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On the Teleconnectivity of the "Arctic Oscillation"

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Abstract. The term "Arctic Oscillation" (AO) has recently been introduced to describe the leading structure of SLP variability over the Northern Hemisphere. A key feature of the AO is its zonally symmetric appearance, with a primary center of action over the Arctic and opposing anomalies in midlatitudes. Does the AO's annular appearance result from significant temporal correlations between SLP anomalies at distant longitudes? The results presented indicate that the temporal coherence between the Arctic and midlatitudes is strongest over the Atlantic sector, with weak correlations between the Atlantic and Pacific midlatitudes, both on intraseasonal and interannual time scales during the past 50 yrs. Hence, the "annular" character of the AO is more a reflection of the dominance of its Arctic center of action than any coordinated behavior of the Atlantic and Pacific centers of action in the SLP field. The AO is nearly indistinguishable from the leading structure of variability in the Atlantic sector (e.g., the North Atlantic Oscillation): their temporal correlation is 0.95 for monthly data.

1. Introduction

In a recent series of papers, Thompson and Wallace (Thompson and Wallace 1998, hereafter referred to as TW; Thompson and Wallace, 1999; Thompson et al., 1999) introduced the nomenclature "Arctic Oscillation" to describe the leading Empirical Orthogonal Function (EOF) of monthly SLP anomalies during winter poleward of 20° N. While the Arctic Oscillation, or AO for short, encompasses the well-known regional "North Atlantic Oscillation" (NAO) pattern in the Atlantic sector, TW emphasized the AO's higher degree of zonal symmetry and suggested that it should be regarded as the more fundamental structure (in their view, the NAO is largely an "historical accident" dictated by station data availability). According to TW, the importance of the AO lies in (a) its structural resemblance to the dominant mode of circulation variability in the lower stratosphere, (b) its similarity to the spatial pattern of circulation variability in the Southern Hemisphere, both in the troposphere and lower stratosphere, and (c) its recent upward trend during the past several decades, indicative of a strengthening of the wintertime polar vortex from sea level to the lower stratosphere. The direction of cause and effect between the troposphere and lower stratosphere was purposely left ambiguous in TW's studies, although they noted that recent general circulation modeling experiments indicate several forcing mechanisms may be operative, including ozone depletion in the lower stratosphere and increasing greenhouse gas concentrations in the troposphere.

The purpose of this note is to examine more closely the degree of zonal symmetry present in the AO using teleconnectivity as a metric. Does the AO's annular appearance result from significant temporal coherence between anomalies at distant longitudes or is it a consequence of the EOF methodology used to define it? Such scrutiny of the AO was not performed in Thompson and Wallace's studies.

2. Data and Methods

To facilitate comparison of our results with those of TW, identical data sets are employed. The primary data set is monthly SLP on a 5° latitude by 5° longitude grid poleward of 15° N for the period 1947–97, obtained from the NCAR Data Library (see Trenberth and Paolino, 1980 for details). Supplementary data sets include monthly tropospheric and lower stratospheric geopotential heights from the NCEP–NCAR Reanalysis Project for the period 1958–97 (Kalnay et al., 1996). Analyses are conducted for the winter season, defined as November–April in the Northern Hemisphere and May–October in the Southern Hemisphere following TW.

TW emphasized that the AO is more evident in monthly data than in winter-mean data, an aspect which they attributed to the competing influence of the El Niño – Southern Oscillation (ENSO) phenomenon on interannual variability over the North Pacific. Accordingly, their calculations were based primarily upon monthly data from which the long-term mean annual cycle had been removed. Note that these "monthly anomalies" include both month-to-month and year-to-year fluctuations, with the former generally dominating over the latter. To reduce further any influence from the tropical Pacific upon the higher latitudes, TW also constructed a dataset of monthly anomalies from which the year-to-year fluctuations had been removed. These "intraseasonal anomalies" were formed by subtracting each winter's mean from the individual monthly anomalies.

