) and is that described by Dufour et al. (submitted) and is briefly described here.

The model is forced at the sea surface by a composite of ERA40 and ECMWF winds (Brodeau et al. 2010) and at 30°S by the output of the ORCA05-G70.112 - Drakkar simulation (Drakkar-Group 2007; Barnier et al. 2006). Simulations are initialized from rest and

with the NODC World Ocean Atlas 1998 climatology for temperature and salinity and run from 1980 to 2004. The resolution is $0.5^\circ \text{Cosine}(\text{Latitude})$ giving a grid size of approximately 28 km at 60°S (equivalent in resolution at ACC latitudes to the FRAM model; The FRAM group 1991). There are 46 vertical levels. No interface height diffusion is employed in the simulations discussed here.

To avoid spurious trends in ACC transport due to the misrepresentation of bottom water, a ubiquitous problem in eddy-permitting z-coordinate models (Lee et al. 2002), we choose to restore temperature and salinity in the deepest layers to climatological values with a 2 year restoring timescale.

In the following section, we will discuss two experiments: 1) a reference/hindcast experiment, named REF05, of Dufour et al. (submitted) and 2) an experiment named CURL05, where the zonal wind velocity at 10m above the sea surface, as felt by the model, is adjusted. This is done such that the wind curl in the western South Atlantic, in CURL05, is more positive than in REF05 and in the remaining latitudes is less positive than in REF05 (as shown later in Fig. 4). As such the integrated wind stress at all latitudes in CURL05 remains equal to or weaker than the integrated wind stress in REF05 (Fig. 6). The precise way in which the wind velocity is adjusted is described in detail in Appendix A.

The wind curl anomaly in the CURL05 experiments is centered at (50°W , 55°S) and with an extent of around 60 degrees of longitude and 10 degrees of latitude. The motivation for this choice is two fold: 1) In this region almost the entirety of the ACC meanders northward between Cape Horn and South Georgia Island and is a shallow plateau across which the entire ACC flows. Because the ACC flows northward it is represented by the left hand side of (4). The right hand side of (4) is then the wind curl and the bottom vertical velocity at this, the

ACC shallowest region (Fig.3). 2) In the REF05 experiment, inter-annual fluctuations in ACC transport are found to be well correlated with the wind curl averaged over the region (56°S, 52.5°S) to (70°W, 30°W) (see Section 6a).

In Section 6 we revisit the experiments of Dufour et al. (submitted) in light of our discussion of the control of ACC transport by both the strength, and pattern of the wind stress. These experiments include: linear increases in the wind velocity of 10% (WIND05+), 20% (WIND05++) and 30% (WIND05+++), and the addition of a wind pattern associated with the standard deviation of the observed SAM index multiplied by 0.5 (SAM05+), 1 (SAM05++) and 2 (SAM05+++ standard deviations.

We will largely discuss the averaged fields from the final 10 years (1995-2004 inclusive) of each simulation. As discussed in Dufour et al. (submitted), REF05 displays realistic water masses and EKE fields across the Southern Ocean. In this study, we are particularly interested in the accuracy of REF05, with respect to its description of the path of the ACC and the stratification at latitudes of Drake passage.

The best observational proxy we have for the ACCs path is the Mean Dynamical Topography (MDT), equivalent to mean sea surface height (SSH) away from the ice zone in our simulations. Comparing observed MDT to SSH from REF05 we see that the model accurately captures the major meanders of the ACC, in particular the abrupt northward flow in the western South Atlantic between Cape Horn and South Georgia Island (Fig.5a and b) . We compare the mean stratification in REF05 to mean hydrographic observations, at 60°S (Fig. 5c and d). REF05 captures the gradual deepening of isopycnals across the Indian and Pacific basins, followed by abrupt shallowing in the western South Atlantic as evident from mean hydrographic data.

5. The effect of wind curl in the western South Atlantic

In what follows we will compare the results of the REF05 and CURL05 experiments, as described in Section 4.

a. Momentum balance and transport response

The zonal wind stress of the two experiments is approximately the same, with the CURL05 experiment in fact having a weaker zonally integrated wind stress at most latitudes. In both simulations, the zonal momentum, imparted by the zonal wind stress, is removed by bottom form stress (Fig. 6). That is, the Ekman transport at the surface is balanced by a return geostrophic flow at the depth of the topography. This demonstrates that the theory, as discussed in Section 2a, is consistent in both experiments.

However, if only the zonal momentum balance were considered, one would be led to the conclusion that the ACC transport, in both the REF05 and CURL05 simulations, would be the same. As measured through Drake Passage, REF05 has a transport of 142Sv while CURL05 has a transport of 148Sv. In fact the zonal transport in CURL05 is, at all latitudes, around 6Sv greater than in the REF05 experiment. It is clear then, that local variations in wind stress play a role in determining the circumpolar behavior of the ACC.

In the CURL05 experiment, the wind curl in the eastern South Atlantic, Indian and South Pacific basins, at latitudes of Drake Passage, is more negative than in REF05. Following Sverdrup theory this, more negative wind curl, would drive more southward flow and hence accelerate the ACC. This is not the mechanism leading to increased ACC transport in the CURL05 experiment. Dufour et al. (submitted) have shown that the ACC transport is

increased when the winds are changed with an increase in the SAM mode pattern (SAM05+, ++ and +++ experiments). An increase in SAM involves a southward shift in the wind stress and hence a change in sign of the wind curl, from negative to positive, at latitudes of Cape Horn and at all longitudes (see Fig. 9). According to Sverdrup theory this would reverse the direction of the ACC.

