

Effect of Solar Activity on the Polar-night Jet Oscillation in the Northern and Southern Hemisphere Winter

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Abstract

Effect of the modulation of the Polar-night jet oscillation (PJO) in winter time by the 11-year solar cycle is examined by the observational data from 1979 to 1999. It is found that zonal wind and the E-P flux anomalies appear commonly in the subtropical upper stratosphere in early winter of both the Northern and Southern Hemispheres as a response to meridional UV heating contrast. These zonal wind anomalies are found to propagate poleward and downward with development as a seasonal march in both hemispheres. Although the length of the record is limited, it is suggested from the available data that the signal due to solar activity appears as the time evolution of the PJO triggered by solar forcing at early winter in both hemispheres. Differences in the signals between the Northern and Southern Hemispheres during late winter are explained in terms of the different characteristics of the PJO in each hemisphere. A significant temperature signal is also found to appear in the Southern Hemisphere in late winter under a solar maximum condition.

1. Introduction

It is important to understand the natural long-term variability of the atmosphere to infer the potential effect of human activity. Consequently, the response of the atmosphere to changes in solar variability has recently been examined by theoretical and observational studies. Through satellite measurements, it is found that the energy flux of the high energy ultraviolet (UV) radiation changes by large (>5%) amounts during the 11-year solar cycle (Rottman 1988; Lean et al. 1997) in contrast with the very small variation of the total solar energy flux (Willson and Hudson 1988; Hickey et al. 1988; Foukal and Lean 1990). Corresponding to the change of the UV radiation, temperature around the stratopause is found to vary significantly (Hood et al. 1993; McCormack

and Hood 1996), which can be regarded as a direct effect of the radiation.

At the same time, however, the variability of the atmosphere at lower altitudes is also found to be related to the solar cycle (Labitzke and van Loon 1997; Hood et al. 1993; Kodera 1995). These signals suggest the existence of an indirect effect of solar radiation by way of amplifying the small solar signal through the interaction with dynamics. However, as the existence of this mechanism is not physically apparent and the record of observation is not sufficiently long, many other possibilities are also proposed (e.g., Salby and Shea 1991).

However, with the progress of the simulation technique of the climate by using general circulation models (GCM), many experiments have been performed for understanding the natural variability of the atmosphere including the effect of solar cycle (Haigh 1996; Shindell et al. 1999, 2001). Shindell et al. (1999, 2001) have shown the existence of indirect effects of the solar cycle, such as the downward propagating signal in association with the solar

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cycle variability, using controlled GCM experiments.

The existence of the downward propagation of anomalous zonal wind is pointed out by observational studies (Kodera et al. 1990, Kodera 1995). Kodera (1995) has shown that the signal due to external forcing, such as solar forcing, can be regarded as a modulation of the internal mode of variability of the atmosphere characterized by poleward and downward movement of the zonal-mean zonal wind anomaly. Kuroda and Kodera (1998, 1999) have further examined the characteristics of this variability and found that it happens through the wave-mean flow interaction of planetary waves of mainly zonal wavenumber one which generally exist in winter of both hemispheres. This phenomenon is now known as the Polar-night jet oscillation (PJO) (Kuroda and Kodera 2001).

These studies suggest the possibility that solar forcing can modulate the appearance of the PJO and leads a climate change in winter of both hemispheres. In fact, if the variation of the UV affects the heating and temperature at the stratopause level of mainly summer Hemisphere, there appears large meridional heating contrast of the temperature in the upper stratosphere of winter Hemisphere. This heating contrast should force the zonal wind in the upper stratosphere through the thermal wind relationship, and this forcing can in turn modulate the primitive PJO in early winter. The whole time evolution of PJO may thus be controlled by the initial forcing. To see if the above mechanism works in the real world, we have examined climate change due to solar cycle activity in both hemispheres and compared them in this paper. Though the record of observation is not very long, comparison of reaction from separate hemisphere will help to compensate for this defect.

This paper is organized as follows. The data and method of analysis are described in Section 2. Section 3 provides the results of analyses in both hemispheres. Section 4 is devoted to discussion and concluding remarks.

2. Data and method of analysis

The stratospheric and tropospheric data used in the present study are updated from Kuroda and Kodera (2001) and cover 21 years, from 1979 to 1999. The original 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 by the non-linear balanced wind relation from a satellite-derived geopotential height produced by CPC, as documented in Randel (1992). The stratospheric data of the NH below the 10 hPa level from April 1996 to April 1997 are completely missing at NCEP. The missing data for this period are compensated by those derived from the Met Office, UK geopotential height data (Bailey et al. 1993), after being adjusted for being continuously connected at the equator to the SH counterpart of the NCEP data. Operational data for the troposphere at 100 hPa and below are taken from the NCEP/National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996). All missing data, except for the above-mentioned period, are linearly interpolated in time, and the monthly mean data are then calculated as 30-day mean data, with the exception of July, which is 35-day mean data. It should be noted that the Eliassen-Palm (E-P) flux, residual velocity, and wave-activity flux by Plumb (1985) are calculated from five-day mean data and the monthly average is taken thereafter. The residual velocity is estimated based on the downward control principle (Haynes et al. 1991) by integrating transformed Eulerian mean (TEM) equation with the boundary condition of null upward velocity at 0.5 hPa level similar to Soel and Yamazaki (1999).

