Thermal Contrast between the Middle-Latitude Asian Continent and Adjacent Ocean and Its Connection to the East Asian Summer Precipitation

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ABSTRACT

To analyze the middle-to-lower-troposphere atmospheric thermal contrast between the middle latitude over the Asian continent and over its eastern adjacent ocean near Japan, an empirical orthogonal function (EOF) analysis of the 40-yr ECMWF Re-Analysis (ERA-40) data of the June–August (JJA) 500-hPa geopotential height over the Asia–Pacific area (10°–80°N, 60°–180°E) during 1958–2000 was done. It shows that the dominating pattern of the thermal contrast may well be represented by a “seesaw” of 500-hPa geopotential height anomalies between a land area (40°–55°N, 75°–90°E) and an oceanic area (35°–42.5°N, 140°–150°E). An index showing the difference between the two areas is defined as the middle-latitude land–sea thermal contrast index (LSI). The LSI has significant interannual and interdecadal variability. Its interannual variation is mainly attributed to the atmospheric thermal condition over the ocean, which has a remarkably regional unique feature, while the interdecadal variability is greatly attributed to that over the land.

The LSI has a close connection to the East Asian summer precipitation. The results show that large (small) LSI is related to high (low) summer precipitation in the middle to lower reaches of the Yangtze River, Korea, Japan, and its eastern adjacent ocean at the same latitude, and low (high) precipitation in the South China Sea and tropical western Pacific, as well as low (high) precipitation in north China and high-latitude northeast Asia. The pattern of correlation between LSI and precipitation resembles the spatial distribution of the principle EOF mode of year-to-year precipitation variations. Furthermore, the variation of LSI is highly correlated to the time series of the first EOF mode of summer precipitation anomalies. This suggests that the middle-latitude land–sea thermal contrast is one of important factors to influence on the summer precipitation variations over the area from the whole East Asia to the western Pacific. The possible physical mechanisms of the land–sea thermal contrast impacting the East Asian summer monsoon precipitation are also investigated.

1. Introduction

As a major component of the global climate system the Asian summer monsoon has a profound social and economic impact. Of particular concern to society are hydrologic disasters, such as floods and severe droughts, which are often connected with abnormal monsoons. The Asian summer monsoon is a complex phenomenon and is commonly divided into two major subsystems, that is, the Indian monsoon system and the East Asian monsoon system (Tao and Chen 1987). In nature, “monsoon” refers to the winter–summer seasonal reversal in wind direction and a wet alternation with a dry period on a seasonal basis (Wang and Murakami 1994). Following this criterion, Wang and Murakami (1994) presented a third subsystem, that is, northeast Pacific monsoon.

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The main feature of a monsoon is seasonal reversals in both the atmospheric circulation and associated precipitation. These changes arise from reversals in temperature gradients between continental regions and the adjacent oceans with the progression of the seasons. Substantial differences in land–sea distribution between India, East Asia, and Southeast Asia leads to a great discrepancy in the land–sea thermal regime that are responsible for the differences in the summer monsoon over separate regions.

It has been recognized that solar heating forms the land–sea heat contrast between the Eurasian continent and the Indian Ocean, and triggers the Indian summer monsoon onset (Yanai et al. 1992; Ueda and Yasunari 1998; Minoura et al. 2003). Li and Yanai (1996) studied the onset and interannual variability of the Asian summer monsoon in relation to the land–sea thermal contrast using a 14-yr (1979–92) dataset, and they suggested that the onset of the Asian summer monsoon is concurrent with the reversal of the meridional temperature gradient in the upper troposphere south of the Tibetan Plateau. In the work of Chou (2004), mechanisms determining the tropospheric temperature gradient, which is related to the intensity of the Asian summer monsoon, are examined in an intermediate atmospheric model coupled with a mixed layer ocean and a simple land surface model with an idealized Afro-Eurasian continent and no physical topography; the associated negative (positive) meridional gradient of the tropospheric temperature anomalies is consistent with the existence of the weak (strong) Asian summer monsoon.

