Associated Summer Rainfall Changes over the Three Rivers Source Region in China with the East Asian Westerly Jet from 1979 to 2015

YUMENG LIU,a,b,c XIANHONG MENG,a,b LIN ZHAO,a,b ZHAOGUO LI,a,b HAO CHEN,a,b LUNYU SHANG,a,b SHAOYING WANG,a,b LELE SHU,a,b AND GUANGWEI LIa,b,c

Key Laboratory of Land Surface Process and Climate Change in Cold and Arid Regions, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China

Zoige Plateau Wetlands Ecosystem Research Station, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China

University of Chinese Academy of Sciences, Beijing, China

ABSTRACT: Under the intensification of global warming, the characteristics of the Three Rivers source region (TRSR; i.e., headwaters of the Yellow River, the Yangtze River, and the Lancang River) in China were diagnosed in the summer season from 1979 to 2015 using observations and reanalysis data. The diagnoses indicate that summer precipitation decreased from 1979 to 2002 [by 9.01 mm day$^{-1}$ (10 yr)$^{-1}$; $p < 0.05$ by Student’s $t$ test] and increased significantly after 2002 [by 5.52 mm day$^{-1}$ (10 yr)$^{-1}$]. This abrupt change year (2002) was further confirmed by the cumulative anomaly method, the moving $t$-test method, and the Yamamoto method. By composing the thermodynamics before and after the abrupt change year (2002), the results reveal that increased water vapor and more substantial lower-level convergence were present over the TRSR during 2003–15. This marked interdecadal variability in the TRSR summer precipitation responded to the interdecadal position and intensity of the large-scale forcing East Asian westerly jet (EAWJ), which is significantly modulated by the low-frequency variability associated with Southern Oscillation index. The connection between the interannual TRSR precipitation and the location and intensity of EAWJ was also explored. The position index of the EAWJ is negatively (with correlation coefficient $R$ of $-0.446$; $p < 0.05$ by Student’s $t$ test) correlated with the precipitation over the TRSR, implying that southward and northward years of EAWJ are respectively associated with intensifying and weakening the TRSR summer precipitation, whereas the intensity of EAWJ is insignificantly correlated with the TRSR summer precipitation.

KEYWORDS: Atmospheric circulation; Precipitation; Climate change

1. Introduction

The Three River source region (TRSR), located in the hinterland of the Tibetan Plateau (TP) in China (Fig. 1), is the headwaters of the Yellow River, the Yangtze River, and the Lancang River. The TRSR provides 25% of the water of the Yangtze River, 49% of the Yellow River, and 15% of the Lancang River. The Yangtze River and the Lancang River are the mother rivers of the Chinese nation, promoting the development of Chinese civilization (Fang 2013; Wei et al. 2020). Accordingly, the TRSR plays a vital role in the hydrological cycle known as the “water tower” of China. Under global warming, TP acts as an amplifier of global climate change while the warming rate of the TRSR is higher than the average of the TP (Pan and Li 1996; Xu et al. 2019; Meng et al. 2020).

The rising temperature is leading to the intensification of the water cycle (Held and Soden 2006). Since the 1960s, seasonal and annual precipitation over the TRSR generally presented an increasing trend (Liang et al. 2013; Yi et al. 2013; Shi et al. 2016). Besides upward linear trend over the TRSR, the cause of precipitation changes on the interdecadal and interannual scale is very complicated because of the TRSR being located in the joint action area of westerly wind and Asian monsoon [i.e., the East Asian summer monsoon (EASM) and South Asian summer monsoon (SASM)]. Specifically, Sun and Wang (2018) found that the interannual variability of the EASM index is significantly correlated with the TRSR summer precipitation because the two time series exhibit inconsistencies during the 1990s and after 2010, although interdecadal EASM index and the TRSR summer precipitation are significantly correlated (Sun and Wang 2018). Based on station precipitation over the TRSR, Li et al. (2020) further reported that the influence of EASM and SASM on the southern and eastern TRSR summer precipitation was significant at the interdecadal scale, while the rest of the TRSR did not show a noticeable correlation with EASM and SASM. Thus, the Asian monsoon may only be one of the dominant factors in modulating interdecadal variations of TRSR summer precipitation.

