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Phase speed spectra and the recent poleward shift of Southern Hemisphere surface westerlies

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[1] The poleward shift of the Southern Hemisphere surface westerlies in recent decades is examined in reanalysis data and in the output of coupled atmosphere-ocean and uncoupled atmospheric models. The space-time spectra of the eddy momentum fluxes in the upper troposphere reveal a trend that marks an increase in the eastward phase speed of the tropospheric eddies accompanied by a poleward displacement of the region of wave breaking in the subtropics. A dynamical mechanism is suggested that may help explain the connections among the lower stratospheric wind anomalies, the increased eastward propagation of tropospheric eddies and the poleward shift of the tropospheric circulation. **Citation:** Chen, G., and I. M. Held (2007), Phase speed spectra and the recent poleward shift of Southern Hemisphere surface westerlies, *Geophys. Res. Lett.*, *34*, L21805, doi:10.1029/2007GL031200.

1. Introduction

[2] The Southern Hemisphere surface westerlies and tropospheric jet have been observed to shift poleward in recent decades. This poleward shift is generally described as a trend of the Southern Hemisphere Annular Mode (SAM) towards its positive phase [e.g., *Thompson and Solomon*, 2002]. This trend, originally detected in reanalyses, has been confirmed in radiosonde data [*Marshall*, 2003] and satellite observations [*Fu et al.*, 2006].

[3] A positive SAM trend is also seen in model simulations of the late 20th century and projections of future climate change. Models predict a consistent positive trend due to increases in greenhouse gas concentrations [e.g., *Fyfe et al.*, 1999; *Kushner et al.*, 2001], as well as to decreases in stratospheric ozone concentrations [e.g., *Kindem and Christiansen*, 2001; *Gillett and Thompson*, 2003]. Recent studies suggest that stratospheric ozone depletion may have been a greater contributor to the observed SAM trend in the late 20th century, but that the response to the greenhouse gas increases is large enough that it will likely sustain the positive trend throughout the 21st century despite the predicted recovery of stratospheric ozone concentrations [e.g., *Arblaster and Meehl*, 2006; *Miller et al.*, 2006].

[4] Evidence has also been found that large anomalies in the strength of the stratospheric polar jet are followed by persistent anomalies in the tropospheric annular mode [e.g., *Thompson et al.*, 2005]. Several idealized models have also shown a robust poleward shift of surface westerlies in direct response to the increased stratospheric winds [e.g., *Polvani and Kushner*, 2002], leaving little doubt as to the plausibility of a causal linkage pointing from the stratosphere to the troposphere.

[5] "Downward control" theory, in which a change in the stratospheric zonal momentum balance can result in a tropospheric response through residual meridional circulations, can explain a small change in surface winds [*Haynes et al.*, 1991], but it cannot explain the observed shift of the tropospheric eddy momentum fluxes that accompanies the lower stratospheric wind anomalies [*Limpasuvan et al.*, 2004] and the modelled trends in the latitude of surface westerlies [e.g., *Polvani and Kushner*, 2002]. From the perspective of angular momentum balance, a substantial change in surface torques associated with the poleward displacement of surface westerlies can only be plausibly maintained by a corresponding poleward displacement of the eddy momentum fluxes in the troposphere.

[6] We consider the possibility that the stratospheric winds affect tropospheric eddy momentum fluxes by modifying the eastward propagation of tropospheric eddies. In a baroclinic eddy life cycle study, *Wittman et al.* [2007] finds that increasing the lower stratospheric wind accelerates the phase speeds of tropospheric eddies in the linear stage, and generates a more poleward displacement of the tropospheric jet in the nonlinear stage. *Chen et al.* [2007] has argued that the poleward shift in the surface westerlies seen when one decreases the strength of surface friction in a model is the consequence of an increase in eddy phase speed. *Chen et al.* [2007] also describes a stochastically stirred shallow water model of the upper troposphere, in which the eddy momentum flux pattern shifts poleward as the phase speed of eddies is increased. These results suggest a unifying mechanism, helping to explain the response of the circulation to stratospheric ozone reduction and to global warming, and more generally, the influence of the stratosphere on tropospheric annular mode-like anomalies: an increase in lower stratospheric/upper tropospheric zonal winds increases the eastward phase speed of tropospheric eddies, and this increase in phase speed, by displacing the region of subtropical wave breaking polewards, shifts the eddy momentum fluxes polewards, as well as the surface westerlies that are maintained by these momentum fluxes.