The East Asian monsoon system is a hybrid type of tropical and subtropical monsoon and its rainfall tends to be concentrated in rain belts that stretch for many thousands of kilometers and affect China, Japan, Korea, and the surrounding areas. Covering the tropics, subtropics, and areas downstream of the Tibetan Plateau, and being under the influence of land–sea thermal contrast both in the north–south and east–west direction and the dynamic impact of the plateau, the East Asian summer monsoon (EASM) is quite a complicated system (Xu and Wu 1999). Through the efforts of more than 60 yr, many advances in the studies on the EASM have been achieved. Ding and Chan (2005) gives a review on the East Asian summer monsoon. Two external forcings, that is, the Pacific and Indian Ocean SSTs and the snow cover in the Eurasia and the Tibetan Plateau, are believed to be primary contributing factors to the land–sea thermal contrast influencing activity of the East Asian summer monsoon (e.g., Li and Yanai 1996; Wu and Zhang 1998, 1999a,b; Wu and Qian 2003; Wu et al. 2004; C. Chou 2004; Andrea and Sun 2005). The Tibetan Plateau acts as an air pump for the Asian summer monsoon onset through sensible heating and plays a triggering role in the monsoon onset (Wu and Zhang 1998, 1999a,b). Wu and Qian (2003) suggested that the Tibetan winter snow was an important factor influencing the Tibetan heating, which has an important influence on the subsequent summer rainfall over the middle and lower reaches of the Yangtze River Valley. A large amount of analyses based on the observational facts and numerical simulations (e.g., Nitta1987; Webster and Yang 1992; Huang and Sun 1994a,b; Zou and Ni 1997; Tao and Zhang 1998; Chang et al. 2000a,b; Wang et al. 2000; Xu and Wang 2000; Huang et al. 2003; Sun and Ma 2003; Annamalai and Liu 2005; Annamalai et al. 2005) have shown that the ENSO cycle and the ocean surface temperature anomalies in the equatorial central and eastern Pacific, tropical Indian Ocean, and western Pacific warm pool strongly influenced on the onset and intensity of the East Asian summer monsoon.

The East Asian summer monsoon and related seasonal rain belts assumes significant variability at intraseasonal, interannual, and interdecadal time scales (Ding and Chan 2005). Apart from the influence of tropical and subtropical external heating on the East Asian monsoon, the internal variability of the atmospheric circulation also plays an important role. In particular, the blocking highs in the mid–high latitudes of the Eurasian continent and the subtropical high over the western North Pacific play a crucial role, which is quite different from the condition for the Indian monsoon (Ding and Chan 2005).

Wu (2002) used the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis for 1948–98 and explored the interaction between the middle-latitude westerlies and the tropical monsoon circulation. He identified a dominant pattern for the interannual variation of upper-level winds over midlatitude Asia in boreal summer. This pattern featuring two anomalous anticyclones, one centered at 37.5°N, 65°E and the other at 42.5°N, 130°E, also has significant influences on East Asian summer monsoon variability. In fact, the middle-latitude climates over oceans and over land are still different, which leads to the thermal difference between the ocean and the land. The present study is aimed at exploring the tropospheric temperature contrast between the midlatitude East Asian mainland and the adjacent northwestern Pacific, and its possible influence on the East Asian summer monsoon rainfall.

The outline of the paper is as follows: Section 2 introduces the data used in the analyses and describes the main feature of the middle-latitude tropospheric ther-
mal contrast between the land and the sea in the boreal summer. Section 3 gives some features about the year-to-year variation of the land–sea thermal contrast during 1958–2000 and their causes. Sections 4 and 5 present the association between the land–sea thermal contrast and the East Asian summer precipitation anomalies and the possible physical mechanism behind the link, respectively. A summary and discussion are given in section 6.

2. Data used and the definition of the land–sea tropospheric temperature contrast index

The data used in this study include the following: 1) the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) data (Xie and Arkin 1997) from 1979 to 2004, with global coverage on 2.5° × 2.5° grids; 2) the 40-yr European Center for Medium-Range Weather Forecasts (ECWMF) Re-Analysis (ERA-40) of monthly 500-hPa geopotential height in 2.5° latitude × 2.5° longitude for the period of 1958–2000 (Gibson et al. 1997); and 3) the observed monthly precipitation at 160 commonly used Chinese gauge stations from the China Meteorological Administration during 1958–2000 (e.g., Wu and Qian 2003).