Solar activity on the 11-year time scale is measured using the monthly mean solar microwave flux (with the unit of 10^{-22} Wm²/Hz) with the wave length of 10.7 cm (called the solar index), produced by the U.S. National Oceanic and Atmospheric Administration (NOAA)/National Geophysical Data Center (NGDC). It should be noted that the solar ultraviolet variability correlates closely with the solar index on the timescale of 11-year solar cycle (e.g., Lean et al. 1997). In this study, we have defined solar maximum years as those with the solar index larger than 180. Similarly solar minimum years are defined as those with solar indices less than 100. To obtain the solar activity of the NH winters, we have used January–February mean solar index. Similarly, July–August mean solar index is used for the SH winter. In

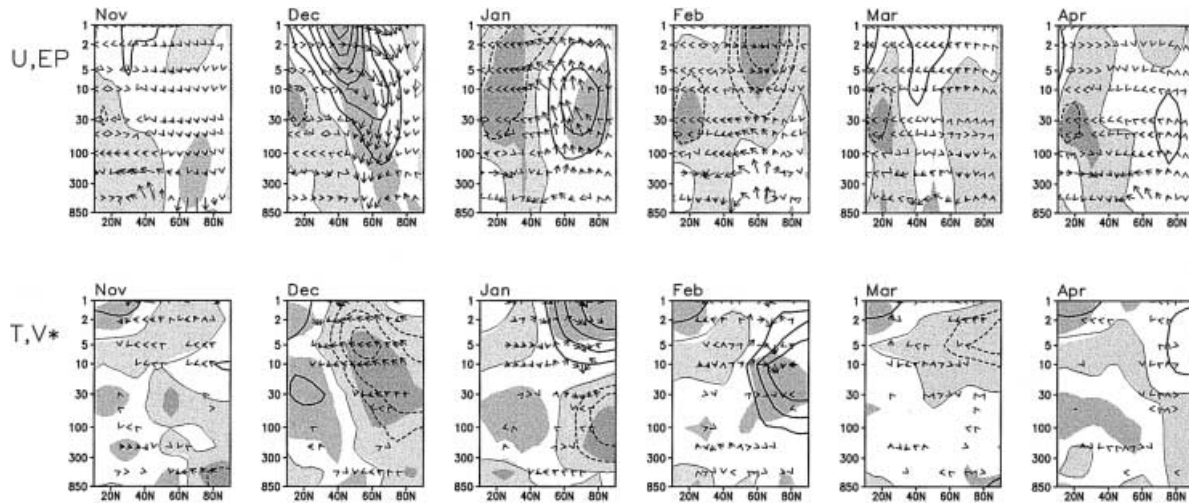


Fig. 1. The zonal-mean zonal wind and the E-P flux anomalies (upper panels), and the zonal-mean temperature and residual velocity anomalies (lower panels) of the solar maximum composite in the Northern Hemisphere winter. Contour interval of the zonal wind and temperature are 2 m/s and 1 K, respectively, and contours of negative value are shown by dashed line. Light shading indicates negative areas, and thick shading indicates areas where absolute value of Student's-t are larger than 1.5. E-P flux has been scaled by the inverse square root of the pressure.

this way, seven solar maximum winters (79/80, 80/81, 82/83, 88/89, 89/90, 90/91, 91/92) and seven solar minimum winters (84/85, 85/86, 86/87, 94/95, 95/96, 96/97, 97/98) are selected for the NH. Similarly, five solar maximum winters (80, 81, 89, 90, 91) and nine solar minimum winters (84, 85, 86, 87, 93, 94, 95, 96, 97) are selected for the SH. All fields, such as the zonal-mean zonal wind and temperature in winter time, are divided into the categories of the solar maximum and minimum, and then they are compared with each other.

In this study, as the record of data is not sufficiently long, we do not extract the signal by simple correlation analysis. Instead, we have examined how the composite signals of the solar maximum or minimum are deviated from the overall climate. Our whole data covers almost 2 solar cycles and each group of solar maximum, minimum or normal consists of approximately the same amount of data. So our data are not biased to either solar maximum or minimum. As the signal due to the 11-year solar activity is very small, we may be able to treat the reaction of the signal as a nearly linear response to the variation of solar activity. So if the response of the anomaly due to solar

maximum and minimum shows the same structure with the opposite sign, this response may be regarded as a real signal. Note that we have divided the whole data into three groups. Therefore, composites of any two groups do not have obvious positive/negative relationship each other, as the data is divided into two groups. Furthermore, comparison of the signals between the hemispheres is made to diagnose the responses.

3. Relationship between the PJO and solar activity

3.1 Zonal-mean structure

The NH-winter composites of the zonal-mean zonal wind and the E-P flux anomalies (upper panels), and the zonal-mean temperature and the residual velocity anomalies (lower panels) of the solar maximum and minimum conditions are shown in Figs. 1 and 2, respectively. Though the ensemble size is very small, the areas whose absolute value of Student's-t are larger than 1.5 are darkly shaded to show the strength of the signal only as a reference.

It can be seen that the subtropical lower stratosphere is warmer (Fig. 1) or cooler (Fig. 2) throughout winter. This will affect the

