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Author(s)	Kuroda, Yuhji; Yamazaki, Koji
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Influence of the solar cycle and QBO modulation on the Southern Annular Mode

Yuhji Kuroda[1] and Koji Yamazaki[2]

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[1] Influence of the 11-year solar cycle and the stratospheric equatorial Quasi-Biennial Oscillation (QBO) on the Southern Annular Mode (SAM) in late winter/spring is examined through the analysis of combined reanalysis data of ECMWF. It is found that the signal is strongly affected by both the solar cycle and the QBO. Regarding the effect of the solar cycle, the signal extends to the upper stratosphere and persists into the following summer in years with high solar activity, but it is restricted to the troposphere and disappears very quickly in years with low solar activity. For the QBO, the signal extends to the upper stratosphere in late winter/spring but disappears in the following summer in QBO-west years. On the other hand, the signal extends vertically as the time evolution and tends to persist into the following summer in QBO-east years. When both the solar cycle and the QBO are considered, the effects from the solar cycle dominate and those from the QBO work as linearly superimposed factors. Role of ozone on the solar cycle and QBO modulation is also discussed. **Citation:** Kuroda, Y., and K. Yamazaki (2010), Influence of the solar cycle and QBO modulation on the Southern Annular Mode, *Geophys. Res. Lett.*, *37*, L12703, doi:10.1029/2010GL043252.

1. Introduction

[2] There has been increasing evidence in recent years that tropospheric climate is strongly affected by the stratosphere through such phenomena as the 11-year solar cycle and the equatorial Quasi-Biennial Oscillation (QBO) [e.g., *Labitzke and van Loon*, 1999]. It has also been found that important stratospheric effects in the troposphere sometime appear as a mode of variability known as the Arctic Oscillation (AO), or as the Northern Annular Mode in the Northern Hemisphere [e.g., *Baldwin and Dunkerton*, 2001] and as the Southern Annular Mode (SAM) in the Southern Hemisphere (SH) [*Limpasuvan and Hartmann*, 2000].

[3] Previous studies have shown that the annular modes (AMs) in the active season, the time of the year when stratosphere-troposphere coupling is strongest [*Thompson and Wallace*, 1998], show very large structural modulation caused by the solar cycle. In fact, *Kodera* [2002] and *Ogi et al.* [2003] found that in winter the spatial and temporal structure of the Northern Atlantic Oscillation (NAO), which is considered to be the Atlantic version of the AO, is greatly modified by the solar cycle. *Kuroda and Kodera* [2005] (hereafter KK05) found that the spatial and temporal structure of the SAM in late winter/spring is similarly considerably modified by the solar cycle.

[4] For these studies, only the effect of the solar cycle is considered. However, previous studies [e.g., *Labitzke and van Loon*, 1988; *Naito and Hirota*, 1997] have shown that the effects of the solar cycle become more clear if the phase of the QBO is considered. Regarding this point, *Kuroda* [2007, hereafter K07] examined the effects of the solar cycle and QBO on the winter NAO, and found that the characteristics of the solar cycle modulation are much more enhanced in the westerly (W) phase of the QBO, but the modulation from QBO alone is not as prominent.

[5] Therefore, it would be interesting to examine how the SAM in late winter/spring, active season in the SH, is affected by the solar cycle under the effect of the QBO, and to compare its characteristics with the NAO. This paper is organized as follows. Section 2 describes the data and principal method of analysis. After showing the results in Section 3, Section 4 offers discussions and remarks.

2. Data and Analysis Method

[6] The meteorological data we used in this study are a combination of two reanalysis data sets of the European Centre for Medium-Range Weather Forecasts (ECMWF), one a set of 40-year reanalysis ECMWF data (ERA-40) [*Uppala et al.*, 2005] and the other a set of Interim data (ERA-Interim) [*Berrisford et al.*, 2009]. Since these two data sets overlap for a few years before the Pinatubo eruption, for each month of these data we calculated the climatological difference from the data of 1989. Then after a bias correction was made for the ERA-40 data before 1988, we combined the two data sets to produce sequential data. The most recent 40-year set from 1968 to 2007, when observations in the SH became more accurate [see, e.g., *Kistler et al.*, 2001, Figure 1], is used in the present study.

