An Index Measuring the Interannual Variation of the East Asian Summer Monsoon—The EAP Index

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ABSTRACT

Based on the EAP (East Asia/Pacific) teleconnection in the summer circulation anomalies over the Northern Hemisphere, an index measuring the strength of the East Asian summer monsoon, i.e., the so-called EAP index, is defined in this paper. From the analyses of observed data, it is clearly shown that the EAP index defined in this study can well describe the interannual variability of summer rainfall and surface air temperature in East Asia, especially in the Yangtze River valley and the Huaihe River valley, Korea, and Japan. Moreover, this index can also reflect the interannual variability of the East Asian summer monsoon system including the monsoon horizontal circulation and the vertical-meridional circulation cell over East Asia. From the composite analyses of climate and monsoon circulation anomalies for high EAP index and for low EAP index, respectively, it is well demonstrated that the EAP index proposed in this study can well measure the strength of the East Asian summer monsoon.

Key words: East Asia/Pacific index, East Asian summer monsoon, interannual variability

1. Introduction

As well known, the interannual variability of the East Asian summer monsoon is very obvious and causes severe droughts and floods in East Asia, especially in the eastern part of China (see Tao and Chen, 1985; Ding, 1994; Ye et al., 1996; Huang et al., 1998; Huang and Zhou, 2002). Therefore, the interannual variability of the East Asian summer monsoon (EASM) is an important issue for Chinese meteorologists. Through the efforts of more than sixty years, Chinese meteorologists have achieved many advances in the studies on the EASM. Tao and Chen (1987) made a systematical review on these advances.

Recently, many scholars have made many efforts to study the interannual variability of EASM and its causes. Nitta (1987, 1996), Huang and Li (1987, 1988), Kurihara (1989), and Huang and Sun (1992) pointed out the significant effect of the thermal state in the tropical western Pacific and the convective activities around the Philippines on the interannual variability of EASM. Nitta (1987), and Huang and Li (1987) showed that there is an obvious teleconnection pattern in the summer circulation anomalies over the Northern Hemisphere, which has been called the PJ (Pacific-Japan) pattern and the EAP (East Asia/Pacific) pattern teleconnection by Nitta (1987), and Huang and Li (1987), respectively.

In order to describe the interannual variability of EASM, a monsoon index measuring the strength of EASM is necessary. Up to now, there are two kinds of definitions of the Asian monsoon index. One is defined from the thermodynamical elements. For example, Tao and Chen (1987), and Murakami and Matsumoto (1994) defined the monsoon index with the strength of monsoon rainfall and OLR, respectively. The other is defined from the dynamical elements, i.e., wind field. Webster and Yang (1992), and Zeng et al. (1994) defined the monsoon index from the difference of the zonal winds between the high level and lower level atmosphere over the Asian monsoon region, while Zhang and Peng (2003) defined the East Asian summer monsoon index with the difference of the zonal winds between the middle latitudes and low latitudes over East Asia. There are some advantages and disadvantages in these definitions. The former may be easily influenced by local thermodynamical conditions, but the latter may be only suitable for the South Asian monsoon. Since the EASM has the feature of a subtropical monsoon and a meridional component (see Huang et

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al., 1998), it may be not suitable to define an index only with the zonal component of the wind field over the regions of EASM. Therefore, how to define a monsoon index measuring the strength of the EASM is still necessary for the study of the interannual variations of EASM.

Guo (1983) and Shi et al. (1996) defined the index measuring the interannual variations of EASM with the difference of sea-level pressure between the North Pacific and Eurasian continent, which is also an element related with the dynamics. As described above, the observational and theoretical studies have shown that the interannual variation of EASM is greatly influenced by the EAP teleconnection pattern suggested by Nitta (1987) and Huang and Li (1987), respectively. This teleconnection pattern has been widely used in the seasonal prediction of climate anomalies in China. Thus, based on this teleconnection shown in Figure 1 (from Huang and Li, 1987), the NCEP/NCAR reanalysis data of height fields at 500 hPa are used to defined an index measuring the strength of the EASM. And the observed data of monthly precipitation in China, Korea, and Japan are further used to study the interannual variations of EASM in this paper.

2. Definition of the EAP index measuring the interannual variation of EASM.

Because the EAP teleconnection pattern has a close relationship with the interannual variations of EASM, an index of EASM is defined based on this pattern. This index is simply called the EAP index, i.e., I_{EAP}. The definition of I_{EAP} is as follows:

$$I_{\mathrm{EAP}} = -\,0.25Z'_{\mathrm{s}}(60°\mathrm{N}, 125°\mathrm{E}) + 0.50Z'_{\mathrm{s}}(40°\mathrm{N}, 125°\mathrm{E}) - 0.25Z'_{\mathrm{s}}(20°\mathrm{N}, 125°\mathrm{E})\ , \quad (1)$$

where $Z'_{\mathrm{s}} = Z \sin 45° / \sin\varphi$ is the standardized seasonal-mean 500-hPa height anomaly at a grid point with the latitude φ, and $Z' = Z - \bar{Z}$ is the summer seasonal-mean 500-hPa height anomaly at the grid point.

Figure 2 shows the interannual variation of I_{EAP} calculated using Formula (1) with the NCAR/NCEP reanalysis data of the 500-hPa height fields from 1951 to 2000.

