The Pacific Center of Action of the Northern Hemisphere Annular Mode: Real or Artifact?

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ABSTRACT

The leading empirical orthogonal function (EOF) of the sea level pressure (SLP) field, referred to as the Arctic Oscillation (AO) or Northern Hemisphere annular mode (NAM), consists of a dipole between the polar cap region and the surrounding zonal ring centered along 45°N. Embedded within the outer ring are centers of action over the Euro-Atlantic and Pacific sectors in which SLP fluctuates in phase. That the observed SLP fluctuations at these two centers of action are virtually uncorrelated raises the question of whether the Pacific center in the annular mode could be an artifact of EOF analysis.

It is argued that sea level pressure fluctuations at the Pacific and Euro-Atlantic centers of action of the AO/NAM would be more strongly correlated were it not for the fact that SLP variability over the North Pacific is dominated by a pattern in which fluctuations over the North Atlantic and North Pacific are inversely related. Evidence of the coexistence of such a pattern, which resembles an augmented version of the Pacific–North American pattern, is presented.

1. Introduction

The North Atlantic Oscillation (NAO) and Northern Hemisphere annular mode [NAM; or Arctic Oscillation (AO) as it is sometimes called] are different ways of characterizing one of the leading modes of Northern Hemisphere variability. The NAO paradigm is inherently sectoral: it places primary emphasis upon the prominent north–south dipole structure in the sea level pressure (SLP) field over the North Atlantic Ocean (Walker and Bliss 1932; van Loon and Rogers 1978; Hurrell 1995). In contrast, the annular mode paradigm is inherently hemispheric: although it recognizes the prominence of the North Atlantic sector in the SLP pattern, it places primary emphasis upon the zonally symmetric components of the geopotential height and zonal wind fields (Thompson and Wallace 1998, 2000; Wallace 2000). The spatial patterns of the NAM, defined here as the leading empirical orthogonal function (EOF) of the hemispheric SLP field, and the NAO defined as the leading EOF of SLP within the Euro-Atlantic sector 60°W–30°E, are contrasted in Fig. 1.

Deser (2000) and Ambaum et al. (2001, hereafter

AHS) have questioned whether the spatial pattern of the NAM is a physically consistent covariance structure in the same sense that the Euro-Atlantic NAO is, and Dommenget and Latif (2002) have implicitly raised the same issue in the context of a critique of EOF analysis (see also Richman 1986). AHS conclude from their analysis that the NAO paradigm may be more physically relevant and robust for Northern Hemisphere variability than the NAM paradigm, though this does not disqualify many of the physical mechanisms associated with annular modes for explaining the existence of the NAO.

2. Issues relating to the interpretation of EOFs

The major point at issue is the nature of the secondary "center of action" in the spatial pattern of the NAM over the Pacific sector (Fig. 1, left) designated by the label "P." AHS conclude that the NAM/NAO pattern is more physically relevant and robust if this center is excluded, whereas we regard it as an integral part of the pattern in question. If it could indeed be shown that there is no correlation between the SLP field in the Pacific sector and the other centers of the NAM pattern and, most notably, the center of action over the Arctic, it would significantly weaken the case for the annular mode paradigm.

Before reviewing the evidence pertaining specifically

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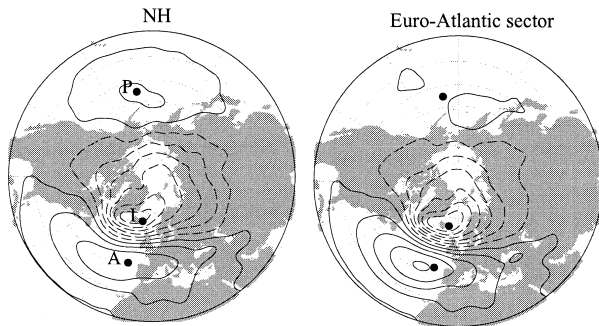E-mail: davet@atmos.colostate.edu

FIG. 1. (left) The leading empirical orthogonal function (EOF 1) of NH (20°–90°N) monthly mean SLP anomalies, referred to here as the NAM and in AHS as the AO. (right) Same as the left, but for EOF 1 of the monthly mean SLP field in the Euro-Atlantic sector (20°–90°N, 60°W–30°E), referred to here and in AHS as the NAO, where the pattern has been extended to include the entire hemisphere by regressing the monthly SLP field upon the corresponding principal component time series. Contour interval is 10 m of 1000-hPa height (−5, 5, 15, . . .); negative contours are dashed. Points P, I, and A denote the principal centers of action (as in AHS), considered to be the same in the two patterns. Here and in subsequent figures the patterns are based on monthly mean fields of the NCEP–NCAR re-analyses for the period 1958–99 (Dec–Mar values for NH results; all months for SH results).

