A STUDY ON THE EFFECT OF SPRING INDIAN OCEAN SSTA ON SUMMER EXTREME PRECIPITATION EVENTS OVER THE EASTERN NW CHINA

JIANG Zhi-hong (江志红) 1, YANG Jin-hu (杨金虎) 1,2, ZHANG Qiang (张强) 3

(1. Key Laboratory of Chinese Ministry of Education for Meteorological Disaster, Nanjing University of Information Science & Technology, Nanjing 210044 China; 2. Chendu Institute of Plateau Meteorology of China Meteorological Administration, Chengdu 610071 China; 3. National Climate Center, Beijing 100081 China)

Abstract: Based on monthly mean wind, geopotential height, specific humidity, and surface pressure of NCAR/NCEP reanalysis, NOAA-reconstructed sea surface temperature (SST) of the Indian Ocean, and daily precipitation data at 97 meteorological stations over the eastern NW China in the past 47 years, the threshold values for extreme precipitation events (EPE) are defined using the percentile method. Singular Value Decomposition and synthetic analysis methods are used to analyze the relationship between summer EPE in the eastern NW China and SSTA in the preceding fall, winter, spring, and the concurrent summer. The result shows that preceding spring SST anomalies (SSTA) in the Indian Ocean are clear indicators for the forecast of summer EPE in the eastern NW China, and a key area of impact is located in the equatorial Indian Ocean. When spring SST is anomalously high in the equatorial Indian Ocean, the meridional circulation averaged over 100°E–110°E will be anomalously ascending near the equator but anomalously descending near 30°N in the middle and upper troposphere from the concurrent to the subsequent summer. In the meantime, the Southwest Monsoon from the Indian Ocean will be anomalously weak and there will be no anomalous water vapor transport to the eastern NW China, resulting in a lack of EPE in the subsequent summer, and vice versa. In addition, in response to anomalously high SST in the equatorial Indian Ocean in spring, the South Asia high pressure tends to be strong in the subsequent summer and more to the west. In the anomalously low SST year, however, the South Asia high tends to be weak in the subsequent summer and more to the east. This is another possible cause of the variation of summer EPE in the eastern NW China.

Key words: extreme precipitation events; SVD; SSTA; eastern NW China; Indian Ocean

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1 INTRODUCTION

In recent years, over the background of global warming there has been widespread attention to extreme climatic events from scientists all over the world. Up-to-date research has shown that heavy precipitation episodes in the United States, China, Australia, and Canada have all shown increases to some extent[1]. Utilizing a variety of models to simulate possible climate changes under different future circumstances, several international scientists found that even though extreme precipitation events possess strong regional characteristics, the overall trend is moving toward extreme outcomes[2-4]. As a region with its vulnerable water environment, China has been hit especially hard by meteorological disasters from extreme precipitation events, resulting in ever increasingly adverse impact on its sustainable socio-economic development. Although extreme precipitation events are rare with small spatiotemporal scales and are characteristic of abruptness and sharp-turn resulting in large uncertainty in prediction, some observational and theoretical studies[5] showed that their response to external forcing are more sensitive compared to average climate. Consequently, it bears important scientific implication and practicality to obtain comprehensive understanding of the change and mechanisms of extreme precipitation...
events over China and to further perform forecast experiments. It is especially important to study the mechanisms of extreme precipitation events over the eastern Northwest China (referred to as eastern NW China hereafter) where precipitation is essential for the agriculture and summer drought is prevalent while light precipitation has little effect on lessening a drought.

It is well known that the oceans play a very important role in short-range climate variation. In recent years many scientists have strived to find oceanic areas of anomalous temperature that are highly correlated with the precipitation over China; they include the Indian Ocean, the South China Sea, the Oyashio Current area, the Kuroshio Current area, the equatorial Pacific Ocean warm pool, and the equatorial eastern Pacific area\(^6\)\(^-\)\(^13\). However, their research has focused mainly on the eastern part of China and has targeted general precipitation. As a matter of fact, the eastern NW China is on the edge of the monsoon region\(^14\) and its main source of moisture in summer is also from the Indian and Pacific Oceans\(^15\)\(^-\)\(^18\). As a result, there must be some relationship between anomalous sea surface temperature (SST) over the Indian and Pacific Oceans and the precipitation in general and even extreme precipitation over the eastern NW China. Recently, Yang et al\(^19\) found that winter anomalous temperatures over the Pacific Ocean have a significant impact on the extreme precipitation events over the eastern NW China in the subsequent summer and the key area for the impact is the equatorial eastern Pacific region. Additionally, other studies found that there is a relationship between the anomalous temperature in the Indian Ocean and that in the equatorial central and eastern Pacific Ocean\(^20\),\(^21\).