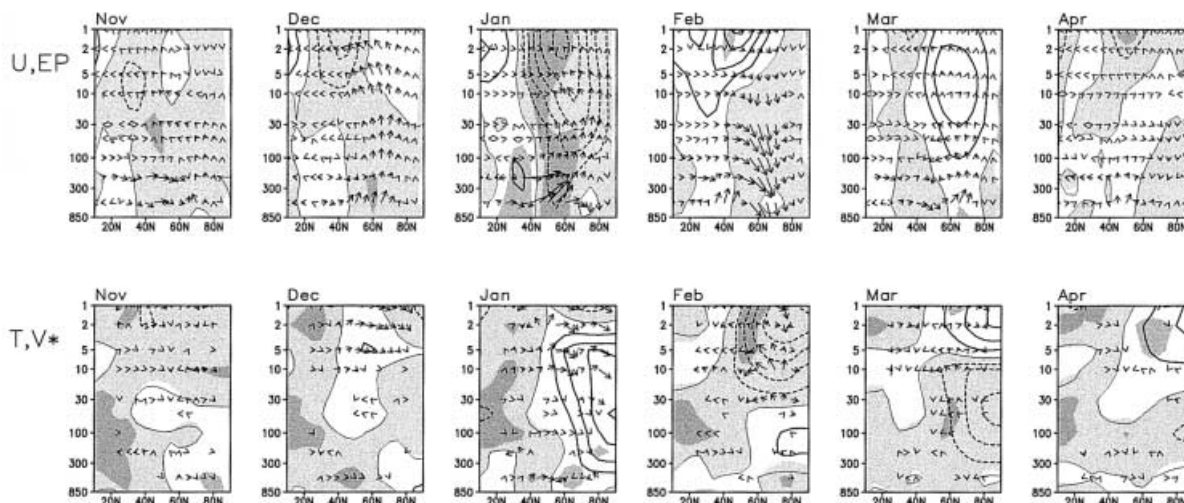


Fig. 2. The same as Fig. 1 except for the solar minimum composite.

changes of the geopotential height in lower stratosphere, as pointed out by van Loon and Labitzke (1990). The heating/cooling anomaly is thought to be created by the variability of the ozone transport (Hood 1997; Shindell et al. 1999). Similarly, it can be seen that the area of subtropical upper stratosphere is warmer (Fig. 1) or cooler (Fig. 2) throughout winter. This is believed to be caused by the direct heating of the UV variability (Hood et al. 1993; McCormack and Hood 1996).

Corresponding with the temperature anomaly at the upper stratosphere, a positive (Fig. 1) or negative (Fig. 2) wind anomaly appears in the subtropical upper stratosphere in November and amplified in December. The upward and equatorward E-P flux in the stratosphere is also weakened (Fig. 1) or strengthened (Fig. 2) corresponding with the variability of the zonal wind. They show almost symmetrical responses between solar maximum and minimum. The response of the zonal wind in November reflects the direct response of solar cycle variability. The variability of the E-P flux corresponding with that of the zonal wind suggests that this variability causes wave-mean flow interaction to occur. In fact, the solar maximum composite (Fig. 1) shows that the well-developed positive wind anomaly in December shifts poleward (January) and then downward while the negative wind anomaly shifts to the upper stratosphere (February) in turn. Similarly, the solar

minimum composite (Fig. 2) shows that the negative wind anomaly in December shifts poleward as it develops (January) and downward with corresponding positive wind anomaly shifts in the upper stratosphere (February). This positive wind anomaly further shifts poleward in March. This time evolution of the zonal wind anomaly corresponds with that of the PJO which is triggered in the subtropical upper stratosphere in early winter by solar activity. Though the time evolutions of the solar maximum and minimum are roughly symmetrical, detailed examination shows that the time evolution in solar maximum is somewhat earlier and stronger than that of the solar minimum. Moreover, the symmetrical response of the zonal wind anomaly becomes weaker as the winter progresses, and they seem to be broken in March.

Corresponding with the time evolution of the zonal wind, the temperature signals also show a nearly symmetrical response until February: in December, cooling (warming) area appears in mid-latitudes of the middle stratosphere corresponding with the anomalous upward (downward) flow induced by the E-P flux convergence anomalies. This temperature anomaly quickly shifts poleward and it descends at the pole with an anomaly of the opposite sign above it. The quasi-periodic nature reflects that of the PJO in the NH (Kuroda and Kodera 2001).

Figure 3 shows the difference of the response between solar maximum (Fig. 1) and minimum

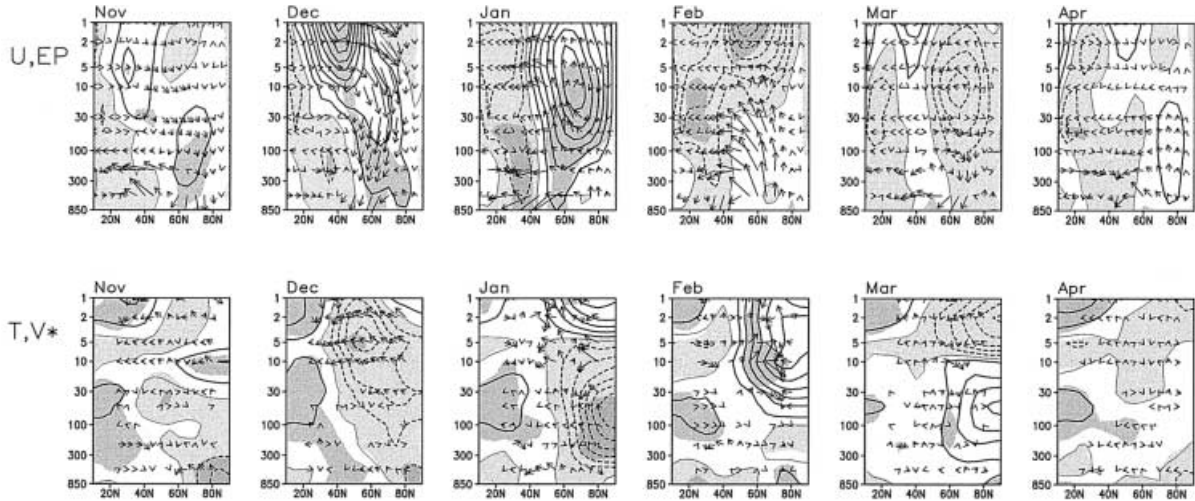


Fig. 3. The same as Fig. 1 except for the difference between the solar maximum and minimum.

