An East Asian Subtropical Summer Monsoon Index and Its Relationship to Summer Rainfall in China*

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ABSTRACT

Using the monthly mean NCEP/NCAR reanalysis data and the monthly rainfall observations at 160 rain gauge stations of China during 1961–1999, and based on major characteristics of the atmospheric circulation over East Asia and the western Pacific, a simple index for the East Asian subtropical summer monsoon (EASSM) is defined. The relationship between this index and summer rainfall in China and associated circulation features are examined. A comparison is made between this index and other monsoon indices. The results indicate that the index defined herein is reflective of variations of both the thermal low pressure centered in Siberia and the subtropical ridge over the western Pacific. It epitomizes the intensity of the EASSM and the variability of summer rainfall along the Yangtze River. Analysis shows that the Siberian low has a greater effect on the rainfall than the subtropical ridge, suggesting that the summer rainfall variability over the eastern parts of China is to a large extent affected by anomalies of the atmospheric circulation and cold air development in the midlatitudes. Taking into account of the effects of both the Siberian low and the subtropical ridge can better capture the summer rainfall anomalies of China.

The index exhibits interannual and decadal variabilities, with high-index values occurring mainly in the 1960s and 1970s and low-index values in the 1980s and 1990s. When the EASSM index is low, the Siberian low and the subtropical ridge are weaker, and northerly wind anomalies appear at low levels over the midlatitudes and subtropics of East Asia, whereas southwesterly wind anomalies dominate in the upper troposphere over the tropics and subtropics of Asia and the western Pacific. The northerly wind anomalies bring about frequent cold air disturbances from the midlatitudes of East Asia, strengthening the convergence and ascending motions along the Meiyu front, and result in an increase of summer rainfall over the Yangtze River.

Key words: East Asia, monsoon index, atmospheric circulation, the Meiyu front, summer rainfall

1. Introduction

The East Asian subtropical summer monsoon (EASSM) is an important weather and climate system in the Asian monsoon region, influencing China, Korea, Japan, and the subtropics of the western North Pacific. Its anomalous behavior usually leads to exceptional summer rainfall. Describing quantitatively the EASSM and understanding systematically its variability have been major challenges in studying the variability of the climate system of East Asia and the world. Previous studies paid much attention to the tropical monsoons over South and East Asia (Li and Yanai, 1996; Li and Zhang, 1999; Wang and Fan, 1999; Gao et al., 2001), and some progress has been made in studying the EASSM.

In the early 1980s, Zhou (1983) used the lower-tropospheric pseudoequivalent potential temperature to indicate the advance and retreat of the EASSM. Because the thermal contrast between land and ocean exerts strong influences on the East Asian monsoon, variations of surface pressure may well reflect those of surface heating. Guo (1983) used a zonal difference of meridionally (10°–50°N) averaged sea level pressure (SLP) between 110° and 160°E to indicate the thermal contrast over the subtropics of East Asia and the western North Pacific, and analyzed the variability of the East Asian monsoon. Similar to the definition of Guo (1983), Shi et al. (1996) defined a new index of the East Asian monsoon using the difference of SLP

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averaged over a more northern region 20°–50°N. Using this monsoon index, Sun et al. (2003) examined the decadal variability of the East Asian summer monsoon (EASM) and associated rainfall over northern China. Sun et al. (2001) defined a complicated index of the tropical and subtropical surface thermal contrast between the mainland of China and its adjacent oceans. They found that this index depicts the interannual variability of summer rainfall along the Yangtze River (YR) well. Recently, Zhao et al. (2007b) defined an index of the Asian summer monsoon using the difference of the tropospheric temperature between Asia and the Pacific and revealed that this index could decently signify variations of the atmospheric circulation and rainfall over the South and East Asian monsoon regions.

Some authors also used winds to define monsoon indices. For example, Zhu et al. (1998) defined an index of the East Asian monsoon through combining the zonal SLP difference of Guo (1983) with the shear of the lower-latitude zonal winds. Their results showed this index might be capable of epitomizing the interannual variability of the YR summer rainfall. Zhou et al. (2001) used a meridional wind average at 10°–25°N over East Asia as an index of the East Asian monsoon. Zhang et al. (2003) defined the East Asian monsoon index as a difference of zonal winds between the tropics (10°–20°N) and subtropics (25°–35°N) of East Asia. They discussed its relationship with the precipitable water in the atmosphere. Clearly, these monsoon indices incorporated features and influences from both subtropical and tropical regions.

Weather analyses have shown that the occurrence and development of summer rainfall over the eastern parts of China are not only affected by transport of warm/wet air masses from the lower latitudes but also modulated by activities of cold air masses from the high latitudes (e.g., Tao et al., 1980; Zhou et al., 2003). On the climatological scale, Zhao et al. (2004, 2006) further notified that the interannual and decadal variations of summer rainfall along the YR are closely related to anomalies of the atmospheric circulation over Siberia. The relationship between the EASSM rainfall and the atmospheric circulation in the midlatitudes of East Asia needs to be focused more, and the two types of effects of the atmospheric circulation systems from both the midlatitudes and the tropical western North Pacific need to be compared and evaluated.

