Role of Local Atmospheric Forcing and Land–Atmosphere Interaction in Recent Land Surface Warming in the Midlatitudes over East Asia

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ABSTRACT

Significant summer land surface warming has been observed in the middle latitudes over East Asia, especially after the mid-1990s, which has evidently affected the East Asian weather and climate. Using multisource observations and reanalysis data during 1979–2013, this study explores the possible reasons for recent land surface warming over this region by considering atmospheric forcing and regional land–atmosphere interaction related to extratropical cyclones (ECs). Results show that there is a close relationship between land surface warming and weakened ECs over East Asia. Recent land surface warming was attributed to local atmospheric forcing and feedback of land–atmosphere interaction associated with weakened ECs. The abnormal large-scale circulation associated with anomalous ECs produced evident dynamic forcing on the land surface. Weakened ECs are usually accompanied by an abnormal high pressure system and anticyclonic circulation around Lake Baikal, which benefit the intensification of anomalous southerly wind in the rear of the anomalous anticyclone, leading to positive temperature advection and temperature increase over East Asia. Meanwhile, the anomalous adiabatic warming caused by abnormal descending motion associated with the anticyclonic anomaly also contributes to local warming. The feedback of local land–atmosphere interaction plays an important role in land surface warming. Weakened ECs increase both incident solar radiation and precipitation. The increased precipitation reduces the soil moisture and in turn weakens the surface evaporation and local cooling effect, resulting in land surface warming. Our findings are helpful for better understanding the mechanisms responsible for recent summer land surface warming over East Asia as well as its climatic effects.

1. Introduction

According to the IPCC AR5, climate warming during the recent 30 years is the strongest since 1850 and the global mean air temperature has risen about 0.85°C during 1880–2012 (IPCC 2013). The Eurasian continent

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is one of the regions with the most significant warming (Hansen et al. 2010). As the largest continent, the land surface thermal anomalies of the Eurasian continent are very important to both regional and large-scale atmospheric general circulations. Recent studies suggested that significant summer land surface warming has been observed in the middle latitudes over East Asia, especially after the mid-1990s (Zhu et al. 2012; Chen and Lu 2014; Chen et al. 2016; Dong et al. 2016, 2017; Chen et al. 2017; Hong et al. 2017). Such warming has close relationships with both temperature and precipitation changes in China as well as with the East Asian summer monsoon circulation (Li et al. 2010; Xu et al. 2011; Zhu et al. 2012; Chen and Lu 2014; Chen et al. 2017). Therefore, it is necessary to investigate possible reasons for the changes in the anomalous thermal conditions over this region before understanding their impacts on weather and climate.

With regard to the reasons for recent land surface warming over the Eurasian continent, previous studies partly attributed the surface thermal anomalies over the Eurasian continent to the atmospheric circulation anomalies caused by the external forcing of the sea surface temperature and sea ice. Such large-scale atmospheric general circulation anomalies play important roles in the decadal variation of the surface temperature over Northeast Asia (Sun et al. 2008; Sutton and Dong 2012; Zhu et al. 2012; Gao et al. 2014; Dong et al. 2016, 2017; Hong et al. 2017). Based on numerical experiments, Dong et al. (2016) suggested that changes in sea surface temperature (SST) and sea ice can explain about 76% of the abnormal warming signal over Northeast Asia. Hong et al. (2017) found that the Atlantic multidecadal oscillation (AMO) can also modulate the activity of the atmospheric Silk Road teleconnection pattern and further amplify the land surface warming in Northeast Asia. In addition, more recent studies emphasized the impacts of greenhouse gases and anthropogenic aerosol emissions on the warming of the continent (Zhu et al. 2012; Dong et al. 2016, 2017). For example, Dong et al. (2016, 2017) investigated the impacts of greenhouse gases and anthropogenic aerosol emissions on the summer surface temperatures in Europe and Northeast Asia based on sensitivity experiments. Their results suggested that increasing greenhouse gases and gradually decreased aerosols can result in persistent warming over these regions in the future. It is noted that most previous studies emphasized the atmospheric general circulation itself or the anomalous circulation forced by the external forcing.

More recently, Zhou et al. (2015, 2016) emphasized the roles of longwave radiation effects and the feedback of land–atmosphere interaction on the warm amplification over arid/semiarid regions. In addition, various studies have explored the possible reasons for the abnormal warming of the Eurasian continent from aspects of changes in cloud amount (Dai et al. 1997, 1999; Tang and Leng 2012; Tang et al. 2012) and precipitation (Dai et al. 1997, 1999; Trenberth and Shea 2005). Dai et al. (1997, 1999) pointed out that increased cloud amount can reduce solar radiation arriving at the land surface and further influence the daily maximum temperature. Tang et al. (2012) reported that the decreasing trend of summer cloud amount is accompanied by an increasing trend of the surface temperature in most parts of Europe, while a slight decreasing trend or no evident trend is found over regions with increased cloud amount. In addition, soil water content can also affect the diurnal temperature range by altering the thermal effect induced by the changed evaporation; that is, lower soil water content usually results in weakened latent heat.

Actually, regional land–atmosphere interaction strongly depends on both the local atmospheric regimes and underlying surface conditions. In East Asia, extratropical cyclones are a typical lower pressure system featuring strong baroclinicity and are a kind of important synoptic-scale eddy, which can affect exchanges of the heat, water vapor, and momentum between the atmosphere and the land surface. Previous studies suggested that the extratropical cyclones (ECs) over East Asia have experienced significant interannual and interdecadal variations (Wang et al. 2009; Zhang et al. 2012a,b; Chen et al. 2017). More recently, Chen et al. (2017) noted that the frequency of EC activity evidently decreases after early 1990, which has the potential to influence the decadal mode of the East Asian summer monsoon via the synoptic-scale feedback through the wave–mean flow interaction. Zhang and Chen (2017) and Chen et al. (2019) found that interdecadal variation of ECs activity during summer over East Asia is closely related to the nonuniform land surface warming in the midlatitudes of East Asia.

On one hand, as the most important synoptic-scale atmospheric activity in the middle latitudes, the cyclones can affect local weather and regional climate as well as the atmospheric general circulations. On the other hand, regional changes of the general circulations will influence the thermal states of the underlying surface. Anomalous EC activity can also induce changes in both cloud amount and precipitation, and further affect the energy balance and the thermal conditions of the land surface. Actually, the surface soil usually shows relatively rapid response to the local atmospheric forcing and the land–atmosphere interaction happens at various time scales.

In this study, we attempt to explore the possible reasons for recent land surface warming in the midlatitudes of East Asia. In particular, we took the typical synoptic eddy in the middle latitudes of East Asia (i.e., ECs) as the key link between the land surface and large-scale atmospheric mean flow. The objective of the study aimed to understand recent land surface warming in the middle latitudes of East Asia from the perspectives of local atmospheric forcing and regional land–atmosphere interaction. Section 2 describes the data and method. Section 3 presents the basic features of the summer EC activity over East Asia during the most recent 30 years. Section 4 discusses the linkage between the land surface warming and the EC activity. Possible mechanisms are explored in section 5, then conclusions and discussion are given in section 6.