3. Results

3.1. Monthly sea level pressure

The AO was originally defined by TW as the leading EOF of monthly SLP anomalies poleward of 20° N during November–April 1947–97, reproduced in the upper lefthand panel of Fig. 1. The AO exhibits anomalies of one sign over the polar cap and anomalies of opposite polarity in midlatitudes over the Atlantic–European and Pacific sectors. How strongly correlated are the Arctic, Atlantic and Pacific centers of action of the AO? Correlation coefficients (r) among regional monthly time series (November–April 1947–97) formed by averaging the area-weighted SLP anomalies within the outer (non-zero) contours of the EOF pattern for the appropriate sector are:

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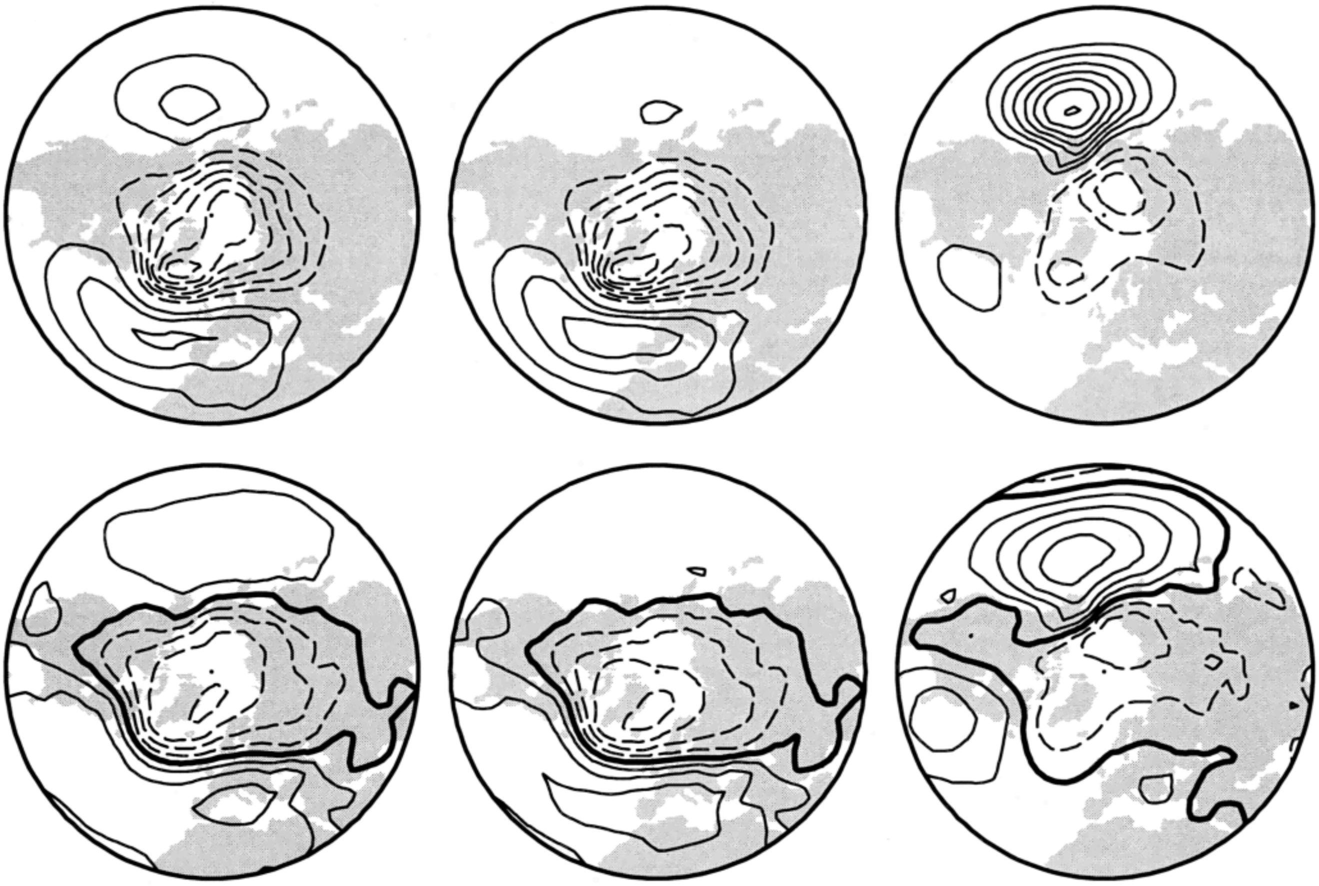

Figure 1. Leading EOF of monthly SLP anomalies poleward of 20° N based on the Northern Hemisphere (*left*), Atlantic (*middle*), and Pacific (*right*) domains. The patterns are displayed in amplitude (*upper*) and correlation (*lower*) form, obtained by regressing or correlating the monthly SLP anomalies over the entire hemisphere upon the leading EOF time series from each domain. The contour interval in the lower panels is 0.2 and the zero contour is darkened.

