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COMPOSITE ANALYSIS OF SUMMER MONSOON ONSET PROCESS OVER SOUTH CHINA SEA

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ABSTRACT: Based on the method of composite analysis, the onset process and preceding signs of summer monsoon over the South China Sea (SCS) is investigated. The result indicates that convection activities appear first over the Indo-China Peninsula prior to the onset of the monsoon, then around the Philippines just at the point of onset, implying that the convection activities around the Philippines serve as one of the reasons leading to the SCS monsoon onset. Before the SCS monsoon onset, the equatorial westerly over the Indian Ocean (75°E ～ 95°E) experiences noticeable enhancement and plays an important role on the SCS monsoon onset. It propagates eastward rapidly and causes the establishment and strengthening of equatorial westerly in the southern SCS, on the one hand, it results in the migration southward of the westerly on south side of the south-China stationary front by means of shift northeastward of the westerly and convection over the Bay of Bengal, on the other. Further study also shows that the intensification of equatorial westerly in the Indian Ocean (75°E ～ 95°E) and the southern SCS is closely related to the reinforcement of the Southern-Hemisphere Mascarene high and Australian high, and cross-equatorial flow northward around Somali, at 85°E and 105°E, respectively.

Key words: South China Sea summer monsoon; onset process; composite analysis

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1 INTRODUCTION

One of the chief findings over the past 20 years in the aspect of monsoon study at home and abroad is the discovery of an East Asian circulation system that is both independent from and associated with the Indian Monsoon system. The region of East Asian Monsoon can be further divided to subregions of South China Sea-west Pacific tropical monsoon and continental-Japan subtropical monsoon. As what Tao and Chen[1] have found, the Asian summer monsoon first breaks out in the northern part of the South China Sea before advancing by phase towards west and north. He, McGinnis and Song et al[2] reported findings of the establishment of two well-defined phases during the onset of the monsoon over the Asian region: the first appearing in May when low-level southwesterly sets off over the South China Sea and the second in June when there are precipitation and southwest Arabic wind on the western coast of India. They further suggested that the general circulation had experienced an abrupt change in association with the onset of the South China Sea summer monsoon, an indication that the onset of the summer monsoon is related not only with local circulation but possibly with seasonal progress of general circulation on large scale. He, Zhu and Murakami[3] analyzed years of T_{BB} data and suggested that it was as early as in early April that

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the Asian-Australian monsoon began its seasonal shift, which mainly displayed as rapid northward migration of high-value T_{BB} in Australia, refreshing of convection over the Indo-China Peninsula and breakage of high-value T_{BB} in the subtropics. It is therefore clear that the study on the onset of South China Sea summer monsoon and its mechanism is essential in our correct understanding of the onset process of summer monsoon for the whole region of Asia and variation subsequent to it.

There are a lot of research on the onset process and mechanism for the South China Sea summer monsoon, which differ in perspective. As what Murakami, Chen and Xie[4] pointed out, the large-scale seasonal shift, which is caused by thermodynamic difference between Asia and Australia, is much more sensitive and intense as compared to that caused by land-sea contrast. The summer monsoon will set off when a wet phase of adequate low-frequency oscillation migrates to the region of South China Sea, which is specifically sensitive to such variation. Chen and Chen[5] noticed in their study of the 1979 data that the South China Sea summer monsoon usually had three processes of low-frequency variation — setting off just as the 30-60 day and 12-24 day low-frequency troughs arrive in the area where the monsoon trough was located in the northern part of South China Sea. They emphasized the triggering effect of low-frequency oscillation on the onset of the South China Sea summer monsoon. In studying the development of southwesterly flow surge at 850 hPa above the northern South China Sea with the aid of ECMWF data from 1980 to 1986, Chang and Chen[6] discovered that the acceleration of southwesterly flow in May depended on baroclinic frontal systems in middle latitudes, which move southward to the coastal areas of south China where they tend to stay around in stationary position with a southwesterly flow to the south. Such mid-latitude systems may trigger the onset of summer monsoon in the South China Sea.

There has not been a concise understanding of the onset process and triggering mechanism for the summer monsoon in the South China Sea, as we summarize what is discussed above. Many issues need to be studied further. The aim of the current work is to exploit the latest data to investigate the onset and possible mechanism.

2 BRIEF ACCOUNT OF DATA

The data used in this work include: (1) day-to-day global outgoing longwave radiation (OLR) from 1979 to 1999 with spatial resolution of 2.5° × 2.5° grid interval; (2) day-to-day wind field of NMC from 1979 to 1996 within a spherical belt at 40°S ~ 40°N and spatial resolution of 2.5° × 2.5° grid interval.

