The Characteristics of Water Vapor Transport and Its Linkage with Summer Precipitation over the Source Region of the Three Rivers

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ABSTRACT: Precipitation is one of the most important meteorological factors affecting the water cycle and ecological system over the Source Region of the Three Rivers (SRTR), where the Yangtze River, Yellow River, and Lantsang River originate. The characteristics of annual and summer water vapor transport and budget over the SRTR are analyzed using monthly observational and reanalysis datasets during 1980–2019. The linkage between water vapor transport and summer precipitation is also explored in this study. The results show that the Global Precipitation Climatology Project (GPCP) data are in agreement with the measured precipitation. The SRTR is a sink region for water vapor, where the water vapor content shows an increasing trend with a rate of 0.2 mm (10 yr) −1 annually and 0.3 mm (10 yr) −1 in the summer. The water vapor mainly flows into the SRTR from the lower (521.2 × 106 kg s −1) and the middle (195.7 × 106 kg s −1) layers of the southern boundary in summer, while it exports from the middle (208.1 × 106 kg s −1) layer of the eastern boundary. The abnormal wind convergence and the low pressure system, combined with the effects of the western Pacific subtropical high and the Mongolian high, provide conditions for the transport of water vapor and precipitation over the SRTR. A close relationship is found between water vapor flux and precipitation from the singular value decomposition (SVD) analysis. The Brahmaputra River basin is the key region of water vapor transport over the SRTR, which contributes to further understanding the mechanisms of water vapor transport and the regional water cycle.

SIGNIFICANCE STATEMENT: Under the background of global warming, the Tibetan Plateau has an obvious trend of warming and humidification. The purpose of this study was to investigate the characteristics of water vapor transport and its linkage with summer precipitation over Source Region of the Three Rivers, which is located in the hinterland of the Tibetan Plateau. We found that the Brahmaputra River basin is the key region affecting the precipitation. These findings contribute to the understanding of the regional water cycle characteristics and the mechanism of the synergistic effect of westerly wind and monsoon on the change of “Water Tower of Asia.”

KEYWORDS: Atmosphere-land interaction; Budgets; Climate change; Water vapor

1. Introduction

The Source Region of the Three Rivers (SRTR) is located in the hinterland of the Tibetan Plateau (TP). It is the highest natural wetland in both China and the world and is reputed as the “Water Tower of Asia” (Meng et al. 2020). Influenced by global warming, the ecological environment and climate change are fragile and sensitive in this region (Xu et al. 2008; Qiang et al. 2019; Jin et al. 2020). Precipitation is one of the most important climatic contributors affecting water resources and the ecological system over the SRTR (Li et al. 2016). In the past few decades, the precipitation overall shows an increasing trend over the SRTR (Liang et al. 2013; Yi et al. 2013). However, the precipitation exhibits significant regional and seasonal discrepancies (Kang et al. 2010; Yang et al. 2014; Hu et al. 2017; Wang et al. 2018). Generally, the precipitation in the eastern and southern parts of the SRTR is significantly more than that in the northwest (Wei et al. 2015). In addition, due to the role of the Indian monsoon (IM) and East Asian summer monsoon (EASM), the precipitation is mainly concentrated in summer (June–August) and there are obvious interannual and interdecadal variability of precipitation over the SRTR, which are regulated by the abnormal easterly and southwesterly airflows, respectively (Li et al. 2009; Liang et al. 2013; Yi et al. 2013; Sun and Wang 2018).

