The Study on the Interannual Variation and the Mechanism of the South China Sea Monsoon①

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ABSTRACT

By using the USA NCAR / NCEP reanalysis data, the characteristics of climatic elements and the temporal and spatial structures of precipitation in the strong and weak years of the SCS monsoon are analyzed, the mechanism of the interannual variation of the SCS monsoon is discussed. It is found that the climatic elements in SCS have great differences, and there are great differences in the spatial and temporal structures of the precipitation anomalies between the strong and weak monsoon years. The variation of climatic elements in the south of Indochina Peninsula in April is a good index of the strength of the SCS monsoon. There is a good connection between the SCS monsoon and the sea surface temperature. The SCS monsoon is weak in the EL Nino years, and strong in the La Nina years. The strength of the SCS monsoon depends on the local heating differences between the eastern continent of China and the western Pacific. It depends on the intensity and the position of the western Pacific Subtropical High. The western Pacific Subtropical High is weak and eastward in the strong monsoon years, and the case is reversed in the weak monsoon years.

Key words: South China Sea monsoon, Strong monsoon year, Weak monsoon year, Wavelet analysis

1. Introduction

The onset of the South China Sea (SCS) monsoon is a sign of the coming of the Asian monsoon. In average, the onset of the SCS monsoon is in the middle of May, but its strength and the onset date differ greatly from one year to another. The anomalies of the SCS monsoon highly depend on not only the precipitation in SCS, but also the anomalies of the circulation in the world. Why is the monsoon onset earliest in SCS? What is the mechanism of the onset and its variation? This is a scientific problem that is interested in by meteorologists both at home and abroad.

Tao and Chen (1987) studied the temporal distribution of the onset of the East Asian monsoon, and proposed that in the variation of Asian monsoon, the earliest onset was that of summer monsoon in SCS, around mid–May, and the onset of Indian monsoon is about mid–June, which is one month later than the onset of the SCS monsoon. Chen et al. (1996) have studied the variation characteristic of convective cloud cluster during the onset period of the SCS monsoon, and found that the onset of the SCS monsoon was related to the first time

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westward movement of the strong convective cloud which moved into SCS from the warm pool of the western Pacific. The onset of the SCS monsoon closely interrelates to the ENSO event. The year with not clear onset of the SCS monsoon is mostly the El Nino year, and in the year when the equatorial eastern Pacific is cold, the convective cloud over SCS jumps northward obviously with the strong convection. Lau et al. (1997) focused on the sudden onset of the SCS monsoon and its relation to the atmospheric and oceanic processes in the entire Asian monsoon region, found that the onset of the SCS monsoon was abrupt, accompanied by substantial changes in the large scale atmospheric circulation and sea surface temperature in the adjacent oceans. Xie et al. (1996) indicated that the establishment of the SCS summer monsoon was caused by the SCS and western Pacific systems. Around the onset, the outstanding feature of the SCS circulation system was the weakening and retreating eastward of the western Pacific Subtropical High in the SCS region in the lower troposphere. Jin et al. (1996) investigated the interannual variations of the convective changes in the East Asian monsoon area, showed that there existed a significant interannual variation of convective activities over SCS.

By using the global pekad precipitation rates, monthly u component winds and pekad surface air temperatures of the USA NCAR / NCEP reanalysis data for the 17–year period from 1979 to 1995 (in which the temperatures in 1990 are missing), the interannual variations of the SCS monsoon and its mechanism are discussed in this paper. The zonal resolution of the data is transformed from $1.875° \times 1.875°$ into $2° \times 2°$ with binary linear interpolation. The studying area is 30–180°E, 10°S–40°N. In Section 2, the strength of the SCS monsoon is defined. In Section 3, the characteristics of climatic elements in the strong and weak years of the SCS monsoon are analyzed. In Section 4, the temporal and spatial structures of precipitation in the strong and weak years are showed. In Section 5, the relation between the SCS monsoon and ENSO is discussed.

2. The definition of the SCS monsoon strength

The strength and the onset date of the SCS monsoon are different from year to year. The strength of the SCS monsoon closely relates to the southwest wind, and accompanies the

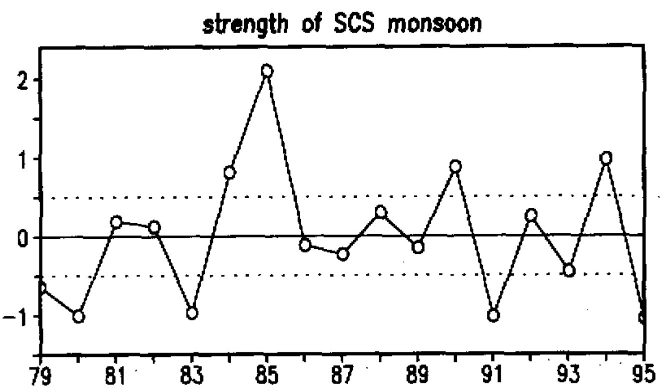

Fig. 1. The strength of the SCS monsoon from year to year.

development of convection. So, when considering the monsoon strength in every year, we select the u component winds and the precipitation in May and June in the SCS region to compute the following factors: (1) the maximum u–wind, (2) the sum of the westerly winds ($u>0$), and (3) the sum of precipitation in the region.

We define the SCS monsoon strength index as the average of above three factors, which have been standardized by variance. According to the strength index, we get the variations of the index in SCS from 1979 to 1995 (see Fig. 1). Fig. 1 shows that the monsoons in the years of 1984, 1985, 1990, 1994 are strong, while in the years of 1980, 1983, 1991, 1995 are weak, and in other years are normal.

