

## Contributions of External Forcings to Southern Annular Mode Trends

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### ABSTRACT

An observed trend in the Southern Hemisphere annular mode (SAM) during recent decades has involved an intensification of the polar vortex. The source of this trend is a matter of scientific debate with stratospheric ozone losses, greenhouse gas increases, and natural variability all being possible contenders. Because it is difficult to separate the contribution of various external forcings to the observed trend, a state-of-the-art global coupled model is utilized here. Ensembles of twentieth-century simulations forced with the observed time series of greenhouse gases, tropospheric and stratospheric ozone, sulfate aerosols, volcanic aerosols, solar variability, and various combinations of these are used to examine the annular mode trends in comparison to observations, in an attempt to isolate the response of the climate system to each individual forcing. It is found that ozone changes are the biggest contributor to the observed summertime intensification of the southern polar vortex in the second half of the twentieth century, with increases of greenhouse gases also being a necessary factor in the reproduction of the observed trends at the surface. Although stratospheric ozone losses are expected to stabilize and eventually recover to preindustrial levels over the course of the twenty-first century, these results show that increasing greenhouse gases will continue to intensify the polar vortex throughout the twenty-first century, but that radiative forcing will cause widespread temperature increases over the entire Southern Hemisphere.

### 1. Introduction

Today's generation of coupled climate models, when forced with historical concentrations of both anthropogenic and natural variations in atmospheric composition, is able to reproduce the global-scale changes in surface temperature over the twentieth century (Mitchell et al. 2001; Stott et al. 2000; Meehl et al. 2004). Yet it is unclear whether these models agree on the corresponding changes in atmospheric circulation.

Away from the Tropics, the leading mode of atmospheric circulation variations is a flip-flop of mass be-

tween the mid- and high latitudes. This pressure fluctuation occurs on daily time scales (with a decorrelation time of about 10 days) and has been shown to exist in an approximately zonally symmetric sense in both hemispheres (Thompson and Wallace 2000), with a wavenumber-3 signature in the Southern Hemisphere (van Loon 1972). In the Southern Hemisphere it is alternately known as the high-latitude mode (Kidson 1988), the Antarctic Oscillation (Rogers and van Loon 1982), and the Southern Hemisphere annular mode (SAM; Limpasuvan and Hartmann 1999).

The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR) (Cubasch et al. 2001) noted that the most consistent feature of the sea level pressure (SLP) response to a doubling of CO<sub>2</sub> in the atmosphere was a decrease at high latitudes and an increase in midlatitudes. This can be expressed as a trend in the SAM toward its high index state, where negative anomalies (decreased pressure) are centered over Antarctica and positive anomalies (increased pressure) are in the midlatitudes, such that the polar vortex

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has intensified and the circumpolar westerlies have increased (Hurrell and van Loon 1994; Meehl et al. 1998; Thompson and Wallace 2000). Changes in the SAM have been observed in present-day climate, with a significant positive trend since the mid-1960s (Thompson and Wallace 2000; Marshall 2003). As positive trends occur in simulations forced solely with greenhouse gases (GHGs) (e.g., Fyfe et al. 1999; Kushner et al. 2001; Cai et al. 2003; Rauthe et al. 2004), it follows that these observed changes in the SH extratropical circulation are consistent in sign with the response to increasing greenhouse gases.

However, Thompson and Solomon (2002) observe that this trend is also consistent with changes in stratospheric ozone, which significantly influence the troposphere during the southern summer and autumn months. Further support for this hypothesis has been given by the modeling study of Gillett and Thompson (2003), which successfully reproduced the observed changes in Antarctic heights and surface temperatures during the December–February (DJF) season with a stepwise perturbation in ozone alone. Shindell and Schmidt (2004) use a model to indicate that the combination of stratospheric ozone decrease and GHG increase produced the observed surface trends in the late twentieth century, with the GHG effect becoming more dominant by the mid-twenty-first century. However, Shindell and Schmidt (2004) did not address the possibility that changes in other forcings or natural variability could have contributed to these changes. Marshall et al. (2004) examined SAM trends in natural and anthropogenic forcing runs of the Hadley Centre Climate coupled model, version 3 (HadCM3) and argued that natural forcings may have played a role in observed SAM changes. Our objective here is to use a global coupled climate model run with a single forcing and combinations of forcings to identify the causes of the SAM trends observed over the previous three decades. We will also consider these results in the context of projected future climate change to the end of the twenty-first century.