Water vapor provides moisture basis for precipitation. The water vapor content, transport, and the budget of water vapor at each boundary are all very important meteorological elements, which affect the occurrence of precipitation. The variation of regional water vapor is mainly affected by atmospheric circulation. Many studies have focused on the sources of water vapor over the SRTR under different climate backgrounds, but the results remain inconclusive. Several researchers have emphasized the important contribution of Somalian cross-equatorial flow to water vapor transport (Zhou and Li 2002; Wang and Xue 2003; Zhou and Yu 2005). Other researchers, however, employed multiple methods to explore the sources of water vapor. For example, Xie et al. (2018) analyzed the budget characteristics of water vapor over the TP by using the box model and considered that water vapor is mainly imported from the southern boundary and exported from the east boundary. Based on the Flexible...
Particle Dispersion Model (FLEXPART), Zhu et al. (2019) analyzed the sources of abnormal water vapor transport over the Source Region of the Yellow River (SRYR) and pointed out that water vapor mainly entered the source region through the southern and northern branch paths. There are three main water vapor sources over the SRTR, including the southwestern water vapor transport from the Indian Ocean to the Arabian Sea and the Bay of Bengal, the midlatitude westerly, and the northwestern airflow transporting from Eurasia (Li et al. 2009; Quan et al. 2016; Zhang et al. 2019). However, which source is more important? There is no consensus so far (Feng and Zhou 2012).

Although many researchers have studied the relationship between the regional water vapor content and precipitation under different backgrounds (Li and Zhang 2003; Wang et al. 2006; Dai and Yang 2009), few researchers have focused on the linkage between water vapor transport and precipitation in areas with complex topography and special climate types, due to the lack of data or low accuracy. Therefore, the following questions need to be addressed: What are the distribution and transport characteristics of water vapor over the SRTR? How much do the different boundaries contribute to the water vapor over the SRTR? What is the linkage between water vapor flux and the local precipitation over the SRTR?

To address the above questions, this research is structured as follows. Materials and methodology are arranged in section 2. The study on the characteristics of water vapor distribution, transport, and budget over the SRTR follow. Then, the spatio-temporal coupling of water vapor flux and summer precipitation is explored. Finally, the discussion and main conclusions are provided in sections 4 and 5.

2. Materials and methodology
a. Materials

1) Study Area

The SRTR (31.39°–36.12°N, 89.45°–102.23°E) lies in the hinterland of the TP, where the Yangtze River, Yellow River, and Lantsang River originate (as shown in Fig. 1), which is one of the sensitive and fragile regions to climate change in East Asia. The terrain and landform over the SRTR are extremely complex with an elevation of 3450.0–6621.0 m (Zhou et al. 2005). Due to the influence of the great topography of the TP, the SRTR belongs to a typical plateau continental climate zone with an annual mean temperature from −10.8°C to 10.9°C, with large temperature difference (about 20.0°C) between day and night (Bai et al. 2017). Besides, the SRTR is reputed as the “Water Tower of Asia” (Zhou et al. 2019; Xu et al. 2019a,b) and plays an important role in the precipitation and water cycle over the TP. Its annual-mean rainfall is about 517.0 mm with great discrepancies in temporal and spatial distributions (Liu and Yin 2001). There is a typical annual cycle of the dry and wet seasons over the SRTR. The east is wetter than the west at a regional scale, due to the role of the water vapor transport channel along the Brahmaputra Grand Canyon. The Brahmaputra Grand Canyon is located in the lower reaches of the Brahmaputra River basin. Affected by the warm and humid airflow of the Indian Ocean, the temperature of the Grand Canyon is 10.0°–17.0°C and the precipitation is about 5000.0 mm. The Brahmaputra Grand Canyon continuously transports water vapor from the Indian Ocean to the hinterland of the plateau (Zhang et al. 2016; Yang et al. 2019). In general, the spatial distributions of temperature and humidity over the SRTR
present a positive gradient from northwest to southeast. The 18 ground meteorological observation stations distributed over the SRTR are as listed in Table 1.

2) DATA

Four types of monthly mean precipitation datasets over the SRTR and its surrounding areas from the time period of 1980–2019 are deployed in this research. The observations of meteorological stations are collected from the National Meteorological Information Center of China, the gridded Global Precipitation Climatology Project (GPCP) data (Adler et al. 2003), the gridded Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) data (Xie and Arkin 1997) and the gridded data of the fifth generation ECMWF Reanalysis (ERA5, Hersbach et al. 2019b) are also applied. The ground station data consist of 18 meteorological stations over the SRTR (Table 1). The data are based on the ground monthly information files of the Chinese National Benchmark and the Basic Climate Stations and have performed strict quality assurance and quality control. The satellite precipitation products of GPCP (2.5° × 2.5°) are high quality products, which combine data from geostationary and polar orbiting satellites and ground stations. The CMAP (2.5° × 2.5°) data merge gauged rainfall over land, satellite observation, and NCEP–NCAR reanalysis data. The estimation based on the satellite provides the most complete analysis of the rainfall data over the global oceans. Besides, the CMAP data add the estimation of the uncertainties in the rainfall analysis. The precipitation data of ERA5 with a resolution of 0.25° × 0.25° are the accumulated liquid and frozen water, comprising rain and snow falling to Earth’s surface.

