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Cold European winters: interplay between the NAO and the East Atlantic mode

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Abstract

Western Europe has experienced a sequence of unusually cold winters culminating in December 2010, which was the coldest December in the United Kingdom for over 100 years. The North Atlantic Oscillation (NAO) is the most important indicator of the climate of the North Atlantic and Western Europe. However, in this article, we argue that the record cold temperatures in December 2010 cannot be explained by appeal to the NAO alone. Rather we show that the consideration of another atmospheric teleconnection pattern, the East Atlantic (EA) pattern, provides for a more robust explanation as to why December 2010 was so cold.

Keywords: **North Atlantic Oscillation; Icelandic Low; Central England Temperature**

1. Introduction

The climate of the North Atlantic is dominated by the North Atlantic Oscillation (NAO) – a meridional seesaw in atmospheric pressure between the Icelandic Low (IL) and the Azores High (AH) (Serreze *et al.*, 1997; Hurrell *et al.*, 2003; Hurrell and Deser, 2010). In recent winters, the NAO has been in its negative phase and this has been associated, through the 'Greenland Above' temperature pattern (van Loon and Rogers, 1978), with colder than usual winters in Western Europe, e.g. December 2010 was the coldest December in the United Kingdom for over 100 years (Eden, 2010, 2011; Osborn, 2011).

Although the IL and AH have well-defined climatological positions, there exists variability in their positions on a month-to-month basis (Machel *et al.*, 1998). For example, during the winter, the center of the IL can be found from 55°N to 75°N and from 60 °W to 10 °E (Sahsamanoglou, 1990). Beginning with the work of Rossby (1939), it has been recognized that variability in the centers of action of a teleconnection can modify its climate impact (Kapala *et al.*, 1998; Bakalian *et al.*, 2007).

In this article, we argue that a more complete description of the NAO and its impact on the climate of the North Atlantic and Western Europe requires information on the meridional positions of its centers of action; information that is not contained in the conventional index used to characterize it. Information that can however be diagnosed through consideration of the phase and magnitude of another climate mode known as the East Atlantic (EA) pattern (Barnston and Livezey, 1987; Woollings *et al.*, 2010; Moore *et al.*, 2011). Recent work has indicated that the EA, the second leading climate mode in the North Atlantic sector (Barnston and Livezey, 1987), can play a role in determining the structure and climate impact of the NAO over the subpolar North Atlantic region (Moore *et al.*, 2011) as well as modulating precipitation over southwest England and the Iberian Peninsula (Rodriguez-Puebla *et al.*, 1998; Murphy and Washington, 2001). In addition, it plays a role in the positioning of the primary North Atlantic storm track and jet streams (Seierstad *et al.*, 2007; Woollings *et al.*, 2010).

The EA pattern consists of a well-defined monopole in the sea-level pressure field to the south of Iceland and west of the United Kingdom near 52.5 °N, 22.5 °W (Barnston and Livezey, 1987; Murphy and Washington, 2001). As discussed by Moore *et al.* (2011), the center of the EA lies along the nodal line of the NAO allowing it to modulate the locations and intensities of the IL and AH.

We show that using the EA to diagnose the location and intensities of the NAO's centers of action explains the extremely cold European temperatures observed during December 2010. We also argue that such an interaction between the NAO and EA may have also played a role in the transition between the Medieval Warm Period and the Little Ice Age in Europe (Trouet *et al.*, 2009) as well as assisting in the interpretation of Irish paleoclimate temperature proxy data that is uncorrelated with the NAO (Holmes *et al.*, 2010).

2. Methods

The sea-level pressure field from the NCEP reanalysis, a widely used atmospheric dataset that uses a frozen data assimilation system to assimilate historical meteorological observations (Kalnay *et al.*, 1996), was used to derive indices of the NAO and the EA for each of the winter months (December, January and February, DJF) during the years from 1948 to 2010. The NAO Index (NAOI) was computed from the normalized sea-level pressure difference between Gibraltar and southwest Iceland (Jones *et al.*, 1997). The EA Index (EAI) was computed as the normalized sea-level pressure anomaly at its primary center (Murphy and Washington, 2001; Moore *et al.*, 2011). During its positive phase, the sea-level pressure is lower in the vicinity of its primary center. In all cases, the NCEP gridded sea-level pressure field was interpolated to the respective centers of action of the NAO and EA for the calculation of the two indices.

