Observational Study on the Onset of the South China Sea Southwest Monsoon

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ABSTRACT

Based on the long-term marine ship observation data, records of meteorological stations and High-Reflective Cloud(HRC) data by satellite remote sensing , this paper has studied the circulation patterns and variability in elements during onset and the established periods of the South China Sea(SCS) southwest(SW) monsoon. The averaged date of the onset SW monsoon in the SCS occurs in the middle of May climatologically. The corresponding date for the northern part is little earlier (May 12) and those for the southern parts are little later (May 20). The interannual range of the onset dates is about one month. Following the onset of the SW monsoon, the cloud amount and the precipitation increase while the convection activities enhance over the SCS. But there is a strong spatial heterogeneity within the domain. After onset of the SW monsoon the strong convective area moves northwards, while the SCS rain band moves to the center and north. Sea surface temperature(SST) increases rapidly before the onset and the leading time is about one month. The increment of SST supplies heat and vapor for the onset. From April to May the surface heat fluxes display obvious changes, e.g., latent heat exchange and evaporation enhancement. It is one of the reasons why the SW monsoon bursts firstly in the SCS.

Key words: South China Sea, Southwest monsoon, Onset, Observational study

I. INTRODUCTION

The South China Sea is a semi-enclosed basin surrounded by the continents and the islands. Although the SCS,the western Pacific warm pool, the Bengal Bay and the Arabian Sea lie in the tropics, the SCS has its independent oceanic circulation and holds a special tropical monsoon climate due to its geographical location and the configuration of lands and seas.

The climatological research has developed rapidly since the 1970s, for example, series of climate atlas were issued, and achievements about formation and variability of the SCS climate were obtained, etc. (Liang, 1991; Chen et al., 1991; Yan et al., 1993). Researches on the East Asian Monsoon formation, on monsoon circulation system and about impacts on weather and climate show the important roles of the SCS by indicating that Asian Summer Monsoon bursts earliest in the north part of the SCS, then expands northward to the China continent and the western Pacific south to Japan and westward to the Bengal Bay and India. The SCS monsoon not only supplies heat and vapor for precipitation in Guangdong–Guangxi, the Changjiang–Huaihe River valley, Taiwan and Japan, but also impacts the northeastern Pacific and America through the way of teleconnection (Chen et al., 1991; Ding et al., 1994; Tao et al., 1988). One of the key problems for the studies of the East Asian Monsoon and prediction of summer rainfall is to detect mechanisms involved in the onset of the SCS monsoon, to understand vapor accumulating and transporting as well as air–sea interaction in the SCS.

The previous researches always focus on structures of the East Asian Monsoon and its impacts on the atmospheric general circulation. Because of the lack of the observational data, researches on the onset process and regional characteristics are lacking. This paper uses the long-term data from island stations, coastal stations, and marine ship records as well as HRC data from satellite remote sensing (National Oceanic and Atmospheric Administration Environmental Research Laboratories, 1985), and describes the onset process of the SCS monsoon and the corresponding climatological feature, in particular, the variability in the fields of circulation, cloud, precipitation and heat exchange between sea and air.

II. CHARACTERISTICS OF SURFACE WIND FIELD AND THE ONSET DATE OF SW MONSOON

The basic feature of sea surface wind in the SCS is the prevailing of summer and winter monsoons and their alternatives. It is shown in the monthly mean field of wind directions that the summer monsoon appears in the SCS in May and ends in the middle of September, then the winter monsoon sets up in October and lasts to the next March. Wind velocities are weak in April and September when the monsoons reverse. It is contrast to the Indian Monsoon in that the SCS winter monsoon is stronger than the summer monsoon.

