The effect of ocean mixing parametrisation on the enhanced CO_2 response of the Southern Hemisphere midlatitude jet

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[1] The use of a more physically based parametrisation scheme for sub-grid scale ocean mixing produces a more spatially uniform surface warming in the Southern Hemisphere in transient global warming simulations of the CCCma climate model than when an older scheme is used. Here we examine the effect of this different warming pattern on the tropospheric circulation response, by comparing simulations of two versions of the model implementing these two mixing parametrisations. It is found that use of either scheme produces a southward shift of the midlatitude jet, but that this shift is considerably smaller when the new parametrisation is implemented. These results suggest that the magnitude of the Southern Annular Mode-like response noted in some global warming simulations may be sensitive to the representation of ocean processes. **Citation:** Stone, D. A., and J. C. Fyfe (2005), The effect of ocean mixing parametrisation on the enhanced CO_2 response of the Southern Hemisphere midlatitude jet, *Geophys. Res. Lett.*, *32*, L06811, doi:10.1029/2004GL022007.

1. Introduction

[2] Many current climate models typically predict a hemispheric asymmetry in the surface temperature response to progressively rising (as against equilibrium) greenhouse gas concentrations [*Cubasch et al.*, 2001]. In particular, while warming tends to increase monotonically with latitude in the Northern Hemisphere, it reaches a minimum in the Southern Hemisphere around 60°S. This difference is ascribed to deep vertical mixing in the Antarctic Ocean which draws heat down from the surface. However, studies comparing the performance of these models against observational measurements suggest that the horizontal/vertical diffusion (HV) parametrisation of sub-grid scale ocean mixing used by many of these models results in too much heat uptake by the deep ocean at these latitudes [*England*, 1995; *Robitaille and Weaver*, 1995; *McDougall et al.*, 1996]. This raises the possibility that the hemispheric asymmetry of the response is overestimated. Indeed, recent models using the more physically based isopycnal parametrisation of *Gent and McWilliams* [1990] (GM) produce a larger warming over the Antarctic Ocean, resulting in a more hemispherically symmetric pattern [*Wiebe and Weaver*, 1999; *Flato and Boer*, 2001].

[3] In the atmosphere, coupled atmosphere-ocean climate models predict a zonally symmetric shift of mass from high to midlatitudes, reflecting a poleward shift of the midlatitude jet, as the dominant response in the Southern Hemisphere troposphere to enhanced greenhouse warming [*Fyfe et al.*, 1999; *Kushner et al.*, 2001; *Stone et al.*, 2001]. This pattern of response resembles the observed zonally symmetric change. However, *Cai et al.* [2003] find that this response is influenced by the state of the surface ocean, reflecting the tight coupling between the troposphere and surface ocean. Thus it stands to reason that the different ocean mixing schemes may result in important differences in the tropospheric response. The models used in these studies (other than that of *Cai et al.* [2003]) implement a HV scheme in the ocean, and so the robustness of the atmospheric response in relation to the ocean mixing parametrisation remains unclear. Considering this, in this paper we examine the consequences of using different ocean mixing schemes on the Southern Hemisphere tropospheric response to transient anthropogenic forcing in climate model simulations.

2. Model

[4] We use simulations from two versions of the Canadian Centre for Climate Modelling and Analysis (CCCma) coupled model [*Boer et al.*, 2000; *Flato and Boer*, 2001]. Each version has an ensemble of three simulations forced with observed and predicted (IS92a scenario) transient increases in greenhouse gases and sulphate aerosols over the 1900–2100 period. These model versions use an identical atmospheric component, consisting of a spectral model with an equivalent horizontal resolution of 3.75° and 10 unequally spaced vertical levels. The oceanic component is a grid point model of 1.875° horizontal resolution with 29 unequally spaced vertical levels. In the first version, CGCM1, sub-grid scale ocean mixing is parametrised with a HV scheme, while the second version, CGCM2, uses the GM parametrisation. For clarity, we refer to these two model versions as CGCMHV and CGCMGM for the remainder of the paper.