3 DETERMINATION OF ONSET DATE OF SOUTH CHINA SEA SUMMER MONSOON

Monsoon is usually considered a reversal of wind direction between winter and summer and seasonal difference (intense variation of precipitation) in the nature of air mass and consequent weather phenomena. It is, however, quite difficult to apply the definition indiscriminately to all kinds of monsoon onset in all regions of their activity. It arises from uncertainty in quantifying relationship of correspondences between changes in wind direction and precipitation, which are significantly shown depending on regional differences. Xie and Zhang[7] suggested the use of OLR and 850-hPa zonal wind to define the onset of summer monsoon, which is justified by previous work — abrupt shift of zonal wind from easterly to westerly and explosive growth of deep convection over the entire South China Sea region appeared when the summer monsoon set off in the South China

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Sea. It is based on the consideration that the method by Xie and Zhang are employed here to define the onset of South China Sea summer monsoon from the perspective of 850-hPa zonal wind and deep convection. The monsoon is specified to be on when day-to-day OLR averaged over the region (105°E ~ 120°E, 5°N ~ 20°N) reduces to 235 W/m^2 and regionally averaged 850-hPa zonal wind shifts from easterly to westerly and maintains for at least a week.

Tab.1 gives the date on which the summer monsoon breaks out in the South China Sea each year during 1979 ~ 1996 as set out by the standard presented above. It should be pointed out that the variation of 850-hPa zonal wind is the only factor in the determination of the monsoon onset between 1994 and 1996 because day-to-day OLR data in 1994 ~ 1996 is absent. It is known from the table that the onset of the South China Sea summer monsoon is marked by obvious variation from year to year. The earliest year of onset is 1985, taking place on April 27 and the latest year is 1993 on June 16, making an average date on May 21. The dates of monsoon onset for individual years are consistent with the results determined by Xie, Liu and Ye[8] who are studying with pentad-mean data of wind field and OLR — being within the pentads determined with pentad-mean field for the onset of the summer monsoon. The difference is that it is the day-to-day data that form our basis in determining the onset dates of the South China Sea summer monsoon so that the whole procedure of onset and preceding signature are better and more finely revealed.

Tab.1 Onset dates of South China Sea summer monsoon 1979 ~ 1996

year	Onset dates	year	Onset date	year	Onset date
1979	May 12	1985	Apr. 27	1991	Jun. 8
1980	May 15	1986	May 14	1992	Jun. 1
1981	Jun. 1	1987	Jun. 7	1993	Jun. 16
1982	Jun. 5	1988	May 20	1994	May 24
1983	Jun. 5	1989	May 17	1995	May 12
1984	Apr. 28	1990	May 17	1996	May 5

4 EVOLUTION OF TROPICAL CONVECTION BEFORE AND AFTER THE ONSET OF SOUTH CHINA SEA SUMMER MONSOON

To examine temporal and spatial evolution of convection in the tropics being associated with the onset of the summer monsoon, we take the day of monsoon onset as Day 0 for 1979 ~ 1993 (15 years) and then conduct a composite analysis of OLR field data. Fig.1 gives the distribution of OLR that has been composed by superimposition 6, 4 and 2 days before and on the very day of onset. The shaded portion in the figure denotes OLR which is less than 235 W/m^2, which indicates well the activity of tropical convection. For the period 10 ~ 20 days before the onset of the summer monsoon (figure omitted), convection is mainly active east of 70°E in the equatorial part of west tropical Pacific while it starts to develop in southern Indo-China Peninsula that extends north along the peninsula. By Day –15, it joins with convection extending southward from the coast of south China. It is a time when a zone of high OLR controls the region South China Sea through west Pacific, corresponding to the subtropical high in west Pacific. By Day –6, the low-OLR belt over the central and eastern equatorial parts of the Indian Ocean has left the equator to come north to around 5°N when convection is widespread over the entire region of Bay of