The diurnal observation records from April to June in two island stations (Shangchuan, Xisha) over the SCS are analyzed to detect variability of sea surface wind around the onset of the summer monsoon (Fig.1). It is found that the southwesterly begins in April and early of May with little persistent tendency, however, most of events last one to three days and the break intervals are 10 to 20 days with little precipitation during the process. This period is the precursor of the onset of the summer monsoon. After the first or second pentad of May, the southwesterly bursts frequently with long maintenance. The maximum of maintenance is more than 20 days. During this period clouds increase, and convections develop with much precipitation. This period corresponds to the onset of the SW monsoon. The date of the onset over SCS is following:

1. *Northern SCS*

The onset of the summer monsoon in the northern SCS is defined as the time when the 850 hPa (or 925 hPa) southwesterly (wind direction 190°–260°) persists for at least 5 days and maximum speed rises over 10 m / s (reference stations: Hong Kong, Beihai and Yangjiang), and ≥ 8 m / s over Indo-China Peninsula (reference stations: Chiang Mai, Bang Kok and Ubon Rachathani). Based on the strong southwesterly over the areas, the definition makes a

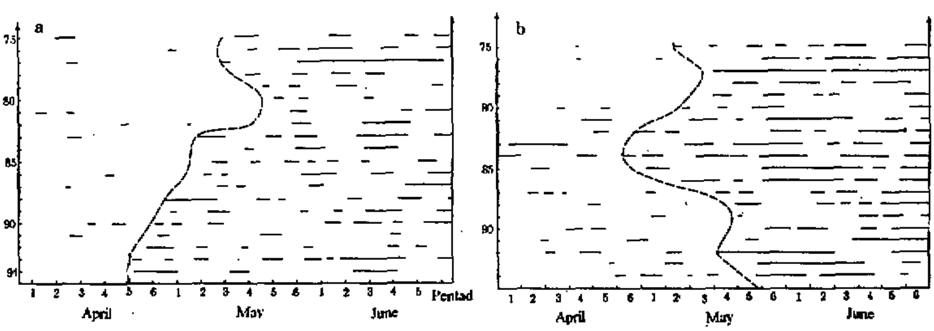

Fig. 1. SW wind date from April to June at Shangchuan island and Xisha.

difference between SW monsoon and the southwest flow in the western subtropical high. The onset date for 1986–1995 was shown in Table 1. It can be seen that the averaged date is May 12, which is slightly later compared to the mean date of the onset (May 10 and May 11) given by Tao et al. (1988) and shen et al. (1983).

Table 1. The Date of SW Mosoon Onset

Year	Northern SCS (20°–22°N)		Xisha (15°50′N)		Nansha (Yongshu) (9°33′N)		Southern SCS (0–5°N)	
	Date	Pentad	Date	Pentad	Date	Pentad	Date	Pentad
1986	5.9	5(2)	5.11	5(3)			5.10	5(2)
1987	5.1	5(1)	5.1	5(1)			6.4	6(1)
1988	5.18	5(4)	5.20	5(4)			5.19	5(4)
1989	5.6	5(2)	5.9	5(2)	5.18	5(4)	5.17	5(4)
1990	5.8	5(2)	5.8	5(2)	5.16	5(4)	5.15	5(3)
1991	5.21	5(5)	5.22	5(5)	6.8	6(2)	6.7	6(2)
1992	5.15	5(3)	5.15	5(3)	5.17	5(4)	5.16	5(4)
1993	5.24	5(5)	5.25	5(5)	6.6	6(2)	6.2	6(1)
1994	5.1	5(1)	5.1	5(1)	5.2	5(1)	5.12	5(3)
1995	5.18	5(4)	5.18	5(4)	5.14	5(3)	5.10	5(2)
Average	5.12	5(3)	5.13	5(3)	5.20	5(4)	5.20	5(4)
Earliest	5.1	5(1)	5.1	5(1)	5.1	5(1)	5.10	5(2)
Latest	5.24	5(5)	5.25	5(5)	6.8	6(2)	6.7	6(2)

2. *Xisha Area*

Xisha station is located in the northern SCS. For most years, the onset date is the same as the areas mentioned above, but later for some years. The averaged onset date at Xisha is May 13.

3. *Nansha Area*

There are no upper–air stations in Nansha areas. However, the surface observational data for this area are highly qualitative and representative. Here the onset of SW monsoon is defined as the time when the surface southwesterly persists for more than 5 days. The averaged date of the onset of SW monsoon for 1989–1995 is May 20 over this area.

