Interannual Variation of the Spring and Summer Precipitation over the Three River Source Region in China and the Associated Regimes

BO SUN AND HUIJUN WANG

Key Laboratory of Meteorological Disaster, Ministry of Education, and Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, and Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

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ABSTRACT

This study analyzes the interannual and interdecadal variability of spring and summer precipitation over the Three River Source (TRS) region in China using four datasets. A general consistency is revealed among the four datasets with regard to the interannual and interdecadal variability of TRS precipitation during 1979–2015, demonstrating a confidence of the four datasets in representing the precipitation variability over the TRS region. The TRS spring and summer precipitation shows distinct interannual and interdecadal variability, with an overall increasing trend in the spring precipitation and an interdecadal oscillation in the summer precipitation. The regimes associated with the interannual variability of TRS spring and summer precipitation are further investigated. The interannual variability of TRS spring precipitation is essentially modulated by an anomalous easterly water vapor transport (WVT) branch associated with the leading mode of Eurasian spring circulation. El Niño–Southern Oscillation (ENSO) may affect the interannual variability of TRS spring precipitation by causing southerly WVT anomalies toward the TRS region. The interannual variability of TRS summer precipitation is essentially modulated by an anomalous southwesterly WVT branch over the TRS region, which is mainly associated with a Eurasian wave train connected with the summer North Atlantic Oscillation. A strong East Asian summer monsoon and an El Niño–decaying summer may also contribute to the southwesterly WVT anomalies over the TRS region.

1. Introduction

The Three River Source (TRS; Sanjiangyuan) region, where the Yangtze River, Yellow River, and Lantsang River originate, is located in the central and eastern Tibetan Plateau, with most areas having an elevation of 3500–4800 m (Fig. 1). Wetlands and lakes are intensively distributed over the TRS region, delivering significant ecosystem services. The ecosystem over the TRS region is sensitive to climate change, and thus climate variability can dramatically impact the ecological balances over this region (X. L. Xu et al. 2008). The roles of “water tower” for China and a unique ecological system make the TRS region a key region in the Tibetan Plateau. Previous studies indicate that the climate variability over the Tibetan Plateau has regional features (e.g., Liu and Chen 2000; Liu and Yin 2001; Z. X. Xu et al. 2008; Kang et al. 2010; Yang et al. 2014). For instance, the interannual variability of summer precipitation is different in the northern and southern parts of the Tibetan Plateau (Liu and Yin 2001). Therefore, the TRS region deserves particular attention with regard to the climate variability during past decades.

During past decades, the precipitation over the TRS region overall exhibited an increasing trend (Liang et al. 2013; Yi et al. 2013). However, precipitation in different seasons has experienced different interannual and interdecadal variability over the TRS region (Li et al. 2010; Yi et al. 2013; Tong et al. 2014). Specifically, Yi et al. (2013) indicated that the variability of spring precipitation over the TRS region is characterized by a noticeable increasing trend during 1961–2010 with interannual variations, while the summer and autumn precipitation over the TRS region exhibits interannual and interdecadal variations but does not show a notable trend. Hence, a comprehensive investigation of the precipitation variability for different seasons is demanded to understand the climate variability over the TRS region. On the other hand, the abovementioned results, which are mostly
obtained from station data, need to be examined by other datasets considering that different choices in the amount and location of stations may lead to different results.

The summer precipitation accounts for a large portion of the annual total precipitation over the TRS region because of the East Asian summer monsoon (EASM). Li et al. (2009) documented that the southwesterly water vapor transport (WVT) associated with the Indian summer monsoon and EASM is the main water resource for the summer rainfall over the TRS region, indicating an important role of EASM on the climatology of summer rainfall over the TRS region. The interannual and interdecadal variability of EASM is influenced by a variety of factors, including the North Atlantic Oscillation (NAO), El Niño–Southern Oscillation (ENSO), Pacific and Indian Ocean sea surface temperatures (SSTs), snow cover, the Pacific decadal oscillation (PDO), the Atlantic multidecadal oscillation (AMO), and so on (e.g., Wang et al. 2000; Wang 2002; Zhang et al. 2004; Lu et al. 2006; Sung et al. 2006; Ding et al. 2009; Wu et al. 2009; Zhu et al. 2011; Sun and Wang 2015). However, most of these studies focus on the climate variability over eastern China, where the population, social and economic activity, and gauge stations are concentrated, whereas the influences of the aforementioned factors on the climate variability over the TRS region lack investigation.

Besides summer rainfall, the spring precipitation over the TRS region is also important considering that the growing season of vegetation begins in April and the spring precipitation also accounts for a considerable portion of the annual total precipitation over the TRS region (Qian et al. 2010). Although several studies investigated the variations of spring precipitation over the TRS region during past decades (Yi et al. 2013; Tong et al. 2014), very few studies have focused on the mechanism underlying the interannual variability of spring precipitation over the TRS region, which remains unclear so far.

Thus, the current study attempts to explore and answer the following questions: What is the interannual and interdecadal variability of spring and summer precipitation over the TRS region in different datasets? What are the primary regimes modulating the interannual variability of spring and summer precipitation over the TRS region?