The geopotential height at the 500-hPa level may be taken as a representative of the mean atmospheric temperature of the column from surface up to the midtroposphere. The empirical orthogonal function (EOF) analysis method is used to explore year-to-year variations of June–August (JJA)-averaged 500-hPa geopotential height anomalies over the East Asian area (10°–80°N, 60°–180°E) for the period of 1958–2000. The climatological mean is the average for 1971–2000. The loading of the first EOF mode is shown in Fig. 1. It accounts for about 31.8% of the total interannual variance of normalized 500-hPa geopotential height anomalies. The second and the third EOF modes only account for 12.6% and 9.0% of the total interannual variance, respectively. In Fig. 1, the first EOF mode is characterized by negative loading over most of the Eurasian continent and the tropical area south to near 35°N, and positive loading over the Korean Peninsula, the Japan Sea, Japan, and the Pacific to its east. This pattern of the spatial distribution reveals that the variations of tropospheric temperature over the East Asian continent are opposite in phase to those over Japan Sea and its surrounding area. The opposite signs over land and sea also imply that there is an evident year-to-year variation in the JJA tropospheric internal thermal contrast between the land and sea.

As shown in Fig. 1, there are three regions of minimum negative values distributed over the tropical western Pacific near the Philippines, over eastern Kazakhstan to the northwest of China, and over eastern Russia; they belong to the tropical, middle-latitude, and high-
latitude circulation systems, respectively. The analyses in this study only focus on the middle-latitude land–sea contrast of 500-hPa geopotential height between the interior land over the Eurasian continent from eastern Kazakhstan to northwest China, and the ocean adjacent to its east at the same latitudes. The minimum over middle-latitude land is centered in area A (40°–55°N, 75°–90°E) and the maximum over middle-latitude ocean is in area B (35°–42.5°N, 140°–150°E).

We calculated one-point correlation coefficients of JJA 500-hPa geopotential height anomalies at the base of the average for areas A and B separately with those at all the other grid points. The correlation maps are shown in Fig. 2. There are similar spatial structures between Figs. 1 and 2a. In Fig. 2a, a large area of correlation coefficient greater than 0.3 (which is higher than 90% confidence level) covers from the eastern part of Kazakhstan and the northwestern part of China where is just to the northwest of the Tibetan Plateau. This area of high positive correlation is connected with another area of high positive correlation to the south of the Tibetan Plateau and South Asia. It implies that there are possibly some associations of geopotential heights between the north and the south of the Tibetan Plateau. (This hypothesis will be tested in Fig. 5a and discussed in the following section.)

As for the correlations with the base point of the average for the oceanic area B (Fig. 2b), there is a zonal

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**Fig. 2.** The one-point correlation coefficients of the 43-yr (1958–2000) June–August averaged 500-hPa geopotential height anomalies at two base areas (top) A and (bottom) B, separately, with those at other grids. The shaded areas are where the correlation coefficient is significant at the 90% confidence level.
belt of relatively high positive correlation in Japan and its eastern and western adjacent regions, and two zonal belts of negative correlation separately to its north and south sides. This means that the geopotential height over region B is partly associated with the South Asian monsoon circulations. However, the negative correlation coefficients in the South Asia are rather low in magnitude (not higher than $-0.4$). It implies that the geopotential height variation over region B has some particularity. (This feature will be also displayed in Fig. 5b and explained in the following section.)

For simplification and convenience, the JJA 500-hPa geopotential height difference between those over area A and area B is defined as a middle-latitude land–sea thermal contrast index (LSI). The LSI series in the period of 1958–2000 are calculated and shown in Fig. 3a. It is highly correlated with the time series of the first EOF mode (with a correlation coefficient of 0.64 for the 43-yr period from 1958 to 2000, not shown).