[7] A necessary condition for this picture to be relevant to the observed shift in the Southern Hemisphere circulation is that there be a trend towards increased eastward eddy phase speeds. In this paper, we study trends in reanalysis data in the upper tropospheric eddy momentum flux spectra, and the corresponding spectra in coupled and atmosphere-only climate models. After first presenting the spectra in the reanalysis data and then in the GCMs, we return briefly to

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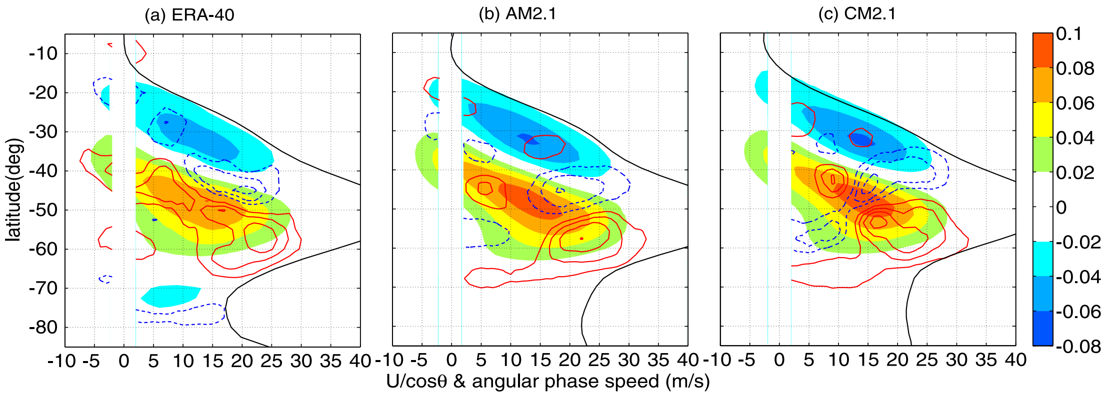

Figure 1. The 40-year (shading) climatological means and (contours) trends of the eddy momentum flux convergence at 250 hPa in DJFM as a function of latitude and angular phase speed in (a) ERA-40, (b) AM2.1, and (c) CM2.1. The contour intervals are 0.01 m/s/day/(40 year) for the trend in ERA-40, and 0.004 m/s/day/(40 year) for the trends in AM2.1 and CM2.1. The black solid line shows the time and zonally averaged zonal wind at 250hPa divided by cos θ for comparison (the values over 40 m/s are not shown). The red (blue) color denotes the eddy momentum flux convergence (divergence).

some of the dynamical issues raised by these results, and, in particular, to the difficult question of whether the observed change in phase speed is a cause of the poleward shift or simply a response to this shift.

2. Reanalysis Data

[8] We first look at the trends in the eddy spectra in ERA-40, the latest reanalysis from the European Centre for Medium-Range Weather Forecasts [*Uppala et al.*, 2005], which has been described by *Marshall* [2003] as providing a reliable representation of the Southern Hemisphere high latitude atmospheric circulation variability. We choose to study a 40-year period from 1961–2000 and focus on the Southern Hemisphere summer (DJFM) when the SAM trend is greatest [*Thompson and Solomon*, 2002; *Marshall*, 2003]. We first compute the space-time co-spectra of (u, v) for the 120-day DJFM time series in each year, using daily data tapered by a Hanning window. Following *Randel and Held* [1991], we transform the (frequency, wavenumber) spectra into (angular phase speed, wavenumber) spectra and then sum over wavenumbers, resulting in plots of these spectra as a function of latitude and angular phase speed. Finally, the least-square best fit linear trends are computed for these phase speed spectra.