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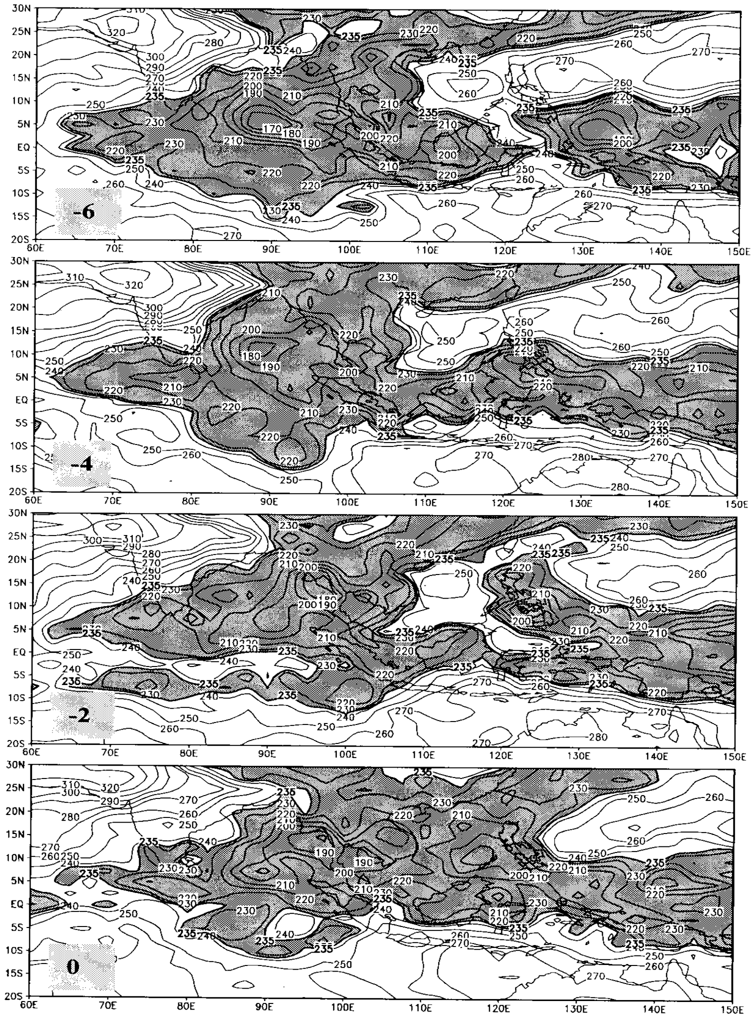

Fig.1 Daily mean OLR for selected day as marked on the top left corner, -6, -4, -2, 0 day, with respect. to the summer monsoon onset over SCS as the zero day, composed for 15 years (1979~1993). Shaded areas denote the OLR values less than 235 W/m^2 with contour interval 10 W/m^2.

Bengal and Indo-China Peninsula. At the same time, the low-OLR belt in the equatorial west Pacific has now shifted to 5°N. By Days –4 to –2, convection undergoes little change over the equatorial eastern Indian Ocean, Bay of Bengal and Indo-China Peninsula as compared to Day –6, though the most dramatic variation takes place near the Philippines Islands. Beginning from Day –4, convection corresponding to the ITCZ over the tropical west Pacific Ocean protrudes north near the Philippines and move along the islands towards the north. By Day –2, two centers of intense convection have formed over the islands to result in distinct breakage of a high-OLR portion from the South China Sea to the subtropical region of the west Pacific and formation of an isolated high-OLR portion over the South China Sea. In contrast, a small-OLR zone, corresponding to the cloud bands over the coast of and quasi-stationary front in south China, remains little changed. On Day 0, the small-OLR zone formally present over the islands of the Philippines makes a shift towards the South China Sea and forms a center there of small OLR, leading to the establishment of

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convection above the sea and full-scale onset of summer monsoon. Over the several days afterwards, the convection further strengthens in the South China Sea so that an intense development zone appears in the central part of the sea with OLR less than 180 W/m^2 (figure omitted).

To have a better understanding of the evolution of cumulus convection in the South China Sea and areas surrounding it at times around the onset of summer monsoon, Fig.2 gives cross section over time for composite OLR fields at 10°N. The figure clearly shows that convection due to cumulus activity has well established about 30 days before the monsoon onset in the sea. Examining together with Fig.1, we can infer that cumulus convection expands north and west after establishment over the Indo-China Peninsula. Employing T_{BB} averaged over years for revealing evolution of the Asian-Australian monsoons, He, Zhu and Murakami[3] presented results that indicated the activity of convection was first established around the Island of Kalimantan, Indonesia, that advanced north and west along the "continental bridge" for the Indo-China Peninsula. With OLR data averaged over pentad, Liu, Xie and Ye et al[9] reported findings of establishment of convection on the southern tip of the peninsula before rapid progress to the north by west. From what is shown in Fig.2, we also recognize that about 3 ~ 4 days before the onset of summer monsoon in the sea, convection is obviously active over the islands of the Philippines, which is accompanied by well-cut features of advancement towards west, i.e. the South China Sea. Before long, intense convection breaks out in the whole area of the sea, followed by the summer monsoon. As shown in the study by Chen, Liu and Wang et al[10], cloud bands powering the summer monsoon in the South China Sea could be categorized by source of origin into 1) tropical pattern contributing from the equator, 2) extratropical pattern contributing from the north and 3) integrated pattern contributing by both tropical and extratropical areas. For the 18 years their work covers, 12 of them have cloud bands originating from the tropics, suggesting the role of tropical disturbances in causing the onset of summer monsoon in the South China Sea in most of the years. Conducting a thorough survey, we also find that convection forms and develops around the Philippines prior to the onset of summer monsoon in the sea in most of the years, which implies that active convection in the former just before the onset may also be one of the underlying factors.