[5] Figure 1 shows the change in annual mean and zonal mean surface temperature in the simulations of these two model versions. The most striking feature in the CGCMHV simulations is the much smaller surface warming occurring over the Antarctic Ocean (∼60°S) than elsewhere. Con-

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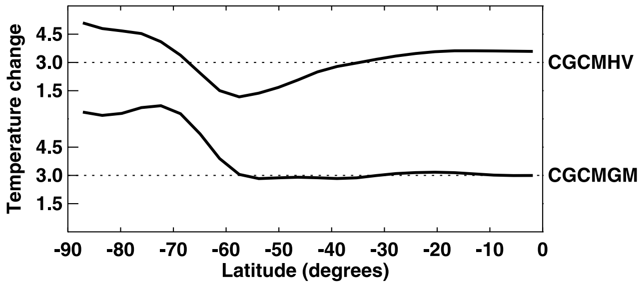

Figure 1. 2050–2099 change from the respective pre-industrial control simulation in annual and zonal mean surface temperature in the ensembles of CGCMHV and CGCMGM global warming simulations. Values have been lightly smoothed and are plotted in °C.

versely, in the CGCMGM simulations there is a much more even warming in the middle and low latitudes, reflecting a much larger warming over the Antarctic Ocean.

[6] The two model versions also use different sea ice schemes and different flux adjustments, although these do not appear to seriously affect the differences in warming response. The use of different sea ice schemes does not substantially impact the long term behaviour of the ice, inasmuch as the climatology in control simulations and the retreat in global warming simulations are similar between model versions (G. Flato, personal communication). Concerning the flux adjustments, these are considerably smaller in CGCMGM than in CGCMHV over the Antarctic Ocean. The need for different flux adjustments must ultimately be due to differences between the physics of the model versions themselves, and the large contrast in ocean heat uptake in this area between the two model versions point to the differences in vertical mixing in the ocean as being ultimately responsible [*Flato and Boer*, 2001]. Thus the indication is that the difference in the Antarctic Ocean surface temperature response between the two model versions ultimately results, either directly or indirectly, from the difference in ocean mixing schemes. While these two model versions are not designed specifically for a sensitivity study, they can be used in a diagnosis of the effect of ocean mixing parametrisation in this area.

3. Results

[7] The annual zonal mean zonal wind at the 200 hPa level in the control simulation of CGCMHV is shown in Figure 2 (solid red line), with the midlatitude jet corresponding to the maximum around 50°S. The 2050–2099 average profile from the ensemble of CGCMHV global warming simulations is also shown (dotted red line) along with the difference from the control simulation (dashed red line). The most important aspect of this change is a poleward shift and acceleration of the jet of about 2°lat and 2 $m \cdot s^{-1}$. This zonally symmetric change dominates the overall response of the wind at the 200 hPa level. This is reflected in the high spatial correlation of 0.82 between the response pattern of the wind vector at each grid cell in the region south of 20°S and the coincident zonal mean zonal wind response. The response is also fairly uniform with height in the troposphere (not shown), as noted with another model [*Kushner et al.*, 2001].

[8] The pattern of change in the 200 hPa wind in the ensemble of CGCMGM global warming simulations (not shown) is quite similar to the pattern in the CGCMHV simulations, with the correlation in the vector wind at each grid cell south of 20° between the two versions being 0.92. This similarity is reflected in the zonal mean zonal wind responses shown in Figure 2 (dashed lines). However, the changes in the CGCMGM ensemble are considerably smaller, corresponding to a poleward shift and acceleration of the jet only about 60% as large.

[9] Following thermal wind balance, the acceleration of the zonal wind at 200 hPa should reflect an increase in the meridional temperature gradient below the 200 hPa level. Figure 3a shows the change in the annual mean and zonal mean meridional temperature gradient at various pressure levels in the troposphere occurring in the CGCMHV global warming simulations. As expected a local maximum in the change in the temperature gradient occurs at 50–55°S. This maximum extends quite uniformly with height down to the northern border of the Antarctic Ocean at the surface.

[10] Figure 3b shows the same field but from the CGCMGM global warming simulations. Once again, a local maximum in the change in the meridional temperature gradient occurs at 50–55°S, but with this version the change is much smaller. Still, this maximum also extends down to the northern border of the Antarctic Ocean at the surface. Because the differences in the Antarctic Ocean surface temperature response between the two versions presumably arise from the use of different ocean mixing schemes, the implementation of these different schemes seems to have substantially altered the global warming response of the midlatitude jet by changing the temperature profile throughout the troposphere. This conclusion is supported by the results of *Cai et al.* [2003], who find that

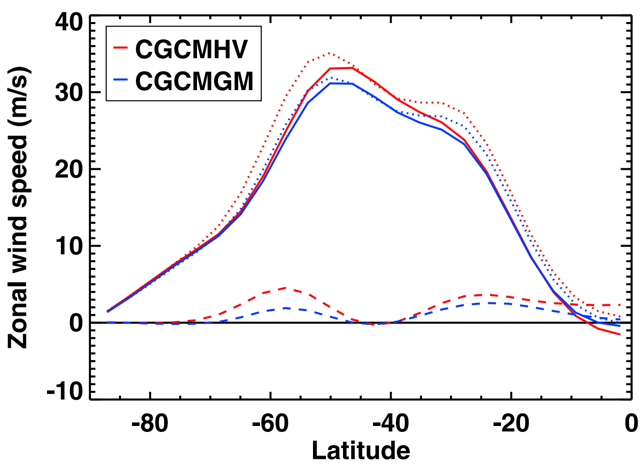

Figure 2. Annual zonal mean 200 hPa zonal wind from simulations of the CGCMHV and CGCMGM models. Solid lines: the average from the pre-industrial control simulations. Dotted lines: the average from years 2050–2099 in the global warming simulations. Dashed lines: the change from the control to the 2050–2099 state.