The monthly data for calculating water vapor content and transport flux are extracted from the ERA5 dataset (Hersbach et al. 2019a), which has been proven to have higher applicability over the TP (Xu et al. 2020; Chen et al. 2022). These include specific humidity (q), zonal (u), and meridional (v) components; surface pressure (p); and geopotential height (z). The integrated water vapor flux is mainly taken from the land to 300 hPa (1000, 925, 850, 700, 600, 500, 400, and 300 hPa). The temporal coverage of these data is from 1980 to 2019. The abovementioned station and reanalysis data are subject to strict quality control (Adler et al. 2003; Ahlgrimm and Forbes 2014; Ma et al. 2014).

### Table 1. Information of the 18 meteorological stations in the present study.

<table>
<thead>
<tr>
<th>Station</th>
<th>Lon (°)</th>
<th>Lat (°)</th>
<th>Elevation (m)</th>
<th>Station</th>
<th>Lon (°)</th>
<th>Lat (°)</th>
<th>Elevation (m)</th>
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</thead>
<tbody>
<tr>
<td>Wudaoliang</td>
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<td>35.13</td>
<td>4612.2</td>
<td>Yushu</td>
<td>97.01</td>
<td>33.01</td>
<td>3681.2</td>
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<tr>
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<td>35.35</td>
<td>3323.2</td>
<td>Maduo</td>
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<td>34.55</td>
<td>4272.3</td>
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<tr>
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<td>35.16</td>
<td>3289.4</td>
<td>Qinshuihe</td>
<td>97.08</td>
<td>33.48</td>
<td>4415.4</td>
</tr>
<tr>
<td>Zeku</td>
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<td>35.02</td>
<td>3662.8</td>
<td>Maqin</td>
<td>100.15</td>
<td>34.28</td>
<td>3719.0</td>
</tr>
<tr>
<td>Tongren</td>
<td>102.01</td>
<td>35.31</td>
<td>2491.4</td>
<td>Dari</td>
<td>99.39</td>
<td>33.45</td>
<td>3967.5</td>
</tr>
<tr>
<td>Tuotuohe</td>
<td>92.26</td>
<td>34.13</td>
<td>4533.1</td>
<td>Zeku</td>
<td>101.28</td>
<td>35.02</td>
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</tr>
<tr>
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<td>Jiuzhi</td>
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<td>3643.7</td>
<td>Henan</td>
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<tr>
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<td>32.56</td>
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</table>

### a. Methodology

In this research, the observed precipitation is interpolated to the gridded data via Cressman interpolation (Benjamin and Seaman 1985) to ensure data compatibility. The characteristics of precipitation over the SRTR are studied by analyzing the spatiotemporal distributions of atmospheric water vapor content and the budget of water vapor transport flux. Besides, the corresponding atmospheric circulation anomaly and the linkage between summer precipitation and water vapor transport are discussed to explain the phenomenon of summer precipitation over the SRTR.

1) MOISTURE CALCULATIONS

The specific humidity vertically integrated from surface pressure to atmospheric top pressure is defined as the atmospheric water vapor content. Water vapor flux (kg m⁻¹ s⁻¹) is divided into zonal water vapor flux (Qₜ) and meridional water vapor flux (Qₐ). The transport flux vector of the entire layer of atmospheric water vapor on a unit air column is expressed as

\[
Q = \frac{1}{g} \int_{P_1}^{P_2} \mathbf{V} \cdot \mathbf{q} \, dp = \frac{1}{g} \int_{P_1}^{P_2} \mathbf{u} q \, dp + \frac{1}{g} \int_{P_1}^{P_2} \mathbf{v} q \, dp, \tag{1}
\]

where \( \mathbf{V} \) is the wind vector (\( \mathbf{V} = \mathbf{u} \rightarrow + \mathbf{v} \rightarrow \)); \( \mathbf{u} \) and \( \mathbf{v} \) represent the zonal and meridional wind components, respectively; \( g \) is gravitational acceleration of 9.8 m s⁻²; \( q \) is specific humidity (kg kg⁻¹); \( P_1 \) is atmospheric top pressure (300 hPa); and \( P_2 \) is surface pressure.

