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Modulation of the Arctic Oscillation and the East Asian Winter Climate Relationships by the 11-year Solar Cycle

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ABSTRACT

The modulation of the relationship between the Arctic Oscillation (AO) and the East Asian winter climate by the 11-year solar cycle was investigated. During winters with high solar activity (HS), robust warming appeared in northern Asia in a positive AO phase. This result corresponded to an enhanced anticyclonic flow at 850 hPa over northeastern Asia and a weakened East Asian trough (EAT) at 500 hPa. However, during winters with low solar activity (LS), both the surface warming and the intensities of the anticyclonic flow and the EAT were much less in the presence of a positive AO phase. The possible atmospheric processes for this 11-year solar-cycle modulation may be attributed to the indirect influence that solar activity induces in the structural changes of AO. During HS winters, the sea level pressure oscillation associated with the AO became stronger, with the significant influence of AO extending to East Asia. In the meantime, the AO-related zonal-mean zonal winds tended to extend more into the stratosphere during HS winters, which implies a stronger coupling to the stratosphere. These trends may have led to an enhanced AO phase difference; thus the associated East Asian climate anomalies became larger and more significant. The situation tended to reverse during LS winters. Further analyses revealed that the relationship between the winter AO and surface-climate anomalies in the following spring is also modulated by the 11-year solar cycle, with significant signals appearing only during HS phases. Solar-cycle variation should be taken into consideration when the AO is used to predict winter and spring climate anomalies over East Asia.

Key words: AO, East Asian winter climate, solar activity, East Asian trough

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1. Introduction

The East Asian winter monsoon (EAWM) is an important climate system that exerts a large social and economic impact on many East Asian countries. For example, a strong EAWM can frequently bring severe cold waves/snowstorms in China, Japan, and Korea (e.g., Ding, 1994; Wang and Chen, 2010). In January and February 2008, an unexpected 3-week-long freezing rain and snowstorm occurred in southern China. Deaths of 129 people and the economic losses of ~150 billion RMB (NCC/CMA, 2008) were attributed to the storm. On the other hand, the EAWM can induce deep convection over the Maritime Continent through the intrusion of cold surges into the tropics, which serves as the major heating source for the atmospheric circulation (Chang et al., 2006). This heating source gives rise to strong mid-latitude–tropical interactions and affects the mid-latitude East Asian jet (Lau and Chang, 1987), which in turn may influence the climate in remote regions such as North America (Yang et al., 2002). Therefore, it is important to understand the variation of EAWM and its related mechanisms.

The most prominent surface feature of the EAWM is the strong northwesterly wind along the east flank of the Siberian high. This northwesterly flow splits into two branches south of Japan. One branch turns eastward toward the subtropical western and central Pacific, while the other flows along the coast of East Asia into the South China Sea (e.g., Academia Sinica,

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1957). At 500 hPa, a broad trough is centered approximately at the longitudes of Japan. The dominant feature at 200 hPa is the East Asian jet, with its maximum located just southeast of Japan. This jet is closely associated with intense baroclinicity, large vertical wind shear, and strong advection of cold air (e.g., Ding, 1994).

The winter climate and the prediction of the variation of the winter monsoon circulation in East Asia have been the subject of many studies (e.g., Zhang et al., 1997; Chen et al., 2000; Chan and Li, 2004; Zhou et al., 2007; Wen et al., 2009; Zhou et al., 2009). The variability of climate over East Asia is complex, with multiple influencing factors. Among them, the impact of the Arctic Oscillation (AO) on the EAWM has been widely documented. The AO is an intrinsic mode which represents the dominant variability of the extratropical Northern Hemisphere (NH) atmosphere on the interannual time scale (Thompson and Wallace, 1998). Several studies reported that the EAWM tends to be weak during the positive phase of the AO (Wu and Huang, 1999; He and He, 2003; Ju et al., 2004; Suo et al., 2009). Gong et al. (2001) suggested that the AO influences the EAWM through the Siberian high, whereas Wu and Wang (2002) argued that the AO directly influences the EAWM, which is independent of the Siberian high. Because the variability of AO is considered to be closely associated with the eddy fluxes of stationary waves (Limpasuvan and Hartmann, 1999, 2000; Chen et al., 2002, 2003), Chen et al. (2005) examined the interannual AO–EAWM relationship from the perspective of quasistationary planetary wave activity. Clearly, the precise relations between the AO and the EAWM and the associated atmospheric processes are not yet well understood.

