

Relationship between the Polar-Night Jet Oscillation and the Annular Mode

Yuhji Kuroda

Meteorological Research Institute, Tsukuba, Japan

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[1] The relationship between the Polar-night Jet Oscillation (PJO) and the Annular Mode (AM) is examined based on a correlation analysis of winter in both the Northern Hemisphere (NH) and Southern Hemisphere (SH). The PJO becomes a nearly zonally symmetric structure from the troposphere to the upper stratosphere when a pattern similar to the AM appears at the troposphere. If the signal of the PJO is removed, the signal of the AM exists only in the troposphere, and the persistency of the signal is largely reduced in the stratosphere. This suggests that the AM is essentially a tropospheric process that tends to strongly interact with the PJO in the active season. *INDEX TERMS:* 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions; 1620 Global Change: Climate dynamics (3309)

1. Introduction

[2] Dynamical coupling between the troposphere and stratosphere is very important for the formation of winter climate [e.g., Baldwin *et al.*, 1994; Perlwitz and Graf, 1995]. Among such process, the role of the annular mode (AM) or the Arctic Oscillation (AO) in the NH [Thompson and Wallace, 1998, 2000] on climate has been recently noted. Baldwin and Dunkerton [1999] reported that the AO signal tends to appear at the upper stratosphere first and propagate downward in the NH winter.

[3] In contrast, Kodera and his colleagues [e.g., Kodera, 1995; Kodera *et al.*, 2000; Kuroda and Kodera, 1998, 1999, 2001 (KK01)] examined different type of coupled variability called the Polar-night Jet Oscillation (PJO). This variability is characterized by slow poleward and downward movements of the anomalous zonal-mean zonal wind, especially in the stratosphere. Interestingly, a signal similar to the AM was found to appear in the troposphere at some stage of the PJO in both hemispheres [Kuroda and Kodera, 1999; KK01]. These studies indicate a close relationship between the PJO and AM in both hemispheres. However, the interrelationships between these variabilities are not well understood. Therefore, in the present paper, we examine how they interrelate with each other in both hemispheres, as an extension of the previous study (KK01).

2. Data and Method of Analysis

[4] The stratosphere and troposphere data used in the present study are the same as in KK01 and cover 20 years, from January 1979 to December 1998. The stratosphere data were analyzed by U.S. National Centers for Environmental Prediction (NCEP)/Climate Prediction Center (CPC) (formerly NMC/CAC). The stratospheric winds were calculated from a satellite-derived geopotential height analyzed by CPC using the non-linear balanced wind relation [Randel, 1992]. Substantial data missing from April

1996 to April 1997 was compensated for by the Met Office, UK geopotential height data [Bailey *et al.*, 1993]. The operational data for the troposphere at 100 hPa and below are from reanalysis data of the NCEP/National Center for Atmospheric Research (NCAR) [Kalnay *et al.*, 1996].

[5] All missing data, except for the above-mentioned missing period, were linearly interpolated in time, and the monthly mean data was then calculated as 30-day mean data, with the exception of July, which is 35-day mean data. The Eliassen-Palm (E-P) flux was calculated from five-day mean data and the monthly average was taken thereafter.

[6] The AMs in this paper are defined by the leading Empirical orthogonal function (EOF) of the month-to-month variability of the 850 hPa levels poleward of 20-degrees latitude in both hemispheres in the present dataset. The AM indices are defined by the time coefficients of the AMs. In contrast, the PJOs were extracted by an extended singular value decomposition (E-SVD) analysis of the zonal-mean zonal wind and the vertical component of the E-P flux, as in KK01. The extended vectors to calculate the SVD are constructed by combining data of five consecutive months for respective cold seasons. Two sets of extended vectors in the cold season from November to April in the NH (June to November for the SH) were used for the calculation. All variables were normalized by their climatological variance prior to the SVD analysis to cover wide range of pressure levels. The PJO indices are defined from the time coefficients of the zonal-mean zonal wind components of the leading SVDs.

[7] For an intercomparison, regression fields of the AM and the PJO in both hemispheres were calculated and compared for each stage of the PJO such as December or January (D/J). The time series of the AM index for the period D/J, for example, is defined by (D1, J1, D2, J2,...) where D1 is the AM index for December of the first winter etc.

