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Earth and Planetary Science Letters 202 (2002) 677–692

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Imprints of the North Atlantic Oscillation on four unusual atmospheric parameters

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Received 25 June 2002; accepted 28 June 2002

Abstract

Using data for 41 yr (1958–1998) from the National Center for Environmental Prediction–National Center for Atmospheric Research reanalysis the authors study the impact of the North Atlantic Oscillation (NAO) on four atmospheric parameters. These four parameters have three common characteristics: their previous limited use as climate diagnosis tools, their high dependence on changes in atmospheric circulation and their relationship with variables associated with the development of synoptic perturbances. They are: (1) relative angular momentum from 500 hPa to 200 hPa and from 55°N to 90°N, (2) advection of temperature at 500 hPa, (3) equivalent temperature at 850 hPa and (4) distribution of upper level low systems (ULL). The most significant results are: (1) a significant positive correlation between the relative angular momentum from 500 hPa to 200 hPa and from 55°N to 90 °N with the NAO index computed as the normalized pressure difference between Ponta Delgada (Azores) and Reykjavik (Iceland), (2) the NAO affects 500 hPa temperature advection from 45°N to 70°N and a positive NAO index is alternatively related to positive or negative anomalies of advection. The relationship is positive over the Atlantic, Asia and Western America and negative over Europe, the Pacific and Eastern America. (3) The correlation pattern between NAO index and the equivalent temperature at 850 hPa shows a semiannular structure with negative correlations over the Arctic and positive correlations over midlatitudes with the exception of the Pacific area, and (4) the distribution of ULL systems is only influenced by NAO over both sides of the Atlantic Ocean and for the latitude belt from 20°N to 50°N.

Keywords: North Atlantic; ocean circulation; angular momentum; advection; temperature

1. Introduction

The North Atlantic oscillation (NAO) is the dominant pattern of atmospheric circulation variability in the North Atlantic region ranging from

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0012-821X/02/$ – see front matter
PII: S0012-821X(02)00798-7

central North America to Europe. The NAO is a seesaw in atmospheric mass between the subtropical high and the polar low. The climate anomalies associated with NAO are most pronounced during winter when the NAO is strongest. During the months December through March, for instance, the NAO accounts for about 60% of the total variance in SLP (sea level pressure) over the North Atlantic. When the NAO is in its positive phase, the subtropical high pressure center is stronger than usual and the Icelandic low pressure center is deeper. The positive phase is associated with stronger-than-average westerlies across midlatitudes, warm and wet winters in Northern Europe, dry winters in Southern Europe, cold and dry winters in Northern Canada and Greenland and mild and wet winter conditions in Eastern USA. The negative phase is associated with the opposite anomalies.

Research on NAO has been very intense during the last decades and the NAO phenomenon has been quantified by means of different indices. In general terms most of them are the difference of normalized surface pressure between a station close to the subtropical high area – Ponta Delgada in Azores [1], Lisbon [2] or Gibraltar [3] – and a station close to the Icelandic low area (typically Reykjavik, Iceland). Differences of more than 15 hPa occur across the North Atlantic between the two phases of the NAO, as has been detected in most of these indices.

The NAO is apparent in meteorological data throughout the depth of the troposphere and it has also been suggested that the NAO is a regional manifestation of a more general annular mode (Arctic oscillation (AO) [4]) characterized by a seesaw of atmospheric mass between the polar cap and the middle latitudes in the whole Northern Hemisphere. This idea has produced an interesting debate in the scientific community about the regional character of the NAO vs. the hemispheric character of the AO [5]. A recent paper by Wallace [6] suggests that NAO and AO are the same phenomena, although he suggests ways of exploring possible differences. Another interesting finding is the fact that there have been more positive phase years than negative over the second half of the past 30 yr [7,8], which has resulted in a positive trend in the NAO indices during this period. There have been sub-periods when a phase of NAO persisted over many consecutive winters, for instance the 1960s were characterized by an unusually persistent negative NAO index; however, the magnitude of the recent upward trend is unprecedented in the observational and even paleoclimatic period. This upward trend accounts for much of the surface warming over Europe and Asia and for the cooling over the northwest Atlantic during the last three decades [9]. It is also linked to other regional changes such as stronger westerlies throughout the troposphere [10,11], regional changes in precipitation patterns [12–17], changes in SST (sea surface temperature) and salinity [18,19], changes in the storm tracks and intensity over the Atlantic [1,2,20,21] characterized mainly by a northward shift in the Atlantic storm activity and changes in the blocking frequency [22].

Characterization of the NAO has been traditionally done using surface pressure or geopotential at different pressure levels as climate diagnostic parameters, while NAO effects have been mostly referred to temperature or precipitation fields. The particularity of this study resided in the fact that we use four atmospheric parameters (relative angular momentum (RAM), advection of temperature (AT), equivalent temperature (ET) and distribution of upper level low systems (ULL)) that (a) have been poorly explored, (b) have the common feature that they are highly dependent on changes in atmospheric circulation, and specially (c) are strongly related to the development of lower scale meteorological systems, such as the position and strength of the jet stream (RAM), baroclinic instability (AT), the content of humidity and the position of fronts (ET) or blocking (ULL distribution). This analysis can be useful in the difficult task of linking phenomena across very different space and time scale in the framework of connecting weather and climate processes.

The expected possibilities of these four parameters as tools to characterize NAO effects are as follows.

1.1. RAM

Variations and zonal wind anomalies are strongly related over the North Atlantic region, so NAO and zonal wind anomalies concur. When NAO is in the positive phase (pressure drops over Iceland and rises over Azores Islands) westerly winds are stronger north of 45°N. The maximum anomaly is centered near 55–57° in the lower troposphere and near 65° in the upper troposphere. A measurement of this anomaly of the westerlies at a planetary scale is the anomaly of the relative atmospheric angular momentum (RAM) integrated from 500 hPa to 200 hPa and from 55°N to 90 °N ($RAM_{500-200,55-90}$). RAM is due to zonal winds and varies by as much as 100% seasonally, essentially doubling between Northern Hemisphere summer and winter due to the strong annual cycle of the jet stream in that hemisphere. However, it is expected that an important percentage of the interannual variation of the $RAM_{500-200,55-90}$ should be due to the phenomenon NAO.