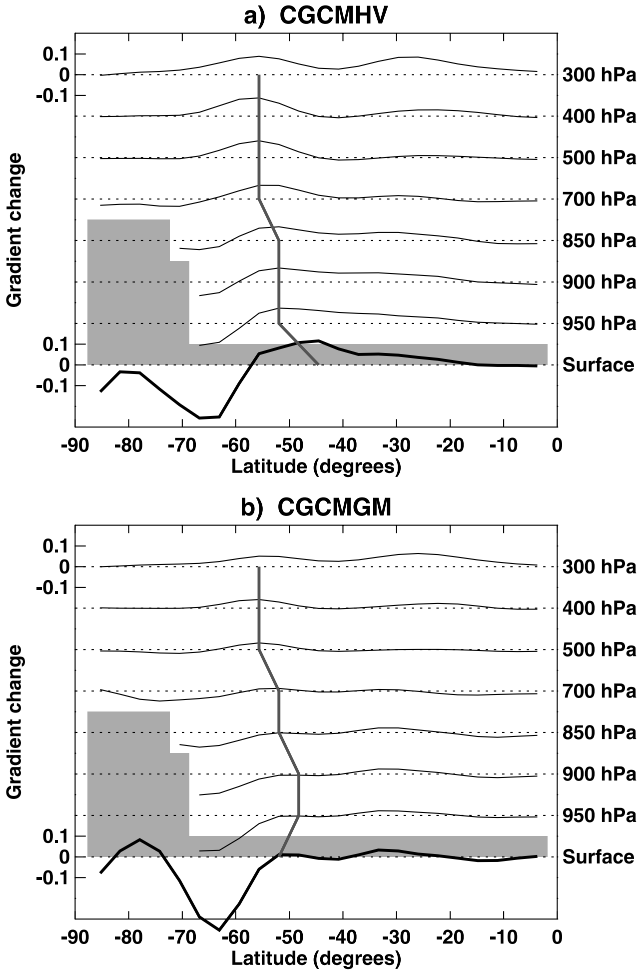

Figure 3. 2050–2099 change from the respective control simulation in the annual and zonal mean meridional temperature gradient in ensembles of a) CGCMHV and b) CGCMGM global warming simulations. Values have been lightly smoothed and are plotted in °C per degree of latitude, with zero change at each pressure level denoted by the dotted lines. The thick black lines show the meridional temperature gradient at the surface. The grey shading represents the zonal mean topography. The dark grey line denotes the location of the local maximum in the 40° to 75° latitude range at each level.

the jet response is linked to surface temperatures over the Antarctic Ocean in simulations of another model.

4. Summary and Discussion

[11] Modelling studies indicate that use of the GM parametrisation of sub-grid scale ocean mixing improves the correspondence of ocean properties between models and observations, both of the climatological mean [*England*, 1995; *Robitaille and Weaver*, 1995; *McDougall et al.*, 1996] and of the long term trend [*Wiebe and Weaver*, 1999; *Flato and Boer*, 2001]. Here we have examined the effect of these changes on CO_2 forced trends in the tropospheric circulation and have found that the choice of ocean mixing parametrisation can have a substantial consequence by modifying the meridional temperature profile. In particular, implementation of the GM scheme produces a much smaller poleward shift of the midlatitude jet than occurs when a more common HV scheme is used in the same model.

[12] Recent Southern Hemisphere climate change also consists of a zonally symmetric poleward shift of the midlatitude jet, reflected in a transfer of mass from high to midlatitudes [*Thompson and Solomon*, 2002]. This shift resembles the positive phase of the Southern Annular Mode (SAM) of tropospheric variability and so the shift is often interpreted through SAM behaviour. Figure 4 shows the first principal component of the annual mean and zonal mean sea level pressure south of 20°S in the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP-NCAR) reanalysis during the years 1979–2003 [*Kistler et al.*, 2001]. This principal component is a traditional measure of the SAM [e.g., *Marshall*, 2003]. The index tends toward positive values in the latter part of the record, a tendency that also occurs in the global warming simulations of both model versions (Figure 4).

