A Test for Annular Modes

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ABSTRACT

The use of empirical orthogonal functions (EOFs) has grown popular as a tool to determine underlying variability from the rapidly increasing volume of climate data. It has been noted that the dominant or first EOF of geopotential heights, in each hemisphere at levels from the surface through the troposphere and into the midstratosphere, appears to be zonally symmetric. It has also been suggested that all of the first EOFs, throughout the atmospheric column are barotropically coupled and annular. Moreover, such modes of variability in both hemispheres are thought to be analogous to each other. To define annularity more objectively and to facilitate comparisons both temporally and spatially, a framework has been formulated within which modes of variability may be tested for their degree of zonal symmetry or annularity. Motivated by previous choices, pressure–height fields in each hemisphere are tested for annularity, one near the surface and the other in the midstratosphere. Periods chosen coincide with times when the troposphere and stratosphere are actively coupled. According to the test for annularity on the first mode of variability, these fields can be ranked in order of degree of annularity: the first EOF of Northern Hemisphere (NH) December–January–February (DJF) 50-hPa geopotential height is annular; the first EOF of Southern Hemisphere November 50-hPa geopotential height is weakly annular; the first EOF of Southern Hemisphere November 850-hPa geopotential height is weakly nonannular; and the first EOF of NH DJF sea level pressure is nonannular.

1. Introduction

A growing body of evidence shows that oscillations of surface pressure between high and midlatitudes exist in both the Northern and Southern Hemispheres and are referred to as the Arctic Oscillation (AO) and Antarctic Oscillation (Thompson and Wallace 1998; Gong and Wang 1999) in their respective hemispheres. Recently there has been great interest to identify and characterize the dynamics of the hemispheric-scale seesaw in atmospheric mass between the high and midlatitudes (Gong and Wang 1999). The seesaw or oscillation in atmospheric mass is thought to take place throughout the troposphere and much of the stratosphere (Baldwin and Dunkerton 1999). The technique most commonly used to identify such hemispheric-scale patterns of variability is eigenvector decomposition, also known as empirical orthogonal function (EOF) analysis. The dominant EOF or mode in both hemispheres exhibits a dipole structure across mid- to high latitudes and exhibits some degree of zonal symmetry. Therefore there has been a growing acceptance to refer to these modes as annular (DeWeaver and Nigam 2000). It has even been suggested that the dominant modes in each hemisphere bear a resemblance and should be referred to as the northern annular mode (NAM) and the southern annular mode (Limpasuvan and Hartmann 2000).

The AO or NAM is strongly correlated with the well-known teleconnection pattern, the North Atlantic Oscillation (NAO). Whether the dominant mode of Northern Hemisphere (NH) atmospheric variability is referred to as the NAO or AO or NAM is more than of academic interest, the title relates to the forcing mechanism of this dominant atmospheric pattern, whether it is regional boundary conditions such as sea surface temperatures (Rodwell et al. 1999) or snow cover (Cohen and Entekhabi 1999), or rather hemispheric-scale forcings such as those originating from the stratosphere (Baldwin and Dunkerton 1999) or even aerosols (Perlwitz and Graf 1995).

While some have favored the NAO nomenclature and its more regional view (Deser 2000; Ambaum et al. 2001) and others advocate the AO and its more annular or hemispheric view (Thompson and Wallace 2000; Wallace 2000), we believe that an objective definition or technique to identify annular modes has been lacking

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in this debate. Therefore we propose below a definition, and a technique to test, for annularity. An added advantage of our test for annularity is its facility to compare the ‘‘annularity’’ of modes derived from geopotential height at different pressure surfaces or over different spatial domains (e.g., Northern Hemisphere versus Southern Hemisphere). In section 2 we describe the test for annularity. In section 3 we describe in more detail the technique used for removing regional variability, upon which the test heavily relies. In section 4 we apply the test to simulated and real data. In section 5 we perform a check on the test results, and finally in section 6 we present our conclusions.

2. Test for annularity

Until recently the dominant modes of variability, at least for the NH, were thought to be regional (Barnston and Livezey 1987). A series of recent papers has proposed that the dominant mode in both hemispheres is annular with dynamic coherency (Thompson and Wallace 2001). The debate carries on as to whether the surface climate is driven regionally by boundary conditions or hemispherically by downward-propagating energy from the stratosphere. The contribution of this paper is to present a more comprehensive method to identify annular and nonannular modes in the atmosphere.

In this section we describe the annularity test. The advantage of this test is twofold over recent attempts to ascribe annularity to atmospheric patterns of variability. First, the test is objective; it does not rely merely on the appearance of ‘‘annular’’ or ‘‘zonally symmetric’’ features. Second, the test lends itself to quantitative measures of the degree of annularity and therefore facilitates comparison of different spatial and temporal modes. Note too that the test is completely confined to EOF space, so there is no need to go back to the raw data to argue annularity or nonannularity. The current discussion of annular modes and their impact on surface climate is greatly motivated by the widespread use of EOF techniques. One potential pitfall of using EOFs is that the shape of the domain can artificially influence the spatial loading patterns produced using unrotated EOFs (Richman and Lamb 1985). We have rigorously tested the sensitivity of our results from EOF analysis to varying boundaries and domain shapes and we could not find any dependence to choice of domain; still we cannot rule out the possibility that the EOFs we present are prone to spurious results.

The technique of identifying teleconnection patterns using EOF analysis of pressure or height anomalies at a given level is commonly used, though EOFs are designed to maximize temporal variance and do not necessarily represent teleconnections (Ambaum et al. 2001). The dominant EOF of geopotential heights in the lower troposphere near the surface and in the stratosphere in each hemisphere is characterized typically by a dipole structure (Thompson and Wallace 1998). One center of action is located around the Pole and a second center of action of opposite sign stretches across the midlatitudes. The structure of the first EOF of geopotential heights at various levels of the atmosphere has been described as zonally symmetric. However Ambaum et al. (2001) have shown that EOFs do not represent covariance structures and therefore same-signed variability at different locations, associated with the same order EOF, can be independent of each other. We argue that even though regional variabilities do not necessarily need to be dependent upon each other (dependence, for the most part, is determined by being significantly correlated), regional variabilities need to be quasi-equally dependent upon the hemispheric mode of variability that is being described as annular. For example, if the NAO is the pattern of variability in the North Atlantic and the Pacific–North American (PNA) pattern is as the pattern of variability in the Pacific and the AO the hemispheric or annular mode, lack of significant correlation between the NAO and the PNA is not enough to demonstrate nonannularity. However, the relationship of the NAO and PNA vis-à-vis the AO needs to be symmetrical.

