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# Contribution of the Precipitation-Recycling Process to the Wetting Trend in Xinjiang, China

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**Key Points:**

- The mean wet-season precipitation over Xinjiang is mainly contributed by externally advected moisture
- The enhanced precipitation-recycling process dominates the wet-season wetting trend over Xinjiang
- Both increasing evapotranspiration and external-cycle precipitation enhance the precipitation-recycling process

**Supporting Information:**

Supporting Information may be found in the online version of this article.

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**Abstract** Xinjiang, China has experienced a significant wetting trend since the mid-1980s in the context of climate warming. However, the features and mechanism associated with the water cycles in this region remain unclear. In this study, the contributions of the precipitation-recycling process to the wet-season (May-August) wetting trend are investigated using a dynamic recycling model and the Modern Era Retrospective analysis for Research and Application version 2 reanalysis product from 1982 to 2020. The results show that the mean precipitation recycling ratio is 37.91%, implying that Xinjiang precipitation is mainly contributed by external moisture. Moreover, the recycling ratio exhibits a significantly increasing trend of 2.29% per decade, and this increased recycled precipitation contributes 55.55% to the wet-season wetting trend in Xinjiang. The amount of externally advected moisture transported to Xinjiang has also increased in recent decades, accounting for 44.45% of the wetting trend. Further analysis reveals that a deepening anomalous trough over Central Asia accompanied by strengthening moisture inflow through the southwest and south boundaries induce the increased inflow of moisture to Xinjiang, thereby increasing external-cycle precipitation in Xinjiang. Along with the strengthened ascending movement in the lower troposphere, the increasing atmospheric moisture content induced by enhanced evapotranspiration is beneficial for recycling precipitation in Xinjiang. These results imply that both the internal and external water cycles deserve further attention when exploring the wetting phenomenon in Xinjiang.

## 1. Introduction

Xinjiang is located in inner Eurasia and is characterized by a typical mountain-basin system composed of "Three Mountains and Two Basins" (Figure 1). Its unique geographic location and topographic features result in a typical arid and semiarid climate that is highly sensitive to global climate change (Wu et al., 2010; Zhao et al., 2010). From the mid-1980s to 2000, the average annual air temperature increased by 0.7°C compared to that measured from 1961 to the mid-1980s in northwest China (Shi et al., 2006; Yao, Chen, Yu, et al., 2020); this increase is much higher than the global average increase of approximately 0.2°C (Shi et al., 2006; L. Wang et al., 2020). In an interesting phenomenon observed in northwest China, the regional climate changed from warm-dry to warm-wet conditions in the mid-1980s under the background of global warming (B. Li, et al., 2016; Peng & Zhou, 2017; Shi et al., 2006; Wang et al., 2013; Zhang et al., 2012), especially in Xinjiang (Peng & Zhou, 2017). Compared to the 1960s–1970s period, the average annual precipitation during the 1980s–1990s increased by 22%–33% in Xinjiang and by 10%–20% in the west and middle Hexi Corridor (B. Li, et al., 2016; Shi et al., 2006). These precipitation increases are defined as a “wetting phenomenon” in this manuscript. To date, this wetting trend in Xinjiang has attracted widespread attention from the scientific community, but its underlying causes are still unclear.

Water vapor plays an important role in the wetting process (Bretherton et al., 2004; Muller et al., 2009). If we regard the atmosphere over a given area as a box, the water vapor within the box is composed of externally advected moisture and regional evapotranspiration moisture (Brubaker et al., 1993; Burde & Zangvil, 2001a; Trenberth, 1999a). We refer to the precipitation originating from local evapotranspiration as “recycled precipitation” (Brubaker et al., 1993; Burde & Zangvil, 2001a). The precipitation recycling ratio, an important index, is defined as the contribution of recycled precipitation to the total precipitation (Dirmeyer & Brubaker, 2007; Eltahir & Bras, 1996; Kumar & Dominguez, 2008). This index links the land and atmosphere through moisture and energy exchanges (Guo & Wang, 2014; MARengo, 2006). Many studies have proven that the precipitation-recycling process is effective in studies of regional climate and hydrologic processes (Dolman & Bisselink, 2008; Hua et al., 2016; Li & Si, 2018). Thus, obtaining a realistic understanding of the precipitation-recycling process