### 3. The feature of LSI variations

Figure 3a shows a significant variability in LSI at the decadal time scale; that is, LSI increased before 1965, decreased until the late 1970s, and increased again in the early of 1980s. It seems that there is an abrupt climate change near 1978. The climatological mean of LSI before 1978 is obviously lower than that after 1978. The time series of LSI also shows large amplitudes of year-to-year variation. By comparing JJA anomalous 500-hPa geopotential heights over the land area A (Fig. 3b) and over the oceanic area B (Fig. 3c) with LSI, one may find out that the interannual variation of LSI is mostly attributed to the variation of tropospheric temperature over the middle-latitude ocean, especially for the period of 1979–97. The behavior of decadal timescale variation of the JJA 500-hPa geopotential height over the land area A is found to be very similar to that of LSI. This means that the trend of interdecadal variation of the land–sea thermal contrast, to a large extent, is determined by the atmospheric thermal variation over the middle-latitude Asian continent. The decadal timescale variation of 500-hPa geopotential height at middle-latitude Asian mainland shown in Fig. 3b is not an isolated phenomenon. The global warming is, to some extent, responsible for its variation. As described by Houghton et al. (2001), global temperature from 1958 to 2000 in the low to middle troposphere shows a warming trend, which is similar to the average rate of warming at the surface. As discussed in Houghton et al. (2001), two distinct periods, that is, 1910–45 (first warming period) and 1976–2000 (second warming period), contain most of the warming in the twentieth century, and the time period from 1946 to 1975 is the period of little global temperature change. In the Northern Hemisphere, the period from 1946 to 1975 shows widespread cooling, the warming in the period of 1976–2000 has been greatest over the midlatitude continents in winter, and most warming is observed over mid- and high-latitude Asia. All of these facts may give reasonable accounts of the interdecadal variation shown in Fig. 3b.

The little change in the JJA 500-hPa geopotential height over oceanic area B from 1958 to 2000 indicates that the warming of tropospheric temperature over the ocean adjacent to east of the middle-latitude Eurasian continent is not evident and is distinct from large-scale warming of the global ocean surface in the twentieth century (Houghton et al. 2001). In fact, the particularity of this area of ocean in comparison to other regions of the Pacific is also exhibited in the EOF spatial distribution of the 500-hPa geopotential in Fig. 1.

The different time-scale variations of the JJA anom-
luous 500-hPa geopotential heights in Figs. 3b,c can be detected using power spectrum analyses. Figure 4 shows the amplitudes of the power spectrum with different oscillation periods for the 1958–2000 time series of the LSI and the anomalous JJA-averaged 500-hPa geopotential heights over the land area A and those over the oceanic area B. As shown in Fig. 4b, the largest peak of the power spectrum appears in the geopotential heights anomalies over land area A at periods of 9–11 yr, which is significantly higher than the 95% confidence level of the $F$ test. However, for the geopotential height anomalies over the oceanic area B, the power largest peak occurs at the period of 3 yr, and the second largest at 5 yr, both of which are also significantly higher than the 95% confidence level of the $F$ test.

As shown in Fig. 4a, the time series of LSI has remarkable oscillations on a decadal time scale at 14–15 yr and the second peak is around 3 yr. Thus, the decadal variation of LSI is evidently caused by the variation of tropospheric temperature over the middle-latitude land, but the interannual variation of LSI is mainly caused by the variation over the middle-latitude ocean. The evidences are also illuminated in Figs. 5a,b, which show the geographical distributions of the power spectrum amplitudes at the oscillation period near 3 yr and those near 10 yr for the anomalies of JJA-averaged 500-hPa geopotential heights, respectively. It is easy to find out that the decadal variations of JJA anomalous 500-hPa geopotential heights are mainly located over the Asian and Africa continents, especially surrounding the Tibetan Plateau, and the variations near the 3-yr period oscillation are mainly distributed over the East Asian coast and its surrounding ocean. As shown in Fig. 5a, there are three maximum centers in land, that is, to the north of the Tibetan Plateau (which covers the land area A in Fig. 1), to the south of the Tibetan Plateau, and subtropical Africa; as well, there is a small area in the central Pacific (which is to the east of the oceanic area B in Fig. 1). This nearly symmetrical structure to the north and south of the Tibetan Plateau reexamines the foregoing deduction that the geopotential height variation over the land area A possibly undergoes the influence of the Tibetan Plateau. In Fig. 5b, the power spectrum near the 3-yr period is evidently distributed in the oceanic area B, shown in Fig. 1, and the East Asian coast. It is further found that the 500-hPa geopotential height over the oceanic area B has its unique feature and implies that this period oscillation is possibly also related to the East Asian monsoon system as well as the interaction between the local ocean and the atmosphere.

