The Effect of Solar Cycle on Climate of Northeast Asia

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ABSTRACT

The impact of solar activity on climate system is spatiotemporally selective and usually more significant on the regional scale. Using statistical methods and solar radio flux (SRF) data, this paper investigates the impact of the solar 11-yr cycle on regional climate of Northeast Asia in recent decades. Significant differences in winter temperature, precipitation, and the atmospheric circulation over Northeast Asia are found between peak and valley solar activity years. In peak years, temperature is higher over vast areas of the Eurasian continent in middle and high latitudes, and prone to producing anomalous high pressure there. Northeast Asia is located to the south of the anomalous high pressure, where the easterlies prevail and transport moisture from the western Pacific Ocean to the inland of East Asia and intensify precipitation there. In valley years, temperature is lower over the Eurasian continent and northern Pacific Ocean in middle and high latitudes, and there maintain anomalous low pressure systems in the two regions. Over the Northeast Asian continent, north winds prevail, which transport cold and dry air mass from the high latitude to Northeast Asia and reduce precipitation there. The correlation coefficient of winter precipitation in Northeast China and SRF reaches 0.4, and is statistically significant at the 99% confidence level based on the Student's *t*-test. The latent heat flux anomalies over the Pacific Ocean caused by solar cycle could explain the spatial pattern of abnormal winter precipitation of China, suggesting that the solar activity may change the climate of Northeast Asia through air–sea interaction.

Key words: solar cycle, solar radio flux (SRF), climate anomalies, Northeast Asia

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1. Introduction

The sun is an important driving force to weather and climate. Research about the influence of the solar activity on earth's weather and climate has achieved some results, especially on timescales of decades to one hundred years. Previous studies showed that the effect of solar activity on modern climate change could not be ignored (Gray et al., 2010). Some scientists proposed that the low solar activity in recent solar cycles might be the main reason for the slow down of global warming since 1998 (Kerr, 2009; Knight et al., 2009; Fyfe et al., 2013; Curry, 2014).

In history, traces of the sun's influence on weather and climate are observed in certain areas around the world (Elizabeth, 1995). During the most significant cold period, i.e., the Maunder Minimum of Little Ice Age (LIA), the solar activity reached a minimum level and the solar radiation was remarkably reduced by 0.1%–1%, which induced a global drop of temperature (Elizabeth, 1995). Sakurai and Mikami (1992) found that the sunspot number decreased significantly during LIA. Another example of regional climate change driven by solar activity is the Holocene presented in a lot of literature, during

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which some anomalous climate phenomena were related to the solar activity directly or indirectly (Crowley, 2000; Hong et al., 2000; Perry and Hsu, 2000; Bond et al., 2001; Hodell et al., 2001; Neff et al., 2001; Fleitmann et al., 2003; Frisia et al., 2003; Hu et al., 2003; Speranza et al., 2003; Kilcik, 2005; Ogurtsov et al., 2005; Wang et al., 2005; Xu et al., 2006; Barron and Bukry, 2007; Haltia-Hovi et al., 2007; Rigozo et al., 2007).

By examining the impact of total solar irradiance variation on global mean temperature, a mean global warming of 0.16 K from solar minimum to solar maximum was suggested by Camp and Tung (2007). In addition, other proxies of solar activity, such as solar radio flux, ultraviolet rays, cosmic rays, and solar wind also play important roles in modulating anomalous weather and climate in some areas of the globe (Gray et al., 2010; Ineson et al., 2011; Xiao and Huo, 2016; Xiao and Li, 2016).

While the solar radiation exerts an overall effect on the earth, in some sensitive regions, its influence could be more significant through an amplification effect. This phenomenon is referred to as the spatiotemporal selectivity of the sun's effect. Solar activity is likely to produce significant effect on regional climate change through amplified process, as pointed out explicitly by the fifth assessment report of IPCC (IPCC, 2013). Xiao and Huo (2016) found that solar activity has a significant impact on the polar atmosphere and the tropical ocean–atmosphere system. The influence of solar activity on climate in middle and high latitudes is usually more obvious in winter, while in low latitudes it is more distinct in summer. The monsoon system is the pathway to connect the propagation of solar signals between equatorial and polar areas (Xiao and Huo, 2016). The difference in summer rainbelt location over China and its northward advancement associated with the East Asian summer monsoon is remarkable between strong and weak solar activity years (Wang and Zhao, 2012; Zhao and Wang, 2014; Song et al., 2016a, b).