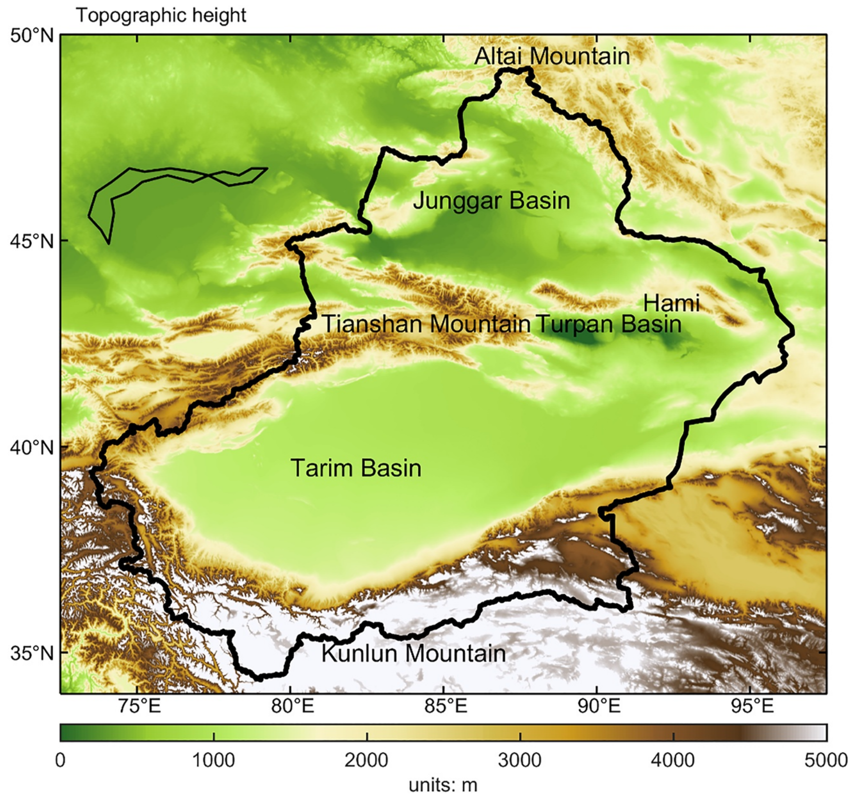


**Figure 1.** Map of the study region. The boundary of Xinjiang is depicted by the thick black outline. The color shading indicates the topographic height.

is crucial for improving our understanding of the wetting mechanism in Xinjiang (Burde & Zangvil, 2001b; Dominguez et al., 2006; Yao, Chen, Yu, et al., 2020).

To date, previous studies have explored the precipitation-recycling process and its associated variables, but many of these works considered the arid and semiarid regions in northwestern China as a whole (B. Li, et al., 2016; Shi et al., 2006; Y. Chen et al., 2019). The western and eastern areas of northwest China are known to be controlled by disparate climatic factors: the former is the core area of the "westerlies-dominated climate regime," while the latter is located in the transition zone between monsoon-dominated and nonmonsoon regions (An et al., 2012; F. Chen et al., 2019; L. Wang et al., 2017). It has been observed that precipitation undergoes an increasing trend in the western area but a decreasing trend in the eastern area (Hua et al., 2016; Wu et al., 2019; Zhang et al., 2019). Further research has indicated that this seesaw tendency is caused by the opposing precipitation trends induced by externally advected moisture between the western and eastern areas (Wu et al., 2019), and the soil moisture-precipitation feedback processes are opposite between the western area (positive feedback) and eastern area (negative feedback) (Hua et al., 2016). In addition, substantial regional differences exist regarding the contributions of evapotranspiration and precipitation to the dryness/wetness characteristics of these areas (S. Wang et al., 2020) and in their evapotranspiration responses to climate warming (Q. Zhang et al., 2018). Thus, it is necessary to investigate the precipitation-recycling process over Xinjiang, in the western area of northwest China, alone.

Recently, several studies investigating the precipitation-recycling process over Xinjiang have been carried out. For example, Yao, Chen, Yu, et al. (2020) revealed that the annual precipitation-recycling ratios derived for Xinjiang were 6.48% and 7.79% when using the Brubaker model and the Schär model, respectively. The regional precipitation-recycling process has been remarkably enhanced since the 1980s (Yao, Chen, Yu, et al., 2020; Zheng et al., 2016). Zhou et al. (2019) explored the sources of moisture in torrential rainfall events in Xinjiang using the flexible particle dispersion model and showed that the contributions of water vapor from Xinjiang and Central Asia were 36.7%, 35.5%, 63.8%, and 14.7% in four subregions of Xinjiang (Altay, Ili Valley, Hami, and Aksu-Kashgar, respectively). Using the stable isotope method, Wang et al. (2016) indicated that the contribution of evapotranspiration to precipitation was approximately 16.2% during summer at the large oases of Urumqi. In conclusion, great uncertainties exist regarding the precipitation-recycling ratios calculated using different methods (the analysis model, Lagrange model, Euler model and isotopic data analyses; Dominguez et al., 2006; Dominguez et al., 2020). Analysis models cannot provide the water vapor sources (Brubaker et al., 1993; Budyko, 1974; Schär et al., 1999). The Lagrange method is largely limited by the complexity of its physical parameterizations and is not applicable in long-term research (Sun & Wang, 2014; Zhou et al., 2019). The Euler method has the disadvantage of model dependency (Numaguti, 1999; Pan et al., 2018). Isotopes analyses are suitable only for short-term and small-scale applications (Wang et al., 2016, 2019). In this study, we use a dynamic recycling model (DRM) constructed using a semi-Lagrangian model that can provide necessary information on water vapor sources and sinks (Dominguez et al., 2006, 2020). More importantly, the utilized model considers changes in the atmospheric water content and can be applied to a range of time scales, from the daily to monthly scales or even longer scales (Dolman & Bisselink, 2008; Dominguez et al., 2006, 2020). Moreover, the DRM can precisely quantify the amounts of moisture contributed by local and remote sources to the total precipitation with a high computational efficiency; thus, it is very suitable for long-term studies on precipitation-recycling processes.

