Causes of exceptional atmospheric circulation changes in the Southern Hemisphere

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[1] We demonstrate that recent observed trends in the annual and austral summer Southern Hemisphere Annular Mode (SAM) are unlikely to be due to internal climate variability, since they exceed any equivalent-length trends in a millennial General Circulation Model (GCM) control run with constant forcings. In contrast we show that observed trends in the SAM are consistent with the combined effects of anthropogenic and natural forcings in GCM simulations. As these trends begin prior to stratospheric ozone depletion we challenge the assertion that this process is primarily responsible for changes in the SAM. Moreover, anthropogenic forcings have a larger effect on the austral summer SAM in combination with natural forcings than when acting in isolation. INDEX TERMS: 1620 Global Change: Climate dynamics (3309); 3309 Meteorology and Atmospheric Dynamics: Climatolgy (1620); 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 3349 Meteorology and Atmospheric Dynamics: Polar meteorology. Citation: Marshall, G. J., P. A. Stott, J. Turner, W. M. Connolley, J. C. King, and T. A. Lachlan-Cope (2004), Causes of exceptional atmospheric circulation changes in the Southern Hemisphere, Geophys. Res. Lett., 31, L14205, doi:10.1029/2004GL019952.

1. Introduction

[2] Southern Hemisphere (SH) extra-tropical atmospheric variability is primarily driven via the SH Annular Mode (SAM), a pattern of zonally symmetric, synchronous pressure anomalies of opposite sign in Antarctica and mid-latitudes. Changes in the SAM have been linked to large-scale variability of the Southern Ocean [Hall and Visbeck, 2002; Hughes et al., 2003] and Antarctic surface temperature change [Kwok and Comiso, 2002; Thompson and Solomon, 2002; van den Broeke and van Lipzig, 2003], and can therefore be considered a robust indication of broad-scale extra-tropical SH climate change. Several, differently defined indexes of the SAM [Limpasuvan and Hartmann, 1999] (also known as the High Latitude Mode [Rogers and van Loon, 1982] or Antarctic Oscillation [Gong and Wang, 1999]) have revealed a positive trend over the last few decades, such that pressures are now more likely to be higher (lower) over SH mid-latitudes (Antarctica) [Thompson et al., 2000; Thompson and Solomon, 2002; Marshall, 2003]. The result is a strengthening of the circumpolar vortex and associated westerlies. Sensitivity experiments with climate models have suggested Antarctic stratospheric ozone depletion as a possible forcing mechanism [Sexton, 2001; Gillet and Thompson, 2003; Gillet et al., 2003]. However, General Circulation Model (GCM) predictions of future climate with increased greenhouse gases also reveal a clear shift in the SAM towards its positive phase [Fyfe et al., 1999; Kushner et al., 2001; Stone et al., 2001; Cai et al., 2003]. Some workers have proposed that synergistic interactions between these two mechanisms are responsible for the pronounced changes [Hartmann et al., 2000]. However, little has been written regarding the possible influences of natural forcings on the SAM.

[3] In this paper we estimate the significance of the recent observed trends in the SAM by evaluating them against those in a millennial length GCM control run with constant forcings. Subsequently we investigate possible forcing mechanisms by comparing the observed magnitude of annual and seasonal trends in the SAM to those derived from GCM simulations with varying external forcings.

2. Methodology

[4] We use an index of the SAM for 1958–2000 that has been determined using a definition based upon mean sea level pressure (MSLP) observations [Marshall, 2003]: note that previous time-series of the SAM based on the National Centers for Environmental Prediction (NCEP) reanalysis are flawed because of a bias in geopotential height at high southern latitudes prior to the assimilation of satellite sounder data into this dataset commencing in the late 1970s [Hines et al., 2000]. Briefly, the zonal MSLP at SH high latitudes (mean of 6 stations located at ~65°S with a good spread of longitudes) is normalized for each season or annually (Dec–Nov) and subtracted from an equivalent mid-latitude value (~40°S) [after Gong and Wang, 1999]. Figure 1 shows the resultant individual seasonal values of the SAM with the annual values superimposed. Since a minimum in 1964 there have been statistically significant (see Santer et al., 2000 for the methodology) positive trends in the annual, autumn (MAM), and summer (DJF) SAM indices.