Many studies have demonstrated the interdecadal variations of the East Asian climate, and most of them attribute the causes to sea-surface temperature anomalies or a global warming effect (e.g., Zhou et al., 2006; Wang et al., 2009; Wei et al., 2010). Solar radiation can be verified on a wide range of temporal scales. The most important interannual–interdecadal time scale is the 11-year solar cycle. In recent decades a growing body of evidence has shown that the troposphere is affected by the 11-year solar cycle. Many studies have identified the effects of solar activity variations in various tropospheric and surface fields, such as temperature, sea level pressure, geopotential heights, and so forth. (van Loon and Shea, 2000; Gleisner and Thejll, 2003; Weng, 2003; Coughlin and Tung, 2004). Possible solar influences on the AO have also been reported. Kodera (2003) found the AO to be confined in the Atlantic sector during low solar activity (LS), whereas it showed a hemispherical structure during high solar activity (HS). Gimeno et al. (2003) showed the AO to be positively correlated to the NH surface temperature during HS winters, while no significant correlation was found during LS winters. Hence, the study question is formulated: Does the relationship between the AO and the EAWM depend on the phases of solar activity?

Following a brief description of the data and analysis methods in section 2, the overall AO-EAWM relationship during the NH winter is presented in section 3. In section 4 the modulation of the relationship by the 11-year solar cycle is examined. Possible atmospheric processes responsible for this modulation are discussed in section 5. Finally, the major findings of this study are summarized in section 6.

2. Data and methods

This study was based on the tropospheric and stratosphereric data from the National Centre for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay et al., 1996; obtained from the NOAA Climate Diagnostic Center) for the period 1958–2010. This reanalysis dataset is probably unreliable at stratospheric levels prior to 1958 due to lack of sufficient observational data in the upper atmosphere (Kistler et al., 2001). The dataset has a 2.5°×2.5° horizontal resolution and extends from 1000 hPa to 10 hPa, with 17 vertical pressure levels. The data used in this study also included the monthly temperature data from 160 Chinese weather observation stations from 1951 to 2010 (acquired from the China Meteorological Administration). In addition, we used the monthly mean values of the 10.7-cm solar flux (F10.7 cm) throughout this study because it is strongly correlated with the 11-year solar cycle and with the UV part of the solar spectrum in particular. The F10.7 cm data are expressed in solar flux units (s.f.u.) where 1 s.f.u. $= 10^{-22}$ W m^{-2} Hz^{-1}. The solar radio flux data were obtained from the National Geophysical Data Center, NOAA (http://www.ngdc.noaa.gov/stp/solar/solardataservices.html), and the AO index data were obtained from the Climate Prediction Center, NOAA (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml).

Seasonal means were constructed from the monthly means by averaging the data of December, January, and February (DJF), which resulted in data fields for 52 winters (1959–2010). The interannual variabilities of the winter AO index and the winter F10.7 cm are shown in Fig. 1. The AO was characterized by obvious interannual variability as well as interdecadal variability, whereas the F10.7 cm varied with a dominant 11-

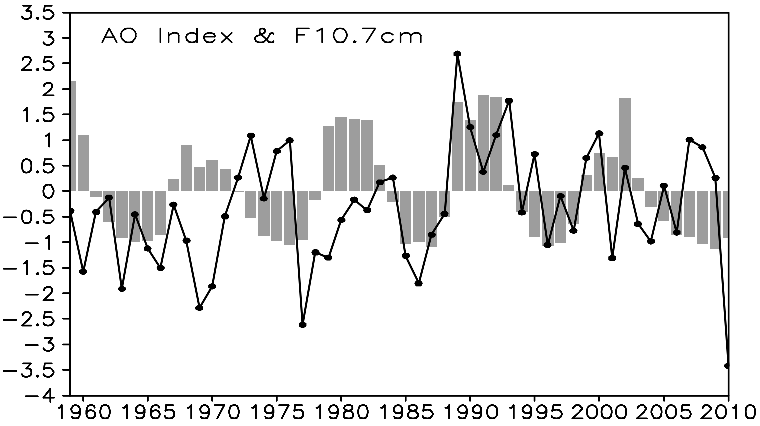


Fig. 1. Normalized time series of the AO index (black circles) and the F10.7cm (light grey shadings) averaged for December–January–February (DJF).

year period. The correlation between these two time series of the AO index and the F10.7 cm was only 0.23 for the whole set of 52 winters from 1959 to 2010, which is not significant if the effective number of degrees of freedom is considered, as indicated by Davis (1976). Correlation studies were adopted throughout this study. Statistical significance in correlation studies was assessed using the Student's two-sided t-tests.

