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Tropical links of the Arctic Oscillation

Hai Lin and Jacques Derome

Department of Atmospheric and Oceanic Sciences and Centre for Climate and Global Change Research, McGill University, Montreal, Quebec, Canada

Richard J. Greatbatch, K. Andrew Peterson and Jian Lu

Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada

Hai Lin, Department of Atmospheric and Oceanic Sciences and Centre for Climate and Global Change Research, McGill University, 805 Sherbrooke Street West, Montreal, PQ, CANADA H3A 2K6. (hai.lin@mcgill.ca)

Abstract. A primitive equation dry atmospheric model is used to investigate the response of the Arctic Oscillation (AO) to diabatic forcing. Integrations are made for 51 winter seasons (DJF) from 1948/49 to 1998/99. For each winter the model uses a time-averaged forcing that is calculated empirically from the NCEP/NCAR reanalyses. The ensemble mean of the simulations reproduces much of the observed AO interannual variability. Two additional sets of experiments are conducted. In one case the interannually varying forcing is prescribed only in the tropics, while in another it is prescribed only in the extratropics. These simulations indicate that a significant part of the interannual variability of the wintertime AO, as well as its trend, is linked to forcing from the tropics, and that extratropical forcing has no role to play, independent of the tropical forcing, in reconstructing the observed AO variability.

1. Introduction

The Arctic Oscillation (AO) is the dominant mode of atmospheric mean-monthly sea level pressure variability over the Northern Hemisphere with an out-of-phase relation between the sea level pressure over the Arctic basin and that at the midlatitudes [*Thompson and Wallace*, 1998]. The interannual and longer-term changes in the wintertime AO have an enormous impact on the climate of the Northern Hemisphere [*Thompson and Wallace*, 2001]. The North Atlantic Oscillation (NAO), whose amplitude is commonly represented by the normalized sea-level pressure difference between stations in the Azores (or Portugal) and Iceland, the NAO index, has long been recognized as the major circulation pattern influencing weather from eastern North America to Europe [*Rogers*, 1990; *Hurrell*, 1995, 1996; *Greatbatch*, 2000]. It is often seen as a regional expression of the AO [*Wallace*, 2000], though a consensus on this point has yet to be achieved [*Ambaum et al.*, 2001; *Deser*, 2001; *Thompson and Wallace*, 2002].

Studies based on atmospheric general circulation models (AGCM) have shown that much of the NAO variability (time scales of 6 years and longer) can be reconstructed from a knowledge of global sea surface temperature (SST) and sea-ice anomalies [*Rodwell et al.*, 1999; *Mehta et al.*, 2000; *Latif et al.*, 2000]. In a recent study, *Peterson et al.* [2002] (hereafter *PGLLD*) used a simple atmospheric model to hindcast the NAO index time series using forcing derived from observations during the period 1948-1999 and obtained a correlation of 0.79 between the model ensemble mean and the observed NAO index. They were able to show that the variability (trend plus interannual variability) of the observed NAO index is better correlated with the model NAO index forced by the extratropical forcing (correlation of 0.55) than with that forced by the tropical forcing (0.39). The upward trend in the index, however, was found to be related to the tropical forcing. The latter result is consistent with *Hoerling et al.* [2001] who suggest that the recent upward trend in the NAO index has a tropical origin. In this paper we show that tropical forcing plays a significant role both in the interannual variability and the trend of the AO. The extratropical forcing has no independent role in reconstructing the AO variability. The different influence of the extratropical forcing on the AO and NAO, which are themselves correlated, is discussed.