[5] In order to estimate whether these observed trends in the SAM lie outside the expected range of natural internal climate variability, we compare them (from 1965–1997, following the minimum in the annual data and up to the end of model runs described later) to those of equivalent length in a GCM control run. This has constant external forcings (a seasonal and diurnal cycle) and therefore represents the internal variability of the Earth’s climate system. The
millennial control run utilized is obtained from the Hadley Centre coupled model HadCM3 [Gordon et al., 2000; Collins et al., 2001]. Prior to calculating the model’s internal variability, we assess whether the model SAM is realistic. Note that the model SAM was derived similarly to the observations: an alternative method, in which we calculate the SAM time-series as the first EOF of extratropical SH MSLP, has a correlation with the empirically derived SAM time-series of 0.98. Thus, the latter effectively captures almost all the variability of the SAM within the model. Spectral analysis determines that neither the model data nor the detrended observations contain any significant periodicity. The variability of the SAM in the model is marginally higher than in the detrended observations with an independent estimate of external forcing (the ALL model run: see next paragraph) removed from them, ranging from 0–4% seasonally and 3% annually. Hence the exaggeration of internal SAM variability in the model is likely to be underestimated and, as a consequence, so is the significance of the observed trends as derived in Section 3. In addition, the vertical and meridional structure of the model SAM—as revealed by the first EOFs of MSLP, 500, 300 and 100 hPa—is similar in the model and European Centre for Medium-range Weather Forecasts ERA-40 reanalysis data. Thus, HadCM3 appears to provide a good facsimile of the observed SAM. This has also been demonstrated with regard to the North Atlantic Oscillation, an approximate northern hemisphere analogue of the SAM [Collins et al., 2001]. Frequency distributions of the trends in the control run were calculated from 50% overlapping samples. This takes account of the likely number of degrees of freedom in the data, which was estimated to be 1.5 times the number of non-overlapping segments [see Allen and Smith, 1996]. The distributions are approximately normal and thus the associated confidence intervals may be calculated.

[6] Next we examine recent trends in the SAM derived from three HadCM3 runs with varying external forcings from 1860–1997 [Stott et al., 2000; Tett et al., 2002]. The first (ALL) is driven by changes in both natural and anthropogenic forcings. Natural forcings are variability in solar irradiance [Lean et al., 1995], and stratospheric aerosol due to explosive volcanic eruptions [Sato et al., 1993]. Anthropogenic forcings incorporate both tropospheric forcings—such as well-mixed greenhouse gases, anthropogenic sulfur emissions and their implied changes to cloud albedo

Figure 1. Seasonal values of the SAM derived from observations (bar chart) with annual values overlain as the black line. The SAM index is a dimensionless quantity.

Figure 2. Annual and seasonal trends in the SAM during 1965–1997 from observations (OBS: represented by a cross) and the ensemble-mean of the all forcings (ALL), natural forcings (NAT) and anthropogenic forcings (ANT) HadCM3 runs (represented by circles). The 95% confidence limits about zero shown in the observations column are the uncertainties due to natural internal climate variability, as simulated by a millennial-scale control run. 95% confidence intervals for the ensemble-mean trends are similarly derived (see text for details).
and tropospheric ozone—and stratospheric ozone depletion. Note that the prescribed ozone losses are up to twice observed estimates in some seasons [Randel and Wu, 1999]. The other two runs examined, NAT and ANT, are driven solely by the natural and anthropogenic forcings, respectively. Each of these runs comprises four ensemble members, with identical initial conditions for a given ensemble member in ALL, NAT and ANT. These conditions are taken from states in the control run separated by 100 years. SAM trends are calculated from the mean of the ensemble members for the period 1965–1997, the period of recent increase in the observed SAM that overlaps with the model data. The internal variability of the mean is estimated by dividing the standard deviation of the control run by the square root of the number of ensemble members [see Karoly et al., 2003]; therefore, with four ensemble members, the confidence intervals of the runs with external forcings are half that of the control run.