TABLE 1. Percentage of variance explained by the leading modes in EOF expansion of monthly mean fields for the region poleward of 20°, based on monthly mean data for Dec–Mar, 1958–99: mode 1 (2, 3).

Field	Variance explained
SLP	23, 14, 9
SLP + Z_{500}	20, 13, 9

to the NAM/NAO, it is illuminating to consider the SLP signature of the leading pattern of variability in the Southern Hemisphere, shown in Fig. 2a. Although this pattern is generally described as ''annular'' and diagnosed as if it were annular (Yoden et al. 1987; Kidson 1988; Shiotani 1990; Karoly 1990; Hartmann and Lo 1998), its outer ring is only weakly reflected in one-point correlation maps (Figs. 2b,c). The correlations between distant points are weak because this annular pattern of variability is not the only phenomenon that causes SLP to vary from month to month at grid points in the outer ring. For example, the pervasiveness of zonal wavenumber 3 in the Southern Hemisphere month-to-month variability (Mo and White 1985) favors negative correlations between grid points in the ring located di-

rectly across the Pole from one another. The leading pattern of Southern Hemisphere variability is annular, not because of the correlations within the outer ring, but because most of the grid points in the outer ring are negatively correlated with SLP over the polar cap region. By virtue of this ''indirect'' correlation via the polar cap, SLP variations at grid points in the outer ring tend to be positively correlated, but there are numerous pairs of grid points for which the correlations are very weak.

Now let us consider the evidence concerning the Northern Hemisphere annular pattern. Deser (2000) and AHS have both examined the observed correlations between SLP fluctuations at the midlatitude Atlantic (A) and Pacific (P) centers of action of the annular pattern in the SLP field (Fig. 1, left). Deser obtained a marginally significant positive correlation between fluctuations at A and P, presumably because point A in her analysis represented an average over a longitudinal sector broad enough to include a portion of the downstream center of action of the Pacific–North American (PNA) pattern over the southeastern United States, where SLP fluctuations vary in phase with those at P. AHS show that if A is defined as a more localized region over the eastern Atlantic, the correlation between fluctuations at A and P is weakly negative.

Lacking positive correlations between SLP fluctuations around the Atlantic and Pacific centers of the annular pattern, the significance of the Pacific center of action in the annular pattern hinges on the correlation between SLP fluctuations near that center and SLP fluc-
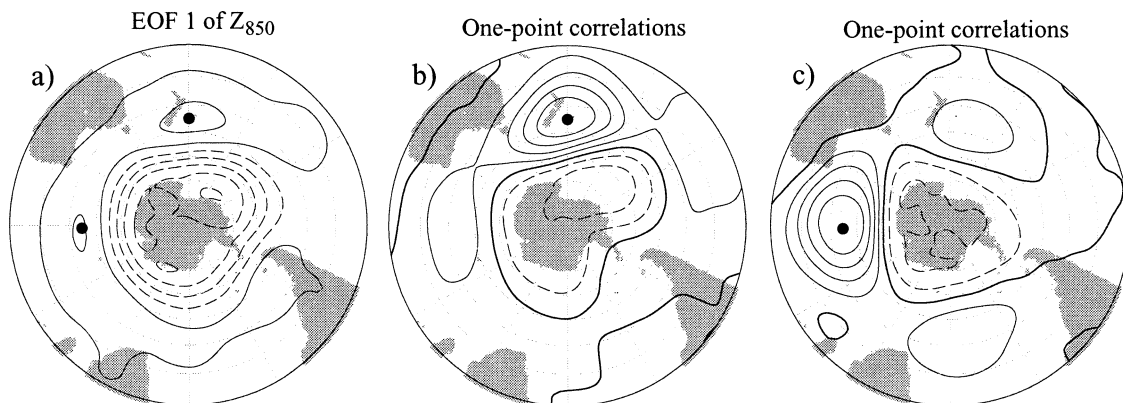