3. The differences of climatic elements between strong and weak monsoon years

3.1 *Precipitation*

Fig. 2 shows the composite patterns of precipitation anomalies in SCS before the monsoon onset (April and the first pekad of May), during the monsoon onset (the second and the last pekad of May and the first pekad of June) and after the monsoon onset (the second and the last pekad of June) in the strong and the weak monsoon years. It is seen that before the monsoon onset, there are almost positive anomalies in SCS in the strong monsoon years, the weak negative anomalies are only located in 115–120°E, 5–10°N. The positive anomaly center is at the SCS basin and the south of the Indochina Peninsula. There are negative anomalies in the north of the Indochina Peninsula and the southeast of China mainland. It is reversed in the weak monsoon years. Thus, the most difference between the strong and the weak monsoon years (the strong years minus the weak years S–W) is in the Indochina Peninsula, with the positive deviation center in its southern and the negative center in the northern. In addition, there is a positive deviation center in the SCS region and the South China coastline, north of which is the negative deviation center. During the monsoon onset, in the strong monsoon years, there are negative anomalies in northeast SCS, positive in southwest SCS, with a center at the southern SCS. In the weak monsoon years, there are negative anomalies except the northeast of SCS. At this time, the difference comes out at the southern SCS, in which the precipitation in the strong monsoon years is much more than that in the weak monsoon years, and there is less precipitation in northeast SCS. After the monsoon onset, in the whole SCS region, there are large positive anomalies in the strong monsoon years, and large negative anomalies in the weak monsoon years with centers near 15°N, 118°E. Therefore, there is a great positive center in the difference diagram.

The above analysis shows that before the monsoon onset, in the strong monsoon years, the precipitation over the land is less, which benefits the arise of the temperature over the land, at the same time, the precipitation over SCS is more, thus there is a great temperature difference between the land and the sea. In the weak monsoon years it is contrary. This is consistent with the result of the surface air temperature anomalies discussed in the following section.

3.2 *Surface air temperature*

Fig. 3 shows the composite patterns of the surface air temperature anomalies in SCS before the monsoon onset, during the monsoon onset and after the monsoon onset in the strong and the weak monsoon years. Before the monsoon onset, in the strong monsoon years, there are positive anomalies in the north of SCS, and negative in the Indochina Peninsula and the

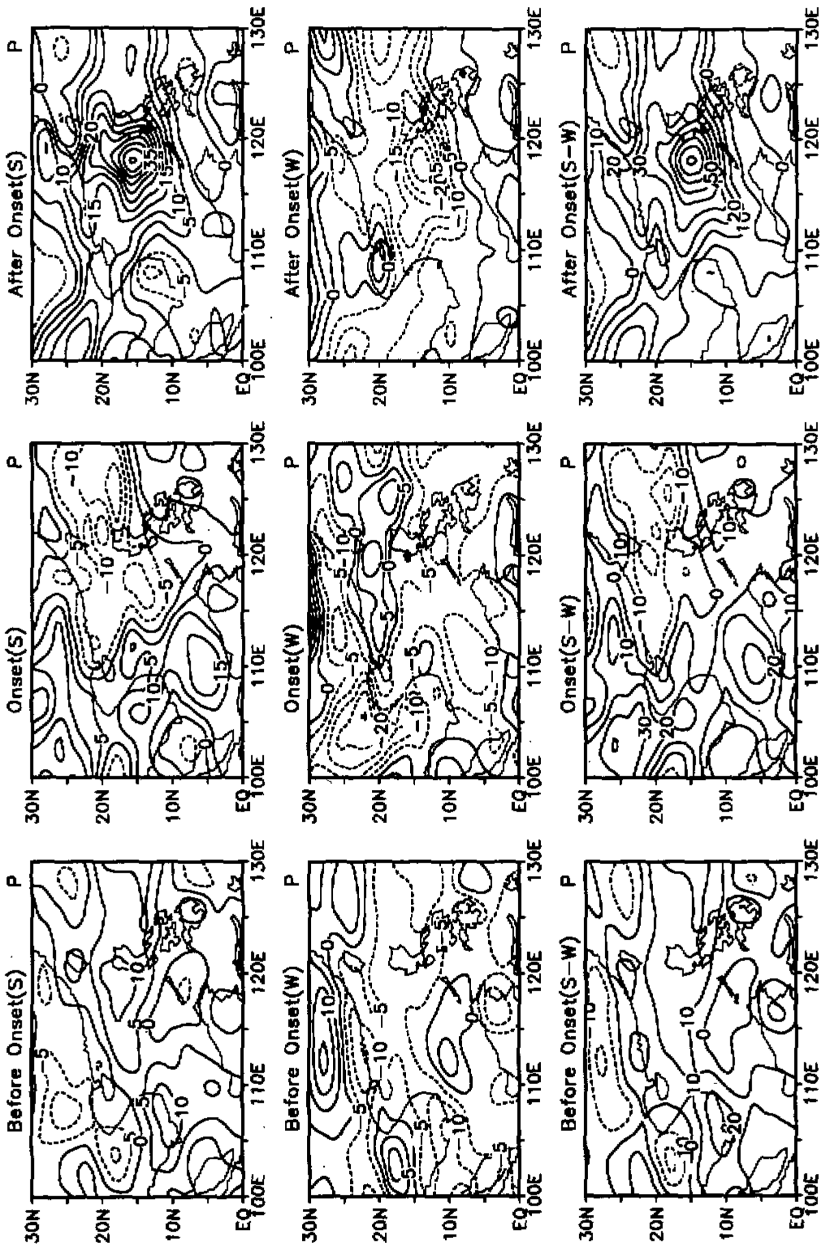

Fig. 2 The pekad precipitation anomalies in strong and weak monsoon years and their differences (unit: mm) before monsoon onset (left column), during monsoon onset (middle) and after monsoon onset (right column) (S: strong, W: weak, S-W: the difference of strong and weak).

