Evidence of nonlinear dynamics in the eastward shift of the NAO

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

Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada B3H 4J1

Abstract. *Hilmer and Jung* [2000] have identified an eastward shift in the sea level pressure (SLP) pattern associated with interannual variability of the North Atlantic Oscillation (NAO) that took place around 1980. We investigate the nature of the eastward shift using a primitive equation, dry atmospheric model driven by diabatic forcing diagnosed from observations. The model results reveal the nonlinear dependence of the spatial pattern of the NAO on the NAO index, the pattern being shifted to the east (west) for high (low) NAO index. General agreement is found between the model and observations. We suggest that the eastward shift noted by *Hilmer and Jung* [2000] is a consequence of the trend towards higher NAO index during the last several decades of the 20th century.

1. Introduction

The North Atlantic Oscillation (hereafter, NAO) is one of the primary modes of variability in the northern hemisphere winter atmospheric circulation [See *Hurrell*, 1995, 1996; *Greatbatch*, 2000, and references therein]. Recently, *Hilmer and Jung* [2000] have noticed an eastward shift in the sea level pressure (SLP) pattern associated with interannual variability of the NAO index, when comparing the period 1978-1997 (P2) with the earlier period, 1958-1977 (P1). The eastward shift appears to be unprecedented in the 20th century [*Jung and Hilmer*, 2001]. *Lu and Greatbatch* [2002] show that the eastward shift was associated with the emergence of a spatially coherent climate regime during P2 in which the NAO index, sea ice export through Fram Strait, Siberian wintertime temperature and North Atlantic storm activity all became significantly correlated with each other. *Jung et al* [2002] further describe additional evidence and effects of the eastward shift on North Atlantic and Eurasian climate and *Beniston and Jungo* [2002] note the increased dependence of Swiss Alpine climate on the NAO index during the last decades of the 20th century. *Mächel et al* [1998] have also noted interannual changes in the location of the centres of action of the NAO. Finally, an eastward shift is found in the ECHAM/OPYC3 coupled model in association with increasing greenhouse gas forcing [*Ulbrich and Christoph*, 1999], suggesting a possible link to anthropogenic climate change.

In a previous paper *Peterson et al* [2002] (hereafter PGLLD) described a dry atmospheric model driven by diabatic forcing diagnosed for each of the 51 winters from 1949 to 1999. PGLLD found that not only did the ensemble mean response of the model reproduce the time series of the observed NAO, but also the eastward shift (see Figure 2 of that manuscript). PGLLD also describe an ensemble of experiments using anomalous forcing obtained by linearly regressing the diagnosed forcing for each winter against the observed NAO index. In these experiments the anomalous component of the forcing does not vary in spatial pattern, only in its amplitude, which is given by the value of the observed NAO index for each winter from 1949-1999. If the model response is linear, then the NAO in the model would have the same spatial pattern in every year, yet PGLLD found the eastward shift in these experiments when comparing P2 to P1. The implication is that the eastward shift is associated with nonlinear dynamics. In the present paper, we again use anomalous forcing obtained by regression against the observed NAO index, but this time to drive ensembles of experiments for specified values of the NAO index. In this way we are able to isolate the dependence of the spatial pattern of the NAO, including the emergence of the eastward shift, on the value of the NAO index.

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2. Methodology and Results

We use a simplified primitive equation AGCM based on dry dynamics and constant forcing [*Hall*, 2000]. The forcing for the model is diagnosed for each of the 51 winters (December-February, or DJF) from 1949 to 1999 using NCAR/NCEP reanalysis data [*Kistler et al*, 2001], exactly as in PGLLD. The forcing for each winter is then regressed against the observed NAO index. Multiplying these regressed forcing patterns by a specified value for the NAO index, and adding the climatological forcing, then gives a forcing to drive the model. It should be noted that the use of regressed forcing does not imply cause and effect, but demonstrates simultaneous relationships. Nevertheless, it is a good first approximation to the forcing seen by the NAO, as is demonstrated by our results. Regressed forcing does, however, provide a valuable tool to investigate non-linearity in the response since we can now investigate the model response for any amplitude of the NAO. We have carried out an ensemble of 30 model experiments for each specified value of the NAO index from -5 to +5 at increments of 0.2. Each ensemble member is initialized with a different initial state chosen randomly from observations, and is run for 120 days, the last 90 days being used for the analysis. We note that the use of 30 ensemble members produces a robust result, similar results being obtained using 20 randomly selected ensemble members.

