The Interannual Variability of East Asian Winter Monsoon and Its Relation to the Summer Monsoon①

Chen Wen (陈 文),
Institute of Atmospheric Physics, Chinese Academy of Sciences, 100080

Hans-F. Graf
Max-Planck-Institute of Meteorology, Hamburg, Germany

Huang Ronghui (黄荣辉)
Institute of Atmospheric Physics, Chinese Academy of Sciences, 100080

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ABSTRACT

Based on the NCEP / NCAR reanalysis data the interannual variability of the East Asian winter monsoon (EAWM) is studied with a newly defined EAWM intensity index. The marked features for a strong (weak) winter monsoon include strong (weak) northerly winds along coastal East Asia, cold (warm) East Asian continent and surrounding sea and warm (cold) ocean from the subtropical central Pacific to the tropical western Pacific, high (low) pressure in East Asian continent and low (high) pressure in the adjacent ocean and deep (weak) East Asian trough at 500 hPa. These interannual variations are shown to be closely connected to the SST anomaly in the tropical Pacific, both in the western and eastern Pacific. The results suggest that the strength of the EAWM is mainly influenced by the processes associated with the SST anomaly over the tropical Pacific. The EAWM generally becomes weak when there is a positive SST anomaly in the tropical eastern Pacific (El Niño), and it becomes strong when there is a negative SST anomaly (La Niña). Moreover, the SST anomaly in the South China Sea is found to be closely related to the EAWM and may persist to the following summer. Both the circulation at 850 hPa and the rainfall in China confirm the connection between the EAWM and the following East Asian summer monsoon. The possible reason for the recent 1998 summer flood in China is briefly discussed too.

Key words: East Asian winter monsoon, Interannual variability, SST, Summer monsoon

1. Introduction

Over the East Asia region, the most prominent surface feature of the winter monsoon is strong northeasterlies along the east flank of the Siberian high and the coast of East Asia. At 500 hPa there is a broad trough centered about at the longitudes of Japan. The dominant feature at 200 hPa is the East Asian jet with its maximum located at just southeast of Japan. This jet is associated with intense baroclinicity, large vertical wind shear and strong advection of cold air (Staff members of Academia Sinica, 1957; Lau and Chang, 1987; Boyle and Chen,

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1987; Chen et al., 1991; Ding, 1994). In the tropics, there is the major convection over the maritime continent of Borneo and Indonesia during winter (Ramage, 1975). Extensive deep cumulus convection supplies a large amount of latent heat to the atmosphere. It is believed to be one of the most energetic heat sources of the atmosphere and plays a substantial role in the atmospheric circulation during the Northern winter. From observations Chang et al. (1979) and Lau and Chang (1987) found that the tropical convection over the maritime continent was intensified by cold surges which are characterized by strong northeasterly winds penetrating deep into equatorial latitudes. The cold surges are suggested to be an important link in midlatitude tropical interactions. Through the midlatitude tropical interaction, the winter monsoon spreads its influence to the planetary and global scales. Generally the East Asian winter monsoon (EAWM) is a phenomenon connected with global scale circulation.

In recent decades there has been substantial progress in the study of summer monsoon. For example, Yasunari and Seki (1992) showed that the Indian summer monsoon plays an important role in the interannual variability of the global climate system particularly relevant at the El Niño–Southern Oscillation (ENSO) time scale. The relation of the East Asian summer monsoon to ENSO has also been addressed by Huang and Wu (1987). However, little attention has been paid to the interannual variation of the winter monsoon. As a matter of fact, Li (1988) found that there are strong and frequent cold wave activities in East Asia prior to the occurrence of El Niño. Tomita and Yasunari (1996) also suggested that the northeast winter monsoon might play a key role in the biennial oscillation of the ENSO / monsoon system. Recent work of Ji et al. (1997) presented a model study on the interannual variability of Asian winter monsoon. Sun and Sun (1994) analyzed the features of the atmospheric circulation in preceding winters for the summer drought and flood in the Yangtze and Huaihe River Valley and found the distinct difference. Thus it is sound to study the interannual variability of East Asian winter monsoon (EAWM) based on the observational data, and further the possible relation of EAWM to the summer monsoon.

