The changing relationship between the NAO and northern hemisphere climate variability

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Abstract. Sea level pressure (SLP) difference across Fram Strait is used as a proxy for ice export through the Strait to verify that a secular change in the link between the NAO and Fram Strait ice export occurred around 1980, and that the change was associated with an eastward shift in the SLP pattern associated with the NAO. Two additional variables, Siberian winter temperature, and an index of North Atlantic storm activity, are also found to switch from being uncorrelated with the ice export proxy in the 1950's and 60's to being strongly correlated in the 1980's and 90's, suggesting the emergence of a new climate regime associated with the NAO. We argue that the establishment of this new climate regime is related to an upward trend throughout the whole of the 20th century in the cross-correlation between the NAO index and Rogers' first storm activity mode for the North Atlantic.

1. Introduction

The North Atlantic Oscillation (NAO) refers to a meridional shift in atmospheric mass between subpolar and subtropical latitudes, and an index for the NAO has been defined by *Hurrell*[1996] as the difference in normalized winter sea level pressure (SLP) anomalies between Lisbon, Portugal and Stykkisholmur, Iceland. The NAO is the most important mode of variability in the northern hemisphere winter atmospheric circulation, is closely related to a hemispheric mode of variability known as the Arctic Oscillation (AO) [*Thompson and Wallace*, 1998], and accounts for roughly one third of the total variance in winter(DJFM) surface atmospheric temperature north of $20°N$ [*Hurrell*, 1996]. Since about 1980, the centres of action of the NAO have shifted eastward. The shift was first noticed by *Hilmer and Jung*[2000] (hereafter HJ2000) who noted, using a combination of modelling and observed data, that the correlation between the NAO index and ice export through Fram Strait increased dramatically between 1958-77 and 1978-97. The eastward shift resulted in northerly (southerly) winds over Fram Strait, implying increased (decreased) ice-export, when the NAO index was positive (negative) during 1978-97, a relationship that did not hold during 1958-77. The eastward shift of the NAO's centers of action appears to be unprecedented during the 20th century [*Jung and Hilmer*, 2001] (hereafter JH2001) and led to pronounced changes in NAO-related interannual variability, such as in near-surface air temperatures, and net surface heat fluxes over the North Atlantic Ocean [*Jung et al.*, 2001].

Given the importance of the NAO for northern hemisphere (especially European) climate variability [*Kushnir*, 1999; *Greatbatch*, 2000], and the possibility that anthropogenic climate change may be implicated [HJ2000], it is important to understand what caused the eastward shift. At the present time, little is known about the shift beyond that in the papers by Jung and colleagues. We know that the poleward eddy flux of momentum associated with synoptic storms is important for maintaining the different phases of the NAO [*Limpasuvan and Hartmann*, 1999; *Greatbatch*, 2000]. This prompted us to examine the relationship between the NAO and storm activity over the North Atlantic to see if this relationship can shed any light on the eastward shift. Our starting point is the work of *Rogers*[1997] who used combined principal component analysis (CPCA) to explore the link between the root mean square of high-pass SLP variability (representing storm activity) and the low frequency variability of monthly mean SLP. Rogers found a dipole structure of low frequency SLP variability associated with the first rotated empirical orthogonal function (REOF) of storm activity that has some similarity to the NAO. Rogers did not identify this SLP pattern as the NAO because its centers of action are more eastward shifted compared to the prototype NAO. This SLP pattern (see Fig.6 in *Rogers*[1997]) nevertheless bears a strong resemblence to the NAO pattern during the decades of 1978-97 (see Fig.4b in HJ2000), with one centre of action over the Bay of Biscay, and the other over northern Scandinavia and the Barents Sea. Meanwhile, the mild Siberian winters during the 1980's are ascribed by *Rogers and Mosley-Thompson*[1995] to an increase in cyclone activity in the northeast Atlantic Ocean and the high Arctic Oceans. Cyclone activity in these areas is a feature of the positive phase of the first REOF of storm activity found by *Rogers*[1997] and referred to above. Furthermore, the SLP difference between extreme warm and cold Siberian winters shown in Fig.2c of *Rogers and Mosley-Thompson*[1995] has a strong similarity to Fig.4c in HJ2000 showing the SLP pattern associated with ice export through Fram Strait. It follows that ice export through Fram Strait, Siberian winter temperature (SWT), and cyclone activity over the high latitude North Atlantic, all have some connection with the NAO and its eastward shift, although the precise relationship is unclear. Here we use cross-correlation analysis to clarify the relationship. We find that all four variables became locked into a coherent pattern of variability about the same time as the NAO shifted eastward (that is, around 1980). We argue that the emergence of this pattern is related to a century long increase in the 20 year cross-correlation between the NAO index and Rogers' first storm activity mode.