4. *Southern SCS*

The southwesterly is weaker in May in this area than in northern SCS. The onset date is defined as the time when the 850 hPa (or 925 hPa) southwesterly persists for at least 5 days (reference stations: Singapore, Knantan, Bintulu, Kota Kinabalu). The averaged date of the onset for 1986–1995 is May 20, which does not differ from the mean date determined by Orgill (1967). It is also similar to the result from Cheang and Tan (1989), who pointed out that the onset of monsoon in 1988 occurred on the 17th May over Peninsular Malaysia and by 19th May, and the southwesterlies have established over Indo–China and the northern Borneo.

It is easily found that there are two sorts of the onset from Table 1. (1) bursting in the south and the north almost simultaneously, (2) earlier in the north and later in the south. On an average, the date of the SW monsoon established earlier in the north than that in the south. The observation fact is consistent with the mean pentad circulation fields at 850 hPa from ECMWF (Matsumoto, 1991). In the second pentad of May (pre–onset) the flow in the western subtropical high appears over the SCS, and the equatorial westerly from the Indian Ocean reaches the northern Malaya Peninsula, while the southwesterly from the northwest side of the subtropical high exists in the northern SCS. The southeasterly prevails over most areas of the SCS. In the third pentad of May the equatorial westerly enhances and moves toward north. The southern Bengal Bay is occupied by the southwesterly which reaches the northern SCS and joins with the southwesterly in the western subtropical high, then enhances the southwesterly in the northern SCS. Meanwhile, the weak wind vectors confuse in the southern SCS due to being covered by the western Pacific subtropical high. In the fourth pentad of May, the center of the western Pacific subtropical high moves toward east to the Philippines and the strong equatorial westerly expands northeastward, which forms strong southwesterly to join the cross–equator flow across the southern Indian Peninsula, the Bengal Bay and Indo–China Peninsula. The southwest wind prevails in the SCS at that time. It means that the onset of the SCS SW monsoon is attributed to retreating eastward of the subtropical high, enhancing and expanding eastward of the equatorial west wind in the Indian Ocean as well as moving northward of the cross–equator flow. Therefore, monsoons burst firstly in the northern SCS.

III. CHARACTERISTICS OF THE CLOUD FIELD

The fields of cloud and precipitation can describe the mean situation of the synoptic activity. There is a good relationship between the distribution of cloud or precipitation and the large–scale divergence and convergence. Besides the obvious seasonal variability, the monthly fields of total cloud amount indicate that a great amount of cloud covers the equatorial area (0–6°N) and the northern SCS while less cloud in the middle of the SCS, especially in March and April.

Table 2. Dekad Average Cloud Amount for 4 Stations

Month	April			May			June		
Dekad	1	2	3	1	2	3	1	2	3
Cloud amount	Total / Low	Total / Low	Total / Low	Total / Low	Total / Low	Total / Low	Total / Low	Total / Low	Total / Low
Hongkong (1961–1990)	8.3 /	7.9 /	7.4 /	7.4 /	7.3 /	7.4 /	7.8 /	7.5 /	7.2 /
Shangchuan (1986–1995)	9.1 / 8.8	8.9 / 8.1	8.1 / 7.2	8.2 / 7.3	8.0 / 6.8	8.3 / 7.0	8.3 / 7.1	8.8 / 7.2	7.9 / 5.8
Xisha (1985–1994)	4.2 / 2.6	4.2 / 2.8	3.7 / 2.2	3.9 / 2.2	5.0 / 2.6	5.6 / 2.8	6.7 / 3.4	6.4 / 3.4	6.7 / 2.6
Yongshu (1989–1994)	4.4 / 3.6	5.5 / 3.2	4.7 / 3.1	5.7 / 3.5	6.5 / 4.1	6.7 / 4.1	7.7 / 4.5	7.5 / 5.0	7.9 / 5.1

The onset of the SCS monsoon causes variation in cloud. Table 2 shows the dekad average total cloud and low cloud amount in April, May and June in Hong Kong, Shangchuan, Xisha and Yongshu stations. It is indicated that in the middle of May the cloud amount in the