There are conceivably other types of annularity, which we do not consider. We only consider stationary structures rather than transient ones. Another is zonally symmetric variability, which is not coherent (most importantly dynamically coherent) or completely random, and which we do not test for. A third type of annularity, along climatological streamlines rather than latitudes, has already been shown not to exist for the NH (Ambaum et al. 2001). Therefore the definition of annularity that we believe to be most relevant to the current discussion of annular modes is *if all centers of variability around a latitude circle are dependent on the hemispheric-scale variability or alternatively, if after all regional (hemispheric scale) variability is removed, the residual is independent of the hemispheric-scale (regional) variability, then the system is considered annular.* Furthermore we propose the following method, as described below, as a test for annularity (see Fig. 1 for schematic, notation from figure will be used in the text). We also borrow the simple three-component system similar to the one described in Ambaum et al. (2001) to illustrate examples of the different cases described in our test for annularity. In our simple three-component system α, β, and γ, components α and β are of unit variance and are active in separate sectors (α is active in the Atlantic and β in the Pacific) and γ is equally active in both sectors. Also the correlation of (α, γ) and (β, γ) is equal to zero.

First an EOF analysis is performed on the full hemispheric data. In most cases for hemispheric data fields, the mode of variability in question for annularity is the first, or dominant, mode referred to as EOF1. Then EOFs are computed regionally. So, for example, in the cases we present we will divide the Northern and Southern

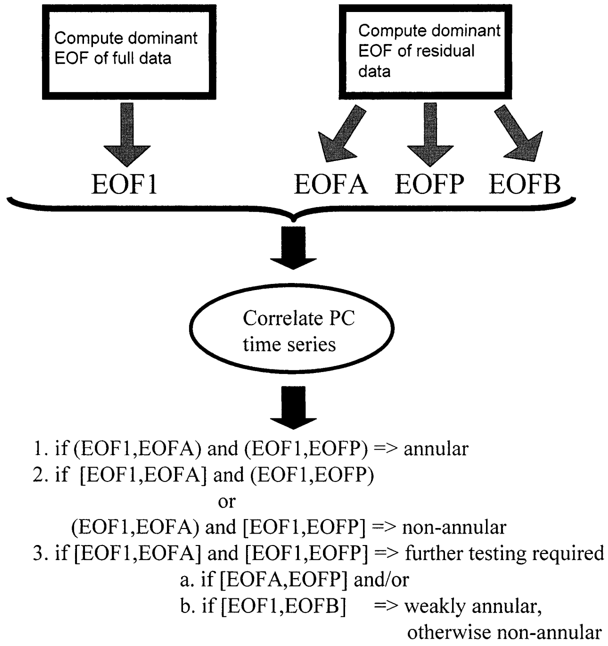


FIG. 1. Schematic of test for annularity. In our example the dominant EOF of original or full data is EOF1; two dominant EOFs with regional variabilities removed are EOFA (Pacific variability removed) and EOFP (Atlantic variability removed); and the dominant EOF with both regional variabilities removed is EOFB. Brackets denote significant correlation between two variables and parentheses denote nonsignificant correlation.

Hemispheres each into two regions: the Atlantic (ATL) and Pacific (PAC). The dominant regional variability is then removed from the entire hemispheric data field (see section 3) and a new set of hemispheric EOFs are computed; only the dominant modes are retained and are referred to as EOFA and EOFP. The principal component (PC) or time series for the first modes with the dominant regional variability removed, EOFA and EOFP, are then correlated with the original time series of EOF1. The results of the correlation calculations will determine to which of three different cases the modes belong:

1) symmetric nonsignificant correlations,
2) asymmetric correlations,
3) symmetric significant correlations.

Please note that two time series that are significantly correlated (at greater than 99% confidence) will be grouped below in brackets, that is, [,]; those that are insignificantly correlated are grouped in parentheses, that is, (,).

The first case occurs when neither dominant mode, calculated with regional variability removed, is significantly correlated with the original dominant mode: (EOF1, EOFA) and (EOF1, EOFP). The nonsignificant results demonstrate this case to be annular because the dominant hemispheric mode of variability is also the dominant mode of variability at the regional scale, in both sectors. An example of this first case from our simple three-component system would be where var(γ) > 2. EOF1 is equal to γ, but because its variance is greater than 1, even in each semihemisphere, it is removed when computing EOFA and EOFP leaving EOFA $= \alpha$ and EOFP $= \beta$. Because (α, γ) and (β, γ), the system is determined to be annular.

The second or nonannular case is when one, but not both, dominant modes, calculated with regional variability removed, is significantly correlated with the original dominant EOF: [EOF1, EOFA] and (EOF1, EOFP), or (EOF1, EOFA) and [EOF1, EOFP]. Here the hemispheric-scale variability is mainly associated with one of the regional variabilities, but not both. In this situation, the hemispheric variability is a superposition of regional asymmetric variability. An example from our three-component system is when var(γ) < 1 and var(α) is greater than var(β) with the Atlantic sector dominating. Therefore EOF1 is identical to α since its variance is greatest both in its sector and at the hemispheric scale. EOFA is equivalent to α and EOFP to β. If α and β are not significantly correlated, then [EOF1, EOFA] and (EOF1, EOFP) hold and the system is determined to be nonannular.