[7] The SAM used in the present study is defined as the dominant month-to-month variability of the 850-hPa geopotential height throughout the year. It is extracted by empirical orthogonal function analysis of the anomalous geopotential height south of 20°S. In this study, we used the October–November (ON) mean index for the basic SAM index following a previous study (KK05). The solar cycle is classified according to the November mean 10.7-cm solar radio flux following the definition of *Kuroda et al.* [2007, hereafter KDS07]. If a year's mean solar radio flux is stronger (weaker) than average, the year is categorized as a high solar (HS) (low solar (LS)) year. Similarly, the phase of the QBO is classified according to the November mean Singapore wind at the 50-hPa level. If the wind is westerly (W) (easterly (E)), the year is categorized as a W (E) year.

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[1] Meteorological Research Institute, Tsukuba, Japan.

[2] Faculty of Environmental Earth Science, Hokkaido University, Sapporo, Japan.

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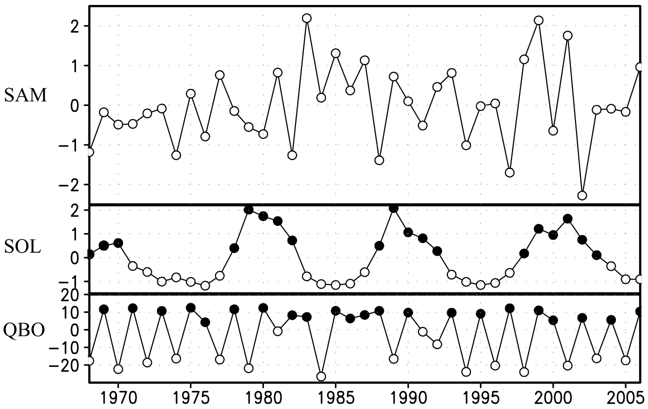

Figure 1. (top) Time coefficients of the October–November mean SAM index, (middle) November mean standardized F10.7 index, and (bottom) November mean Singapore wind at the 50-hPa level used in the present study. Black solid (open) circles in Figures 1 (middle) and 1 (bottom) indicate years when the time coefficient was positive (negative).

[8] Figure 1 shows the time series of these indices. Here, except for the time series of the ON-mean SAM index shown in Figure 1 (top), the solid and open circles indicate positive and negative index years, respectively. The year in Figure 1 indicates the year of October. The numbers of years used in the present analysis are summarized in Table 1.

[9] Most of the figures in this paper present the correlation with the ON-mean SAM index. This means that data presented in the figures are relative to a *positive change* in the ON-mean SAM index.

3. Results

[10] Figure 2 shows the time evolution of the correlation map of the zonal-wind with the ON-mean SAM index, calculated separately for each phase of the solar cycle and the QBO. The correlation is contoured for areas greater than or equal to 0.5 in steps of 0.1, and shading indicates areas of 95% significance by Student's-*t* statistics. Note that the large areas of statistical significance of all years come solely from far larger numbers of data. To clarify the difference in the correlations among categories, we have highlighted the 0.5 contours by making them thicker.

[11] For all years, a significant SAM signal appears from October to December and is especially strong in the troposphere in November. Note that October to December is the active season, when coupling between the stratosphere and troposphere is the strongest in the SH [*Thompson and Wallace*, 1998]. The present results represent this characteristic well.

[12] When the data are stratified according to the solar cycle, the results based on the new extended data set are almost the same as those shown in a previous study (KK05): The zonal-wind signal extends to the upper stratosphere from October to December, and the signal persists in the lower stratosphere until February in HS years, but it is almost confined in the troposphere from October to December and disappears in the following months in LS years.