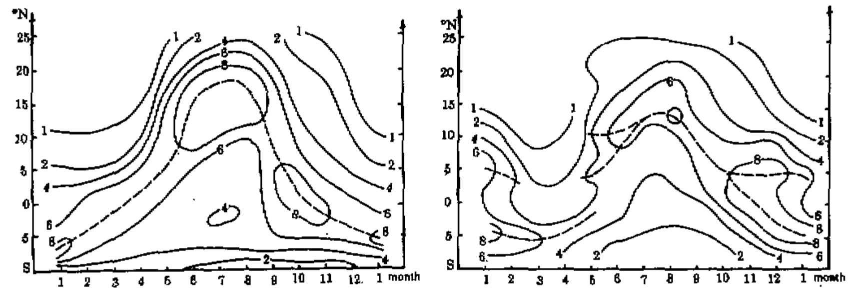
Fig. 2. Time-latitude section of HRC center spanning the land bridge to west (a) and eastern SCS (b).

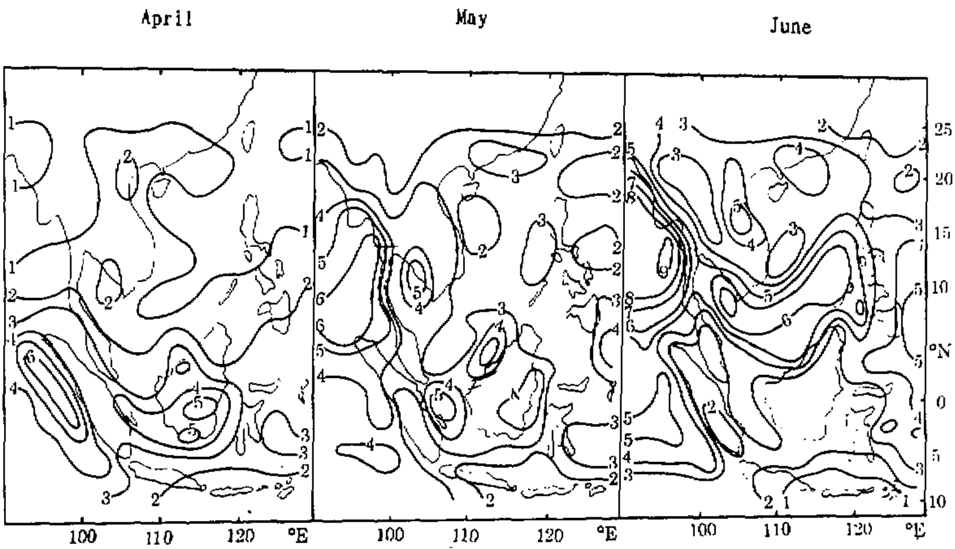

Fig. 3. Mean High Reflective Cloud (HRC) from April to June over SCS.

center and south parts of the SCS increases, which matches the beginning of the SW monsoon. Since Shangchuan and Hong Kong stations are at the Pre-Typhoon Rain-season and reach 80 percent of the mean cloud amount, cloud increase is little after the onset of monsoon.

HRC is an index of the tropical convective activities and displays the time varying process of the monsoon onset. The standard coefficient C_v of the monthly mean HRC fields is derived based upon data from 1971 to 1983 in a longitude by a latitude resolution. The larger the value is, the stronger the convection develops. It is shown that there are two centers of strong convection activities over Sumatera Island and the Java Sea in January and February (i.e., $C_v \geq 6$) and then they move northward along the two tracks from spring till summer. One track reaches the Bengal Bay along the west part of the "land bridge" of the maritime continent and stands steadly in the Bengal Bay and India in the mid-summer with C_v8-9 in its core. Following retreat of the summer monsoon in September, the strong convection center moves southward, and returns to the equator in November, then reaches the south to Sumatera Island in December. This track is continuous during the annual period (see Fig 2a). The other track directs to the SCS. It stands over the Java Sea in February, March and April with weak strength. In May it expands northward so an area with C_v more than 3 turns out in the northern SCS and the west coast of Philippines but the convection is weak in the most parts of SCS. The band of strong convective activity is formed in the 6–10°N sea region in June. In boreal summer, the center locates in 12–18°N. During the period of retreat of the summer monsoon in October, November and December, the center lies in the south and north sides of the Kalimantan Island and it moves southward more slowly than that in the track mentioned above. The latter track directing to the SCS breaks in April (see Fig. 2b). The differences in movement of the two convective centers and their strength as well as their source show that the East Asian Monsoon and the Indian Monsoon are two independent systems.

