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Subtropical High Anomalies over the Western Pacific and Its Relations to the Asian Monsoon and SST Anomaly①

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ABSTRACT

Using the data of 500 hPa geopotential height from 1951 to 1995, SST roughly in the same period and OLR data from 1974 to 1994, the relation between the anomalies of subtropical high (STH for short) and the tropical circulations including the Asian monsoon as well as the convective activity are studied. In order to study the physical process of the air–sea interaction related to STH anomaly, the correlation of STH with SST at various sea areas, lagged and simultaneous, has been calculated.

Comparing the difference of OLR, wind fields, vertical circulations and SST anomalies in the strong and weak STH, we investigate the characteristics of global circulations and the SST distributions related to the anomalous STH at the western Pacific both in winter and summer. Much attention has been paid to the study of the air–sea interaction and the relationship between the East Asian monsoon and the STH in the western Pacific. A special vertical circulation, related to the STH anomalies is found, which connects the monsoon current to the west and the vertical flow influenced by the SST anomaly in the tropical eastern Pacific.

Key words: Subtropical high, SST anomaly, Monsoon current, Vertical circulations

1. Introduction

It is well known that the tropical and extra–tropical circulations are linked by the subtropical high belt (STH for short). Its anomalies of intensity and position influence on the general circulation and climate variability. The study on the persistent anomaly of STH in the western Pacific in summer time shows that its anomaly not only closely connects with the anomalies of westerlies in certain regions, but also with the Indian monsoon as well as the tropical systems (Li et al., 1998; Zhuang et al., 1997). It indicates that the anomalies of circulation in subtropics must be closely related to the general circulation.

Studying the influence of El Niño on the general circulations, scientists noticed, in recent years, a certain kind of relation between the El Niño events and the position and strength of STH, especially in the western Pacific. However, the effect of El Niño with its different phases on the STH is different. Therefore, the relation between El Nino and STH is rather complicated and is not clear so far. Studying on the influence of SST anomaly at the warm pool area, Nitta (1987) and Huang et al. (1989) indicated that there existed a certain kind of teleconnection pattern in the eastern Asia to the Pacific in summer, which may strongly

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①This work is supported by the National Natural Science Foundation of China No. 49635170 and the "China–Japan cooperation Program of Asian Monsoon".

②Present addiliation: shanghai Typhoon Institute, shanghai 200030 influence the climate anomaly in those regions. The important role of SST in the Indian Ocean on the variation of global circulation is also studied by meteorologists in recent years (Chen et al., 1985).

Much attention has been paid, in present work, to the study of the variation of the strength of STH in the western Pacific, and the relationship with the tropical circulations, including the Asian monsoon as well as the convective activity. In order to study the physical process of the air–sea interaction related to STH anomaly, the correlation of STH with SST at various sea areas, lagged and simultaneous, has been calculated.

The data used are 500 hPa geopotential height H, from 1951 to 1995, and SST roughly in the same period. The Outgoing Longwave Radiation (OLR) data from 1974–1994 and wind data from NCEP/ NCAR reanalysis one are also used. Two indices are adopted to measure the strength of STH using 500 hPa height. For the STH of the Northern Hemisphere, the belt from 10–40°N is adopted for calculation. The intensity index of STH is defined as the average value of H for all the grid points where $H > 5860$ gpm. And the total number of the grid points with $H > 5860$ gpm in the domain is referred to as the area index of STH. For the STH over the western Pacific, the domain is 10–40°N, 110°E–180°, which contains the center of the high in that region, and is somewhat larger than the one used by China Meteorological Administration.

