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The Arctic and Antarctic Oscillations and their Projected Changes Under Global Warming

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Abstract. The Arctic Oscillation (AO) and the Antarctic Oscillation (AAO) are the leading modes of high-latitude variability in each hemisphere as characterized by the first EOF of mean sea-level pressure. Observations suggest a recent positive trend in the AO and it is speculated that this may be related to global warming. The CCCma coupled general circulation model control simulation exhibits a robust and realistic AO and AAO. Climate change simulations for the period 1900-2100, with forcing due to greenhouse gases and aerosols, exhibit positive trends in both the AO and the AAO. The model simulates essentially unchanged AO/AAO variations superimposed on a forced climate change pattern. The results do not suggest that a simulated trend in the AO/AAO necessarily depends on stratospheric involvement nor that forced climate change will be expressed as a change in the occurence of one phase of the AO/AAO over another. This pattern of climate change projects exclusively on the AAO pattern in the southern hemisphere but not in the northern hemisphere where other EOFs are involved. The extent to which this forced climate change pattern and the unforced modes of variation are determined by the same mechanisms and feedbacks remains an open question.

1. Introduction

The leading modes of variability in the northern and southern hemispheres have been shown to have similar, roughly zonally symmetric, structures [*Thompson and Wallace*, 1998; *Thompson and Wallace*, Annular Modes in the Extratropical Circulation Part I: Month-to-month Variability (and references contained therein), submitted to the *Journal of Climate*, 1999; hereafter referred to as TWa and TWb respectively]. These modes, termed the Arctic Oscillation (AO) and Antarctic Oscillation (AAO), emerge as the leading empirical orthogonal function (EOF) of northern and southern hemisphere mean sea-level pressure with associated regression patterns of temperature, zonal wind, and geopotential height from the surface to the stratosphere. Observations suggest that the AO, and the more spatially confined North Atlantic Oscillation (NAO), have exhibited a positive trend since the early 1980s (TWa; *Hurrell*, 1995), which *Shindell et al.* [1999] attribute to greenhouse gas induced climate warming based on model simulations.

Results from the Canadian Centre for Climate Modelling and Analysis (CCCma) coupled climate model are examined to demonstrate its ability to simulate the AO and AAO and to investigate their evolution in forced climate change simulations. The coupled model is described in *Flato et al.* [The Canadian Centre for Climate Modeling and Analysis Global Coupled Model and its Climate, submitted to *Climate Dynamics*, 1998] and the forced climate change simulations in *Boer et al.* [A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate change in the 21st century, submitted to *Climate Dynamics*, 1998] hereafter referred to as BFR.

The atmospheric component of the coupled model is a global primitive equation spectral model with T32 triangular truncation and 10 unequally-spaced vertical levels with the top level at 12 hPa (*McFarlane et al.*, 1992). The ocean component is a global primitive equation grid-point model at with 1.875°resolution and 29 vertical levels, based on the GFDL MOM1.1 code (*Pacanowski et al.*, 1993). A 200-year control simulation and an ensemble of three independent climate change simulations forced with changing greenhouse gas (GHG) concentrations and aerosol loadings (following the forcing specification of *Mitchell et al.*, 1995), are available for the period 1900 to 2100.

2. Results

The analysis of the model results parallels the observational analyses of TWa and TWb to facilitate comparison. Plate 1 displays the first three simulated EOF patterns for the northern hemisphere (north of 20°N), wintertime (using November-April monthly means), mean sea-level pressure (SLP) calculated from the 200-year control simulation. These first three EOFs account for 24, 11, and 9 percent of the variance respectively. The first EOF is identified as the AO, the second apparently includes variability that is partly identified with the more localized NAO, and the third is dominated by the variability of the Aleutian low. Plate 1 also displays the first three EOF patterns calculated from observations for the period 1900-1992 (updated from Trenberth and Paolino, 1980), with EOF2 and EOF3 interchanged to make the correspondence with the simulated patterns clearer. These first three observed EOFs account for 18, 12, and 11 percent of the variance. The observed and simulated patterns are remarkably similar and account for similar percentages of the variance, although the midlatitude centers of action in the simulated AO are somewhat weaker than observed. All the EOFs displayed in Plate 1 are separated according to the criterion of *North et al.* [1982]. In the southern hemisphere the first EOF dominates the variability in the simulations (observations are not readily available) and accounts for 28 percent of the variance.