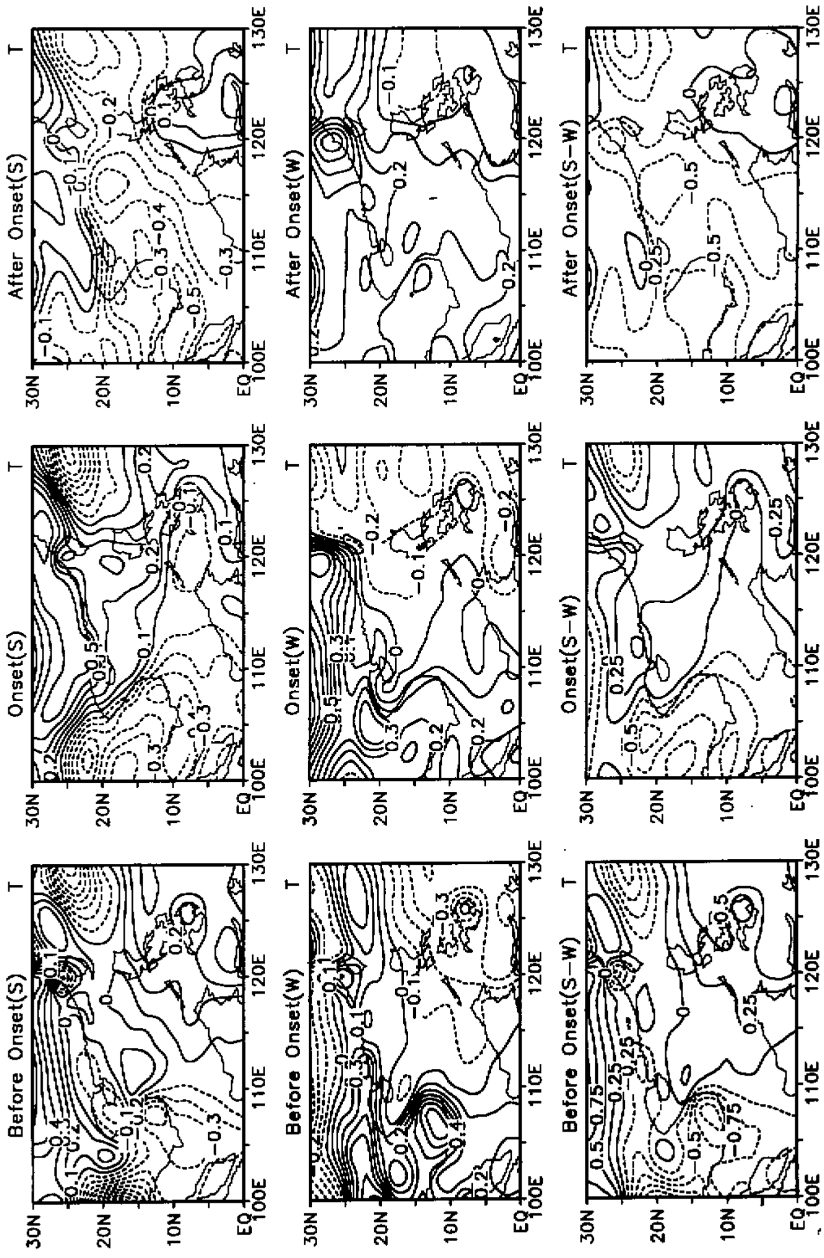

Fig. 3. Same as Fig. 2 except for the surface air temperature (unit: (°C)).

south of SCS. The negative center is over the western Pacific and the positive center in Southeast China. In the weak monsoon years, except the middle of SCS, over all of SCS is positive, the centers are in the north and the south of the Indochina Peninsula and the western Pacific. There are two strong negative centers in the difference figure, one is in the south of the Indochina Peninsula and the other is over the western Pacific. During the monsoon onset, in the strong monsoon years, the positive is in northeast SCS, and negative in southeast SCS and the western Pacific. In the weak monsoon years, it is just contrary. After the monsoon onset, there are large area negative anomalies in the strong monsoon years, while positive in the weak monsoon years. The largest difference between the strong and the weak monsoon years is over the western Pacific.

As stated above, before the monsoon onset, when the temperature anomalies to the north of 25°N in the east of China are positive, and those over the western Pacific are negative, then the strong monsoon is coming, otherwise the weak monsoon is to come. This indicates that the strong or the weak SCS monsoon is mostly affected by the local thermal difference between the east land of China and the adjacent western Pacific.