## 2. Model and experiments

The Parallel Climate Model (PCM) is a global coupled model of the atmosphere, land surface, ocean, and sea ice and has been optimized to run on parallel supercomputers. The atmospheric component is the National Center for Atmospheric Research (NCAR) Community Climate Model version 3 (CCM3; Kiehl et al. 1998), with a resolution of T42 (about  $2.8^\circ \times 2.8^\circ$ ) and 18 levels in the vertical, and it incorporates the Land Surface Model (LSM; Bonan 1998). The ocean

component is the Parallel Ocean Program (POP) ocean model (Smith et al. 1995) configured with  $2/3^\circ$  resolution down to  $1/2^\circ$  resolution in the equatorial Tropics and a displaced pole over Hudson Bay, which simplifies calculations in the Arctic Ocean and results in increased resolution in the Gulf Stream and North Atlantic. The sea ice model includes both thermodynamic and dynamic components. Further information regarding the individual components and features of the climate simulation can be found in Washington et al. (2000). The PCM exhibits a stable control climate without employing flux correction, and a 1000-yr control run of the PCM shows relatively small drift at the surface (Washington et al. 2000). El Niño–Southern Oscillation (ENSO) and decadal variability in the PCM are of a similar magnitude to the observations (Meehl et al. 2001; Arblaster et al. 2002).

Commencing in the late 1800s, the coupled model is run with estimates of observed forcings through to the end of the twentieth century. The natural forcings are volcanic aerosols (Ammann et al. 2003) and variations in solar input (Hoyt and Schatten 1993). The anthropogenic forcings include greenhouse gases ( $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , CFC11, and CFC12), the direct effect of anthropogenic sulfate aerosols resulting from the combustion of fossil fuels, and stratospheric and tropospheric ozone changes (Kiehl et al. 1999; Dai et al. 2001). In addition to four-member ensembles of each of the single forcing experiments, there are four-member ensemble simulations with various combinations of forcings, as outlined by Meehl et al. (2004). Averaging over multiple members enhances the forced signal and reduces noise from internally generated variability.

When all forcings are combined, the PCM is able to reproduce most features of the time series of globally averaged surface temperature over the twentieth century (Meehl et al., 2003, 2004; Ammann et al. 2003), which is a similar result to other state-of-the-art coupled models (e.g., Stott et al. 2000). The model shows that the global warming early in the century was mostly because of natural forcings and the warming in recent decades was mostly because of anthropogenic forcing. The warming is overlaid with short cooling episodes in response to individual volcanic eruptions (Meehl et al. 2003).

## 3. Results

The Southern Hemisphere has undergone large changes in its climate and circulation patterns over the last 30–50 yr. However, a number of recent studies have highlighted problems with the reanalysis products prior to the 1970s, meaning that the changes as represented

TABLE 1. Trends from 1958–99 of the SAM index (normalized units: 30 yr<sup>-1</sup>). The SAM index is defined as the difference in normalized zonally averaged sea level pressure between 40° and 65°S. The brackets indicate the 95% confidence intervals obtained from the 1000-yr control run and the asterisk (\*) indicates the trends are significant at the 90% level.

