The dynamics of the North Atlantic Oscillation during the summer season

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ABSTRACT: This study examines the dynamical characteristics of the North Atlantic Oscillation (NAO) life cycle for the summer season. The diagnostic techniques, which use NCEP/NCAR Reanalysis data, include composites of the 300 hPa stream function, a projection analysis with each term in the stream-function tendency equation, and composites of potential temperature on the 2 PVU potential-vorticity surface.

For both phases, the NAO life cycles take about two weeks to complete. The NAO anomalies are found to be driven by both high-frequency (period < 10 days) and low-frequency (period > 10 days) transient eddy vorticity fluxes. The decay of the NAO is accomplished by both low-frequency transient eddy vorticity fluxes and horizontal divergence. The breaking of synoptic-scale waves is found to play a crucial role during the summer NAO life cycle. For the positive NAO phase, the southern centre of action of the dipole arises from anticyclonic wave-breaking, and the northern centre of action from anticyclonic wave-breaking followed by trough intensification. For the negative NAO phase, both centres of action develop from cyclonic wave-breaking. These characteristics are very similar to those for the NAO life cycle during the winter season, the primary differences being the weaker anomalies, shorter zonal and meridional scales, and less intense wave-breaking of the summer NAO. Copyright © 2007 Royal Meteorological Society

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1. Introduction

Over the past two decades, most research on the North Atlantic Oscillation (NAO) has focused on the winter season. However, studies such as Barnston and Livezey, (1987); Portis et al., (2001) have shown that the NAO is a prominent teleconnection pattern during all months of the year, including the summer. Similarly, Thompson and Wallace (2000) and Ogi et al. (2004) have found that the very similar northern annular mode is also a dominant pattern throughout the year. For each of the summer months of June, July, and August, Barnston and Livezey (1987) find that the NAO is the pattern with the largest fractional variance, with values ranging between 9.5% (June) and 10.1% (August). Recent studies (Feldstein, 2003; Benedict et al., 2004; Franzke et al., 2004) have examined the dynamical processes that account for the growth, maintenance and decay of NAO anomalies during the winter. These studies find that NAO events are driven by nonlinear processes. The NAO anomalies are shown to correspond to the remnants of breaking synoptic-scale waves. Furthermore, the modelling calculations of Franzke et al. (2004) have found that the presence of the NAO is dependent on the existence of a sufficiently strong horizontal stretching deformation field. Therefore, since this stretching deformation field is strongest during the winter season, it is not obvious a priori that NAO events during other seasons should arise from processes similar to those during the winter season.

In this study, we investigate the dynamical processes that drive NAO events during the summer season. In Section 2, we present the data and diagnostic techniques. This is followed in Section 3 by a calculation of the NAO life cycle during the summer season, and in Section 4 by a projection analysis of each term in the stream-function tendency equation. Section 5 presents the results of an investigation of the wave-breaking properties of the NAO. Conclusions are given in Section 6.

2. Data and diagnostic techniques

Daily NCEP/NCAR Reanalysis data for 00 UTC are examined in this study. The variables investigated include the stream function, the zonal and meridional winds, the vorticity and divergence, and the geopotential height, all on the 300 hPa surface. The last quantity is determined by vertical integration of the hydrostatic equation from the Earth’s surface, while the other variables are obtained by logarithmic interpolation from sigma surfaces. We also examine potential temperature on the 2 PVU surface (1 PVU = \(10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}\)); poleward of about 25°N this surface closely corresponds to the tropopause. The data cover the months of May through September,

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for the years 1958–1997. At each grid point, the seasonal cycle is removed. The seasonal cycle is obtained by applying a 20-day low-pass digital filter to the calendar mean for each day. The data are evaluated at rhomboidal-30 horizontal resolution. All data are slightly smoothed by using a 31-point, 10-day, low-pass digital filter (further details on the filtering can be found in Feldstein (2003)).

