Hindcasting the NAO using diabatic forcing of a simple AGCM

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Abstract. A primitive equation dry atmospheric model with a rudimentary representation of the model physics is used to hindcast the winter NAO using diabatic forcing diagnosed from NCAR/NCEP reanalysis data in the period 1949-1999. Using ensembles of experiments we are able to reproduce the observed NAO index in the ensemble mean with a correlation of 0.79. By prescribing time dependent forcing only in the tropics (30^oS–30^oN), or only in the extratropics, we show that the recent upward trend in the NAO is related to tropical forcing. The implication is that coupling with the mid-latitude or Arctic ocean is not important for the trend. The model also exhibits the recent eastward shift in the sea level pressure signature of the interannual NAO variability and shows that this is associated with non-linear dynamical processes.

1. Introduction

The North Atlantic Oscillation (NAO) is the most important mode of atmospheric variability for climate in and around the North Atlantic [See *Hurrell*, 1995, 1996; *Greatbatch*, 2000, and references therein]. As such, much research has gone into attempting to hindcast the NAO using historical sea surface temperature (SST) and sea ice anomalies from the global ocean [*Rodwell et al*, 1999; *Mehta et al*, 2000; *Latif et al*, 2000; *Hoerling et al*, 2001]. Most notably, *Rodwell et al* [1999] were able to reproduce the low frequency (> 6.5 years) variability of the NAO in an ensemble of experiments using an atmospheric general circulation model (hereafter AGCM), whilst *Hoerling et al* [2001] were able to show a possible link between tropical SST anomalies and the recent upward trend in the NAO index. However, *Bretherton and Battisti* [2000] raise some questions as to the interpretation of these experiments, since the SST anomalies, especially in the North Atlantic, may simply be a symptom of forcing by the NAO. In addition, the ability of different AGCM's to accurately hindcast the NAO is a function of their response to SST anomalies. There is still a great deal of ongoing research and uncertainty in regards to this issue, especially an AGCM's response to midlatitude SST anomalies [*Kushnir et al*, 2001; *Barsugli and Battisti*, 1998; *Frankignoul*, 1985]. Here, we bypass this last issue by investigating the response of a simple AGCM to specified diabatic forcing computed from observations. The forcing used to drive the model contains all the diabatic heating, including that which is not a direct result of oceanic forcing.

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2. Methodology

We use a simplified primitive equation AGCM based on dry dynamics and constant forcing [*Hall*, 2000; *Hoskins and Simmons*, 1975]. A detailed description of the model may be found in *Hall* [2000] and *Hall et al* [2001a, b], as well as a demonstration of the model's ability to adequately represent the observed atmospheric state. The model also reproduces a realistic NAO with centers of action near Iceland and Portugal. Time independent forcing terms, which are a proxy for the diabatic heating, are calculated for each winter (December-February) in the period 1949-1999 from the NCAR/NCEP reanalysis [*Kistler et al*, 2001] following the method discussed in *Hall* [2000]. It should be noted this method uses only the large scale fields from the reanalysis, which are strongly constrained by the input observations, and does not use the diabatic heating computed by the reanalysis itself. An ensemble of 30 model experiments is carried out for each winter separately, the ensemble members differing only in the choice of initial condition, these being chosen randomly from the 4550 realizations of winter daily data available in the NCAR/NCEP reanalysis. Each ensemble member is integrated for 4 months and the analysis is carried out on the final 3 months. The NAO index is calculated using the difference in normalized sea level pressure (hereafter SLP) between the model's Gaussian grid boxes located over Portugal and Iceland respectively, and compared with the NAO signature in the NCAR/NCEP reanalysis projected onto the same Gaussian grid. In all cases the SLP anomalies used to calculate the NAO index are normalized by the standard deviation of the winter SLP anomalies in the NCAR/NCEP data set. The NAO index calculated from the NCAR/NCEP reanalysis is essentially the same as that of *Hurrell* [1995][1], the correlation between the two indices being 0.95.

Due to the inherent simplicity of the model, we are able to run large member ensembles (typically 30 members), with multiple forcing regimes. This represents a vast improvement in statistics over what a full AGCM may offer. As well, since the diabatic forcing in our model is specified from data, our model has the advantage of eliminating some of the uncertainty in the way fully interactive AGCM's compute diabatic heating.