1958–99	Annual	DJF	MAM	JJA	SON
Observations (after Marshall 2003)	1.51* ( $\pm 1.78$ )	1.56* ( $\pm 1.63$ )	1.33 ( $\pm 1.60$ )	0.52 ( $\pm 1.40$ )	0.04 ( $\pm 1.40$ )
Volcanic	-0.16 ( $\pm 0.89$ )	-0.18 ( $\pm 0.82$ )	-0.56 ( $\pm 0.80$ )	0.26 ( $\pm 0.70$ )	-0.02 ( $\pm 0.70$ )
Solar	0.34 ( $\pm 0.89$ )	0.46 ( $\pm 0.82$ )	0.32 ( $\pm 0.80$ )	0.21 ( $\pm 0.70$ )	-0.09 ( $\pm 0.70$ )
GHG	0.80* ( $\pm 0.89$ )	0.37 ( $\pm 0.82$ )	0.60 ( $\pm 0.80$ )	0.59 ( $\pm 0.70$ )	0.49 ( $\pm 0.70$ )
Sulfate	-0.25 ( $\pm 0.89$ )	-0.44 ( $\pm 0.82$ )	-0.08 ( $\pm 0.80$ )	-0.25 ( $\pm 0.70$ )	0.22 ( $\pm 0.70$ )
Ozone	0.71 ( $\pm 0.89$ )	1.27* ( $\pm 0.82$ )	0.33 ( $\pm 0.80$ )	0.07 ( $\pm 0.70$ )	-0.10 ( $\pm 0.70$ )
All	1.80* ( $\pm 0.89$ )	1.77* ( $\pm 0.82$ )	1.67* ( $\pm 0.80$ )	0.42 ( $\pm 0.70$ )	0.58 ( $\pm 0.70$ )

in these data may be significantly in error (Hines et al. 2000; Thompson and Solomon 2002). Marshall (2003) compared the trends from National Centers for Environmental Prediction (NCEP)–NCAR reanalysis (NNR) and European Centre for Medium-Range Weather Forecasts (ECMWF) 40-Year Re-Analyses (ERA-40) with station data from various latitudes, and found the trend in the SAM index to be overestimated by both products. However, a significant trend was still found in their station-based index, suggesting that the climate trends in the Southern Hemisphere over the last 30–50 yr are indeed real. Our purpose here is to attempt to understand these trends in the light of various external forcings on the climate, and to estimate changes for the twenty-first century.

We calculate the trends over different time periods for comparison with various observational datasets and to be consistent with previous studies. One of these periods is 1969–98, which begins prior to the rapid decrease in stratospheric ozone (around 1970; Kiehl et al. 1999), and is also consistent with periods chosen by the observational and modeling studies of Thompson and Solomon (2002) and Marshall et al. (2004). For comparison, we also show trends from 1979 to 1999 for ERA-40 and the model because this covers the period of satellite observations, and from 1958 to 1999 because this period ranges over the period of radiosonde observations and has been used by Marshall (2003).

Trends in the SAM index over 1958–99 are documented in Table 1 for the observations and model experiments. The SAM index used here is based on the definition of Gong and Wang (1999) and is similar to that used by the observational study of Marshall (2003), that is, the difference between the normalized zonally averaged sea level pressure between 40° and 65°S. We choose this definition to enable a comparison with the changes observed. It should be noted, however, that this index in the model is highly correlated with a SAM index based on the first EOF of sea level pressure or 500-mb geopotential height on interannual time scales. Ensemble mean results are shown for the five forcings