2. Interannual variation of STH in the western Pacific

The STH in the western Pacific is the most strong one, comparing to other cells. The correlation coefficients between the indices of the whole subtropical belt and the ones of the western Pacific, the Atlantic and Indian Ocean are 0.8, 0.7, and 0.7 respectively in winter, but 0.6, 0.7, and 0.4 in summer. The area and intensity of STH present every clearly year–to–year variability. Figure 1 gives the variation of STH, Fig. 1a for January and Fig. 1b for July, where the variables are normalized. It can be seen that the trends of the area index and intensity index are basically in agreement, both showing pronounced interannual variation. The magnitudes of anomalies for particular strong or weak years might exceed two standard deviations (SD). We adopted SD as a threshold, i.e. absolute departure greater than 1, to define

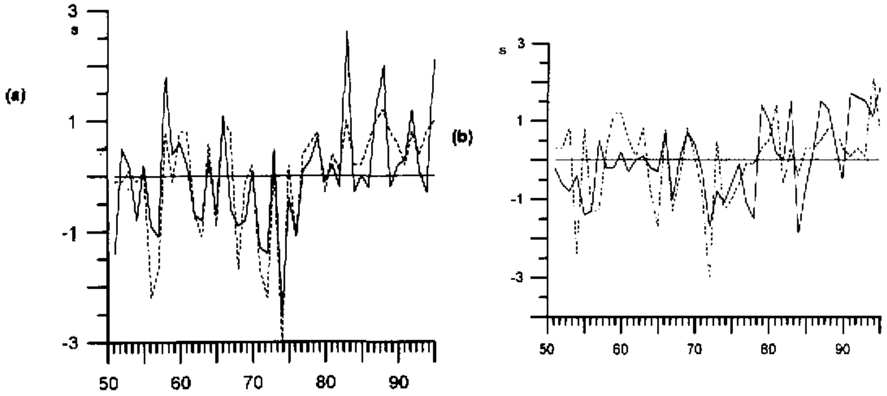

Fig. 1. Annual variation of intensity (solid line) and area (dashed line) of STH in the western Pacific. (a) January, (b) July.

strong or weak STH years. Based on this definition, composites of various elements for strong (weak) STH years could be made.

3. The relation to tropical flows and Asian monsoon

3.1. *The convection and monsoon current*

The correlation maps between the intensity of STH and OLR both in winter (DJF) and summer time are given in Fig. 2. In winter, there exist a strong negative correlation coefficient center in the tropical central and eastern Pacific and a positive one in the western Pacific. It means that a stronger STH in the western Pacific is accompanied with stronger convection in the tropical central and eastern Pacific. However, in the warm pool area, the convection is