The evolution of HRC coefficients from April to June is analyzed in order to detect the variability of the convective activity in the SCS at the onset of the summer monsoon. The value of April is 3–4 in the Malay Pen. (see Fig 3) and Kalimantan Island, 2 in the Indo–China Pen. and China coast, and 0 in the SCS, which means weak convection in April over the SCS. The convection enhances in May over the SCS with sparse distribution and different situation of development. The values in land around here increase because the convective activity grows due to quick warming in land, e.g., 3–4 in the Indo–China Pen. and 5 in the Kalimantan Island. In the windward side of islands, the convection develops rapidly through dynamic effects, 4–5 in the west side of the Luzon Island and the eastern coast of the Gulf of Thailand. In the leeward side, C_v keeps low due to dry flow by the foehn wind effect, i.e., 1 the open sea east to Vietnam. In the most parts of the SCS including the warm water area in the south, C_v is 2, and little increase can be seen since April. In June, C_v increases in the SCS with higher values in the band (5–6) and the eastern Gulf of Thailand (7–8). C_v decreases to 2–3 in the Malay Pen. and the Kalimantan Island because of the equatorial buffer zone. Since then, the western area of the SCS convection becomes weak, while the eastern area extends northward, locating in the western Luzon Island in July and 10–19°N in August. Convection in the western Beibu Gulf and the coast around there becomes more active. The convection over sea is stronger than that over islands except for the limited area east to Vietnam in July and August. All of the above–mentioned facts shows the different dynamic and thermodynamic effects at the different stages and over different underlying surfaces. In short, the dynamic lifting plays an important role in the convection developing in the windward area in the beginning of the monsoon onset, but it is replaced by the thermodynamic effect in the sea surface during the development stage.

IV. CHARACTERISTICS IN THE FIELDS OF PRECIPITATION

The impact of tropical synoptic systems on the rainfall in the SCS displays a regional contrast in seasonal variation and interannual variability. The basic pattern of the annual rainfall is 1500–2200 mm in the northern coast of the SCS, 1500 mm in vicinity of Xisha, 1900–2000 mm around Nansha, and 2000–2500 mm in the western coast of the Luzon Island due to upwind of the SW monsoon.

Fig.4 shows the monthly mean field of rainfall over the SCS and its adjacent areas. It can be found that the 8°N latitude should be regarded as a dividing line between the equatorial and the tropical monsoon regions. Much of the rainfall is brought in winter south to 8°N,while the rainfall is mostly caused by the SW monsoon in the north. In the tropical monsoon region (8–20°N) rainfall mainly falls from May to September, where rainfall increases

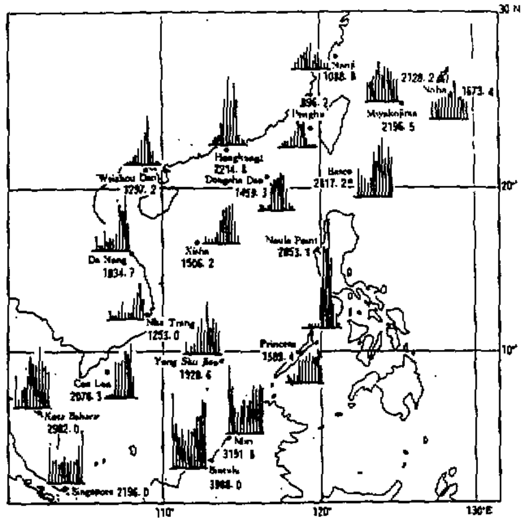

Fig. 4. The long-term mean monthly precipitation distribution for stations over the SCS and its surrounding area. Unit: mm