run separately and for the all-forcings run from the model using an ensemble of four runs for each experiment. Following the method of Marshall et al. (2004), the 95% confidence intervals are given in brackets for the observations and forcing runs based on a distribution of trends determined from the PCM 1000-yr control run. The observational trends are calculated from the SAM index of Marshall (2003) (updated online at <http://www.nerc-bas.ac.uk/icd/gjma/sam.html>) and show positive trends in all seasons and for the annual value, with the summer season and annual values having a large significant positive trend, and DJF and March–May (MAM) having the largest relative positive seasonal trends, consistent with Thompson and Solomon (2002). The model all-forcing ensemble reproduces this seasonality, obtaining significant trends of a similar magnitude to the observations in both DJF and MAM seasons as well as annually. Examining the individual forcing ensembles, only the GHG ensemble reaches significance at the 90% level on the annual time scale, although the GHG trends are consistently strong and positive across all seasons. The ozone-forcing ensemble has a significant positive trend in DJF, as found in previous studies. The volcanic, sulfate, and solar experiments have trends that are smaller and have mixed signs, and none are statistically significant; however, there is some indication that solar forcing is contributing to trends in DJF. It is also worth noting that the SAM trends for the five individual forcings do not equal the all-forcings trend, and for all seasons, excepting June–August (JJA), the sum of the combined trends is smaller than the all-forcing trends. This is consistent with Meehl et al. (2004) who documented additivity for temperature trends globally but not regionally. This is also consistent with results from Hartmann et al. (2000) and Marshall et al. (2004), which suggest that a combination of GHG increases and stratosphere ozone losses, and possibly natural forcings, could produce rapid changes to atmospheric circulation patterns through feedbacks. Additional combined forcing experiments with the PCM show increased trends when

ozone is combined with either greenhouse gases or natural forcings, although without a full set of combined forcing runs it is difficult to make any definitive statements in this regard.

To illustrate how these trends are manifested geographically, Fig. 1 shows SLP trends from the five individual forcing runs and the all-forcings run from the period of 1958–99 for DJFMAM, which are the months used by Thompson and Solomon (2002). The DJFMAM period also combines the seasons when the largest amplitude trends are evident, as seen in Table 1. As could be expected from Table 1, the strong SLP decreases over Antarctica and increases in southern midlatitudes are most evident in the GHG and ozone simulations in the geographic patterns of the trends in Fig. 1. To compare these simulated SLP trends from the all-forcing simulations in Fig. 1, Fig. 2a shows the trends over the satellite era (1979–99) for ERA-40. There are negative SLP trends over the polar latitudes and positive trends in midlatitude regions in the reanalyses. The simulated trends in Fig. 2b for the all-forcings experiment capture the spatial pattern of the observations, with maximum positive trends at 45°–50°S and the largest negative trends over the Antarctic, and are similar to those shown in Fig. 1f. The observed negative trends extend farther equatorward than those in the model, and exhibit a pattern more indicative of a wavenumber-3 mode of variability of the Southern Hemisphere circulation. (van Loon 1972; van Loon et al. 1993; Hurrell and van Loon 1994; Raphael 2004). However, this observed wavenumber-3 pattern does show variability based on time period and reanalysis product, and may be related to sampling from a strong mode of variability. Trends in DJFMAM SST from the ERA-40 and PCM all-forcing runs are presented in Figs. 2c and 2d, respectively, for the 1979–99 period. As noted by Thompson and Solomon (2002), the observed surface temperatures have decreased over most of the Antarctic continent, with the exception of warming over the Antarctic Peninsula. The model captures these details in the pattern of SH recent warming remarkably well, though the poleward shift of the SLP anomalies in the model in Fig. 2b (compared to the observations in Fig. 2a) produces a comparable poleward shift of the warming–cooling pattern in Fig. 2d (compared to the observations in Fig. 2c).

The paper by Thompson and Solomon (2002) presented results for changes in the vertical structure of temperature and geopotential height around the Antarctic as a function of month. In Fig. 3, tropospheric and stratospheric trends for these same variables are shown from their paper and are compared to the model all-

forcings experiment and the most dominant contributors to the SAM trends as shown in Table 1 and Fig. 1—ozone and greenhouse gases. As in Thompson and Solomon (2002), we show trends for the period of 1969–98 from the model experiments calculated over a comparable latitude range of 65°–70°S. The all-forcings ensemble captures the timing and structure of the observed trends quite well, although the simulated trends are larger than observed for both temperature and height, as was the case for the SLP SAM index in Table 1. It is clear that trends in the stratosphere for both temperature and geopotential height are directly linked to ozone forcing in the model, with little trend found in the experiment forced only with changes in GHGs. Note, however, that the ozone-forced height trends are small and not significant in the lower troposphere in comparison to those observed. Seasonal cooling resulting from ozone at 70°S (Fig. 3) enhances the baroclinicity of latitudes farther north (not shown), strengthening the westerlies and producing a positive SAM trend. A similar effect occurs throughout the year resulting from GHGs with greater tropospheric warming at 50° compared to 70°S (not shown).