The rest of this paper is organized as follows. The data and methods used in this study are described in section 2. In section 3, the interannual and interdecadal variability of spring [March–May (MAM)] and summer [June–August (JJA)] precipitation over the TRS region are analyzed and compared for different datasets. Section 4 focuses on the regimes modulating the interannual variability of spring and summer precipitation over the TRS region, including the WVT regimes and the mechanisms underlying WVT anomalies. Section 5 gives a brief discussion on the regimes of the interdecadal variability of spring and summer precipitation over the TRS region. A summary is provided in section 6.

2. Data and methods

2a. Data

In this study, the domain of the TRS region is defined as a rectangular region (31.5°–36.5°N, 89.5°–102.5°E), as shown in Fig. 1. The area for this domain is approximately 600,000 km². To analyze the variability of precipitation over the TRS region, four monthly datasets...
are employed in this study for the period 1979–2015: gridded CN05.1 data, station data derived from the China Meteorology Administration observation archives, gridded Global Precipitation Climatology Project (GPCP; version 2.3) data, and gridded Climatic Research Unit Time Series (CRU TS; version 4.01) data. The CN05.1 dataset is a quality-controlled gridded dataset (0.25° × 0.25°) constructed from more than 2400 stations over China (Wu and Gao 2013). The station data consist of data from 38 stations within the TRS region (Fig. 1), which are also quality controlled and span from 1979 to 2009. The GPCP Version 2.3 Combined Precipitation Data (2.5° × 2.5°) is a high-quality dataset that combines data from satellites, gauge stations, and sounding observations (Adler et al. 2003). The CRU TS, version 4.01, data (0.5° × 0.5°) are based on more than 4000 weather stations over the global land area (Harris et al. 2014).

The monthly data for geopotential height, zonal and meridional winds, zonal and meridional vertically integrated water vapor fluxes, and vertical velocity are derived from the ERA-Interim dataset (Dee et al. 2011), which has a resolution of 1° × 1°. The SST data used in this study are derived from the NOAA Extended Reconstructed SST, version 4 (2.5° × 2.5°) (Huang et al. 2015).

The EASM index defined by Wang (2002) is used as a measure of the EASM strength, which is calculated by the areal mean 850-hPa wind speed anomalies over the region (20°–40°N, 110°–125°E) for summer. The monthly Niño-3.4, NAO, AMO, and interdecadal Pacific oscillation (IPO) indices derived from the NOAA Climate Prediction Center are also used (https://www.esrl.noaa.gov/psd/data/climateindices/list/). Specifically, the Niño-3.4 index is defined as the areal mean SST for the east-central tropical Pacific Ocean covering 5°S–5°N and 170°–120°W. The NAO index is defined as the time series corresponding to the leading mode of a rotated empirical orthogonal function analysis for 500-hPa geopotential height over the Northern Hemisphere (20°–90°N) (http://www.cpc.ncep.noaa.gov/data/teledoc/teledindcalc.shtml). The AMO index is defined as the area-weighted average of SST over the North Atlantic Ocean (0°–70°N), which is detrended for the period from 1856 to present (https://www.esrl.noaa.gov/psd/data/timeseries/AMO/). The IPO index is defined as the difference between the areal mean SST anomalies over the central equatorial Pacific (10°S–10°N, 170°E–90°W) and the areal mean SST anomalies over the northwestern (25°–45°N, 140°E–145°W) and southwestern (50°–15°S, 150°E–160°W) Pacific (https://www.esrl.noaa.gov/psd/data/timeseries/IPOTPI/).

b. Methods

The time series for anomalies of areal mean precipitation over the TRS region are computed and utilized for the following analysis. This study uses the anomalies of TRS precipitation because we only care about the variability of TRS precipitation instead of the absolute values of TRS precipitation. For brevity, the time series for anomalies of areal mean precipitation over the TRS region are referred to as the time series of TRS precipitation in the following discussions unless otherwise specified.

A linear regression analysis is performed in this study with a method of least squares, whereby a linear relationship between time series of variable $X$ and time series of variable $Y$ is estimated by

$$Y = a + bX,$$

where $a$ is the intercept (the value of $Y$ when $X = 0$) and $b$ is the regression coefficient. Particularly, when using anomalies of $X$ and $Y$, the intercept $a$ in the above equation becomes zero and the above equation becomes

$$Y' = bX',$$

where $X'$ and $Y'$ represent the anomalies of $X$ and $Y$, respectively. In this study, the regression analysis is performed for a standardized time series of $X'$. Considering that $Y' = b$ when $X' = 1$, the regression coefficient $b$ represents the value of $Y'$ corresponding to a standard deviation of $X'$. Hence, the regression coefficient $b$ is used to denote the linear relationship between $X'$ and $Y'$ in this study. For instance, the 500-hPa geopotential height anomalies regressed on the standardized time series of TRS precipitation represent the 500-hPa geopotential height anomalies corresponding to a standard deviation of TRS precipitation. The significance level of a regression coefficient is tested using Student’s $t$ test. Using the abovementioned method of regression analysis, the anomalies of 500-hPa geopotential height, vertically integrated WVT, 500-hPa vertical velocity, and SST are regressed on the detrended and standardized time series of TRS precipitation to illustrate the climate regimes associated with TRS precipitation. In addition, these atmospheric circulation and SST anomalies are also regressed on the detrended and standardized time series of climate indices such as the NAO, Niño-3.4, and EASM indices to illustrate climate effects of the atmospheric modes and/or air–sea interaction modes represented by these climate indices. The Pearson’s correlation coefficient is utilized in this study to estimate the correlation between two time series. The significance level of a correlation coefficient is tested using Student’s $t$ test.