2. Data

The basic data set used here is 47 years (1953-1999) from the NCEP/NCAR reanalysis [*Kalnay et al.*,1996]. Only

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winter months (December, January and February; DJF) are considered. *Kwok and Rothrock*[1999] and *Kwok*[2000] have demonstrated the high correlation (r = 0.89) between the area flux of ice through Fram Strait and the average monthly gradient in SLP across the Strait. We therefore use the winter mean (DJF) SLP difference across the Strait $[(81°N, 15°W)$ minus $(80°N, 10°E)]$, normalized with respect to its own standard deviation, as a proxy for ice export (denoted by IF). The NAO index (denoted by NAO) is calculated following *Hurrell*[1996], except that we use DJF for the winter season. The index of Siberian winter temperature (SWT) is simply a normalized time series of the area mean surface temperature over Siberia spanning $55° - 70°N$, $70° - 100°E$. It is calculated by using the monthly mean 1000 mb temperature from the NCEP/NCAR reanalysis data. To compute a storm index, we follow the procedure of *Rogers*[1997] applied to once daily 12z SLP data from the NCEP/NCAR dataset spanning the period 1 December−28/29 February from 1953-1954 to 1998-1999. The data are high-pass filtered using a binomial filter. The filter has maximum response in the 2-8-day periodicity range, typically corresponding to the passage of synoptic systems. A varimax rotated principal component analysis (RPCA) was performed on monthly rms values of the high-pass filtered data extending from 20° to $80°N$, and from $80°W$ to $60°E$. The first component pattern is a dipole centred in the northeast Atlantic and Norwegian Sea and over the eastern Atlantic around Portugal. It is this storm activity mode that is associated with the SLP pattern shown in *Rogers*[1997]'s Fig.6, and which resembles the shifted NAO pattern during 1978-1997. We obtain a winter storm index, ST, by averaging the principal component time series for the three winter months and normalizing so as to be consistent with Rogers' index. Rogers' index spans the winter months from 1900 to 1992. During the overlap period (1954-1992), the correlation coefficient between his winter index and ST is 0.94, the difference from a correlation of 1 being attributable to the different data set used by Rogers. This verification allowed us to reconstruct a longer storm index, shown in Fig.2a, by connecting our 1954-1999 index to Rogers' index truncated after 1954. All four climate indices are shown for the period 1954-99 in Fig.1a.

We also make use of monthly mean SLP data set from the Climate Research Unit at the University of East Anglia(UEA), UK. This SLP record is 123 years long spanning from 1873 to 1995 and available on a 10° longitude ×5° latitude grid. However, because of lack of data coverage over the Eurasian continent in the early part of the record, we use only data after 1940.

3. Results

The running cross-correlations between pairs of indices using a window-length of 20 years are shown in Fig.1b (choosing window lengths of 15 or 25 years does not significantly change the results). The correlations of the ice flux proxy with the other three indices are depicted by solid curves. All three solid curves show a rapid rise from near zero correlation in the first 20 year period centred around 1960 to much higher correlations that jump above the 1% significance level around 1980. This is the same behaviour as seen in Fig.10 of JH2001 who compared model-simulated ice volume export through Fram Strait with the NAO index. The jump in the correlations shown by all three solid curves suggests the establishment of a new climate regime in which Fram Strait ice export suddenly becomes phase locked with the NAO, the storm index, and Siberian winter temperature, having previously been unconnected to any of these variables.

The correlations, other than those with the ice flux, increase more gradually during the period of record, although

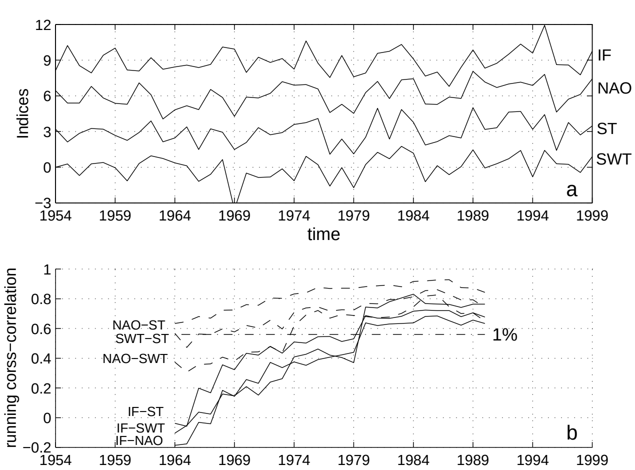

Figure 1. a) Winter mean(DJF) time series of the ice flux proxy IF, the NAO index NAO, the storm index ST, and the Siberian winter temperature index SWT. Note the vertical offset of 3 units between indices for plotting purposes. b) Running cross-correlation functions (20 year window) between every two time series in a). The 1%-confidence level (dash-dot) indicates correlation coefficients which are significantly different from zero.