Shindell and Schmidt (2004) suggest from their future climate change scenario experiments that the recovery of stratosphere ozone in the first half of the twenty-first century will not be sufficient to reverse the positive trend in the SAM index observed during the late twentieth century. Increasing GHGs would maintain a positive SAM index trend, and the increasingly positive radiative forcing would produce more spatially uniform warming over the entire hemisphere. As noted above, this is also a likely outcome given the multimodel results for the idealized CO<sub>2</sub> increase in the IPCC TAR, which showed a positive SAM phase and more uniform warming over the hemisphere for a doubling of CO<sub>2</sub>.

To investigate this possibility in the PCM, Fig. 4 shows SLP and surface temperature differences for the end of the twenty-first century compared to a 1980–99 base period for three Special Report on Emission Scenarios (SRES) scenarios of future emissions for the low range (B1), midrange (A1B), and high range (A2). Consistent with the TAR and the Shindell and Schmidt (2004) results, an anomalously positive phase of the SAM is evident for the climate change at the end of the twenty-first century, with negative SLP differences over high southern latitudes and positive differences over midlatitudes (Fig. 4, top). The bottom panels of Fig. 4 show large warming over most of the Southern Hemisphere, such that the circulation anomalies accompanying the SLP anomalies (e.g., stronger westerlies near