In fact, the difference in transport between the REF05 and CURL05 experiments, can be understood in terms of changes in the wind curl in the western South Atlantic.

b. Stratification and interfacial form stress response

In both the REF05 and CURL05 experiments the vertical velocity, at latitudes of the ACC between 1000 m and 2000m depth, is largest and most consistently positive, between 70°W and 30°W where the ACC interacts with topography (Fig.7). In both cases, this large vertical velocity is concurrent with a large northward flow and a large change in the depth of isopycnals setting up a strong East-West density difference (Fig.7).

There is a slight decrease in vertical velocity in the western South Atlantic in the CURL05 experiment and a slight eastward shift in the peak in potential density, consistent with the decrease in vertical velocity and an increase in zonal transport (Fig.7).

The standing eddy component of the interfacial form stress averaged between 1000 m and 2000 m in REF05 is around 60% of the total form stress(Fig.7). This suggests that the principle way in which the ACC transfers zonal momentum downward, in this model, is through standing eddy processes, consistent with previous results (Stevens and Ivchenko 1997).

The interfacial form stress changes subtly between REF05 and CURL05, with less form stress in the, now lighter, western South Atlantic, and more in the, now denser, eastern South Atlantic. The form stress in both the REF05 and CURL05 simulations sums to the same value, suggesting that the circulation in the Southern Ocean simply adjusts, to give the same downward transfer of momentum.

What is of interest here is the way in which the change in advection and the change in stratification effect the form stress. We have calculated the standing eddy interfacial form stress, from the density fields of REF05, ρ_{REF} , and the velocity fields of CURL05, v_{CURL} . Taking its difference from the standing eddy interfacial form stress of REF05 we isolate the effect of the change in mean advection between REF05 and CURL05. Here we are computing ΔFS such that

$$\begin{aligned} \Delta FS &= FS(\bar{v}_{CURL}, \bar{\rho}_{REF}) - FS(\bar{v}_{REF}, \bar{\rho}_{REF}) \\ &= f\rho_0 \left(\frac{\langle \bar{v}_{CURL} \bar{\rho}_{REF} \rangle}{\langle \bar{\rho}_{REF} \rangle_z} - \frac{\langle \bar{v}_{REF} \bar{\rho}_{REF} \rangle}{\langle \bar{\rho}_{REF} \rangle_z} \right). \end{aligned} \quad (7)$$

The change in advection greatly enhances the interfacial form stress (Fig.7). This change in interfacial form stress occurs most strongly in the western South Atlantic where the wind curl has been adjusted. Changes in form stress across the Indian Ocean are largely compensated by changes in the eastern South Pacific. If we repeat this calculation, but now taking the density from CURL05 and velocity from REF05, we find that the change in stress is almost exactly the same but of the opposite sign, demonstrating that the change in density acts to reduce the interfacial form stress (not shown).

By changing the wind curl in the CURL05 experiment, the density field is changed,

reducing the interfacial form stress. As such, the advection in the CURL05 experiment changes, such that the interfacial form stress remains the same. The ACC transport in our experiments is set, not only by the input of momentum by the zonally integrated winds stress, but also by the rate of downward transfer of that momentum, by interfacial form stress. Interfacial form stress may be strongly modulated by the wind curl in the western South Atlantic. Hence, the strength of the ACC is strongly controlled by the wind curl in the western South Atlantic.

6. Realistic changes in wind curl in the western South Atlantic

We have demonstrated that the wind curl in the western South Atlantic effects the transport of the ACC. Here we show that year to year variations in wind curl in the western South Atlantic are likely to be the main driver of year to year variations in ACC transport. We also demonstrate that both localized wind curl changes and integrated wind stress changes concurrent with changes in the Southern Annular Mode (SAM) are equally effective at accelerating the ACC. Hence, we demonstrate that both the change in the magnitude and structure of the Southern Hemisphere Westerlies are of equal importance in setting the ACC's response.

a. Year to Year fluctuations in ACC transport

Here we compare inter-annual fluctuations in zonal wind stress and western South Atlantic wind curl to fluctuations in the ACC transport as measured through Drake Passage (Fig 8). The zonal wind stress is averaged along latitudes of Drake Passage. We find little difference between this measure and averages made over nearby latitude bands nor averaging the wind stress, streamwise, along the path of the ACC. The western South Atlantic wind curl is averaged over the region (56°S, 52.5°S) and (70°W, 30°W). This region is chosen both for the dynamical reasons outlined in Section 4 and because we find a strong correlation between wind curl and ACC transport there. Tests were made averaging the wind curl at longitude bands extending to Kerguelen Plateau (around 70°E) and over just Drake Passage. In each case the wind curl was less correlated with the ACC transport. Correlations are calculated for the period 1988 to 2004 inclusive removing effects of the initial spin up phase while still allowing for a statistically reasonable sample. Moving this window by 1-2 years either way does not significantly change any results.

Fluctuations in wind curl are highly correlated with the transport ($r=0.74$, r being the correlation coefficient, significant at the 95% confidence level for $r=0.48$). The wind stress is not as significantly correlated with the transport ($r = 0.45$) over this 17 year period. Also, the wind stress is more correlated with the wind curl ($r = 0.52$) than the transport. Wind curl variations in the western South Atlantic are dramatic and hence strongly affect the ACC transport fluctuation.

Fluctuations in wind curl in the western South Atlantic, as driven by the ERA40 reanalysis, are far more effective at driving fluctuations in ACC transport. Accurate observations

of the wind curl in the western South Atlantic are hence crucial to accurate simulations of the ACC.

b. The Southern Annular Mode and changes in wind curl in the western South Atlantic

A major result of Dufour et al. (submitted) was the finding that, a wind increase consistent with a strengthening of the SAM (experiments SAM05+, SAM05++ and SAM05+++), accelerated the ACC more than a homogenous wind increase (WIND05+, WIND05++ and WIND05+++). That is the ACC transport was greater in experiment SAM05+++ than WIND05+++ even though the zonal wind stress in WIND05+++ was greater at all latitudes. Although not as pronounced, a similar effect is found in the $1/4^\circ$ experiments.

