Arctic Oscillation or North Atlantic Oscillation?

Maarten H. P. Ambaum, Brian J. Hoskins, and David B. Stephenson

Department of Meteorology, University of Reading, Reading, United Kingdom

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ABSTRACT

The definition and interpretation of the Arctic oscillation (AO) are examined and compared with those of the North Atlantic oscillation (NAO). It is shown that the NAO reflects the correlations between the surface pressure variability at its centers of action, whereas this is not the case for the AO. The NAO pattern can be identified in a physically consistent way in principal component analysis applied to various fields in the Euro-Atlantic region. A similar identification is found in the Pacific region for the Pacific–North American (PNA) pattern, but no such identification is found here for the AO. The AO does reflect the tendency for the zonal winds at 35° and 55°N to anticorrelate in both the Atlantic and Pacific regions associated with the NAO and PNA. Because climatological features in the two ocean basins are at different latitudes, the zonally symmetric nature of the AO does not mean that it represents a simple modulation of the circumpolar flow. An increase in the AO or NAO implies strong, separated tropospheric jets in the Atlantic but a weakened Pacific jet. The PNA has strong related variability in the Pacific jet exit, but elsewhere the zonal wind is similar to that related to the NAO. The NAO-related zonal winds link strongly through to the stratosphere in the Atlantic sector. The PNA-related winds do so in the Pacific, but to a lesser extent. The results suggest that the NAO paradigm may be more physically relevant and robust for Northern Hemisphere variability than is the AO paradigm. However, this does not disqualify many of the physical mechanisms associated with annular modes for explaining the existence of the NAO.

1. Introduction

Following the earlier studies of Lorenz (1950) and Kutzbach (1970), Thompson and Wallace (1998, 2000) and Thompson et al. (2000) have given impressive evidence for the importance of the pattern of variability they refer to as the Arctic oscillation (AO). This pattern is highly correlated with the North Atlantic oscillation (NAO) pattern (Walker and Bliss 1932), which has also been subject of much interest in recent years (e.g., Wallace and Gutzler 1981; Hurrell 1995). Although the two patterns are highly correlated, there is a clear distinction that could play a guiding role in how we attempt to understand physical mechanisms in the Northern Hemisphere variability (Wallace 2000). This paper is a further contribution to the discussion of the relative merits of the two perspectives based on empirical orthogonal function (EOF) and correlation analyses of data.

EOFs are the eigenvectors of the covariance matrix obtained from calculating covariances of time series at different spatial points (e.g., Jolliffe 1986). EOFs are optimal in explaining as much total variance as possible with any specified number of spatial patterns. The first EOF explains most of the temporal variance in the dataset among all possible spatial fields. The subsequent EOFs are mutually orthogonal (in space and time) and successively explain less variance. The interpretation of EOFs as physical/dynamical modes of variability has always to be made with much care.

By construction EOFs are constrained by their mutual orthogonality. This constraint applies equally to all EOFs, including the leading one. If a dataset is a linear superposition of two patterns that are not orthogonal, the EOF analysis will not yield these patterns. At the same time, EOFs show a strong tendency to have the simplest possible spatial structure inside the domain. This tendency leads to strong dependence of EOFs on the shape of the spatial domain (e.g., Richman 1986).

EOF analysis is nonlocal in that the loading values at two different spatial points in an EOF do not simply depend on the time series at those two points but depend on the whole dataset. This can lead to locally counterintuitive results. This contrasts with the one-point correlation analyses used to define teleconnections (Wallace and Gutzler 1981), for which the patterns can be interpreted locally. An example will be given in section 2: two same-signed points in an EOF do not necessarily have correlated time series. The nonlocal nature of EOFs necessitates a careful interpretation of the pattern structure of any particular EOF.

Corresponding author address: Dr. M. H. P. Ambaum, Department of Meteorology, University of Reading, P.O. Box 243, Reading RG6 6BB, United Kingdom.
E-mail: m.h.p.ambaum@reading.ac.uk

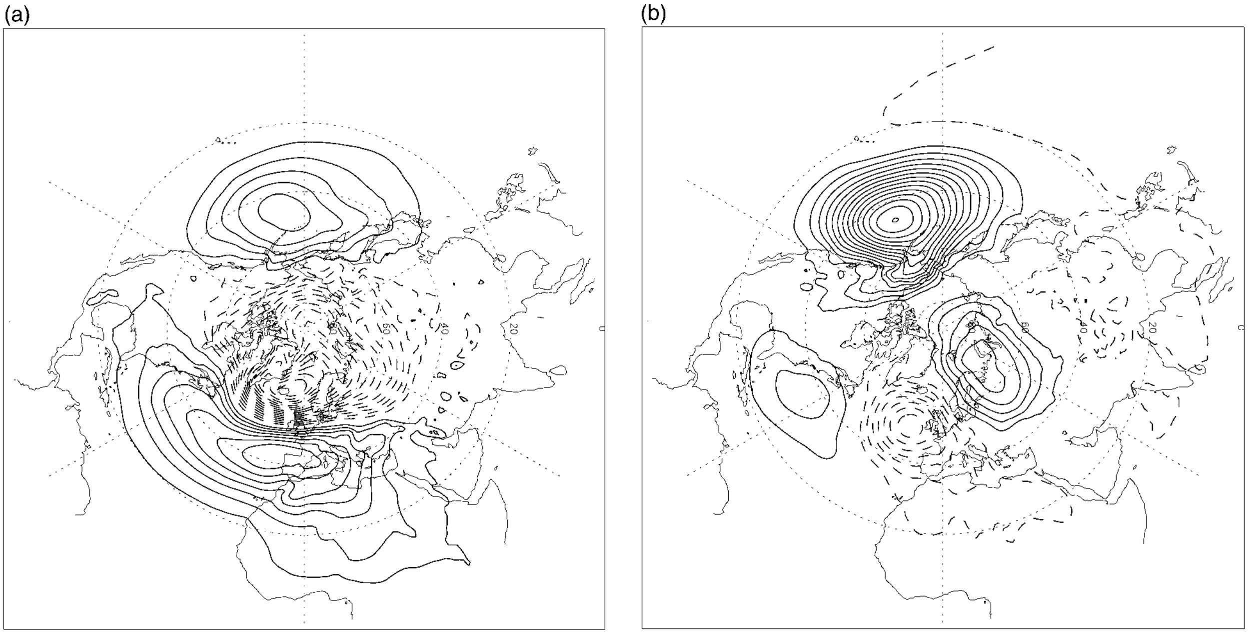

FIG. 1. First two EOFs [(a) EOF1 and (b) EOF2] for the DJFM mean sea level pressure. These EOFs explain 25% and 14% of the variance, respectively. The contour interval is 0.5 hPa.

The AO is usually defined as the first EOF of the mean sea level pressure field in the Northern Hemisphere, and it is a robust result from EOF analysis of this field on timescales from weeks to decades in any season (Kutzbach 1970; Thompson and Wallace 1998). Figure 1a shows this EOF based on monthly mean data from an extended European Centre for Medium-Range Weather Forecasts reanalysis (ERA) dataset[1] (here comprising 1979–97). Similar analyses have been performed using the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis dataset, and the results presented here are robust to the use of either set. Data from the extended winter (December–March, DJFM) have been used, and EOFs were constructed using the full hemispheric domain.