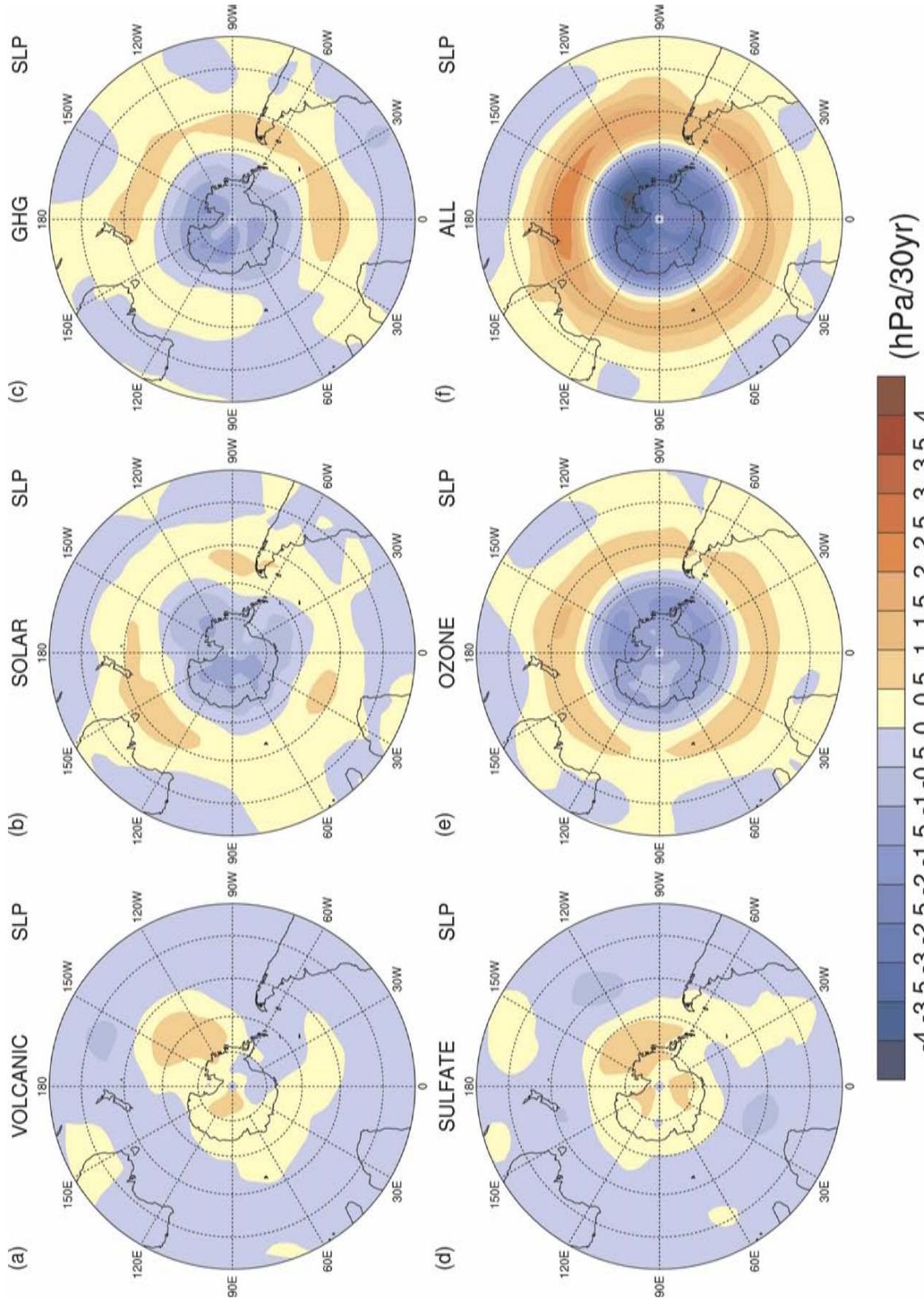


FIG. 1. Ensemble mean DJFMAM sea level pressure trends (hPa,  $30 \text{ yr}^{-1}$ ) for the period of 1958–99 of the (a) volcanic, (b) solar, (c) GHGs, (d) sulfate aerosols, (e) ozone, and (f) all-forcings simulations from the PCM.