The results of Nitta (1987), Huang and Li (1987), Kurihara (1989), and Huang and Sun (1992), show that the convective activities are strong around the Philippines in the warming state of the West Pacific warm pool; in this case, the western Pacific subtropical high shifts northward, and the summer monsoon rainfall may be below normal in the Yangtze River and Huaihe River valley of China, and in South Korea and Japan. Then the Z'_{s} at the grid point of (40°N, 125°E) is positive, and Z'_{s} at the grid point of (60°N, 125°E) and (20°N, 125°E) are both negative. Thus, I_{EAP} will be positive. Therefore, if the EAP index shown in Fig. 2 is positive, the East Asian summer monsoon rainfall may be weak in the Yangtze River and Huaihe River valley of China, and in South Korea and Japan. On the other hand, in the cooling state of the West Pacific warm pool, the convective activities are weak around the Philippines. Then the western Pacific subtropical high shifts southward, and the summer monsoon rainfall may be above normal in the Yangtze River and Huaihe River valley of China, and in South Korea and Japan. In this case, the I_{EAP} shown in Fig. 2 is negative. Therefore, if the index is negative, the East Asian summer monsoon rainfall may be strong in the Yangtze River and Huaihe River valley of China, and in South Korea and Japan.

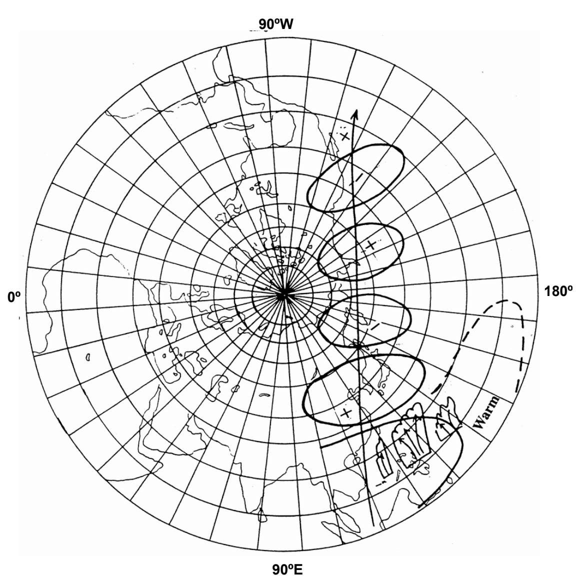

Fig. 1. The schematic map of the EAP teleconnection pattern (from Huang and Li, 1987). The "+" and "–" in the figure denote the positive and negative height anomalies at 500 hPa, respectively.

3. Relationship between the EAP index and the summer monsoon rainfall in East Asia

Ramage (1971) pointed out that monsoon exhibits not only wind reversal, but also the seasonal precipitation criterion. Therefore, a good monsoon index should indicate well the variation of precipitation in the monsoon region. In order to investigate whether the EAP index can well describe the interannual variations of EASM or not, the point correlations between the summer monsoon rainfall anomalies in China and

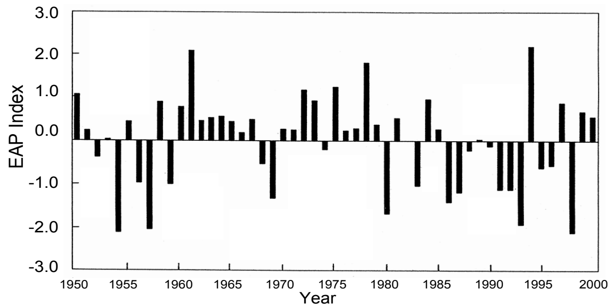

Fig. 2. Interannual variation of $I_{\rm EAP}$ calculated by using Formula (1) with the observed data of the 500-hPa height fields from 1951 to 2000.

the EAP index are calculated by using the observed data of summer (June–August) monthly precipitation at 160 observational stations in China from 1951 to 1996. Figure 3 presents the distribution of the correlation coefficients between the summer rainfall anomalies in China and the EAP index. It may be clearly seen from the figure that there are large negative correlations in the Yangtze River valley and the Huaihe River valley. This means that in a summer with positive EAP index the summer rainfall is below normal. For example, in the summers of 1961, 1978, and 1994, the EAP index was larger than or equal to 1, and correspondingly, severe droughts occurred in this region. However, in a summer with negative EAP index such as in 1954, 1957, 1980, 1987, 1996, and 1998, the EAP index was smaller than or equal to −1, and serious floods were caused in this region.

This negative correlation between the EAP index and summer rainfall anomalies in the Yangtze River valley and the Huaihe River valley is also seen from the interannual variations of the normalized summer rainfall anomalies in the (29°–33°N, 114°–125°E) region of the Yangtze River and Huaihe River valley and the EAP index shown in Fig. 4. It shows that there is a good out of phase relationship between the summer rainfall in the Yangtze River and Huaihe River valley and the EAP index. The maximum correlation coefficience between them can reach 0.58, which greatly exceeds the confidence level of 95%. This indicates that the EAP index can well reflect the summer monsoon rainfall anomalies in the Yangtze River valley and the Huaihe River valley.

The EAP index can reflect the interannual variation of summer monsoon rainfall in South Korea. Figure 5 shows the normalized summer rainfall anomalies in South Korea and indicates a negative correlation between the summer rainfall anomaly in South Korea and the EAP index. The maximum negative correlation coefficient can reach –0.37, which is significant at the confidence level of 95%.