3. Relationship between AO and EAWM

Because the EAWM circulation is more remarkable in the lower troposphere than in the upper troposphere, in this study we focused on the associated variations of the lower tropospheric temperature and circulation over East Asia with the AO. The field of correlation between the AO index and the lower tropospheric temperature at 850 hPa in the reanalysis data is shown in Fig. 2a. This correlation pattern is similar to that found in earlier studies (e.g., Chen and Kang, 2006), which depicts a significant effect of the AO on the temperature in East Asia. A large positive area can be seen extending from Siberia eastward to Japan, with weak negative correlations over Alaska as well as the region south to the Tibet Plateau. As the shading in the figure shows, the correlations significantly exceed the 95% confidence level. The temperature variations associated with the AO were also confirmed by analyzing the surface temperature data from 160 Chinese weather observation stations. Figure 2b shows clear positive correlations in Northeast and North China with the AO. During the positive AO winters, the lower tropospheric temperature tended to be abnormally warm over northeastern Asia. The reverse situation emerged during winters with negative AO indices.

Many studies have shown that the East Asian winter monsoon is associated closely with the East Asian

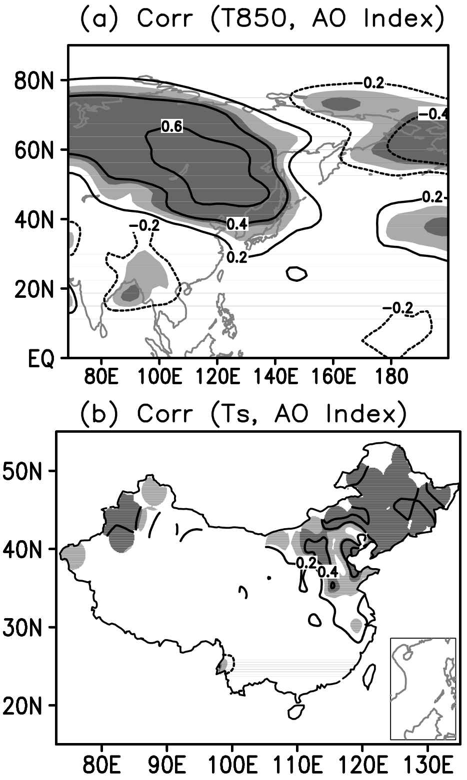


Fig. 2. DJF correlation (a) between the temperature at 850 hPa and the AO index, and (b) between the surface temperature of 160 Chinese observation stations and the AO index. Contour interval is 0.2, and dashed lines indicate negative values. Heavy and light shading indicate the correlations exceeding the 99% and 95% confidence levels, respectively.

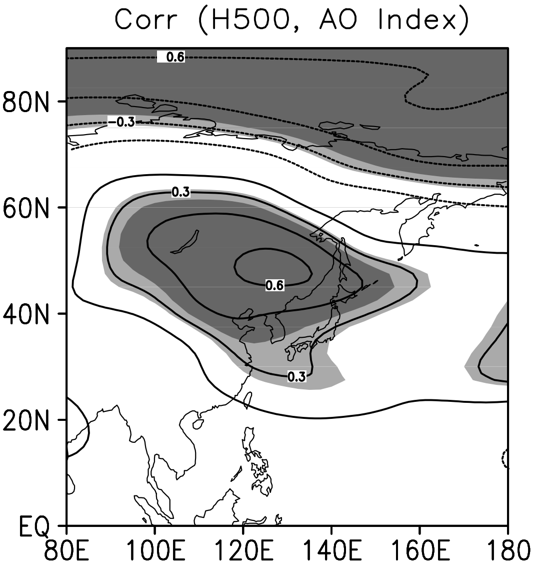


Fig. 3. DJF correlation between the geopotential height at 500 hPa and the AO index. Contour interval is 0.15, and dashed lines indicate negative values. Heavy and light shading indicate the correlations exceeding the 99% and 95% confidence levels, respectively.

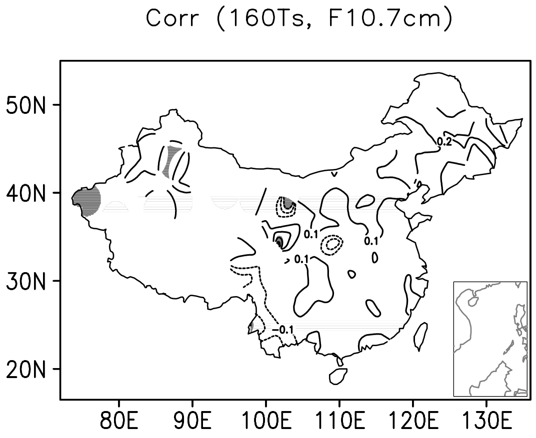


Fig. 4. DJF correlation between the surface temperature of 160 Chinese observation stations and the F10.7 cm. Contour interval is 0.1, and dashed lines indicate negative values. Shading indicates the regions of 95% confidence level.

