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The North Atlantic Oscillation and its relationship with near surface temperature

Victoria C. Slonosky[1] and Pascal Yiou

Laboratoire des Sciences du Climat et de l'Environnement, UMR CEA—CNRS, CE Saclay, l'Orme des Merisiers, 91191 Gif-sur-Yvette, France

Abstract. A new NAO index is presented here using homogenized surface pressure data from Reykjavik and Gibraltar (for November to March) and Reykjavik and Ponta Delgada (for April to October). This index suggests that the positive trend in recent years is not unprecedented, as the early 20th century was also a period of persistently positive NAO values. The relationship between the secular warming trend and the influence of the NAO on near-surface temperatures over the North Atlantic region and surrounding land masses is examined on a seasonal basis using standardized temperature anomalies since 1900. The near-surface temperature field separates into two independent modes, which we designate a "warming" mode and dynamic ("NAO") mode, with distinct seasonal cycles.

1. Introduction

The North Atlantic Oscillation (NAO) has been the subject of considerable interest in recent years, following an apparently increasing trend in the winter values of the NAO index from the 1980s to the mid-1990s [*Hurrell*, 1995; 1996; *Jones et* al., 1997; *Osborn et al.*, 1999; *Paeth et al.*, 1999]. The NAO is an important indicator of atmospheric circulation variability [*Barnston and Livezey,* 1987], as it is related to the westerly winds and temperature advection over Eurasia [*Hurrell,* 1995; *Thompson and Wallace,* 1998] in the winter season. The NAO index is generally defined as the difference in pressure between the Azores High and the Icelandic Low [*Walker and Bliss,* 1932; *van Loon and Rogers,* 1978, *Osborn et al.,* 1999].

Possible connections between surface warming due to anthropogenic climate change and the atmospheric circulation over the North Atlantic, manifested by changes in the NAO or the similar Arctic Oscillation (AO) have been suggested recently, particularly in regard to the recent positive trend in the winter NAO/AO [*Hurrell,* 1995; *Thompson and Wallace* 1998; *Corti et al.,* 1999; *Osborn et al.,* 1999; *Paeth et al.,* 1999; *Schindell et al.,* 1999]. The recent Northern Hemisphere warming, especially the warming in winter temperature over Eurasia [*Hurrell,* 1996] might be explained in part by temperature advection connected to the NAO/AO as well as the radiative forcing due to increased greenhouse gases, although the interaction between the NAO/AO and global warming is still far from clear in the coupled models [*Zorita and Gonzàles-Rouco,* 2000]. In this context, it is important to document the relative effects of both mechanisms on North Atlantic climate.

Here we show that an NAO index based upon carefully homogenized station records presents a slightly different perspective on recent variations in the NAO (Sec. 2), and we identify the fingerprints of two independent modes of variability in near surface temperatures (Sec. 3).

2. Surface pressure and temperature data

The NAO index presented here is a composite index, using the difference in normalized pressure between Gibraltar and Reykjavik for the winter months (November–March) for 1821-1997. As the Azores High migrates westward in the summer months, Gibraltar pressure variations do not adequately capture the southern pole of the NAO in summer, and so the pressure differences between Ponta Delgada and Reykjavik are used to represent the NAO in the summer months (April–October) for 1865-1995. The winter NAO series presented here (Fig. 1a) is based on the same data as the *Jones et al.* [1997] NAO index, with, however, a few differences arising from a homogenization procedure performed on these stations as part of a set of 51 pressure series from Europe [*Jones et al.,* 1999a; *Slonosky et al.,* 1999]. These differences result primarily in a higher relative amplitude for the NAO in winter during the early 20th century than in *Jones et al.* [1997]. When compared to the *Hurrell* [1995] index, the magnitudes for the 1980s and 1990s are relatively lower in our index (Fig. 1), although they are in agreement with those of *Jones et al.* [1997] for this last period. We feel that this index, based on homogenized pressure data, reconciles well the differences in the 1920s and the 1980s and 1990s between the *Jones et al.* [1997] index and the *Hurrell* [1995] index. The NAO is susceptible to the normalization period used (here 1871–1995) and, for the winter index, the months included in forming the winter average, both of which can affect the magnitude and sign of the winter average NAO series. This makes it difficult to place the recent positive trend in the NAO in the context of the last century. The temperature analyses are based on monthly gridded near surface temperature data; the data set is a blend of land surface temperature and sea surface temperature [*Parker et al.,* 1995; *Jones et al.,* 1999b] over the North Atlantic and surrounding areas (80°W–25°E, 0–75°N). The temperature values are given as departures from the 1961–1990 mean values for each grid box.