FIG. 2. (a) As in Fig. 1, but for the SH 850-hPa height field based on data for all months of the year, referred to here as the ''Southern Hemisphere annular mode.'' (b), (c) One-point correlation maps are shown for the points (45°S, 90°E) and (45°S, 180°E). Contour interval is $r = 0.2$ (−0.2, 0, +0.2, . . .); negative contours are dashed.
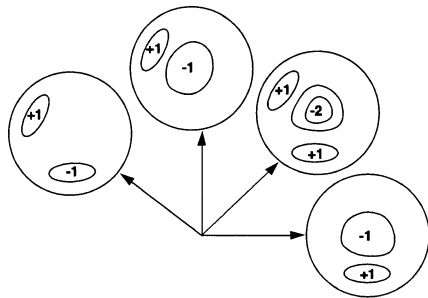
FIG. 3. Idealized two-dimensional phase–space and sea level pressure patterns in the idealized three-component system discussed in section 2.
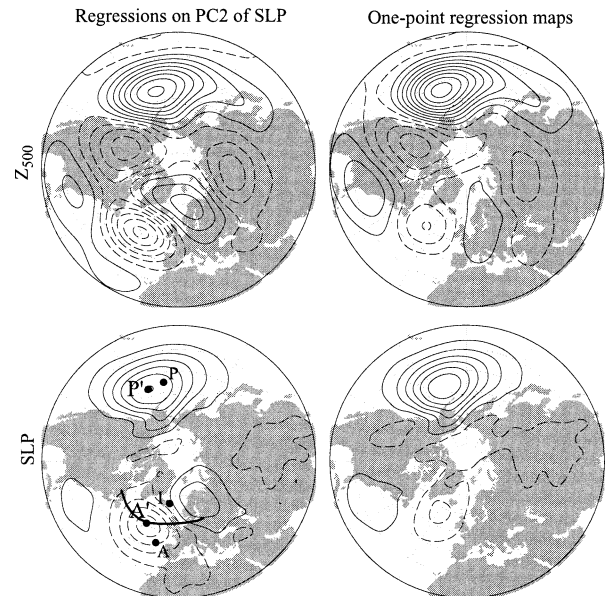

FIG. 4. (top) The 500-hPa height field and (bottom) SLP field regressed on standardized time series corresponding to (left) PC 2 of the NH monthly mean SLP field; (right) standardized values of SLP at point P. Points P, I, and A in the bottom-left are transcribed from Fig. 1; A′ and P′ denote the secondary centers of action of EOF 2 of SLP. The solid heavy line denotes the nodal line of the NAM in SLP over the North Atlantic. Contour intervals are 10 m (−5, 5, 15, . . .). Negative contours are dashed.

tuations within the Arctic. Deser and Ambaum et al. (2002) both found SLP fluctuations averaged over these regions to be negatively correlated at p levels less than 0.02, though the correlations were substantially weaker than those between A and I.

In view of the statistically significant negative correlations between SLP fluctuations near point P and those over the Arctic and between fluctuations over the Arctic and those near point A, there is a positive indirect correlation between fluctuations at P and A by way of the Arctic. The fact that such a positive correlation is not observed means that the indirect correlation is cancelled by other pattern(s) of variability characterized by negative correlations between fluctuations at P and A. AHS provided an idealized example that serves to illustrate how such a cancellation is reflected in the EOFs. They considered the idealized three-component system (A, P, I), where the time series A and P have unit variance and are uncorrelated with one another, and I is given by $I = -A - P$. It follows that A and P are correlated with I at a level of $(0.5)^{1/2}$. The leading (NAM-like) EOF $(1, 1, -2)$ derived from the covariance matrix of this system accounts for 75% of the variance and the second mode, a seesaw between A and P accounts for the remainder. Qualitatively similar results are obtained when AHS repeat the analysis on the covariance matrix for the three observed centers of action of the annular mode, despite the much stronger correlations over the Atlantic sector.

The idealized three-component system considered by AHS is illustrated graphically in Fig. 3. Plotted on the x and y axes are the amplitudes of the idealized Atlantic and Pacific dipole patterns sketched in the figure, which are assumed to vary linearly independently in time with equal root-mean-squared amplitude. Addition of the two dipole patterns (equivalent to a 45° rotation of the phase space) yields a NAM-like pattern and subtraction (equivalent to a 135° rotation) yields an Atlantic–Pacific seesaw, as indicated by the sketches along these axes. These rotated patterns correspond to the EOFs of the three-component system. AHS have argued that the NAO and the PNA pattern (Wallace and Gutzler 1981), the real world counterparts of the dipole patterns in Fig.