This result can be explained in the context of the present study: an increase in the SAM involves both a southward shift and strengthening of the Southern Hemisphere westerlies. The southward shift in the westerlies, due to increases in the SAM, changes the sign of the wind curl in the western South Atlantic. This more positive wind curl reduces the bottom pressure torque at the shallowest topographic features and hence accelerates the ACC.

The WIND experiments of Dufour et al. (submitted) demonstrate that increases in the total wind stress at latitudes of Drake Passage can accelerate the ACC in the absence of more positive wind curl (Fig.9). By the same token, the CURL05 experiments, of this study, demonstrate that the ACC can be accelerated in the absence of changes in total zonal wind stress. Strikingly, the SAM experiments demonstrate that the Southern Annular Mode is likely to accelerate the ACC, both due an increase in total wind stress and changes in the localized wind curl.

7. Conclusion

We have demonstrated that the ACC transport is strongly influenced by localized wind curl variations in the western South Atlantic. The processes by which this occurs has been demonstrated using an eddy permitting ocean model. An idealized forcing change in the model, making the wind curl in the South Atlantic more positive, accelerates the ACC. This acceleration occurs because the change in curl reduces the interaction of the flow with topography, reducing the downward transfer of momentum. The ACC must then accelerate in order that the momentum imparted by the wind stress be transferred to the sea floor.

In addition, we have shown that variations in wind curl in the western South Atlantic are major drivers of variations in ACC transport. The wind curl is the dominant driver of year to year fluctuations in ACC transport, in our model. Wind curl changes, associated with changes in the SAM, are likely to have had an accelerating influence on the ACC. The magnitude of this acceleration is equivalent to that caused by the overall increase in wind stress associated with the SAM (Fig. 9) . As a consequence, projected changes in Southern Hemisphere winds are likely to have a two fold effect of accelerating the ACC: 1) an increased wind stress increasing the momentum input of the ACC, and 2) changes in wind curl in the western South Atlantic reducing the downward transfer of that momentum.

We have demonstrated that for an ocean model to accurately capture the response of the Southern Ocean to changes in wind forcing, the model must accurately resolve the topography along the path of the ACC. At present, this is neither done in coarse resolution climate models, nor high resolution QG models which do describe continental boundaries, for example.

The effect of wind curl in the western South Atlantic is clearly crucial to the description of the wind forced ACC. However, the accuracy of wind curl estimates in the western South Atlantic is unknown and the comparison of products and in situ observations is needed. If accurate hindcast simulations of the Southern Ocean are to be produced, accurate wind forcing fields from the South Atlantic are a prerequisite. By the same token, of great interest are projected changes in the wind curl in the western South Atlantic, as predicted by climate simulations.

The exact relative contributions of localized wind curl and zonal wind stress in controlling the ACC transport is as yet unclear. We have here discussed only one model configuration at eddy permitting resolution. The role of localized wind forcing in an eddy resolving regime and from observations is the subject of ongoing work.

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APPENDIX A

Adjustment of wind stress fields for CURL05 experiment

In the CURL05 experiment we take the same zonal wind speed a 10 m as in the REF05 experiments but with the addition of Δv_{10} . This additional speed is intended to increase the wind curl in the western South Atlantic without increasing the zonally averaged wind stress at any latitude. It is also desired that the effect of the additional velocity reduce to zero far from the target latitudes. For this reasons we derive Δv_{10} using the function

$$\Delta v_{10} = a \frac{(y - y_0)}{\Delta y^2} e^{-\frac{(y-y_0)^2}{2\Delta y^2}} - b \frac{(y - y_0)}{\Delta y^2} e^{-\frac{(y-y_0)^2}{2\Delta y^2} - \frac{(x-x_0)^2}{2\Delta x^2}} - c. \quad (\text{A1})$$

which is the meridional derivative of two exponential functions plus a constant offset (x being longitude and y latitude). The constants are chosen as follows: $y_0 = -55$, $x_0 = -50$, $\Delta y = 10$ and $\Delta x = 30$. Assuming wind stress increases with wind speed, this centers a maximum in the meridional gradient of the zonal wind stress (a component of the wind curl) over the western South Atlantic. The coefficients are chosen as $b = 40$, $a = b\sqrt{2\pi}\Delta X/360$, and $c = 0.1$. This means the first two terms in (A1) integrate to zero at all latitudes.

As the wind stress is a nonlinear function of the wind velocity (magnitude and direction) and the properties of surface ocean (particularly the ocean velocity), we choose to reduce the overall zonal wind velocity by $c = 0.1 \text{ m s}^{-1}$ to be sure that the zonally averaged zonal wind stress in the CURL05 experiment is less than that in the REF05 experiment.

The effect of the difference in zonal wind velocity between REF05 and CURL05 is evident from the difference in zonal wind stress in the two experiments (Fig. 4). Also evident, is the feedback of the change in the circulation and surface properties (such as sea ice) on the wind stress and wind curl fields.