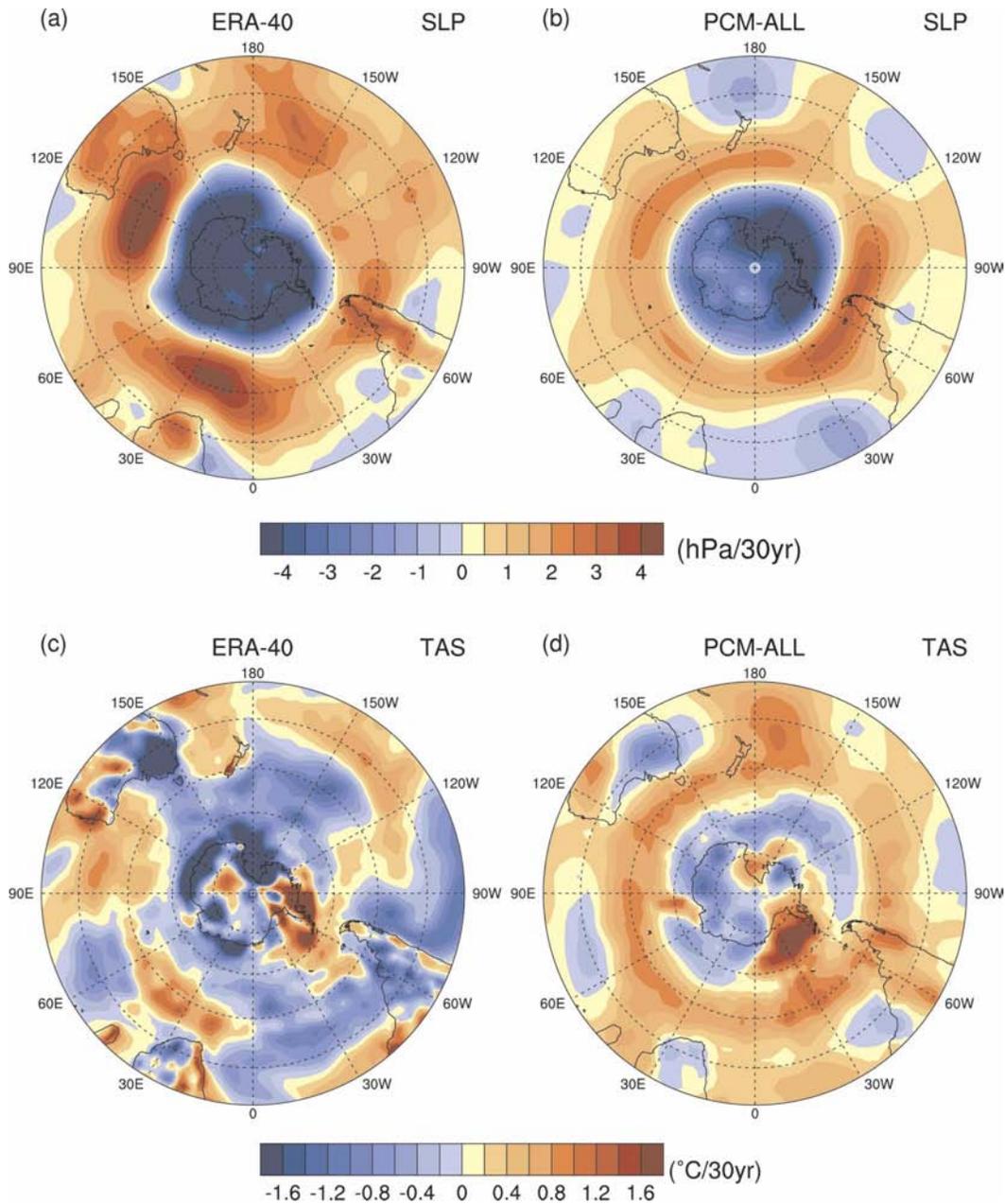


FIG. 2. (a) DJFMAM sea level pressure ( $\text{hPa } 30 \text{ yr}^{-1}$ ) and (c) surface air temperature ( $^{\circ}\text{C } 30 \text{ yr}^{-1}$ ) trends from ERA-40 for the period of 1979–99; and (b) sea level pressure ( $\text{hPa } 30 \text{ yr}^{-1}$ ) and (d) surface air temperature ( $^{\circ}\text{C } 30 \text{ yr}^{-1}$ ) trends from the all-forcings ensemble from the PCM for the period of 1979–99.

$50^{\circ}\text{S}$ ) are reflected only in somewhat less warming at those latitudes resulting from the more vigorous ocean mixing, while temperatures increase over Antarctica and the rest of the hemisphere.

#### 4. Discussion and conclusions

Climate change over the latter part of the twentieth century in the Southern Hemisphere has involved an

intensification of the polar vortex and circumpolar trough. This change was noted to occur in conjunction with changes in ozone that likely affected the Southern Hemisphere circulation (Thompson and Solomon 2002). Here we use a global coupled climate model in experiments with five separate forcings (two natural and three anthropogenic) to show that ozone and GHG changes have contributed most to the trends in the SAM, and that most of the observed changes in the



