Simulation of solar-cycle modulation of the Southern Annular Mode using a chemistry-climate model

Yuhji Kuroda[1] and Kiyotaka Shibata[1]

Received 3 November 2005; revised 29 December 2005; accepted 2 February 2006; published 3 March 2006.

[1] Using a coupled chemistry-climate model, we simulated the structural modulation of the Southern Annular Mode (SAM) caused by the change in ultraviolet radiation (UV) associated with the 11-year solar cycle. In an enhanced UV run, the SAM signal in late winter extended to the upper stratosphere and persisted until the following autumn. In a reduced UV run, the signal was mostly confined to the troposphere and disappeared very quickly during the following summer. This greater persistence in an enhanced UV run is connected to the formation of an ozone anomaly in the polar lower stratosphere, produced by the modulation of the Brewer-Dobson circulation in late winter.

Citation: Kuroda, Y., and K. Shibata (2006), Simulation of solar-cycle modulation of the Southern Annular Mode using a chemistry-climate model, *Geophys. Res. Lett.*, *33*, L05703, doi:10.1029/2005GL025095.

1. Introduction

[2] Estimation of the effect of the solar cycle on the Earth's climate is an important factor in understanding the climate system. Studies on this subject include results from the general circulation model (GCM) simulations [e.g., *Shindell et al.*, 1999; *Matthes et al.*, 2004] and various observations [e.g., *Labitzke and van Loon*, 1988; *Kodera and Kuroda*, 2002].

[3] Past studies of the solar cycle have mainly considered its effect on mean climate. More recent studies, however, have found that the solar cycle affects the variability of the climate "mode." Observations analyzed by *Kodera* [2002, 2003] and *Ogi et al.* [2003] showed that the 11-year solar cycle significantly affected the normal variability associated with the winter-mean North Atlantic Oscillation (NAO). They found that at high activity or "high" solar (HS) years, the winter-mean NAO extends higher to the upper stratosphere, and lasts longer until next summer. In contrast, in low activity or "low" solar (LS) years, it is mostly confined to the troposphere and disappears very quickly.

[4] *Kuroda and Kodera* [2005], analyzing observations, showed also that variability associated with the Southern Annular Mode (SAM) in late winter behaves very similarly to that of the winter-mean NAO; the signal extends to the upper stratosphere and persists until the next autumn in HS years, whereas it is restricted in the troposphere and disappears very quickly in LS years.

[5] Because of insufficient records, especially in the upper stratosphere, a sufficiently long integration of a GCM is needed to reproduce the observed results. We will also examine the origin of the solar-cycle modulation in the climatic mode. *Tourpali et al.* [2005] was the first to reproduce the solar-cycle modulation of the winter-mean Arctic Oscillation (AO) using a chemistry-climate model (CCM). As a modulation of the AO, they reproduced the vertical extension and some duration of the AO signal by varying the strength of the UV radiation.

[6] The purpose of this study is to reproduce the solar-cycle modulation of the SAM found by *Kuroda and Kodera* [2005] using a CCM, and to examine the origin of the solar-cycle modulation using a self-consistent data set from the CCM.

2. Model Design and Method of Analysis

[7] The model used in this study was a CCM developed in the Meteorological Research Institute/Japan Meteorological Agency (MRI/JMA). The dynamic package was based on the standard, middle-atmosphere version of the MRI-spectral GCM [*Shibata et al.*, 1999], which includes major physical processes such as convection, radiation, planetary boundary layers, and ground hydrology. For simplicity, we used Rayleigh friction in the upper atmosphere as a gravity-wave parameterization. The model was triangularly truncated at a total wave number of 42 and had 45 layers in the hybrid pressure-sigma coordinate with an upper boundary at 0.01hPa. The chemical package contained major stratospheric species, i.e., 34 long-lived and 15 short-lived species with 79 gas-phase reactions, six heterogeneous reactions on polar stratospheric clouds, and three heterogeneous reactions on sulfate aerosols. See *Shibata et al.* [2005] for more detail. Boundary conditions for the chemistry in the model runs, such as concentration of carbon dioxide and CFCs, were set as those in middle 1990's.

