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Role of solar activity in the troposphere-stratosphere coupling in the Southern Hemisphere winter

Yuhji Kuroda,[1] Makoto Deushi,[1] and Kiyotaka Shibata[1]

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[1] The effect of the 11-year solar cycle on the troposphere-stratosphere (TS) coupling in the Southern Hemisphere (SH) late winter/spring is examined through the analysis of observations and simulations with a chemistry-climate model. It is found that the TS coupling in the SH late winter/spring is significantly modified according to the solar cycle; the dynamical coupling between the troposphere and stratosphere becomes stronger with the increasing solar activity. Such modulation of the strength of the TS coupling is found to be the source of the solar-cycle modulation of the annular mode in late winter/spring. A possible mechanism of the solar-cycle-TS-coupling relationship is also discussed.

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1. Introduction

[2] It is important to examine the effect of the 11-year solar cycle activity on climate to understand the climate system and to forecast the future climate. Research analyzing the solar cycle effects on climate includes numerous observational and modeling studies [e.g., *Hood et al.*, 1993; *Kodera*, 1995; *McCormack and Hood*, 1996; *Labitzke and van Loon*, 1988; *Shindell et al.*, 1999; *Kodera and Kuroda*, 2002; *Matthes et al.*, 2004].

[3] Recent studies indicate that the solar cycle affects the structure of the North Atlantic Oscillation (NAO) and the Southern Annular Mode (SAM) when the interaction between the troposphere and stratosphere is active. In fact, *Kodera* [2002, 2003] and *Ogi et al.* [2003] found that in the high solar (HS) years the winter-mean NAO signal in the Northern Hemisphere (NH) extends to the hemisphere and to the upper stratosphere in mid-winter, and tends to persist until the following summer, whereas in the low solar (LS) years it is restricted in the local tropospheric variability in mid-winter and disappears quickly. *Kuroda and Kodera* [2005] also found that in the HS years the late winter/spring SAM signal extends to the upper stratosphere and persists until the following March, whereas in the LS years it is restricted in the troposphere and disappears quickly. Mid-winter in the NH and late winter/spring in the Southern Hemisphere (SH) correspond to the season when troposphere-stratosphere (TS) coupling is very active [*Thompson and Wallace*, 1998].

[4] For the duration of the modes, *Kuroda and Kodera* [2005] and Y. Kuroda et al. (Role of ozone in the solar cycle modulation of the North Atlantic Oscillation, submitted to *Journal of Geophysical Research*, 2007) considered that the lower stratospheric anomalous ozone works as a memory for the following summer in the HS years. In fact, an anomalous ozone is created in association with the vertical extension of the modes in winter in the HS years. Such anomalous ozone becomes a heat source in the summer and creates the summer signal. Thus, understanding why the signal vertically extends so high only in the HS years is a key issue for the solar-cycle modulation of the NAO/SAM. We seek to investigate this issue by extending our studies on the solar-cycle modulation in the SH.

[5] Previous studies [*Kuroda and Kodera*, 2005; *Kuroda and Shibata*, 2006] examined variability associated with the surface SAM. To understand the relationship with the stratosphere, it is necessary to examine the signal associated with the dominant variability of the stratosphere. Thus, in this study we performed analyses based on the stratospheric SAM and compared them with the surface one to gain more insight into the solar-cycle effect.

2. Data and Method of Analysis

[6] The observational data we used in this study are from the 40-year reanalysis data of the European Center of Medium-range Weather Forecasts (ERA40) [*Uppala et al.*, 2005]. We used 33 years of monthly mean data from 1968 to 2000.

[7] We first extracted the dominant mode of variability for the 30-hPa geopotential height south of 20°S for each month by year-to-year Empirical Orthogonal Function (EOF) analysis. We then computed the lagged correlation based on the dominant stratospheric principal component (SC1) in November. The dominant mode, which explained 61% of the total variance, was much larger than the second one (18%). We selected November as a reference month for the stratosphere because it is the center of active months in the SH [*Thompson and Wallace*, 1998].