Then what kind of relationship exists between the anomalous temperature over the Indian Ocean and extreme summer precipitation events over the eastern NW China? Based on these findings, this paper attempts to analyze the impact of the anomalous SST over the Indian Ocean on extreme summer precipitation events over the eastern NW China, in order to provide more evidence to support the short-term prediction of the extreme precipitation events over the eastern NW China.

2 DATA AND METHODOLOGY

2.1 Data

In this paper, the following data are used: Daily precipitation data for the years 1960–2006 at 97 observation stations over the eastern NW China, monthly mean wind, height, humidity, and surface pressure reanalysis datasets from National Center for Atmospheric Research/ National Centers for Environmental Prediction (NCAR/NCEP, USA), and reconstructed monthly mean sea surface temperature (SST) data from the National Oceanic and Atmospheric Administration (NOAA, USA) for the years 1959–2006 over the Indian Ocean (40°S–20°N, 30°E–130°E). The NCAR/NCEP data have a grid point of 2.5°×2.5° while the SST data have a grid point of 2°×2°. In this paper, the eastern NW China consists of Sha’anxi, Ninxia, and the area of Gansu east of the Yellow River (31.5°N–39°N, 102.5°E–110.5°E).

2.2 Definition of extreme precipitation events

Due to uniform national standards adopted, previous definitions of the threshold values of extreme precipitation events (such as thunderstorm, heavy rainfall) result in overwhelming extreme precipitation events in eastern China. In fact, China is a country with vast territory and complex terrains, a precipitation event, defined as in the middle grade according to the national standard, can cause geological disasters such as flash floods and mudslides in the western part of China, whereas even heavy precipitation in the western part of the country by the national standard can hardly cause any geological disasters in the eastern part of the nation. Thus, in this paper we use an internationally prevalent method, which is based on percentage, to define the threshold values for extreme precipitation events (EPE) at various observation stations. Refer to Zhai and Pan\(^22\) for detailed methodology.

3 COUPLING OF SSTA OVER THE INDIAN OCEAN AND EPE OVER EASTERN NW CHINA

In this paper, the Indian Ocean SST anomaly (SSTA) is referred to be the left field, and the EPE frequency in summer (monthly averaged over June, July and August) at stations over the eastern NW China is referred to be the right field. The coupling of these two fields is analyzed with different time lags. Specifically, the Indian Ocean SSTA for the preceding autumn (monthly averaged over September, October and November), preceding winter (monthly averaged over December, January and February), preceding spring (monthly averaged over March, April and May), and the concurrent summer (monthly averaged over June, July and August), as the left fields, and the summer EPE over eastern NW China, as the right field, will be combined respectively to form four coupling schemes to conduct Singular Value Decomposition (SVD) analysis.

Table 1 shows the percentage of squared covariance explained and the correlation coefficients of the first two modes from the four coupling relations. There exists a significant relationship between SSTA...
over the Indian Ocean in spring and the EPE over the eastern NW China in the succeeding summer in which not only the contribution of cumulative squared covariance of the first two modes is the highest but also the correlation coefficient of the left and right fields for these two modes is the largest. This demonstrates that spring Indian Ocean SSTA has a very good predictive value for change in EPE over the eastern NW China in the succeeding summer. Therefore, next we will focus on analysis of the coupling relationship between summer Indian Ocean SSTA and the EPE over the eastern NW China in the subsequent summer. Furthermore, based on the fact that the percentage of squared covariance explained by the first two modes is as high as 88.9% and correlation coefficient of the two modes (0.41) passes the confidence test at the 95% level of significance, the first two modes can represent the two fields in terms of their coupling.