For this and other calculations described here the seasonal cycle has been removed by subtracting the calendar monthly means. The data were not detrended. Linear trends over the ERA period are larger than the standard deviation of the monthly mean data only over limited areas over western Europe and over the Arctic. Nowhere are the trends larger than 2 standard deviations. Because of the dominance of the month-to-month variability over the linear trend it has been found that the leading EOFs are not affected by these trends (not shown). Here no attempt has been made to highlight intraseasonal anomalies by subtracting the winter means (cf. Thompson and Wallace 1998; Deser 2000). If this is done, the signature of the Pacific–North American (PNA) pattern in the EOFs is weakened, but otherwise the EOFs are not radically altered (not shown), and the conclusions presented in the paper are not changed. Thus, apart from the removal of the mean seasonal cycle, no further preprocessing has been performed on the data.

The first EOF of mean sea level pressure, the AO pattern (Fig. 1a), explains 25% of the variance. It is well separated from the second EOF, which explains 14% of the variance (Fig. 1b). As discussed by North et al. (1982), when EOFs are well separated, it means that their definition is less likely to be affected by statistical sampling errors. One of the most interesting features of the AO pattern is the presence of two same-signed centers of action over the Pacific and Atlantic Oceans.

The NAO has several definitions, but it is always associated with a north–south-oriented dipolar structure in the pressure field over the Atlantic, very much like the AO pattern but without the center of action over the Pacific (e.g., Wallace and Gutzler 1981; Hurrell 1995). In section 3, a definition is given in terms of EOFs confined to the Atlantic region. Because of the overlap of the NAO and AO patterns in the Atlantic sector, the time series of the two patterns are highly correlated (with our definitions the linear correlation is as high as 0.92). Wallace (2000) notes that the original definition of the NAO by Walker and Bliss (1932) is more like the modern definition of the AO than like the currently accepted definitions of the NAO.

Although the NAO and AO time series are highly correlated, the differences of the patterns suggest dif-

[1] Dr. P. Berrisford is acknowledged for preparing these data as part of the Joint Diagnostics Project. For 1979–95 it is drawn from the European Centre reanalysis. For subsequent years, routine operational analyses are used.

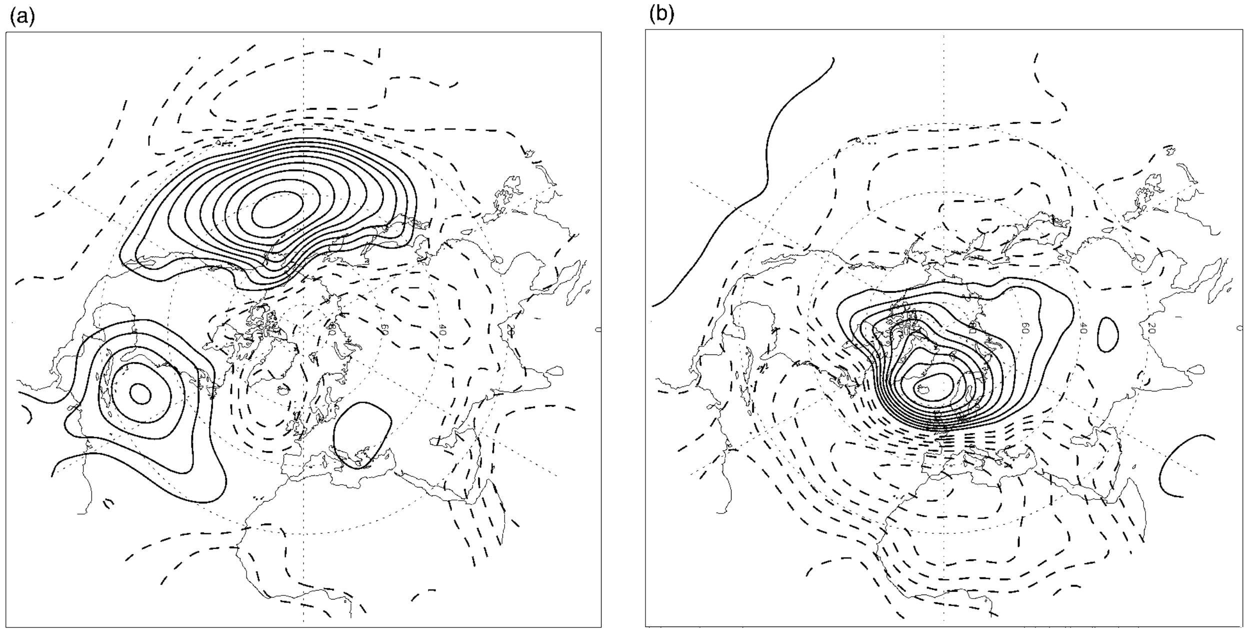

FIG. 2. Correlation maps of the mean sea level pressure field with the field value at points 44°N, 168°W and 67°N, 9°W, respectively. To reduce sampling noise, a Gaussian kernel (of 5° width) average around these two centers was chosen instead of the field values at the points themselves. The contour interval is 0.1.

ferent underlying basic physical mechanisms. The NAO points to a mechanism local to the Atlantic region, whereas the more zonal structure of the AO, on the other hand, led Thompson and Wallace (2000) to suggest that the AO may be a representation of a fundamentally zonally symmetric mode—an ''annular mode''—modified by zonally asymmetric forcings, such as topography. We will refer to the AO as the pattern in Fig. 1a and to the annular mode as the set of implied mechanisms pertaining to essentially zonally symmetric variations in the atmosphere. The importance of the distinction between NAO and AO has been highlighted by Wallace (2000). There it is argued that the two patterns may represent two different paradigms of the Northern Hemisphere variability, namely the ''sectoral paradigm'' (associated with the NAO) and the ''annular paradigm'' (associated with the AO). Wallace (2000) concludes that it is important to come to a consensus as to which of them is more appropriate. This paper is a contribution to the debate that may eventually lead to that consensus.

In the following section, the covariance structure of the AO is examined in detail. Section 3 discusses the consistency of the NAO and AO definitions for different fields. Section 4 discusses the signatures of both patterns and the PNA pattern in the zonal winds. Conclusions and a discussion are presented in the last section.

2. Covariance structure

As mentioned above, despite explaining large amounts of total variance, leading EOFs do not necessarily represent teleconnections (covariance structures) in a dataset. For example, if a leading EOF has same-signed values at two different spatial points, this does not imply that the data at those two points are significantly correlated. This is due to the nonlocality of EOF analysis; the loading values of EOFs at points will reflect global aspects of the datasets rather than local behavior.

The teleconnectivity of the AO has been studied extensively in Deser (2000). There it is concluded that the correlation between the Pacific and Azores centers of action is not significant and that the AO therefore cannot be viewed as reflecting such a teleconnection. This is reconfirmed below in a related test, but in our formulation even the correlation between the Pacific and Icelandic–Arctic centers of action is not significant, contrary to Deser (2000). The lack of correlation between the Pacific and Atlantic regions has also been observed in the strengths of the zonal jets by Ting et al. (2000). In sea level pressure, the lack of correlation has also been noted by Barnett (1985), who hypothesized that on longer timescales the signatures of the Southern Oscillation and the NAO may be joined in the first EOF.