In this study, an NAO life cycle, or a persistent event, is defined to have taken place if two criteria are satisfied. First, the amplitude of the NAO pattern (the NAO index) must exceed one standard deviation on the first day of the life cycle (called the lag-0 day). We use the daily NAO index of the Climate Prediction Center (CPC), which corresponds to the amplitude time series of the first rotated empirical orthogonal function (REOF) of the 700 hPa geopotential-height field. This index was selected in preference to that of Feldstein (2003) because it yields a composite 300 hPa geopotential-height pattern that explains a greater proportion of the summer variance (8.3% versus 6.1%). With the methodology of Feldstein (2003), it was found that the NAO was the sixth REOF. (Note that we use the CPC NAO index that was generated before changes to that index were adopted on 1 June 2005.) Secondly, the pattern correlation for the 300 hPa geopotential-height field must stay above a particular threshold value for at least 5 consecutive days. The threshold value is that for a one-sided $t$-test at the 99% confidence level for a zero null hypothesis. The number of degrees of freedom $N$ is obtained with Fisher’s $Z$-transformation, where the variance of $Z$ is equal to $(N - 3)^{-1}$ (see Feldstein and Lee (1996) for additional detail). This method is based on the methodology of Horel (1985) and Mo (1986). The pattern correlations are taken over the entire Northern Hemisphere. To ensure that NAO events do not blend together, we require that successive events be separated by at least 15 days.

The primary equation that we will use in this study is the stream-function tendency equation (Cai and van den Dool, 1994; Feldstein, 2003). This equation can be written as:

$$\frac{\partial \psi}{\partial t} = \sum_{i=1}^{8} \xi_i + R. \quad (1)$$

The variable $\psi^L$ is the low-pass-filtered 300 hPa stream-function field. The $\xi_i$ are defined in Appendix A. Very briefly: the quantity $\xi_1$ corresponds to planetary-vorticity advection by the anomalies, $\xi_2 (\xi_3)$ to relative-vorticity advection that involves the interaction between the anomalies and the zonally symmetric (asymmetric) climatological flow, $\xi_4$ to the divergence term, and $\xi_5 (\xi_6)$ to the driving by the interaction among low-frequency (high-frequency) transient eddies. The cut-off period between the high- and low-frequency eddies is 10 days. The quantities $\xi_7$ and $\xi_8$ represent the driving due to the interaction between high- and low-frequency transient eddies, and the tilting term respectively. These two terms are very small, and are not discussed further in this study. The residual $R$ is similar in value to that found for the winter season (not shown), indicating that Equation (1) is reasonably well balanced. For further detail about the decomposition of these terms, see Feldstein (2003).

3. NAO life cycle

We first examine the composite NAO life cycle. A total of 56 events contribute to the positive-phase composite, and 34 to the negative-phase composite. This is in contrast to the winter NAO, where the numbers of events are similar for the two phases. A possible dynamical explanation for this asymmetry in the frequency of positive and negative NAO events will be discussed in Section 5. The time-scale of the NAO life cycle can be determined by examining the composite evolution of the NAO-index time series (see Figure 3(a) for the positive phase and Figure 4(a) for the negative phase). If we define the time-scale of the NAO life cycle to be the time period over which the NAO index exceeds 0.5 standard deviations, then both NAO phases show a time-scale for the life cycles of about two weeks, the same as for the winter season Feldstein (2003).

The temporal evolution of the low-pass 300 hPa stream-function anomaly field is illustrated in Figure 1 for the positive NAO phase, and in Figure 2 for the negative NAO phase. By lag 0, a typical NAO dipole anomaly is observed for both phases, with one centre of action near Greenland and the other extending over the midlatitude North Atlantic. Several similarities are found between the anomaly evolutions in Figures 1 and 2 and those for the winter season (compare with Figures 2 and 3 of Feldstein (2003)). For example, for the positive phase, prior to lag 0, a wave train can be seen over the northeastern Pacific and North America during both the summer and the winter seasons. For the negative phase, before lag 0, a retrograding anticyclone that originates over northern Europe is observed. For both seasons, the 300 hPa stream-function anomalies over the North Atlantic are noticeably stronger for the negative phase. A theoretical explanation for this behaviour that involves asymmetries in eddy growth for the two NAO phases has been offered by Riviere and Orlanski (2007).