It is confirmed by some studies that anomalous climate in some regions are indeed closely related to solar activity. For example, solar flares could cause precipitation increase over some gauge stations around the world (Takahashi, 1966). Since 8000 B.P., the Indian monsoon precipitation decreased gradually in response to changing Northern Hemisphere summer solar insolation, with decadal to multidecadal variations in monsoon precipitation being linked to solar activity (Fleitmann et al., 2003). Periodic droughts in the Yucatan Peninsula and Mexico had a close connection to changes of cosmic rays related to solar activity (Hodell et al., 2001). In northern–central China (33°–41°N, 108°–115°E), summer rainfall over the past 500 yr (1470–2002) was found to be associated with solar activity (Zhai, 2017). The annual precipitation in Beijing during 1749–2001 was significantly correlated with sunspots (Zhao and Han, 2005). Precipitation in Gansu Longxi area of China was closely related to the Northern Hemisphere temperature and solar activity since 960 AD (Tan et al., 2008). Wang et al. (2015) pointed out that solar activity correlated well with the winter atmospheric circulation over East Asia, but there were differences between strong and weak solar activity periods, exhibiting an asymmetric influence on the East Asian winter climate.

Most previous studies focused on extracting the solar cycle in the time series of climate elements, while related spatial response analyses have been lacking. The spatial distribution of climate response to solar activity is helpful for us to identify the areas that are more significantly influenced by solar activity. This study aims to identify such sensitive areas through examining the response of regional climate in the Eurasia continent and northern Pacific Ocean in winter to the solar forcing during the peak and valley years of the 11-yr solar cycle. The anomalous atmospheric circulation associated with solar activity is examined to understand the spatial anomalies of temperature and precipitation in Northeast Asia, and we try to explain such spatial anomalies of climate through diagnosis of anomalous latent flux over the Pacific Ocean in response to the solar activity. The present study on the spatial response to solar cycle of the Northeast Asian climate serves to help further recognize the response mechanism of regional climate to solar activity.

2. Data and method

The solar activity is represented by solar radio flux (SRF). The SRF data at 10.7 cm (F10.7; in sfu and 1 sfu = 10^{-22} W m^{-2} Hz^{-1}) from 1947 to 2016 used in this study were obtained from NOAA of USA. The winter SRF is the average of SRF data in December, January, and February. The atmospheric circulation data were derived from the NCEP/NCAR monthly averaged global reanalysis (Kalnay et al., 1996). Winter precipitation over 160 observation stations in China was retrieved from the National Meteorological Information Center of China Meteorological Administration. The climatological mean of all datasets used in this study refers to a 30-yr average from 1981 to 2010.

Specifically, the SRF time series data were downloaded from http://www.esrl.noaa.gov/psd/data/correlation/solar.data. The NCEP/NCAR reanalysis data were obtained from www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html. The winter precipitation gauge data of China were retrieved from the China Meteorological Administration meteorological service internal network.

We chose winter SRF to examine its impact on winter climate anomalies in Northeast Asia. In this study, Northeast Asia is a geographical concept referring to the northeastern Asian region, including eastern Russia, Northeast China, Japan, South Korea, North Korea, and Mongolia, namely the entire Pacific Rim. The SRF time series exhibits an obvious 11-yr cycle, with alternating peak and valley solar activity years (Fig. 1). In this study, we prescribe that the standardized SRF values larger than zero in the peak half of the 11-yr period need to be three years or more in order to be classified into the peak year group. The peak years of solar activity meeting the above condition are found to be 1957/58, 1967/68, 1979/80, 1990/91, and 2001/02, respectively. Similarly, the standardized SRF values smaller than zero in the valley half the 11-yr period also have to be three years or more to be classified into the valley year group. The valley years satisfying such a condition are 1963/64, 1975/76, 1986/87, 1995/96, and 2008/09, respectively. The years of volcanic eruptions, e.g., El Chichón in March 1982 and Pinatubo in June 1991, are not included in the peak and valley years we chose. Thus, the data used in this study are free from contamination by volcanic forcing.

Figure 2 shows the power spectrum of winter SRF. As can be seen, SRF has a remarkable 11-yr cycle signal. The power spectrum is much larger than the standard spectrum and significantly higher than the 0.05 significant test level of red noise. The 11-yr cycle of SRF is very significant and can easily be discerned from other cycle signals in the curve of standardized data time series. Figure 1 indicates that solar activity has six 11-yr cycles, including six peaks (larger than 0) and six valleys (smaller than 0) from 1947 to 2016.

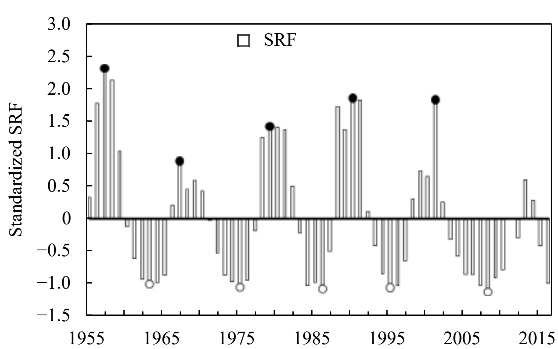

Fig. 1. Time series of standardized solar radio flux (SRF) with the solid (empty) circles representing peak (valley) years of solar activity.