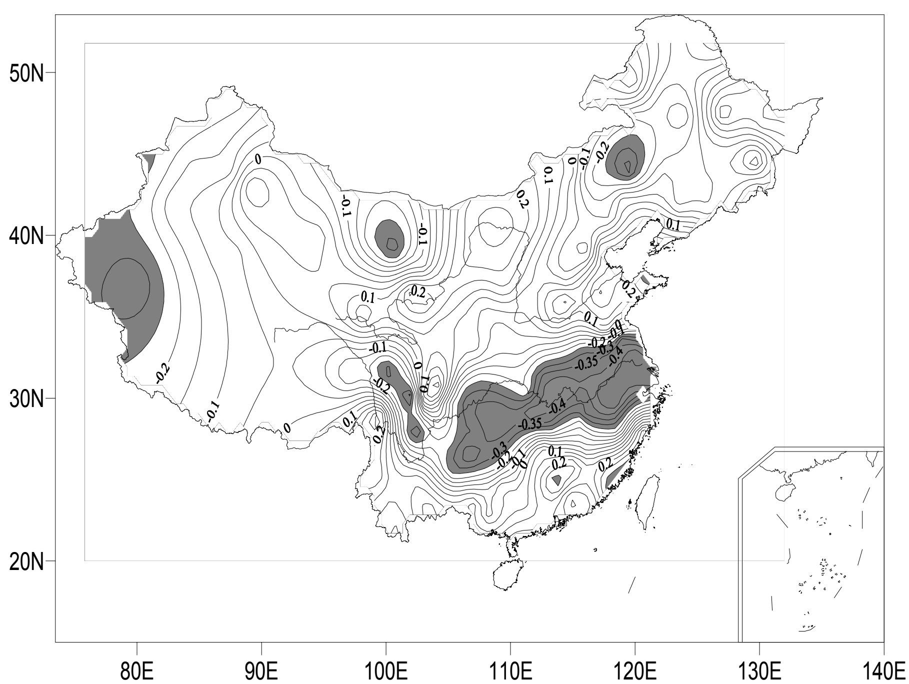

Fig. 3. Distribution of the correlation coefficients between the summer (June–August) rainfall anomalies in China and the EAP index from 1951 to 1996. The shaded areas indicate where the confidence level is over 95%.

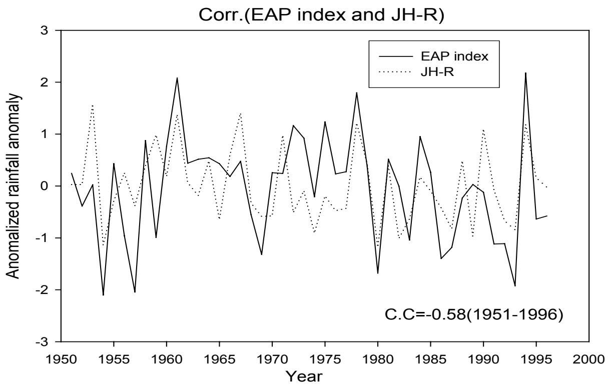

Fig. 4. Interannual variations of the normalized summer monsoon rainfall anomalies in the region of (29°–33°N, 114°–125°E) of the Yangtze River and Huaihe River valley (dashed line) and the EAP index (Solid line).

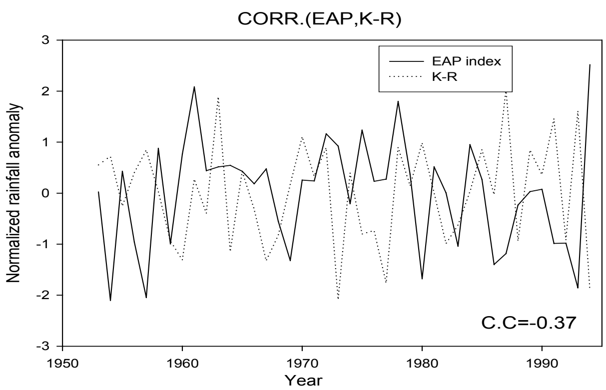

Fig. 5. Same as Fig. 4 but for the normalized summer monsoon rainfall anomalies in South Korea (dashed line).

We also calculate the correlation coefficients between the summer monsoon rainfall in East Asia and the EAP index, the summer monsoon index (SM index) suggested by Guo (1983), and the Webster-Yang index (WY index) proposed by Webster and Yang (1992), respectively, by using the Xie-Arkin precipitation data for 1979 to 1998.

Figures 6a–c are the distributions of the correlation coefficients between the summer monsoon rainfall anomalies in East Asia and the SM index, WY index, and EAP index, respectively. Comparing Fig. 6c with Figs. 6a and 6b, it may be clearly seen that the correlation between the summer monsoon rainfall anomalies in East Asia and the EAP index proposed in this study is larger than the other correlations, especially in the positive correlation region of the lower reaches of the Huaihe River, and South Korea and Japan, and in the negative correlation region of the southeastern coast of China and around the Philippines. Thus we can conclude that the EAP index defined in this study can better describe the interannual variations of the East Asian summer monsoon.

4. Relationship between the EAP index and the summer surface air temperature in East Asia

Generally, the interannual variability of summer surface air temperature has an out of phase relationship with the variability of summer rainfall in the East Asian monsoon region. Therefore, it is also possible that there is a close relationship between the summer surface air temperature anomalies and the EAP index. Figure 7 is the distribution of the correlation coefficients between the summer surface air temperature anomalies in China and the EAP index. It may be seen from the figure that there are large positive correlations in the Yangtze River valley, the Huaihe River valley, North China, and Northeast China. The maximum correlation coefficient reaches 0.6 in Northeast China and the Korean Peninsula, which greatly exceeds the confidence level of 95%. That is to say, in a summer with high EAP index, the summer surface air temperature may be high and a hot summer may occur in these regions. For example, in the summers of 1961, 1978, and 1994, drought and hot summers occurred in the middle and lower reaches of the Yangtze River and the Huaihe River valley. Our results suggest that the EAP index proposed in this study can describe the interannual variations of summer surface air temperature not only in the Yangtze River valley and the Huaihe River valley, but also in North China and Northeast China.

Table 1. The correlation coefficients among the summer rainfall (YH-R) and surface air temperature anomalies (YH-T) in the Yangtze River valley and the Huaihe River valley, and the summer rainfall (K-R) and surface air temperature anomalies (K-T) in South Korea, and the EAP index for 42 summers.