3, are the fundamental dynamical building blocks for planetary-scale patterns of variability and that the EOFs are largely mathematical constructs. In contrast, we have argued that the NAM-like leading EOF is a dynamically significant mode of variability in its own right. Here we argue that the PNA-like second EOF of the SLP field, the real world counterpart of the Atlantic–Pacific seesaw along the 135° axis in Fig. 3, may also be a dynamically significant mode of variability.

EOF 2 of the SLP field, shown in the bottom left of Fig. 4 (see also AHS: Fig. 1b) exhibits a primary center of action (P′) in the Pacific sector, just a few hundred km to the east of the Pacific center P in the NAM. It also exhibits a secondary center in the Atlantic sector (A′) just a few hundred km to the northwest of the center A of the NAM–NAO. Although the Atlantic center of action of EOF 2 overlaps with the Arctic center of action of the NAM–NAO, it is clear from Fig. 4 that it also contributes to the variability of SLP at point A. It is in this sense that the observed pattern is analogous to the Atlantic–Pacific seesaw on the 135° axis in Fig. 3.

In the projection of the 500-hPa height field upon the associated second principal component (PC 2) of SLP (Fig. 4, top-left), the familiar PNA wave train appears in combination with a secondary wave train over the Atlantic and Eurasian sectors. One-point regression maps, shown in the right-hand columns of Fig. 4 support the existence of these features. At the 500-hPa level the covariance at A′ is larger in absolute magnitude than

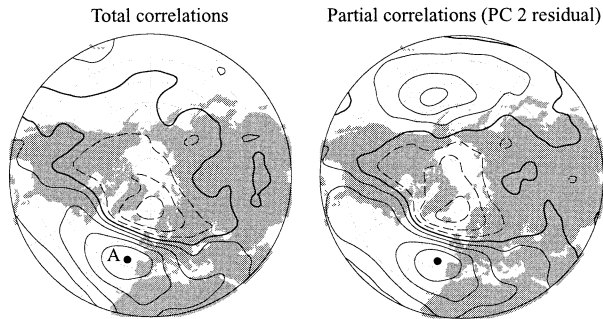Total correlations   Partial correlations (PC 2 residual)

FIG. 5. (left) Total and (right) partial one-point correlation maps for point A. The latter was formed from the residual SLP field that remained after regressing out PC 2 of the hemispheric SLP field whose corresponding EOF is shown in the previous figure. Contour interval is 0.2; negative contours are dashed.

that at the Florida center of action of the PNA pattern. Hence, if Wallace and Gutzler had used covariance (rather than correlation) as a basis for defining the dominant teleconnection patterns in the 500-hPa height field their "PNA pattern" might well have been subsumed into a more hemispheric pattern resembling the structure in the top panels of Fig. 4. Further support for this interpretation is derived from Table 4 of Wallace and Gutzler, which shows substantial temporal correlations between indices of the PNA, Eurasian (EU) and West Atlantic (WA) teleconnection patterns and from works of van Loon and Rogers (1978) and Honda and Nakamura (2001), which report negative correlations between the depth of the Icelandic and Aleutian lows.

If the augmented PNA pattern identified with EOF 2 is envisioned as coexisting with the annular mode, the apparent lack of correlation between SLP fluctuations at grid points A and P is understandable. Figure 5 compares one-point correlation maps for point A in the total SLP field (left) and in the residual SLP field formed by removing EOF 2 (right). The former exhibits a weak negative correlation between SLP fluctuations at A and P, in agreement with results of AHS. In contrast, the one-point correlation map for the residual field exhibits a NAM-like pattern with a correlation of $+0.64$, qualitatively consistent with the pattern along the $45°$ axis in Fig. 3.

3. Other perspectives

In the context of the idealized three-component system depicted in Fig. 3, the NAO–PNA perspective favored by AHS and the NAM-augmented PNA perspective described above are equally valid. In this section, we describe yet another way of envisioning the coupling between the circulation in the Pacific and Atlantic sectors.

Chang and Fu (2002) have examined the principal modes of variability of the Northern Hemisphere circulation from the perspective of the storm tracks, using the variance of the high-pass-filtered 850-hPa meridi-

onal wind component as a measure of the amplitude of baroclinic wave activity, defined at each grid point and for each month. In their leading EOF, the amplitude of the Pacific and Atlantic storm tracks varies in unison. The associated pattern in the SLP field, as inferred from linear regression upon the index of the "storm track mode," is characterized by in-phase fluctuations between the depths of the Aleutian and Icelandic lows, rather than out-of-phase fluctuations as in both the NAM-augmented PNA and the NAO–PNA perspectives. Both at the surface and aloft, their mode exhibits streamwise zonal symmetry with respect to the climatological-mean wintertime circulation.

