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CLIMATIC CHARACTERISTICS OF THE ONSET OF SOUTH CHINA SEA SUMMER MONSOON II. INTER-DECADAL VARIATION

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ABSTRACT: By using the 40-year NCEP (1958-1997) grid point reanalysis meteorological data, we analyzed the inter-decadal variation on the climatic characteristics of the onset of South China Sea summer monsoon. The results are as follows. (1) There was great difference on the onset date of the SCS summer monsoon between the first two decades and the last two decades. It was late on the 6th pentad of May for the first two decades and was on the 4th and 5th pentad of May for the next two decades. (2) Except for the third decade (1978-1987), the establishment of the monsoon rainfall was one to two pentads earlier than the onset of the summer monsoon in all other three decades. (3) The onset of the SCS monsoon is the result of the abrupt development and eastward advancement of the southwesterly monsoon over the Bay of Bengal. The four-decade analysis shows that there were abrupt development of the southwesterly monsoon over the Bay of Bengal between the 3rd and 4th pentad of May, but there was great difference between its eastward movement and its onset intensity. These may have important effect to the earlier or later onset of the SCS summer monsoon. (4) During the onset of the SCS summer monsoon, there were great difference in the upper and lower circulation feature between the first two and the next two decades. At the lower troposphere of the first two decades, the Indian-Burma trough was stronger and the center of the subtropical high was located more eastward. At the upper troposphere, the northward movement of the center of subtropical high was large and located more northward after it landed on the Indo-China Peninsula. After comparison, we can see that the circulation feature of the last two decades was favorable to the establishment and development of the SCS summer monsoon.

Key words: South China Sea summer monsoon; onset climate characteristics; inter-decadal variation

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1 INTRODUCTION

By using the 12-level 40-year NCEP (1958-1997) reanalysis meteorological data, we obtained some meaningful results from the study of the climatic characteristics [1, 2] on the onset of South China Sea (SCS) summer monsoon and Asian summer monsoon. The analysis reveals the large inter-decadal variation of the climate characteristics of the onset of South China Sea summer monsoon. For example, during the 40 years, the onset of the SCS summer monsoon was comparatively late in the first 20 years than the next 20 years with one to two pentads in differences. The onset of the SCS summer monsoon is closely related to the advance of the summer monsoon in Mainland China. The study of inter-decadal variation of climatic characteristics of the onset of the South China Sea summer monsoon is meaningful to the analysis and prediction of the advance of the summer monsoon in Mainland China. Therefore, we

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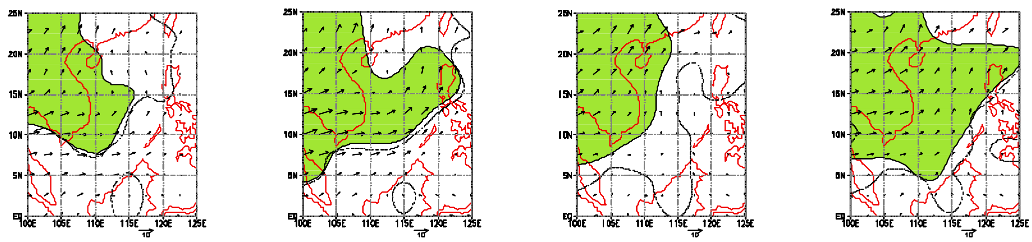
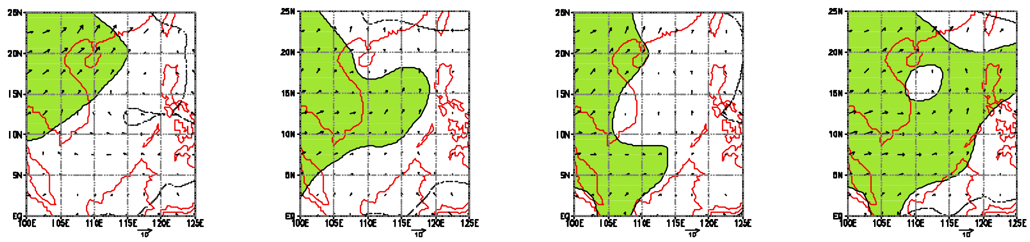
analyzed the inter-decadal variation of the climate characteristics of the onset of South China Sea summer monsoon using the aforesaid data. The results are explained as follow.