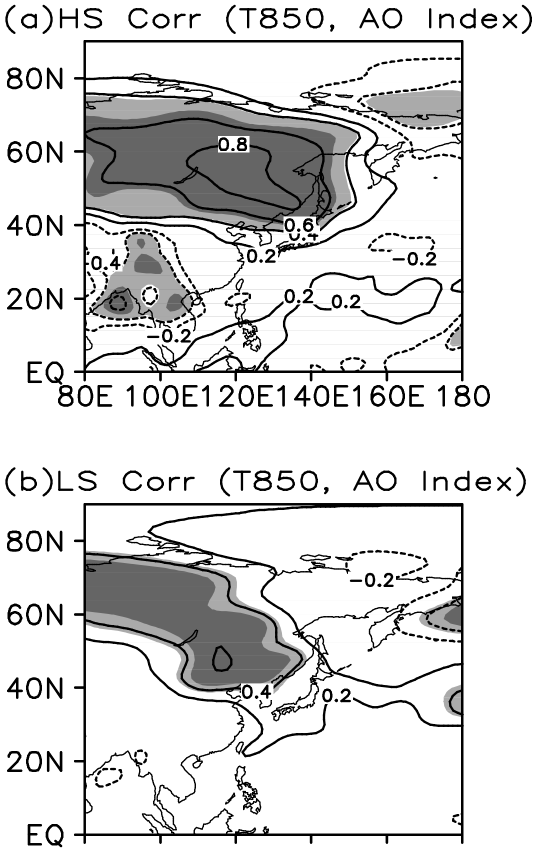


Fig. 5. DJF correlation between the 850 hPa temperature and the AO index for (a) HS years and (b) LS years. Contour interval is 0.2, and dashed lines indicate negative values. Heavy and light shading indicate the correlations exceeding the 99% and 95% confidence levels, respectively.

trough (e.g., Wang et al., 2009). Hence, the correlations between the 500 hPa geopotential height and the AO index are presented in Fig. 3. The mid-tropospheric atmospheric circulation over extratropical East Asia is dominated by a trough along the East Asian coast. Positive correlations over East Asia and negative correlations over the polar region can be seen in Fig. 3. These results imply that the East Asian trough at 500-hPa is weakened and the geopotential height in the polar region decreases during positive AO winters. A weak trough indicates that the cold waves affecting East Asia, which are characterized by cold continental air flowing off the continent to the east and also being tunneled equatorward, became relatively inactive. Therefore, the warming in northeastern Asia was likely caused by the weaker East Asian trough in association with the positive AO index.

4. Modulation of the AO–EAWM relationship by the 11-year solar cycle

In the field of correlation between the DJF mean F10.7 cm value and surface temperature in China (Fig. 4), generally no significant signals suggest that the solar cycle has no direct impact on the winter surface temperature in China. Because the winter AO signal is largely modified according to the solar cycle (Kodera, 2003), we further analyzed the solar influence on the relationship between the AO and the EAWM. First we divided the winters into years with the high solar activity (HS year) and years with the low solar activity (LS year), as did Kuroda (2007). If the DJF mean F10.7 cm was stronger than the average, the year was categorized as an HS year year; if the DJF mean F10.7 cm was weaker than the average, the year was categorized as an LS year. Based on this criterion, the selected 22 HS winters were 1959, 1960, 1967, 1968, 1969, 1970, 1971, 1979, 1980, 1981, 1982, 1983, 1989, 1990, 1991, 1992, 1993, 1999, 2000, 2001, 2002, and 2003. Here, the winter of 1959 refers to the 1958/1959 winter. The other 30 years were categorized as LS winters. After the winters were separated into two groups of HS or LS, the correlations between the temperature at 850 hPa and the AO index depicted important distinctions. For all winters, the correlation was robustly positive over northeastern Asia (Fig. 2a). During HS winters (Fig. 5a), both the positive correlation values and the domain increased. The negative correlations show similar changes compared with Fig. 2a. On the contrary, during LS winters both the positive and negative correlations were dramatically reduced (Fig. 5b). Again, the effect of the solar cycle modulation on the lower tropospheric temperature variations associated with the AO were confirmed by the correlation patterns of observation-station temperature fields (Fig. 6). The pattern during HS winters (Fig. 6a) is quite similar to that in Fig. 2b, but with greatly increased correlation values, especially in Northeast and North China. However, during LS winters, significant correlations were confined to Northeast China, with reduced correlation values (Fig. 6b). Therefore, the temperature anomalies in northeastern Asia associated with the AO tend to be strongly dependent on the phase of solar cycle. During the HS winters, both the domain and strength of temperature anomalies in northeastern Asia enlarged in relation to the AO variations. However, the temperature anomalies became much weaker and occupied a smaller region during the LS winters.