3. Results of correlation and EOF analysis

The winter NAO series presented in Figure 1a for 1821–1997, using homogenized pressure data, shows that the recent

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[1] Now at Climate Research Branch, Environment Canada, 4905 Dufferin St, Toronto Ontario M3H 5T4, Canada

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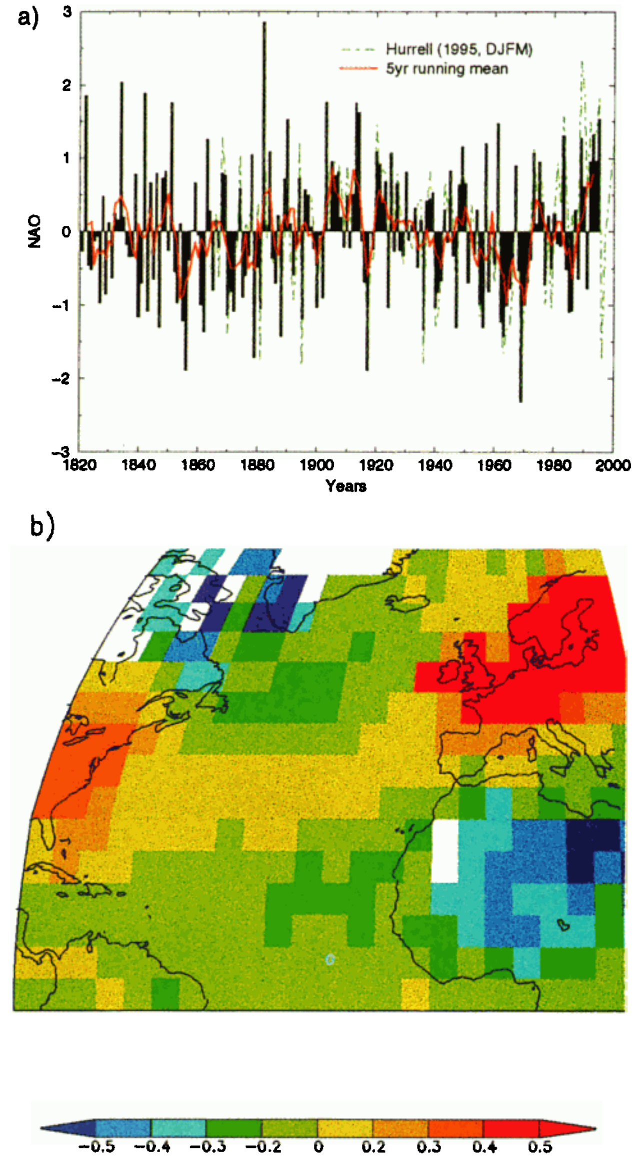

Figure 1. a) Time series of winter NAO Gibraltar-SW Iceland, November-March average of the monthly data, using the normalization period 1871–1995. Values for 1996 and 1997 were taken from *Jones et al.* [1999a] and *Osborn et al.* [1999]. A 5-year moving average is also shown in red; values for *Hurrell* [1995] index are shown in green (dashed lines). Because the values for Hurrell's index were normalized over the seasonal mean using a slightly different period, we have scaled his index values by the standard deviation of his index and our new NAO index; 1b) Correlation map between surface temperature gridded data and NAO index. Gridboxes with less than 25 months of data are considered missing. .

