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The Relationship of Land-Ocean Thermal Anomaly Difference with Mei-yu and South China Sea Summer Monsoon

WANG Zhifu[1,2] (王志福) and QIAN Yongfu*[1] (钱永甫)

[1] *Department of Atmospheric Sciences, Nanjing University, Nanjing* 210093

[2] *Key Laboratory of Meteorological Disaster of Ministry of Education,*

Nanjing University of Information Science & Technology, Nanjing 210044

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ABSTRACT

Based on the NCEP/NCAR reanalysis data for the period of 1948–2004 and the monthly rainfall data at 160 stations in China from 1951 to 2004, the relationships among the land-ocean temperature anomaly difference in the mid-lower troposphere in spring (April–May), the mei-yu rainfall in the Yangtze River-Huaihe River basin, and the activities of the South China Sea summer monsoon (SCSSM) are analyzed by using correlation and composite analyses. Results show that a significant positive correlation exists between mei-yu rainfall and air temperature in the middle latitudes above the western Pacific, while a significant negative correlation is located to the southwest of the Baikal Lake. When the land-ocean thermal anomaly difference is stronger in spring, the western Pacific subtropical high (WPSH) will be weaker and retreat eastward in summer (June–July), and the SCSSM will be stronger and advance further north, resulting in deficient moisture along the mei-yu front and below-normal precipitation in the mid and lower reaches of the Yangtze River, and vice versa for the weaker difference case. The effects and relative importance of the land and ocean anomalous heating on monsoon variability is also compared. It is found that the land and ocean thermal anomalies are both closely related to the summer circulation and mei-yu rainfall and SCSSM intensity, whereas the land heating anomaly is more important than ocean heating in changing the land-ocean thermal contrast and hence the summer monsoon intensity.

Key words: land-ocean thermal anomaly difference, South China Sea summer monsoon, Yangtze River-Huaihe River mei-yu rainfall, correlation analysis, composite analysis

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1. Introduction

As a major component of the global climate system, the Asian summer monsoon (ASM) not only has a remarkable impact on the Asian climate but also plays a significant role in the global climate. It has been pointed out that the South China Sea summer monsoon (SCSSM) is an important part of the ASM (Zhu et al., 1986) and has a crucial effect on the atmospheric general circulation and on climate change. SCSSM not only influences the East Asia region but also exerts a significant effect on the weather and climate over the downstream remote regions through the teleconnection process (Li and Zhang, 1999; Wang and Wu, 1997).

The monsoon system originates from the complex interactions in the land-sea-air processes, so the factors for the monsoon and its variability are extremely complicated. It is generally believed that the monsoon circulation results from the seasonal variation of land-ocean thermal contrast (Kuo and Qian, 1982; Murakami and Ding, 1982; Webster, 1987). However, Zeng and Li (2002) pointed out that planetary thermal convection is the primary driver forcing the monsoon and the land-sea thermal contrast is the secondary forcing. Although the opinions differ, any of them

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*Corresponding author: QIAN Yongfu, qianzh2@netra.nju.edu.cn

emphasizes the important impact of land-ocean thermal difference on the monsoon activities. The relation of the land-ocean heating contrast and the ASM has been investigated by Li and Yanai (1996). It is concluded in their paper that the onset of ASM is concurrent with the reversal of the meridional temperature gradient in the upper troposphere south of the Tibetan Plateau, the intensity of ASM is clearly related to the strength of the temperature gradient due to the land-ocean heating contrast, and the strengthened temperature gradient is favorable to a more intense ASM. Chou (2003) examined the influence of the Eurasian continent, the Tibetan Plateau, and the sea surface temperatures (SSTs) on determining the tropospheric temperature gradient to study their linkage with the intensity of the ASM by using an intermediate atmospheric model with an idealized Afro-Eurasian continent. Their conclusion is that higher prescribed heating over land and colder tropical SST anomalies strengthen the meridional temperature gradient and therefore enhance the ASM circulation, which makes the corresponding monsoon rainbelt extend northward and northeastward.

As the thermal status over land is inhomogeneous and has an obvious seasonal variation, many studies emphasize the importance of the anomalous thermal condition over land in changing the land-ocean temperature gradient and consequently affecting the monsoon activities. Zhang and Qian (2002) analyzed the temporal and spatial variations of surface air temperatures in the SCS monsoon region and the association with the onset of the SCSSM and found that the variations of surface air temperatures might play a key role in the onset and interannual variation of the SCSSM. Qian et al. (2004) came to a conclusion that the land thermal low pressure, due to the heating effect of the mid-high latitudes continent, makes the mid-high latitudes high pressure belt break, which introduces the southwesterly air flow to the SCS area and thereby makes the SCSSM begin. It is also pointed out in the paper that the effect of the heating anomaly difference, namely the heating gradient between ocean and land, may be much more effective on the onset date and intensity of SCSSM than the heating anomaly of ocean or land alone. Moreover, the thermal differences between different regions throughout the continent are studied in other papers. For example, Yan et al. (2005) studied and found that the wintertime surface air temperature anomaly over Northeast Asia contrasted well with that over South Asia, and their difference was closely associated with the interannual variation of the ASM intensity.

In addition to the land heating anomaly, another causative factor affecting monsoon activities is the ocean thermal situation. For example, ENSO, the strongest signal on interannual scales, which has an out-of-phase relation with the strength of the following ASM, has been discussed in papers (Webster and Yang, 1992; Li and Yanai, 1996; Yang and Lau, 1998; Chou, 2003). Besides the planetary-scale thermal effect, the local SST anomaly may obviously affect the monsoon activities too. Sun and Ma (1999) showed that SSTs in the SCS and its adjacent area became cooler during strong SCSSM years while warmer during weak SCSSM years. Jiang and Qian (2002) used a P-σ regional climate model and found that positive SST anomalies in the SCS in April and May would lead to a strong SCSSM and vice versa. Huang et al. (2005) analyzed the characteristics of the interannual variations at onset and advance of the East Asian summer monsoon and their associations with the thermal status of the western tropical Pacific. The conclusion was drawn that when the western topical Pacific is in a warmer state in spring, the onset of the SCSSM will be earlier and the monsoon rainfall in the middle and lower reaches of the Yangtze River will be below normal.