2 THE INTER-DECADAL VARIATION OF THE ONSET OF SCS SUMMER MONSOON

We have defined the SCS summer monsoon and its establishment. The SCS summer monsoon belongs to the tropical southwesterly monsoon. The latter is very warm and humid. Its maximum wind center is located at lower troposphere and with easterly winds at the upper level. We used the warm humid southwesterly winds at 850 hPa to define the monsoon area. The warm humid southwesterly winds required the conditions that the q_{se} (pseudo equivalent potential temperature) should be greater than 335°K and the southwesterly wind speed should be greater than 2 m/s. The onset of the SCS summer monsoon is defined to set off when half of the area of the SCS (105°E ~ 120°E, 5°N ~ 20°N) is controlled by the summer monsoon. Fig.1 is the 850-hPa pentad average before and after the onset of the SCS summer monsoon in four decades (1958 ~ 1967, 1968 ~ 1977, 1978 ~ 1987, 1988 ~ 1997). Fig.1 shows that the onset of the SCS summer monsoon was comparatively late in the first 20 years, both were in the 6th pentad of May. It was comparatively early in the next 20 years, one in the 4th pentad and the other in the 5th pentad of May. The difference of one to two pentads is considered to be a large period in inter-decadal variation. In the first ten years (1958 ~ 1967), the southwesterly monsoon over the Bay of Bengal advanced very early to the region of SCS after its abrupt development. Most of the SCS areas were controlled by the southwesterly winds in the 4th pentad of May. Before this happened, however, the SCS was very dry and cold, modification of air mass was slow, therefore the summer monsoon was not established until the 6th pentad. The three other decades were



(a) 5th pentad of May averaged over 1958～1967 | (b) 6th pentad of May averaged over 1958～1967 | (c) 5th pentad of May averaged over 1968～1977 | (d) 6th pentad of May averaged over 1968～1977



(e) 3rd pentad of May averaged over 1978～1987 | (f) 4th pentad of May averaged over 1978～1987 | (g) 4th pentad of May averaged over 1988～1997 | (h) 5th pentad of May averaged over 1988～1997

Fig.1 The pentad average of 850 hPa before and after the onset of the SCS summer monsoon in the four decades (The shaded part represents the summer monsoon region and the dashed line is the q_{se} =355°K line) different in that modification of air mass was fast and summer monsoon established as southwesterly winds arrived.

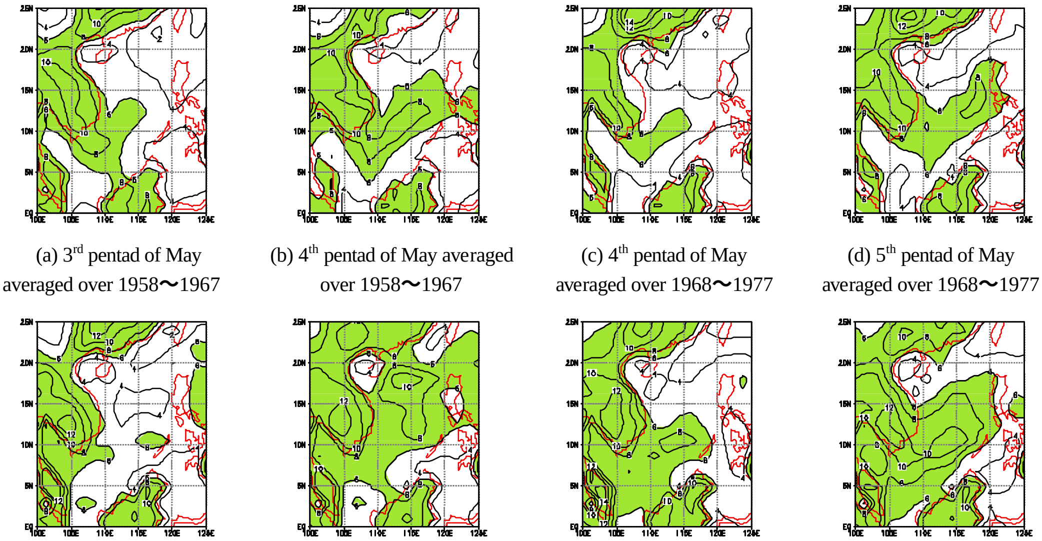
From the analysis result of the 40-year mean, it is concluded that the onset of the SCS summer monsoon is in the 4th pentad of May. It seems strange as it coincides with the earliest time of the four decades. We discovered some reasons after careful studies: (1) The q_{se} of the SCS has on average reached 335°K in the four decades. (2) The southwesterly winds of the SCS in the 4th pentad of May had exceeded 2 m/s in the first decade. (3) For the four decades, if the sum of the southwesterly winds in the 4th pentad of May had exceeded 8 m/s in any region of the SCS, then the average of the region will reach the standard of summer monsoon. In other words, the onset date of the 40-year mean will become earlier due to the stronger southwesterly winds or the higher θse in certain years or regions. After referring the SCS summer monsoon onset date of the four decades, it is more reasonable to define the mean onset date on the 5th pentad of May.