3. Results

In our first set of experiments we force the model with the derived forcing specified over the global domain. Fig. 1a shows a plot of the model's NAO index for each ensemble member (dotted blue lines), the ensemble average (dashed red line), as well as the observed NAO index as derived from the NCAR/NCEP reanalysis (solid green line). The agreement between the model results and the reanalysis is remarkable. The NAO index for the ensemble mean and the NAO index calculated from the reanalysis correlate at 0.79, significantly different from zero at the 99% confidence level. Likewise the average correlation between an individual ensemble member's NAO index with the NCAR/NCEP NAO index is 0.74. Note also that since the NAO index in all cases is normalized using the NCAR/NCEP data, the amplitudes of the curves in Fig. 1 can all be compared directly. This shows that the amplitude of our model response is comparable to that in the observations. We have also regressed the model's ensemble mean SLP against the ensemble mean NAO index and obtain a pattern in amplitude and shape similar to that in the reanalysis data (not shown).

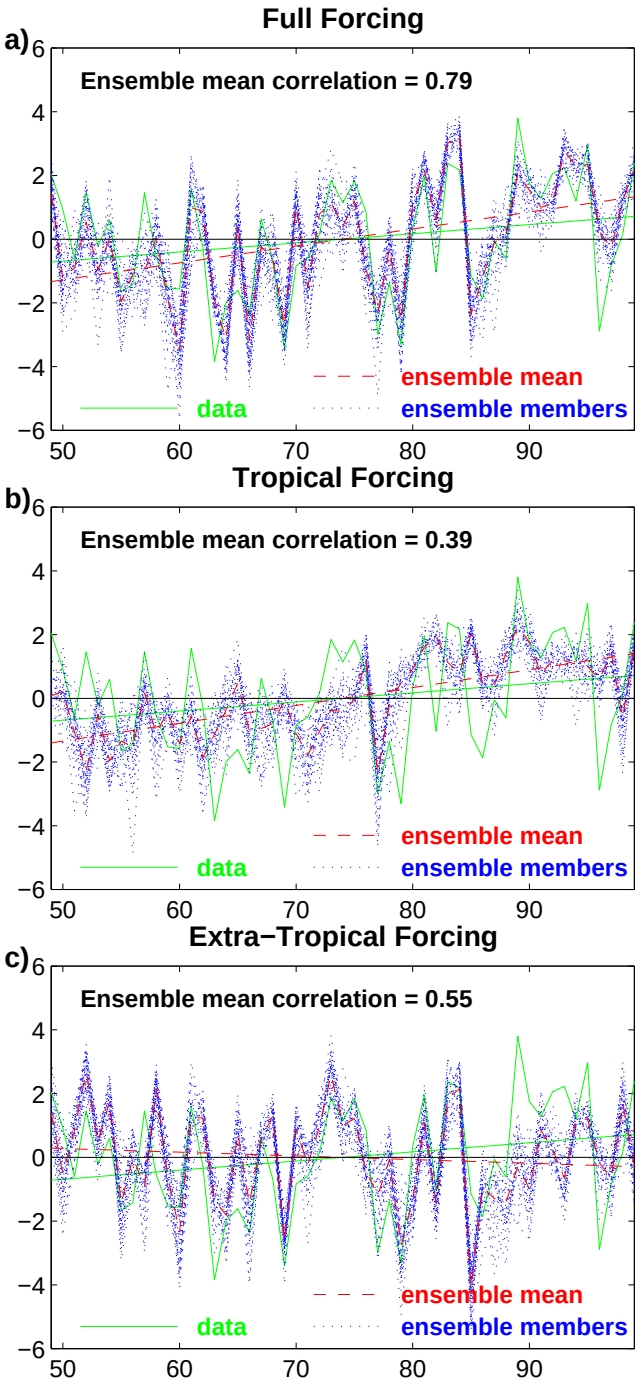

Figure 1. Time series of NAO for three different forcing scenarios. Dotted blue lines are the individual ensemble members, dashed red lines are the ensemble means, and the solid green lines are from NCAR/NCEP data. Linear lines underlying time series are linear trends. a) Full forcing, b) tropical forcing, c) extra-tropical forcing.

