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SEASONAL AND INTER-ANNUAL VARIABILITY OF THE SOUTH CHINA SEA WARM POOL AND ITS RELATION TO THE SOUTH CHINA SEA MONSOON ONSET

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ABSTRACT: The South China Sea warm pool interacts vigorously with the summer monsoon which is active in the region. However, there has not been a definition concerning the former warm pool which is as specific as that for the latter. The seasonal and inter-annual variability of the South China Sea warm pool and its relations to the South China Sea monsoon onset were analyzed using Levitus and NCEP/NCAR OISST data. The results show that, the seasonal variability of the South China Sea warm pool is obvious, which is weak in winter, develops rapidly in spring, becomes strong and extensive in summer and early autumn, and quickly decays from mid-autumn. The South China Sea warm pool is 55 m in thickness in the strongest period and its axis is oriented from southwest to northeast with the main section locating along the western offshore steep slope of northern Kalimantan-Palawan Island. For the warm pools in the South China Sea, west Pacific and Indian Ocean, the oscillation, which is within the same large scale air-sea coupling system, is periodic around 5 years. There are additional oscillations of about 2.5 years and simultaneous inter-annual variations for the latter two warm pools. The intensity of the South China Sea warm pool varies by a lag of about 5 months as compared to the west Pacific one. The result also indicates that the inter-annual variation of the intensity index is closely related with the onset time of the South China Sea monsoon. When the former is persistently warmer (colder) in preceding winter and spring, the monsoon in the South China Sea usually sets in on a later (earlier) date in early summer. The relation is associated with the activity of the high pressure over the sea in early summer. An oceanic background is given for the prediction of the South China Sea summer monsoon, though the mechanism through which the warm pool and eventually the monsoon are affected remains unclear.

Key words: South China Sea warm pool; seasonal and inter-annual variability; South China Sea monsoon onset

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1 INTRODUCTION

It is well known that the region spanning from the tropical western Pacific to tropical Indian Ocean concentrates the largest bulk of warm water in the world, part of which is always above 28°C for the whole year and known as a "warm pool". It is called the west Pacific warm pool for the tropical western Pacific Ocean and the Indian Ocean warm pool for the tropical Indian Ocean. For the South China Sea which is between the two, warm water higher than 28°C can also be found there in most of the year. It is known as the South China Sea warm pool. The South China Sea is situated on the passage of a cross-equatorial air current that originates from the Southern Hemisphere in early summer. It is therefore easily conceived that the thermodynamic conditions of

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the South China Sea warm pool plays an important role in the onset of the summer monsoon in the region and in turn the timing and intensity of the monsoon contributes importantly to the variation of the local warm pool in the subsequent period. In view of such essential predictive significance of the warm poll placing on the summer monsoon in the South China Sea, quite a few researchers[1~7] have devoted in the study of the effects of the anomalies of South China Sea SST on the weather and climate in China and achieved a lot of results that have rich implications.

There is no much work on the study of the climatic characteristics of morphology, size and intensity of warm pools and their relationship with the onset of summer monsoons in the South China Sea. Discussing the temporal and spatial variations with the 20-m layer sea temperature, He[4] indicates that a well-defined seasonal pattern of being weak in winter vs. strong in summer is present in the variation of the warm pool in the South China Sea, which goes in the opposite annual phase with the warm pool in the west Pacific but in the same annual phase with that in the equatorial eastern Pacific. Yan[8] also argues that the South China Sea warm pool (⩾28°C) appears just about a month before the onset of the summer monsoon there. With the onset, the axis zone of the maximum sea temperature in the South China Sea warm pool coincides with an intense convection zone in the subsequent period.