We have compared the NAO index computed from the ensemble mean with the specified NAO index used to drive each ensemble. The two are generally in good agreement, although there is a tendency for the ensemble mean NAO

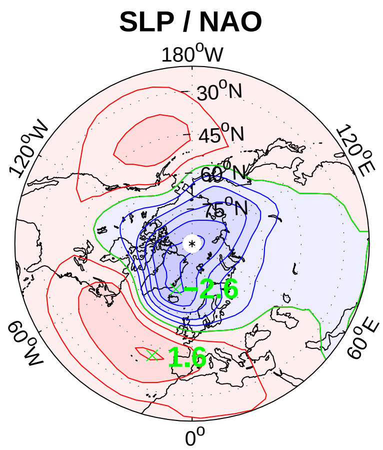

Figure 1. Linear regression of the ensemble mean SLP against the specified NAO index for our model experiments. The plot is normalized to correspond to a specified NAO index of +1. Contour interval is 0.5 mb.

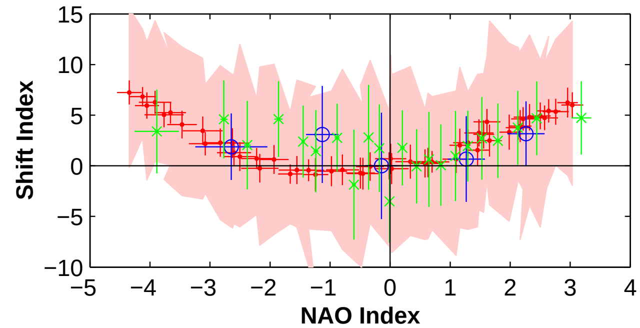

Figure 3. Plot of the shift index (see text) as a function of NAO index. Red cross hatches are ensemble mean shift index versus ensemble mean NAO index, with shaded regions showing the range of the shift index for each ensemble. Blue cross hatches (∘) are computed using 50 winters of the NCAR/NCEP data set sorted by NAO index into 5 bins of 10 members each, while green cross hatches (×) are for the East Anglia data set sorted into 22 bins of 22 members each. Cross hatches denote the 95% significance interval for the ensemble or bin mean.

index to be weaker in magnitude than the specified NAO index for all positive values of the specified NAO index, and all values less than -1 of negatively specified NAO index. Clearly the discrepancy is an example of the nonlinear behaviour of the model.

Our next step is to compute the pattern, shown in Figure 1, obtained by regressing the ensemble mean SLP against the specified NAO index. The pattern is very similar to the standard SLP pattern associated with the NAO [*Hurrell*, 1995]. Multiplying this regression pattern by the specified NAO index gives the expected linear response to that forcing. Nonlinearity distorts this pattern, as illustrated in Figure 2a,b where we show the ensemble mean SLP for specified NAO indices of +4 and -4 as a departure from climatology (the ensemble mean with a specified index of 0), and Figure 2c,d which shows the difference from the expected linear response. The similarity of the SLP patterns in Figure 2c,d is remarkable, and is indicative of similiar patterns calculated for specified values of the NAO index above and below ±2. Repeating the calculation of the non-linear distortion pattern for each individual ensemble member, we are able to perform a local t-test. The regions which are significantly different from zero at the 95% confidence level are denoted by heavy black contour lines in Figure 2c,d.

Both extreme positive and extreme negative values of the specified NAO index are associated in the model with anomalously low pressure over Scandinavia and anomalously high pressure over southern Greenland. The result is an eastward shift in the spatial pattern of the NAO in association with anomalously high index, and a westward shift in association with anomalously low index, as can be seen by comparing Figure 2a,b with Figure 1 (bearing in mind that when the NAO is negative, the positive and negative contours in Figure 1 are reversed). Furthermore, the patterns in Figure 2c,d are very similar to the observed change in the SLP pattern associated with the NAO between P1 and P2 (see Figure 2b in PGLLD or Figure 4d in *Hilmer and Jung* [2000]). Thus we suggest that the eastward shift in the NAO pattern between P1 and P2 is a consequence of the high index during P2 [average DJF index of 0.48] versus the low index of P1 [average DJF index of -0.74], which implies a difference in interannual regression patterns between P1 and P2 akin to the sum of Figure 2c,d.

In order to quantify the amplitude of the spatial pattern associated with the nonlinear distortion we have calculated a shift index, which is simply the SLP difference between 60^oN/50^oW and 65^oN/25^oE, the approximate centers of the anomalous high over southern Greenland and the anomalous low over Scandinavia, after the removal of the both the climatological mean and the linear contribution from the NAO. Figure 3 shows that the relationship between the shift index and the specified NAO index is predominantly quadratic and smoothly varying.