3 THE INTER-DECADAL VARIATION ON THE STARTING DATE OF MONSOON RAINFALL OVER THE SCS

There is close relationship between the summer monsoon and monsoon rainfall. The monsoon will result in abundant rainfall, so the Indians used rainfall to define the monsoon[3]. Strictly speaking, the monsoon is not equivalent to the monsoon rainfall and the monsoon region is not the rainfall region. Rainfall in the monsoon region of low-latitude tropical region requires convergence and convective conditions. Precipitation in the subtropical monsoon region requires the interaction of cold and warm air mass. Therefore, we can see from the following description that the onset of the monsoon is not always in accordance with the establishment of the monsoon rainfall.

Lau et al. have defined the advance of monsoon rain band[4] in Asian monsoon regions by using the global average precipitation index GPI that is estimated from satellite observations. The boundary of this monsoon rain band was defined by the 6 mm/day of mean pentad rainfall and this is quite reasonable. We also use the 6 mm/day as standard for the monsoon rainfall in the following discussion. We define the starting date of the monsoon rainfall over the SCS as the date when the pentad rainfall reached 6 mm/day over half of the areas in the SCS. Fig.2 is the mean pentad precipitation before and after the establishment of the SCS monsoon rainfall in four decades. We can see from Fig.2 that except for the third decade (1978-1987), the establishment of the monsoon rainfall was one to two pentads earlier than the onset of the summer monsoon in all other three decades. It is not difficult to understand. As the southwesterly winds of the Bay of Bengal propagate toward the SCS with less fast movement, it will then interact with the southeasterly winds coming from the southwest of the subtropical high over the western Pacific. Precipitation then forms over the SCS. Therefore, the establishment of monsoon rainfall is earlier than the summer monsoon. It is obvious that the SCS monsoon rainfall belongs to the tropical convective rain.

4 RELATIONSHIP BETWEEN THE ONSET OF SCS SUMMER MONSOON AND THE ABRUPT DEVELOPMENT OF THE SOUTHWESTERLY MONSOON OVER THE BAY OF BENGAL



(a) 3rd pentad of May averaged over 1958～1967
(b) 4th pentad of May averaged over 1958～1967
(c) 4th pentad of May averaged over 1968～1977
(d) 5th pentad of May averaged over 1968～1977
(e) 3rd pentad of May averaged over 1978～1987
(f) 4th pentad of May averaged over 1978～1987
(g) 3rd pentad of May averaged over 1988～1997
(h) 4th pentad of May averaged over 1988～1997

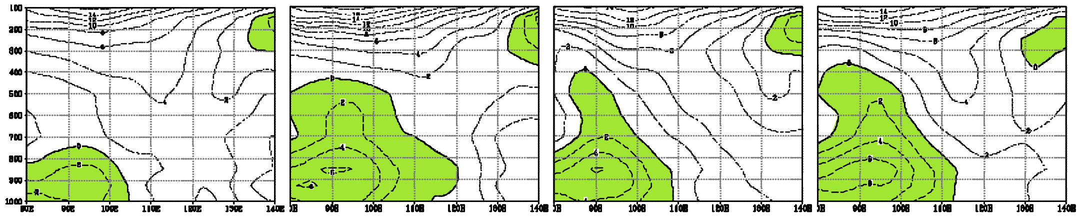
Fig.2 Mean pentad rainfall before and after the establishment of the SCS monsoon rainfall in the four decades (unit: mm/day; the shaded part represents the daily rainfall ＞6 mm/day).