The East Asian westerly jet (EAWJ) is an essential component in the Asian monsoon climate system, modulating local climate by changes in its north–south migration and intensity. Many studies reported that precipitation in China had been dramatically impacted by the changes in the position and intensity of EAWJ (Zhang and Guo 2005; Zhao et al. 2014b; Peng and Zhou 2017; Wei et al. 2017; Herzschuh et al. 2019; Lai et al. 2020) because EAWJ oscillates back and forth in the south and north of the TP during winter and summer (Schiemann et al. 2009). However, the influence of EAWJ varies in different parts of China. For example, a northward displacement of EAWJ is associated with increased rainfall.
anomalies in North China and no apparent anomalies in the Yangtze River valley while a southward displacement of EAWJ is associated with decreased rainfall anomalies in North China and increased anomalies in the Yangtze River valley during 1979–2013 (Wang and Zuo 2016). Meanwhile, most of the above studies focus on the influence of EAWJ on low-altitude regions in China, such as Xinjiang Province, North China, and Yangtze River valley, whereas the impact of EAWJ on the high-altitude region (i.e., the TRSR, with altitude no less than 3500 m) has not been adequately addressed.

In this study, we aim to diagnose the interdecadal and interannual variability of summer rainfall in the TRSR region and understand the role of EAWJ on the spatiotemporal variability of TRSR summer precipitation. Interdecadal variability of the TRSR summer rainfall and its mechanism was analyzed by examining the thermodynamic structure difference before and after the abrupt change. The interannual variability of TRSR summer rainfall was explored by detecting the impact of the location and intensity of EAWJ on the TRSR summer precipitation. The paper is organized as follows: The second section introduces the data used and some related statistical methods. The third section presents the spatial and temporal distribution of precipitation, the statistical tests of abrupt changepoints, and the change of the position of the subtropical westerly jet and its influencing mechanism. The fourth section presents the discussion and conclusions.

2. Data and methods

a. Data

The observed precipitation of 17 stations over the TRSR used in this study was taken from the China Surface Climatic Data Daily Value Dataset (version 3.0), obtained from the China Meteorological Administration (Fig. 1). Three other gridded precipitation datasets were adopted to understand spatial variability of precipitation: the Climate Prediction Center Merged Analysis (CMAP) dataset (Xie and Arkin 1997), the Global Precipitation Climatology Centre (GPCC) dataset, and the China Meteorological Forced Dataset (CMFD; Yang et al. 2010; Yang and He 2019; He et al. 2020). The CMAP is on a 2.5° × 2.5° latitude/longitude grid and extends back to 1979. The GPCC is the centennial Full Data Monthly Product of monthly global land surface precipitation, which contains the monthly accumulation on a regular grid with a spatial resolution of 0.5° × 0.5° latitude by longitude. The CMFD is based on the internationally available Princeton reanalysis data, Global Land Data Assimilation System (GLDAS) data, Global Energy and Water Exchanges–Surface Radiation Budget (GEWEX-SRB) data, and The Tropical Rainfall Measuring Mission (TRMM) precipitation data, combined with the conventional meteorological observation data of the China Meteorological Administration, and its horizontal spatial resolution is 0.1°.

Isobaric variables such as winds and humidity were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis dataset (ERA-Interim; Dee et al. 2011) at a 0.75° resolution from 1979 to 2015. Previous studies showed that ERA-Interim has relatively better performance over the TP (Bao and Zhang 2013; Zhao et al. 2015; Wang et al. 2017). The South Asian summer monsoon index (SASMI) is given by

\[ S_i = \frac{\langle \mathbf{V}_1 - \mathbf{V}_7 \rangle}{|\mathbf{V}|} \]

where \( \mathbf{V}_1 \) and \( \mathbf{V}_7 \) are the mean of January and July climatological wind vectors, respectively, and \( \mathbf{V} \) is the mean of January and July climatological wind vectors. [The SASMI can be obtained from the homepage of Professor J. Li (http://lijianping.cn/dct/page/65576).]

b. Methods about changepoint test

Three methods were conducted to detect the abrupt changepoints in summer precipitation over the TRSR: the cumulative anomaly method, the moving \( t \)-test method, and the Yamamoto method.

The cumulative anomaly is the accumulation of the anomaly values. It can be used to locate the change of the trend in the curve. The anomaly value increases when the trend is upward; when the trend is downward, the anomaly value
decreases, thus effectively diagnosing the abrupt change approximate time. It is calculated by using

\[ \hat{x}_t = \sum_{i=1}^{t}(x_i - \bar{x}), \quad t = 1, 2, \ldots, n, \]  

where

\[ \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i, \]

\( x_i(i = 1, 2, \ldots, n) \) is the time series to be tested, \( n \) is the sample size, and \( \hat{x}_t \) is the cumulative anomaly at time \( t \). The prominent peaks or troughs of the cumulative anomaly are the abrupt changepoints of the time series.

