

Effect of zonal asymmetries in stratospheric ozone on simulated Southern Hemisphere climate trends

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[1] Stratospheric ozone is represented in most climate models by prescribing zonal-mean fields. We examine the impact of this on Southern Hemisphere (SH) trends using a chemistry climate model (CCM): multi-decadal simulations with interactive stratospheric chemistry are compared with parallel simulations using the same model in which the zonal-mean ozone is prescribed. Prescribing zonal-mean ozone results in a warmer Antarctic stratosphere when there is a large ozone hole, with much smaller differences at other times. As a consequence, Antarctic temperature trends for 1960 to 2000 and 2000 to 2050 in the CCM are underestimated when zonal-mean ozone is prescribed. The impacts of stratospheric changes on the tropospheric circulation (i.e., summertime trends in the SH annular mode) are also underestimated. This shows that SH trends related to ozone depletion and recovery are underestimated when interactions between stratospheric ozone and climate are approximated by an imposed zonal-mean ozone field.

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1. Introduction

[2] It is now well established that the ozone hole has played a major role in changes in the summer tropospheric circulation of the southern hemisphere (SH) over the last two decades, and that the expected recovery of Antarctic ozone will likely also be a major factor in SH climate change over the next fifty years [e.g., *Thompson and Solomon*, 2002; *Marshall*, 2003; *Gillett and Thompson*, 2003; *Perlwitz et al.*, 2008; *Son et al.*, 2008, 2009]. As a result it is important to include the impact of ozone depletion and recovery in simulations (predictions) of changes in SH climate.

[3] However, *Perlwitz et al.* [2008] and *Son et al.* [2008] suggest that the impact of changes in stratospheric ozone on the tropospheric climate may not be fully captured in the World Climate Research Programme's Coupled Model Inter-comparison Project phase 3 (CMIP3) multi-model dataset

used in the Fourth Assessment of the Intergovernmental Panel on Climate Change [*Intergovernmental Panel on Climate Change*, 2007]. They showed that, even in the CMIP3 models that prescribed ozone recovery, the tropospheric response is weaker than that in the coupled chemistry models (CCMs) in the SPARC Chemistry-Climate Model Validation Activity (CCMVal), which calculate stratospheric ozone interactively.

[4] There are several possible reasons for the difference in the tropospheric response in CMIP3 and CCMVal models, including lack of interactive chemistry, incorrect specification of ozone, inadequate representation of the stratospheric circulation in the CMIP3 models, or the lack of a dynamic ocean in the CCMVal models. Here we focus on the importance of interactive stratospheric chemistry and the impact of prescribing monthly-mean zonal-mean ozone (as is done in the CMIP3 models). *Sassi et al.* [2005], *Crook et al.* [2008], and *Gillett et al.* [2009] have shown that the Antarctic vortex is weaker and warmer in simulations without zonal asymmetries in O₃. This suggests that the use of prescribed zonal-mean ozone in the CMIP3 models may be the cause of the difference from CCMVal models. However, the above studies considered only conditions with high levels of ozone depleting substances (ODSs) and a large ozone hole, and they did not examine the impact on long-term trends in the stratosphere or troposphere.

[5] In this study we examine the impact of zonal asymmetries in ozone on simulated trends by comparing simulations for 1955 to 2055 from the NASA's Goddard Earth Observing System Chemistry-Climate Model (GEOS CCM) [*Pawson et al.*, 2008], which has full, interactive stratospheric chemistry, with parallel simulations using the same CCM except that the monthly-mean zonal-mean stratospheric ozone from the first simulation is prescribed.

2. Model and Simulations

[6] The GEOS CCM includes representations of atmospheric dynamics, radiation, and stratospheric chemistry and their coupling through transport and radiative processes. *Pawson et al.* [2008] show that the climate structure and ozone in GEOS CCM agree quite well with observations. Additional evaluations of GEOS CCM [*Eyring et al.*, 2006; *Perlwitz et al.*, 2008; *Oman et al.*, 2008; *Waugh and Eyring*, 2008] reveal good comparisons with observations.