A longer term index of the NAO extending back to 1825 was derived from sea-level pressure data from southwest Iceland and Gibraltar (Jones *et al.*, 1997). With regard to the EA, sea-level pressure data from Valentia Island, Ireland, were used to derive an index extending back to 1870. Although the Valentia Island station is not collocated with the center of the EA, the correlation coefficient between its sea-level pressure and the NCEP reanalysis sea-level pressure at the center of the EA for winter months over the period 1948–2010 was 0.82 indicating a high degree of correlation between the two.

We use a bivariate linear least squares regression model (Draper and Smith, 1998; Junge and Stephenson, 2003) to diagnose the impact that the NAO and the EA have on the climate of the North Atlantic and Western Europe. For simplicity, we restrict our attention to the sea-level pressure and 1000 mbar temperature fields from the NCEP reanalysis (Kalnay *et al.*, 1996) for the winter months (DJF) during the period 1948–2010. The 1000 mbar temperature field was chosen to represent surface air temperature variability. Similar results were obtained with other thermal fields, such as the 2 m air temperature and the 925 mbar temperature as well as the 1000–500 mbar thickness field – which represents the mean atmospheric temperature in this layer.

3. Results

The Central England temperature (CET) record is the longest continuous temperature record in existence and it is well correlated with surface temperatures throughout Western Europe (Manley, 1974; Jones *et al.*, 1986; Junge and Stephenson, 2003; Parker and Horton, 2005). Figure 1 shows the monthly mean CET time series for December during the period 1825–2010. Starting in 2007, there has been a trend toward colder temperatures in December culminating in 2010, which, with a monthly mean temperature of $-0.7\,°C$, was the second coldest December during this period (indeed back to the start of the record in 1659) and the coldest in over 100 years. Figure 1 also shows the monthly mean NAOI plotted against the monthly mean CET for December as well as the linear least squares regression with error bars representing estimates of the standard deviation of the error in fit. As has been previously discussed (Junge and Stephenson, 2003; Osborn, 2011), the NAOI and CET are correlated during the winter months with the NAOI explaining approximately 50% of the variability in the CET. Based on this regression, December 2009 was warmer than expected, while December 2010 was colder than expected. For example, one would have expected the monthly mean CET during December 2010 to be $-0.7 \pm 1.3\,°C$ lower than that during December 2009, rather than the observed $-3.8\,°C$ lower. Clearly there are other factors that contribute to variability in the CET and by inference on the severity of winters in the United Kingdom and Western Europe.

Figure 2 shows the NAOI plotted against the EAI for December 1870–2010. As has been discussed previously (Moore *et al.*, 2011), Figure 2 indicates that the NAOI and EAI are uncorrelated with an approximate equipartition among the four quadrants. Figure 2 also illustrates that the NAOI was of similar magnitude while there was a change in sign of the EAI between December 2009 and 2010. Table I confirms this by showing the NAOI and EAI values for December 2009 and 2010.

Figure 3 shows anomalies in the monthly mean sea-level pressure and 1000 mbar temperature fields from the NCEP reanalysis for December 2009 and 2010. One can see an increase in the magnitude of the pressure anomaly associated with the IL in 2010, as compared to 2009, consistent with the more negative NAOI, as well as a southward shift in its location. The location of the AH was also shifted southward in 2010, as compared to 2009. In addition, there existed a secondary pressure anomaly to the south of Nova Scotia, Canada, during December 2010 that was absent in 2009. The 1000 mbar temperature anomaly is characterized by a well-defined meridional temperature dipole with centers over Baffin Island and Western Europe. This dipole, referred to as the ‘Greenland Above/Greenland Below’ pattern, was first identified by Danish Missionaries in the 18th century who noted that mild winters in Denmark tended to be associated with severe winters in Western Greenland and vice versa (van Loon and Rogers, 1978). Consistent with the CET record, the cold anomaly over Western Europe extended farther south and was of a larger magnitude in 2010, as compared to 2009, while the magnitude of the warm anomaly over Baffin Island was also larger. Indeed, December 2010 was also the warmest December on record in Iqaluit (63.7 °N, 68.5 °W), the largest settlement on Baffin Island.

Table I. Values of the NAO Index (NAOI) and the EA Index (EAI) for the months of December 2009 and 2010.