[13] When the data are stratified according to the QBO phase, the difference in the signal is also very prominent. In the W years, the signal extends to the upper stratosphere from October to November, but the upward extension diminishes in December and the signal almost disappears after January. In the E years, on the other hand, the extension of the signal to higher altitude develops with the time evolution from October to December, and the zonal wind at high latitude extends to the upper stratosphere in December. The signal is still present in the center of the lower stratosphere from January to February, and the signal in the troposphere is especially prominent in February. To summarize, the signal is present only until December in the W years, but it is present from late winter/spring to summer in the E years. Such modulation by the QBO phases is a unique feature of the SAM and is not observed in the NAO modulation in winter (K07).

[14] The present analysis is based on the QBO wind at the 50-hPa level. However, if we stratify the data according to the wind at the 20-hPa level, for example, the signals for the W and the E years are found to be very similar to the present ones except that E and W are exchanged (not shown). This reflects the fact that the 20- and 50-hPa winds tend to have different directions.

[15] We have seen that the SAM signal is affected by both the solar cycle and the QBO, so we examined what happens if we take both the solar and QBO effects into account. It should be noted, however, that when we consider both the solar cycle and QBO effects, the number of data becomes about one-quarter (10) the number of the original set, so the statistical significance of the analysis decreases. Since the number of data is smaller, we changed the lowest (and highlighted) value for contouring to 0.6, but kept shading for areas of 95% significance. Figure 3 shows the correlation map of the zonal-mean zonal winds with the ON-mean SAM index for the four possible categories of HS/W, HS/E, LS/W, and LS/E years.

[16] In the case of the HS/W years, the zonal wind signal extends to the upper stratosphere from October to November, but the extension reduces in December. The center of action is in the lower stratosphere around 60°S and 100 hPa during these months and the signal persists until January, but it nearly disappears after February. In the HS/E years, the SAM-related signal exists separately in the subtropical upper stratosphere and in the troposphere in October. The signal from the troposphere extends to the upper stratosphere and the signal in the subtropical upper stratosphere weakens in November. The signal strongly extends to the upper stratosphere in December and is present until February, although it weakens in January.

[17] In the LS/W years, the signal in the troposphere is very weak in October. It extends to the lower stratosphere in

Table 1. Numbers of Samples Used in the Present Study[a]

Year	Number of Samples Used
ALL	39(28)
HS	19(14)
LS	20(14)
West	22(16)
East	17(12)
HS/W	9(7)
HS/E	10(7)
LS/W	13(9)
LS/E	7(5)

[a] HS, high solar; LS, low solar; W, QBO-west; E, QBO-east. The numbers in parentheses indicate those from 1979 to 2007.