1.2. AT

The influence of NAO on Northern Hemisphere surface temperature is estimated to be about one-third of its total variance. The influence could be in the sense suggested by Wallace et al. [23] and Wallace [24]. If hemispheric circulation has negative temperature anomalies over the oceans and positive temperature anomalies over the continents, the result is a positive temperature anomaly over the entire Northern Hemisphere, as a consequence of the larger heat capacity of the oceans than of the continents and the fact that the continents occupy a much larger area of this hemisphere than the oceans. The AT at 500 hPa may be a good measurement of the influence of circulation on temperature. The patterns of winter anomalies of AT for those years when NAO is in a positive phase should differ considerably from those when NAO is in a negative phase. The difference in AT patterns should illustrate better the effects of changes in the circulation due to NAO than the difference between patterns of anomalies of temperature. The choice of the 500 hPa level instead of 850 hPa, which is a level more widely used in thermal advection [25], is due to two facts: the current use of AT at 500 hPa in vertical velocity diagnosis in weather forecasting and the extensive use of 500 hPa to calculate temperature anomalies due to NAO.

1.3. ET

While the influence of NAO on the Northern Hemisphere surface temperature has been relatively well estimated, the influence of NAO on humidity distribution is very limited. In the three recent global humidity climatologies [26–28] nothing is said about how NAO can influence the humidity distribution. In a recent study of the distribution and trends in USA surface humidity and temperature [29,30], consistent trends in both variables were found. These trends were also consistent with apparent temperature, a measurement of human comfort that combines temperature and humidity. However, they found no detectable influence of large-scale dynamics on interannual humidity variations. Neither ENSO (El Niño–Southern Oscillation) nor NAO was significantly correlated with specific humidity anomalies. However, this study was limited to the USA while the largest changes of circulation due to NAO are produced over Europe. In this study the influence of NAO on the temperature–humidity pair at a hemispheric scale is analyzed. We use the ET, defined as the temperature to which air would rise if all the water vapor were to condense in an adiabatic, isobaric process to combine both quantities in a single variable. Furthermore, ET characterizes an air mass when only quasi-isobaric condensations and evaporations happen, so ET changes involve advection of other air mass and consequently are very sensitive to changes in circulation.

1.4. Distribution of ULL

The distribution of ULL could be an interesting climate diagnosis parameter in the sense that ULL includes cutoff low pressure (COL) systems. COL systems are usually closed circulations in the middle and upper troposphere that developed from a deep trough in the westerlies [30,31]. COL systems are largely influenced by blocking and consequently their number, size, temporal and spatial distribution should be affected by the NAO. Previous studies done in the Northern Hemisphere (Price and Vaughan [32] for a 1-yr period – October 1982–September 1983 – and Kentarchos and Davies [33] for the period 1990–1994) showed that: (1) COLs form more often in summer than in winter, (2) there are favored regions of occurrence (Europe, China–Siberian region, the north Pacific, the north–east USA, the western part of the USA and the north-east Atlantic), with Europe the most favored region (33% of the total number) and (3) there was some interannual variability in the total number of COLs (the maximum was 275 in 1994 and the minimum was 181 in 1991). These studies were done using subjective analysis, which consisted in analyzing visually daily 200 mb, 500 mb and surface charts. Any search for a relationship with NAO requires a period of at least 30 yr. The intensive work of estimating COLs over such a long time period is beyond the scope of this article. An indirect way of measuring the distribution of COLs is by means of measuring ULLs, assuming that the main variability in the number of ULLs due to NAO is produced in the number of COLs, especially for low latitudes.

2. Data

Data for 41 yr from 1958 to 1998 from the National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis were used. The NCEP reanalysis [34] is an intermittent data assimilation scheme performed with a T62 model with 28 vertical sigma levels and the Operational Statistical Interpolation (SSI) procedure for assimilation. The data sources include rawinsonde profiles, surface marine reports from the Comprehensive Ocean–Atmosphere Data Set (COADS), aircraft observations, surface land synoptic reports, satellite soundings from the TIROS Operational Vertical Sounder (TOVS) and other platforms, surface wind speeds from the Special Sensor Microwave Imager, and satellite cloud drift winds.

The reanalysis results in fields of atmospheric data for the period 1958–present. It provides daily mean atmospheric data with global coverage. The wind, geopotential height, vertical motion, temperature, and specific humidity at multiple levels have a horizontal resolution of 2.5°×2.5°, the one used in this study. To quantify NAO, the 41 winter values of the NAO index, computed as the normalized pressure difference between Ponta Delgada (Azores) and Reykjavik (Iceland) were used.

3. Method

3.1. RAM

Zonal wind (u) data at the 500 and 200 hPa levels were used to calculate daily values of $RAM_{500-200,55-90}$ according to the following expression:

$$M_{(\varphi,\varphi+2.5)(p,p+\Delta p)} = R^3 \frac{2\pi\Delta p}{g}[\sin(\varphi+2.5)-\sin\varphi]$$

$$\frac{\bar{u}_{\varphi,p}\cdot\cos\varphi + \bar{u}_{(\varphi+2.5),p}\cdot\cos(\varphi+2.5) + \bar{u}_{\varphi,(p+\Delta p)}\cdot\cos\varphi + \bar{u}_{(\varphi+2.5),(p+\Delta p)}\cdot\cos(\varphi+2.5)}{4}$$

M = relative momentum; R = Earth mean radius; $\bar{u}$ = mean zonal wind; φ = latitude; p = pressure.

This quantity was integrated between 500 and 200 hPa and from 55°N to 90°N.

3.2. *AT*

Daily values of temperature advection at 500 hPa were calculated for every grid point using zonal (u) and meridional (v) components of wind at every point and temperature values from the four surrounding points to calculate the temperature gradient. So at a gridpoint (λ, φ) advection was calculated according to the following expression:

Advection of

$$T = -\frac{u_{\lambda,\varphi}(T_{\lambda+2.5°,\varphi} - T_{\lambda-2.5°,\varphi})}{2\Delta x}$$

$$-\frac{v_{\lambda,\varphi}(T_{\lambda,\varphi+2.5°} - T_{\lambda,\varphi-2.5°})}{2\Delta y}$$

φ = latitude; λ = longitude; $\Delta x = R_T \quad 2.5\cos\varphi$; $\Delta y = R_T$ 2.5; R_T = 6350 km (mean Earth radius).

3.3. *ET*

Daily values of ET at 850 hPa for every grid point of the NCEP–NCAR reanalysis were calculated according to the following expression:

$$T_e = T\left[1 + \left(\frac{Lw}{c_{pd}T}\right)\right]$$

T_e = equivalent temperature; L = latent heat; w = mixing ratio; c_{pd} = dry air specific heat; T = temperature.