The moving \( t \)-test method detects abrupt changepoints by examining whether the difference between the mean values of two groups of samples is significant. The formula is

\[ t = \frac{\bar{x}_1 - \bar{x}_2}{s \times \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}, \]  

where

\[ s = \sqrt{\frac{n_1 s_1^2 + n_2 s_2^2}{n_1 + n_2 - 2}}. \]

For the time series \( x \) with sample sizes \( n \), a specific moment is arbitrarily set as the reference point. The samples of two subsequences \( x_1 \) and \( x_2 \) are before and after the reference point; namely, \( n_1 = n_2 \). Then, according to the mathematical expression, the statistical values of the two subsequences are calculated sequentially by using the moving method to set the reference point consecutively; third, the means of the two samples are compared at a given significance level for successive changes in subsequence length before and after the reference point. (Wei 2007; Yin et al. 2015).

The Yamamoto method also estimates abrupt changepoints by testing whether the difference between the mean values of two subsequences is significant. The formula is given by

\[ R_{SN} = \frac{[\bar{x}_1 - \bar{x}_2]}{s_1 + s_2}. \]  

Likewise, the mean values of the two subsequences are \( \bar{x}_1 \) and \( \bar{x}_2 \), and the standard deviations are \( s_1 \) and \( s_2 \), respectively; \( R_{SN} \) is the signal-to-noise ratio, where the variabilities of the two subsequences (expressed by standard deviation) can be regarded as noise (Yamamoto et al. 1986). It can be seen from the formula that the Yamamoto method is easier to calculate than the moving \( t \)-test method. Both methods can correctly and efficiently detect the abrupt points in means, trends, and dynamic structures (Zhao et al. 2016), but they share the disadvantage that they need to manually set the reference point, so the difference of subsequences may make abrupt changepoint drift. Therefore, we should try several subsequence sizes.

The above three methods have advantages and disadvantages, and so we combine them for comparison and determination.

3. Results

a. TRSR precipitation changes

Figure 2 shows the spatiotemporal characteristics of the monthly precipitation over the TRSR from 1979 to 2015. It indicates that the summer rainfall season [June–August (JJA)] receives more rainfall than the average for the other months, contributing 57.86% of the yearly rainfall, while July is the wettest month (Fig. 2a). In terms of spatial distribution, summer precipitation over the TRSR displays a pattern of more precipitation in the southeast than in the northwest, ranging from 40 to 130 mm month\(^{-1}\) (Fig. 2b). From 1979 to 2015, a notable change was around 2002 when the TRSR summer precipitation began to change from its previous downward trend to an upward region, both in terms of interannual and interdecadal variability (Fig. 2c).

The abovementioned abrupt change of the TRSR summer precipitation was confirmed by the cumulative anomaly method, the moving \( t \)-test method, and the Yamamoto method (Fig. 3). The cumulative anomaly method indicates an apparent interdecadal transition around 2002. After 2002, the summer precipitation over the TRSR shows an increasing trend. Both the moving \( t \)-test and the Yamamoto methods show that 2002 is the only peak that passed a Student’s \( t \) test at the 95% significance level. On the curve of the test of the abrupt changepoint, the trend is generally increasing before 2002 and decreasing after 2002. Therefore, three methods suggest that 2002 is the abrupt changepoint in the time series from 1979 to 2015, and the summer precipitation increased remarkably after 2002. Four different subsequences of \( n_1 = 7, 8, 9, 10 \) are tested here, and the results are omitted in the figure except for \( n_1 = 9 \).

