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The Characteristics of Longitudinal Movement of the Subtropical High in the Western Pacific in the Pre-rainy Season in South China

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ABSTRACT

Using the NCEP/NCAR reanalysis data, the China rainfall data of the China Meteorological Administration, and the sea surface temperature (SST) data of NOAA from 1951–2000, the features of the anomalous longitudinal position of the subtropical high in the western Pacific (SHWP) in the pre-rainy season in South China and associated circulation and precipitation are studied. Furthermore, the relationship between SHWP and SST and the eastern Asian winter monsoon is also investigated. Associated with the anomalous longitudinal position of SHWP in the pre-rainy season in South China, the flow patterns in both the middle and lower latitudes are different. The circulation anomalies greatly influence the precipitation in the pre-rainy season in South China. When the SHWP is in a west position (WP), the South China quasi-stationary front is stronger with more abundant precipitation there. However, when the SHWP is in an east position (EP), a weaker front appears with a shortage of precipitation there. There exists a good relationship between the longitudinal position of SHWP and SST in the tropical region. A negative correlation can be found both in the central and eastern tropical Pacific and the Indian Ocean. This means that the higher (lower) SST there corresponds to a west (east) position of SHWP. This close relationship can be found even in the preceding autumn and winter. A positive correlation appears in the western and northern Pacific and large correlation coefficient values also occur in the preceding autumn and winter. A stronger eastern Asian winter monsoon will give rise to cooler SSTs in the Kuroshio and the South China Sea regions and it corresponds to negative SST anomaly (SSTA) in the central and eastern Pacific and positive SSTA in the western Pacific in winter and the following spring. The whole tropical SSTA pattern, that is, positive (negative) SSTA in the central and eastern Pacific and negative (positive) SSTA in the western Pacific, is favorable to the WP (EP) of SHWP.

Key words: longitudinal position of the subtropical high, large-scale circulation, precipitation, Sea Surface Temperature (SST), East Asian winter monsoon

1. Introduction

South China is the area with most abundant precipitation, most frequent heavy rain and longest rainy season (from April to November) in China. Most heavy rainfall results from the interaction between cold air and the moist warm current from the Tropics. The period of April to June is the first stage of the rainy season called the pre-rainy season, comprising 40%–50% of the precipitation of the whole rainy season. Generally, the period of pre-rainy season is from the fifth pentad of April to the fifth pentad of June (Guo and Wang, 1981). Serious floods usually appear in that period. The precipitation in the pre-rainy season has a marked interannual variation (Wu and Liang, 1992), which is influenced by the longitudinal position of the subtropical high in the western Pacific (Gao et al., 1999) and sea surface temperature (SST) in the tropical eastern Pacific and the warm pool region in the preceding winter and spring (Deng and Wang, 2002; Chang et al., 2000a, b).

This suggests that the longitudinal position of the subtropical high in the western Pacific (SHWP) is closely related to the precipitation of the rainy season

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in South China. To study its features and relationship to the SST anomaly (SSTA) is an important topic. The East Asian winter monsoon influences the circulation of the coming spring and summer and SSTs at the South China Sea and the adjacent sea region near the Asian continent and the tropical Pacific in winter and spring (Chen and Sun, 1999; Sun and Chen, 2000; Chen, 1999). Sea surface temperature plays an important role in the connection between winter and summer circulation. Consequently the relationship between the winter monsoon and the longitudinal position of SHWP is also studied.

It is well known that a few studies have focused on the longitudinal displacement of SHWP (Lu and Dong, 2001; Lu, 2001, 2002; Yang and Sun, 2003). In Lu (2001), the index of the longitudinal location of SHWP was defined as the geopotential height anomaly averaged in the subtropical area of 10°–30°N, 110°–130°E, at 850 hPa. But the interannual variation of the longitudinal movement of SHWP reveals an increasing trend of height. According to our previous study (Yang and Sun, 2003), a new index for measuring the longitudinal position of SHWP is proposed. We use the relative vorticity averaged over a specific area to avoid the ambiguity posed by previously used indices based on geopotential height. Following this method, a time series of longitudinal position of SHWP in the pre-rainy season has been calculated in this paper. Then the influence of the anomalous longitudinal position of SHWP on the precipitation in South China is studied. The relationship between SSTA in different sea regions and different seasons and the longitudinal position of SHWP is also investigated. In order to reveal the influence of the eastern Asian winter monsoon on the position of SHWP, anomalies of some atmospheric variables (geopotential height at 500 hPa, wind at 1000 hPa) will be analyzed comparatively.

The data used are the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data on a 2.5° × 2.5° grid during 1951–2000. The rainfall data at 730 stations in China compiled by the China Meteorological Administration and SST data of NOAA are also used. The period of the pre-rainy season in South China as defined by Guo and Wang (1981) is adopted.