In the present study, we used the monthly mean National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data and the monthly rainfall observations at 160 surface stations of China to statistically investigate major features of the summer atmospheric circulation over East Asia and its adjacent areas. Based on these features, a simple index of the EASSM is defined and the relationship between the index and the variability of East Asian circulation and China rainfall is examined. Finally, a comparison among different monsoon indices is performed.

2. Definition of the EASSM index

Two different datasets were employed in this study. One is the monthly mean NCEP/NCAR reanalysis data (Kalnay et al., 1996) with a horizontal resolution of 2.5°×2.5° in 1961–1999. The other is the monthly total precipitation of 160 rain gauge stations in China in the same period. Correlation and composite analyses were conducted. The statistical significance of composite differences and correlation coefficients was assessed using the student t-test. All the significances in this study are at the 90% level unless otherwise stated. The summer refers to the period of June, July, and August (JJA).

Before defining the index of the EASSM, we examine the climatology of the atmospheric circulation over Asia and the North Pacific. Figures 1a and 1b show the distributions of SLP and surface air temperature during summer. Three pressure systems are noticed over East Asia and the North Pacific (Fig.1a). One is the low-pressure system over the East Asian continent. Its center of 1002 hPa appears over Siberia near 43°N and coincides with a warm center of 22°C (Fig. 1b), indicating a warm low-pressure system, here called the Siberian low for convenience. The Siberian low extends southward to southern China, exerting influences on the climate over there. The second is the subtropical high over the North Pacific at 30°–40°N and its ridge stretches westward to the western

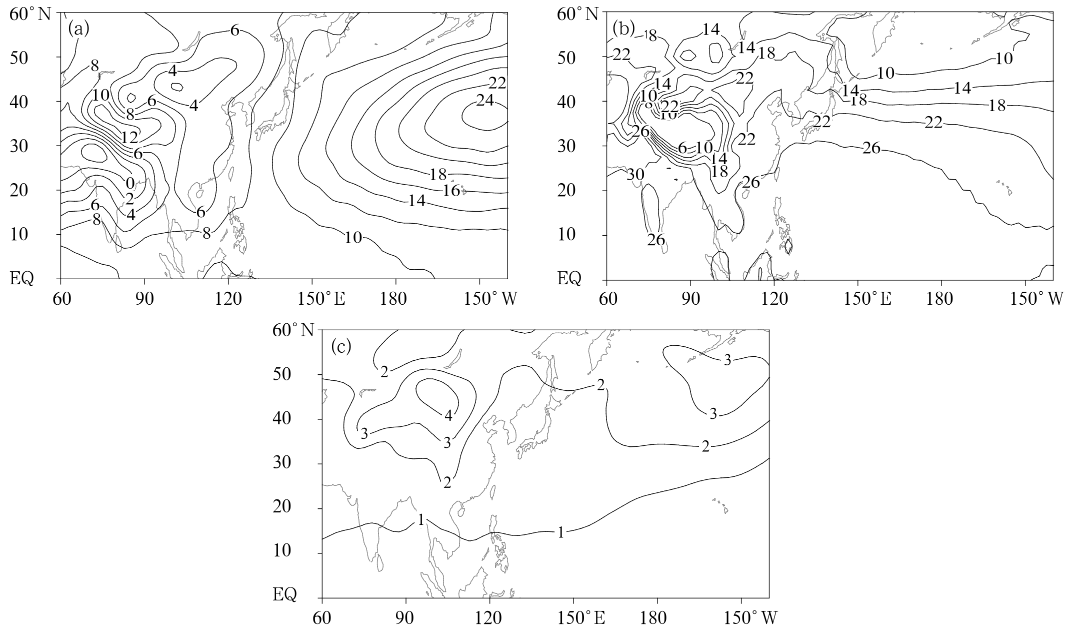

Fig.1. Distributions of multi-year (1961–1999) mean (a) JJA SLP (unit: hPa; the value plus 1000); (b) JJA surface air temperature (unit: °C); and (c) standard deviation of JJA SLP (unit: hPa) during 1961–1999.

Pacific. The third is also a warm low-pressure system to the southwest of the Tibetan Plateau at 20°–30°N, called the Indian low. Figure 1c shows the standard deviation of SLP during summer. It is seen that large standard deviation values exceeding 3 hPa appear in the midlatitudes of East Asia and over the extratropical eastern Pacific corresponding to the Siberian low and the subtropical high. This indicates a larger variability of the Siberian low and the subtropical high. Compared to these large standard deviations, the standard deviation is smaller in India, less than 2 hPa (Fig. 1c). This indicates a relatively small variability of the Indian low.