Parameters	I_{EAP}	YH-R	YH-T	K-R	K-T
I_{EAP}	1.00				
YH-R	–0.59	1.00			
YH-T	0.54	–0.68	1.00		
K-R	–0.37	0.33	–0.25	1.00	
K-T	0.77	–0.56	0.66	–0.50	1.00

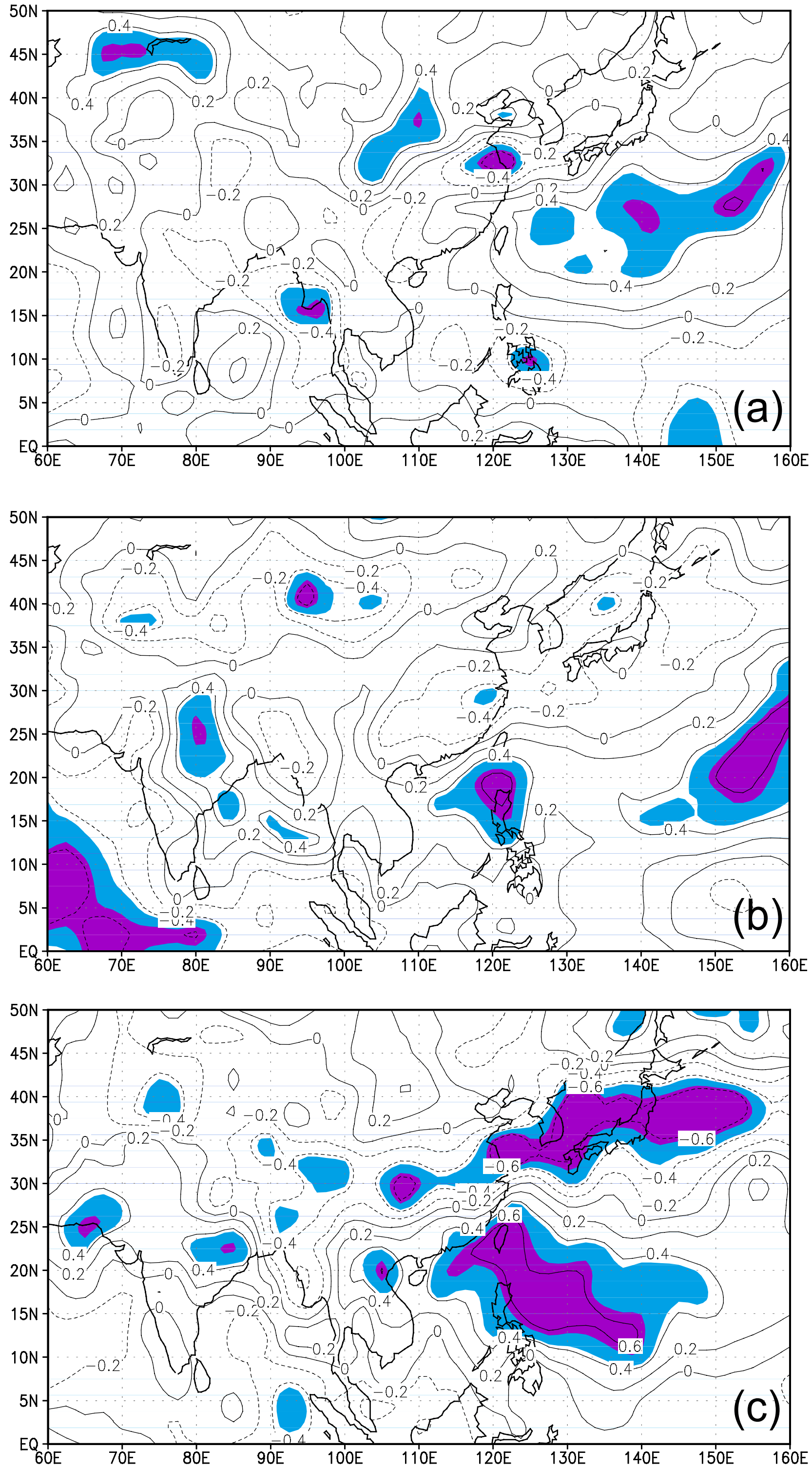

Fig. 6. Distribution of the correlation coefficients between the summer (June–August) rainfall anomalies in China with (a) the SM index, (b) the WY index, and (c) the EAP index. The shaded areas in the figure denote where the confidence level is over 95%.

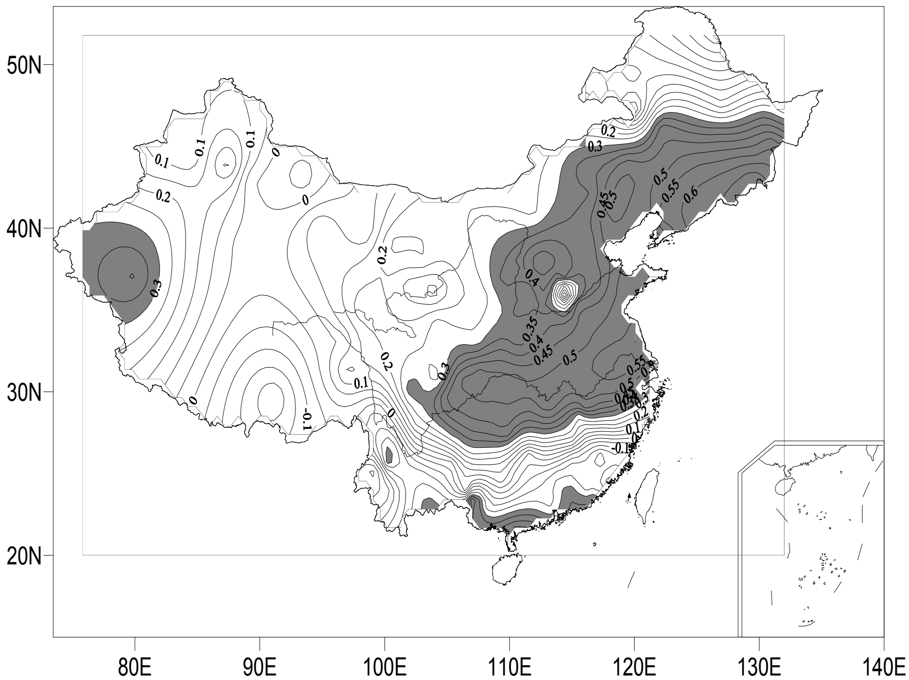

Fig. 7. Distribution of the correlation coefficients between the summer surface air temperature anomalies in China and the EAP index. The shaded areas denote where the confidence level is over 95%.

