Article ID: 1006-8775(2000) 02-0123-10

PRELIMINARY STUDY OF RELATIONSHIP BETWEEN INTERANNUAL VARIATIONS OF SST IN SOUTH CHINA SEA AND TROPICAL INDIAN OCEAN AND SOUTH CHINA SEA MONSOON OUTBREAK

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ABSTRACT: Conclusions are divided regarding the role of the variations of thermodynamics in the monsoon activity for the South China Sea region. In this study, primary eigenvectors are studied for the SSTA from East Asia to the tropical eastern Indian Ocean in May. The results show that temperature anomalies that center on Sumatra are closely related with the outbreak of the South China Sea monsoon. When the SST is warmer (cooler) than average year, it is likely that the monsoon set in late (early). It may be caused by the changes in meridional difference in thermodynamics between the Indochina Peninsula and its southern tropical oceans. Studying the temporal and spatial evolution of primary eigenvector distribution of the SSTA in the South China Sea-tropical eastern Indian Ocean from winter to summer, we find that the temperature anomalies that center around Sumatra in late spring and early summer can be traced back to the variations of the SST fields in the South China Sea in the preceding winter. Being well associated with the outbreak of the South China Sea monsoon, the latter is a significant index for it. The work helps understanding the atmospheric and oceanic background against which the South China Sea monsoon breaks out and behaves.

Key words: South China Sea; outbreak of South China Sea monsoon; meridional thermodynamic differences between land and sea

CLC number: P732.6 **Document code:** A

1 INTRODUCTION

Being in the channel for the cross-equatorial current from the Southern Hemisphere in early summer, the South China Sea exerts important influence on the outbreak of the South China Sea monsoon. Investigating how the variations of SST in the South China Sea and zonal thermodynamic differences between the Indian Ocean and the South China Sea would affect the monsoons in Asia, Luo and Jin (1986), Chen (1988), Chen, Jin and Luo (1988) and Chen (1991) have made comprehensive studies, suggesting that high (low) SST in the South China Sea versus low (high) SST in the Somali coast and Arabian Sea is accompanied by strong (weak) Indian Southwest Monsoon and the southeast monsoon in west Pacific versus weak (strong) cross-equatorial southwest monsoons. They stress the important role of the differences in zonal thermodynamics

Received date: 1999-06-02; **revised date:** 2000-09-06

Foundation item: "Comprehensive study on the activity of South China Sea monsoon and the influence" —a major project of the Chinese Academy of Sciences; "South China Sea Monsoon Experiment"— a scaling project of China; "Role of thermodynamic variations in upper oceanic layers of the South China Sea in the outbreak of monsoon " (49676278)

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of the tropical oceans in affecting the summer monsoons in Asia. The South China Sea monsoon originates from the cross-equatorial current from the Southern Hemisphere in early spring. No definite conclusions have been made regarding whether and how the changes in thermodynamic conditions in the underlying South China Sea ~ tropical eastern Indian Ocean would affect the cross-equatorial airflows. In a separate work, Jin and Luo (1986) point out that for high (low) SST in the South China Sea during previous wintertime, it is more likely for floods (drought) to occur during the Mei-yu (sustained rain) periods of the middle and lower reaches of the Changjiang River (the Yangtze), which are just in the years in which there is weak (strong) monsoon in the region. Similar conclusions are drawn in Sun and Ma's (1999) recent work. Nonetheless, Chen, Liu and Wang et al. (1999) have come to a completely opposite conclusion. It is now obvious that there has been no agreement in regard to how the thermodynamic variations of the South China Sea waters would affect the regional monsoon. It is the attempt of the current work, with the use of latest data, to study more extensively with the focus on patterns of distribution of SSTA from East Asia to tropical eastern Indian Ocean and their influence on the outbreak of the South China Sea monsoon and discuss possible processes of the latitudinal thermodynamic differences between the Indochina Peninsula and the southern tropical oceans in early summer affecting the outbreak of the South China Sea monsoon, with investigations of the relationship between SSTA in preceding winters and monsoon outbreaks in the region.