To depict the regional water vapor convergence and divergence, defining the amount of water vapor that flows into or diverges from a unit volume per unit time as the water vapor flux divergence (\( Q_{dv} \)). It is divided into the moisture advection term (the first term on the right) and the wind divergence term (the second term on the right):

\[
Q_{dv} = \nabla \cdot Q = \frac{1}{g} \int_{P_1}^{P_2} \mathbf{V} \cdot \nabla q \, dp + \frac{1}{g} \int_{P_1}^{P_2} q \cdot (\nabla \cdot \mathbf{V}) \, dp, \tag{2}
\]

where the unit of \( Q_{dv} \) is kg m⁻² s⁻¹.

To better understand the characteristics of water vapor transport over the SRTR, the differences in the water vapor transport flux of the four boundaries over the SRTR are defined as the net budget of water vapor, which is based on
Green’s theorem. Their calculation formulas are as follows (Xie et al. 2014):

\[ F_u = \int Q_u \cos \varphi \, d\lambda, \]  
\[ F_T = \sum (F_u, F_v), \]

\[ F_v = \int Q_v \cos \varphi \, d\lambda, \]  
\[ F_T = \sum (F_u, F_v). \]
where $F_u$ and $F_v$ are zonal and meridional water vapor transport flux, respectively; $F_T$ is the net revenue and expenditure (kg s$^{-1}$); $a$ represents the radius of Earth ($6.37 \times 10^6$ m); $\lambda$ and $\phi$ are longitude and latitude.

2) THE SINGULAR VALUE DECOMPOSITION METHOD

The singular value decomposition (SVD) is a statistical method which can be used to extract and analyze the temporal and spatial information of coupling field of meteorological elements. The homogeneous array of modes mainly reflects the change degree of its own field, while the heterogeneous array reflects the extent of the affected by another field, which illustrates the key area of two meteorological element fields (Wei 1999; Xu et al. 2020). It is mainly used to analyze the linkage between water vapor transport flux and summer precipitation in this research.

To establish the typical correlation relationship reflected by the left and right meteorological element fields, the significance $t$ test is carried out and written as

$$R_c = \sqrt{\frac{t_o^2}{n - 2 + t_o^2}},$$

where $R_c$ is the critical value of significance $t$ test, $n$ is the number of samples, and $\alpha$ is the significance level, which takes 0.05 here.

3. Results

a. Spatiotemporal characteristics of precipitation

The precipitation is an important segment of the regional water cycle over the TP and its surrounding areas, and there are extensive discrepancies in the spatiotemporal distribution characteristics over different regions. Based on the four types of precipitation datasets (stations, GPCP, CMAP, and ERA5), the annual mean and annual cycle distributions of precipitation are investigated over the SRTR. The spatial distributions (Figs. 2a–d) of precipitation over the SRTR and its surrounding areas from different datasets demonstrate a southeast–northwest gradient: the precipitation decreases from the southeast (annual precipitation about 600.0 mm) to the northwest (annual precipitation about 300.0 mm). Comparing with the observations, the GPCP dataset resembles the spatial distribution derived from the station data, which has been proved by a large number of studies (Adler et al. 2003). The average precipitation of CMAP is close to the observations, but the spatial distribution is different, especially in the northwestern TP. The precipitation data from ERA5 have a modest portrayal of its distribution and overestimate the precipitation amount over the SRTR. In conclusion, the spatial distribution of GPCP precipitation data is closer to the observations at the regional scale.