[8] We performed two sets of 21-year runs with annually repeating sea-surface temperatures (SSTs) from the same initial condition, which was created from a long time-integration. The only difference between these two sets was the strength of the UV radiation; one under the HS condition, and the other under the LS condition. The difference of the UV spectrum is taken from the observations by *Lean et al.* [1997].

[9] We based our analysis on monthly mean data sets and on 20-year sub-data sets from winter to the following autumn. The second-order quantities such as the Eliassen-Palm (E-P) flux and the residual velocity was calculated based on the daily mean data and then converted to monthly mean data.

[10] The SAM index was calculated by Empirical Orthogonal Function analysis of the month-to-month variability of 850-hPa geopotential height, south of 20°S, the same as the original definition by *Thompson and Wallace* [1998, 2000].

[1]Meteorological Research Institute, Tsukuba, Japan.

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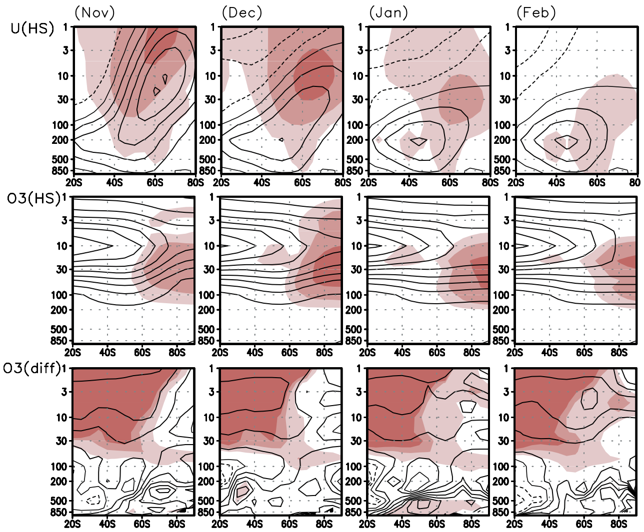

Figure 1. Twenty-one-year climate of the mean zonal wind (upper panels), ozone (middle panels) in the HS run, and difference of ozone between HS and LS runs (lower panels) from November to February. The contour intervals are 10m/s (upper panels), 1 ppmv (middle panels), 1% (lower panels) and dashed lines represent negative values. The zero line is indicated by a thin solid line. Shading indicates year-to-year variability (upper and middle panels) or Student's-t (lower panels). The light, middle, and heavy shading indicate regions where standard deviation is greater than 2, 5, and 10m/s for upper panels, 0.1, 0.2, and 0.5 ppmv for middle panels, and 2 (significant for 95% levels), 4, and 6 for lower panels, respectively.

[11] Most of figures in this paper are for correlations with the November–December (ND) mean SAM index. This means that the figures are relative to a *positive change* in the ND mean SAM index. Note that all the signs should be reversed if changes associated with negative ND mean SAM index are considered.

[12] In this paper, we called a season as "winter" ("summer") when westerly extends to the upper stratosphere (lower stratosphere), and "spring" and "autumn" as transition periods.

3. Results

[13] Figure 1 depicts the seasonal march of the climatological zonal-mean zonal wind and ozone for the HS run, and difference of ozone between HS and LS runs, from November through February. The zonal wind was almost the same between HS and LS runs, although its variance was somewhat greater in the HS run (not shown). Compared to observations, however, the simulated seasonal march from winter to summer was delayed by about one month; i.e. the overall features of November, December, and January in the model were similar to those of October, November, and December in the observations. Such a bias is common in many GCMs [*Pawson et al.*, 2000]. The variability of the zonal wind was very similar to observations. However, as a result of delayed breakdown of the polar vortex, the summer season was approximately one month shorter than observations.

[14] Except for the delayed seasonal march, the simulated ozone well describes overall features of observations [e.g., *Shibata et al.*, 2005], including a maximum in the tropical middle stratosphere and smaller ozone in the polar lower stratosphere in the latter half of the winter, although the area of ozone-hole was about half size of observations in middle 1990's (not shown). It should be noted that significant 2 to 3 % increase of ozone in the stratosphere is obvious in the HS run compared with the LS run.