[9] The 40-year climatological mean and trend of the eddy momentum flux convergence at 250 hPa in DJFM are shown as a function of latitude and angular phase speed (Figure 1a). The climatological mean of the eddy spectrum displays the familiar eddy momentum flux convergence in midlatitudes and divergence near the critical latitudes, where the phase speed equals the background zonal mean wind. The midlatitude convergence and subtropical divergence are both dominated by eastward propagating disturbances with angular phase speeds between 5 and 20 m/s, with maximum values at 10–15 m/s.

[10] The trend in the phase speed spectrum shows that the phase speed of the eddies transporting momentum increases with time. Most of the convergence trend at 60°S is due to eddies with phase speeds between 15 and 30 m/s, with the largest contribution from phase speeds close to 25 m/s, far above the maximum in the climatological convergence pattern. The trend in subtropical divergence is also due to eddies with larger phase speeds than the typical eddies contributing to the subtropical divergence in the mean climate. One can describe the change in the latitude-phase speed spectrum as a shift towards faster eddies accompanied by a poleward shift, roughly following the slope of the subtropical critical latitude.

[11] We have also looked at the reanalysis product from National Centers for Environmental Prediction - National Center for Atmospheric Research (NCEP/NCAR) [*Kalnay et al.*, 1996], and calculated the trend over the modern satellite era (1979–2006) that largely accounts for the poleward shift of surface westerlies in the observation (Figure 2). The 28-year trends of eddy momentum flux spectra in NCEP/NCAR are qualitatively similar to the 40-year trends in ERA-40, confirming the observed trend towards faster eastward phase speeds (not shown).

3. GFDL Climate Models

[12] We further examine the GFDL global atmosphere and land model, “AM2.1” [*Anderson et al.*, 2004], and coupled atmosphere-ocean model, “CM2.1” [*Delworth et al.*, 2006]. The CM2.1 integrations are composed of 5 ensemble members, forced by estimates of the observed changes in well-mixed greenhouse gases, tropospheric and stratospheric ozone, volcanic and anthropogenic aerosols, solar irradiance, and land use. The AM2.1 simulations consist of 10 ensemble members using the same changes in forcing functions, but with sea surface temperatures (SSTs) and sea ice prescribed at observed values.

[13] Figure 2 shows the ensemble means and spreads of the latitude of the DJFM and zonal mean 10 meter surface westerly maximum from 1961–2000 in AM2.1 and CM2.1. This latitude is obtained by computing the meridional derivative of DJFM and zonally averaged zonal winds, and using a cubic interpolation to estimate the location of the zero in the derivative near the grid point of the surface westerly maximum. The ensemble means of the simulated poleward shifts in AM2.1 and CM2.1 are comparable to the