[7] In this study we compare GEOS CCM simulations with identical greenhouse gas (GHG), ODSs, and SSTs but different ozone fields in the radiation scheme. In the "control" (CTL) simulations the O₃ field is three-dimensional and determined interactively within the CCM, whereas in the "zonal mean O₃" (ZM) simulations the monthly-mean zonal-

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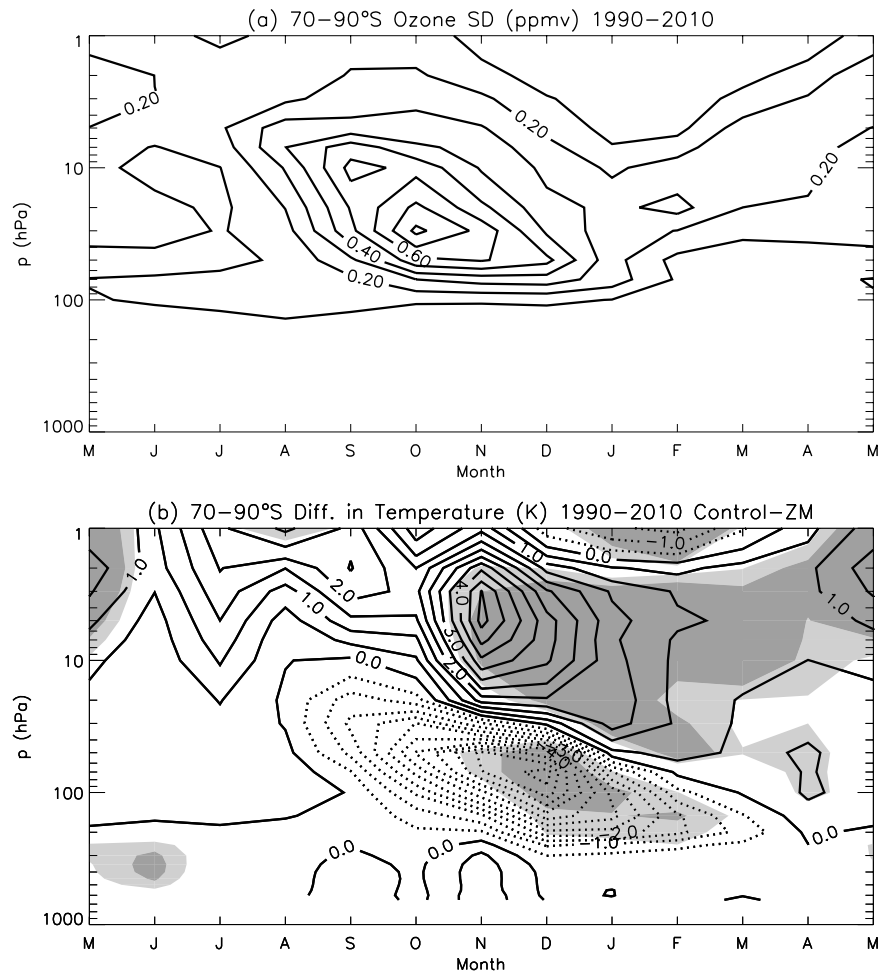


Figure 1. Pressure–time variation of the southern polar cap (70°–90°S) average of (a) standard deviation of O₃ (ppmv) about zonal mean from CTL simulations, and (b) difference in temperature (K) between the CTL and ZM simulations (CTL–ZM), averaged from 1990 to 2010. Shading Figure 1b shows regions where differences are statistically significant at the 90% (light) and 95% (dark) confidence level. The plotted fields were calculated by combining output for 1990 to 2004 from the past CTL simulation and 2000 to 2010 from the future CTL simulation, and are therefore an average for 26 simulated years.

mean O₃ from a control simulation is used in the radiative transfer scheme (linear interpolation between monthly-mean values is used to determine the zonal mean ozone at each time step). The fields of all other gases used in the radiative transfer scheme are three-dimensional. Note, the ZM simulations still contain a three-dimensional ozone field that is transported and used in the chemistry, but it is not used in the radiation.

[8] Separate CTL simulations were performed for the past (1951–2004) and the future (2000–2099), and the simulations considered here are the “P-1” and “C21-CSST” simulations described and analyzed by Perlwitz *et al.* [2008] [see also Pawson *et al.*, 2008; Waugh *et al.*, 2009]. The past runs use observed SSTs, sea ice concentrations, and surface concentrations of GHGs and ODSs, whereas the future runs used GHGs from the IPCC scenario A1b, SSTs and sea ice from an AR4 integration of CCSM3.0 [Collins *et al.*, 2006] using the same GHG scenario, and ODSs from the *World Meteorological Organization and United Nations Environment Programme* [2003] Ab scenario. For each of the above simulations a ZM simulation was performed using exactly the same surface conditions. (The ZM future simu-

lation was only run until 2055.) In addition we consider past and future CTL simulations in which the ODSs are fixed at 1960 values [Perlwitz *et al.*, 2008; Waugh *et al.*, 2009].