Figure 3 shows the annual cycles of precipitation over the SRTR (30°–37.5°N, 90°–102.5°E). The precipitation during
summer accounts for more than 50.0% of the annual precipitation, while the winter precipitation (December–February) is only 2.2%. The percentage of precipitation is slightly different in June–August among the four types of data. The four types of precipitation data exhibit a single peak within an annual cycle. The peak of the first three precipitation data appears in July (Figs. 3a–c), while the precipitation of the ERA5 appears in June (Fig. 3d). Based on annual cycle of precipitation averaged, it is seen clearly that the precipitation over the SRTR is mainly concentrated in summer (59.8%), so summer is selected as the main study period when analyzing the linkage between precipitation and water vapor flux.

To more intuitively compare the applicability of different precipitation reanalysis data over the SRTR, Fig. 4 exhibits the Taylor diagrams (Taylor 2001) for monthly mean precipitation among reanalysis products with observations of 18 meteorological stations. The correlation coefficients between most precipitation products and observations are higher than 0.8. The standardized deviation ratios of the ERA5 to the observations are between 1.1 and 2.2 with great root-mean-square error (RMSE), which means that the ERA5 data are poorly applicable to precipitation over the SRTR and greatly overestimate the amount of precipitation. The GPCP data are better than the CMAP in the description of the precipitation over the SRTR, since their standardized deviation ratios are closer to 1.0 and they have greater correlation coefficients with the observations.

b. Characteristics of water vapor transport and budget

It is well known that water vapor is the moisture contribution of precipitation. To explore the distribution and evolution of the atmospheric water vapor resources over the SRTR, the characteristics of water vapor are studied from aspects, such as water vapor content, transport and budget at different levels and boundaries.

Figure 5 shows spatial distributions of annual and summer mean water vapor content and evolution trend over the SRTR and its surrounding areas during 1980–2019. It exhibits that there is a low value region of water vapor over the TP and the content is higher in the southeast, but lower in the northwest. The annual-mean water vapor content is 2.0–9.0 mm over the SRTR, while it is 4.0–12.0 mm in summer. In the past 40 years, the water vapor content manifests an increasing trend. The increasing rate in summer [0.3 mm (10 yr)\(^{-1}\)] is significantly higher than the annual mean [0.2 mm (10 yr)\(^{-1}\)] and has passed the 95% confidence level. It means that the humid area expands and the value of atmospheric humidity is increasing with the onset of the IM and the EASM, which indicates they play an important role in summer precipitation over the SRTR.

As mentioned above, the atmospheric circulation has an important influence on the regional water vapor content. Therefore, it is necessary to study the variation characteristics of water vapor transport flux and its divergence over the SRTR. Figure 6 demonstrates the integrated water vapor flux and its divergence. There are three main sources of
integrated water vapor (Figs. 6a,c) over the SRTR: the first is the strong southwestern water vapor transport from the Arabian Sea and the Bay of Bengal, which is associated with the Somali jet. The importance of the Somali jet has been emphasized in extensive researches (Huang et al. 1998; Zhang 2001). Besides, there are several north–south valleys over the southeastern TP, such as the Jinsha River, and the Lantsang River valleys. Especially in the Brahmaputra Grand Canyon area, there are obvious water vapor flux convergence centers in summer (Fig. 6d). The second and the third are the westerly water vapor transport from midlatitude and the northwestern water vapor transport from Eurasia, respectively. The westerly branch is divided into two parts when encountering the barrier of the western TP. The southern branch westerly flow and the southwestern flow form a cyclonic circulation in the Indian Peninsula. Due to the weak westerly water vapor transport, the obvious water vapor flux gradient is formed when merging with the strong water vapor transport in the south, then a water vapor transport channel is formed in the Brahmaputra Grand Canyon. The northwestern water vapor transport is very weak and usually transports water vapor from the northern boundary to the SRTR. In conclusion, the water vapor transport in summer is stronger than the annual mean due to the influence of summer monsoon.