Some important seasonal differences in the NAO evolution are also found. For the negative phase, a wave train upstream of the NAO region is found during the summer season (Figure 2(c)), whereas a similar wave train is not observed during the winter season. Furthermore, the summer NAO anomaly pattern appears to be spatially more fixed, undergoing much less change in shape over time. In addition, the summer NAO appears to decay in situ, whereas the decay of the winter NAO is clearly associated with strong linear dispersion. Another difference is that the longitudinal extent of the summer NAO is markedly shorter than that for the winter (Ogi et al., 2004), which suggests that the summer NAO may be regarded as a local phenomenon. A possible explanation for these differences may be based on the
findings of Benedict et al. (2004), who attribute the winter NAO to the breaking of synoptic-scale waves. In the summer season, the combination of weaker eddies and a smaller meridional shear of the background zonal wind is expected to lead to weaker wave-breaking and thus a shorter longitudinal scale. Perhaps the most marked seasonal difference involves the NAO amplitude: the amplitudes of the 300 hPa stream-function anomalies for both phases of the summer NAO are about one-third to one-half those of the winter.

4. Projection analysis

The dynamical properties of the NAO life cycle are summarized by projecting each term on the right-hand side of Equation (1), at different time lags, onto the lag +2 days composite stream-function pattern. At this particular lag, the composite NAO index is near its maximum value (Figures 3(a) and 4(a)). The equations below show that these projections can succinctly highlight the properties of each term in Equation (1) throughout the NAO life cycle. As discussed in Feldstein (2003), the projection $P_i$ can be written as

$$P_i = \sum_j \xi_{ij}(\lambda, \theta, t) \psi_{Mj}(\lambda, \theta) \cos \theta,$$

where $\xi_{ij}$ is the $i$th term in Equation (1) and $\psi_{Mj}$ is the lag +2 days stream-function anomaly pattern, each expressed at the $j$th grid point. The longitude is
represented by \( \lambda \) and the latitude by \( \theta \). The summation
in Equation (2) includes all grid points in the Northern
Hemisphere. We next express the anomalous stream-
function field \( \psi \) as

\[
\psi(\lambda, \theta, t) = a(t) \psi_{Mj}(\lambda, \theta) + \psi'(\lambda, \theta, t),
\]

where \( a(t) \) is the amplitude of the lag+2-days stream-
function pattern. If we specify that \( a(t) \) take the form

\[
a(t) = \sum_j \frac{\psi(\lambda, \theta, t) \psi_{Mj}(\lambda, \theta) \cos \theta}{\sum_j \psi_{Mj}^2 \cos \theta},
\]

then \( \psi_{Mj} \) becomes orthogonal to \( \psi' \). If we neglect the residual \( R \) in Equation (1), we obtain (see Feldstein

(2003) for details):

\[
\frac{da}{dt} = \sum_{i=1}^{8} P_i \sum_j \psi_{Mj}^2 \cos \theta.
\]

Therefore, the projections in Equation (2) represent the influence of the individual \( \xi_i \) on the temporal rate of change of \( a(t) \).

The projections for the two NAO phases are shown in Figures 3 and 4. They are rather similar, except that the projections for the negative phase are larger by about a factor of two. These differences are consistent with the stronger stream-function anomalies for the negative phase, as shown in Figure 2. For both phases, the
nonlinear transient eddy vorticity fluxes in Equation (1) drive the NAO life cycle, and the linear terms in Equation (1) contribute to the NAO decay (Figures 3(b) and 4(b)). A decomposition of the nonlinear and linear projection terms illustrates that the growth of the NAO pattern is through both the high- and the low-frequency transient eddy vorticity fluxes and the divergence term. Figures 3(c) and 4(c)) and its decay is through both the low-frequency transient eddy vorticity fluxes and the divergence term. Figures 3(d) and 4(d) show that the contribution from the divergence term opposes that of the sum of the linear and nonlinear vorticity-advection terms. This is consistent with the findings of Feldstein (2003), which suggest that the divergence term corresponds to the secondary circulation that is induced by the vorticity advection. All of the above results are the same, for both NAO phases, as during the winter season. Furthermore, as stated in Section 1, the model results of Franzke et al. (2004) show that the occurrence of the NAO is closely linked to both the breaking of synoptic-scale waves and the presence of a strong stretching deformation field. This suggests that one role of the stretching deformation field is to modify the synoptic-scale eddies in a manner that strengthens the horizontal divergence.

