On the Sensitivity of the Drake Passage Transport to Air–Sea Momentum Flux

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(Manuscript received 14 January 2011, in final form 8 October 2011)

ABSTRACT

An eddy-permitting state estimate and its adjoint are used to analyze the influence of wind stress perturbations on the transport of the Antarctic Circumpolar Current (ACC) system through Drake Passage. The transport is found to be sensitive to wind stress perturbations both along the ACC path and also in remote regions. The time scale of influence of wind stress perturbations is on the order of 100 days. Regarding spatial scales, the sensitivity of transport to wind stress is relatively smooth in regions of flat topography. In boundary regions and regions with complex topography, however, the sensitivity is enhanced and characterized by shorter length scales of order 100 km. Positive perturbations to the zonal wind stress usually increase the ACC transport, though the wind stress curl is of primary influence where the currents are steered by topography. Highlighting locations where the ACC is especially responsive to air–sea momentum fluxes reveals where an accurate determination of atmospheric winds may best enhance ocean modeling efforts.

1. Introduction

The Antarctic Circumpolar Current (ACC) is the largest system of currents on earth. Driven largely by the westerly winds, the ACC carries and distributes nutrients, salt, and heat throughout the Southern Hemisphere (Rintoul et al. 2001). The winds driving the ACC are highly variable and, in recent decades, have been increasing in strength (Marshall 2003). How the wind drives the ACC is a matter of debate. Theoretical arguments have promoted the ACC transport being governed by the Cape Horn Sverdrup transport (Warren et al. 1996; Hughes et al. 1999), proportional to the square root of the zonal wind stress at the latitude of Drake Passage (Johnson and Bryden 1989), or some combination of processes (Gill 1968). Numerical experiments with coarse-resolution models suggest the transport depends on the vertical mixing coefficient (Cai and Baines 1996) or the isopycnal diffusivity coefficient in the model (Gent et al. 2001). These numerical experiments also suggest a strong sensitivity to the zonal wind speed at the Drake Passage latitudes and to the strength of the overturning in the polar gyres. In short, what sets the mean ACC transport through Drake Passage is still a major outstanding question in physical oceanography, and this confusion makes it difficult to predict how the ACC will react to changing winds.

The response of the ACC to surface buoyancy and momentum fluxes has been investigated extensively with numerical models. The models used, however, have employed simplified dynamics or coarse resolution such that they can computationally afford to run a reasonable ensemble of simulations to equilibrium (Gent et al. 2001). Hallberg and Gnanadesikan (2006) did run experiments with higher-resolution models and found the response of the ACC to changes in the mean wind stress is quite different in models that explicitly resolve eddies. Other work has investigated changes in the ACC state to atmospheric indices (Meredith and Hogg 2006) or to an evolving modeled climate system (Fyfe and Saenko 2006). These previous investigations have focused, by necessity, on large-scale changes in the forcing, and have had difficulties separating various controls. These works have determined that the ACC transport is determined by thermodynamics, as well as dynamics, making a simple relationship impossible to find (Cai and Baines 1996; Gnanadesikan and Hallberg 2000).

The Southern Ocean winds are highly variable on all time scales. To fully understand the ACC response to a changing climate it is necessary to have a record long
enough to be able to separate out the relevant time scales. Unfortunately, the observational record of ACC transport is too sporadic and short to make this possible. Thus, a thorough understanding of the high-frequency ocean response to wind fluctuations is necessary to be able to separate this component from the climate signal. In this paper the response of the ACC transport through Drake Passage to wind stress perturbations is investigated.

This study follows that of Losch and Heimbach (2007) who used an adjoint model to investigate the sensitivity of the Drake Passage transport to atmospheric forcing and bottom topography. The primary difference here is the use of a model that resolves many of the scales believed to be vital to the dynamics of the Antarctic Circumpolar Current. Losch and Heimbach (2007) used a 4° resolution model and found that doubling the resolution qualitatively changed the sensitivity results. The sensitivity patterns in the 4° resolution model were much smoother than the 2° resolution model. We show that increasing to 1/6° resolution results in the sensitivities becoming much more localized, and even, in some cases, changing signs as they react to the resolved eddies and topography. There is a significant effort underway to determine how the ocean will react to large-scale shifts in the Southern Hemisphere winds (e.g., Cai 2006; Meredith and Hogg 2006; Fyfe et al. 2007; Böning et al. 2008; Hogg et al. 2008; Tréguier et al. 2010). We find the sensitivity of the ocean circulation to changes in winds to have strong spatial dependence.