2. Methodology

The model used and experimental design in this study are the same as those of *PGLLD*. Briefly, we use a primitive equation dry atmospheric model as described in detail in *Hall* [2000] and *Hall et al.* [2001a, b]. An important difference between this model and a full AGCM is that this model uses a time-averaged forcing calculated empirically from observed daily data. As in *PGLLD* our forcing is computed from the NCEP/NCAR reanalyses [*Kalnay et al.*, 1996] in the manner of *Hall* [2000], thereby ensuring consistency with the model. More specifically, the forcing is obtained as the residual in the model's time tendency equations, when the dynamical terms, including a linear damping of velocity and temperature, are evaluated with observations and the equations are averaged over time. This forcing thus includes all processes that are not resolved by the model's dynamics such as diabatic heating (including latent heat release related to the transient eddies) and boundary processes. The model has a T21 horizontal resolution and five levels in the vertical. With a forcing that is averaged over several winters, the model reproduces rather well the time-averaged state and transients of the observed atmosphere [*Hall*, 2000]. In our case, to represent the interannual variability a forcing field is calculated separately for each of the 51 winters (December, January and February) (DJF) from 1948/49 to 1998/99. As in *PGLLD*, an ensemble of 30 members of 4 month integrations is conducted for each winter. The initial conditions for the individual runs are randomly chosen from the winter daily data in the NCEP/NCAR reanalyses. The analysis is done over the final 3 months in order to allow time for the model to adjust to the forcing.

An EOF analysis is conducted on detrended DJF mean sea level pressure (SLP) north of 20°N using the NCEP/NCAR reanalyses. The first mode corresponds to the Arctic Oscillation of *Thompson and Wallace* [1998] and accounts for about 30% of the total variance. The AO index, whether for the model output or the observations, is calculated as the projection of the seasonal mean SLP on this first EOF, normalized by the standard deviation of the observed Principal Component (PC) of this mode.

3. Results

In the first set of experiments the model is driven with the forcing specified over the global domain for each winter. Figure 1a shows curves of the AO indices for the model ensemble average and for the observations. The model simulates rather well the observed interannual variability of the AO as well as its upward trend, with a correlation of 0.61 that is significant at the 99% confidence level. With the linear trend removed the correlation is 0.55, again significant at the 99% confidence level. **Figure 1**

When the model ensemble mean AO index is regressed against the ensemble mean SLP, the resulting structure (Figure 2) is very similar to that of the observed AO [*Thompson and Wallace*, 1998], showing that the model is able to reproduce the observed structure of the AO as well as a significant fraction of its time variability. **Figure 2**

To see the relationship between the AO variability and the forcing field, linear regressions between the global vertically averaged thermal forcing and the time series of the observed and simulated AO indices are calculated and shown in Figure 3. A belt of heating with a maximum south of the equator around the global tropics is associated with the positive phase of the AO. **Figure 3**

To isolate the role of the interannual variability of the tropical forcing, a second set of experiments is conducted by driving the model with a forcing that varies interannually only in the tropics (30°S-30°N), while it is kept at its climatological average over the 51 DJFs elsewhere. The resulting AO index for the model ensemble average is shown in Figure 1b. As can be seen, with only the tropical forcing anomalies the model is still capable of reasonably simulating the variability of the AO and its upward trend. The correlation between the ensemble mean AO index and the observed AO index is 0.54, and 0.49 after removing the linear trend. Both correlations are significant at the 99% confidence level. The link between the interannual variability in the AO and the tropical forcing is thus evident.

In the third set of experiments we force the model with the derived interannually-varying forcing only in the extra-tropics, and the DJF climatological forcing in the tropics. This time, no correlation ($|r| < 0.01$) can be found between the ensemble mean AO index and the observed AO index, indicating that the extratropical forcing plays no role, independent of the tropical forcing, in generating the observed AO index.