Month	NAOI	EAI
December 2009	−2.1	1
December 2010	−2.7	−0.6

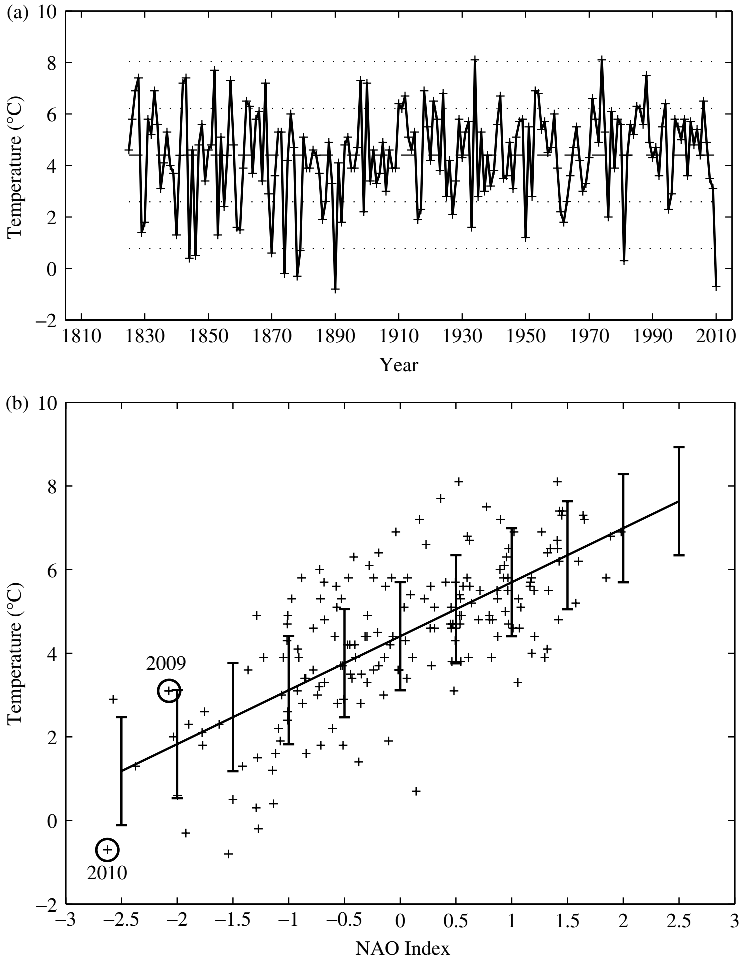

Figure 1. The Central England Temperature time series (a) and its relationship with the North Atlantic Oscillation (b) for December during the period 1825–2010. Also shown in (a) is the mean value (dashed line) as well as one and two standard deviations above and below the mean (dotted lines). Also shown in (b) is the least squares regression and error estimates.

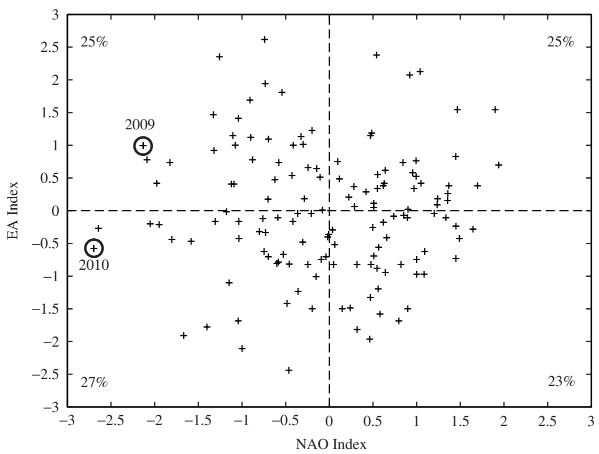

Figure 2. Scatterplot of the monthly mean North Atlantic Oscillation (NAO) Index versus the monthly mean East Atlantic (EA) Index for December during the period 1870–2010. Also shown are the percent occupancy in the four quadrants as well as the index values for 2009 and 2010.

Figure 4 shows the univariate regressions of the winter (DJF) monthly mean sea-level pressure and 1000 mbar temperature fields from the NCEP reanalysis against the NAOI and EAI for the period 1948–2010. The NAO regressions illustrate the classical structure of the NAO with circulation centers associated with the IL and AH (Hurrell *et al.*, 2003), and a meridional temperature dipole (van Loon and Rogers, 1978). The EA regressions illustrate a monopolar circulation structure with a center along the nodal line of the NAO (Woollings *et al.*, 2010, Moore *et al.*, 2011), with a primarily dipole structure in temperature. For positive values of the EAI there is a warm anomaly over Western Europe and a cold anomaly over the North Atlantic to the east of Newfoundland. Similar results were obtained for regressions against the CRUTEM3 dataset (not shown).