2. Longitudinal position of SHWP in the pre-rainy season in South China

The relative vorticity in the western flank of SHWP is calculated because of the large curvature curl there. Figure 1a gives the distribution of the standard deviation of relative vorticity at 500 hPa in the pre-rainy

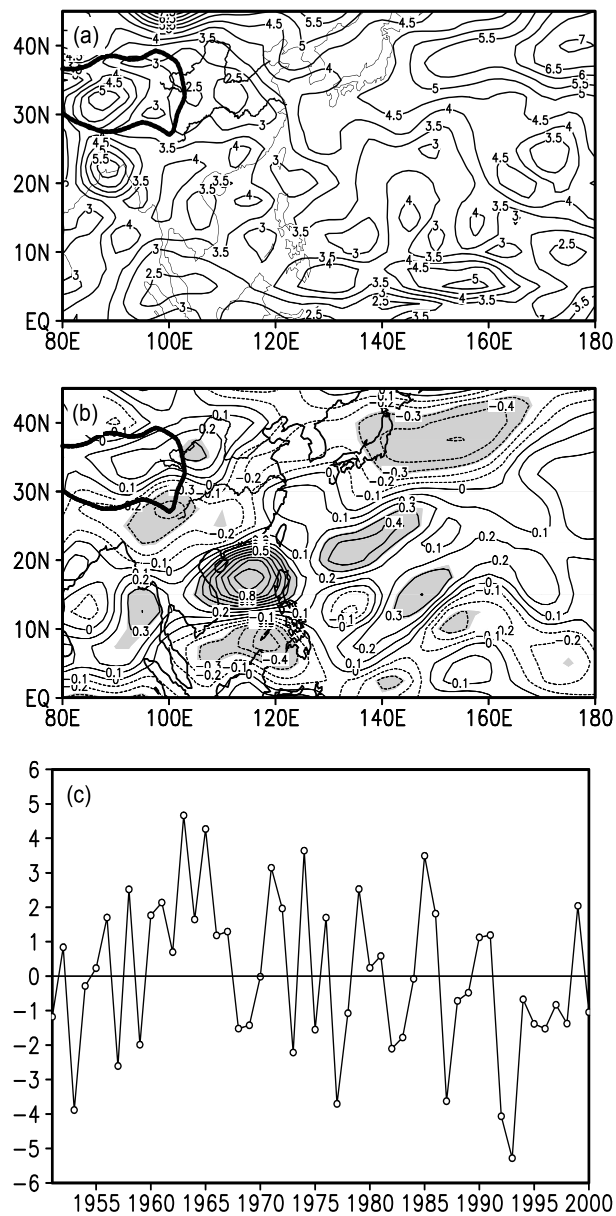

Fig. 1. (a) Standard deviation, (b) correlation coefficient (base point: 17.5°N, 115°E; where the thick line stands for 3000 m of the Tibetan Plateau), and (c) normalized deviation of the SHWP index of relative vorticity averaged over 12.5°–22.5°N, 110°–135°E at 500 hPa. Unit of standard deviation: 10^{-6} s^{-1}.

Table 1. Years of anomalous longitudinal position of SHWP.

For the west position (WP)	For the east position (EP)
1951, 1953, 1957, 1959	1956, 1958, 1960, 1961
1968, 1969, 1973, 1975	1963, 1964, 1965, 1966
1977, 1978, 1982, 1983	1967, 1971, 1972, 1974
1987, 1992, 1993, 1995	1976, 1979, 1985, 1986
1996, 1998, 2000	1990 1991, 1999

season for 1951–2000. It is clear that there is a region with large values in SHWP over the South China Sea indicating a large interannual variation of SHWP in this region. In order to better define this area, we choose the point with the largest value of standard deviation in this region to calculate the correlation coefficient with the vorticity of every point at 500 hPa as shown in Fig. 1b. It can be found that the area with high correlation coefficient value in the South China Sea region is in good agreement with the large standard deviation one in Fig. 1a. Therefore, we use the region of 12.5°–22.5°N, 110°–135°E to calculate the mean relative vorticity to define the index of the longitudinal position of SHWP. Apparently, a negative anomalous vorticity (or large anticyclone vorticity) means a westward extension of the SHWP position. On the contrary, a positive anomalous vorticity (or smaller anticyclone vorticity) represents its location rather to the east. Figure 1c gives the series of normalized deviation of the longitudinal position index of SHWP year by year. The years of anomalous longitudinal position of SHWP with absolute value larger than one normalized deviation are selected as shown in Table 1. The composite study in the following sections is based on these samples.

3. Circulation associated with anomalous longitudinal position of SHWP

3.1 500 hPa *geopotential height*

Figures 2a and 2b respectively show the composites for the west position and east position of SHWP during the pre-rainy season in South China. In the case of WP, the west end of the ridge in terms of the 5860 gpm contour moves westward to the west of the Indochina Peninsula and positive anomalies occur over a large area from the South China Sea to the Bay of Bengal. This is in marked contrast with the case of EP in which the west end of the 5860 gpm contour retreats to the east of the Philippines and negative geopotential height anomalies appear from the tropical western Pacific to the Bay of Bengal. This clearly indicates the different subtropical circulations between the WP and EP of SHWP.