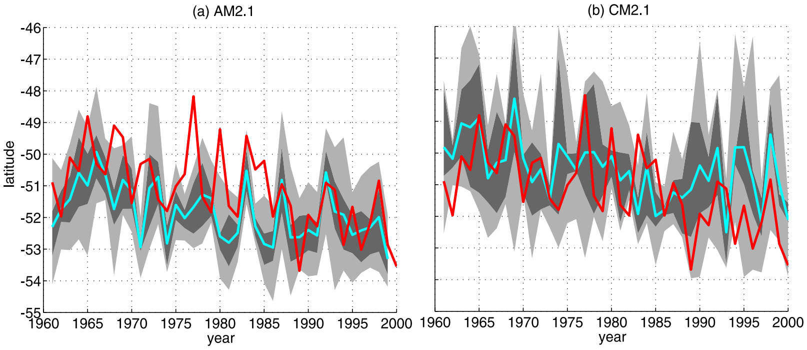

Figure 2. The ensemble means and spreads of the latitude of the DJFM and zonal mean 10 meter surface westerly maximum from 1961–2000 in (a) AM2.1 and (b) CM2.1. The red and cyan lines denote the westerly latitudes for ERA-40 and the model ensemble mean, respectively. Years on the axis represent the year of JFM being averaged. The westerly latitudes in each year for the ensemble experiments are ranked in an ascending order as $y_i (i = 1, \cdots, 10$ for AM2.1 and $i = 1, \cdots, 5$ for CM2.1). The shading in AM2.1 is between $(y_1 + y_2)/2$ and $(y_9 + y_{10})/2$, in which the dark shading is between $(y_3 + y_4)/2$ and $(y_7 + y_8)/2$. The shading in CM2.1 is between y_1 and y_5, in which the dark shading is between y_2 and y_4.

observed shift in ERA-40, and their ensemble spreads about the trends encompass the observed fluctuations in most years. While AM2.1 and CM2.1 both show a gradual poleward movement in 40 years, the surface westerly shift in ERA-40 is especially abrupt in the 1980s. This rapid shift in the reanalysis can be attributed to the roughly concurrent development of Antarctic ozone hole, but it may be also related to changes in the available data sources around this period. The ensemble spread in CM2.1 is somewhat larger than that in AM2.1, due to the SST variability in the coupled model.

[14] Figure 3 shows the linear trends of DJFM-averaged zonal mean zonal wind, transient eddy momentum flux convergence and zonal mean surface stress for ERA-40, and for the ensemble means of AM2.1 and CM2.1. The transient eddy flux is obtained by first calculating the total eddy flux from daily data, and then subtracting the stationary component defined by the DJFM mean for each year.

[15] From the upper row of panels, the vertical structure of simulated wind trends resembles the observed pattern in the troposphere and the lower stratosphere. The zonal wind trend in the troposphere displays an equivalent barotropic increase on the poleward side of the midlatitude jet. The increase of zonal wind in the subpolar lower stratosphere is similar in the models and observations. Such an increase is expected from the increased meridional temperature gradients due to polar stratospheric cooling, but we do not attempt a decomposition into the effects of ozone and greenhouse gases here.

[16] The amplitude of the simulated trends in the winds is smaller than that in the reanalysis, however, in both the troposphere and lower stratosphere. The ensemble mean trend simulated in AM2.1 is roughly 50% of the ERA-40 trend, while the CM2.1 trend is somewhat larger but still below the reanalysis trend. This difference is also apparent in the eddy momentum flux convergence in the center row of panels, and the surface stress in the bottom row. The ensemble mean stress trend in CM2.1 is roughly a factor of 2 smaller than that in ERA-40, while the mean stress trend in AM2.1 is closer to a factor of 3 too weak. Because the stress is quadratic in the surface winds, the stress is more sensitive than the winds, consistent with Figure 3. The trend in the reanalysis is a poleward shift plus a strengthening of the westerlies, whereas the model trends are closer to being simply a poleward shift.

[17] To the extent that the tropospheric winds are, in fact, driven by the lower stratospheric winds, these differences between models and reanalysis may result from model deficiencies in producing too weak a stratospheric wind signal. Since the models provide rather accurate simulations of the climatological stress distribution, as also shown in Figure 3, it is more difficult to argue that horizontal resolution or some other deficiency in the tropospheric simulations is the primary cause of this discrepancy. Reference to *Miller et al.* [2006] suggests that the trend in winds in CM2.1 is at least as large as that in other coupled models compared in that study. As discussed by *Marshall* [2003], the annular mode trend in the reanalysis may be overestimated due to the data quality in early decades.