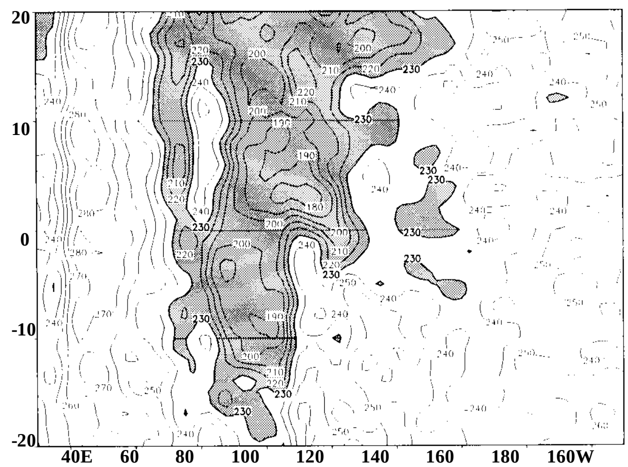

Fig.2 Time-longitude cross section of the composite OLR along 10 °N. Shaded areas denote the OLR values less than 230 W/m^2 with contour interval 10 W/m^2. The ordinate is t / day.

Using the ECMWF data from 1980 to 1986, Chang and Chen[6] studied the development of 850-hPa surge of southwesterly air flow over northern South China Sea and found that the acceleration of the southwesterly flow in May depends a mid-latitude baroclinic frontal system, which moves south to reach the coast of south China and stay quasi-stationary over some point and a southwesterly flow prevails to the south. This is a mid-latitude system that may cause the onset of summer monsoon in the South China Sea. To confirm whether it does have such effect, Fig.3 gives

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temporal evolution of composite OLR field on 115°E. The figure shows that the region of South China Sea is controlled by a high-OLR zone (5°N ~ 20°N) before the onset of monsoon, which correspond respectively to the cloud bands of ITCZ and quasi-stationary front in south China. Three to four days before the onset, as shown clearly in the figure, the low-OLR zones corresponding to the quasi-stationary front begins decreasing in magnitude but increasing in domain and expands south to northern South China Sea. In the meantime, ITCZ begins traveling north and expands to the southern part of the South China Sea. When cloud bands in the north and south of the sea enlarge rapidly to its central part, the summer monsoon sets off in the whole of the sea, forming features of rapid onset within the region. The study shows that the development of disturbances on the quasi-stationary front on the coastal areas of south China could have, as indicated by Chang et al[6]'s suggestion, some degree of impact on the summer monsoon in the South China Sea. As regards what effects the quasi-stationary coastal front is subjected to and what their precursory signs may be, discussions will be held in the next section.

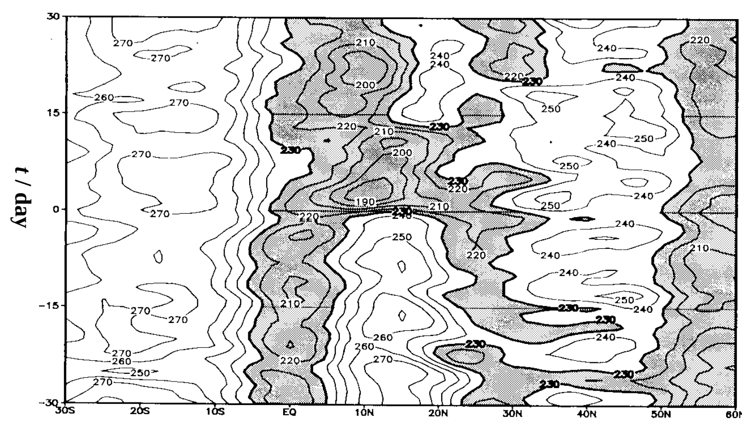

Fig.3 Time-latitude cross section of the composite OLR along 115 °E. Shaded areas denote the OLR values less than 230 W/m^2 with contour interval 10 W/m^2.

