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Solar cycle modulation of the seasonal linkage of the North Atlantic Oscillation (NAO)

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[1] The influence of the winter NAO on the high-latitude summer climate is examined by separating the years according to the 11-year solar cycle. During the solar maximum years, the winter NAO has a significant relation with the spring-summer climate, while the winter-to-summer linkage is very weak during the solar minimum years. During the solar maximum years, the winter NAO affects spring snow cover over the Eurasian continent and sea ice over the Barents Sea. In summer, the NAO signal shows a strong annular-like structure only during solar maximum years. The results suggest that the influence of the winter NAO on the summer climate is modulated by the solar cycle through the surface cryospheric processes. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1739 History of Geophysics: Solar/planetary relationships; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3319 Meteorology and Atmospheric Dynamics: General circulation. **Citation:** Ogi M., K. Yamazaki, and Y. Tachibana, Solar cycle modulation of the seasonal linkage of the North Atlantic Oscillation (NAO), *Geophys. Res. Lett.*, *30*(22), 2170, doi:10.1029/2003GL018545, 2003.

1. Introduction

[2] In the northern hemisphere winter, a seesaw between high latitudes and subtropics in the North Atlantic is regarded as a dominant mode of the atmospheric variability, denoted as the North Atlantic Oscillation (NAO) [e.g., *van Loon and Rogers*, 1978]. Recently, *Ogi et al.* [2003] reported that the summer high-latitude climate in the northern hemisphere is influenced by the NAO of the previous winter. The summertime NAO signal is annular but its meridional scale is much smaller than the winter annular mode. They suggested that the signal of the winter NAO is memorized in snow, sea ice and sea surface temperature fields during spring and summer, and these anomalies influence the summer atmospheric circulation.

[3] *Kodera* [2002, 2003] found that the structure of the winter NAO is modulated by the 11-year solar cycle. During the solar maximum phases, the winter NAO has a hemispherical structure, which is similar to the Arctic Oscillation (AO) [*Thompson and Wallace*, 1998], and winter temperature anomalies widely extend beyond the Atlantic region throughout the northern Eurasian continent. On the other hand, during the solar minimum phases, the NAO is confined to the Atlantic region. His analysis is, however, limited to winter, and the NAO signal according to the phase of the solar cycle in other seasons has not been examined yet.

[4] Just as the structure of the winter NAO is modulated by the solar cycle, so the winter-to-summer linkage of the NAO, reported in the previous study [*Ogi et al.*, 2003], may be modulated by the solar cycle. In this study, we statistically examine the solar cycle modulation of the winter-to-summer linkage of the NAO by separating the years into the solar maximum and minimum phases.

2. Data

[5] The NAO index defined by *Hurrell* [1995] for the period from 1958 to 2001 is used in this study in which tri-monthly averaged NAO index from December through February (DJF) is defined as a representative of the wintertime NAO. Other atmospheric data used in this study are from the NCEP/NCAR reanalysis dataset for the period from 1957/1958 to 2000/2001 [*Kalnay et al.*, 1996, *Kistler et al.*, 2001]. The winter (DJF) mean 10.7 cm solar radio flux is used for a measure of the solar activity. Monthly values of the snow cover are from the digital NOAA-NESDIS Weekly Northern Hemisphere Snow Charts from 1971 to 1995, compiled by *Robinson et al.* [1993]. The snow charts are derived from the manual interpretation of AVHRR, GOES and other visible-band satellite data. Weekly values are binary where (1/0) indicated coverage or no coverage. Monthly percent of coverage values are calculated from the weekly values for that month and are therefore not integral. The monthly mean sea surface temperature (SST) and sea-ice concentration, which are issued by the global sea ice coverage and SST data (GISST2.3b) with a $1^\circ \times 1^\circ$ resolution from 1958 to 2001, are also used. All the years are separated into two phases of the solar cycles based on the winter solar activity data; solar maxima (max) and solar minima (min), depending on whether the solar fluxes are above or below the mean value. The 20 years (58–60, 67–71, 79–83, 89–92, 99–01) are classified as the solar-max years, and the 24 years (61–66, 72–78, 84–88, 93–98) as the solar-min years. The classification is the same as that used in *Kodera* [2002] except for 1993. The year 1993 is classified as a solar min year in this study, while it is classified as a solar max year in *Kodera* [2002], due to longer record used in this study.