Under the background of current warming and wetting trends, the balance between the internal and external water cycles is significantly affected; therefore, quantitative evaluations of changes in the precipitation-recycling process and its contribution to wetting are needed. Based on the Modern Era Retrospective analysis for Research and Application version 2 (MERRA2; the reason that we choose this reanalysis data set is discussed in the Data section) and the utilized DRM, we aimed to address the following issues in this study: (a) quantify the contributions of local and remote moisture to precipitation in Xinjiang; (b) clarify the long-term changes in the precipitation-recycling process in Xinjiang; and (c) explore the physical mechanism of this process. The rest of the manuscript is organized as follows. Section 2 describes the data and related methodology. In Section 3, we first examine the wet-season precipitation-recycling process and quantify its contribution to the wetting trend; then, we investigate the underlying reasons for the precipitation variations in induced by the internal and external water cycles and present the wet-season water budget over Xinjiang. Section 4 discusses and concludes the results of this study.

## 2. Data and Methods

### 2.1. Data

MERRA2 is a reanalysis data set generated by the National Aeronautics and Space Administration (NASA) Global Modeling and Assimilation Office (GMAO) based on the Goddard Earth Observation System Model version 5 (Gelaro et al., 2017). Previous studies have shown that MERRA2 performs better than other reanalysis datasets when analyzing precipitation and precipitable water in Central Asia and northwestern China (Jiang et al., 2019; Li et al., 2021; Yao, Chen, Zhao, et al., 2020). In this study, observed precipitation and temperature data provided by the China Meteorological Agency (CMA; available online at http://data.cma.cn/) and evapotranspiration data from the Global Evaporation Amsterdam Model (GLEAM; Martens et al., 2017) were used to evaluate the performance of MERRA2 and another widely used reanalysis data set produced by the European Center for Medium-Range Weather Forecasts (ECMWF) Reanalysis product (ERA5; Hersbach et al., 2020) in Xinjiang. Due to the irregular distribution of observation stations, an interpolation process was applied to reduce regional deviations in the area-averaged data. Therefore, we used a gridding method utilizing distance-weighted averaging (Dai et al., 1997; the details of the method can be found in the supplementary materials) to interpolate the station-recorded precipitation and temperature data into gridded data with a resolution of 0.5° × 0.5° (Dai et al., 1997, 2011), and then compared these data with the reanalysis data. As indicated in Figure 2 and Table 1, the correlation coefficients between the observed precipitation and the precipitation reflected in ERA5 and MERRA2 were both greater than 0.70 at the 95% confidence level. However, the climatic mean precipitation value in ERA5 is much larger than that in the observations, and its trend is also opposite to that reflected by the observations. Compared to ERA5, the climatic mean evapotranspiration value in MERRA2 is closer to the observations, and its trend is also consistent with that indicated by the observations. Regarding the air temperature, MERRA2 and ERA5 both performed well, although the mean temperature produced by ERA5 was far below the observed value. Overall, MERRA2 performed better than ERA5 in terms of reflecting climate features and