2. Data

The monthly mean surface and pressure level data from the NCEP / NCAR reanalysis are used for the period of 1968–1997 in the study. These data are provided through the NOAA Climate Diagnostics Center. The surface quantities include wind (10 m), air temperature (2 m), and sea level pressure (SLP). The pressure level data are wind and geopotential height. The sea surface temperature (SST) data are obtained through NCAR's Data Support Section. From November of 1981 to May of 1997 the data are Reynolds SST, and the reconstructed Reynolds SSTs are used from June of 1967 to October of 1981. The data used also include the precipitation of 160 monthly land station reports in China from 1951–1990.

3. The interannual variability of East Asian winter monsoon

In many cases winter temperature is used to describe the intensity of EAWM (e. g. Chen et al., 1991). However, the investigations of the climate change in East Asia in the last one hundred years (Wang and Ye, 1993) have shown a significant warming trend in North China, and a cooling trend in the middle regions of China. With the data of monthly temperature of China in 160 stations from 1951 to 1989 Chen et al. (1991) also pointed out that in winter there were negative anomalies in the mainland of China south of 35°N and east of 102°E in the 1980's, and there were warming outside the above–mentioned region in the mainland of

China. Actually, after analyzing the interannual variation of winter temperature over East Asia, we found that the variation of temperature differs significantly with different regions because of these long-term trend. Furthermore, the main factor causing the monsoon phenomena is generally considered as the thermal contrast between the continent and the ocean. Any index representing the strength of monsoon should have a good ability to reflect this feature. Thus among the parameters which may be used to represent the EAWM activity, we think that the temperature difference, the pressure difference between the continent and the ocean and the wind along coastal East Asia may be more suitable for defining the monsoon intensity of its interannual variation. For the surface air temperature and pressure we find that there are different trends over different regions in East Asia as we mentioned above. This makes it a complex process to define an index for describing the intensity of EAWM. While it is much simple for the wind along coastal East Asia, since the interannual variations of the wind intensity are generally consistent over different regions. In fact, after choosing the East China Sea (25–40°N, 120–140°E), the South China Sea (10–25°N, 110–130°E), the area from the East China Sea to the South China Sea and the area (10–30°N, 115–130°E) as Ji et al. (1997) we get very similar results for the interannual variations of northerly wind intensity. Therefore in this paper we only choose the wind to define an EAWM intensity index, which is the averaged v component over the area from the East China Sea to the South China Sea (SCS) as shown in Fig. 1. The reason why we choose this area is that we can get the highest correlation with the geopotential height at 500 hPa around East Asia. Figure 1 also shows the mean surface wind across East Asia from 1968 / 1969–1996 / 1997 averaged for November to March (NDJFM). There occur strong northeasterlies along coastal East Asia. The northeasterly flow splits into two branches south of Japan. One branch turns eastward toward the subtropical western and central Pacific, while the other flows along the coastline of East Asia into the South China Sea. This winter monsoon circulation has been documented by many authors (Krishnamurti et al., 1973; Lau and Chang, 1987; Chen et al., 1991; Ji et al., 1997).

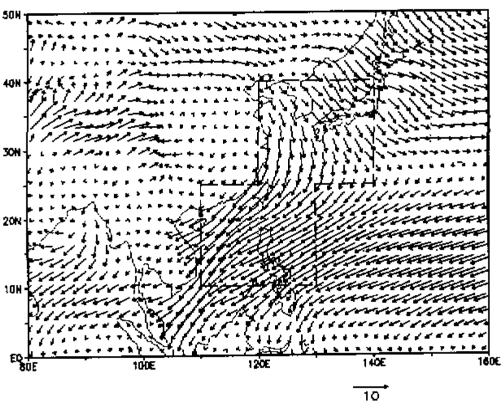

Fig. 1. The averaged East Asian surface (10 m) wind from November to March (NDJFM) of 1968 / 1969–1996 / 1997. Unit: m / s. The area enclosed in dashed line indicates where the EAWM intensity v index is averaged.

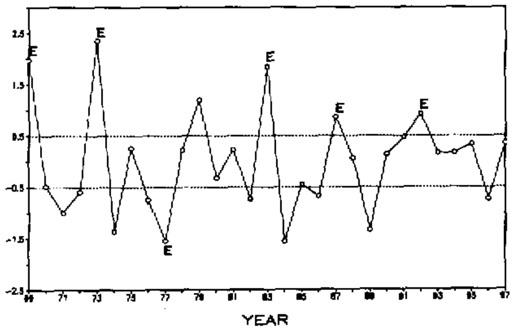

Fig. 2. The normalized interannual variation of the EAWM intensity index averaged for NDJFM from 1968 / 1969–1996 / 1997. "E" denotes the El Niño year.