To better understand the characteristics of water vapor transport over the SRTR, a quantitative measure of water vapor flux across the boundaries of the SRTR is shown in Table 2 and Fig. 7. The southern, western, and northern boundaries are the main import boundaries of water vapor flux, while the eastern boundary is the export boundary. The value of water vapor import is greater than that of export, so there is a net surplus of water vapor over the SRTR. Comparing with the annual mean water vapor transport (the maximum transport is in western boundary), the maximum \(243.66 \times 10^6\) kg s\(^{-1}\) of water vapor import boundary in summer is in the southern boundary, because of the significant impact of the monsoon (Li et al. 2009; Zhang et al. 2019). It is also verified from Fig. 7a that the water vapor fluxes of the four boundaries are fluctuating and the net water vapor budget in summer accounts for about 66.6% of the total annual water vapor import. In the past 40 years, the interannual variations of import boundary water vapor transport shows an increasing trend. The annual-mean water vapor transport (Fig. 7b) of the export boundary is increasing while it is decreasing in summer (Fig. 7c). This is consistent with the warming and wetting trend of the SRTR in recent years.

### Table 2

<table>
<thead>
<tr>
<th></th>
<th>South</th>
<th>North</th>
<th>West</th>
<th>East</th>
<th>Net</th>
</tr>
</thead>
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<td>Annual</td>
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<td>252.18</td>
<td>815.34</td>
<td>-1190.31</td>
<td>667.79</td>
</tr>
<tr>
<td>Summer</td>
<td>243.66</td>
<td>108.40</td>
<td>233.41</td>
<td>-249.76</td>
<td>335.71</td>
</tr>
</tbody>
</table>

FIG. 6. Mean distributions of the integrated water vapor flux (vectors; kg m\(^{-1}\) s\(^{-1}\)) and its divergence (kg m\(^{-2}\) day\(^{-1}\)) (a),(b) annually and (c),(d) in summer over the SRTR and its surrounding areas for the time period of 1980–2019. The red arrows represent the water vapor transport paths. The dotted and solid lines represent the negative and positive water vapor flux divergence, respectively.
To illustrate the vertical distributions of water vapor transport and find out the layer of water vapor transport which has the greatest impact on the summer precipitation over the SRTR, the whole atmosphere column is divided into three layers, including the lower (1000–600 hPa), middle (600–400 hPa), and upper (400–300 hPa) layers. The contributions of different layers and boundaries to water vapor transport are calculated, and the features of water vapor flux over the SRTR for the period 1980–2019 are as follows.

In terms of annual mean water vapor budget (Fig. 9a), it exhibits that the water vapor imports from the lower layer of the southern boundary (1344.8 × 10^6 kg s^{-1}) is dominant, while the middle layer is western boundary (528.7 × 10^6 kg s^{-1}). The upper layer of eastern boundary (104.6 × 10^6 kg s^{-1}) is an export boundary. The transport of western and eastern boundaries has a relatively weak magnitude, but at the middle layer the transport is stronger than that at the lower layer and the upper layer is weak due to the reduction of atmospheric humidity. The water vapor importing from the southern boundary in summer (Fig. 9b) accounts for 38.8% of the annual amount. Because of the influence of the IM and EASM, the water vapor imports from the eastern boundary of the lower layer in summer over the SRTR, while the western boundary is an export boundary. The middle water vapor importing from the south boundary is the most proportion of water vapor transport in summer. In general, it is mainly affected by the water vapor transport at the middle layer, since the average elevation of the SRTR is above 4000.0 m. There is a net import of water vapor at the middle and lower layers, due to the influence of plateau topography and weather systems. There is a net export of water vapor in the upper layer owing to strong westerly. The annual mean water vapor mainly comes from the western boundary, while it is mainly from the southern boundary in summer (as shown in Table 2), which provides the basis for precipitation.

b. Atmospheric circulation corresponding to water vapor transport

Relevant researches (Zou and Liu 2002; Cai et al. 2004; Liang et al. 2005) elucidate that the three main factors which
affect the distribution of water vapor are geographical latitude, altitude, and atmospheric circulation. In general, the geographical latitude and altitude are almost constant, so the anomaly of atmospheric water vapor distribution in summer is mainly affected by the atmospheric circulation. The variation of atmospheric circulation will lead to the change of water vapor transport, and then further change the distribution of precipitation. Here, 500 hPa is used to represent the low level of the study area in this research.