3.4. *Distribution of ULL*

In this analysis, ULLs in the 41-yr period (1958–1998) were computed using geopotential data at the 200 hPa level. So, occurrence, position and duration of ULL systems for the 20°N–70°N latitude belt were calculated according to the following procedure. First, for every day, those grid points whose geopotential was lower than at least six of the eight surrounding grid points were selected. Once this set of data was chosen, only those grid points where the minimum geopotential difference with the surrounding points were of 10 m were selected. This threshold was taken to fit as much as possible with the COL climatology for the 1-yr period (October 1982–September 1983) by Price and Vaughan [32]. When these criteria persisted at a grid point or any of the adjacents, we considered the same ULL system.

Once daily values for the four parameters were calculated, monthly, winter and annual means were constructed from them. As winter were considered January, February and March. For winter and annual values, anomalies from the period 1958–1998 were calculated. The winter anomaly series should be most influenced by NAO, so it was used in this study. For *AT* and distribution of *ULL*, anomaly fields were then used to calculate composites consisting of where NAO was either more positive or negative in phase. Thresholds of the 41-yr mean NAO index ±1 S.D. were used to define positive and negative phases. Years chosen for the positive phase were 1961, 1983, 1989, 1990, 1992, 1993 and 1995 and the negative phase years were 1960, 1963, 1965, 1969, 1979, 1985 and 1996. It is worth noting that, due to the positive trend in NAO index, the positive phase is strongly dominated by the 80s and 90s whereas the negative phase is dominated by the 60s and 70s. When removing the trend we found that 60% of the years coincide with those for the non-detrended series, and so the results are not very different.

4. Results

4.1. *RAM*

The yearly evolution of NAO and momentum anomalies (Fig. 1) shows three common features: significant positive trends (95%) caused by predominantly positive anomalies in the latter half of the period, the fact that 1988–1995 anomalies are exclusively positive, and similar maximum and minimum peaks (i.e. max. 1967, 1973, 1989). The cross-correlation of $RAM_{500-200,55-90}$ anomalies with NAO shows a significant positive value.

When prewhitening was done, the correlation coefficient between NAO and RAM exceeded 0.5 both for original and for prewhitened series. A linear regression between NAO and RAM series was also calculated (Fig. 2). The most significant result is the fact that NAO accounts for 26.4% of the interannual RAM variance. This result is consistent with the study by Thompson and Wallace [10], who found that the percentage of monthly variance explained by the Arctic oscillation was 45% for the zonal-mean geopotential height (1000–50 hPa) and 35% for the zonal-mean zonal wind (1000–50 hPa).

4.2. AT

The winter advection averaged over 1958–1998 is displayed in Fig. 3a. As expected, high values of AT for 500 hPa are restricted to the region poleward of 40°N, due to the higher variance in the wintertime wind field. Both oceans (Pacific and Atlantic) are dominated by positive AT while continental areas of America, Europe and Asia are characterized by negative advection of temperature. This is due to the strong zonal asymmetries in the Northern Hemisphere climatological mean

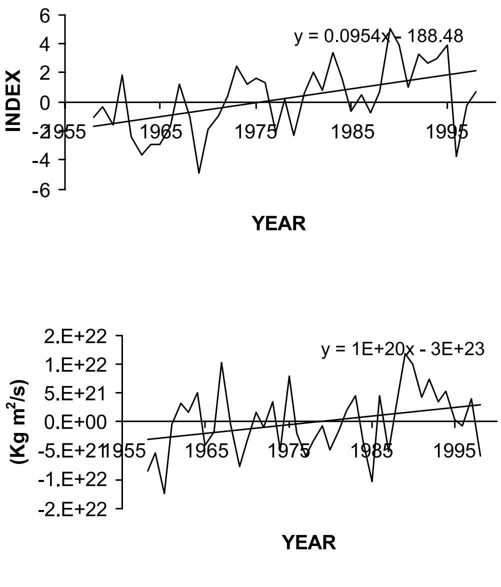

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Fig. 1. Annual evolution of (a) NAO index and (b) relative angular momentum anomalies together with significant trends (95%).

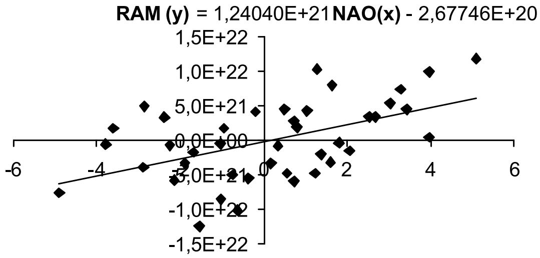

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Fig. 2. (b) Regression of $RAM_{500-200,55-90}$ anomalies on NAO index.

wintertime circulation by the continent–ocean heating contrast and the existence of important orographic elements such as the Rockies or the Himalayas. Fig. 3b shows the wintertime mean 500 hPa height field in order to display better this asymmetry and to understand the field of wintertime AT. Due to the meridional gradient of temperature, regions placed from the axis of the trough to the axis of the ridge of wintertime mean 500 hPa height (positive meridional velocity) exhibit positive AT while those regions located from the axis of the ridge to the axis of the trough (negative meridional velocity) exhibit negative AT. So, the pattern of meridional velocity v (Fig. 3d) is very similar to the pattern of mean wintertime AT. There are, however, slight differences that happen mainly at the East and at the West of continents, where the zonal AT due to zonal velocity u (Fig. 3c) is significant because of the zonal gradient of temperature. The most significant example of this happens in Western Europe, where the weaker than expected anomalies of v do not result in negative anomalies of AT.