From the studies mentioned above, it is apparent that a consensus has not been reached on understanding the factors for the SCSSM variability as to whether it is due to the land heating anomaly or the ocean heating anomaly. Furthermore, most of the previous research mainly focused on the Tibetan Plateau as an elevated heating source, while few of them concentrated on the thermal effect from the mid-high latitude continent on the summer monsoon circulation. Therefore it needs further examining. In this paper, we examine the thermal anomalies over mid-high latitude land and that over the ocean in spring (April–May), and discuss the impact of their difference on the activities of SCSSM and mei-yu rainfall. In addition, the relative importance of the two is also compared.

2. Data and methods

The data employed in the present work are the NCEP/NCAR reanalysis data (Kalnay et al., 1996) for the period of 1948–2004 with a horizontal resolution of $2.5^\circ \times 2.5^\circ$, including not only the monthly air temperature and specific humidity but also the monthly and pentad mean horizontal wind and geopotential height. Also used are the monthly precipitation compiled for 160 stations in China from 1951 to 2004 by the National Meteorological Information Centre of the China Meteorological Administration (CMA).

The area and intensity indices of the western Pacific subtropical high (WPSH) are defined according to Chen et al. (2001): the area index is the total number of grid points at which the 500 hPa geopotential height is equal to or greater than 586 dagpm in a domain of 10°–40°N, 110°–180°E. The accumulated difference of 500 hPa geopotential height minus 585 dagpm in the same domain is referred as the intensity index of the WPSH. The ridge latitude, the north border and the western extension point of the WPSH, are taken from the 74 circulation parameters obtained from the Climate Diagnostics and Prediction Division of the National Climate Center of the CMA.

The mean precipitation of twelve key stations (including Nanjing, Hefei, Shanghai, Hangzhou, Anqing, Tunxi, Jiujiang, Wuhan, Zhongxiang, Yueyang, Yichang, and Changde, after Wang et al., 1999) in the middle and lower reaches of the Yangtze River in June–July is taken as the mei-yu rainfall index. The mid-lower tropospheric temperature (MLTT) mentioned hereafter is the mean air temperature between 700 hPa and 500 hPa in spring (April–May), as high correlation regions are identified over both land and ocean during this period. Correlation analysis and composite analysis from these data are used to find out the relations among the time series.

3. Land-ocean thermal anomaly and its effect

3.1 *Relation between mei-yu rainfall and the mid-lower tropospheric temperature*

The air temperature in mid-lower troposphere (700–500 hPa) has a good association with that at the surface and in the lower-troposphere. Therefore, the difference between the MLTT over the ocean and that over the land can represent the thermal difference between ocean and land. Besides, MLTT is less influenced by the surface topography so that the mean temperature between 700 hPa and 500 hPa is chosen for analyzing the effect of land-ocean thermal anomalies.

In order to show the linkage between MLTT in April to May and mei-yu rainfall in the Yangtze River-Huaihe River Basin, the correlation coefficient between mei-yu rainfall index and the preceding MLTT are plotted in Fig. 1; the shaded area is statistically significant at the 0.01 significance level. The correlation pattern clearly shows that the negative correlation area is located in the mid-higher latitude region while the area with positive correlation is located in the mid-lower latitude region. There are two significant correlation centers with opposite correlation coefficients in the northwest-southeast direction: the negative one is situated to the southwest region of the Baikal Lake with a central value of -0.43, while the positive one lies in the middle latitudes of the western Pacific with a maximum coefficient of 0.37. This correlation pattern implies that when the preceding April–May air temperature is lower (higher) over the mid-higher latitude continent or higher (lower) over the ocean, the following mei-yu rainfall in the Yangtze River and Huaihe River basin will be above (below) normal.

3.2 *Definition of index of the land-ocean thermal anomaly difference*

The above analysis indicates that the mei-yu rainfall has a close linkage with the preceding MLTT, which shows that the rainfall correlation with the temperature over mid-higher latitude continent is opposite to that over mid-lower latitude ocean. The geographical distribution of the correlation indicates an anomalous land-sea thermal contrast in an approximately northwest-southeast direction in association with the mei-yu rainfall variability. In order to understand the influence of preceding land-ocean thermal contrast on the activities of the SCSSM and mei-yu rainfall, the two significant areas representing respectively for the correlation centers are chosen as key regions, i.e., 42.5°–52.5°N, 95°–105°E and 27.5°–32.5°N, 160°–170°E (see the rectangular A and B as shown in Fig. 1). The index of land-ocean thermal anomaly difference (IDX for short) is then defined after the temperature anomalies for the layer of 700–500 hPa have been averaged respectively in the two key areas and normalized to calculate the standardized difference between the two regions. That is,

$$\mathrm{IDX} = ([\bar{T}]^*_A - [\bar{T}]^*_B)^* \ ,$$

where $\bar{T}$ is the MLTT averaged in April to May, $[\ ]_i$ $(i = A, B)$ denotes spatial average in the key regions, and "$*$" denotes the normalization.

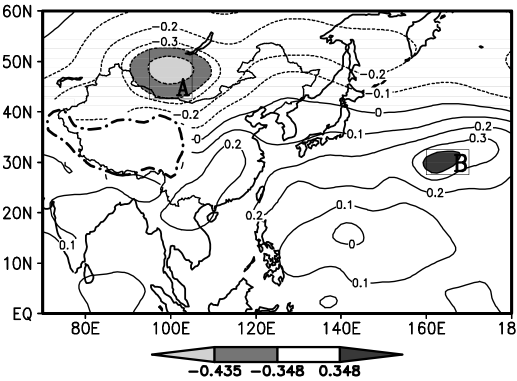

Fig. 1. The relationship between the mei-yu rainfall index in the middle and lower reaches of Yangtze River and the temperature averaged for the mid-lower troposphere in April to May. The regions exceeding the 0.01 significance level are shaded. Rectangles A and B indicate key areas respectively over the land and the ocean.