Figure 2 shows the normalized interannual variations of the EAWM intensity index averaged for NDJFM from 1968 / 1969–1996 / 1997. It is obvious that the winter monsoon possesses pronounced interannual variation. It also seems that the amplitude of the interannual variation becomes smaller and winter monsoon tends to become weaker beginning at the end of the 1980s. To facilitate further study, the weak and strong EAWM cases are identified by the criterion that the index exceeds ± 0.5 standard deviations from the average. It should be noted that the northerlies are negative, i. e. strong EAWM is indicated by strong negative anomalies in Figure 2. So the selected strong EAWM cases are 1971, 1972, 1974, 1976, 1977, 1982, 1984, 1986, 1989, 1996; and the weak cases are 1969, 1973, 1979, 1983, 1987, 1992. Here, 1969 indicates the 1968 / 1969 winter etc.. Making composites of the two groups we get the mean differential surface wind field for strong minus weak cases as shown in Fig. 3. It is clear that during strong EAWM the northeasterlies are enhanced along East Asia coast and extend to equatorial latitudes. During strong EAWM an anomalous cyclonic

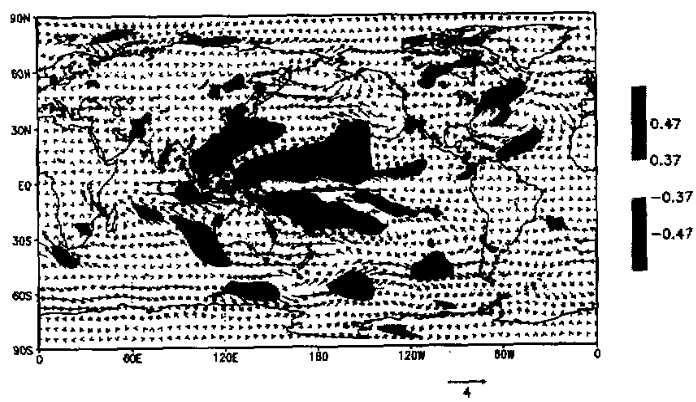

Fig. 3. Composite difference of surface (10 m) wind between strong and weak monsoon winter (NDJFM). Unit: m / s. The heavy shaded area denotes that the differences are significant above the 99% level, and the light shaded area denotes above the 95% level.

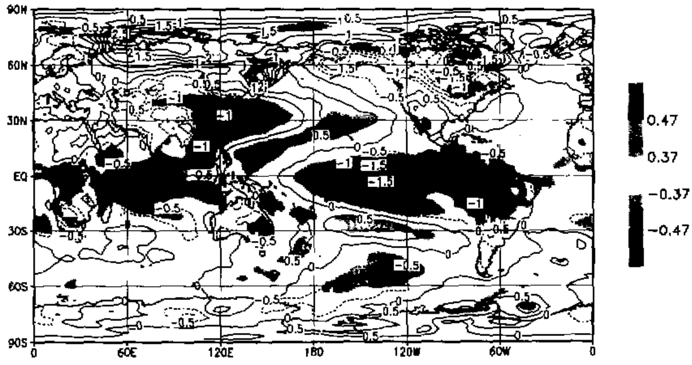

Fig. 4. Same as Fig. 3 except for the surface (2 m) air temperature. Unit: °C.

circulation appears around the Philippines. The marked differences also show that there is a much stronger confluence over the maritime continent and a slightly stronger divergence over the eastern Pacific in strong cases than in weak cases. The correlation coefficients between the EAWM intensity index and global surface v components for 29 years are calculated, too. The minimum correlation coefficient is 0.37 to be significant at the level $\alpha=0.05$ and 0.47 at the level $\alpha=0.01$. The shaded areas in Fig. 3 denote the correlations which are significant at least at the level $\alpha=0.05$. The main differences we mentioned above are all exceeding the 95% statistical level.