To illustrate the NAO influence on the AT, NAO signal strength was measured by composite anomaly means. The left panel of Fig. 4 displays the mean anomaly of AT, temperature (T), zonal velocity (u) and meridional velocity (v) for the positive NAO year composite. The NAO positive phase signal consists of six areas of AT anomalies at latitudes higher than 45°N, which alternate in sign with longitude. So there are positive AT anomalies over the Atlantic, Asia and Western America and Eastern Pacific and negative anomalies over Europe, Western and Central Pacific and

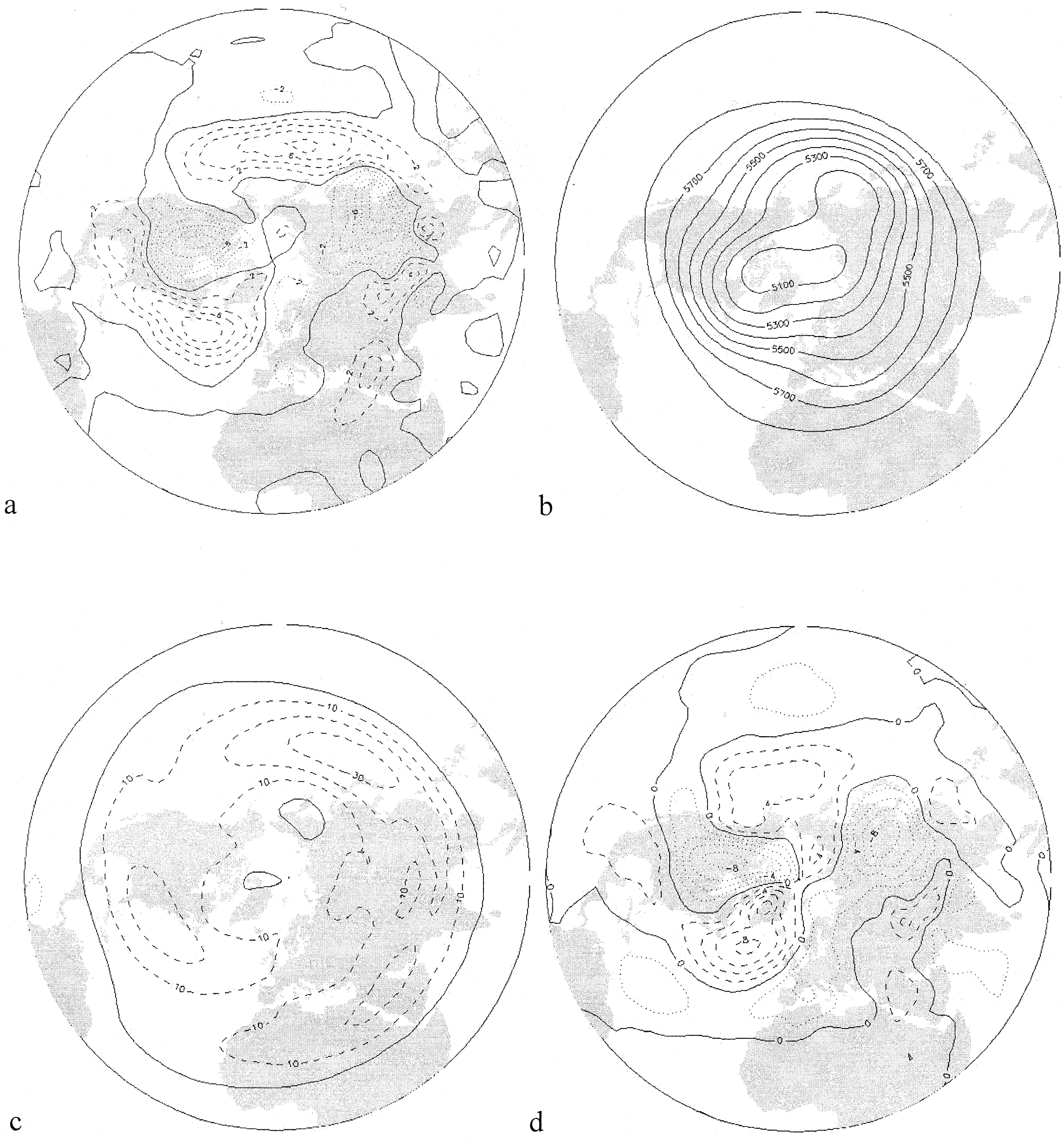
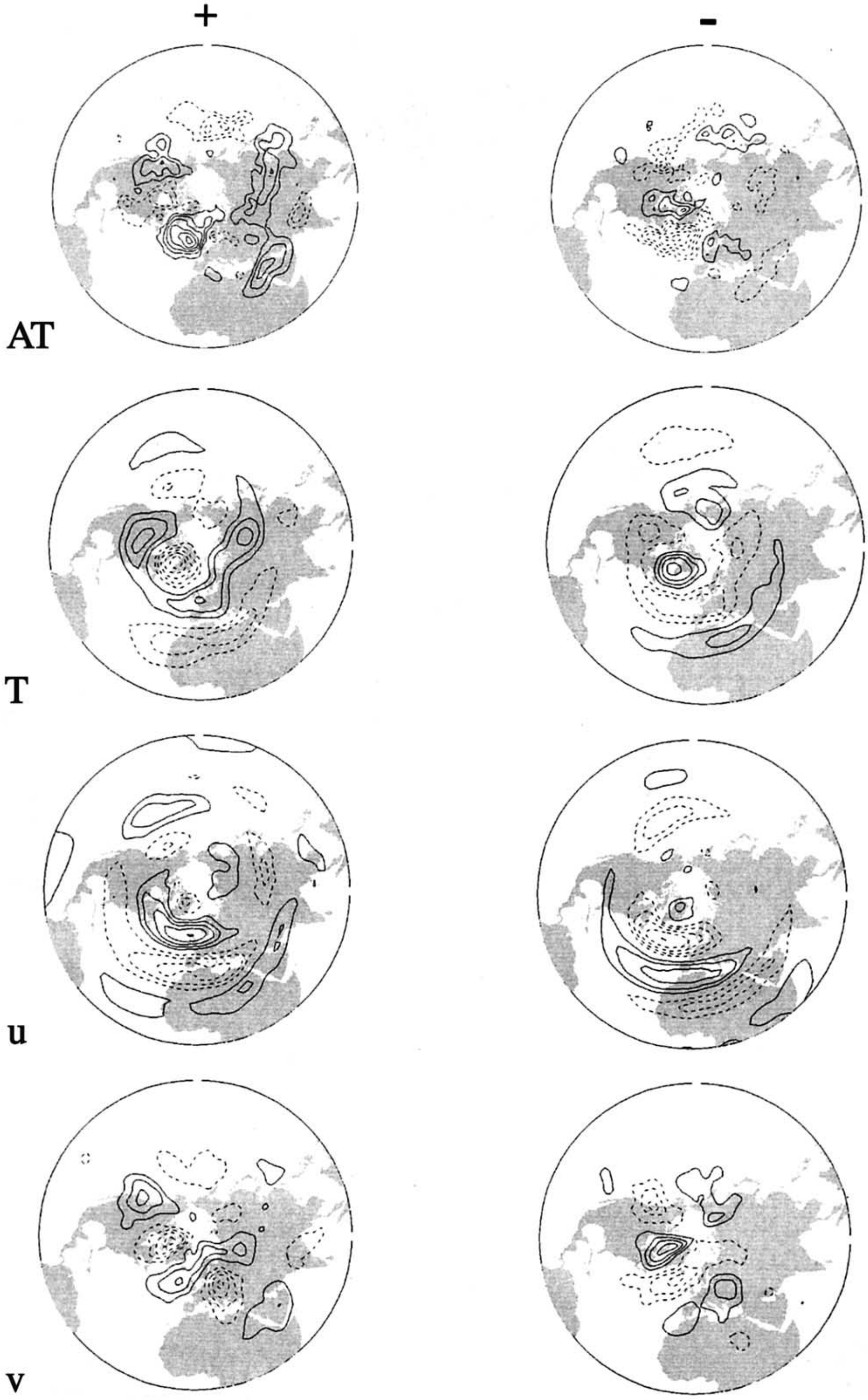