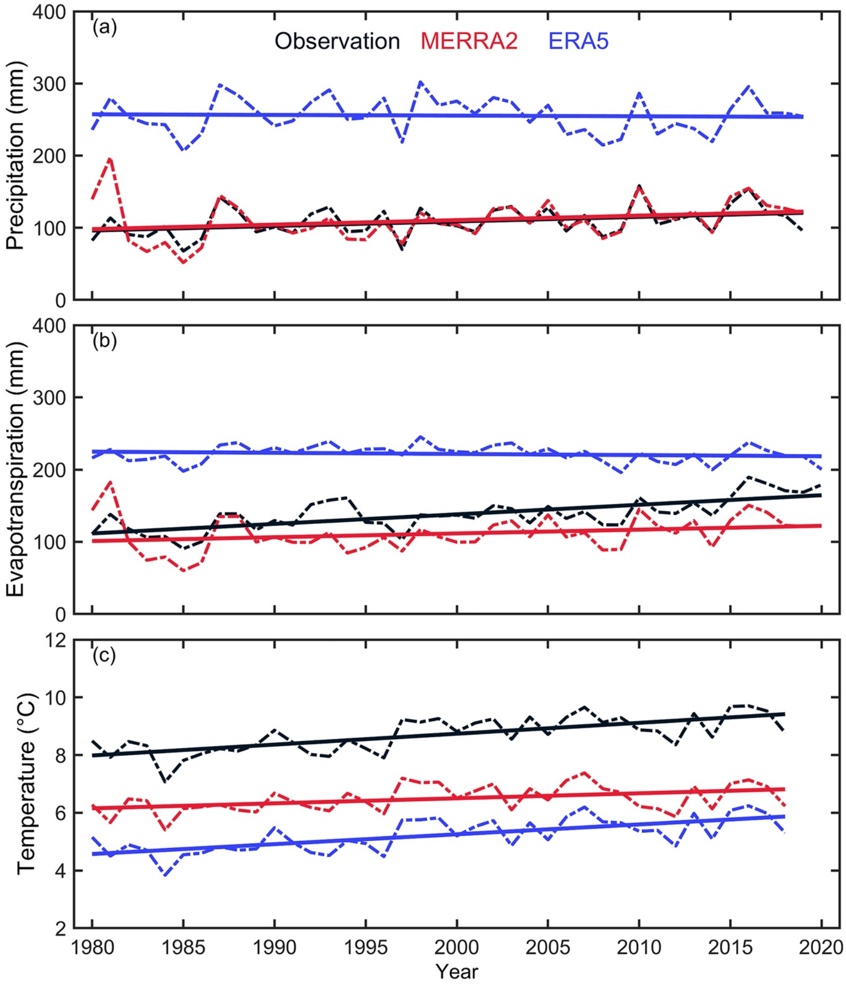


**Figure 2.** (a) Time series of annual precipitation in Xinjiang from 1980 to 2019. Panels (b) and (c) are the same as (a) but for the evapotranspiration and mean temperature series from 1980 to 2020 and from 1980 to 2018, respectively. The solid lines represent the trends.

**Table 1**
*Statistical Values of Some Main Meteorological Variables*

| | | Correlation coefficient | Mean (mm) | Trend (mm $yr^{-1}$) |
|---|---|---|---|---|
| Precipitation | Observation | 1[a] | 108.45[a] | 0.63[a] |
| | MERRA2 | 0.74[a] | 110.31[a] | 0.62[a] |
| | ERA5 | 0.79[a] | 255.53[a] | −0.09 |
| Evapotranspiration | GLEAM | 1[a] | 138.07[a] | 1.32[a] |
| | MERRA2 | 0.62[a] | 111.62[a] | 0.52 |
| | ERA5 | 0.32[a] | 221.64[a] | −0.16 |
| Temperature | Observation | 1[a] | 8.70[a] | 0.04[a] |
| | MERRA2 | 0.89[a] | 6.49[a] | 0.02[a] |
| | ERA5 | 0.98[a] | 5.24[a] | 0.03[a] |

[a]represents that statistical significance exceeds 95% confidence level.

long-term trends in Xinjiang. However, Reichle et al. (2017) mentioned that the first few years of each published MERRA2 stream contain undesirable data due to spin-up effects. Moreover, Ren et al. (2021) also revealed that the 1981 MERRA2 data were abnormal in Central Asia. The Math Works Inc., 2020 was excluded in this work due to the abnormal precipitation and evapotranspiration values over Xinjiang in this year (Figures 2a and 2b).

Therefore, the MERRA2 data set was selected in this study from these reanalysis. The monthly precipitation and temperature data covering the 1982–2020 period from MERRA2 were used to analyze warming and wetting trends. The hourly precipitation, evapotranspiration, precipitable water, and wind field data in MERRA2, at a horizontal resolution of 0.5 × 0.625 and 37 vertical levels, were used to drive the DRM. To further study the mechanisms by which local and remote moisture contribute to the wetting trend over Xinjiang, the monthly geopotential height, wind field, vertically integrated moisture flux, and vertical velocity data from MERRA2 were also assessed.

### 2.2. DRM

The DRM used herein is a quantitative and computationally effective tool to estimate land-atmosphere interaction (Dolman & Bisselink, 2008). It is based on the water vapor balance equation shown in Equation 1, which describes the water vapor changes in the atmosphere (Dolman & Bisselink, 2008; Dominguez et al., 2020):

$$\frac{\partial \mathrm{w}}{\partial \mathrm{t}} = (F_{\mathrm{in}} - F_{\mathrm{out}}) + (E - P) + \mathrm{res} \tag{1}$$

where $w$ is the atmospheric water content; $F_{\mathrm{in}}$ and $F_{\mathrm{out}}$, on the right-hand side of the equation, represent the vertically integrated moisture flux components transported into and out of the study area, respectively, and together reflect the horizontal water vapor flux divergence; $E$ and $P$ represent evapotranspiration and precipitation, reflectively, characterizing water exchanges between the atmosphere and land; and *res* represents the residual term that forces the equation to close and is associated with data assimilation in the reanalysis data set (Dominguez et al., 2006).

In contrast from most recycling models that assume that the atmospheric water content changes only slightly and can be ignored at monthly or longer scales (Brubaker et al., 1993; Schär et al., 1999), the DRM utilized herein takes these changes into account and has the ability to calculate the precipitation-recycling ratio at the daily scale (Dominguez et al., 2006). In addition, the DMR makes the basic assumption that water vapor from different origins is vertically well mixed, implying an equal chance of precipitation formation. Therefore, the ratio of evapotranspiration to advected water vapor in the atmospheric column is equal to the ratio of the recycled precipitation to the precipitation induced by advected moisture (Goessling & Reick, 2011):

$$\frac{P_a}{P_e} = \frac{W_a}{W_e} \quad \text{or} \quad \frac{P_e}{P} = \frac{W_e}{W} \quad \text{or} \quad \frac{P_a}{P} = \frac{W_a}{W} \tag{2}$$

where the subscripts $a$ and $e$ represent the advected and recycled constituents, respectively.