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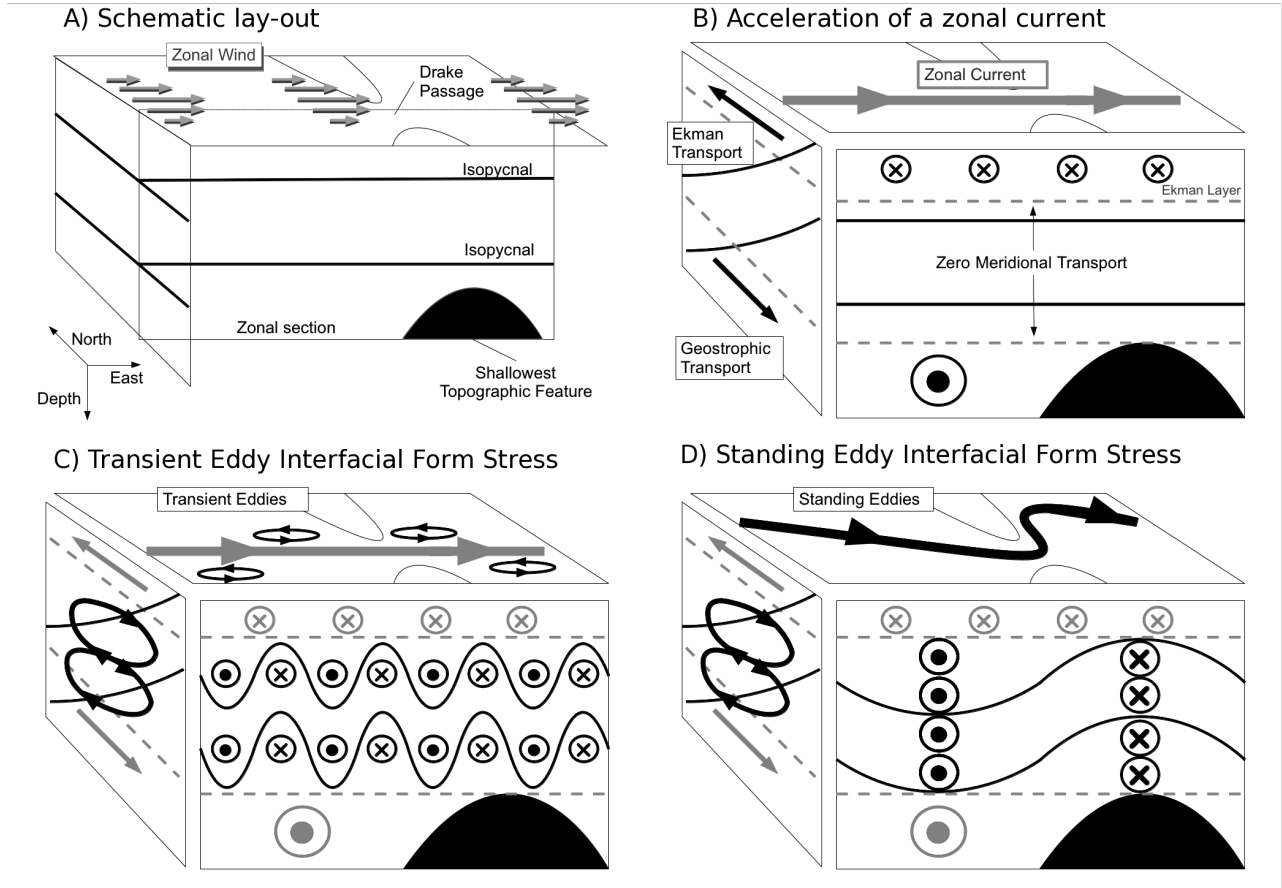


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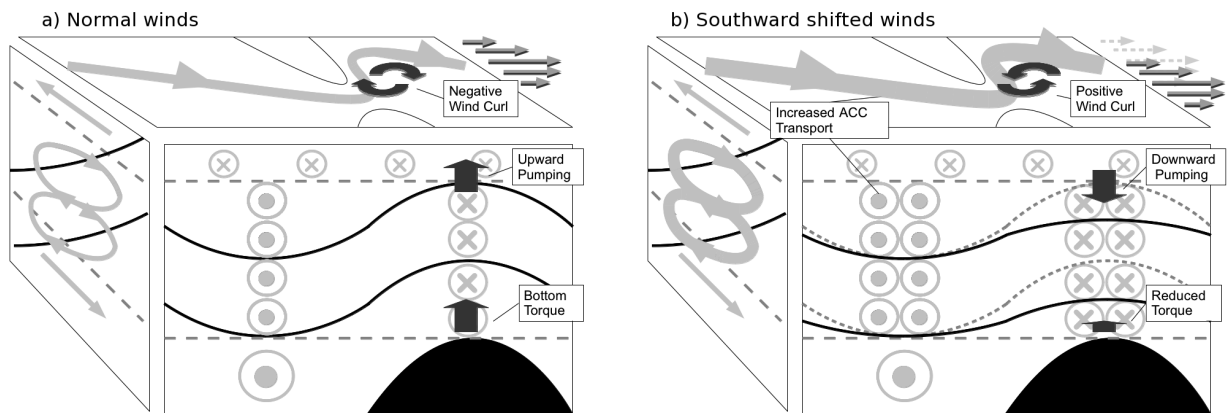