Fig. 3. (a) Wintertime mean AT at 500 hPa for the period 1958–1998. Solid line, null advection; dashed line, positive advection; dotted line, negative advection; interval = 2×10^{-5} K s^{-1}. (b) Wintertime mean 500 hPa geopotential (m) for the period 1958–1998. (c) Wintertime mean zonal velocity at 500 hPa for the period 1958–1998 (m s^{-1}). Solid line, null velocity; dashed line; positive velocity. (d) Wintertime mean meridional velocity at 500 hPa for the period 1958–1998 (m s^{-1}). Solid line, null velocity; dashed line, positive velocity; dotted line, negative velocity.

Eastern America. In general terms these AT anomalies are due to anomalies of meridional wind since the two patterns are very similar. However, the anomalies of zonal wind and temperature are also able to produce areas with AT anomalies and both have an important effect on the strength of the signal. The strongest signal is located over the Atlantic where positive anomalies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of v are coincident with an anomalously high temperature gradient. On the other hand, over Europe the signal strength is very low or nonexistent, even though there is an important negative anomaly of v. The reason is the presence of a negative anomaly in the temperature gradient due to the fact that the positive anomaly of temperature over Northern Europe is higher than the positive anomaly over Southern Europe. The negative AT anomaly over Eastern America has two centers. The Northern center is due to a negative anomaly of v because of an anomalous positive zonal AT (zonal winds are higher than normal and there is an important positive anomaly of temperature over Middle America). The southern center is produced by anomalous negative zonal wind in an area with an east to west temperature gradient. Over Eastern Asia, a negative anomaly of v combined with a west to east temperature gradient produces the positive AT anomalies.

During negative NAO years (right panel of Fig. 4) a pattern roughly the inverse of the NAO positive phase is evident. However, the zonal advection over Southeastern America is not present and there is an important positive AT anomaly over Europe due to the combination of a positive anomaly of v and the temperature anomaly dipole (positive over Southern Europe, negative over Northern Europe). There are also inverse AT anomalies in the other regions but their magnitude is lower than for the NAO positive phase. This difference is especially important over Asia. The lack of a concordance between AT and temperature anomalies is remarkable and in terms of influence of circulation for the temperature fields may be due to the dominance of the meridional component in our calculation of global AT (zonal plus meridional), while anomalies of temperature are mainly maintained by advection by the zonal wind [10]. It is also important to comment that there are other factors such as local radiative and heating processes that have a significant influence on the temperature field, so both ocean–atmosphere and snow–atmosphere interactions can be responsible for the disagreement between AT and temperature anomalies. For instance anomalies of North Atlantic SSTs might affect the atmosphere through atmospheric heating processes due to evaporation and precipitation [35] and a decrease in the Eurasian snow cover during autumn raises the surface temperature over Eurasia [8]. This last effect could also be responsible for the high difference between AT and temperature anomalies over Asia.

The difference between NAO positive phase and NAO negative phase composites (Fig. 5a) is a good way to quantify the amplitude of the AT signal. The AT signal strength is a maximum over the Atlantic Ocean and a minimum over Europe. The pattern of positive NAO phase minus negative NAO phase represents the linear behavior of the AT signal. To know if the AT signal is not simply linear with respect to NAO phases the addition of positive and negative NAO year wintertime mean AT was calculated (Fig. 5b). Main areas of nonlinearity are found in those regions where there are anomalies in the meridional temperature gradient or anomalies of zonal wind together with an important zonal temperature gradient. The main example of this first possibility happens over Northern Europe where NAO negative phase influence is much stronger than NAO positive phase influence. The contrary happens over Southwestern America, which can be a good example of the second influence.

4.3. ET

The wintertime mean equivalent temperature ET pattern (Fig. 6a) is similar to the wintertime mean temperature T pattern (Fig. 6b) although there are important differences due to the second component of TE, the specific humidity (q). The highest values of water vapor content occur in the

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Fig. 4. Composite of the wintertime temperature advection anomalies (AT), temperature anomalies (T), zonal velocity (u) and meridional velocity (v) on positive NAO years (left) and on negative NAO years (right). Solid line, positive values; dashed line, negative values; intervals for $AT = 1\times10^{-5}$ K s^{-1}, for $T = 0.5$ K, for $u = 1.5$ m s^{-1} and for $v = 1.0$ m s^{-1}).