Up till now, there has not been any definition for the South China Sea warm pool that is as specific as that for the west Pacific warm pool. In this work, the sea temperature (T = 28°C) is used to define its domain and the number of gridpoints encircled by the 28°C contour and the number of weighted gridpoints encircled by contours warmer than 28°C are used to denote respectively the area and intensity of the warm pool. The intensity of the warm pool is calculated as follows. When $28°C \leqslant T < 29°C$, it is set as 1; when $29°C \leqslant T < 30°C$, it is set as 2; when $T \geqslant 30°C$, it is set as 3. By calculating the anomalies of the warm pool area and intensity for elimination of its annual variation, indexes of the warm pool area and intensity are obtained, which are then used to study the characteristics of inter-annual variation. Our work first employs the Levitus data to analyze the 3-dimensional structure and seasonal fluctuations of the South China Sea warm pool and then uses the 1982 ~ 1997 monthly SST data (1° lat. ×1° long. mesh, as provided by NCEP/NCAR) to derive area and intensity indexes for the warm pool. Afterwards, their variation features are studied in the relation with warm pools in the west Pacific and Indian Ocean and possible influence of the inter-annual variation of the South China Sea warm pool on the summer monsoon onset are discussed, so as to seek foundations for the prediction of the summer monsoon.

2 SEASONAL VARIATION OF SOUTH CHINA SEA WARM POOL

Fig.1 gives the seasonal distribution of SST that has been averaged over years (1982 ~ 1997). To have a understanding of the background of the tropical Pacific-Indian Ocean warm pool against which the South China Sea warm pool undergoes seasonal variations, the paper presents the SST distribution within the domain bounded by 40°E ~ 80°W and 30°S ~ 30°N. As shown in the figure, the warm pool for the whole of tropical Pacific and Indian Oceans is southward located in the boreal winter when the sun is straight above the Southern Hemisphere and the 28°C contour is south of 10°N. In February, particularly, warm water higher than 28°C is present only in the Bay of Thailand and the outlet linking the southern South China Sea with the Java Sea, a phenomenon that is resulted from frequent advancement of Asian winter monsoon and reduced water temperature over extensive parts of the South China Sea. The figure then shows the coverage in May of warm water of higher than 28°C over all but the northern part of the sea as the sun travels across the equator and enters the Northern Hemisphere and the bulk of the warm pool also accompanies it in the northward shift. The warm pool is shown to acquire its prime intensity in summer when the sun

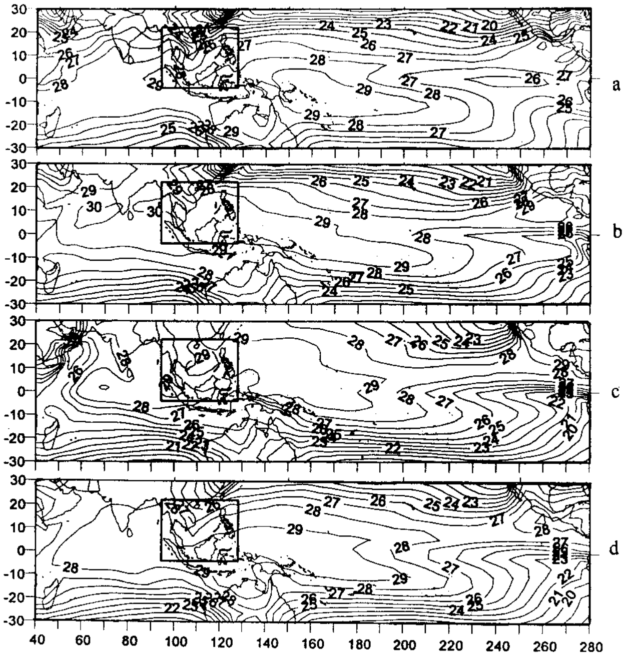

Fig.1 Seasonal distribution of warm pool SST in the South China Sea and tropical Pacific-Indian Ocean in February (a), May (b), August (c) and November (d)

directly insolates over the Tropic of Cancer and the whole South China Sea is dominated by warm water above 28°C. In autumn, the 28°C contour and warm pool begin moving south as straight incidence area retreats south. The figure finally presents the appearance of seawater at 26°C in November in the northern part of the sea as the solar incidence and the 28°C contour move southward and so does the warm pool. It is apparent that the changes are closely related with corresponding changes of solar radiation caused by those in the solar azimuth of elevation.