We have analyzed the 40-year mean climatic characteristics of summer monsoon onset in the SCS[1]. From the result we know that the onset of SCS summer monsoon is closely related to the development of the southwesterly monsoon over the Bay of Bengal, which is caused by the development and eastward propagation of the southwesterly monsoon over the Bay of Bengal. From the viewpoint of 40-year mean, it shows that the southwesterly monsoon over the Bay of Bengal developed quite slowly from the 1st to 3rd pentad of May. It dramatically developed from the 3rd to 4th pentad of May. The southwesterly monsoon propagated eastward across the Indo-China Peninsula and controlled most of the SCS region. It also extended from about 700 hPa up to 400 hPa. If we compare the analysis of 40-year mean with that of the four decades, it is interesting to find that the abrupt development of the southwesterly monsoon over the Bay of Bengal has no obvious inter-decadal variations. Fig.3 is the vertical cross-section of the westerly components from the 3rd to 4th pentad of May along 10 ° N for the four decades. Fig.3 shows that the explosive development of the southwesterly monsoon over the Bay of Bengal is fairly stable between the 3rd to 4th pentad of May. Comparably speaking, the “abrupt” development of the southwesterly monsoon over the Bay of Bengal in the second decade was not as strong as in the other three decades, although our analysis shows that it was the most “abrupt” variation between the 3rd to 4th pentad of May after the establishment of the southwesterly monsoon over the Bay of Bengal. Fig.3a and 3b show that the 2m/s isotach extended from about 700 hPa to about 550 hPa and it had obvious influence on the onset of the SCS monsoon. Fig.2 shows that the establishment of the monsoon rainfall in the second decade was the latest among the four decades. It occurred in the 5th pentad of May, which was one pentad later than the other three decades. Fig.1 also shows that the onset of SCS summer monsoon in the second decade was the latest among the four decades and occurred in the 6th pentad of May. The onset date of the first decade was also in the 6th pentad of May, but, as we have described, most of the SCS areas were controlled by the southwesterly monsoon over the Bay of Bengal in the 4th pentad of May. The only question is the slow modification of air mass.

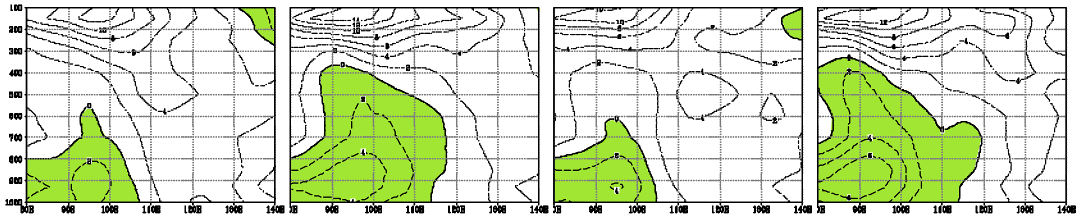
In summary, the onset of the SCS monsoon is the result of the abrupt development of the southwesterly winds over the Bay of Bengal. Therefore, if the “abrupt” development of the southwesterly winds over the Bay of Bengal is not strong enough, then the establishment of both SCS monsoon and monsoon rainfall will become late. Obviously, this means a lot to prediction.