Because the low over southern China is an extension of the Siberian low, variations of the two are highly consistent and the Siberian low likely plays a more dominant role than the southern low. In the present study, SLP over Siberia is used to reflect the midlatitudes effect. Similar to the definitions of Guo (1983) and Shi et al. (1996), we used the meriodionally (40°–50°N) averaged normalized SLP along the longitude 110°E to represent the variability of the Siberian low, called the $P_{\rm SIB}$ index, while the meriodionally (30°–40°N) averaged normalized SLP along the longitude 160°E is used to represent the variability of the subtropical ridge over the western North Pacific, called the $P_{\rm SUB}$ index. Finally, the difference between the $P_{\rm SUB}$ and $P_{\rm SIB}$ indices is defined as an intensity index of the EASSM, called the $I_{\rm SSM}$ index, that is

$$I_{\rm SSM} = P_{\rm SUB} - P_{\rm SIB}.$$

Clearly, when the development of both the Siberian low and the subtropical ridge over the western North Pacific are stronger (weaker), the ISSM index is higher (lower), i.e., the EASSM is more (less) intense. Compared to the indices of Guo (1983) and Shi et al. (1996), our index emphasizes a thermal contrast between the midlatitudes of East Asia and the subtropics of the western North Pacific.

Figure 2 shows the temporal curve of the JJA ISSM index. This index exhibits a long-term downward trend during 1961–1999. It is mostly positive in the 1960s and 1970s, indicating a stronger Siberian low and a stronger subtropical ridge over the western North Pacific. It is nearly persistently negative in the 1980s and 1990s, indicating a weaker Siberian low and a weaker subtropical ridge. To detect variations of the

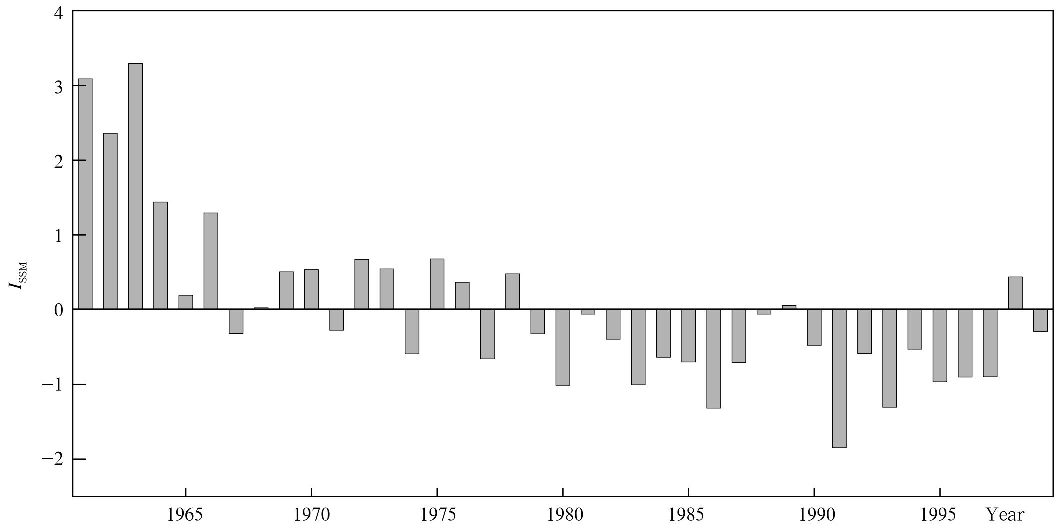

Fig.2. The temporal curve of the JJA ISSM index during 1961–1999.

atmospheric circulation associated with the variability of the summer ISSM index, we selected seven high and low ISSM-index years to do a composite analysis. They are 1961, 1962, 1963, 1964, 1966, 1972, and 1975 for the high ISSM-index years, called the high-index cases (the HI cases), and 1980, 1983, 1986, 1991, 1993, 1995, and 1996 for the low ISSM-index years, called the low-index cases (the LI cases).

3. The atmospheric circulation and rainfall in China associated with I_{SSM}

3.1 The atmospheric circulation

Figure 3a shows correlation coefficients between the summer I_{SSM} index and the synchronous surface pressure (SP) at each point during 1961–1999. Significant negative correlations appear over the East Asian continent, with the highest negative correlations of -0.8 appearing to the northeast and east of the Tibetan Plateau, while significant positive correlations appear over the western North Pacific. In the low ISSM-index case (Fig. 3b), positive anomalies of SP exceeding 2 hPa appear to the north and northeast of the plateau, with the maximum value of 3 hPa over Siberia, indicating a weaker warm low over the East Asian continent. Negative anomalies of SP below -1 hPa appear at the midlatitudes of the western North Pacific near 160°E, indicating a weaker subtropical ridge. Corresponding to these variations of SP, there are anomalous zonal pressure gradients (∇p) from ocean toward land over the subtropics of East Asia and the western North Pacific, with anomalous northerly winds prevailing over the midlatitudes and tropics of East Asia. Thus, the low ISSM index indicates a weaker EASSM. In the high ISSM-index case (Fig. 3c), negative anomalies of SP appear over the East Asian continent, with the central value of -6 hPa over Siberia, indicating a stronger warm low over the land, while small positive anomalies appear over the subtropical western North Pacific, indicating a stronger subtropical ridge over the ocean. Meanwhile, there are anomalous zonal pressure gradients from land toward ocean over the subtropics of East Asia and the western North Pacific. Anomalous southerly winds prevail over the eastern parts and coastal areas of China and stretch northward to 55°N, corresponding to a stronger EASSM.