Given the importance of water vapor flux to precipitation variability over East Asia (Zhou and Yu 2005; Sun et al. 2011; Zhu et al. 2011; Wang and Chen 2012;
Sun and Wang (2014, 2015), the vertically integrated water vapor fluxes crossing the southern, eastern, northern, and western boundaries of the TRS region are computed using the method developed by Sun et al. (2011). The tendency of the Niño-3.4 index from preceding winter to summer is used as an indicator of ENSO-decaying summer, which is calculated by the summer mean Niño-3.4 index minus the preceding winter (December–February) mean Niño-3.4 index. A negative (positive) anomaly of the tendency of the Niño-3.4 index denotes an El Niño–decaying (La Niña decaying) summer. The SST anomalies of the preceding winter and spring and concurrent summer regressed on the tendency of the Niño-3.4 index indicate that the tendency of the Niño-3.4 index is a good indicator for representing the ENSO decaying from winter to the subsequent summer.

3. Interannual and interdecadal variability of spring and summer precipitation

Figure 2 shows the time series of spring and summer precipitation over the TRS region during 1979–2015. The four datasets show a general consistency in the interannual and interdecadal variability of TRS spring and summer precipitation, demonstrating a robustness of the results revealed in this study. The average linear trend in spring precipitation among the four datasets is 0.05 mm day$^{-1}$ (10 yr)$^{-1}$, with a relatively large trend in the GPCP data [0.07 mm day$^{-1}$ (10 yr)$^{-1}$] and CN05.1
data \([0.06 \text{ mm day}^{-1} \ (10 \text{ yr})^{-1}]\) and a relatively small trend in the station data \([0.04 \text{ mm day}^{-1} \ (10 \text{ yr})^{-1}]\) and CRU data \([0.03 \text{ mm day}^{-1} \ (10 \text{ yr})^{-1}]\). The trends in GPCP, CN05.1, and CRU data are all significant at the 95\% confidence level, whereas the trend in station data is of less significance, which might be partially due to the lack of length of the station data. No significant trend in summer precipitation is found for the four datasets.

For interannual variability, the interannual variations of TRS spring precipitation are consistent among the four datasets for most years, except that the GPCP data show an inconsistency with the other three datasets in the early 2000s (Fig. 2a). The correlation coefficients for pairs freely combined among the detrended time series of TRS spring precipitation derived from the four datasets are all above 0.70 and significant at the 99\% confidence level, indicating a confidence in representing the interannual variability of TRS spring precipitation of the four datasets. Similarly, the interannual variations of TRS summer precipitation are essentially the same among the four datasets (Fig. 2b), with the correlation coefficients for pairs freely combined among the detrended time series of TRS summer precipitation derived from the four datasets all being above 0.80 and significant at the 99\% confidence level. Specifically, the detrended time series of TRS spring (summer) precipitation derived from the CN05.1 data have a significant correlation with that derived from the station data, GPCP data, and CRU data, with correlation coefficients of 0.79 (0.85), 0.73 (0.83), and 0.85 (0.96), respectively. All of these correlation coefficients are significant at the 99\% confidence level. The consistency between CN05.1 data and the other three datasets indicates that the CN05.1 data can reasonably represent the interannual variability of TRS precipitation. Hence, the following analysis and discussions on climate regimes associated with interannual variability of TRS precipitation are mainly based on CN05.1 data.

For interdecadal variability, the 5-yr running-mean time series of TRS precipitation are computed to remove the interannual variation and to analyze the interdecadal variation. As shown in Fig. 2c, the spring precipitation had an oscillation during the 1980s and 1990s and increased after this oscillation. The four datasets are consistent in the oscillation during the 1980s and 1990s, whereas the GPCP data exhibit a noticeable larger increase from the 1990s to the 2000s than the other three datasets. Considering that the CN05.1 data and CRU data are constructed based on gauge stations, this inconsistency in GPCP data may be caused by the data from satellites and/or sounding observations. It is difficult to decide whether the GPCP data or the other three datasets are correct with regard to this issue. Thus, one should be careful when dealing with the TRS spring precipitation for the 2000s.