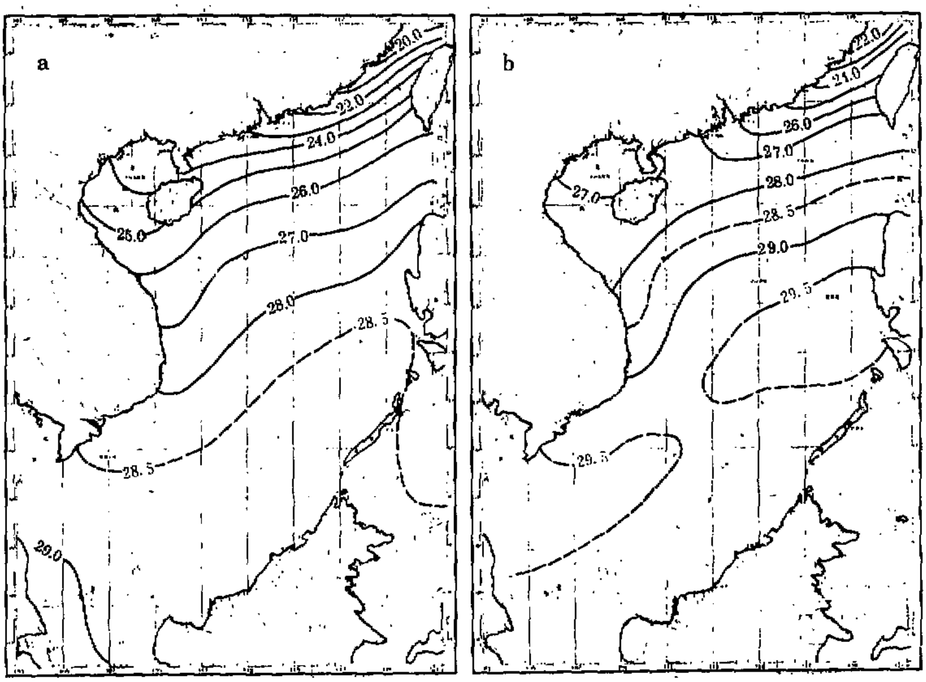

Fig. 5. Monthly mean sea surface temperature (°C) over SCS for April (a) and May (b).

month-by-month without jumping of rain band like in China continent. North to 20°N is the subtropical monsoon region where the monthly rainfall holds a kind of double-peak variation.

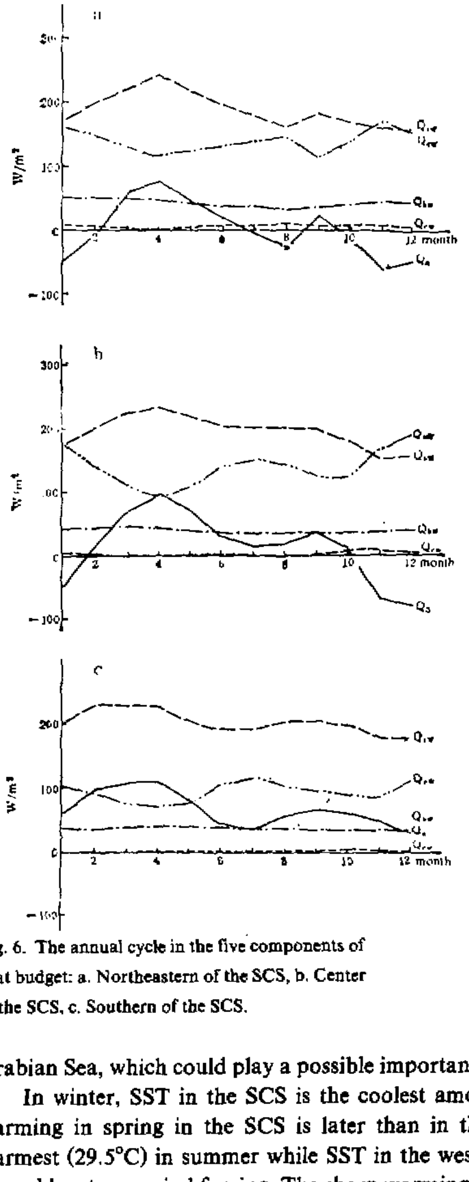

Fig. 6. The annual cycle in the five components of heat budget: a. Northeastern of the SCS, b. Center of the SCS, c. Southern of the SCS.