5 THE ONSET OF SCS SUMMER MONSOON AND THE EVOLUTION OF UPPER AND LOWER CIRCULATION

According to our analysis of the 40-year mean climatic characteristics of summer monsoon onset in the SCS, the subtropical high in the lower troposphere withdrew from the SCS[1] with the SCS monsoon outbreak. Fig.1 shows the same result for all the four decades, with the only different in the position of the ridge of subtropical high locating more northward in the first 20 years than in the next 20 years. The ridge was at its most northward position in the first decade, near 21°N over the northward part of the SCS in the 5th pentad of May before the withdrawal of the subtropical high. It then located at about 19°N, a little southward, in the second decade. The withdrawal of the subtropical high was earlier in the third decade in the 4th pentad of May and the ridge located at about 13°N ~ 17°N in the 3rd pentad of May. The subtropical high withdrew from the SCS in the 5th pentad of May in the 4th decade. The ridge located at about 13°N ~ 21°N in the 4th pentad of May, which was similar to the third decade, but with the position more



(a) 3rd pentad of May averaged over 1958～1967 (b) 4th pentad of May averaged over 1958～1967 (c) 3rd pentad of May averaged over 1968～1977 (d) 4th pentad of May averaged over 1968～1977



(e) 3rd pentad of May averaged over 1978～1987 (f) 4th pentad of May averaged over 1978～1987 (g) 3rd pentad of May averaged over 1988～1997 (h) 4th pentad of May averaged over 1988～1997

Fig.3 Vertical cross-section of the southwesterly component from the 3rd to 4th pentad of May along 10°N for the four decades (unit: m/s; the shaded part represents the southwesterly).

southward and inclined.

After analyzing the SCS summer monsoon by using the 40-year mean data[1], we found that the withdrawal of the subtropical high in the lower troposphere occurred in different time at different levels during the establishment of the SCS summer monsoon. The result is equivalent to the four decades. As described above, we used the 850-hPa data to define the onset of SCS summer monsoon. Therefore, it can be seen clearly from Fig.1 that the time when the subtropical high withdrew from the SCS was the onset time of the SCS summer monsoon. The withdrawal of the subtropical high at other levels was either before or after this onset time. In summary, the withdrawal was earlier at levels above 850 hPa and later at levels below it, as compared with that of 850 hPa. Fig.4 shows the evolution of the western position of the subtropical ridge at 500 hPa from the 1st to 6th pentad of May in the four decades. We can see from the figures that except for the second decade, the withdrawal of the subtropical high was earlier than the onset of the summer monsoon in all other three decades. The first decade was the earliest and the other two were one pentad earlier. The withdrawal of the subtropical high occurred at the same time as the onset of the monsoon in the 2nd decade and was in accordance with the analysis of 40-year mean. The withdrawal of the subtropical high at 925 hPa was later than that at 850 hPa and was

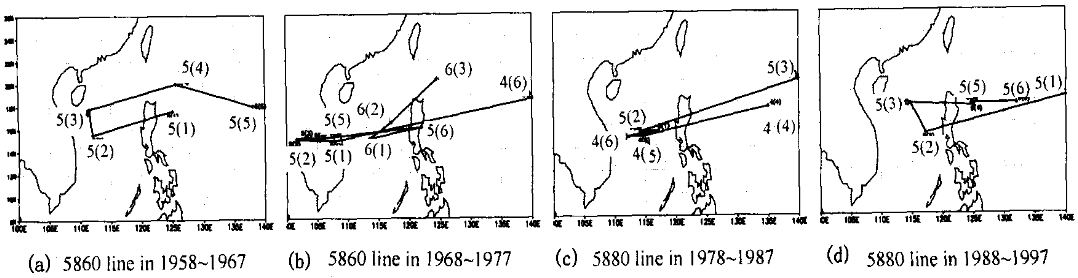


Fig.4 Pentad-based evolution of the western ridge point of the subtropical high at 500 hPa before and after the establishment of the SCS monsoon in the four decades.

opposite to the situation at 500 hPa. Figures are not shown for the sake of text.

It is necessary to point out that the onset of the SCS summer monsoon was quite late in the first two decades and the subtropical high of the western Pacific was weak. We can see from Fig. 4 that the west position of the subtropical ridge determined by the 5860 contour and the 5870 contour cannot be drawn. But the relationship between a weak subtropical high and a late monsoon onset is still unclear.