Deser (2000) argues that the AO is a reflection of the prominence of the Icelandic–Arctic center of action. Here we argue that the AO is mainly a reflection of similar behavior in the Pacific and Atlantic basins, namely, the tendency in both ocean basins for anticorrelation between geostrophic winds near 35° and 55°N (see next section). A simple example is obtained by considering a three-component system with components *A*, *I*, and *P*, where *A* and *P* have unit variance and uncorrelated time series, and $I = -A - P$. The covariance matrix **C** for this three-component system (A, I, P) is given by

$$\mathbf{C} = \begin{pmatrix} 1 & -1 & 0 \\ -1 & 2 & -1 \\ 0 & -1 & 1 \end{pmatrix},$$

where the rows/columns correspond to the A, I, and P components, respectively. The EOFs are (in unnormalized form) (1, −2, 1), explaining 75% of the variance, and (−1, 0, 1), explaining 25% of the variance. The third EOF (1, 1, 1) explains 0% of the variance because the three components are not linearly independent. The first EOF has positive loading values for both the A and P components, even though they are uncorrelated. Thus, although the first EOF predominates, its structure has no straightforward interpretation as a covariance structure.

The three-component calculation, as above, has been repeated for the three mean sea level pressure centers of action in the AO (Azores 42°N, 15°W; Iceland 67°N, 9°W; Pacific 44°N, 168°W). The covariance matrix for this system, using a 5° width Gaussian kernel average around these centers, is

$$\mathbf{C} = \begin{pmatrix} 27.0 & -23.9 & -3.6 \\ -23.9 & 62.1 & -14.9 \\ -3.6 & -14.9 & 43.8 \end{pmatrix},$$

where the rows/columns correspond to the Azores, Icelandic, and Pacific centers of action, respectively, and the units are hectopascals squared. The covariance between the Pacific and the other two centers is small, because of the uncorrelated nature of the Pacific and Atlantic sectors (see below). The leading EOF of this reduced system is (0.38, −0.86, 0.33), explaining 59% of the total variance, and crudely represents the AO in this reduced system. The second EOF is (−0.43, 0.15, 0.89), explaining 32% of the total variance. It resembles the second EOF, in Fig. 1b, with its dominant Pacific center of action. Thus, although the coupling between the Atlantic and Pacific regions is weak, as expressed by their covariances in the matrix above, the dominant EOF for this system has strong loadings in both regions.

The covariances in **C** can be used to estimate the correlation between the three centers of action: −0.64 (Azores–Iceland), −0.22 (Pacific–Iceland), and −0.10 (Azores–Pacific). Note that here the Azores–Pacific correlation is in fact weakly negative, contrary to what was reported by Deser (2000), who found a positive correlation of 0.10. This can be understood by looking at Fig. 2a in which the correlation is plotted of all points with the Pacific center of action. The Pacific center is negatively correlated with the eastern Atlantic where the maximum of the Azores center of action is located, but it is positively correlated with the western Atlantic, which dominates when the sea level pressure is averaged over the area inside the outer contour of the Atlantic center of action in Fig. 1, as was done in Deser (2000). Under the null hypothesis of no correlation, the statistic $t = r\sqrt{n-2}/\sqrt{1-r^2}$ is Student distributed with $\nu = n - 2$ degrees of freedom, where n is the number of independent samples. For $n = 76$ winter months (DJFM 1979–97), this implies a 95% confidence interval of correlations from −0.23 to 0.23. In other words, the null hypothesis of no correlation can only be rejected at 95% confidence if the absolute value of the correlation exceeds 0.23 (two-tailed test).[2] Therefore, only the correlation in the Atlantic sector between Azores and Iceland is significantly different from zero at 95% confidence. This is in agreement with the conclusions made by Deser (2000) for winter-mean values over the longer period of 1947–97. Based on the less stringent one-sided test, Deser (2000) found that the correlation of 0.10 between monthly mean values from 1947 to 1997 in the Atlantic and Pacific was only marginally significant at 95% confidence (C. Deser 2000, personal communication). However, this correlation is not significantly different from zero at 95% confidence if one uses the more appropriate two-sided test.

So in analogy with the simple three-component system, the AO pattern has no straightforward interpretation as a covariance structure. It does, however, reflect the tendency in both ocean basins for anticorrelation between geostrophic winds near 35° and 55°N. The teleconnections between the three centers of action do not match the AO pattern. Figure 2 shows the one-point correlation maps for both the Pacific and Icelandic centers of action in the AO. The one-point correlation map for the Azores center of action gives a pattern similar to Fig. 2b but with reversed sign. These correlation maps suggest that the Pacific center of action is related to PNA variability [Wallace and Gutzler (1981) and references therein], whereas the Atlantic centers are related to NAO variability.

3. Physical consistency between different fields

The use of mean sea level pressure for identifying patterns of variability is somewhat arbitrary. Other fields such as velocity, streamfunction, or temperature (at different or multiple levels) can equally be used to identify patterns of variability. If a distinct physical process produced a pattern of variability, then this would happen in a dynamically consistent way in the sense that related fields are equally related in the pattern of variability. Such a physical process may be called a dynamical mode of variability. For example, consider the zonal velocity field u and the streamfunction field ψ at some level. In the nondivergent approximation, these are related by $u = -\partial\psi/\partial y$. Any dynamical mode of variability

[2] This is actually an underestimate of the confidence interval because it ignores serial correlation in the time series caused by trends.

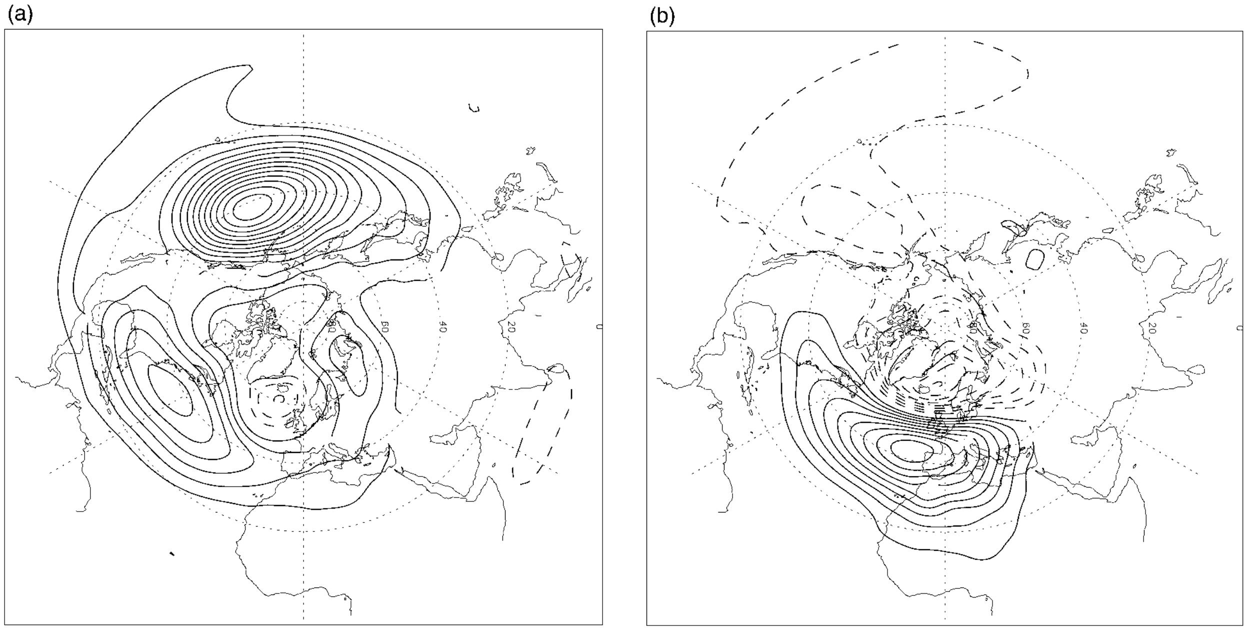

FIG. 3. First two EOFs [(a) EOF1 and (b) EOF2] for the DJFM streamfunction field at 850 hPa. These EOFs explain 28% and 16% of the variance, respectively. The contour interval is 5×10^5 m^2 s^{-1}.