In order to compare the variations of the surface circulation with other parameters which may be used to represent the EAWM activity, the composite differences of surface air temperature, SLP and geopotential height at 500 hPa between strong and weak EAWM cases are presented in Fig. 4, Fig. 5a and Fig. 5b respectively. The correlation coefficients between EAWM intensity index and these parameters are also given. The shaded areas in Fig. 4 and Fig. 5 again denote that the correlations are statistically significant at the 95% level. As can be seen from Fig. 4, over coastal East Asian continent and around the sea from the East China Sea to the South China Sea there prevails cold surface air temperature, which may be due to strong winter monsoon northerlies. Another remarkable difference appears in the equatorial belt, especially over the tropical eastern Pacific. The results indicate that the surface air temperature is much colder over the tropical central–eastern Pacific if strong winter monsoon cases are compared with weak winter monsoon cases. The temperature is reduced also over the Indian Ocean in strong EAWM cases. Besides, from the subtropical central Pacific to the tropical western Pacific there is a warm region, which also exceeds the 95% significance level. While the composite difference of SLP (Fig. 5a) shows the obvious contrast between East Asian continent and the adjacent ocean. In East Asian continent the two key areas are Siberia and the northern China where the pressure becomes higher in strong EAWM cases than in weak EAWM cases. The most significant differences appear over the tropical Pacific with negative anomalies over the western Pacific and positive anomalies over the eastern Pacific. These correspond well to the difference of surface circulation with strong confluence over the maritime continent and weak divergence over the eastern Pacific. In Fig. 5b, it can be seen that the East Asian trough at 500 hPa is much deepened in strong EAWM cases compared to

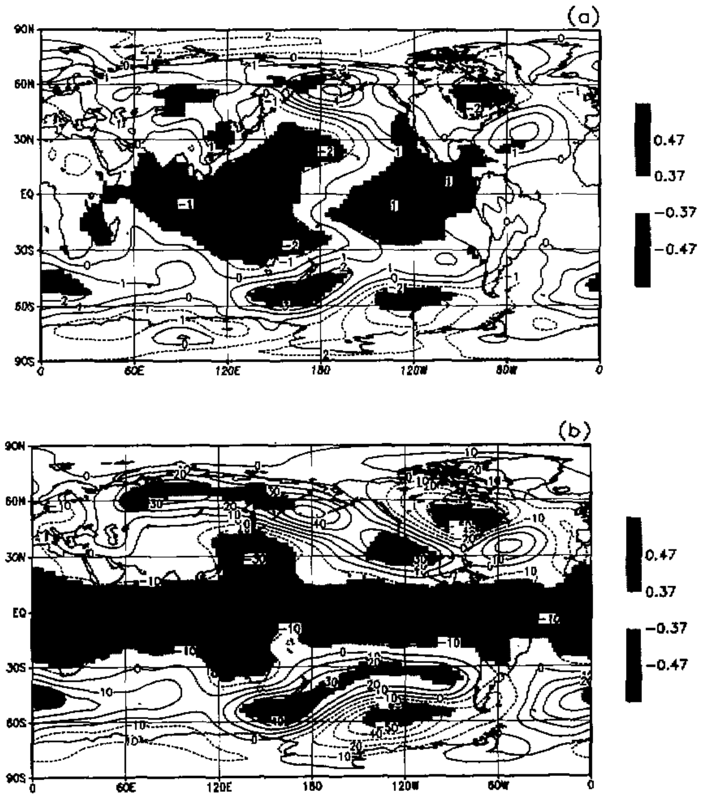

Fig. 5. Same as Fig. 3 except (a) for the sea level pressure (Uni: hPa), and (b) for the 500 hPa geopotential height (Unit: m).

weak cases. The most striking feature is the negative anomalies of geopotential height appearing over the whole tropics. The values show that the evident difference is over the central-eastern Pacific. There is also a remarkable teleconnection in the negative phase of the PNA pattern (with negative height anomalies over the tropical eastern Pacific and North America, and positive anomalies over the northern Pacific). Thus, the EAWM intensity index we defined indicates that a strong EAWM corresponds to strong northerly winds along coastal East Asia, cold East Asian continent and surrounding sea and warm ocean from the subtropical central Pacific to the tropical western Pacific. The features of a strong EAWM also include high pressure in East Asian continent, low pressure in the adjacent ocean and much deep East Asian trough. While a weak EAWM corresponds to the reverse situations. The results also show that there are marked differences in the global scale which are closely associated with, but not necessarily all due to, the interannual variability of EAWM.