By contrast, the interdecadal variability of summer precipitation is generally characterized by above-normal anomalies during the 1980s and 2000s and below-normal anomalies during the 1990s in the four datasets (Fig. 2d). The interdecadal decrease from the 1980s to the 1990s is most (less) significant in the station (CRU) data, with a decrease of 0.36 (0.09) mm day\(^{-1}\) from the period of 1979–90 to the period of 1991–2002 (Fig. 2d). The interdecadal increase from the 1990s to the 2000s and 2010s is relatively large (small) in the GPCP (CRU) data, with an increase of 0.37 (0.27) mm day\(^{-1}\) from the period of 1991–2002 to the period of 2003–15. The interdecadal change from the period of 1991–2002 to the period of 2003–15 is significant at the 95\% confidence level in the four datasets, whereas the interdecadal change from the period of 1979–90 to the period of 1991–2002 is significant at the 95\% confidence level only in the station and GPCP data. Overall, the correlation coefficients for pairs freely combined among the 5-yr running-mean time series of the four datasets are all above 0.80 and significant at the 95\% confidence level for the summer precipitation, demonstrating a generally good quality of the four datasets in representing the interdecadal variability of TRS summer precipitation.

4. Regimes of interannual variability of TRS precipitation

a. Spring

Figure 3a shows the vertically integrated WVT anomalies regressed on the detrended and standardized time series of TRS spring precipitation. Primarily, the interannual variability of TRS spring precipitation is associated with an anomalous easterly WVT branch crossing the eastern boundary of the TRS region, which conveys moisture anomalies from northern China into the TRS region. The detrended time series of TRS spring precipitation and easterly water vapor flux anomalies crossing the eastern boundary of the TRS region exhibit a significant correlation, with a correlation coefficient of 0.45 at the 95\% confidence level. Another considerable influencing factor for the interannual variability of TRS spring precipitation is an anomalous southerly WVT branch toward the TRS region, which conveys moisture anomalies from the southern Tibetan Plateau into the TRS region. These southerly WVT anomalies toward the TRS region are mostly below the 95\% confidence level but are above the 80\% confidence level, indicating a less important role for modulating the interannual variability of TRS
spring precipitation than the abovementioned easterly WVT anomalies crossing the eastern boundary of the TRS region. The detrended time series of southerly water vapor flux anomalies crossing the southern boundary of the TRS region are significantly correlated with the detrended time series of TRS spring precipitation, with a correlation coefficient of 0.33 significant at the 95% confidence level. For comparison, the correlation coefficient between the detrended time series of TRS spring precipitation and westerly (northerly) water vapor flux anomalies crossing the western (northern) boundary of TRS region is $-0.28$ ($-0.12$), which is below the 95% confidence level, indicating relatively minor roles of WVT anomalies crossing the western and northern boundaries of the TRS region in affecting the interannual variability of TRS spring precipitation. Overall, a significant correlation coefficient of 0.71 is found between the detrended time series of

**FIG. 3.** Anomalies of (a) vertically integrated WVT (kg m$^{-1}$ s$^{-1}$), (b) 500-hPa geopotential height (gpm), and (c) SST ($^\circ$C) regressed on the detrended and standardized time series of TRS spring precipitation. Dark-gray and light-gray shadings in (a) denote the 95% and 80% confidence levels, respectively. Stippling in (b) and (c) denotes the 95% confidence level.
TRS spring precipitation and net water vapor flux over the TRS region, suggesting a substantial impact of WVT on the interannual variability of TRS spring precipitation. Thus, the anomalous easterly WVT branch crossing the eastern boundary of the TRS region is critical to the interannual variability of TRS spring precipitation. The anomalous southerly WVT branch toward the TRS region is also worth considering, which plays a secondary role in modulating the interannual variability of TRS spring precipitation.

The anomalous easterly WVT branch is associated with an anticyclonic regime to the north of the TRS region, which is exerted by an anomalous high centered over the west of Lake Baikal (Fig. 3b). This anomalous high pressure center is a node of an anomalous wave train over Eurasia, which consists of an anomalous high centered over the Mediterranean Sea, an anomalous low pressure area centered north of the Caspian Sea, and the aforementioned anomalous high centered over the west of Lake Baikal, as shown in Fig. 3b. To understand this anomalous wave train, the empirical orthogonal function (EOF) modes of 500-hPa geopotential height over Eurasia (20°–70°N, 0°–120°E) are computed. The results indicate that the leading EOF mode resembles the anomalous Eurasian wave train associated with TRS spring precipitation, characterized by an anomalous high over Europe and the Mediterranean Sea, an anomalous low north of the Caspian Sea, and an anomalous high centered over Lake Baikal (Fig. 4a).

The influence of this leading mode of Eurasian spring circulation on the interannual variability of TRS spring precipitation is demonstrated by the significant correlation between the time series of TRS spring precipitation and leading mode of Eurasian spring circulation. As shown in Figs. 4b and 4c, the time series of the leading EOF mode of Eurasian spring circulation present a general consistency with the time series of TRS spring precipitation with regard to the interannual variations, with a correlation coefficient of 0.54 (0.40) for the original (detrended) time series significant at the 95% confidence level. Noteworthy is that, besides the consistency in interannual variations, the time series of the leading EOF mode of Eurasian spring circulation also exhibit an increasing trend similar to the TRS spring precipitation, indicating a contribution of this leading mode of Eurasian spring circulation to the increase of TRS spring precipitation during past decades. Thus, the leading mode of Eurasian spring circulation is not only an important influencing factor for the interannual variability of TRS spring precipitation, but also at least partially accounts for the increasing trend of TRS spring precipitation during past decades. Of particular note is the inconsistency between the time series of the leading mode of Eurasian spring circulation and TRS spring precipitation during a few episodes, for instance the recent years after 2010 (Figs. 4b,c), implying other influencing factors of TRS spring precipitation.