The anomalies in the middle and high latitudes for the two situations are also out of phase. In the case of WP, positive anomalies are found over the Ural Mountains and the areas from the eastern Siberia to Okhotsk, which means that the ridges over those regions are developed. Negative height anomalies are found to the west of Lake Baikal, which means that the trough in the westerlies over that region is intensified. Anomalous height fields in westerlies in the case of EP exhibit a remarkable difference from WP, being even out-of-phase with the latter, which means that the zonal flow prevails with weaker meridionality. This suggests that the longitudinal shift of SHWP is related to the change of circulation in the westerly belt.

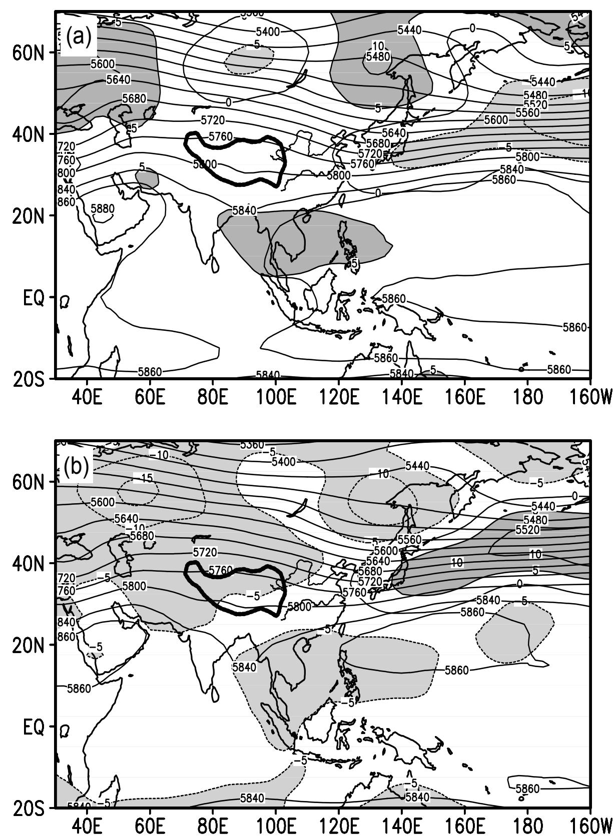

Fig. 2. Composite maps of geopotential height and anomaly at 500 hPa in the pre-rainy season for (a) WP years, and (b) EP years. The anomalies greater than 5 gpm are in dark shading and those less than –5 gpm are in light shading. Units: gpm.

3.2 850 hPa *wind*

Figure 3 depicts the composites of anomalous wind at 850 hPa. In the case of the WP of SHWP, an anomalous anticyclonic circulation is located right over the western Pacific stretching to the Bay of Bengal. This indicates that the SHWP stretches westward and controls those areas. In the case of EP, an anomalous cyclonic circulation is located south of 20°N, which means the SHWP is weaker and withdraws eastward. Now let us see the pattern over South China to the north of SHWP. In the case of WP, the southwesterly wind on the northwest side of the anomalous anticyclonic circulation meets with the anomalous northerly wind forming a strong convergence zone over South China, which is associated with the South China quasi-stationary front. However, in the case of EP, South China is dominated by the anomalous divergent flow

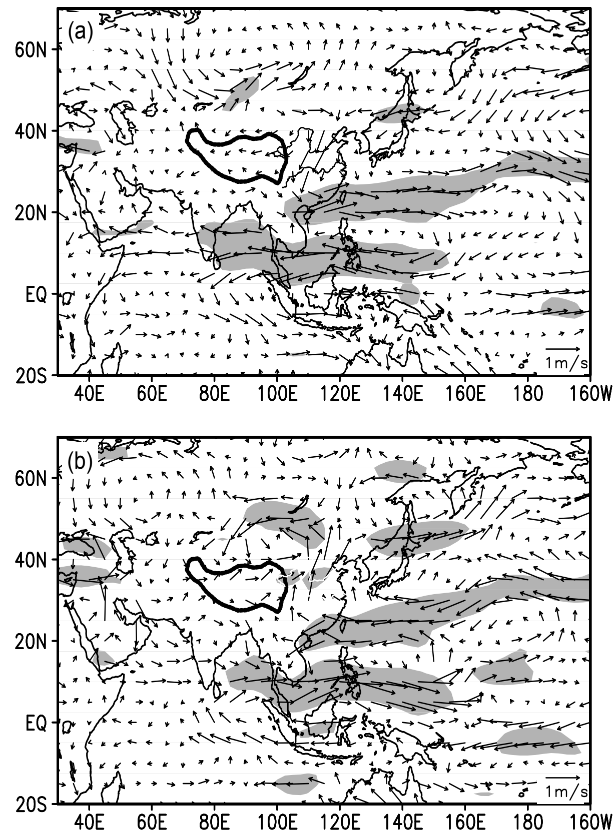

Fig. 3. The composites of the 850hPa wind vector anomalies for (a) WP and (b) EP. Units: m s^{-1}. The shading shows the t-test significance at the 0.05 level.

composed of the northwesterly wind on the northwest side of the anomalous cyclonic circulation and anomalous southerly wind. This pattern is distinctly unfavorable to the maintenance of the South China quasi-stationary front. This indicates that the anomalous longitudinal position of SHWP will result in anomalous precipitation over South China.