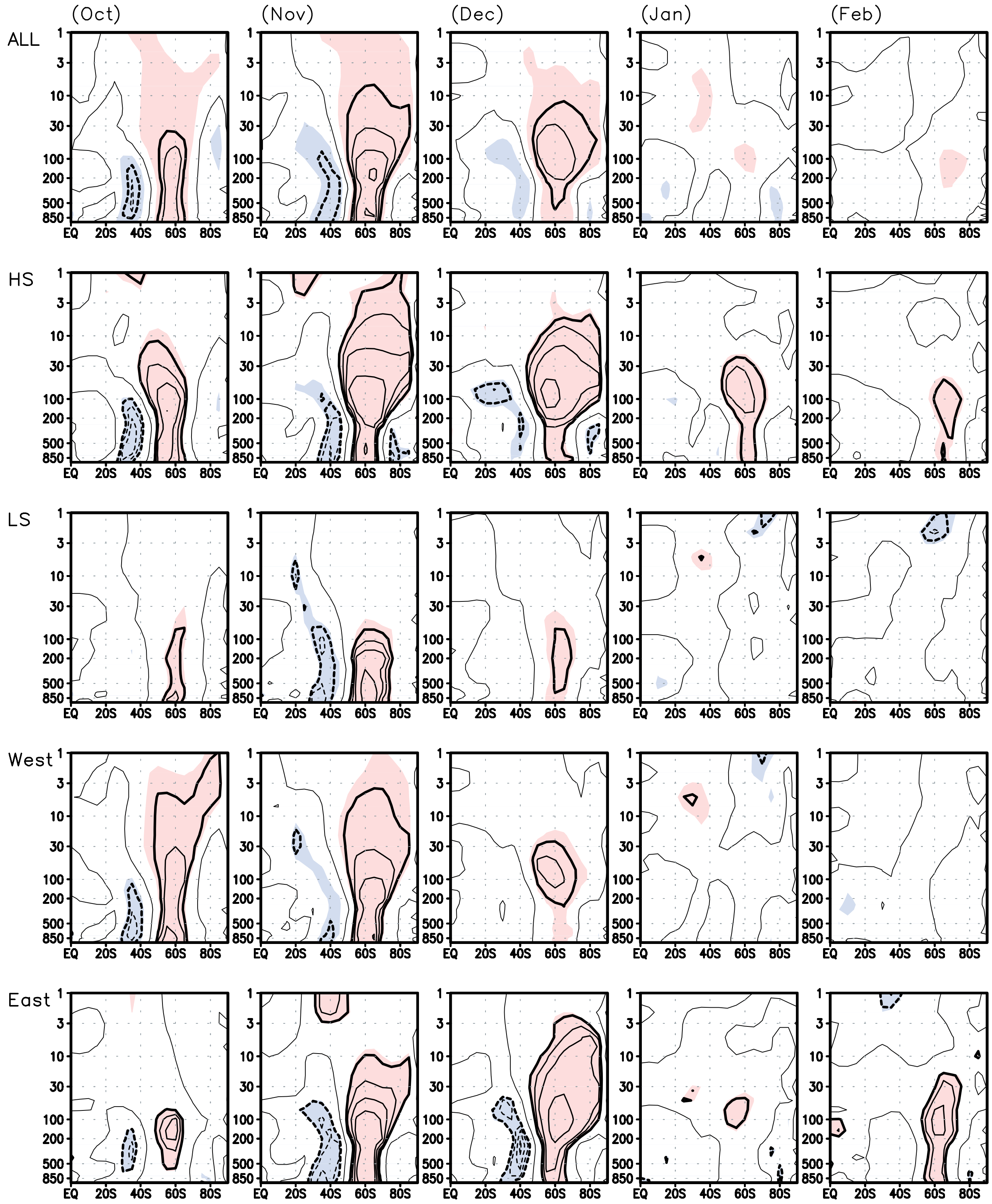

Figure 2. Correlation coefficients between the October–November mean SAM index and the zonal-mean zonal wind from October to February. From top to bottom, each plot shows the correlation from all data, HS, LS, QBO-west, and QBO-east years, respectively. The contour interval is 0.1. Contours are drawn for absolute values greater than or equal to 0.5 and for zero. Thick contours indicate a correlation of 0.5. Shading is applied to regions where the statistical significance exceeds 95% by Student's-*t* statistics. Dashed lines indicate negative values.