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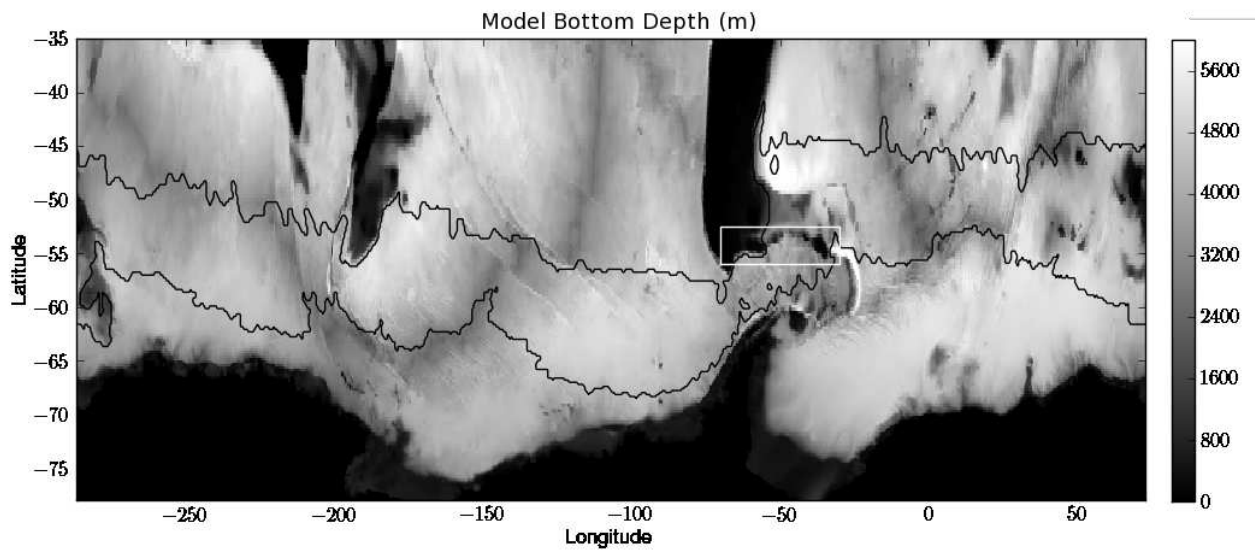


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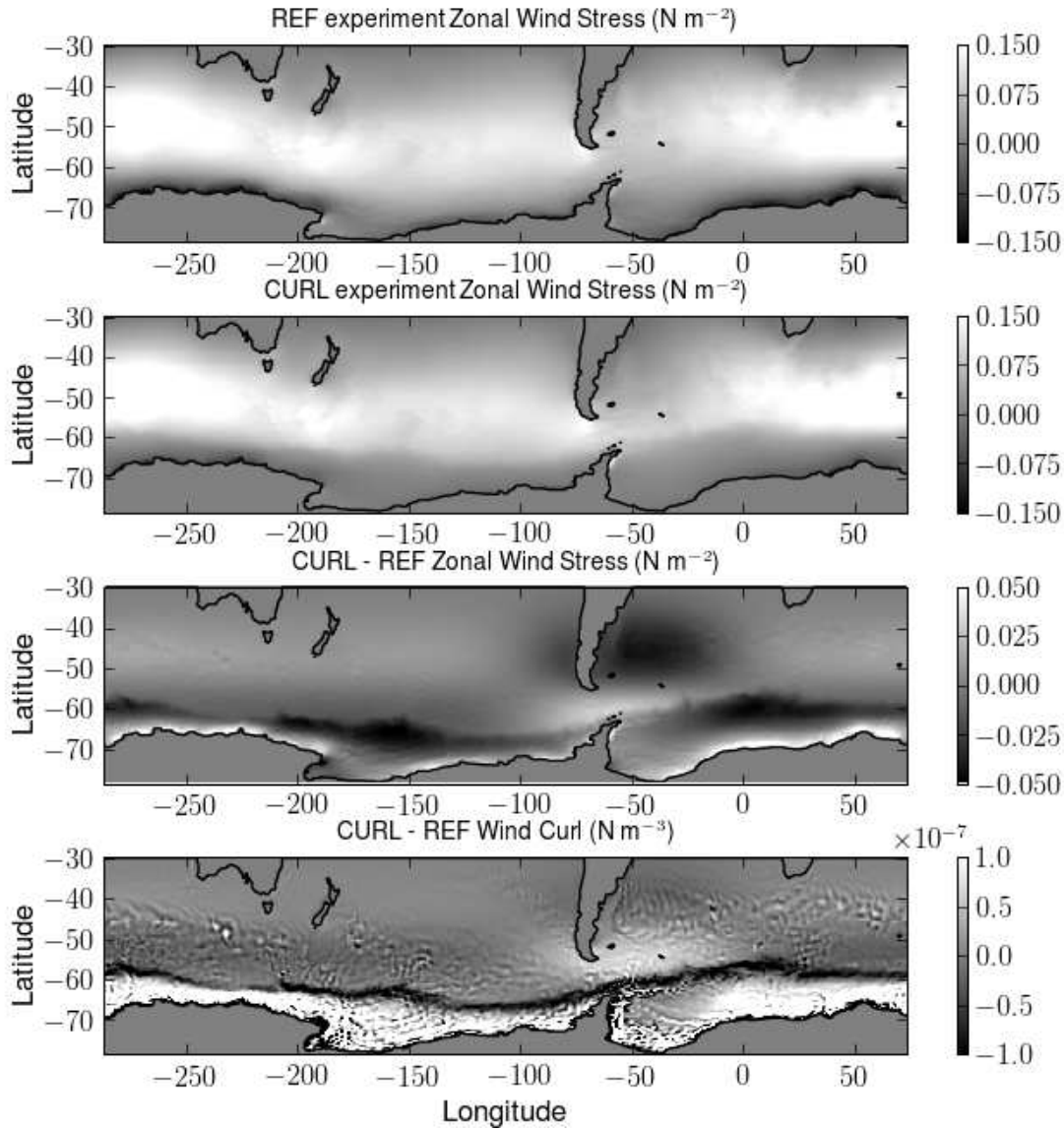