[6] The classification based on the summer solar activity data is the same as that based on the winter solar activity data except only for 1971, 1978, and 1988. Because the results according to the summer solar activity classification were quite similar to those classified by the winter solar

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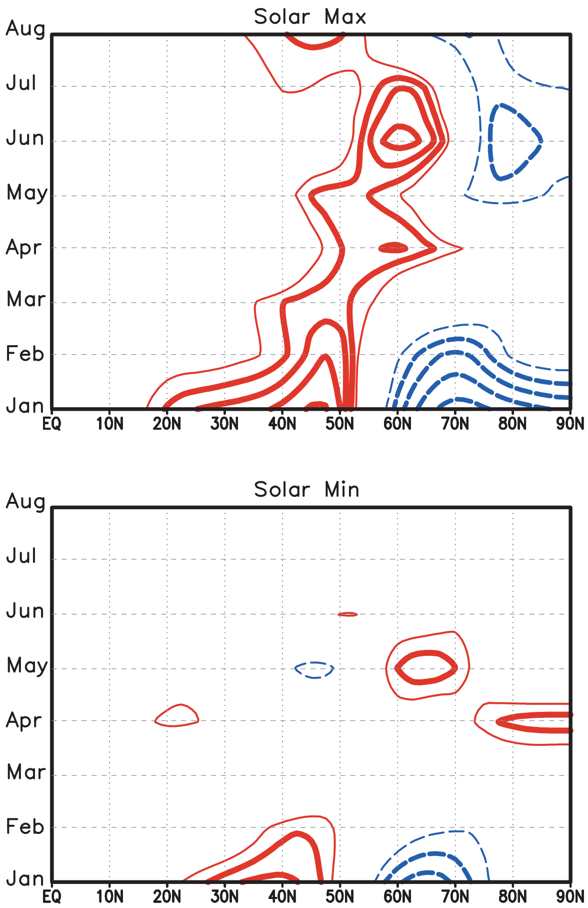

Figure 1. Lagged correlation coefficients of monthly averaged zonal mean 500-hPa geopotential height with the winter (DJF) NAO index during the solar (a) maximum and (b) minimum phases. The contour interval is 0.1, and absolute values below 0.3 are omitted (thin lines are 0.3). Positive values are indicated by solid lines (red), and negative ones are dash lines (blue).

activity, we in this study show the results classified by the winter solar activity.

3. Results

[7] Figure 1 shows the lagged correlation coefficients between the monthly averaged zonal mean 500-hPa geopotential height and the winter NAO index for the solar max and min years. During the solar max years (Figure 1a), the correlation pattern in winter obviously shows a seesaw between mid and high latitudes. In April and May, the location of the positive correlation in mid-latitudes shifts poleward and this pattern persists through July. The statistically significant areas shown in Figure 1a are larger than those in Figure 1 of *Ogi et al.* [2003], in which the same analysis as the present study was made without separating years by the solar cycle. During the solar min years (Figure 1b), in contrast, the winter seesaw pattern is weak and the significant areas in spring and summer can be hardly seen.

[8] Figure 2 shows the interannual variations of the winter NAO index and the zonal-mean 500-hPa geopotential height at 60°N in June. The correlation coefficient for all the years (Figure 2a) is 0.37, which is significant at a 95% confidence level. Figures 2b and 2c show the time series for the solar max (Figure 2b) and the solar min (Figure 2c) years. During the solar max years (Figure 2b), the correlation coefficient between the winter NAO and the zonal-mean 500-hPa geopotential height in June is as high as 0.64, which is significant at a 99% level. On the other hand, the correlation coefficient during the solar min years (Figure 2c) is 0.17, showing no statistical significance.