The current work has calculated the monthly mean area and intensity over years for the warm pools in the South China Sea, west Pacific Ocean, Indian Ocean and the entire tropical Pacific-Indian Oceans. Fig.2 presents their annual variations in area and intensity. As shown in the figure, the minimum area and intensity appear in January, the maximum area in August, the maximum intensity in June, with the period May through October having little changes in area and intensity, for the South China Sea warm pool; the minimum area and intensity appear in January, the maximum area and intensity in September for the west Pacific warm pool while the minimum area and intensity appear in August and the maximum in April for the Indian Ocean warm pool. The differences in the seasonal variation of the three warm pools may be related with their individual geographical locations. For instance, the warm pool in the Indian Ocean varies in a way different from those in the west Pacific and the South China Sea, being out-of-phase with that in the west Pacific in prime summer when the minimum area and intensity occur. It may be associated with the fact that northern Indian Ocean is adjacent to a mass of landform. It is clear from Fig.1 that as the warm pool in the Indian Ocean is expanding northward when it changes from winter to summer, its northern boundary is so blocked by the South Asia continent that the area does not have any gains while it dramatically decreases in the part of the Southern Hemisphere, reducing in the boreal summer the warm pool to the minimum in the year. In contrast, the South China Sea warm pool shows annual variations of its own in apparent association with where it is geographically located

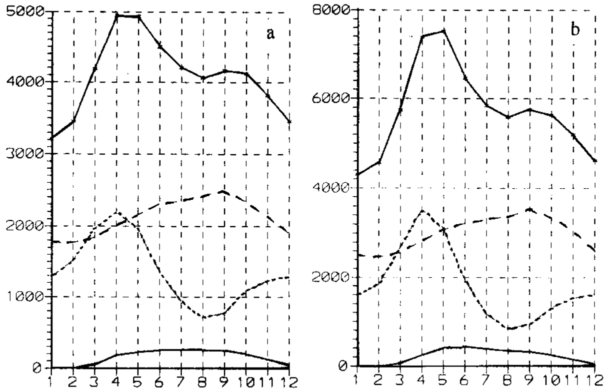

Fig.2 Annual variation of the index in area (a) and intensity (b) for the warm pool in tropical west Pacific-South China Sea-Indian Ocean

and extended. There are generally two maximal centers across the entire tropical Pacific-Indian Oceans, the larger one appearing in April ~ May, which is contributed mainly by the Indian Ocean warm pool and the secondary in September, which is mainly a result of the warm pool in the west Pacific. It is noted that the maximum area is 1 month and the maximum intensity 3 months earlier in the South China Sea warm pool than in the west Pacific, a phenomenon that may relate to the closeness of the South China Sea to the Asian continent, the smaller depths of water and more rapid response to thermodynamics over land as compared to the tropical west Pacific.

To have a clearer understanding of the vertical distribution of sea temperature in the South China Sea warm pool, vertical distributions of monthly mean SST at depths 0 ~ 300 m are drawn for the year in the domain spanning from 0.5°N to 24.5°N and from 107.5°E to 119.5°E. Specifically in January and February, homogeneous waters of 26°C are distributed for depths of upper 40 m south of 14°N, with mild vertical and horizontal gradient of temperature. The horizontal gradient is, however, quite large (close to 0.5°C/latitude) north of 14°N due to the impact of cold air activity; the vertical homogeneous layer is between 30 and 50 m thick with no trace of warm water at 28°C. When it gets to spring, the warm pool rapidly develops and moves northward, the 28°C contour arriving at 6°N in March, 15°N in April, and 19°N in May, and forming a 40-m thick zone of warm water of 28°C between 10°N and 12°N with the highest water temperature at 29.5°C. The 28°C warm water is dominant over the entire South China Sea from June to September with warm water thicker in the south than in the north and the thickest point being 50 m. The northern boundary withdraws southward from October, the 28°C contour reaching 18°N in October, 8°N in November, and 3°N in December, with the warm water reducing the thickness by the month. Fig.3 is the vertical distribution of seawater temperature in the South China Sea warm pool in February, May, August and November.