3.3 *Wind*

Fig. 4 presents the composite patterns of the u–component anomalies in SCS before the monsoon onset, during the monsoon onset and after the monsoon onset in the strong and the weak monsoon years. Before the monsoon onset, in the strong monsoon years, there are large area positive anomalies in the middle and the south of SCS. The center is in the middle of SCS. There are weak negative anomalies to the north of 20°N, and the negative center is over the western Pacific. It is just opposite in the weak monsoon years. The negative anomalies are in the middle and the south of SCS, and the absolute values of the negative anomalies in the south of SCS are larger. There is a positive center over the western Pacific to the north of Taiwan. Therewith, the obvious difference between the strong and the weak monsoon years is in the middle of SCS before the monsoon onset. The easterly current in this region in April is rife. In the strong monsoon years, the easterly current is weaker, which is against the enhancing and extending westward of the western Pacific Subtropical High. In the weak monsoon years, the easterly current is stronger, which indicates that the western Pacific Subtropical High is stronger in the weak monsoon years than that in the normal years. During the monsoon onset, in the strong monsoon years, the positive anomalies of westerly winds present in the middle and the southern SCS, and the center is in the southern. There are negative anomalies in the northern SCS, and the negative center is over the western Pacific. In the weak monsoon years, there are negative anomalies in whole SCS, and the center is to the south of the Indochina Peninsula. The strong monsoon years, comparing to the weak monsoon years, have stronger westerly winds in the southern SCS, especially to the south of the Indochina Peninsula, and stronger easterly winds over the western Pacific. After the monsoon onset, in the strong monsoon years, there are very strong positive anomalies in whole SCS, and the center is in the middle of SCS. In the weak monsoon years, there are negative anomalies in the whole region, and the center is also in the middle of SCS. The westerly winds in the strong monsoon years are much stronger than those in the weak monsoon years.

Thus it can be seen that if the western Pacific Subtropical High is weaker and locates in the east in the April before the monsoon onset, it will be the strong monsoon year, if the western Pacific Subtropical High is stronger and extends to the west, it will be the weak monsoon year. Therefore, the strong or the weak SCS monsoon is primarily related to the position and the strength of the western Pacific Subtropical High.

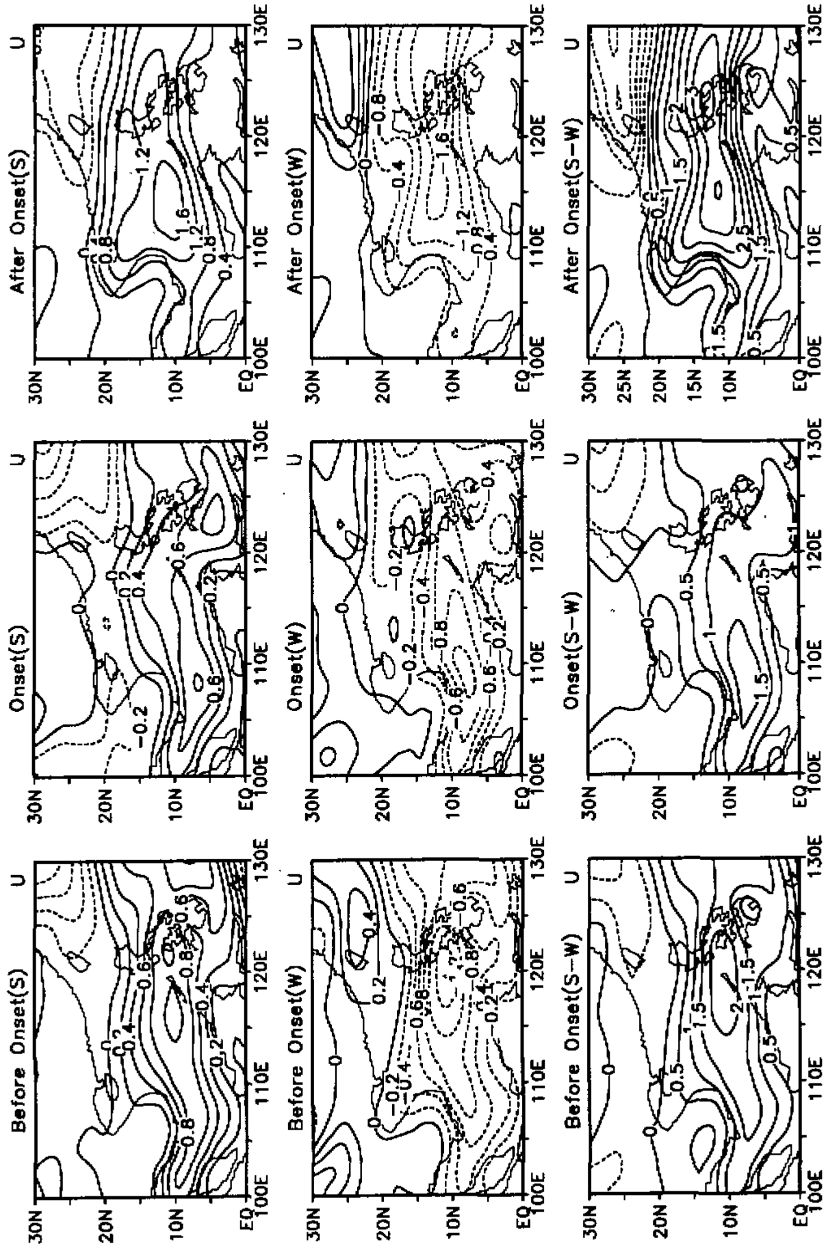

Fig. 4. Same as Fig. 2 except for the u-component wind (unit: m s^{-1}).