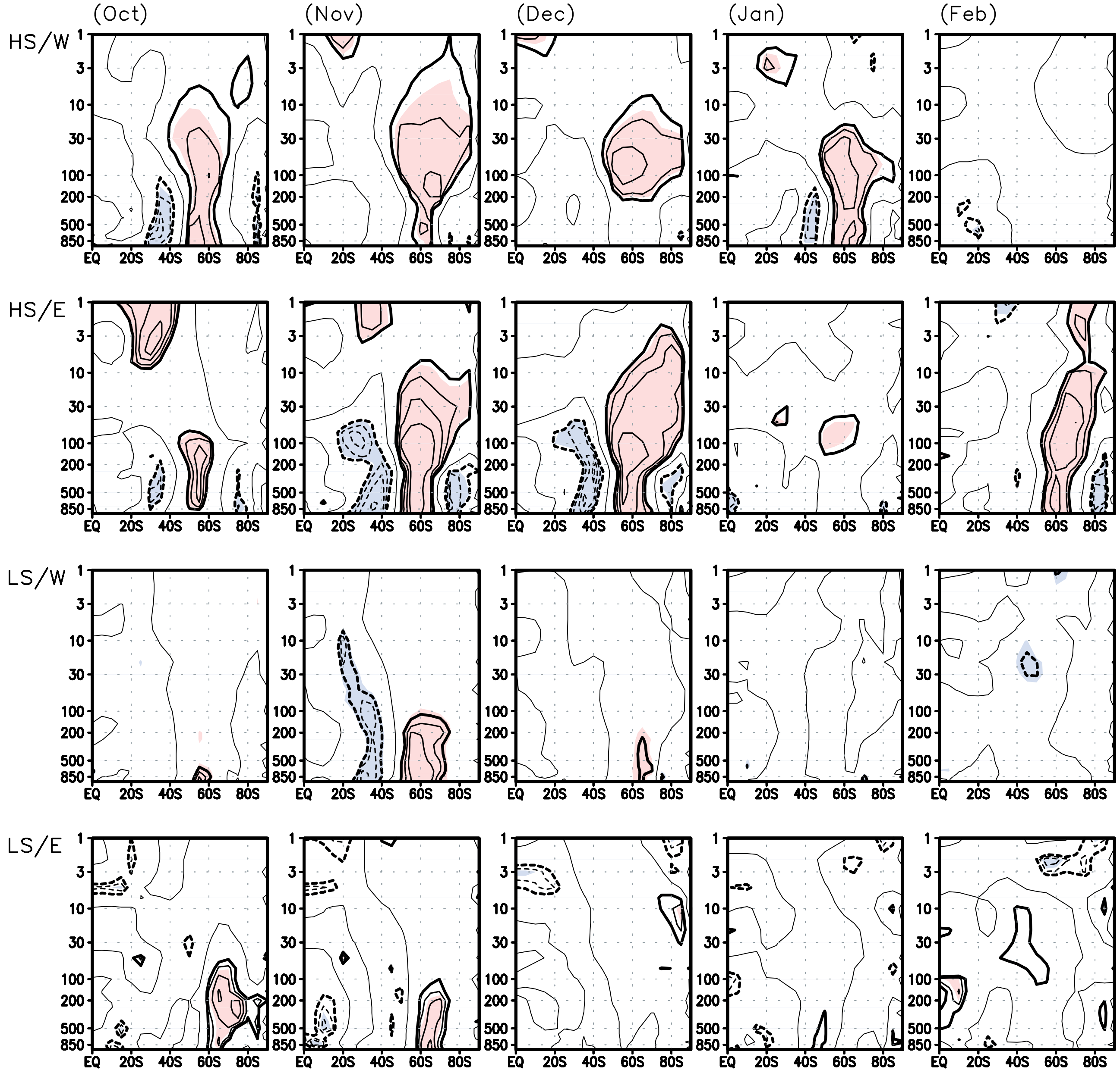

Figure 3. Same as Figure 2, except showing the correlation in the HS and LS years under each phase of the QBO. The plots show the correlation calculated from HS-west, HS-east, LS-west, and LS-east years. The contours are drawn for absolute values greater than or equal to 0.6 and for zero, and thick contours indicate a correlation of 0.6.

November, but weakens in December and almost disappears in January and later. In the LS/E years, the signal is present in the troposphere from October to November, but almost vanishes after December.

[18] In both HS/W and HS/E years, vertical extension of the signal to the upper stratosphere is observed around November, and the signal is very persistent. In comparison, in both LS/W and LS/E years, vertical extension of the signal occurs around November and persistency of the signal is poor. These characteristics are very similar to those of the solar cycle. This means that the effect of the solar cycle dominates that of the QBO for the modulation of the late winter/spring SAM. However, the difference between HS/W and HS/E clearly reflects the effect of the QBO. In fact, the persistence of the SAM signal into summer is stronger in HS/E years than in HS/W years, similar to the characteristics of the E years compared to the W years. However, when LS/W and LS/E years are compared, such QBO effects are not clear.