2. Data and method

a. Data

Data used in this study include the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim; Dee et al. 2011; http://apps.ecmwf.int/datasets/) and the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996; https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html). The meteorological variables used include 4-times-daily sea level pressure, monthly horizontal wind, geopotential heights, surface soil temperature (0–7 cm), incident and absorbed solar radiation at the surface, and surface latent heat flux. Cloud fraction data are from the NOAA Advanced Very High Resolution Radiometer (AVHRR) PATMOS-x cloud fraction datasets (Heidinger et al. 2012). The precipitation data used are the gridded gauge-analysis products provided by the Global Precipitation Climatology Centre (GPCC) (Schneider et al. 2015). The monthly soil moisture is provided by NOAA/CPC (van den Dool et al. 2003). The horizontal resolutions of the temperature and the precipitation are $1^\circ \times 1^\circ$, cloud fraction has a resolution of $0.1^\circ \times 0.1^\circ$, and the resolutions of other datasets are all $2.5^\circ \times 2.5^\circ$. The time period of the cloud fraction covers 1982–2015 and for other datasets is 1979–2015.

b. Method

In this study, an objective identification and tracking algorithm of the cyclone activity proposed by Murray and Simmonds (1991a,b) and refined by Simmonds et al. (1999) was used to acquire the statistics of the cyclone activity based on the 4-times-daily sea level pressure data. Pinto et al. (2005) evaluated the performance of this method in recognizing the cyclone in the Northern Hemisphere and pointed out that it can reasonably represent various types of cyclones. This method has been widely used in recent studies. For example, Zhang et al. (2012a) and Chen et al. (2017) used this method to investigate the cyclone activity in East Asia. Details of this method can be found in Chen et al. (2017). With such a method, we calculated the statistics of the summer ECs activity during 1979–2013 and defined the numbers of the summer cyclone passing a grid cell of $2.5^\circ \times 2.5^\circ$ as the frequency of the cyclone activity, which is used to characterize the ECs activity over this region.

In addition, statistical methods including correlation, composite, linear regression, and the Mann–Kendall (M-K) test have been used in our analysis. Also, the *t*-test method was used to examine the significance of the statistical results. To further investigate the possible linkage between surface soil temperature and cyclone activity, 40°–55°N, 100°–120°E has been selected as the target area for the summer EC activity. We further calculated the normalized regional average of the frequency of summer cyclones over 40°–55°N, 100°–120°E as an EC activity index (hereinafter EAMC) and regressed the summer surface soil temperature anomalies onto EAMC. Meanwhile, typical years for the anomalous cyclone activity have been selected according to EAMC for composite analysis. Years with EAMC above 0.8 are selected as strong cyclone activity years, including 1980, 1983, 1984, 1986, 1987, and 1991. Years with EAMC below −0.8 are selected as weak cyclone activity years, including 1998, 1999, 2001, 2002, 2005, 2011, and 2012.

3. Basic features of summer extratropical cyclone activity over East Asia

Figure 1a shows the average frequency of summer cyclone activity over the last 35 years. It was found that large variability of summer cyclone activity mainly appeared in regions south of Lake Baikal (i.e., midwestern Mongolia and northeastern China). Therefore, the region 40°–55°N, 100°–120°E has been selected as the target area for the ECs activity and we mainly focused on summer cyclone activity over this area. To further understand the basic feature of summer cyclone activity over the target area, we further calculated the normalized regional average of the frequency of summer cyclone activity as the index EAMC (Fig. 1b). It was noted that there was an evident declining trend in EAMC during 1979–2013, which indicated a significant weakening of summer cyclone activity in recent years. The results of an 11-yr running average suggest that EAMC also exhibits an evident decadal variation in the early 1990s. The frequency of summer cyclone activity shows an evident decreasing trend and the cyclone activity over this region also shows abrupt changes around 1993.

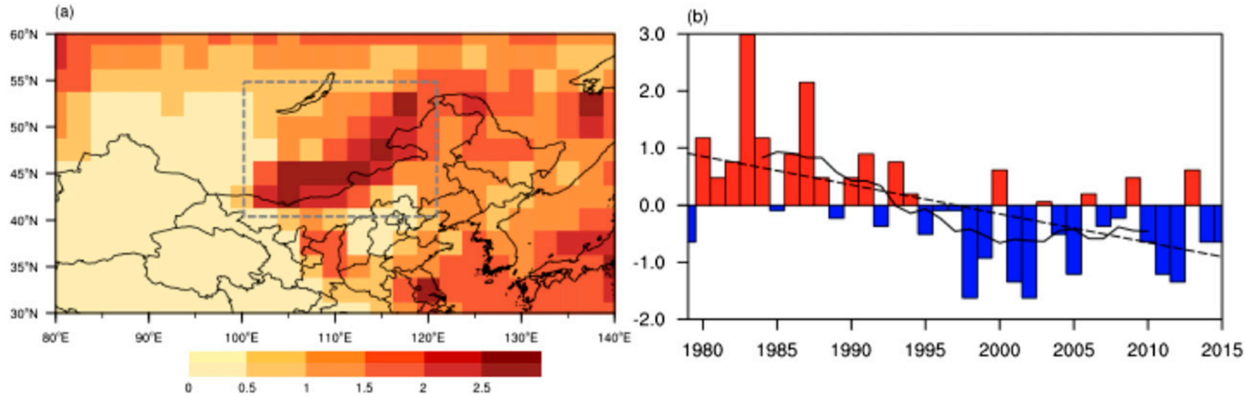

FIG. 1. (a) Geographic distributions of interannual variability of the midlatitude cyclone activity frequency (number of cyclone centers in a 2.5° × 2.5° grid) in summers (June–August) over East Asia during 1979–2015; the dashed rectangle shows the key region of summer cyclone activity (40°–55°N, 100°–120°E). (b) Normalized regional average of the frequency of summer cyclone activity index (EAMC) (bars) with the linear trend (dashed line) and 11-point moving average (solid line).

The cyclone activity is generally strong before 1993 but becomes weaker after that.

4. Linkages between land surface warming in the midlatitudes of East Asia and summer extratropical cyclone activity

Figure 2a explored the basic features of the variations in summer land surface thermal conditions in the middle latitudes over East Asia. The geographic distribution of the linear trend of summer surface soil temperature shows that a significant warming of the land surface happens over regions around Lake Baikal, which is one of the regions with greatest variability and most significant warming.

From Fig. 2b, it is found that significant negative values of the regressed surface soil temperature anomalies mainly appeared over the southwest region to Lake Baikal, indicating that strong (weak) cyclone activity is linked to anomalously cooling (warming) land surface over this region. It is noted that the regions with evident soil temperature anomalies are basically consistent with the area with strong linear trend of the surface soil temperature (Fig. 2a). According to the composite results (strong minus weak cyclone activity years) as shown in Fig. 2c, a significant difference in the surface soil temperature occurs near Lake Baikal and its southern region, implying that summer cyclone activity has the potential to alter the thermal states of the land surface over this area. In addition, it is noted that the spatial pattern of the soil temperature (strong minus weak cyclone activity years) agrees very well with that of the regressed results and the linear trends of the surface soil temperature.

We further calculated the regional averaged surface soil temperature over the land surface temperature target region 45°–55°N, 85°–115°E and acquired its normalized time series STL1, which is presented together with EAMC in Fig. 3. Note that the surface soil temperature shows an evident increasing trend whereas the frequency of the cyclone exhibits a decreased trend. Their correlation coefficients are −0.64 and −0.44 before and after removing the linear trend, respectively (both significant at 0.01 confidence level), implying that the soil temperature over this region is closely related to the cyclone activity. Strong cyclone activity tends to be accompanied by low soil temperature, whereas weak cyclone activity tends to be accompanied by high soil temperature. In addition, the average values of both the soil temperature and the frequency of cyclone activity exhibit significant differences before and after 1993. Before 1993, the soil temperature over this region was generally below the normal but became above the normal after that, while the cyclone activity exhibited opposite behavior.