Anomalies of the atmospheric circulations during the low and high ISSM-index cases also appear in the middle and upper troposphere. Figure 4a shows the composite difference of JJA 500-hPa geopotential height. It is seen that significant positive anomalies cover most areas of Asia, with the central value of 50 m at the mid and high latitudes, and significant

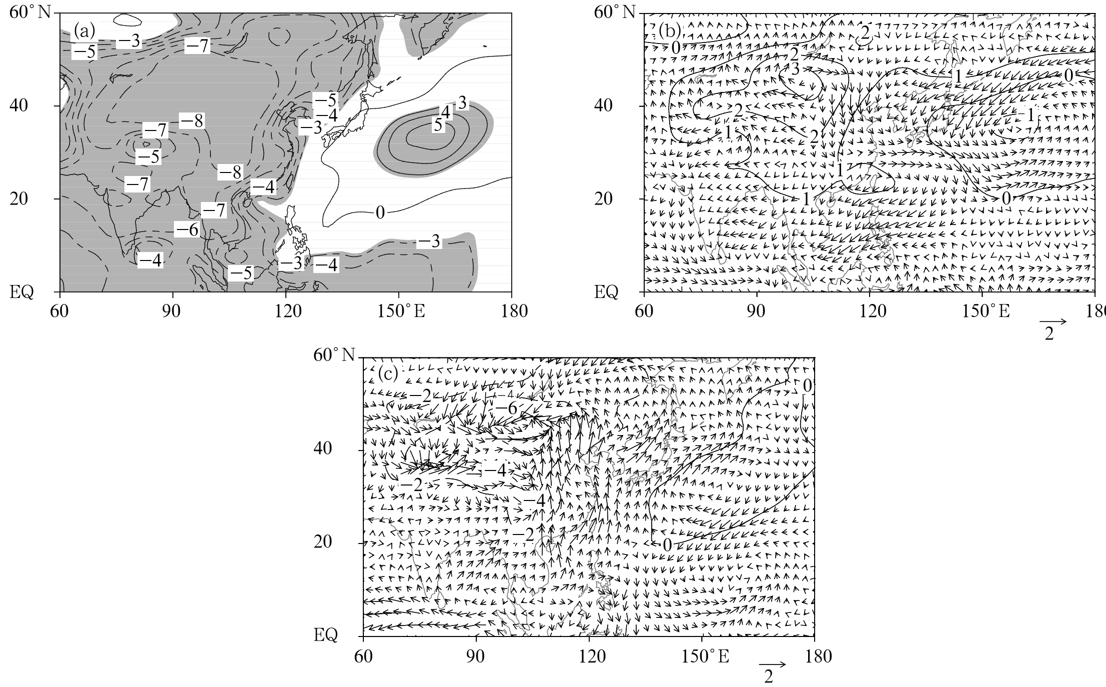

Fig.3. (a) Correlation coefficient (unit: $\times 0.1$) between the JJA $I_{\rm SSM}$ and the synchronous SP at each point during 1961–1999 (shaded areas denote the 90% confidence level); (b) composite JJA SP (contour; unit: hPa) and surface wind (vector; unit: m s^{-1}) for the low ISSM-index case; and (c) as in (b), but for the high ISSM-index case.

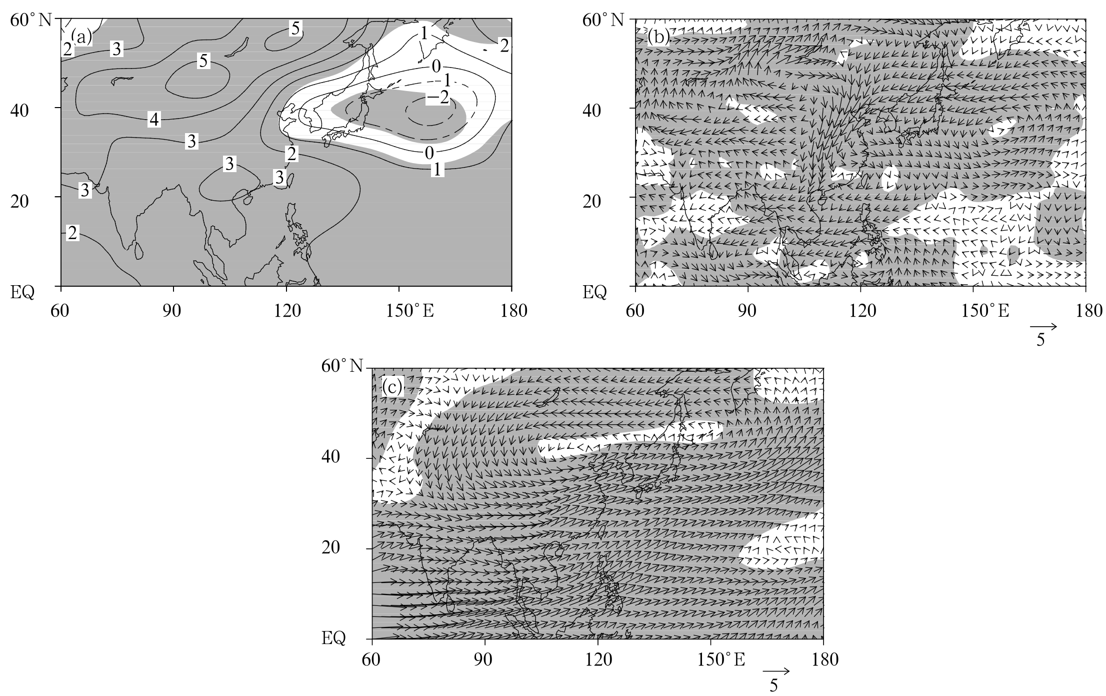

Fig.4. (a) Composite difference (low minus high) of JJA 500-hPa geopotential height (unit: $\times 10$ m) between the low and high ISSM-index cases (shaded areas denote the 90% confidence level); (b) as in (a), but for JJA 850-hPa winds (unit: m s^{-1}); and (c) as in (a), but for JJA 100-hPa winds.