Comparing the structures of the univariate regressions suggests that when the two indices are of the same sign, there would be a southward shift in the centers of the IL and AH, and an increase in the magnitude of the associated sea-level pressure anomalies. In contrast, when the indices are of opposing sign, one would expect a northward shift in the centers, and a decrease in the magnitude of the associated sea-level pressure anomalies. For example, February and March 2007 was a period in which the NAOI and EAI were both positive resulting in such a southward movement and intensification of the IL (Moore *et al.*, 2011) that had

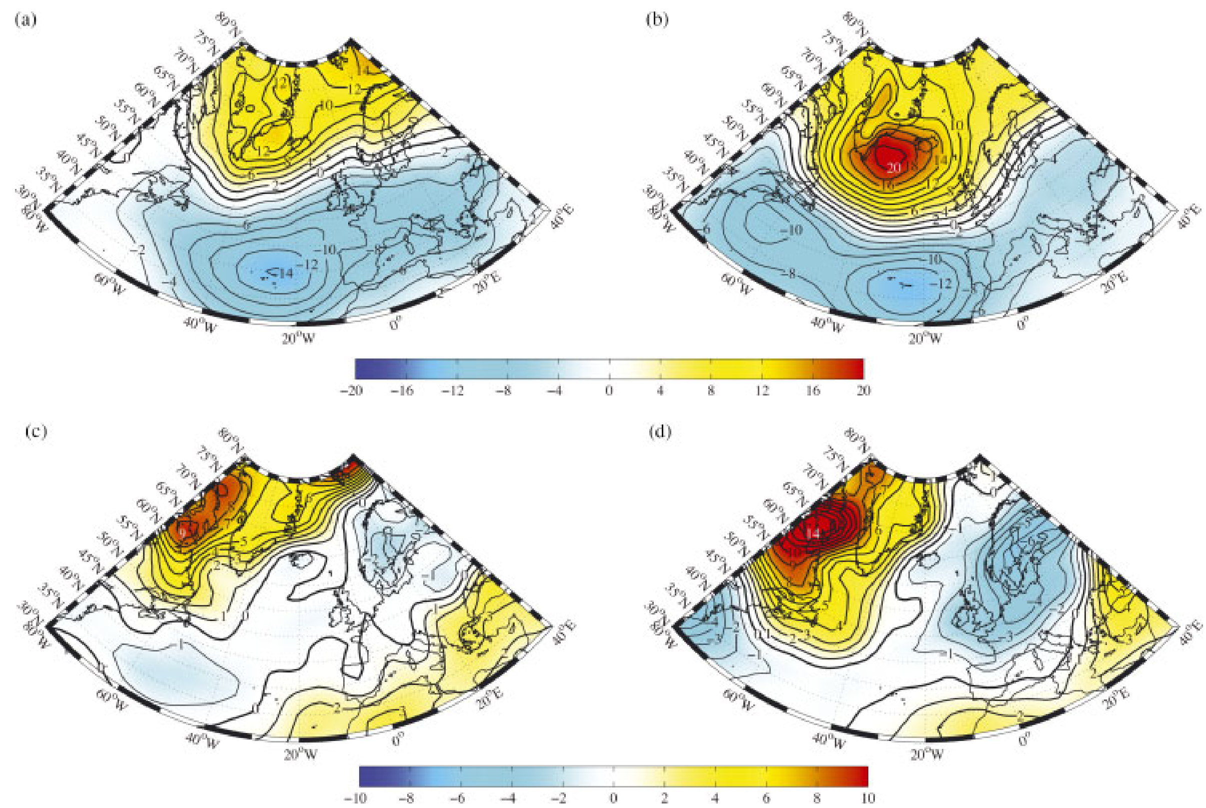

Figure 3. Anomalies of the monthly mean sea-level pressure (mbar, upper row) and 1000 mbar temperature (°C, lower row) for December 2009 (left column) and December 2010 (right column) from the NCEP reanalysis. Anomalies are based on the climatological mean fields for December 1948–2010.