3. Results

[7] The observed (OBS) trends for 1965–1997 and the control run-derived 95% confidence intervals (centered on zero) are shown in Figure 2. This reveals that, based on the model’s estimate of the natural variability of the SAM, the recent observed annual and summer trends are statistically significant at <5% level (actually both <1% while in autumn the trend is significant at <10%). We note that the estimate of internal SAM variability in the model is likely to be underestimated [see Mitchell et al., 2001, Figure 12.2 caption] and, as a consequence, the significance level of the observed trends will be somewhat conservative. Further evidence that the observed trends in the SAM lie outside the range of internal climate variability is indicated by the largest trends of similar length (33 years) in the control run, calculated using a moving window, having a magnitude of only 87% and 71% of those observed annually and in summer, respectively.

[8] Equivalent mean trend and associated 95% confidence intervals in the SAM from 1965–1997 derived from the three runs with varying external forcings are also illustrated in Figure 2. Both annual and seasonal SAM trends in the ALL mean are consistent with those observed, increasing our confidence that the model is able to accurately represent the SAM during this period. The summer SAM in the ALL run is illustrated in Figure 3, together with observations and the 1965–1997 trend in both datasets. We see that the rapid decline in the mid-1960s is identifiable in the model mean, and while values before this are clearly not as high as observed, they are above average compared to the earlier model data. The subsequent recent trend in the SAM in the ALL mean is seen to be of greater magnitude than any previously. Thus the model simulation provides further evidence that the observed trend is exceptional. We note that the overstated ozone losses may exaggerate the ALL trend following the establishment of the ozone hole in about 1980, but the fact that the model data show good agreement with observations both before and after this date suggests these effects are slight relative to the magnitude of the trend itself.

[9] The annual, autumn and summer SAM trends in the ALL run are significantly different from zero at the 5% level (cf. Figure 2). In contrast, none of the trends derived from the NAT mean are significant, and are therefore consistent with those in the observations and ALL run only in winter and spring. Most of the SAM trends in the ANT mean are also not statistically significant, and many of these are closer to the NAT mean than the observed trend. The one exception is in summer, when the ANT trend is significantly different from zero (although only half the magnitude of that in the observations and ALL) but not statistically different from the summer NAT trend. Thus, it seems that the effects of anthropogenic forcing are concentrated in austral summer.

4. Conclusions

[10] Our results imply that a non-linear combination of anthropogenic and natural forcings is responsible for the observed changes in the SAM since the mid-1960s. Previous studies have focused attention only on the former. The anthropogenic forcing component is clearly most prominent
in summer, the season with the largest trend—suggesting agreement with those studies proposing ozone depletion as the principal cause of changes in the SAM [Sexton, 2001; Thompson and Solomon, 2002; Gillett and Thompson, 2003]. Nevertheless, observations and both the ALL (cf. Figure 3) and ANT runs reveal that the recent summer trend in the SAM begins at least a decade before any ozone loss. Furthermore, Kushner et al. [2001] show that the largest seasonal response to greenhouse gas increases in another GCM is also in summer. Therefore we conclude that increases in greenhouse gases are an important component of the forcing and disagree with the assertion that ozone depletion alone is primarily responsible for the observed shift in the SAM [Gillett and Thompson, 2003]. Finally, the requirement to include natural forcings in the model in order to reproduce observed SAM trends points to a complex combination of physical processes being responsible [Hartmann et al., 2000; Karoly, 2003]. Partitioning the contributions of the various forcing factors influencing the SAM, both anthropogenic and natural, and understanding how they interact will allow us to better predict its role in determining future climate change in the SH.

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