In each grid cell, the precipitation recycling ratio $\rho_i$ is defined as the ratio of precipitation derived from evapotranspiration within the study region ($P_{e_i}$) to the total precipitation in the cell ($P_i$), as shown in Equation 3.

$$\rho_i = \frac{P_{e_i}}{P_i} \tag{3}$$

Under the well-mixed assumption (Equation 2), using the definition of the precipitation-recycling ratio (Equation 3) and the water vapor balance equation (Equation 1), we can rewrite the equation in grid $i$ as follows:

$$\frac{\partial \rho_i}{\partial t} + \vec{V} \cdot \nabla \rho_i = \frac{E(1 - \rho_i)}{w} \tag{4}$$

where $\vec{V}$ is the moisture velocity deduced from the average wind velocity of each layer weighted by the specific humidity.

To solve the above equation for $\rho_i$, we introduce a Lagrangian coordinate system and integrate Equation 4 along the backward moisture trajectory, resulting in the local recycling ratio $\rho_i(s)$ over grid cell $i$ at time $t$ being expressed as follows:

$$\rho_i(s) = 1 - \exp\left[-\oint_{s_0}^{s} E/w\right] ds \tag{5}$$

where $s$ represents the moving trail of the moisture particle, indicating the path linking the moisture source and sink, and $s_0$ is the starting point of the moisture particle. Moreover, we can obtain the regional precipitation-recycling ratio $R$ in any given area as follows (Eltahir & Bras, 1994; Hua et al., 2016):

$$R = \frac{P_e}{P} = \frac{\sum_{i=1}^{n} \rho_i P_i \Delta A_i}{\sum_{i=1}^{n} P_i \Delta A_i} \tag{6}$$

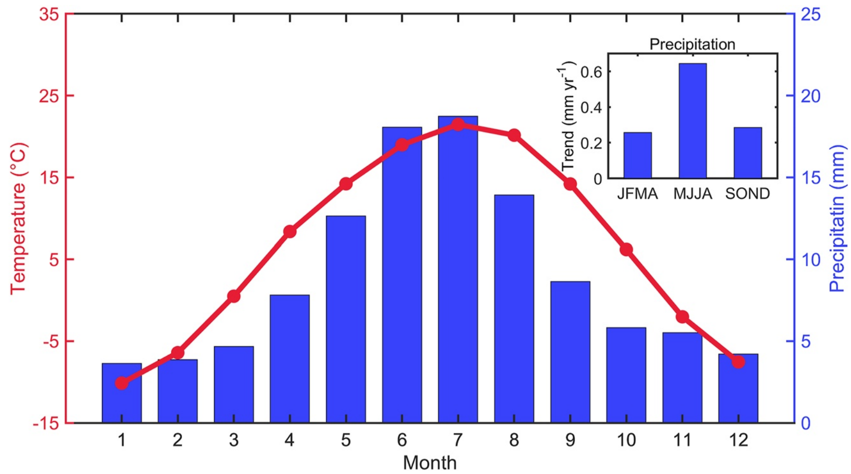


**Figure 3.** Monthly climatology of temperature (lines) and precipitation (bars) during the 1982–2020 period. The top-right corner represents the long-term precipitation trends in January-February-March-April (JFMA), May-June-July-August (MJJA), and September-October-November-December (SOND).

where $\Delta A_i$ represents the area of grid cell $i$ and $P_e$ and $P$ are the recycled precipitation and total precipitation over the whole study area, respectively.

The DRM used herein is a single-layer model that cannot provide tracks on each layer and is thus unsuitable for areas with large vertical wind shear, such as tropical regions. However, as westerly circulation dominates in Xinjiang, the vertical wind shear is relatively small (Dominguez et al., 2020). Therefore, the DRM is suitable for use in this region. In addition, the DRM represents a significant improvement over other models because it considers moisture storage changes and uses a Lagrangian trajectory tracking method, which is crucial for obtaining an accurate and reliable recycling ratio. More details about the DRM can be found in the paper of Dominguez et al. (2006).

## 3. Results

### 3.1. Warming and Wetting Trends in Xinjiang

As shown in Figure 3, precipitation mainly fell in Xinjiang from May to August during the study period, accounting for 58.89% of annual precipitation. Moreover, the growing precipitation trend during May–August, at 6.44 mm decade$^{-1}$, was obviously larger than that in other seasons and contributed 54.31% to the increasing annual precipitation trend. Moreover, May–August is the warmest season, with the largest precipitation amounts and largest increasing trend. Therefore, we mainly focus on the wet season (May–August) when investigating the precipitation-recycling process over Xinjiang in this study.

Figure 4 depicts the spatiotemporal precipitation and temperature distributions in the wet season during the 1982–2020 period. The results reveal that precipitation decreased from northwest to southeast in Xinjiang, with high center located around the Tianshan Mountains with a value of more than 250 mm. In recent decades, precipitation exhibited a significantly increasing trend in almost all of Xinjiang except the Hami region (Figure 4b). In particular, precipitation in the western and middle Tianshan Mountains experienced the strongest increases. However, the spatial distributions of the temperature climatology and linear trends disagree with those of precipitation (Figures 4a–4e). The temperature distribution was characterized by cold temperatures in mountainous areas and warm temperatures in basins, and significant increasing trends were observed in most areas of Xinjiang except in southwestern Xinjiang. Notably, the Hami region experienced the strongest warming trend, which may have been related to the decreased local precipitation. Thus, Xinjiang has suffered from a wetting trend at a rate of 6.44 mm decade$^{-1}$ and from a warming trend at a rate of 0.14°C decade$^{-1}$ (Figures 4c and 4f). The following research was designed to comprehensively explore the contribution of the precipitation-recycling process to this wetting trend in Xinjiang.