By contrast, the regime of the anomalous southerly WVT branch toward the TRS region is not as clear as that of the anomalous easterly WVT branch because of the relatively low significance of these southerly WVT anomalies (Fig. 3a). These southerly WVT anomalies over the southern Tibetan Plateau are mainly associated with meandering WVT anomalies over southern China and northern Indochina, which are characterized by northeasterly WVT anomalies over southern China and easterly WVT anomalies over northern Indochina (Fig. 3a). The connections of these meandering WVT anomalies with an anomalous cyclone and an anomalous low over the Bay of Bengal, and an anomalous cyclone over the western North Pacific imply influences from low-latitude oceans (Figs. 3a,b). Considering that the SST anomalies associated with TRS spring precipitation exhibit a La Niña pattern in the Pacific (Fig. 3c), which is suggested to induce an anomalous cyclone over the western North Pacific (Wang et al. 2000), the influence...
of ENSO on the regime associated with the anomalous southerly WVT branch toward the TRS region is investigated.

To illustrate the influences of a La Niña SST pattern, the climate anomalies regressed on the sign-reversed Niño-3.4 index [i.e., Niño-3.4 index \times (-1)] are computed. As shown in Fig. 5a, under a La Niña condition, the convection over the tropical western Pacific is strengthened by the underlying warm SST anomalies (Fig. 3c). In response to the strengthened convection over the tropical western Pacific, a classical Matsuno–Gill pattern is induced over the Indian and Pacific Oceans that is characterized by a pair of anomalous cyclones over the northern and southern Indian Ocean and easterly wind anomalies over the tropical central Pacific (Fig. 5b), being the Rossby-wave response and
the Kelvin-wave response, respectively (Matsuno 1966; Gill 1980). Accordingly, an anomalous low and an anomalous cyclone are generated over the Bay of Bengal and Indochina (Figs. 5a,b).

Moreover, the vertically integrated WVT anomalies regressed on the sign-reversed Niño-3.4 index indicate an important role of the La Niña SST pattern in causing an anomalous cyclone over the western North Pacific, as shown in Fig. 5b. The mechanism of how the warming (cooling) in the tropical central and eastern Pacific induces an anomalous anticyclone (cyclone) over the western North Pacific is elaborated in Wang et al. (2000), and is termed the “Pacific–East Asian teleconnection.” From Wang et al. (2000), the cooling in the tropical central Pacific can induce poleward wind anomalies to the west of the cooling (Fig. 5b). These poleward wind anomalies would subdue the mean northeast trade winds and hence suppress evaporative cooling over the western North Pacific, resulting in a warming in the western North Pacific (similar to the SST anomalies shown in Fig. 3c). This warming in the western North Pacific further causes an anomalous cyclone to its west as a Rossby wave response (Fig. 5b). This anomalous cyclone is maintained by a positive feedback of local air–sea interaction.

The anomalous cyclones associated with La Niña SST pattern over the Bay of Bengal, Indochina, and the western North Pacific result in meandering WVT anomalies over southern China, northern Indochina, and the southern Tibetan Plateau that are characterized by northeasterly WVT anomalies over southern China, easterly WVT anomalies over northern Indochina, and southerly WVT anomalies over the southern Tibetan Plateau (Fig. 5c), resembling the meandering WVT anomalies associated with TRS spring precipitation (Fig. 3a). A discrepancy is observed between the WVT anomalies associated with La Niña SST pattern and TRS spring precipitation, where most of the southerly WVT anomalies associated with TRS spring precipitation (La Niña SST pattern) are southeasterly (southwesterly) WVT anomalies over the southern Tibetan Plateau. Notwithstanding this discrepancy, the WVT anomalies associated with TRS spring precipitation largely resemble the WVT anomalies associated with La Niña SST pattern over the Indian and Pacific Oceans (figure not shown), suggesting an impact of ENSO on the meandering WVT anomalies, contributing to the anomalous southerly WVT branch toward the TRS region. Specifically, southerly WVT anomalies are observed crossing the southern boundary of the TRS region during spring for some La Niña years (e.g., 1989 and 2011) but are not observed for some other La Niña years (e.g., 2000 and 2008). Thus, the impact of ENSO on interannual variability of TRS spring precipitation should be considered carefully, although the detrended time series of TRS spring precipitation and sign-reversed Niño-3.4 index exhibit a consistency in interannual variations, with a correlation coefficient of 0.35, significant at the 95% confidence level (Fig. 5d).

