NOTES AND CORRESPONDENCE

Human-Induced Change in the Antarctic Circumpolar Current

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ABSTRACT

Global climate models indicate that the poleward shift of the Antarctic Circumpolar Current observed over recent decades may have been significantly human induced. The poleward shift, along with a significant increase in the transport of water around Antarctica, is predicted to continue into the future. To appreciate the magnitude of the poleward shift it is noted that by century's end the concomitant shrinking of the Southern Ocean is predicted to displace a volume of water close to that in the entire Arctic Ocean. A simple theory, balancing surface Ekman drift and ocean eddy mixing, explains these changes as the oceanic response to changing wind stress.

The Antarctic Circumpolar Current (ACC) encircles the Antarctic continent, flowing eastward through the southern portions of the Pacific, Atlantic, and Indian Oceans. It is the world's largest, and arguably most influential, ocean current (Nowlin and Klink 1986; Rintoul et al. 2001). While the speed of the ACC is not extraordinary (about 0.5 m s^{-1} at the surface), it's depth (about 4 km) and width (500–1000 km) results in a massive transport of about 140×10^6 m^3 of water per second, equivalent to about 150 times the flow of all the world's rivers combined. Because the Pacific, Atlantic, and Indian Ocean basins are almost entirely surrounded by land except at their southern boundaries, the ACC is the primary means by which water, heat, and other properties are exchanged between ocean basins. At the same time water found at abyssal depths in the ocean at low latitudes rises along the sloping density surfaces associated