In a previous study *Hoerling et al* [2001] found that non-local effects outside the North Atlantic may be quite influential on the low frequency behaviour of the NAO. In an effort to address this question, we have forced our model using the derived forcing only in the tropics (30°S–30°N), and the climatological average forcing for the 51 years elsewhere in the domain. In addition, the complementary set of experiments was performed with the derived forcing only in the extra-tropics. The NAO index from these two sets of experiments is shown in Fig. 1b and Fig. 1c respectively. For the ensemble mean, the correlation with the observed NAO index is 0.55 for the extra-tropical forcing case and 0.39 for the tropical forcing case, showing that the extra-tropical forcing is more influencial overall. However, the extra-tropical forcing case lacks the observed upward trend in the index during the simulation period. The trends in the NAO index for all three forcings, along with the trend in the observed data are shown by the straight lines in Fig. 1. One can clearly see that the trend in the full forcing and tropical forcing cases are very similar, and both are in reasonable agreement with the observed trend. In agreement with *Hoerling et al* [2001] we conclude that tropical forcing is required to account for the upward trend. By corollary, coupling with the mid-latitude or Arctic oceans does not appear to be important since such coupling would require a signature in the extra-tropical forcing seen by the model and hence in the set of extra-tropical forcing experiments.

Hilmer and Jung [2000] have identified an eastward shift in the spatial structure of the NAO that took place around 1980. We have regressed the detrended ensemble mean SLP anomalies against the detrended ensemble mean NAO index separately for the two periods 1958-1977 and 1978-1997 considered by *Hilmer and Jung* [2000]. The difference between these two fields is plotted in Fig. 2, as well as the result of the same analysis applied to the NCAR/NCEP data. It should be noted that the areas of significant correlation between SLP and the NAO index are essentially as shown in *Hilmer and Jung* [2000] even though our analysis is applied to December-February whilst *Hilmer and Jung* [2000] also include March. The generally good agreement between

model and observations shows that our model reproduces the eastward shift.

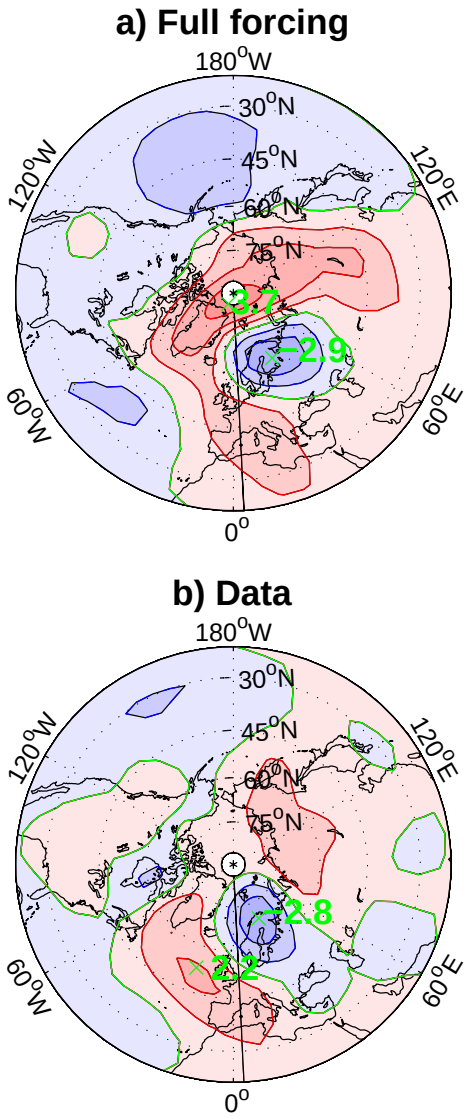

Figure 2. Difference between ensemble mean SLP regressed against ensemble mean NAO for periods 1978-1987 minus 1958-1977. Both NAO and SLP have been detrended separately for each period. a) Full forcing case, b) NCAR/NCEP reanalysis data. Contour interval is 1 mb.