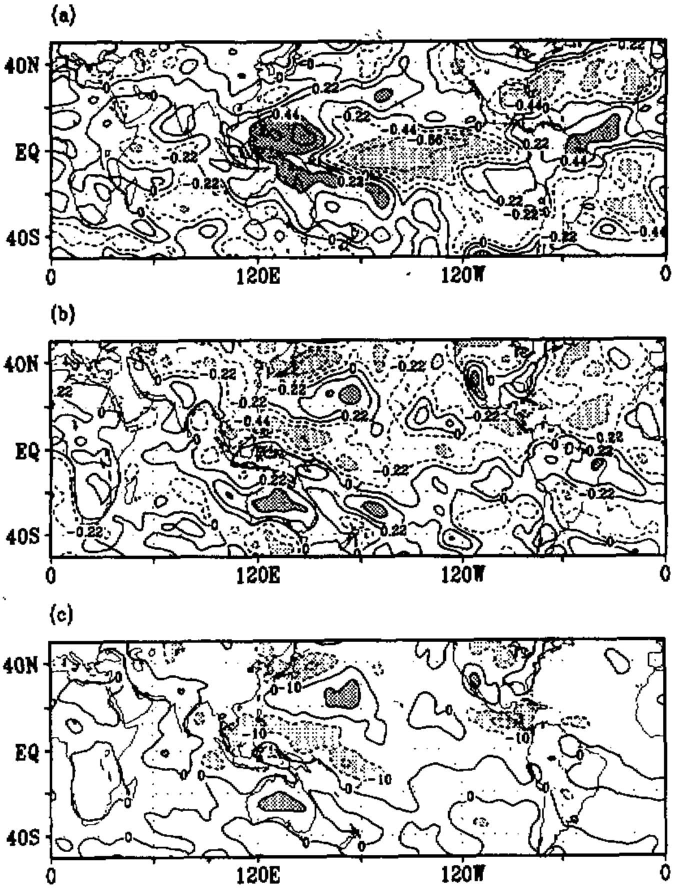

Fig. 2. The correlations between the intensity of STH in the western Pacific and OLR. (a) January, (b) July. (c) Difference between strong and weak STH in July. The areas reaching the requirement of significant level of 95% are shaded.

weaker. This result differs from the one in summer, which we are familiar to.

In summer (Fig. 2b), a negative belt encircles the whole tropic regions. The most strong area locates from the South China Sea to about 160°E with correlation coefficient values lower than −0.66. It indicates a stronger convection in the tropical western Pacific connected to the strong STH, in line with the result given by Nitta (1987). The difference map of strong and weak cases (Fig. 2c) shows a positive center over the STH region indicating a stronger high there, and a negative belt covering the whole tropics. Noticing the Asian monsoon regions, we may find that in East Asia, the difference of OLR is negative, but in the Indian Peninsula, it is positive. It means that in the stronger STH years, the East Asian monsoon will be stronger but the Indian monsoon weaker.

Analyzing the composite of low level wind fields for the strong and weak cases of STH in the western Pacific and making their difference map (Fig. 3), we find that there appears a southerly current over the coastal area of the eastern Asian continent in winter, showing a weaker winter monsoon in the stronger STH situation. A wind convergence occurs in the tropical eastern Pacific associated with the negative departure of OLR indicated in Fig. 2. However, in the tropical western Pacific, divergence prevails showing a weaker convection.

In summer (Fig. 3b), the cross-equatorial currents east of 100°E are stronger than normal, but the ones in the East Africa are much weaker for strong STH. Therefore, the southerly winds in the East Asian monsoon area as well as the south side of the Meiyu front are considerably stronger. On the contrary, in the weak cases, there appears a region of anomalous southerly winds in the Somali area, and a westerly wind departure from Indian Peninsula to the Bay of Bengal, showing a stronger Indian monsoon. However, an anomalous northerly wind current is found in the East Asia region indicating a weaker East Asian monsoon consistent to the result from OLR analysis.

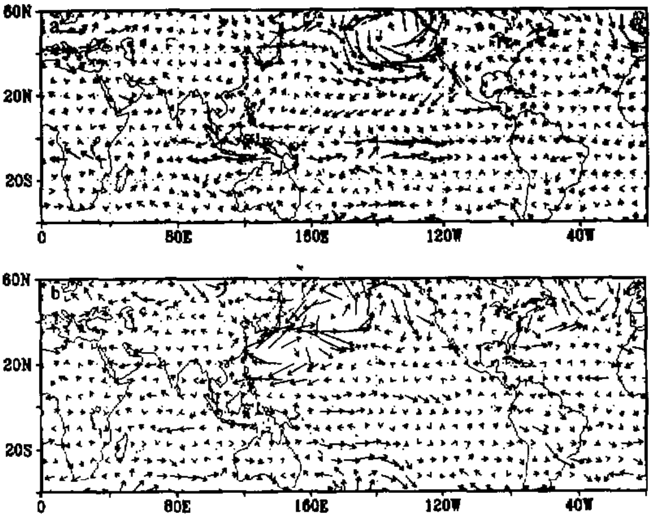

Fig. 3. The difference map of wind vectors at 850 hPa. (a) winter, (b) July.