2. Method

The Massachusetts Institute of Technology (MIT) general circulation model (MITgcm; evolved from Marshall et al. 1997 and its adjoint (Wunsch and Heimbach 2007) is the primary tool used in this study; they are described below. Additional information on the methodology can be found in Losch and Heimbach (2007).

a. The forward model

The forward model is the Southern Ocean State Estimate (SOSE; Mazloff et al. 2010). In brief, it is the MITgcm configured to a domain from 78° to 24.7°S (Fig. 1) with 1/6° horizontal resolution and 42 levels in the vertical. Partial cells are used in an attempt to best resolve the topography, which is prescribed using a blend of Global 30 Arc-Second Elevation Data Set (GTOPO30) (Smith and Sandwell 1997) and 5-minute gridded elevations/bathymetry for the world (ETOPO5) (NOAA 1988.). The governing equations are stepped forward with a 900-s time step. An atmospheric state is optimized using the adjoint method and is constrained to be consistent with the National Center for Atmospheric Research (NCAR)–National Centers for Environmental Prediction (NCEP) reanalysis (Kalnay et al. 1996). Similarly, the initial conditions are optimized but are constrained to be consistent with a 1°-resolution global state estimate (Forget 2010). The northern open boundary conditions are derived from the state estimate of Forget (2010). Runoff is prescribed at the southern boundary in attempt to account for the Antarctic ice shelves. The ocean model is coupled to a sea ice model (Hibler 1980; Heimbach et al. 2010; Losch et al. 2010). The model also employs the nonlocal K-profile vertical mixing parameterization (KPP) (Large et al. 1994) and the Gent–McWilliams Redi eddy parameterization (Redi 1982; Gent et al. 1995) parameterizations. See Mazloff et al. (2010) for more on the SOSE setup, which includes a table of prescribed parameters.

b. The adjoint method

In traditional forward model sensitivity experiments a perturbation is made to a model input, for example, to wind stress. The model is then integrated forward in time. The difference between the perturbed and reference run gives the sensitivity of the forward model to the perturbation. To determine the sensitivity of the ACC transport through Drake Passage to wind stress using this traditional forward model approach would therefore require many simulations with a whole suite of model input perturbations.

In contrast the adjoint model steps backward in time (Wunsch 2006). In essence, one perturbs the ACC

Fig. 1. Model bathymetry (m). The thick black line spanning Drake Passage shows the line of integration for calculation of zonal transport. Topographic features discussed in the text are denoted.
transport and iterates the ocean physics backward to determine what model inputs are capable of making such a change. In practice, the adjoint model determines the gradient of a scalar objective function $J$ with respect to the earlier model state. For this work, $J$ is the meridional and vertical integral [from the bottom depth $H(x, y)$ to surface $\eta$] of zonal velocity $u$ at 70°W (i.e., the Drake Passage transport—see Fig. 1). Thus,

$$J = T^{-1} \int_{t_1}^{t_1+T} \int_H \int_{y_n}^{y_s} u(x = 70^\circ W, y, z, t) \, dz \, dy \, dt,$$

where $y_s$ and $y_n$ are the southern and northern limits of Drake Passage, and the temporal duration that the objective function is evaluated over (i.e., $T$) is discussed below. With the exception of the recirculation through the Indonesian Throughflow there is relatively little volume divergence in the ACC (Mazloff et al. 2010), and thus $J$ is a good proxy for the ACC transport at all longitudes.

The adjoint model determines sensitivity information for independent components of the model solution (i.e., partial derivatives), thus solving for $\partial J/\partial s(x, y, z, t)$, where $s$ represents all model variables (Giering and Kaminski 1998). The analysis focus in this paper is on the sensitivity of $J$ with respect to air–sea fluxes of momentum, such that the components of $s$ evaluated are $\tau^{(x)}$ and $\tau^{(y)}$, denoting the zonal and meridional components of wind stress, respectively.