4. Relationship between LSI and precipitation

To examine the relationship between LSI and precipitation, we calculated the correlation coefficients of LSI and gridded JJA CMAP precipitation over the region from the eastern Asia to the western Pacific ($0^\circ$–$60^\circ$N, $100^\circ$–$180^\circ$E) during the period of 1979–2000. As shown in Fig. 6a, the correlation map displays the “negative–positive–negative” pattern from the lower to the higher latitudes. The shaded areas are where the Student’s $t$ test exceeds the 95% significance level. The maximum region of positive correlation is located in the north of Japan and the nearby ocean, stretching westward to the central part of China. There are two minimum zones of negative correlation separately covering the high-latitude region in Okhotsk and the adjacent marginal mainland, and covering the tropics from the South China Sea to the Philippines and the adjacent western Pacific. The positive correlation means that the rainfall is above normal when LSI is larger than normal, and vice versa for negative correlation.

Figure 6b shows the leading EOF mode of summer precipitation over East Asia and the Pacific ($0^\circ$–$60^\circ$N, $100^\circ$–$180^\circ$E) for the period of 1979–2000. It should be noted that the spatial EOF pattern for JJA precipitation in Fig. 6b is very similar to that of the correlation coefficients shown in Fig. 6a, that is, the highly positive/negative values of correlation between LSI and summer precipitation in Fig. 6a approximately coincide with the maximum/minimum values of the first EOF loading of summer precipitation, respectively.

The time series of LSI and the first EOF mode for precipitation are shown in Fig. 7. There is a high correlation of 0.77 between them during the 22-yr period from 1979 to 2000, which exceeds the 95% significance level of the $F$ test. However, for the geopotential height anomalies over the oceanic area B, the power spectrum near the 3-yr period is evidently distributed in the oceanic area B, shown in Fig. 1, and the East Asian coast. It is further found that the 500-hPa geopotential height over the oceanic area B has its unique feature and implies that this period oscillation is possibly also related to the East Asian monsoon system as well as the interaction between the local ocean and the atmosphere.

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![Fig. 4. The power spectrum density of the (a) LSI, and the JJA 500-hPa geopotential height anomalies at (b) area A and (c) area B. The oscillations at the peaks in b and c are at the 95% level of the $F$ test.](image-url)
The spatial patterns in Figs. 6a,b and a high correlation in Fig. 7 give a hint that the principle variation of the year-to-year JJA precipitation over East Asia and the western Pacific have close connection to the middle-latitude land–sea atmospheric thermal difference.

The relationships between LSI and JJA precipitation over China in Figs. 8a,b are reexamined using the observed rainfall from 160 Chinese stations during the 43-yr period of 1958–2000. The correlation map of LSI and JJA precipitation and the spatial distribution of the first EOF mode of JJA precipitation are shown in Figs. 8a,b. In the eastern China to the east of 100°E, the correlation map in Fig. 8a also exhibits a positive–negative–positive–negative wave-like pattern from the north to the south, which resembles that shown in Fig. 6a. The highly positive correlations are located in the Yangtze River Valley (central China), the southeastern part of the Tibetan Plateau, and the eastern part of northwest China, where the maxima of correlation coefficients are higher than 0.30, which are significant at the 95% confidence level. The negative correlations mainly cover the Yellow River Valley and north China, and most of south China. The leading EOF mode of precipitation at 160 stations, which account for about 11% of the total variance, also displays the positive–negative–positive–negative pattern in the east of China. This kind of sandwich pattern has been discussed in many papers (e.g., Huang et al. 2006a). Regions of the highly positive (negative) correlations (Fig. 8a) are, re-
respectively, coincident to those of negative (positive) spatial loadings of the first EOF mode (Fig. 8b).