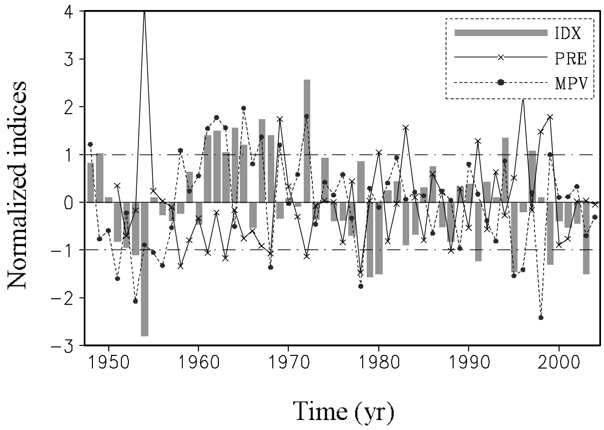

Fig. 2. Interannual variation of the index of land-ocean thermal anomaly difference (IDX, bar), the normalized mei-yu rainfall index in the middle and lower reaches of Yangtze River (PRE, solid line) and the SCS summer monsoon index (MPV, dotted line).

Although regions A and B have their limited areas, it is evident from Fig. 1 that they coincide well with the high correlations. As the monsoon is mainly caused by the thermal contrast between ocean and land, the main factor influencing the intensity of the summer monsoon is the heating difference between ocean and land (Qian et al., 2004). According to results based on multi-year data, the summertime thermal pattern over the monsoon region is characterized by higher temperatures over the continent compared to that over the ocean (Sun et al., 2002). There are heat lows over the former and high pressure over the latter; the direction of the heating gradient is from ocean to land while the direction of the pressure gradient is reversed. Under such conditions, the thermal anomaly over land or ocean will cause a pressure gradient anomaly between land and ocean, and consequently the anomaly of monsoon intensity. The IDX is just a standardized measurement of the magnitude of the heating anomaly difference between land and ocean superposed on the large-scale mean land-sea thermal contrast.

Figure 2 gives the time series of IDX (bar) for 1948–2004. Also shown are the mei-yu rainfall index in the middle and lower reaches of the Yangtze River (PRE, solid line) and the index of the SCSSM intensity in June-July defined as the regional mean of the vertical component of moisture potential vorticity over the region of 0°–10°N, 105°–120°E (MPV, dotted line) (Yao and Qian, 2001). It can be found that IDX differs remarkably from one year to another, having a maximum value of 2.57 in 1972 and a maximum negative value of −2.80 in 1954. Besides the interannual variability, it can be easily seen from a 5-point moving average of IDX (curve not shown) that it also has a feature of interdecadal variation. During the 1950s, IDX was mainly negative. In the following period from 1960s to mid-1970s, a positive index was dominant. Since mid-1970s, it has been in a relative stable period of negative values. Apparently, SCSSM has also experienced a weakening trend since the 1970s (Wang, 2001; Wu et al., 2005). For examining the climate effect of the strong and weak land-ocean thermal anomaly difference, the years of IDX with absolute value larger than one normalized deviation are selected. Thus, eleven positive IDX years (1949, 1961, 1962, 1963, 1964, 1965, 1967, 1968, 1972, 1994, and 1997) and eight negative IDX years (1953, 1954, 1979, 1980, 1991, 1995, 1999, and 2003) are chosen respectively as the strong and the weak difference years. It can also be seen from the above anomalous years that a strong thermal anomaly difference mainly occurred in the period from 1960 to the mid-1970s, while a weak difference appeared mainly in the 1950s and after the mid-1970s. Comparing the curve of IDX with those of mei-yu rainfall (PRE, solid line) and the SCSSM index (MPV, dotted line), one can see that there exists a negative correlation between PRE and IDX, and a positive correlation between MPV and IDX. The correlation coefficient is −0.549 for the former and 0.35 for the latter, which will be discussed in more details later in the next section.

3.3 *Relationship between land-ocean thermal anomaly difference and mei-yu rainfall*

Figure 3 depicts the relation of IDX with the June–July mean rainfall at 160 stations in China. The correlation map clearly shows significant positive correlation over South and Southwest China with the maxi-

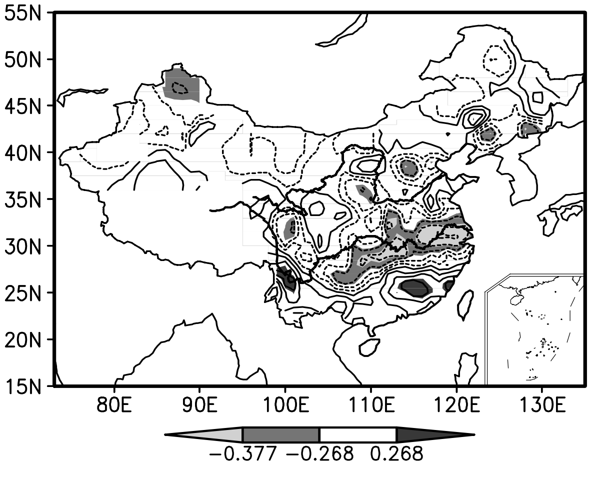

Fig. 3. The relationship between IDX and the precipitation averaged from June to July. The regions exceeding the 0.05 significance level are shaded.

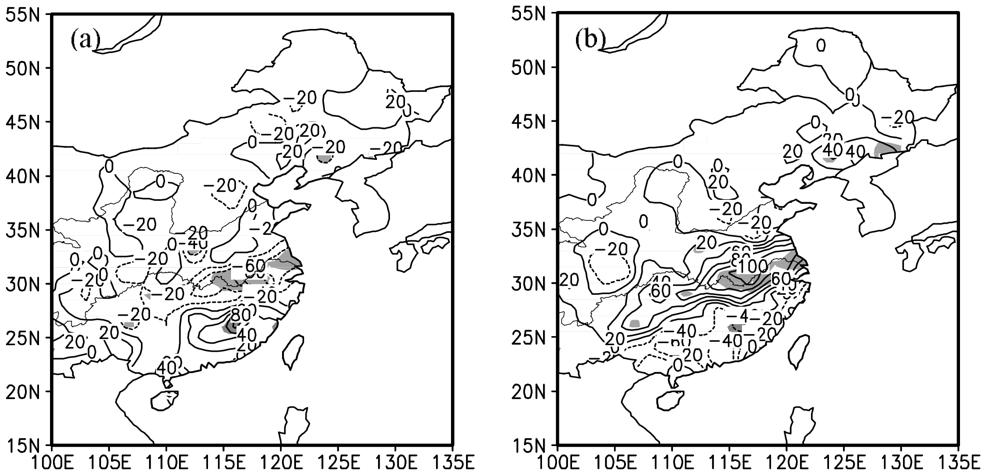

Fig. 4. Composite maps of the precipitation anomaly (mm) averaged from June to July in East China for (a) the strong and (b) weak thermal anomaly difference years. Shading indicates the area over the 0.05 significance level of the student's t-test.