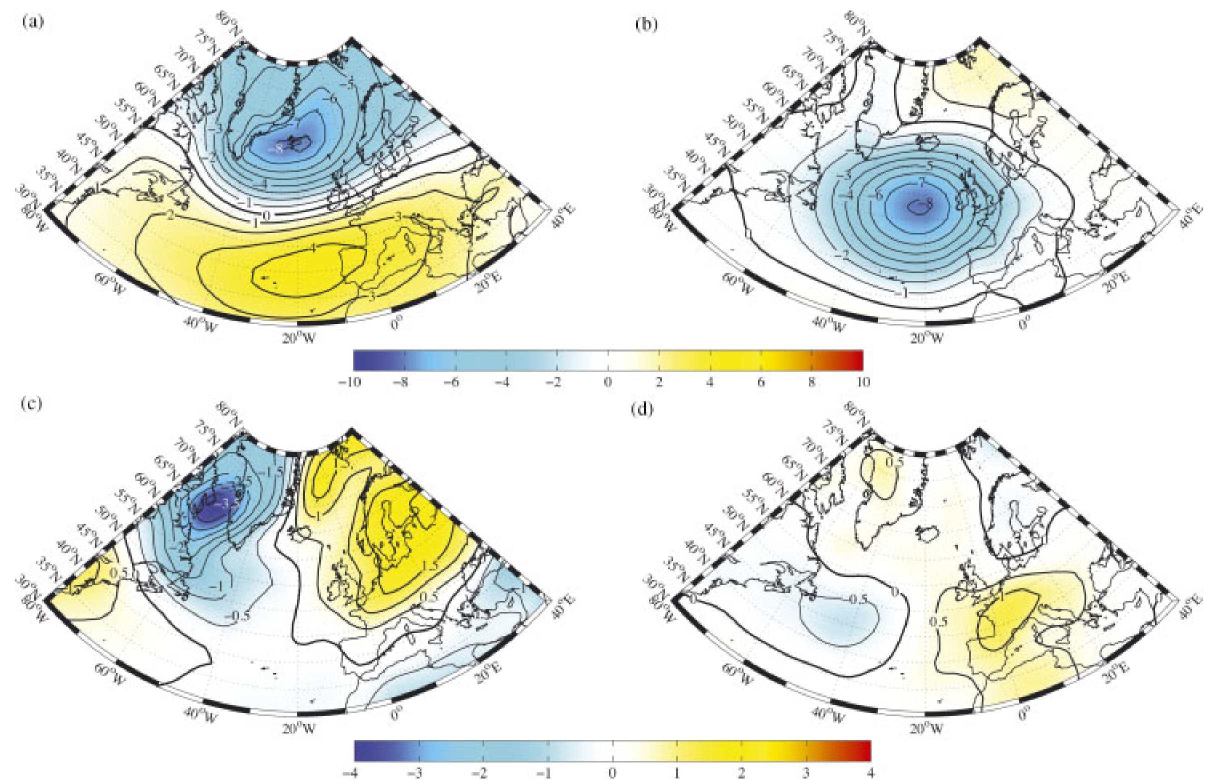

Figure 4. Regressions of the monthly mean sea-level pressure (mbar, upper row) and 1000 mbar temperature (°C, lower row) against the NAO Index (left column) and the EA Index (right column). Regressions are based on the winter monthly mean fields (DJF) from the NCEP reanalysis for 1948–2010.