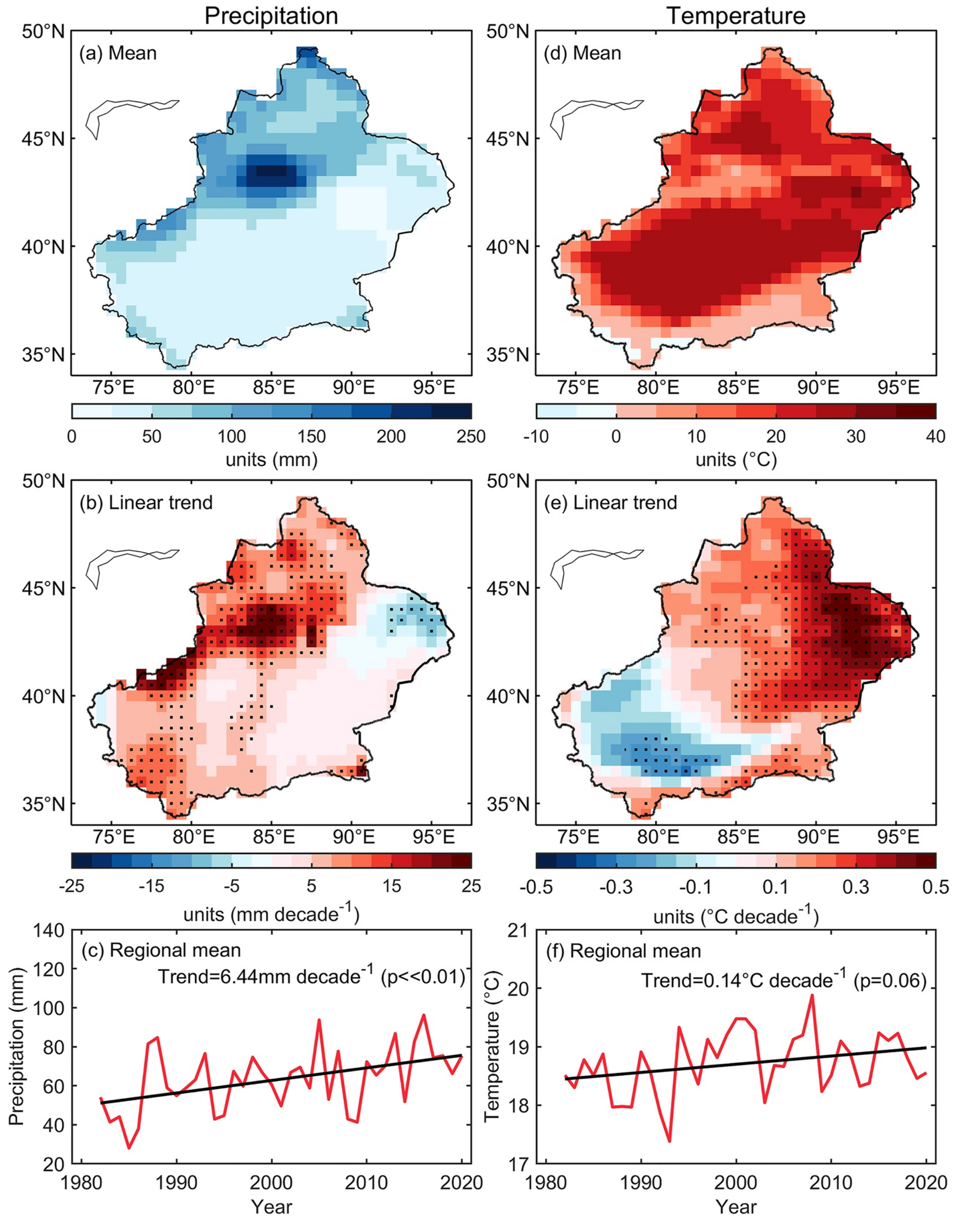


**Figure 4.** Spatial distributions of the (a) climatology and (b) linear trend of precipitation in the wet season from 1982 to 2020 in Xinjiang. (c) Time series of the regional mean precipitation in Xinjiang in the wet season from 1982 to 2020. Panels (d–f) are the same as (a–c) but for the temperature. The black dots indicate statistical significance exceeding the 95% confidence level.