3. Results

[9] We first examine the impact of imposing zonal-mean ozone for current, high levels of ODSs when there is a strong Antarctic ozone hole, and then examine the impact on long-term variations between 1955 and 2055. We focus on the differences in the SH, as this is where the largest impacts of ozone on tropospheric climate have been detected.

3.1. High ODSs Conditions

[10] The largest zonal asymmetries in O₃ in the CTL simulations occur in polar lower stratosphere in spring to early summer, because of the ozone hole. This is illustrated in Figure 1a, which shows, as a measure of the zonal asymmetry in O₃, the southern polar cap average of the standard deviation of O₃ about its zonal mean. Although the vortex in model tends to break up late, the variations in the O₃ zonal asymmetries (e.g., maximum in October, local minimum in January) agree well with satellite observations (not shown).

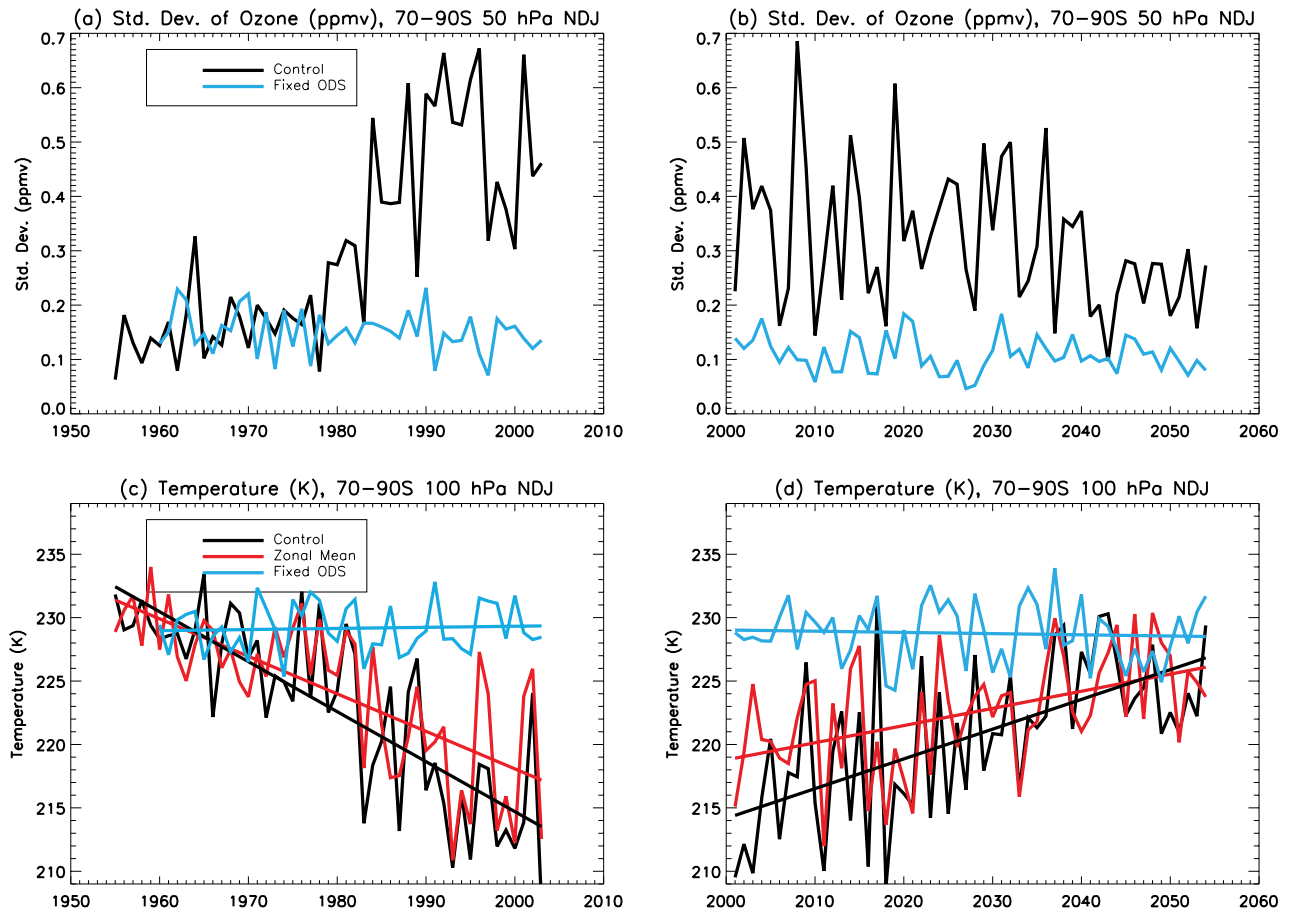


Figure 2. Time series of (a and b) southern polar cap average of standard deviation of O₃ (ppmv) about zonal mean for November–January from CTL (black) and fixed-ODS (blue) simulations, and (c and d) southern polar cap average temperature (K) at 100 hPa for November–January from the CTL (black curves), ZM (red), and fixed-ODS (blue) simulations.

[11] The removal of O₃ asymmetries in the ZM simulations has a large impact on the simulated temperatures for the same location and period. Figure 1b shows the difference between the temperatures from CTL and ZM simulations averaged from 1990 to 2010. The polar lower stratosphere in spring and summer is up to 6 K colder in the CTL simulations than in the ZM simulations. There are also temperature differences of the opposite sign (i.e. CTL is warmer) in the middle-upper stratosphere above the region of ozone depletion, which also moves down with time. These higher temperatures in the CTL simulations are due to dynamical warming in response to the changes in the lower stratospheric winds and temperatures [e.g., Langematz *et al.*, 2003; Stolarski *et al.*, 2006].