with the ACC and toward the surface in the Southern Ocean. Where these surfaces outcrop, intense air–sea ice interactions drive water mass transformations. In fact, the characteristics of more than 50% of the World Ocean volume reflects the air–sea ice interactions taking place in the Southern Ocean. In short, the ACC profoundly influences, and is influenced by, the regional and global climate.

The Southern Ocean is remote and historical data are relatively scarce. Even so, an examination of autonomous float observations collected during the 1990s and historical shipboard measurements suggests that the middepth (700–1100 m) Southern Ocean temperatures have risen since the 1950s (Gille 2002). This warming is faster than that of the global ocean and is concentrated in the ACC, where temperature rates of change are comparable with Southern Ocean atmospheric temperature increases (Gille 2002). A comparison of the data with earlier hydrographic data indicates that the warming is associated with a southward migration of the ACC since the 1950s of about 50 km in the Pacific (Swift 1995), as well as the Atlantic and Indian Oceans (Gille 2002). A more recent analysis of 32 yr (1966–98) of subsurface layer (200–900 m) temperature observations in the Indian sector of the Southern Ocean similarly show a warming trend concentrated in the ACC, indicative of a southward shift of the ACC of about 50 km (Aoki et al. 2003). These changes may be associated with long-term changes in the overlying atmospheric circulation as seen in National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996; Thompson et al. 2000; Fyfe 2003), as well as in

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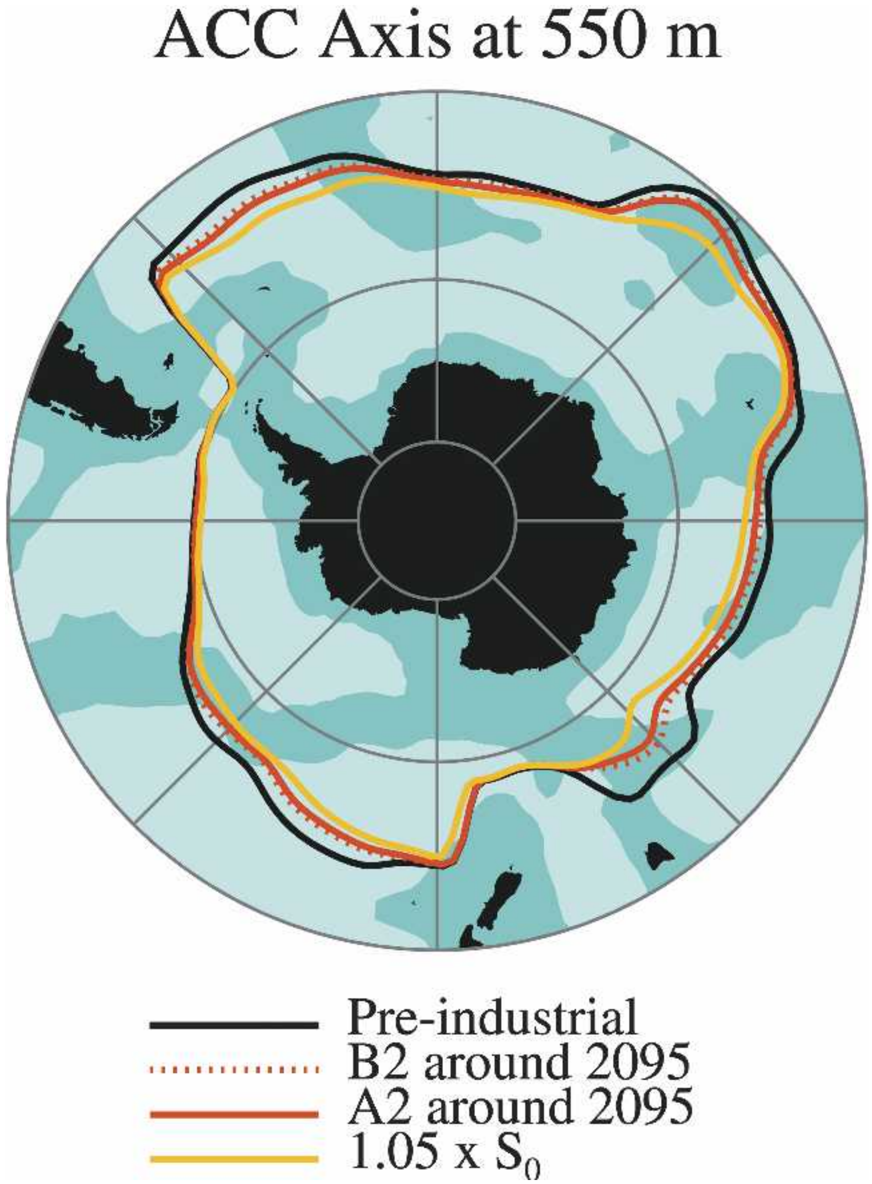