Similarly, the EAP index can also describe the interannual variations of summer surface air temperature anomalies in South Korea (figures not shown). Table 1 shows that the correlation between the summer surface air temperature anomalies in Korea and the EAP index is significant with a correlation coefficient of 0.77, which exceeds the confidence level of 99%.

From the above results and the correlation coefficients shown in Table 1, it is clearly seen that the EAP index based on the EAP teleconnection pattern can well describe not only the interannual variations of summer rainfall, but also the interannual variations of summer surface air temperature anomalies in the East Asian summer monsoon region, especially in the Yangtze River valley and the Huaihe River valley of China, and in South Korea and Japan. Therefore, the interannual variation of the EAP index defined in this study can be used to denote the interannual variability of monsoon climate in East Asia.

5. Relationship between the EAP index and the East Asian summer monsoon circulation

As mentioned above, there is a close relationship between the EAP index and the interannual variations of summer rainfall and surface air temperature in East Asia. But what causes the close relationship between the EAP index and the interannual variability of monsoon climate in East Asia? This may be due to the fact that the EAP index can well indicate the interannual variability of the East Asian summer monsoon circulation. In order to demonstrate this, the composite anomalous distributions of the 500-hPa height fields, the wind fields and their meridional component at 700 hPa over East Asia for the summers with high EAP index, (i.e., $I_{\rm EAP} \geqslant 1$), namely, 1961, 1978, and 1994 and for the summers with low EAP index, ($I_{\rm EAP} \leqslant -1$), namely, 1954, 1957, 1980, 1987, 1996, and 1998, are respectively analyzed.

Figures 8a and 8b indicate the composite distributions of the 500-hPa height anomaly fields over East Asia for the summers with $I_{\rm EAP} \geqslant 1$ and for the summers with $I_{\rm EAP} \leqslant -1$, respectively. Comparing Fig. 8a with Fig. 8b, it may be seen that the composite anomaly pattern of summer monsoon circulations for the summers with high EAP index is opposite to those for the summers with low EAP index. In a summer with high EAP index, as shown in Fig. 8a, the western Pacific subtropical high shifts northward. The positive 500-hPa height anomaly area is located over the Huaihe River valley, North China and the southern part of Northeast China, the Korean Peninsula and Japan, and the negative 500-hPa height anomaly areas are located over South China and eastern Siberia. Therefore, in a summer with high EAP index, the

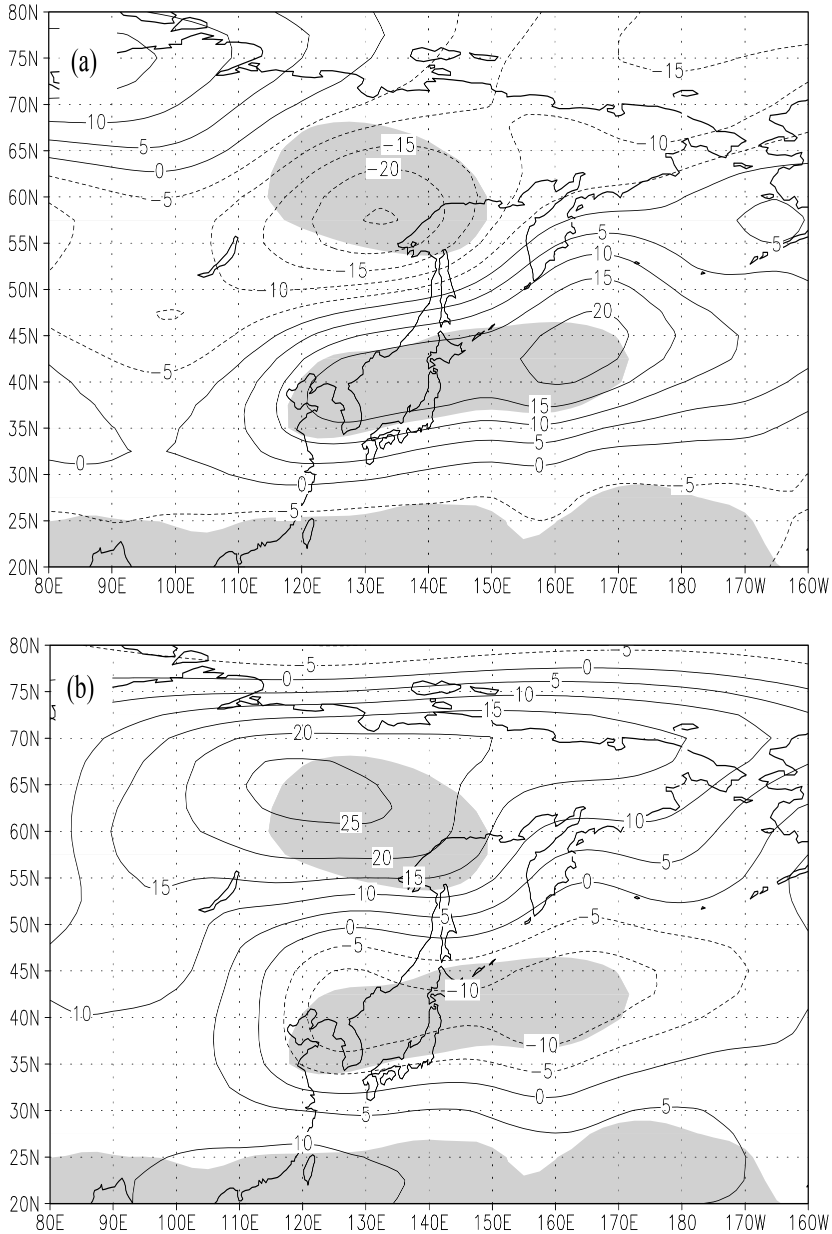

Fig. 8. Composite anomaly distributions of the 500-hPa height fields over East Asia for (a) the summers with high EAP index ($I_{\rm EAP} \geqslant 1$) and (b) the summers with low EAP index ($I_{\rm EAP} \leqslant -1$). Units: 10 gpm. The shaded areas in the figure indicate where the confidence level is over 95%.