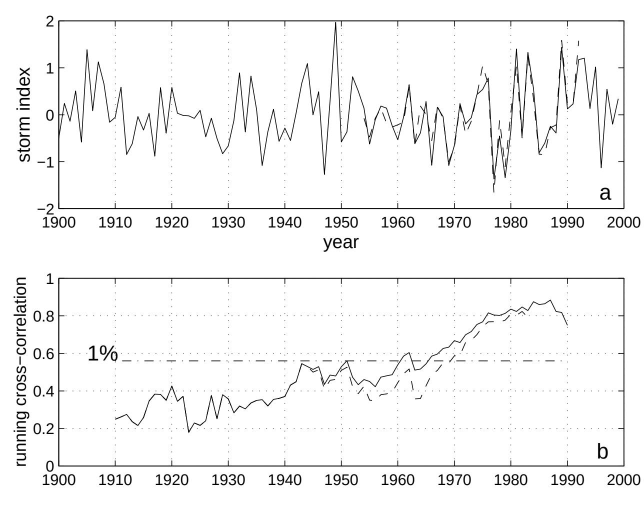

Figure 2. a) Storm index from 1900 to 1999 reconstructed by connecting Rogers' 1900-1953 time series to the index calculated by using NCAR/NCEP 12z SLP from 1954 to 1999. Dashed curve is the later part of Rogers' index (1954-1992). b) Running cross-correlation function (20 year window) between the storm index and Hurrell's winter (DJF) NAO index during 1900-1999. The dashed cross-correlation function comes from using of the dashed part of Rogers' storm index shown in a). The straight dash-dot line is the 1%-confidence level.

in all cases the increase is significant at the 10 % level, as determined using Student's t-test. Note that the NAO is most highly correlated with the storm index. What is interesting, however, is that the link between the NAO and this particular mode of storm activity (the first rotated EOF of rms high-pass variability) did not hold up in the early part of the century. Fig.2b shows the same running cross-correlation, but this time between the 100 year extended storm index (using Rogers' data before 1954) and Hurrell's winter (DJF) NAO index over the period 1900-1999, the dashed curve using Rogers' data after 1953. There is a long-term increasing trend during all the 20th century, and it is only after the early 1960s that this mode of storm activity became significantly linked (at the 1 % level) to the NAO. Indeed, in the early part of the century, the link was weak. Fig. 3a shows the result of regressing the UEA winter mean SLP on the storm index using data from 1940 to 1995. The pattern is very similar to *Rogers*[1997]'s SLP pattern obtained from CPCA (his Fig.6). In particular, there is a northern center over northern Scandinavia and the Barents Sea and a (weak) anomalous south-north wind component over Fram Strait. Given the high correlation (above 0.8) between the storm index and the NAO index during the 1980's and 90's it is not surprising that the pattern in Fig.3a is also very similar to the shifted NAO pattern shown in Fig.3b. Viewed in this way, the eastward shift in the NAO can be interpreted as the result of the century long increase in the correlation (shown in Fig.2b) between the NAO index and the principal component of Rogers' first rotated EOF of rms high-pass variability.