The adjoint model is derived from the linearized forward model (i.e., the tangent linear model). This is a shortcoming of the method as the linearization renders the sensitivities an approximation because feedbacks to the mean state are excluded. For example, the sensitivity to a wind stress perturbation will be heightened if that perturbation can cause an instability in the solution. Once that instability has occurred, however, the mean state releases available potential energy, the front becomes more stable, and the sensitivity should now diminish. The implicit linearity of the adjoint model, however, will not allow the front to become more stable, and that heightened sensitivity will likely continue to grow. Thus, the more nonlinear the solution, the shorter time window the adjoint model will be relevant. Losch and Heimbach (2007) assessed the validity of this linearity assumption with perturbation experiments and concluded for a coarse-resolution (4°) model that on the time scale of 100 years the adjoint sensitivities are accurate to within ~30%. For yearlong runs, like the one we are considering, they found the accuracy far greater, estimating it to be within 5%. The model used in this work is eddy permitting, and thus nonlinearities play a larger role in the dynamics. Nevertheless, a comparison of the adjoint model sensitivities with a forward model perturbation experiment (presented below) suggests the error is less than 10%. The sensitivities analyzed in this paper are therefore valuable, though one is cautioned in extrapolating the quantitative results beyond a perturbative regime as errors due to linearization of the system may become large.

c. Numerical experiments carried out

The numerical experiments are described in detail in the following section. For clarity a brief list is provided here.

- A forward model experiment in which a 5 m s$^{-1}$ perturbation to wind speed is applied at (181°W, 56°S) on approximately 4 January 2005.
- An adjoint model experiment where the objective function is the transport through Drake Passage from 0000 to 0015 UTC ($T = 15$ min) on 1 January 2006.
- An adjoint model experiment where the objective function is the mean transport through Drake Passage for all model run time (1 January 2005–31 December 2006). Thus $t_1$ is the first model time step and $T$ is 2 years.

The first two experiments are analyzed to introduce the method and determine the accuracy of the adjoint model sensitivities. The output from these runs is used in Fig. 2. The remaining figures, and the bulk of the analysis in the paper, rely on output from the last numerical experiment. Differences in the magnitude of the sensitivities between the two adjoint experiments reflect the fact that one is probing the instantaneous response (the objective function averaging over 15 min), while the other determines the sensitivity of the time-mean response (averaging over the length of the run).

3. Results

a. Comparison of adjoint-derived sensitivities and a forward perturbation experiment

A forward perturbation experiment sheds light on the sensitivity while providing a basis for testing the accuracy of the adjoint model. A wind perturbation was applied, having a Gaussian spatial structure with a standard deviation of 1° and centered at 181°W, 56°S (location shown in Fig. 1). The wind perturbation amplitude at the center of the Gaussian was zero on 2 January 2005, increased linearly to peak at 5 m s$^{-1}$ on 4 January, and then reduced linearly back to zero on 6 January. The transport response reaches a peak with approximately a 1-day lag (Fig. 2a). The perturbation to wind speed occurs 7000 km east of Drake Passage, such that a 1-day lag means barotropic waves are propagating wind stress signals at a rate of at least 80 m s$^{-1}$. The falloff is well fit to an exponential with an e-folding time of approximately 3 days.
The transport response to the wind stress perturbation is negligible after a month.

The wind stress perturbation accelerates the fluid and the perturbation propagates through advection and wave dynamics to the Drake Passage. The response eventually propagates away and is damped by dissipation. The same fundamental physics occur in the adjoint model, except backward in time. The adjoint model determines the sensitivity of the Drake Passage transport by calculating the derivative of this transport at a given time and propagating that signal back in time by applying the chain rule to the governing dynamics. Thus the signal, which originates as a sensitivity to the zonal velocity at Drake Passage, propagates backward in time via advection by the background state and wave dynamics throughout the ocean to be eventually damped by dissipation. The dynamics dictate that the sensitivity to the zonal velocity at Drake Passage has a signature in all model state variables and most forcing terms. The adjoint thus gives a response function of the Drake Passage transport at all locations and times.

To reproduce the forward model perturbation response with the adjoint model, an objective function is designed that is the transport through Drake Passage on 1 January 2006 over a 15-min period [i.e., for Eq. (1), \( t_1 = 1 \text{ January 2006} \) and \( T = 15 \text{ min} \)]. The specific date chosen, however, is insignificant, as the analysis of this response focuses on short time scales where the background state is of secondary importance. (In the following section the temporal dependance is investigated in greater detail.) The sensitivity at the center of the perturbation location shows that the response peaks after 1 day, then falls off quickly (Fig. 2b). Fitting the falloff to an exponential gives an e-folding time of approximately 4 days. Again, as found in the forward perturbation experiment, the sensitivity is negligible after a month.