should show this relationship between its associated patterns of u and ψ.

Is EOF analysis able to extract the patterns of these dynamical modes? In fact it is expected that related fields in general lead to different sets of EOFs because different eigenvalue problems are solved. It may be the case that certain isolated EOFs in the two sets (not necessarily with the same rank) are related, perhaps because they are dominated by the same physical mechanism, but the rest of the EOFs may be unrelated. It may also be possible that a descriptive analytical method such as EOF analysis is more successful in extracting patterns related to dynamical modes from one field than another. Two such patterns may be more orthogonal in one field than in another, in which case EOF analysis applied to the former may be more successful in finding these patterns. This possibility will be hard to judge without prior knowledge about the structure of patterns of the dynamical modes.

The potentially limited ability to extract patterns of dynamical modes with EOF analysis may also be due to the linearity assumption inherent in EOF analysis. This linearity assumption has been dropped in studies such as Corti et al. (1999) and Monahan et al. (2000). Corti et al. (1999) argue that the atmosphere organizes in regimes visible as clusters in smoothed probability density functions of principal component time series. Monahan et al. (2001) propose that a nonlinear curve may join those clusters better than may a straight curve. Using a nonlinear analysis, they conclude that the AO does not result from an independent mode of variability but that it is an optimal linear compromise between preferred quasi-stationary states of the circulation. This analysis has not been attempted here because the dataset used here has only 76 independent fields, in which case such a nonlinear analysis would suffer considerably from sampling noise.

The first EOFs of the geopotential height at 850 hPa have very similar structures to those of the mean sea level pressure, MSLP. However, those for the 850-hPa streamfunction are significantly different (Fig. 3). In fact, the leading EOF of the streamfunction resembles a PNA pattern (Fig. 2a), whereas the second EOF closely resembles the NAO pattern (Fig. 2b); neither of the two EOFs in Fig. 3 strongly suggests a zonal symmetry. It is interesting that it is the PNA pattern that dominates for streamfunction but the AO for surface pressure or height. There is no reason to believe that the mean sea level pressure is in some sense dynamically more fundamental than the streamfunction at 850 hPa, yet their EOF analysis leads to very different leading patterns. Similar analyses of temperature or velocity fields also gives unrelated patterns. This result shows that hemispheric EOFs do not give dynamically consistent patterns for different fields. Based on this information alone, it is not possible to decide which, if any, of these patterns have a physical background and which are the results of the statistical data reduction technique.

Another approach to this problem is to study regional EOFs that include additional prior information about the region of primary interest. To demonstrate this approach, EOFs for the Euro-Atlantic and the Pacific sectors are analyzed separately. A similar approach has been used by Deser (2000) to show that the AO cannot be fully recovered from Atlantic regional or Pacific regional EOFs. Here we show that these regional EOFs do give physically consistent pictures for different fields, in contrast to the hemispheric EOFs.

The Euro-Atlantic sector is defined here as the region between latitudes 0° and 90°N and longitudes 60°W and 30°E. Other reasonable choices for the region give very similar results. Again the EOFs were calculated for the months DJFM only. The hemispheric fields were regressed upon the corresponding time series to give hemispheric patterns. Figure 4 shows the first EOFs for the mean sea level pressure MSLP, streamfunction at 850 hPa Ψ850, the velocity at 850 hPa U850, and the temperature at 2 m T2m. These leading EOFs all explain more than 40% of the variance in the Euro-Atlantic sector except for the temperature EOF, which explains 33%. The second EOFs for these fields all explain about a factor of 2.5 less total variance than the leading EOFs, so they are well separated. The correlation table, below, of the time series of these EOFs shows that the four patterns are well correlated:

	Ψ850	U850	T2m
MSLP	0.959	0.966	0.885
Ψ850		0.980	0.856
U850			0.856

The consistency between the different fields that is implied by this correlation analysis could not be concluded on the basis of regression techniques, which are frequently used to bring out connections between different fields. For example, regressing the temperature field at 2 m upon a time series of any pressure pattern will give a consistent connection based on anomalous temperature advection. Such a connection is a demonstration of the physical consistency of the dataset, not of the physical relevance of the pressure pattern. So the above correlation analysis shows that, unlike the hemispheric EOFs, the independently determined regional EOFs of these four fields are all representing essentially the same mode of variability, namely, the NAO.

A similar analysis for the Pacific sector, defined as the longitudes between 150°E and 120°W, gives analogous results for the four aforementioned fields. The first EOF of the streamfunction at 850 hPa is practically indistinguishable from the first hemispheric EOF for this field (shown in Fig. 3), but for the Pacific sector it explains 49% of the total variance. The temperature-field EOFs are somewhat less clearly related to this pattern, because the first two EOFs are not well separated. Both show features of anomalous temperature advection toward the Canadian west coast, though, and straddle the Pacific basin.

These results are similar to results obtained by rotation of principal components. A rotation is a linear combination of EOFs that generally reduces the size of the support of the EOF, such as in the well-known ''VARIMAX'' rotation algorithm (e.g., Richman 1986). Calculating EOFs over smaller regions may put a similar constraint on the EOFs. Rotation of the first few EOFs of the mean sea level pressure field (not shown) gives a first rotated EOF that is very similar to the NAO-type pattern of the first Euro-Atlantic EOF in Fig. 4; the second rotated EOF is very similar to the PNA-type pattern of the first hemispheric streamfunction EOF in Fig. 3.

This analysis shows that the introduction of prior information, here the boundedness of the region of interest, may lead to a more consistent definition of patterns. The four fields used here give EOFs that are dynamically consistent with each other: the pressure and streamfunction EOFs are consistent with a scaling proportional to the Coriolis parameter, the zonal wind and the streamfunction are consistent with the geostrophic relation, and the temperature EOF is consistent with the anomalous temperature advection due to the anomalous wind field. The Euro-Atlantic and the Pacific sectors both support separately a set of consistent patterns. In the case of the Euro-Atlantic region, this is the NAO pattern; in the case of the Pacific region, this is the PNA pattern.