The above result should be compared with our previous work on the NAO (rather than the AO) which showed that the extratropical forcing is an important source of the NAO interannual variability [*PGLLD*]. The different relationships between the extratropical forcing on the one hand, and the AO and NAO on the other, may appear surprising in view of the high correlation between the AO and the NAO. In our data set (same as *PGLLD*) this temporal correlation is 0.81. This means that about 34% of the variance in the NAO index is not linearly related to the AO index, which makes it possible for the NAO to be partly related to the extratropical forcing, while the AO is not. To illustrate this, we show in Table 1 the correlations between the NAO index and the PCs of the first 6 EOFs calculated from the DJF mean SLP of the NCEP/NCAR reanalyses. The NAO index is calculated as the difference in normalized SLP between the grid points of (10°W,40°N) and (20°W, 65°N), close to Portugal and Iceland, respectively. The correlation of our NAO index with Hurrell's index [*Hurrell*, 1995] which was calculated from station data is 0.95. As already mentioned, the NAO index is well correlated (0.81) with the AO index (PC of EOF 1), which means that about 66% of the variance of interannual variability of the NAO index is associated with that of the AO. The AO, however, is not the only EOF mode that is correlated with the NAO index. The correlations of the NAO index with the PCs of EOF 3 and EOF 4 are 0.31 and 0.37, respectively. The horizontal structures of EOF 3 and EOF 4 are shown in Figure 4, both of which have SLP values of opposite signs over Portugal and Iceland as in the NAO. Thus the NAO index includes signatures of multiple EOFs. The correlations between the projections of the ensemble average SLP of the extratropical forcing experiments to the first 6 EOFs and the corresponding observed PCs are shown in Table 2. In contrast to EOF's 1 and 2, the PC's of the following 4 EOF's have significant correlations (95% level) between the simulations and the observations, indicating that the extratropical forcing is a significant source of interannual variability for these EOF's. The fact that the NAO index includes signatures of these EOF's explains why in *PGLLD* the

Table 1

Figure 4

Table 2

correlation between the simulated and the observed NAO indices is high (0.55) for the extratropical forcing case. In short, in *PGLLD* the extratropical forcing influences the higher EOF's, and their projection onto the NAO index results in a relation between the extratropical forcing and the NAO index as defined in that study.

4. Conclusions and Discussions

Based on experiments with a simple general circulation model, we have shown that the interannual variability and upward trend of the winter Arctic Oscillation are correlated with the tropical forcing. A positive phase of the AO is associated with a belt of heating along the global tropics with a maximum south of the equator. For the genesis of the AO, a common understanding is that atmospheric internal processes involving eddy-mean flow interactions play an important role [*Kidson and Watterson*, 1999; *von Storch*, 1999; *Limpasuvan and Hartmann*, 1999]. Our study reveals another important source for the AO variability, namely, the tropical forcing. It is possible that the above two sources of AO variability are related, but that remains an open question.

Several studies [*Rodwell et al.*, 1999; *Mehta et al.*, 2000; *Latif et al.*, 2000] argue that the NAO variability is partly forced by global SST and sea-ice anomalies and *PGLLD* demonstrate an important role for forcing in the extratropics. We have found that although the NAO and AO indices are highly correlated, the NAO variability is linked to the middle latitude forcing, whereas the AO is not. The reason for this is that, when defined by a two-point index involving the SLP over Portugal and Iceland, the NAO index tracks not only the time evolution of the AO (the first EOF; correlation of 0.81) but also that of higher EOF's. The latter are correlated with midlatitude forcing, and induce a correlation between the NAO and the midlatitude forcing.

The mechanism responsible for the link between the AO and the tropical forcing is not yet clear. The enhancement of midlatitude westerly and transient eddies related to tropical heating may contribute. Further observational and/or modeling studies will be required to fully understand the connection between the AO and the tropics.

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Figure 1. Time series of the AO indices. Dotted lines are from the NCEP/NCAR reanalysis, and solid lines are the ensemble means. Error bars represent ranges of one standard deviation among ensemble members. a) Full forcing; b) tropical forcing; c) extra-tropical forcing.

Figure 2. Linear regression of the ensemble mean SLP onto the ensemble mean AO index for the full forcing experiments. Amplitudes are pressure in hPa corresponding to one standard deviation of the AO index. The contour interval is 1 hPa. Dashed lines represent negative values.