3. Results

3.1. Horizontal Structure of the PJO

[8] The squared covariance fraction of the leading SVD mode in the NH is 28% and is similar to the second mode (explaining 23%), reflecting the periodic nature of the NH-PJO [KK01]. In fact, the spatial patterns of the second mode are very similar to the one-month-delayed component of the leading mode. In the SH, on the other hand, the leading SVD mode (explaining 57%) dominates the second mode (explaining 10%). Poleward and downward movements of the anomalous zonal-mean zonal winds appear in both hemispheres. However, the speed of movement is faster and shows quasi-periodicity in the NH, whereas the speed is slow and the interannual variability is more dominant in the SH [KK01].

[9] Another notable characteristic of the PJO is the appearance of AMs in the troposphere at some periods (called annular stages) in both hemispheres [KK01]. These are D/J (leading mode) or J/F (second mode) for the NH, and O/N for the SH. Note that these periods approximately agree with the "active seasons" described by Thompson and Wallace [1998, 2000]. We will consider only the annular stage of D/J in the NH, because the overall features due to the second mode are very

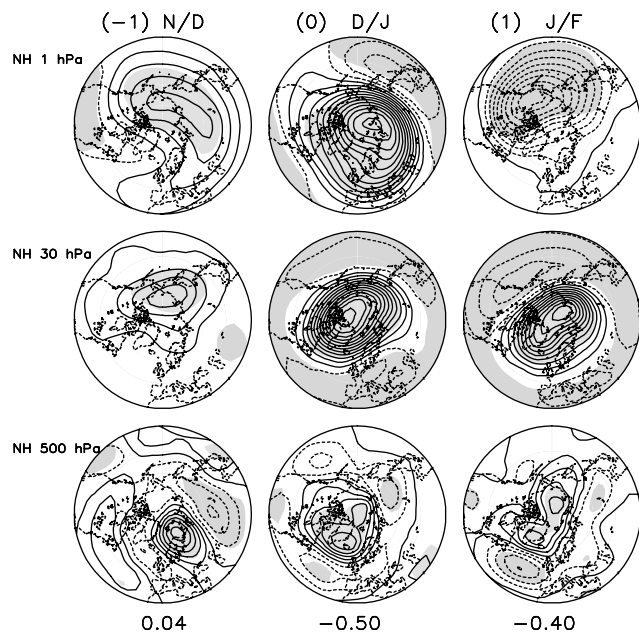


Figure 1. Regression maps of the geopotential heights in the NH around the annular stage (lag time -1 , 0 , 1 months, from left to right) due to the PJO index. Levels of 1 , 30 , and 500 hPa are shown from top to bottom. Contour intervals for levels of 1 , 30 , and 500 hPa are 50 , 30 , and 10 m, respectively, and the dashed lines indicate negative values. The zero contour line is plotted by a thin solid line. Shading denotes significant regions at the 95% level. Numbers below the panels represent the correlation coefficients of the AM index with the PJO index for the respective months.

similar to the leading ones. To illustrate the time evolution of the three-dimensional structure of the geopotential height around the annular stage, the anomalous geopotential heights at the 1 hPa, 30 hPa, and 500 hPa levels are shown by the regression of the PJO indices (Figures 1 and 2 for the NH and SH, respectively). The regions where the correlation coefficients exceed the 95% significance level ($0.32/0.31$ for NH/SH) are shaded. The numbers below the panels indicate the correlation coefficients between the AM and the PJO indices. The numbers above the panels indicate the lag in months from the annular stages (D/J and O/N for the NH and SH, respectively). Note that this definition of lag in months differs from that used in KK01.

[10] In the NH, a structure similar to the AM in the troposphere appears at lag 0 , and it deforms to the pattern similar to the North Atlantic Oscillation (NAO) at lag 1 . Anomalous wave activity flux is directed northwestward, and this corresponds to the anomalous E-P flux directed toward the weaker zonal wind [KK01]. The structure at the 30 hPa level at lag 0 is very similar to the AO obtained by Baldwin and Dunkerton [1999]; it is characterized by an anomalous large high at the north pole surrounded by a low belt in the mid-latitudes, whose two centers exist over Europe and the North Pacific. The high center shifts toward Europe and the low in the North Pacific enlarges, but that at Europe reduces at lag 1 . At 1 hPa, a weak high over Siberia at lag -1 shifts at the North Pole with enhancement at lag 0 . The high center is not so zonally symmetric as at 30 hPa and is shifted somewhat more toward Europe than that obtained by Baldwin and Dunkerton [2001]. The center of the low in the mid-latitudes locates over Japan at lag 0 shifts to the North Pole with enlargement, but the high at lag 0 significantly diminished at lag 1 .

