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Annular modes in global daily surface pressure

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Abstract. Annular modes are patterns characterized by synchronous fluctuations in surface pressure of one sign over the polar caps and the opposite sign at lower latitudes. The Southern Annular Mode (SAM) and Northern Annular Mode (NAM, also called the Arctic Oscillation) patterns are the leading empirical orthogonal functions (EOFs) of slowly-varying, hemispheric, cold-season, sea-level pressure anomalies (deviations from climatology). Daily indices of the SAM and NAM are a measure of the similarity between surface pressure anomaly patterns and the annular modes. Here it is shown that the first two EOF time series of daily, global, year-round, zonally-averaged surface pressure are nearly identical to the SAM and NAM indices. Together they account for more than 57% of the daily variance of zonally-averaged surface pressure. The SAM and NAM patterns extend through the tropics, well into the opposite hemispheres. Fluctuations of the SAM and NAM indices are accompanied by interhemispheric transfer of mass.

Introduction

The leading pattern of low-frequency variability of the northern winter circulation was first identified by *Kutzbach* [1970], and was called the Arctic Oscillation by *Thompson and Wallace* [1998] and the Northern Annular Mode (NAM) by *Limpasuvan and Hartmann* [1999]. The term "mode" is taken to mean a dominant pattern, in this case the leading empirical orthogonal function (EOF). As such, annular modes are not normal modes of a physical system; rather, they are the patterns that account for the greatest fraction of variance in a field. "Annular" is a description of a pattern that, despite zonal asymmetries, is largely ring-like. As shown in Figure 1c, the NAM is characterized by pressure anomalies of one sign over the polar cap, and the opposite sign equatorward of ~55°N, with centers of action near Greenland and the Azores, similar to the North Atlantic Oscillation (NAO). The Southern Hemisphere exhibits a similar pattern [*Rogers and van Loon*, 1982; *Gong and Wang*, 1999; *Thompson and Wallace*, 2000] which is now called the Southern Annular Mode (SAM, Figure 1a).

Thompson and Wallace [2000] argued that the similarity between the SAM and the NAM, despite the striking contrast in land/sea distribution and orography, is evidence that these two modes are the result of the same physical processes. Simple atmospheric models (e.g., *Williams*, [1979]) suggest that the structure of the annular modes is a fundamental consequence of the Earth's size, rotation rate, and stable stratification. *Wallace* [2000] has further argued that the NAO is a regional expression of the NAM. The concept of annular modes is not restricted to surface data. Annular modes are the leading EOFs of cold-season geopotential at every pressure level from the surface to the lower mesosphere [*Baldwin and Dunkerton*, 2001].

This paper investigates the robustness of the annular mode concept by examining the leading EOFs and EOF time series of daily, global, year-round, zonally-averaged surface pressure anomalies ($\overline{P_s}$) during 1958–1999. By using $\overline{P_s}$ instead of sea-level pressure or 1000-hPa geopotential, any problems with fictitious atmospheric mass below the Earth's surface are avoided [*Christy et al.*, 1989]. This approach extends the usual annular mode calculation in four ways: 1) daily unfiltered data are used instead of monthly means or smoothed data; 2) data from the entire globe are used instead of a single hemisphere, 3) year-round data are used instead of winter only, and 4) since the data are zonally averaged, the EOF patterns are, by definition, annular.

The SAM and NAM patterns in Figure 1a and 1c are each defined as the first EOF of slowly-varying, cold-season 1000-hPa geopotential anomalies poleward of 20°. Anomalies are defined as deviations from the seasonal cycle (the 90-day low pas filtered average for each longitude, latitude, and day of year). These patterns are calculated with 1958–1999 NCEP data [*Kalnay et al.*, 1996]. In the Northern Hemisphere November–April is used to define the winter season, while August–December (late winter and spring) is used in the Southern Hemisphere. These periods were chosen to match the season of dynamical coupling between the troposphere and stratosphere. The results would be nearly identical if midwinter had been used in the Southern Hemisphere. The data are weighted by the square root of the cosine of latitude, which is equivalent to using an equal-area grid. The first EOF defines the annular mode for each hemisphere. The spatial patterns (Figures 1a and 1c) are shown by regressing (at each grid point) the time series of 1000-hPa geopotential anomalies that were used in the EOF calculation onto the first EOF time series. These results are not sensitive to the details of filtering (e.g., monthly means or 90-day low pass) or spatial domain (e.g., poleward of the equator or 20°).