mum coefficient above 0.3, and significant negative correlation in some parts of North and Northeast China and in the middle and lower reaches of the Yangtze River with the greatest coefficients exceeding -0.5, at a statistical significance level much higher than 0.05. This indicates that the June–July precipitation increases (decreases) in South China and decreases (increases) in the middle and lower reaches of the Yangtze River and in North and Northeast China when the thermal anomaly difference is strong (weak) in April–May. The relation is the most significant in the middle and lower reaches of the Yangtze River. This result is consistent with what Fig. 2 shows if one recalls that there is a negative correlation between IDX and the mei-yu rainfall index (PRE, solid line as shown in Fig. 2), and the correlation coefficient is -0.549, at a significance level much higher than 0.01.

In order to further investigate the characteristics of precipitation during a mei-yu season in the strong and the weak IDX years, Fig. 4 shows the composite maps in precipitation anomaly averaged from June to July over East China respectively for the strong and the weak IDX years. The shaded regions indicate that the differences between the strong and weak IDX years are significant at the 95% confidence level according to the Student's t-test. It shows that in the strong IDX years (Fig. 4a) there are significant positive anomalies over South China and significant negative anomalies in the middle and lower reaches of the Yangtze River. In the latter region, the precipitation is reduced by more than 40 mm. On the contrary, in the weak IDX years, it increases evidently in the middle and lower reaches of the Yangtze River with a maximum anomaly exceeding 100 mm but reduced rainfall in South China (Fig. 4b). The composite maps agree well with the correlation results shown above. As the rainy season in North China has not yet commenced in June and July, the composite difference in North China is not significant.

In summary, the thermal anomaly difference in the mid-lower troposphere between land and ocean in spring shows a close relation with precipitation anomaly during the mei-yu season, especially that over the Yangtze River valley. Therefore, the land and ocean thermal anomaly difference may be used as one of the indicators for the forecasting of mei-yu rainfall in this region.

4. Climatic effect of land-ocean thermal anomaly difference

4.1 *Relationship between land-ocean thermal anomaly difference and geopotential height at 500 hPa*

Figure 5 shows the correlation map of IDX with June-July geopotential height at 500 hPa. It is obvious that IDX is inversely correlated to the geopotential height field except for the region from the Korean Peninsula to the northwest Pacific Ocean where the correlation coefficient is small. The most striking feature is that there exists an extensive area of a negative correlation coefficient over the WPSH region with its minimum value less than -0.55 at a significance level much higher than 0.001.

The spatial distribution of the correlation coefficient suggests that the variation in thermal anomaly difference between land and ocean may have considerable influence on the large-scale circulation in the following summer. The composite maps of the geopo-

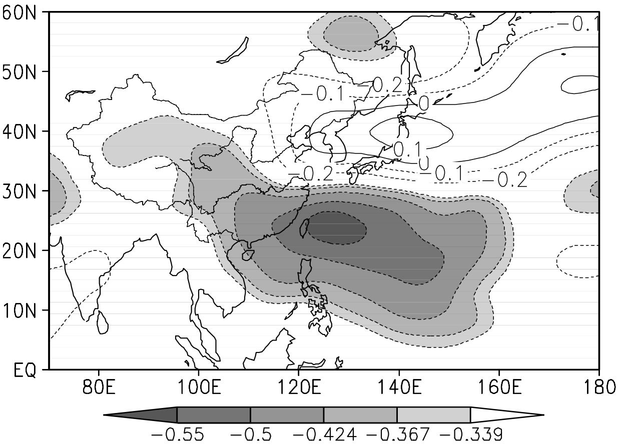

Fig. 5. The relationship between index of land-ocean thermal anomaly difference and the geopotential height at 500 hPa averaged from June to July. The regions exceeding the 0.01 significance level are shaded.

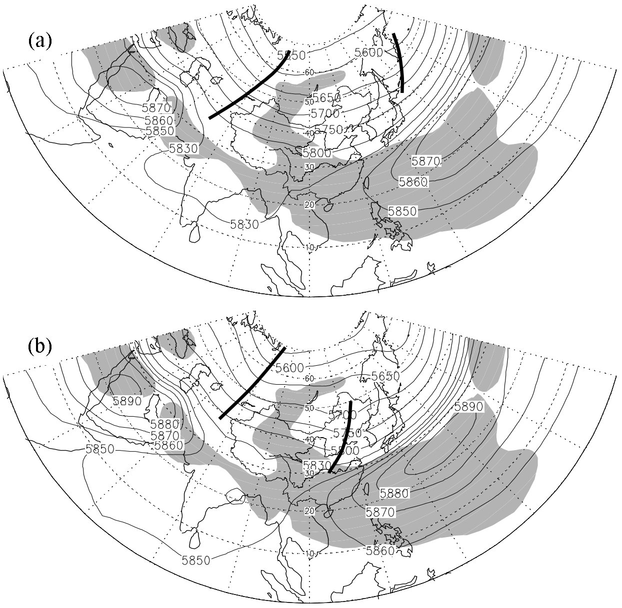

Fig. 6. Composite maps of the geopotential height at 500 hPa (gpm) averaged from June to July for (a) the strong and (b) the weak thermal anomaly difference years. Shaded area is for the significance level better than 0.05 in the student's *t*-test.