Figure 9 shows the interannual variation of LSI and the EOF time series for summer rainfall in China. LSI is positively correlated to the first EOF time coefficients of summer precipitation with a correlation coefficient of 0.40 for the period of 1958–2000, and the correlation coefficient exceeds the 95% significance level. The temporal change of the summer precipitation in China is consistent with that of LSI, and even an abrupt change at about 1978 is similar to that of the LSI. The abrupt change of summer rainfall in the late of 1970s has been found in many previous studies (e.g., Li and Hi 2002; Huang et al. 2006b). The patterns in Figs. 8a,b and the high correlation in Fig. 9 provide additional evidence about the associations between LSI and precipitation shown in Figs. 6a,b and 7.

As discussion in section 3, the LSI has an obvious interdecadal variation before and after 1978. Figures 10a,b show the correlation maps of the LSI and JJA precipitation over China before 1978 (the period of 1958–77) and after 1978 (the period of 1979–2000), respectively. There is a similar sandwich pattern of negative–positive–negative correlation coefficients from south to north China before and after 1978. Nevertheless, it seems that this sandwich pattern of correlations is slightly moved northward after 1978. In the period of 1958–77, the negative correlations are located in the entire Yellow River Valley and north China, and the positive correlations dominate the southwestern part of China and the Yangtze River Valley. After 1978, the negative correlations are moved northward to the northern part of north China and the southern part of northeast China, and the positive correlations are shifted from the upper reach of the Yangtze River Valley to its middle and lower reaches and the Huaihe River. There is an evident negative correlation in south China and adjacent coast.

5. Physical mechanism of the land–sea thermal contrast impacting the East Asian summer precipitation

Figure 11 gives the intercomparison between the composites of anomalous geopotential heights at the tropospheric upper layer of 200 hPa, the middle layer of
500 hPa, and the lower layer of 850 hPa for 10 typical summers of higher LSI during the period of 1958–2000 (i.e., years 1965, 1968, 1982, 1983, 1986, 1988, 1993, 1996, 1997, and 1998; see Fig. 11a), and those for 10 typical summers of lower LSI (i.e., 1960, 1961, 1963, 1970, 1972, 1973, 1975, 1976, 1978, and 1984; see Fig. 11b). In the summers of higher LSI (Figs. 11a–c), it is evident that a strong positive center is located in the middle-latitude Asian interior, which exactly covers the land area A as shown in Fig. 1, and a remarkable negative center covers Japan and the nearby ocean. An important feature is that they are nearly geographically fixed from the lower to upper troposphere, except the negative anomalies centered over Japan expand in a zonal direction and slope westward with height. Not only at the lower level but also at the upper level, both of them have high statistical confidences higher than the 95% significance level. This means that the middle-latitude geopotential height anomaly has some barotropic feature. It partly undergoes the influence of the large-scale quasi-stationary planetary wave at middle latitudes.

![Fig. 8. As in Fig. 6, but for (a) the correlation coefficients between the LSI and precipitations over China during 1958–2000 and (b) the first EOF loadings of the precipitation anomalies of 1958–2000 over China. The percentage of total variance explained by the mode is 11.4%.](image-url)
In Figs. 11a–c, from south to northeast Asia, the geographical distribution of geopotential height in high LSI summers is characterized as the pattern of positive-negative-positive anomalies, which is clearer at the 850- and 500-hPa levels than that at the 200-hPa level. This wave-like pattern implies that the negative anomalies of the geopotential height in the lower-to-middle troposphere centralized over Japan and its surrounding ocean undergo the impact of the large-scale planetary wave from the middle latitudes, and also undergo another impact of the East Asian monsoon and even the South Asian monsoon. As for the lower LSI summers (Figs. 11d–f), the main patterns are nearly opposite to those for the higher LSI summers in all three layers of 850, 500, and 200 hPa (Figs. 11a–c), respectively.