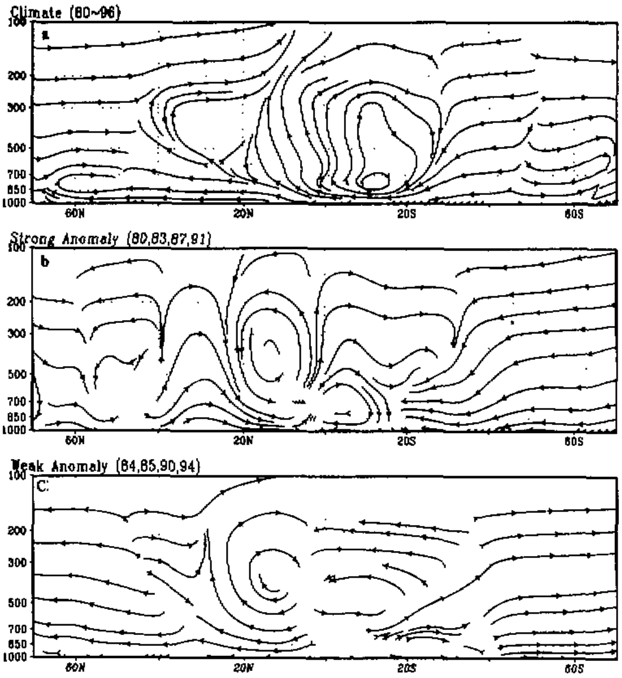

Fig. 4. Local Hadley cells averaged in 140°E–180° in July. (a) Mean map of 1980–1996, (b) composite departure for strong STH cases, (c) for weak cases.

3.2 *Comparing study of vertical circulations*

3.2.1 *Hadley cell*

The Hadley and Walker circulation are calculated for illustrating the difference of the wind fields both in tropics and subtropics.

Using the wind data from 1980 to 1995, we made a set of meridional cross–sections averaged for 140°E to 180° in July. Fig. 4a is the mean circulation showing a clear Hadley cell with the ascending branch in summer hemisphere and descending in winter hemisphere. Figs. 4b and 4c are the composite departure maps for the strong STH and the weak years respectively. In the strong STH years (4b), a descending current occurs in the subtropical region *near 15–35°N, and an ascending one over tropics. Comparing with Fig. 4a for the mean* circulation, one may find that the shape of the vertical circulations is totally different. But in the weak cases (Fig. 4c), the departure circulation shows an opposite direction to the strong one. A strong ascending departure current appears over the subtropical region, and a downward flow over the tropics and the Southern Hemisphere.

Another cross–section averaged in the region of 115–140°E representing the west side of STH is made for comparison (not shown). It is interesting that whether for strong or weak cases, an upward current covers the whole subtropical regions. It is well known that the summer eastern Asian monsoon, which brings about a strong convergent ascending flow, dominates the west side of STH. The descending flow connecting the strong STH is confined to the central Pacific.

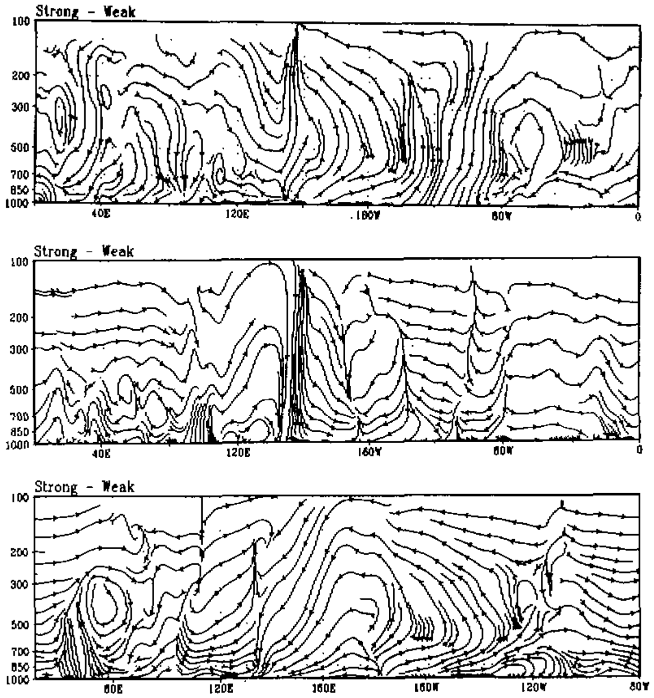

Fig. 5. Difference zonal circulations between strong and weak STH. (a) Averaged for 0°–10°N, (b) for 15–35°N, (c) inclined from tropics to subtropics (see text).