The distribution of moisture flux at 850 hPa is consistent with the wind field (figure omitted). The case of WP features a strong anomalous moisture convergence over South China. In the case of EP, the moisture convergence there decreases largely with a strong anomalous moisture divergence.

3.3 *Vertical circulation*

3.3.1 500 hPa *vertical velocity*

The anomalous longitudinal position of SHWP is accompanied by a different vertical velocity field. Figure 4 presents the vertical p-velocity ω at 500 hPa. The broad distinction of vertical velocity between WP and EP is obvious. The WP exhibits a positive vertical p-velocity ω anomaly from the South China Sea to the Western Pacific around 15°N with a center over the South China Sea. This means that the descending flow is strengthened over the South China Sea, which indicates the westward stretching of SHWP in Fig. 2a. On the contrary, a notable negative vertical p-velocity ω anomaly lies over the South China Sea. From Fig. 2b, we see that the descending flow withdraws eastwards associated with the eastward movement of the SHWP.

Furthermore, a noticeable difference in the vertical p-velocity patterns appears over South China. Negative vertical velocity anomalies are found over South China as SHWP is located in the WP, which means that the ascending flow over that region is stronger than normal. In the EP situation, a positive anomaly of vertical velocity is found over South China, which means that the ascending flow is weakened. This corresponds to the results of wind in Fig. 3. Thus, in WP, the convergences of both wind and moisture flux are strengthened over South China resulting in the stronger ascending flow. In EP, the convergences of both wind and moisture flux are weakened resulting in the weaker ascending flow.

3.3.2 *Vertical circulation*

The vertical circulations over the tropical zone for

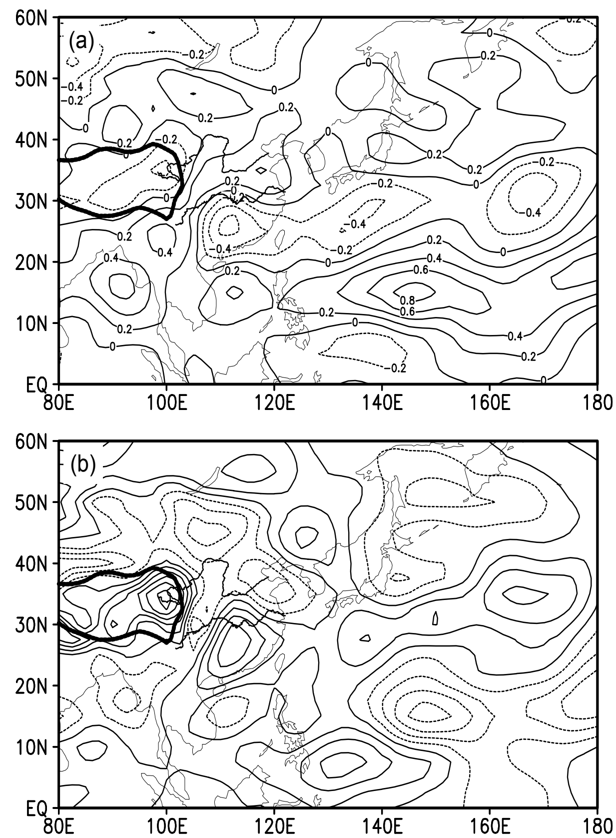

Fig. 4. Same as Fig. 3 but for the anomalous vertical p-velocity ω for (a) WP and (b) EP. Units: 10^{-4} hPa s^{-1}.

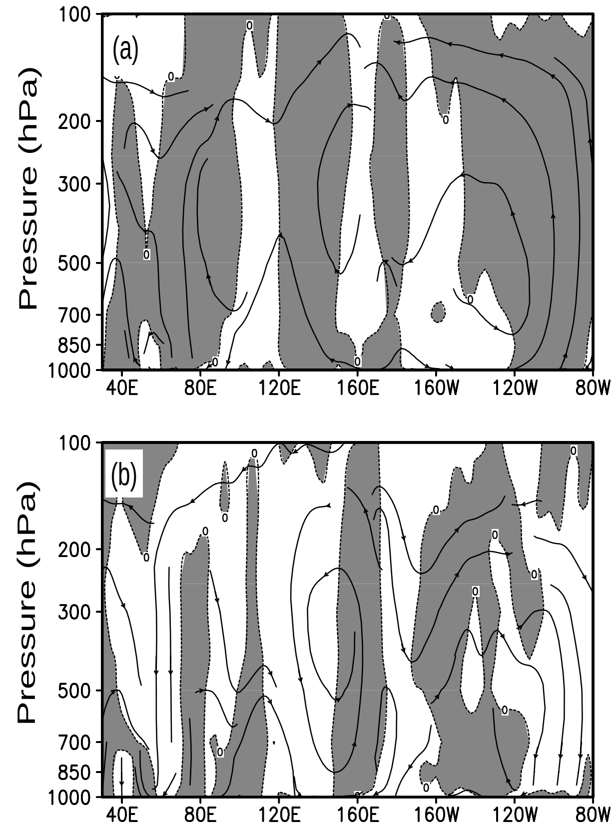

Fig. 5. Anomalous vertical circulation along 0–5°N for (a) WP years, and (b) EP years. The areas of ascending currents are shaded.