To see if the quadratic relationship holds up in the observations, we have analyzed monthly mean SLP data for the winters (defined as December-March) of 1873/74-1994/95 using the University of East Anglia sea level pressure data set [*Jones*, 1987]. We first used linear regression to find the standard monthly mean SLP pattern associated with the NAO corresponding to Figure 1. Then, for monthly mean NAO indices both below -2.5 and above 2.5, composite fields of anomalous SLP (departure from each month's mean SLP) were obtained. The linearly regressed pattern is then multiplied by the average NAO index for each composite and removed from the SLP composites to produce Figure 2e,f. Regions significantly different from zero at the 90% confidence level are denoted by a heavy black contour line. We see that in the observations (Figure 2e,f), as in the model (Figure 2c,d), the departure from linearity is similar for both large positive and large negative NAO index, although there are differences in the details of the spatial pattern associated with the model compared to the observations. Nevertheless, for both extremes, the departure from linearity shows anomalously low pressure over Scandinavia in both the model and the observations and anomalously higher pressure over Southern Greenland as compared to Scandinavia. Note however, that it is only the anomalously low pressure over Scandinavia that is significantly different from zero in the observations. Area weighted pattern correlation (restricted to the region 60^oN to 80^oN and 60^oW to 30^oE) between both Figure 2e,f and the equivalent of Figure 2c,d, but for each specified NAO index, rises above 0.5 for