[11] In the SH, a structure similar to the AM in the troposphere appears at lag 0 , but it becomes a local blocking at lag 1 , as in the NH [KK01]. At that time wave activity flux due to high-frequency transient wave is directed toward the pole as the stationary wave in the NH [Limpasuvan and Hartmann, 2000; KK01]. The structure at the 30 hPa level is characterized by an anomalous large high at the pole surrounded by a low belt in the mid-latitudes. The anomalous high has a crescent-shape centered in the south Indian Ocean that corresponds to the large amplitude of zonal wavenumber 1 at lags -3 and -2 , but it gradually becomes circular at lags 0 and 1 . The time evolution of the horizontal pattern at 1 hPa is similar to that at 30 hPa except that the amplitude reduction of zonal wavenumber 1 occurs earlier.

[12] It is interesting that the PJO variability pattern becomes almost zonally symmetric from the troposphere to the upper stratosphere at the annular stage in both hemispheres. The structure of the NH PJO at the annular stage is very similar to that obtained by Baldwin and Dunkerton [1999, 2001].

3.2. Effect of the PJO on the AM

[13] To examine the interrelationship between the AMs and PJOs in both hemispheres, we performed a correlation analysis of the zonal-mean zonal wind. Since the correlation coefficients between them becomes substantial at the annular stage, we compared them in this period. Figure 3 shows the lagged regression of the zonal-mean zonal wind and the E-P flux based on the AM indices at the annular stages.

[14] In the NH, the AO signal first appears one month prior (lag -1) when the zonal wind anomaly exhibits a meridional deep dipole structure with an anomalous E-P flux directed toward the high latitudes. The signal of the zonal wind is stronger at the high-latitude part, and it extends toward the upper stratosphere; the center is in the upper stratosphere. At lag 0 , the signal of the zonal wind at high latitude descends with amplification and exhibits a strong meridional dipole structure. The poleward E-P flux anomaly is greatly enhanced. The wind anomaly at high latitudes extends toward the middle stratosphere, while that at low latitudes extends only to the lower stratosphere. The high-latitude zonal wind descends more with weakening and the reduced poleward E-P flux anomaly at lag 1 . The time evolution of the zonal wind

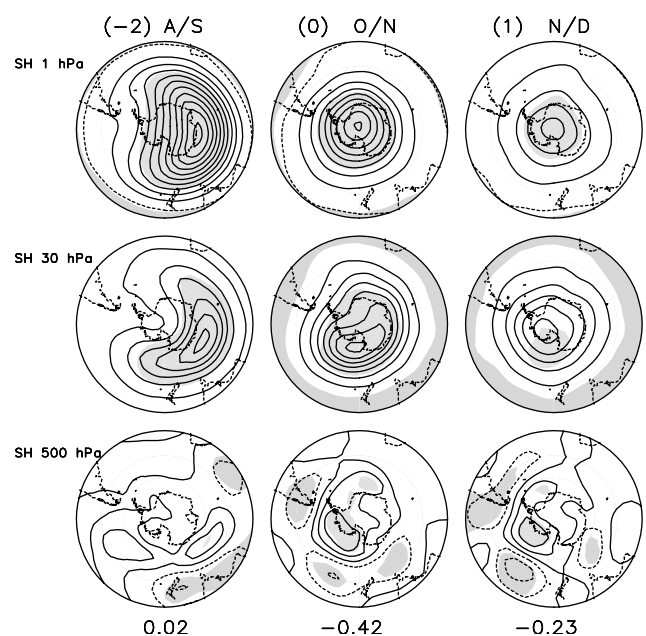


Figure 2. The same as Figure 1, except for the SH winter, and the lag times are -2 , 0 , and 1 month.

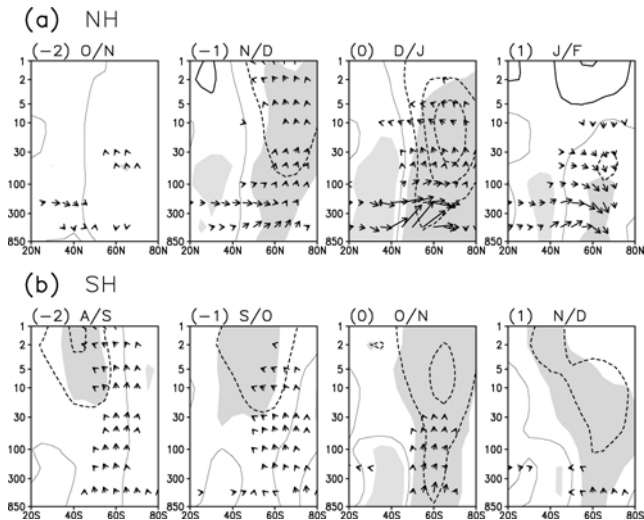


Figure 3. Lagged regression of the zonal-mean zonal wind (contour) and the E-P flux (arrow) by the AM indices of the annular stage of the NH (upper panels) and SH (lower panels) winters (D/J for NH and O/N for SH). Contour intervals are 2 m/s, and the dashed lines indicate negative values. The zero contour line is plotted as a thin solid line. Shading denotes significant regions at the 95% level. E-P flux has been scaled by the inverse square root of the pressure.

anomaly displays a downward propagation of the signal, which suggests strong inclusion of the PJO signal.