FIG. 1. Ensemble- and decadal-averaged position of the ACC at 550-m depth. The yellow curve corresponds to a simulation wherein the present-day solar constant, S_0, was abruptly increased by 5%. The light (dark) blue shading indicates topography below (above) 3750-m depth from the CCCma model.

European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data and station data (Marshall 2003). From the global ocean modeling standpoint it is known that a change in the position of the surface wind stress over the Southern Ocean can affect a change in the position of the ACC (Hall and Visbeck 2003; Oke and England 2004).

Could the change in the position of the world's most powerful and influential ocean current be human induced? We explore this question using an updated version of the Canadian Centre for Climate Modeling and Analysis (CCCma) global climate model (GCM; Flato et al. 2000). The atmospheric component of the updated system is a spectral model with an equivalent surface grid resolution of 3.75° in longitude and latitude and 31 vertical levels. The oceanic component is a grid-point model with a resolution of roughly 1.85° in longitude and latitude and 29 vertical levels. The effects of unresolved oceanic eddies are parameterized using an isopycnal mixing scheme. Annual-mean heat and moisture flux adjustments are applied. Transient climate change simulations were performed using observed at-

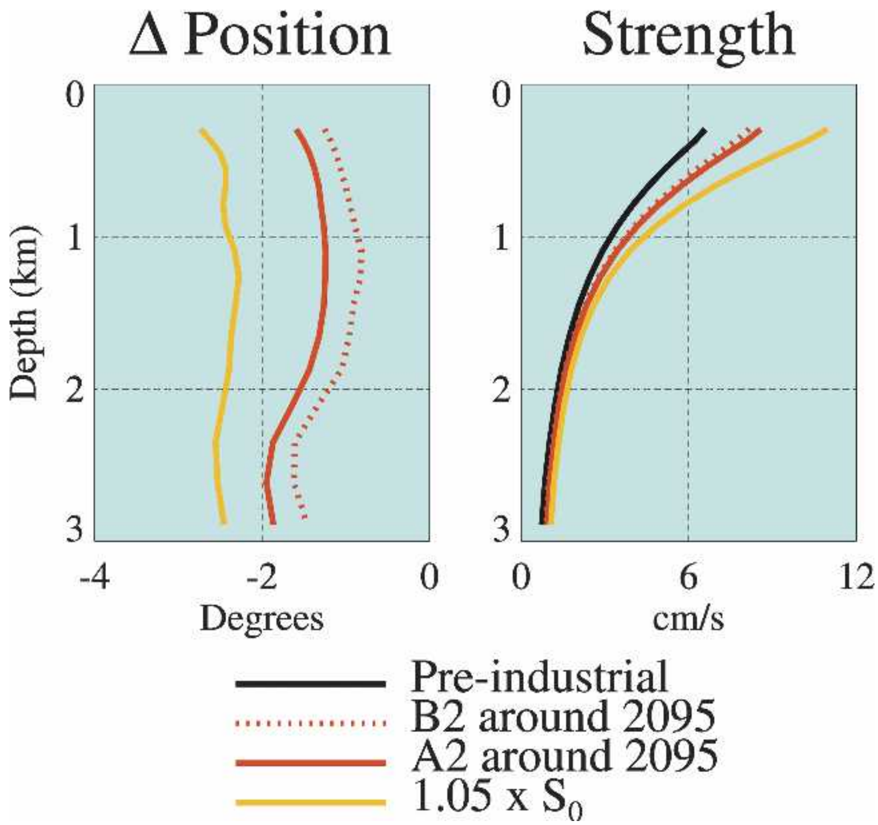

FIG. 2. Ensemble-, longitude-, and decadal-averaged (right) strength (cm s^{-1}) and (left) position (°) of the ACC. The yellow curve corresponds to a simulation wherein the present-day solar constant, S_0, was abruptly increased by 5%.

mospheric greenhouse gas and observationally based estimates of the radiative forcing impact of changes in sulphate aerosols to the year 1990 and then following the Intergovernmental Panel on Climate Change (IPCC) A2 and B2 emissions scenarios to the year 2100 (Nakićenović et al. 2000). The A2 and B2 emissions scenarios cover a range of the main demographic, economic, and technological driving forces of future greenhouse gas and aerosol emissions. We note that these scenarios do not include changes in stratospheric ozone that have recently been linked to changes in the observed Southern Hemisphere surface climate (Thompson and Solomon 2002).

The model shows a mean poleward shift of the ACC of about 0.4° ≈ 45 km since preindustrial times, with about half of that occurring since the 1950s (Table 1). Take note that the changes seen in Table 1, which are based on the ensemble average of three independent transient climate change simulations, rise significantly above the natural fluctuations obtained from a control preindustrial simulation (i.e., are statistically significant at the 99% level determined using a standard difference of means test). Also note that even though the shift is smaller than the spatial resolution of the model it is still resolved given the relatively large scale of variation of the current itself (i.e., 500–1000 km). We conclude that perhaps as much as half the observed shift in the ACC since the 1950s may be due to human activity. This

TABLE 1. Change in the ACC parameters from preindustrial times. The changes are for the decade centered on the indicated year and are from an ensemble of three independent transient simulations. The ACC parameters were derived from the ensemble- and decadal-averaged Southern Ocean zonal current after fitting at each longitude and depth to $S \exp[(\phi - P)/2W]^2$, where ϕ is latitude and S, P, and W are the strength (cm s^{-1}), position (°), and width (°), respectively. The width was suitably adjusted to reflect the width of the current in the cross-stream direction. The parameter differences are longitude and depth averaged. All differences are significant at the 99% confidence level as determined using a standard difference of means test.

			2095	
	1955	1995	B2	A2
ΔPosition (°)	−0.2	−0.4	−1.2	−1.5
ΔStrength (cm s^{-1})	+0.2	+0.2	+0.6	+0.8
ΔWidth (°)	−0.0	−0.0	−0.0	−0.1