2 DATA AND SELECTION OF INDEX AREAS

The SST in East Asia ~ the tropical eastern Indian Ocean and surface air temperature (SAT) are monthly mean data, provided by the National Climate Center from NCEP/NCAR of the U.S.A., covering January 1982 through December 1997. The area of interest is bounded by 30°S ~ 30°N and 80°E ~ 130°E, including the East Asia continent, the South China Sea and the tropical eastern Indian Ocean, where the monsoon is active. According to Yu, Zhou and Fu et al. (1994), the interannual oscillations of the SST mainly happen in deep-depth basins of the South China Sea. It is therefore reasonable that the mean SST values within 8°N ~ 16°N and 110°E ~ 116°E are used to represent the sea temperature of the South China Sea and the SSTA is taken as the index for the variation of the SST in the region. To remove disturbances on scales less than 5 months, a 5-month running filtering is conducted for the SST index.

3 MAIN CHARACTERISTICS OF SST VARIATIONS IN SOUTH CHINA SEA AND THE RELATIONSHIP WITH SOUTH CHINA SEA MONSOONS

In view of the close relationship between the South China Sea monsoon and the 105°E air flow that crosses the equator from Australia, .any changes in meridional thermodynamic differences across the East Asia continent and its southern extensive oceanic region including the South China Sea may be of serious consequences to the outbreak of the South China Sea monsoon. By taking an EOF study of the anomalies of SST and SAT within 80°E ~ 130°E and 30°S ~ 30°N between 1982 and 1997, attempts are made to understand the variation of the thermodynamic differences and the relationship with the South China Sea monsoon. As we know, the monsoon breaks out in the 4^{h} pentad of May on the average. The variation of the meridional thermodynamic differences between East Asia and its southern oceans is a key factor in determining the onset date of the monsoon in the South China Sea. Fig.1 gives the fields of the first and second eigenvector of SST and SAT (unit: 0.1°C) and corresponding coefficients of time. The first eigenvector field is featured by extensive distribution of positive values in the tropical waters centered around Sumatra, with the