5 EVOLUTION OF 850-hPa TROPOSPHERIC WIND FIELD AROUND THE OUTBREAT OF SOUTH CHINA SEA SUMMER MONSOON

5.1 *Evolution of horizontal flow field at 850 hPa*

Fig.4 gives the composite wind field at 850 hPa obtained through the same method with Fig.2. On Day –20 (figure omitted), the northern part of Arabian Sea and South China Sea is controlled by anti-cyclonic circulation, the western edge of the subtropical high of the west Pacific is locating in the central part of Indo-China Peninsula and a northeast-southwest-aligned trough is over the southern end of the Indian Peninsula. The trough's trailing northwesterly flow dominates the whole of the Indian Peninsula while its preceding westerly flow joins the easterly flow on southeast side of the subtropical high over the "continental bridge" and Indo-China Peninsula. It may attribute to the fact that convection first develop in this region when the Somalia cross-equatorial flow is still

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Fig.4 Daily mean 850 hPa wind field for selected day as marked on the top left corner, -6, -4, -2, 0 day, with respect to the summer monsoon onset over SCS as the zero day, composed for 17 years (1980~1996). Shaded areas denote the wind speed greater than 10 m/s .

quite weak. On Day –10 (figure omitted), the anti-cyclone formally controlling the northern Arabian Sea has now moved to North Africa, the Somalia cross-equatorial flow has much strengthened, the west Pacific subtropical high has withdrawn east to eastern Indo-China Peninsula and the trough along the eastern coast of Indian Peninsula is also much increased, whose preceding southwest flow meets the southwesterly flow on the northwest side of the subtropical high. This converged southwesterly flow has controlled northern Indo-China Peninsula and coastal areas of south China. On Days –6 to –2, the Somali jet stream has gained much strength, the Bay of Bengal trough has deepened further and the Indian Peninsula is still controlled by strong northwesterly flow behind the trough. A strong equatorial westerly wind is generated on the southern tip ahead of the trough near 75°E ~ 90°E, with the maximum above 10 m/s (as indicated by shaded portion in the figure). It expands significantly to the east and north from Day –6 to –2. In addition, what the wind field undertakes another obvious change in this period is that there is on Day –4 a tropical disturbance being similar to easterly wave within the easterly belt south of the subtropical high in the west Pacific, which gains further development from Day –4 to Day –2 and forms a closed cyclonic circulation center on Day –2. With the westward movement and development of this disturbance, the ridge on the western section of the west Pacific subtropical high weakens significantly and withdraws east and the southwesterly, formally locating on the south China coast, begins advancing southward, and the equatorial westerly before the trough over the Bay of Bengal also expands east. On Day 0, what is the largest difference of flow field between the monsoon onset day and two days before it is that the west Pacific subtropical high withdraws east to areas east of the Philippines and the southwesterly controls the whole region of South China Sea. The strong equatorial westerly near 75°E ~ 95°E enlarges its domain towards east and north to form a powerful zone of southwest air flow that starts from the southern tip of Indian Peninsula, crosses the Bay of Bengal, Indo-China Peninsula and central South China Sea and plunges into northern Philippines. The air current near 105°E converges into this southwest flow. In the meantime, the disturbance in southern Philippines islands has gained further development and formed a closed cyclonic center by Day +2 (figure omitted).

As shown in the study above, the most significant change before and after the onset of the South China Sea summer monsoon is the eastward retreat of the subtropical high ridge of the west Pacific, the withdrawal of the easterly from the South China Sea and the establishment of the westerly there. As revealed from the evolution of field around the onset of summer monsoon, a significant enhancement of the equatorial westerly in equatorial Indian Ocean (75°E ~ 90°E) about 6 days before the onset is another major feature in the period leading up to the monsoon. Such role of

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the equatorial westerly is also emphasized in earlier studies[11], which suggest that its establishment in 75°E ~ 90°E is a prerequisite condition for the establishment of summer monsoon in East Asia. Next, we will have more discussion on the causes for abrupt increase of the equatorial westerly.

5.2 *Causes for abrupt increase of equatorial westerly in Indian Ocean and links of circulation between Southern and Northern Hemispheres*

Fig.5 gives the time-latitude cross-section of composite fields for the zonal wind between 75°E and 90°E both before and after the onset of summer monsoon in the South China Sea. It clearly shows that an obvious process of strengthening has taken place in the equatorial westerly between the onset day of the monsoon and 6 ~ 7 days before it in regions from the equator and 5°N, with the maximum more than 10 m/s. Fig.5 shows another interesting phenomenon: Whenever the westerly enhances in the equatorial region, it accompanies with a similar process of the easterly flow near 15°S over periods leading up to it. It may indicate that the increase of equatorial westerly in 75°E ~ 90°E may be associated with disturbances in the Southern Hemisphere. To examine whether synoptic systems in the hemisphere should have any impact on changes of intensity of equatorial westerly in 75°E ~ 90°E, Fig.6 plots the variation over time of the air flows crossing the equator around the onset of summer monsoon in the South China Sea. It shows that the Somali jet is significantly increasing over time around the point of monsoon onset. The cross-equatorial flow heading north is present near 85°E and has undergone a process of large enhancement just a few days before the onset. The process is consistent with that of the equatorial westerly in 75°E ~ 90°E. It can be drawn that the enhancement of the equatorial westerly in 75°E ~ 90°E before the onset of summer monsoon in the South China Sea is associated with the abrupt increase of easterly flow on the northern side of the Mascarene high over the southern Indian Ocean in the Southern Hemisphere. By increasing the north-going cross-equatorial air flows over Somali and near 85°E, it enables the equatorial westerly to set off in the upper stream of the sea in 75°E ~ 90°E. Huang and Tang[12] pointed out that two of the most essential basic members in the whole summer monsoon system of East Asia were the subtropical high in west Pacific and the Mascarene high in the south

