POSSIBLE RELATIONSHIPS AMONG SOUTH CHINA SEA SSTA, SOIL MOISTURE ANOMALIES IN SOUTHWEST CHINA AND SUMMER PRECIPITATION IN EASTERN CHINA

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Abstract: By using 1958-2001 NOAA extended reconstructed sea surface temperature (SST) data, ERA40 reanalysis soil moisture data and precipitation data of 444 stations in China (east of 100°E), the possible relationships among South China Sea (SCS) SST anomaly (SSTA), soil moisture anomalies (SMA) and summer precipitation in eastern China as well as their possible physical processes are investigated. Results show that the SSTA of SCS bears an evidently negative correlation with spring soil moisture in the east part of Southwest China. More (less) precipitation happens in the Yangtze River basin and less (more) in the Southeast China in summer when the SSTA of SCS is higher (lower) than normal and the soil in the east part of Southwest China is dry (wet) in spring. Further analysis shows that when the SSTA of SCS is high (low), the southwesterly wind at low level is weak (strong), decreasing (increasing) the water vapor transport in South China, resulting in reduced (increased) spring precipitation in the east part of Southwest China and more (less) soil moisture in spring. Through the evaporation feedback mechanism, the dry (wet) soil makes the surface temperature higher (lower) in summer, causing the westward extension (eastward retreat) of the West Pacific Subtropical High, eventually leading to the summer precipitation anomalies.

Key words: statistics; correlation analysis; SSTA; soil moisture; summer precipitation; eastern China

1 INTRODUCTION

China is one of the areas in the world affected most significantly by the monsoon activity. From the beginning to the end of a rainy season, both the changes of main rain belts and precipitation anomalies in eastern China are closely related to the monsoon activity. Located upstream of the summer monsoon airflow, the South China Sea (SCS) is an important source of water vapor and energy. The sea surface temperature (SST) anomalies in this area have great impacts on the general circulation of the tropical atmosphere and the summer climate in China, which has drawn much attention from the Chinese scholars. The relationship has been studied since the 1980s between the SST of the Indian Ocean and the SCS and the summer rainfall around the middle and lower reaches of the Yangtze River, as shown in Chen et al.[1], Luo et al.[2], Luo and Jin[3], Jin and Luo[4], and Shen and Jin[5]. Their studies pointed out that SST of SCS, Arabian Sea and Bay of Bengal in the preceding season can affect the Chinese precipitation in the rainy season. There is also a close link between the SCS SST anomalies (SSTA) and the Western Pacific Subtropical high. Based on numerical experiments, Sun et al.[6] and Liang and Lin[7] confirmed that the SST of the SCS, Asian monsoon circulation and the droughts/floods in the Yangtze River basin are closely linked with each other. Chen[8], Zhao et al.[9] and Liang et al.[10] found that the thermal conditions over the SCS and the eastern tropical Indian Ocean have significant impact on the monsoon system in the western Pacific, India and the SCS. Min et al.[11] showed that SSTA in the SCS, the Bay of Bengal and the Arabian Sea shows consistent variations and has significant interaction with the monsoon system and

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can influence the summer precipitation in China significantly. In recent years, the impacts of the SCS SST on the monsoon circulation and summer precipitation have been widely investigated via numerical simulations[12-15].