5. Mechanisms responsible for recent land surface warming in the middle latitudes of East Asia

a. Role of background circulation related to anomalous cyclone activity

ECs are the most important synoptic-scale atmospheric disturbance and also an important component of the atmospheric general circulation system in the middle and high latitudes in the Northern Hemisphere. As pointed out by Chen et al. (2017), abnormal cyclone activity can alter the mean flow through the wave–mean flow interaction. More specifically, the abnormally strong cyclone activity can cause significant negative anomalies of sea level pressure and geopotential field

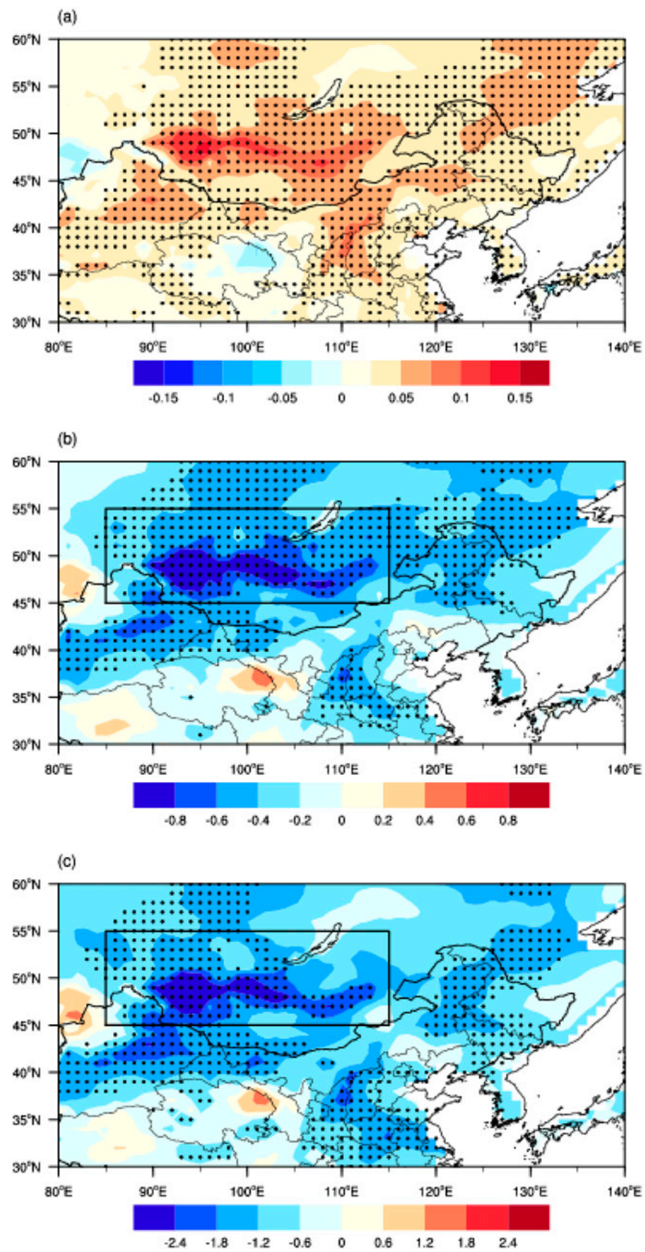

FIG. 2. (a) Linear trend of summer surface soil temperature (°C yr^{-1}), (b) regressed summer mean surface soil temperature anomalies onto EAMC, and (c) composite of summer surface soil temperature (high EAMC minus low EAMC years).The dotted areas are statistically significant at the 1% level, and the rectangle in (b) and (c) shows the key area of land surface temperature (45°–55°N, 85°–115°E).

near Lake Baikal through the poleward transport of the vorticity flux, resulting in anomalous cyclonic circulation in these areas, while the southerly anomaly to the southeast of the anomalous cyclonic circulation near Lake Baikal is favorable for the significant enhancement of the East Asian summer monsoon (EASM). Here, we investigated the atmospheric general circulation related to the anomalous cyclone activity to provide background for understanding the possible impacts of the local atmospheric forcing on the recent land surface warming in the middle latitude of East Asia.

We calculated the regressions of 500-hPa zonal and meridional wind anomalies onto the EAMC, respectively. Figures 4a and 4b show the geographic distribution of the

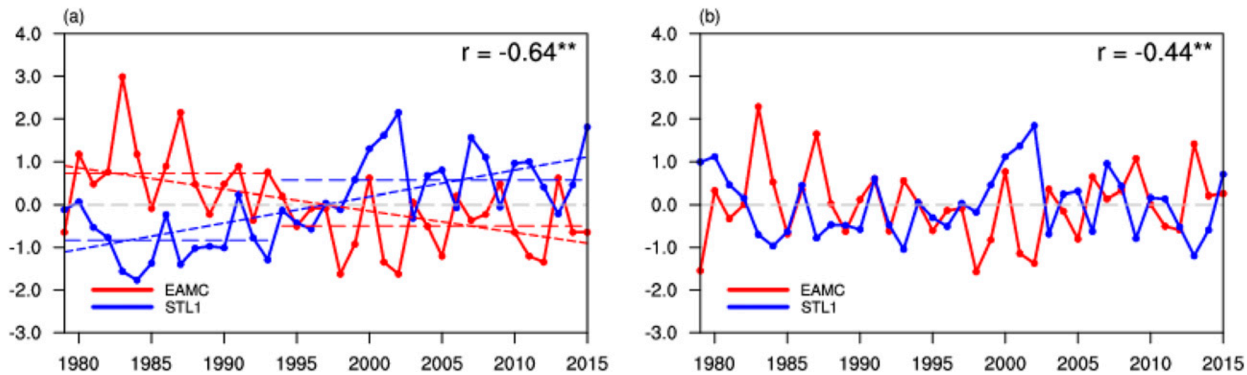

FIG. 3. (a) EAMC and normalized regional average of summer land surface temperature (STL1) over the key area (45°–55°N, 85°–115°E) (solid lines) with the linear trend (dashed lines), and (b) detrended EAMC and STL1. The correlation coefficients between EAMC and STL1 are given in the upper-right corner, and the asterisks indicate statistical significance at the 1% level.

regressed 500-hPa wind anomalies onto EAMC as well as the composite difference between strong and weak cyclone activity years. When there is more frequent summer cyclone activity, an evident anomalous cyclonic circulation appears near Lake Baikal and an anomalous anticyclonic circulation is located in the east of the Ural Mountains. Such a spatial pattern of circulation anomalies corresponds to intensified northerly wind in the northwest (southeast) of the anomalous cyclonic (anticyclonic) circulation and zonal westerly wind around 40°N in the midlatitudes. Further analysis suggests that the regressed 500-hPa geopotential height anomalies based on ERA-Interim and NCEP–NCAR reanalysis onto EAMC both feature significantly positive anomalies in the high latitudes north to 60°N, with two positive centers located at the east of the Ural Mountains and north to the Sea of Okhotsk, respectively, but negative anomalies in the south to Lake Baikal (Figs. 4c,d). It is evident that strong cyclone activity is usually accompanied with negative anomalies of the 500-hPa geopotential height near Lake Baikal, but positive anomalies at the east of the Ural Mountains and north to the Sea of Okhotsk. A similar anomalous circulation pattern was also found at 300 hPa (figure not shown). Such a situation will intensify the zonal westerly wind south to the anomalous cyclonic circulation. On the whole, intensified zonal wind (westerly wind) will reduce the meridional heat exchange.