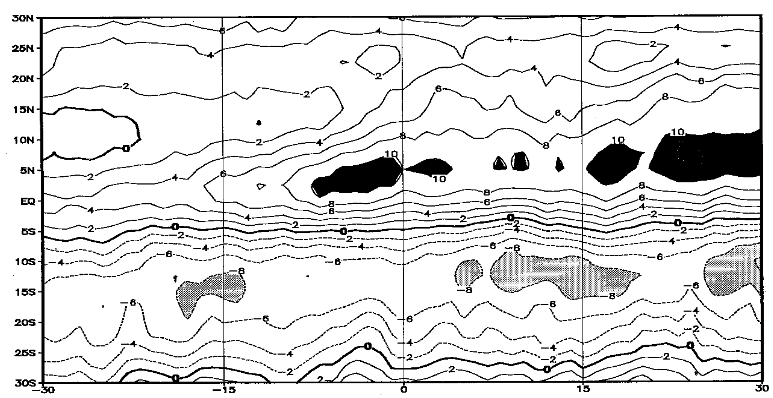

Fig.5 Time-latitude cross section of the composite 850 hPa zonal wind along 75°E ~95 °E . Zonal wind with its values greater than 10 m/s or less than –8 m/s is shaded. Contour interval is 2 m/s.

Indian Ocean, the intensity of the latter being capable of having influence on the changes of intensity in East Asian summer monsoon. While they focus on the effect of the Mascarene high on the summer monsoon, our results indicate similar creation of the equatorial westerly in 75°E ~ 90°E before the summer monsoon due to the changes in the intensity of the Mascarene high in southern

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Indian Ocean. It suggests well that there is significant interaction between the two hemispheres. What is also shown in Fig.6 is that a significant increase also exists with the cross-equatorial flow near 105°E just before the onset of the summer monsoon. It appears that the strengthening of the cross-equatorial flow is associated with the fact that the equatorial westerlies in southern South China Sea and disturbances around the Philippines have earlier development.

Fig.7 gives the time-latitude cross section of mean zonal wind between 100°E and 125°E. It

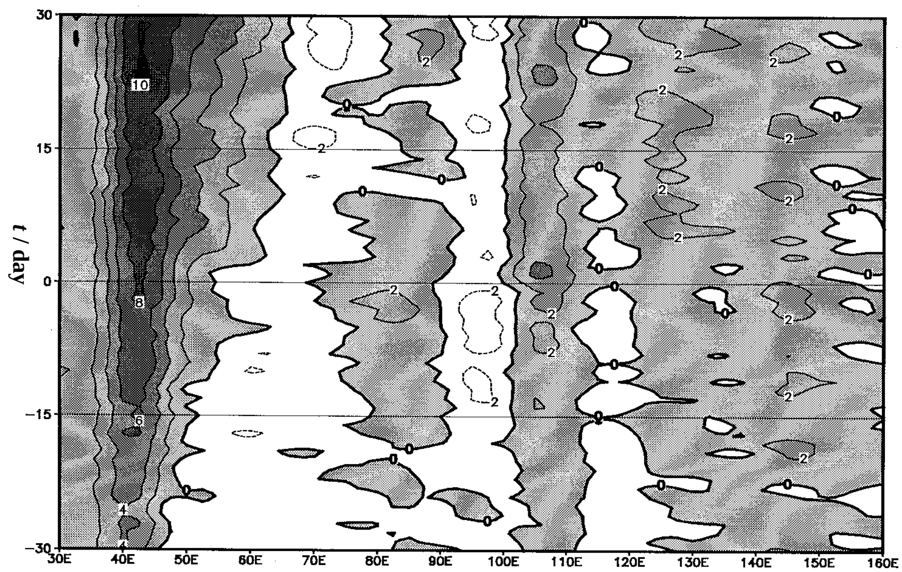

Fig.6 Time-longitude cross section of composite 850 hPa meridional wind along the equator. Shaded area denotes the wind speed greater than 0. Contour interval is 2 m/s.