WP and EP of SHWP also show a distinction. Figure 5 is the vertical-longitudinal cross section of anomalous vertical circulation averaged along 0–5°N, with the shaded area for ascending motion. In the case of WP, both the tropical eastern Pacific and Indian Ocean are dominated by anomalous ascending motion. But the pattern over the western Pacific is complicated, with anomalous ascending motion over the warm pool region and anomalous descending motion over the South China Sea. It is interesting to note that the case of EP is the other way around, i.e., with anomalous descending motion over the tropical eastern Pacific and Indian Ocean and the warm pool, and anomalous ascending motion over the South China Sea. It is clear that those vertical circulations are associated with the anomalous longitudinal position of SHWP. We will see that those vertical circulations are also related to the tropical sea surface temperature anomalies in section 5.

4. The longitudinal position of the SHWP and the precipitation of the pre-rainy season in China

The longitudinal position of SHWP influences the precipitation in East China. Figure 6a shows the correlation coefficient between the SHWP index in the pre-rainy season and precipitation in the pre-rainy season at 730 stations in China. The correlation map clearly shows significant correlation coefficient regions over South China. The greatest coefficients are above 0.3, which are much higher than the 0.05 statistical significance level. This indicates that the precipitation in South China in the pre-rainy season increases when the SHWP extends westward. On the contrary, the precipitation decreases when the SHWP withdraws eastward.

Figure 6b shows the composite difference in precipitation in the pre-rainy season at 730 stations in China between the WP and EP of SHWP. It shows that the differences in South China are above 2 mm d^{-1}, which means that the total pre-rainy precipitation differences are above 130 mm. It is also found from Fig. 6 that both the correlation coefficients and the differences are very small in the Changjiang River valley and North

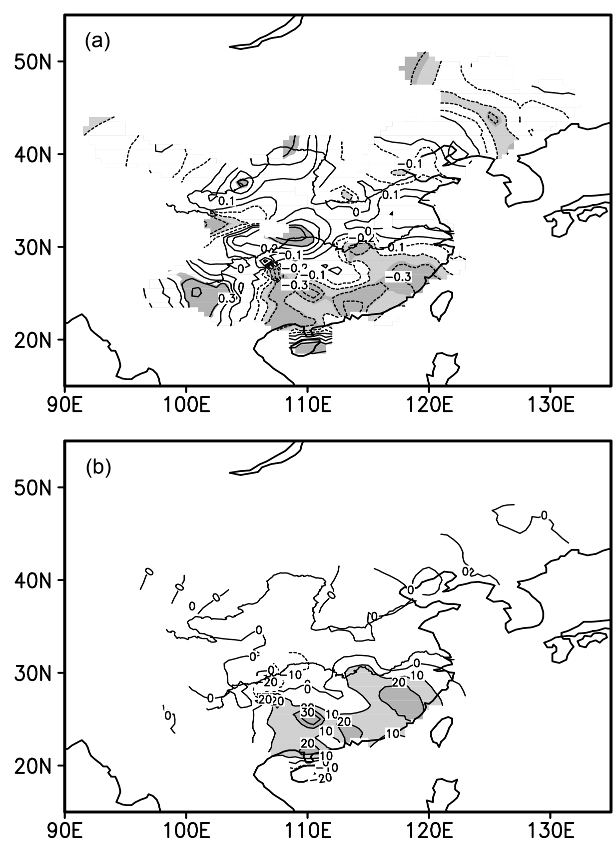

Fig. 6. (a) Correlation coefficients between the SHWP index and precipitation in the pre-rainy season (dark shading indicates t-test significance at the 0.05 level). (b) Composite difference (WP minus EP) of precipitation in the pre-rainy season (units: 0.1 mm d^{-1}).