negative anomalies appear over the western North Pacific near 40°N, with a center of −20 m. Corresponding to the 500-hPa anomalous high, there is a large-scale anomalous anticyclonic circulation over Asia, with its center over Siberia at 850 hPa (Fig. 4b), and strong anomalous northerly winds prevail from Northeast Asia to southern China. At 100 hPa (Fig.4c), a large-scale anomalous cyclonic circulation covers the midlatitudes and subtropics of Asia and the western North Pacific, with its center over northern China, and anomalous southwesterly winds prevail over the tropics and subtropics of Asia and the western Pacific.

The foregoing analyses show that the low and high ISSM indices do reflect two different types of atmospheric circulations over East Asia. When the ISSM index is lower, the land thermal low over Siberia and the subtropical ridge over the western North Pacific are weaker. Low-level anomalous northerly winds prevail over the midlatitudes and subtropics of East Asia. Under such a circumstance, cold air masses occur more frequently over northern China.

Figure 5a shows the composite difference of JJA 925-hPa pseudoequivalent potential temperature (θ_{se}) between the low and high ISSM-index cases. θ_{se} is computed by using the NCEP/NCAR reanalysis data. In Fig. 5a, significant large-scale negative anomalies of θ_{se} appear in the midlatitudes of East Asia, with the central value of −8 K over northern China, indicating a drier and colder air mass, while smaller positive anomalies appear over the tropics of East Asia, showing that warm and wet air activities over southern China enhance slightly. These variations of θ_{se} over eastern China favor the Meiyu front development along the YR. Moreover, the low-level anomalous northerly winds also strengthen the convergence over the YR. This results in anomalous upward motions at 27°−32°N of eastern China (Fig. 5b).

3.2 Rainfall

Figure 6a shows the composite difference of JJA rainfall between the low and high ISSM-index cases. There are significant large-scale positive anomalies of summer rainfall along the YR between 105° and 120°E, with the maximum value of 300 mm over the middle and lower valleys of the YR. This indicates an increase of the local rainfall. Negative anomalies of the rainfall occur over both the southeastern and northern parts of the eastern areas of China, indicating a decrease of the local rainfall. Clearly, corresponding to a weaker EASSM with a low ISSM index, the Meiyu front and associated upward motions strengthen over the YR and cause an increase of the local rainfall.

Figure 6b further shows correlation coefficients between the areal (28°–32°N, 105°–120°E) mean JJA rainfall and the synchronous rainfall at each grid point during 1961–1999. There are 19 rain gauge stations inside the region used for average. It is seen that significant positive correlations appear over the YR between 105° and 120°E, with the highest correlation up to 0.8. This exhibits a consistent variation of JJA rainfall

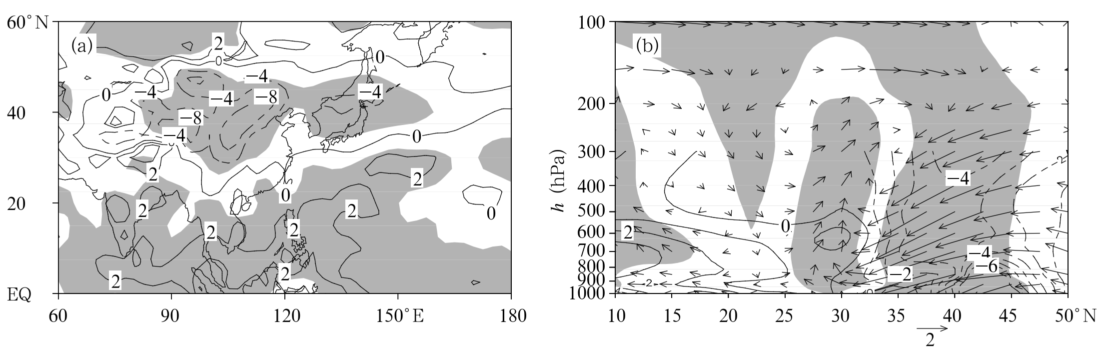

Fig.5. (a) Composite difference (low minus high) of JJA 925-hPa θ_{se} (unit: K) between the low ISSM-index cases (shaded areas denote the 90% confidence level); and (b) as in (a), but for the latitude-height cross section of JJA velocities (vector; unit: v: m s^{-1}, ω: ×0.02 Pa s^{-1}) and θ_{se} (contour; unit: K) (shaded areas denote the 90% confidence level of the vertical velocity) along 118°E.