Table 1. Percentage of squared covariance explained and correlation coefficients of the first two coupled modes

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<td>1</td>
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<td>12.40</td>
<td>0.51</td>
<td>24.71</td>
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Figure 1 displays the spatial distribution of the homogeneous correlation coefficient of the first coupled modes with spring Indian Ocean SSTA and the EPE over the eastern NW China in the subsequent summer. It can be seen that for the summer EPE over the eastern NW China (Fig. 1a) the values are negative and uniformly distributed and with the exception of Southeastern Sha’anxi all other areas show significant correlation (with the coefficient less than -0.5). On the other hand, for the Indian Ocean SSTA field in the preceding spring (Fig. 1b) positive values prevail everywhere and the correlation coefficient is greater than 0.4 for most of the area with the most significant correlation area located in the equatorial Indian Ocean (with the correlation coefficient greater than 0.8). Since the first pair of modes for the EPE and SSTA fields account for 45.68% and 42.58% respectively of the squared covariance, they contain the main information of the two fields. These demonstrate that anomalous high SST over the equatorial Indian Ocean in spring will be followed by an overall declining of EPE over the eastern NW China in the subsequent summer and vice versa. In addition, the curve of the time coefficients of the first coupled modes (figure not shown) suggests that in the past 47 years, SST over the Indian Ocean in spring has been constantly in the rise, resulting in a downward trend of extreme precipitation events over the eastern NW China in the subsequent summer, which is basically consistent with the variation of summer rainfall over the same region[24]. Furthermore, a study by Yang[25] revealed a trend of slight increase in rainfall for summer extreme precipitation events over the eastern NW China. Decreases in the extreme precipitation events imply a trend of increasing intensity of the precipitation over the eastern NW China.

Homogeneous correlation coefficient maps of the second coupled modes with the spring SSTA of the Indian Ocean and with the subsequent summer EPE over the eastern NW China (Fig. 2) show that the distribution of summer EPE (Fig. 2a) is uniformly negative with significant correlation areas mainly located in the southeastern part of Northwest China (with the correlation coefficient greater than 0.7). At the same time, the homogeneous correlation map for
Spring SSTA of the Indian Ocean (Fig. 2b) also displays the same characteristic of overall negative values with significant correlation areas located mainly in the southeastern part of the Indian Ocean (with the correlation coefficient greater than 0.6). The percentages of squared covariance explained by the second coupled modes of EPE and SSTA are 20.05% and 7.44%, respectively. The second mode of EPE contains more information while that of SSTA is relatively small, implying smaller probability for the existence of this mode. On the other hand, the correlation between these coupled modes is 51. This shows a significant relationship between these two coupled modes, and when SST is anomalously high over the southeastern Indian Ocean in spring, there will be more EPE over the southeastern NW China in the subsequent summer, and vice versa.

4 POSSIBLE CAUSE OF SPRING INDIAN OCEAN SSTA AFFECTING THE SUBSEQUENT SUMMER EPE IN THE EASTERN NW CHINA

From the analysis above, we find that the squared covariance contribution from the first SVD mode is 76.5%, and the variance contribution from the first modes of both fields is also fairly large. This implies that the first coupled modes contain major information about the two fields. In order to further determine the key area of the impact of the equatorial Indian Ocean SSTA in spring on the EPE in the eastern NW China in the succeeding summer, we calculated the regional average of SST for the equatorial Indian Ocean (50°E–100°E, 10°S–10°N) in spring. Furthermore, we found that the correlation coefficient of the time series for the first SVD mode of SSTA and the regional average SST is as high as 0.98. Therefore, the key area of spring Indian Ocean SSTA impact on the eastern NW China EPE in the subsequent summer is located in the equatorial Indian Ocean region. Next, we will focus on analyzing the possible cause of the impact of equatorial Indian Ocean SSTA in spring on the EPE over the eastern NW China in the subsequent summer.

To identify years with anomalous SST in the equatorial Indian Ocean, we normalize the expansion coefficient (time series) of the first SVD mode for SSTA and select the years for which the value is greater than 1.2 $\sigma$ or less than -1.2 $\sigma$ as anomalously high and low years for the equatorial Indian Ocean SST. As a result, we have years 1988, 1998, 2001, 2003, and 2005 as anomalously high SST years, and years 1963, 1965, 1968, 1971, 1974, and 1975 as anomalously low SST years. Then, we will use synthetic analysis to identify the possible cause of the impact of equatorial Indian Ocean SSTA in spring on the EPE over the eastern NW China in the subsequent summer.

4.1 Characteristics of meridional circulation in years of anomalous SSTA over the equatorial Indian Ocean in spring

Many studies have shown that oceans have long memory and their impact on climate possesses are apparently lagged behind[7-10]. Our analysis so far has demonstrated the existence of significant impact of spring equatorial Indian Ocean SSTA on the EPE over the eastern NW China in the subsequent summer. In order to understand the cause of this impact, Fig. 3 shows sectional averaged (100°E–110°E) meridional circulation anomaly in the concurrent spring and the subsequent summer of the years when the equatorial Indian Ocean SST is anomalously high or low.