Soil moisture plays an important role in the process of land-atmosphere interactions, which is one of the most important physical parameters in both climatic and hydrological study. Soil moisture can affect the ground evaporation, run-off, surface albedo, emissivity, and even the sensible and latent heat flux, which in turn affect the climate significantly. Studies suggest that the impact of soil moisture on the atmosphere is second only to that of the SST on the global scale, and even more important than that of SST over the land. Due to large spatial and temporal variability of the soil moisture and lack of observations, studies on soil moisture anomaly itself and its climatic effect have been greatly limited. Until now, our understanding about the relationship between the soil moisture anomaly and climate variations is still preliminary[16-18]. In recent years, soil moisture reanalysis data has been gradually used in the relevant research filed. Besides, issues related to soil moisture anomaly and its climatic impacts become heated scientific topics again, which greatly deepens our understanding about the interaction between the soil moisture and the climate. Trenberth and Sheg[19], and Dery and Wood[20] pointed out that the interaction between the soil moisture and precipitation/temperature is an important part of the land-atmosphere feedback system. Koster et al.[21, 22] found a close linkage between the soil moisture anomaly and the precipitation. Abnormal rainfall usually causes evident change of the soil moisture, and the soil moisture anomaly in turn can induce the subsequent precipitation anomalies. In addition, studies suggested that the soil moisture anomalies and temperature anomalies are also closely related[23-25], and the soil moisture has been considered as a key predictor for the temperature prediction. In China, significant advancement has been achieved in this field. For example, Ma et al.[26] suggested that the surface soil moisture bears evident lead and lag correlation with the temperature and precipitation. Based on the combination of statistical and dynamic methods, Sun et al.[27] explored the possible relationships among the rainfall anomaly, general atmospheric circulation and soil moisture/temperature over the Huaihe River basin, and disclosed their dynamic linkages as well as the impacts of the soil moisture and soil temperature in the preceding season on summer precipitation. Zuo and Zhang[28], Dai and Zuo[29] investigated the possible impacts of spring soil moisture anomalies of North China on Chinese summer precipitation, indicating that the soil moisture anomalies can affect summer precipitation by altering the East Asian summer monsoon intensity. Liang and Chen[30] explored the possible linkage between the spring soil moisture in South China and summer rainfall and disclosed a strong linkage between them.

Since both the SCS SST anomalies and soil moisture anomalies can influence the general circulation and the monsoon system, they have been used as good indicators of the precipitation anomalies and the movement of the rain belt in the successive season. China is located in the East Asian monsoon region, and the monsoon activity has long been considered closely related to the land-sea thermal contrast. So both the SCS SST anomalies and the soil moisture anomalies have the potential to affect land-sea thermal contrast, and then the East Asian monsoon system and summer rainfall in China. It is noted that most current studies emphasized the impact of SCS SST anomaly and soil moisture anomaly separately but ignored their coordinated influence. This study aims at exploring the possible linkage of the spring SCS SST anomaly with the soil moisture anomaly and their coordinated role on the climate anomaly, especially the precipitation anomalies and the rain belt in Eastern China in the following summer, which will provide some references for better understanding the mechanism of summer precipitation anomalies in China.

The rest of this paper is organized as follows. Section 2 introduces the datasets used in the analysis. Sections 3 and 4 present the relationships among the SCS SSTA, SMA and precipitation in Eastern China. In section 5, the possible process through which the SCS SSTA and SMA have impact on the precipitation in Eastern China is investigated. Section 6 is a summary.

2 DATA

Because of lack of soil moisture observations, the ERA40 soil moisture monthly reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF), with a horizontal resolution of 2.5°×2.5°, is used in this research. The soil moisture data consists of four layers of thickness, i.e. 7 cm, 21 cm, 72 cm, and 189 cm, respectively. Li et al.[31] and Zhang et al.[32, 33] compared several sets of reanalysis data and pointed out that the ERA40 soil moisture data is consistent with existing observations in aspects of both its inter-annual variability and spatial pattern. Zuo and Zhang[34] compared the ERA40 soil moisture data with the station observations in Eastern China (east of 100°E) and suggested that the ERA40 data can reflect the basic characteristics of the geographical distribution of the observed soil moisture. They found that the correlation coefficients between the ERA40 and the observation are statistically significant at the 1% level over most areas in China and soil moisture at shallow soil layers is
more accurate. Therefore, the soil moisture data of the first layer (7 cm) was selected to characterize the surface soil moisture in our study. The study period is set to 1958-2001 since the ERA40 data is only available from September 1957 to August 2002.