$r(Arctic, Atlantic) = -0.64\ (-0.56)$
$r(Arctic, Pacific) = -0.22\ (-0.27)$
$r(Atlantic, Pacific) = 0.10\ (0.16)$

where the values in parentheses are based on intraseasonal anomalies. A correlation coefficient exceeding 0.09 in absolute value is significantly different from zero at the 5% confidence level, taking into account the effective number of degrees of freedom in the time series according to Trenberth (1984). Of the three pairs, the Atlantic and Arctic time series are the most closely related, while the Atlantic and Pacific indices share less than 3% of their respective variability.

To what extent can the AO be recovered from the leading EOF of the Atlantic sector alone, or alternatively, from the

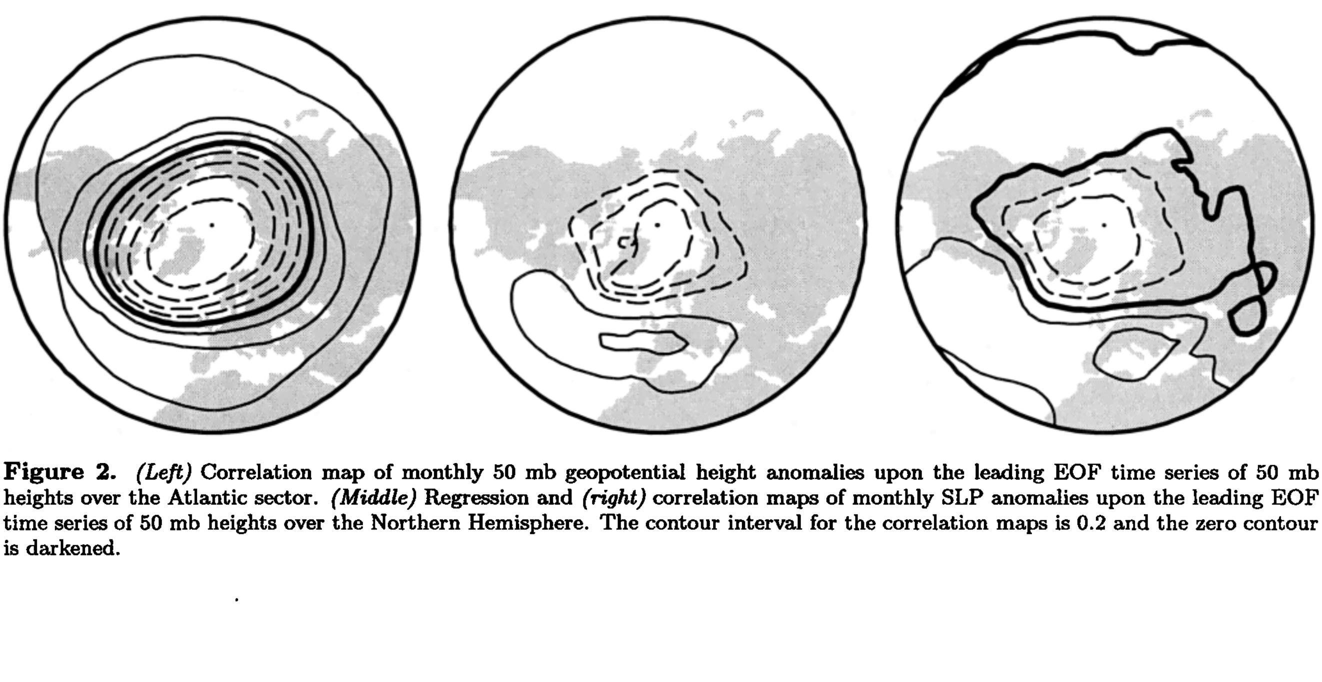

Figure 2. *(Left)* Correlation map of monthly 50 mb geopotential height anomalies upon the leading EOF time series of 50 mb heights over the Atlantic sector. *(Middle)* Regression and *(right)* correlation maps of monthly SLP anomalies upon the leading EOF time series of 50 mb heights over the Northern Hemisphere. The contour interval for the correlation maps is 0.2 and the zero contour is darkened.

Figure 3. Leading EOF of monthly 850 mb geopotential height anomalies poleward of 20° S based on data for May–October 1958–97.

leading EOF of the Pacific sector alone? Figure 1 shows the leading EOF of monthly SLP anomalies based on the full Northern Hemisphere domain (*left*), the Atlantic (90° W – 90° E) domain (*middle*), and the Pacific (90° E – 270° E) domain (*right*). The patterns are displayed in amplitude (*upper panels*) and correlation (*lower panels*) form, obtained by regressing or correlating the monthly SLP anomalies over the entire hemisphere upon the leading principal component (PC) time series from each domain. The leading EOF accounts for 21.9%, 30.8% and 27.2% of the variance over the Northern Hemisphere, Atlantic and Pacific domains, respectively, and all are well separated from the higher order EOFs.