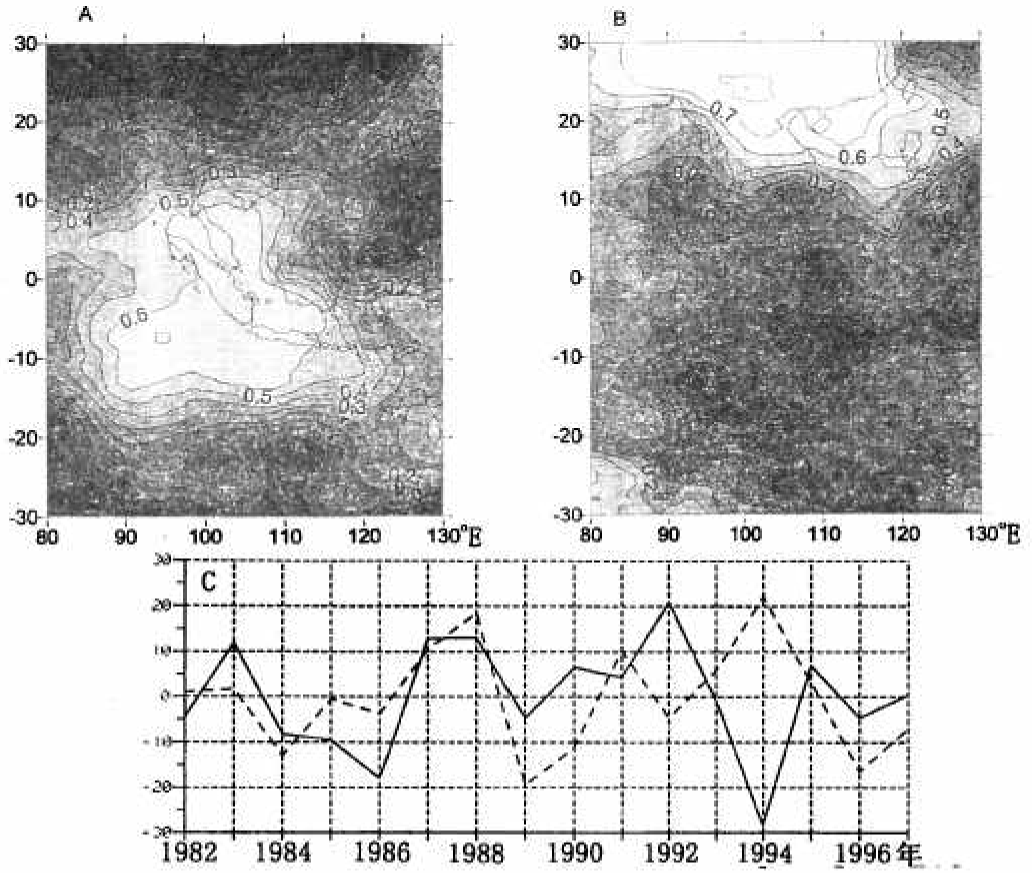

Fig.1 Primary eigenvector fields of SSTA and the time coefficients for East Asia ~ tropical eastern Pacific; (A) the first eigenvector field; (B) the second eigenvector field; (C) time coefficient (solid line for the first and dashed line for the second eigenvector fields)

maximum going above 0.6℃ over a large area while the East Asia continent, the Australian continent and waters to the west are dominated by weak negative eigenvectors. This field contributes 19.6% of the total variance, suggesting that changes in the tropical oceanic waters are one of the major components of the interannual variation of the thermodynamic field. The second eigenvector field is characterized by the presence of positive values in northern domain, with a large positive zone in the continent of East Asia and the maximum positive anomaly center in Yunnan province, China. The maximum exceeds 0.7℃ over a large area while tropical waters south of the continent are controlled by weak negative eigenvectors. This field contributes 16.9% of the total variance, representing the interannual variations of the thermodynamic variation over East Asia continent. The third eigenvector field (figure omitted) mainly shows a pattern of negative south but positive north with a large negative zone in Australia and waters west of it. The minimum is lower than –0.8℃ over a large area with weak positive values over the Indochina Peninsula and the ocean south of it, describing the intensity of cold air activity coming from Australia. This eigenvector field takes up 12.1% of the total variance contribution.

Following a standard for determination of monsoon outbreak in the South China Sea (Liu, Xie and Ye et al., 1998) and in accordance with the division of outbreak dates defined by the National Climate Center (CMASCC, 1998), a year in which the monsoon breaks out in and before the 4th pentad of May is defined as the year of early monsoon outbreak and a year in which the monsoon sets in during the 5th pentad or afterwards is set as the year of late monsoon outbreak. As a result, for the 16 years from 1982 to 1997 we have early outbreaks in 1984, 1985, 1986, 1989, 1990, 1994, and 1996 and late outbreaks in 1982, 1983, 1987, 1988, 1991, 1992, 1993, 1995, and 1997. Comparing the time coefficients for the first 3 eigenvector fields in May, we find that by a fitting rate of 13/16 the positive values of the field all correspond to the late outbreak years of the South China Sea monsoon and the negative values the early outbreak years, with the exception of years 1990 and 1993. For the field of the first eigenvector, the tropical ocean that centers around Sumatra is of positive characteristic values and thus renders a positive coefficient of time, suggesting a warmer SST than normal over the waters and vice versa. For the years stated above, both the years with much higher SST (time coefficient $\geqslant$ 10.0), namely 1983, 1987, 1988, and 1992, and the years with much lower SST (time coefficient $\leqslant$ –5.0), namely 1984, 1985, 1986, and 1994, well correspond to the timing of monsoon outbreak in the South China Sea with a fitting rate of 8/8. In contrast, much poorer corresponding relations are between the 2nd and 3rd eigenvector fields and the monsoon outbreak with fitting rates only 10/16 and 7/16, respectively. It is concluded that the anomalous distribution of SST in the tropical waters centering on Sumatra may be playing an important role in the set-in of the South China Sea monsoons and anomalous thermodynamic conditions in southern East Asia and northern Australian continent may have smaller influence on it.