### 3.2. Contribution of the Precipitation-Recycling Process to Xinjiang Wetting

Figure 5 demonstrates the spatiotemporal variations in the wet-season precipitation-recycling ratio during the 1982–2020 period. Generally, the precipitation-recycling ratio increased from west to east in almost all of Xinjiang, apart from Hami and its adjacent areas, where the ratio increased from east to west. The highest recycling ratio was observed in the middle of the Tianshan Mountains, with a value of more than 60%. The Turpan

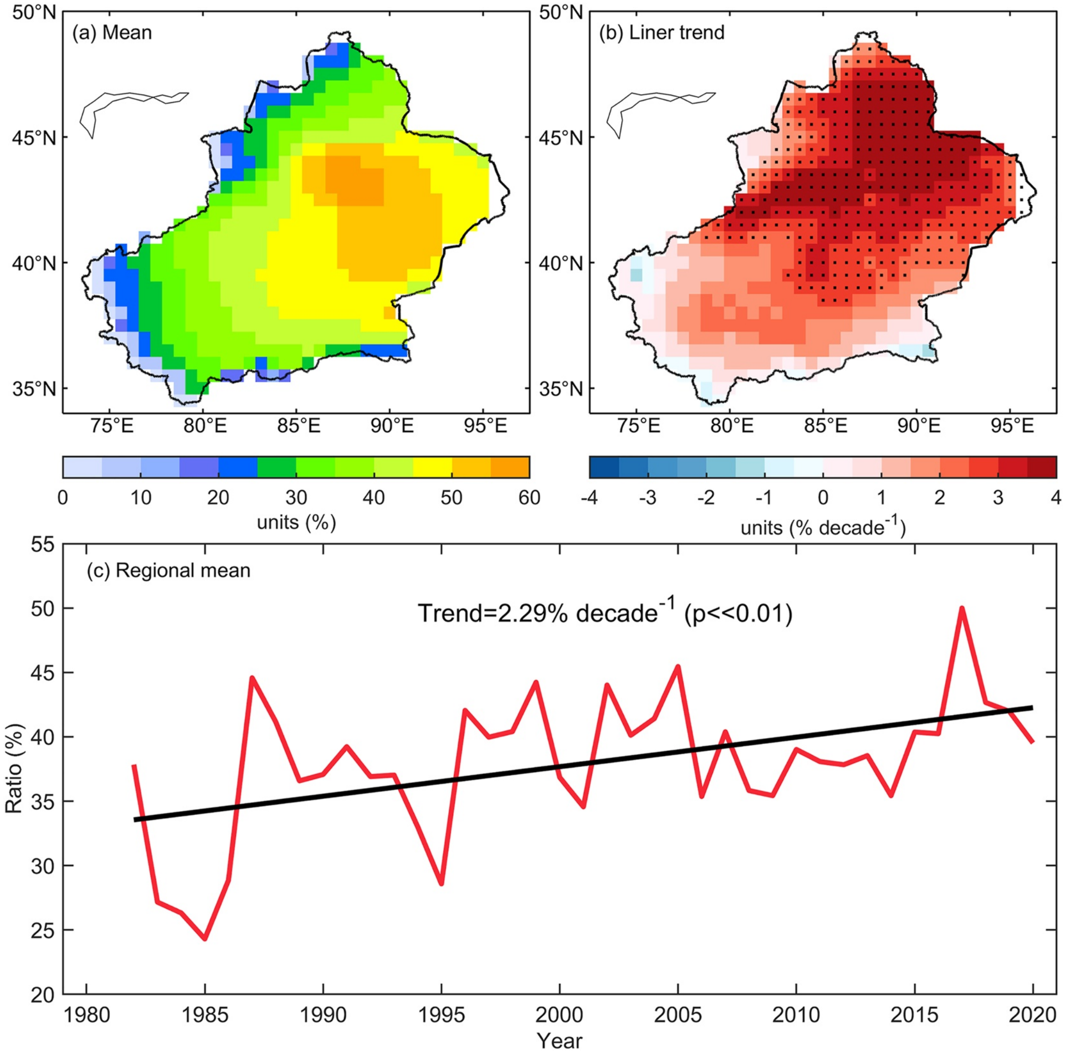


**Figure 5.** Distributions of the (a) climatology and (b) linear trend of the precipitation-recycling ratio in the wet season from 1982 to 2020 in Xinjiang. (c) Time series of the regional mean precipitation-recycling ratio in Xinjiang in the wet season from 1982 to 2020. The black dots indicate statistical significance exceeding the 95% confidence level.

Basin had the second-highest ratio with a value greater than 50% (Figure 5a). Previous studies have revealed that such a precipitation-recycling ratio pattern may be connected with the transport of moisture influenced by atmospheric circulation (Yao et al., 2021; Zhang et al., 2019). The water vapor advected by the prevailing westerlies in the mid-latitude region contributes to the west-to-east growth of the recycling ratio in Xinjiang (Yao et al., 2021; Zhang et al., 2019). The East Asian monsoon is responsible for the recycling ratio pattern in eastern Xinjiang due to the transport of moisture from the northwest Pacific Ocean and the South China Sea along the northeast edge of the Tibetan Plateau (Chen et al., 2021; Zhou et al., 2019). The climatic mean regional precipitation-recycling ratio in Xinjiang was found to be 37.91% in the wet season, indicating that the amount of precipitation in Xinjiang is mainly contributed by the externally advected water vapor rather than by internal water vapor. Regarding the change trend, it is worth noting that the precipitation-recycling ratio shows an increasing trend over almost all of Xinjiang, especially in the northern region (Figure 5b). The reasons for this phenomenon may be related to the increasing water vapor transported by external advection in southern Xinjiang and the enhanced evapotranspiration in northern Xinjiang (this process is explained in detail in Sections 3.3 and 3.4). In addition, the regional precipitation-recycling ratio increased with a trend of 2.29% decade$^{-1}$, implying that the contribution of the recycling process to precipitation increased during the wet season throughout these decades in Xinjiang.