positive trend in the NAO is not unprecedented in the 20th century, as values in the early decades (1900s–1930s) are also persistently positive, with magnitudes similar to those of the late 20th century. This is consistent with evidence of increased storminess and westerly winds at that time [*Hurrell,* 1995; *Mächel et al.,* 1998]. Fig. 1b shows a correlation map between winter temperature anomalies and the NAO index over the North Atlantic and surrounding land-masses. There are four main regions of correlation between the NAO and surface temperature in winter; positive correlations over Europe and south-eastern North America, and negative correlations over Greenland and the Labrador Sea region and over north-west Africa [*Hurrell,* 1996; *Kelly et al.,* 1999; *Stephenson et al.,* 2000]. The influence of the NAO on North Atlantic surface temperature captures the combined effect of the Icelandic Low influencing the advection of cold air over Greenland and warm air over Europe, and the Azores High controlling warm air advection over the southwestern North Atlantic and cold air advection over Africa. The dipole in temperature between Greenland and Europe is a well-known characteristic associated with the NAO [*Walker and Bliss,* 1932; *van Loon and Rogers,* 1978].

In order to further investigate the influence of atmospheric circulation on surface temperatures, an EOF analysis was performed on the normalized near-surface temperature field. The analysis was performed on the correlation matrix of the monthly values for each season (winter: November–March; spring: April–May; summer: June–August; autumn: September–October). The correlation matrix was used to give equal weighting to all points in the domain. An analysis based on the covariance matrix over the same domain of mixed land and sea placed most weight on the northern landmasses for physical (the difference in heat capacity between land and

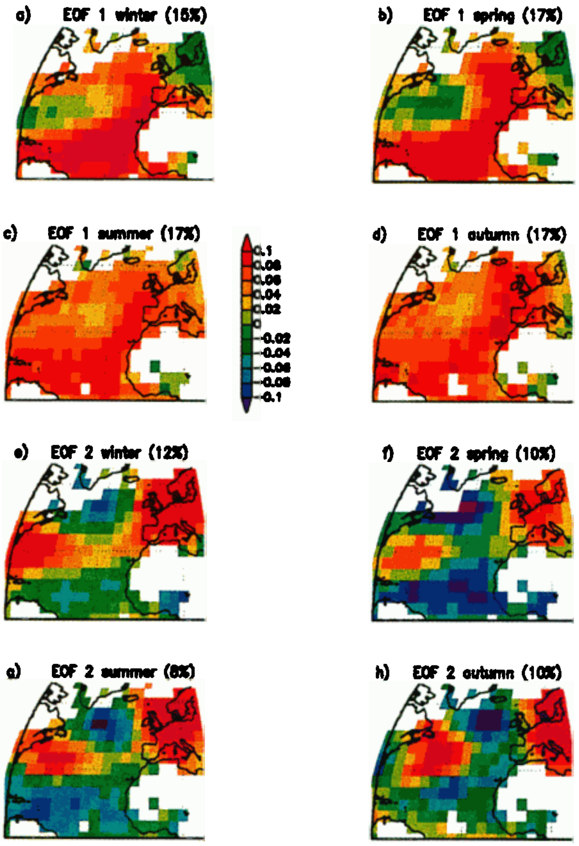

Figure 2. Spatial patterns of normalized surface temperature: EOF 1 a) winter, b) spring, c) summer d) autumn; EOF 2 e) winter, f) spring, g) summer and h) autumn. The percentage of variability accounted for by each EOF is indicated in brackets. Gridboxes with more than 20% data missing were removed in the analysis [note that this is a more stringent classification of missing gridboxes than that used in Fig. 1b].