The above results suggest a dominant influence of the leading mode of Eurasian circulation and a considerable influence of ENSO on the interannual variability of TRS spring precipitation. However, it should be noted that neither the leading mode of Eurasian circulation nor ENSO accounts for a few interannual variations of the spring precipitation, such as the recent negative precipitation anomaly in 2014 and the positive precipitation anomaly in 2015 (Figs. 4c and 5d). This implies that there are other factors affecting the interannual variability of TRS spring precipitation that demand further study.

b. Summer

To illustrate the WVT regime associated with the interannual variability of TRS summer precipitation, Fig. 6a shows the vertically integrated WVT anomalies regressed on the detrended and standardized time series of TRS summer precipitation. Evidently, the most important contributor to the moisture over the TRS region is the anomalous southerly WVT branch transporting moisture from India toward the TRS region. This anomalous WVT branch over the TRS region and the southerly WVT anomalies over southwestern China suggest an influence of EASM. The detrended time series of EASM index and TRS summer precipitation have an insignificant correlation because the two time series have an out-of-phase relationship after 2010 and they exhibit a low-frequency inconsistency during the 1990s, although overall they are consistent in the interannual variations. A further analysis indicates that the 9-yr high-pass-filtered (Duchon 1979) time series of EASM index and TRS summer precipitation are significantly correlated, with a correlation coefficient of 0.41 significant at the 95% confidence level. The circulation anomalies regressed on the 9-yr high-pass-filtered time series of EASM index suggest that a strong EASM is mainly associated with an anomalous high extending from the western North Pacific to India, which causes southerly wind anomalies over the TRS region and eastern China.

Nevertheless, for the following reasons it is superficial to conclude that the interannual variability of summer precipitation over the TRS region is determined by the interannual variability of EASM, where a strong (weak) EASM may result in increased (decreased) summer precipitation over the TRS region. The concept “monsoon” refers to the circulation caused by the thermal contrast between land and sea. Although conventionally
the variability of summer circulation over East Asia is deemed the variability of EASM, the variability of summer circulation over East Asia is not only modulated by the land–sea thermal contrast but is also modulated by other factors such as ENSO and NAO (Wang 2002; Wu et al. 2009; Sun and Wang 2012, 2015; Gao et al. 2013; Gao 2017). More important, our results indicate that the circulation anomalies associated with TRS summer precipitation are different from the circulation anomalies associated with EASM, implying an important regime modulating the interannual variability of TRS summer precipitation other than EASM. Thus, it is essential to clarify the fundamental reason(s) for the interannual variability of summer precipitation over the TRS region.

Figure 6b shows the 500-hPa geopotential height anomalies regressed on the detrended and standardized time series of TRS summer precipitation to illuminate the regimes modulating the interannual variability of TRS summer precipitation. As shown in Fig. 6b, an above-normal summer precipitation over the TRS region is mainly associated with an anomalous low over the TRS region and to its west. This anomalous low causes cyclonic WVT anomalies over western China and central Asia, exerting southwesterly WVT anomalies toward the TRS region (Fig. 6a), indicating a critical role in affecting the interannual variability of TRS summer precipitation. What causes this anomalous low? One possible reason is the local thermal forcing. However, the surface temperature anomalies and surface sensible
and latent heat flux anomalies regressed on the detrended and standardized time series of TRS summer precipitation denote an insignificant impact of local thermal forcing on this anomalous low. Another possible reason is a teleconnection effect of an anomalous southeastward-propagating wave train over Eurasia, which features negative geopotential height anomalies over northern Europe, positive geopotential height anomalies extending from western Siberia to the Mediterranean, and negative geopotential height anomalies over the TRS region and to its west (Fig. 6b). The origination of this anomalous wave train is associated with a meridional seesaw pattern over the North Atlantic, resembling a negative-phase NAO mode. Correspondingly, the SST anomalies regressed on the detrended and standardized time series of TRS summer precipitation exhibit a tripole pattern in the North Atlantic (Fig. 6c), which is a recognized SST pattern coupled with the NAO mode (Rodwell et al. 1999; Hurrell et al. 2003; Peng et al. 2003; Hurrell and Deser 2010). These results imply a connection of the interannual variability of TRS summer precipitation with summer NAO.

To examine the influence of summer NAO mode on the summer precipitation over the TRS region, the anomalies of 500-hPa geopotential height and vertically integrated WVT regressed on the detrended and standardized time series of sign-reversed summer NAO index are computed. As shown in Fig. 7a, the 500-hPa geopotential height anomalies associated with a negative-phase summer NAO are characterized by a meridional seesaw pattern over the North Atlantic and a southeastward-propagating wave train over Eurasia, resembling the circulation anomalies affecting the interannual variability of TRS summer precipitation revealed in Fig. 6b. This anomalous wave train induces an anomalous low over the TRS region and to its west. Accordingly, this anomalous low causes cyclonic WVT anomalies and exerts southwesterly WVT anomalies toward the TRS region (Fig. 7b), which would contribute to the summer precipitation over the TRS region. Thus, the critical influence of southwesterly WVT anomalies toward the TRS region is largely attributed to the anomalous wave train associated with summer NAO.