[12] The temperature differences shown in Figure 1b are very similar to those of Sassi *et al.* [2005], Crook *et al.* [2008], and Gillett *et al.* [2009]. (The temperature differences in our simulations are slightly larger than in Gillett *et al.*, but there is a similar difference in the magnitude of the ozone asymmetries.) The differences in zonal-mean geopotential height and in the horizontal structure of temperature anomalies are also similar to previous studies (not shown).

[13] The above results show that the polar vortex is weaker and warmer in the simulations using zonal mean O₃. The exact cause is not known, however Crook *et al.* [2008] presented evidence that the lack of zonal asymmetries leads

to increased upward flux of wave activity, which weakens the vortex. Other studies show that zonal asymmetries in ozone can play an important role on wave propagation [e.g., Gabriel *et al.*, 2007; Nathan and Cordero, 2007]. Nathan and Cordero [2007] showed that in the upper stratosphere the “photochemically accelerated cooling” arising from zonally asymmetric ozone can enhance wave damping and weaken the wave driving, resulting in a stronger and colder polar vortex. In the mid to lower stratosphere, they showed the situation is more complicated, with the net wave damping depending on the relative importance of ozone advection and ozone photochemistry. However, they did not explicitly consider wave propagation in SH spring and more research is required to determine if this mechanism is the cause of the decrease in wave propagation in ZM simulations of SH spring.

3.2. Long-Term Trends

[14] Prescribing zonal mean ozone has a significant impact for current conditions when there is a large ozone hole, but this may not be the case for earlier or later decades when there is no ozone hole and the zonal asymmetries in ozone are much smaller. In the CTL simulation the ozone hole forms around 1980, reaches peak values between 1990 and 2010, and then shrinks and disappears around 2060 years as the concentrations of ODSs return to 1980 values [e.g., Perlwitz