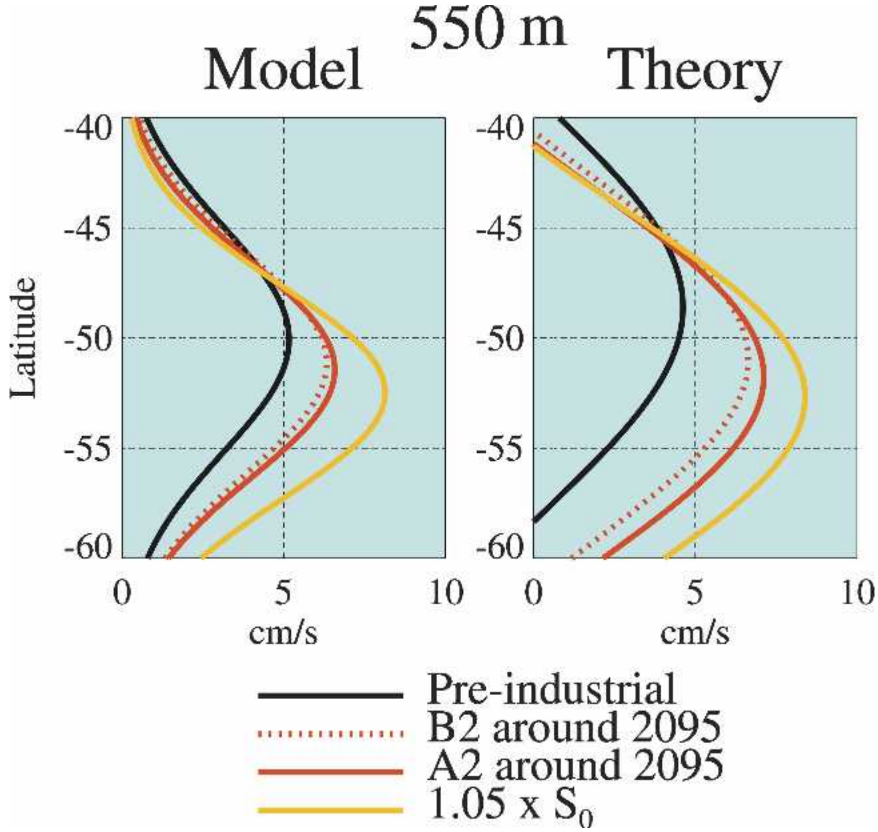

FIG. 3. Ensemble- and decadal-averaged ACC at 550-m depth (fitted as described in Table 1). The yellow curve corresponds to a simulation wherein the present-day solar constant, S_0, was abruptly increased by 5%.

attribution statement is subject to at least two important caveats: 1) there is substantial uncertainty in the quantitative estimate of the observed shift of the ACC and 2) the result is dependent on the fidelity of the single model simulation—an issue we partially address later in this note.

In the A2 and B2 scenarios the GCM predicts that human activity will cause the ACC to continue shifting poleward into the future (Table 1). The shift occurs over all depths and longitudes, and is largest where the current is least constrained by bathymetry (Figs. 1 and 2). By century's end the scenario-averaged mean poleward shift is about 1.4° (relative to preindustrial times, Table 1). While this shift may not appear extraordinary we note that because of the great depth of the ACC it displaces about 16×10^6 km^3 of water from the Southern Ocean, which is close to the 19×10^6 km^3 of water estimated to reside in the entire Arctic Ocean (Jakobsson 2002). The GCM also predicts a substantial speedup of the ACC (Table 1 and Fig. 2). By century's end the latter translates into a scenario-averaged increase in the volume transport of water through the Drake Passage of about 16 Sverdrups (1 Sv $\equiv 10^6$ m^3 s^{-1}), which is comparable with the 15 $\pm$ 2 Sv associated with the flow of North Atlantic Deep Water (Ganachaud and Wunsch 2000). Take note that these references to the global ocean circulation are for comparisons sake alone—the actual global impacts of such ACC changes on the global climate system remain to be assessed. Finally, Figs. 1 and 2 also show that these ACC changes are not unique to these scenarios but are also seen when the solar constant S_0 is increased.

A simple theory links the predicted changes in the ACC with changes in the zonal wind stress. The steady zonal momentum balance is approximately $-\rho_o f v = -p_x + \tau_z$, where v is the meridional current, p is pressure, and τ is Reynolds stress. Integrating from the surface (where $\tau = \tau^s$) to an arbitrary isopycnal at depth $z = -h$ in the interior (i.e., below the Ekman layer and above the shallowest topography, where $\tau \approx 0$) and zonally averaging yields $-\rho_o f \overline{V_{\text{upper}}} = -\overline{p'_x h'} + \overline{\tau^s}$. Here the overbars and primes denote zonal means and their deviations, respectively; V_{upper} is the meridional volume flux between the surface and the given isopycnal, and