[9] Figure 3 shows 500-hPa geopotential height horizontal patterns related to the winter NAO during the solar max and min years. The left- and right-hand panels correspond to the solar max and the solar min, respectively. The simultaneous correlation pattern shows a planetary-scale annular structure over the mid-latitudes and the Arctic during the solar max winter, while, during the solar min, a north-south seesaw is observed only over the Atlantic Ocean. This wintertime solar cycle modulation of the NAO is in a good agreement with *Kodera* [2002].

[10] The spring (April–May; AM) pattern during the solar max years (Figure 3c) also shows a seesaw pattern between the Arctic and the mid-latitudes with smaller correlations than the seesaw pattern in winter. However, the positive values over the Eurasian continent, the Bering Sea and the north Atlantic Ocean, which are located at about 50–60° N, are significant. During the solar min years in spring (Figure 3d), however, neither annular-like patterns nor NAO-like patterns can be seen.

[11] The summer (June–July; JJ) 500-hPa height signatures related to the winter NAO are shown in Figure 3e and

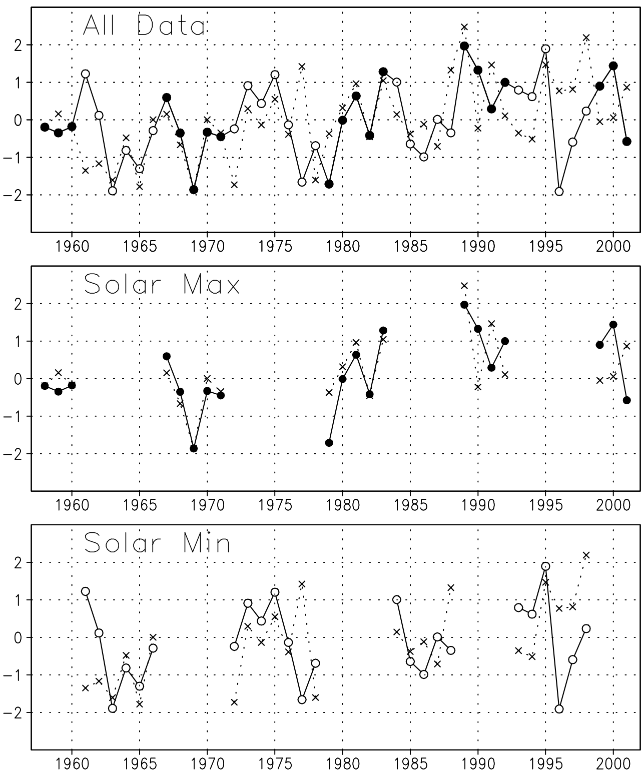

Figure 2. Standardized time series of the winter (DJF) NAO index (solid lines) and the zonal mean 500-hPa geopotential height along 60°N in June (dash lines); (a) all the years (b) solar max (c) solar min.