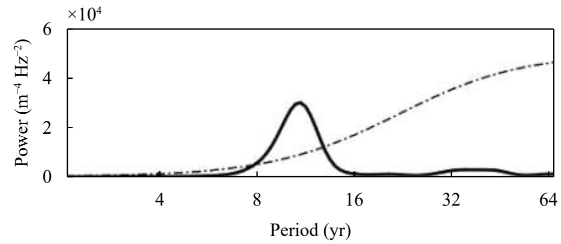

Fig. 2. Power spectrum of SRF. The dot-dashed line is the red noise standard spectrum at the 0.05 significance level.

The various statistical methods used in this investigation include power spectral analysis, synthetic analysis, regression, correlation analysis, and Student's *t*-test.

3. Results

3.1 *The solar cycle effect on temperature and atmospheric circulation*

The temperature anomalies at 850 hPa over Northeast Asia during the solar peak and valley years are shown in Figs. 3a, b, respectively. The warm (cold) colors indicate positive (negative) temperature anomalies, while the purple dots denote the confidence level greater than 95%. Figure 3 shows that the areas of significant anomalies are not randomly distributed but tend to cluster into large blocks. The centers of temperature anomalies are mainly located in the high latitudes of the Eurasian continent and the extratropical and tropical Pacific Ocean in the Northern Hemisphere. The differences of temperature anomaly (Fig. 3c) between solar peak (Fig. 3a) and valley (Fig. 3b) years show that two remarkable positive anomalous centers over the Asian continent with the 95% confidence level appear over the western Siberian plain (50°–70°N, 60°–90°E) and the Sea of Okhotsk region (45°–60°N, 120°–150°E). Over East Asia, there is an anomalous temperature gradient pointing from northeast to southwest. As a result, anomalous thermal wind blows from Pacific to inland of the East Asian continent. It can be seen that some area of Northeast Asia is obviously warmer in solar peak years than in solar valley years, which is consistent with the result of Wang et al. (2015).

Figure 3 demonstrates that in peak (valley) years of solar activity, the temperature anomalies are mostly positive (negative) over vast high-latitude areas of the Eurasian continent, with two positive (negative) anomalous centers. Comparatively, the temperature anomalies in low latitudes are not so strong. Compared to valley years, the solar activity in peak years might have produced significant warming in the Northern Hemisphere, especially over the high latitudes (Fig. 3a).

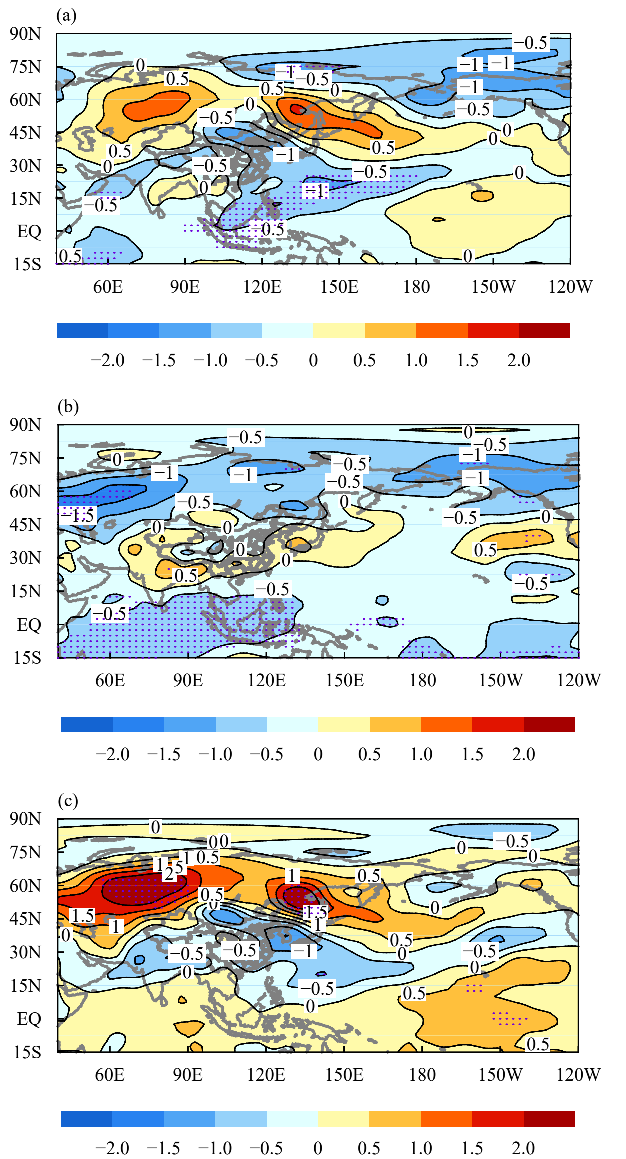

Fig. 3. Anomalous 850-hPa temperature fields in (a) peak and (b) valley years of solar activity, and (c) the difference between them. The warm/cold shadings indicate positive/negative temperature anomalies. The contour interval is 0.5°C. The purple dots indicate the areas exceeding the 95% confidence level.