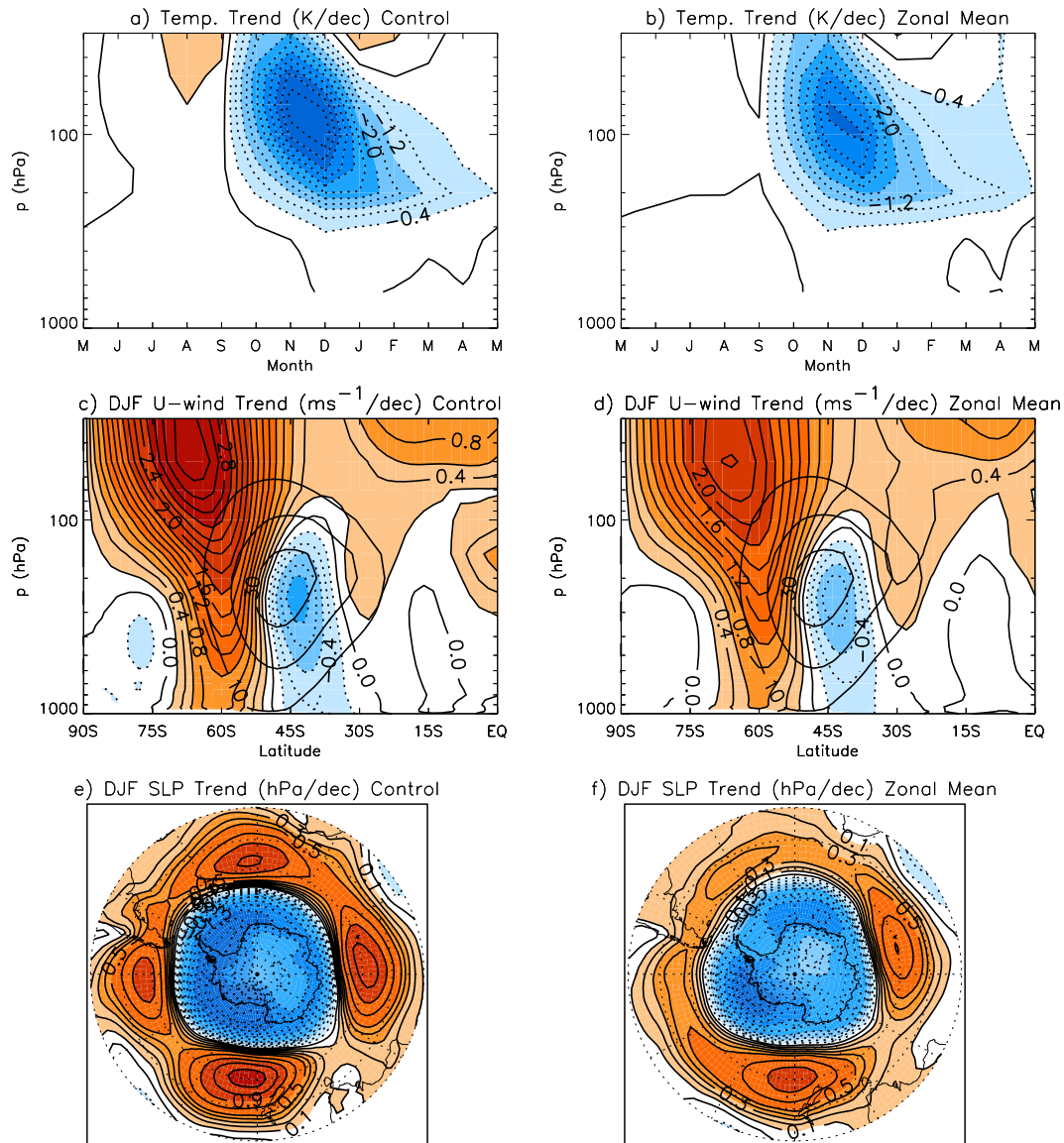


Figure 3. Trends between 1960 and 2000 in zonal-mean temperature (contour interval 0.4 K per decade), zonal-mean zonal wind (contour interval 0.2 m/s per decade), and surface pressure (contour interval 0.1 hPa per decade for $[-1.1, 1.1]$ and 0.2 outside this range). (a) Pressure–time variation of the southern polar cap (70° – 90° S) average T trend from the CTL simulation, (b) as in Figure 3a except for the ZM simulation. (c) Pressure - latitude variation of trend in zonal wind for DJF from the CTL simulation; (d) as in Figure 3c except for the ZM simulation. (e) Map of trend in surface pressure for DJF from the CTL simulation; (f) as in Figure 3e except for the ZM simulation.

et al., 2008]. The zonal asymmetries in polar O₃ evolve in a very similar manner, with much smaller values in the 1960s and 2040s than during the 2000s (Figures 2a and 2b). The impact of neglecting these O₃ asymmetries is therefore smaller during the 1960s and 2040s, and the CTL and ZM temperatures are similar during these periods (Figures 2c and 2d). As a consequence the past and future trends have smaller magnitudes in the ZM simulations (black lines in Figures 2a and 2b). (The difference between CTL and ZM trends is significant at least at the 90% (95%) confidence level for the past (future) simulations.) For reference the results of CTL simulations with ODSs fixed at 1960 levels are also shown in Figures 2c and 2d. This shows that although the ZM simulations underestimate the temperature trends, the trends

in these simulations are still significantly different from the fixed ODS simulations.