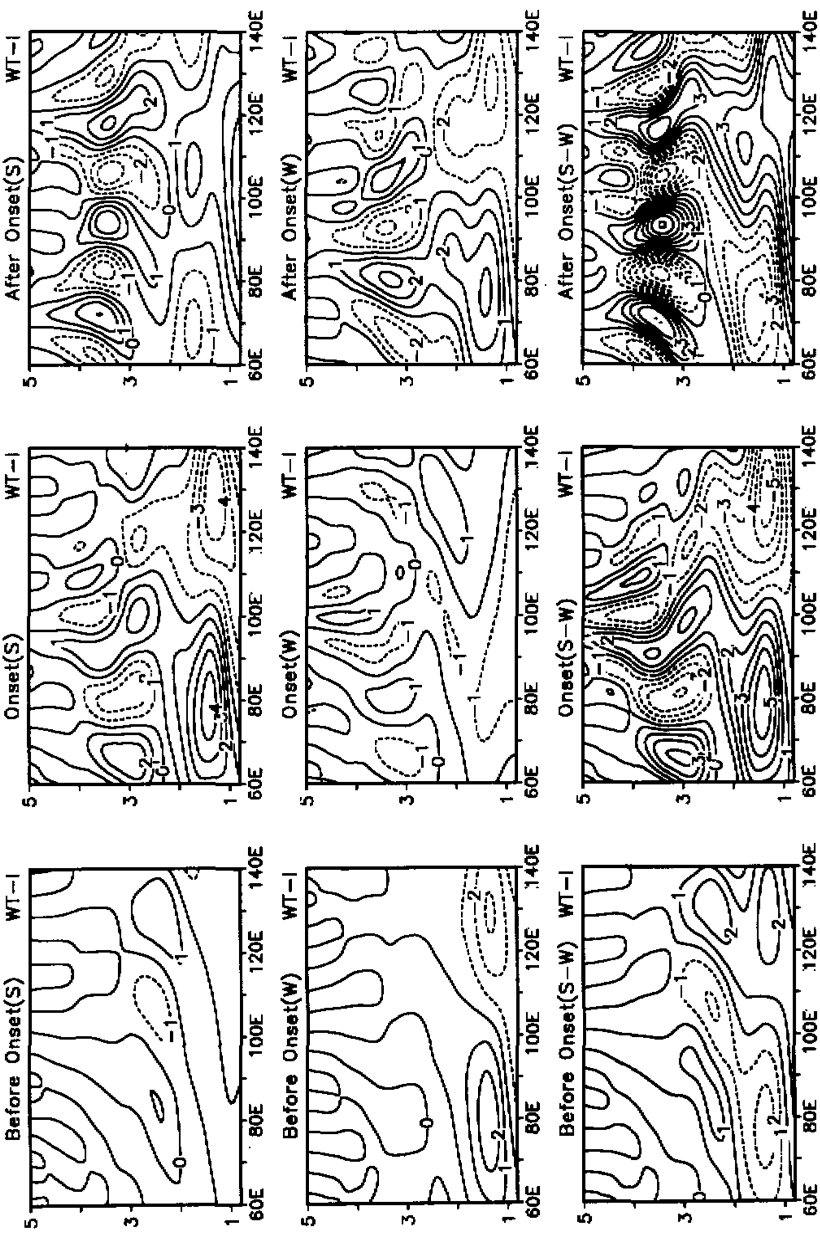

Fig. 5. Same as Fig. 2, but for the wavelet transformation coefficients of precipitation anomalies in SCS, the abscissa is longitude, ordinate is the spatial scale of wavelet transformation, 1 = 128 latitudes, 2 = 64 latitudes, 3 = 32 latitudes, 4 = 16 latitudes, 5 = 8 latitudes.

4. The differences of the precipitation structures between the strong and the weak monsoon years

In order to understand the differences of the precipitation structures between the strong and weak monsoon years, we perform the wavelet analysis of precipitation anomalies averaged along latitudinal circles and the anomaly time serial in SCS.

4.1 *Spatial structure*

Fig. 5 presents the composite patterns of the spatial wavelet transformation coefficients of precipitation anomalies before the monsoon onset, during the monsoon onset and after the monsoon onset in the strong and weak monsoon years. Before the monsoon onset, in the strong monsoon years, the spatial variations of precipitation anomalies are small, the main variation is the precipitation with 32–64 latitudes, which is stronger to the east of 115°E, weaker to the west of 115°E. There are great differences between the weak monsoon years and the normal years. The most difference is on 64–128 latitudes scale. Taking 100°E as the boundary line, the precipitation is weak to the east, and strong to the west. The chief differences between the strong and weak monsoon years are as follows: the large scale precipitation with 64–128 latitudes scale to the east of 100°E (the SCS region) in the strong monsoon years is stronger than that in the weak monsoon years, and it is opposite in the west. As for 32–64 latitudes scale, the precipitation is separated by 115°E, strong in the east and weak in the west in the strong monsoon years. During the monsoon onset, the precipitation in SCS on various scales is weaker in the strong monsoon years than that in the normal years, especially to the east of 110°E, and it is stronger at 90–100°E. There is a little difference between the weak years and normal years. On 64 latitudes scale, there are positive anomalies to the east of 110°E, negative to the west. Generally, in the strong years, it is weaker to the east of 100°E, stronger to the west. The maximum difference of the precipitation on 32 latitudes scale is at 60–90°E, and that of 16 latitudes is at 80–110°E. After the monsoon onset, in the strong monsoon years, the positive anomalies on 128 latitudes scale are at 65–135°E, those on 64 latitudes scale are at 90–130°E, and those on 16–32 latitudes scale are at 65–75°E, 90–100°E and 115–125°E. The variations on 16–32 latitudes scale are very strong at 60–140°E. In the weak monsoon years, the structures of precipitation are just reverse. The main differences between the strong and weak monsoon years are on two scales, one is large scale (64–128 latitudes scale), the other is middle scale (16–32 latitudes scale). There are the positive differences on

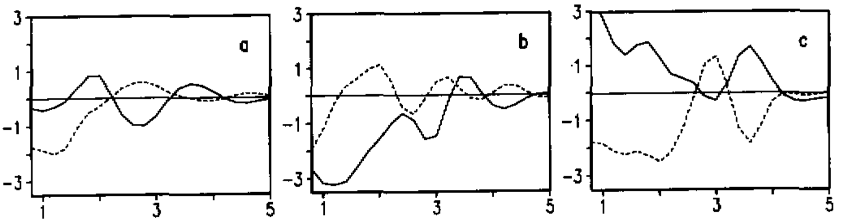

Fig. 6. The wavelet coefficients on various scales in SCS (112–116°E) before the monsoon onset (a), during the monsoon onset (b) and after the monsoon onset(c). abscissa: spatial scale (see Fig. 5), ordinate: the wavelet coefficient. solid line: strong year. dashed line: weak year.

the large scales in SCS, but on the middle scale, there are positive differences in the east of SCS (east to the 110°E), negative in the west. That is to say, the middle scale precipitation in the east and the west of SCS is in opposite phase.