The EOF time series are defined only for the months used in the EOF calculation; the SAM and NAM indices are defined for all days in the data record by projecting daily, year-round geopotential anomaly patterns onto the SAM and NAM spatial patterns. For example, on each day the NAM index is defined as the projection of the geopotential anomaly pattern onto the NAM pattern in Figure 1c. The calculation of the SAM and the NAM are based on data for separate hemispheres, but the correlation between the SAM and NAM indices is 0.02, (not statistically different from zero).

Annular modes in surface pressure

The calculation of the EOFs of $\overline{P_s}$ is the same as that for the SAM or the NAM, except that daily, global, zonally-averaged data are used, so the EOF time series have daily reso-

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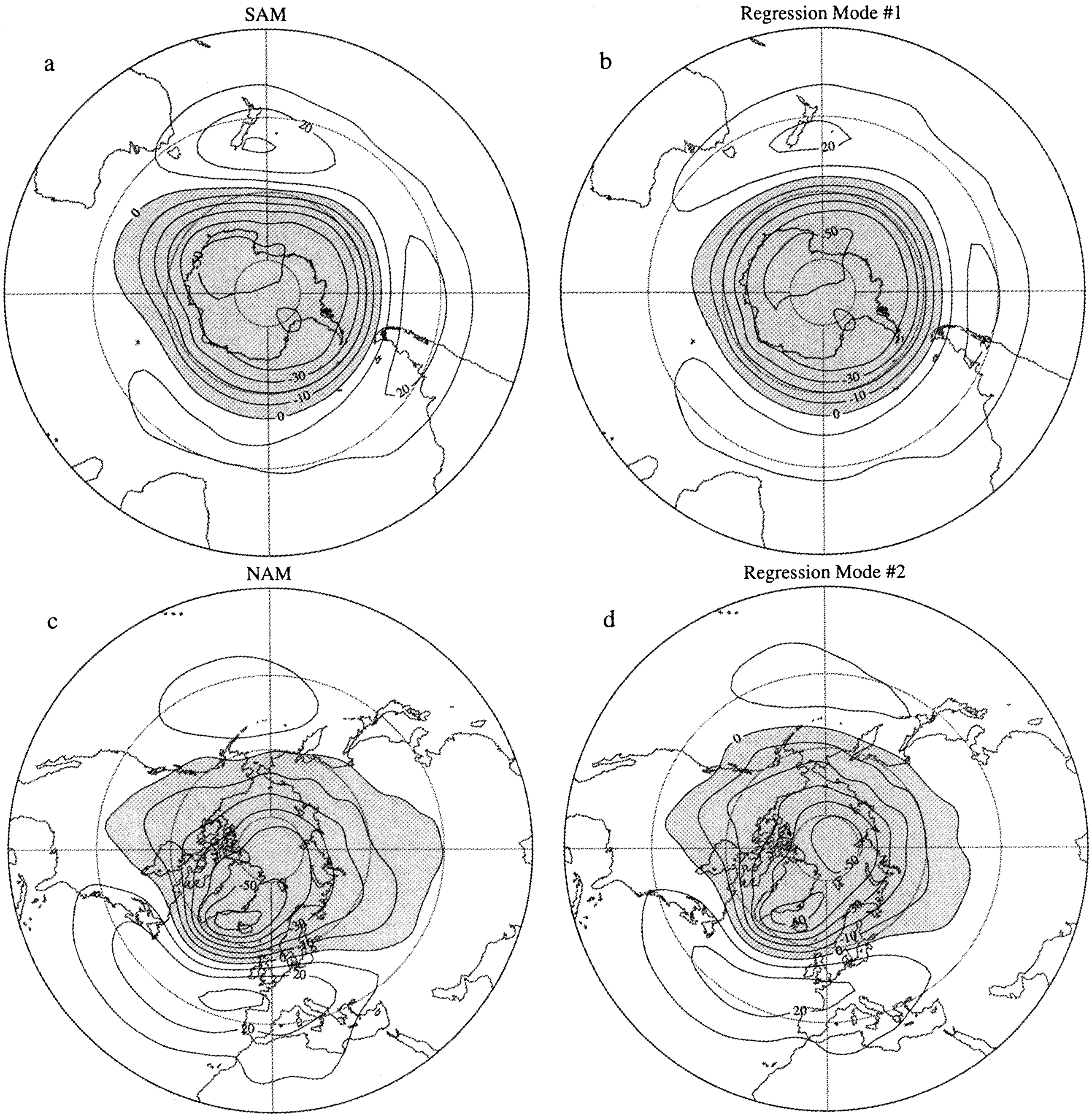