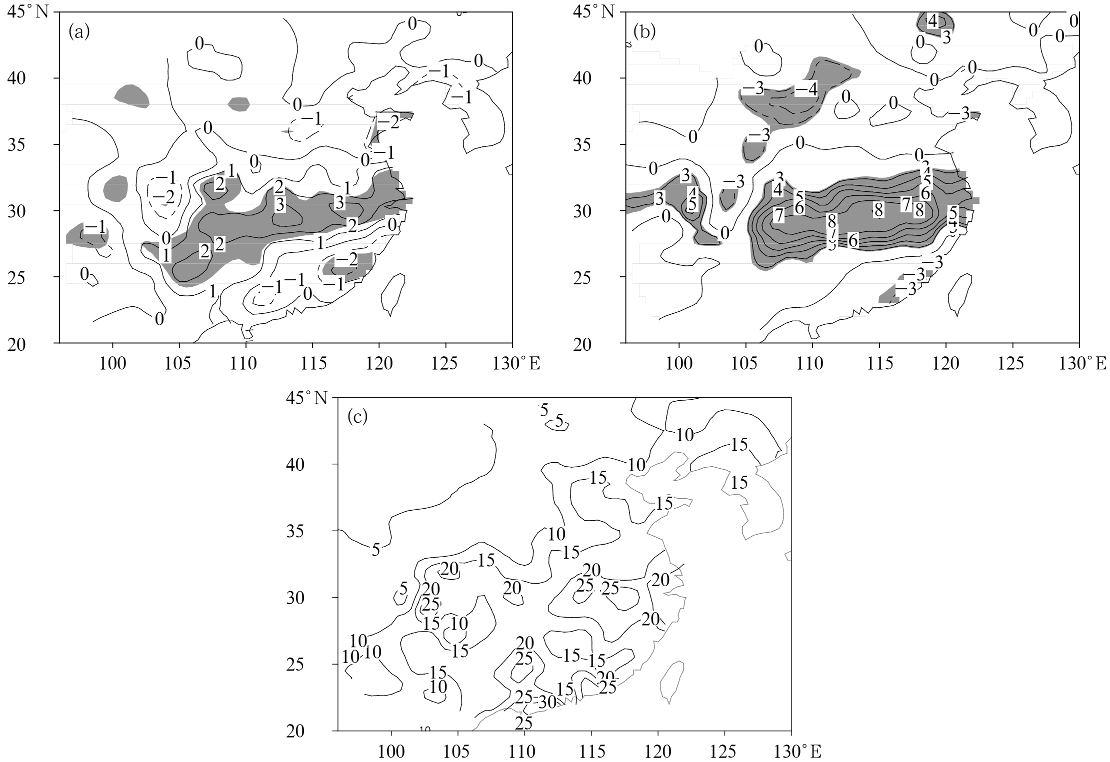

Fig.6. (a) Composite difference (low minus high) of JJA rainfall (unit: ×100 mm) between the low and high ISSM-index cases (shaded areas denote the 90% confidence level); (b) correlation coefficients (unit: ×0.1) between summer rainfall averaged over the region 28°–32°N, 105°–120°E and the synchronous rainfall at each point during 1961–1999 (shaded areas denote the 90% confidence level); and (c) standard deviation of JJA rainfall (unit: ×10 mm) during 1961–1999.

over this region. Figure 6c shows the standard deviation of JJA rainfall during 1961–1999. The standard deviation exceeds 200 mm over the middle and lower valleys of the YR, with the maximum value of 250 mm. It is evident that the composite difference of summer rainfall over the YR between the low and high ISSM-index cases (shown in Fig.6a) is comparative to the local standard deviation. This shows that the ISSM index signifies the variation of summer rainfall over the YR very well.

4. Comparing different monsoon indices

4.1 A comparison between $P_{\rm SIB}$ and $P_{\rm SUB}$

The variability of the $I_{\rm SSM}$ index reflects a variation of summer rainfall over the YR and is determined by anomalies of the Siberian low and the subtropical western Pacific ridge. Then, which one plays a more important role in contributing to the variability of the rainfall? To answer this question, we selected seven low- and high-index years for the $P_{\rm SIB}$ and $P_{\rm SUB}$ indices, respectively, and performed composite analyses.

Figure 7a shows the composite difference of JJA rainfall between the seven high and low $P_{\rm SIB}$-index cases. When the $P_{\rm SIB}$ index is higher, corresponding to a weaker Siberian low, significant positive anomalies of summer rainfall exceeding 200 mm occur over the YR between 110° and 120°E, with the central value of 400 mm. Figure 7b shows the composite difference of JJA rainfall between the seven high and low $P_{\rm SUB}$-index cases. When the $P_{\rm SUB}$ index is higher, corresponding to a stronger subtropical ridge over the western North Pacific, significant positive anomalies of rainfall appear over a northern region near 33°N along the coasts of eastern China, and cover a much smaller area compared with that in Fig.7a. This exhibits that the Siberian low has a more pronounced effect on variations of summer rainfall over the YR compared to the