To explore the relationship among the cyclone activity, zonal wind, and the vertical structure of the geopotential heights, we calculated the regressed zonal wind and geopotential height onto EAMC. The regressed fields are averaged over 85°–115°E and presented in latitude–height cross section as shown in Figs. 4e and 4f. It is evident that strong cyclone activity usually causes intensified zonal westerly wind in the midlatitudes to the south of the cyclone activity center but weakened westerly wind to its north. As a result, weakened zonal wind around 60°N benefits southward movement of the cold air in the high latitudes to the middle latitudes around Lake Baikal and intensified zonal wind around 40°N hampers the warm air transport from the low latitudes to regions near Lake Baikal. This type of circulation pattern tends to decrease the surface soil temperature over 45°–55°N, 85°–115°E. Negative anomalies of the geopotential heights over 40°–60°N (Fig. 4f) indicate that strong cyclone activity can cause cyclonic anomalous circulation from the lower to upper troposphere. The westerly (easterly) wind anomalies occur to the south (north) of the anomalous cyclonic circulation and tend to intensify (weaken) the zonal wind.

We further calculated the regressed 850-hPa horizontal temperature advection onto EAMC and its composite difference (Fig. 5a). The spatial pattern is basically consistent with that of the composite results (Fig. 5b), implying that the background circulation related to the strong cyclone activity can result in negative temperature advection and be conducive to decrease of the temperature over western part of the land surface target region. It is noted that the temperature advection caused by the abnormal large-scale circulation is opposite in the eastern part of the target region, which is a possible reason why significant land surface temperature change appears in the western part of the target region. This is generally consistent with the results given by the correlation analysis. Meanwhile, the anomalous large-scale background circulation related to the strong cyclone activity can cause adiabatic cooling accompanied by the abnormal ascending motion, which can also contribute to the local cooling over this region. On the contrary, weak cyclone activity can contribute to the local warming over this region.

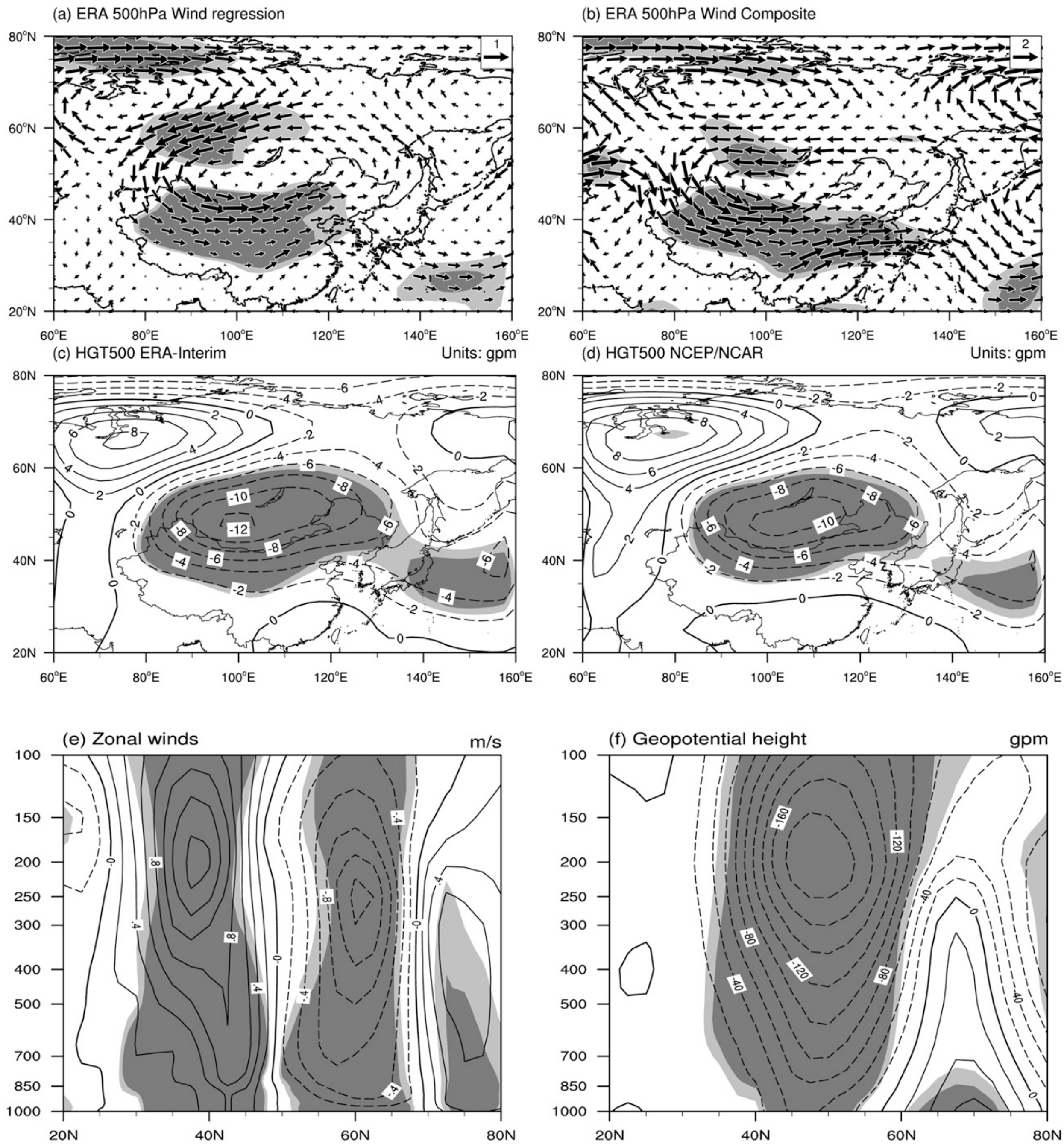

FIG. 4. (a) Regression of summer mean 500-hPa horizontal winds anomaly (m s^{-1}) onto EAMC and (b) composite (strong EAMC minus weak EAMC years) of 500-hPa horizontal winds (m s^{-1}). Also shown are regressions of (c) ERA-Interim and (d) NCEP–NCAR reanalysis summer mean 500-hPa geopotential height anomalies (gpm) onto EAMC and regression of vertical distribution of (e) zonal wind anomalies (average of 85°–115°E) and (f) zonal mean of geopotential height anomalies (average of 85°–115°E) onto EAMC. Dark or light shading indicates statistical significance at the 5% or 10% level, respectively.

b. Impacts of cloud fraction change induced by anomalous cyclone activity

Cloud cover has been well known as one of the dominant atmospheric factors controlling the land surface temperature. Decreased cloud fraction will increase the incident solar radiation to the land surface and benefit the warming of the land surface. Especially in summertime, clouds can produce more significant impacts on the solar radiation due to relatively strong solar radiation

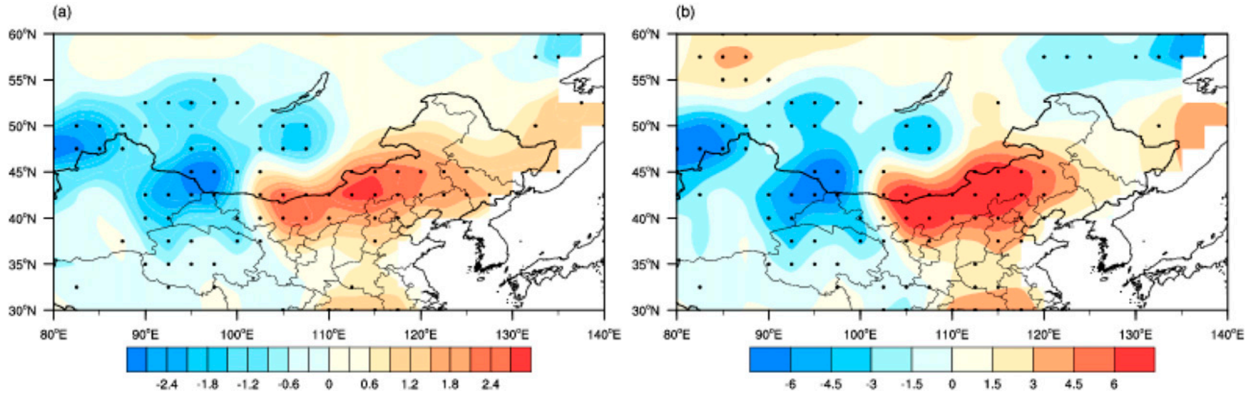

FIG. 5. (a) Regression of summer mean 850-hPa horizontal temperature advection anomalies onto EAMC, and (b) composite (high EAMC minus low EAMC years) of 850-hPa horizontal temperature advection. Dotted areas are statistically significant at the 5% level.