4. The relationship between EAWM and SST

The composite difference of SST between strong and weak monsoon winter (DJF) is presented in Fig. 6. In the tropical Pacific, it is very similar to the SST anomaly pattern in the La Niña phase. From the central to eastern Pacific a large negative SST anomaly area with maximum over −2.5°C is presented. Positive SST anomalies appear in the western Pacific from the tropics near the Philippines to the subtropical central Pacific. It is also found that along the east coast of the Asian continent there are negative SST anomalies which extend to the north of Australia, these anomalies may be due to outbreaks of northeasterlies from higher latitudes. In the Indian Ocean further weak negative SST anomalies are found. All these major differences are above 95% significance level. As a matter of fact, the striking feature of SST anomalies in the tropical central and eastern Pacific starts to appear in the summer preceding the winter monsoon season and can persist to the following spring (figure not shown). In order to see clearly this feature, the lag–correlations between the EAWM intensity index and the SST anomalies in the tropical eastern and western Pacific are given in Fig. 7. The SST anomalies are smoothed by three–month running means in order to deduce the relationships for seasonal means. The significant positive correlation of the SST anomaly in the eastern Pacific to the EAWM intensity index above 95% significance level appears in the preceding summer and increases gradually to reach the maximum in winter. This significant correlation persists until the following spring. The correlation between the SST anomaly in the tropical western Pacific and the EAWM intensity index is negative and out of phase with the tropical eastern Pacific. Since the SST anomaly is well known to exhibit high season–to–season persistence, the significance of these correlations between the EAWM intensity index and the SST anomalies needs to be checked carefully. As indicated by Davis (1976) and Chen (1982), the effective number of degrees of freedom (EDOF) may not be the same as the number of data that enter into the calculation of the result of Fig. 7. The relationship between the autoregressive nature and the EDOF is discussed in detail by Davis (1976). Applying Davis's method, the EDOFs are evaluated for different seasons. The results show that generally the EDOF is smaller in winter than in other seasons. Thus we choose the winter as the critical example. For the SST anomalies (DJF) in the tropical eastern Pacific and the EAWM intensity index, the EDOF is 22. The cross–correlation value is 0.40 at 95% significance level and 0.52 at 99% significance level. For the SST anomalies (DJF) in the tropical western Pacific and the EAWM intensity index, the EDOF is 21. The cross–correlation value is 0.41 at 95% significance level and 0.53 at 99% significance level. With these values as the new criteria of significance, from Fig. 7 we can still draw the same conclusion as above. So the EAWM is dominantly influenced by the tropical Pacific SST anomaly. The relationship between the EAWM and El Niño shows that the EAWM generally becomes weak when there is a positive SST anomaly in the tropical eastern Pacific (El Niño), while the EAWM becomes strong when there is a negative SST anomaly (La Niña). Actually, apart from the 1978 / 1979 winter all the other weak EAWM years correspond to El Niño years (see Fig. 2).

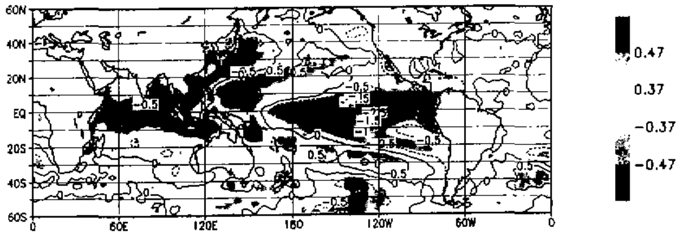

Fig. 6. Same as Fig. 4 except for SST in the peak winter (DJF). Unit: °C.

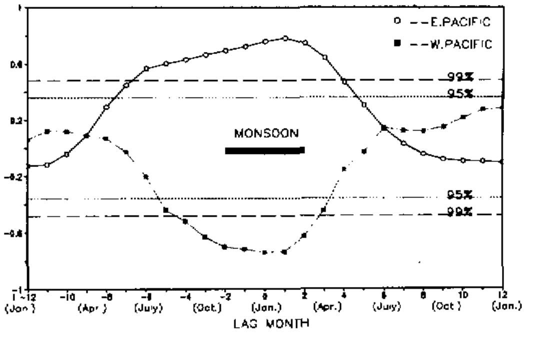

Fig. 7. Lag-correlations between EAWM intensity index and SST anomalies in the eastern (5°S-5°N, 170-150°W) and western (5-10°N), 130-150°E) Pacific. The reference monsoon is shown thick black bar.