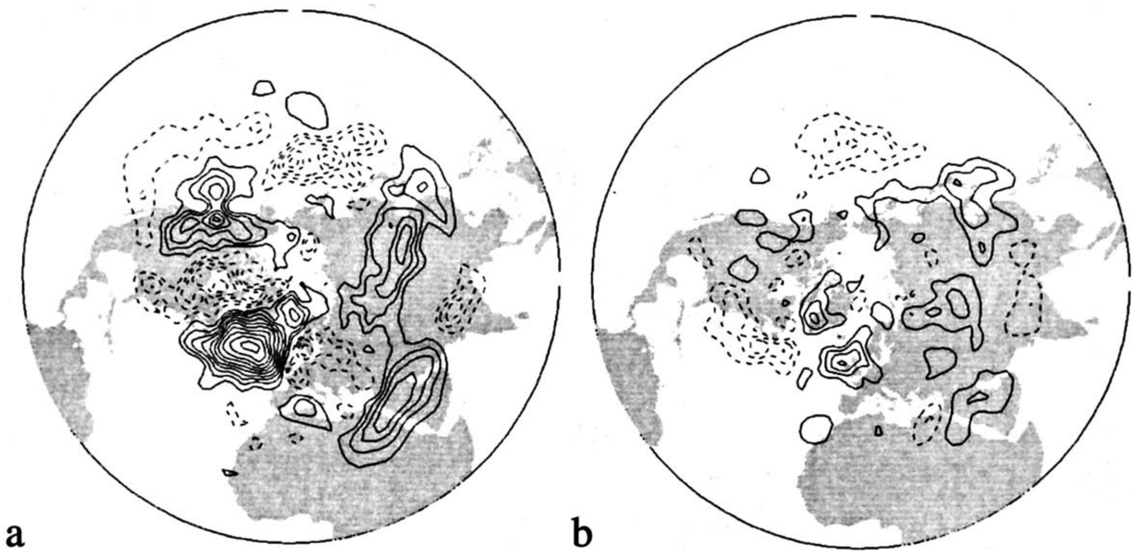


Fig. 5. (a) Difference between wintertime mean temperature advection anomalies in positive and negative NAO years. (b) Addition between wintertime mean temperature advection anomalies in positive and negative NAO years. Solid line, positive anomalies; dashed line, negative advection; interval = 1×10^{-5} K s^{-1}).

equatorial zone. The strong vertical transport and diffusion of water vapor associated with the ascending branch of the Hadley cell lead to high specific humidity. So, the maximum over the equatorial zone (especially over Africa) is more evident in the ET field than in the *T* field. The water vapor content in the subtropics produced by the upward vertical transport is suppressed by mean downward motion in the subtropical high pressure belts. This is more evident over the Atlantic where a pronounced trough of ET occurs. This trough is not so evident in the temperature field. The advection of moisture from the subtropics opposes the temperature decrease in mid- and high latitudes. So in those regions, such as Europe, where the baroclinic disturbances are more active, the meridional gradient of ET is not so high. This gradient intensifies in regions poleward of 60°N latitude more intensively in the ET field than in the *T* field. The best example occurs on Greenland. The orographic effect on water vapor content is also evident on the ET pattern. So, the subsidence on the lee side of the great mountain ranges favors the formation of very dry areas such as the regions on the lee side of the Rocky Mountains or Himalayas that are characterized by zonal minima of ET. The best example of this occurs on Western America.

The correlation patterns between NAO and wintertime ET (Fig. 7a) and between NAO and wintertime *T* (Fig. 7b) are very similar. Both present high negative values over the Northwestern Atlantic and high positive values in a region that extends from Northern Europe across much of Eurasia. The negative correlations over Northern Africa are also common features. A relevant difference occurs over the Atlantic Ocean. There are no significant correlations either in midlatitudes or in the subtropical areas for ET, but positive significant correlations occur over the midlatitude Atlantic and negative significant correlations occur over the subtropical Atlantic for *T*. So the pattern of correlations between NAO and *T* is semiannular with negative correlations over the Pole, positive correlations over midlatitudes and negative correlations again over the subtropical area, with the Pacific showing little NAO influence. This latter result agrees with others found in the literature (i.e. [5]).

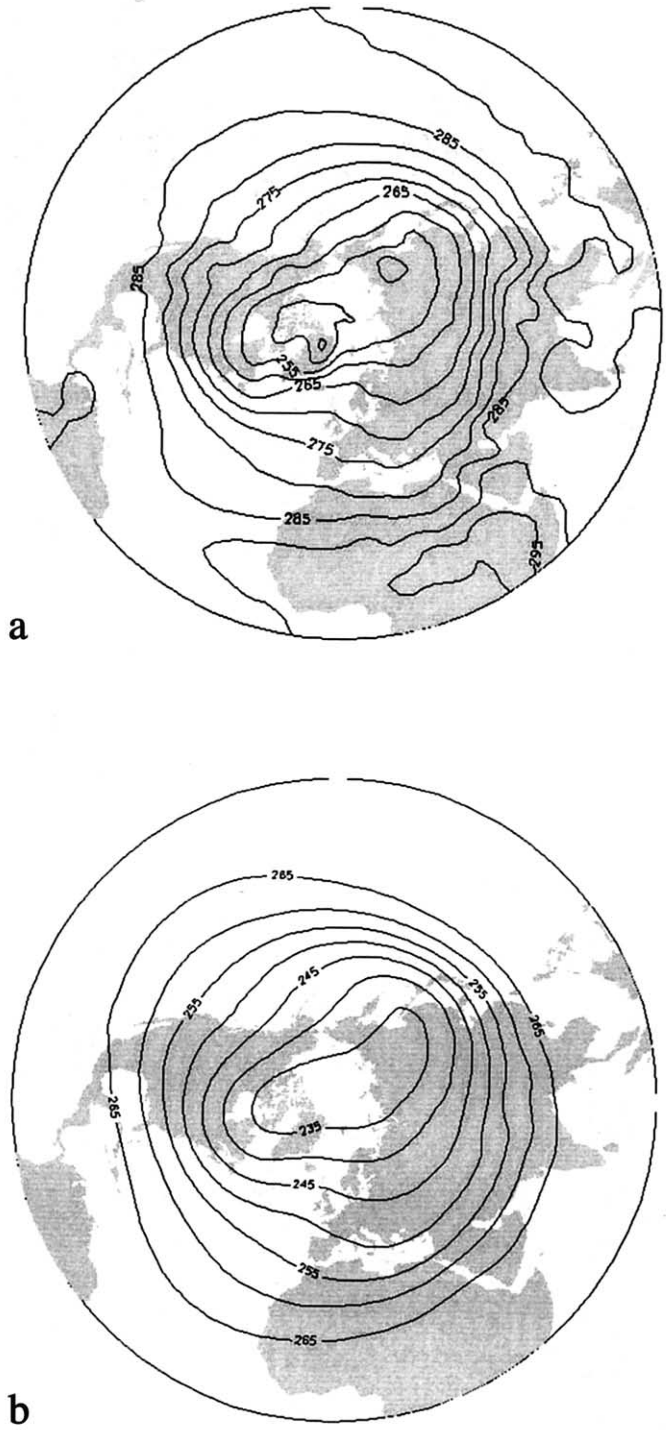
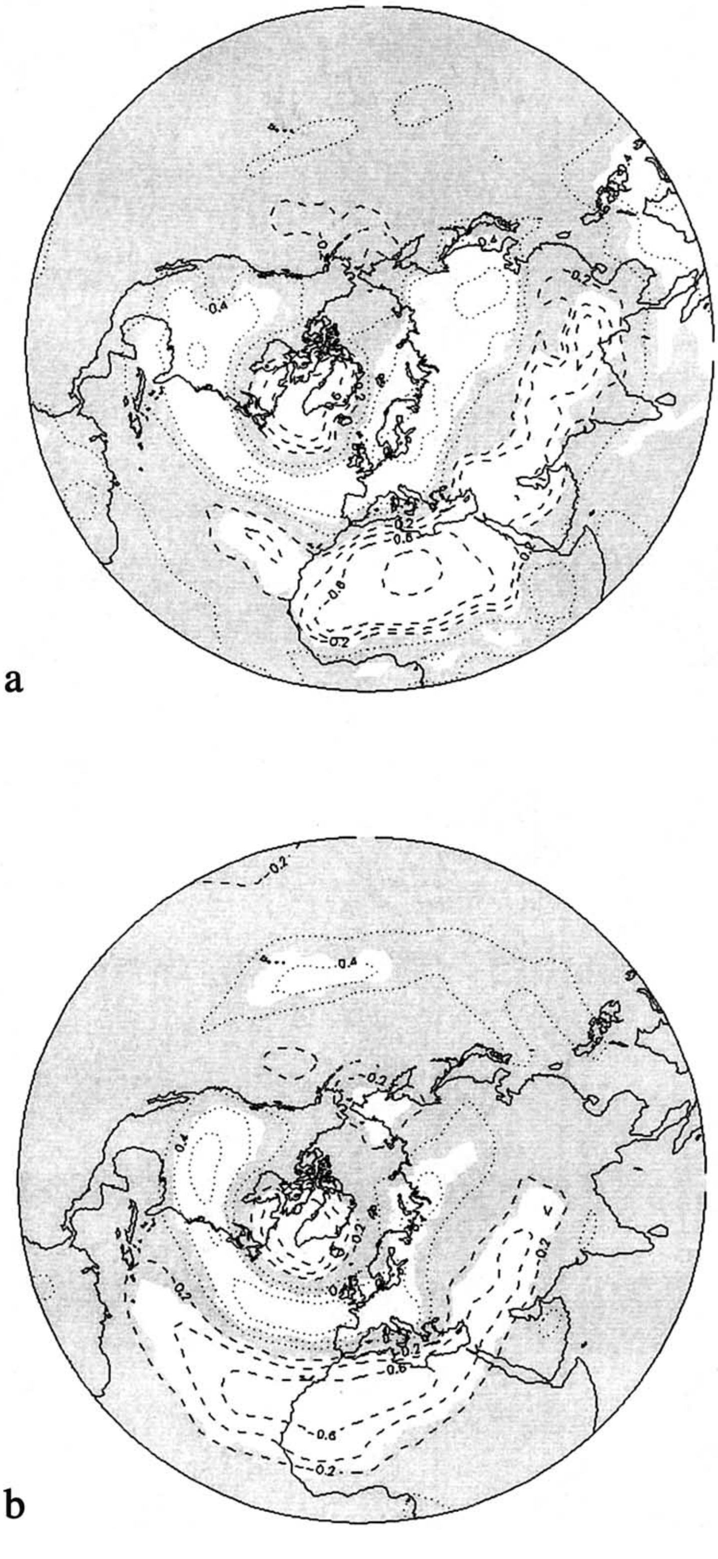