The leading EOF for the Northern Hemisphere is comprised of the leading EOF within each subdomain (*Fig. 1, upper panels*). However, the Atlantic EOF does not project strongly onto the Pacific sector, as evidenced by the low correlation coefficients (less than 0.2) over the North Pacific (*Fig. 1, lower middle panel*). While the Pacific EOF does project onto the Atlantic sector, the connection is strong only over the western portion of the Atlantic (via the well-known "Pacific–North American (PNA)" teleconnection pattern) and weak (correlation coefficients less than 0.2 in magnitude) in the eastern portion (*Fig. 1, lower right panel*) where the Atlantic EOF has its largest amplitude. These results are consistent with the strength of the correlations among the regional SLP indices cited above. The Northern Hemisphere and Atlantic (Pacific) subdomain PC time series contain 90% (29%) of their variance in common, while the Atlantic and Pacific sector PCs share only 10% of their respective variability. Nearly identical results are obtained for the intraseasonal anomalies (*not shown*).

Similar EOF analyses were conducted for monthly geopotential height anomaly fields at 850 mb and 300 mb. The results (*not shown*) support the findings based upon SLP: namely, that the correlations between the leading EOF over the Atlantic sector and height anomalies over the Pacific are weak (less than 0.2 in magnitude over the central North Pacific) as are the correlations between the leading EOF over the Pacific sector and height anomalies over the Atlantic–European region [the links to the far western Atlantic are stronger (0.4–0.6), in association with the downstream centers of action of the PNA pattern].

3.2. Connection to the lower stratosphere

According to TW, an important aspect of the AO is its structural resemblance to geopotential height variability in the lower stratosphere during winter (however the AO is also present during the warm season when coupling to the stratosphere is absent). Figure 2 (*left panel*) shows correlation coefficients between the time series of the leading EOF of monthly 50 mb height anomalies in the Atlantic sector (20° – 90° N, 90° W – 90° E) during November–April 1958–97 and 50 mb height anomalies at each grid point over the Northern Hemisphere. The dominant structure of variability in the lower stratosphere is clearly annular, as evidenced by the similarity of the correlation coefficients along a given latitude circle. Similar results are obtained for the leading EOF over the Pacific domain (and the Northern Hemisphere), as well as for the intraseasonal anomalies (*not shown*).

How zonally–symmetric is the SLP anomaly pattern that occurs in association with the leading EOF of 50 mb geopotential height anomalies? The middle (right) panel of Fig. 2 shows the result of regressing (correlating) the monthly SLP anomaly fields upon the leading 50 mb PC time series (the PC time series is based on data for the entire Northern Hemisphere, but nearly identical results are obtained when the PC time series from the Atlantic or Pacific subdomains are used). It is evident that SLP anomalies over the Atlantic and Arctic sectors project substantially upon the 50 mb PC time series (maximum correlation coefficients around 0.4–0.5), whereas SLP anomalies over the Pacific project only weakly (maximum correlation coefficients near 0.1), in agreement with earlier findings of Perlwitz and Graf (1995). Similar results are obtained for the intraseasonal anomalies (*not shown*).

When the analysis is restricted to the months January–March, which Thompson and Wallace (1999) define as the "active season" for the lower stratosphere when the 50 mb geopotential height variance over the polar cap reaches a maximum, the SLP regression and correlation coefficients increase slightly in magnitude; however, the maximum correlation coefficients over the North Pacific are only 0.2, compared to 0.5 for the Atlantic and Arctic sectors (*not shown*). When intraseasonal anomalies are used in place of monthly anomalies for January–March (both in the 50 mb EOF computation and in the SLP field), the regression and correlation maps weaken substantially (*not shown*).

3.3. Comparison with the Southern Hemisphere

TW suggest that the AO is the Northern Hemisphere analogue of the annular mode in the Southern Hemisphere. How similar is the AO to the leading structure of variability south of 20° S ? Figure 3 shows the leading EOF of monthly (May–October) 850 mb geopotential height anomalies poleward of 20° S during 1958–97, which accounts for 26.8% of the variance: nearly twice as much as the second mode. Like its Northern Hemisphere counterpart (*Fig. 1. upper left*), the leading EOF in the Southern Hemisphere exhibits anomalies of one sign over the polar cap region and anomalies of opposite polarity in midlatitudes, split into two centers. The primary midlatitude center of action occurs in the western Pacific–Indian Ocean sector, with a secondary center near the tip of South America.