4. Discussion and Remarks

[19] We examined how the signal associated with the late winter/spring SAM is modified by the solar cycle and the QBO. We found that both the solar cycle and the QBO have large effects on the modulation of the SAM in late winter/spring. In fact, the signal extends to the upper stratosphere in late winter/spring and persists into the following summer in HS years, but the extension to the stratosphere is very weak in late winter/spring and does not persist into summer

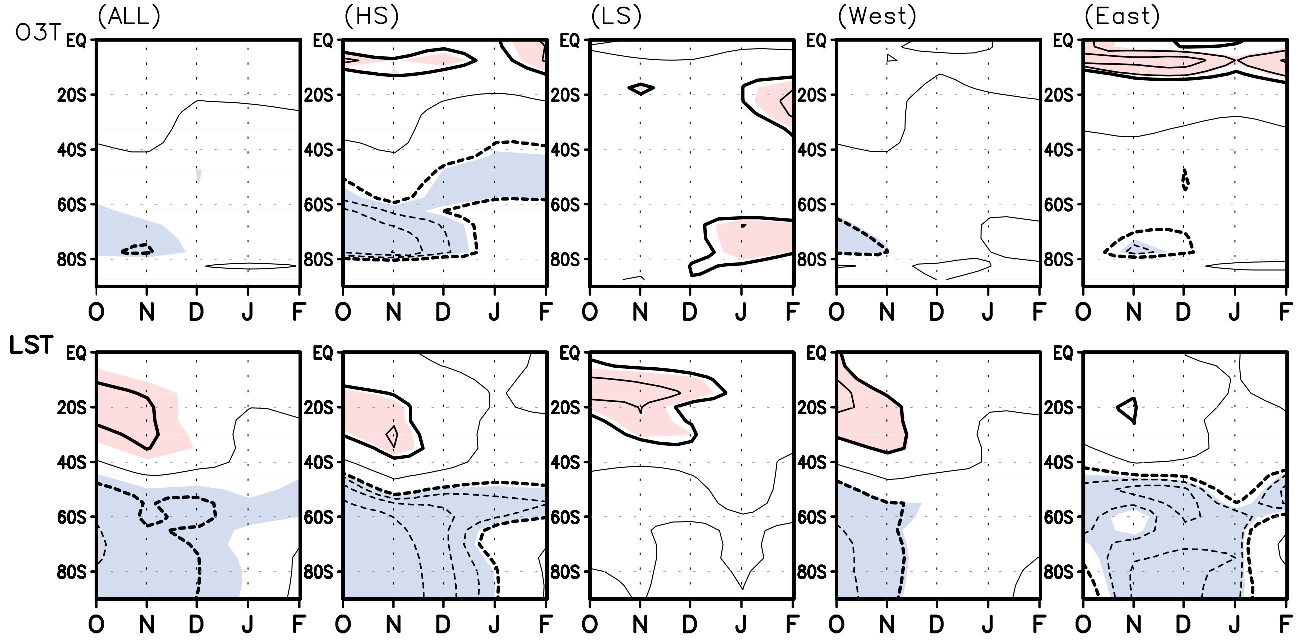

Figure 4. Same as Figure 2, except showing the time evolution of the OMI-TOMS monthly zonal-mean total column ozone and ERA lower stratosphere temperature averaged from the 200- to 50-hPa levels using data from 1979 to 2007.

in LS years. For QBO effects, the signal extends to the upper stratosphere in late winter/spring, but does not persist into the following summer in W years, and the vertical extension becomes larger in late winter/spring and persists into the following summer in E years. Moreover, when the effects of both the solar cycle and the QBO are considered, both effects appear approximately as if they are superimposed. However, when the solar cycle and QBO effects are compared, the effect from the solar cycle appears to be stronger.