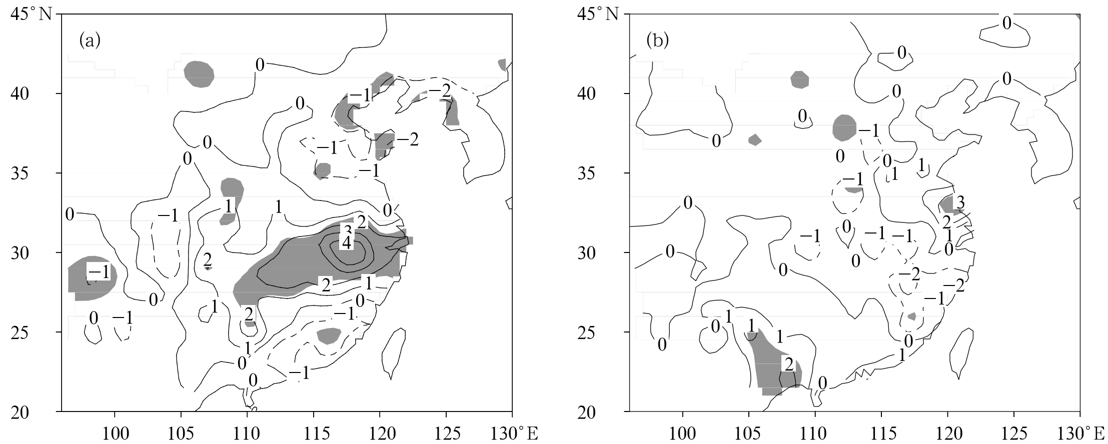

Fig.7. (a) Composite difference (high minus low) of JJA rainfall (unit: ×100 mm) between the seven high and low $P_{\rm SIB}$-index cases (shaded areas denote the 90% confidence level); and (b) as in (a), but for the $P_{\rm SUB}$ index.

subtropical ridge. Moreover, it should be noted that anomalies of summer rainfall over the YR shown in Figs. 7a, b cover also a smaller area relative to that in Fig. 6a. Thus, using the difference between the $P_{\rm SIB}$ and $P_{\rm SUB}$ indices, namely the $I_{\rm SSM}$ index, can better reflect the variability of the rainfall than using only the $P_{\rm SIB}$ or $P_{\rm SUB}$ index.

4.2 A comparison between $I_{\rm SSM}$ and the indices of Guo and Shi

In order to compare $I_{\rm SSM}$ with the indices of Guo (1983) and Shi et al. (1996), we computed their indices and called them $I_{\rm GUO}$ and $I_{\rm SHI}$, respectively. Similarly, we selected seven high and low index years for these two indices. For the $I_{\rm GUO}$ index, they are 1961, 1962, 1963, 1964, 1973, 1975, and 1998 for the high-index years; and 1980, 1982, 1986, 1990, 1991, 1996, and 1997 for the low-index years. For the $I_{\rm SHI}$ index, they are 1961, 1962, 1963, 1964, 1966, 1975, and 1998 for the high-index years; and 1980, 1983, 1986, 1990, 1991, 1996, and 1997 for the low-index years. Clearly, there are four different years between $I_{\rm SHI}$ and $I_{\rm SSM}$ and there are five different years between $I_{\rm GUO}$ and $I_{\rm SSM}$.

Figures 8a and b show the composite differences of JJA rainfall based on $I_{\rm GUO}$ and $I_{\rm SHI}$, respectively. There is a similar pattern in the distributions of summer anomalous rainfall over eastern China in Figs. 8a

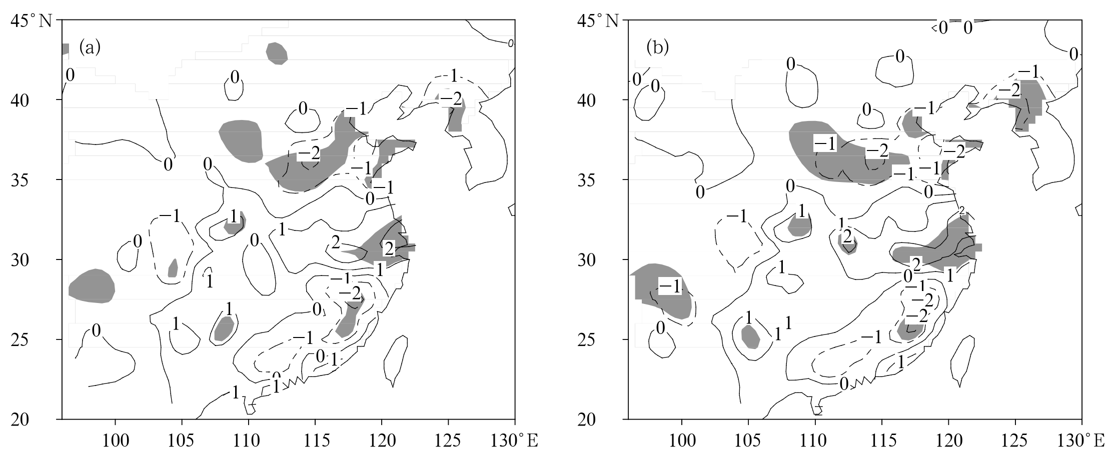

Fig.8. (a) Composite difference (low minus high) of JJA rainfall (unit: ×100 mm) between the seven low and high $I_{\rm GUO}$-index cases (shaded areas denote the 90% confidence level); and (b) as in (a), but for the $I_{\rm SHI}$ index.