[8] We separated all the years into HS and LS activity years based on the strength of the November-mean of the 10.7 cm microwave flux (F10.7). Though this criterion is slightly modified from *Kuroda and Kodera*'s [2004] July-to-October-mean, we selected this criterion for simplicity. If the mean F10.7 flux in a particular November was greater (smaller) than the average of the 33 winters, the winter was categorized as the HS (LS). In this way 16 (17) winters were identified as the HS (LS) winters. Correlation analysis was then performed for the HS or LS winters separately, based on the SC1 of November, similar to that performed in previous studies [*Kodera*, 2002, 2003; *Ogi et al.*, 2003; *Kuroda and Kodera*, 2005].

[1]Meteorological Research Institute, Tsukuba, Japan.

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[9] The model used in the present paper is the same as that used by *Kuroda and Shibata* [2006], a chemistry-climate model (CCM) developed by the Meteorological Research Institute (MRI-CCM) [*Shibata et al.*, 2005]. We integrated the model for 21 years with seasonally varying climatological sea-surface temperature. Three runs were performed from the same initial and boundary conditions except for the strength of ultraviolet (UV) radiation. The first and second runs used the same intensity as in LS and HS years, and we refer to these two runs as LS and HS runs. These two runs were the same as those performed by *Kuroda and Shibata* [2006]. The third was an ultra solar (US) run. For the US run, the ratio of the strength of the UV to that of the HS was set to be the same as the corresponding ratio for the HS runs relative to the LS runs. The UV spectrum of the HS and LS runs was taken from the observation by *Lean et al.* [1997]. Climatologically, as the seasonal evolution of the model was delayed one month after the observation, we performed the same correlation analysis based on the first principal component of the EOF for the geopotential height at 30-hPa (called SC1) in December.

[10] Most figures in this paper are for correlation with the November (observed) or December (simulated) SC1. Therefore, the figures are relative to a *positive change* in the SC1.

3. Results

[11] First, we calculated the lagged correlation of zonal wind in each month with the November SC1 (Figure 1). Here a correlation greater than 0.5 is contoured in steps of 0.1, and regions of correlation greater than 0.4 are shaded, as by *Kuroda and Kodera* [2005]. As the 95% level of statistical significance corresponds to 0.50 (0.48) for 16 (17) samples, the area of correlation greater than 0.5 corresponds to about the 95% significance level. A correlation of 0.4 corresponds closely to the 90% level of significance. In Figure 1, arrows indicate the correlation of the E-P flux. Only arrows with absolute values greater than 0.5 are plotted.

[12] In the HS years, greater correlation of the zonal wind is found in the whole stratosphere in October, associated with reduced upward propagation of the planetary waves. The zonal wind signal also extends down to the surface though it is not strong. In November, the tropospheric signal is amplified, and clear meridional dipole structure with a positive signal centered at 60°S and negative one at 40°S is created. A strong stratospheric signal extends to the whole high-latitude stratosphere and to the polar side of the troposphere. The surface signal is very similar to the SAM. It should be noted that wave activity in the troposphere is also significant, and should have sustained the surface SAM signal. Though the connection to the surface becomes weaker in December, the signal in the stratosphere retains its strength. In contrast, in the LS years, the signal of the zonal wind is weaker and exists almost exclusively in the stratosphere, and the extension to the surface is very weak. It should be also noted that wave activity in the stratosphere in October is very low compared with that of the HS years.

[13] It can be seen that in the HS years stratospheric variability is stronger, extended to the whole stratosphere, and reaches the surface (Figure 1). In particular, it should be noted that the correlation between the SC1 and SAM index on 850 hPa (called the tropospheric principal component (TC1)) in November is 0.58 (0.43) in the HS (LS) years, as shown below the panel in Figure 1. The present analysis indicates that the correlation between the stratospheric and tropospheric SAM index, which expresses the strength of stratosphere-troposphere (ST) coupling, tends to be stronger in the HS years than in the LS years.

[14] To examine this point in more detail, we separated all data according to the strength of the November mean F10.7 index and calculated the correlation between SC1 and TC1. As correlation from a small number of samples is statistically unstable, we used 11 winters for each calculation. Each winter was selected from winters of consecutive F10.7 indices when sorted according to the F10.7 indices. Figure 2a presents the result of such calculation. Abscissa and horizontal bar of each closed circle indicate the averaged value and the range of F10.7 index of 11 winters used for the calculation. Calculation is done for the smallest, middle, and the largest 11 winters of F10.7 indices from 33-year data. Also calculated are two more 11-winters whose centers are on the boundaries between them. Note that every other circle in Figure 2a is statistically independent each other.