(Dai et al. 1997, 1999, 2004; Tang and Leng 2012). As given in Fig. 6a, the surface soil temperature bears a significantly negative correlation with the cloud fraction, implying that the changes in the cloud fraction play important roles in the variation of soil temperature.

Figure 7a presents the spatial pattern of the linear trend of the summer cloud fraction during the most recent 34 years. An evident decreasing trend of summer cloud fraction has been observed over the land around Lake Baikal (significant at 0.01 confidence level). Results from the cloud fraction of the ERA-Interim reanalysis are generally consistent to those from the PATMOS-x data (Figs. 7a1, 7a2). We further calculated the regressed summer cloud fraction onto EAMC as shown in Figs. 7b1 and 7b2. The evidently positive values of the regressed summer cloud fraction (significant at the 0.05 confidence level) mainly appear over the land around Lake Baikal. Furthermore, the geographic distribution of composite results of the cloud fraction during strong and weak cyclone activity years gives a similar conclusion (Figs. 7c1, 7c2). In general, there is a close relationship between the ECs activity and local cloud fraction over this region; that is, strong or weak cyclone activity is usually related to increased or decreased summer cloud fraction, respectively.

It is well known that cloud fraction is usually closely related to the incident solar radiation. The relationship between the cloud amount and the cyclone activity was examined here by calculating the regressed incident solar radiation onto EAMC (Fig. 8a). It is noted that a large negative value locates near Lake Baikal and its southern region. On the whole, in the case of strong cyclone activity, more cloud fraction and reduced incident solar radiation are observed over this region. On the contrary, weak cyclone activity can increase the incident solar radiation. The composite results (Fig. 8b) also show the same results.

In summary, the linkage between the cyclone activity and the surface soil temperature actually reflects the following physical processes: strong cyclone activity tends to increase the could fraction over the target region 45°–55°N, 85°–115°E, further causing decreased

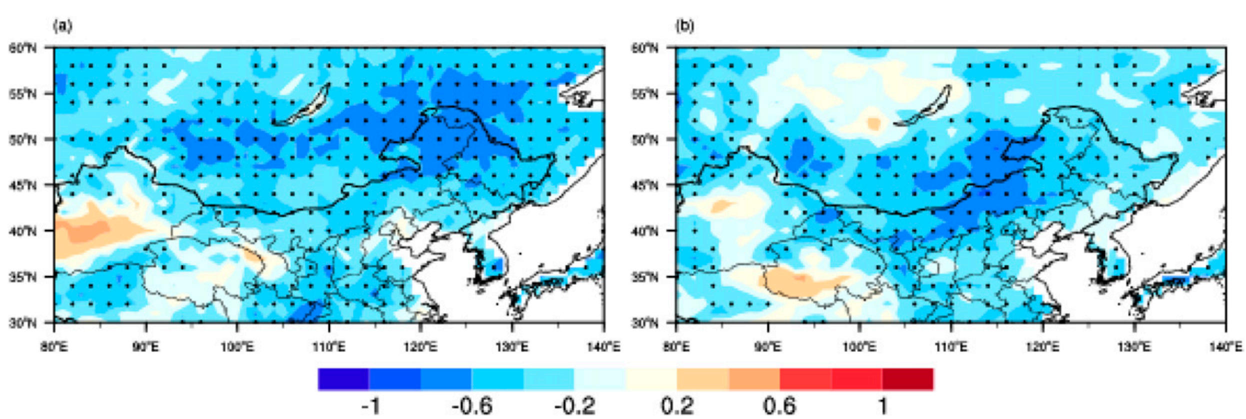

FIG. 6. Geographic distribution of correlation between STL1 and summer (a) cloud cover and (b) precipitation. Dotted areas are statistically significant at the 1% level.

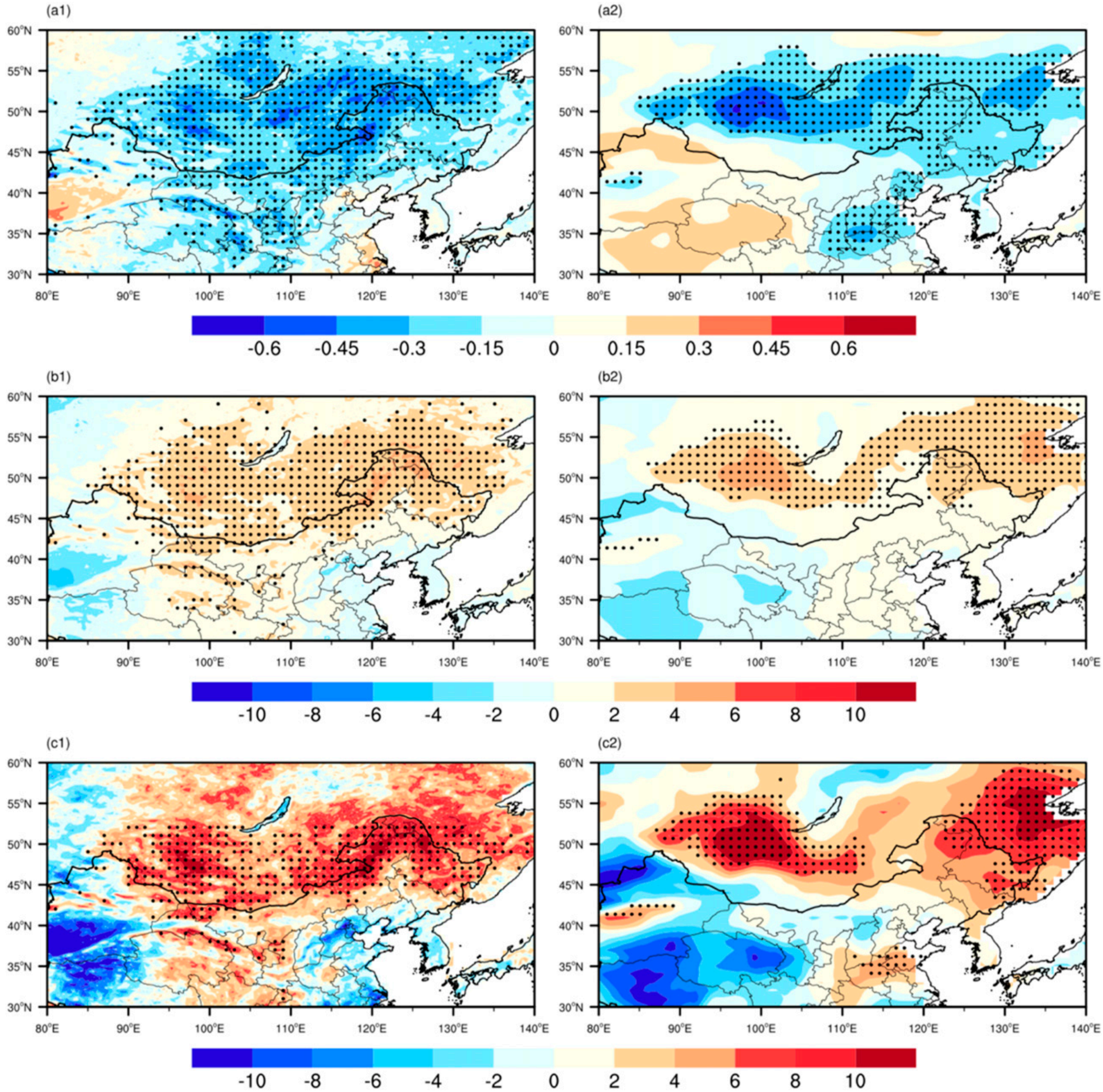

FIG. 7. (a1),(a2) Linear trend of cloud cover (% yr^{-1}); (b1),(b2) regression of summer mean cloud fraction anomalies onto EAMC; and (c1),(c2) composite (high EAMC minus low EAMC years) of cloud fraction for (left) NOAA AVHRR PATMOS-x and (right) ERA-Interim data. Dotted areas are statistically significant at the 1% level.