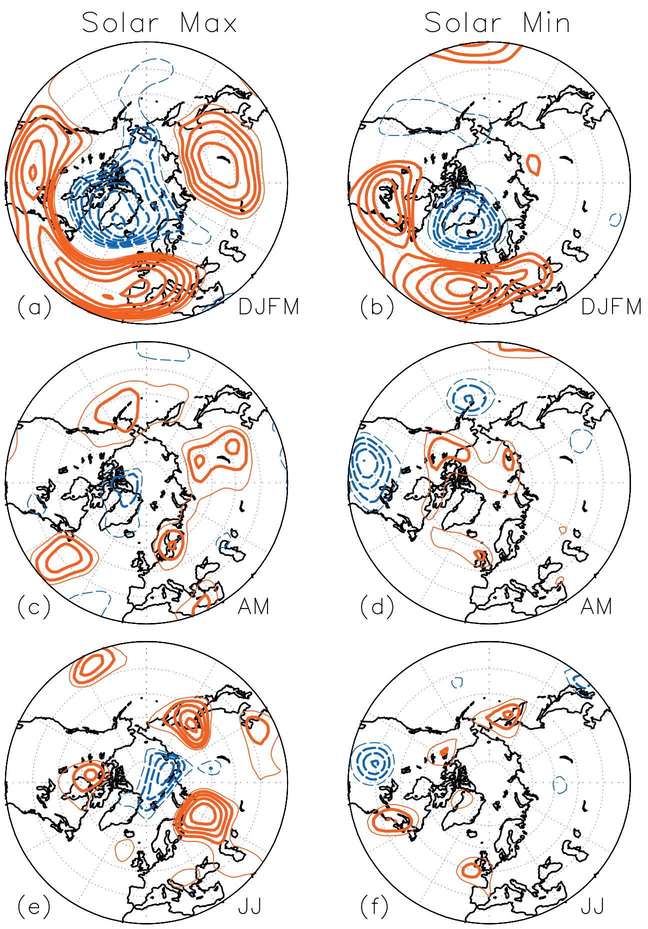

Figure 3. Horizontal maps for correlation coefficients of 500-hPa geopotential height with the wintertime (DJF) NAO index. (a) 500-hPa geopotential high in the winter (DJFM) for the solar max, (b) the winter for the solar min, (c) the spring (AM) for the solar max, (d) the spring for the solar min, (e) the summer (JJ) for the solar max, (f) the summer for the solar min. The definition of the contours are the same as noted in Figure 1. The red lines are positive correlation, and the blue lines are negative one.

Figure 3f. During the solar max years (Figure 3e), a planetary-scale north-south seesaw or an annular-like pattern is seen. Above all, strong negative correlations still occupy the Arctic, and strong positive correlations cover western Siberia, the Sea of Okhotsk and northern North America. The spatial pattern is in a good agreement with Figure 2e of *Ogi et al.* [2003], and the correlations are stronger than *Ogi et al.* [2003]. During the solar min years, the correlation is weak (Figure 3f).

[12] Figure 4 shows the correlation coefficients between the winter NAO index and the zonal-mean zonal winds in the latitude-height cross section. The relation of the wintertime zonal winds with the winter NAO index during the solar max years (Figure 4a) clearly shows a negative correlation area located at 10–40° N and a positive correlation area at 45–80° N from the surface to the stratosphere. This deep structure suggests a strong dynamic coupling of the stratosphere and troposphere during the solar max years. During the solar min years, significantly correlated seesaw areas are mainly confined in the troposphere (Figure 4b), suggesting a weak dynamic coupling of the stratosphere and troposphere. The solar activity affects the subtropical upper stratosphere in early winter as a response to meridional UV heating contrast and the effect propagates downward and poleward during winter owing to the interaction between the mean flow and planetary waves [*Kodera and Yamazaki*, 1990; *Kuroda and Kodera*, 2002, and references therein]. However, the mechanism of the solar modulation of the NAO has not clarified yet, and further studies are needed.

[13] The lag-correlations between the springtime zonal-mean zonal wind and the winter NAO index (Figures 4c and 4d) are weaker than the simultaneous ones. The north-south seesaw pattern with poleward movement can still be seen during the solar max years, while the signal is weak during the solar min years. In summer, during the solar max years, the significant positive correlation over the high latitude is observed from the troposphere to the lower stratosphere (Figure 4e) and this summer pattern is shifted more poleward than the winter one (Figure 4a). On the contrary, during the solar min years, significant correlations almost disappear (Figure 4f). The correlation coefficient between the winter NAO and the JJ-mean zonal-mean zonal wind at 70°N, 500 hPa is 0.75 for the solar max years and −0.07 for the solar min years.