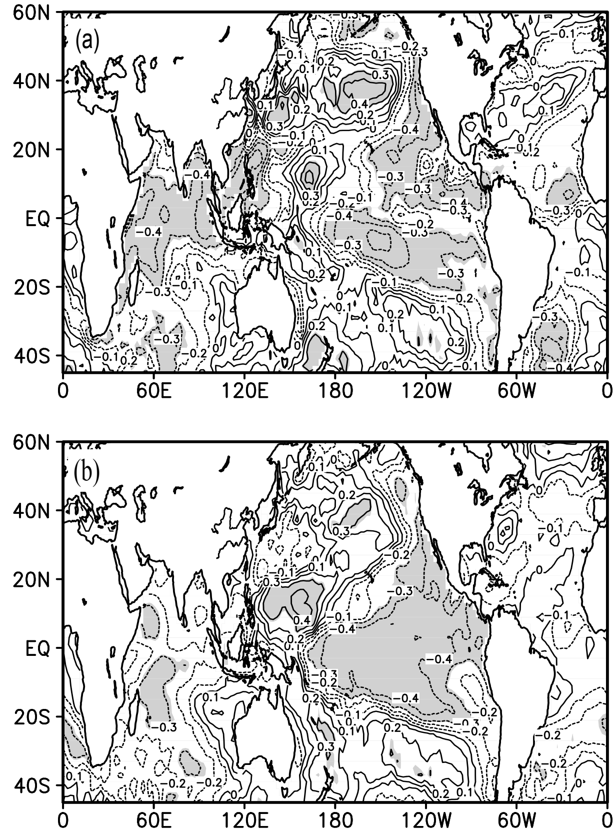

Fig. 7. Correlation coefficients (a) between the SHWP index and SSTA in May–June and (b) between the SHWP index and SST in the preceding winter (DJF). The shading shows the t-test significance at the 0.05 level.

China. This indicates that the longitudinal position of SHWP considerably influences the precipitation in South China during the pre-rainy season, which is consistent with the wind, moisture flux and vertical velocity discussed above.

5. The response of the longitudinal position of SHWP to SSTA

5.1 *Relationship between SSTA and the anomalous longitudinal position of SHWP*

The location of SHWP in the pre-rainy season in South China is rather to the south and largely over the sea region. Its anomalous position may be influenced by SST. Therefore, the correlation coefficient has been calculated to investigate the relationship between the longitudinal position of SHWP and SSTA (Fig. 7a). It can be seen that there exist three negative correlation coefficient regions of the tropical eastern Pacific, the tropical Indian Ocean and the South China Sea with a significance level higher than 0.05. This means that when the SHWP is in the WP, the SST in those three regions is higher than normal. On the contrary, in EP years, the SST is lower than normal. For the tropical western Pacific, higher (lower) SST is favorable to the eastward (westward) shift of SHWP (Chen, 1999).

5.2 *Lag response of SHWP to SSTA*

A series of lag correlation coefficients have been calculated to examine the relationship between the longitudinal position of SHWP and the preceding SSTA. Figure 7b is the correlation coefficient between the SHWP index in the pre-rainy season and the SSTA in the preceding winter (DJF). Comparing Fig. 7b to Fig. 7a, it may be found that the correlation coefficient in the tropical eastern Pacific is obviously larger than that in Fig. 7a. However, in the South China Sea and its adjacent sea region, the correlation coefficient values are smaller than those in Fig. 7a. Besides, the positive correlation exists in the tropical western Pacific with a larger magnitude and extent than that in Fig. 7a.

Actually, this kind of relationship exists early in the preceding autumn. A time cross section of correla-

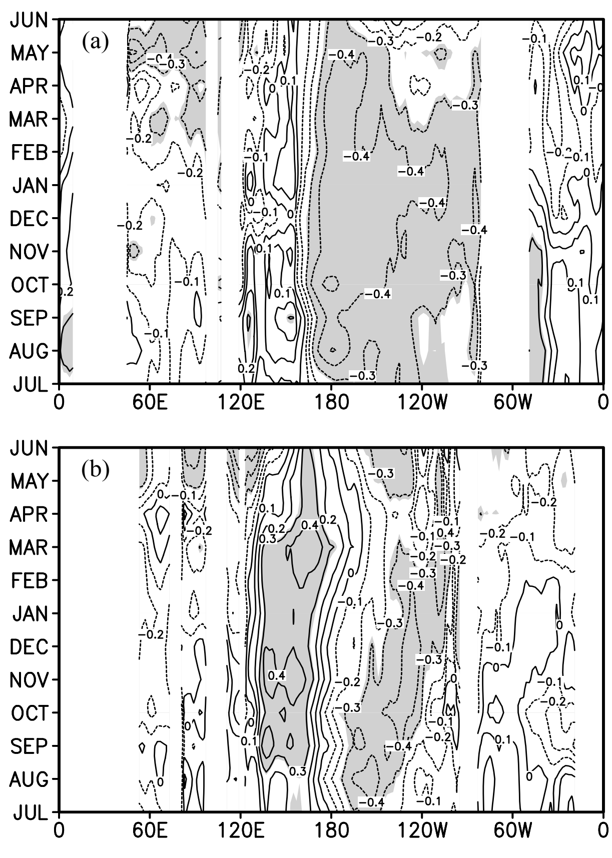

Fig. 8. Time cross sections of correlation coefficients between the SHWP index and SST along (a) 0°N, and (b) 15°N. The shading shows the t-test significance at the 0.05 level.

tion coefficient is made in Fig. 8a. It can be seen from the figure that in the tropical Indian Ocean (60°–100°E), the higher correlation coefficient values appear in the preceding spring and pre-rainy season. Negative correlation coefficients less than –0.4 appear in the preceding autumn and winter in the tropical eastern Pacific. This indicates that SST in the tropical eastern Pacific in the preceding autumn and winter may act as a good indictor for predicting the anomalous position of SHWP in the pre-rainy season. In the section along 15°N as shown in Fig. 8b, the higher correlation coefficient values occur at the South China Sea (105°–120°E) only in the pre-rainy season. However, in the warm pool region, a high positive correlation can be found early in the preceding autumn and it lasts to the pre-rainy season. This indicates that when SST is cooler (warmer) in the warm pool area in the preceding autumn to spring, the longitudinal position of SHWP in the pre-rainy season is located rather to the west (east).