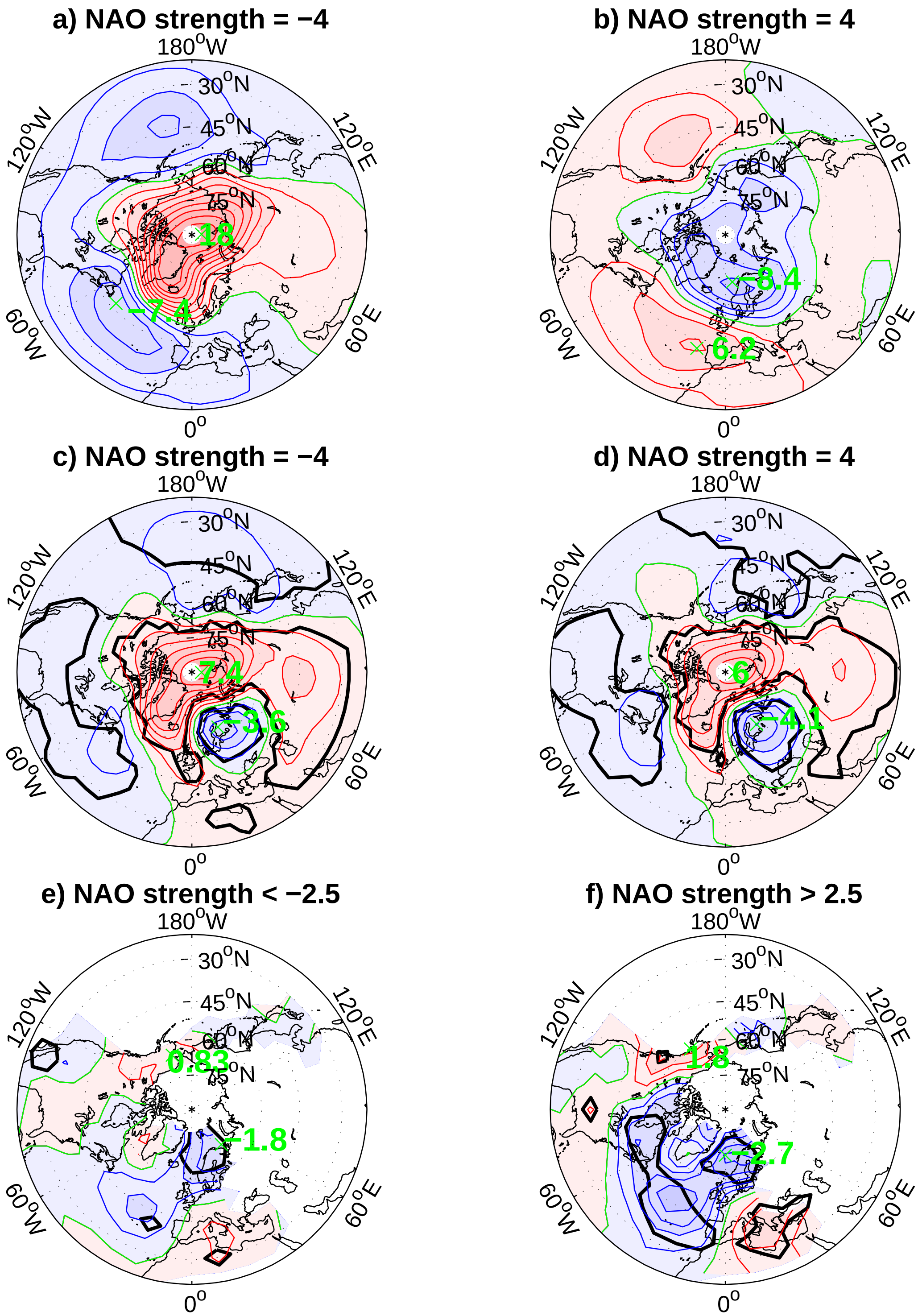

Figure 2. (a) Plot of the ensemble mean SLP anomaly for a specified NAO index of -4. Anomalies are expressed as departures from climatology (the ensemble mean with a specified NAO index of 0). Contour interval is 2 mb. (b) Similar to (a), except for specified NAO index of +4. (c) and (d) Nonlinear component of SLP response in (a) and (b), respectively. Plotted is the difference between the SLP anomaly in (a) and (b) and the product of the specified NAO index with the regressed pattern shown in Figure 1. Regions significantly different from zero at the 95% confidence level, as determined by a t-test using all 30 ensemble members, are confined within the heavy black contour lines. Contour interval is 1.0 mb. (e) Observed departure from linearity for NAO index less than -2.5. Plotted is the composite SLP departure from climatology minus the product of the composite average NAO index and the pattern obtained by linear regression of the winter mean SLP against the NAO index for the whole data set. Regions significantly different from zero at the 90% confidence level are confined within the heavy black contour lines. Contour interval is 0.5 mb. (f) Similar to (e), except for NAO index greater than +2.5.

all specified values of the NAO index below -3 and above 1.5, quantifying the similiarity between model and observations. Furthermore, observational estimates are made of the eastward shift index displayed in Figure 3. Both data sets generally confirm the eastward shift for positive NAO values and a westward shift for negative values.

3. Summary and Discussion

We have investigated the eastward shift of the NAO [*Hilmer and Jung*, 2000] by performing a set of idealized model experiments driven by diabatic forcing obtained by regression against the observed NAO index. Ensembles of model experiments are run for each value of the NAO index from -5 to +5 at increments of 0.2. We find that during extreme high (low) phases of the NAO, the anomalous SLP pattern associated with the index is shifted to the east (west) (Figure 2) compared to the linear pattern (Figure 1). Given the relatively high NAO index in P2 (1978-1997) versus the relatively low NAO index during P1 (1958-1978), our results provide a possible explanation for the eastward shift observed by *Hilmer and Jung* [2000].

The fact we obtain these deviations from the linearly regressed pattern using our experimental setup implies that nonlinear dynamics must be playing a role, in particular, eddy fluxes by the transient eddies in the model, and/or anomalous advection by the changed mean flow. We have performed several experiments with a model linearized about the climatological mean state (corresponding to a specified NAO index of zero). The results show the importance of the eddy fluxes in establishing the eastward shift between P1 and P2. Anomalous advection by the changed mean flow also has an influence for extreme values of the index. We noted that the eastward shift in the spatial pattern of the NAO after about 1980 was first pointed out by *Hilmer and Jung* [2000] in the context of the relationship between the NAO index and ice export through Fram Strait. *Kwok and Rothrock* [1999] and *Kwok* [2000] have demonstrated the high correlation between the area flux of ice though Fram Strait and the average monthly SLP gradient across the Strait. As shown by *Hilmer and Jung* [2000], during the period 1978-97, the eastward shift in the NAO resulted in interannual variations in the NAO index being associated with interannual variations in the SLP gradient across the Strait and hence in ice export through the Strait, a relationship that did not hold in the period 1958-77. Figure 2c,d shows that non-linearity adds an anomalous component of wind along Fram Strait over and above the linear NAO result (Figure 1). Therefore during periods of both predominantly positive and/or negative NAO, the NAO and Fram Strait ice export could become linked, as happened during the decades of predominantly positive NAO at the end of the 20th century. The connection between Fram Strait ice export and the extreme negative phase of the NAO is less clear in the observations, although it may not be a coincidence that the Great Salinity Anomaly of the 1960's and 1970's [*Dickson et al*, 1988] has been associated with anomalously large ice export through Fram Strait during the extreme negative NAO winters of the late 1960's [e.g. *Aagaard and Carmack*, 1989; *Häkkinen*, 1993].

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R.J. Greatbatch, Jian Lu and K. A. Peterson, Department of Oceanography, Dalhousie University, Halifax, NS, Canada, B3H 4J1. (drew.peterson@dal.ca)

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