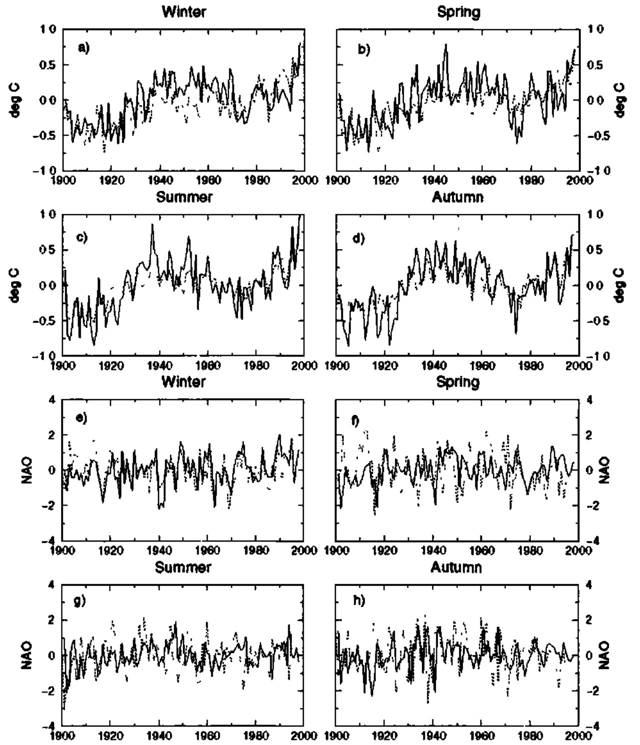

Figure 3. PC 1 (solid) and Northern Hemisphere average temperature anomalies (relative to 1961-1990) from *Jones et al.* [1999b] (dashed) for a) winter, b) spring, c) summer and d) autumn. The PCs are dimensionless; temperature anomalies are in degrees Celsius. PC 2 (solid) and the NAO (dashed) for e) winter f) spring, g) summer and h) autumn. The NAO values are dimensionless. The PC values were normalized by the ratio of their standard deviation to that of winter temperatures (panels a–d) or winter NAO (panels e–h).

ocean, and the larger seasonal cycle in high latitudes) rather than dynamical reasons. By using the correlation matrix in an eigenvector analysis we examine here temperature anomalies that are continuous over the land-sea boundaries and coherent in space. This means, however, that the patterns represent relative, and not absolute, temperature anomalies. For this reason, we refer to relative temperature anomalies when discussing the spatial EOF patterns.

The first two spatial EOF patterns are shown in Fig. 2, and their associated principal components (PCs) in Fig. 3. These spatial patterns are consistent from season to season, with EOF 1 always depicting an area of strongly positive relative anomalies over the southern and eastern Atlantic ocean (Fig. 2a–d), although with some seasonal changes. In winter, there are low relative temperatures over Europe and the south-western Sargasso Sea (Fig. 2a), but in summer the relative anomalies are positive over the entire domain (Fig. 2c). EOF 2 shows a general pattern in all seasons of positive relative anomalies over Europe and the western Atlantic (Fig. 2e–h). A zone of negative relative anomalies in the western-central North Atlantic creates a dipole pattern reminiscent of that associated with the NAO (Fig. 1b), prompting us to designate EOF 2 as an dynamic, NAO-related mode of surface temperature variability (see also *Kelly et al.* [1999]). The correlation coefficient between map of the spatial correlation between temperature and the NAO (Fig. 1b) and EOF 2 (Fig. 2e) is 0.93. A seasonal cycle appears in EOF 2, with both the positive anomalies in Europe and the western Atlantic and the negative anomalies in the northern Atlantic shifting eastward in summer and autumn. The broad band linking the anomalies in surface temperature between the Gulf Stream/North Atlantic Current (NAC) and Europe suggests the wind driven circulation, associated with the NAO, may be related to surface temperature anomalies over this whole region.

The PCs of the EOF 1 show an overall trend which is similar to that of the Northern Hemisphere (NH) temperature curve [*Jones et al.,* 1999b] (Fig. 3a–d). The PCs of EOF 2, on the other hand, are more closely related to the NAO (Fig. 3e–h).

The correlation coefficients (squared, or variance in common) between the first two PCs of near surface temperature, the NH average temperature, and the NAO are shown in Table 1, for the whole 20th century (1900–1998) and the first and second halves of the century (1900–1949, 1950–1998). It can be seen that PC 1 has a large fraction of variance in common with the NH average temperature, and, especially in summer and autumn, is essentially the same as the average temperature over the North Atlantic region. PC 2 on the other hand is related to the NAO in winter and autumn. PC 1 is more closely related the Northern Hemisphere average in the first half of the century than in the second in all seasons, suggesting a de-coupling between the evolution of temperature in the North Atlantic region and the Northern Hemisphere as a whole. There is no evidence of an increasing correlation between the NAO index and PC 1 of temperature, the "warming" mode, or between PC 2 and the Northern Hemisphere average temperature. Correlations calculated over 25 year periods throughout the century (not shown) support these conclusions.