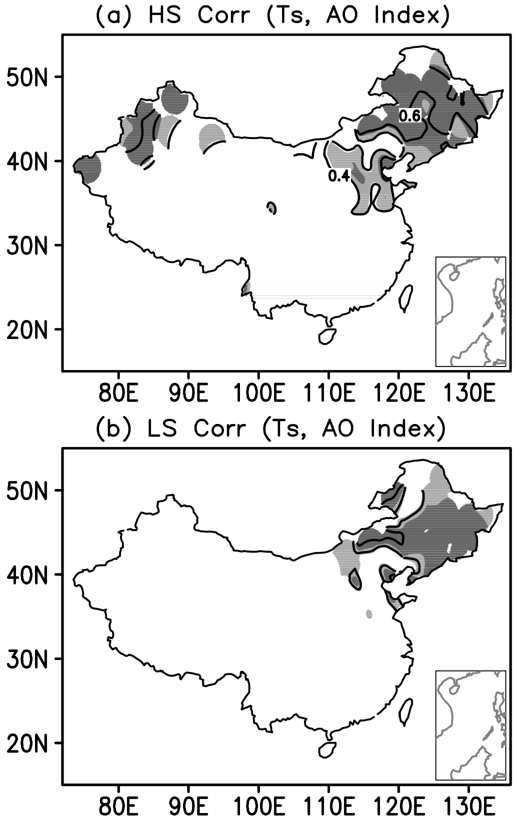


Fig. 6. As in Fig. 5, but for the surface temperature of 160 Chinese observation stations. Only the absolute values >0.4 have been plotted.

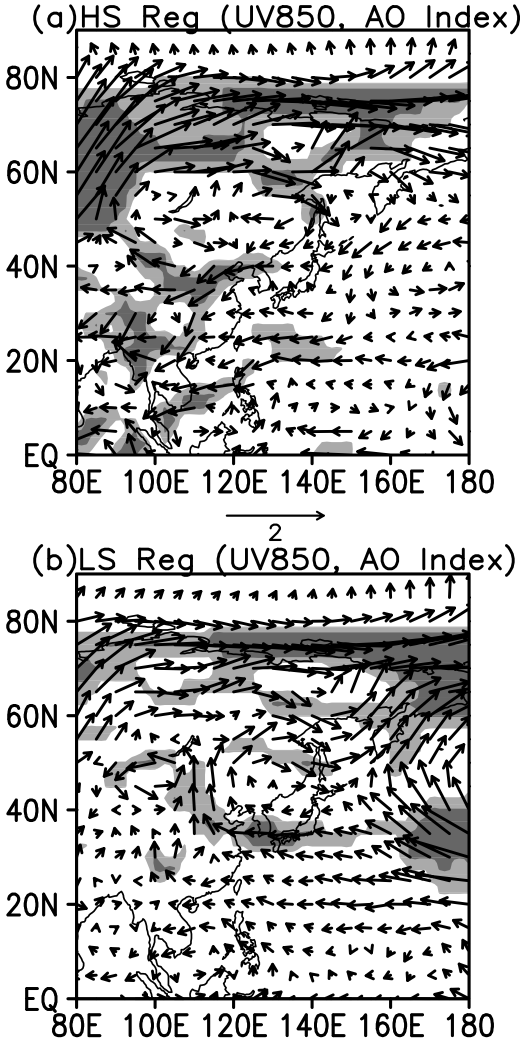
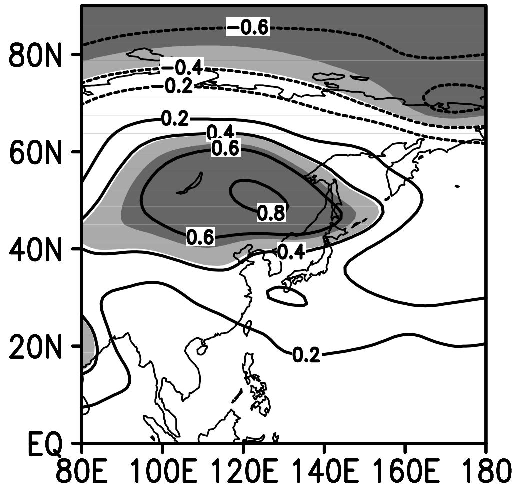


Fig. 7. DJF Regression of 850 hPa winds on the AO index for (a) HS years and (b) LS years. The unit for vectors is m s^{-1}. Heavy and light shading indicate the confidence levels exceeding 99% and 95%, respectively.