To further explore the spatial changes of the TRSR summer precipitation on the interdecadal scales, three gridded data were plotted to show the means, differences, and relative changes in the two periods before (1979–2002) and after (2003–15) the abrupt changepoint (Fig. 4). It is noted that the difference is the mean of the later period minus the previous period, while the relative change is defined as the difference divided by the mean of 1979–2015. In general, observed station data and the three gridded data (CMAP, GPCC, and CMFD) show uniform noticeable changes in pattern and intensity of the TRSR summer precipitation (rightmost column in Fig. 4). In comparing the climatological rainfall before and after 2002, it is seen that the southwest–northeast rainfall belt (88 mm month\(^{-1}\)) around 34°N is advancing to the northwestern TRSR (top and middle column in Fig. 4). The whole area over the TRSR is getting wetter after an abrupt change year, and the most significant increase in precipitation occurred in the northwest TRSR. In comparison with the period before the
abrupt changepoint (1979–2002), the relative change of precipitation is reaching 30% (rightmost column in Fig. 4). Although the southeast region receives more precipitation in summer, the relative precipitation change is less than 15%.

b. Change of water vapor flux

Adequate water vapor supply is a crucial factor for precipitation changes. As mentioned above, the TRSR summer precipitation experienced a decline before the abrupt change year while increasing in recent years. The impact of water vapor flux on precipitation is investigated in this section. Figure 5 displays the climatology of vertically integrated water vapor flux (1000–100 hPa; vectors) and vertically integrated water vapor flux divergence (shading) in the summer from 1979 to 2015. It shows that the TRSR mainly has two channels of water vapor transport for normal climatological conditions in summer: one is the vital transport by SASM (or southwest), which brings abundant moisture from the Arabian Sea and the Bay of Bengal into the TRSR; the other is a relatively weak water vapor source transported by mid-latitude westerlies (Fig. 5a). Meanwhile, from the divergence of water vapor flux, it is evident that water vapor converges over the whole Asian monsoon domains, including South China Sea and northwestern Pacific coastal area and north Indian Ocean and Bay of Bengal coastal area, especially over the southeastern of TP (Fig. 5a).

To further reveal the spatial variation of water vapor transport before and after the abrupt change year, the...
difference of the water vapor flux climatology (vectors) and its divergence (shading) before and after 2002 is analyzed. The water vapor flux is vertically integrated and calculated as

\[ Q = \frac{1}{g} \int_{p_1}^{p_s} V \cdot q dp, \]

where \( q \) is the specific humidity, \( g \) is the acceleration of gravity, \( p_s \) is the surface pressure, \( p_i \) is the air pressure at the top level, considering that there is little water vapor in the upper level, and \( p_i \) is set as 300 hPa.

First, a quantitative measure of summer water vapor transport across the four boundaries of the TRSR as a box (31°–37°N and 87°–104°E) is shown in Fig. 6. The results indicate that the main summer water vapor source of the TRSR is from the southern and western boundary, while the main summer water vapor outputs of the TRSR are from the eastern boundary. In comparison with 1979–2002, the integrated summer water vapor flux from the southern and western boundaries respectively increased 19.2% and 2.83% in the latter period, whereas summer water vapor outputs from the eastern boundary decreased 16.66%. Despite the small contribution to water vapor of the TRSR from the northern boundary, it changes from a water vapor input to a water vapor output. Using the abrupt change test methods described above for the water vapor at the four boundaries, it is found that the changepoint of water vapor entering from the southern boundary also occurred in 2002 (figure omitted).

In comparison with the stage from 1979 to 2002, the summer water vapor transport from the Indian Ocean and the Arabian Sea has increased significantly from 2003 to 2015 (Fig. 5b). The “up and over” [or “conditional instability of the second kind (CISK)-like process”], which was reported by Dong et al. (2016) and Xu et al. (2014), means that the water vapor transports through the Yarlung Tsangpo River water...
Fig. 5. (a) Climatology and (b) difference of vertical water vapor (vectors) (kg m$^{-1}$ s$^{-1}$) and its divergence (shading; kg m$^{-2}$ s$^{-1}$) in summer. (c) Vectors (m s$^{-1}$) of meridional and vertical
that is, convective systems on the Indian plains carry water vapor and water to the mid- and upper-level, and then the southwestern flow in the mid- and upper-level transports this water vapor to the southwestern part of the TP, eventually forming precipitation. This process has been intensified from southeastern TP to the TRSR, initiated from strong convergence over Myanmar (Figs. 5b,c,d). Based on the difference of water vapor at a given pressure level TP and nonelevated areas in summer, tropospheric lower-level convergences in the SASM regions and upper-level divergence over the southeastern TP-slopes, as well as whole tropospheric layers convergences are all enhanced. These enforce more moisture from the oceans crossing the SASM regions up to the TRSR (the orange box represents the TRSR, Figs. 5e). A similar process has been found for water vapor transport by zonal circulations into the TRSR. At the same time, the strength of divergence around 72°E is weaker than the meridional circulations (Figs. 5b and 5e).

c. Relationship between EAWJ and summer precipitation on the interdecadal scales

The above section indicates that summer precipitation and water vapor transport over the TRSR have typical interdecadal variation. As reported by Zhao et al. (2018), the variability of the EAWJ can influence the regional climate on multiple time scales, and the role of EAWJ on precipitation in central Asia is very stable in the context of climate warming (Zhao et al. 2018). Thus, the influence of EAWJ on the interdecadal variability of the TRSR summer precipitation was explored in this section.