Using the Levitus data to calculate the horizontal distribution of the depths of the 28°C seawater in the South China Sea warm pool (by taking the readings at intervals of 1 m), we know that there is basically no presence of warm water above 28°C in January in the sea; the warm water appears in the northern Bay of Thailand in February, though with limited domain and thickness (30 m); March is the month that sees the occurrence of warm water with a 25-m thickness at the inlet of the Java Sea next to the southern tip of the South China Sea, which then swiftly expands towards the northeast by the month and brings in April the 28°C contour to 18°N, the northernmost point of its shift, the thickness being over 20 m over large portions of the sea. The analysis also indicates that the whole region is controlled by the 28°C warm water from June to September with

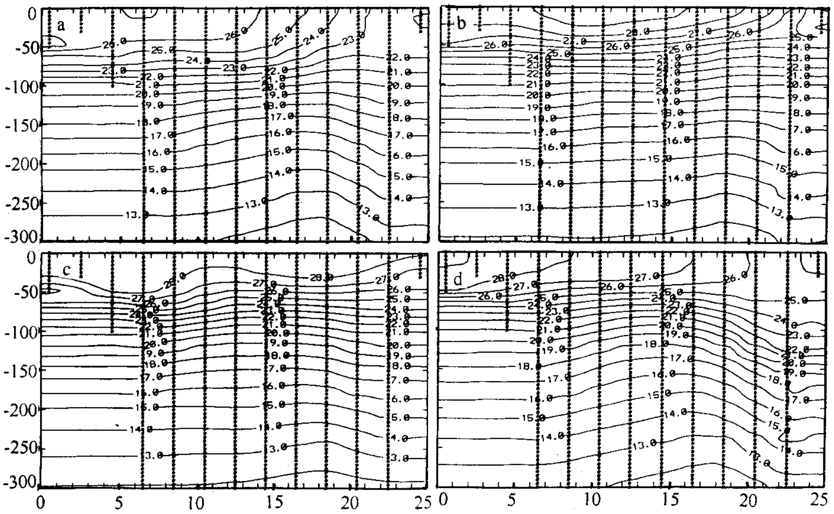

Fig.3 Seasonal variation of vertical distribution of sea temperature along the section from 0.5°N, 107.5°E to 24.5°N to 119.5°E in the South China Sea in February (a), May (b), August (c) and November (d)

most of the sea in depths over 30 m and maximum thickness at 55 m; the warm water rapidly withdraws from northwest to southeast in October ~ November such that it remains west of the northern Kalimantan Island on the southeast side of the South China Sea in December. Fig.4 is the distribution by thickness of the 28°C warm water in March, April, July, and October, which shows the phases of growing (March ~ May), intensifying (June ~ September), and decaying (October ~ November) for the South China Sea warm pool. In general, the warm water rapidly extends towards the northeast and northwest from early spring until it dominates the whole sea. The axis is southwest-northeast aligned with the primary section going through the steep slope off the coast of the northern Kilimantan ~ western Palawan Island, and the layer of warm water is relatively shallower on the side close to the continent and the Indo-China Peninsula.