5. Wave-breaking properties

The wave-breaking associated with the NAO life cycle has recently been examined by Benedict et al. (2004) and Franzke et al. (2004). These studies show that the winter NAO life cycle is characterized by anticyclonic wave-breaking for the positive phase and cyclonic wave-breaking for the negative phase, where anticyclonic (cyclonic) wave-breaking is characterized by southwest–northeast (southeast–northwest) tilt of the trough–ridge pair (Thorncroft et al., 1993). For both phases, synoptic-scale waves amplify and then break, and it is the remnants of this wave-breaking that correspond to the two NAO centres of action. For the positive NAO phase, two wave-breakings take place, one off the western coast of North America – followed by intensification of a trough that propagates eastward across North America until it reaches the high-latitude North Atlantic – and the other over the midlatitude North Atlantic. In contrast, for the negative NAO phase, a single wave-breaking over the mid- and high-latitude North Atlantic accounts for both centres of action.

We examine the extent to which the above picture for the winter season also describes the NAO life cycle.
for the summer season. The summer NAO life cycle is illustrated with a sequence of maps of the composite potential-temperature field on the 2 PVU surface. To help with visualization of the wave-breaking, values of potential temperature that are below 345 K (325 K) for the positive (negative) phase are shaded. The maps indicate the total potential-temperature fields. The composite potential-temperature anomalies (not shown) have spatial patterns that very much resemble those of the 300 hPa stream-function fields in Figures 1 and 2. The corresponding $t$ values for these potential-temperature anomalies all exceed the 95% confidence level for a two-sided $t$-test.

Figure 4. As Figure 3, but for the negative NAO phase.

For the positive phase, at lag $-2$ days (Figure 5(a)), a deep trough is seen along the western coast of North America, as for the winter NAO (Benedict et al., 2004). However, in contrast to the winter, this trough does not undergo wave-breaking. Also at lag $-2$ days, an intensifying trough is located over northern Quebec (Figure 5(a)). This trough advects cold air out over the North Atlantic as it propagates eastward toward Greenland. Between lag $-2$ days and lag +1 day, wave-breaking is observed over the subtropical and midlatitude North Atlantic, advecting warm subtropical air poleward and reaching its greatest strength at lag 0 (Figure 5(c)). (In this study, we define the strength of the wave-breaking by the magnitude of the positive potential-temperature gradient on the 2 PVU surface.) Thus, the life cycle for the positive-phase summer NAO very much resembles that of the winter NAO in the sense that the two centres of action arise from trough intensification and North Atlantic wave-breaking.

Figure 6 shows the sequence of 2 PVU maps for the negative NAO phase. For this phase, weak cyclonic wave-breaking can be seen over Greenland (Figure 6(c) and (d)). Warm air is advected northwestward over the southern tip of Greenland, and cold air is advected southeastward from eastern Canada toward the midlatitude North Atlantic. A cut-off centre of cold air is observed off the coast of Labrador at lag +1 day (Figure 6(d)). Overall, for the negative NAO phase, the summer and winter NAO are dynamically very similar.

For both phases, the primary difference in the wave-breaking characteristics between the summer and winter NAO is that the summer wave-breaking is markedly weaker (compare Figures 5 and 6 with Figures 3 and 5 of Benedict et al. (2004)) and has much shorter zonal and meridional scales. It seems plausible that these seasonal differences can be explained in part by the weaker eddy activity in the North Atlantic during the summer. Weaker eddy activity implies smaller meridional
particle displacements, but large particle displacements are necessary for the occurrence of strong wave-breaking with large zonal and meridional scales.