Fig. 3 shows the difference in the detrended SLP regressed against the detrended NAO index, 1978-1997 minus 1958-1987, for each of the tropical and extra-tropical ensemble means. Although the extra-tropical and tropical forcing cases have features in common with the full forcing case and the observations, especially the tropical forcing case, it is clear that the shift can only be accounted for by the full forcing case. Also shown is the same difference in the regressed SLP pattern, this time for an ensemble of experiments with global anomalous forcing obtained by linear regression of the forcing against the observed NAO index. In this case, there is again good agreement with the observed difference field shown in Fig. 2, except for a reduction in amplitude. It is important to realize that the spatial pattern of the anomalous forcing in this experiment is the same for every year, differing only in its amplitude which is given by the observed NAO index. If the dynamics is linear, then the model response would have the same spatial structure in every year and there would be no eastward shift. The presence of the eastward shift in Fig. 3c can therefore be attributed to non-linear dynamical processes.

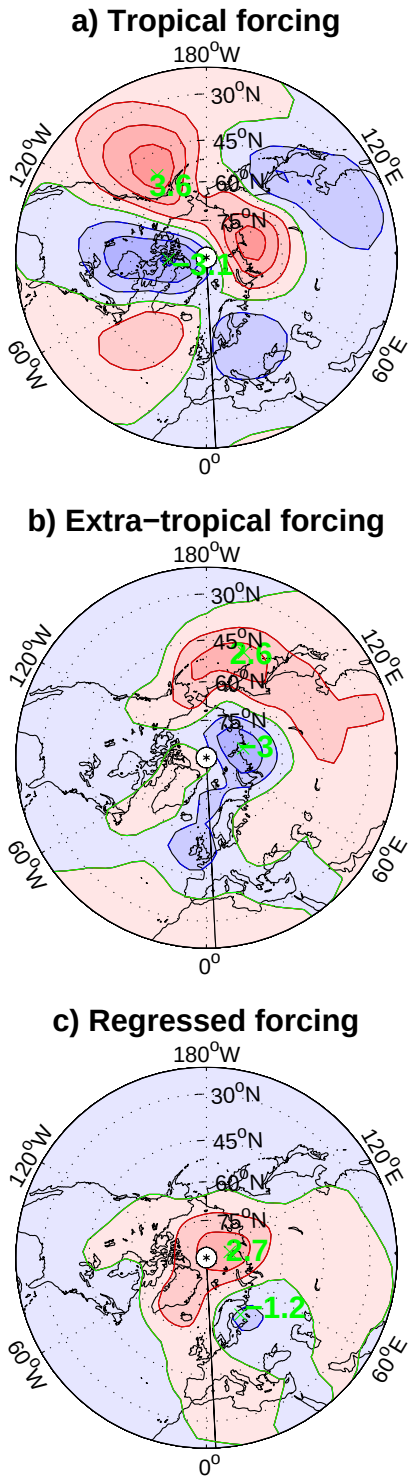

Figure 3. Same as Fig. 2, except for a) tropical forcing case, b) extra-tropical forcing case, c) regressed forcing case. Contour interval is 1 mb.

4. Conclusion and Summary

We have investigated the structure and variability of the NAO using a primitive equation model driven by time independent diabatic forcing derived for each of the winters 1949-1999. Using global forcing we find that we can realistically hindcast the winter NAO for this period. Furthermore, the model also reproduces the eastward shift in the NAO pattern from the 1958-1977 to the 1978-1997 period reported by *Hilmer and Jung* [2000]. In the model the eastward shift is induced by non-linear dynamical processes. Confining the variability of the forcing to only tropical or extra-tropical regions leads us to believe that interannual variability in the NAO is related to both extra-tropical and tropical forcing, whilst the low frequency variability (upward trend in this period) is related to forcing in the tropics. By corollary, coupling with the mid-latitude or Arctic ocean is not important for the recent upward trend in the NAO.

In our study the model is driven by diabatic forcing that is essentially computed from observations and so includes the influence of SST anomalies implicitly. It follows that the success of our study confirms the results obtained by *Rodwell et al* [1999]; *Mehta et al* [2000]; *Latif et al* [2000] and *Hoerling et al* [2001] using AGCM's driven by observed SST and sea-ice anomalies. The higher correlation we obtain here between our ensemble mean NAO index and the observed NAO index can be attributed to the forcing seen by our model, which also includes observed diabatic effects related to internal atmospheric dynamics and other external forcing. As cautioned by *Bretherton and Battisti* [2000] our results do not necessarily imply predictability of the NAO because of the difficulty in actually predicting the diabatic forcing.

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Notes

1. Or see http://www.cgd.ucar.edu/~jhurrell/nao.html

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