The transient response of the Southern Ocean pycnocline to changing atmospheric winds

Daniel C. Jones,[1] Takamitsu Ito,[1] and Nicole S. Lovenduski[2]

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[1] The vertical density structure of the Southern Ocean is dynamically linked to wind stress at the surface, but the nature of this coupling is not fully understood. Observations from the last several decades show a significant increase in the strength of westerly winds over the Southern Ocean, but an appreciable change in the tilt of constant density surfaces (isopycnals) has not yet been detected there. Using a combination of theory and idealized numerical simulations, we show that the response of the density structure occurs on centennial timescales, making it difficult to detect significant changes with a few decades of hydrographic observations. Dynamic coupling between the circumpolar current and northern basins regulates the slow adjustment of the density structure. Our results provide a new interpretation for recent observations and highlight the importance of the interaction between regional Southern Ocean dynamics and global ocean circulation. **Citation:** Jones, D. C., T. Ito, and N. S. Lovenduski (2011), The transient response of the Southern Ocean pycnocline to changing atmospheric winds, *Geophys. Res. Lett.*, *38*, L15604, doi:10.1029/2011GL048145.

1. Introduction

[2] The atmosphere overlying the Southern Ocean has been undergoing significant multi-decadal climate change characterized by an intensification and poleward shift of midlatitude westerly winds, which may be driven by ozone depletion and global warming [*Thompson and Solomon*, 2002; *Marshall*, 2003; *Miller et al.*, 2006]. Figure 1a shows the variation of the eastward surface wind speed averaged over the ocean between 40–50°S based on several meteorological reanalyses [*Kalnay et al.*, 1996; *Uppala et al.*, 2005; *Onogi et al.*, 2007; *Dee and Uppala*, 2009], which exhibits a positive trend on decadal timescales. Increased wind-driven Ekman flow tends to steepen the meridional tilt of density surfaces across the ACC by moving cold, high-latitude water northward, but recent analysis of float and hydrographic measurements show that the warming of the past several decades [*Gille*, 2002, 2008] is not correlated with a significant change in the tilt of the isopycnals (Figure 1b) [*Böning et al.*, 2008]. It has been hypothesized that an increase in eddy activity may have cancelled out the effect of increased Ekman flow, leading to a muted response of the mean isopycnal slope to stronger wind stress [*Straub*, 1993; *Völker*, 1999; *Böning et al.*, 2008]. *Allison* [2009] suggested the alternative hypothesis that the response of the isopycnal tilt and ACC transport involves communication between the Southern Ocean and global ocean circulation over centennial timescales. In this view, the apparent insensitivity of the isopycnal tilt to wind stress may be an artifact of attempting to diagnose a slow adjustment process with a relatively short observational record. Here we investigate the transient response of the Southern Ocean using a conceptual model and a suite of numerical simulations at both coarse and eddy permitting horizontal resolution.

2. Conceptual Model

[3] To illustrate the mechanism at work we use a conceptual model of the global pycnocline [*Gnanadesikan*, 1999], in the transient mode [*Allison*, 2009], with a generalized eddy parameterization scheme. The depth of the pycnocline reflects the volume of upper ocean water masses, which is assumed to set the isopycnal slope across the ACC. The tendency of the pycnocline depth can be calculated by taking the residual of the mass fluxes into the upper ocean, including sinking in the high-latitude Northern Hemisphere, low-latitude upwelling, and upwelling in the Southern Ocean (which is the residual of Ekman flow and oceanic eddies),

$$A\frac{dD}{dt} = T_L - T_N + \left(T_{Ek} - T_{eddy}\right), \tag{1}$$

where A is the area of the global low-latitude oceans and $D(t)$ is the depth of the pycnocline. The right-hand side of equation (1) consists of volume fluxes associated with low-latitude upwelling (T_L), sinking in the Northern Hemisphere (T_N), Ekman flow (T_{Ek}), and the poleward, eddy-induced transport across the ACC (T_{eddy}). We employ previously published [*Gnanadesikan*, 1999] functional forms and parameters for T_L (proportional to $1/D$), T_N (proportional to D^2), and T_{Ek} (independent of D), and we set the diapycnal diffusivity parameter to 3×10^{-5} m^{2}s^{-1}. The dependence of eddy-induced transport on the isopycnal slope is parameterized in a nonlinear fashion,