The SST data used is the National Oceanic and Atmospheric Administration (NOAA) extended reconstructed SST data (2.0°×2.0°). The precipitation data with continuous records at 444 stations in Eastern China during 1958-2001 provided by the National Meteorological Center is also used in our current study. Fig. 1 shows the geographic distribution of the selected 444 rainfall stations.

In addition, the ERA40 geopotential height, wind field, water vapor and surface air temperature monthly reanalysis data are also used in this study.

For the convenience of comparison, Fig. 4 presents the inter-annual variation curves of both the

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The region (110–120°E, 10–20°N) in SCS is selected as the study area and an index of spring SCS SSTA is defined by normalizing the time series of the average March SST over the target region during 1958–2001 to reflect the inter-annual anomaly of the SCS SST (shown in Fig. 2). The SCS SSTA exhibits an obvious inter-annual variability and a weak warming trend. SST is cold before 1978 but warm after that.

Figure 3 presents the distribution of the correlation coefficients between the SCS SSTA index and the late spring (May) soil moisture in China (east of 100°E). It is noted that the SCS SSTA bears a negative correlation with the soil moisture in the Yangtze River basin with the most significant negative correlation region located in the east part of Southwest China. Weak positive correlations are also found in North China and coastal regions in South China, while weak negative correlation is located in Northeast China. While Zuo et al.[28] and Liang et al.[30] emphasized the relationship between the summer precipitation anomalies with the spring soil moisture anomalies over the last three regions, our study focused on the soil moisture anomalies in the east part of Southwest China as well as its impacts. The regional averaged soil moisture in May over the east part of Southwest China (102.5°–110°E, 25°–30°N) is normalized to define an index of the soil moisture anomalies (SMA), which can be used to reflect inter-annual anomalies of the soil moisture in the late spring over this region.

For the convenience of comparison, Fig. 4 presents the inter-annual variation curves of both the
SCS SSTA index and SMA index. On the whole, there is an evident negative correlation between them, i.e., dry (wet) soil in the east part of Southwest China is always accompanied by warmer (colder) SCS SST. Further analysis shows that the correlation coefficient between them is -0.52, which is statistically significant at the 1% level, implying a very close relationship between the spring SCS SSTA and the late spring SMA in the east part of Southwest China.

Figure 4. Interannual variations of SCS SSTA index for March (solid line) and Southwest China SMA index for May (dashed line).

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Figure 5 shows the geographic distributions of the correlations of the SMA index with spring and summer precipitation over Eastern China, indicating the possible relationships between the late spring SMA in Southwest China and the rainfall anomaly. The late spring SMA bears a significant positive correlation with the spring precipitation in the east part of the Southwest China, implying that the soil tends to be wet when there is more precipitation (Fig. 5a). The above results also demonstrated the reliability and capability of the ERA40 soil moisture data in representing the soil moisture state over this region. From Fig. 5b, it is found that the spring SMA index and anomalies of summer precipitation, especially the rainfall in the Eastern China, are closely related. An evident positive correlation is located in Southeast China but a significant negative correlation in the Yangtze River basin.

For the need of further discussion, we calculated the regional averaged summer (June-July) precipitation over Southeast China (112°-120°E, 23°-28°N) and the Yangtze River basin (105°-123°E, 28°-33°N), respectively, which are normalized to get the indexes for the summer rainfall in the Southeast China and the Yangtze River basin (Rdn and Rcj) to reflect the rainfall anomalies over those two regions. Fig. 6 presents the time series of SMA, Rdn and Rcj. It is noted that the variation of Rdn is very consistent with that of SMA, while the variation of Rcj is generally opposite to that of SMA. Further calculation shows that the correlation coefficient between Rdn and SMA is 0.37, and that between Rcj and SMA is -0.36. Both of them are statistically significant at the 5% level.