[13] While increased greenhouse gas concentrations could contribute to the observed changes, there is evidence that stratospheric ozone depletion may have an important influence as well. It is possible that changes in the stratospheric polar vortex due to ozone depletion may influence the troposphere and result in a poleward shift of the midlatitude jet at times when the two circulations are coupled [*Sexton*, 2001; *Thompson and Solomon*, 2002; *Gillett et al.*, 2003; *Polvani and Kushner*, 2002]. Indeed, *Gillett and Thompson* [2003] find that an atmospheric climate model forced with historic changes in stratospheric ozone also produces a tropospheric response pattern similar

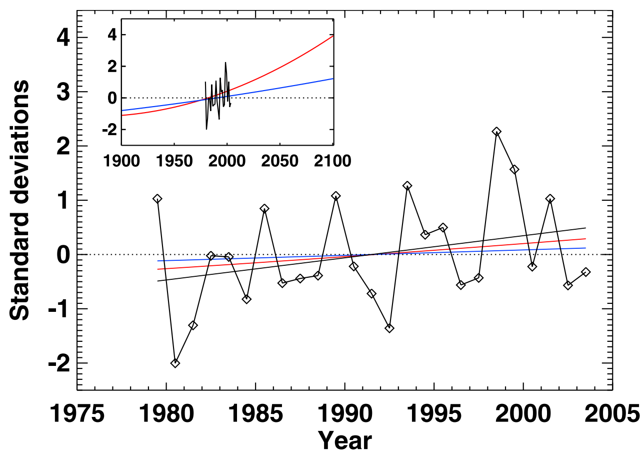

Figure 4. Variations in the first principal component of 1979–2003 annual and zonal mean sea level pressure south of 20°S. Black diamonds: NCEP reanalysis. Black line: the linear fit to the NCEP reanalysis data. Red and blue lines: the linear fits to the CGCMHV and CGCMGM global warming simulations respectively. The inset shows an extension to the 1900–2100 period. Red and blue: the second order polynomial fit to the first principal component of the CGCMHV and CGCMGM global warming simulations respectively. The model time series are extended to the 1900–2100 interval by regressing onto the spatial pattern corresponding to the first principal component derived for the 1979–2003 period.

to that observed, although *Shindell and Schmidt* [2004] find better agreement when both ozone and greenhouse gas forcings are included.

[14] This raises the question of whether enhanced greenhouse warming or ozone depletion is primarily responsible for the observed shift of the jet. *Marshall* [2003] finds evidence that the NCEP reanalysis overestimates the trend in the SAM index (used in Figure 4) by about a factor of two. As can be seen from Figure 4, this suggests that the actual trend in the SAM index is close to that produced in the CGCMHV simulations. However if the inclusion of stratospheric ozone depletion in the simulations increases the simulated trend substantially then CGCMHV would overestimate the real world trend. Use of CGCMGM, which incorporates more physically based ocean mixing processes, would then bring the trend into closer agreement with the real world trend. Some other models produce a smaller trend in the SAM index under enhanced greenhouse forcing [*Kushner et al.*, 2001; *Stone et al.*, 2001] than CGCMGM (although reasons for the differences are not known) and thus could improve on the agreement with the real world. In fact, when using a different coupled model including the GM parametrisation, *Marshall et al.* [2004] find good agreement with observations when both natural and anthropogenic (including greenhouse gases and ozone) forcings are included. This agreement is not as strong when the natural forcings are omitted, however, suggesting that changes in natural forcings may also be important. At this stage, however, the large variability of the SAM index and the relatively short period of observations implies that it is difficult to put tight constraints on these possibilities.

[15] The analysis indicates that in the Southern Hemisphere the response of tropospheric circulation to enhanced greenhouse forcing in a coupled climate model is sensitive to the response of the surface ocean, and in particular to the method used to parametrise ocean mixing. Thus the change in Southern Hemisphere atmospheric circulation found in previous modelling studies of global warming [*Fyfe et al.*, 1999; *Kushner et al.*, 2001; *Stone et al.*, 2001] may be overestimated, since the models involved all use simple schemes for representing the sub-grid scale ocean mixing which likely overestimate heat uptake by the Antarctic Ocean. Considering that stratospheric ozone depletion appears to induce a similar response pattern [*Gillett and Thompson*, 2003], it would seem that meridional shifts in the midlatitude jet are a preferred response in the Southern Hemisphere to a variety of external forcings, and may not be robust as a "fingerprint" indicator that can distinguish, for example, between the effects of ozone depletion and enhanced greenhouse warming.

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