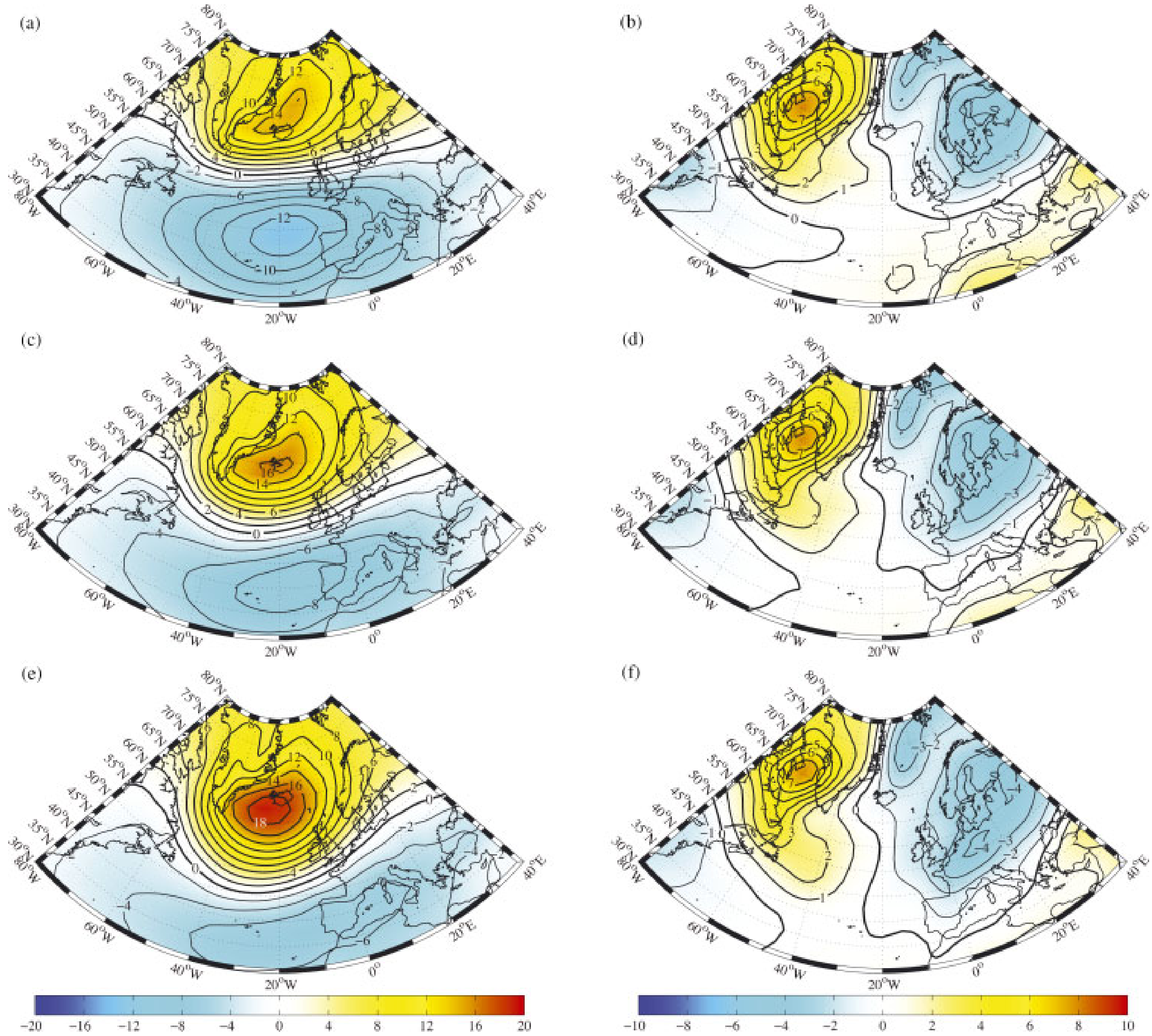

Figure 5. Reconstructions of the monthly mean sea-level pressure (mbar, (a,c,e)) and 1000 mbar temperature (°C, (b,d,f)) fields predicted by bivariate regression model against the corresponding monthly mean winter (DJF) NCEP reanalysis fields 1948–2010 for the case where the NAO Index is −2 with an EA Index of 1 (a,b), with an EA Index of 0 (c,d) and with an EA Index of −1 (e,f).

a profound impact on a field campaign investigating atmospheric flow distortion by Greenland (Renfrew *et al*., 2008). Similar shifts in the 1000 mbar temperature regressions can also be inferred.

In Figure 5, we quantify these changes through reconstructions of the sea-level pressure and 1000 mbar temperature fields based on bivariate regressions against both the NAOI and EAI; for cases when NAOI is −2 and EAI is either 1, 0 or −1. The first and third cases mimic the situations that occurred in December 2009 and 2010, respectively (Table I and Figure 2), while the middle control case is included for completeness. With regard to the sea-level pressure reconstruction, one can see that the progression from EAI = 1 to EAI = −1 results in a southward movement in the location of both the IL and AH as well as an increase in the magnitude of the anomaly associated with the IL and a decrease in the magnitude of the AH anomaly. The reconstructions of the 1000 mbar temperature field indicate that the transition from the case where EAI = 1 to that where EAI = −1 is associated with a southward extension of the 'Greenland Above/Greenland Below' meridional dipole that results in colder temperatures extending southward to cover much of Western Europe including the British Isles.