summer surface air temperature is high and the summer monsoon rainfall is less in the middle and lower reaches of the Yangtze River and the Huaihe River valley, Korea, and Japan. In contrast, in a summer with low EAP index, as shown in Fig. 8b, the western Pacific subtropical high shifts southward. The negative 500-hPa height anomaly area is located over the Huaihe River valley, North China and Northeast China, the Korean Peninsula and Japan, and the positive 500-hPa height anomaly areas are located over South China and eastern Siberia. Therefore, in a summer with low EAP index, the summer surface air temperature is normal or below normal, and the summer monsoon rainfall is strong in the middle and lower reaches of the Yangtze River and the Huaihe River valley, Korea, and Japan.

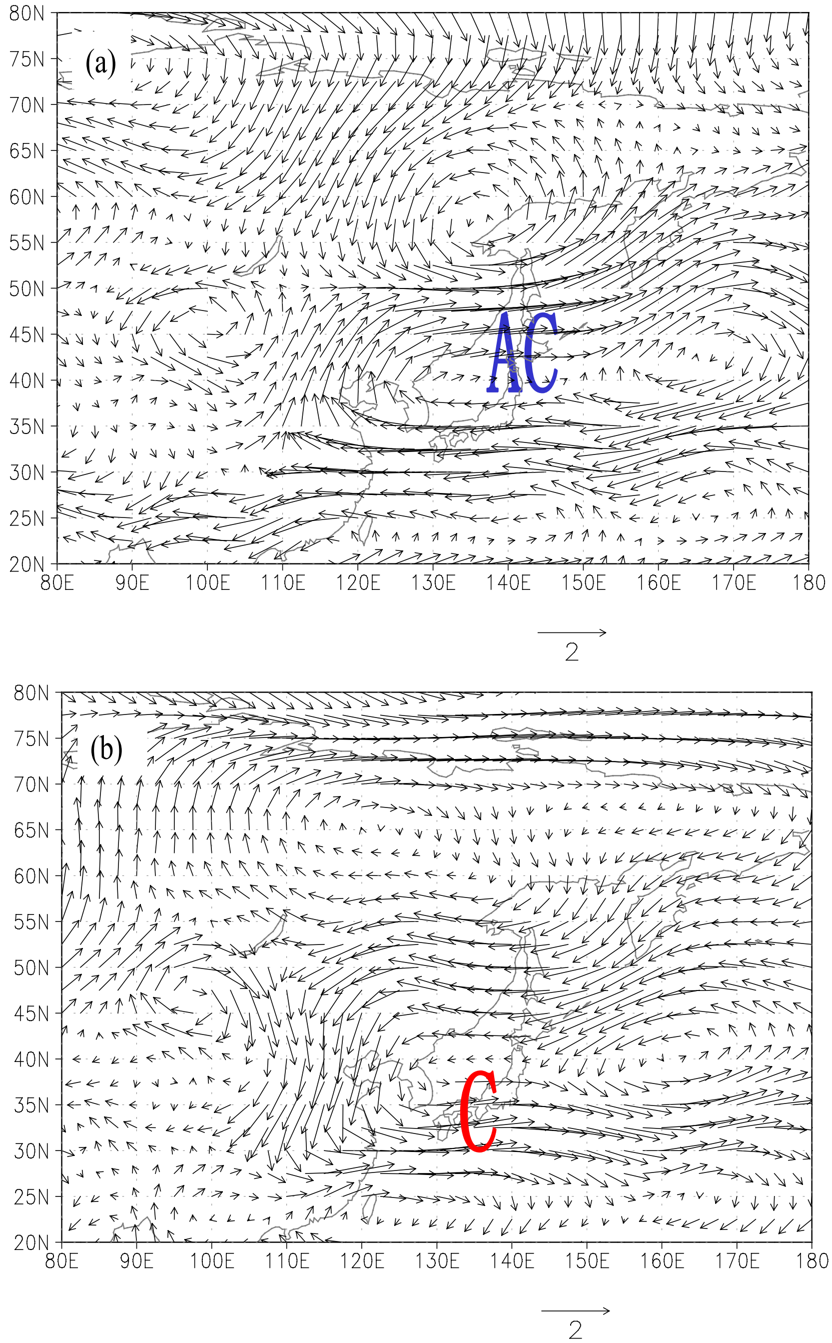

Fig. 9. Same as Fig. 8 but for the horizontal wind anomaly distribution at 700 hPa.