The anomalies of the atmospheric circulation must adapt to the anomalous geopotential heights. Figures 12a,b present the composites of the anomalies of JJA-averaged wind and water vapor flux at the 850-hPa level for 10 higher LSI summers and those for 10 lower LSI summers, respectively. In the summer of high LSI, there is an area dominated by anomalous anticyclone at 850 hPa over the eastern part of Kazakhstan and the northeastern part of China. This corresponds exactly to positive geopotential height anomalies, as shown in Fig. 11c. As shown in Fig. 12a, there is a center of an anomalous cyclone over Japan and a center of an anomalous anticyclone over the South China Sea, respectively. They are also correspondent to negative anomalies and positive anomalies of geopotential height in Fig. 11c, respectively.

In Fig. 12a, we can easily find that the anomalous anticyclone over East Asia and the anomalous cyclone over Southeast Asia are located close to each other, and that they possibly undergo the impacts of the East Asian and the Southeast Asian summer monsoon systems. However, it seems that the anomalous anticyclone over the Eurasian middle-latitude interior and the cyclone over Japan and the nearby ocean are separated from each other by smaller-scale anomalous circulations. This may be attributed to the location of the 850-hPa level, which is adjacent to the surface and undergoes the influence of the boundary layer. For the middle-troposphere 500-hPa level (Fig. 13), both areas of opposite anomalous circulations seem to be connected together.

As shown in Figs. 12a and 13a, the spatial pattern of anomalous circulation from the south to the north of East Asia, that is, an anticyclone to the south of 30°N over Southeast Asia and a cyclone to the north of 30°N near Japan, is remarkable. This can cause rich and warm water vapor transport by anomalous southwesternly winds along the northwestern side of the anticyclone, as well as dry and cold airflow by anomalous northeasterly winds along the western side of the cyclone. Then, the wet, warm airflow and the dry, cold airflow meet near 30°N from the mid–low reaches of the Yangtze River, Korea, Japan, and the adjacent ocean, which results in more-than-normal precipitation there in high LSI summer. The anomalous northerly wind that prevails in the northwestern part of the cyclone near Japan in high LSI summers dominates the largest part of north China that spans 30°–50°N, 80°–120°E. This anomalous wind brings cold and dry air from higher latitudes and easily causes less-than-normal precipitation in north China in high LSI summer.

In summers of lower LSI (Figs. 12b and 13b), there are also three remarkable centers of anomalous cyclone or anticyclone that are correspondent to negative and positive anomalous geopotential heights (Figs. 11d–f), respectively. The composites of anomalous circulations and the water vapor for lower LSI summers are also opposite those of the composites for higher LSI summers, respectively. As shown in Figs. 12b and 13b, anomalous northeasterly wind coming from the western Pacific prevails in south China where it is controlled by the anomalous cyclone, and causes more-than-normal summer precipitation in south China. In north China, the opposite occurs: there is a stronger anomalous southeasterly wind from the western Pacific. It brings warm and rich water vapor to north China and leads to much more precipitation in the lower LSI summer there. Therefore, in the zonal region from the Yangtze River to Japan, anomalous divergence forms in the lower troposphere and causes less precipitation.
6. Conclusions and discussion

Utilizing EOF analysis, we have discussed the spatial distribution of JJA 500-hPa geopotential height anomalies over East Asia, which reveals the main feature of the opposite year-to-year variation in phase of every JJA atmospheric internal thermal conditions over the middle-latitude East Asian continent and over the adjacent marginal ocean. The difference of the 500-hPa geopotential height anomalies between the land area A (40°–55°N, 75°–90°E) and the oceanic area B (35°–42.5°N, 140°–150°E) is regarded as being representative of the middle-to-lower-troposphere atmospheric temperature or thermal contrast between the continent and the ocean. The difference is defined as a middle-latitude land–sea thermal contrast index (LSI). LSI may reflect dynamic interactions between the East Asian monsoon and the westerlies-dominated climate systems. The LSI has significant interannual and interdecadal variability. Its interannual variation is mainly attributed to the atmospheric thermal condition over the ocean, while the interdecadal variability is mainly attributed to that over the land.