[15] The pressure-time variations in the temperature trends for the CTL and ZM past (future) simulations are shown in Figures 3a and 3b (Figures 4a and 4b). There is a cooling in the Antarctic lower stratosphere in spring and summer in both past simulations, and a warming in both future simulations. However, consistent with Figure 2, the cooling/warming is weaker in the ZM simulations.

[16] The decrease in polar temperatures between 1960 and 2000 cause an increase in meridional temperature gradients and a resulting increase in high-latitude zonal winds in the stratosphere (Figures 3c and 3d), while the 2000 to 2050 increase in polar temperatures causes a decrease in zonal winds

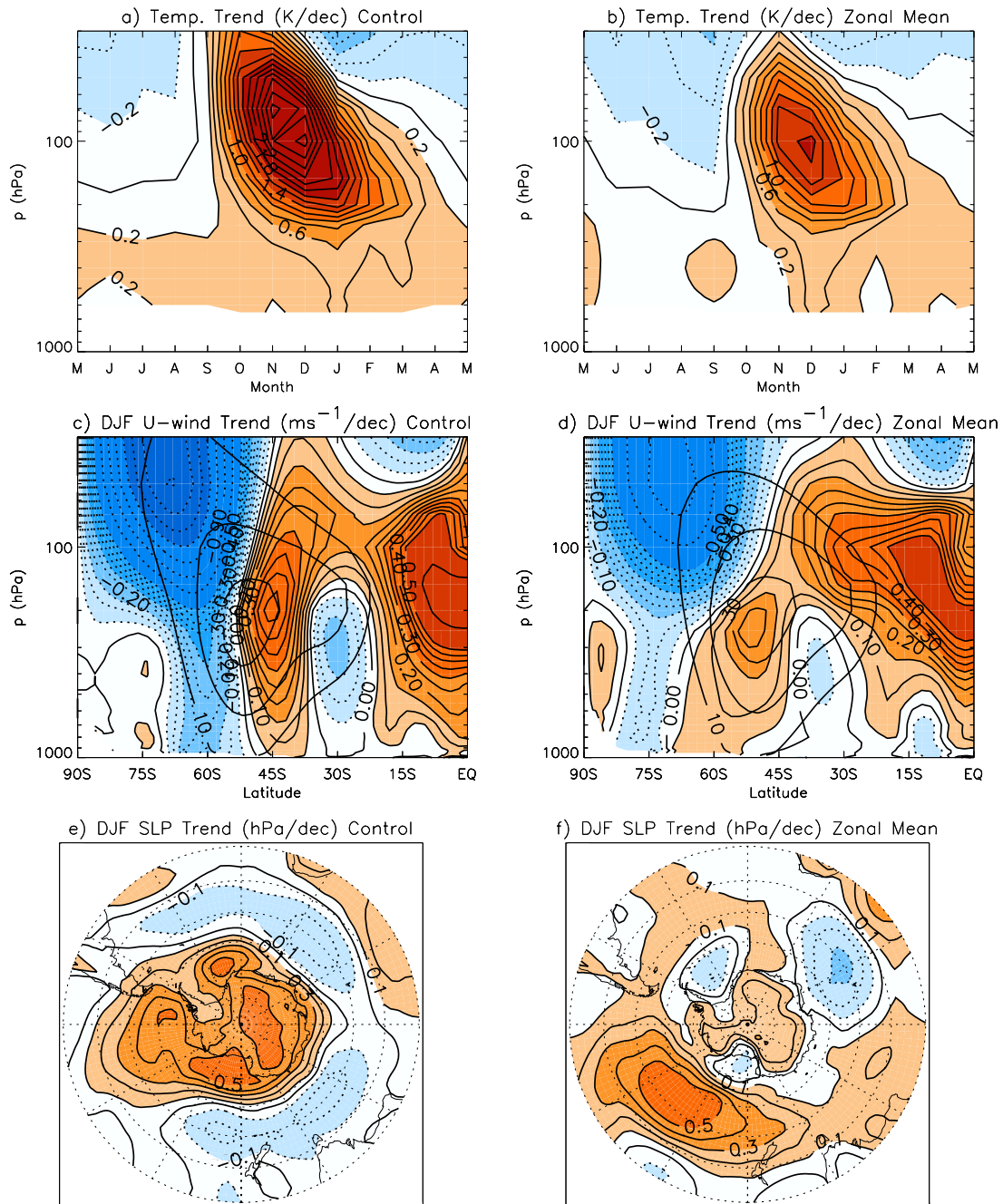


Figure 4. As in Figure 3 except for trends between 2000 and 2050.

(Figures 4c and 4d). In both cases the smaller temperature trends in the ZM simulations produce smaller trends in the zonal winds. The changes in zonal flow also occur in the troposphere, with again weaker changes in the ZM simulations. The difference is most striking in the future simulations: In the CTL simulation there is a deceleration of tropospheric westerlies south of the jet, with an acceleration on the northern side (Figure 4c), whereas in the ZM simulation there is a weak acceleration south of the jet (Figure 4d).

[17] There are also differences in the surface pressure trends between the CTL and ZM simulations. Both the CTL and ZM past simulations show a decrease in polar surface pressure between 1960 and 2000, but the trend is much larger in the CTL simulation (Figures 3e and 3f).

Between 2000 and 2050 there is a large increase in polar surface pressure in the CTL simulation, but very little change in the ZM simulation (Figures 4e and 4f). It is important to note that the changes in tropospheric flow and surface pressure are impacted by increases in GHGs as well as changes in stratospheric ozone, and between 2000 and 2050 the increase in GHGs, and hence SSTs, cause a positive SAM trend whereas ozone recovery causes a negative SAM trend [e.g., *Perlwitz et al.*, 2008]. The trends in Figure 4 are the balance between these competing forces.

[18] As a result of the above changes in tropospheric westerlies and surface pressure there are important differences in the trends in the location of the 850 hPa jet and the southern annular mode (SAM). The CTL future simulation