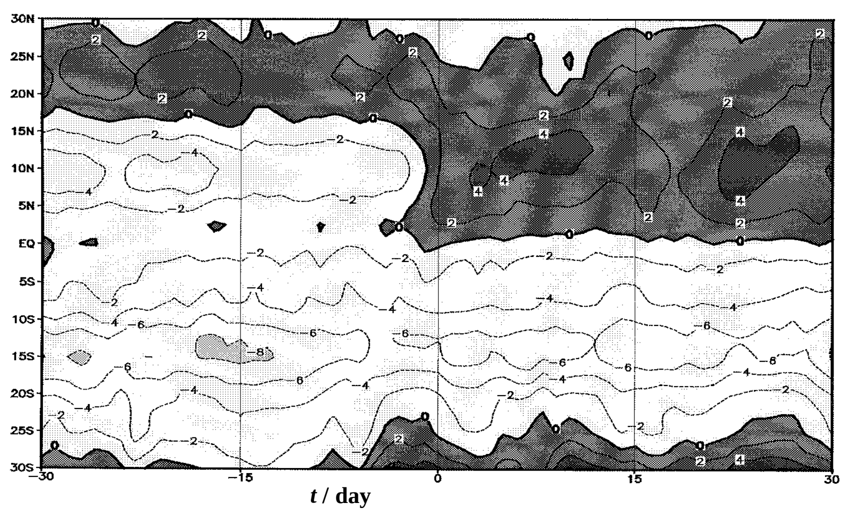

Fig.7 Time-latitude cross section of the composite 850 hPa zonal wind along 100°E ~125 °E. Zonal wind with its values greater than 0 m/s or less than –8 m/s is shaded. Contour interval is 2 m/s.

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shows that the equatorial westerly in the southern waters and the westerly in the northern waters are already established before the summer monsoon breaks out. While the equatorial westerly and the local westerly in southern South China Sea are advancing separately towards the central part, summer monsoon is set off throughout the whole region of the sea. In addition, about 15 days before the establishment of the equatorial westerly in the southern part of South China Sea, the easterly flow on the north side of the Australian cold high (near 15°S) also experiences an obvious enhancement. It can be inferred together with Fig.6 that prior to the onset of the South China Sea summer monsoon, the increase of equatorial westerly in southern part of the sea is also linked with abrupt strengthening of the cold high in Australia over preceding periods.

Summarizing from what is presented above, we know that about 15 days before the onset of the South China Sea summer monsoon, the Mascarene high in the Southern Hemisphere and the Australian high are strengthening at the same time and affect the appearance, through the cross-equatorial flows near 85°E and 105°E, of the equatorial westerlies upstream of South China Sea in 75°E ~ 95°E and in the southern part of the sea. Huang and Tang[13] pointed out that there is close relationship between the Mascarene high in Southern Hemisphere and the Australian high and the increase of the former would, via the dispersion of energy, result in the strengthening of the Australian high, which is downstream on the long ridge of a quasi-stationary wave, thus increasing the cross-equatorial flow near 105°E and diverting it to strengthen the equatorial westerly. Yang and Huang[14] used the GCM to simulate the effects of intensity change of the Mascarene high on the general circulation and suggested that it was really possible for the strengthened Mascarene high to increase the Australian high through energy dispersion. Going with it, the cross-equatorial flow at 105°E ~ 120°E enhanced, cyclonic circulation developed from southern South China Sea to the Philippines and precipitation increased. As shown in the previous part, the appearance of convection around the islands of Philippines just before the onset of summer monsoon may somewhat affect the process itself. Again, the study here further indicates such possibility that the development of convection and disturbances near the Philippines are associated with the strengthening of the Australian cold high and the Mascarene high.

5.3 *Effects of strengthened equatorial westerly in Indian Ocean on onset of South China Sea summer monsoon*

The study above has indicated that before the onset of the South China Sea summer monsoon, the equatorial westerly at 75°E ~ 95°E had an obvious process of strengthening. But how does it affect the onset of the monsoon? Fig.8 gives the time-latitude cross section of mean zonal wind between 2.5°N and 5.0°N around of point of onset. It shows that the earliest of the equatorial westerly appeared between 75°E ~ 95°E and strengthened with time, acquiring the largest intensity a few days before the onset with maximum wind more than 12 m/s. With the increase in intensity, the equatorial westerly rapidly expands east to arrive in the southern part of South China Sea and equatorial part of the Pacific Ocean (reaching 135°E at the most eastern point). It joined the equatorial westerly that was formed by crossing the equator near 105°E turning the direction of movement. It is now known that the abrupt increase and eastward advancement of the equatorial westerly at 75°E ~ 95°E is favorable for the strengthening of the westerly in the southern part of South China Sea. As indicated in the foregoing discussion of evolution around the point of onset of the summer monsoon, the strengthening and southward progression is also one of the important factors. In the meantime, the evolution of horizontal flow field at 850 hPa around the onset also indicates that the southwest flow in front of the trough in the Bay of Bengal significantly expands to the northeast when the equatorial westerly rapidly enhances at 75°E ~ 95°E. For more discussion of its