[15] In the SH, the signal of the AM first appears two months prior (lag -2) as a weakening of the zonal wind in the mid-latitudes of the upper stratosphere. It gradually shifts poleward with the anomalous E-P flux toward the weaker zonal wind area (lag -1). At lag 0, the signal of weaker wind locates at a high-latitude; it extends from the surface to the upper stratosphere and exhibits a meridional dipole structure in the troposphere. The signal of the positive zonal wind anomaly at low latitudes exists only in the troposphere, and the anomalous E-P flux is still directed toward the weaker wind in the middle stratosphere. The signal of the zonal wind persists until one month later (lag 1). The time evolution of the anomalous zonal wind signal suggests a strong coupling with the stratospheric process (PJO).

[16] Since the PJO and AM indices have significant correlations in the annular stages, the time evolution of the AM should contain a contribution from the PJO. To examine the effects of AMs without PJOs, an AM index without the PJO is defined as follows:

$$r' = r - \langle r, s \rangle s, \quad (1)$$

where r and s are the normalized AM and PJO indices, and the bracket represents time averaging. Note that $\langle r', s \rangle = 0$ by the definition, so the new AM index has no correlation with that of the PJO.

[17] Figure 4 shows the regression of the zonal-mean zonal wind and the E-P flux based on AM indices without the PJO. In the NH time coefficients of both the leading and second modes of the E-SVD have been removed, because the second mode also has a significant time-delayed component of the PJO.

[18] In the NH, the signal of the AM appears at lag -1 with the poleward E-P flux anomaly, and exhibits an almost symmetrical meridional dipole structure. However, the signal of the zonal wind is significant only in the troposphere. The amplitude of zonal wind is enhanced with the poleward E-P flux anomaly at lag 0, but it is significant only up to the lower stratosphere, and it almost disappears at lag 1.

[19] In the SH, the signal of the AM appears only at lag 0 with an almost meridionally symmetric structure, and it is significant only in the troposphere with the upward E-P flux anomaly at high latitudes. The signal at high latitudes lasts until lag 1, but is very weak.

[20] It is interesting that the AM signal of the zonal wind exists only in the troposphere in both hemispheres after removal of the PJO signal. The persistence of the signal is largely reduced by removing the PJO signal, particularly in the stratosphere. This is more apparent in the SH.

4. Discussion

[21] The structure of the PJOs becomes almost zonally symmetric from the troposphere to the upper stratosphere at the annular stage of both hemispheres. This is consistent with the relatively small E-P flux and large temperature anomalies at the annular stages [KK01]. In fact, the annular stage corresponds to the turnip point from a positive to a negative upward E-P flux anomaly in the NH, whereas it is a period of reducing anomalous upward E-P flux in the SH. Large amplitude of temperature in the polar areas from the upper troposphere to the middle stratosphere at the annular stage [KK01] is fairly zonally symmetric, and it contributes little to the vertical component of the E-P flux. Since the geopotential heights are the accumulation of the temperatures below their levels, the structures of the geopotential heights also become almost zonally symmetric at the annular stages.

[22] Baldwin and Dunkerton [1999] noted the downward propagation of the AO signal from the upper stratosphere to the surface in NH winter. Their AO structure at the stratosphere is very similar to that of the PJO in the NH at the annular stage (Figure 1). However an almost zonally symmetric structure appears at the same time, and no downward propagation can be seen in the figure. This may be because one-month averaging is too long to detect any downward propagating signal. It must be noted that the signal of the zonal wind or temperature due to the PJO shows a downward propagation with time [KK01; Christiansen, 2001]. This suggests