The accuracy of the adjoint model derived response function is checked by convolution of the sensitivity (blue line in Fig. 2b) with the wind stress perturbation (red line in Fig. 2a) to derive a hindcast (green dashed line in Fig. 2a). The hindcast tracks well with the true forward-model-determined transport perturbation. Differences may reflect changes in the background ocean state because of the different times when the forward wind speed perturbation was made and when the adjoint objective function was calculated. Differences may also result from nonlinearities in the response that the adjoint is not able to fully capture. The primary discrepancy between the two curves, however, is likely due to the adjoint sensitivity being diagnosed with 12-h snapshots, which is fairly coarse sampling for the fast barotropic response. Nevertheless the adjoint response function is deemed accurate to lowest order; for the first 12 days after the perturbation is initiated the average difference between the perturbed transport and the hindcast is 8%, with a maximum difference of 13%.

The effect of wind stress perturbations on the Drake Passage transport is short lived, having little contribution after 10 days and becoming insignificant after about

![Fig. 2. A wind stress perturbation [spatial maximum given by red line (N m^{-2})] is applied at 56^\circ S, 181^\circ W. Changes in ACC transport through Drake Passage lag by about 1 day and last several weeks [blue line in upper plot (Sv)]. The sensitivity of transport through Drake Passage to a wind stress perturbation at 56^\circ S, 181^\circ W is derived by the adjoint model [blue line in lower plot [Sv (Nm^{-2})^{-1}]]. Peak sensitivities occur 1 day after calculation of the objective function and asymptote to zero after about 3 weeks. Convolution of the adjoint-derived sensitivities with the wind stress perturbation [green dashed line in upper plot (Sv)] compares well with the modeled ACC response.](image-url)
20 days. Thus, wind stress changes would have to be sustained to affect the mean transport. Investigating the details of a sustained wind stress change on Drake Passage is accomplished by designing an objective function that is the mean transport through Drake Passage; that is, in Eq. (1) setting $t_1$ to be the first model time step, and letting $T$ be the duration of the run. The remainder of the paper analyzes the sensitivity of this objective function.

b. Temporal dependence

The temporal dependence of the sensitivity of the mean Drake Passage transport to momentum flux rises quickly to reach an equilibrium level in less than a month’s time (Fig. 3a). This is consistent with the forward perturbation experiment, showing sensitivities to momentum fluxes propagate quickly via barotropic waves, and is diminished quickly as well. The sensitivities to buoyancy fluxes, which act solely to change the ocean stratification, propagate slowly via baroclinic waves and grow gradually (Fig. 3b). The sensitivity to buoyancy fluxes also has a strong seasonal dependence, as the interior is more exposed in austral winter and spring when the stratification is weak and water masses are being created. In austral summer and fall the stratification is strong, and the interior is isolated from surface buoyancy fluxes. Thus, the sensitivity to buoyancy flux accumulates fastest approximately June–November and diminishes or remains flat December–May. This analysis is focused on short-term variability, and the slow evolution and seasonal dependence of sensitivity to buoyancy flux makes this subject more suitable for future investigation using different methods. Furthermore, over the relatively short analysis period the sensitivity to buoyancy flux is far less significant than the sensitivity to wind stress. For these reasons, the focus of this paper is solely on air–sea momentum fluxes, which reach a quasi-equilibrium state on the order of 100 days.

c. Spatial dependence

The sensitivity of the Drake Passage transport to air–sea momentum flux is rather independent of the current ocean state, and the slowly evolving baroclinic signature of the momentum fluxes is insignificant over the study’s temporal period (note consistent sensitivity magnitude in Fig. 3a). That the sensitivity quickly reaches a quasi-steady state allows a robust analysis of the spatial structure after only a 1-yr run. Losch and Heimbach (2007) compared sensitivities from a 2°- and 4°-resolution model and found that as resolution was increased, the structure of the sensitivities became finer, shifting from the interior to the boundary regions. This makes sense, as coarse-resolution models typically have weak and diffuse boundary currents (Large et al. 1997), and thus increasing resolution allows for boundary layer transports to play a larger role. Nevertheless, 2° resolution is still very coarse, and thus Losch and Heimbach (2007) report the sensitivity of the Drake Passage transport to wind stress to have a very smooth basin-scale structure. This is especially true with respect to the zonal wind stress (their...
Fig. 6a). They found the sensitivity to meridional wind stress is somewhat more localized. Carrying out the same calculation at eddy-permitting resolution shows that, though the basin-scale sensitivity to wind stress remains, the dominant sensitivities occur at the much finer scales of the oceanic mesoscale dynamics (Figs. 4a,b).