Generally, the monsoon flow is most obvious at 700 hPa over East Asia. Thus, the composite anomaly distributions of the wind fields at 700 hPa over East Asia for the summers with high EAP index ($I_{\mathrm{EAP}} \geqslant 1$), namely, 1961, 1978, and 1994, and for the summers with low EAP index ($I_{\mathrm{EAP}} \leqslant -1$), namely, 1954, 1957, 1980, 1987, 1996, and 1998, are respectively analyzed (see Fig. 9). As shown in Fig. 9a, in a summer with high EAP index, the strong anomalous anticyclonic circulation is located over the Huaihe River valley, North China, and Northeast China, and the anomalous cyclonic circulation is located over South China and eastern Siberia. In contrast, in a summer with low EAP index, as shown in Fig. 9b, the anomalous cyc-

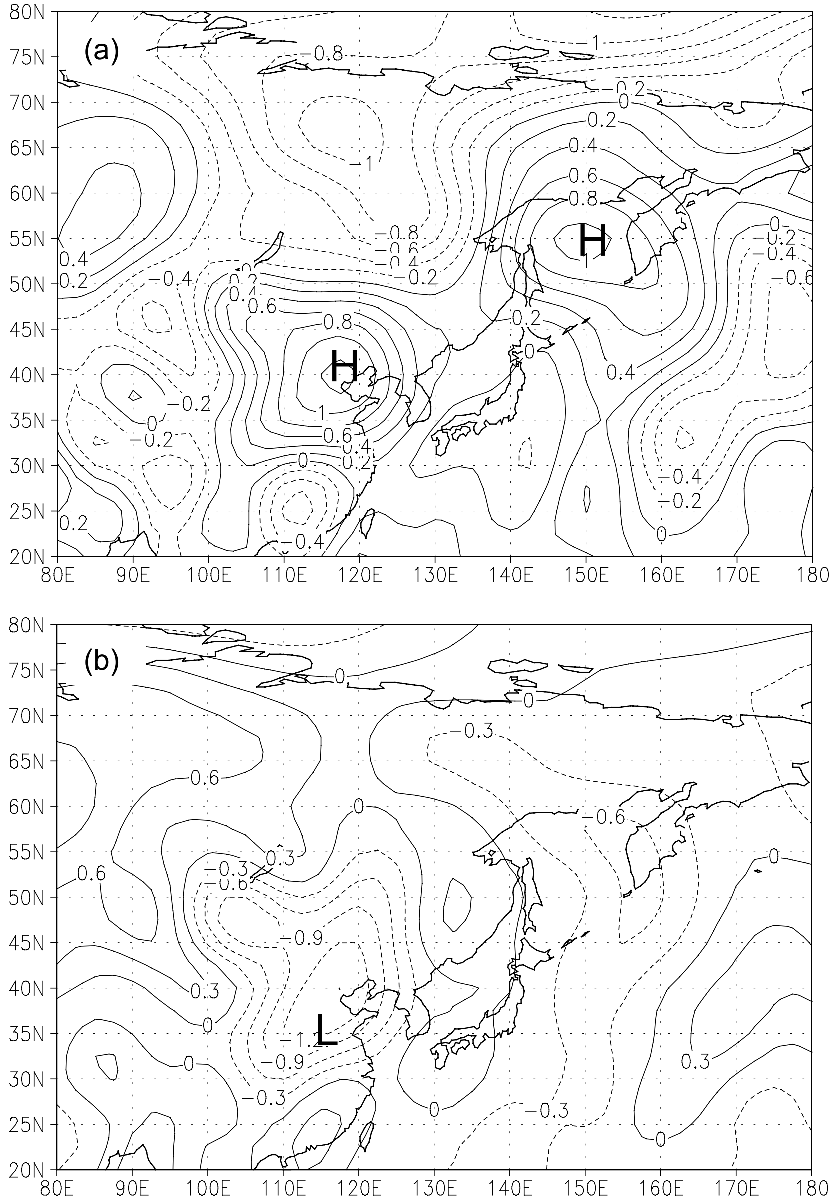

Fig. 10. Same as Fig. 8 but for the meridional wind anomalies at 700 hPa. Units: m s^{-1}.

lonic circulation is located over the Huaihe River valley, North China and Northeast China, the Korean Peninsula, and Japan, and the anomalous anticyclonic circulations are located over South China and eastern Siberia. Therefore, the anomaly circulation pattern shown in Fig. 9a is opposite to that shown in Fig. 9b. These patterns are similar to the distributions of the 500-hPa height anomaly field shown in Fig. 8.

From the above analyses, it is clear that the EAP index can well describe the interannual variability of summer monsoon circulation over East Asia.

An important characteristic of the summer monsoon flow over East Asia is its large meridional component. Huang et al. (1998) pointed out that the meridional component of water vapor transport associated with the East Asian summer monsoon is dominant. The convergence of water vapor transport, which can cause rainfall, is closely associated with the meridional transport of water vapor from south to north by monsoon flow. Therefore, the composite distributions of the meridional component of the wind fields at 700 hPa over East Asia for the summers with high EAP index and for the summers with low EAP index are also analyzed and shown in Figs. 10a and 10b, respec-

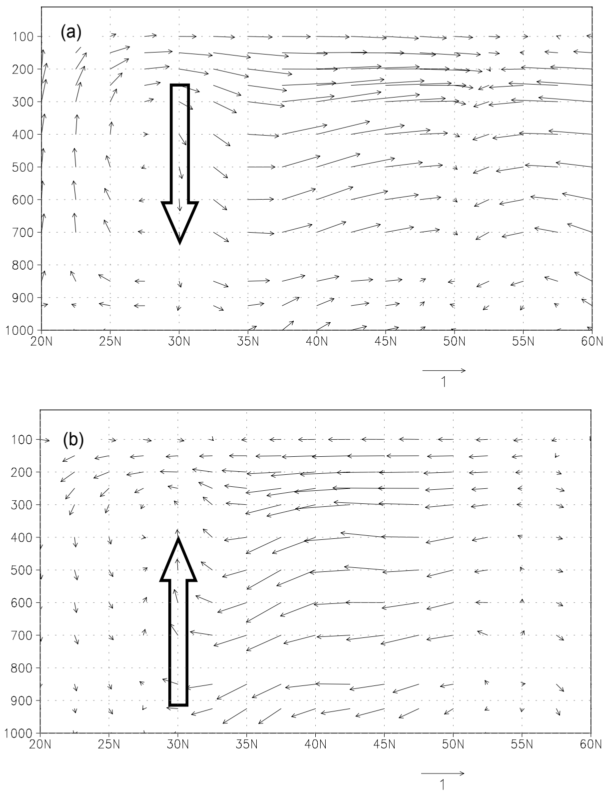

Fig. 11. Same as Fig. 8 but for the vertical-meridional circulation anomalies averaged between 110°–125°E.

tively. Comparing Fig. 10a with Fig. 10b, the anomalous meridional component of the wind fields at 700 hPa for the summers with high EAP index is different from that for the summers with low EAP index. In a summer with high EAP index, the positive meridional wind anomalies appear over the Huaihe River valley, North China, and the Korean Peninsula, i.e., the strong southerly winds of the monsoon flow over these regions. However, in a summer with low EAP index, the negative meridional wind anomalies appear over the Huaihe River valley, North China, and the Korean Peninsula, as shown in Fig. 10b. This indicates that in a summer with low EAP index, the southerly monsoon flow is weak over these regions.