Fig. 6. (a) Wintertime mean equivalent temperature (K); (b) wintertime mean temperature (K).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4.4. Distribution of ULL systems

The number of ULL systems for the seven NAO positive phase years and for the seven NAO negative phase years as well as the means for the two sets of years were calculated. Although the number of ULL systems is slightly higher during NAO positive phase than during NAO negative phase, the difference is too small to be meaningful. Similar conclusions can be inferred when the analysis is done splitting the total number of ULL systems as a function of their duration. To study the frequency of ULL systems based on geographic location, the spatial distribution of the ULLs was calculated in 18 boxes according to Fig. 8. The division in latitude was done at 50°N whereas boxes of 40° longitude were chosen in the same way that the main areas of occurrence of COLs [33] were selected.

The first conclusion we inferred from this analysis is that the difference in the number of ULLs between NAO positive phase and NAO negative phase was not produced in the belt 50°N–70°N latitude (Fig. 8a,b). The variability in the number of ULL systems due to NAO happened only in the belt 20°N–50°N latitude but not in all eight sectors (Fig. 8c,d). There were only important differences in the two boxes that included both sides of the Atlantic. So, there were 109 ULL systems in the Eastern Atlantic coast box during NAO positive phase years while there were only 81 in the same box during NAO negative phase years. The opposite variations happened in the Western Atlantic coast box where there were 26 ULL systems during NAO positive phase years and 39 during NAO negative years. This result is in agreement with the study by Shabbar et al. [36], who found that differences in blocking frequency between phases of NAO only occur from 0° to 90°W. When the NAO is in the negative phase, there is an amplified meridional wave-like flow (favorable for block formation), with the average 500 hPa trough axis located in the band 70–90°W (region where more ULL should appear). On the other hand, when the NAO is in the positive phase, the flow is more zonally oriented and consequently unfavorable for block formation. However, the average 500 hPa trough axis is located in the band 0–20°W, which explains the higher number of ULLs at these longitudes during positive NAO phases.

5. Concluding remarks

Because the NAO is responsible for generating systematic large amplitude patterns in the anomalies of wind speed, latent and sensible heat fluxes, temperature meridional heat flux by the atmosphere [25] and Atlantic storm tracks, it was hypothesized and found in this study that it has a strong impact on four atmospheric variables related to those anomalies. These were: RAM (related to wind), AT (meridional heat flux), ET (latent heat flux and temperature) and distribution of ULLs (storm tracks).

The *RAM from 500 hPa to 200 hPa and from 55°N to 90 °N* was chosen because of its hemispheric character. According to this, RAM can be useful to estimate the influence of NAO on the westerly wind anomalies at a planetary scale. The results confirm the strong relationship between the NAO index and RAM anomalies with correlations higher than 0.5 indicating a strong influence of the NAO on the global extratropical circulation in the Northern Hemisphere. The analysis of the anomalies of *AT at 500 hPa* shows some interesting results. Firstly, the analysis shows that the AT field is mostly affected by meridional advection. So its sign is almost coincident with the sign of the meridional wind field, and the null value of advection is along the axis of long-range geopotential trough and ridges. Zonal advection is only important in the vicinity of con-

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Fig. 7. (a) Correlation coefficients between wintertime mean equivalent temperature (ET) anomalies and the NAO index. Dashed line, negative correlations; dotted line, positive correlations; white areas means correlations statistically significant at 95%. (b) Correlation coefficients between wintertime mean temperature (T) anomalies and the NAO index. Dashed line, negative correlations; dotted line, positive correlations; white areas means correlations statistically significant at 95%.