Figure 1. Annular mode patterns in 1000-hPa geopotential, 1958–1999. The top panels are for the Southern Hemisphere, and the bottom panels are for the Northern Hemisphere. (a) SAM pattern; August–December 90-day low-pas filtered data poleward of 20°S regressed onto its leading EOF time series; (b) regression of daily unfiltered 1000-hPa geopotential anomalies onto the first EOF time series of global $\overline{P}_s$; (c) as in (a) except NAM, and (d) as in (b), except second EOF time series, for the Northern Hemisphere.

lution, similar to the SAM and NAM indices. By definition, the correlation between any two EOF time series is zero.

The first two $\overline{P}_s$ EOFs (hereafter, mode #1 and mode #2), which account for 34.1% and 23.4% of the variance, are shown in Figure 2 as correlations between the EOF time series and daily $\overline{P}_s$. The value at each latitude is the correlation coefficient between the EOF time series and $\overline{P}_s$ at that latitude. Each mode has high values poleward of ~70°, a change of sign near 55°, and extends with correlations of the opposite sign into midlatitudes of the opposite hemisphere. *Guan and Yamagata* [2001] reported essentially similar EOFs using monthy-mean (rather than daily) $\overline{P}_s$ data. Modes #1 and #2 represent latitudinal movement of atmospheric mass between the regions poleward and equatorward of ~55°, extending into the opposite hemisphere.

Modes #1 and #2 correspond closely to the SAM and NAM. The meridional correlation between the SAM and mode #1 curve in Figure 2 is 0.997, while the meridional correlation between the NAM and mode #2 is 0.991. The temporal correlation between the mode #1 EOF time series and the SAM index is 0.95 and that between the mode #2 EOF time series and the NAM index is 0.92. The close correspondence between

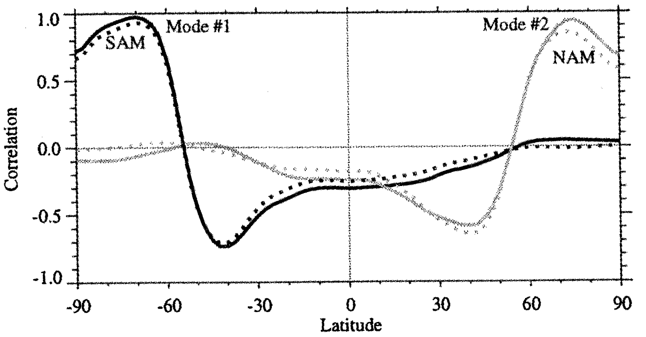

Figure 2. The first (solid black) and second (solid gray) EOFs of $\overline{P}_s$, shown as correlations between the EOF time series and daily $\overline{P}_s$ anomalies for 1958–1999. The SAM (dashed black) and NAM (dashed gray) are shown as correlations between the SAM and NAM indices and daily $\overline{P}_s$.

the leading EOFs of $\overline{P}_s$ and 1000-hPa geopotential suggests that both methodologies identify the same phenomenon.