During the establishment of the SCS monsoon, the obvious change occurred at the upper troposphere before the SCS monsoon established. Before and after the onset of monsoon over the Bay of Bengal, the center of the subtropical high moved from the sea to the Indo-China Peninsula and then quickly shifted northward. The northward movement of the center of the subtropical high was the fastest in this period. Fig.5 shows the evolution of the center of the subtropical high at 200 hPa from the 6th pentad of April to the 1st pentad of June in the four decades. It can be seen from the figures that the northward movement of subtropical high center was quite large in the first 20 years after it landed on the Indo-China Peninsula. It was 7 degrees of latitude in the first decade mean and 9 degrees of latitude in the second decade mean. The northward movement then became shorter in the next 20 years, both was 5 degrees of latitude, and moved from 13°N to 18°N. The largest movement all occurred at the same time in the pentad as the center of the subtropical high landed over the Indo-China Peninsula. It can be seen that the center of the subtropical high could move northward beyond 18°N for all the four decades. Because the center of the subtropical high located over the Indo-China Peninsula, so the upper air over the SCS and the Indo-China Peninsula were controlled by the easterly winds during the onset of the SCS summer monsoon. The easterly winds over the Indo-China Peninsula were stronger than that over the SCS. So it formed a divergence area over the SCS and the Indo-China Peninsula. This is obviously beneficial to the abrupt development of the summer monsoon over the Bay of Bengal

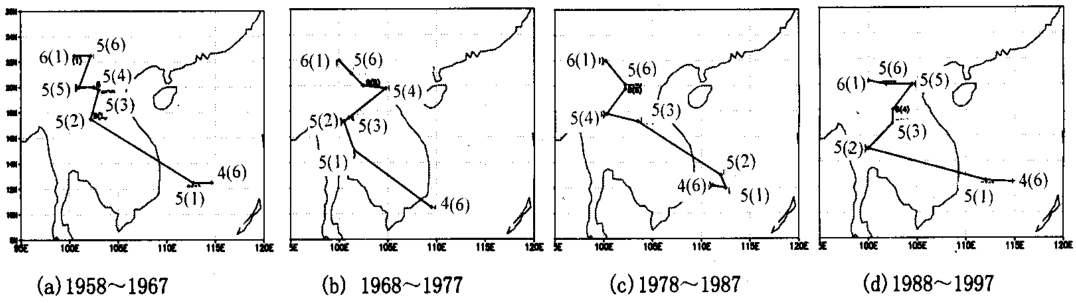


Fig.5 Pentad-based evolution of the subtropical high center at 200 hPa from the 6th pentad of April to the 1st pentad of June in the four decades.

and the onset of the SCS summer monsoon.

The abrupt development of the summer monsoon over the Bay of Bengal is the decisive condition for the onset of the SCS summer monsoon. According to our analysis, there is close relationship between the establishment and development of the summer monsoon over the Bay of Bengal and the development of Indian trough. Fig.6 shows the pentad evolution of the Indian-Burma trough at 850 hPa from the 1st to 6th pentad of May in the four decades.