If Chang and Fu's streamwise symmetric annular mode were the dominant pattern in the geopotential height field, the geopotential height pattern that they identified should be clearly evident in one-point covariance maps and it should emerge among the leading EOF's of the SLP field. Yet in the observed statistics, SLP fluctuations in the vicinity of the Icelandic and Aleutian lows tend to be negatively, rather than positively correlated (see also Honda and Nakamura 2001), and variations in the intensities of the Atlantic and Pacific storm tracks are linked to separate EOFs (the former to the EOF 1 of the SLP field, and the latter to EOF 2). Likewise, if streamwise symmetry were dominant in the Southern Hemisphere, there should be a strong longitudinal and seasonal correspondence between the Southern Hemisphere annular mode and the storm tracks. Yet the Southern Hemisphere annular mode maintains virtually the same configuration year-round (Thompson and Wallace 2000; Fig. 5), despite substantial seasonal variations in the background flow and the storm track configuration. During wintertime, in particular, the leading EOF of the Southern Hemisphere SLP field is much more annular than the jet streams and storm tracks. Hence it is apparent that in both the Northern and Southern Hemispheres the leading EOF of the SLP field exhibits a simpler meridional structure and a higher degree of axial symmetry than the climatological mean zonal winds and storm tracks upon which it is superimposed. Even though it does not capture the dominant structure of the anomalies in the SLP field, the "storm track pattern" identified by Chang and Fu is notable for its strong projection upon the climatological-mean flow. Its temporal variations should thus be strongly correlated with variations in available potential and kinetic energy of the hemispheric circulation.

4. Conclusions and remaining issues

Through their analysis of a simplified three-component system defined by the covariances between the three primary centers of action of the NAM, AHS have illustrated how the leading mode in an EOF expansion can comprise centers of action at which fluctuations of the variable under consideration are uncorrelated. Jolliffe (1987) has argued that such an apparent inconsis-

tency may be a reflection of the coexistence of two patterns of variability in which the covariances between the primary centers of action are of opposite polarity. We have argued that the lack of correlation between the Atlantic and Pacific centers of the NAM may be due to the coexistence of a second dynamically significant pattern that incorporates the PNA pattern of Wallace and Gutzler (1981). We have shown that if this coexisting pattern is defined as EOF 2 of the SLP field, the coupling between the NAM's Atlantic and Pacific centers of action in the residual field is nearly as strong as that between its Atlantic and Arctic centers. A similar result is obtained if it is defined as the second EOF of the equally weighted, combined SLP and 500-hPa height fields (not shown). On the other hand, if the coexisting mode is defined in a more sectorally localized manner, as in Wallace and Gutzler (1981), the intersectoral coupling via the NAM is correspondingly reduced.

The NAO–PNA perspective advocated by AHS, the NAM-augmented PNA perspective proposed herein, and the alternative perspective based on EOF analysis of storm track variability, proposed by Chang and Fu (2002) each illuminate different facets of the structure of Northern Hemisphere wintertime low-frequency variability. The first most clearly reveals the relationships between the fluctuating storm tracks and background flow over the respective ocean sectors; the second highlights the role of the zonally symmetric component of the hemispheric circulation and offers an interpretation of the intersectoral linkages in the geopotential height field; and the third draws attention to the covariability of the Atlantic and Pacific storm tracks. In our view, these perspectives are best regarded as complementary, rather than competing, pending the development of a more integrated framework for interpreting time variations in the hemispheric circulation.

The leading EOFs of the SLP field and the combined SLP and 500-hPa height fields correspond to the NAM and an augmented PNA pattern. On the other hand, as noted by AHS, NAM-like patterns are not recovered as the leading EOFs of all fields. For example, an augmented PNA pattern is recovered as the leading 850-hPa streamfunction, but the second mode in this expansion is more NAO-like than NAM-like (AHS; Fig. 3). A more rational framework is needed for deciding which of the myriad leading EOFs that can be recovered from multivariate, three-dimensional fields in the climate system correspond most closely to the dynamically significant modes of variability. Our purpose in this article is not to present the definitive analysis of the linkages between the geopotential height field in the Atlantic and Pacific sectors, but only to argue that such linkages are not precluded by the lack of a significant correlation between SLP fluctuations at the Atlantic and Pacific centers of the annular mode.

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