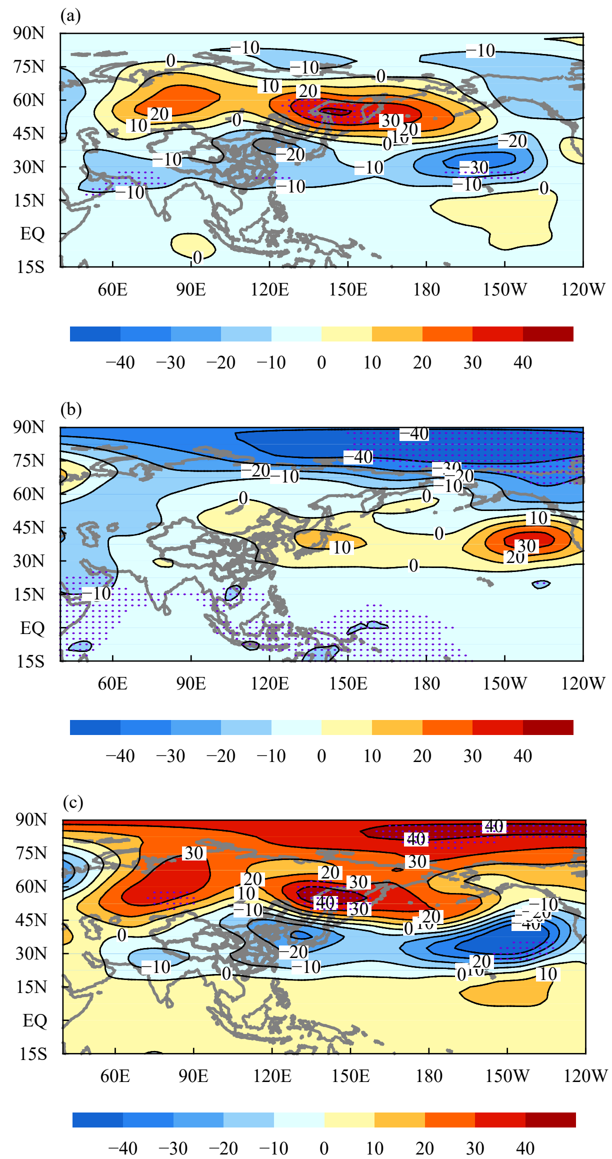

Fig. 4. Anomalous 500-hPa geopotential height fields in (a) peak and (b) valley years of solar activity and (c) the difference between them. The warm/cold shadings indicate positive/negative height anomalies. The contour interval is 10 gpm. The purple dots indicate the areas exceeding the 95% confidence level.

The response of temperature field to the solar 11-yr cycle, as shown above, could change the geopotential height field and thus the atmospheric circulation. Corresponding to the response of temperature at 850 hPa to the sun, the change of geopotential height at 500 hPa is shown in Fig. 4, which shows similar spatial patterns to those in Fig. 3. The responses of 500-hPa geopotential height to SRF are obviously different in peak (Fig. 4a) and valley years (Fig. 4b), as also shown in Fig. 4c. In peak years of solar activity, the geopotential height anomalies over the high-latitude Eurasian continent are mainly positive, consistent with the positive temperature anomalies in Fig. 3a, especially in the West Siberian plain and the Okhotsk Sea area to the Aleutian Low area; whereas negative geopotential height anomalies are found around 20°–40°N, indicating that the East Asian trough is weaker Fig. 4. These features are consistent with the results obtained by van Loon et al. (2007), Christoforou and Hameed (1997), and Wang et al. (2015). It is deduced that the high pressure or blocking high tends to be built and developed in these two regions. In the south of the two regions, there is a vast area of negative geopotential height anomalies, which is in favor of the development of low pressure or cutoff low.

Consequently, an anomalous anticyclone is prone to being generated around the Northeast Asia area. In this region, an anomalous southward pressure gradient force exists, which points from Heilongjiang Province of China and Vladivostock of southeastern Russia to the southwest direction, where anomalous easterlies could develop and help transport warm moist air mass from the Pacific Ocean to the east coast and inland of China to intensify winter precipitation in Northeast Asia and Northeast China. This feature is more obvious in solar peak years than in valley years.