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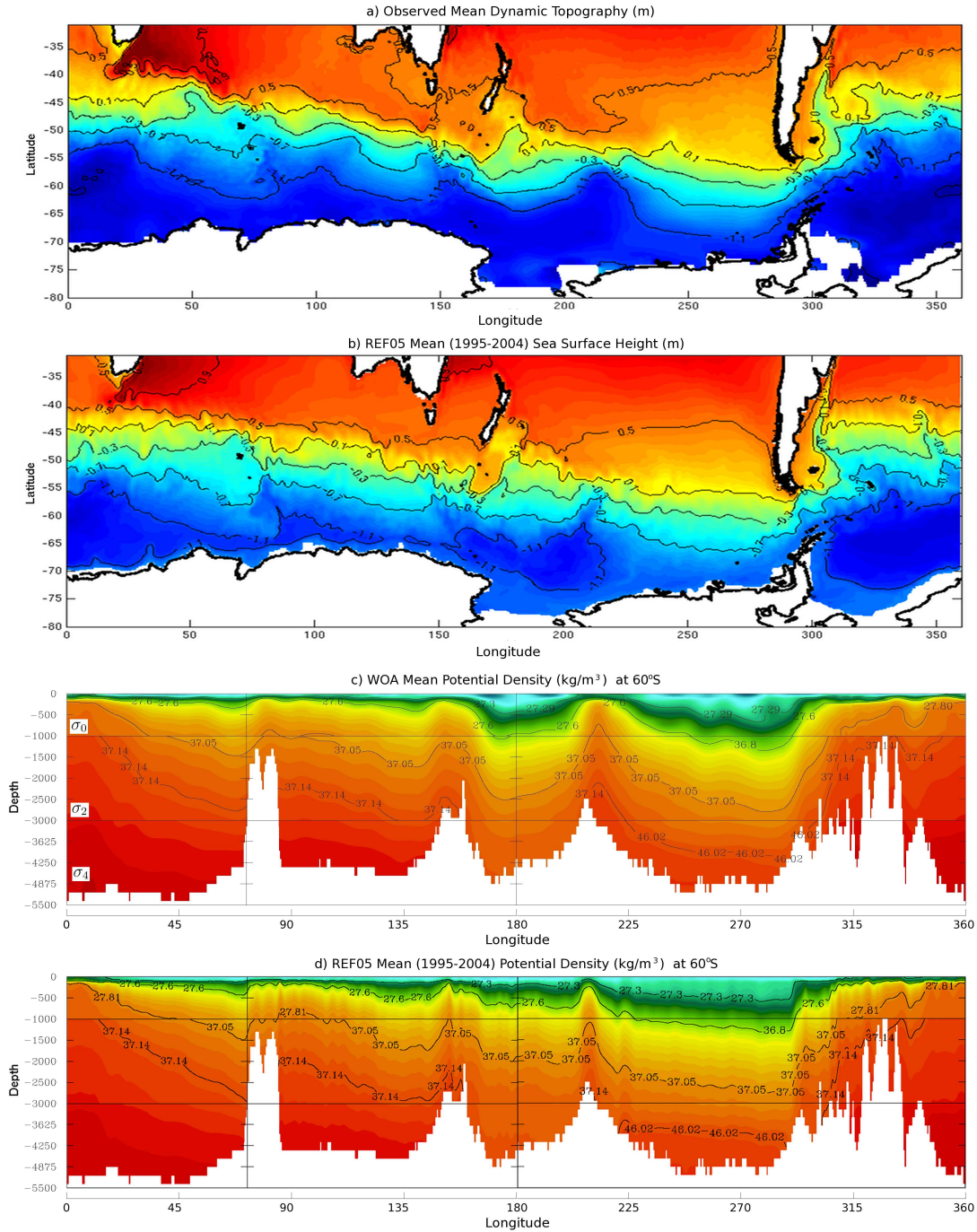


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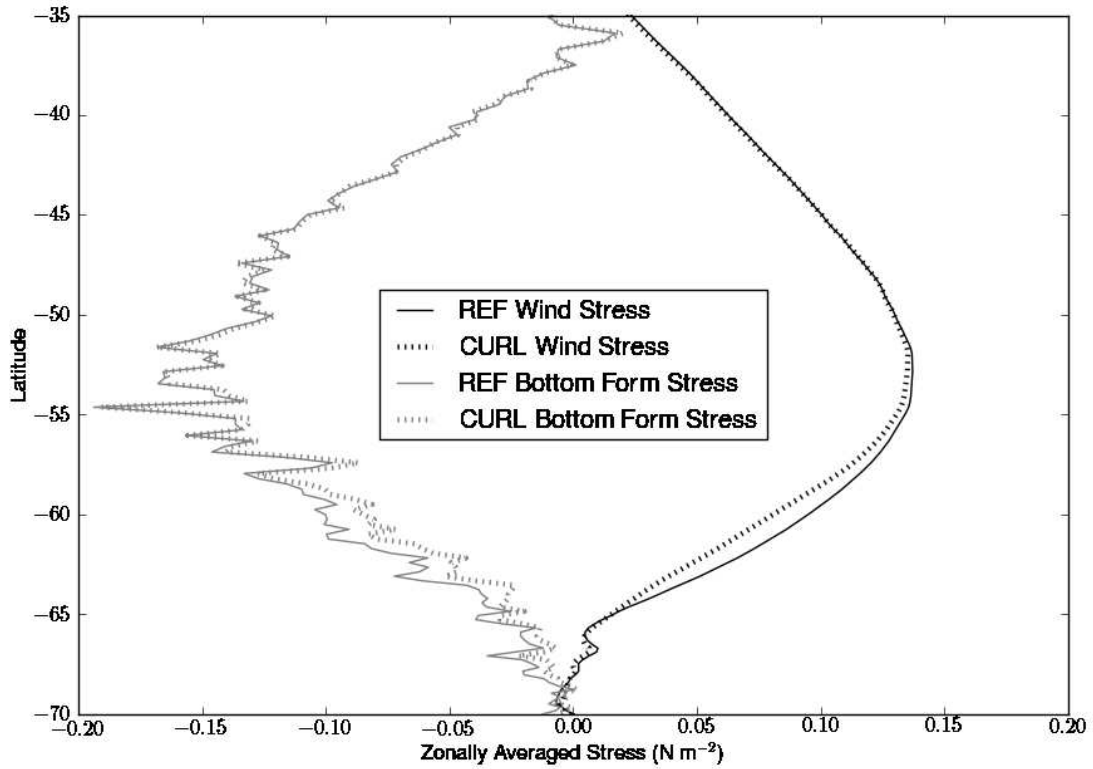