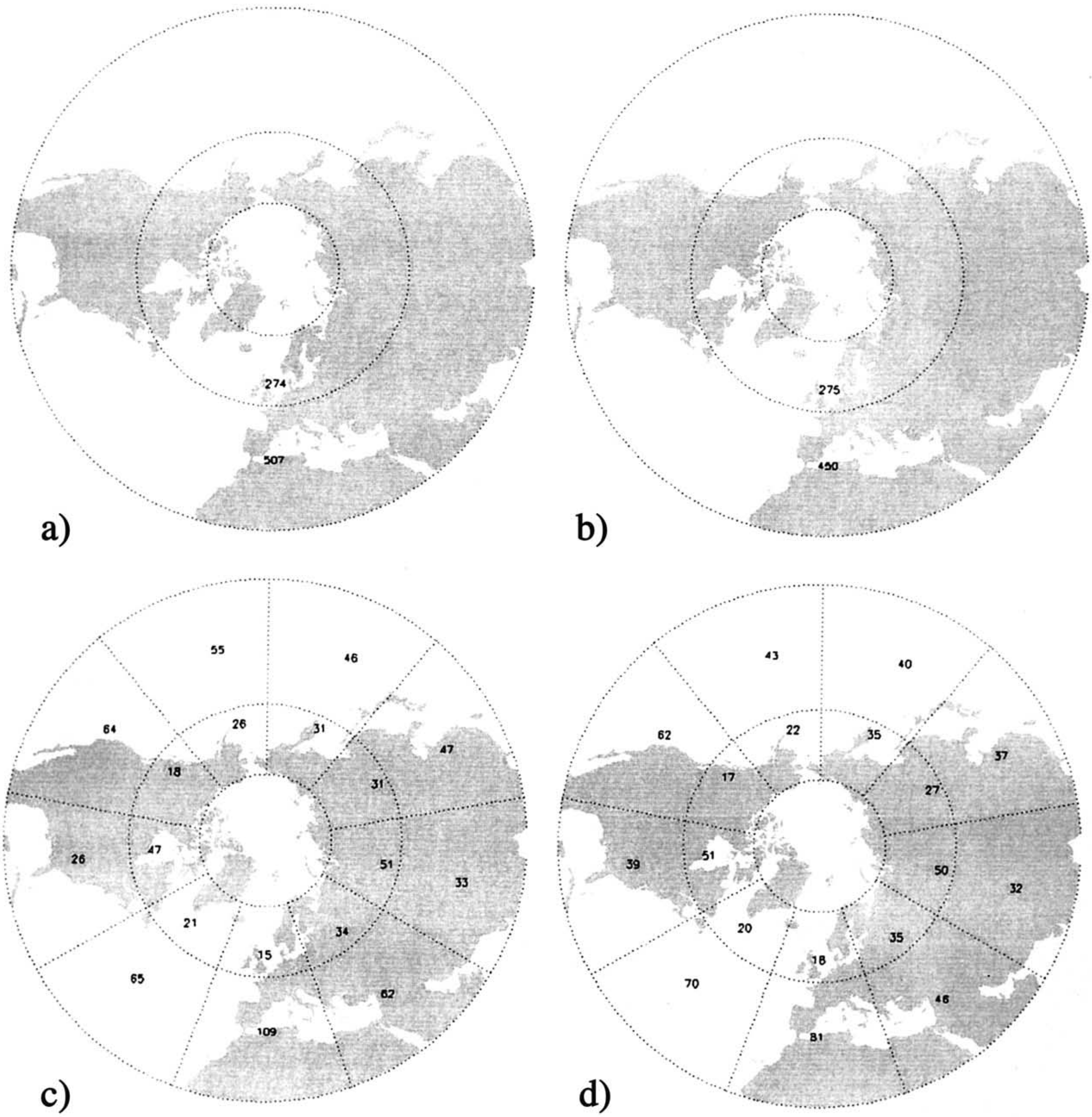

Fig. 8. (a) Number of ULLs for positive NAO years for the belts 20°N–50°N latitude and 50°N–70°N latitude. (b) Number of ULLs for negative NAO years for the belts 20°N–50°N latitude and 50°N–70°N latitude. (c) Number of ULLs for positive NAO years for the 16 selected boxes. (d) Number of ULLs for negative NAO years for the 16 selected boxes.

tinents due to the zonal gradient of temperature. Secondly, anomalies of AT due to NAO phases are also due to anomalies of meridional wind although the concurrence of anomalies of zonal wind and temperature has an important effect on the strength of the signal. Finally, the linear response of AT to NAO phases is maximal over the Atlantic Ocean and the most important area of nonlinearity is located over Northern Europe. This nonlinearity must be due to the interplay of different factors influencing NAO such as local radiative and heating processes that have significant influence on the temperature field.

To investigate the simultaneous effect of NAO on temperature and humidity the *ET* is used. The field of anomalies of ET was not absolutely coincident with the field of anomalies of temperature. However, the regions where NAO has a strong influence on temperature are also those where NAO strongly influences the ET. The main differences occur over the midlatitude and subtropical Atlantic where there are no significant correlations between NAO and temperature but there is a positive correlation with equivalent temperature for midlatitudes and a negative correlation for the subtropical Atlantic. Another interesting finding is that the correlation pattern between NAO and ET is semiannular without significant correlation over the Pacific. Finally the *frequency of ULLs* was also dependent on the NAO phase but only in the Atlantic area from 20°N latitude to 50°N latitude. The concentration of ULLs rises over Western Europe, close to the Atlantic Ocean, in positive NAO years while in negative years, this increase happens over Eastern America. As the main interannual variability in the number of ULL systems is due to the variability in the number of cutoff low systems and this number is very dependent on blocking activity, the results suggest changes in the frequency of blocking in the North Atlantic sector.

The fact that these four magnitudes are strongly related to the development of lower scale meteorological systems, such as the position and strength of the jet stream, baroclinic instability, and the content of humidity makes this study useful in the difficult task of linking phenomena across a very different space and time scale in the framework of connecting weather and climate processes.

Acknowledgements

The authors are grateful to the anonymous reviewers, whose remarks and suggestions helped to improve the paper.***[AC]***

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