The analyses above are confirmed further by the surface wind vector field at 850 hPa given in Fig. 5. It is shown in Fig. 5a (5b) that two significant anomalous anticyclones (one anticyclone and one cyclone) appear over the West Siberian plain and Okhotsk Sea region in peak (valley) years of solar activity, especially in the Northeast Asian region; while a significant anomalous cyclone (anticyclone) is found in the central North Pacific. In peak years of solar activity, Northeast Asia is located to the south of the anomalous anticyclone over the junction of the east coast of Asian continent and the western Pacific, where anomalous easterlies prevail. The east wind anomalies from the north of the anomalous cyclone pass by the warm moist ocean surface of the Pacific and flow into the east coast of the Asian continent. Then they enter the Northeast Asian region and lead to warm and wet abnormal weather and climate in this region. In valley years of SRF, however, there exists an anomalous cyclone in Northeast Asia and an anomalous anticyclone in the Lake Baikal region. The abnormal northerly winds bring a lot of cold and dry air mass into the Northeast Asian region from the Siberian area, and cause dry and cold weather and climate there. Cold air mass from the Siberian area flows far into Northwest Pacific and finally merges with the anomalous westerly wind in the north of the anomalous anticyclone over the central–northern Pacific Ocean.

It is concluded from the above analyses that different abnormal climate over the Eurasian continent could occur in association with different phases of the solar 11-yr cycle, especially over the Northeast Asian area. The temperature anomaly in peak and valley years of solar activity could alter geopotential height field and the atmospheric circulation, and finally result in abnormal regional climate. Based on observation data analysis, Xiao and Huo (2016) found that such an influence has spatiotemporal selectivity at the regional scale, and the impact of solar activity on regional climate in the high latitude is amplified in certain sensitive regions. Therefore, the effect of solar activity must be considered in the prediction of the climate in these regions.

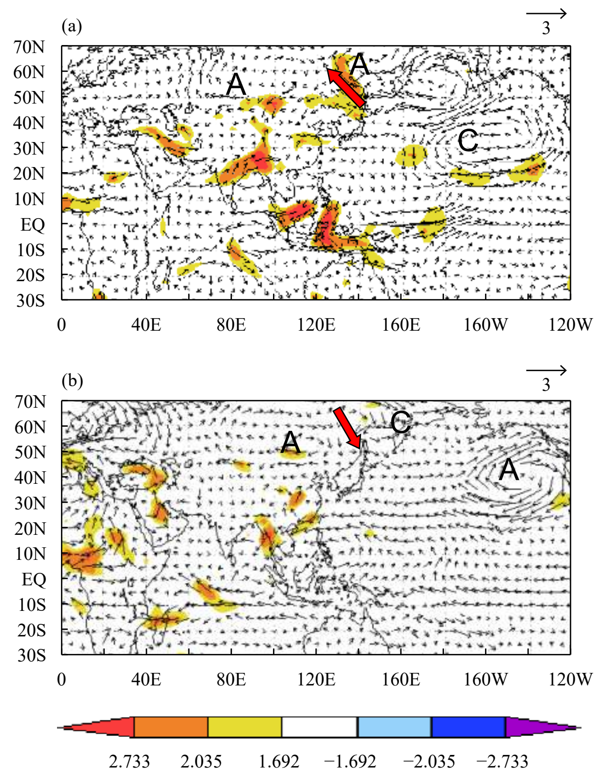

Fig. 5. Anomalous wind fields (vectors) at 850 hPa in (a) peak and (b) valley years of solar activity. Letter A indicates anticyclone and letter C indicates cyclone. Red arrows indicate flow directions. The yellow, orange, and red color shaded areas indicate the 90%, 95%, and 99% confidence levels, respectively.

3.2 *The solar cycle effect on winter precipitation*

In order to further detect the regional climate anomalies in Northeast Asia caused by solar cycle, the response of precipitation in Northeast Asia to solar activity is analyzed. Figure 6 shows the significance test of differences of precipitation between peak and valley years of solar cycle. More (less) winter precipitation is found in Northeast Asia in peak (valley) years of solar cycle at the 95% confidence level. This is consistent with the anomalies of temperature and atmospheric circulation shown in Figs. 3–5.

The difference of winter rainfall in Northeast China between peak and valley years of solar activity is shown in Fig. 7. The winter precipitation anomalies in China are in the shape of a belt oriented from northeast to southwest. They are totally different in peak and valley years of the solar cycle. Especially, Northeast China, North China, central China, and Southwest China seem to be more sensitive to solar activity. In peak years, there are obvious positive precipitation anomaly centers over Northeast and Southwest China, while a significant negative precipitation anomaly center lies over North and central China.