[14] *Ogi et al.* [2003] pointed out that the winter NAO index does not have a significant auto-correlation after March. The signal of the winter NAO can be memorized in the snow-cover, sea ice and surface oceans, and the anomalies memorized in them then influence the summertime atmospheric circulations. To determine the relations to

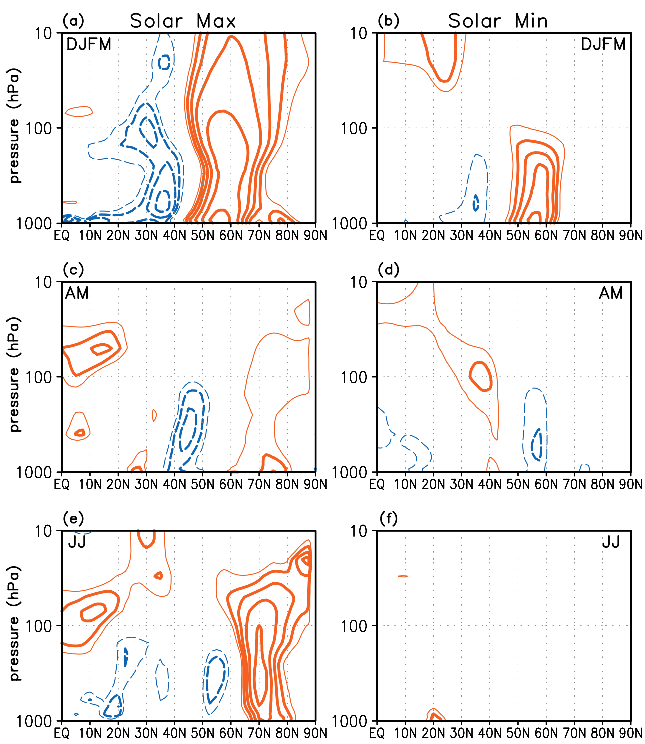

Figure 4. Same as in Figure 3, but for the correlation coefficients between the wintertime (DJF) NAO index and the zonal-mean zonal wind from 1000 hPa to 10 hPa over the northern hemisphere.

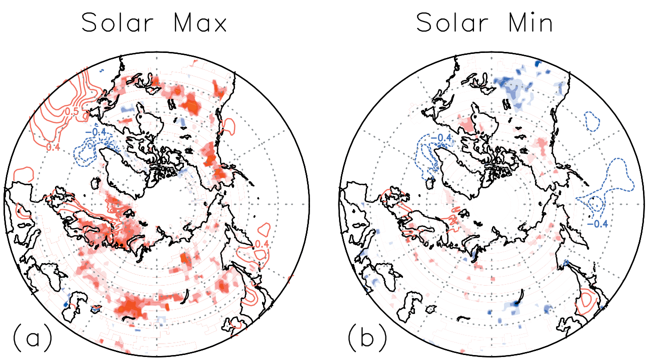

Figure 5. Correlation coefficients between the winter (DJF) NAO and the spring (AM) snow cover, sea ice and SST. (a) years during the solar max and (b) years during the solar min. The shadings over lands are correlations with snow cover. Red denotes negative, blue denotes positive. The shadings over oceans are correlations with sea-ice. Contours over oceans are correlations of the SST. Solid (red) and broken (blue) lines show the positive and negative correlations, respectively. The contour interval is 0.1, and absolute values below 0.4 are omitted.

the surface conditions depending on the solar cycle, we examined the lag correlation for surface conditions in the same way as was executed by *Ogi et al.* [2003]. Figure 5 shows the correlation coefficients between the spring (AM) snow, sea ice and SST and the winter NAO separated by the solar cycle. The warm (cold) color in the figure denotes less (more) snow, less (more) sea ice and warmer (colder) SST for the positive (negative) NAO index in winter. Less snow cover over the Eurasia continent and northern North America and less sea ice over the Eurasian coastal side, especially over the Barents Sea, in the years of the positive phase of the winter NAO during the solar max years (Figure 5a) are more significant than during the solar min years (Figure 5b).