In the years of anomalously high SST in spring in the equatorial Indian Ocean, anomalous ascending flow appears in the concurrent spring in areas from 20°S to the equator while a descending flow prevails at 28°N–35°N and in 600–200 hPa (Fig. 3a). In the subsequent summer, apparent ascending flows also prevail near the equator, while at around 30°N and above 500 hPa the descending flow is more obvious than in spring (Fig. 3b). In the years of anomalously low SST in spring in the equatorial Indian Ocean, descending flows are present uniformly in the
concurrent spring at 20°S–25°N, while ascending flows prevail at 28°N–35°N and at 600–200 hPa (Fig. 3c). Fig. 3d shows that in the subsequent summer, uniform descending flows are present at 5°S–15°N and from the ground level to 200 hPa, while uniform ascending flows prevail at 27°N–40°N and above 700 hPa.

It is now clear from the analysis above that in the years when the equatorial Indian Ocean SST is anomalously high in spring, averaged meridional (100°E–110°E) flow anomaly is ascending at and near the equator, while descending flow anomaly appears in the middle and upper troposphere at around 30°N from the concurrent spring to the subsequent summer. The absence of anomalous descending flow in the lower troposphere may be due to the impact of the heating effect of the Tibetan Plateau. In the years with anomalously low equatorial Indian Ocean SST, anomalously descending flow appears in the averaged meridional (100°E–110°E) circle while anomalously ascending flow appears at around 30°N.

4.2 Characteristics of 700 hPa wind anomaly in years of anomalous SST over the equatorial Indian Ocean in spring

Low-level wind fields can better demonstrate the monsoon circulation. To further understand the impact of equatorial Indian Ocean SSTA in spring on the monsoon circulation over south Asia and to better reveal the possible cause for the variation of spring EPE in the eastern NW China, Fig. 4 shows wind anomaly fields at 700 hPa in the concurrent spring and the subsequent summer when equatorial Indian Ocean SST is anomalous in spring. Fig. 4a shows that in the years when equatorial SST is anomalously high in spring, in the concurrent spring strong southwesterly anomaly prevails over the area from the equatorial Indian Ocean through the Bay of Bengal and all the way to Myanmar, but it turns westward over Myanmar and blows from Bangladesh to India, while the eastern NW China is under the influence of northeasterly anomaly from northern China. In the subsequent summer (Fig. 4b) the wind field experiences a marked change from spring. A slightly easterly anomaly comes from the equatorial western Pacific and turns cyclonically over the equatorial Indian Ocean area, while the eastern NW China is under the influence of northerly anomaly from the anti-cyclonical southerly
flow over the western part of northern China. In the years when spring equatorial Indian Ocean SST is anomalously low, weak anti-cyclonic wind anomaly is prevalent over the Bay of Bengal, Bangladesh, and Myanmar in the concurrent spring (Fig. 4c) and the subsequent summer (Fig. 4d), meanwhile in summer, part of the southwesterly anomaly, coming from the Bay of Bengal and passing over Bangladesh, blows toward the eastern NW China. In another word, southwesterly anomaly appears over the eastern NW China.

In summary, from the analysis of the wind anomaly at 700 hPa we found that in the years of anomalously high SST in spring over the equatorial Indian Ocean, the southwest monsoon from the Indian Ocean passing over the Bay of Bengal weakens, while the southwest monsoon strengthens in the years of anomalously low SST.

4.3 Characteristics of whole layer moisture flux anomaly in years of anomalous SST over the Indian Ocean in spring

In order to further analyze the impact of the Indian Ocean SSTA in spring on the EPE over the eastern NW China in the subsequent summer, Fig. 5 presents the vector anomaly field of the whole layer moisture flux in the subsequent summer of years of anomalous SST over the equatorial Indian Ocean in spring. In the years of anomalously high SSTA, we can see from Fig. 5a that there is a belt of anomalously eastward moisture transport from the equatorial western Pacific to the Bay of Bengal, passing over India and turning over Bangladesh, and going all the way toward the area south of the Yangtze River. In this case, a little anomalous moisture is transported toward the eastern NW China. In the years of anomalously low SST (see Fig. 5b), however, a belt of southwesterly moisture transport originated in the Bay of Bengal goes northward along northeast Thailand. This moisture transport can reach northern China and some can reach the eastern NW China.
China. In addition, there is another belt of westerly moisture transport over India that transports moisture to southwest China via Bangladesh, and part of the moisture can be transported to the eastern NW China.