The mean sensitivity to wind stress of the 2006 mean Drake Passage transport (Figs. 4a,b) is significant over much of the domain. The signal is heightened, however, in a few regions. There is significant sensitivity to alongshore wind stress at the continental boundaries. There are three regions away from major continents where the sensitivity to wind stress is heightened: the Kerguelen Plateau (~60°E), the Campbell Plateau (~160°E), and the Drake Passage (~60°W). Heightened sensitivity, though not as significant as these three regions, is also apparent where the ACC crosses the Pacific–Antarctic Ridge (~150°W). Smooth basin-scale sensitivities are apparent in the southeastern Pacific and southeastern Indian Oceans. The sensitivity to wind stress along the ACC path, however, is strongly dependent on longitude and far from smooth [see (Fig. 6b) below].

The overall magnitude of the sensitivity is relatively steady (section 3b), as are the locations of heightened sensitivity to momentum flux. The specific structure in these regions of heightened sensitivity, however, changes dramatically. The difference between the mean sensitivity of Drake Passage transport to wind stress and of the sensitivity to the wind stress at an arbitrary time (here taken to be on 1 January 2006) shows the influence of the ocean mesoscale (Figs. 4c,d). One may also infer how the sensitivity fields vary by considering the standard deviation over the year (Figs. 5a,b). The changes are greatest in the Drake Passage, the Campbell Plateau, and the Kerguelen Plateau. These are regions where the ACC exhibits significant meanders (Gille 2003); as the currents move so too do the locations of heightened sensitivity to wind stress. Normalizing the mean sensitivity to wind
stress by the standard deviation (Figs. 5c,d) shows that in these specific regions the variability is a significant part of the signal, while over most of the domain the signal is relatively steady.

d. Sensitivity to large-scale wind stress perturbations

The 2006 mean ACC transport sensitivity to perturbations in the 2006 mean air–sea momentum fluxes are investigated as functions of latitude and longitude independently (Fig. 6). The sensitivity to the zonal wind stress has many small-scale features, but in general increases poleward to peak just south of the Drake Passage, then quickly drops off poleward of 70°S. The sensitivity is always positive, implying a longitudinally independent increase in zonal wind stress at any latitude poleward of 30°S will increase the strength of the ACC.

The ACC is vertically coherent, and thus the vertically integrated transport streamlines approximate Lagrangian ACC streamlines. Wind stress perturbations acting on these streamlines flux momentum directly into the ACC and are able to power the geostrophic ocean circulation (Wunsch 1998). The sensitivity to zonal wind stress perturbations averaged along ACC streamlines has a similar...
The sensitivity to meridional wind stress perturbations along ACC streamlines, however, is quite different. This sensitivity implies that an increase in meridional wind stress around the Subantarctic Front (i.e., the equatorward flank of the ACC) will have little effect on the ACC transport, while an increase around the Polar Front (i.e., the southern flank of the ACC) will likely accelerate the flow. This acceleration contrasts with the deceleration that results from a meridional wind stress perturbation along a constant latitude circle, highlighting the importance of averaging path and the small-scale signature of the sensitivities.

The small-scale signature and highly varying magnitude of the ACC transport sensitivity to air–sea momentum flux is apparent when averaged meridionally across the ACC streamlines (Fig. 6b). Sensitivities with respect to the meridional wind stress rise an order of magnitude at the Kerguelen Plateau (~60°E), the Campbell Plateau (~160°E), and the Drake Passage (~300°E). Sensitivities with respect to the zonal wind stress are smoother but still greatly enhanced in these regions. Peak ACC transport sensitivities to meridional and zonal wind stress generally occur at the same locations, suggesting a connection between the two. The signs of the peaks, however, are not always in phase.