and b. Significant positive anomalies appear mainly over the middle and lower valleys of the YR, with their maximum values at 200 mm, while there is almost no significant positive anomaly over the YR to the west of 115°N. Compared to the anomalous rainfall associated with the I_{SSM} index (shown in Fig. 6a), the significant anomalous rainfall over the YR in Figs.8a and b has a much smaller area and is weaker in magnitude. This shows that the I_{GUO} and I_{SHI} indices do not well reflect a variation of the rainfall over the YR like I_{SSM}. Therefore, I_{SSM} has a pronounced improvement in reflecting the variability of the summer YR rainfall. The improvement is due to the different latitudes used in defining the index. Although the indices of Guo (1983) and Shi et al. (1996) also include some signals of the atmospheric circulation in the midlatitudes of East Asia, features of the atmospheric circulation in the lower latitudes are more embedded in the two indices. The mid-latitude signals are relatively weak, and insignificant relationships of I_{GUO} and I_{SHI} to the summer rainfall over the YR seem to exist.

5. Conclusions and discussion

Using the monthly mean NCEP/NCAR reanalysis data and the monthly total rainfall observations at 160 rain gauge stations in China during 1961–1999, a simple index of the East Asian subtropical summer monsoon (EASSM) and its relationship with the atmospheric circulation and summer rainfall in China are examined.

Because the thermal low centered in Siberia and the subtropical ridge over the western North Pacific are modulated by heating conditions over both land and ocean, using a difference of surface pressure between these two regions can reflect the thermal contrast between the East Asian continent and the western North Pacific to a certain degree. Accordingly, we defined an index of the EASSM, namely, I_{SSM}. This index indicates not only variations of the Siberian low and the western North Pacific subtropical ridge but also variations of the atmospheric circulation over the EASSM region. It may also be considered as an indicator of summer rainfall variations over the YR. The I_{SSM} values tend to be positive during the 1960s and 1970s, and negative during the 1980s and 1990s, displaying a striking long-term downward trend.

Corresponding to a lower I_{SSM}, the Siberian low and the subtropical ridge over the western North Pacific are weaker, with an anomalous zonal pressure gradient from ocean toward land over the subtropics of East Asia. Anomalous low-level northerly winds prevail in the midlatitudes and subtropics of East Asia, indicating vigorous cold air activities, while anomalous southwesterly winds prevail in the upper troposphere over the tropics and subtropics of Asia and the western Pacific. The active cold air development caused by the anomalous northerly winds strengthen the convergence and upward motions along the Meiyu front over the YR, leading to an increase of the local rainfall. Compared to the subtropical ridge, the Siberian low has more important effects on summer rainfall over the YR. This implies that a variation of summer rainfall over the eastern areas of China is largely affected by anomalies of the atmospheric circulation and cold air development in the midlatitudes. Moreover, considering both roles of the Siberian low and the subtropical ridge helps to better capture variations of the YR rainfall.

Historically, rainfall is often used to indicate the intensity of the Asian tropical summer monsoon, e.g., more (less) rainfall usually signifies a stronger (weaker) summer monsoon. For the eastern areas of China, the wind-rainfall correlation is positive, e.g., rainfall often occurs in front of the southwesterly wind maxima (Zhao et al., 2007a) and the major rain belt shows a pronounced northward shift with the northward advance of the southwesterly winds (e.g., Dao and Chen, 1957; Chen et al., 1991; Ding, 2004). It stays in the YR in the early summer, corresponding to the Meiyu, and moves to the northern parts of China in the middle summer. When the EASM circulation is strong (weak), the southwesterly winds are strong (weak). They move more frequently into the more northern (southern) parts. This makes the rain belt more northern (southern), causing less (more) rainfall in the YR and more (less) rainfall in the northern parts of China. Thus, the interannual or decadal variability of summer rainfall in the YR is usually opposite to that in the northern parts (shown in Fig.6b; Ding et al., 2007; Zhao et al., 2007b). For a year with strong southwesterly winds over East Asia, it is right to call a weak EASM because there is less rainfall in the YR, or call it a strong EASM year since there is more rainfall in the northern parts of China. Clearly, using rainfall to signify the EASM intensity may cause misunderstanding. Instead, using the atmospheric circulation (e.g., the low-level southwesterly winds) to indicate the EASM may avoid this misunderstanding.

In order to emphasize the effect of the tropical monsoon over Asia and that of the subtropical ridge over the western North Pacific on summer rainfall over eastern China, Guo (1983) and Shi et al. (1996) selected more southern latitudes (10°–50°N and 20°–50°N, respectively) in defining the monsoon indices. Compared to their indices, the I_{SSM} index, defined by using more northern latitudes (40°–50°N), can better reflect variations of larger-scale features of summer rainfall over the YR. Surface heating in Siberia and the atmospheric circulation and cold air activities in the midlatitudes affect the variability of the Siberian low, while the variability of the subtropical ridge is modulated by the subtropical and tropical oceanic heating over the western North Pacific. Thus, much attention should be paid to the influences of the thermal conditions over the East Asian continent and the subtropical oceans on the EASSM and associated rainfall.

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