Figure 8 shows the regression coefficients of SRF data to the winter precipitation in China. It is noticed that the winter precipitation anomalies in Northeast China are indeed highly correlated with solar activity. The stronger the solar activity is, the more the winter precipitation in Northeast China. Note that over North, central, and Southwest China where there occur significant rainfall anomalies in Fig. 7, no significant coefficients are observed correspondingly in Fig. 8. Significant positive rainfall anomaly only occurs in Northeast China as shown in Fig. 8. Therefore, Northeast China is a highly sensitive response area to the solar cycle, and the impact of the sun's 11-yr cycle must be considered in the prediction of winter climate in this region. The spatially anomalous climate in Northeast Asia might reflect the amplified influence of the solar activity.

Furthermore, winter precipitation data over seven rain gauge stations (Qiqihar, Tongliao, Jixi, Mudanjiang, Hailun, Changchun, and Yanji) in Northeast China are employed to calculate their correlation coefficient with SRF to further confirm their relationship. The two time series of the averaged standardized data of the winter precipitation at the seven stations and the SRF are shown in Fig. 9. A rather high correlation coefficient of 0.38 is obtained at more than the 99% confidence level. It should be noted that the rainfall data in Northeast China are raw rain gauge data without any filtering or running mean. The correlation coefficient of gauge rainfall over Northeast China and SRF is 0.41 after detrending, higher than that of the raw gauge rainfall data. Apparently, the solar 11-yr cycle signal shows traces in the winter rainfall data in Northeast China. This further confirms that the anomalous precipitation in Northeast Asia is closely correlated to the solar activity.

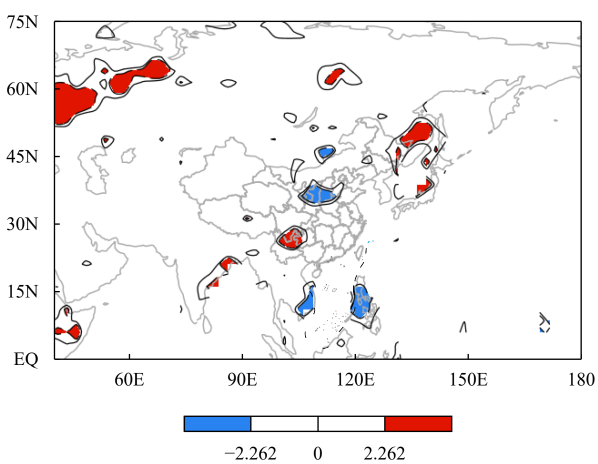

Fig. 6. Significance test of winter precipitation difference between peak and valley years of the 11-yr solar cycle. The red/blue color indicates the area with more/less precipitation at the 95% confidence level, and the areas circled by solid lines indicate the 90% level.

3.3 *The role of latent heat flux anomalies*

In order to explore the reason for the anomalous pattern of winter precipitation in China shown in Fig. 7, we analyze the latent and sensible heat flux anomalies in peak and valley years of solar cycle, respectively. It is found that the latent heat flux anomaly plays a more important role in the distribution of anomalous precipitation. Figure 10 shows the difference in latent heat flux between peak and valley years. There are three anomaly centers over the Pacific Ocean, which are labeled as Zone A (44°–58°N, 140°–158°E), Zone B (27°–40°N, 130°–155°E), and Zone C (23°–35°N, 180°–210°E), respectively. We define an index I_{latent} to represent the net anomalous latent heat flux over the Pacific induced by solar cycle. The index I_{latent} equals to the sum of anomalous latent heat flux in zone B and C, and minus that in zone A (shown in Fig. 10):

$$I_{\mathrm{latent}} = \mathrm{Latent_B} + \mathrm{Latent_C} - \mathrm{Latent_A}.$$

We calculate the correlation coefficients between winter precipitation in China and I_{latent} (Fig. 11). It is manifested that the distribution of the correlation coefficient is remarkably similar to the anomalous precipita-

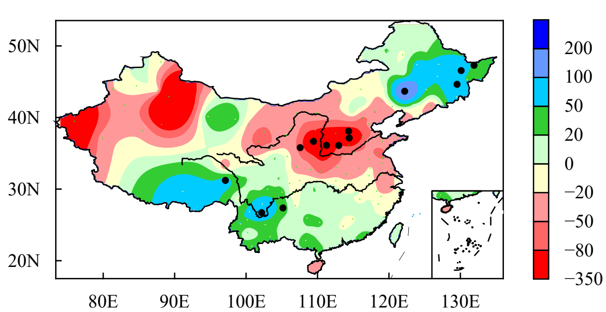

Fig. 7. Difference of China winter precipitation between peak and valley years of the 11-yr solar cycle. Black dots indicate the stations with values exceeding the 95% confidence level.