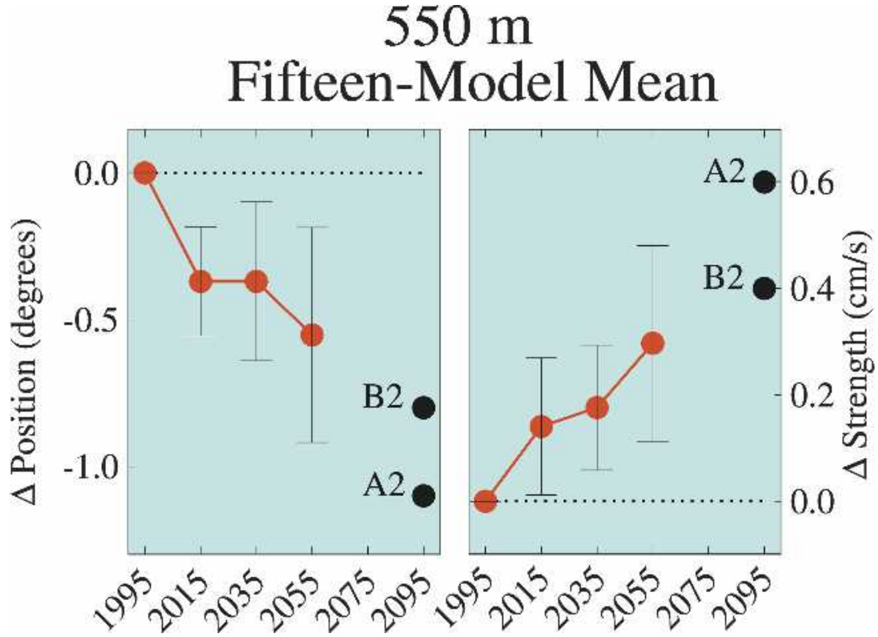

FIG. 4. Ensemble-, longitude-, and period-averaged ACC parameters (relative to present day) at 550-m depth. Red indicates that the ensemble average is over output from 15 modern GCMs run with the concentration of effective greenhouse gas increasing at a rate of 1% yr^{-1}. The ACC parameters were derived using the zonal wind stress available from the models. The error bars reflect the intramodel standard deviation scaled such that statistical significance at the 95% level is implied when the error bars exclude the origin. Black indicate that the ensemble average is over three independent realizations of the CCCma GCM under the A2 and B2 scenarios.

$\overline{p'_x h'}$ is interfacial form stress. Returning to the first equation and integrating from the bottom at $z = -H$ (where $\tau \approx 0$) to the given isopycnal yields $-\rho_o f V_{\text{lower}} = \overline{p'_x h'} - \overline{H p^b_x}$. Here V_{lower} is the meridional volume flux in this lower layer, $\overline{H p^b_x}$ is topographic form stress, and p^b is bottom pressure. In the special case where the eddies transfer the surface stress undiminished to the bottom where it is taken up by topographic form stress then $\overline{\tau^s} = \overline{p'_x h'} = \overline{H p^b_x}$ implying no net residual circulation (i.e., $V_{\text{upper}} = V_{\text{lower}} = 0$). Substituting $h' = \rho'/\overline{\rho}_z$ and $p'_x = \rho_o f v'$ in this equation yields $\overline{\tau^s}/(\rho_o f) = \overline{\rho' v'}/\overline{\rho}_z$, which represents a balance between northward Ekman transport and southward eddy-induced transport. Allowing for nonzero net residual circulation and parameterizing the effect of the eddies as $\overline{\rho' v'}/\overline{\rho}_z = K s_\rho$, where s_ρ is the zonal-mean meridional isopycnal slope and $K = 10^3$ m^2 s^{-1} we obtain $\overline{u}_z = -(g/\rho_o f)\overline{\rho}_z s_\rho = -(g/\rho_o f K)\overline{\rho}_z[\overline{\tau^s}/(\rho_o f) - \Psi^r]$. Here $\overline{u}$ is the zonal mean baroclinic velocity and Ψ^r is the residual streamfunction.

To isolate the effects of changing $\overline{\tau^s}$ we use $\overline{\tau^s}$ from each of the climate change simulations and representative values of $\overline{\rho}_z$ and Ψ^r obtained from the preindustrial simulation. The theory shows that the accelerated and poleward-shifted ACC (Fig. 3) is effectively caused by an accelerated and poleward-shifted zonal wind stress. The robustness of these single model results is indicated when applying the simple theory to the zonal wind stress available from 15 other modern GCMs (Meehl et al. 2000) forced with increasing greenhouse gases (Fig. 4). There is clear consensus among these GCMs for a poleward-shifted and strengthened ACC, however we note that a few models do show negligible, or small oppositely signed, changes. Take note that these results are, of course, dependent on the validity of the simple theoretical model. Regarding previous modeling work we note that these changes are consistent with the simulated upward trend in the Southern Annular Mode (SAM) reported, for example, in Fyfe et al. (1999), Kushner et al. (2001), and Cai et al. (2003). Also relevant is the study of Cai and Gordon (1998) who report a weakening of ACC transport with increasing CO_2 in a version of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) GCM. However, Bi et al. (2002) show that in a more recent version of the CSIRO GCM the ACC transport increases with increasing CO_2 as here.

In summary, transient climate change simulations suggest that about half of the observed poleward shift of the ACC seen since the 1950s is the consequence of human activity. The full extent of the observed changes likely results from a combination of natural climate processes and human influences (possibly also including decreases in stratospheric ozone; Thompson and Solomon 2002; Gillett and Thompson 2003; Karoly 2003). In the future the ACC is predicted to continue to shift poleward, as well as to accelerate. A simple theory, balancing surface Ekman drift and ocean eddy mixing, explains these changes as the oceanic response to changing surface wind stress. The potential impacts of these changes on the global climate system are currently under investigation.

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