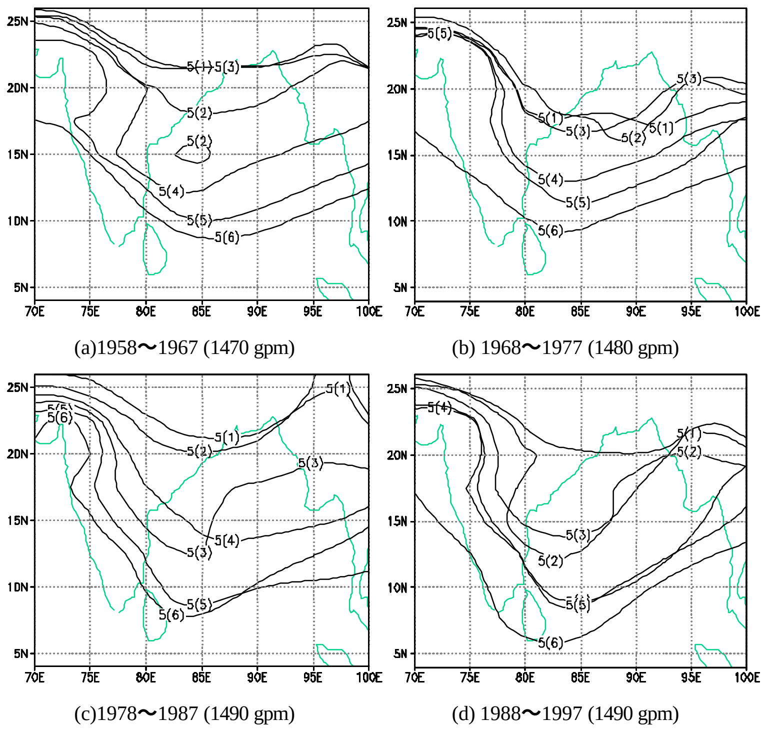


Fig.6 Pentad-based evolution of the Indian-Burma trough at 850 hPa from the 1st to 6th pentad of May in the four decades.

In the figures, we use a potential vorticity contour at 850 hPa to represent the Indian-Burma trough. We set three standards for the value of the potential vorticity contour: (1) The potential vorticity contour can reflect the evolution development of the Indian-Burma trough before the onset of the onset of the Asian summer monsoon. (2) We have indicated in Section 4 that the onset of the SCS summer monsoon is the result of the abrupt development of the southwesterly monsoon over the Bay of Bengal. Therefore, during the onset of the SCS summer monsoon the position of this contour should be near the position of streamline of the southwesterly monsoon that flows from the Bay of Bengal to the SCS. (3) Over the region of the Bay of Bengal, the position variation of the contour is very small after the establishment of the Asian summer monsoon, so it is very stable. According to the three standards, we choose the 1470 contour for the first decade, 1480 contour for the second decade and 1490 contour for the third and forth decade. It is clear that the choice of potential vorticity contours for the last two decades is larger than the previous two decades. This means the Indian-Burma trough was weaker in the last two decades.

Fig.6 shows that the Indian-Burma trough over the eastern Bay of Bengal had the fastest development from the 3rd to 4th pentad of May in all the four decades. That means the fastest development period of the Indian-Burma trough was just before the onset of the SCS summer monsoon and coincide with the onset of the southwesterly monsoon over the Bay of Bengal. It is found after careful study that although the fastest development period of the Indian-Burma trough over the eastern Bay of Bengal were all between the 3rd to 4th pentad of May, there were great difference between the first two decades and the last two decades. It was a trough area over the eastern Bay of Bengal in the 3rd pentad of the first two decades, but was a ridge area in the last two decades. The development of the Indian-Burma trough advanced from North to South from the 3rd to 4th pentad of May in the first two decades, but the advancement was from West to East for the last two decades. The North to South advancement in the first decade was larger than in the second decade. The development of West to East advancement in the fourth decade was faster than in the third decade.

In the next section we will discuss the aforementioned established stages of the SCS summer monsoon and its relevant inter-decadal variation of the upper and lower circulation features.

6 DISCUSSIONS

With the analysis of long-term air temperature variation in England, Maneley[5] proposed that it can represent the long-term global variation since there is very close relationship between them. He also suggested that there was an additional 20-year periodic oscillation in the long-term tendency of long-term air temperature variation in England.

From the analysis result of the aforementioned established stages of the SCS summer monsoon and its relevant inter-decadal variation of the upper and lower circulation features, we can see that there were great difference between the first 20 years and the next 20 years. We do not know if it has any relationship with the 20-year periodic oscillation suggested by Maneley.

From both the analyses of the 40-year mean and averages for each of the four decades, we can see that the onset of the SCS summer monsoon is the result of the abrupt development of the southwesterly monsoon over the Bay of Bengal. Wu et al.[6] indicated that the onset of the Asian monsoon has great dependence on the heating effect of the Tibetan Plateau. Their studies revealed that before the onset of the SCS summer monsoon, which was also during the abrupt development of the southwesterly monsoon over the Bay of Bengal, the temperature over the troposphere of Tibetan Plateau increased suddenly. The contribution of the heating effect of the Tibetan Plateau was shown in the effect on the heat low-pressure area and the Indian-Burma trough in the lower troposphere as well as the development of the subtropical high in the upper troposphere of the Tibetan Plateau[7]. Both the heat low-pressure areas on mainland and the