Following the definition of the westerly jet index by Sun et al. (2020), the EAWJ position index is defined as the latitude average where the maximum wind speed is located in the area that passed the significance test in Fig. 7a, while the EAWJ strength index is the average value of the maximum wind speed. With the above definition of the EAWJ, the connection between the position and intensity of the EAWJ and the TRSR precipitation was examined. The 6-yr running-mean position and intensity indices of the EAWJ are negatively and positively correlated with the precipitation over the TRSR (Figs. 7b,c), respectively, with correlation coefficients of $-0.381$ and $0.391$, respectively ($p < 0.05$ by Student’s $t$ test). These results indicate that the interdecadal TRSR summer precipitation statistically coincides with southward and intensified EAWJ on the interdecadal scale. To investigate interdecadal stability and variations of the strength of links between EAWJ and summer rainfall in the TRSR, we further perform a running correlation

<table>
<thead>
<tr>
<th>Month</th>
<th>Position Index</th>
<th>Intensity Index</th>
</tr>
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<tbody>
<tr>
<td>1979-2002</td>
<td>141.33</td>
<td>526.96</td>
</tr>
<tr>
<td>2003-2015</td>
<td>145.33</td>
<td>592.72</td>
</tr>
<tr>
<td>Change Ratio</td>
<td>2.83%</td>
<td>12.48%</td>
</tr>
</tbody>
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Fig. 6. Monthly mean water vapor budget ($10^6$ kg s$^{-1}$) during 1979–2002 and 2003–15. The change ratio is the average of the later period minus the average of the previous period, divided by the absolute value of the average of the previous period. The water vapor transport across the four boundaries of the TRSR is regarded as a box (31°–37°N and 87°–104°E). The arrows indicate the direction of water vapor.
between the position and intensity index of the EAWJ and the TRSR summer precipitation time series. In general, the running correlation between EAWJ’s position and the TRSR summer precipitation is negatively correlated with summer precipitation. In particular, the strength of this relationship is getting stronger from 1990 (Fig. 7d). Note that there is a clear relationship between the position of the EAWJ and the TRSR summer precipitation after the 1990s, which would partly explain the interdecadal variation of the TRSR summer precipitation. However, the correlation between the intensity of the EAWJ and the TRSR summer precipitation is statistically insignificant most of the time, although there are some fluctuations (Fig. 7e).

Given the aforementioned interdecadal variation of the TRSR summer precipitation associated with EAWJ’s position, we are led to question how the atmospheric circulation modulates the TRSR summer precipitation. To answer this question, the spatiotemporal feature of atmospheric circulation was examined. By applying the empirical orthogonal function (EOF) analysis on the summer 200-hPa zonal wind in the domain 20°–50°N and 60°–150°E, the first two leading EOFs are shown in Figs. 8a–d. Note that data here were low-pass filtered with a 6-yr running mean to capture the interdecadal variability. The first two modes output 48.1% and 20.5% of the total variance, respectively (Fig. 8). The spatial pattern of EOF1 (Fig. 8a) corresponds to an increasing trend.
whereas the EOF2 spatial pattern depicts a tripole \(- + -\) wave-train pattern (Fig. 8c) with an interdecadal variation (Fig. 8d). This pattern is similar to Fig. 7a, and the spatial correlation is 70.15\%, indicating that the pattern appears to be an essential factor in regulating the TRSR climate. To establish the evidence of teleconnection between EOF2 pattern and climate index Southern Oscillation index (SOI), the linear regression pattern of SOI with 200-hPa zonal wind is examined (Fig. 8e). It shows a similar feature to the pattern of EOF2. The pattern correlation is 0.84 \((p < 0.05 \text{ by Student's } t \text{ test})\). It presents that the interdecadal variation of EAWJ is highly correlated with the South Oscillation. In other words, the interdecadal ocean–atmospheric variation can produce detectable impacts on the TRSR through atmospheric teleconnections. Such an interdecadal teleconnection process appears to have persisted for multiple years and, in turn, modulated the TRSR summer precipitation.