4. Discussion and Conclusions

[15] The present study has investigated the winter-to-summer atmospheric connectivity associated with the winter NAO in the interannual time scale by separating the years according to the phase of the solar cycle. It is confirmed that the winter NAO pattern during the solar max years is a planetary-scale annular structure over the Northern Hemisphere, while during the solar min years it covers only around the Atlantic Ocean [*Kodera*, 2002, 2003]. We have, moreover, disclosed that the winter NAO during the solar max years is well correlated to the spring-summer atmospheric circulations, whereas during the solar min years, no significant correlations were found. The linkage of the winter NAO and summer high-latitude climate found in *Ogi et al.* [2003] is modulated by the 11-year solar cycle and the significant linkage takes place only in the solar maximum years.

[16] During the solar max years, the largest signal of the winter surface temperature anomalies related to the winter NAO appears over the Eurasian continent [*Kodera*, 2002]. The surface temperature anomalies persist through spring during the solar max years (figures not shown). The spring snow-cover over the Eurasian continent and sea ice over the Barents Sea show a much stronger NAO signal during the solar max years than during the solar min years. Table 1 in *Ogi et al.* [2003] showed that the winter NAO does not have a significant auto-correlation after March. In addition, the winter NAO does not have significant auto-correlations even by separating the years into the solar max and min phases (Table not shown). Our results suggest that the winter NAO signal is memorized in the Eurasian snow-cover and sea-ice over the Barents Sea, both of which have larger thermal inertia than the atmosphere. These spring-summer surface conditions are likely to cause the high-latitude circulation anomalies in summer, affecting the heat contrast between the cold central Arctic and the warm surrounding lands and coastal oceans. This heat contrast probably influences the upper-tropospheric zonal wind and the eddy activity in Arctic frontal zone shown by *Serreze et al.* [2001]. The present study adds further credence to the idea that the winter NAO, especially during the solar max years, widely influences the spring-summer atmosphere through cryosphere processes. This influence of the cryosphere on the summertime atmosphere should be investigated further. In addition, the reason why the NAO is modulated by the solar cycle should be clarified.

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References

Hurrell, J. W., Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, *Science*, *269*, 676–679, 1995.
Kalnay, E., et al., The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteor. Soc.*, *77*, 437–471, 1996.
Kistler, R., et al., The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteor. Soc.*, *82*(2), 247–267, 2001.
Kodera, K., Solar cycle modulation of the North Atlantic Oscillation: Implication in the spatial structure of the NAO, *Geophys. Res. Lett.*, *29*(8), 1218, doi:10.1029/2001GL014557, 2002.
Kodera, K., Solar influence on the spatial structure of the NAO during the winter 1900–1999, *Geophys. Res. Lett.*, *30*(4), 1175, doi:10.1029/2002GL016584, 2003.
Kodera, K., and K. Yamazaki, Long-term variation of upper stratospheric circulation in the Northern Hemisphere in December, *J. Meteor. Soc. Japan*, *68*, 101–105, 1990.
Kuroda, Y., and K. Kodera, Effect of solar activity on the polar-night jet oscillation in the northern and southern hemisphere winter, *J. Meteor. Soc. Japan*, *80*, 973–984, 2002.
Ogi, M., Y. Tachibana, and K. Yamazaki, Impact of the wintertime North Atlantic Oscillation (NAO) on the summertime atmospheric circulation, *Geophys. Res. Lett.*, *30*(13), 1704, doi:10.1029/2003GL017280, 2003.
Robinson, D. A., K. F. Dewey, and R. R. Heim Jr., Global snow cover monitoring: An update, *Bull. Am. Meteor. Soc*, *74*, 1689–1696, 1993.
Serreze, M. C., A. H. Lynch, and M. P. Clark, The Arctic frontal zone as seen in the NCEP-NCAR reanalysis, *J. Clim.*, *14*, 1550–1567, 2001.
Thompson, D. W. J., and J. M. Wallace, The Arctic Oscillation signature in the wintertime geopotential height and temperature fields, *Geophys. Res. Lett.*, *25*, 1297–1300, 1998.
van Loon, H., and J. C. Rogers, The seesaw in winter temperatures between Greenland and northern Europe, Part I: General description, *Mon. Wea. Rev.*, *106*, 296–310, 1978.

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