4. Zonal wind relationships

The AO pattern has been associated with an annular mode that apparently extends over the full depth of the troposphere and stratosphere, giving rise to more or less zonally symmetric variations of the circumpolar flow (Baldwin and Dunkerton 1999; Hartmann et al. 2000; Thompson and Wallace 2000). An important consideration, though, is that the Northern Hemisphere climatological flow is not zonally symmetric. This fact can be clearly seen in the mean sea level pressure: in the AO pattern the Pacific center of action has the same sign as the Azores center of action. However, the Pacific center is collocated with the Aleutian low, whereas the Azores center is collocated with the Azores high. An increase of the AO index, on average, corresponds to a deepening of the Azores high but to a weakening of the Aleutian low.

The climatological flow is zonally asymmetric throughout the depth of the troposphere. To see how the zonal flow covaries with the AO index and NAO index, the zonal velocity fields were regressed upon the index time series. For simplicity, the NAO index is here defined as the second EOF of the streamfunction at 850 hPa (Fig. 3), but the results presented here are not essentially altered by using other definitions, such as the leading Atlantic regional mean sea level pressure EOF. Results of these regressions for the 250-hPa level can be seen in Figs. 5b,c. The zonal wind field covarying with the NAO (Fig. 5c) shows signs of extension of the polar jet over northern Europe and a strengthening of the subtropical jet over the North Atlantic and of the Arabian jet as seen by comparing the regression map with the climatological mean (Fig. 5a). There is also a weaker signature over the Pacific. An analysis of 250-hPa height field correlations with the NAO center of

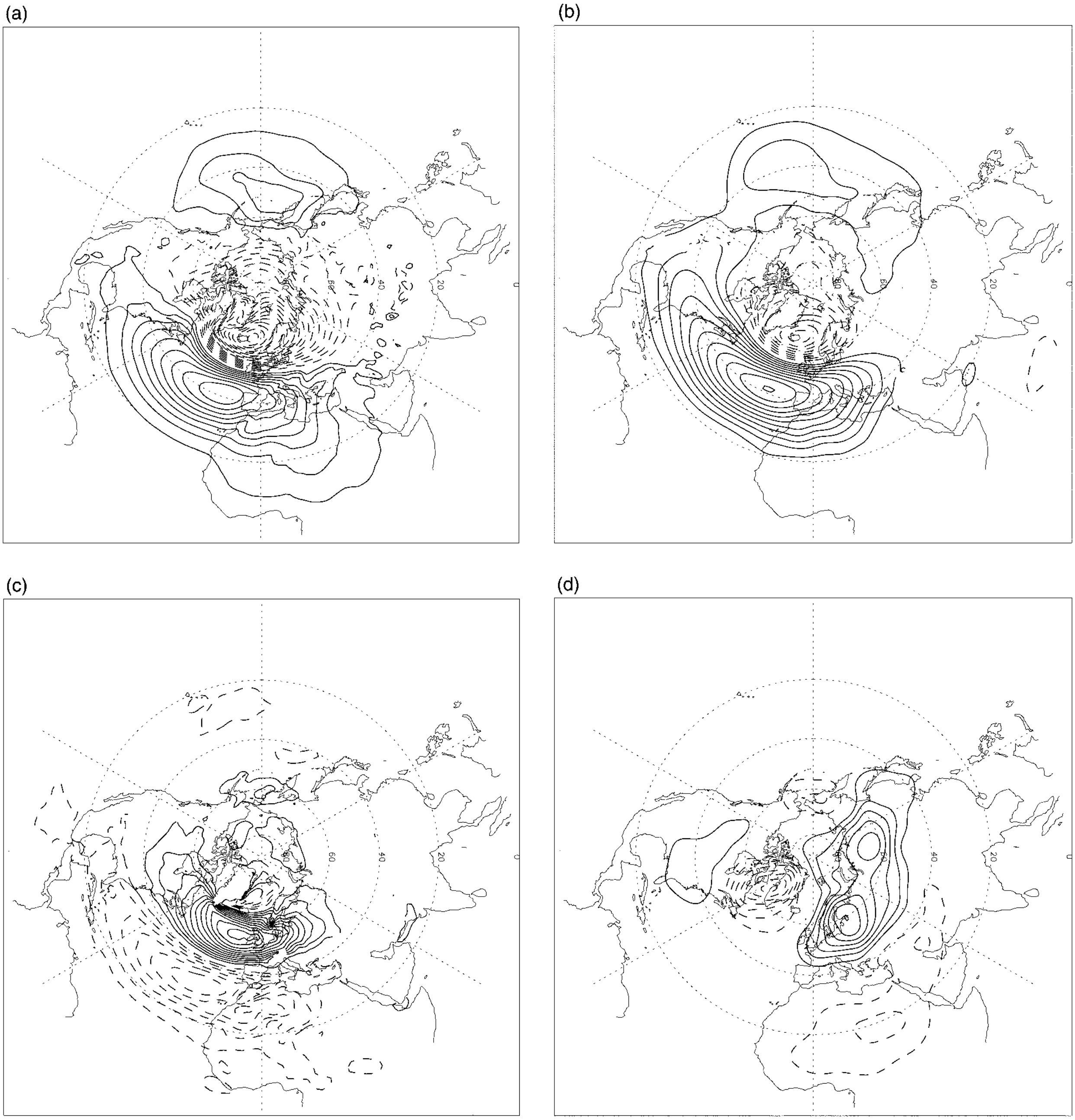

FIG. 4. Leading EOFs based on variability in the Euro-Atlantic sector only for the DJFM (a) mean sea level pressure (contour interval: 0.5 hPa, explaining 47.7%), (b) streamfunction at 850 hPa (5×10^5 m^2 s^{-1}, 40.3%), (c) zonal wind at 850 hPa (0.5 m s^{-1}, 44.2%), and (d) temperature at 2 m (0.5 K, 33.5%). The temperature EOF has been smoothed with a Gaussian kernel of 3° width.

action near 73°N, 20°W (not shown) gives height field patterns for which the implied geostrophic flow is supportive of the features in Fig. 5c highlighted in this discussion. The field covarying with the AO (Fig. 5b) shows much the same behavior over the Euro-Atlantic region but has a stronger signature over the Pacific. This aspect is in accord with the surface patterns that define both indices.

The anomaly pattern associated with the AO shows something of a zonally symmetric variation of the 250-hPa zonal wind, namely a dipole in the zonal wind strength at about 35° and 55°N over both ocean basins. However, the positive phase of the AO corresponds to *strengthening* of the polar and subtropical jets over the Euro-Atlantic region and to a *weakening* of the Pacific jet. Relative to the position of the main Northern Hemisphere jet, the AO-related anomalies significantly vary in latitudinal position. Hence, the AO is not associated