[18] The model deficiency in the amplitude of the trends is more dramatic in the eddy momentum fluxes themselves, where, despite the agreement in the pattern of the trends, the magnitude is a factor of 4 smaller than ERA-40 in CM2.1 and even smaller in AM2.1. This difference in scaling is surprising given the zonal momentum balance between the eddy momentum flux convergence and surface stress. This discrepancy may be related to the absence of an exact balance in the angular momentum budget in the reanalysis [*Huang et al.*, 1999], whereas the models have a more consistent balance.

[19] Since the poleward shifts of surface westerlies and tropospheric zonal winds are simulated by the models fairly well, although the magnitude of the wind response is weak, we proceed to test our hypothesis on eddy phase speeds by computing the ensemble means of eddy momentum flux convergence spectra in the upper troposphere for AM2.1 (Figure 1b) and CM2.1 (Figure 1c). The models do indeed generate trends similar in structure to the observed trend in Figure 1a, although the amplitudes are weak as expected from Figure 3. As is especially clear in the AM2.1 composite, the model results confirm that the poleward shift of

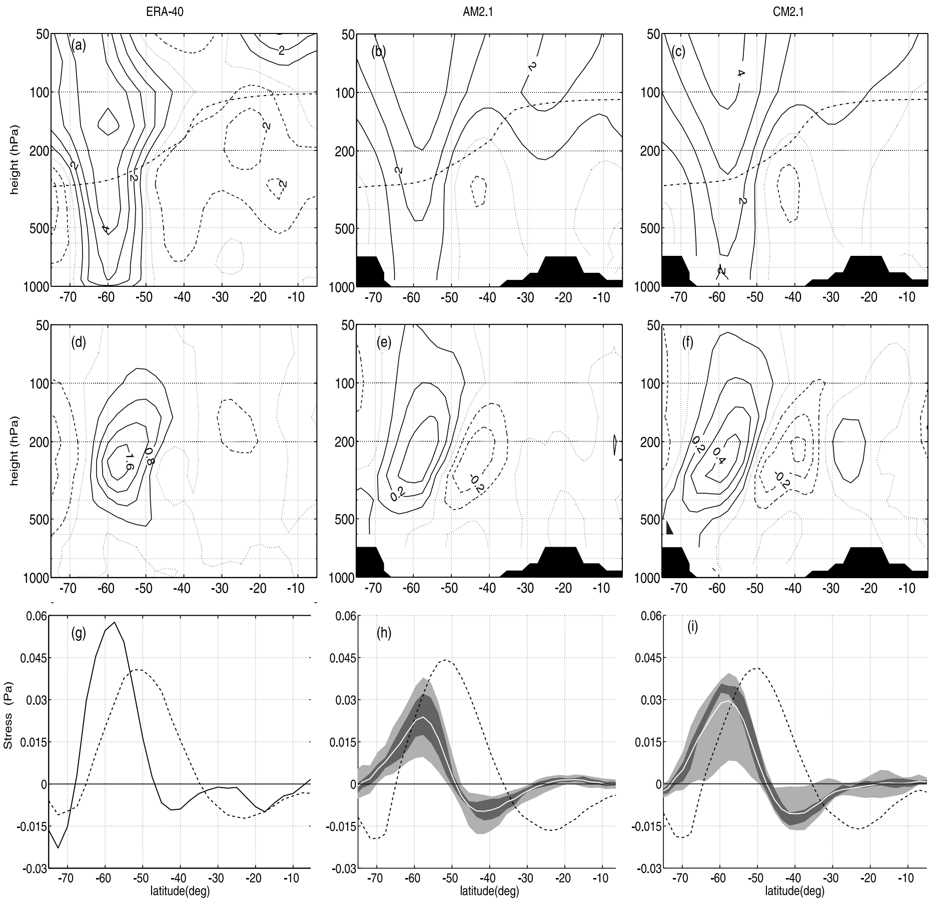

Figure 3. The linear trends of DJFM-averaged (top) zonal mean zonal wind, (middle) transient eddy momentum flux convergence, and (bottom) zonal mean surface stress for (left) ERA-40, and for the ensemble means of (middle) AM2.1 and (right) CM2.1. (a, b, c) The heavy dashed line is the tropopause level, estimated by the standard WMO lapse-rate criterion. The contour intervals are 1 m/s/(40 year). In the center row, the contour intervals are (d) 0.4 m/s/day/(40 year), and (e, f) 0.1 m/s/day/(40 year). (g, h, i) The black/white solid lines are the ensemble mean surface stress trends, and the dashed lines are 1/4 of the mean surface stress climatologies. The surface stress trends for the ensemble experiments are ranked and plotted in the gray shading for Figures 3h and 3i as in Figure 2.

the momentum flux convergence is associated with an increase in the contribution from the fastest waves.

[20] While the vertical resolution of AM2.1 and CM2.1 is not optimal for studies of troposphere-stratosphere interactions, the zonal wind trends in the lower stratosphere should not be strongly influenced by resolution, as the wind trends are in a simple thermal wind balance with the temperature changes associated with the strong forcing by the ozone hole. Furthermore, the comparison with the observations suggests that the effect of these wind changes on the phase speed of midlatitude eddies can be qualitatively captured in a model of this type, but it is possible that there are quantitative deficiencies due to inadequate vertical resolution.

4. Conclusion and Discussion