[15] Because of the delayed breakdown of the polar vortex, we performed correlation analysis not for the October-November mean SAM index as in the work of *Kuroda and Kodera* [2005], but for the ND mean SAM index.

[16] Figure 2 compares the correlation pattern of the zonal wind from November to March with ND mean SAM indices for the HS and LS runs. In the HS run (upper

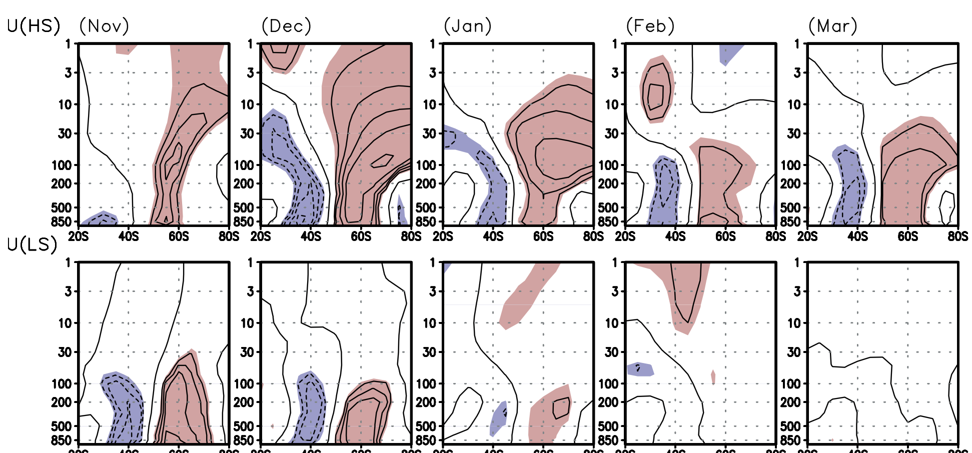

Figure 2. Correlation coefficients between November–December mean Southern Annular Mode index and the zonal-mean zonal wind at each grid point for the 20-year time frame of the HS (upper panels) and LS (lower panels) runs. The contour interval is 0.1 and contours are drawn for zero and for absolute values greater than or equal to 0.5. Shading is applied to regions where the absolute value of the correlation is significant for 95% levels (greater than 0.44). Dashed lines indicate negative values.

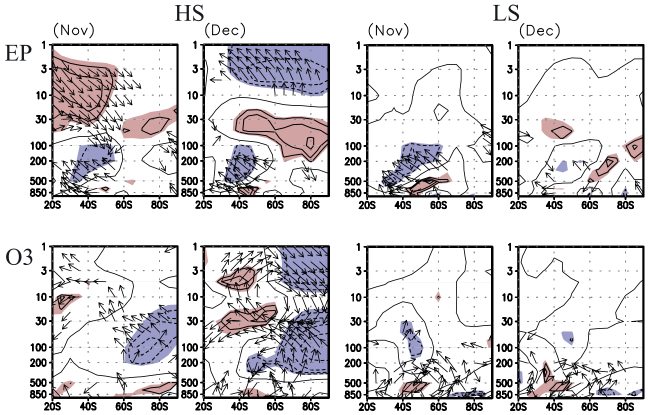

Figure 3. Same as Figure 2, except showing the lagged correlation of the E-P flux (arrow) and its divergence (contour, upper panels), or the residual circulation (arrow) and ozone density (contour, lower panels) from November to December for HS run (left panels) and LS run (right panels). Only arrows whose correlations are significant for 99% levels (greater than 0.56) are shown.

panel), a significant positive signal first appeared in September, in the lower stratosphere, at approximately 55°S (not shown). After weakening in October, the signal increased significantly in November, extending from the surface to the upper stratosphere, although a significant area was confined to a narrow latitudinal area at approximately 60°S. In December, the high-latitude positive signal extended higher with a vertically extended low-latitude negative signal, which produced a meridional dipole structure. With the evolution of the seasonal march, the vertical extension decreased in January, but the meridional dipole structure in the troposphere persisted until the following March.