To compare the difference of the spatial scale of the precipitation in SCS in the strong and weak monsoon years, the wavelet coefficients with various scales in SCS (112–116°E) before the monsoon onset, during the monsoon onset and after the monsoon onset are shown in Fig. 6. Before the monsoon onset, the most differences are on 32 latitudes scale and 64 latitudes scale. The precipitation is mostly on the middle scale (32 latitudes) in the weak years, the larger scale (64 latitudes) and the smaller scale (16–32 latitudes) in the strong years. During the monsoon onset, the stronger precipitation is only on 16–32 latitudes scale in the strong years, while the stronger precipitation in the weak years is with large scale and middle scale, especially 64 latitudes scale. After the monsoon onset, except the 32 latitudes scale, the precipitation in the weak years is much weaker than that in the strong years, especially on large scale (128 latitudes).

4.2 *Temporal structure*

Fig. 7 is the temporal wavelet transformation of the precipitation anomalies in SCS. Before monsoon onset, the low frequency oscillations with 30–90–day period are strong in both the strong and weak monsoon years, and the seasonal variations are also strong. But it is meaningful that the phases in the strong and weak years are completely opposite on many scales, which can be seen even more obviously on single scale (Fig. 8). Fig. 8 demonstrates the wavelet transformation coefficients on each scale, the solid line is that in the strong years, and the dashed line is that in the weak years. For the 16–year scale, it is positive in the strong years, negative in the weak years. On 2–year scale from April to August, it is positive in the strong years, negative in the weak years. As to the annual variation, it turns to positive from negative in the strong years, and from positive to negative in the weak years. On the half–year scale, the phases almost reverse in the strong and the weak years. The variation of 3–month is much greater in the strong years than that in the weak years, especially after the monsoon onset. As to the low frequency oscillation with 30–45–day period, after the monsoon onset, the range of the variation is almost the same in the strong and the weak years, but the phase is just opposite. Additionally, seen from Fig. 9, it has great differences on 8–9 months scale between the strong and the weak years before and during the monsoon onset, which implies that the strength of the SCS monsoon has quite good connection with the 8–9 months scale precipitation. After the monsoon onset, the precipitation in the strong monsoon years is strong on most scales, especially the 30–90 days low frequency oscillation.

5. The SCS monsoon key regions and the relations of the monsoon strength with the ENSO

Seen from the differences of the climatic elements (Fig. 2–Fig. 4) of the strong and weak monsoon years, three key regions are found: the u component key region in the middle SCS (116–120°E, 14–16°N), the precipitation key region in the south of Indochina Peninsula (106–108°E, 10–12°N), and the surface air temperature key region also in the south of Indochina Peninsula (106–108°E, 10–12°N). The annual variations of the corresponding elements in the strong and weak monsoon years in the three key regions are given in Fig. 10.

The u component key region (Fig. 10a): generally, the easterly winds appear in the middle of SCS from January to April, then the winds change to westerly winds in May and reach

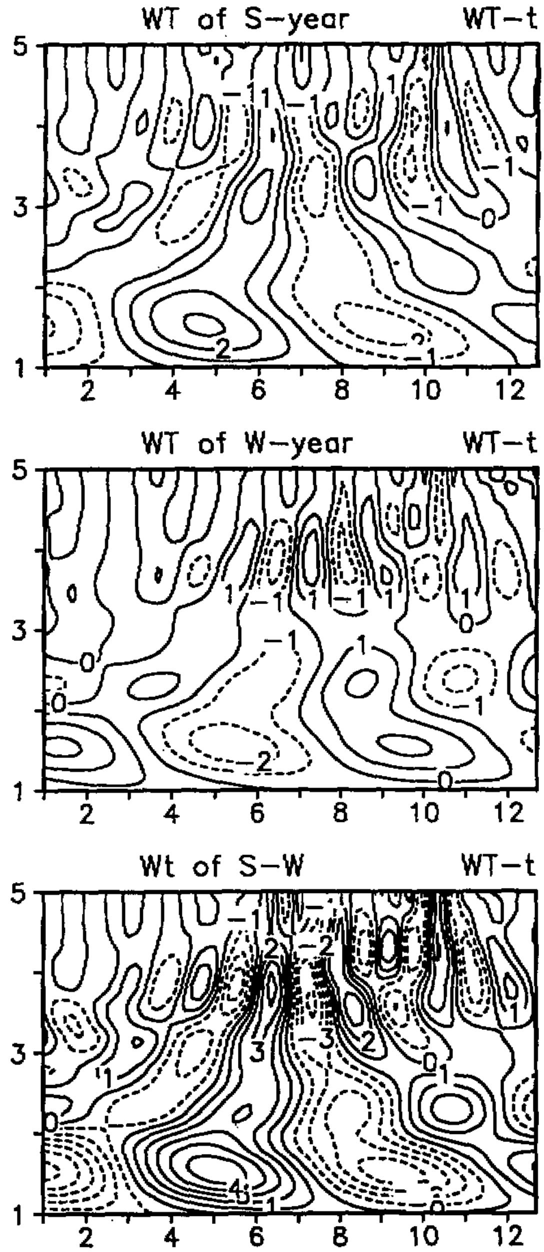

Fig. 7. The temporal wavelet coefficients of precipitation in SCS, abscissa: time(month), ordinate: the wavelet transformation scale, 1 is annual variation, the other scales half of it successively.