[20] Regarding the impact of the QBO on the AMs, the NAO signal extends to higher altitudes in E years, but the SAM signal does not (Figure 2 of K07). However, higher persistency of the signal into the following summer is commonly observed both for the NAO and the SAM in E years (Figures 2 and 3 of K07).

[21] Previous studies (KK05; KDS07) suggested that the persistence of the signal in HS years comes from ozone. Therefore, it would be interesting to see how the ozone signal associated with the solar and QBO signal behaves. Here, we examined satellite total ozone data (OMI-TOMS combined data) because they are more reliable [*Kroon et al.*, 2008]. Since data are available only after 1979, we have analyzed them for the period from 1979 to 2007. We repeated the present analysis for this period and found that the overall SAM signals in this period are very similar to those in the previous analysis. The numbers of years for each category are listed in parentheses in Table 1. Figure 4 shows the time-latitude section of the correlation of total ozone and the lower stratospheric temperature with the ON-mean SAM index. It can be seen that prominent ozone and temperature signals are present in the HS years, but they are almost absent in the LS years. These results strongly support the hypothesis that the ozone signal becomes a memory to the following season. In contrast, in QBO-E years, the total ozone signal is not so prominent compared with the lower stratospheric temperature after December. However, analysis of profile ozone shows there is a prominent negative signal in the polar-to middle-latitude lower stratosphere, and the total ozone signal is masked by a positive signal in the middle stratospheric ozone. In addition, it is found that mean ozone in the lower stratosphere has a markedly higher value for the E years. In fact, the total mid-latitude ozone (averaged from 40°S to 60°S, where total ozone has maximized) for the QBO-E years was 2% and 2.4% larger in October and November, respectively, but it decreased to 0.8% in February compared with the QBO-W years. In comparison, it was 2.7% larger in October, but decreased to 1.8% in February for HS years compared to LS years. These results are very consistent with the ozone memory hypothesis, namely that the ozone concentration in the lowermost stratosphere plays a key role in causing a long-lasting lower stratospheric temperature.

[22] For the case of the combined solar and QBO effects, a long-lasting strong negative signal of total ozone in the polar area appears in both HS/W and HS/E years, but not in LS/W and LS/E years (not shown). Although the number of samples is too small for a clear conclusion to be drawn, the results also support that the solar signal is more important than the QBO signal when the combined effect is considered.

[23] The reason why higher persistency of the AM can be observed for the E years compared with the W years can be understood as follows. In the case of positive AM under QBO-E winds, the critical latitude shifts more to the polar area owing to easterly tropical winds and stronger zonal winds with positive AM. As a result, the upward propagation of the planetary wave is more enhanced in the polar area. Such an enhanced planetary wave produces more wave forcings in the stratosphere, which create more ozone in the polar lower stratospheric because of the enhanced Brewer-Dobson circulation, and such enhanced ozone exerts a memory effect in the following season.

[24] The present results for both the solar and the QBO effects show that it is almost possible to superimpose these two effects. Moreover, the results show that the effect of the

solar cycle is stronger than that of the QBO. This result is very simple and easy to understand by linear dynamics. In contrast, in the case of the NAO, the analysis in a previous study (K07) showed that neither the solar nor the QBO effects can be understood by the superposition of these effects, and non-linear effects dominate. Such contrasting features of the solar and the QBO modulation between the NAO and the SAM originate from climatologically weaker wave forcings in the SH compared with the NH.

[25] We examined how the AMs changed in the presence of the solar cycle and the QBO. However, the question of why the signal associated with the AM extends to higher altitude in HS years is still not solved. It should be resolved in a future study.

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

K. Yamazaki, Faculty of Environmental Earth Science, Hokkaido University, North 10, West 5, Kita-ku, Sapporo, Hokkaido 060-0810, Japan. (yamazaki@ees.hokudai.ac.jp)