d. Relationship between EAWJ and summer precipitation on the interannual scales

Figures 7b and 7c show that, on the interannual scales, the position index of the EAWJ is negatively correlated with the precipitation over the TRSR, with a correlation coefficient of \(-0.446 \,(p < 0.05 \text{ by Student's } t \text{ test})\). In contrast, the EAWJ strength index is insignificantly correlated with the precipitation, with a correlation coefficient of 0.241. These interannual correlations indicate that the increased TRSR precipitation statistically coincides with southward EAWJ but not intensity. Therefore, we only discuss the impact of the interannual variation of the EAWJ's position on the summer precipitation in the TRSR. Given the importance of water vapor flux to the precipitation over the TRSR, the followings first examine the relationship between the position of the EAWJ and water vapor transport. We define the years with the normalized index exceeding \(\pm 1\) standard deviation as northern/southern EAWJ years. Therefore, 1984, 1985, 1994, 1996, 1997, 2002, 2006, and 2013 are northward years, and 1982, 1987, 1993, 1998, 2004, and 2012 are southward years of the jet stream. Figure 9a shows the composited anomalies of the vertical integral of water vapor flux and its divergence in the southward year. There is a water vapor transporting belt from 75\(^\circ\) to 105\(^\circ\)E with a center around 30\(^\circ\)N in the EAWJ southward years. Two important sources of water vapor contribute to this moisture belt, originating from the Arabian Sea and Siberia. However, it is reasonable that the Arabian Sea plays a most crucial role in the moisture supply because the moisture provided from inland Siberia should be limited. Under the impact of such circulation anomalies, intensified water vapor convergence
FIG. 9. (a) The mean water vapor flux (vector) and its divergence (shaded) in the (a) southward and (b) northward year of the jet stream are subtracted from the mean water vapor flux and its divergence during 1979–2015 and then
increased the TRSR summer precipitation in the EAWJ southward years. This moisture supply process over the TRSR is further illustrated by the longitude–pressure cross section of zonal water vapor flux (Fig. 9c), where the airflow over the TRSR region rises to produce precipitation, along with tropospheric lower-level convergences and upper-level divergence. Figures 9b and 9d show the composite phenomenon in the EAWJ northward years. Opposite to the moisture supply process in Figs. 9a and 9c, eastern or northeastern water vapor is transporting belt anomalies that dominate from 130° to 75° E with a center around 30° N. Although this moisture belt could transport moisture from eastern Asia, it blocked water vapor from south Asia, resulting in less water vapor entering the TRSR (Fig. 9b). Consistent with the spatial pattern of water vapor transport, the downward flow suppressed precipitation over the TRSR (Fig. 9d). In general, the above results suggest that the channel of water vapor transport from SASM may be essential to the TRSR, which is linked to the position of the EAWJ.

4. Discussion

Jet streams are essential because they create weather systems and steer them along the midlatitudes. As a critical component of midlatitude jets, changes in EAWJ’s location and intensity would cause variations in the TRSR summer precipitation on interdecadal and interannual time scales. Although the interdecadal variability of EAWJ has been linked with SOI, understanding how SOI influences EAWJ’s position and, therefore, causes the interdecadal variation of the TRSR summer precipitation needs further study, and it is beyond the scope of this study.

The relationship between the Asian monsoon (SASM and EASM) and the TRSR summer precipitation was also examined. The regimes between interdecadal and interannual TRSR summer precipitation and the Asian monsoon are complicated. For example, the interannual variability of SASM and EASM is insignificantly correlated with the TRSR summer precipitation, whereas interdecadal TRSR precipitation shows a noticeable negative correlation with SASM (−0.648; \( p < 0.05 \) by Student’s \( t \) test) and EASM (−0.406; \( p < 0.05 \) by Student’s \( t \) test), especially after the 1990s (Figs. 10a and 10b). The latter results are consistent with Fig. 7d, suggesting that at least the interdecadal changes of EAWJ’s location may be associated with moisture transport from SASM and EASM from the 1990s. A significant positive correlation further confirmed this interaction between SASM and EAWJ’s location on the interannual scales (Fig. 10c) (0.387; \( p < 0.05 \) by Student’s \( t \) test), indicating that SASM was weak when EAWJ was southward, consistent with (Zhao et al. 2014a; Wei et al. 2017). Despite the mutual modulation relationship between SASM and EAWJ’s location, past studies also pointed out (Li et al. 2016; Dong et al. 2020) that the strong SASM would bring a large amount of water vapor to South China, contributing to intense precipitation over the TRSR.