$$T_{eddy} = \frac{L_X}{L_Y}\frac{K_{ref}}{D_{ref}^{n-1}}D^n,$$

where L_X is the zonal length, and L_Y is the meridional width of the circumpolar current. The meridional width is assumed to have a constant value of 1500 km. K_{ref} is the reference eddy thickness diffusivity (1000 m^{2}s^{-1}) associated with the reference equilibrium solution, D_{ref}. The choice of $n = 1$ is equivalent to a constant eddy thickness diffusivity [*Gent and McWilliams*, 1990], and the choice of $n = 2$ reflects a parameterization based on baroclinic instability theory [*Visbeck et al.*, 1997]. The power n is an effective measure of

[1]Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, USA.

[2]Department of Atmospheric and Oceanic Sciences and Institute of Arctic and Alpine Research, University of Colorado at Boulder, Boulder, Colorado, USA.

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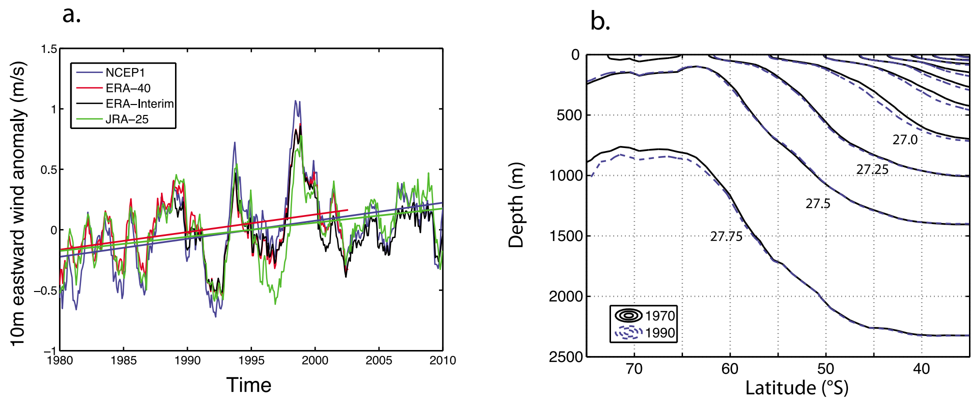

Figure 1. (a) Area-weighted mean eastward wind speed 10m above the sea level between 40°S and 50°S, based on several meteorological reanalyses [*Kalnay et al.*, 1996; *Uppala et al.*, 2005; *Onogi et al.*, 2007; *Dee and Uppala*, 2009]. Plotted values are anomalies from the climatological mean values. Thin lines are 1-year running mean, and thick lines are the linear regression. (b) Comparison of the zonally averaged ocean density structure between the 1970s and the 1990s based on the ECCO state estimates [*Köhl et al.*, 2007]. Contour levels are evenly spaced in potential density (kgm^{-3}).

stabilizing feedback provided by the eddy buoyancy flux, so allowing for a varying n permits a wide range of sensitivities as seen in eddy resolving simulations [*Hallberg and Gnanadesikan*, 2001, 2006; *Screen et al.*, 2009].

[4] Figure 2a shows the equilibrium pycnocline depth as a function of wind stress parameter τ_s for $n = 1, 2, 3$ and 4. An increase in τ_s deepens the pycnocline, while its sensitivity is slightly weakened with increasing nonlinearity. To evaluate the temporal adjustment of the pycnocline in response to an increase in wind stress, we linearize equation (1) about a reference equilibrium solution (D_{ref}). The timescale of pycnocline adjustment can then be written as

$$(timescale) = \frac{AD_{ref}}{T_{L,ref} + 2T_{N,ref} + nT_{eddy,ref}},$$

where $T_{L,ref}$, $T_{N,ref}$, and $T_{eddy,ref}$ are the values of the three mass fluxes for the reference state. Figure 2b shows the sensitivity of the adjustment timescale to τ_s and n. Our theory predicts that the adjustment of the pycnocline occurs over multi-decadal timescales regardless of the particular model parameters, which limits the variability of baroclinic transport of the ACC on decadal and shorter timescales.