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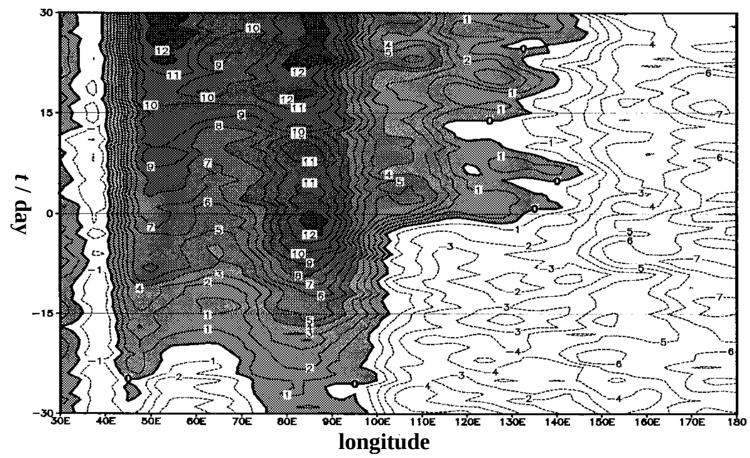

Fig.8 Time-longitude cross section of the composite 850 hPa zonal wind along 2.5°N ~5.0 °N. Shaded area denotes the wind speed greater than 0 m/s. Contour interval is 1 m/s.

role in strengthening and southward-pushing of southwesterly flow in the coastal areas of south China, we selected a number of points from the equatorial Indian Ocean (80°E, 0°) to the coast of south China (120°E, 25°N) for observation of evolution of zonal wind over time (figure omitted). The selected points are plotted on the ordinate of the figure. It shows that the coastal areas of south China are controlled by component of stable westerly while the central part of South China Sea by the easterly on the southern side of subtropical high in the period leading up to the onset. It also shows that about 6 days before the onset of summer monsoon, the equatorial westerly in the Indian Ocean has a process of significant enhancement with the maximum more than 12 m/s. With its increase in intensity, the westerly component rapidly expands to the northeast till the central part of Indo-China Peninsula and northern South China Sea, in which it merges with the westerly component along the south China coast and induces the westerly to press southward. From the evolution of OLR with time (figure omitted), it clearly shows that severe convection with OLR smaller than 190 W/m^2 is produced north of the equatorial westerly at 75°E ~ 95°E when the latter intensifies to 12 m/s. The convection moves northeast accompanying the equatorial westerly that expands east and north and migrates to northern Bay of Bengal on the day of monsoon breaking out in the South China Sea and has maintained a strong presence there ever since. The figure also reveals that as the strong convection moves to the northern part of the Bay of Bengal, disturbance arising from the convection also makes swift expansion to the east to cover northern Indo-China Peninsula and northern South China Sea before connecting with frontal cloud systems on the coast of south China, making it develop and move southward. To summarize, the abrupt intensification of westerly flows in the equatorial Indian Ocean is important for the onset of the summer monsoon. It is achieved by the eastward expansion of the equatorial westerly for establishment and enhancement of its counterparts in the southern part of the sea on the one hand, and north movement of the westerly and inducement of convection disturbance over the Bay of Bengal and its northward and eastward transportation on the other, so that the westerly on the south China coast is strengthened and pushed southward. Owing to joint action by the two systems, summer monsoon is able to set off across the whole region of the sea. As a last note, it should be pointed out that the features of the establishment of summer monsoon in the South China Sea in 1998 are consistent with those that are revealed with the composite analyses above[15], suggesting that the results so obtained well reflect the reality.

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6 CONCLUDING REMARKS

a. Before the onset of summer monsoon in the South China Sea, convection appears first in the Indo-China Peninsula and then around the Philippines when it is near of point of onset. It suggests that the appearance of convection activity over the islands is also one of the reasons for the onset of summer monsoon in the sea.

b. A significant intensification has happened to the equatorial westerly in the equatorial Indian Ocean (75°E ~ 95°E) before the monsoon onset. Its role in the process is realized by the eastward expansion of the equatorial westerly for establishment and enhancement of its counterparts in the southern part of the sea on the one hand, and north movement of the westerly and inducement of convection disturbance over the Bay of Bengal and its northward and eastward transportation on the other, so that the westerly on the south China coast is strengthened and pushed southward, leading to the overall onset of the summer monsoon.

c. The strengthening of equatorial westerly in the Indian Ocean and southern South China Sea are separately associated with the enhancement of the Mascarene high, Australian high and cross-equatorial north-going flows in Somali and at 85°E and 105°E.

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