As can be seen in Fig. 6a, a zonal wind stress increase will have the largest effect south of the Drake Passage. Figure 6a also shows, however, that the mean zonal winds are weak at these latitudes, and thus a percentage increase in the Southern Hemisphere zonal winds just north of the Drake Passage would have the greatest effect on ACC strength. Projecting a wind stress perturbation onto the zonally integrated sensitivity to zonal wind stress reveals a predicted mean transport perturbation (Table 1). The perturbations chosen are a shift of the mean winds by 0.5° north or south, an increase in the mean winds over the region, and a series of local increases. The regional increases chosen are 1) an addition of magnitude 0.001 N m⁻² and 2) an increase in the mean 2006 winds of 1%. The local increases are boxcar functions the width of the Drake Passage, ΔDP, here taken as spanning 62.9° to 55.5°S (ΔDP = 7.4° of latitude). One boxcar perturbation is chosen to be exactly the latitudes of the Drake Passage and each other perturbation is offset by half ΔDP. The calculation is precise; however, the accuracy of the calculation is limited, as is suggested by the by the average ~8% difference between the forward and adjoint model experiments (section 3a). The emphasis here is on the relative differences in the response to various perturbations, not the actual magnitude value. Thus to best enable this comparison the transport response is rounded to two decimal places, as opposed to being rounded to significant digits.

Models suggest that in a warming climate the winds may shift poleward and strengthen (e.g., Kushner et al.)
Table 1. Predicted change of the 2006 mean ACC transport (Sv) resulting from changes to the 2006 mean zonal wind stress. The top five rows of perturbations span latitudes 30°S to 70°S. The lower rows are for local perturbations that span a latitudinal extent equivalent to the approximate width of the Drake Passage: ΔDP = 7.4° of latitude. The row marked with an asterisk coincides to the Drake Passage latitudes, and all other local perturbations are then offset by half ΔDP. (Note ΔTr = [∂f/∂f](i)|Δf|, such that decreases in wind stress would result in transport perturbations of the opposite sign.)

<table>
<thead>
<tr>
<th>Wind stress perturbation, Δf(i)</th>
<th>ACC transport perturbation, ΔTr (Sv)</th>
</tr>
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<tbody>
<tr>
<td>0.001 N m⁻²</td>
<td>1% of (Δf(i))</td>
</tr>
<tr>
<td>Shift 0.5° south, no change in strength</td>
<td>0.06 0.06</td>
</tr>
<tr>
<td>Shift 0.5° north, no change in strength</td>
<td>-0.06 -0.06</td>
</tr>
<tr>
<td>Increase in strength, no shift</td>
<td>0.10 0.07</td>
</tr>
<tr>
<td>Increase over ΔDP centered at 33.5°S</td>
<td>0.03 0.00</td>
</tr>
<tr>
<td>Increase over ΔDP centered at 37.2°S</td>
<td>0.03 0.01</td>
</tr>
<tr>
<td>Increase over ΔDP centered at 40.9°S</td>
<td>0.02 0.02</td>
</tr>
<tr>
<td>Increase over ΔDP centered at 44.5°S</td>
<td>0.02 0.03</td>
</tr>
<tr>
<td>Increase over ΔDP centered at 48.2°S</td>
<td>0.02 0.03</td>
</tr>
<tr>
<td>Increase over ΔDP centered at 51.9°S</td>
<td>0.02 0.02</td>
</tr>
<tr>
<td>Increase over ΔDP centered at 55.5°S</td>
<td>0.02 0.02</td>
</tr>
<tr>
<td>Increase over ΔDP centered at 59.2°S*</td>
<td>0.01 0.01</td>
</tr>
<tr>
<td>Increase over ΔDP centered at 62.9°S*</td>
<td>0.01 0.01</td>
</tr>
<tr>
<td>Increase over ΔDP centered at 66.5°S</td>
<td>0.01 0.00</td>
</tr>
<tr>
<td>Increase over ΔDP centered at 70.2°S</td>
<td>0.01 0.00</td>
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2001; Fyfe and Saenko 2006). Table 1 shows that either a poleward wind shift or a strengthening of the winds would increase the ACC transport. Were the 2006 zonal mean winds to increase in strength by 1% and shift 0.5° poleward, the mean ACC transport is predicted to increase in strength by about 0.13 Sv (1 Sv = 10⁶ m³ s⁻¹). This calculation is a linear perturbative analysis, and one may conjecture that a doubling of the wind (100% increase) over 2006 would result in a 13 Sv increase in ACC transport. The linearity of the analysis allows for wide speculation to be made; however, the uncertainty in the prediction becomes much greater as the perturbative regime assumption made in this work becomes invalid. One expects large changes to the mean state to result in dynamical changes, and thus changes to the sensitivities. For example, as suggested by the work of Hallberg and Gnanadesikan (2006), a multyear increase in wind stress may lead to an increase in eddy activity, balancing the excess Ekman transport, and leaving the mean ACC transport unchanged (the theory of eddy saturation, e.g., Meredith and Hogg 2006).