Table 1. Seasonal correlation coefficients between PCs and NAO. "*N. Atl.*" represents the area 0-75N, 80W-25E.

		Winter	Spring	Summer	Autumn
PC 1					
NAO	1900-98	-0.49*	-0.34*	0.05	0.02
	1900-49	-0.50*	-0.41*	0.10	-0.04
	1950-98	-0.48*	-0.24	-0.03	0.11
N. Hem.	1900-98	0.68*	0.64*	0.86*	0.77*
	1900-49	0.74*	0.67*	0.90*	0.79*
	1950-98	0.43*	0.49*	0.80*	0.69*
N. Atl.	1900-98	0.84*	0.86*	0.99*	0.98*
	1900-49	0.86*	0.87*	0.99*	0.98*
	1950-98	0.71*	0.82*	0.99*	0.98*
PC 2					
NAO	1900-98	0.63*	0.26	0.34*	0.58*
	1900-49	0.70*	0.48*	0.34*	0.57*
	1950-98	0.71*	0.01	0.33*	0.61*
N. Hem.	1900-98	0.29	0.33*	0.26*	0.33*
	1900-49	0.20	0.48*	0.39*	0.36*
	1950-98	0.20	0.08	0.12	0.27
N. Atl.	1900-98	0.43*	0.39*	0.44*	0.36*
	1900-49	0.42*	0.51*	0.55*	0.37*
	1950-98	0.32*	0.16	0.26	0.31*

* significantly different from zero at the 95% level

The decomposition of the surface temperature field into a "background" mode and a "dynamic" mode is well known for both the North Atlantic region [*Deser and Blackmon,* 1993; *Kushnir,* 1994] and for the Northern Hemisphere [*Wallace et al.,* 1993, 1995; *Mann and Park,* 1996; *Corti et al.,* 1999; *Stephenson et al.,* 2000]. Here we see that the separation between the warming trend, or background mode, and the dynamic NAO mode has been consistent throughout the century, and that there is no evidence for an increasing influence of the atmospheric circulation or the dynamic temperature mode on the background mode of an increasing temperature trend.

4. Conclusions

The winter NAO series presented here, based on homogenized pressure data, suggests that the recent positive trend in the NAO towards the end of the 20th century is not unprecedented, and that the early 20th century was another period of persistently positive winter NAO values, with magnitudes similar to or exceeding those of the 1990s.

The normalized EOF analysis decomposes the near-surface temperature field over the North Atlantic into a warming mode (EOF 1), associated with the Northern Hemisphere average temperature trend, and a dynamic mode (EOF 2). The dynamic ("NAO") mode is closely linked to the atmospheric circulation in winter, with almost 50% of variance in common between the NAO and PC 2. In other seasons the correlation is lower, although the time series show that PC 2 usually has the same sign and relative magnitude as the NAO; this is most noticeable in years of strong positive or negative NAO. Further analyses need to be done to investigate the links between circulation and PC 2 in other seasons. There appears to be a de-coupling of the temperature trend in the North Atlantic region (PC 1) from the Northern Hemisphere average during the latter half of the 20th century, although the relationship between the dynamic mode (PC 2) and the NAO has remained unchanged over the course of the 20th century. On the basis of this analysis, we find no evidence for an increasing link between the atmospheric circulation (NAO) and the North Atlantic temperature trend, or between the dynamic component of the temperature field (PC 2) and the average temperature trend.

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V. Slonosky, P. Yiou, Laboratoire des Sciences du Climat et de l'Environnement, UMR CEA—CNRS, CE Saclay, l'Orme des Merisiers, 91191
(e-mail: vicky.slonosky@ec.gc.ca or pyiou@cea.fr)

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