3.2.2 *Longitudinal circulation*

Three zonal cross–sections are made for different latitudes to examine the STH circulation in larger scale. Fig. 5a shows the vertical cross–section of wind difference between strong and weak cases in July, averaged for 0°–10°N. The upward difference current covers from the eastern Pacific to about 140°E and a very narrow belt with downward motion appears around 120°E, indicating a roughly opposite Walker circulation strong STH years.

Examining the cross–section in subtropical area (15–35°N) in Fig. 5b, we can find, in the mean map (not shown), a strong upward current dominating the whole Asian monsoon region, and downward flows both in the eastern Pacific and Indian Ocean also showing a similar Walker circulation. However, for the strong or weak subtropical high situation, a remarkable change of the circulation occurs. Fig. 5b gives the difference circulations between the strong and weak cases. A strong descending current appears over the subtropical Pacific region with the center near 160°E, which is just the center of STH in the Pacific. The ascending branch occurs to the west, where just lies in the East Asian monsoon region, constructing a specific vertical circulation. It indicates that when the STH in the western Pacific is stronger, a vertical anomalous circulation over the western Pacific region occurs with the upward branch over the East Asian monsoon area and the downward one over the center of STH. The circulation in the weaker STH takes an opposite direction. This illustrates a characteristic of interaction between the East Asian monsoon and STH in the western Pacific.

In the Indian monsoon area, there is a weaker descending difference current indicating a strong STH in the western Pacific accompanied with the weaker monsoon, consistent with the results in OLR analysis.

Combining Figs. 5a and 5b, we drew a new cross-section of wind flow difference to link the vertical zonal circulations both in tropics and subtropics. The cross-section starts from 20°S, 50°E in the Indian Ocean, to 30°N, 120°E, roughly the position of the center of the STH, then turns southeastwards ending at 20°S, 80°W of the tropical eastern Pacific. The difference wind flow in Fig. 5c shows that for strong years, the anomalous circulations show an opposite Walker circulation with the descending branch near 120–160°E region, associating with the stronger STH there, and ascending ones both at the tropical eastern Pacific and the western Indian Ocean. On the contrary, for the weak years, the descending branches are located at the western Indian Ocean and tropical eastern Pacific respectively, and the ascending branch appears in the western Pacific, constructing an extra positive Walker circulation.

4. The response of STH to the SST anomalies

4.1 *Relation between the intensity of STH and SST anomaly*

The anomaly of STH is closely related to the variation of SST. The contemporary and lagged correlation coefficients between the strength of STH and SST both in winter (DJF) and summer (see Figs. 6a and 6b) are calculated. There exist three key regions with higher positive correlation coefficient values over tropics whether in winter or summer. They are in the tropical central and eastern Pacific, Indian Ocean and West Atlantic Ocean repectively. In the first one, the maximum value of correlation coefficient reaches 0.56, much higher than the needs of significant level of 99%. It means that the strong STH in the western Pacific may be accompanied with the positive SST anomalies in the tropical eastern Pacific, no matter it occurs in winter or summer. The second positive center locates from the Indian Ocean to the Bay of Bengal. One may conclude that during the stronger STH years, the positive anomalies of SST in those two regions may bring about a stronger convection and an additional ascending current constructing an opposite Walker circulation, consistent with the analysis above.