3. Numerical Models

[5] To test the theoretical predictions made in section 2, we perform a suite of numerical experiments using MITgcm [*Marshall et al.*, 1997a, 1997b] configured as a sector model, which is an interhemispheric basin connected to a circumpolar channel. We purposefully choose to use simple geometry and surface forcing because it is easier to understand the behavior of such a system than that of a more complex global model. The qualitative results of such experiments can be fruitfully compared with more complex simulations. To investigate the importance of horizontal resolution, we perform experiments using coarse (1° × 1°) and eddy permitting (1/6° × 1/6°) variants of the model. The model setup and forcing is described in greater detail in the auxiliary material.[1]

[6] The equilibrium pycnocline depth of the coarse resolution (1° × 1°) sector model is shown in Figure 3a for a range of wind stress values. Equilibrium depth is determined by running the model for several centuries under constant wind stress forcing. The simulated equilibrium pycnocline depth increases with Southern Ocean wind stress, as predicted by the conceptual model (Figure 3a). Doubling the wind stress from 0.13 Nm^{-2} to 0.26 Nm^{-2} leads to a deepening of the equilibrium pycnocline depth by approximately 18% (70 m).

[7] To investigate the transient response of the density structure to a doubling of surface wind stress, we perform a numerical sensitivity experiment analogous to a step-response test from control theory. Using initial conditions from the spin-up model, we run two parallel simulations – a control run with a Southern Ocean wind stress parameter of 0.13 Nm^{-2}, and a perturbation run with a step-function doubling of wind stress to 0.26 Nm^{-2} (see Figure S1b in the auxiliary material). This change in forcing is admittedly unrealistic, but it gives us a clear view of the system's approach to equilibrium. Time series of the anomalous pycnocline depth (perturbed minus control values) during the first 400 years after the change in forcing are shown in Figure 3b (coarse resolution) and Figure 3c (eddy permitting resolution) in different sections of the sector model domain.

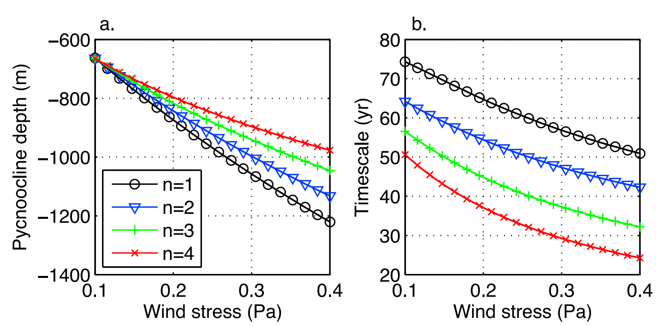

Figure 2. Theoretically estimated (a) equilibrium pycnocline depth and (b) e-folding time scale versus Southern Ocean wind stress for eddy parameterizations of different sensitivity (n = 1, 2, 3 and 4) and geometric parameters appropriate for the global ocean.

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL048145.