Figure 6 presents the percentage of the variability in the winter monthly mean sea-level pressure and 1000 mbar temperature fields from the NCEP reanalysis that are described by the NAOI and EAI individually as well as collectively. For the univariate cases, the percentage of the variability explained tends to follow the magnitude of the corresponding regressions (Figure 4). One can see that in the corresponding maxima in the magnitude of the sea-level regressions, both teleconnections are able to explain 80–90% of the variability, while with respect to the 1000 mbar temperature regressions, the teleconnections can explain 30–50% of the variability. Of more interest is the percentage of the variability that can be explained by both the NAO and EA. With respect to the sea-level pressure field one can see that across much of the

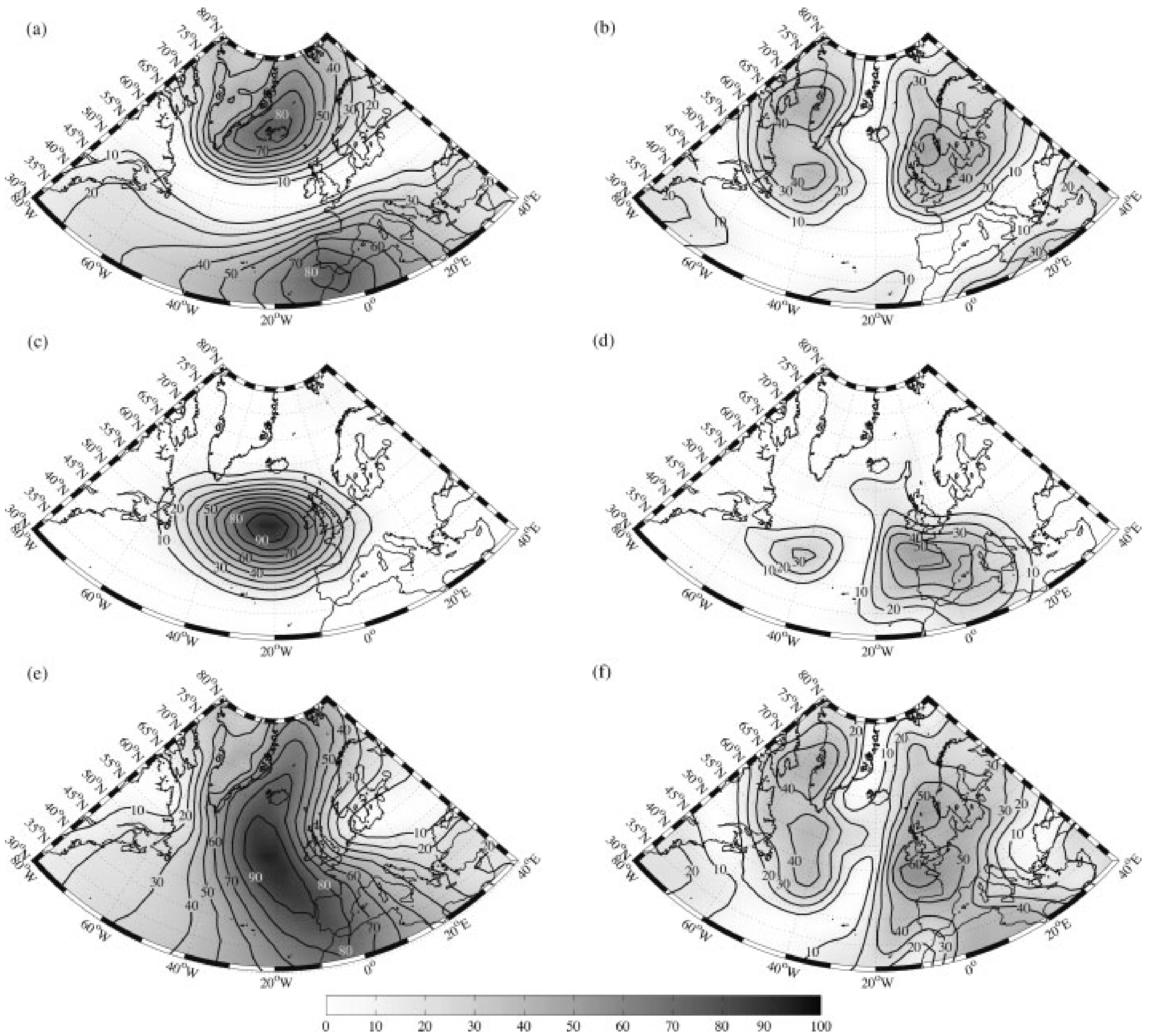

Figure 6. Percentage of variability in the monthly mean winter (DJF) sea-level pressure (a,c,e) and 1000 mbar temperature (b,d,f) described by the NAO Index (a,b), the EA Index (c,d) and both the NAO and EA Indices (e,f).