Plate 2 displays both the AO and AAO and the associated regression maps of surface air temperature (SAT) and mean zonal wind ([U]) for the control simulation. The simu-

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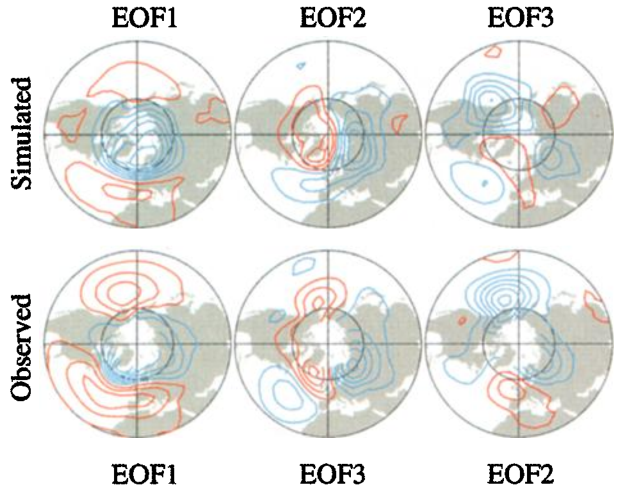

Plate 1. Leading EOF patterns of the November-April monthly mean SLP anomaly fields as calculated from the 200-year control simulation and 1900-1992 observations (scaled by the standard deviation of their associated principal component (PC) time series). Contour intervals are 1 hPa (...-1.5,-0.5,0.5...) with blue and red (or pink) contours indicating negative and positive values, respectively. Observational grids points with less that 25 percent temporal coverage are excluded from the calculation.

lation results are remarkably similar to those based on observations in TWb (their Plates 4 and 9) including, perhaps fortuitously, the asymmetry in the temperature pattern across Antarctica. The coupled model produces a robust and realistic AO and AAO.

Plate 3 displays the same results as Plate 2 for one of the GHG+aerosol forced simulations (all of which give similar results). Plate 4 gives the principal component (PC) time series (i.e. the amplitude) of the AO and AAO from the observations, the control simulation, and each of the three

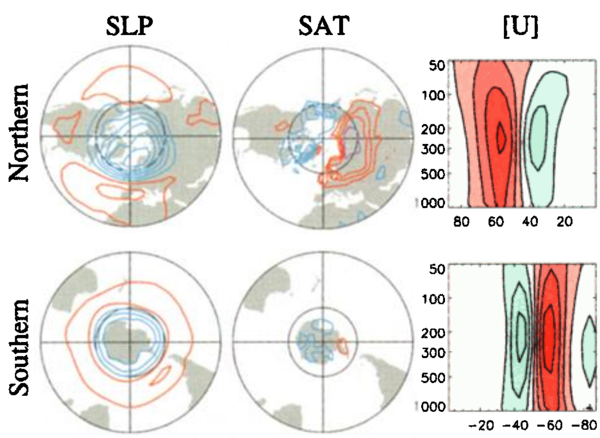

Plate 2. The AO and AAO and associated regression patterns of November-April SAT and zonal-mean zonal wind. Contours for SLP, SAT and [U] are 1 hPa (...-1.5,-0.5,0.5...), 0.5°K (...-0.75,-0.25,0.25...) and 0.5 m/s (...-0.75,-0.25,0.25...), respectively

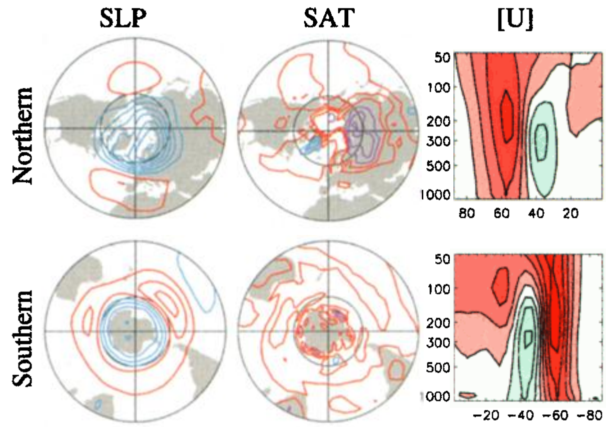

Plate 3. As in Plate 2, but for a climate change simulation from 1900-2100 with greenhouse gas and aerosol forcing.