Furthermore, Fig. 7c shows the detrended and standardized time series of TRS summer precipitation and sign-reversed summer NAO index. It can be seen that the two time series are mostly consistent in the interannual variations, with a correlation coefficient of 0.50 significant at the 95% confidence level, demonstrating the importance of summer NAO to the interannual variability of TRS summer precipitation. Particularly, the impact of the NAO-associated wave train may essentially account for the interannual variations of TRS summer precipitation during the 1990s, the late 2000s, and the early 2010s, considering the good consistency between the two time series during these periods. Nevertheless, the inconsistency between the two time series during the mid-1980s and mid-2000s indicates a smaller influence of NAO on the interannual variations of TRS summer precipitation for these episodes, implying other influencing factors in addition to summer NAO.

Another contributor to the southwesterly WVT anomalies toward the TRS region is likely ENSO. The SST anomalies associated with TRS summer precipitation imply a connection between TRS summer precipitation and tropical central and eastern Pacific SSTs (Fig. 6c). However, the WVT anomalies regressed on the detrended and standardized time series of summer Niño-3.4 index do not exhibit an impact on the southwesterly WVT anomalies over the TRS region. On the other hand, it has been learned that during an El Niño–decaying summer, significant circulation anomalies can be caused over East Asia by the Indian Ocean warming following an El Niño event and the associated effects (Wu et al. 2009; Xie et al. 2009). To illustrate the influence of an El Niño–decaying summer on precipitation over the TRS region, the summer circulation anomalies regressed on the preceding winter (December–February) Niño-3.4 index are computed. The results indicate that, during a summer that follows an El Niño event, an anomalous anticyclone is induced over the Bay of Bengal and exerts southwesterly WVT anomalies toward the TRS region. In this study, we show the climate anomalies regressed on the tendency of the Niño-3.4 index from the preceding winter to summer, which are similar to the climate anomalies regressed on the preceding winter Niño-3.4 index but exhibit clearer features.

Figure 8a shows the WVT anomalies corresponding to a negative tendency of the Niño-3.4 index for summer. The results indicate that, during an El Niño–decaying summer, anticyclonic WVT anomalies are induced over the Bay of Bengal and northern India, exerting southwesterly WVT anomalies toward the TRS region, which demonstrates a contribution of El Niño–decaying summer to the southwesterly WVT anomalies toward the TRS region. Previous studies revealed that the Indian Ocean warming during an El Niño–decaying summer plays an important role in causing the anomalous anticyclone over the western North Pacific (Wu et al. 2009; Xie et al. 2009). Our results suggest that the warming in the Arabian Sea may have an important impact on the anomalous anticyclone over the Bay of Bengal during an El Niño–decaying summer (Fig. 8b). The strengthened convection over
the Arabian Sea resulting from the warming in the Arabian Sea can cause easterly wind anomalies over the Bay of Bengal and India and result in an anticyclonic wind shear to the north of the Bay of Bengal that is responsible for the anticyclonic regime affecting the TRS region (Fig. 8a). The time series of TRS summer precipitation and sign-reversed tendency of the Niño-3.4 index indicate that the interannual variations of TRS summer precipitation from the late 1990s to the mid-2000s are at least partially attributed to the effect of El Niño–decaying summer (Fig. 8c). However, the time series of TRS summer precipitation and sign-reversed tendency of the Niño-3.4 index overall show an inconsistency with regard to the interannual variability, with an insignificant correlation coefficient of 0.22, denoting an overall minor role of ENSO in modulating the interannual variability of TRS summer precipitation. The above results are preliminary, and an in-depth study on the influences of ENSO–decaying summer on TRS summer precipitation during different periods is warranted.

5. Discussion

As mentioned previously, the leading mode of Eurasian circulation during spring suggests influences from both the interannual variability and the increasing trend of TRS spring precipitation. There is a significant correlation between the 5-yr running-mean time series of the leading mode of Eurasian spring circulation and TRS spring precipitation, with a correlation coefficient of 0.63 significant at the 99% confidence level (Fig. 9a). During past decades, the Eurasian spring snow cover exhibited a notable decreasing trend (Brown and Robinson 2011). This decreasing trend in Eurasian spring snow cover may be partially responsible for the
trend of the leading mode of Eurasian spring circulation toward a positive phase (Fig. 4) because the leading modes of Eurasian circulation and snow cover are strongly coupled during spring (Sun 2017). In addition, an SST pattern resembling a negative-phase IPO mode (Power et al. 1999; Henley et al. 2015) is observed for the SST differences between the period of 1999–2015 and the period of 1989–98, which are periods of above-normal and below-normal TRS spring precipitation, respectively. The 5-yr running-mean time series of sign-reversed spring IPO index and TRS spring precipitation exhibit a consistency in the interdecadal oscillation during the 1980s and 1990s, as well as an increasing trend, with a correlation coefficient of 0.82 significant at the 99% confidence level (Fig. 9b). The IPO is a predominant mode of interdecadal variability of Pacific SSTs, which is closely related to the PDO and is characterized by an ENSO-like pattern (Zhang et al. 1997; Parker et al. 2007; Henley et al. 2015; Hao et al. 2016). Our preliminary results suggest that the spring IPO may influence the interdecadal variability of climate over the TRS region through a mechanism similar to the mechanism of ENSO impacting TRS spring precipitation suggested in section 4a, which requires further study.