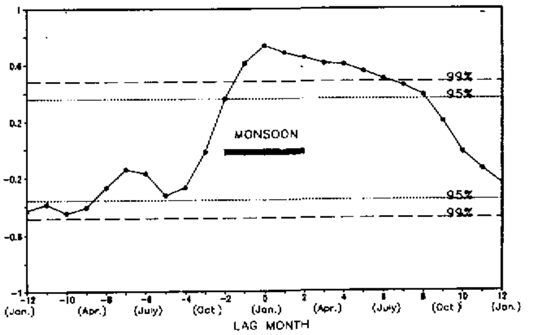

Fig. 8. Same as Fig. 7 except for SST anomaly in the SCS (10-20°N, 110-120°).

However, the EAWM is not completely passive under the influence of the tropical Pacific SST. The SST anomalies do not appear in the preceding season in the region from the east coast of East Asia to the northern Australia, especially in the SCS. The SST anomalies in this region might be influenced mainly by the EAWM. Figure 8 shows the lag-correlations between the EAWM intensity index and the SST anomalies in the South China Sea. The SST anomalies are smoothed as above by three-month running means in order to deduce the relationships for seasonal means. It is obvious that the significant positive correlation coefficient starts abruptly in winter and persists until the following summer above the significance level of 95%. Relatively high correlations with opposite signs are also found in the winter of the year before. Probably this indicates the strong biennial nature of the SST anomaly in the SCS. Here the significance is also checked with Davis's method. For the SST anomalies (DJF) in the SCS and the EAWM intensity index, the EDOF is 24. The cross-correlation value is 0.39 at 95% significance level and 0.50 at 99% significance level. The new criteria of significance support our conclusion too.

5. The relation of the EAWM to the summer monsoon

The results in Section 4 present that the SST anomalies in the SCS were closely related to the EAWM and may persist to the following summer. It is known that the onset of summer monsoon starts from the SCS in May and then propagates to the Asian continent (Chen et al., 1991). This anomaly should exert influences on the following summer monsoon. Figure 9 presents the composite difference of circulation at 850 hPa in the summer (JJA) following the strong and weak EAWMs. The most significant difference appears over the subtropical western Pacific, which indicates the subtropical high tending to shift to the north in the summer after a strong EAWM and to the south after a weak EAWM. The shaded area denotes the lag-correlation coefficients between the EAWM intensity index and zonal wind at 850 hPa in the following summer which exceed the significance level of 95%. However, we did not find any anomalies over the Indian region that exceed the significance level 95%. The close relationship between the subtropical western Pacific high and the strength of the East Asian summer monsoon has been stressed by Guo (1985) in observational research. Her results suggested that the subtropical western Pacific high shifted to the north in a strong monsoon summer and to the south in a weak monsoon summer. Therefore, in this sense the anomalous East Asian summer monsoon may be closely related to the preceding EAWM. The SST anomaly in the South China Sea may be a possible medium responsible for this relationship. Since northward movement of the subtropical western Pacific high corresponds to drought at the Meiyu region of the eastern China and the reverse for the southward movement, the predictability of anomalous East Asian summer monsoon is implied with the preceding EAWM. Figure 10 presents the composite difference of monthly rainfall at stations in China during the following summer season (JJA) between strong and weak EAWM cases for the period 1968–1990. A remarkable negative anomaly appears in the central region of the eastern China. The shaded area indicates a lag-correlation coefficient between the EAWM intensity index and rainfall in the following summer above 0.3. Actually the maximum coefficient

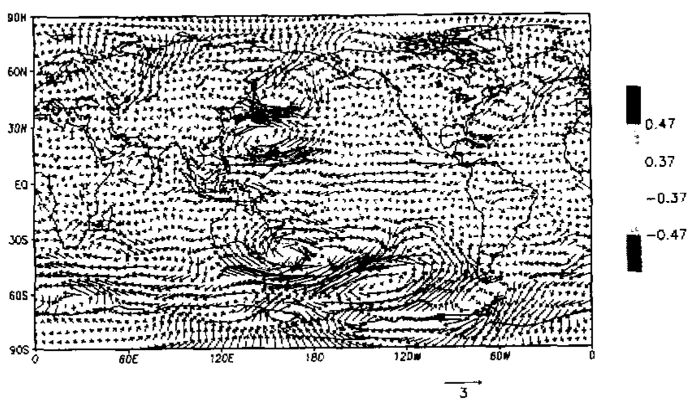

Fig. 9. Similar with Fig. 3 but at 850 hPa in the following summer (JJA). Unit: m / s.