In the third case, both dominant modes, calculated with regional variability removed, are significantly correlated with the original dominant mode: [EOF1, EOFA] and [EOF1, EOFP]. Here, the hemispheric variability is a superposition of regional symmetric variability (in that no one region completely dominates the variability as in case 2). For this case we argue that the test for annularity has failed and secondary tests need to be conducted. If one of the following two conditions occur, then the hemispheric variability can be considered weakly annular:

3a) both dominant modes, calculated with regional variability removed, are significantly correlated with each other: [EOFA, EOFP]; or
3b) the dominant mode computed after *all* dominant regional variabilities are removed, referred to as EOFB, is significantly correlated with the original dominant mode: [EOF1, EOFB].

If in cases 3a and 3b no significant correlations are found, then (EOFA, EOFP) and (EOF1, EOFB) hold and case 3 is also considered nonannular.

When EOFA and EOFP are significantly correlated, case 3a demonstrates some characteristic of annularity in that the regional variabilities occur in tandem in such a way that the superposition of the regional variabilities resembles zonal symmetry. An example of this from our simple three-component system is when var(γ) is negligible and the system then degenerates to a two-component system where EOFA $= \alpha$, EOFP $= \beta$ and EOF1 $= \alpha + \beta$. If $\alpha + \beta$ is significantly correlated with α and β then [EOF1, EOFA] and [EOF1, EOFP] are valid and the test fails. However if [α, β] is true then the system is considered weakly annular, and if (α, β) is true, it is considered nonannular. Another example is when $1 < \mathrm{var}(\gamma) < 2$ then EOF1 = EOFA = EOFP = γ. The test for annularity fails but is determined to be weakly annular because [EOFA, EOFP] applies.

An example of case 3b from our simple three-component system is similar to case 1 where $\mathrm{var}(\gamma) > 2$, but instead of (α, γ) and (β, γ) holding, now [α, γ] and [β, γ] apply. Then EOF1 = γ, EOFA = α, and EOFP = β and EOFB = $\alpha + \beta$. If [EOF1, EOFB] is true, then the system is considered annular. The positive test for annularity in case 3b demonstrates that some aspect of annularity exists but is masked by the strong regional variabilities. If (EOF1, EOFB) is true then the system is considered nonannular.

Clearly as the correlations approach $r = 1.0$ for significance and $r = 0.0$ for insignificance, in cases 1, 2, 3a, and 3b, the more robust are the results of the test for annularity. On the other hand, as the correlations approach (from either direction) the critical value of significance at greater than 99% confidence (in the examples we present below $r = 0.36$) the test results become more ambiguous. This will become an issue in sections 4 and 5.

3. Technique for removing regional variability

The use of nonrotated EOFs can predispose the analysis to merging or blending of independent centers or patterns (Karl and Koscielny 1982). For example the dominant hemispheric EOF can be a grouping of two or more distinct and independent patterns of variability. In order to test for such a possibility, we compute regional EOFs and then remove each regional EOF or pattern separately from the hemispheric data and recompute a new set of EOFs.

The first step in our technique to remove regional variability is to divide the hemisphere into sectors. In the examples presented below, we chose the simplest sector division, two semihemispheres. However, this technique is applicable to any number of sectorial divisions. After the sectorial division, we proceed through an iterative process where we calculate the dominant mode of the height field for each sector and correlate the PC of each regional sector with each other. The final choice of the dividing line is the one found to minimize the correlation of the regional PCs. The dividing lines in each hemisphere used to produce regional variabilities are 90°E–90°W in the NH and 160°E–20°W in the SH (the two semihemispheres are referred to as ATL and PAC). We tested the sensitivity of the results to the choice of the dividing line; perturbing the dividing line over a range of 70° longitude did not substantially change the results. Then gridpointwise multiple linear regression is performed with the PC of all regional modes and the original field used to compute EOF1. So for example, in the case of NH December–January–February (DJF) sea level pressure (SLP), the PCs of the dominant modes of ATL and PAC are used as predictors in a regression with SLP. To produce residual data, with one (both) regional variability removed, we subtract the single (multiple) regressed regional PC(s) from the original data and retain the remainder. The final step is to compute EOFs on the residual data. Therefore the projection of the regional patterns on the residual data is uncorrelated with the time series of the regional patterns. In our example, we create three EOFs from the residual height field, one with PAC variability removed (EOFA), another with ATL variability removed (EOFP), and a third with both PAC and ATL variability removed (EOFB). Using this technique in section 4, we perform sample tests for annularity on observed atmospheric variables produced by the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data for 1949–2000 (Kalnay et al. 1996; Basist and Chelliah 1997).

TABLE 1. Correlation between dominant EOFs, dominant EOF for full data (EOF1), dominant EOF with Pacific regional variability removed (EOFA), dominant EOF with Atlantic regional variability removed (EOFP), EOF with zonal-mean removed (EOFZ), EOF with both Pacific and Atlantic regional variability removed (EOFB). First row is for simulated symmetric data (SIM SYM DAT), second row for simulated asymmetric data (SIM ASY DAT), third row for NH DJF SLP, fourth row for NH DJF Z50, fifth row for SH NOV Z850, and last row for SH NOV Z50. All values significant at greater than 99% confidence level are shown in bold type.

Height field	EOF1–EOFA	EOF1–EOFP	EOF1–EOFB	EOFA–EOFZ	EOFP–EOFZ
SIM SYM DAT	−0.25	−0.25	−0.25	**0.91**	**0.91**
SIM ASY DAT	**−0.40**	**0.92**	−0.06	**−0.51**	**−0.85**
NH DJF SLP	**0.88**	0.02	−0.20	0.23	**−0.92**
NH DJF Z50	0.30	0.13	0.06	**0.78**	**−0.92**
SH NOV Z850	**0.43**	0.25	−0.05	**−0.68**	**0.94**
SH NOV Z50	**−0.58**	**0.67**	**−0.58**	**−0.68**	**−0.77**

4. Testing hemispheric data for annularity

As a check on our definition for annularity we will first perform the test described above on simulated data, which we know a priori to be annular and nonannular. For simulated annular data we use NH DJF SLP, remove SLP from the North Pacific, and replace it instead with SLP from the North Atlantic. Therefore East and West Hemispheres are just mirror images of each other [simulated symmetric data (SIM SYM DAT)]. For simulated nonannular data we also start with NH DJF SLP, remove North Pacific SLP, and replace it instead with South Pacific June, July, and August SLP [simulated asymmetric data (SIM ASY DAT)]. We then correlate the first EOFs generated by the full data and data with regional variability removed; results are listed in Table 1. For 51-sample members, according to the Student's *t* test, a correlation of 0.36 is significantly different from 0.00 at greater than 99% confidence (bold type in Table 1).