From the above discussion, we may conclude that anomalous SST in the preceding seasons may serve as a good indicator to predict the longitudinal location of SHWP in the pre-rainy season. However, the effect of SSTA on the SHWP in different sea areas is different.

6. Relationship between the eastern Asian winter monsoon and longitudinal position of SHWP

As shown in the last section, the anomalous SST in the preceding winter and spring will, to a large extent, influence the longitudinal position of SHWP. Previous studies (Chen and Sun, 1999; Sun and Chen, 2000; Chen, 1999) have pointed out that SSTs in the South China Sea and the adjacent sea region near the Asian continent and the tropical Pacific in winter and spring are closely related to the eastern Asian winter monsoon. A stronger (weaker) winter monsoon will bring about lower (higher) SST in the South China Sea and the adjacent sea region near the Asian continent, and it corresponds to negative (positive) SSTA in the central and eastern Pacific and positive (negative) SSTA in the western Pacific. Therefore, there may be a certain relationship between the winter monsoon and the longitudinal position of SHWP.

Using the flow pattern at 500 hPa to describe the strength of the winter monsoon, we draw the composite chart of the 500 hPa height anomaly in the preceding winter both for the WP and EP years of SHWP (Fig. 9). In the years of WP (Fig. 9a), there are positive anomalies of height in the major trough region in East Asia indicating a weaker trough in this situation. On the contrary, in the EP years (Fig. 9b), a negative

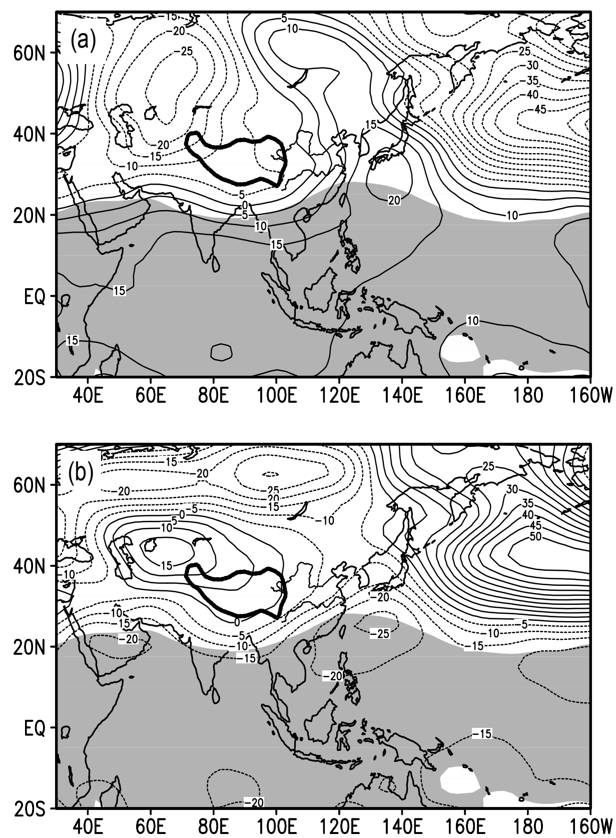

Fig. 9. Anomalious geopotential height at 500 hPa in the preceding winter for (a) WP years, and (b) EP years. Units: gpm. The shading shows the t-test significance at the 0.05 level.

anomalous height appears in the trough region showing a deeper trough. This means that when the major trough extends southward and becomes deeper, showing a stronger winter monsoon in the preceding winter, the longitudinal position of SHWP in the pre-rainy season is located rather to the east. On the contrary, a weaker winter monsoon will give rise to the WP of SHWP. This is consistent with the relationship between SST and the longitudinal position of SHWP as discussed above.

Sun and Chen (2000) and Chen and Sun (1999) used the mean v-component of the wind vector in a specific region at 1000 hPa to measure the strength of the winter monsoon. The composite charts of the anomalous wind vector at 1000 hPa in winter (DJF) both for WP and EP years are drawn in Fig. 10. In the WP years of SHWP (Fig. 10a), there are southerly anomalies from the continental coast to the Philippine Sea region indicating a weaker winter monsoon. However, in the EP years (Fig. 10b), there appears an anomalous northerly wind showing a stronger winter monsoon. This coincides with the result from Fig. 9.