The pentad mean rainfall at the 4 stations from April to June is listed in Table 3. There is a great increment of rainfall in Hongkong and Shangchuan in the third pentad of May, and in Yongshu in the fifth pentad when the SW monsoon bursts in view of statistics. It does not mean that there is rainfall after onset of the SW monsoon because much of the precipitation in summer over the SCS is brought by typhoons and monsoon lows, etc. For example, the strong process of southwest wind did not result in rainfall in Xisha during the period from May 24 to June 16,1993, though there was southwest wind there with a maximum mean velocity of 7.5 m / s. Statistics on the marine ship data also indicates that rainfall occurs at phase of westerly and northwesterly instead of that of southwesterly.

V. CHARACTERISTICS OF THE SST FIELDS

Results of previous researches showed that air-sea interaction is the key reason for the onset of the SCS monsoon. The factors of controlling SST in the SCS include solar radiation, sea current, evaporation, precipitation, and impacts of land and islands. So SST in the SCS is independent of the adjacent areas, e.g., the western Pacific warm pool, the Bengal Bay and the Arabian Sea, which could play a possible important role in the monsoon onset.

In winter, SST in the SCS is the coolest among the seas at the same latitude, and the warming in spring in the SCS is later than in the Bengal Bay. The northwestern SCS is warmest (29.5°C) in summer while SST in the western Arabian Sea is cold due to upwelling caused by strong wind forcing. The sharp warming in the seas occurs in April and May before the summer monsoon bursts. SST in the SCS is less than 28°C in March, then the isotherm jumps to 15°N in April. In May, the 29°C isotherm arrives here by jumping 12 degrees of latitude with a high SST area (above 29.5°C) in the Gulf of Thailand and within the band of 10–12°N, but SST south to 15°N decreases. Then the SCS is separated to two parts, sharp warming in the north and weak cooling in the south. SST is uniform in July and August, and SST above 29°only exists in the Beibu Gulf in August.

Table 3. The Pentad Mean Rainfall for 4 Stations

Month	April						May						June					
Pentad	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Hongkong (1961–1990)	31.5.	31.5	23.0	17.0	24.0	34.5	40.0	33.0	60.5	61.5	38.0	71.5	76.0	64.5	64.0	80.0	38.5	56.0
Shangchuan (1980–1995)	21.2	39.5	34.9	22.4	39.2	32.4	37.5	43.2	60.9	34.7	55.4	85.7	49.9	108.3	27.3	33.4	45.0	67.4
Xisha (1980–1994)	10.7	5.7	8.2	2.4	8.3	10.4	9.8	5.1	6.2	19.0	8.3	16.6	22.9	54.8	47.4	58.0	27.0	51.8
Yongshu (1989–1994)	4.4	24.8	11.0	21.1	12.6	5.7	10.4	4.9	30.6	6.7	39.7	14.3	3.3	36.6	43.2	46.6	48.6	21.8

In brief, the warm pool (above 28°C) is formed in the SCS, leading the summer monsoon onset by about one month. Following the onset, SST in the most part of the SCS keeps increasing and drives an active area of convection just over the former region of high SST, i.e. the axis of active convection areas in June covers the high SST region in May. Convection lagging SST means that the high SST in the SCS provides heat and vapor for onset and maintenance of the summer monsoon.

VI. CHARACTERISTICS OF THE AIR-SEA HEAT FLUX

The sea heat budget is determined by three components. One is the radiation heat exchange which can be explained as a budget between the solar radiation absorbed by sea and the reflected effective radiation. Another is the sensible heat exchange and the third is the latent heat exchange. So the formula for the surface net heat budget can be written as

$$Q_n = Q_{sw} - Q_{bw} - Q_{cw} - Q_{ew} \quad , \tag{1}$$

where

$$Q_{sw} = Q_s(1-r) = Q_0(1-K_c N)(1-r) \ , \tag{2}$$

$$Q_{bw} = S\sigma T_0^4(a_1 - b\sqrt{e_a})(1-K_c N) + 4S\sigma T_0^4(T_w - T_a) \ , \tag{3}$$

$$Q_{cw} = C_p \rho_a C_H (T_w - T_a) v_{10} = 1.298 \times 10^3 C_H (T_w - T_a) v_{10} \ , \tag{4}$$

$$Q_{ew} = \rho_a L C_E (q_w - q_a) v_{10} = 3.365 \times C_E (597 - T_w)(e_w - e_a) v_{10} \ . \tag{5}$$

In above, Q_n is the net heat budget, Q_{sw} the short-wave solar radiation, Q_{bw} the net long-wave radiation at the sea surface, Q_{ew} the latent heat flux, Q_{cw} the sensible heat flux, K_c a coefficient for cloud cover, C_E a factor of evaporation, C_H a coefficient of sensible heat flux, C_D the drag coefficient, N the total cloud amount, $T_w - T_a$ the temperature difference between sea and air.