More study is done of the major eigenvector fields of SST/SAT anomalies for the region December through May. The first eigenvector fields for individual months are featured by positive values throughout the region (Fig.2) and zones of large eigenvectors are mostly over the ocean. In other words, the variation of SST always provides the most contribution among all the changes in temperature anomalies in winter and spring within the region. For December and January, large positive zones all appear in the South China Sea, with the contour of 0.5 for January shifting a little to the south and the center a little larger as compared to December. In February, the positive center that is formerly in the sea has now extended southward. The large positive zone has now moved much to the south in March with the center starting to be over waters off Sumatra. By April and May, a large positive zone has formed centering on Sumatra and becomes much more significant in May. Comparing the time coefficients for individual winter and spring months and the first eigenvector of May (figure omitted), we find that the variation tends to go quite consistently except for February in a limited number of years. The result shows that changes in the SSTA field of the region is marked with obvious continuity and the variational feature of the SST that centers around Sumatra in May can be traced back to the changes in the SST field in January for the South China Sea.

4 RELATION BETWEEN INTERANNUAL VARIATION OF WINTERTIME SST AND MONSOON OUTBREAK IN SOUTH CHINA SEA

Computing the correlation coefficient, $r = 0.55$, between SSTA index for the South China Sea for January and the time coefficients of the first eigenvector field for May, we find that the SSTA of the South China Sea for January is well correlated with that of the South China Sea ~ tropical eastern Indian Ocean on the 98% confidence level. It is suggested then that the SSTA in prime wintertime can be indicative to some extent for the timing of the outbreak of monsoon in the South China Sea. Fig.3 gives the curves of interannual variations of the SSTA for January and outbreak pentads of the summer monsoon from 1979 to 1997, of which the SST data of the South China Sea from 1979 to 1981 are supplemented with COADS. In this work, the division standards by the

National Climate Center are followed, i.e. the year in which the monsoon sets off in or before the 4th pentad of May (to be depicted as 5.4, same below) is defined as the early outbreak year and the year in which the monsoon sets off in or after the 5th pentad is defined as the late outbreak year. It is then clear from Fig.3 that except for 5 years, specifically, 1985 (4.4), 1987 (6.2), 1990 (5.3), 1993 (6.4), and 1994 (5.4), the remaining 14 years all have good corresponding performance. For example, for such early outbreak years as 1979 (5.3), 1980 (5.4), 1981 (5.3), 1984 (5.1), 1986