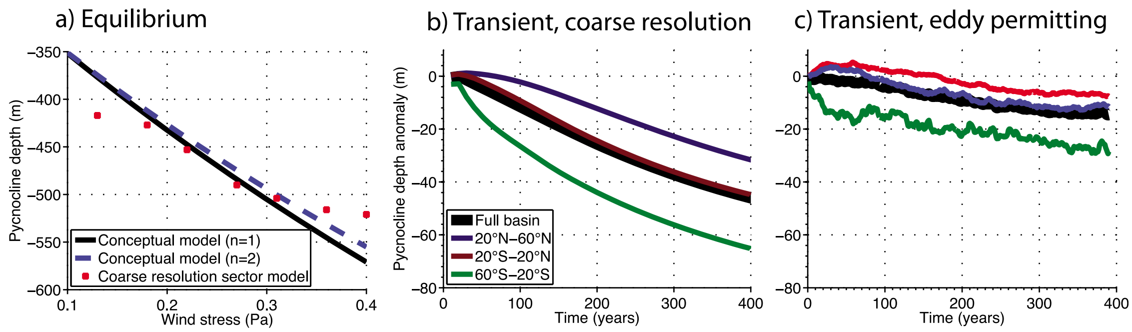

Figure 3. (a) A comparison of theoretical solutions for the equilibrium pycnocline depth with values from several coarse resolution sector model simulations with varying wind stress intensity. The basin area and zonal length scale in the conceptual model have been set to values appropriate for the sector model, and the isopycnal and diapycnal diffusivity constants are identical in both the conceptual and sector models. Also shown are two anomalous pycnocline depth (perturbed minus control) time series for the first 400 years of a (b) coarse resolution and (c) eddy permitting step response experiment. Averages are taken over different areas of the sector model domain.

During this period, the global pycnocline depth deepens by ~50 m in the coarse resolution run, while it deepens by only ~15 m in the eddy permitting run. The relatively weak response exhibited by the eddy permitting run is consistent with the idea that an eddying model should be less sensitive to changes in wind stress than a model where eddies are parameterized. Both resolutions are still adjusting to the sudden change in forcing 400 years after it is applied. The anomalous pycnocline depth averaged over the Southern Ocean alone is ~20 m deeper than the global average in the coarse resolution case (~14 m deeper in the eddy permitting configuration). Though a direct comparison of equilibration timescale is difficult, the conceptual model presented in section 2 predicts a much *shorter* *e*-folding timescale (20–25 years when using geometric parameters appropriate for the sector model) than the adjustment timescales seen in numerical integrations using the sector model (100+ years). The conceptual model may not be capable of capturing the longest, centennial-order response timescales associated with the adjustment of Antarctic Bottom Water circulation. The simple nature of the theoretical scalings might also explain the difference in timescale between the conceptual and numerical models. Despite this limitation, the conceptual model still makes useful predictions for multi-decadal adjustment.

[8] We examine the temporal evolution of the zonally averaged buoyancy structure in Figure 4. Note that the response of the density structure in the eddy permitting run to an increase in wind stress is remarkably similar to that of coarse resolution simulations, though the subtropical subsurface warming is less diffuse in the high-resolution case. A slight surface cooling occurs due to increased Ekman