The following treatments are made in order to take the calculation more accurate:

(1) K_C, the coefficient for cloud cover is calculated monthly for each latitude based on the observation at the coastal and island stations.

(2) C_E, C_H and C_D are not constants which vary with observational data.

(3) The sensible and latent heat fluxes are averaged as $\overline{N} = \overline{A \cdot B}$ instead of $\overline{N} = \overline{A} \cdot \overline{B}$.

The annual cycle in the five components of heat budget in the northeast, central and south parts of the SCS is shown in Fig.6. The variabilities in the three regions are similar. The annual ranges in Q_{cw} and Q_{bw} are little while those in the other three components are quite large, in particular, sudden changes occur in April. To describe in detail:

(1) Q_{ew} reaches its maximum in winter due to the large wind velocities, while has its minimum in April. It increases quickly from May until August (July in the southern SCS);

(2) Q_{sw} reaches its maximum in April due to the least cloud and decreases in May with increment of cloud. Among the three regions, Q_{sw} in the northeastern holds sharpest decrease, indicating that development of convection here is stronger than that in the other regions, and,

(3) Q_n reaches its maximum in April. It decreases since then until August. There is negative Q_n in the northern SCS in July and August which shows that the sea loses heat.

The annual cycle of evaporation in 115°E in the SCS is plotted in Fig. 7. It is found that evaporation takes its minimum 7–10 cm / m^2 in April. It increases rapidly in May, 10–12 cm / m^2 till the mid–summer, 15–17 cm / m^2 in the band of 8–16°N. It means that the SCS supplies much vapor for the onset and maintenance of the summer monsoon.

In summary, sudden changes in the latent heat flux, evaporation, solar radiation at sea surface and the net heat budget from April to May are caused by adjustment of atmospheric circulation before the summer monsoon bursts. Increment in heat fluxes and vapor flux provides a favorable condition for maintenance of summer monsoon. The air–sea interaction in the SCS impacts the synoptic systems in this region and causes synoptic variability in China mainland, Japan and even the areas more far away.

VII. CONCLUSIONS

It is demonstrated by analysis of upper–air and surface winds that the mean date of the onset of the SW monsoon in the SCS is the middle of May, May 12 in the north, later in the south, i.e., May 20, respectively. There is the interannual variability in date and characteristics of the onset, which is determined by retreat of the subtropical high and by movement eastward of the equatorial westerly.

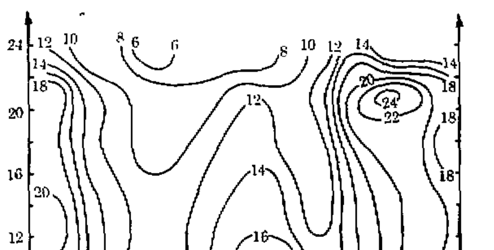

Fig. 7. Time section of evaporation in 115°E of the SCS.

Following the onset, the mean total cloud amount, the low cloud amount and the precipitation increase in the SCS. There is not exact link between precipitation and the SW monsoon surges over some regions. Rainfall often occurs at the phases of westerly and northwesterly instead of that of southerly.

It is not uniform for the developing of convection in the SCS when the onset starts. The strength of convection is the strongest in the eastern Gulf of Thailand, and it strong in the western side of the Luzon islands and off-shore to the northern boundary. The main part in the central SCS presents weak development of the convection. Dynamic lifting in the windward side enhances convection firstly. Warming in the SCS leads to convection and both of them match each other in location, which implies that warm SST provides heat and vapor for the onset of monsoon.

The obvious change in the surface heat fluxes, such as latent heat fluxes,occurs in April before onset of the SW monsoon. This is a kind of mechanism involved in triggering of the SW monsoon.

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