Figure 10a depicts the standardized anomaly of the 500-hPa wind field. There are cyclonic circulation anomalies in the Bay of Bengal located in the south of the TP and Mongolia located in the north of the TP, then the convergence of wind field is enhanced, especially in the southeastern plateau. This strengthens the upward movement and is conducive to the formation of precipitation. Figure 10b illustrates that the geopotential height in most parts of the TP is negative anomaly, which means that the low pressure system of the plateau is stronger in summer. Additionally, there are four obvious centers of positive and negative anomaly: the positive anomaly centers located in Pakistan and the Pacific Ocean. The western Pacific subtropical high (WPSH) is the most important high pressure system affecting precipitation in China, especially in summer. The southward airflow in the west of the WPSH brings lots of warm and moist air, forming a large-scale rain belt when colliding with cold airflow from the north. There are negative anomalies of geopotential height and cyclonic circulation in the Arabian Sea and Mongolia, respectively. To sum up, all the systems abovementioned provide favorable circulation conditions for the occurrence of summer precipitation over the SRTR.

c. The linkage between water vapor transport and summer precipitation

The water vapor transported to the area is closely related to the distribution and variation of regional precipitation and

FIG. 8. (a)–(c) Annual and (d)–(f) summer averaged distributions of the integrated water vapor flux (vectors; kg m\(^{-1}\) s\(^{-1}\)) at different layers [(bottom)1000–600 hPa, (middle) 600–400 hPa, and (top) 400–300 hPa] over the SRTR and its surrounding areas for the time period of 1980–2019.
is the basis of precipitation. The SVD method is used to explore the linkage between water vapor flux and summer precipitation over the SRTR in this research. Table 3 shows the variance contribution rates and the correlation coefficients of the first four pairs of principal component modes. The cumulative contribution rate of the first four modes is 75.20%, the correlation coefficients are positive and pass the 95% confidence level. The variance contribution rates of the first two modes are the largest (36.52% and 19.82%), which reflect the main characteristics of the linkage between the water vapor flux and precipitation. Therefore, this research mainly analyzes the relevant features of the first two modes.

From the first mode of SVD analysis of water vapor transport and precipitation (Figs. 11a,b), it manifests that there are obvious coupling modes between water vapor flux and summer precipitation over the SRTR. The anomaly of water vapor flux over the main part of the TP is basically positive except for the northern TP and the belt of the positive anomaly is in the southern TP, especially in the Brahmaputra Grand Canyon. The corresponding precipitation has similar spatial distribution to water vapor flux, which demonstrates positive anomalies over the SRTR. The first mode exhibits that there is a positive correlation between the water vapor transport and precipitation over the SRTR, and their spatial...
correlation coefficient is 0.36 (the dotted area has passed 95% significance test). The time series (Fig. 11c) of the first mode illustrate there are significant interannual variations of water vapor transport and precipitation in summer over the SRTR and the overall variation trend shows an increasing trend. Their correlation coefficient is 0.96, which has passed the 95% significance test.

In terms of the second mode of SVD analysis (Figs. 12a,b), the water vapor flux over the SRTR is positive anomaly except for the Brahmaputra River basin, while the corresponding precipitation exhibits a center of negative anomaly. It illustrates that the water vapor transport in the Brahmaputra River basin has significant effects on precipitation over the SRTR, which is the key region of water vapor transport to the SRTR. When the water vapor flux decreases, the corresponding precipitation also reduces. The time series of second mode (Fig. 12c) indicate that the trend of water vapor transport flux and precipitation with time is not as good as that of the first mode, their time correlation coefficient is 0.92. The temporal variation of precipitation is out of phase with water vapor. This means that water vapor is only the basis of precipitation, the local upward movement and water vapor condensation core are the factors which affect the occurrence of precipitation.

The first, second mode of the summer precipitation and water vapor flux illustrates that there is a close linkage between water vapor transport and precipitation over the SRTR and its surrounding areas. In particular, they highlight the importance of water vapor flux in the Brahmaputra River basin to local precipitation over the SRTR, since this key region is indicative to the occurrence of precipitation.