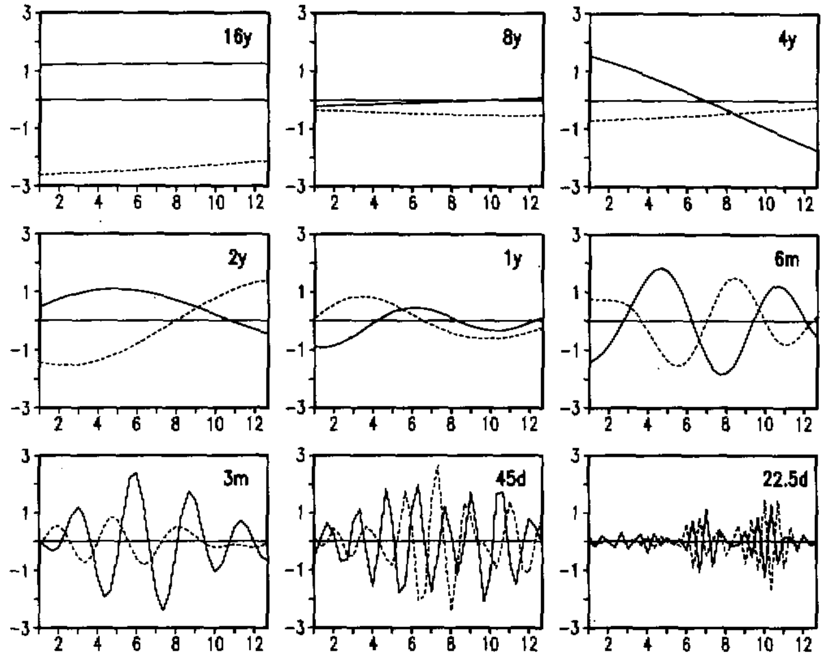

Fig. 8. The wavelet coefficients on various time scales in SCS, abscissa: month, ordinate: wavelet coefficient, solid line: strong year, dashed line: weak year.

the maximum in August, then they begin to decrease and change to east in September. The basic characteristics of the annual variations of the *u* component in the strong and weak monsoon years are consistent with the normal years, whereas the values of the *u* component have greater differences, especially during the monsoon period from April to September. The positive anomalies appear in the strong years and negative in the weak years. The westerly winds appear earlier in the strong years than those in the normal years, while they are later in the weak years. The maximum differences between the strong and weak monsoon years appear in June, then in August. Most of importance, there are great differences between the strong and weak monsoon years in April before the monsoon onset, that is positive anomalies appear in the strong years, negative in the weak years. The *u* components in the strong and weak monsoon years before the monsoon onset in the south of Indochina Peninsula also have great differences (Fig. omitted).

The precipitation key region (Fig. 10b): the precipitation in this region increases abruptly in the middle of March and increases slowly with oscillation after the middle of may, then reaches the maximum in the middle September, after that it decreases quickly. The precipitation increases quickly in the strong monsoon years from the middle of April to the middle of May (especially in the second and last pekad of April before the monsoon onset), which is different from that in the weak monsoon years. However, the precipitation in the strong monsoon years is less than that in the normal years after the monsoon onset, while it is more in the weak monsoon years.

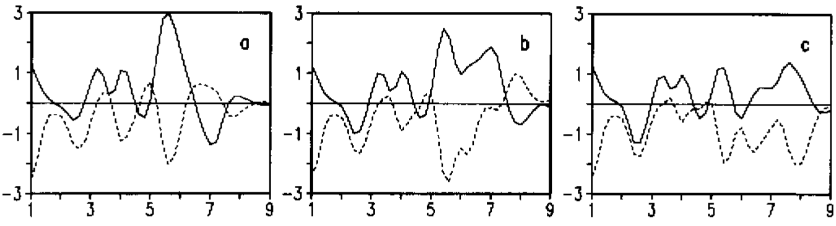

Fig. 9. The wavelet coefficients on various time scales before the onset of monsoon (a), during the onset of monsoon (b) and after the onset of monsoon (c) in SCS, solid line: strong year, dashed line: weak year(ordinate: the wavelet coefficient, abscissa: time scales, 1 = 16 a, 2 = 8 a, 3 = 4 a, 4 = 2 a, 5 = 1 a, 6 = 6 months, 7 = 3 months, 8 = 45 d).

The surface air temperature key region (Fig. 10c): the temperatures in the Indochina Peninsula increase abruptly in the middle of February and reach the maximum in the middle of March, then the temperatures decrease slowly because of the approaching of rain seasons. The greatest differences appear in the last pekad of April between the strong and weak monsoon years, great positive anomalies appear in the strong years, and great negative anomalies in the weak years.