produces a positive trend (+0.13°/decade) in the jet location and a negative trend in the SAM index (−0.08 units/decade), but the corresponding ZM simulation produces trends of the opposite sign (−0.06°/decade in the jet location and +0.07 units/decade in the SAM index). The trends in the past simulations are the same sign for the CTL and ZM simulation, but differ in magnitude, i.e., the trend in jet location (SAM index) is −0.74°/decade and −0.44°/decade (0.52 units/decade and 0.36 units/decade) in the CTL and ZM simulations, respectively. The above differences in jet location and SAM trends between the CTL and ZM simulations are not statistically significant when tested against inter-annual variability, and it would likely require a large ensemble of simulations to determine statistical significance of the difference in the tropospheric circulation trends. However, the differences are consistent with expectations and with the multi-model analysis of Son *et al.* [2008].

4. Conclusions

[19] Comparison of GEOS CCM simulations with interactive three-dimensional stratospheric ozone with those using prescribed zonal-mean ozone indicates that simulations with zonal-mean ozone will underestimate the impact of changes in the ozone hole on SH tropospheric trends. During current conditions with high levels of ODSs and a large ozone hole the prescribed zonal mean ozone simulations have a warmer, weaker Antarctic vortex in spring-early summer. In contrast there are only small differences in polar stratospheric temperatures during periods with low ODSs and weak or no ozone hole (e.g., before 1980 and after 2040). As a consequence, the simulations with zonal mean O₃ underestimate 1960 to 2000 cooling and 2000 to 2050 warming trends in Antarctic temperature. Furthermore, these simulations also underestimate the impact of stratospheric changes on trends in the SH troposphere circulation, e.g., trends in the jet location and SAM index.

[20] These differences in the GEOS CCM simulations are consistent with the differences in mean trends from the CCMVal and CMIP3 multi-model archives [Son *et al.*, 2008]. It therefore appears that climate models that prescribe time-dependent zonal-mean ozone fields instead of predicting three-dimensional stratospheric ozone will likely underestimate SH climate trends related to ozone depletion and recovery. This ought to be considered when interpreting the results of prior climate-change studies, such as CMIP3, and in formulating experimental conditions for future model assessments of climate change.

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