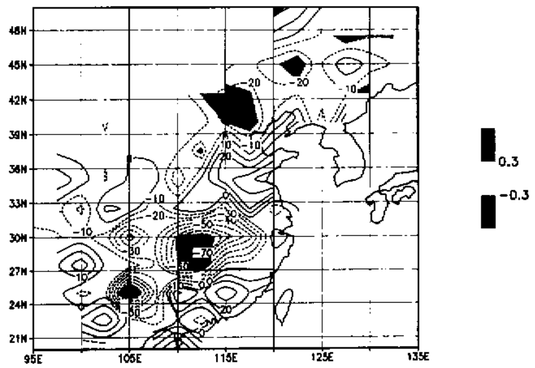

Fig. 10. Composite difference of monthly mean rainfall in China during the following summer (JJA) after strong and weak EAWM for the period 1968–1990. The shaded area denotes the lag–correlation coefficient between the rainfall and the preceding EAWM intensity index above 0.3. Unit: mm / month.

reaches 0.49 which is higher than 0.42 (the significance level of 95%). This means that following a strong EAWM is generally a summer with drought in the central region of the eastern China, while following a weak EAWM is generally a summer with flood in the same region. By analyzing the evolution processes of the abnormal general circulation patterns for the drought / flood years in the Yangtze River and Huaihe River valley in China from preceding winter to summer, Sun and Sun (1994) found that more active cold surge related to strong winter monsoon was in the preceding winter for the drought summer and that the cold air did not invade southward in the preceding winter for the flood year. Thus the results of Sun and Sun (1994) and ours complement each other well. Besides, from Fig. 10 it is also noticed that in the northeastern China there is a similar variation as in the central region of eastern China, which is also closely connected with the preceding EAWM.

In 1997 / 1998 there occurred the strongest El Niño event of this century. This El Niño event began in early 1997 and peaked in the winter of 1997 / 1998, then the SSTA decreased rapidly. The winter monsoon in 1997 / 1998 is analyzed by presenting the anomalous surface wind and the geopotential height anomalies at 500 hPa. In Fig. 11a the anomalous surface wind (DJF mean) indicates that there are large southerly components along the coast of East Asia. At 500 hPa there are positive geopotential height anomalies over East Asia in Fig. 11b, which means that the East Asian trough is weakened. Both anomalies show that the winter monsoon in 1997 / 1998 is weak. In the summer of 1998, China experienced the severe flood in the Yangtze River Valley and the northeastern China. Figure 12 presents the percentage of rainfall anomaly in the summer (JJA). It is clear that there are positive anomalies in the central China along the Yangtze River and in the northeastern China, where the percentage of rainfall anomaly is over 100%. Comparing Fig. 12 with Fig. 10, we can see that the distributions of rainfall anomaly correspond well with each other. Thus the summer flood of 1998 in China may be closely connected with the weak 1997 / 1998 winter monsoon and the 1997 / 1998 El Niño event.