[15] Figure 2a clearly reveals that the ST coupling tends to be stronger with stronger solar activity. However, this analysis did not indicate the key factor of the solar activity to control the ST coupling. Relatively smaller number of winters of analysis is another problem.

[16] To clarify this point, we performed numerical experiments using a CCM. Correlations of the zonal-mean zonal wind with the December SC1 are compared (Figure 3). As we analyzed 20 winters, the correlation of 0.4 (0.5) corresponds to 93% (98%) significance. The numbers shown below the panels indicate correlations between the SC1 and the SAM index on 850 hPa.

[17] It can be clearly seen that the correlation of the stratospheric and tropospheric SAM indices becomes stronger with increasing UV strength. In fact, stratospheric SAM has no significant correlation (0.18) with the troposphere in the LS run, whereas it has high correlation of 0.49 (0.76) in the HS (US) run. Comparison of these three runs indicates that TS coupling tends to be stronger with stronger UV. As is expected from this result, the signal associated with the late winter/spring SAM on the surface extends more strongly to the upper stratosphere in the US run (not shown).

4. Discussion and Remarks

[18] The present analysis clearly reveals that the TS coupling tends to be stronger with the solar activity. Previous study [*Kuroda and Kodera*, 2005] indicates that the SAM signal in late winter/spring extends to the upper stratosphere in the HS years but is confined in the troposphere in the LS years. Comparison of the previous and present results reveals that such differences result from different strength of TS coupling; it is stronger in the HS years but weaker in the LS years. Numerical experiments with a CCM confirmed that such differences of the TS coupling are due solely to the strength of UV radiation.

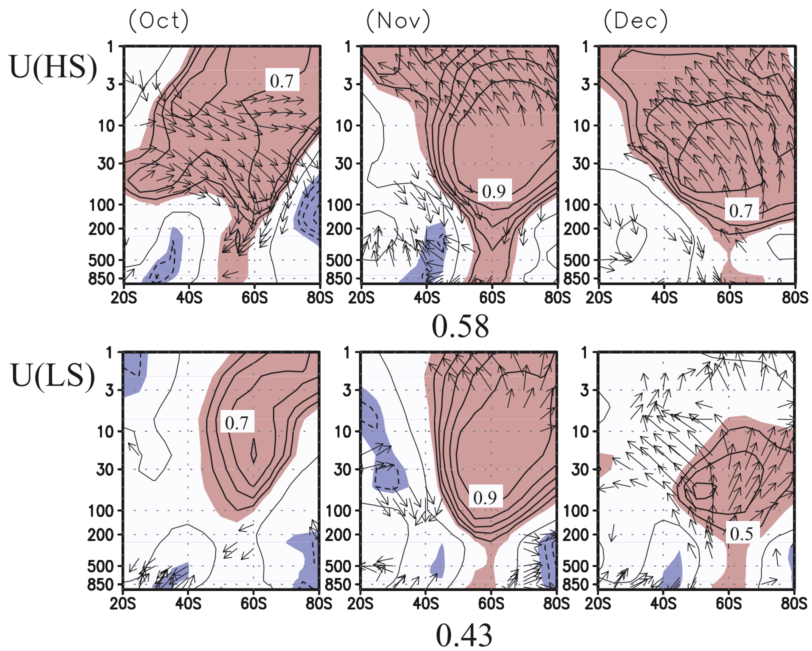

Figure 1. Correlation coefficients between the November SAM index at the 30-hPa level and the E-P flux (arrow) and zonal-mean zonal wind (contoured) from October to December at each grid point for the period of 1968 to 2000 for the HS years (upper panels) and the LS years (lower panels). The contour interval is 0.1, and contours are drawn for absolute values greater than or equal to 0.5 and for zero. Shading is applied to regions where the absolute value of the correlation is greater than 0.4. Dashed lines indicate negative values. Only arrows with absolute values larger than 0.5 are plotted. The number below the panel indicates the correlation between the 30- and 850-hPa SAM indices.