tential height at 500 hPa respectively for the strong and the weak IDX years are drawn in Fig. 6. In the strong IDX years, there are two relatively shallow long-wave troughs along 75°E and 160°E. The corresponding isolines are rather smooth over the mid-latitudes of East Asia, suggesting that zonal circulation prevails over this region, and WPSH is weaker and further eastward (Fig. 6a). Different from the features shown in Fig. 6a, Fig. 6b shows that the two relatively deep troughs are over West Siberia and East Asia. The corresponding meridional circulation is strengthened and WPSH is stronger and extending further westward in the weak IDX years. For instance, the WPSH intensity in Fig. 6a has a value of 5870 gpm while its intensity in Fig. 6b reaches 5890 gpm, about 20 gpm stronger. As for the westward extension, only the 5850 gpm isoline can reach Taiwan in the strong IDX years while the 5870 gpm isoline extends into the mainland of China in the weak IDX years. The composite anomalies (figures omitted) exhibit a "negative-positive-negative" pattern in the order from north to south over East Asian/western Pacific region in the strong IDX years. This is favorable for the intensification and further northward migration of the summer monsoon, but unfavorable not only for the formation and maintenance of the blocking high but also for the southward intrusion of cold air from high latitudes. This situation may reduce the monsoon rainfall over the Yangtze River-Huaihe River basin. However, the case is reversed in the weak IDX years for which there is a "positive-negative-positive" north-south wave pattern. In this situation, it is now unfavorable for the northward migration of the monsoon but favorable for the formation and persistence of the East Asia blocking high. This situation may easily make cold air come down the Yangtze River valley to meet with the warm and wet southwest flow, resulting in abundant precipitation over the region. The features of the anomalous patterns respectively in the strong and the weak IDX years are in good agreement with previous reports (e.g. Sun et al., 2002; Zhou et al., 2003; Zhang et al., 2003).

The correlation and composite results both show a close relation between the land-ocean thermal anomaly difference and the WPSH activities. Table 1 shows the relationship between IDX and various WPSH indices. It can be found that IDX has better correlations with the area index, the intensity index, and the westward extending points of WPSH. Their correlation coefficients are respectively −0.401, −0.443 and 0.376, at a significance level higher than 0.01. This indicates that when the thermal anomaly difference is larger in spring, WPSH in June–July is obviously weaker in strength, smaller in area, and retreats eastward, and vice versa. It is also found that IDX is hard to relate to the WPSH ridge latitude, only with weak negative correlation to the WPSH north border, indicating no obvious connection between the land-ocean thermal anomaly difference and the north-south movement of the WPSH. Zhou et al. (2003) attributed it to the short-term variation in the longitudinal position of the WPSH.

Table 1. Correlation of the index of land-ocean thermal anomaly difference and various indices of the Western Pacific Subtropical High (WPSH) averaged from June to July. Values in bold indicate statistical significance at the 0.01 level.

Parameters of WPSH	Area	Intensity	Ridge latitude	North border	Western point
Correlation coefficients	**−0.401**	**−0.443**	0.076	−0.112	**0.376**

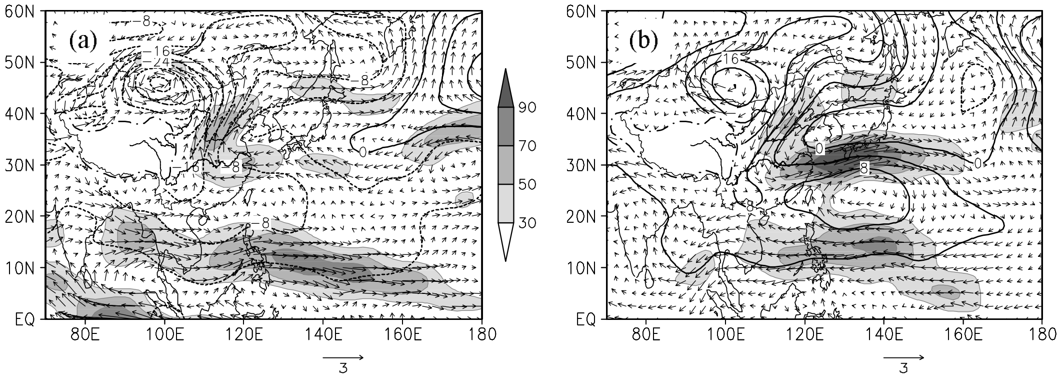

Fig. 7. Composite maps of the anomalies of geopotential height (contours, gpm), wind vector at 850 hPa (vectors, m s^{-1}), and vertically integrated water vapor flux anomaly (shaded area, kg m^{-1} s^{-1}) averaged from June to July for (a) the strong and (b) the weak thermal anomaly difference years.

4.2 *Relationship between land-ocean thermal anomaly difference and SCS summer monsoon*

It has been found that the year-to-year variation of the SCSSM has a close negative correlation with the rainfall over the Yangtze River-Huaihe River basin in summer (Li and Zhang, 1999; Sun and Ma, 1999; Wu et al., 2003). We will now examine the linkage between land-ocean thermal anomaly difference and the activities of the SCSSM, and the impact of the thermal difference on the mei-yu rainfall. The MPV is closely correlated to IDX with a correlation coefficient of 0.35, at a significance level higher than 0.01. This further proves that strong land-ocean thermal anomaly difference is followed by an intensified SCSSM while a weakened monsoon is corresponding to the weak IDX.

Figure 7 presents the composite maps of the June–July geopotential height anomaly and the anomalous wind vectors at 850 hPa and the vertically integrated (from the surface through 300 hPa) moisture flux anomaly respectively for the strong and weak IDX years. In the case of the strong IDX (Fig. 7a), the geopotential height anomalies are negative in almost the entire region except for the Northwest Pacific Ocean. A weak anomalous cyclonic cell is located to the east of Taiwan and a strong one is seen to the southwest of the Baikal Lake. Meanwhile an anomalous anticyclonic circulation is situated over the Korean Peninsula and an anomalous southerly wind prevails over Okhotsk Sea. There is abnormal easterly flow over the middle and lower reaches of the Yangtze River while the area north of 30°N is dominated by anomalous southwesterly flow. It can be found by comparing with the climatological mean fields that the westerly flow is weakened with moisture transport notably reduced along the mei-yu front, and the southwesterly flow is enhanced in North and Northeast China with moisture transport slightly increased. The extensive westerly wind anomaly in the monsoon trough (between 10°N and 20°N) indicates that the SCSSM is strengthened. On the other hand, in the weak IDX years (Fig. 7b), geopotential height anomalies are mostly positive except for an elongated negative area from the Bohai Sea to the northwest Pacific Ocean. The cyclonic circulation pattern to the southwest of the Baikal Lake during the strong IDX years is replaced by an anticyclonic one. Anomalous northerly flow prevails over the Okhotsk Sea and it turns to be northeasterly in North China and meets the flow from southwest of the Baikal Lake, resulting in northeasterly flow dominating over the region north of the Yangtze River. The northeasterly flow then converges with the recurved southwesterly flow from the western part of the anticyclone east of Taiwan forming an anomalous westerly flow around 30°N. The middle and lower reaches of the Yangtze River is dominated by this westerly flow. The anomalous moisture transport extends from the middle and lower reaches of the Yangtze River to the region east of Japan providing the mei-yu front with sufficient water vapor. The abnormal easterly flow over the monsoon trough implies