We also examine the individual events that comprise the potential-temperature composites (Figures 5 and 6). For both NAO phases, almost every event exhibits the general wave-breaking and trough intensification (for the positive phase) characteristics of the corresponding composite. However, as for the winter NAO (Benedict et al., 2004), there is much variability between cases. This variability involves the longitude of the North Atlantic wave-breaking, which ranges from 20°W to 70°W, the strength of the wave-breaking, and the spatial structure of the waves undergoing the breaking. This variability is found to be even more pronounced off the western coast of the US, where trough intensification is preceded by anticyclonic wave-breaking in about two-thirds of the positive-phase events. This enhanced variability between events probably accounts for the absence of anticyclonic wave-breaking along the western US coast in the summer positive-phase composite.

As discussed in Section 3, there are almost twice as many positive-phase as negative-phase NAO events. This situation contrasts with the winter NAO, where there are similar numbers of positive- and negative-phase events.

To examine these differences, we illustrate the winter (Figure 7(a)) and summer (Figure 7(b)) climatological potential-temperature fields on the 2 PVU surface. For the winter, in the jet exit region over the eastern North Atlantic, the potential-temperature contours are approximately symmetric, exhibiting similar degrees of spreading poleward and equatorward. This indicates that the stretching deformation rate must be similar on the two sides of the jet axis. As shown in Franzke et al. (2004), the presence of a strong stretching deformation field is crucial for generating wave-breaking followed by an NAO event of either phase. This similarity in the stretching deformation rates on the two sides of the jet is consistent with there being similar numbers of positive and negative NAO events during the winter. In contrast, during the summer, the potential-temperature contours exhibit spreading only in the southern part of the jet exit region. In the northern part of the jet exit region, the potential-temperature contours have a zonal orientation. This asymmetry in the spreading of the potential-temperature contours indicates that the stretching deformation is much stronger on the equatorial side of the jet. Thus, these characteristics suggest that during the summer, those disturbances that enter the southern part of the jet exit region are more likely to break and lead...
Figure 6. As Figure 5, but for the negative NAO phase; shading indicates values less than 325 K.

to an NAO event than those disturbances that propagate into the northern part of the jet exit region. Since wave-breaking that occurs on the equatorward side of the jet is a precursor to positive NAO events, this asymmetry in the stretching deformation field may account for the predominance of positive NAO events during the summer.

Although, as discussed above, the latitudinal asymmetry in the climatological stretching deformation may account for the more frequent occurrence of positive NAO events, it is also possible that the eddy vorticity fluxes associated with more frequent positive NAO events may drive the latitudinal asymmetry in the time-mean flow. To address this possibility, we have performed a composite calculation that includes all days when the NAO index is less than one standard deviation. This yields a 2 PVU potential-temperature field with a stretching deformation field (not shown) only slightly weaker than that illustrated in Figure 7(b). These results suggest that the positive NAO phase has little impact on the stretching deformation field of the time-mean flow.