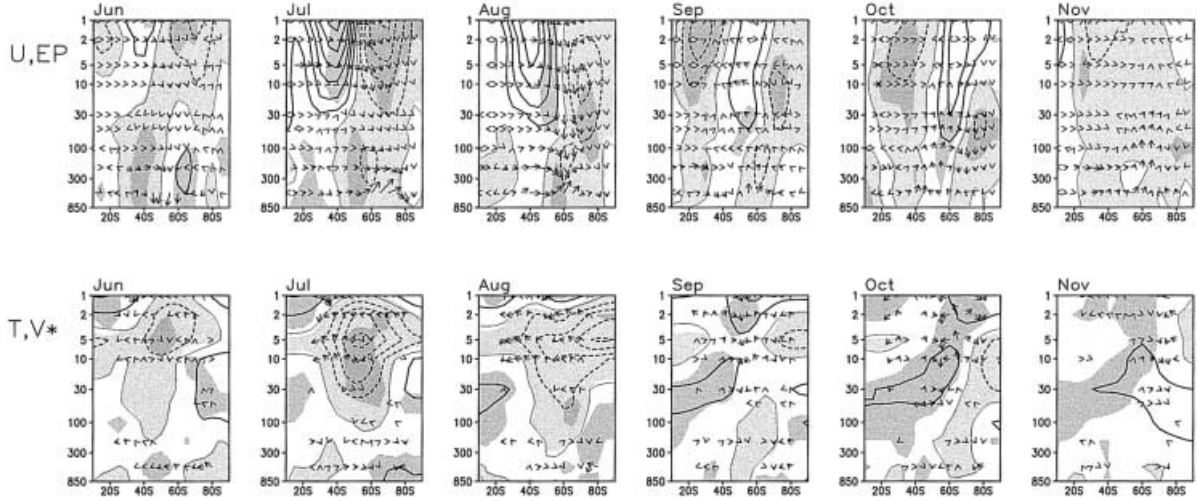


Fig. 4. The same as Fig. 1 except for the solar maximum of the Southern Hemisphere winter.

(Fig. 2) as a summary. Note that the result is almost the same as that obtained by the regression with the solar index. It is clearly seen that the PJO in NH is started at the subtropical upper stratosphere in early winter. It should be noted that the time evolution of the zonal wind and E-P flux is very similar to that of the PJO in the NH with reversed polarity (Kuroda and Kodera 2001) if lag 0 month is set to be December. However, it should be remembered that the symmetrical response due to the solar activity between solar maximum and minimum

is violated in March and later. So the signal after March cannot be regarded as the response due to the solar activity in a linear-response sense, although there may still exist a possibility that these are due to the non-linear response of solar forcing.

The SH winter composites of the zonal-mean zonal wind and the E-P flux anomalies (upper panels), and the zonal-mean temperature and the residual velocity anomalies (lower panels) of the solar maximum and minimum conditions are shown in Fig. 4 and 5, respectively.

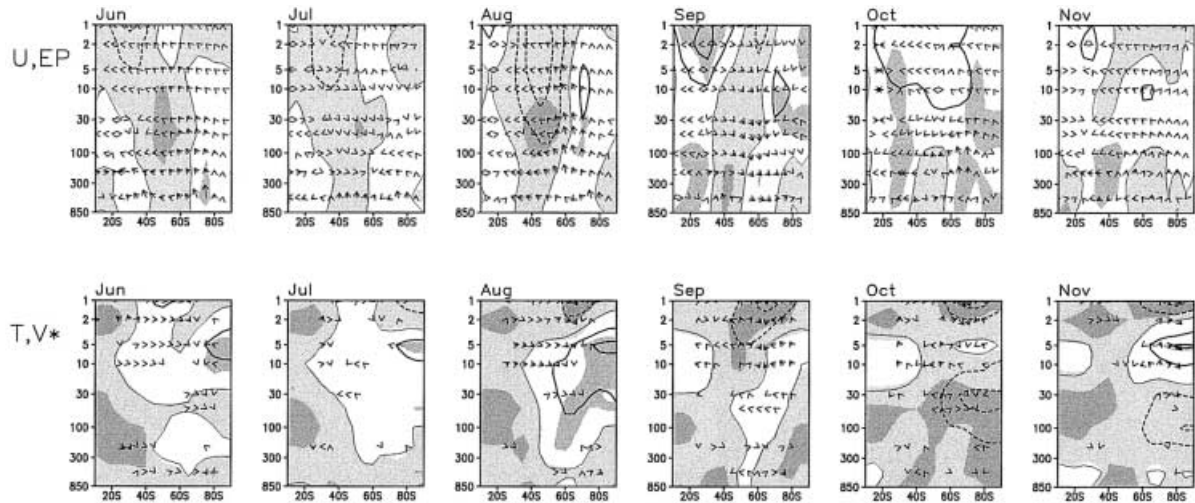


Fig. 5. The same as Fig. 1 except for the solar minimum composite of the Southern Hemisphere winter.

The temperature signal at the subtropical lower stratosphere and upper stratosphere can be clearly seen throughout winter similar to the NH. Corresponding with the temperature signal at the upper stratosphere, a positive (Fig. 4) or negative (Fig. 5) zonal wind anomaly appears in the subtropical upper stratosphere in June and amplify in July. The upward and equatorward E-P flux is also weakened (Fig. 4) or strengthened (Fig. 5) corresponding with the variability of the zonal wind, and shows almost symmetrical responses between solar maximum and minimum as that seen in the NH. The response of the zonal wind in June is regarded to reflect the direct response of solar cycle variability as in the NH, but the time evolution of the zonal wind anomaly to follow is very different from that of the NH. In fact, the zonal wind anomaly in the subtropical upper stratosphere in June is developed mainly downwardly and it shifts poleward only minimally until August. In case of solar maximum (Fig. 4), the low-latitude positive zonal wind anomaly accompanies high-latitude strong negative zonal wind anomaly and shows meridional dipole structure in early winter. However the positive zonal wind anomaly accompanied at high-latitude is very weak in the solar minimum. Also the signal of low-latitude zonal wind anomaly is weaker for the solar minimum than the solar maximum similar to the NH.