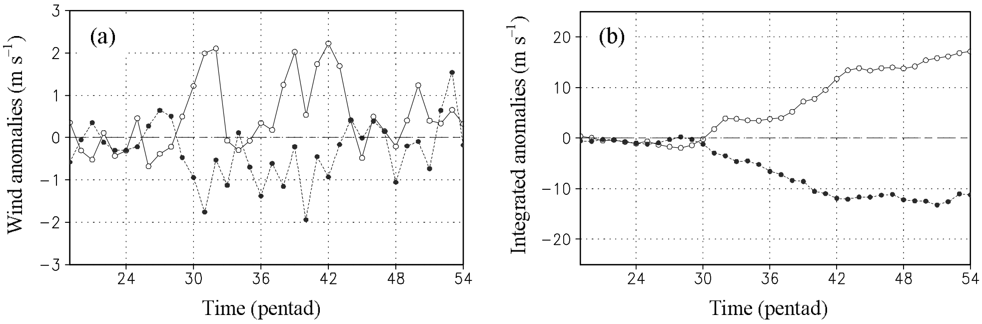

Fig. 8. (a) Time variations of the composite zonal wind anomalies at 850 hPa averaged in SCS region and (b) the integrated anomalies (m s^{-1}, solid lines and dotted lines depict the strong and the weak thermal anomaly difference years, respectively).

a weakened SCSSM. Comparing Fig. 7a and Fig. 7b, it can be found that in the strong IDX years SCSSM is stronger and reaches further northward resulting in the reductions of moisture transport along the mei-yu front and thereby the mei-yu rainfall. On the other hand, in the weak IDX years, SCSSM is weakened and migrates relatively southward resulting in more moisture supply along the mei-yu front and the mei-yu rainfall increases. The results above are consistent with previous research.

Figure 8 shows time variations of the composite zonal wind anomalies at 850 hPa and the integrated anomalies in the SCS region (7.5°–20°N, 110°–120°E) during Pentads 19–54. It is clear that there exist obvious differences of zonal wind between the strong and the weak IDX years. During the period between late May and early August (Fig. 8a), the zonal wind anomalies mainly have positive values in the strong IDX years but negative values in the weak IDX years. As shown more clearly from the integrated anomalies (Fig. 8b), there is no notable difference between the strong and the weak years before Pentad 26. However, after Pentad 28 the integrated anomaly becomes increased, especially during Pentads 28–32 and 36–43, in the strong IDX years. To the contrary, it decreases consistently in the weak IDX years. This contrast becomes less obvious after Pentad 44. This indicates that the zonal wind over the SCS region, i.e., SCSSM is intensified (weakened) in the strong (weak) IDX years. The most obvious difference between the two mainly occurs during Pentads 28–43, when the southwesterly monsoon is prevailing over East Asia.

4.3 *Relative importance of land and ocean thermal effect*

It could be better to simultaneously consider the land thermal effects and the ocean effects on the intensities of the summer monsoon and mei-yu rainfall, since the variability of the land thermal status cannot be simultaneously related to that of the ocean, and the correlation between the mei-yu rainfall and IDX is higher than that between the mei-yu rainfall and temperature anomaly over either the land or the ocean. A question we are interested in is which one is more important, the land or the sea. We will try to answer this question by comparing the relationship between geopotential height and regional averaged air temperature over land key area with that over ocean.

As shown by Sun et al. (2002), the main weather systems influencing the summer precipitation over the East Asia monsoon region are the subtropical high and the cold air, and their variations in intensity are possibly related to the land-ocean thermal difference. The correlation coefficients between air temperature averaged over land or ocean are key areas in April–May. The June–July geopotential height as well as the wind vector at 500 hPa were respectively calculated to investigate their impacts on the circulation at 500 hPa (Fig. 9). From Fig. 9a, the land thermal anomaly is inversely correlated to the geopotential height field except for the region from the Korean Peninsula to the northwest Pacific Ocean. Significant correlations are located in the area to the west of the Okhotsk Sea and in the western Pacific to the east of Taiwan. There are cyclonic circulations in the two significant regions and in the mid-west of Inner Mongolia, and southerly flow dominates over East China north of 30°N. Figure 9b shows that the ocean thermal anomaly is positively correlated to the geopotential height field except for the region over the Japan Sea and significant correlations are located in the extensive area of the western Pacific south of 30°N. There are anti-cyclonic flows to the west of Mongolia, in South China, and in the central Pacific north of 30°N, while a cyclonic circulation is located in the Japan Sea allowing East China north of 30°N to be mainly affected by northerly flow. The correlation coefficient distribution shows that higher temperatures over land and lower temperatures over

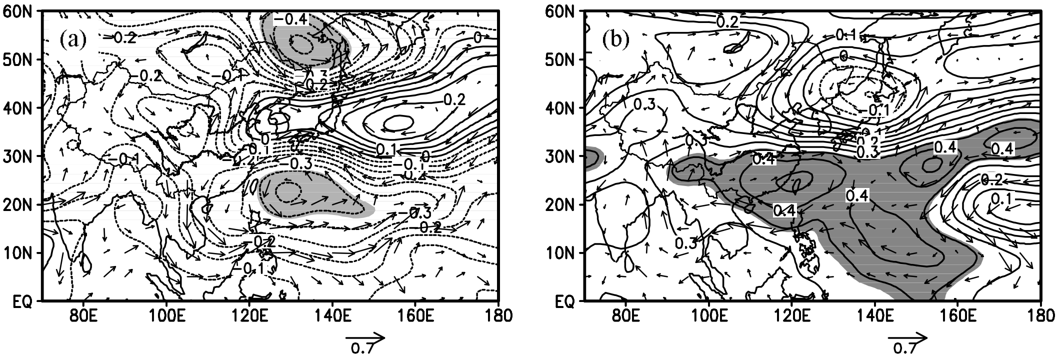

Fig. 9. The correlation maps of 500 hPa geopotential height (contours, the regions exceeding the 0.01 significance level are shaded) and wind vector (vectors) in June-July with regional mean air temperature over (a) the land and (b) ocean key regions in April–May.