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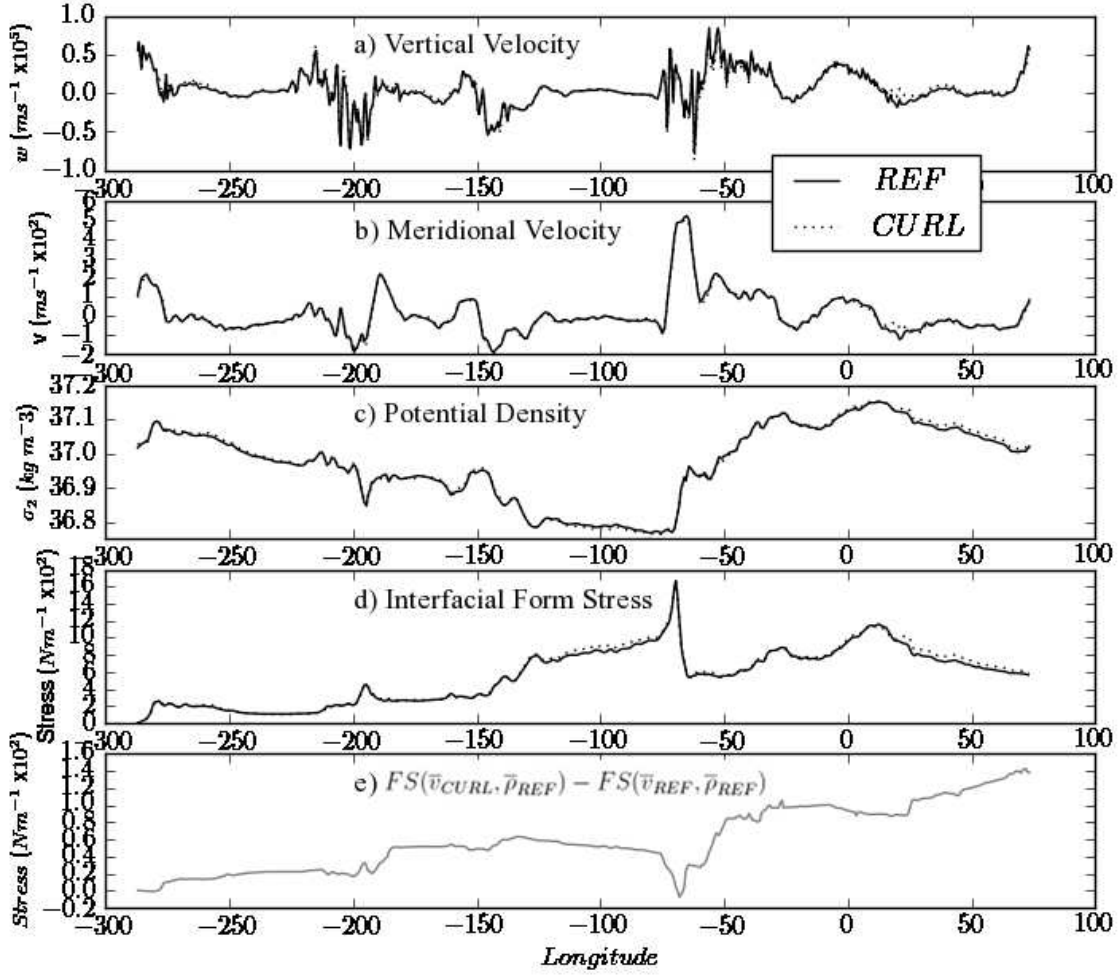