[21] In order to understand the recent poleward shift of Southern Hemisphere surface westerlies, we have examined the 40-year trend of eddy momentum flux spectra in the ERA-40 reanalysis and GFDL climate models. While the amplitude of model trends is smaller than the observed trend, the models can simulate the structure of the poleward shifts in surface westerlies and tropospheric zonal winds fairly well. Both observations and models suggest that this movement is associated with an increase in momentum flux in midlatitude eddies with fast eastward phase speeds.

[22] The question remains as to whether this shift towards faster phase speeds is a consequence of the shift in the circulation or the cause. The results of *Chen et al.* [2007] support the view that the increase in phase speed can cause a shift in circulation. Furthermore, the shallow water model of the upper troposphere described by *Chen et al.* [2007] provides a simple dynamical framework within which one can displace the eddy momentum fluxes by manipulating the eddy phase speeds. The picture that emerges is that the increase in phase speeds does not allow as much penetration of the eddies into the subtropics, moving the subtropical breaking region polewards. Since it is the coupling between the upper troposphere and lower troposphere that results in baroclinic eddy production, the picture is completed by the claim that this shift in upper tropospheric eddies is accompanied by a shift in the eddy production as well.

[23] A similar increase in the momentum flux contribution from faster eddies is also found to accompany the poleward jet shift in global warming scenarios using CM2.1 (not shown here). We suggest that both the observed shift in the Southern Hemisphere and the projected shift in both hemispheres in the future may be explained, at least in part, as a consequence of increased zonal winds near the tropopause or in the lower stratosphere. In the case of global warming, tropical upper tropospheric warming and stratospheric cooling combine with the sloping tropopause to create this increase in winds; in the late 20th century, the polar stratospheric cooling due to the Antarctic ozone hole has contributed to, if not dominated, this increase in winds aloft in the Southern Hemisphere. The suggestion is that these increased winds accelerate the eastward phase speeds of midlatitude eddies, shifting the subtropical breaking region polewards, resulting in a poleward shift of the eddy momentum flux convergence and the associated surface and tropospheric winds.

[24] Our main concern in this paper is to suggest a plausible dynamical mechanism, that is consistent with diagnoses in GCMs and observations and our understandings gained from idealized model studies. The hope is that it will help to explain the response of the tropospheric circulation to climate change, but sharper methods for isolating causes from effects will be needed to make a definitive case for this central role of the increase in phase speed as a causal agent in the poleward shift.

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