ocean are favorable to the intensification of southwesterly flow in East China. However, it is unfavorable to the southward intrusion of the cold air; the cyclonic circulation east of the continent weakens the WPSH. In contrast, lower temperatures over land and higher temperatures over the ocean will weaken the southwesterly monsoon over East China and favor the southward invasion of the cold air; when the anticyclonic circulation is predominant to the east of the continent, it strengthens the WPSH and favors the westward extension of the WPSH.

Comparing the significant correlation areas in Fig. 9a and Fig. 9b, we can see that the land thermal effect influences most obviously the circulation in both the mid-lower latitudes region and the high latitudes region whereas the ocean thermal effect mainly influences the circulation in the low latitudes. This implies that the land and ocean thermal effects both contribute to the WPSH variability. The relationships between the WPSH indices and the land and ocean temperature anomalies were respectively calculated. It shows that the land thermal anomaly is significantly positively correlated to the western extension point of the WPSH (correlation coefficient of 0.394), and the ocean thermal anomaly is significantly positively correlated to the WPSH intensity and area (correlation coefficients of 0.387 and 0.375, respectively). The above results indicate that the land thermal effect contributes to the mei-yu rainfall and the SCSSM intensity by influencing the blocking high and the cold air in the high latitudes region and by impacting on the west-east movement of the WPSH, whereas the ocean thermal effect maintains the area and intensity of the WPSH. As land has a lower heat capacity than water, the land temperature has larger seasonal variation compared to the ocean, thus, it would largely change the land-ocean thermal contrast (Li and Yanai, 1996; Qian et al., 2004) and may play the triggering role in the activities of the cold air and the summer precipitation. In addition, comparing the variability of the land and ocean temperature anomalies can also reveal the relative importance of the land and ocean thermal effects to a certain extent. The standard deviations of them are respectively 1.201 and 0.568, with a ratio of approximately 2:1. Therefore, for the interannual timescale, the land temperature varies much more remarkably than the ocean.

Based on the above analysis, one can see that land temperature varies more obviously than the ocean temperature on both the seasonal and interannual timescale and seems to link to the high latitude systems more strongly. Therefore, the land heating effect might be more important to the mei-yu rainfall and monsoon intensity variability than the ocean.

5. Concluding remarks

The associations among the spring MLTT, the mei-yu rainfall over the Yangtze River valley, and the SCSSM activities are investigated by use of the NCAR/NCEP reanalysis data and the monthly observational rainfall data at 160 stations in China. The mei-yu rainfall over the mid-lower Yangtze River basin is significantly related to MLTT in spring, with positive high values over the middle latitude western Pacific and negative ones over Western Mongolia. Such a correlation pattern reflects the influences of the thermal contrast between land and ocean on the mei-yu activities. An index of land-ocean thermal anomaly difference (IDX) is hence introduced to measure the relative magnitude of the heating anomaly difference between these two regions. It is found that IDX is significantly positively correlated to the June–July precipitation over South China and significantly negatively correlated to that over the mid-lower reaches of the Yangtze River and part of Northern China. When the thermal anomaly difference is strong (weak) in spring, the precipitation decreases (increases) remarkably over the middle and lower reaches of the Yangtze River while increases (decreases) notably over South China. Since the correlation coefficient between IDX and the mei-yu rainfall index is as high as -0.549, we believe that the land-ocean thermal anomaly difference in spring may play an indicative role in the forecasting of the mei-yu rainfall over the Yangtze River-Huaihe River basin.

Anomalies in the thermal status over land and ocean in spring would cause a large-scale atmospheric circulation abnormity. It is the processes of different surface heating to air that have maintained this abnormal signal before summer, causing the circulation anomaly in summer. A stronger land-ocean thermal anomaly difference in spring is followed by a weakened WPSH, strengthened summer monsoon, and a summer drought in the Yangtze River valley. On the other hand, a weaker thermal anomaly difference may result in a stronger and further westward extending WPSH, and weaker summer monsoon, favorable for the cold air intrusion and moisture transportation along the mei-yu front, and plentiful precipitation over this region.

An anomaly in weather systems is determined by the anomaly of the gradient of the pressure system, including the effects of temperature and geopotential height variability, it can be understood that the temperature anomalies over land and ocean play an important role for the pressure systems. However, due to the much more remarkable seasonal and interannual variability in temperature, and closer relationship with the weather systems in the high latitudes region, the land heating anomaly may be more important than that over the ocean to cause the heating gradient between land and sea, and consequently, the intensity of summer monsoon.

It was pointed out that the NCEP-NCAR reanalysis has large uncertainties over East Asia for interdecadal changes in sea level pressure (Yang et al., 2002; Inoue and Matsumoto, 2004; Wu et al., 2005) and low-troposphere geopotential heights and lower-level winds (Wu et al., 2005). Because the strong IDX years chosen in the composite analyses are mainly in the 1960s to mid-1970s, and weak IDX years are mainly in the 1980s and 1990s, which are biased to different decades, it is likely that the results of this study may overestimate the differences seen over East Asia.

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REFERENCES

Chen, Y. J., H. Zhang, R. J. Zhou, and H. F. Wu, 2001: Relationship between the ground surface temperature in Asia and the intensity and location of subtropical high in the western Pacific. *Chinese J. Atmos. Sci.*, **25**(1), 515–522. (in Chinese)

Chou, C., 2003: Land-sea heating contrast in an idealized Asian summer monsoon. *Climate Dyn.*, **21**, 11–25.