For simulated symmetric data, the dominant mode of the full data is insignificantly correlated with both dominant modes after regional variability is removed [(EOF1, EOFA) and (EOF1, EOFP), see Table 1]. By our proposed test for annularity, the symmetric simulated data is confirmed as annular.

For simulated asymmetric data, the tests for significance are also symmetric; however, both dominant modes, after regional variability is removed, are significantly correlated with the dominant full mode ([EOF1, EOFA] and [EOF1, EOFP]; see Table 1). This is the case where our initial test fails, and we need to test further for annularity. The first mode with North Pacific variability removed and the first mode with North Atlantic variability removed, are not correlated ($r = 0.00$). Also the first mode with both regional variabilities removed is only weakly correlated with the dominant full mode ($r = -0.06$). The simulated asymmetric data, therefore, qualifies by definition, as nonannular [(EOFA, EOFP) and (EOF1, EOFB)]. Our test for annularity correctly identified the symmetric and asymmetric data fields as annular and nonannular, respectively, and we will now apply it to the real data.

Motivated by previous studies to investigate annularity (Thompson and Wallace 1998; Deser 2000; Ambaum et al. 2001), we will test the following observed fields for their inherent annularity: NH DJF SLP; NH DJF 50-hPa geopotential heights (Z50); SH November (NOV) 850-hPa geopotential heights (Z850); and SH NOV 50-hPa geopotential heights for the period 1949–2000. The months are chosen to represent the period when the troposphere and the stratosphere are actively coupled in their respective hemisphere. In Fig. 2a we present the first EOF for NH SLP, in Fig. 2b the first EOF for NH SLP after North Pacific variability has been removed, and in Fig. 2c the first EOF for NH SLP after North Atlantic variability has been removed. Figure 2a should be recognizable as the AO (Thompson and Wallace 1998), Fig. 2b as the NAO, and Fig. 2c as the PNA pattern (Barnston and Livezey 1987). Similar analysis is computed for NH DJF Z50 (Fig. 3), SH NOV Z850 (Fig. 4), and SH NOV Z50 (Fig. 5). Note that our technique for removing regional variability reproduced similar results to using rotated EOFs. Comparison tests of results utilizing our methodology with those from rotation were found to be robust.

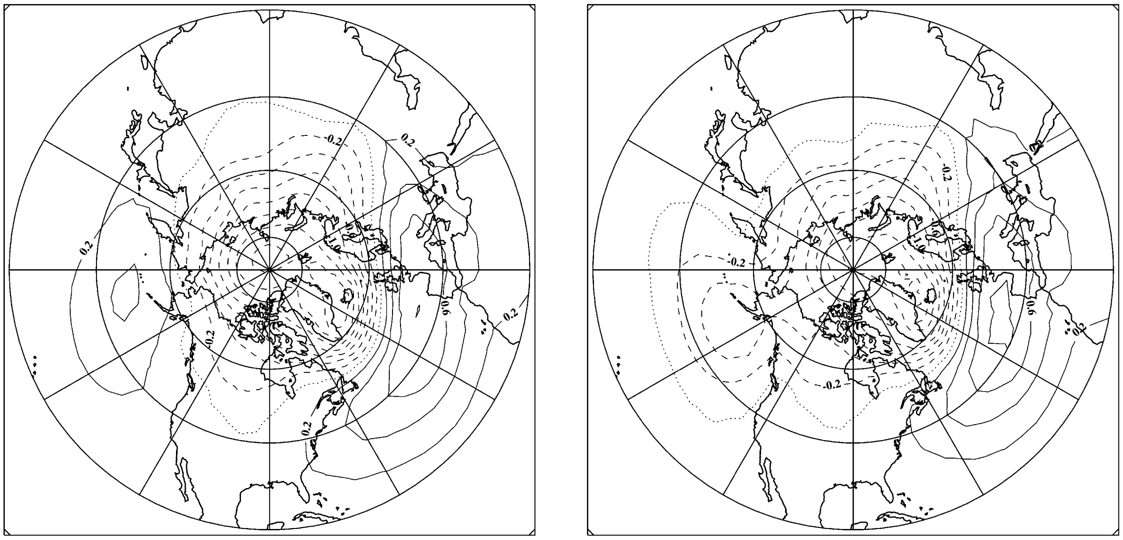
Listed in Table 1 are the correlation results for the first full mode for NH DJF SLP or the AO with the two modes when regional variability is removed (the NAO and the PNA). As seen from Table 1, NH DJF SLP presents a strong case 2, in our test for annularity. The correlation of the first full mode and the first mode after North Pacific variability is removed ([EOF1, EOFA]) is close to 0.9, while the first mode after North Atlantic variability is removed [(EOF1, EOFP)] is close to 0. This is about as large an asymmetric response possible and therefore must be considered, by our test for annularity, as nonannular. Also given the large spread in the correlations, the result is robust. The hemispheric-scale variability is almost completely driven by regional variability in the North Atlantic and is independent of the North Pacific regional variability.

Next we present the correlations for the first full mode for NH DJF Z50 and the two modes when regional variability is removed. As seen from Table 1 the results are symmetric with both correlations less than the 99% confidence level [(EOF1, EOFA) and (EOF1, EOFP)]. We would argue that in contrast to SLP, therefore, the regional variability in NH DJF Z50 is dominated by or associated with the hemispheric-scale variability. Based on our test for annularity, NH DJF Z50 is to be considered annular.