How strongly correlated are these centers of action? Defining regional monthly SLP anomaly time series according to the outer contours of the EOF pattern, we find:

r(Antarctic, IndoPacific) = −0.61 (−0.67)
r(Antarctic, South America) = −0.38 (−0.40)
r(IndoPacific, South America) = 0.10 (0.19)

where the values in parentheses are based on intraseasonal anomalies, and $|r| \geq 0.09$ is significantly different from zero at the 5% confidence level. The strongest correlations occur between the polar and primary midlatitude (Indo–Pacific) centers, while the weakest correlations are found between the two midlatitude centers of action, similar to the results for the Northern Hemisphere.

3.4. Winter–mean sea level pressure

TW have drawn attention to the strong upward trend in the winter–mean AO time series since 1968, indicative of a deepening of the polar vortex during the past 3 decades. However, when EOF analysis is applied to winter–mean SLP anomalies during 1968–1997, the leading mode of interannual variability over the Northern Hemisphere contains only the Arctic and Atlantic centers of action of the AO, while the second mode contains the Pacific center (*not shown*). This result is consistent with the weak values of *r(Arctic, Pacific)* and *r(Atlantic, Pacific)* and strong value of *r(Arctic, Atlantic)* based on winter–mean SLP anomalies during 1968–97 (−0.15, 0.02, and −0.86 respectively, where $|r| \geq 0.28$ is significantly different from zero at the 5% confidence level).

For a more robust estimation of the interannual correlations among the 3 centers of action of the AO, the longer 1947–97 period of record is used:

r(Arctic, Atlantic) = −0.83 (−0.81) (−0.81)
r(Arctic, Pacific) = −0.07 (−0.15) (−0.26)
r(Atlantic, Pacific) = −0.07 (0.00) (0.06)

where $|r| \geq 0.22$ is significant at the 5% confidence level. The values in the first column are based on raw winter–mean SLP anomalies. The correlations in the second column are based on high–pass filtered data so as to reduce the influence of low–frequency trends on the correlations (the filter has a gaussian response with a half–power point at approximately 12 yrs). The values in the third column are based on high–pass filtered data from which variability linearly–related to ENSO has been removed by subtracting out the regressions associated with high–pass filtered winter SLP anomalies at Darwin, Australia. The results indicate that high–pass filtering and regressing out the ENSO–related variability as represented by the Darwin time series has almost no impact upon *r(Arctic, Atlantic)*, but brings *r(Arctic, Pacific)* [and to a lesser extent *r(Atlantic, Pacific)*] more into line with the results based on monthly data (recall Section 3.1). A more comprehensive assessment of the influence of ENSO upon the Pacific and Arctic centers of action of the AO is left to future work.

3.5. Summary and Discussion

The intent of this study was to examine (using teleconnectivity as a metric) the degree of annular symmetry present in the "Arctic Oscillation" pattern defined by TW on the basis of EOF analysis of the monthly SLP anomaly field during winter. The results presented indicate that the teleconnectivity between the Arctic and midlatitudes is strongest over the Atlantic sector, and that the temporal coherence between the Atlantic and Pacific midlatitudes is weak, both on intraseasonal and interannual time scales, during the past 50 yrs. Hence, the "annular" character of the AO is more a reflection of the dominance of its Arctic center of action than any coordinated behavior of the Atlantic and Pacific centers of action in the SLP field.

The AO time series is nearly indistinguishable from the leading structure of variability in the Atlantic sector (e.g., the NAO): their temporal correlation is 0.95 for monthly SLP anomalies during November–April 1947–97. It is worth noting, however, that the correlation between the leading PC in the Atlantic sector and the traditional station-based index of the NAO (e.g, the normalized SLP difference between Iceland and the Azores) is only 0.71 (0.83) for monthly (winter mean) anomalies during November–April 1947–97, reflecting that the two station NAO index is not the optimal representation of the spatial pattern associated with it.

A "teleconnection pattern" in a meteorological field may be defined as a spatial structure with two or more distinct and strongly coupled centers of action. By that definition, the NAO (e.g., the Arctic–Atlantic SLP anomaly dipole) clearly qualifies as a teleconnection pattern. In contrast, the AO and its Southern Hemisphere counterpart are distinctive, not for the strength of the teleconnections between their various centers of action, but for the remarkably large areal coverage and zonal symmetry of their primary (Arctic / Antarctic) centers of action.

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