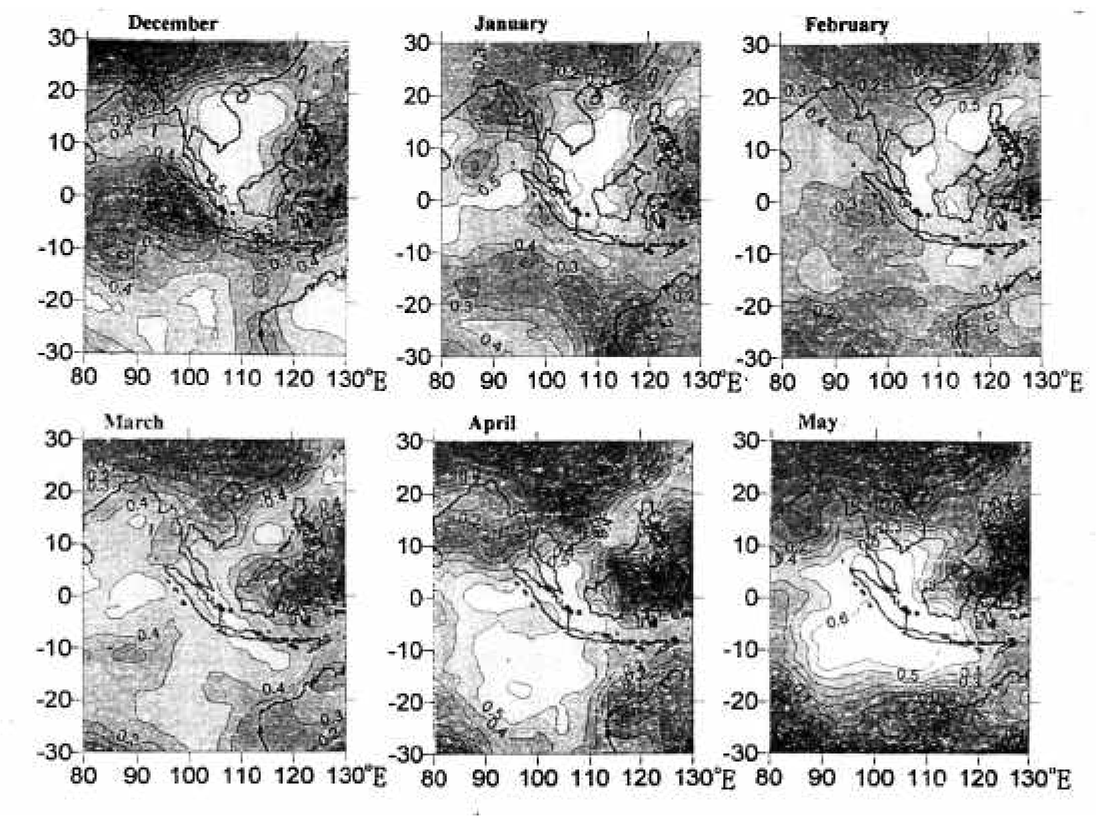

Fig.2 The first eigenvector fields of SSTA on the surface of East Asia continent ~ tropical eastern Indian Ocean in December through May.

(5.2), 1989 (5.4), and 1996 (5.2), the SST is all colder in the preceding winters in the South China Sea; for such late outbreak years as 1982 (6.1), 1983 (6.2), 1988 (5.5), 1991 (6.3), 1992 (6.1), 1995 (6.2), and 1997 (5.5), the SST there is warmer, hitting a fitting rate of 14/19.

If we divide the outbreak time into three categories: the year with the monsoon starting in or before the 2nd pentad of May is defined as an early outbreak year, the year with the monsoon starting in the 3rd or 4th pentad of May a normal outbreak year, and the year with the monsoon starting in or after the 5th pentad of May a late outbreak year, with additional definition for the SST anomaly in the South China Sea — being cold if it ≤ –0.2℃, being normal if it is between –0.2℃ and 0.2℃, and being warm if it ≥ 0.2℃, then what we can know from Fig.3 is that with the exception of 1985, 1987, 1989, 1990, 1993, and 1994 (6 years), the years 1979, 1980, and 1981 are the time with normal SST corresponding to the normal outbreak time of the monsoon, 1982, 1983, 1988, 1991, 1992, 1995, and 1997 are the 7 years with warm SST corresponding to the late outbreak time of the monsoon, and 1984, 1986, and 1996 are the 3 years with cold SST corresponding to the early outbreak time of the monsoon, by a fitting rate of 13/19.