forced GHG+aerosol warming simulations. The forced climate change simulations all show a trend to increasingly positive values (the positive phase of the AO/AAO has lower pressures over the polar regions) which is absent in the unforced control simulation. Whereas lower tropospheric anomalies appear coupled to month-to-month fluctuations of the winter stratospheric polar vortex (*Baldwin et al.*, 1994; *Perlwitz and Graf*, 1995; *Cheng and Dunkerton*, 1995; *Kitoh et al.*, 1996; *Kodera et al.*, 1996; TWa, b) the connection of the AO and AAO to the stratosphere does not appear to play a controlling role in the forced change we see here since the model does not resolve the stratosphere in any detail. This is in constrast to *Shindell et al.* [1999], who conclude that a detailed stratosphere is required to capture an AO trend in their model.

The AO and AAO represent dynamical and linked thermodynamical behaviour of the system and account for an important part of the variance. A change in the behaviour of the AO and AAO under forced climate change could take a number of forms. The AO/AAO could exhibit no change, although this is not the case for the CCCma coupled model (while it is the case for some models according to *Shindell et al.*, 1999). The AO/AAO could express the forced climate change as a change in the frequency of the modes as suggested by *Palmer* [1993]. This would seem to imply that the PC time series of Plate 4 would preferentially exhibit positive values but also that the (less frequent) negative values would still span the same range of values. This is not the case in Plate 4 where both positive excursions increase and negative excursions decrease in tandem. The AO/AAO could exhibit important changes in structure and there is some suggestion for this in Plate 3.

Alternatively, the AO/AAO could be essentially unchanged but superimposed on the forced climate change in mean sea-level pressure, temperature and zonal wind. This is the case here. The linear trend in the first PC time series of Plate 4 is removed and the detrended series is used to construct Plate 5 which is virtually identical to Plate 2 from the unforced control simulation. This detrending procedure is equivalent to removing the linear trend (shown in Plate 6) from the mean sea-level pressure itself. The modelled AO/AAO behaviour (i.e. amplitude and structure) in

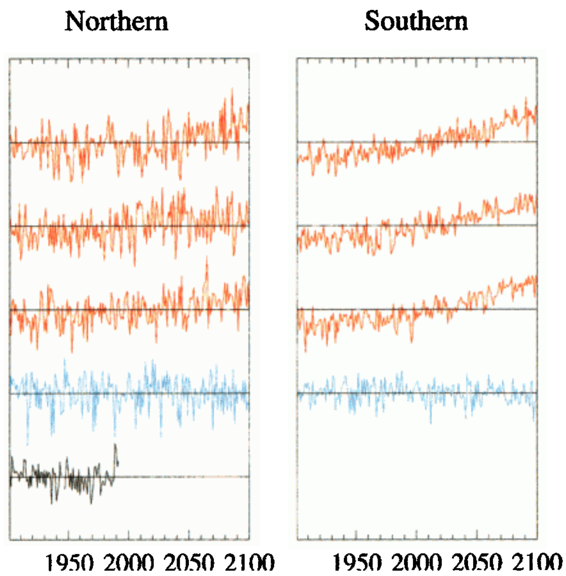

Plate 4. AO and AAO PC time-series (November-April averages). Black curve: observed; blue curve: control simulation; Red curves: transient simulations.

a warmer world has not changed fundamentally but rather is superimposed on the forced climate change.