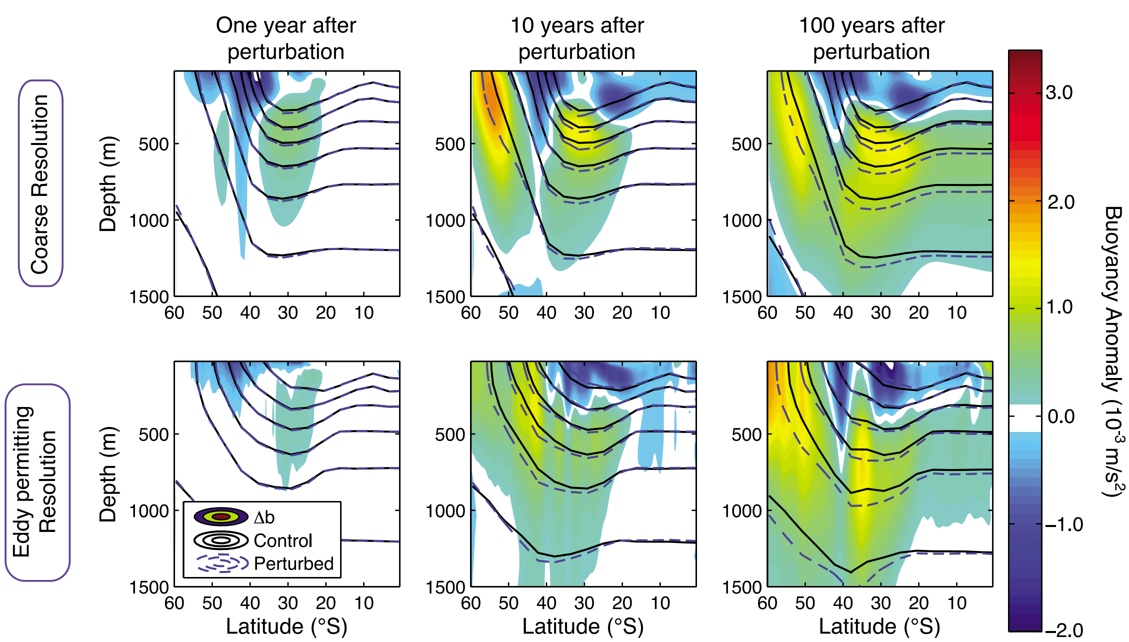

Figure 4. Control (solid lines) and perturbed (dashed lines) zonal-mean surfaces of constant buoyancy (left) 1 year, (middle) 10 years, and (right) 100 years after the wind stress is doubled. The color scheme shows the buoyancy difference Δb between the perturbed and control simulations in units of ms^{-2}. Snapshots from the (top) coarse resolution experiment and (bottom) eddy permitting simulation. Contours are shown every 2°C up to 16°C.

transport of cold water from high latitudes. A subsurface warming occurs in both the high latitudes and the subtropics, reflecting two distinct mechanisms. The subsurface warming at high latitudes is consistent with a southward shift of the circumpolar current and associated fronts, i.e. stronger winds increase the large-scale meandering of the circumpolar current, especially where the bottom topography is flat (see auxiliary material) [*Gille*, 2008]. This adjustment is relatively rapid, occurring on interannual to decadal timescales following an increase in westerly wind. The subsurface warming in the subtropics is likely due to enhanced wind-driven ventilation of the thermocline equatorward of the circumpolar current, which spins up the subtropical gyre circulation and deepens the subtropical thermocline by 5.2% over the first 100 years of integration in the coarse resolution simulation and 4.5% in the eddy permitting run [*Roemmich et al.*, 2007; *Cai et al.*, 2010]. The deepening initially occurs at relatively shallow depths below the surface mixed layer on interannual timescales and then progressively deepens to the depth of the main pycnocline over multi-decadal to centennial timescales. The long-term deepening of the main thermocline involves interactions between the Southern Ocean and northern basins over centennial timescales, which is consistent with theoretical predictions.

4. Concluding Remarks

[9] Our theoretical and numerical calculations suggest that the depth of the pycnocline and the slope of Southern Ocean isopycnal surfaces can potentially increase if strong westerly winds persist for multiple decades to centuries. However, due to the slow adjustment timescale of the density structure, it is difficult to detect these changes using existing observations from the past few decades. Our results are broadly consistent with those of *Allison* [2009], in which the adjustment timescale of the ACC is shown to be centennial using both a conceptual model and a reduced gravity model. In our primitive equation simulations, an increase in westerly wind stress intensifies eddy activity over interannual and longer timescales, but the enhanced eddy flux does not entirely cancel out the increased wind-driven Ekman flow. The small residual between wind and eddy-driven fluxes allows for communication between the Southern Ocean and the rest of the ocean through the global pycnocline on multi-decadal timescales.

[10] While we do get a robust result from our hierarchy of models, care must be taken when comparing our idealized calculations to observations. Observed changes may reflect processes that are not accounted for in our sensitivity experiments, such as complex basin geometry and bathymetry, changes in freshwater fluxes and sea ice distributions. With this in mind, we note that qualitatively similar subsurface heating trends have been observed in the synthesis of historic hydrographic and autonomous float data [*Roemmich et al.*, 2007; *Gille*, 2008]. We anticipate that in order to detect the long-term impact of climate variability on the Southern Ocean, continued monitoring of the subsurface density structure will be crucial. Simulations using more realistic basin geometry and climate forcing are also needed to project future changes in the density structure and to explore possible implications for the evolution of the Southern Ocean carbon dioxide sink.

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T. Ito and D. C. Jones, Department of Atmospheric Science, Colorado State University, 1371 Campus Delivery, Fort Collins, CO 80523-1371, USA.

N. S. Lovenduski, Department of Atmospheric and Oceanic Sciences and Institute of Arctic and Alpine Research, University of Colorado at Boulder, Campus Box 450, Boulder, CO 80309-0450, USA.