We now switch hemispheres and present correlations for the first full mode for SH NOV Z850 and the two modes when regional variability is removed. The response is asymmetric ([EOF1, EOFA] and (EOF1, EOFP)) but much less so than for NH SLP (see Table 1). The correlation between the first full mode and the first mode after South Pacific variability is removed is greater than the 99% confidence level. However as discussed in section 2, when a correlation approaches the significant level, results may become ambiguous. Further contributing to the ambiguity, the first mode with South Pacific variability removed and the first mode South Atlantic variability removed are strongly correlated ($r = -0.74$). Still based on our definition, SH NOV Z850 should be considered nonannular (though the probability of the test results being correct are less so than test results for NH DJF SLP). We argue that for SH NOV Z850, the hemispheric-scale variability is associated with two strong regional variabilities (rather than just one as in the case for NH DJF SLP), which are also strongly related to each other and can be characterized as annular. Yet despite this, because the Atlantic sector variability dominates, and no underlying coherent hemispheric-scale variability can be determined, therefore by our definition, SH NOV Z850 is defined as nonannular.

Finally we present correlations for the dominant full mode for SH NOV Z50 and the two dominant modes when regional variability is removed. The significance results are symmetric with both dominant modes, when regional variability is removed, significantly correlated with the dominant full mode ([EOF1, EOFA] and [EOF1, EOFP]; see Table 1). This is the case where our initial test fails, and we need to test further for annularity. The first mode with South Pacific variability removed and the first mode with South Atlantic variability removed are weakly correlated [(EOFA, EOFP); $r = 0.05$]. However, the first mode with both regional variabilities removed is significantly correlated with the dominant full mode ([EOF1, EOFB]; $r = -0.58$), thereby qualifying as annular. We would argue that, even though for SH NOV Z50, the hemispheric-scale variability is driven by two strong regional variabilities, which are not significantly correlated, because a significant hemispheric-scale variability remains in the residual (the raw field after removal of all the regional

a) EOF1 MSLP NH (18.8%) **b) EOF1 MSLP NH, PAC-removed (18.9%)**



c) EOF1 MSLP NH, ATL-removed (12.6%) **d) EOF1 MSLP NH, ZA-removed (13.6%)**

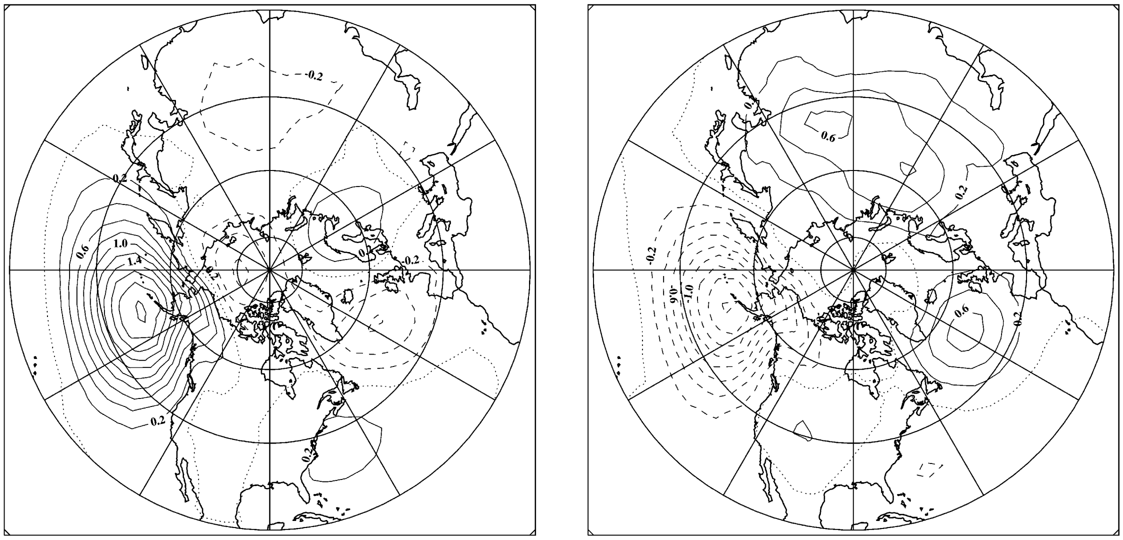


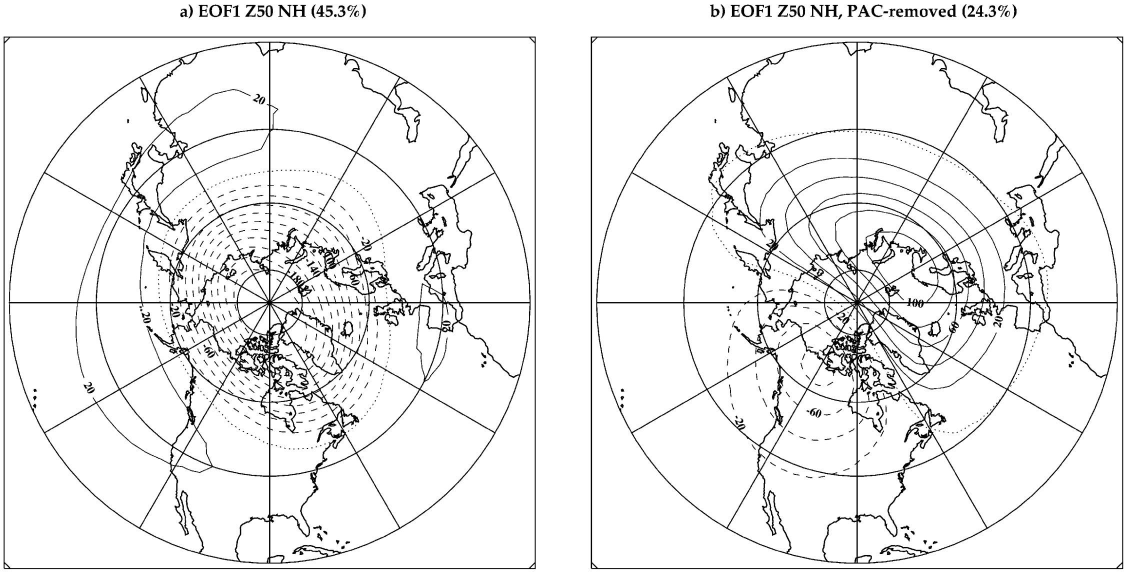
FIG. 2. First EOF for NH DJF SLP (a) full data, (b) with North Pacific variability removed, (c) with North Atlantic variability removed, and (d) with zonal-mean removed. Shown in parentheses is explained variance.

variabilities), SH NOV Z50 can therefore be characterized as annular.