The upper panels in Plate 6 show the patterns of forced climate change in SLP as the average rate of change (or trend) over the period. The lower panels show how these trends are represented in terms of the first ten EOFs. In the southern hemisphere, essentially all of the trend projects onto the first EOF (the AAO). This is not the case in the northern hemisphere where the trend is projected on the first EOF (the AO) but even more strongly on the third EOF. The latter reflects a deepening of the Aleutian Low in the pattern of mean climate change. Both the first and second EOFs are significantly correlated with the usual NAO index (correlation coefficients are 0.84 and 0.35 respectively);

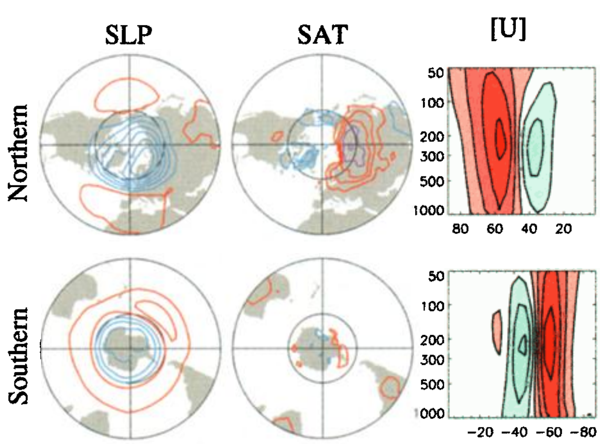

Plate 5. As in Plate 3, but constructed from the PC time-series with the trend removed.

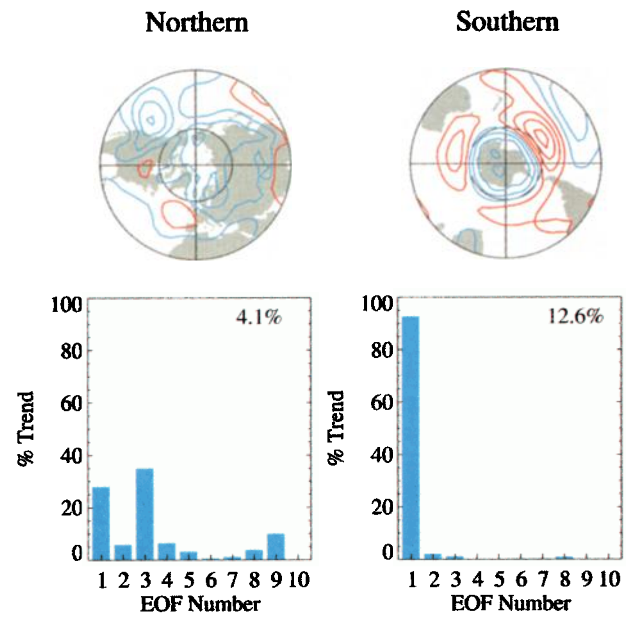

Plate 6. Top: Simulated SLP mean climate trends (contours are 1.0 hPa/century). Bottom: Percentage of trend variance explained by each EOF. The number in the upper-right of each panel is the percentage of total variance accounted for by the forced trend.

however, the modelled NAO index (not shown) has no apparent trend. The upper left panel of Plate 6 shows that both Iceland and the Azores lie near minima in the SLP trend, indicating that the forced climate change projects in such a way as to have little influence on the NAO index. The implication here is that the NAO index may not be a particularly sensitive indicator of climate warming.

The pattern of forced climate change may resemble one or more states of the system's dominant modes of variation if both are controlled and amplified by the same mechanisms and feedbacks (see *Reader and Boer,* 1998 and *Fyfe and Flato,* 1999 for a discussion in the context of aerosol effects and elevation effects, respectively). As well as the trends in the AO/AAO discussed here, a number of coupled models exhibit an "El Nino-like" response in the tropical Pacific (e.g. *Meehl et al.,* 1997; BFR). The extent to which this is a general result and the reasons for exceptions to it (such as the lack of a mean El Nino response and/or of an AO/AAO trend in some models) deserves further study.

3. Summary

The CCCma coupled general circulation model exhibits a robust and realistic AO and AAO in its control simulation. Observations suggest a recent positive trend in the AO, possibly associated with global warming. The simulated AO and AAO show a positive trend in forced climate change simulations. The model results suggests that this results from the combination of an essentially unchanged AO/AAO superimposed on a forced climate change pattern. The forced climate change pattern projects almost exclusively on the AAO pattern in the southern hemisphere but not in the northern hemisphere where other EOFs are involved.

The results do not suggest stratospheric involvement in the evolution of the AO/AAO nor that the forced climate change is expressed as a change in the occurence of one phase of the AO/AAO over another. The extent to which the forced climate change pattern and the unforced modes of variation are determined by the same mechanisms and feedbacks remains to be determined.

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