[19] We did not consider effects of the Quasi-Biennial Oscillation (QBO) and trend in the present study. However, additional analysis shows that the effect of the QBO and trend was found to be very small. This is contrasting with the North Atlantic Oscillation (NAO) whose solar-cycle modulation with the QBO and trend is very prominent [*Kuroda*, 2007].

[20] The present analysis of the observation and CCM experiments indicates a strong relationship between TS coupling and UV radiation. However, it is important to understand why TS coupling becomes stronger with the increased strength of UV. Previous and present analyses indicate that both the stratospheric and tropospheric SAM patterns have a more wavy structure in the HS winters than in the LS winters [*Kuroda and Kodera*, 2005]. Also, observation reveals prominent wave propagation in October in only the HS years (Figure 1). A larger difference in the wave propagation is also apparent in the CCM experiments. Also observed was a large difference in the signal in the meridional circulation; signals of wave forcings and deep meridional circulation tend to be stronger with stronger UV (not shown).

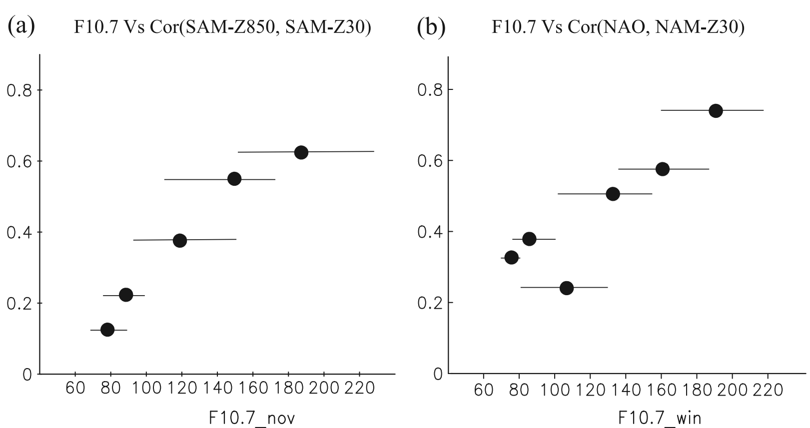

Figure 2. Scatter plots indicating the relationship between (a) the correlation between the November-mean 30-hPa and 850-hPa SAM indices and mean F10.7 index in the SH and (b) the correlation between the DJF-mean 30-hPa NAM and NAO indices and mean F10.7 index in the NH. The horizontal bar indicates the range of F10.7 indices of each winter for the calculation. See the text for more detail.

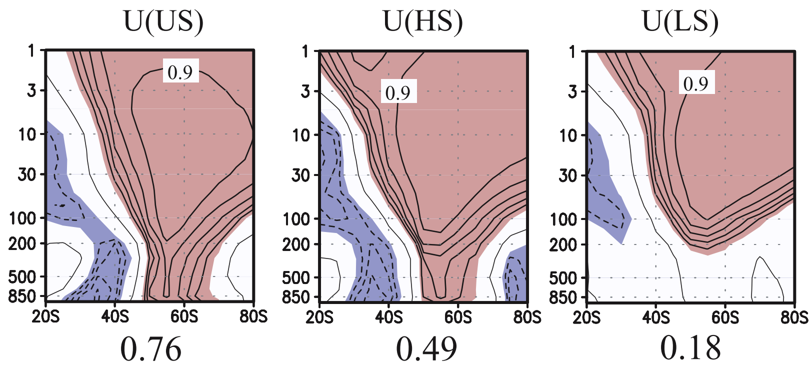

Figure 3. Same as Figure 1 except for the correlation of the December SAM index from the model-experiments of a chemistry-climate model (CCM) with changing ultra-violet radiation. From left to right, panels illustrate ultra-solar (US), high-solar (HS), and low-solar (LS) runs.