The low-latitude zonal wind anomalies begin to shift poleward in both the solar maximum and minimum cases in September. This feature of the time evolution of zonal wind anomaly is similar to that of the PJO in the SH (Kuroda and Kodera 1998), except that the zonal wind anomaly of the opposite sign appears in low-latitude and it is developed in the following months. Therefore, a meridional tripole structure appears in September and moves poleward in the following months. These features are common and nearly symmetrical between solar maximum and minimum.

On the whole, the time evolution of the zonal wind anomaly can be explained by the time evolution of the SH-PJO (see Kuroda and Kodera 2001), which is triggered in subtropical upper stratosphere by the solar activity in early winter, though an apparent non-PJO signal due to solar activity also exists in late winter.

There is also a temperature variability corresponding with that of the zonal wind. In fact, similar to the time evolution of the temperature in the NH, the cooling anomaly in June is enlarged in the mid-latitudes of middle stratosphere in July due to the upward flow induced by the E-P flux convergence anomaly, and it shifts poleward in August and is diminished in September in the solar maximum case (Fig. 4). Similar signal can be seen for the solar minimum (Fig. 5), however, the signals are very

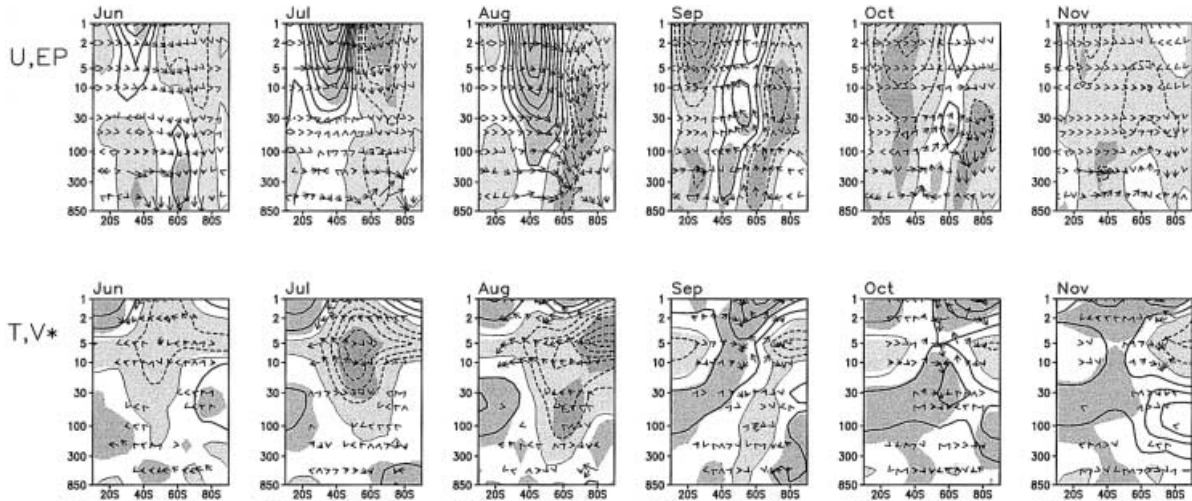


Fig. 6. The same as Fig. 1 except for the difference between the solar maximum and minimum of the Southern Hemisphere winter.

weak compared to solar maximum, especially in early winter. This situation is similar to the NH.

Figure 6 shows the difference of the response between the solar maximum (Fig. 4) and minimum (Fig. 5) as a summary of the SH. It is clearly seen that the PJO in SH is started at the subtropical upper stratosphere in early winter, although there is also an apparent non-PJO signal due to solar forcing after September. From June to August, the nature of the time evolution of the zonal wind and E-P flux is very similar to that of the PJO in the SH with reversed polarity (Kuroda and Kodera 1998). It should be noted that the signal shows almost symmetrical reaction between the solar maximum and minimum throughout winter, which is different from the NH where the symmetry is violated in late winter.

3.2 Relationship to the annular mode

As shown by Kuroda (2002), the structure of the PJO becomes zonally symmetric from surface to the upper stratosphere and is closely related to the annular mode (Thompson and Wallace 1998, 2000) at the annular period when the zonal wind anomaly in the troposphere shows a meridional dipole structure (Kuroda and Kodera 2001).

Figure 3 shows that in this case, the annular period corresponds to January in the NH. In

the SH, the annular period should always be October or November (Kuroda and Kodera 2001) but the meridional dipole structure is not clear in Fig. 6, due to the inclusion of the non-PJO signal.

To see the development of the horizontal structure of the geopotential height around the annular period, the differences of the composites between solar maximum and minimum for three consecutive months including the annular period are shown in Fig. 7 and 8 for the NH and the SH, respectively. Here we have shown only the differences because the signals show an almost symmetrical response between solar maximum and minimum. The horizontal component of the wave activity flux of Plumb (1985) is also shown by arrows in the troposphere (500-hPa level).