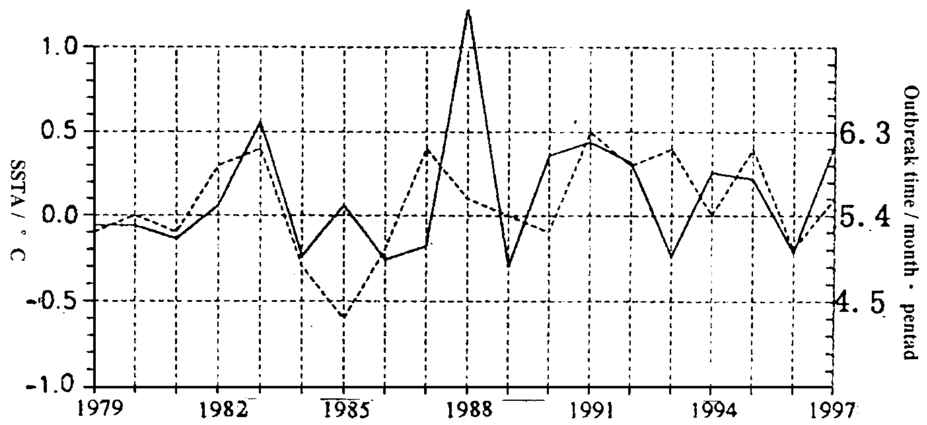

Fig.3 Relations between the SSTA index in winter (solid line) and monsoon outbreak pentad (dashed line) in the South China Sea

According to the SST data for November and December 1997 and the monthly SSTA charts (from the monthly maritime reports of JMA), the SST is warmer in the South China Sea for the preceding winter of 1998, which is a late year for the monsoon outbreak (in the 5th pentad of May). It is suggested in the statistic facts presented above that it is more likely for the South China Sea monsoon to have a late outbreak when the SST is warmer in the previous winter and otherwise is true. It is consistent with the conclusions by Jin et al. (1986) and Chen (1988) that anomalies of the SST in previous winters are closely related with the intensity of the monsoon (the southwest monsoon that has crossed the equator in East Asia) in the South China Sea.

In addition, comparisons are also made of the relationship between the index of SST in May and the outbreak of the monsoon in the South China Sea, which indicates that the two are poorly correlated with a fitting rate of 11/19.

5 DISCUSSIONS AND CONCLUDING REMARKS

The fundamental reason for the generation of monsoons is the thermodynamic contrast between land and sea and the variation of the difference is causing changes in monsoons from year to year. Studying their important influence on the precipitation of the Changjiang River valleys, Chen (1988) and Chen (1991) point out that the zonal anomalies of the SST in the Indian Ocean and the South China Sea are such a physical mechanism that it causes the variations of the Indian Southwest Monsoon and the southeast monsoon in East Asia by altering the intensity and location of the Walker cell. In his research findings, Chen states that the zonal anomalies of the SST in the Indian Ocean and the South China Sea do not have any direct influence on the outbreak of the summer monsoon in that region. What has been found in this work, however, is that it is the variation of the thermodynamic state, which is within the cross-equatorial airflow entering the South China Sea from the Southern Hemisphere and centers on Sumatra, that is responsible for immediate effects on the outbreak of the monsoon there. When the SST varies anomalously, it may speed up or slow down the airflow that starts from Australia in early spring.

As what Chen, Zhu and Luo et al. (1991) suggest, the north-south gradient of temperature is quite mild within 0° ~ 20°N because the continent area is relatively small near 20°N in the East Asia continent and the ocean is full of islands near the equator. It accounts for the fact that the South China Sea monsoon does not appear to behave in close association with any sharp land-sea gradient of temperature, which is just present in the South Asia continent where the Indian summer monsoon is active. Fig.4 gives the distribution of mean temperature from East Asia to tropical eastern Indian Ocean in April and May. The figure shows that the contour of 29°C in the tropical ocean has extended towards the Northern Hemisphere when the sun moves northward to the northern side of the equator in April while the warmer temperature zone stays around the equator in the area of islands south of the South China Sea. By May, the sun has shifted north over 10°N ~ 15°N, resulting in a rapid rise of temperature in the Indochina Peninsula such that an east-west oriented zone of high temperature (30°C) forms in the southern part of the peninsula. In the meantime, the variation of temperature in the tropical waters tends to narrow in amplitude, generating a north-south oriented gradient of temperature between the peninsula and the vast area between the tropical ocean to the south and the Australian continent.