[21] One possible source of the stronger TS coupling with enhanced UV is a larger interaction between the planetary waves and radiation during HS winters. In the HS years ozone has a higher mean density in the stratosphere [e.g., *Soukharev and Hood*, 2006], which has a large impact on the waves. Figure 4 compares the correlation of temperature and ozone waves at 60°S with the SC1 during the HS winters in the ERA40 data. It can be seen that the temperature and ozone waves have almost the same phase structure in the lower to middle stratosphere in October. A similar result is obtained in the CCM experiments (not shown). These results suggest that heating of ozone due to UV have a large impact on the wave propagation in the HS winters [*Nathan and Cordero*, 2007]. It should be noted that the phase structure of the climatological wave in October is almost the same as in Figure 4, except for the sign. Therefore, if a planetary wave in the troposphere has smaller amplitude and the same phase as the climatological wave, the wave should reduce its amplitude significantly with upward propagation by the interaction of ozone and wave propagation will become weaker (Figure 1). Such a reduction of wave amplitude produces larger anomalous wave forcings in the stratosphere during the HS winters. As wave forcings in the stratosphere produce meridional circulation that extends to the surface, zonal wind at the surface is also produced through Coriolis forcing and acts

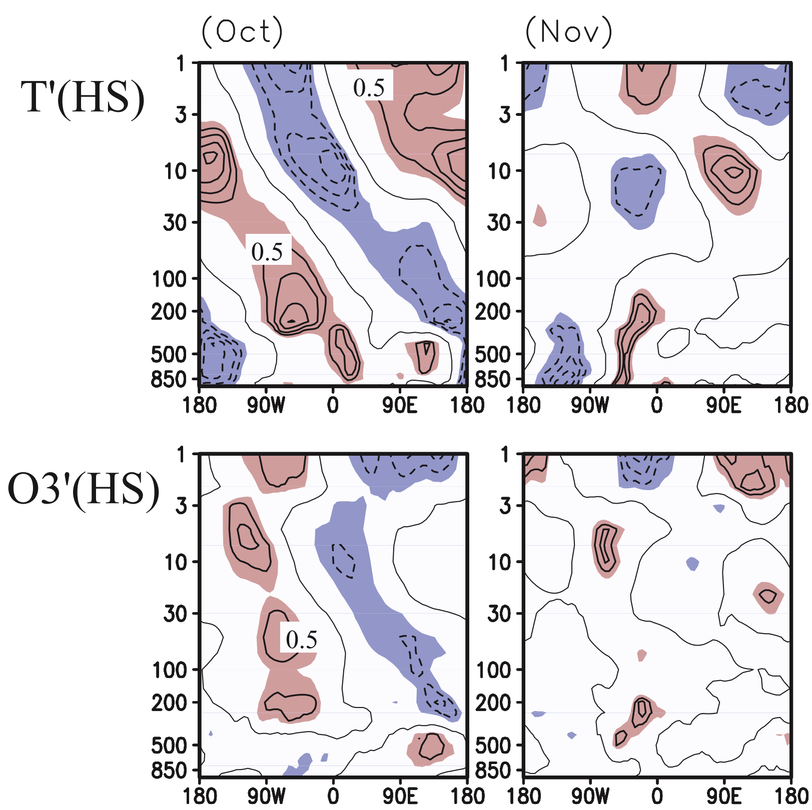

Figure 4. Same as Figure 1 except for the longitude-height cross section of the temperature and ozone wave at 60°S from October to November.

as the wave generator. As such processes work as positive feedback [*Kuroda and Kodera*, 2004], ozone-wave interaction in the stratosphere produce stronger ST coupling during the HS winters.

[22] Solar-cycle modulation of the NAO was also observed in the NH winter [*Kodera*, 2002, 2003]. As the structural modulation was similar to that in the SH, it is expected that the same mechanism (i.e., the strengthening of TS coupling with the solar activity) works for modulation in the NH. Therefore we performed a similar analysis as Figure 2a based on the stratospheric Northern Annular Mode (NAM) index [*Baldwin and Dunkerton*, 2001] at the 30-hPa level and the NAO index. Figure 2b compares the correlation of the winter-mean NAO index [*Hurrell*, 1996] and stratospheric NAM index, and winter-mean F10.7 index. Here, we used data from 1958 to 2000 and used 12 years for each calculation of the correlations. Figure 2b also indicates that the ST coupling tends to be stronger with the solar activity.

[23] The present analysis suggests that the modulation of the TS coupling due to enhanced UV and ozone is an important process for the understanding of the solar cycle effect on tropospheric climate. Additional studies will be needed to clarify more details in the future.

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M. Deushi, Y. Kuroda, and K. Shibata, Meteorological Research Institute, 1-1 Nagamine, Tsukuba-city, Ibaraki 305-0052 Japan. (kuroda@mri-jma.go.jp)