3 INTERANNUAL VARIATION OF SCS WARM POOL AND ITS RELATION WITH WEST PACIFIC AND INDIAN OCEAN WARM POOLS

With monthly SST data (for a mesh of 1°long. × 1°lat.) from 1982 to 1997 which is provided by NECP / NCAR, computations are done for obtaining the indexes of area and intensity of the warm pools in the South China Sea, west Pacific and Indian Oceans. To remove the effects of perturbations at scales below 5 months, a 5-month running filter is conducted for the area and intensity indexes of the warm pools. Fig.5a gives the curves of inter-annual variations of the intensity index that suggests that there are identical trends of variation over long periods for all of the warm pools, like the high-temperature periods in 1983, 1987 ~ 1988, and 1997, and low-temperature periods in 1984 ~ 1986, 1989, and 1993. Fig.5b is the result of spectral analysis of the intensity index for all the warm pools. For easy comparison with the ENSO cycle, the figure also gives the FFT spectral analysis for the SST anomalies in Nino3 (4°S ~ 4°N, 150°W ~ 90°W). It is seen that the warm pools are all predominantly with a primary period around 4.8 years, being consistent with that for Nino3. In addition, there is a secondary period at 2.5 years for the warm pools in the South China Sea and the Indian Ocean and an ill-defined period at about 2 years for the west Pacific warm pool. These features are also confirmed in the cross-spectral analysis between the South

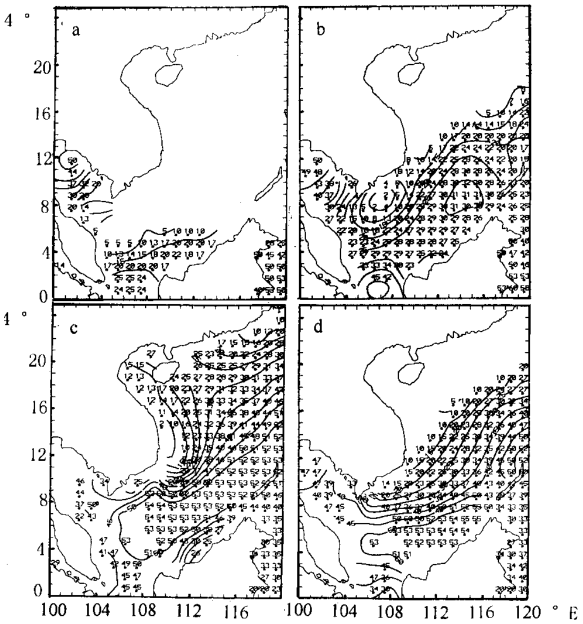

Fig.4 Seasonal variation of horizontal distribution of the warm pool thickness in the South China Sea for (a) March, (b) April, (c) July and (d) October

China Sea and the west Pacific/Indian Ocean (Fig.5c). The FFT study of the area index also points to the same result (figure omitted).

To investigate the mutual relationship between the South China Sea and west Pacific in terms of the warm pool varying at scales of about 1 year, we have calculated their time-lagging correlation. As shown in Fig.6, the area index for the warm pool in the South China Sea correlates the best with that in the west Pacific and the Indian Ocean by 1 or 0 month lagging, respectively. Examination of the correlation curves appears to show that the area for the west Pacific warm pool first changes, followed by those for the South China Sea and Indian Ocean, which happen almost simultaneously and have good correlation with each other for up to a few months. For the intensity index, the 5-month lagging correlation is the best between the South China Sea and the west Pacific and can be reliable till the current month. As in the area correlation, it is also almost concurrent between the two regions. Of the correlations above, the best one is found between the South China Sea and the Indian Ocean as far as the intensity and area indexes are concerned, which are respectively 0.78 and 0.71 for the simultaneous periods with the significance level surpassing 0.001.

It is now obvious that the warm pools in the west Pacific, South China Sea and Indian Ocean are all active within the same long period of oscillation (about 4.8 years), which is consistent with the period of Nino3. In other words, the tropical west Pacific-Indian Ocean warm pool varies in phase with the ENSO cycle and is subjected to the same macro-scale general circulation over the tropical oceans while the South China Sea and Indian Ocean warm pools are both subjected to the air-sea coupling system of the Indian Ocean region that oscillates about every 2.5 years. For time scales of 1 year or so, the warm pool in the South China Sea is in phase with that in the Indian Ocean but lags behind that in the west Pacific. It is obvious that the area and intensity of the warm pool in the former two regions are closely related with that in the west Pacific in addition to their own periodic oscillations. As a matter of fact, the tropical Indian Ocean, South China Sea and tropical south Pacific are all subjected to the ENSO and changes in the location and intensity of the Walker cell in the tropical Pacific inevitably result in responses from the anti-Walker cell in the Indian Ocean. It is therefore almost certain that long periodic oscillations of ENSO will lead to simultaneous response from the 3 warm pools. Besides, both the South China Sea and Indian Ocean are located west of the most intense convection area of the tropical Pacific-Indian Oceans (over the islands of Indonesia) and dominated by the circulation system of the Indian Ocean, causing in-phase oscillations being different from that in the tropical western Pacific. Moving with the intense convection zone in the Walker cell that is active above, the west Pacific warm pool