Indian-Burma trough were quite strong in the first 20 years. It can also be said that the heating effect of the Tibetan Plateau was strong, too. But they became weaker in the next 20 years. The Indian-Burma trough over the eastern Bay of Bengal had very clear development from the 3rd to 4th pentad of May in both the first 20 years and the coming 20 years. Correspondingly, the abrupt development of the southwesterly monsoon over the Bay of Bengal was also very stable and occurred from the 3rd to 4th pentad of May in all the four decades. But there was obvious inter-decadal variation to the degree of "abrupt" development of the southwesterly monsoon over the Bay of Bengal and its advance speed toward the SCS during the "abrupt" change. The variation had direct influence on the onset of SCS summer monsoon. The southward advancement was quite slow in the first 20 years and quite fast in the next 20 years. The onset of the SCS summer monsoon was then late by one to two pentads in the first 20 years compared to that in the next 20 years. The reason may be due to both heat low-pressure areas on the mainland and the Indian-Burma trough being stronger in the first 20 years than in the next 20 years. The stronger heat low-pressure area on the mainland and the Indian-Burma trough in the first 20 years resulted in the eastern shift of the subtropical high over western Pacific in the lower troposphere. Before June, the 5880 contour at 500 hPa had not been shown to the west of 155°E over the western Pacific. It is not difficult to understand, because the subtropical high of lower troposphere over the Eurasia and North America were in zonal form in winter. Even the summer subtropical high in North America could extend across the Florida into Mexico. The break of summer subtropical high in East Asia was mainly due to the development of the heat low-pressure area over the mainland and the Indian-Burma trough. Obviously, the stronger the low-pressure area and the trough were, the more eastward the subtropical high would be. The more eastward of the subtropical high was unfavorable for the onset of the SCS summer monsoon. If the western region of the subtropical high was close to the SCS (i.e. the western region of the subtropical high was over the SCS or a bit eastward), it may favor the eastward advancement of the southwesterly monsoon over the Bay of Bengal. The first reason was that the pressure gradient force over the Indo-China Peninsula and the Bay of Bengal was intensified if the subtropical high was close to the SCS. The second reason is that there were southwesterly winds over the northwestern region of the subtropical high. Both of them contributed to the intensification and eastward advancement of the southwesterly monsoon over the Bay of Bengal. The two effects were greatly decreased if the subtropical high is located more eastward. Of course it may also be unfavorable for the eastward advancement of the southwesterly monsoon over the Bay of Bengal if the subtropical high extends more westward, i.e. to the Indo-China Peninsula. Because the track of the eastward advancement of the southwesterly monsoon may then shift more northward and cannot reach to the middle and southern region of the SCS. It may also be unfavorable for the eastward retreat of the subtropical high during the establishment of the SCS monsoon. To put it simply, the eastward retreat of the subtropical high was caused by the intensification and development of both the heat low-pressure area over the mainland and the Indian-Burma trough. But the small or large retreats were both unfavorable to the establishment of the SCS monsoon. The late onset of the SCS summer monsoon in the first 20 years may relate to the large retreat of the subtropical high.

There is similar situation at the upper troposphere. As described above, during the onset of the SCS summer monsoon, the center of the subtropical high at 200 hPa landed on the Indo-China Peninsula and then quickly moved northward. It formed a divergence over the SCS and favored the establishment and development of the SCS summer monsoon. We should note that there is close relationship between the establishment and development of the SCS summer monsoon and the center of the subtropical high as well as the corresponding divergence center. During the onset of the SCS summer monsoon the center of the subtropical high as well as the corresponding divergence center were located more northward in the first 20 years. Therefore, its contribution to the establishment and development of the SCS summer monsoon was not as obvious as that of the last 20 years.

The description above is only qualitative. There are some suppositions. For example, the relationship between the establishment and development of the SCS summer monsoon and the intensification of the heat low-pressure area over the mainland and the Indian-Burma trough as well as the location of the subtropical high over the western Pacific are to be studied in more diagnostic analysis and numerical simulation for confirmation.

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