incident solar radiation and less solar radiation absorbed by the land surface. As a result, evident cooling of the surface occurs. In contrast, weak cyclone activity usually causes warming of the surface soil. It is noted that the most significant changes of the cloud fraction mainly happen in the eastern part of the land surface temperature target region, which is not consistent with the largest changes in the land surface temperature. The possible physical explanation is that the superposition of the large-scale temperature advection effect and cloud effect cause significant changes in land surface temperature in the western part of the target area. However, the temperature advection offsets part of the cloud effect and cause slightly weak temperature changes in the eastern part of the target area.

c. *Impacts of precipitation change induced by anomalous cyclone activity*

Another dominant atmospheric factor controlling the land surface temperature is precipitation, which can

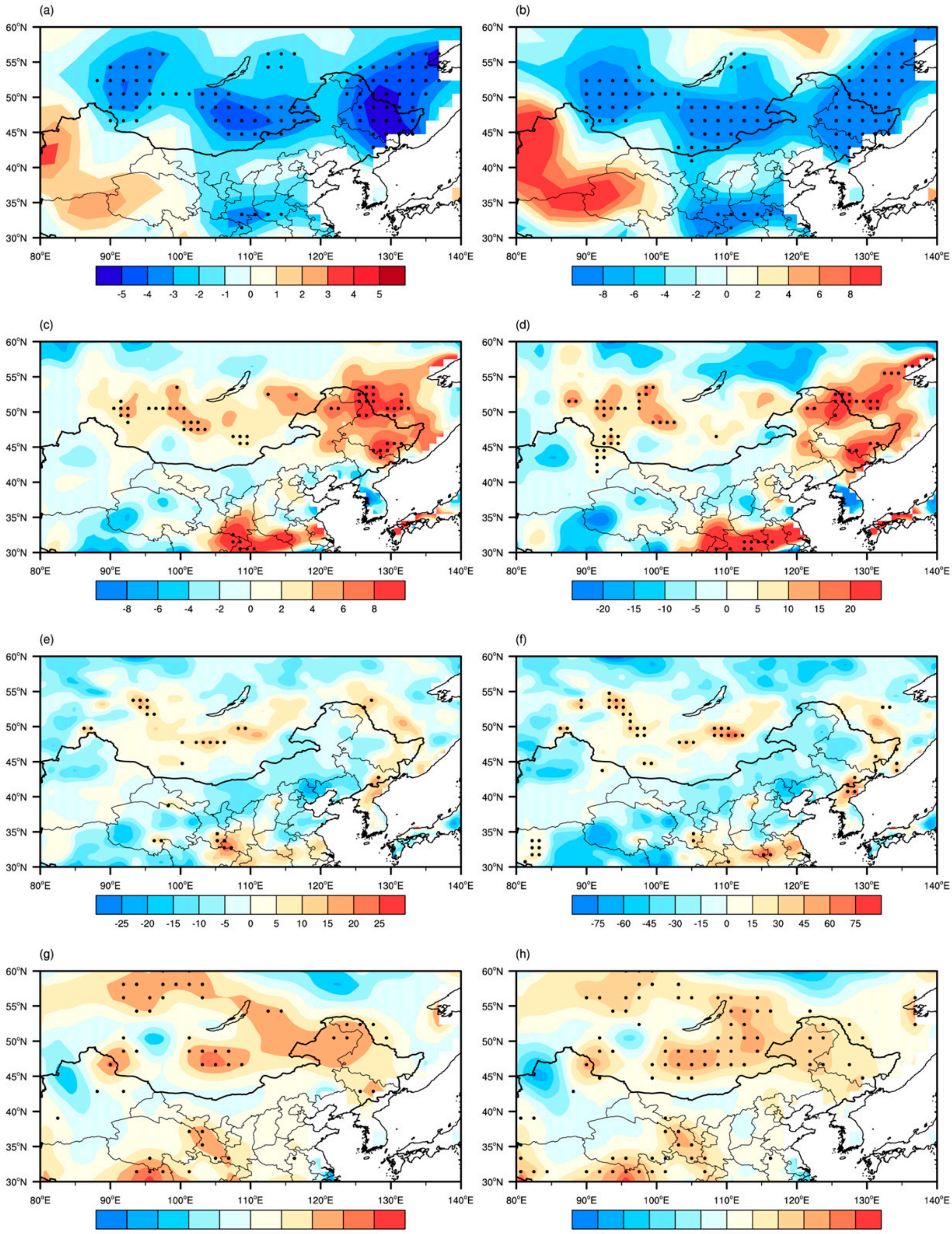

FIG. 8. Regression of summer mean (a) downward solar radiation, (c) precipitation, (e) soil moisture, and (g) latent heat anomalies onto EAMC, and composite (high EAMC minus low EAMC years) of (b) downward solar radiation, (d) precipitation, (f) soil moisture, and (h) latent heat. Dotted areas are statistically significant at the 5% level.

directly affect the soil water content. In summer, relatively high temperature usually enhances the evaporation and cools the surface soil. For this reason, dry conditions tend to increase the solar radiation but weaken the evaporation cooling. However, the case for wet summer is opposite (Trenberth and Shea 2005; Tang et al. 2012). Such a relationship can be testified to by the correlation between the soil surface temperature and precipitation as shown in Fig. 6b.

Cyclones accompanying the frontal system can produce important impacts on regional atmospheric circulation, weather, and climate, in turn affecting the changes of the underlying surface. The possible relationship between the summer cyclone activity and local precipitation was examined based on GPCC rainfall data. Figures 8c and 8d show that the large positive values of the regressed meteorological variables based on EAMC mainly locate in the area 45°–55°N, 85°–115°E (i.e., near and south of Lake Baikal), indicating that the cyclone activity over 45°–55°N, 85°–115°E is closely related to the local precipitation and strong cyclone activity corresponds to increased precipitation over this region.

Changes of precipitation can directly alter the soil water content. In summer, the evaporation usually happens much more easily because of an increase in shortwave radiation accompanied by relatively high temperature. Increased soil water content benefits the land surface evaporation and thus cools the land surface. Therefore, we further examined possible linkages among the cyclone activity, soil moisture, and surface latent heat flux related to the surface evaporation. From Figs. 8e and 8f, it is noted that strong cyclone activity can result in increased soil moisture over regions near Lake Baikal. The spatial pattern of the anomalous soil moisture is generally in agreement with that of the precipitation. From the spatial pattern of the latent heat (Figs. 8g,h), it can be concluded that strong summer cyclone activity leads to the increase in the surface latent heat due to enhanced land surface evaporation over Lake Baikal and to its south (45°–55°N, 85°–115°E), which is consistent with results from the regression analysis. Overall, anomalous cyclone activity can alter the precipitation and further affect the land surface temperature; that is, more frequent ECs activity increases the precipitation and hence the soil moisture, which can result in intensified evaporation and cooling effect on the land surface temperature.