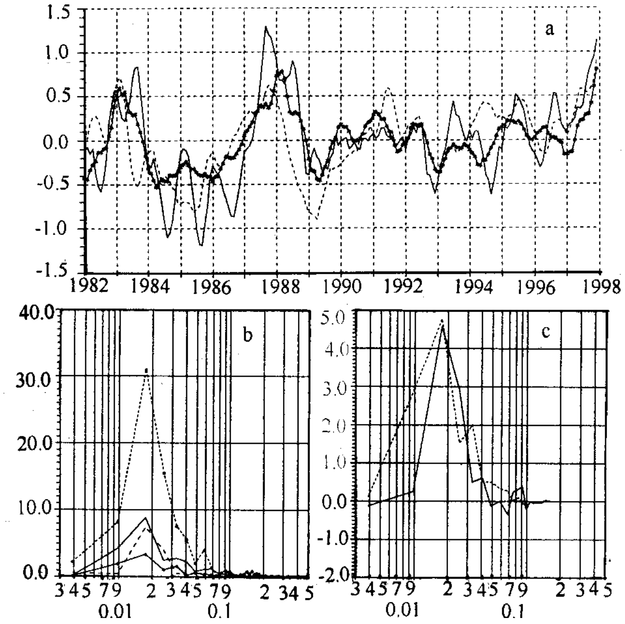

Fig.5 (a) Inter-annual variation of intensity index of warm pools in the South China Sea (solid line), west Pacific (dashed line) and Indian Ocean (dotted- solid line); (b) Autospectrum of the warm pool strength index (line captions as (a) with the cross and dashed line for Nino3); (c) Cross spectrum of the warm pool intensity index for South China Sea vs. west Pacific (solid line) and South China Sea vs. Indian Ocean (dashed line)

produces changes being consistent with the ENSO circulation.

4 RELATION BETWEEN WARM POOL VARIATION AND MONSOON ONSET IN SOUTH CHINA SEA

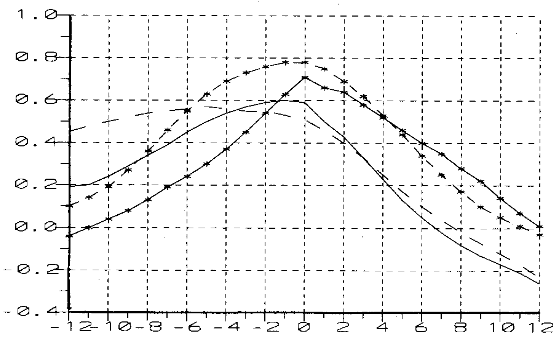

Fig.6 Lag correlation between index of warm pool area (solid line) and intensity (dashed line) for the South China Sea / west Pacific and that of warm pool area (cross & solid line) and intensity (cross & dashed line) for the South China Sea / Indian Ocean

Following the definition of the onset of the South China Sea monsoon given by Liu et al[9], or, it is thought to break out when the OLR values averaged over the region of South China Sea decrease to 235 W/m^2 while the regional mean zonal winds change from the easterly to westerly. In the meantime, specifications by the National Climate Center[10] are used to set the year with monsoon breaking out in the 4th pentad of May or earlier as an early onset year and the year with monsoon breaking out in the 5th pentad of May or later as a late onset year. By this criteria, in the 16 years from 1982 to 1997, late onsets occur in 1982, 1983, 1987, 1988, 1991, 1992, 1993, 1995, and 1997, and early onsets happen in 1984, 1985, 1986, 1989, 1990, 1994, and 1996, for the monsoon in the South China Sea. Fig.7a presents the evolution of the indexes of area and intensity of the warm pool in the sea, in