4. Discussion

In the context of global warming, the trend of warming and humidification over the SRTR is becoming more and more notable, the extreme precipitation events occur frequently and present significantly regional and seasonal differences (Sun and Wang 2018). The circulation systems affecting distribution of regional precipitation are very complex. Many researchers considered that this is closely related to the IM and the EASM (Huang et al. 1998; Xu et al. 2002; Sun et al. 2011; Chen et al. 2012; Zhang et al. 2017). However, the annual and interannual variations of the summer monsoon are affected by many factors, such as El Niño–Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO; Wang et al. 2000; Hurrell and Deser 2010; Gao 2017). Our results revealed that the coordination of the upper and lower atmospheric circulation is also an important factor affecting the water vapor transport and precipitation over the SRTR. Additionally, the water vapor transport over the Brahmaputra

<table>
<thead>
<tr>
<th>SVD mode</th>
<th>Variance (%)</th>
<th>Accumulate variance (%)</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36.52</td>
<td>36.52</td>
<td>0.96</td>
</tr>
<tr>
<td>2</td>
<td>19.82</td>
<td>56.34</td>
<td>0.92</td>
</tr>
<tr>
<td>3</td>
<td>12.38</td>
<td>68.72</td>
<td>0.94</td>
</tr>
<tr>
<td>4</td>
<td>6.48</td>
<td>75.20</td>
<td>0.91</td>
</tr>
</tbody>
</table>

FIG. 11. The (a),(b) spatial distributions and (c) time series of the first SVD mode for water vapor flux and precipitation in summer over the SRTR from 1980 to 2019. Dotted areas passed 95% significance test. The dotted and solid lines here and subsequent represent water vapor flux and precipitation, respectively.
River basin has a significant impact on precipitation over the SRTR and is the key area of water vapor transport. The physical mechanisms behind them deserve further exploration.

Besides, there are yet few issues which have not been addressed in this research. Since the sparse and uneven distribution of stations over the SRTR, the reanalysis precipitation products were employed in the research, which further increases the uncertainties to the results. Atmospheric water balance is important for the hydrological cycle (Yan et al. 2020). The characteristics of water vapor distribution, transport and budget at each boundary over the SRTR are explored using the isobaric surface data of ERA5. Then the linkage between water vapor flux and summer precipitation are investigated. The following conclusions have been drawn:

1) The spatial distributions of the precipitation exhibit a decreasing trend from southeast to northwest over the TP, the GPCP data are in agreement with the measured precipitation well, and their correlation coefficients are more than 0.9.

2) The SRTR is a water vapor sink where the linear increasing trend of water vapor content is 0.2 mm (10 yr)$^{-1}$ in annual and 0.3 mm (10 yr)$^{-1}$ in summer. The water vapor transport is strong with a significant water vapor flux convergence over the Brahmaputra Grand Canyon. The southern, northern and western boundaries are the main import boundaries, while the eastern boundary is the export boundary. The water vapor mainly imports into the SRTR from the lower ($521.2 \times 10^6$ kg s$^{-1}$) and the middle ($195.7 \times 10^6$ kg s$^{-1}$) layers of the southern boundary, while it exports from the middle ($208.1 \times 10^6$ kg s$^{-1}$) of the eastern boundary in summer.

3) The wind field convergence, low pressure system over the SRTR, the impact of the Mongolian high and the WPSH, which bring warm and wet airflows, provide basic conditions for the occurrence of precipitation when converging with the dry and cold air.

4) There is a close spatial–temporal coupling between water vapor flux and precipitation over the SRTR and its...
surrounding areas, with the time series correlation coefficients of the first two modes are 0.96 and 0.92, respectively. The Brahmaputra River basin is the key region of water vapor transport over the SRTR and has a significant impact on the regional precipitation.

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Data availability statement. The station data were downloaded from CNMSC (http://data.cma.cn/), the GPCP and CMAP gridded data were provided by NOAA (https://psl.noaa.gov/data/gridded/tables/precipitation.html), and the ERA5 data were available from ECMWF (https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset).

REFERENCES