So far, the mechanism of the mutual modulation relationship between SASM and EAWJ’s location is still under debate. In other words, it is unclear which factor is dominant in influencing the TRSR summer precipitation. Ramaswamy (1962) argued

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normalized. (c) Vectors of meridional and vertical wind components (multiplied by 100) and vertical water vapor flux of the latitude–vertical section averaged over 30.5°–37.5° N are subtracted from their mean in the (c) southward and (d) northward year. Both the thick black line and the orange dash-outlined box denote the location of the TRSR.

FIG. 10. Time series of the standardized TRSR-averaged precipitation in summer and (a) SASM and (b) EASM. (c) The time series of the standardized westerly jet position index and SASM. The dashed lines indicate the corresponding interdecadal variations, obtained by a 6-yr running mean; \( R \) is the correlation coefficient between the two interannual series, and \( R_r \) is the correlation coefficient between the two interdecadal series after 6-yr running mean.
that the northward shift of the westerly jet at the beginning of summer was an essential factor in the onset of the SASM. However, Zhao et al. (2014a) concluded that the weak SASM would cool the upper troposphere of central Asia, leading to the westerly jet moving southward. Peng et al. (2018) had also pointed out that when the westerly jet moves southward, it will cause anomaly southerly winds over central Asia and bring more warm air. Such warm advection anomaly is conducive to upward movement and will lead to increased precipitation over the TRSR.

5. Conclusions

The interdecadal and interannual variabilities of the TRSR summer precipitation were analyzed in meteorological diagnostics from 1979 to 2015. Using the cumulative anomaly method, the moving t-test method, and the Yamamoto method, an abrupt change in the summer precipitation in the TRSR was detected in 2002 during 1979–2015. Then, the interdecadal and interannual variation of the TRSR precipitation before and after 2002 and its relationship to EAWJ were analyzed. The main conclusions are as follows:

1) Summer rainfall over the TRSR ranges from 40 mm day$^{-1}$ (in the northwest) to 130 mm day$^{-1}$ (in the southeast), and over a year, 58% of the precipitation that falls over the TRSR occurs during summer. Relative to the period before the abrupt changepoint (1979–2002), most TRSR summer precipitation is getting wetter. The wettest area is in the northwestern TRSR (Yangtze River source region), the relative precipitation change reaches 30%.

2) The interdecadal variation of the TRSR summer precipitation is statistically linked to EAWJ’s location and intensity. EOF and regression analyses found that the TRSR summer precipitation associated with EAWJ at the interdecadal scale was modulated by the low-frequency variability associated with SOI.

3) On the interannual scale, the southward shift of EAWJ years would couple with the South Asian high and South Asian monsoon, intensifying water vapor transport from South Asian monsoon regions and updraft over the TRSR, facilitating the formation of precipitation.

Caution should be exercised when interpreting these results derived from the gridded data. The diagnosis process of water vapor transport over the TRSR is only based on one set of reanalysis data; different data sources may introduce bias into the thermodynamic structure. In subsequent studies, further modeling work will use the regional climate model to explore the feedback between atmospheric circulation and land surface processes. Their impact on precipitation under climate warming will help us understand the mechanisms of the role of land surface processes in modulating precipitation over the TRSR.

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Data availability statement. Expression data are openly available from the following data providers. The China Surface Climatic Data Daily Value Dataset (version 3.0) was obtained from the China Meteorological Administration (https://data.tpdc.ac.cn/en/data/52c77e9c-df4a-4c27-8e97-d363fdce10a/). The CMAP dataset is provided by the NOAA/OAR/ESRL PSL (https://psl.noaa.gov/data/gridded/data.cmap.html). The GPCC dataset was retrieved online (https://climatedataguide.ucar.edu/climate-data/gpcc-global-precipitation-climatology-centre). The CMFD is provided by National Tibetan Plateau Data Center (http://data.tpdc.ac.cn). The South Asian summer monsoon index (SASMI) is obtained from the homepage of Professor Jianping Li (http://lijianping.cn/dct/page/65576).

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