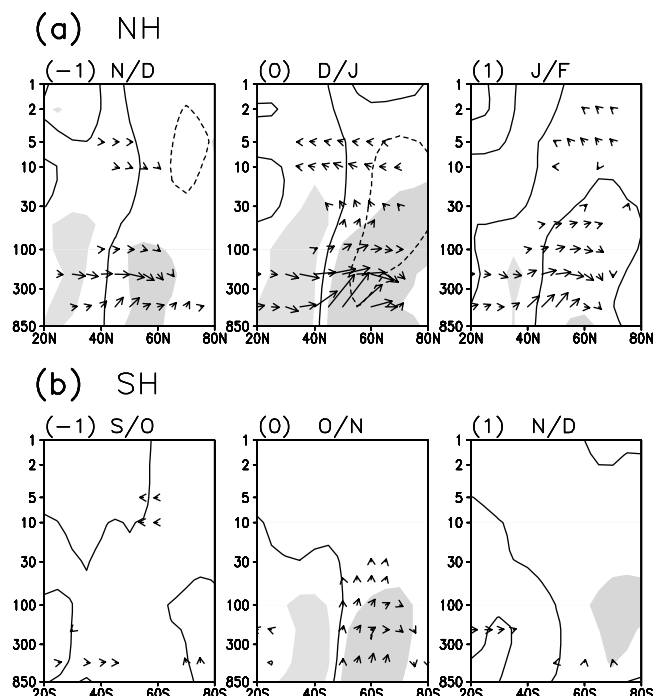


Figure 4. The same as Figure 3, except that the signal due to the PJO has been removed (see text for detail).

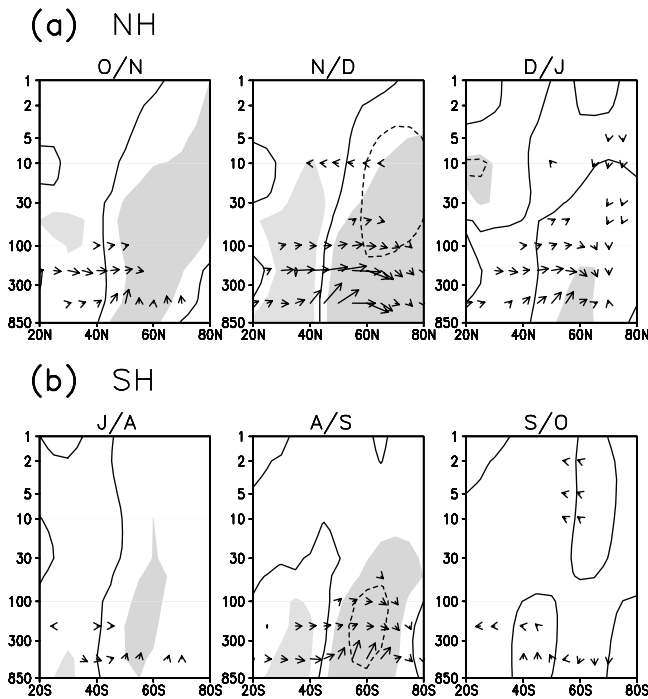


Figure 5. The same as Figure 3, except using the AM indices of N/D and A/S for the NH and SH, respectively.

that the downward propagation of the AO signal captures the same signal as the time evolution of the PJO around the annular stage.

[23] When the effect of the PJOs is removed from the variability related to the AMs, the variability is limited only in the troposphere and lower stratosphere. This result is consistent with that by Kodera and Kuroda [2000], who found that about half of the large AO in the NH cold season does not couple with the stratospheric process. These results suggest that the variability due to the AM is essentially a tropospheric process, but it tends to couple with the stratospheric process (PJO) at some stage of its evolution. The stratospheric process precedes the tropospheric process; this indicates that the stratospheric process has the potential ability to induce the AM in the troposphere to create an almost zonally symmetric structure from the surface to the upper stratosphere. Baldwin and Dunkerton [1999] proposed a possible mechanism for the formation of the tropospheric AM by the stratospheric process through induction of the meridional cell in the troposphere.

[24] It would be interesting to compare an AM that is coupled with the PJO to one that is not coupled. The correlation between the PJOs and the AMs in the cold season are very small at N/D for the NH and A/S for the SH (see Figures 1 and 2), so we compared the results with the AM in these periods (Figure 5). In the NH, the zonal feature of the AM in N/D is more similar to the PJO-removed AM (Figure 4a) than to that of the full AM in D/J (Figure 3a), especially in the stratosphere. In the SH, the structure of the zonal

wind due to the AM in A/S is also similar to the PJO-removed AM in O/N. This again suggests the role of the PJO in both maintaining and enhancing the AM in the annular stage. However, the structure of the E-P flux due to the AM in A/S is somewhat different from both AMs in O/N, reflecting the different role of waves in generating the AM in mid-winter or late winter.

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Y. Kuroda, Meteorological Research Institute, Tsukuba, Ibaraki, 305-0052 Japan. (kuroda@mri-jma.go.jp)