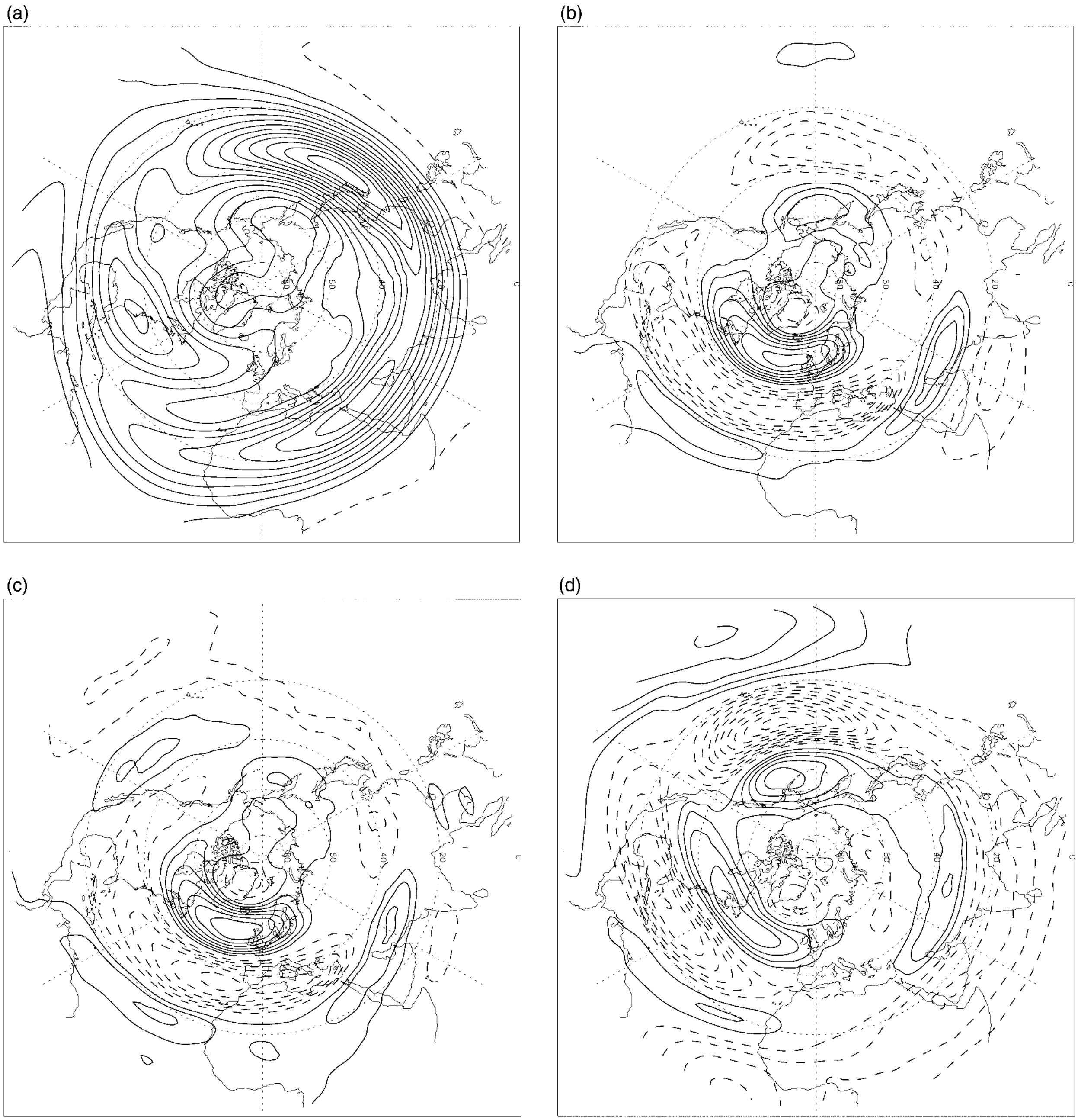

FIG. 5. (a) Climatological mean of 250-hPa zonal wind (contour interval: 5 m s^{-1}), regression of 250-hPa zonal wind on (b) AO, (c) NAO, and (d) PNA indices (contour interval: 1 m s^{-1}).

with uniform increases or decreases in the jet speeds in the Northern Hemisphere.

These results are essentially the same throughout the full depth of the troposphere and the lower stratosphere. To clarify the point further, we present in Fig. 6 the zonal winds averaged over the Atlantic and Pacific basins for low and high AO indices. The Atlantic basin zonal winds show a splitting and strengthening of the subtropical and polar tropospheric jets on increasing AO index. Low-index states correspond to effectively one subtropical jet, high-index states to a double jet. It has been hypothesized that the earth's atmosphere is close to a regime transition between being able to support either one or two tropospheric zonal jets (J. M. Wallace 1999, personal communication), and in that picture the AO may reflect the alternating of the atmosphere between the one-jet and two-jet states.

In Figs. 7a,b and 7e,f, results of a similar analysis, but now with regression on the NAO index (defined as principal component 2 of the 850-hPa streamfunction),