Certainly, it is noted that the spatial variations of the climatic variables discussed are not just limited to the target areas of our study. The large-scale adjustment of the atmospheric circulation can cause significant variation of the climatic variables in other regions of East Asia. However, we noticed that the significant changes of those climatic variables are mainly located near the land surface temperature target region.

To describe the possible impacts of the cyclone activity on the surface soil temperature, Fig. 9 shows the scatterplots for different physical variables related to the cyclone activity and correlation coefficients among them. It is evident that strong EC activity benefits increased cloud fraction above Lake Baikal and to its south (45°–55°N, 85°–115°E) (Fig. 9b), which reduces the incident solar radiation (Fig. 9e). According to the surface energy balance and Fig. 9f, the solar radiation absorbed by the underlying surface bears an evident positive correlation with incident solar radiation, and decreased incident solar radiation will lower the surface soil temperature. Meanwhile, the frequent cyclone activity and increased cloud fraction are conducive to the increase of the precipitation (Fig. 9c). As a result, both soil water content and surface evaporation over this region will increase (Fig. 9h), leading to cooling of the land surface (Fig. 9i). The above results provide further explanation on the significant negative correlation between the EC activity and the surface temperature over the target region 45°–55°N, 85°–115°E. On the contrary, weak cyclone activity usually corresponds to smaller cloud fraction and increased solar radiation, resulting in less precipitation, drier soil, reduced latent heat, and warmer land surface.

To eliminate effects of the long-term trend on our results, we further presented similar results after removing the linear trend of all variables (discussed in Fig. 10). Basically, such relationships still exist on interannual time scales. In summary, even the physical variables discussed do not exhibit completely consistent spatial patterns. However, the relationship and mechanism proposed before are generally reasonable according to the regional average results given by Figs. 9 and 10.

6. Conclusions and discussion

This study explored the possible reasons for recent land surface warming in the middle latitudes of East Asia by considering the roles of the local atmospheric forcing and regional land–atmosphere interaction. Our main conclusions are as presented below.

During 1979–2015, the land surface experienced significant and rapid warming over the middle latitudes of East Asia around Lake Baikal, which bears a significantly negative correlation with the summer ECs activity over this region. Overall, the weakening of the summer ECs activity is generally consistent with the warming of the land surface. Strong summer cyclone activity generally corresponds to lower summer surface

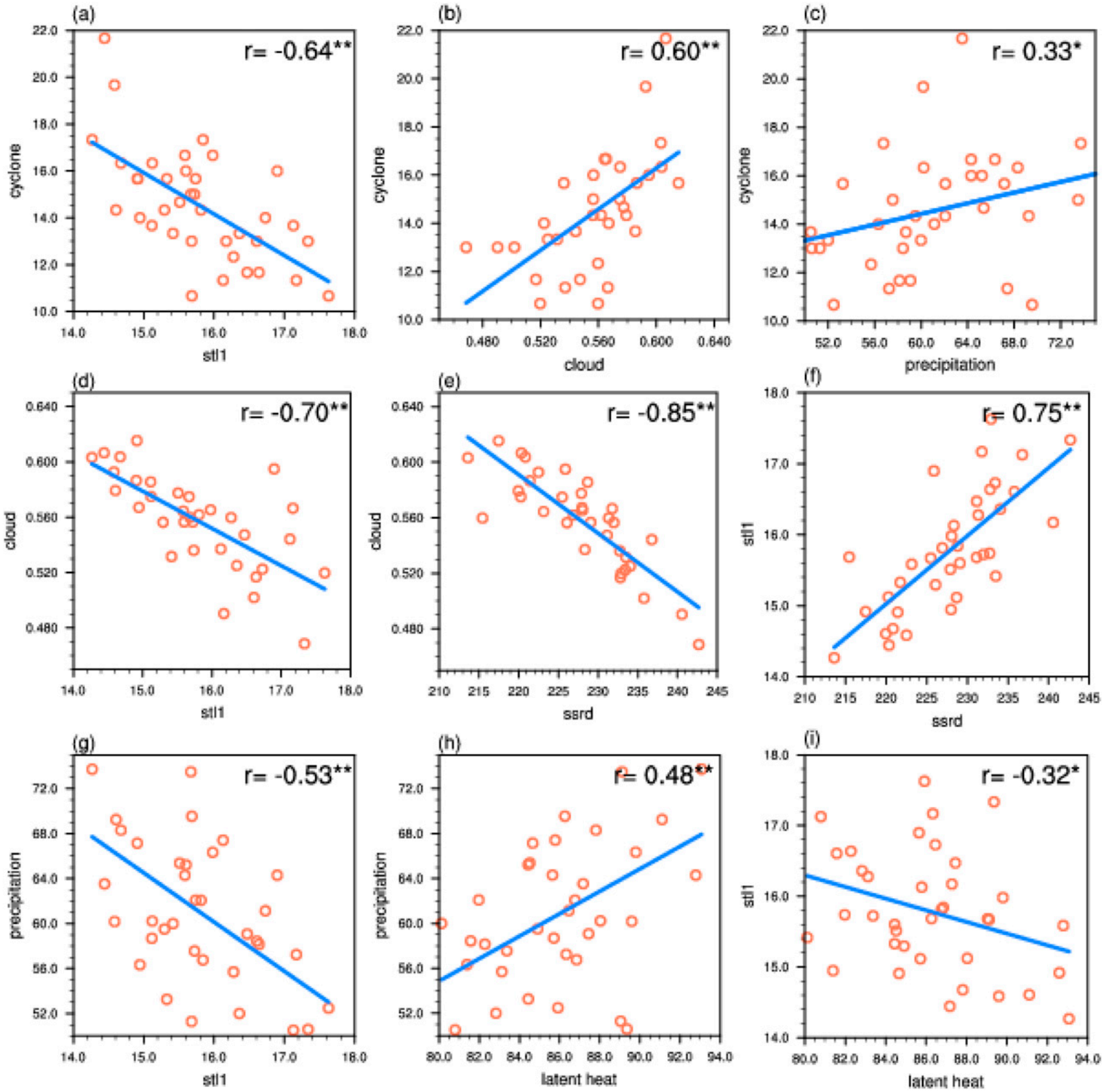

FIG. 9. Scatterplot and correlation coefficient between EAMC and regional average (45°–55°N, 85°–115°E) of soil surface temperature, cloud cover, precipitation, downward solar radiation of surface, and latent heat. A single asterisk indicates statistical significance at the 5% level. Two asterisks indicates statistical significance at the 1% level.

soil temperature. In contrast, weak summer cyclone activity generally corresponds to higher summer surface soil temperature. Further analysis suggests that the land surface warming over this region can be attributed to roles of local atmospheric forcing and feedback of land–atmosphere interactions associated with the weakening of the cyclone activity, as summarized in Fig. 11.