4. Discussion

Wind perturbations drive barotropic waves that influence the ACC transport over several days, with a diminished effect after several weeks. Because of the rapid temporal decay, the primary response of the ACC transport through Drake Passage to a step-function increase in air–sea momentum flux comes to a quasi-equilibrium in a period of about a month. Temporal changes in the sensitivity to wind stress reflect the current state of the eddy field and location of meandering currents, but the overall amplitude is relatively constant throughout the strong seasonal cycle of the Southern Ocean. This indicates that the primary effect on transport of wind field perturbations with length scales that are large compared to the oceanic mesoscale will be independent of the current ocean state. In other words, the lowest-order ACC response to a large-scale wind perturbation in the summer will be approximately the same as the wintertime response. This primary response, however, is barotropic, and it remains to be determined whether or not the sensitivity of the baroclinic state to momentum flux fluctuates seasonally. Indeed, the sensitivity of the ACC transport to air–sea buoyancy flux is strongly seasonally dependent. A thorough analysis of the sensitivity of the baroclinic state to air–sea buoyancy and momentum flux is deferred to future work, which will likely need to employ simulations run over longer periods.

The ACC transport sensitivity to air–sea momentum flux varies greatly in space, becoming especially heightened near land boundaries and also in the open ocean where the strong ACC currents interact with significant topographic features. Interpretation of this result is given below, including a discussion of the dynamics determining the sign of the sensitivity.

a. The sensitivity near land boundaries

The strength of the ACC transport through Drake Passage is given by the across passage difference of the vertically integrated transport streamfunction (e.g., Gill 1968). This streamfunction has been shown to be approximately proportional to sea level in the Drake Passage (Meredith et al. 2004), and thus the strength of the ACC becomes proportional to the sea level difference between the land boundaries to the north (i.e., Africa, Australia, and South America) and south (i.e., Antarctica). Consistent with this inference, the ACC transport is found to be strongly sensitive to alongshore wind (Figs. 4a,b).

Alongshore winds are able to drive fluid toward or away from the coast. In the Southern Hemisphere, a southward meridional wind stress along an eastern land boundary (e.g., along Chile) will converge water along the coast, and thus raise the coastal sea level. A westward wind stress along a northern zonal boundary (e.g., much of the Antarctic continent) will drive a divergence and reduce coastal sea level. The sensitivity maps (Figs. 4a,b) show the ACC responds to this effect, and that either Ekman convergence on continents north of the ACC,
or divergence around Antarctica, acts to increase the strength of the ACC. Lack of propagation pathways prevents sensitivity from accumulating on some coasts north of the ACC. The sensitivity can readily propagate to the north along western land boundaries (eastern ocean boundaries) and to the east along southern land boundaries via coastally trapped waves. In the forward ocean model, a perturbation on these western and southern land boundaries would excite coastal waves and influence the ACC, while waves excited on eastern land boundaries north of the ACC would propagate equatorward away from the ACC.

b. The sensitivity where the ACC interacts with topography

The ACC is sensitive to basin-scale changes in the wind. In general, an increase in westerlies will cause an increase in the ACC transport (Fig. 6a). The story, however, is more complicated. The sensitivity of the ACC transport to wind stress increases by an order of magnitude near the Kerguelen Plateau, the Campbell Plateau, and the Drake Passage. These three regions are locations of extreme topographic steering of the ACC (Marshall 1995), as can be seen by the sharp convergence of streamlines in Fig. 4.

Vorticity constraints on the ACC become significant in regions of complex topography where \( f/H \) contours (here \( f \) is the Coriolis parameter, and \( H \) is the ocean depth) are obstructed, and free barotropic mode responses to wind stress fluctuations are prevented. It has been determined that stretching of the water column, through changes in baroclinicity (Olbers and Eden 2003) or wind stress perturbations (Weijer and Gille 2005), allow a strong “almost-free-mode” response (Hughes et al. 1999). The findings here of an increased sensitivity to wind stress at topographic obstructions, where interactions with almost-free-modes are most important, are consistent with these previous results.