Figure 3. Linear regression of vertically averaged thermal forcing onto a) the observed AO index; b) the ensemble mean AO index for the full forcing experiments. Amplitudes are heating in K°/day corresponding to one standard deviation of the AO index. The contour interval is 0.3 K°/day.

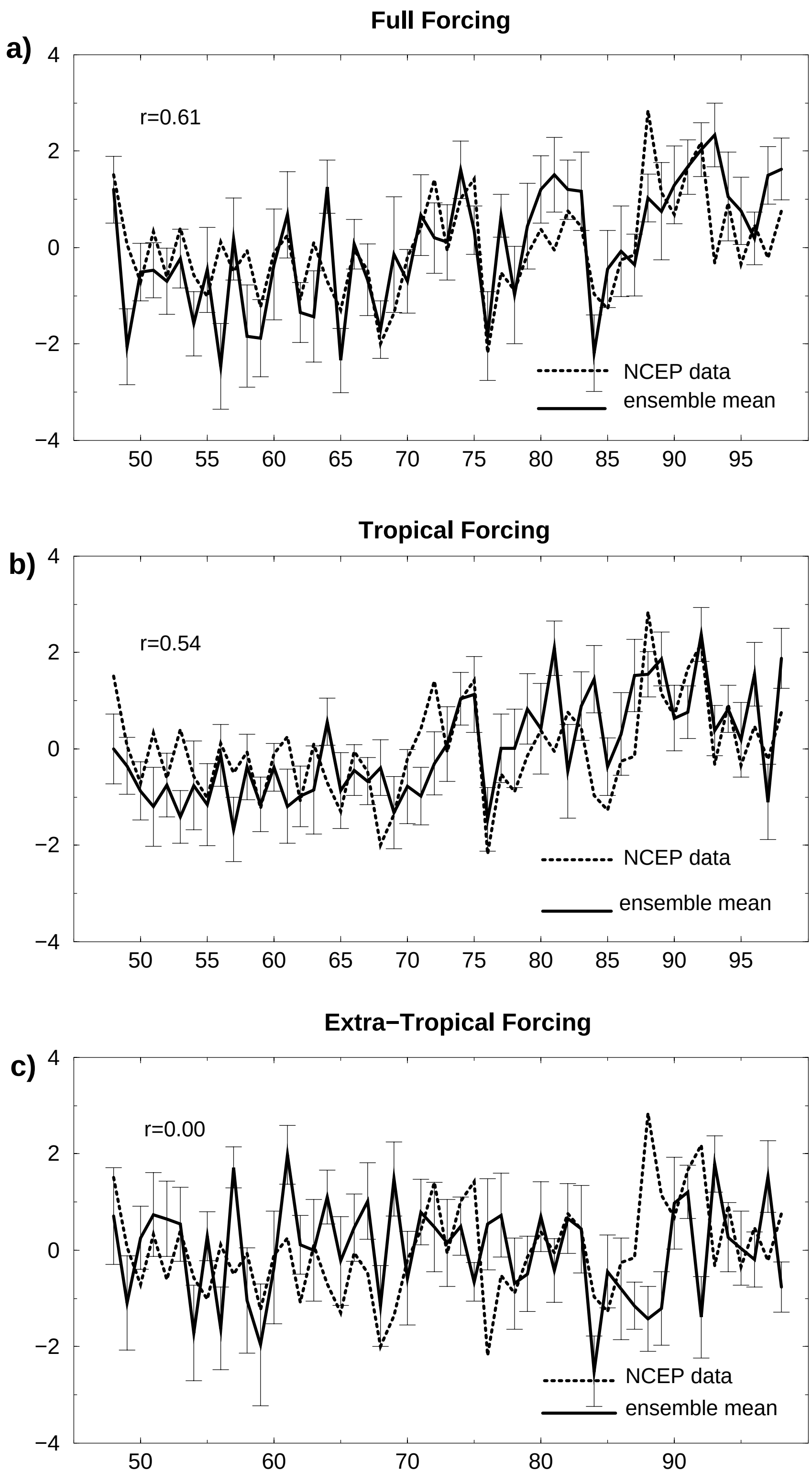
Figure 4. Linear regressions of sea level pressure (SLP) onto the PC of a) EOF 3, and b) EOF 4. Amplitudes are pressure in hPa corresponding to one standard deviation of the PC. The contour interval is 0.5 hPa.