North Atlantic east of Greenland from 30°N to 80°N, the simultaneous consideration of both of these teleconnection patterns can explain in excess of 60% of the variability in this field. Over Western Europe and to a lesser degree over the western North Atlantic, the simultaneous consideration of both of these teleconnections can explain in excess of 40–60% of the variability in the 1000 mbar temperature field.

4. Discussion

A comparison of the bivariate reconstructions (Figure 5(a), (b), (e) and (f)) with the observed anomalies during December 2009 and 2010 (Figure 3) shows a remarkable structural similarity: capturing the southward movement and amplification of the IL anomaly, a more modest southward movement of the AH and the southward movement of the 'Greenland Above' temperature pattern leading to colder temperatures over Western Europe.

These qualitative similarities can be quantified by noting that the change in NCEP monthly mean 1000 mbar temperature at London (51.5 °N, 0 °W) between December 2009 and 2010 was −3.3 °C. Considering only the change in the NAOI (from −2.1 to −2.7) predicts a change in this temperature of −0.63 °C; while the inclusion of the change in the EAI (from 1 to −0.6) predicts a change in this temperature of −1.7 °C. So inclusion of the EA mode explains over 50% of the signal, compared to only 20% when considering the NAO alone.

As we have shown, consideration of the phase of the EA pattern can have a significant impact on the structure of the NAO. These include changes to the location and strength of its centers of action, the IL and AH, resulting in changes in the location and magnitude of the temperature anomaly over Western Europe and the British Isles. These changes can help explain why December 2010 (when the EA was negative) was much colder than December 2009 (when the EA was positive) despite similar NAOI values. Based on this analysis, it is our hypothesis that a more complete characterization of the NAO and its climate impact requires additional information than that contained in the NAOI, information provided by the magnitude and phase of the EA pattern.

It should be noted that there are other processes such as sea-ice, snow and cloud cover, that can impact the surface temperature through changes in the surface energy balance. Although all these processes are influenced by circulation changes such as the NAO and EA (Serreze *et al*., 1997; Hilmer and Jung, 2000; Bednorz, 2004; Petoukhov and Semenov, 2010), there is also variability in these processes that is not captured by such changes and that also have an impact on European winters. In a similar vein, there are other teleconnections such as the Scandanivian pattern (Barnston and Livezey, 1987) or El Nino (Bronnimann, 2007) that also impact the severity of European winters. However, a cursory examination of these modes, in the context of the cold December of 2010, suggests that in this case these modes play a tertiary role.

The approach in which climate variability is considered not as being represented by distinct structures but rather as a continuum formed by the linear combination of these structures (Franzke and Feldstein, 2005) warrants further consideration in light of this work. It is also interesting to conjecture that the relative phases of the NAO and EA may have, along with other modes of climate variability, played a role in the transition from warm to cold conditions in Europe between the Medieval Climate Anomaly and the Little Ice Age. Across these two events, a modeling study suggests that there was a weakening in the NAO as well as a northeastward shift in the locations of the IL and AH that has been proposed to be responsible for the change in the atmospheric circulation that occurred between these two events (Trouet *et al*., 2009). The changes in the structure of the NAO associated with the phase of the EA may also contribute to the interpretation of the oxygen isotope records from an Irish lake that suggests a southward shift in moisture source region is associated with transitions from more negative to more positive δ18O phases, transitions associated with temperature fluctuations in the historical record that are not correlated with the NAO (Holmes *et al*., 2010).

Given the uncorrelated nature of the NAOI and EAI (Figure 2), it is also likely that the changes in the structure of the NAO and its climate impact that we have shown to arise out of the consideration of the phase of the EA may also contribute to the documented complexity in the predictability of the climate of Western Europe (Woollings, 2010).

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