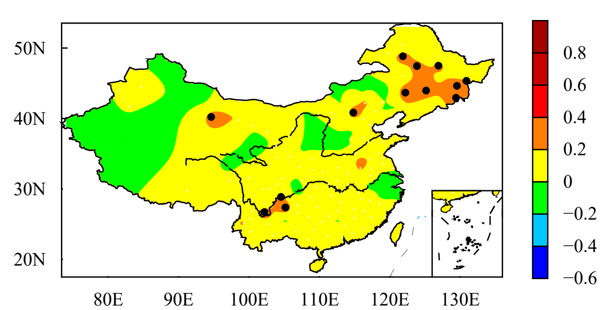

Fig. 8. Distribution of the regression coefficient of SRF to China winter precipitation. Black dots indicate the gauge stations with values exceeding the 95% confidence level.

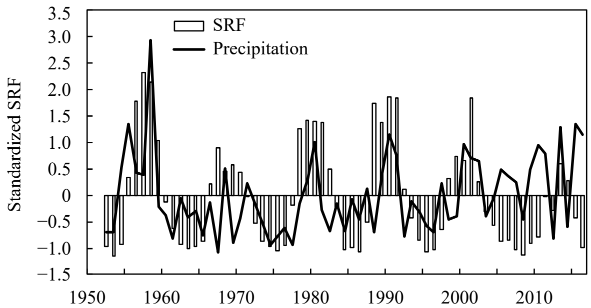

Fig. 9. Time series of standardized winter precipitation over seven gauge stations in Northeast China (solid line) and solar radio flux (SRF; rectangle).

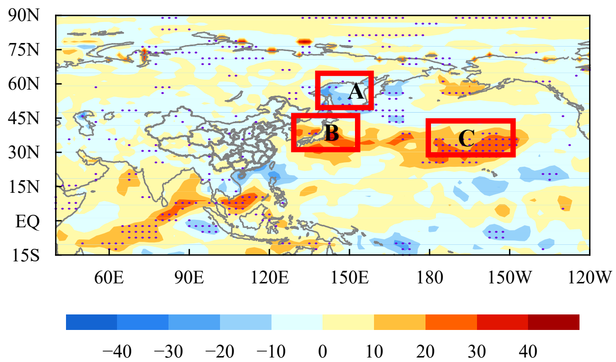

Fig. 10. Difference of latent heat flux in winter between peak and valley years of solar 11-yr cycle. Blue dots indicate the grid points with values exceeding the 95% confidence level.

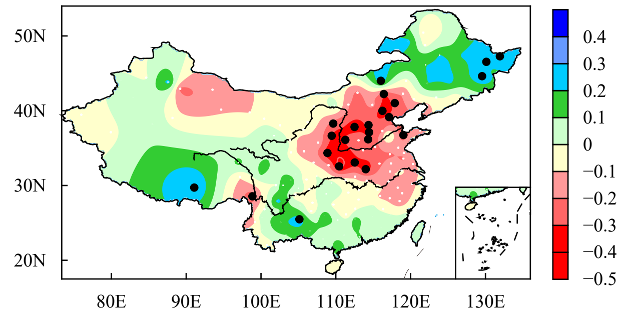

Fig. 11. Distribution of the correlation coefficient of I_{latent} to China winter precipitation. Black dots indicate the gauge stations with values exceeding the 95% confidence level.

tion pattern in Fig. 7 caused by solar cycle. Especially, the anomalous latent heat flux in zone C is highly related to the abundant precipitation in Northeast China in the peak years of solar 11-yr cycle (figure omitted). The regression analysis has the same result (figure omitted). It is thus further speculated that the abnormal latent heat flux associated with solar 11-yr cycle might be responsible for the anomalous winter precipitation pattern in China through interaction and energy exchange between the Pacific Ocean and the overlying atmosphere.

The regression coefficients of I_{latent} to wind field at 850 hPa (Fig. 12) indicate that the latent heat flux over the Pacific Ocean is an important physical factor to affect the winter airflow in Northeast Asia. Strong thermal exchange between sea and air could induce east and south wind anomalies around Northeast Asia. The spatial pattern of wind anomalies in Fig. 12 is very similar to that in Fig. 5a, especially over the Northeast Asian area. It is inferred that peaks in solar forcing produce greater energy input to the ocean surface, evaporating more moisture that can be carried by the south and east winds to the Northeast Asian convergence zones, where more precipitation occurs.