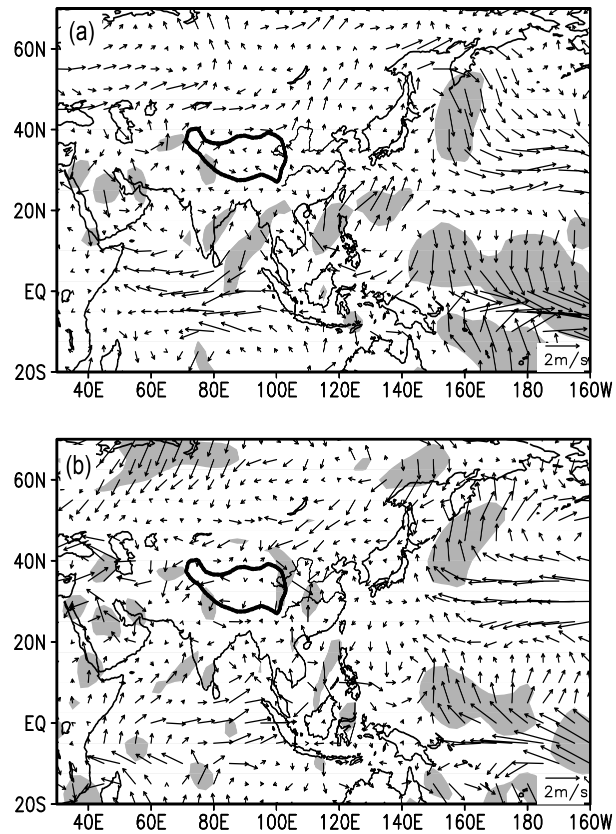

Fig. 10. Anomalious wind vectors at 1000 hPa in the preceding winter for (a) WP years, and (b) EP years. Units: m s^{-1}. The shading shows the t-test significance at the 0.1 level.

Examining the significant tests in Figs. 9 and 10, the regions where their levels reach 95% or 90% are mainly located in low latitudes. This is just the position of the subtropical high in the coming spring and summer. This implies that the impacts of the winter monsoon outbreak on the coming season largely depend on how it alters the circulation at low latitudes. This is consistent with the results about the relationship between the winter and summer monsoons given by Sun and Chen (2000).

The sensitivity experiments of Chen (1999) pointed out that a strong (weak) winter monsoon corresponds to the tropical Pacific SSTA pattern [negative (positive) SSTA in the central and eastern Pacific and positive (negative) SSTA in the western Pacific] from winter to summer. The SSTA pattern is favourable to the circulation (ascending/descending motion) over the South China Sea (SCS). The SSTA pattern creates the anomalous cyclone (anticyclone) in the western Pacific and SCS, which causes the SHWP to withdraw eastward (stretch westward). This indicates that the whole tropical SSTA pattern plays an important role in interseasonal connection of circulation and is favorable to the longitudinal movement of SHWP. Chang et al. (2000a) pointed out that a warm equatorial eastern Pacific makes the western North Pacific subtropical ridge extend farther to the west from the previous winter to the following fall, resulting in an 850-hPa anomalous anticyclone near the southeast coast of China. This is a result of the positive feedback that involves the anomalous Hadley and Walker circulations, an atmospheric Rossby wave response to the western Pacific complementary cooling, and the evaporation–wind feedback. This anticyclone induces anomalous warming of the South China Sea surface through increased downwelling. Thus, the physical mechanism on the relationship of the eastern Asian winter monsoon-SST–subtropical ridge needs further investigation.

7. Conclusions

(1) Associated with the anomalous longitudinal position of SHWP in the pre-rainy season, the flow patterns in both the middle and lower latitudes are different. The circulation is more meridional with stronger ridges and a deeper trough in Asia and the North Pacific in the year of WP. On the contrary, in the year of EP, the circulation is more zonal with weaker ridges and troughs. In the lower troposphere in the WP years, the South China quasi-stationary front is strong with an anomalous convergence zone there. However, in the EP years, an anomalous divergence appears indicating a weaker front. The anomalous vertical circulations in the tropical region and the subtropical region are also opposites.

(2) The anomalous longitudinal position of the SHWP greatly influences the precipitation in the pre-rainy season in South China. When the SHWP is in the west position, the rainfall in the pre-rainy season in South China is more abundant. However, when the SHWP is in the east position, a shortage of precipitation in that period is found.

(3) There exists a good relationship between the longitudinal position of SHWP and SST in the tropical region. A negative correlation can be found in both the central and eastern tropical Pacific and the Indian Ocean. This means that the higher (lower) SST there corresponds to a western (eastern) position of SHWP. This kind of relationship can be found even in the preceding autumn and winter. A positive correlation appears in the western and northern Pacific and large correlation coefficient values also occur in the preceding autumn and winter. In the South China Sea and adjacent sea regions near the East Asian continent,

correlation coefficients over the 0.05 significance level can be found only in the pre-rainy season.

(4) A strong (weak) winter monsoon gives rise to a cooler (warmer) SST in the Kuroshio and the South China Sea regions and corresponds to negative (positive) SSTA in the central and eastern Pacific and positive (negative) SSTA in the western Pacific in winter and the following spring. The whole tropical SSTA pattern, that is, negative (positive) SSTA in the central and eastern Pacific and positive (negative) SSTA in the western Pacific, is favorable to the EP (WP) of the SHWP.

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