In conclusion all four categories of test cases were found in the six datasets tested for annularity. SIM SYM DAT and NH DJF Z50 were found to be case 1 or annular, NH DJF SLP and SH NOV Z850 were found to be case 2 or nonannular, SH NOV Z50 was found to be case 3b or annular, and finally SIM ASY DAT was found to be nonannular for cases 3a and 3b.

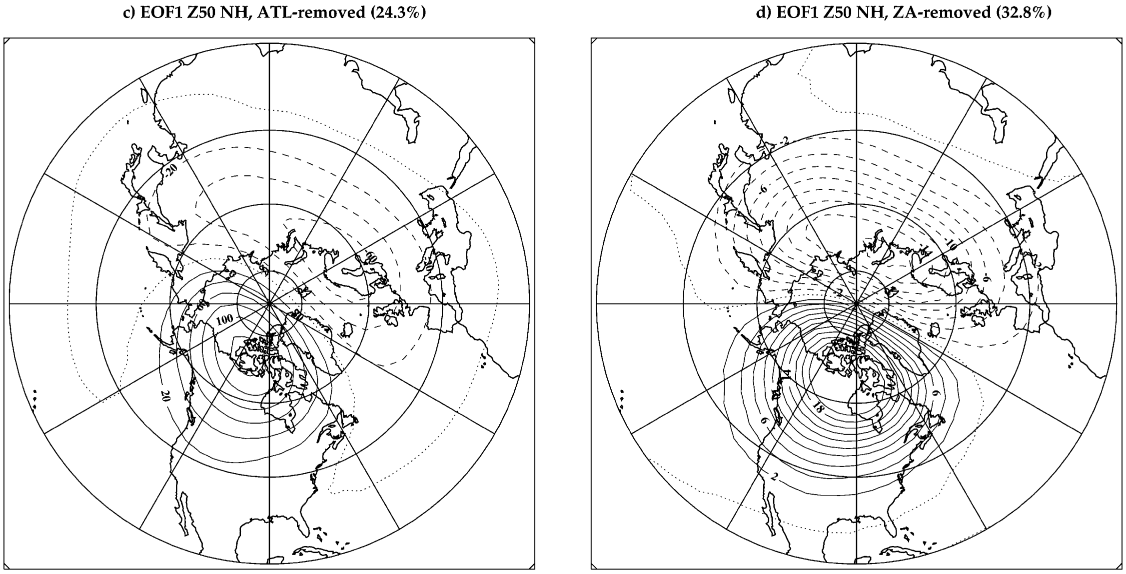
5. EOF analysis with zonal average removed

As a further check of the definition of annularity presented, we decided to also compute EOFs on the pressure/height fields presented above after the zonal mean was removed from all grid points (EOFZ). In the strictest sense, the zonal average, computed at each latitude, is equivalent to the hemispheric-scale annular mode. We will then correlate the PC of the dominant mode, after the zonal mean is removed, with the PC of the dominant modes after regional variabilities are removed. We posit that a lack of significant correlation between the dominant mode, with the zonal mean removed and both dominant modes, after regional variabilities have been removed, that is, (EOFA, EOFZ) and (EOFP, EOFZ), is characteristic of annularity. In this situation, the hemispheric-scale variability dominates all regional variability. When the dominant mode, with the zonal mean



a) EOF1 Z50 NH (45.3%)

b) EOF1 Z50 NH, PAC-removed (24.3%)



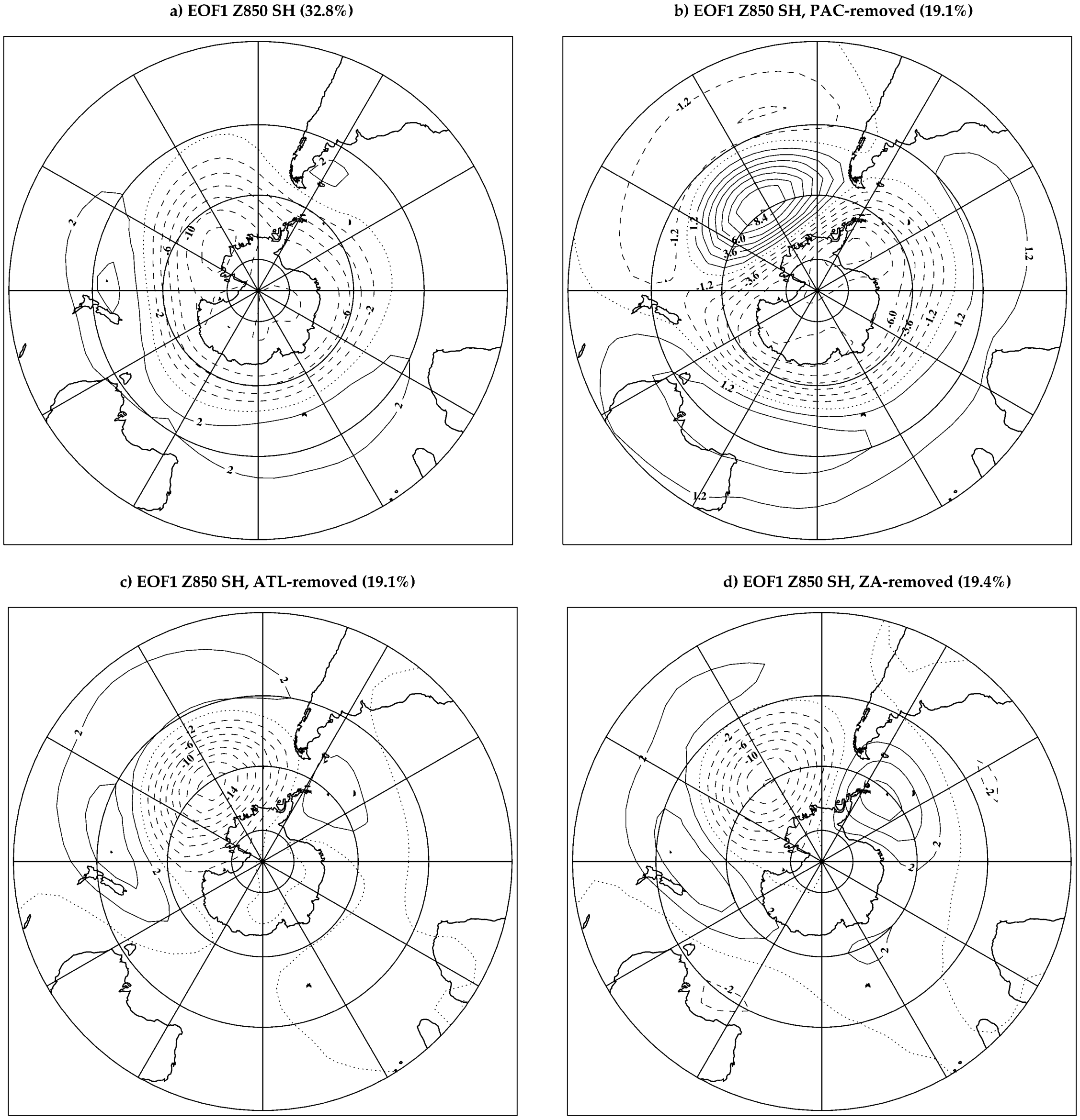
c) EOF1 Z50 NH, ATL-removed (24.3%)