Figure 7 presents the regression DJF mean winds at 850 hPa on the AO index. During HS winters (Fig. 7a), a strong anticyclonic flow over northeastern Asia may have caused positive temperature anomalies associated with positive AO, as shown in Fig. 5a. In addition, northerly anomalies in Southwest China correspond well to negative anomalies (also shown in Fig. 5a). However, the anticyclonic flow decreased significantly and covered a smaller region of Northeast China during LS winters (Fig. 7b). In addition, the northerly anomalies in Southwest China nearly disappeared. All these factors suggest that the wind anomalies associated with the AO are the main cause for the differences in the lower tropospheric temperature between HS and LS winters.

The solar-cycle modulation in the relationship between the AO and East Asian winter climate is further demonstrated by the manifestation of the East Asian trough at 500 hPa (Fig. 8). The positive correlations over northeastern Asia became much larger, with the maximum >0.8, during HS winters (Fig. 8a), whereas they become much weaker, with the correlations <0.6, during LS winters (Fig. 8b). These results show that the East Asian trough tends to be more closely associated with the AO during HS winters than LS winters. During an HS winter, the East Asian trough usually becomes much weaker in relation to a positive AO phase and much stronger in relation to a negative AO phase. A weaker trough indicates the weakening of cold air intrusion into East Asia; the results in Fig. 8 are consistent with the modulation of the surface temperature variations over East Asia in association with the AO by solar cycle. Therefore, the solar cycle tends to strongly modulate the relationship between the AO and East Asian winter climate.

(a)HS Corr (H500, AO Index)



(b)LS Corr (H500, AO Index)

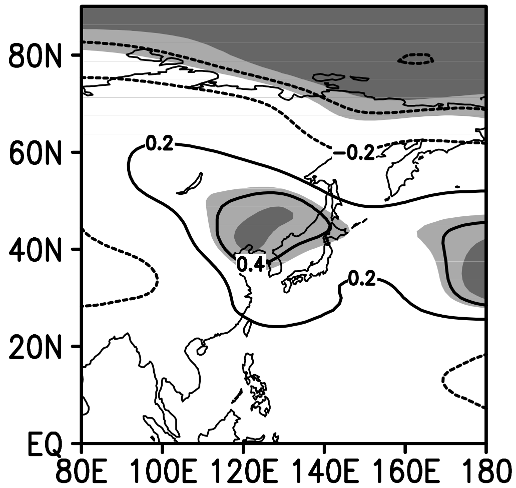


Fig. 8. As in Fig. 5, but for the 500 hPa geopotential height.

5. Discussions

Why is the relationship of East Asian winter climate with the AO dependent on the solar-cycle activity? The atmospheric processes for this solar cycle modulation are discussed in this section. The AO was defined by Thompson and Wallace (1998) as the leading empirical orthogonal function mode of wintertime sea level pressure (SLP) anomalies over the extratropical NH. The AO was dominated by a zonally symmetric, meridional seesaw in atmospheric mass between the Arctic and the mid-latitudes. Thus, we further examined the correlations between the AO index and sea level pressure (SLP) during HS and LS years. The results show a significant difference between HS and LS winters (Fig. 9). During HS winters (Fig. 9a), the correlation values in both the polar region and Western Europe became larger and more significant. Particularly, significant, positive correlations extended eastward to East Asia. However, the correlation pattern shows a compact north–south seesaw over the Atlantic Ocean and Western Europe region during LS winters, with decreased correlation values (Fig. 9b). In addition, a significant, positive correlation occurred in a small area over the North Pacific. Therefore, the AO tends to be more active during an HS winter than during an LS winter, with more significant influence on the climate of East Asia.

The AO also corresponded to a north–south seesaw of zonal-mean zonal winds between 35°N and 55°N (Thompson and Wallace, 2000). Thus, we calculated the correlations between the AO index and the zonal-mean zonal winds during HS and LS winters, respectively. Both correlation patterns were associated with the north–south fluctuation of zonal-mean zonal wind anomalies across the mid-latitudes (Fig. 10). The distinct difference was that the significant correlations extended farther into the stratosphere during HS winters than during LS winters. This result suggests more pronounced coupling between the stratosphere and troposphere during an HS winter. As we know, solar-cycle variations of solar irradiance are strongly dependent on wavelength. Whereas the total irradiance varies by only 0.1% over the solar cycle, variations in the UV radiation are larger by almost two orders of magnitude (Lean, 1991). This implies that the linkage between solar activity and climate may be through the effect of UV radiation on the Earth's atmosphere (Lean and Rind, 2001). The solar-cycle variations in UV radiation can cause temperature and ozone changes at the top of the stratosphere (Hood et al., 1993). The variations in the stratosphere can further impact surface climate directly by inducing an annular pattern of zonal wind perturbations with an extension downward through the troposphere to the Earth's surface (Black, 2002) or indirectly by altering the propagation characteristics of tropospheric planetary waves (Hartmann et al., 2000). Therefore, solar cycle variations may have a more pronounced influence on the winter climate in the NH, with much stronger coupling between the stratosphere and troposphere during HS winters via the mechanisms aforementioned.