6. Conclusions

This study examines the life-cycle characteristics of the NAO during the summer season. For both NAO phases, it is found that the process of growth and decay of the NAO anomalies is completed within a two-week time period. A projection analysis involving composites of each term in the stream-function tendency equation shows, for both phases, that the summer NAO life cycle is driven by both high- and low-frequency transient eddy vorticity fluxes, and that the decay is via low-frequency transient eddy vorticity fluxes and horizontal divergence. Furthermore, an examination of potential temperature on the 2 PVU potential-vorticity surface reveals the important role of synoptic-scale wave-breaking for the summer NAO. For the positive phase, the southern centre of action of the NAO dipole develops via anticyclonic wave-breaking, and the northern centre of action arises from anticyclonic wave-breaking (in the majority of events) followed by the intensification and eastward propagation of a trough over northeastern Canada. For the negative phase, both centres of action develop from a single cyclonic wave-breaking. These dynamical characteristics are very similar to those for the winter NAO (Benedict et al., 2004; Franzke et al., 2004). The primary seasonal differences are that the winter NAO has a stronger amplitude, with a larger zonal and meridional extent and more intense wave-breaking. Lastly, the results of this study suggest that latitudinal asymmetries in the summer stretching deformation field within the North Atlantic jet exit region account for positive NAO events occurring much more frequently than
negative NAO events. It is plausible that similar asymmetries in the background stretching deformation field on much longer time-scales may account for some of the interannual and interdecadal variability of the NAO. For example, in some years, the stretching deformation rate may be stronger on the poleward side of the jet axis, resulting in a preponderance of negative NAO events; in other years, a stronger stretching deformation rate on the equatorward side of the jet axis may result in the more frequent occurrence of positive NAO events. This interannual and interdecadal variability in the stretching deformation field may ultimately be determined by the sea-surface-temperature field. These ideas provide one mechanism by which synoptic-scale wave-breaking and short-time-scale NAO events may be related to atmospheric variability that takes place on much longer time-scales.

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A. Appendix

The individual terms in the stream-function tendency equation are:

\[ \xi_1 = \nabla^{-2} \left( - (v_1^r + v_2^r) \frac{1}{a} \frac{d f}{d \theta} \right); \]
\[ \xi_2 = \nabla^{-2} \left( - [v_1^r] \cdot \nabla \xi^L - v_1^L \cdot \nabla [\xi^L] \right) + \nabla^{-2} \left( - [v_2^r] \cdot \nabla \xi^L - v_2^L \cdot \nabla [\xi^L] \right); \]
\[ \xi_3 = \nabla^{-2} \left( - [v_3^r] \cdot \nabla \xi^L - v_3^L \cdot \nabla [\xi^L] \right); \]
\[ \xi_4 = \nabla^{-2} \left( - (f + \zeta) \nabla \cdot v_2^L - \xi^L \nabla \cdot v_2^L \right); \]
\[ \xi_5 = \nabla^{-2} \left( - [v_1^r] \cdot \nabla \xi^L + \xi^H \nabla \cdot [v_1^H] \right); \]
\[ \xi_6 = \nabla^{-2} \left( - [v_2^r] \cdot \nabla \xi^L + \xi^H \nabla \cdot [v_2^H] \right); \]
\[ \xi_7 = \nabla^{-2} \left( - [v_3^r] \cdot \nabla \xi^L + \xi^H \nabla \cdot [v_3^H] \right); \]
\[ \xi_8 = \nabla^{-2} \left( - k \cdot \nabla \times (\omega \frac{\partial v^L}{\partial p}) \right) + \nabla^{-2} \left( - k \cdot \nabla \times (\omega \frac{\partial v^L}{\partial p}) \right); \]
\[ \xi_9 = \nabla^{-2} \left( - k \cdot \nabla \times (\omega \frac{\partial v^L}{\partial p}) \right) + \nabla^{-2} \left( - k \cdot \nabla \times (\omega \frac{\partial v^L}{\partial p}) \right); \]

Here \( \psi \) is the stream function, \( \xi \) is the relative vorticity, \( v \) is the meridional wind component, \( \omega \) is the vertical wind component, \( a \) is the Earth’s radius, \( f \) is the Coriolis parameter, and \( \theta \) is latitude. The subscripts ‘\( r \)’ and ‘\( d \)’ indicate the rotational and divergent components, respectively, of the horizontal wind. The superscripts ‘\( H \)’ and ‘\( L \)’ indicate the application of a 10-day high-pass and low-pass digital filter, respectively. The summer time-mean values are subtracted from the low-pass-filtered quantities. Time means are indicated by an overbar, and deviations from the time mean by a prime. Zonal averages are indicated by square brackets, and deviations from the zonal average by an asterisk. \( k \) is the vertical unit vector.

References