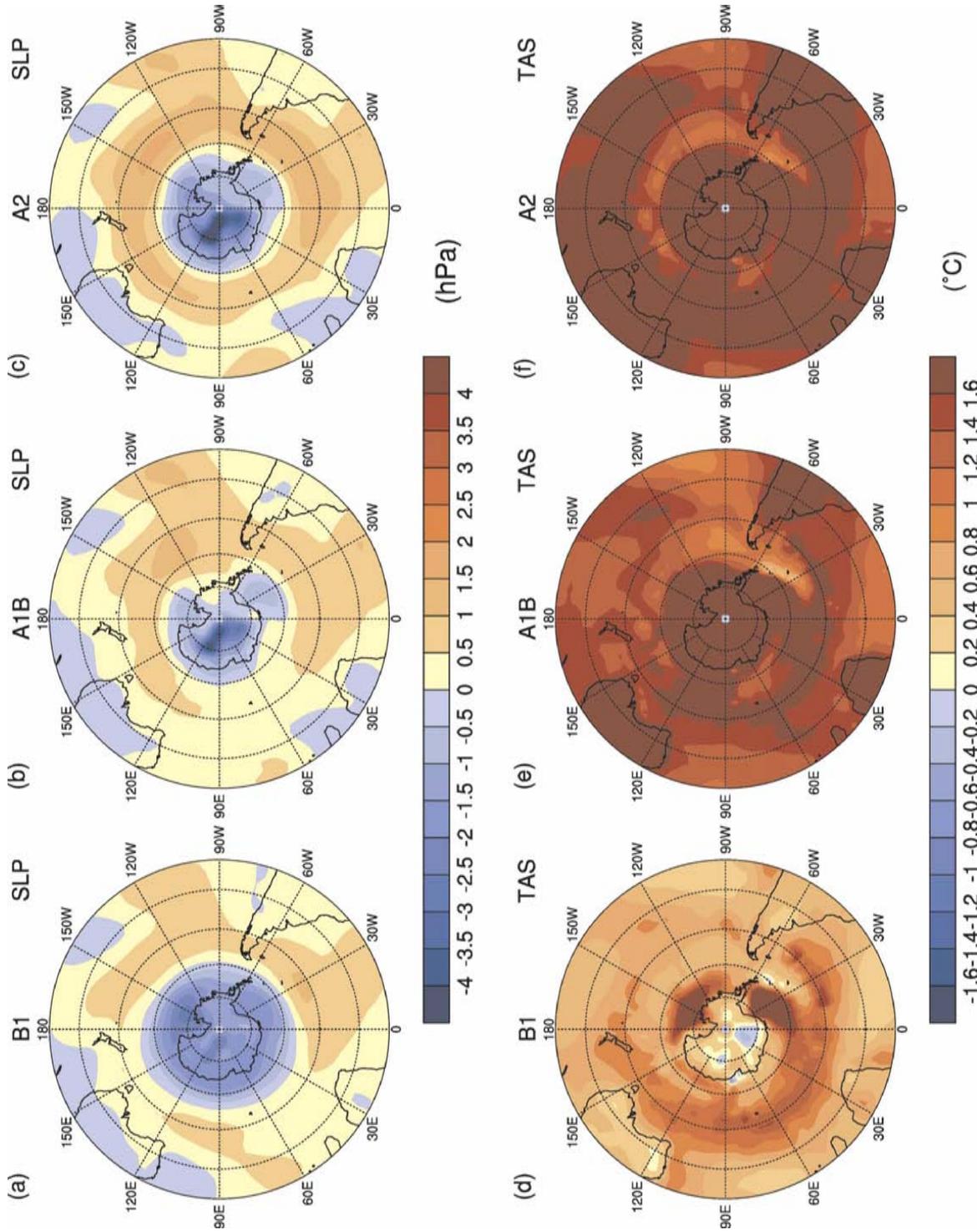


FIG. 4. Ensemble mean sea level pressure differences (hPa) for SRES scenarios (a) B1, (b) A1B, and (c) A2, 2080-99 minus 1980-99; surface air temperature differences (°C) for SRES scenarios (d) B1, (e) A1B, and (f) A2, 2080-99 minus 1980-99 from the PCM.

twenty-first-century findings in that even though ozone recovers in the stratosphere, ever-increasing GHGs continue the changes in the SAM observed in the latter part of the twentieth century. The radiative forcing from those increasing GHGs produces large warming over most of the Southern Hemisphere by the end of the twenty-first century. Although the low-range (B1) scenario still exhibits some weak, presumably SAM-induced, cooling at higher latitudes, the surface warming amplifies as the radiative forcing increases, implying that the recent local cooling over the Antarctic will reverse at some point in the future.

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