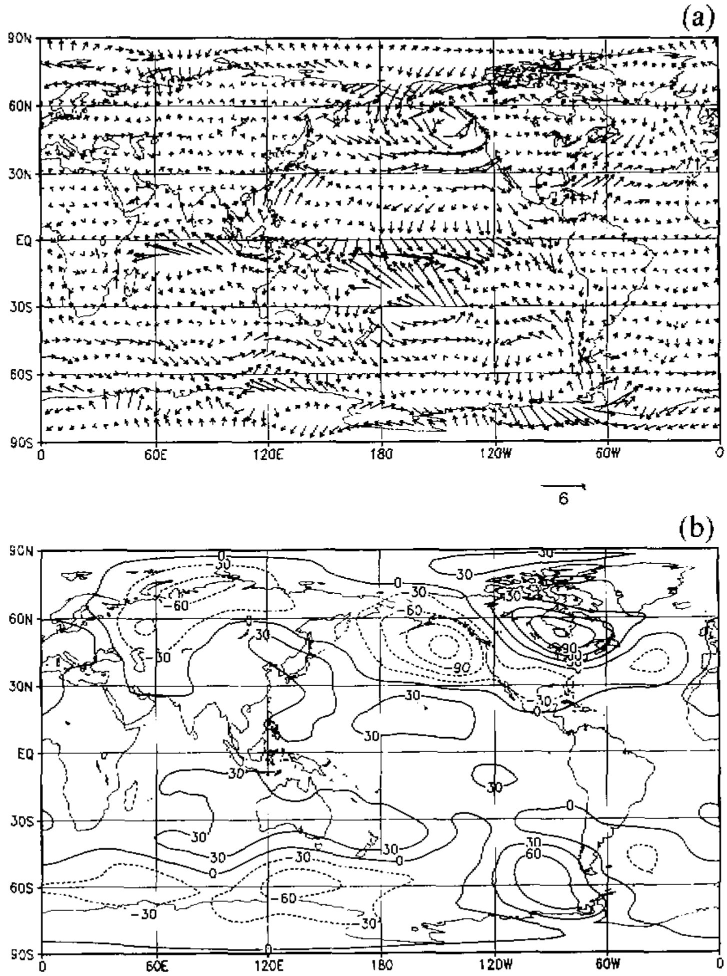

Fig. 11. The distributions of the anomalous surface (10 m) wind (a) and the geopotential height anomalies at 500 hPa (b) in the winter (DJF) of 1997 / 1998.

6. Conclusions and discussions

The interannual variability of the EAWM is studied based on a newly defined EAWM intensity index in this investigation. The index indicates that a strong EAWM corresponds to strong northerly winds along coastal East Asia, and a weak EAWM corresponds to weak northerly winds. The related anomalies in East Asia are cold East Asian continent and surrounding sea, *high pressure in East Asian continent and deep East Asian trough at 500 hPa* for a strong EAWM. The situation is reverse for a weak EAWM. Besides, the marked differences closely associated with the interannual variability of EAWM appear in the global scale,

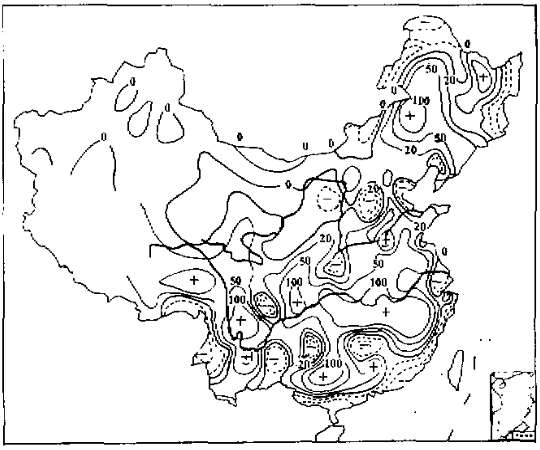

Fig. 12. The percentage of rainfall anomaly of China in the summer (JJA) of 1998.

especially in the tropical regions. These include the surface convergence (divergence) over the maritime continent and the surface divergence (convergence) over the eastern Pacific in a strong (weak) monsoon winter, and the teleconnection at 500 hPa in the negative (positive) phase of the PNA pattern for a strong (weak) monsoon winter. Most of the features above may be attributed to the distribution of SST anomaly in the tropical Pacific. The results indicate that the interannual variations of the EAWM are closely associated with both the tropical eastern and tropical western Pacific SST anomalies. It suggests that the strength of EAWM is mainly influenced by the processes associated with the SST anomaly over the tropical Pacific. Clearly further studies are needed to explain the physical processes how the tropical SST anomaly influences the winter monsoon. The passive EAWM under the influence of the tropical Pacific SST anomalies presents that the EAWM generally becomes weak when there is a positive SST anomaly in the tropical eastern Pacific (El Niño), and the EAWM becomes strong when there is a negative SST anomaly (La Niña).

The SST anomaly in the SCS has been shown to be closely related to the EAWM and may persist to the following summer. Thus it provides a possible medium to carry information from winter to the next summer. The subtropical western Pacific high is found to shift northward in the summer after strong EAWM and vice versa after weak EAWM. Since the strength of the East Asian summer monsoon is closely related to the subtropical western Pacific high, the anomalous summer monsoon may be predicted to some extent by the preceding EAWM. The rainfall in China shows that following a strong EAWM is generally a summer with drought in the central region of the eastern China, and the situation is opposite for a weak EAWM. The analysis of the 1997 / 1998 winter monsoon and the severe flood in the Yangtze River Valley and the northeastern China confirms this connection between the EAWM and the following East Asian summer monsoon.

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