Figure 5. The geographic distribution of the correlation coefficients of Southwest SMA index for May with (a) spring and (b) summer rainfall in China. The solid and hollow circles represent the positive and negative value, respectively. The small circles and big circles show they are statistically significant at the 5% and 1% level, respectively.

Figure 6. Interannual variations of Southwest China SMA index (solid line), Rdn index (dashed line) and Rcj index (dotted line).

In summary, there is a close relationship between soil moisture anomalies over the east part of the Southwest China and the rainfall in the Southeast China and the Yangtze River basin. Opposite variations are found in the precipitation anomalies over these two regions. Less summer precipitation happens in the Yangtze River basin and more in the
Southeast China accompanied by wet spring soil in the east part of the Southwest China, and vice versa.

5 POSSIBLE PROCESSES OF SCS SSTA AND SMA AFFECTING PRECIPITATION IN EAST CHINA

The analysis above shows that spring precipitation anomalies will directly lead to the soil moisture anomalies in the east part of Southeast China (Fig. 5a). Fig. 7 shows the distributions of the correlation coefficients of SCS SSTA and spring precipitation in China. The SCS SSTA bears a significant negative correlation with the precipitation anomalies in the east part of the Southwest China, whose spatial pattern is similar to that of Figs. 3 and 5a. Therefore, it is concluded that the early spring SCS temperature has a close link with the spring precipitation in the east part of Southwest China, and the SSTA can cause abnormal spring rainfall in the east part of Southwest China, leading to the variation of the soil condition (to be dry or wet).

Figure 7. The geographic distribution of the correlation coefficients between March SCS SSTA index and spring rainfall in China. The solid circle and hollow circle represent the positive and negative value, respectively. The small circles and big circles respectively show they are statistically significant at the 5% and 1% level.

In order to further examine the results mentioned above, the regionally averaged spring (April-May) precipitation over the east part of Southwest China (102.5°–110°E, 25°–30°N) was calculated and normalized as the index of spring rainfall anomaly (Rxn) to reflect the inter-annual variability of the rainfall over this region. The inter-annual variations of the three indexes (SCS SSTA, SMA and Rxn) are shown in Fig. 8. Results suggest that the correlation coefficient between SCS SSTA and Rxn is -0.31 (significant at the 5% level). The correlation coefficient between Rxn and SMA is as much as 0.54 (significant at the 1% level). It is then concluded that the precipitation anomalies in the east part of Southwest China is closely linked with the SCS SST and is the direct cause for the variation in SMA. Less (more) spring precipitation in Southwest China is corresponding to warm (cold) SCS SST, resulting in dry (wet) soil at the end of spring.

![Figure 8. Interannual variations of SCS SSTA index (solid line), Southwest China SMA index (dashed line) and Rxn index (dotted line).](image)

Figure 9 shows the spatial distributions of the correlation coefficients of SCS SSTA index with the spring 850-hPa wind and relative humidity. There is an anomalous northeasterly wind component from the Yangtze River basin to the east part of Southwest China when the spring (March) SCS is warmer than usual. This weak southwesterly wind reduces the transfer of water vapor into the region of interest and decreases the relative humidity, and eventually leads to a decrease in precipitation. On the contrary, more precipitation happens when the SCS is cooler than normal. It is therefore concluded that the SCS SSTA usually causes the anomalous southwesterly wind and results in spring precipitation anomaly in the east part of Southwest China, which is the possible cause of the spring soil moisture anomaly in Southwest China.