The similarity between the SAM and the NAM curves in Figure 2 is also remarkable. The meridional correlation between the SAM and the (meridionally-reversed) NAM is 0.992, which bolsters the arguments of *Thompson and Wallace* [2000] that the same physical process acts in each hemisphere to produce the SAM and the NAM.

The spatial patterns in 1000-hPa geopotential for modes #1 and #2 are shown in Figures 1b and 1d. The patterns were calculated by regressing daily, year-round, unfiltered 1000-hPa geopotential anomalies onto the mode #1 and mode #2 EOF time series. Figures 1b and 1d are remarkably similar to the SAM and NAM, respectively, but they are slightly more zonally symmetric (especially Figure 1b). They illustrate that patterns almost identical to the SAM and NAM can be obtained with global, unfiltered, zonally-averaged data, without restricting the analysis to the cold season.

Interhemispheric transfer of mass

The daily resolution of the $\overline{P}_s$ data can be exploited to determine if the $\overline{P}_s$ profiles in Figure 2 (which extend into the opposite hemispheres) occur simultaneously or if there is a time lag as a function of latitude. Figure 3 illustrates lag correlations between the EOF time series and lagged $\overline{P}_s$ data. A positive lag indicates that EOF time series leads the $\overline{P}_s$ data. At most latitudes the highest correlations are seen at zero lag for both mode 1 and mode 2. This indicates that the movement of atmospheric mass is nearly synchronous. However, there is a hint in mode #1 (Figure 3a) that the tropical and Northern Hemisphere part of the $\overline{P}_s$ signature lags by one or two days. Although the profiles for mode #1 and mode #2 are very similar at lag zero, the time scale for mode #1 appears to be somewhat longer, especially at high latitudes, so that the correlations at lags ±10 days are higher for mode #1.

Guan and Yamagata [2001] found that the third EOF of monthly-mean $\overline{P}_s$ was an "interhemispheric oscillation" and was the dominant mode of mass transfer between the hemispheres. However, since the annular mode patterns in Figure 2 extend into the opposite hemispheres, interhemispheric mass transfer must also occur with fluctuations in the annular modes. To investigate interhemispheric mass transfer, the $\overline{P}_s$ data set must conserve mass in the sense that fluctuations

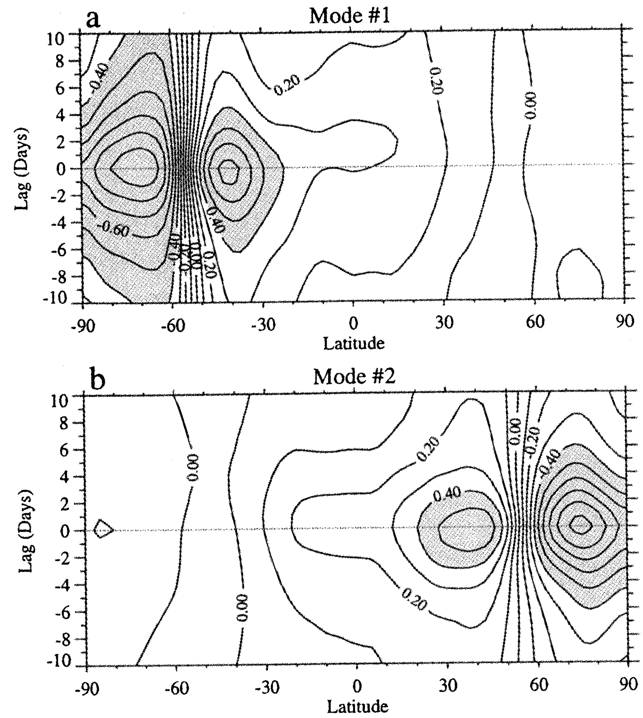

Figure 3. (a) Lag correlations between the Mode #1 EOF time series and $\overline{P}_s$. Positive lag indicates that the EOF time series leads $\overline{P}_s$. Correlations less than –0.40 and greater than 0.40 are shaded. (b) as in (a), but for Mode #2.