Comparing Fig. 7 in NH with the time evolution of the geopotential height of the PJO around the annular period (see Fig. 1 of Kuroda 2002), it is found that the structure due to solar forcing is very similar to that of the standard PJO except that the low-latitude above 30 hPa levels have a strong positive bias (van Loon and Labitzke 1990) and the tropospheric structure is slightly modified. In particular, the structure of the Arctic Oscillation (AO) extending from the surface to the upper stratosphere (Baldwin and Dunkerton 1999) appears in January. In the troposphere, the AO signal with positive

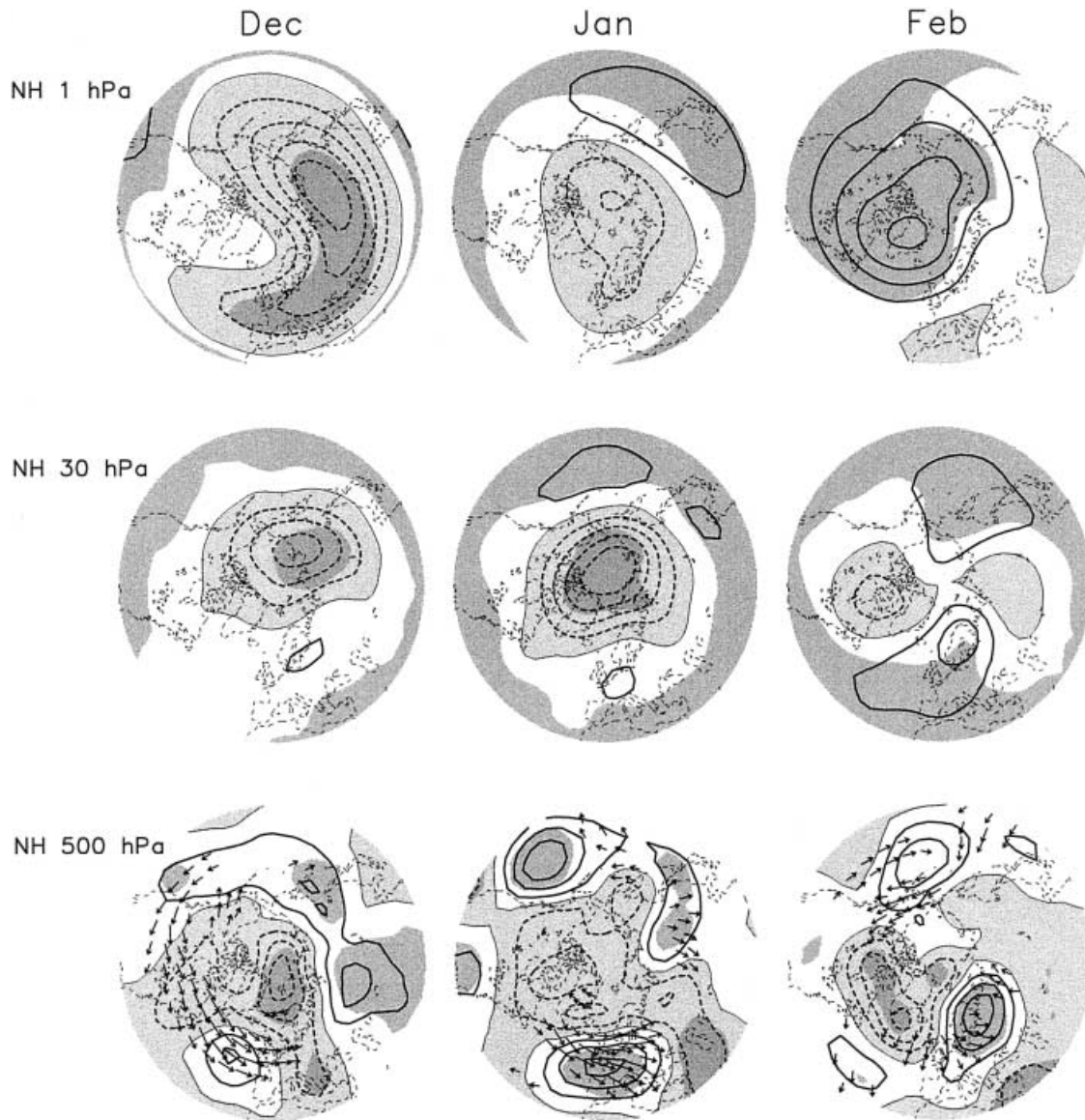


Fig. 7. Time evolution of the geopotential height differences between solar maximum and minimum from December to February in the Northern Hemisphere winter. Levels of 1 hPa, 30 hPa, and 500 hPa are shown at upper, middle, and lower panels, respectively. Contour intervals for 1-hPa, 30-hPa, and 500-hPa levels are 200 m, 100 m, and 30 m, respectively, and contours of negative value are shown by dashed line. Light shading indicates negative areas, and thick shading indicates areas where absolute values of Student's-t are larger than 1.5. Arrows at 500-hPa levels show the difference of the horizontal component of wave activity flux by Plumb (1985).

AO index appears, though the trace of the mid-latitude high pressure belt appears separately in western Europe, East North America, the northwest Pacific, and in the Far East. In this sense, the AO signal with positive AO index preferentially appears in January of the

solar maximum year compared with the solar minimum year.