6. Relationship between the EAP index and the vertical-meridional circulation over East Asia

Tao and Chen (1987) pointed out that the mean vertical-meridional circulation over the East Asian summer monsoon region is different from that over the Indian monsoon region. In East Asia there is no high mountain barriers and the flow can frequently penetrate from the mid-latitudes into the subtropical region of East Asia. In the climatological mean state, the convective activities are strong over the monsoon trough (or ITCZ) located at about 15°N. The outflow in the upper troposphere caused by the convective activities can be directed equatorward and northward from 15°N. Another ascending flow can be caused by the strong convective activities over the mei-yu front in the Yangtze River valley and the Baiu front in Japan. Thus the northward flow from the monsoon trough converges with the southward outflow due to the strong convective activities over the mei-yu front. This convergence can form a strong descending flow, which contributes to the formation of the western Pacific subtropical high.

Here the results show that the vertical-meridional circulation over the East Asian summer monsoon region in a summer with high EAP index is very different from that in a summer with low EAP index. Figures 11a and 11b are the composite anomaly distributions of vertical-meridional circulation averaged along 110°–125°E for the summers with $I_{\mathrm{EAP}} \geqslant 1$ and for the summers with $I_{\mathrm{EAP}} \leqslant -1$, respectively. Comparing Fig. 11a with Fig. 11b, it may be found that the vertical-meridional circulation in a summer with high EAP index is opposite to that in a summer with low EAP index. As shown in Fig. 11a, the positive anomaly distribution of vertical-meridional circulation, i.e., the Hadley cell-like circulation, is located over the region from South China to the Yangtze River valley. And there are strong southerly wind anomalies not only in the lower troposphere but also in the upper troposphere over the area to the north of 30°N. In this case, there is strong descending anomaly flow at 30°N. This means that the ascending flow is not strong over the mei-yu front in China and the Baiu front in Japan. Thus, the monsoon rainfall and the convective activities are not strong in these regions. However, there are strong southerly wind anomalies over the Yellow River valley, North China, and North Korea, which may cause strong rainfall. In a summer with low EAP index, as shown in Fig. 11b, the anomaly distribution of vertical-meridional circulation exhibits an anti-Hadley cell-like circulation, or a monsoon cell-like circulation, over the region from South China to the Yangtze River valley. There are strong northerly wind anomalies in both the lower and upper troposphere over the area to the north of 30°N. In this case, there is a strong ascending anomaly flow at 30°N, indicating a strong ascending flow over the mei-yu front in China and the Baiu front in Japan. The monsoon rainfall and the convective activities are strong in these regions. However, the southerly winds are weak over the Yellow River valley, North China, and North Korea. And the monsoon rainfall is weak in North China and North Korea in this case.

Therefore, our results also show that the EAP index proposed in this study can describe well the interannual variability of vertical-meridional circulation over East Asia.

7. Conclusion and discussion

Based on the EAP (East Asia/Pacific) teleconnection pattern in the summer atmospheric circulation anomalies over the Northern Hemisphere suggested by Nitta (1987), and Huang and Li (1987, 1988), respectively, an index measuring the strength of the East Asian summer monsoon is defined in this paper. This index is called the EAP index. The composite analyses of observed data clearly show that the EAP index can well describe not only the interannual variations of summer rainfall and surface air temperature in the Yangtze River valley and the Huaihe River valley, the Korean Peninsula, and Japan, but also the interannual variability of the East Asian summer monsoon system including the horizontal monsoon circulation and the vertical-meridional circulation cell over East Asia.

With the NCEP/NCAR reanalysis data and summer rainfall and surface air temperature data from the observational stations of China and Korea, it is shown that in a summer with high EAP index, the monsoon rainfall is weak in the Yangtze River valley and the Huaihe River valley, South Korea, and Japan. And the surface air temperature is also high in the Huaihe River valley, North China and Northeast China, and North Korea. In this case, the anticyclonic anomaly circulation is located over the Yangtze River valley and the Huaihe River valley, Korea, and Japan. The southerly monsoon flow is strong over East Asia. A positive vertical-meridional anomaly circulation cell is located over the area from South China to the Yangtze River valley, and there is a descending anomaly flow at about 30°N. However, in a summer with low EAP index, the monsoon rainfall is strong in the Yangtze River valley and the Huaihe River valley, South Korea, and Japan. The surface air temperature is low in the Huaihe River valley, North China and Northwest China, and North Korea. In this case, the cyclonic anomaly circulation is located over the Yangtze River valley and the Huaihe River valley, Korea, and Japan. The southerly monsoon flow is weak over East Asia. A reverse vertical-meridional anomaly circulation cell is located over the area from South China to the Yangtze River valley, and there is an ascending anomaly flow at about 30°N.

The analyses of observed data show that the EAP index can well denote the interannual variations of summer monsoon climate in East Asia because the index can well describe the East Asian summer monsoon circulation system. However, our study is preliminary. Further research is needed to improve the definition of this index so that it can be more suitable for measuring the interannual variations of the East Asian summer monsoon.

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