The difference of the correlations between winter and summer occurs in the region from the South China Sea to the western Pacific. In winter, a positive correlation belt extends from the South China Sea to the Kuroshio Current regions. It implies that a stronger STH may bring about stronger southerly wind over the west coast of the Pacific accompanied with the eastward movement of the major trough, which, in turn, results in a weaker winter monsoon in the eastern coast of Asia continent, and the less drop of the SST over the coast area. In summer, the correlation between SST and STH is positive in the western Pacific, but only the area from the South China Sea to about 120°E reaches the requirement of the significant level of 95%.

Comparing Fig. 6 to the vertical circulation across the STH in Fig. 5, we may find that two upward currents in the strong STH situation are just at the regions with positive SST anomalies. In the weak cases, there are the downward flows accompanied with the negative SST anomalies. Therefore, the remarkable change of the zonal vertical circulations corresponding to the strong and weak intensity of STH respectively, is closely related to the SST anomalies in the tropical regions. It is interesting that the anomalous ascending flow

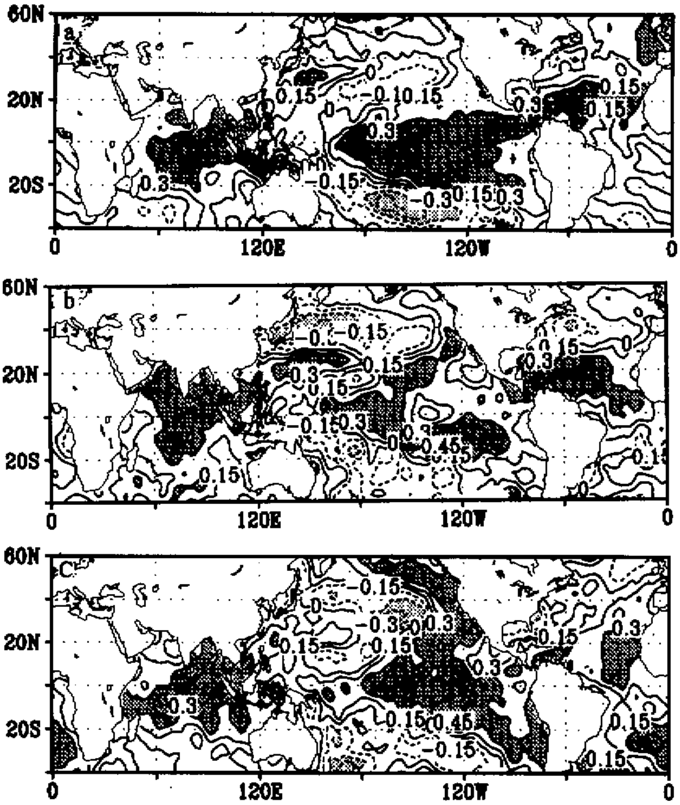

Fig. 6. The correlation between STH and SST. (a) winter (DJF), (b) July, (c) lagged correlation between STH in July and SST in April.

associated with the positive SSTA at the tropical eastern Pacific turns westward then descends not mainly in the tropical latitudes, but in the subtropics, maintaining and strengthening the intensity of the STH. For the weaker STH cases, by contrast, the anomalous ascending currents appear over the center of STH and the downward ones over the tropical eastern Pacific, associated with colder SST there.

4.2 *The lagged correlation between STH and SST*

The correlations between the intensity of STH in the western Pacific in summer and the SST both in preceding winter and spring are examined month by month. There appear three main regions, similar to the contemporary correlations. However, the values of the correlation coefficients change from month to month. Fig. 7 is the time cross–section of lagged correlation coefficient averaged in the latitudes of 10°S–10°N in July. The horizontal line indicates the simultaneous correlations. It is clear that for the main two positive areas, the maximum values appear in the period from April to June for the Indian Ocean and March to May for the tropical eastern Pacific. It means that the response of the intensity of the STH has a seasonal lag to the SST variations. For the STH in summer, the variation of SST both in