Table 1. Correlations between the NAO index and PCs of EOFs. Numbers in bold represent correlations that are significant at a confidence level higher than 95% (or $t <$ 0.05).

EOF index	1	2	3	4	5	6
Correlation	**0.81**	0.17	**0.31**	**0.37**	-0.01	-0.02
t value	0.000	0.232	0.029	0.007	0.949	0.864

Table 2. Correlations between the projections of the ensemble average of the extra-tropical forcing experiments to the first 6 EOFs and the corresponding observed PCs. Numbers in bold represent correlations that are significant at a confidence level higher than 95% (or $t < 0.05$).

EOF index	1	2	3	4	5	6
Correlation	0.00	0.08	**0.31**	**0.45**	**0.52**	**0.40**
t value	0.976	0.568	0.029	0.001	0.000	0.004



Full Forcing
a)
r=0.61
NCEP data
ensemble mean
Tropical Forcing
b)
r=0.54
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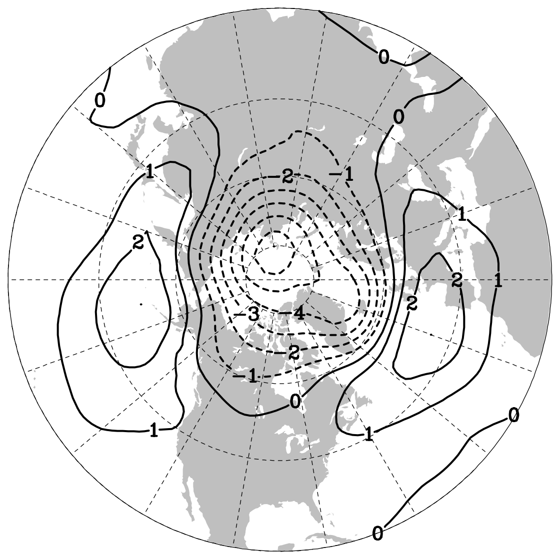
Extra−Tropical Forcing
c)
r=0.00
NCEP data
ensemble mean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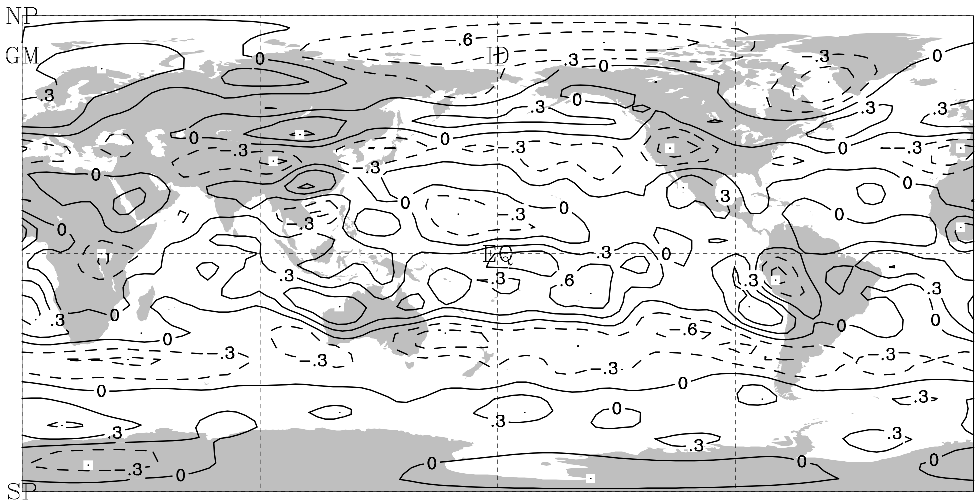
a)