Finally, we discuss the solar-cycle influence on the time-lag relationship between the AO and the surface climate in China. The correlations between the winter AO index and the following March–April–May (MAM) surface temperature data from 160 Chinese observation stations were robustly positive in North China, Northeast China, and a small region in Northwest China (Fig. 11a). This result means that higher

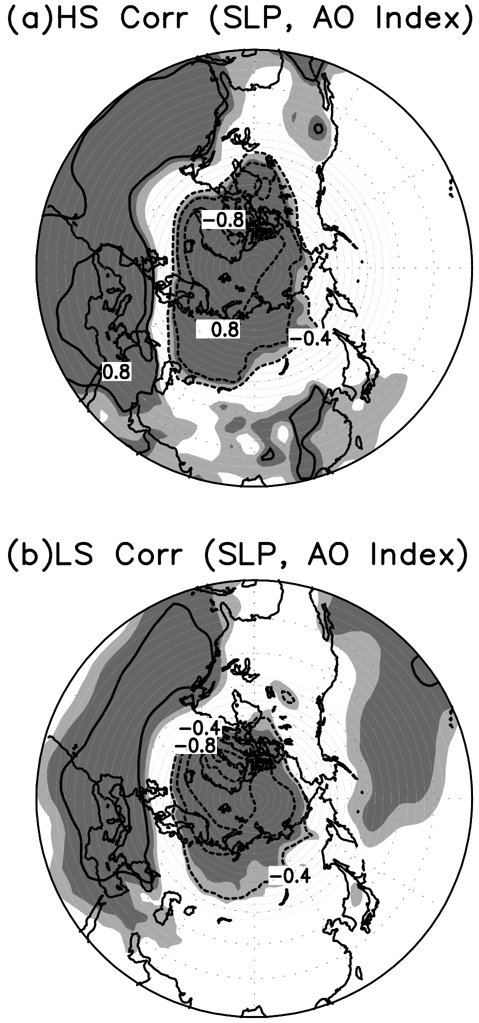


Fig. 9. As in Fig. 5, but for the sea level pressure. Only the absolute values >0.4 have been plotted.

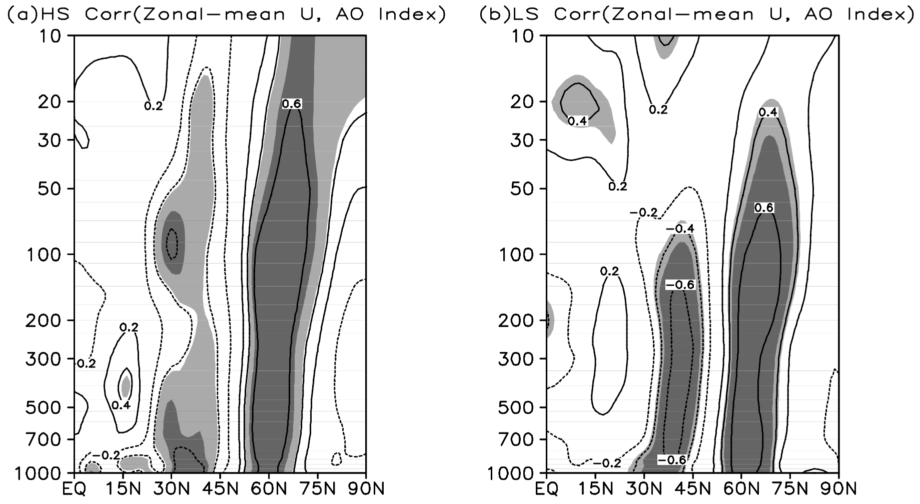


Fig. 10. As in Fig. 5, but for the zonal-mean zonal winds.