Similarly, Fig. 8 is compared with the time evolution of the geopotential height of the PJO in the SH around annular period (see Fig. 2 of Kuroda 2002). It can be seen that the geo-

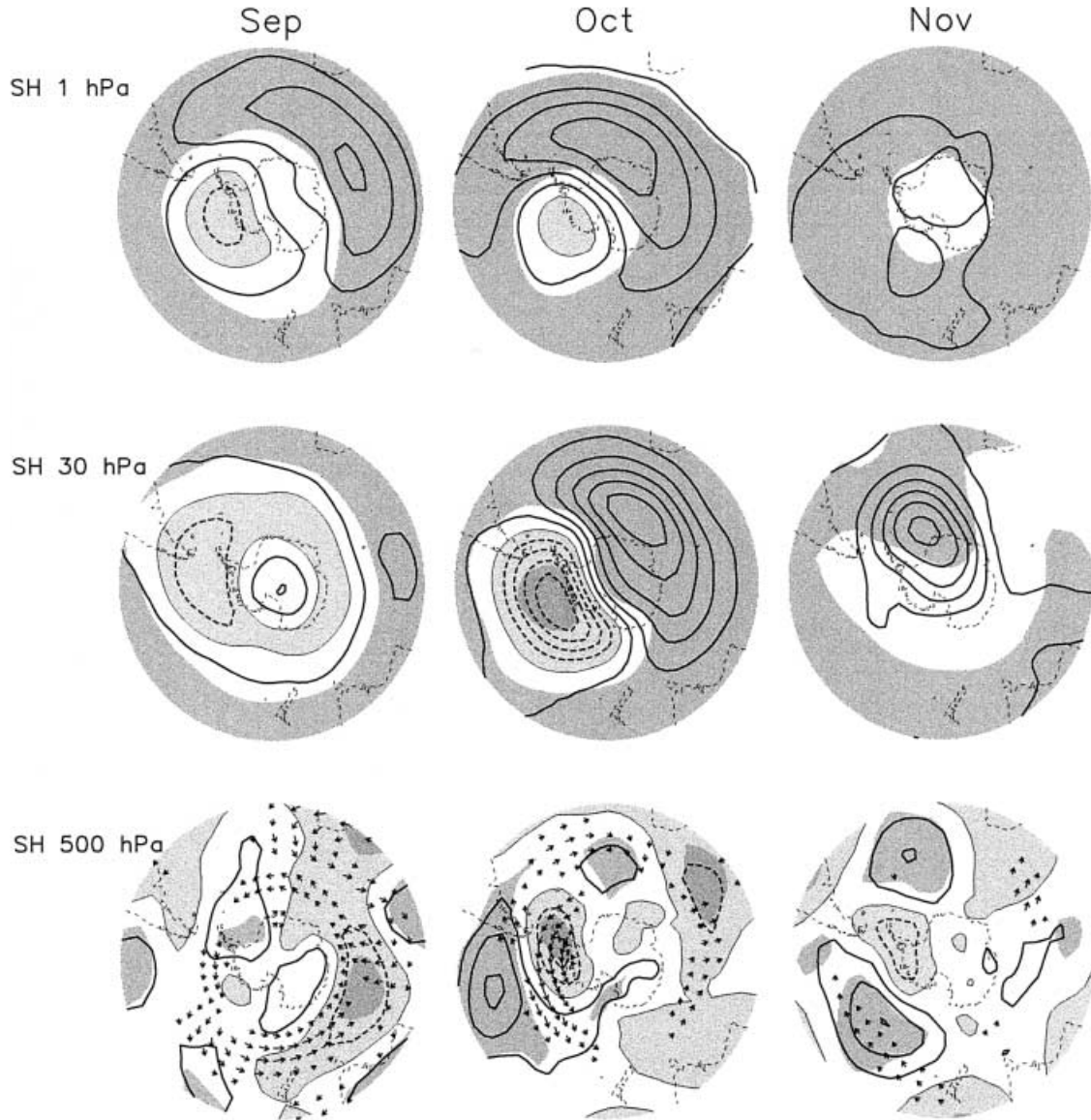


Fig. 8. The same as Fig. 7 except for the September to November of the Southern Hemisphere winter. Contour intervals for 1-hPa, 30-hPa, and 500-hPa levels are 100 m, 50 m, and 30 m, respectively.

potential heights above 30-hPa levels are more strongly biased positively than that of the NH. This is consistent with the fact that in late winter a high temperature anomaly is extending from the subtropical lower stratosphere to the high-latitude upper stratosphere as can be seen in Fig. 6. In spite of this bias, some annular feature of low pressure area surrounded by high pressure belt continues above 30-hPa

levels until October. In October, though the feature is largely deformed from the standard annular feature of the PJO, the signal of the low pressure is connected from the troposphere to the upper stratosphere. Also the trace of the center of the Antarctic Oscillation (AAO) pattern (Thompson and Wallace 1998) with positive AAO index is seen around the Antarctic Peninsula and it persists until November.

However, the signal of the AAO in the SH is not clear compared with that of the AO in January of the NH.

4. Discussion and remarks

We have examined the influence of solar cycle variability on the climate through the modulation of the PJO, by the composite analysis of both winter Hemispheres. It is suggested that the solar cycle variability can modulate the PJO so that it starts at the specific phase in early winter of both hemispheres. Though the signals in the early winter of both hemispheres are similar, the time evolution is very different between hemispheres corresponding with the characteristics of PJOs of each hemisphere. In the NH winter, the positive AO pattern preferentially appears in the troposphere in January at solar maximum, whereas an unclear positive AAO pattern appears in late winter in the SH.

In early winter, the reactions of the atmosphere to solar activity are very similar regardless of the climatological difference of the hemispheres. This suggests that only the timing (early winter) and area (low-latitude upper stratosphere) are the key factors for the formation of the initial signal and the climatological difference is not crucial. The timing is closely linked to a situation when the dynamical effect becomes large enough to start wave-mean flow interaction in both hemispheres. However it should also be noted here that the signals are stronger for the solar maximum (Fig. 1 and 4) than that of the solar minimum (Fig. 2 and 5) for both hemispheres. This will be explained by the fact that the heating becomes more and more stronger as the UV becomes stronger (because the heating depends on both the ozone density and the UV strength, and also the ozone density itself depends on the UV strength), and the change of the high energy UV flux above normal is generally larger for solar maximum than for solar minimum (see e.g., Fig. 16 of Lean et al. (1997)).