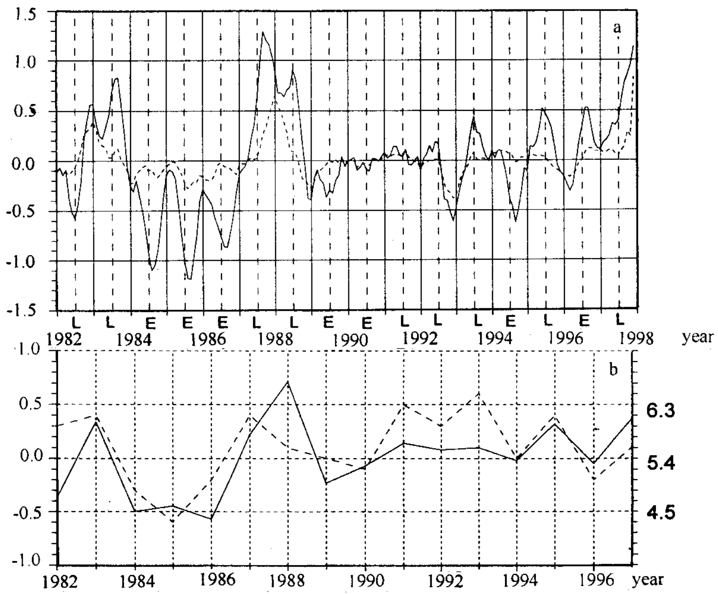

Fig.7 Inter-annual variability of the warm pool area (dashed line) and intensity (solid line) and the monsoon onset (L; late; E: early) in the South China Sea (a) and the date of the South China Sea monsoon onset (dashed line: right ordinate, unit: month. pentad) (b)

which L on the abscissa denotes a late onset year and E an early onset year. It is understood that the late monsoon onsets usually correspond to the years with large area and intensity and the early monsoon onsets usually accompany with the years with small area and intensity, with the exception of 1982. Specially, the intensity index of the South China Sea warm pool is better correlated with the onset of monsoon as compared with the area index. With more thorough study, we find that among 15 out of the 16 years (the exception being 1982), 1984, 1985, 1986, 1989, and 1996 are the years with continuously larger negative anomalies of the intensity index, which all fall in the category of early monsoon onset; 1983, 1988, 1995, 1997 are the years with continuously larger (and 1991 are the year with continuously small) positive anomalies of the intensity index, which all fall in the category of late monsoon onset. In addition, in 1990 and 1994 (1987, 1992, and 1993) which have small negative (positive) index of intensity of warm pool only in April or May, the monsoon has an early (late) onset in the South China Sea. In the preceding winter and early spring of these years, the intensity index is transiting from positive to negative anomalies. In such circumstances, the date of monsoon onset is mainly determined by the changes in the warm pool intensity in the current month (May) in the sea. Fig.7b is the inter-annual variation of intensity index of May and onset dates of the current years for the South China Sea monsoon. It is clear that the correlation is good in all but 1982.

The monsoon broke out in the 2nd pentad of May in 1996, belonging to the early group while it had its onset in the 5th pentad of May in 1997, falling in the late group. Fig.8 is the expendable bathythermograph (XBT) data along the profile of 10°N, 110°E ~ 20°N, 119°E for May 1996 and 1997 across the South China Sea. The observation took place from May 20 to 22 in 1996 and from May 24 to 27 in 1997. On average (Fig.3b), in May the 28°C contour reaches 19°N and the 29°C contour reaches 19°N, with the 28°C warm water generally in the thickness of 30 m. From Fig.8, we know that the 28°C contour arrived at 16°N in May 1996, about 3 latitudes more southward than normal while the 29°C contour was present only in a limited domain. In May 1997, the 28°C contour appeared in the normal position but the 29°C contour arrived at 18°N, about 2 latitudes more northward than normal. Even 30°C appeared in small enclosures. It is now clear that a weak (strong) warm pool year may correspond to early (late) onset of the monsoon in the South China Sea.