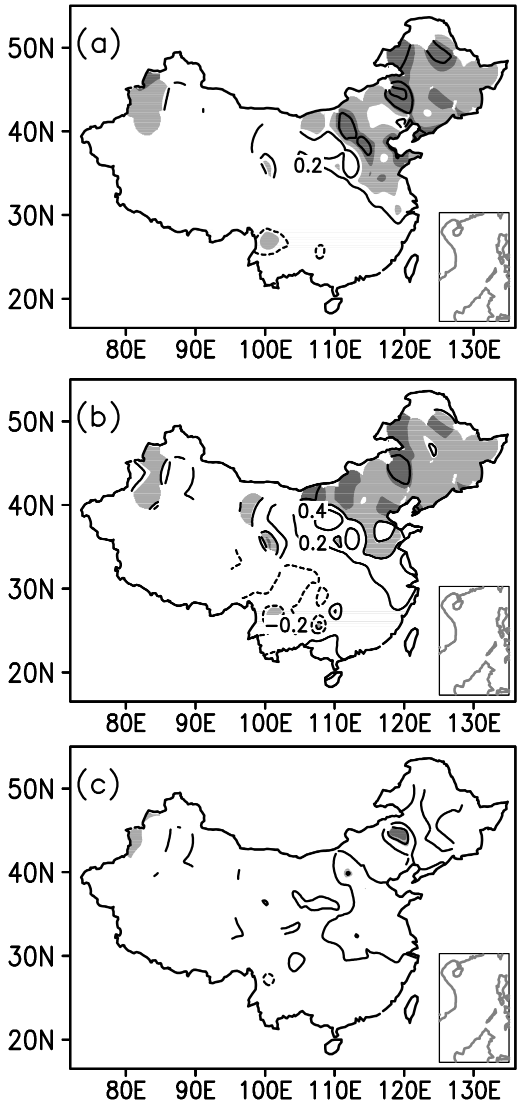


Fig. 11. Correlation maps between the DJF mean AO index and the following March–April–May (MAM) mean surface temperature of 160 Chinese observation stations for (a) all years, (b) HS years, and (c) LS years, respectively. Contour interval is 0.2, and dashed lines indicate negative values. Heavy and light shading indicate the correlations exceeding the 99% and 95% confidence levels, respectively.

surface temperature generally appears in northern China after a positive AO winter. The largest warming occurs in North China and Northeast China, a feature similar to that shown in Fig. 2b for the DJF temperature. Hence, Fig. 11a seems to indicate a predictive potential of winter AO anomaly for the spring climate of China. The interesting point is that this predictability tends to be very different during the HS and LS winters. During HS winters (Fig. 11b), the correlation pattern is very similar to that in Fig. 11a. However, there is little correlation during LS winters (Fig. 11c). Therefore, the solar-cycle variation should be taken into consideration when the winter AO is used to predict the spring climate in China.

6. Summary

In this study, we investigated the 11-year solar-cycle modulation on the relationship between the AO and the East Asian winter climate. Generally the AO has a significant impact on the temperature anomalies in East Asia during the NH winter. The lower tropospheric temperature becomes abnormally warm over northeastern Asia during positive AO winters. The reverse situation emerges during winters with negative AO indices. Our results show that these impacts are strongly dependent on the phase of the 11-year solar cycle. These findings suggest a trend toward remarkable warming in northeastern Asia in response to positive AO during HS winters, and for the reduced warming covering a smaller domain in northeastern Asia during LS winters. Differences in the lower tropospheric temperature between the HS and LS winters can be well explained by the wind anomalies associated with the AO. Further research revealed that the East Asian trough at 500 hPa tends to be more closely associated with the AO during HS winters than LS winters. These results are physically consistent, because a weaker trough implies a weakening of cold air intrusion into East Asia.

The results of this study show that the solar-cycle modulation of the relationship between the AO and the East Asian winter climate appear to result from the indirect influence of the solar cycle via the structural changes of AO. During HS winters, the SLP oscillation between the polar region and the mid-latitudes associated with the AO became more active, and the significant influence of AO extended farther eastward to East Asia. In addition, the zonal-mean zonal wind anomalies associated with the AO tend to extend more into the stratosphere in response to an HS phase, which implies a more pronounced coupling between the stratosphere and troposphere. In this case, the variations in the stratosphere associated with the AO may further influence surface climate directly or indirectly via different processes that are already known (Hartmann et al., 2000; Black, 2002). Therefore, the temperature anomalies in northeastern Asia associated with the AO may be enhanced by comparing data from HS winters to data from LS winters. These findings extend earlier ones (e.g., Chen and Kang, 2006) by emphasizing the modulation effect of solar cycle on the AO and the East Asian winter climate relationship, which has practical use for climate prediction.

Further analysis indicates that the time-lag relationship between the AO and the surface climate in China is also significantly influenced by the 11-year solar cycle. Higher surface temperatures generally appeared in North China, Northeast China, and a small region in Northwest China during the spring following a positive AO winter. The temperature anomalies in northern China were larger and more robust after HS winters. However, temperature anomalies became very small and insignificant after the LS winters. Therefore, the solar cycle variation should be taken into consideration when the winter AO is used to predict both the winter and spring climate in China.

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