The central Pacific region of the Southern Ocean is examined in greater detail to further investigate the role of the topography in determining the structure of the ACC transport sensitivity to wind stress (Fig. 7). This region is characterized by a relatively smooth basin straddled by the Campbell Plateau and the Pacific–Antarctic Ridge (Fig. 1). To the west of the Pacific–Antarctic Ridge the ACC is rich with eddies and lee waves as it has just passed over the Campbell Plateau. The bathymetry in this location, however, is flat and there is little topographic steering. Here the sensitivity to zonal wind stress in the Drake Passage latitudes is positive and relatively smooth (see longitude \( \sim 180^\circ \)–160\(^\circ\)W in Fig. 7a). Where the ACC interacts with the Pacific–Antarctic Ridge at \( \sim 150^\circ\)W, denoted in Fig. 7 by the 3500-m contour, the sensitivity magnitude becomes enhanced by a factor of \( \sim 3 \) (this increase is also apparent in Fig. 6b). The sensitivity at the ridge also exhibits ocean mesoscale features, including a strong dipole at 55\(^{\circ}\)S, \( \sim 155^\circ\)W. This dipole, which is also apparent in the
sensitivity to meridional wind stress (Fig. 7b), has an orientation indicative of a sensitivity to wind stress curl—a strong meridional (zonal) gradient in zonal (meridional) wind stress. Thus this location of significant topographic steering is also where the ACC is acutely sensitive to vorticity input by the winds. Here the winds may flux potential vorticity into the ocean breaking the $\beta H$ bathymetric constraint that is obstructing the mean ACC. The sensitivity maps reveal where the barotropic response is most dynamically constrained. It follows that in these locations interactions between the barotropic and baroclinic states will most significantly alter the ACC transport.

5. Conclusions

The subpolar Southern Hemisphere winds and ocean currents are energetic and predominantly westward. That they are largely aligned allows the winds to input a significant amount of power into the ocean, thus providing a mechanism for atmospheric climate change to directly influence the large-scale ocean circulation (Wunsch 1998). An adjoint model was used to analyze the sensitivity of the ACC transport to wind stress. Large-scale changes in the Southern Hemisphere winds will affect the ACC transport, but the specific structure of these changes is important. The findings show that the ACC sensitivity to wind stress is strongly dependent on both latitude and longitude. In regions where topography is less influential, the ACC transport is most affected by wind stress perturbations driving barotropic flows. In regions where topographic interactions are strong the influence of the wind stress curl is dominant, as wind vorticity input opens pathways for so-called almost-free-modes of variability (Hughes et al. 1999). This is consistent with the finding that bottom pressure gauges in the ACC are highly correlated with the large-scale wind stress in some locations (e.g., the Drake Passage as reported in Meredith et al. 2004), and, in other locations, the gauges are most influenced by local wind stress curl (e.g., near Kerguelen Island as reported in Meredith and Hughes 2004).

The transport through Drake Passage is strongly sensitive to forcing occurring outside the path of the ACC. Averaging the transport sensitivity along streamlines is significantly different than averaging zonally, and this is especially true for the sensitivity to meridional wind stress. The primary difference between zonal and streamline averaging is that zonal paths cross into the subtropical and polar gyres and also the boundary currents within these regions. This finding highlights the influence of remote forcing on the ACC.

The southern annular mode (SAM) index, which is defined as the difference in the normalized zonal-mean sea level pressure between 40° and 70°S (Gong and Wang 1999), is associated with anomalous SST gradients and westerly winds. The findings here reveal that while the ACC transport is sensitive to anomalous westerlies, the magnitude of the sensitivity depends strongly on longitude, and thus it is proposed that investigating the correlation between ACC transport and independent weather stations may be informative. Marshall (2003) shows various weather stations that may be used to infer sea level pressure. Independent weather stations are able to capture variability in regions of enhanced sensitivity to wind stress. For example, the ACC transport is strongly sensitive to the meridional winds over the Campbell Plateau and just west of South America. The local wind fields in these regions are especially strong and variable and may be poorly correlated with the zonal-mean SAM index. Analyzing weather stations in these specific regions independently may provide significant added value. The results here suggest that continued wind observations and improved atmospheric reanalysis products in these highly variable locations can provide a clear impact on the success of ocean modeling.

Acknowledgments. The author is grateful to Sarah Gille, Teri Chereskin, Bruce Cornuelle, and anonymous reviewers for valuable comments on this work. Support for this work was provided by NSF Office of Polar Programs Grant ANT0961218. Computer resources were provided by Texas Advanced Computing Center under Teragrid Grant MCA06N007.

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