d) EOF1 Z50 NH, ZA-removed (32.8%)

FIG. 3. Same as Fig. 2 except for NH DJF 50-hPa geopotential heights.

removed, is significantly correlated with one of the dominant modes, with regional variability removed, and insignificantly correlated with the other, that is, [EOFZ, EOFA] and (EOFZ, EOFP) or (EOFZ, EOFA) and [EOFZ, EOFP], it is characteristic of nonannularity. Here the opposite of the previous case exists; one, but not both regional variabilities are linked with the hemispheric-scale variability. The third possibility is that the dominant mode, with the zonal-mean removed, is significantly correlated with both dominant modes, after regional variability has been removed ([EOFZ, EOFA] and [EOFZ, EOFP]). In this case if the two dominant modes, after regional variability has been removed, are significantly correlated with each other ([EOFA, EOFP]), then this mode of variability may also be considered annular (both regional variabilities are linked with the hemispheric-scale variability and are related or codependent); while a lack of significant correlation with each other [(EOFA, EOFP)], indicates nonannularity (both regional variabilities are associated with the hemispheric-scale variability and are not related or are independent).

Beginning with the simulated data we see that in both cases the dominant mode, with the zonal mean removed, is significantly correlated with both dominant modes with regional variability removed ([EOFZ, EOFA] and [EOFZ, EOFP]). However, for simulated symmetric data the two dominant modes, with regional variabilities removed, are significantly correlated ([EOFA, EOFP]; $r = 1.0$) and is therefore annular; while for simulated


a) EOF1 Z850 SH (32.8%)

b) EOF1 Z850 SH, PAC-removed (19.1%)

c) EOF1 Z850 SH, ATL-removed (19.1%)

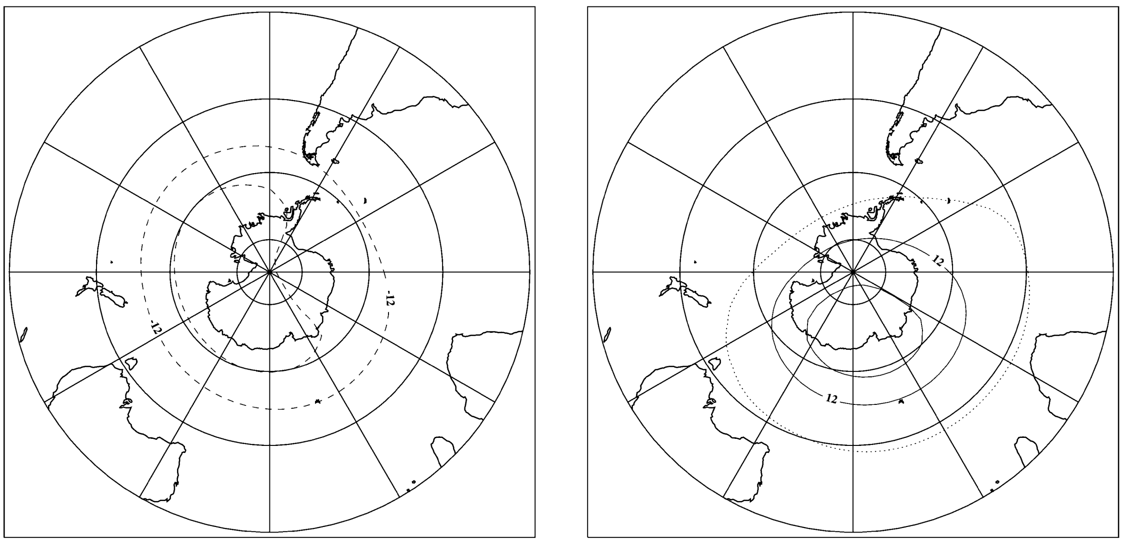
d) EOF1 Z850 SH, ZA-removed (19.4%)

FIG. 4. Same as Fig. 2 except for SH NOV 850-hPa geopotential heights.

asymmetric data the two dominant modes, with regional variabilities removed, are insignificantly correlated [(EOFA, EOFP); $r = 0.0$)] and is therefore nonannular.