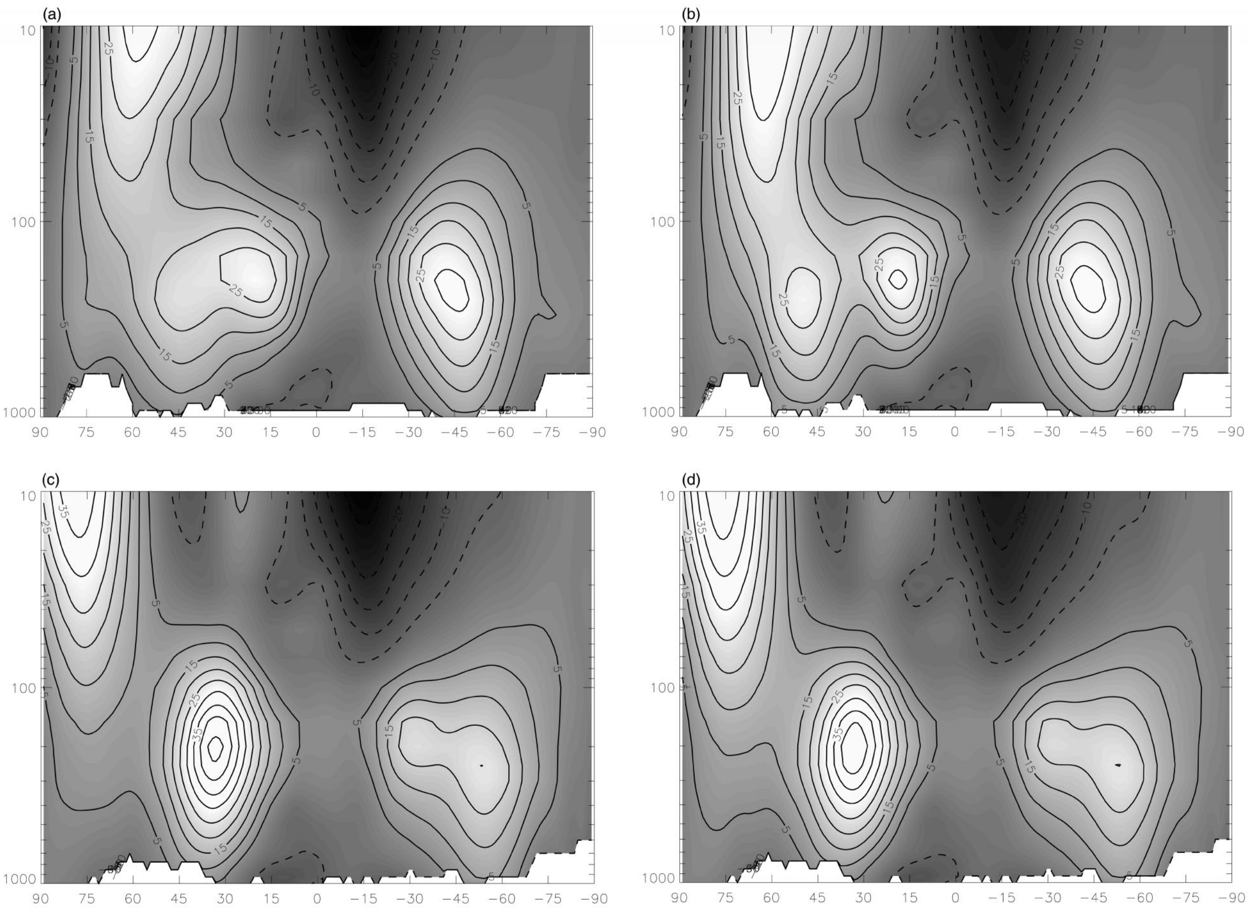

FIG. 6. Climatological mean of zonal winds in the Atlantic sector (60°W–0°) for an AO index of (a) −1 std dev and (b) +1 std dev. (c) and (d) The same as (a) and (b), but for the Pacific sector zonal winds (150°E–120°W).

are shown. The results are essentially the same as those using the AO index. In particular, the North Atlantic again shows a transition from a single to a double jet with increases in NAO index. However, the Pacific basin winds show a negligible change in the subtropical jet, on an increasing NAO index. On the polar side of the jet, the shear weakens and there are stronger westerly winds, as there were for the AO (Fig. 6d).

The winds in the stratosphere are also strongly associated with the NAO index. As can be seen in Fig. 7, when this index increases, the strength of the polar night jet increases by nearly 10 m s^{-1} in both the Atlantic and Pacific sectors. The connection of the NAO index to the strength of the polar night jet is well established and can be related to the propagation of planetary waves from the troposphere to the stratosphere [Charney and Drazin (1961); see also Hartmann et al. (2000)]. There are also suggestions that independent changes of the stratospheric circulation may force a tropospheric response in the NAO or AO (Baldwin and Dunkerton 1999; Hartmann et al. 2000), although these links appear to be weaker and are only present in winter-mean data. Either way, the link between the NAO signal and the strength of the polar vortex seems well established and is confirmed here. In the North Atlantic and to a lesser extent in the North Pacific, increasing NAO index gives an increasing tendency for a smooth transition between the stratospheric and polar tropospheric jets.

It is of interest to also look in a similar manner at the PNA-related zonal wind changes, using principal component 1 of the 850-hPa streamfunction as its index. The regressed field of 250-hPa zonal wind is given in Fig. 5d. As expected, the strongest features are now in the Pacific, east of the date line, with extremes of opposite signs near 55° and 35°N. There is also another extreme near 5°N. The more unexpected aspect is the existence of other extremes that are very similar to those associated with the NAO (Fig. 5c). The major Atlantic extremes are now slightly equatorward of 30° and 50°N and centered near the North American coast. The extremes to the north and south are almost identical to those for the NAO and there are now indications of an equatorial extremum. Near 70°E, there is a dipole that is very similar to that found for the NAO. An analysis of 250-hPa height field correlations with the PNA center of action near 45°N, 161°W (not shown) gives height field patterns for which the implied geostrophic flow is supportive of the features in Fig. 5d highlighted in this discussion.

Using the same Atlantic sector of 60°W–0°, the mean climate of zonal winds for low and high PNA index (Figs. 7c,d) gives a very similar behavior to that shown in Figs. 7a,b for NAO index but with slightly smaller difference between the two phases. Extending the sector westward into the North American continent would increase the difference in behavior between the phases but would complicate the picture because of the SW–NE tilt in the climatological jet. The climatological mean of zonal winds in the Pacific sector for low and high PNA index is presented in Figs. 7g,h. The Pacific jet is some 10 m s^{-1} weaker for high PNA index. Because the changes in westerlies to the north are similar to those for the NAO, there is markedly reduced shear on the northern side of the jet for positive PNA. The reduced horizontal and vertical shear in this region where synoptic-timescale transients grow and decay would be expected to have significant impact on them. The PNA-related zonal winds in both the Atlantic and the Pacific imply a positive correlation between the zonal wind indices [U(55°N)–U(35°N); cf., Ting et al. 2000] in the Pacific and the Atlantic, but in the troposphere this correlation does not exceed the 95% significance level.

Despite the fact that the tropospheric signature in the Atlantic of the PNA is similar to that of the NAO, it has negligible signature at 10 hPa. In the Pacific sector there is PNA-related variation at 10 hPa but it is about one-half that associated with the NAO.

The strength of climatological easterlies in the quasi-biennial oscillation (QBO) region apparently decreases with increasing NAO or AO indices. The correlation of the winds in the QBO region with our NAO/AO indices is weak, though, and not significantly different from zero at the 95% confidence level. Indeed, the signal in the QBO region nearly vanishes on restricting the dataset to the first 10 yr of data. It is of interest to note that a westerly phase of the QBO leads to an enhanced polar night jet because of the inhibition of planetary wave propagation to the stratosphere (Dunkerton and Baldwin 1991). This result is in accord with the signs of the changes in the winds in Fig. 6, but our data are inconclusive as to whether the NAO–AO indices and the QBO index are indeed related.

5. Conclusions and discussion

The main conclusions of this paper are as follows.

1) The NAO reflects the correlations between the surface pressure variability at all of its centers of action, whereas the AO does not. A simple three-variable example shows how totally uncorrelated locations can still result in large loading values at both locations in the leading EOF. This example is directly relevant for the definition of the AO: monthly mean sea level pressure in the Pacific and Atlantic are not significantly correlated yet both locations have large loading values in the AO pattern. The only significant correlation between centers of action in the AO pattern is between the Iceland and the Azores regions. However, the leading EOF of surface pressure, the AO, does reflect the tendency in both ocean basins for anticorrelation between the geostrophic winds near 35° and 55°N.
2) Hemispheric EOF analyses on different lower-tropospheric fields that might be expected to be dynamically related generally yield very different results and patterns that are not obviously related. The leading two EOFs of 850-hPa streamfunction are, however, clearly representations of PNA and NAO, respectively.
3) If the domain is limited to the Euro-Atlantic region, the NAO can be identified as the dominant EOF in dynamically related lower-tropospheric fields. Similarly the PNA emerges for the Pacific region.
4) An AO pattern with the same latitudinal behavior in the two ocean basins and some element of zonal symmetry does not correspond to a uniform modulation of the climatological features, because these features occur at different latitudes in different sectors. An increase in the AO implies a strengthening of the polar jet over northwest Europe and of the subtropical jet in the same sector but a weakening of the Pacific jet.
5) The PNA has strong related variability in the Pacific jet exit with fluctuations of opposite sign in polar and tropical regions. Elsewhere, the pattern of 250-hPa zonal wind variation is remarkably similar to that for the NAO, though the central North Atlantic dipole is weaker and is farther west.
6) For positive NAO, the tropospheric subtropical and polar jets are strong and separated, with the latter linking through to an enhanced stratospheric polar vortex.
7) For positive PNA, in the Atlantic sector, the tropospheric subtropical and polar jets are separated but there is no change in the stratospheric vortex. In the Pacific sector, the subtropical jet is weaker than for negative PNA but there are stronger, more uniform westerlies on its poleward flank linking through to somewhat stronger stratospheric winds in this sector.