If the PJO is truly an internal mode of variability of the atmosphere, there is no need for any special external forcing to generate the variability. Any initial forcing will control the appearance of the variability. However, there exist many external forcings that may possibly control the feature of appearance of the PJO,

including the equatorial quasi-biennial oscillation (QBO), volcanic aerosols, global warming, El Niño-Southern Oscillation (ENSO), and so on in addition to solar forcing (Kodera 1995). So, the forcing due to solar cycle is only one candidate that may control the PJO. Thus, the strength of solar cycle variability in controlling climate will depend on the strength of other factors in early winter, and hence can be estimated in principle. According to the analysis presented here, the response of zonal wind in early winter is less than 1.5 of Student's-t value, so the signal is not very strong though not very weak either.

Kodera et al. (2000) have shown that the PJO signal is very prominent in the NH winter when stratospheric major sudden warmings take place. Naito and Hirota (1997) have shown that major warmings occur mainly at QBO easterly/solar minimum or QBO westerly/solar maximum. So, we have also conducted the analysis presented in this paper by including QBO effect to see the cross effect as a trial. As is suggested, in the NH winter the overall signal is clearer in case of QBO easterly/solar minimum or QBO westerly/solar maximum (not shown). In the SH, on the other hand, the signal seems to be clearer in the case of QBO easterly/solar maximum or QBO westerly/solar minimum (not shown). However, the data record is too short to allow fine conclusions and this should be examined using more data in the future.

It can be seen that the positive/negative relationship of the zonal wind anomaly in the NH between solar maximum and minimum becomes very weak in late winter. This does not occur in the SH. This can be explained from the behavior of the PJOs of both hemispheres. In the NH, the period of the PJO varies from about 3 to 5 months depending on the situations of respective years (Kodera et al. 2000). So even the phases of the PJO are completely set in November, the difference in phases from one year to the other becomes large with the seasonal march. This mechanism will violate the relationship between the month and phase especially in late winter. On the contrary, the PJO in the SH is closely locked to the seasonal cycle. So the phase does not deviate from one year to another. This mechanism will keep the solar activity forcing strong throughout the winter in the SH.

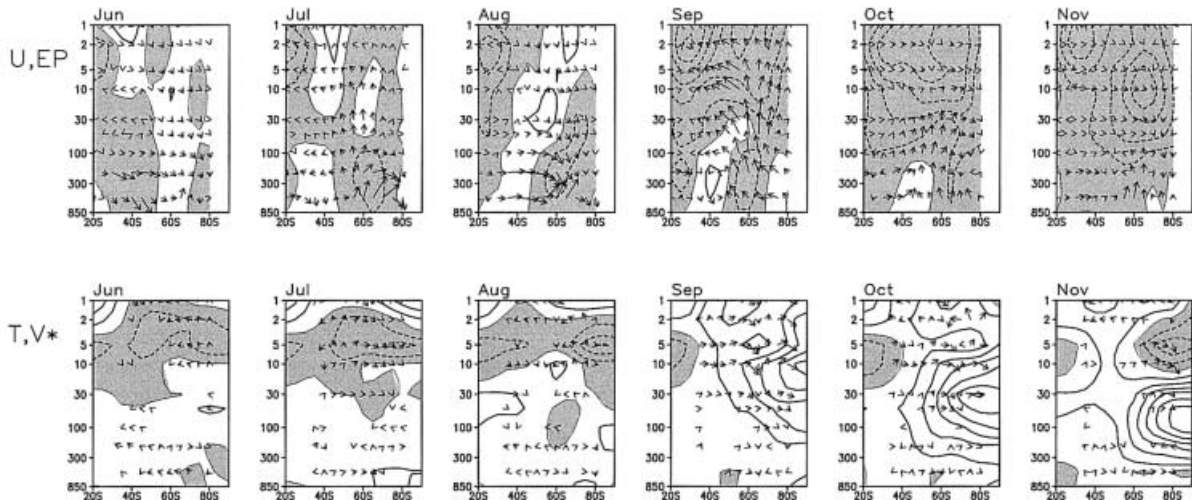


Fig. 9. The same as Fig. 6 except that the regressed PJO signal with the strength from June to August is removed statistically and shading indicates negative areas. (see text for details).

In the SH winter, the time evolution of the zonal wind until August is very similar to that of the typical PJO (Fig. 6). However, the signal is largely modified after September. This can be understood if some special signal related to the solar activity is included with the PJO signal. So we have statistically removed the regressed PJO signal from the composite difference in Fig. 6 (Fig. 9). The strength of the PJO is set to correspond with that of the early winter (Kuroda and Kodera 2001). It is apparent that the PJO signal in early winter is almost vanished by this operation. However, a high temperature anomaly suddenly appears in September with downward flow, and a negative wind anomaly in the upper stratosphere and enhanced upward E-P flux appears at that time. The downward flow anomaly originates from a large convergence of the E-P flux anomaly in the upper stratosphere. The high temperature signal gradually descends at the pole during late winter with negative wind anomalies in the stratosphere. The source of the appearance of the high temperature in September and the following months will relate partly to the adiabatic heating but mainly from the heating of ozone which is transported from the upper stratosphere. In fact, the figures of Hood et al. (1993) (their Figs. 7a to 9a) suggests the ozone transport at mid-latitude upper stratosphere in mid-late winter of the SH. However, this should

be further examined by the ozone data in the future.

We have shown as to how the solar cycle variability can influence the climate through the modulation of the PJO by the analysis of the observational data in this paper. However, the data record is not sufficiently long to calculate, for example, the probability for appearance of some specific pattern. In this sense, conducting controlled experiments with a GCM, which can reproduce the PJO realistically, would be an ideal tool for understanding of the underlying mechanism. We intended to do this in the near future.

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