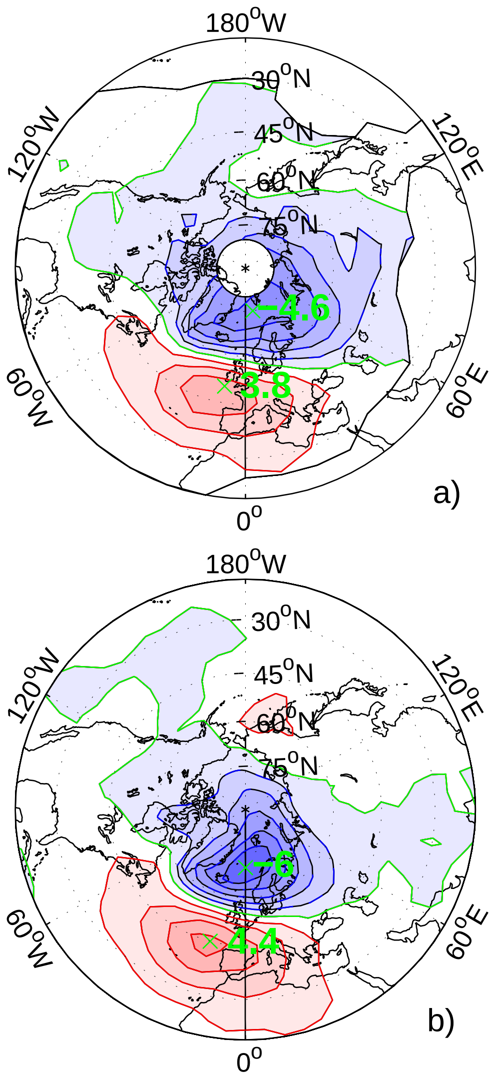

Figure 3. a) Pattern obtained by regressing UEA winter (DJF) mean SLP against the reconstructed storm index using data from 1940-1995. b) Pattern obtained by regressing NCAR/NCEP winter mean SLP against the NAO index using data from 1978-1997. Contour interval is 1hPa.

We now discuss the other two dashed cross-correlation curves shown in Fig.1b, *SWT-ST* and *NAO-SWT*. The link between the cyclone activity and Siberian winter temperature has been addressed by *Rogers and Mosley-Thompson*[1995]. These authors attributed the mild Siberian winters of the 1980's to an increase in the frequency of cyclones that entered the extreme northeastern Atlantic and traverse the Barents and Kara Seas bringing strong westerly flow into Siberia along with extensive cyclone warm sectors. The high correlation (greater than 0.7) between the storm index and SWT since the mid 1970s concurs with this view. Since they were not aware of the shift in the NAO, Rogers and Mosley-Thompson did not relate the mild Siberian winter temperatures to the NAO. Curve *SWT-NAO*, denoting the correlation between SWT and the NAO index shows that the 20 year correlation became significantly different from zero (at the 1% level) sometime during the 1970's, and that the NAO accounts for as much as 60% of the variance of SWT in recent decades.

We may summarise the whole story as follows. Since the mid 1950s, the first REOF of rms high-pass SLP variability has become more and more dominant over the NAO, with the result that the pattern of low frequency SLP variability associated the NAO has become more and more like the SLP pattern associated with this mode of storm activity. After the late 1970s, when a shifted NAO pattern was established, the NAO index, this storm activity mode, our Fram Strait ice flux proxy and Siberian winter temperature all started to be significantly correlated with each other. This suggests the emergence of a new, spatially coherent, climate regime during the last few decades of the 20th century.

4. Concluding remarks

It is natural to ask whether the new pattern of climate variability noted above is part of the natural variability of the climate system or if it is a result of anthropogenic forcing? We know that during the last 40 years of the 20th century, the NAO index showed a strong upward trend that is coincident with the establishment of the eastward shift in the NAO's centers of action. Unlike the eastward shift, the upward trend has been the focus of considerable attention. It has been suggested that the trend may be linked to anthropogenic climate change through the link between the winter AO/NAO and the stratosphere [*Shindell et al.*, 1999, *Hartmann et al.*, 2000], to tropical ocean influences [*Hoerling et al.*, 2001], or that it may simply be part of the natural, internal variability in the climate system [*Wunsch*, 1999]. A similar level of uncertainty exists concerning the eastward shift.

The increasing correlation between Rogers' first storm activity index and the NAO index shown in Fig.2b nevertheless hints at a special role played by the storm track in the NAO shift. In a coupled GCM simulation, *Ulbrich and Christoph*[1999] found an increase in storm activity over northwest Europe, as well as an eastward shift in the model's NAO under increasing greenhouse gas forcing, behaviour that was not found in a control run with fixed greenhouse gas forcing. Meanwhile an increase in storm track activity as well as a decrease of mean surface pressure at the downstream tail of the storm track are common features in scenario runs in many different CGCM simulations under increasing greenhouse gas forcing [*Ulbrich and Christoph*, 1999]. Thus, an argument can be made that anthropogenic climate change might be responsible for the changing relationship we have documented here between the NAO and North Atlantic storm activity, and hence for the eastward shift. Furthermore, as pointed out by JH2001, the eastward shift appears to be unprecedented in the instrumental record. Nevertheless, it is still possible that the eastward shift may simply be part of the natural, low frequency (century time scale) variability of the climate system [*Wunsch*, 1999]. Further work, especially using coupled ocean/atmosphere models that can be run for many hundreds of years, may be required to resolve this issue.

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