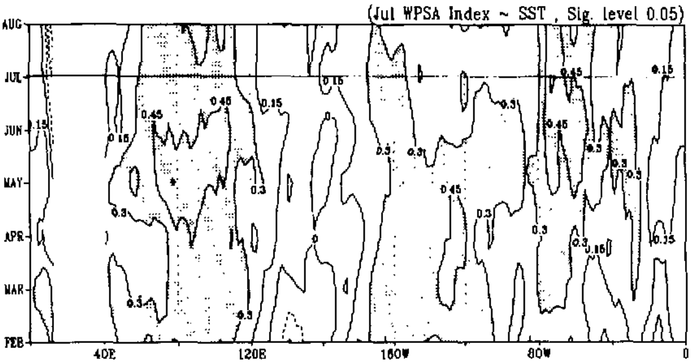

Fig. 7. The cross-section of lagged correlation between STH in July and SST averaged in 10°S–10°N. The horizontal line shows the simultaneous correlations for July.

preceding winter and spring may highly influence the anomaly of STH.

It has been discussed above that there exists a positive simultaneous correlation between the STH and SST in the western Pacific. In the preceding spring (see Fig. 6c), there exists a positive region from the South China Sea to the western Pacific, and a smaller negative one over the central Pacific. However, from Fig. 7 we may find a negative center to the east of 120°E from the preceding December to February. It indicates that the influence of SST in the warm pool area on the STH varies from winter to summer. This result is consistent to the analysis of OLR above.

5. Concluding remarks

(1) The variation of STH in the western Pacific dominates an important part in the anomalies of the STH in the northern subtropical belt. A strong STH in the western Pacific is accompanied with a strengthened ITCZ and stronger convection especially in the tropical western Pacific. However, there is a weaker convection at the Indian monsoon area. In winter, the negative departure of OLR corresponding to the strong STH is over the tropical eastern Pacific where the convergence of wind prevails.

(2) There is close relationship between the variation of the STH and SST. Areas of high positive correlation have been found between the intensity of STH and SST. They are located at the equatorial middle and eastern Pacific with highest correlation and large extension, the Indian Ocean and the tropical Atlantic. The correlation clearly appears in preceding winter, reaches its peak largely in spring and becomes weak in the current month. Generally, the persistent SST anomalies from winter to spring in those area would have a pronounced effect on the STH in summer.

(3) The longitudinal vertical cell associated with the STH of the western Pacific appears to be a kind of tropical–subtropical linked circulation. In the years of strong STH, there are anomalous ascendings over the equatorial eastern Pacific, Indian Ocean and the Asian monsoon region as well. They have a common descending area, i.e, the location of the western Pacific STH. While in the year of weak STH, the direction of the anomaly cell is just reverse, which means that the classic Walker circulation is not that typical. The vertical circulation as-

sociated with strong western Pacific STH might be described as follows. To the east, the anomaly ascending flows due to the SST anomalies at the equatorial eastern Pacific turn to the west and descend at the subtropical area. To the west of the STH, the intensified upward branch over the eastern Asian monsoon region descends at the Pacific region to the east. These two cells jointly form an anti–Walker type diverse from normal circulation. The anomaly vertical circulation for the weak STH years is reverse.

(4) In their studies on the formation of STH over North Africa in summer, Hoskins et al. (1995) posed that it is the combined effect of latent heating due to the Asian monsoon and the westerlies Yu and Yang (1995) also stressed that the secondary circulation led by the Asian monsoon rain belt may play an " inducing role" in the activity of the western Pacific STH. This point of view is in good agreement with the present analysis. Our work has shown that the classic Hadley cell is rather weak in summer. And it is only in the year of strong STH that there would be narrow anomaly descending flow over the central Pacific. Therefore, it may be concluded that the Asian monsoon system and SST anomalies play an indispensable role in the maintenance and variability of the subtropical high.

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