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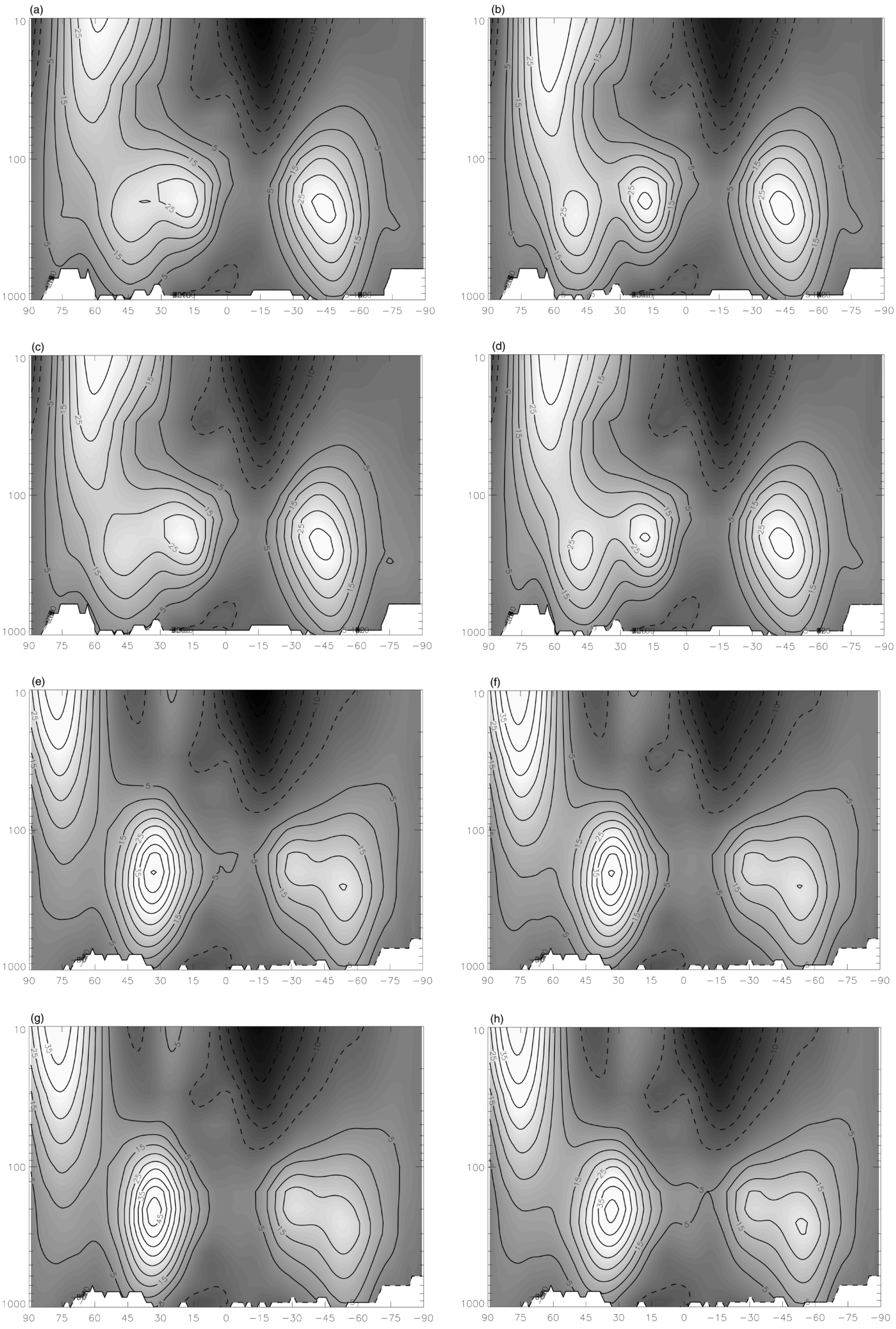
FIG. 7. Climatological mean of zonal winds in the Atlantic sector (60°W–0°) for an NAO index (based on the second EOF of 850-hPa streamfunction) of (a) −1 std dev and (b) +1 std dev. (c) and (d) The same as (a) and (b), but for the PNA index (based on the first EOF of the 850-hPa streamfunction). (e)–(h) The same as (a)–(d), but for the Pacific sector zonal winds (150°E–120°W).


(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
10
100
1000
90 75 60 45 30 15 0 −15 −30 −45 −60 −75 −90

The AO not only shows up as the first principal component of the mean sea level pressure but is also identified in multilevel EOF analyses (Baldwin and Dunkerton 1999) or stratospheric data (Kodera et al. 1999). As such it is an apparently robust signal. However, it could be that the robustness of the AO is a result of the strong domain-shape dependence of EOF patterns. Because of this domain-shape dependence, a multilayer analysis would tend to yield deep phenomena with a tendency for zonal symmetry, as observed.

The results presented here and elsewhere naturally raise the question as to whether the NAO–PNA or AO perspective is to be preferred. Based on the descriptive methods used in this study, we cannot answer questions about the physical background of phenomena conclusively. If anything, our study suggests that, rather than the AO, it is the NAO and PNA patterns that are candidates for patterns with a separated set of physical processes involved in their variability and that, consequently, they may show a potentially predictable behavior. The main positive argument for this here is the ubiquitous appearance of these patterns in various local analyses such as teleconnections, regional EOFs, or rotated EOFs of different fields.

In our view, the NAO–PNA or AO question is different from the question as to whether an annular or sectoral paradigm is to be preferred. Indeed, what is meant by the words annular and mode? As shown previously by Ting et al. (1996, 2000) the zonally averaged zonal flows near 35° and 55°N in the two ocean basins are negatively correlated. Is it a coincidence that the latitudinal structure for anomalies in the two ocean basins is similar or is it a sign of annular behavior? However, zonally symmetric behavior affects climatological features at different latitudes in different sectors differently. Would one expect annular behavior to be organized along latitude circles or along climatological streamwise coordinates? Yu and Hartmann (1995) showed that the dominant pattern of natural variability in their model went smoothly from zonally symmetric to zonally asymmetric as the zonal symmetry of the domain was removed by the gradual raising of a mountain. Similar, if it could be shown that the dominant variability in a model with gradually increasing Northern Hemisphere continentality changed smoothly from zonally symmetric to NAO-like, then the basic mechanism might be considered to be annular.

The independence of the subpolar centers of action (such as the Pacific and the Azores sea level pressure in the case of the AO) does not necessarily exclude an annular-mode mechanism. For example, random changes of the subpolar flow at random longitudes lead to noncovariant subpolar centers of action while the mechanism is zonally symmetric (there is no prefered longitude). A case in point is the Southern Hemisphere flow. There is evidence (Gong and Wang 1999; Thompson and Wallace 2000) that the Southern Hemisphere may indeed have a zonally symmetric mode of oscillation, even though the midlatitudes in different zonal sectors are uncorrelated.

The results given here suggest that the NAO paradigm may be more physically relevant and robust for Northern Hemisphere variability than is the AO paradigm. However, this result does not disqualify many of the physical mechanisms associated with annular modes for explaining the existence of the NAO.

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