Therefore, in the years of anomalously high SST over the equatorial Indian Ocean in spring, little moisture anomaly is transported in the eastern NW China in the subsequent summer. In the years of anomalously low SST, on the other hand, there is a belt of anomalous westerly moisture that transports moisture to the eastern NW China.

4.4 Characteristics of South Asia high in the subsequent summer in years of anomalous SST over the Indian Ocean in spring

A study has shown that there is a close relationship between summer climate conditions in the eastern NW China and the South Asia high\[26]. Then, is it possible that spring SSTA over the equatorial Indian Ocean results in the South Asia high anomaly in the subsequent summer and further impacts the EPE in the eastern NW China? To answer this question, Fig. 6 shows the height field at 100 hPa in the subsequent summer of anomalous SST over the equatorial Indian Ocean in spring. We found that in the years of anomalously high SST over the equatorial Indian Ocean in spring (Fig. 6a), the isobar circle of 1680 is located within 40°E–100°E in the subsequent summer. Furthermore, a maximal isobar circle of 1684 is located over the border between Pakistan and Afghanistan, indicating an apparent ‘western pattern’. In anomalously low SST years (Fig. 6b), in the subsequent summer the maximal isobar circle is only 1680 and located over Tibet, indicating an apparent ‘eastern pattern’.

In summary, there is significant difference in South Asia high in the subsequent summer of the years of anomalous SST over the equatorial Indian Ocean in spring. In anomalously high SST years, the South Asia high is stronger and shows the ‘western pattern’, while in anomalously low SST years, it is weaker and shows the ‘eastern pattern’.
5 CONCLUSIONS AND DISCUSSION

By analyzing the coupling between summer EPE in the eastern NW China and the SSTA over the equatorial Indian Ocean in the preceding fall, winter, and spring, and concurrent summer, we found that the relationship between spring SSTA over the equatorial Indian Ocean and the subsequent summer EPE in the eastern NW China is most significant. This indicates that spring SSTA over the Indian Ocean has clear significance in predicting the subsequent summer EPE in the eastern NW China. Furthermore, the key area of the impact is located in the equatorial Indian Ocean. When spring SST in the equatorial Indian Ocean is anomalously high, the subsequent summer EPE in the eastern NW China tends to be decreasing, and vice versa. In the past 47 years, the summer EPE in the eastern NW China appears to have experienced a decreasing tendency, precisely as a result of the ever increasing spring SST over the Indian Ocean. In the years of anomalously high SSTA over the equatorial Indian Ocean in spring, from the concurrent spring to the subsequent summer, meridional circulation over 100°E–110°E comprises an anomalously ascending flow at and near the Equator and an anomalous descending flow in the upper troposphere near 30°N. At the same time, low-level southwest monsoon flows from the Indian Ocean and the Bay of Bengal are anomalously weak, resulting in little moisture transport anomaly to the eastern NW China in the subsequent summer. The EPEs are decreasing as a result of the lack of moisture transport. In the years of anomalously low SST over the equatorial Indian Ocean in spring, the case is just the opposite. From the concurrent spring to the subsequent summer, meridional circulation over 100°E–110°E appears to be an anomalous descending flow at and near the Equator, and an anomalous ascending flow near 30°N. Meanwhile, the low-level southwest monsoon from the Indian Ocean and the Bay of Bengal is anomalously strong, leading to anomalously high moisture transport to the eastern NW China. Due to the existence of relative abundance of moisture, there are increasing EPEs. In addition, it was shown that in the years of anomalously high SST over the equatorial Indian Ocean in spring, in the subsequent summer the South Asia high tends to be stronger and shows the ‘western pattern’. A study by Zhang et al. [26] indicated that under the control of this type of circulation, a vertically uniformed high pressure system exists in the upper troposphere and the eastern NW China is under the control of a strong high pressure ridge, resulting in decreased EPEs. While in the anomalously low SST years, the South Asia high weakens and shows the ‘eastern pattern’. Under the control of this type of circulation, in the lower troposphere the subtropical high over the western Pacific extends westward to near 110°E, at the northwest edge of which is the eastern NW China. With eastward traveling longwave and shortwave troughs from the westerly belt, there will be increased EPEs. This can be another possible reason that anomalous SST over the Indian Ocean causes the variation of EPE in the eastern NW China in summer.

So far, we have only discussed, statistically and by using synthetic analysis, the causes of the existence of the EPE in the eastern NW China. There was no exploration of its dynamical mechanism. This is obviously not enough to understand the underlying physical mechanisms of the EPE in the eastern NW China in summer, which should be a topic for further studies.

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