in the mass of one hemisphere should be matched by opposite fluctuations in the other hemisphere. Mass conservation in the NCEP data is not expected to be perfect because there are annual and semiannual cycles in water vapor. The total mass of the atmosphere includes an annual cycle in water vapor with an amplitude of ~0.37 hPa, reflecting the greater annual cycle in temperature (and moisture) in the Northern Hemisphere [*Trenberth and Guillemot*, 1994]. The Northern and Southern Hemisphere mass anomaly time series used here are not explicitly corrected for the annual cycle in water vapor, but the annual cycle in hemispheric mass is subtracted from each time series. With sparse observations in the Southern Hemi-

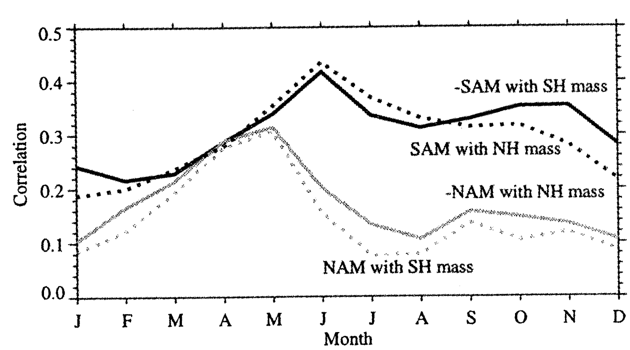

Figure 4. Correlation between the SAM index and Southern Hemisphere mass anomalies (solid black) and Northern Hemisphere mass anomalies (dashed black). Each monthly value represents the correlation for a three-month period (e.g., the February value was obtained using January–March data). The gray curves are for the NAM index.

sphere, especially during the early years, there are data quality problems in the NCEP data. For the analysis of interhemispheric transfer of mass, a measure of conservation of mass in the NCEP data is the correlation between the mass of the two hemispheres on a daily basis. The daily correlation between Northern and Southern Hemisphere mass anomalies averaged –0.56 prior to 1965, -0.81 during 1965–1983, and rose to an average value of -0.92 for 1984–1999. The following calculations are therefore restricted to 1984–1999, and are performed separately for the Southern and Northern Hemispheres.

Although atmospheric angular momentum changes are, in general, dominated by changes in relative angular momentum [*Abarca del Rio et al.*, 2000], angular momentum anomalies associated with the SAM and NAM are dominated by Ω (solid body) angular momentum [*von Storch*, 2000], which is expressed as a latitudinal integral of zonally-averaged surface pressure. Fluctuations in the SAM and NAM therefore have an effect on Ω angular momentum (not shown).

Cancellation between mass fluctuations related to the SAM and those related to the NAM are negligible, since the correlation between the SAM and NAM indices is 0.02. Figure 4 shows the correlation, as a function of month, between the SAM and NAM indices and both the Southern and Northern Hemisphere mass anomalies. Each value represents the average of a 3-month period (e.g., the February point includes all days during January, February, and March). The average correlation for the SAM curves is 0.30, with slightly higher values during the cold season, when the SAM index is larger. The corresponding curves for the NAM index have an average value of 0.16. Peak values occur during spring. Correlations using 1965–1999 data have the same features and magnitudes, but the Northern and Southern Hemisphere curves are more separated (not shown).

Discussion

The two dominant modes of variability of global, daily, zonally-averaged surface pressure represent the synchronous movement of atmospheric mass between the polar caps and regions equatorward of 55°, and are essentially similar to the SAM and the NAM; this similarity suggests that longitudinal asymmetries are not fundamental to the annular modes. The annular modes are not dependent on restricting the analysis to one hemisphere, the cold season, or to low-frequency variability. The use of global data demonstrates that the annular modes are not artifacts of the horizontal domain of the analysis. The annular modes extend across the Equator, well into the opposite hemisphere. Fluctuations in the annular modes imply a circulation that moves mass between the hemispheres. The striking symmetry between the northern and southern annular modes is evidence that the same physical process produces both modes.

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