This work emphasized the significance of the impact
of middle-latitude atmosphere on the East Asian summer monsoon (EASM) precipitation. The relationships between LSI and gridpoint JJA rainfall over the region from East Asia to the western Pacific and those between the LSI and Chinese station–observed precipitation are investigated. The correlation maps illustrate that when LSI is large, there is above-normal precipitation over the belt from the middle to lower reaches of the Yangtze River Valley eastward to Korea, Japan and the adjacent ocean, and below-normal precipitation over the tropics covering south China, the South China Sea, the western Pacific, and over high-latitude northeast Asia. The precipitation distribution pattern is reversed when LSI is small. The spatial patterns of the correlation map resemble to those of the first EOF mode of boreal summer anomalous precipitation. This implies that LSI is an important index to represent the East Asian precipitation variation.

The physical mechanism of LSI impacting the East Asian summer precipitation is also investigated. In high LSI summers, a strong land–sea thermal contrast, that is, warm air over land and cold air over ocean, causes
anticyclonic anomalies over the Asian middle-latitude inland centered in the eastern part of Kazakhstan and the northwestern part of China and cyclonic anomalies over the East Asian middle-latitude ocean near Japan and around the ocean. At the same time, an anomalous anticyclone over the tropical region from South China Sea to the western Pacific also appears to match the anomalous cyclone near Japan. This spatial pattern causes more-than-normal summer monsoon precipitation from the middle to lower reaches of the Yangtze River Valley to Japan and west Pacific, and less-than-normal precipitation to its north and south sides, that is, south and north China. The anticyclonic anomalies over the Asian inner continent likely play an important role in this precipitation pattern.

Fig. 12. Composites of JJA wind anomalies at 850-hPa (vector, ms$^{-1}$) and JJA water vapor flux anomalies (shaded, m g g$^{-1}$ s$^{-1}$) for (a) 10 high LSI years and (b) 10 low LSI years in the period of 1958–2000.
role in strengthening the anomalous north wind in north China and also positively act on the maintenance of the anomalous cyclone over Japan. In addition, the anomalous cyclone over the ocean adjacent to Japan possibly acts as a bridge connecting the high-latitude systems like blocking highs and the lower-latitude systems like the Asian summer monsoon. Nevertheless, the possible mechanism to account for the association between the LSI and the East Asian summer precipitation needs more analyses, especially using the numerical modeling to test it in the future.

This paper mainly focuses on the effect of the middle-latitude land–sea thermal contrast on the variations of the EASM precipitation. As mentioned in the introduction, the EASM is a hybrid type of tropical and subtropical monsoon. To quantify variations of the
EASM, there are several different monsoon indices proposed to describe the characteristics and variation of the Asian summer monsoon. For example, the monsoon index of Guo (1983) is based on sea level pressure (SLP) difference between 160° and 110°E over the latitudes from 10° to 50°N, the index in Webster and Yang (1992) is defined by zonal wind shear between 850 and 200 hPa averaged over south Asia from the equator to 20°N and from 40° to 110°E, and the index in Zhu et al. (2000) is the composite using both the zonal wind shear between 850 and 200 hPa and the sea level pressure difference between 160° and 110°E. Wang and Fan (1999) used the region-averaged (8.75°–21.25°N, 115°–140°E) OLR to describe the Southeast Asian summer monsoon. These previous indices mainly represent the tropical and subtropical monsoon activities. This work shows that the LSI reflects complex Asian monsoon variability, including north–south and east–west thermal contrasts, as well as global warming–like continental and oceanic change. Future works are needed to explore the associations between LSI and the previous monsoon indices. In addition, the LSI represents the tropospheric atmospheric temperature from the surface to 500 hPa in a mean sense, and its variability over the East Asia region may be attributed to the remote forcing from the South China Sea and the western North Pacific (Nitta 1987; Huang and Li 1987, 1988), Indian monsoon (Ding and Wang 2005), and so on. The surface temperature or its land-sea contrast is also an important factor to influence on the atmospheric LSI. Its role in the Asian monsoon will be discussed in the future work.

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