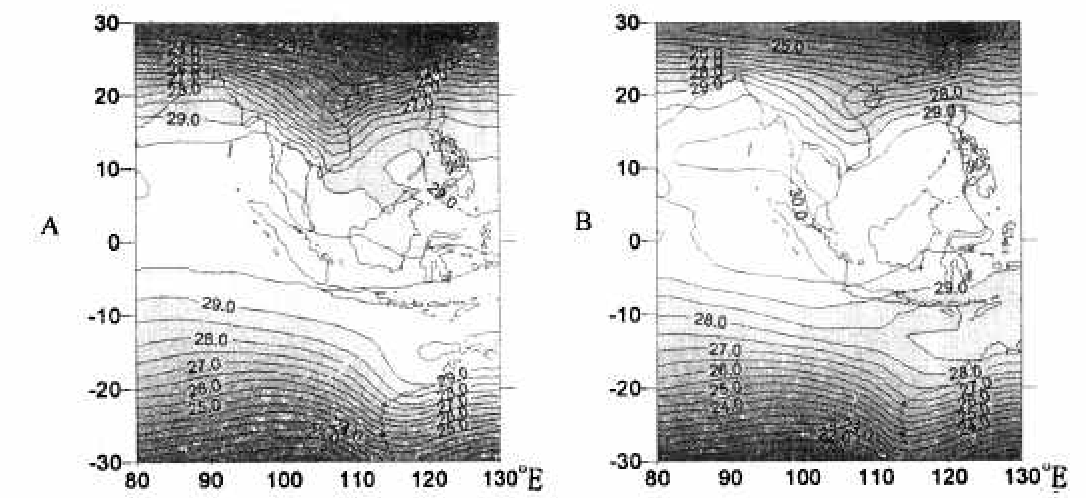

Fig.4 Distribution of surface temperature in East Asia ~ tropical eastern Indian Ocean in April (A) and May (B)

Composites of temperature anomalies for years with obvious low temperature and high temperature are respectively retrieved using the first eigenvector fields of SSTA in May in association with the mean time coefficients for 4 obviously low temperature years (1984, 1985, 1986, and 1994) and 4 obviously high temperature years (1983, 1987, 1988, and 1992). Then Region A (95°E ~ 105°E, 10°N ~ 15°N) is selected from Fig.4 to represent the area of higher temperature in the Indochina Peninsula and Region B (95°E ~ 110°E, 0° ~ 10°S) is selected to represent the tropical waters around Sumatra for computation of mean temperature for Regions A and B, mean SSTA for the years of high and low temperature, and differences between the two regions. The results are shown in Tab.1. It is clearly shown that the thermodynamic difference is small (the value being 0.65°C) in May between the Indochina Peninsula and its southern tropical ocean. It is in conformity with the finding that the region is featured by a small north-south gradient of temperature (Chen et al., 1991). When the SST is higher than normal in the tropical waters centering around Sumatra, the thermodynamic difference becomes much smaller between the peninsula and the tropical waters to the south with a value of only 0.16°C; when the SST is lower than normal, thermodynamic difference will be much greater, reaching a value of 1.17°C. It is now obvious that

Tab.1 Meridional thermodynamic differences between the Indochina Peninsula and its southern tropical ocean in May, which is associated with years of obviously high and low SST in the tropical waters centering on Sumatra (unit:) °C

Region	Monthly mean	Years of high SST		Years of low SST	
		Mean anomalies	Mean temperature	Mean anomalies	Mean temperature
A	30.14	0.48	30.62	–0.53	29.61
B	29.49	0.97	30.46	–1.05	28.44
A–B	0.65	–0.49	0.16	0.52	1.17

a higher SST anomaly in the tropical waters surrounding Sumatra will decrease the meridional differences in thermodynamics between the Indochina Peninsula and the southern tropical ocean, which is in turn unfavorable for passages of cold air to migrate into the South China Sea from Australia and further results in a weakened and delayed summer monsoon in the sea. On the other hand, a lower SST anomaly in waters near Sumatra will increase the meridional differences in thermodynamics between the Indochina Peninsula and the southern tropical ocean, which is in turn favorable for passages of cold air to move into the South China Sea from Australia and further results in a strengthened and brought-forward summer monsoon there.