[17] In the LS run (lower panel), a significant positive signal at approximately 50°S in the troposphere first appeared in September, as in the HS run (not shown). With developing in October, the signal propagated poleward and created a meridional dipole structure with a negative signal at approximately 35°S, and a positive one at approximately 60°S in November. The signal maintained its strength until December but weakened rapidly in January. In February and afterward, the signal nearly vanished. Even in the mature stage, from November to December, the signal did not extend to the upper stratosphere as it did in the HS run.

[18] The SAM signal extended to the upper stratosphere in late winter and lasted until the following autumn in the HS run. In the LS run, it was almost confined to the troposphere, and did not last very long in the following summer. These features were very similar to those observed by *Kuroda and Kodera* [2005].

[19] To determine the source of the difference between the HS and LS runs, we diagnosed the wave activity associated with the ND mean SAM indices. The upper panel of Figure 3 compares the correlation of E-P flux and its divergence with ND mean SAM indices in November and December when the different features of these two runs become apparent. Arrows indicate the correlation with the E-P flux. The variability of the E-P flux extended toward the upper stratosphere from November to December in the HS run, but there was no such variability in the LS run. Corresponding to the variability of the E-P flux, there is a significant anomaly of the E-P flux divergence (ED) in the stratosphere in the HS run, but it is absent in the LS run.

[20] In the HS run, the poleward and downward arrows of the E-P flux in the low-latitude upper stratosphere represent the weakening of the E-P flux, which corresponds to the positive correlation of the ED from the subtropical upper stratosphere to the polar middle stratosphere in November. The regions of positive ED correspond with the positive zonal-wind anomaly in the upper stratosphere in November. The area of positive ED shifted poleward and downward in December and this corresponds to the shift of zonal wind at high latitude in this month. The feature of the E-P flux and its divergence was very similar to that observed from October to November in the HS years (not shown).

[21] The ED induces residual circulation in addition to accelerating zonal wind. The lower panel of Figure 3 compares the correlation of residual circulation and ozone density with ND mean SAM indices from November to December. An anomalous residual circulation extended to the upper stratosphere in the HS run, but was mostly confined to the troposphere in the LS run.

[22] In the HS run, arrows point upward and equatorward for the residual circulation in the polar lower-stratosphere corresponding to the weakening of the downward residual circulation from November to December. Such circulation should be driven by the anomalous positive ED above them. Here, it should be noted that residual velocity corresponded well to the material velocity. Ozone is transported to the polar lower stratosphere from the middle to the upper tropical stratosphere by the residual circulation, called the Brewer-Dobson circulation. Thus, corresponding with the weakening residual velocity, the ozone density should be reduced in the polar lower stratosphere. It was directly verified by the data set of ozone change (not shown). This appears as a negative anomaly of the ozone density in the polar stratosphere in the HS run in response to a positive change in the ND SAM index. Such an anomaly is absent in the LS run, corresponding with the absence of the anomalous residual velocity in the stratosphere.

[23] Once anomalous ozone is created in the lower stratosphere in late winter, it should remain at least until the next winter because the wave forcing in the stratosphere is very small in summer and the lifetime of ozone is very long in the lower stratosphere. Figure 4 depicts the correlation of temperature and ozone density with ND mean SAM indices from November to March in the HS run. Time evolution of the ozone density (lower panel) indicates that anomalous ozone in the lower polar stratosphere in late winter lasts through the following months. Because the energy of short-wave radiation is strongest in the summer season, this anomalous ozone will affect the temperature because ozone is a major radiative heat source in the stratosphere. Examining the heating rate from short-wave radiation indicated that the pattern was very similar to the ozone density (not shown). Although the infrared radiation should also have had a significant impact on the temperature, the activity in the lower stratosphere was passive,