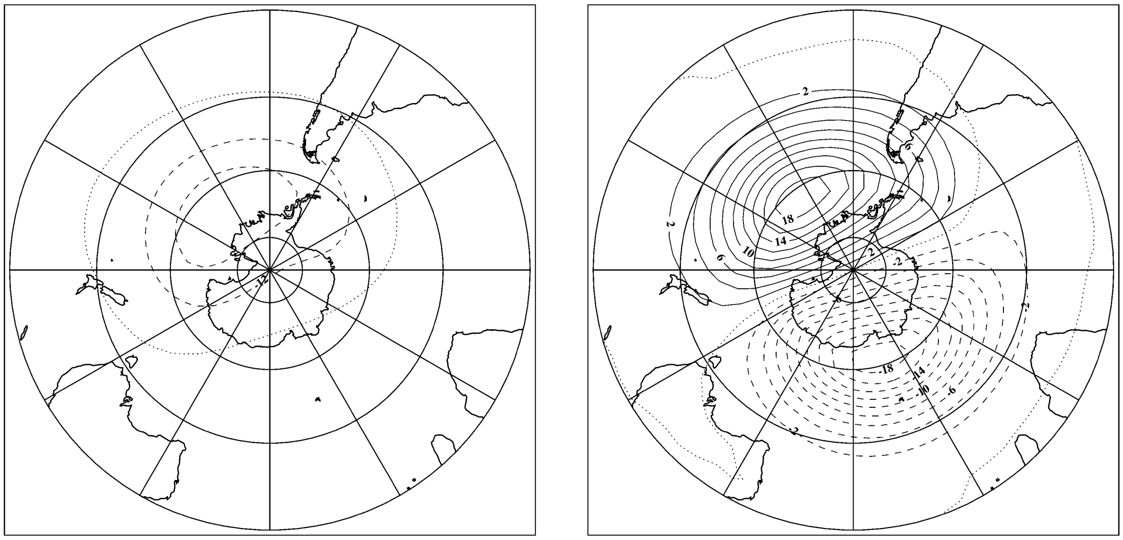
For observed data we first compute the dominant EOF, with the zonal average removed from every grid point for NH DJF SLP, which is shown in Fig. 2d. The EOF strikingly resembles the dominant EOF after North Atlantic variability is removed (or the PNA). Therefore it is not surprising that the correlation between the time series of the dominant mode, with the zonal mean removed, and the dominant mode, with North Atlantic variability removed, is significant ([EOFZ, EOFP]); while the correlation between the time series of the dominant mode, with the zonal mean removed, and the dominant mode, with North Pacific variability removed, is insignificant [(EOFZ, EOFA); see Table 1]. The asymmetric significance of the correlations are further demonstration that the hemispheric-scale variability is mostly associated with the regional variability of the North Atlantic and is mostly independent of the variability of the North Pacific. Again, given the large spread in the correlations, the result appears quite robust.

Next we compute the dominant EOF, with the zonal average removed, for the other three height fields, NH DJF Z50 (see Fig. 3d), SH NOV Z850 (see Fig. 4d), and SH NOV Z50 (see Fig. 5d). Correlations between the dominant EOF, with the zonal mean removed and the two dominant EOFs with regional variability removed are listed in Table 1. The results for all three height fields are similar: correlations between the time



a) EOF1 Z50 SH (43.5%)

b) EOF1 Z50 SH, PAC-removed (26.2%)



c) EOF1 Z50 SH, ATL-removed (25.8%)

d) EOF1 Z50 SH, ZA-removed (30.0%)

FIG. 5. Same as Fig. 2 except for SH NOV 50-hPa geopotential heights.

series of the dominant mode, with the zonal mean removed, and both the dominant modes, with regional variability removed, are significant ([EOFZ, EOFA] and [EOFZ, EOFP]). Therefore we need to check the correlation between the two dominant modes, after regional variability has been removed, for all three. In the case of NH DJF Z50 they are significantly correlated ([EOFA, EOFP]; $r = -0.90$); for SH NOV Z850 they are also significantly correlated ([EOFA, EOFP]; $r = -0.74$); and for SH NOV Z50 they are insignificantly correlated [(EOFA, EOFP); $r = 0.05$]. Therefore, NH DJFZ50 and SH NOV Z850 demonstrate annularity. However the result for NH DJF Z50 is a more robust result given the larger correlation. For the last field, SH NOV Z50, we have not been able to demonstrate annularity as produced in the test. As it turns out, the check for annularity is deficient in that no good analogous situation exists for case 3b of the test for annularity ([EOF1, EOFB]).

The important conclusion is that this second, independent check for annularity confirms the following two results: NH DJF SLP demonstrates nonannular characteristics, and NH DJF Z50 demonstrates annular characteristics. On the other hand, the more ambiguous results obtained for both SH NOV height fields after the test for annularity (section 4) are no less ambiguous after the check performed in this section. Somewhat conflicting results have been shown for SH NOV Z850 in that it tested negative for annularity but results from the check demonstrated annular characteristics. Therefore, the best way to consider SH NOV Z850 may be as neutral with respect to annularity. Finally the check has been deemed as inadequate to test for the type or case of annularity found for SH NOV Z50 (a coherent hemispheric-scale variability can be detected only after the removal of all regional variabilities).

6. Conclusions

We have proposed a new definition and test for annularity. We believe the important advantages of the test are its increased objectivity and that it allows for easier comparison between modes of different time and spatial scales. Here we tested four different pressure/height fields for the reanalysis period 1949–2000. Based on the test results presented above we have shown that first mode of variability for NH DJF Z50 can be considered annular, while the first mode of variability for NH DJF SLP is nonannular. An independent check confirmed these results. Tests of annularity for the first modes of variability for SH NOV Z850 and SH NOV Z50 were less definitive. By our definition, the first mode of variability for SH NOV Z850 was shown to be nonannular. However a further check found the opposite. Therefore it may be best to consider the SH NOV Z850 height field as possessing annular and nonannular features and, hence, being neutral with respect to annularity. Finally the first mode of variability for SH NOV Z50 was defined as annular and the check was considered inappropriate for confirming this result.

Furthermore, based on our test for annularity the four pressure/height fields can be ranked according to degree of annularity with the NH DJF Z50 being the most strongly annular and the NH DJF SLP being the most strongly nonannular. Finally an extension of the results presented may be applied to characterizing the nature of stratosphere–troposphere coupling in each hemisphere. The degree of annularity in the lower-tropospheric and midstratospheric height fields in the SH is close, while in the NH it is far apart. Therefore the proposed forcing of the lower troposphere by annular modes existent in the stratosphere appears more straightforward in the SH than in the NH.

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