Combining what Chen (1988) has found and what the current paper concludes, we can argue that the variation in meridional thermodynamic differences between the Indian Ocean and the South China Sea may be one of the important reasons for the changes in the Indian Southwest Monsoon and the southeast monsoon in East Asia and the variation in meridional thermodynamic differences between the Indochina Peninsula and its southern tropical ocean may be the immediate determining factor for the intensity and the date of monsoon outbreak in the South China Sea. Compared with the land-sea contrast in and around South Asia, the meridional thermodynamic differences between the Indochina Peninsula and its southern tropical ocean are quite small. It should be noted that the tropical oceanic area centering on Sumatra, which plays a decisive role in altering the intensity of such meridional thermodynamic contrast, is just below the cross-equatorial air flow and becomes the key region for the outbreak of the South China Sea monsoon. It is therefore believed that changes in the SSTA on Sumatra first cause the changes in the meridional thermodynamic differences between the Indochina Peninsula and waters nearby and then exert essential influence on the date of outbreak of the summer monsoon in the South China Sea.

Using T_{BB} data, He, Zhu, Murakami et al. (1996) study the characteristics associated with the Asian summer monsoon and find that the set-up of the summer monsoon in the South China Sea is closely related with the successive eastward retreat of the subtropical high in west Pacific Ocean. As indicated in Yan (1997), the summer monsoon sets off in the South China Sea because of the eastward retreat of the subtropical high, the strengthening and eastward extension of the equatorial easterly in the Indian region and the northward advancement of the equatorial air flows near 105°E. It is then clear that the timing of the monsoon outbreak in the South China Sea is highly linked with the intensity of the high pressure in the sea and the time of its withdrawal from there. According to Jin et al. (1986), the SST and the high-pressure zone in the South China Sea are well correlated with the westward extension of the west Pacific subtropical high. When the SST in the South China Sea stays high (low) in preceding winters, the South China Sea high is strong (weak) in summer and the western tip of the subtropical high ridge in the west Pacific Ocean is more westward (eastward). It is now concluded that the appearance of SSTA in the winter South China Sea is well related not only with the thermodynamic anomalies of the tropical ocean centering around Sumatra in late spring and early summer, but also with the westward extension of the South China Sea high and the west Pacific subtropical high in summertime. The date on which the latter withdraws from the sea basically determines whether the set-up is early or late concerning the South China Sea monsoon. It is therefore possible to take the wintertime SSTA as the preceding physical indicator for the date of the summer monsoon outbreak in the region.

There are two types of heat source that can influence the land-sea thermodynamic difference, one being the ocean, as what we have discussed above, the other being the land. The role of Asian continent and Australian continent is very important and the Tibetan Plateau is especially so for the Northern Hemisphere. Tao and Zhang (1998) also discuss the issue. When the interannual variation of the Asian monsoons, including the monsoon in the South China Sea, is studied, the thermodynamic conditions of the ocean and land and changes thus resulted in the land-sea thermodynamic contrast must be included in the consideration.

Through the study of the causes and related atmospheric processes for the variation of these thermodynamic differences and the interactions between the changes in the meridional thermodynamic differences between the Indian Ocean and the South China Sea, we are on our way of further understanding the atmospheric and oceanic background with which the monsoon breaks out and behaves in the South China Sea.

Acknowledgements: It is much appreciated that Mr. CAO Chao-xiong, who works at the Guangzhou Institute of Tropical and Oceanic Meteorology, has translated our paper into English.

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