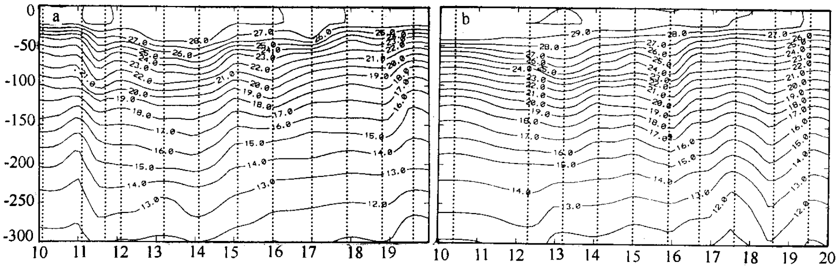

Fig.8 Vertical distribution of sea temperature along the section from 10°N, 110°E to 20°N, 119°E in the South China Sea in the months of May 1996 (a) and 1997 (b)

In their study, Luo and Jin[1] show that when the SST is high, the western ridge of the west Pacific will intensify, develop towards the South China Sea and relocate southward; when the SST is low, the ridge will weaken, withdraw eastward and relocate northward. As indicated in the studies on the monsoon onset in the South China Sea[9,11], the monsoon breaks out in close association with the time when the South China Sea high moves out of the sea. It can then be understood this way: the South China Sea high will be strong (weak), moving out of the sea on a late (early) date and in turn the monsoon will set off late (early) if the warm pool there is strong (weak) in the preceding winter and spring, especially when it comes to the key month (May) for the onset. The results above set up an oceanic background for predicting the timing of monsoon onset in the South China Sea. To be more specific, it is more likely that the monsoon begins late (early) when there is a persistent large positive (negative) anomaly in the warm pool of the South China Sea; it is, however, quite difficult to forecast the monsoon if the warm pool is in a transitory phase between positive and negative anomalies around this season of the year, because the anomaly in May becomes an extra factor in the consideration.

5 CONCLUDING REMARKS

a. The South China Sea warm pool is of considerable seasonal variability, being weak in winter but strong in summer. March is the month when it intensifies substantially so that it expands from waters off the western coast of the northern Kalimantan, at the southern end of the sea, all the way towards the northeast. April and May see the rapid growing period, June through September inclusive have vigorous developing period, October and November mark the rapid decaying period, and December through February inclusive note the weakest period, in the life cycle of warm pool. Its axis stretches from southwest to northeast with the main section going through the steep slope between the northern Kalimantan and western Palawan. The 28°C warm water is 55 m deep at the thickest point. For the seasonal variation, the warm pool in the South China Sea is closely linked with the changes in the solar azimuth of elevation.

b. The warm pools all have 4.8-year periodic oscillations in the South China Sea, west Pacific Ocean and Indian Ocean. Being in the same macro-scale air-sea coupling system, they are closely related with the ENSO cycle. The warm pools in the first two oceanic basins have 2.5-year periodic oscillations and similar inter-annual variations, suggesting that the South China Sea appears to have a closer link with the Indian Ocean than with the west Pacific in terms of the warm pool fluctuation. For the warm pool, the area index is lagging behind by a month and intensity index by 5 months when the South China Sea compares with the west Pacific.

c. The warm pool intensity index is closely related with the monsoon onset in the South China Sea. When the warm pool is persistently strong (weak) in preceding winter and spring, the monsoon will break out late (early); when it transits between positive and negative anomalies in this period, the monsoon will break out late (early) provided that the warm pool is strong (weak) in the current month of onset (May).

The study above has only revealed the possible links that are present between the basic features of the warm pool and the onset of the monsoon in the South China Sea. Physical mechanisms through which the warm pool affects the general circulation and then the monsoon in the region remain unknown. It is of great importance to the prediction of the South China Sea summer monsoon to further investigate these mechanisms.

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