An important way by which the soil moisture anomalies affect the atmosphere is to change the surface thermal forcing and thus induce the atmospheric circulation anomalies. Fig. 10 shows the distributions of the correlation of the SMA index with the surface air temperature and the 500-hPa geopotential height. There is a significant negative correlation between the SMA index and the surface air temperature in the east part of Southwest China, and there is also a significant negative correlation at the mid- and upper-troposphere over these regions. The distributions suggest that the surface air temperature is obviously higher when the soil in the east part of Southwest China is dry (Fig. 10a). The abnormal surface heating causes the variation of the geopotential height in the upper atmosphere, which increases the 500-hPa geopotential height significantly over Southwest China and its nearby areas (Fig. 10b). Such a situation tends to strengthen the summer western Pacific subtropical high and make it move westward.
In order to explore the basic feature of the atmospheric circulation anomalies related to the SSTA and SMA more directly and to better understand the mechanisms of summer rainfall anomalies, four typical years (1988, 1998, 2000 and 2001) are selected as warm SST/dry soil years in which the spring SCS SST is warm (with the SSTA index > 0.8) and the spring soil is dry (with the SMA index < -0.8). At the same time, eight years (1962, 1964, 1965, 1967, 1968, 1971, 1972 and 1974) are also selected as cold SST/wet soil years, in which the spring SCS SST is cold (with the SSTA index < -0.8) and the spring soil is wet (with the SMA index > 0.8). Both are used in composite analysis.

Figure 11 shows the composites of spring 500-hPa geopotential high for the years of warm SST/dry soil moisture and the years of cold SST/wet soil moisture, where the dashed line indicates the climatology of 588 dagpm contour. The most significant difference of the soil moisture anomaly years is mainly related to the changes in the intensity of the subtropical high and its position. In the dry soil case, the subtropical high is much stronger and extends westward to 123°E, with its ridge located at about 20°N (Fig. 11a). However, in the wet soil case, the subtropical high is much weaker and retreats eastward to 141°E with its ridge located at about 25°N (Fig. 11b).

In summary, warm SCS SST in March usually produces low spring soil moisture in the east part of Southwest China. Through an evaporation feedback, dry soil increases the summer surface temperature and intensifies the thermal heating in the low level of the atmosphere. As a result, the geopotential height at the 500-hPa level was uplifted, causing the westward
extension of the western Pacific subtropical high. Such a situation hampers the northward advance of the summer monsoon, resulting in more summer precipitation over the Yangtze River basin but less summer precipitation in Southeast China. On the contrary, when the SCS SST is cold in March, there is less summer precipitation over the Yangtze River basin and more rainfall in Southeast China. Liang and Chen[30] pointed out that the low spring soil moisture in South China is beneficial to the westward extension of the western Pacific subtropical high and the precipitation anomalies, which is basically consistent with our results.

6 CONCLUSIONS AND DISCUSSION

Based on the observational analysis, the possible relationships among the spring SCS SSTA, SMA and the summer precipitation in Eastern China are disclosed in this study. Main conclusions are summarized as follows.

1) The spring SCS SST bears a significant negative correlation with the spring soil moisture in the eastern part of Southwest China (east of 100°E). The spring soil in this area is usually dry (wet) when the spring SCS is abnormally warm (cold).

2) The spring SMA in the eastern part of Southwest China bears a significant negative correlation with the summer precipitation over the Yangtze River basin but a positive correlation in Southeast China. More (less) summer precipitation happens in the Yangtze River basin and less (more) in Southeast China when the soil spring moisture is low (high).

3) When SCS SST is high (low), the southwesterly wind at the low level is weak (strong), decreasing (increasing) the water vapor transport in South China and resulting in reduced (increased) spring precipitation in the east part of Southwest China and more (less) soil moisture in spring.

4) Through the evaporation feedback mechanism, the dry (wet) soil increases (decreases) the surface temperature in summer, causing the westward extension (eastward retreat) of the West Pacific subtropical high. Changing the surface thermal condition and causing the atmospheric circulation anomalies, the soil moisture anomalies can be one of the possible causes for the summer precipitation anomalies.

The possible linkages among the early spring SCS SSTA, the late spring SSTA and the summer precipitation anomalies were investigated in this study, which can help us understand more about the mechanisms by which SSTA affects the precipitation. However, the results are still preliminary and further studies are needed. The results are acquired only by the observational analysis and should be verified by numerical experiments in the future.

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