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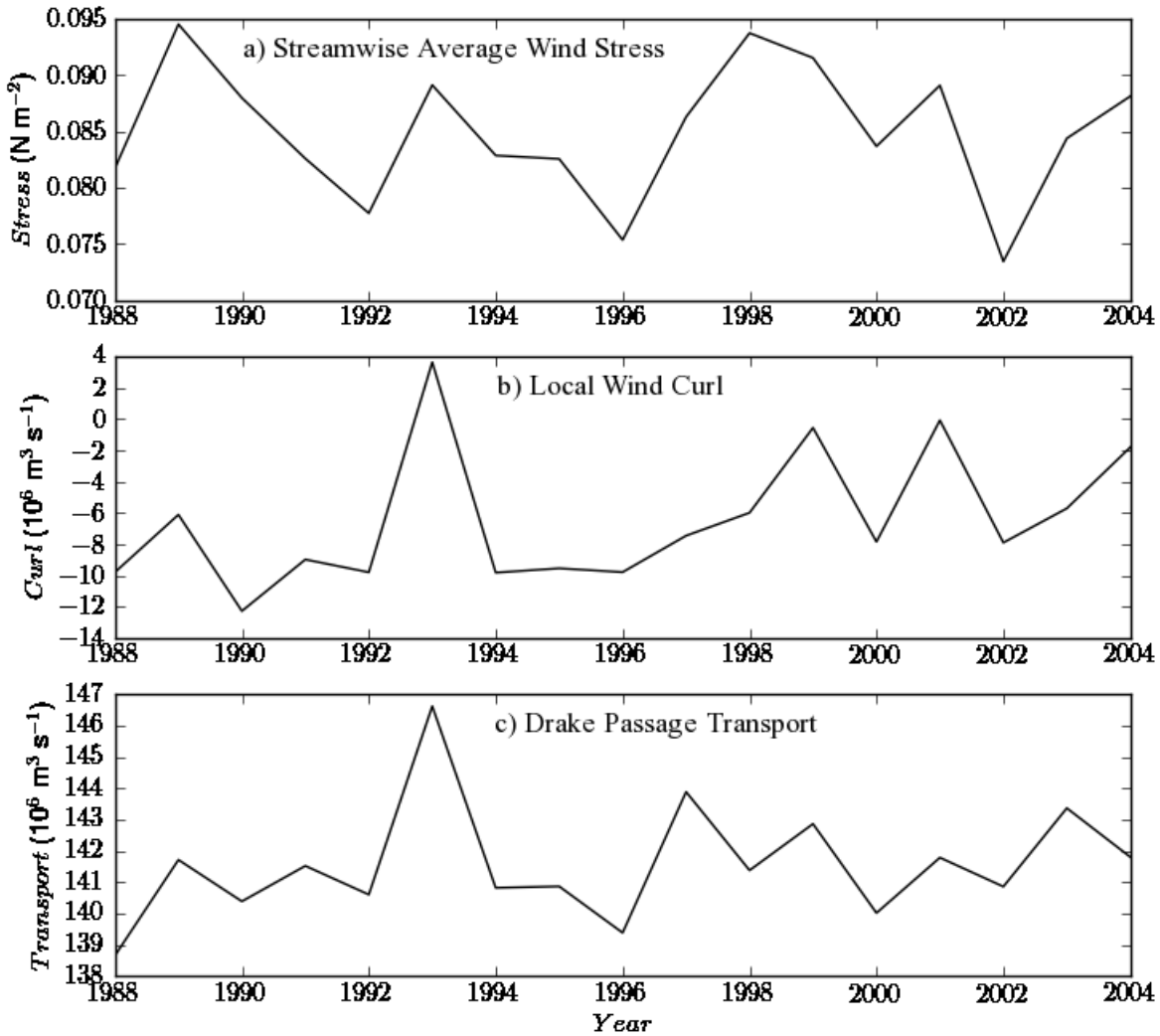


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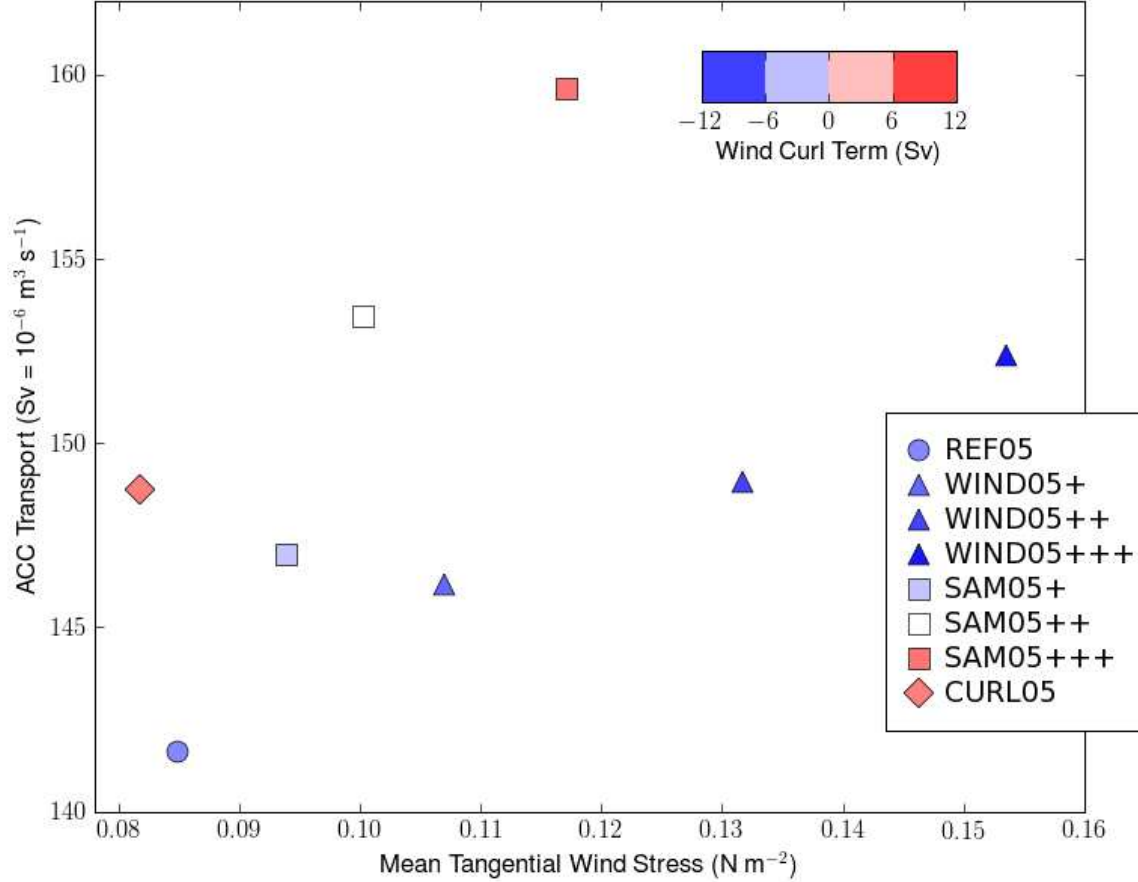


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