Huang, R. H., L. Gu, Y. H. Xu, Q. L. Zhang, S. S. Wu, and J. Cao, 2005: Characteristics of the interannual variations of onset and advance of the East Asian summer monsoon and their associations with thermal states of the tropical western pacific. *Chinese J. Atmos. Sci.*, **29**(1), 20–36. (in Chinese)

Inoue, T., and J. Matsumoto, 2004: A comparison of summer sea level pressure over east Eurasia between NCEP-NCAR reanalysis and ERA-40 for the period of 1960–99. *J. Meteor. Soc. Japan*, **82**, 951–958.

Jiang, J., and Y. F. Qian, 2002: Numerical experiments of impacts of sea surface temperature in South China Sea on South China Sea monsoon. *Journal of Nanjing University* (Natural Sciences), **38**(4), 556–564. (in Chinese)

Kalnay, E. M., and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.

Kuo, H. L., and Y. F. Qian, 1982: Numerical simulation of the development of mean monsoon circulation in July. *Mon. Wea. Rev.*, **110**(12), 1879–1897.

Lau, K. M., and S. Yang, 1997: Climatology and interannual variability of the Southeast Asian summer monsoon. *Adv. Atmos. Sci.*, **14**(2), 141–161

Li, C., and M. Yanai, 1996: The onset and interannual variability of the Asian summer monsoon in relation to land-sea thermal contrast. *J. Climate*, **9**, 358–375.

Li, C. Y., and L. P. Zhang, 1999: Summer monsoon activities in the South China Sea and its impacts. *Chinese J. Atmos. Sci.*, **23**(3), 257–266. (in Chinese)

Murakami, T., and Y. H. Ding, 1982: Wind and temperature changes over Eurasia during the early summer of 1979. *J. Meteor. Soc. Japan*, **60**, 183–196.

Qian, Y. F., J. Jiang, Y. Zhang, Y. H. Yao, and Z. F. Xu, 2004: The earliest onset area of the tropical Asian summer monsoon and its mechanisms. *Acta Meteorologica Sinica*, **62**(2), 129–139. (in Chinese)

Sun, S. Q., and S. J. Ma, 1999: Characteristics of persistent anomaly of South China Sea summer monsoon and its relation to large scale circulation. *Onset and evolution of the South China Sea Monsoon and Its Interaction with the Ocean*, Ding and Li, Eds., China Meteorological Press, Beijing, 301–306.

Sun, X. R., L. X. Chen, and J. H. He, 2002: Index of land-sea thermal difference and its relation to interannual variation of summer circulation and rainfall over East Asian. *Acta Meteorologica Sinica*, **60**(2), 165–172. (in Chinese)

Wang, B., and R. Wu, 1997: Peculiar temporal structure of the South China Sea summer monsoon. *Adv. Atmos. Sci.*, **14**(2), 177–194.

Wang, H. J., 2001: The weakening of the Asian monsoon circulation after the end of 1970's. *Adv. Atmos. Sci.*, **18**(3), 376–386.

Wang, Y. H., Q. Q. Wang, and Y. C. Zhao, 1999: Characteristics of precipitation anomaly over the middle-lower reaches of the Yangtze River related to precipitation and temperature anomalies of China. *Journal of Nanjing Institute of Meteorology*, **22**(4), 685–691. (in Chinese)

Webster, P. J., 1987: The elementary monsoon. *Monsoons*, J. S. Fein, and P. L. Stephens, Eds., John Wiley, New York, 3–32.

Webster, P. J., and S. Yang, 1992: Monsoon and ENSO: Selectively interactive systems. *Quart. J. Roy. Meteor. Soc.*, **118**, 877–926.

Wu, B. Y., 2005: Weakening of Indian summer monsoon in recent decades. *Adv. Atmos. Sci.*, **22**(1), 21–29.

Wu, R., J. L. Kinter III, and B. P. Kirtman, 2005: Discrepancy of interdecadal changes in the Asian region among the NCEP-NCAR reanalysis, objective analyses, and observations. *J. Climate*, **18**, 3048–3067.

Wu, S. S., J. Y. Liang, and C. H. Li, 2003: Relationship between the intensity of South China Sea summer monsoon and the precipitation in raining seasons in China. *Journal of Tropical Meteorology*, **19**(Suppl.), 25–36. (in Chinese)

Yan, H. M., M. H. Qi, Z. N. Xiao, and Y. Chen, 2005: The influence of wintertime thermal contrast over the Asian continent on Asian monsoon. *Chinese J. Atmos. Sci.*, **29**(4), 549–564. (in Chinese)

Yang, S., and K. M. Lau, 1998: Influences of sea surface temperature and ground wetness on Asian summer monsoon. *J. Climate*, **11**, 2330–2346

Yang, S., K. M. Lau, and K. M. Kim, 2002: Variations of the east Asian jet stream and Asian-Pacific-American winter climate anomalies. *J. Climate*, **15**, 306–325.

Yao, Y. H., and Y. F. Qian, 2001: A study on the South China Sea monsoon index and the relationship between the index and regional rainfalls of China. *Journal of Nanjing University* (Natural Sciences), **37**(6), 781–788. (in Chinese)

Zeng, Q. C., and J. P. Li, 2002: Interactions between the northern and southern hemispheric atmospheres and the essence of monsoon. *Chinese J. Atmos. Sci.*, **26**(4), 433–448. (in Chinese)

Zhang, Q. Y., S. Y. Tao, and L. T. Chen, 2003: The inter-annual variability of East Asian summer monsoon indices and its association with the pattern of general circulation over East Asia. *Acta Meteorologica Sinica*, **61**(5), 559–568. (in Chinese)

Zhang, Y. C., and Y. F. Qian, 2002: Characteristics of surface temperature variations in the SCS monsoon region and connections with the monsoon onset. *Journal of Nanjing Institute of Meteorology*, **25**(2), 192–198. (in Chinese)

Zhou, B., J. H. He, G. X. Wu, and G. R. Han, 2003: Characteristics of East Asian subtropical monsoon index and its definition. *Chinese J. Atmos. Sci.*, **27**(1), 123–135. (in Chinese)

Zhu, Q. G., J. H. He, and P. X. Wang, 1986: A study of circulation difference between East Asian and Indian summer monsoon with their interactions. *Adv. Atmos. Sci.*, **3**(4), 466–477.