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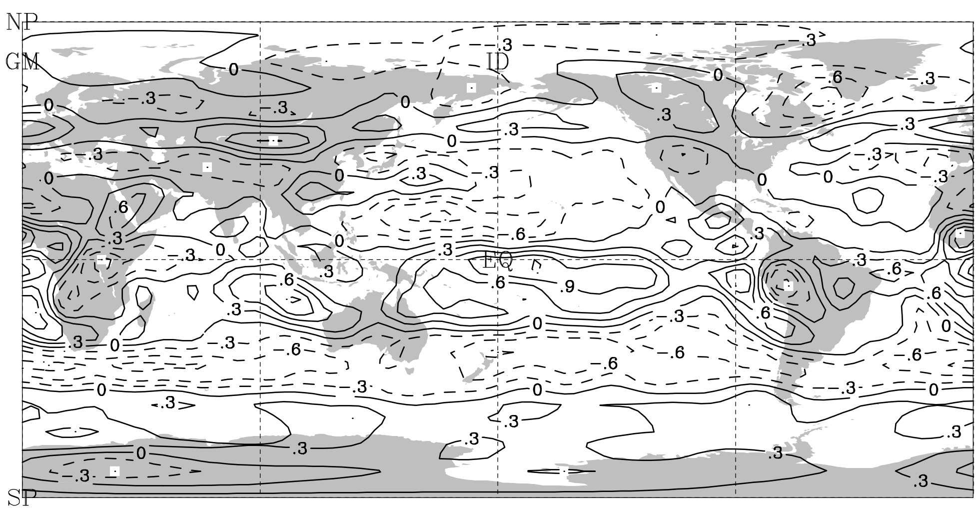
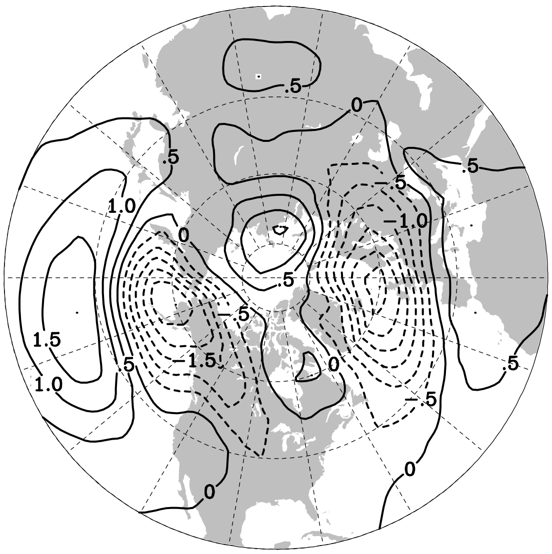


a) EOF 3



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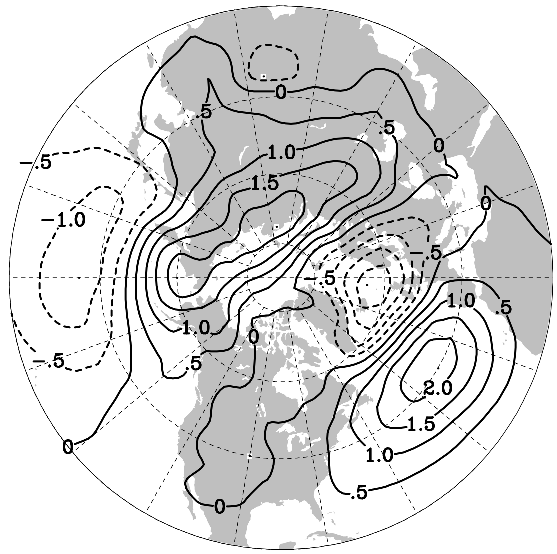

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