Based on the above analyses on winter temperature, precipitation, and atmospheric circulation in Northeast Asia in peak and valley years of solar 11-yr cycle, it is concluded that the impact of solar activity on regional climate in East Asia should not be neglected. Particularly, the role of the sun in anomalous climate of Northeast Asia is amplified compared with other regions as a result of the geophysical selectivity of the sun's effect. The regional climate anomalies in East Asia caused by solar activity may not be an accidental coincidence, but rather a part of the whole climate system's response on the earth to solar activity. The anomalous latent heat flux over the Pacific Ocean associated with the solar 11-yr cycle might be responsible for the abundant winter precipitation in Northeast Asia in peak years of solar cycle.

4. Conclusions and discussion

Using various statistical methods and SRF data, this study has investigated the impact of the solar 11-yr cycle on regional climate in Northeast Asia in recent decades.

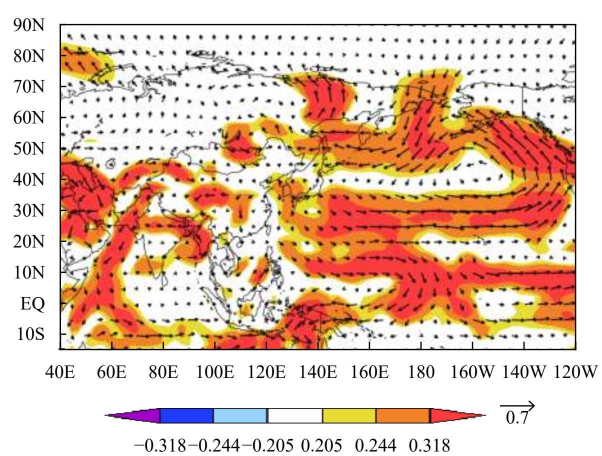

Fig. 12. Distribution of the regression coefficient (× 10) of I_{latent} to 850-hPa wind field in winter. The yellow, orange, and red shadings indicate the 90%, 95%, and 99% confidence levels, respectively.

Based on the comparative statistical analyses between peak and valley solar activity years, we obtain the following results.

In winters of peak (valley) years of solar cycle, the 850-hPa temperature field is mainly characterized by warming (cooling) over vast land and ocean areas in high latitudes of the Northern Hemisphere. In peak years, a significant positive center of temperature anomaly is located over Northeast Asia; meanwhile, from the northern Asian continent to North Pacific, the geopotential height centers present a meridional distribution of positive and negative anomalies from north to south, indicating a high pressure anomaly in the north and a low pressure anomaly in the south, with a significant positive anomalous center over Northeast Asia. Northeast Asia is located to the southwest of the anomalous high pressure, where significant anomalous southeast wind prevails, which brings warm and moist air mass from the Pacific Ocean to the inland area. Warm and wet weather and climate anomalies tend to be generated there, resulting in the increase of winter precipitation in Northeast Asia. The above situations are reversed in valley years. Observation data analysis further confirms that in Northeast China, the variation of winter rainfall is consistent with that of SRF and they are highly correlated at the 99% confidence level.

The anomalous latent heat flux over the Pacific Ocean associated with the solar 11-yr cycle is highly correlated to the pattern of anomalous winter precipitation in China. It may be responsible for the abundant winter precipitation in Northeast Asia in peak years of solar cycle through air–sea interaction and energy exchange.

At present, there are two ways for the sun to affect earth climate, which are summarized as "top-down" and "bottom-up" mechanisms. The "bottom-up" mechanism represents the response of sea surface temperature (SST) to solar activity, which could affect the atmospheric circulation above the sea (Meehl et al., 2003, 2008). The "top-down" mechanism was discussed by Meehl et al. (2003, 2008) and Wang et al. (2015). Here we speculate that the impact of the sun's 11-yr cycle on winter climate in Northeast Asia is via the "bottom-up" mechanism. The anomalous latent heat flux over the Pacific Ocean induced by solar activity could alter the heat exchange and interaction between the ocean surface and the atmosphere, especially over the A, B and C anomaly centers (see Fig. 10) over the Pacific Ocean, thus influencing the sea surface temperature and air temperature fields and the atmospheric circulation over East Asia, eventually inducing anomalous winter precipitation in Northeast Asia (with corresponding figures omitted). Therefore, when predicting climate in Northeast Asia, it is necessary to consider the influence of the solar 11-yr cycle.

According to the analysis results obtained by Roy and Haigh (2010) that any proposed mechanism of the response to variations in solar irradiance needs to be analyzed in the context of ENSO variability, we have checked the strong ENSO events represented by Oceanic Nino Index (ONI) from Climate Prediction Center of NOAA at the website www.cpc.noaa.gov/data/indices. It is found that except for 1957/1958 winter, which is a strong warm ENSO year, other peak years of solar activity that we choose are mild or near normal years. Among the five valley years of solar activity, there are three cold events and two warm events. We thus infer that the solar influence discussed here is not related to ENSO and its variability in our study.

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