On the one hand, abnormal large-scale background circulation associated with the anomalous ECs activity tends to produce an evident dynamic forcing on the land surface. More specifically, the anomalous circulation pattern related to weakened cyclone activity features an anomalous high pressure system and anticyclonic circulation around Lake Baikal but an anomalous low pressure system and cyclonic circulation to the east of the Ural Mountains. Such anomalous circulation patterns are conducive to intensification of the anomalous southerly wind in the rear of the anomalous anticyclone, resulting in positive temperature advection and an increase of the temperature over the middle latitudes of

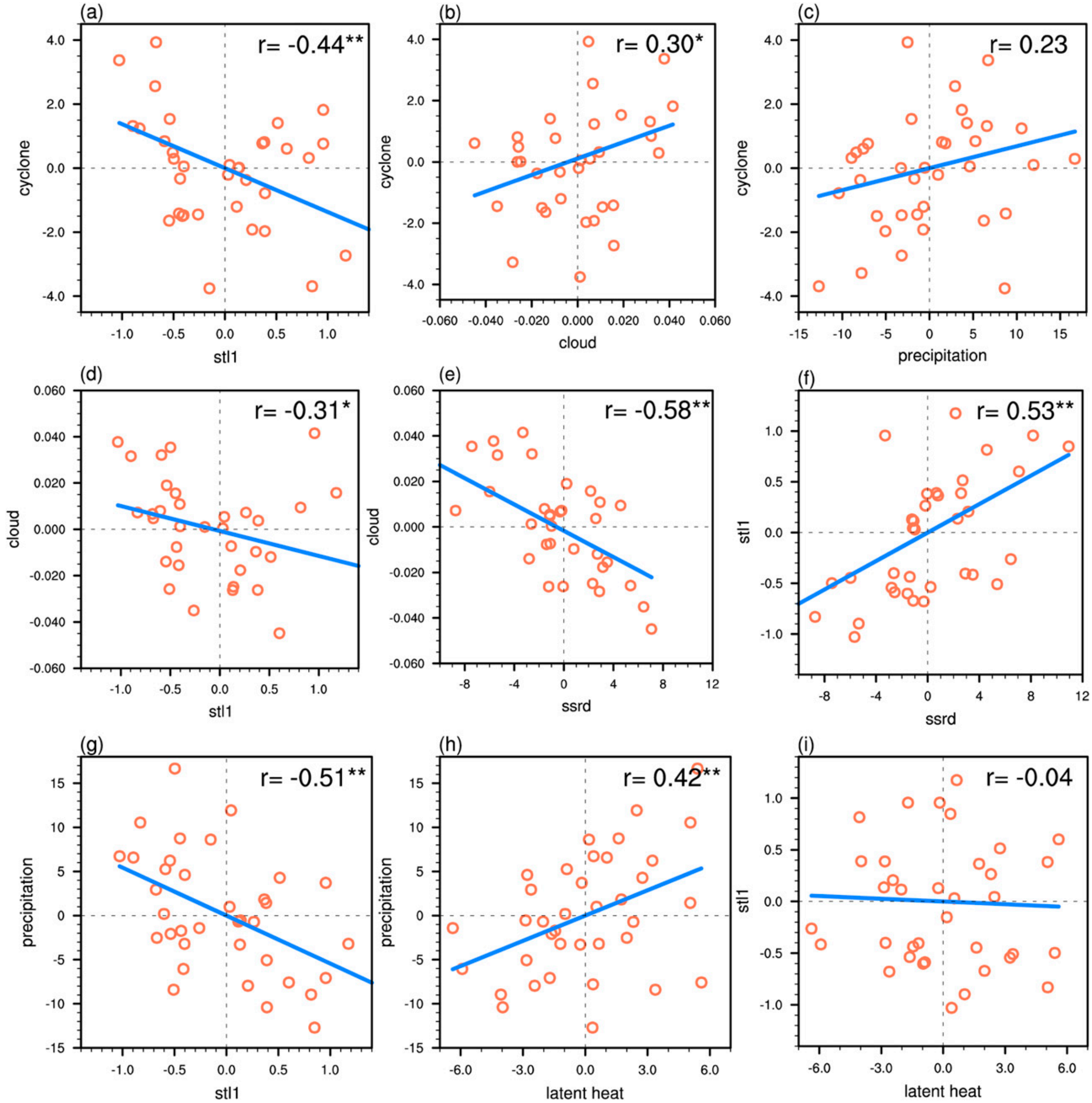

FIG. 10. As in Fig. 9, but the linear trends have been removed.

East Asia. Conversely, the anomalous circulation patterns are conducive to intensification of the anomalous southerly wind in the front of the anomalous cyclone, resulting in positive temperature advection and a decrease of the temperature over the middle latitudes of East Asia. Meanwhile, anomalous adiabatic warming caused by the abnormal descending motion of the large-scale background circulation related to the weakened cyclone activity can also contribute to the local warming.

On the other hand, the feedback of local land–atmosphere interactions in the case of weak cyclone activity also plays an important role in recent land surface warming over the middle latitudes of East Asia. Weak cyclone activity will increase both the incident solar radiation and the solar radiation absorbed by the land surface. Meanwhile, decreased precipitation will reduce the soil moisture, which in turn weakens the surface evaporation and local warming effect, finally resulting in increase of the surface soil temperature and land surface warming.

This study explored the possible reasons for the recent warming in the midlatitudes over East Asia from the

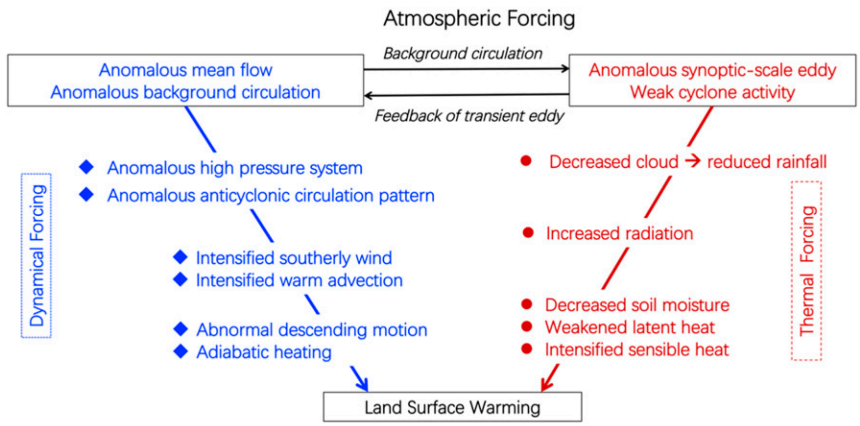

FIG. 11. Schematics on local atmospheric forcing and regional land–atmosphere interaction feedback on summer land surface warming in the midlatitudes of East Asia.

perspective of the anomalous cyclone activity, which can provide a clue to better understand recent land surface warming over this region. Our study emphasized the roles of the local atmospheric forcing and regional land–atmosphere interactions, which are acquired only based on the observational and reanalysis data. It is noted that the observations of the land surface variables such as surface soil temperature, soil moisture, and surface fluxes are very limited. Most land surface variables used in current study are from reanalysis, which can introduce uncertainty of the results, as mentioned by Santanello et al. (2015). Therefore, it deserves further investigation on this issue with more comprehensive and multisource data in the future. In addition, it is noted that the land surface strongly interacts with the atmosphere. Chen et al. (2017, 2019) pointed out that the nonuniform land surface warming itself can cause anomalous activity of the cyclone and further contributes to the decadal variation of EASM. The two-way interactions between the land surface warming and the cyclone activity deserve further exploration in the future. In addition, complex feedbacks among the cyclone activity, cloud, radiation, precipitation, and land surface processes are involved, which need further investigation in the future. As mentioned before, previous studies partly attributed the surface thermal anomalies over the Eurasian continent to the external forcing of the sea surface temperature and sea ice. More recent studies emphasized the impacts of greenhouse gases and anthropogenic aerosol emission on the warming of the continent (Zhu et al. 2012; Dong et al. 2016, 2017). Therefore, the regional atmospheric general circulation and the cyclone activity can be closely related to the impacts of different external forcing even the anthropogenic forcing including the greenhouse gases, which is still unclear. In addition, this study mainly focuses on the frequency of extratropical cyclones; the impact of cyclone intensity is also worthy of being investigated. Therefore, a better understanding of the reasons for the regional warming and regional land–atmosphere interactions over this region should be paid more attention and deserves further exploration in the future.

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