![Figure 8: Anomalies of (a) vertically integrated WVT (kg m$^{-1}$ s$^{-1}$) and (b) SST (°C) regressed on the detrended and standardized time series of sign-reversed tendency of the Niño-3.4 index. Gray shading in (a) and stippling in (b) denote the 95% confidence level. Also shown are the (c) detrended and standardized time series of TRS summer precipitation (blue) and sign-reversed tendency of the Niño-3.4 index (red), with the correlation coefficient labeled in the top-right corner of the panel. The green circle in (c) highlights the period during which the two time series are consistent.](image-url)
The regimes of interdecadal variability of TRS summer precipitation are very complex. The interdecadal decrease from the 1980s to the 1990s and the interdecadal increase from the 1990s to the 2000s of TRS summer precipitation suggest different regimes. For the interdecadal decrease from the 1980s to the 1990s, the interdecadal change of TRS summer precipitation suggests an association with an anomalous Eurasian wave train of atmospheric circulation originating from the North Atlantic. Considering that the AMO is a predominant mode of multidecadal variability in the Atlantic Ocean, the relationship between the interdecadal variability of summer AMO and TRS summer precipitation is examined. The 5-yr running time series of summer AMO index do not exhibit a phase change from the 1980s to the 1990s, which is inconsistent with the time series of TRS summer precipitation (Fig. 10a). For the interdecadal increase from the 1990s to the 2000s, the interdecadal change of TRS summer precipitation suggests an association with an anomalous cyclone over southern China and the western North Pacific, which is connected with an SST pattern resembling a negative-phase IPO mode in the Pacific. The 5-yr running time series of sign-reversed summer IPO index do show an interdecadal increase from the 1990s to the early 2000s. Moreover, the interdecadal variation of TRS summer precipitation and EASM show a notable inconsistency for the 1990s (Fig. 10c), during which period the southwesterlies over southern China were strong and the southwesterlies over the TRS region were weak. Thus, the regimes of interdecadal variability of TRS summer precipitation remain mysterious.

6. Summary

This study investigated the interannual and interdecadal variability of spring and summer precipitation over the TRS region. A general consistency is revealed among the four datasets used in this study with regard to the variability of TRS precipitation, demonstrating a confidence of the four datasets in representing the precipitation variability over the TRS region. The spring and summer precipitation over the TRS region exhibits distinct interannual and interdecadal variability during past decades and is associated with distinct climate regimes. The interannual variability of TRS spring precipitation is essentially modulated by an anomalous easterly WVT branch, which is associated with the leading mode of Eurasian spring circulation characterized by an anomalous wave train over mid- and high-latitude Eurasia. ENSO may also impact the interannual variability of TRS spring precipitation by influencing southerly WVT anomalies toward the TRS region. The interannual variability of TRS summer
precipitation is mainly modulated by southwesterly WVT anomalies induced by an anomalous low over the TRS region, which is a node of an anomalous atmospheric wave train over Eurasia associated with summer NAO. The Indian Ocean warming during an El Niño–decaying summer may also induce southwesterly WVT anomalies toward the TRS region by causing an anomalous anticyclone over the Bay of Bengal.

The results of this study indicate an instability of the relationship between the interannual variability of TRS precipitation and the associated regimes. For instance, the interannual variability of TRS summer precipitation has a significant correlation with ENSO from the late 1990s to the mid-2000s but has an insignificant relationship with ENSO during other episodes. Thus, it is worthy of attention that the regimes of interannual variability of TRS precipitation might vary with periods (Wang 2001, 2002; Wu and Wang 2002; Sun and Wang 2012). This unstable relationship between TRS precipitation variability and its influencing factors may be due to an interdecadal change in the mean state and/or interannual variability of tropical SSTs and an interdecadal change in the phase of the North Pacific Oscillation, PDO, AMO, and so on (Chang et al. 2000; He and Wang 2013; Feng et al. 2014; Han et al. 2018; Luo et al. 2018).

Besides large-scale WVT, regional evaporation may also play a role in affecting the variability of precipitation over the TRS region by influencing the regional hydrological cycle. The pan evaporation in CN05.1 data indicates an out-of-phase relationship with TRS precipitation with regard to the interannual and interdecadal variability for both the spring and summer. Previous studies suggested a complementary relationship between actual evaporation and pan evaporation that might result in opposite variations of actual evaporation and pan evaporation (Brutsaert and Parlange 1998; Huntington 2006; Yang et al. 2011; Zuo et al. 2016). Thus, the out-of-phase relationship between pan evaporation and precipitation suggests a consistency between the variability of actual evaporation and precipitation. The interdecadal decrease of TRS summer precipitation from the 1980s to the 1990s might be partially attributed to the impact of the regional hydrological cycle.

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