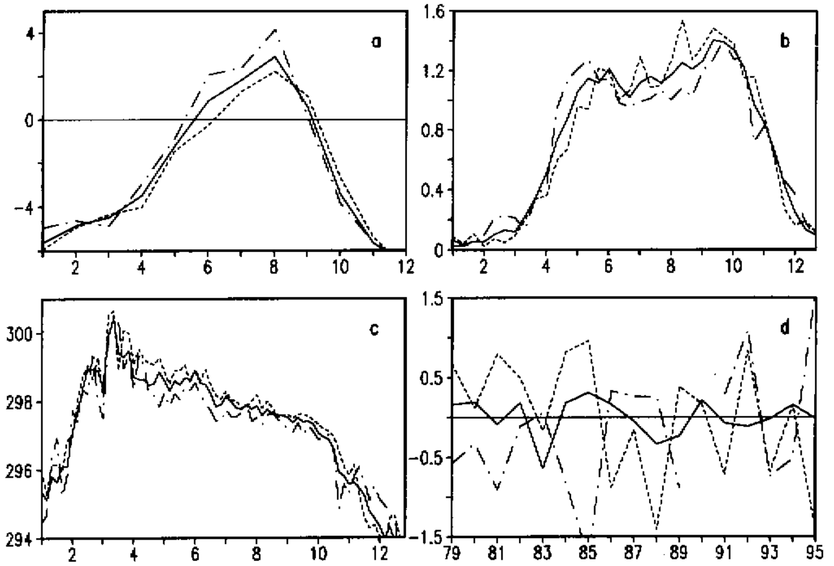

Fig. 10. The annual variations of climatic elements in key regions (a) u component, (b) precipitation, (c) surface air temperature, solid line: the annual average, dot dash line: the strong year, dashed line: the weak year; (d) the annual variations of elements in April, solid line: precipitation, dot dash line: air temperature, dashed line: u component.

Seen from the above analysis on the three key regions, it is found that the climatic elements in April could predict the strength of the SCS monsoon. So the annual variations of the climatic elements in April in three key regions are given in Fig. 10d. Compared with Fig. 1, these curves have a good agreement with the strength of the SCS monsoon. The u component in the middle SCS and precipitation in the Indochina Peninsula have positive correlation with the strength of the monsoon, whereas the surface air temperature in the Indochina Peninsula has negative correlation with the SCS monsoon strength, which implies that when the easterly winds in the middle of SCS in April are weak, and those in the Indochina Peninsula are also weak, while the precipitation is strong, surface air temperatures are low, then the SCS monsoon in that year will be strong. Comparing the Fig. 10d with the SST anomalies in NINO3–4 area (Fig. omitted), it is found that they have a good agreement. The SCS monsoon is weak in the El Nino year, and strong in the La Nina year. So there is a connection between the SCS monsoon and the SST anomalies in the equatorial eastern Pacific.

6. Summary

According to above analysis, we get the conclusions as follows:

(1) The climatic elements in SCS have great differences between the strong and weak monsoon years. Before the monsoon onset, the precipitation in SCS is above the normal in the strong years, and less in the weak years. The temperatures in the south of SCS are obviously below the normal in the strong years, and higher in the weak years. The easterly winds in the middle and southern SCS are weaker in the strong years, stronger in the weak years. During the monsoon onset, the variations of precipitation and temperature in the northeast of SCS are opposite with those in the southwest, which are especially obvious in the strong years. There are stronger westerly winds in the south and the middle of SCS in the strong years, and weaker westerly winds in the weak years. After the monsoon onset, there are more precipitation, lower temperature and stronger westerly winds in the strong years, and the case is entirely opposite in the weak years.

(2) There are great differences in the spatial and temporal structures of precipitation between the strong and weak monsoon years. Before the monsoon onset, the main variations of precipitation are on large scale (64 latitudes) in the strong monsoon years, and on middle scale (32 latitudes) in the weak years. The precipitation with 8–9 months period is very strong in the strong years. During the monsoon onset, the strong precipitation is only on 16–32 latitudes scale and in 8–9 months period in the strong monsoon years. The precipitation is very strong on large scale and middle scale in the weak years. After the monsoon onset, the precipitation with large scale (128 latitudes) is very strong in the strong years. The stronger precipitation is only on 32 latitudes scale in the weak monsoon years. The precipitation in the strong monsoon years is strong on most temporal scales, especially the low frequency oscillations with 30–90–day period.

(3) The variation of climatic elements in the south of Indochina Peninsula in April is a good index to indicate the strength of the SCS monsoon. It can be regarded as an index to predict the strength of the SCS monsoon.

(4) There is a good connection between the SCS monsoon and the sea surface temperature in the equatorial eastern Pacific. The SCS monsoon is weak in the EL Nino years, and strong in the La Nina years.

(5) The strength of the SCS monsoon depends on the local heating difference between the eastern continent of China and the western Pacific.

(6) The SCS monsoon is related to the intensity and the position of the western Pacific Subtropical High. The western Pacific Subtropical High is weak and eastward in the strong monsoon years, and it is strong and westward in the weak monsoon years.

REFERENCES

Chen Longxun, and Song Yi, 1996: The Characteristics of Convective System Change during the Onset Period of Summer Monsoon. *The Recent Advances in Asian Monsoon Research*, China Meteorological Press, 54–64 (in Chinese).

Jin Z., and M. Murakami, 1996: The Interannual Variation of Convective Activities in East Asian Monsoon Area and Its Relation to the Drought and Flooding over the Yangtze and Huaihe River Valley. *The Recent Advances in Asian Monsoon Research*, China Meteorological Press, 88–98 (in Chinese).

Lau K. M., and Song Yang, 1997: Climatology and interannual variability of the Southeast Asian summer monsoon. *Adv. Atmos. Sci.*, **14(2)**, 141–162.

Tao Shiyan, and Chen Longxun, 1987: A review of recent research on the East Asian summer monsoon in China. *Monsoon Meteorology*, edited by C. P. Chang, and T. N. Krishnamurti, Oxford University Press, 60–92.

Xie An, Liu Xia, and Ye Qian, 1996: The Climatic Characteristics of Summer Monsoon Onset over South China Sea, *The Recent Advances in Asian Monsoon Research*, China Meteorological Press, 132–142 (in Chinese).