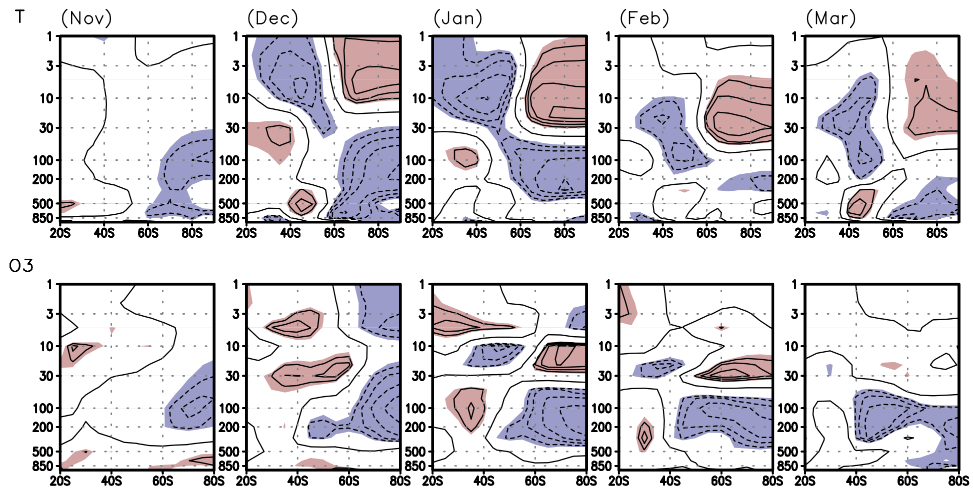

Figure 4. Same as Figure 2, except showing the lagged correlation of the zonal-mean temperature (upper panels) and ozone density (lower panels) for HS run.

rather than active as for the short-wave radiation. It is likely that the temperature pattern is strongly affected by the ozone density in the lower stratosphere. In fact, the time evolution of the temperature anomaly (upper panel) indicates that the lower polar stratosphere tends to remain colder until the following autumn, although the center of the colder region shifts into the troposphere in March through a downward advection of the colder air. Such a temperature anomaly should create a zonal-wind anomaly through the thermal-wind relationship. This explains why zonal-wind anomalies are so persistent in the HS run. Such an ozone anomaly in late winter is absent in the LS run (Figure 3), so ozone and temperature anomalies do not appear in the summer season (not shown).

4. Discussion and Remarks

[24] This study indicated that the simulation of a CCM would reproduce the main feature of the observed solar-cycle modulation [*Kuroda and Kodera*, 2005]. The model accurately simulated the higher extension and greater persistence of the SAM signal in late winter in the HS condition, and the lower extension and shorter lifetime of SAM in the LS condition. We found that the persistence of the SAM in summer comes from the lower stratospheric-ozone anomaly that was produced by the modulation of the Brewer-Dobson circulation in late winter in the HS condition. Such anomalous ozone became a radiative heat source in summer, created a zonal-wind anomaly through the thermal-wind relationship, modified wave propagation, and created a mechanical-forcing anomaly and meridional circulation that should create surface pressure changes to generate the SAM signal on the surface [*Kuroda*, 2005]. Note that this explanation corresponds to the positive ND mean SAM, but a situation with the negative change in the ND mean SAM corresponds to the same physical mechanism with quantities of opposite sign.

[25] From the scenario above, it is apparent that the different duration of the SAM signal originates from different upper extensions of the SAM signal in late winter. Richer ozone and stronger UV in the HS run may have caused the higher extension of SAM signals. In fact, the ozone density in the HS run was approximately 2 to 3% greater than that of the LS run in the stratosphere (Figure 1). Future study is needed to determine how such a small difference in ozone and UV radiation can create such a large structural difference of SAM.

[26] In this experiment, the difference in forcing between the HS and LS runs was only a small change in the UV radiance. All other parameters, such as the SST, were kept the same in both runs. Results thus demonstrated that the solar-cycle modulation of the SAM came solely from UV radiation, and not from other agents (such as cosmic rays) associated with the 11-year solar cycle.

[27] **Acknowledgments.** The authors are grateful to M. Deushi for model runs. This work was supported in part by a Grant-in-Aid (15340155, 16340144, 17340143) for Science Research of the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

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