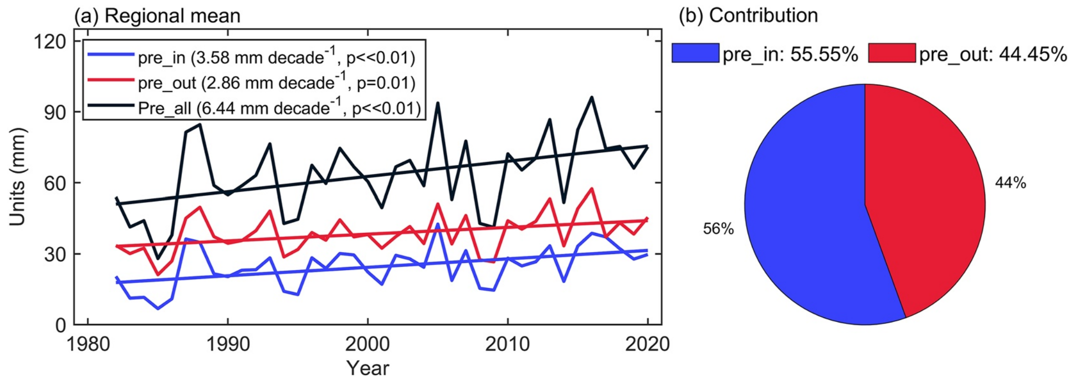


**Figure 6.** (a) Time series of the total precipitation (black line) and precipitation associated with the external (red line) and internal (blue line) cycles in the wet season from 1982 to 2020 in Xinjiang. (b) Pie chart representing the contributions of linear precipitation trends associated with the external and internal cycles to the total precipitation trend.

Furthermore, we explored the separate contributions of the internal and external water cycles to the total precipitation trend. As shown in Figure 6, the precipitation patterns induced by the internal and external water cycles both showed increasing trends, with rates of 3.58 mm decade$^{-1}$ and 2.86 mm decade$^{-1}$, respectively (Figure 6a). By our estimate, the increasing trend of total precipitation in Xinjiang is mainly contributed by recycled precipitation, with a contribution of 55.55% (Figure 6b); this contribution is larger than that of the precipitation induced by externally advected moisture (44.45%). These results are similar to those of Peng and Zhou (2017), who determined that more than 50% of the wetting trend was balanced by increased evapotranspiration by dividing the contributing factors to increasing precipitation into evapotranspiration and the dynamic component of wind convergence in summer over northwest China. Therefore, to explore the causes of the increasing precipitation related to the internal and external water cycles, we explored the underlying mechanisms in Section 3.3 and Section 3.4.

### 3.3. Mechanism of Increasing Precipitation Produced by External Moisture

Figure 7 presents the climatology of the vertically integrated water vapor flux in the wet season during the 1982–2020 period. The climate of Xinjiang is dominated by westerly circulation, and the water vapor in this region is supplied mainly by the midlatitude westerlies in the wet season (F. Chen et al., 2019; Huang, Feng, et al., 2015; Zhang et al., 2019). Additionally, the frequent heavy rainfall events in Xinjiang are mainly caused by anomalous water vapor from Eurasia, the North Atlantic (Huang et al., 2017; Zhou et al., 2019), and the Indian Ocean (Huang, Feng, et al., 2015). This moisture transported by the westerlies into Xinjiang mainly through the northwest and southwest boundaries (Figure 7c). Due to the blocking effect of the large Pamir Plateau at the southwest edge of the study area, the water vapor flux through the southwest boundary ($1.65 \times 10^7$ kg s$^{-1}$) is obviously smaller than that through the northwest boundary ($7.28 \times 10^7$ kg s$^{-1}$). The eastern boundary is the main channel by which water vapor outflows. In addition, a slight moisture outflow can also be observed at the south boundary, and this outflow mildly contributes to the northern-boundary inflow on the Tibetan Plateau (Zhao & Zhou, 2021). Xinjiang is estimated to be a moisture sink in the wet season, with a climatic moisture inflow of approximately $8.20 \times 10^6$ kg s$^{-1}$.

The water vapor flux time series derived at the four boundaries are shown in Figure 8. Obviously, the southwest and south boundary series exhibit increasing trends (Figures 8a and 8b), especially at south boundary where transported water vapor is transformed from outflow to inflow (this trend is significant at the 0.05 level). This change is consistent with the water vapor transport variations recorded at the northern edge of the Tibetan Plateau (He et al., 2021) and may be influenced by the weakened South Asian monsoon and strengthened Plateau monsoon (Dong et al., 2017; Xun et al., 2012; Zhao et al., 2019). In contrast, the water vapor flux measured at the northwest boundary presents a nonsignificant decreasing trend due to recovery in the early 21st century (Figure 8c). This decreasing trend may be related to the weakening of the westerlies and is explained in detail below. The water vapor flux at the east boundary shows obvious interdecadal variations without any significant

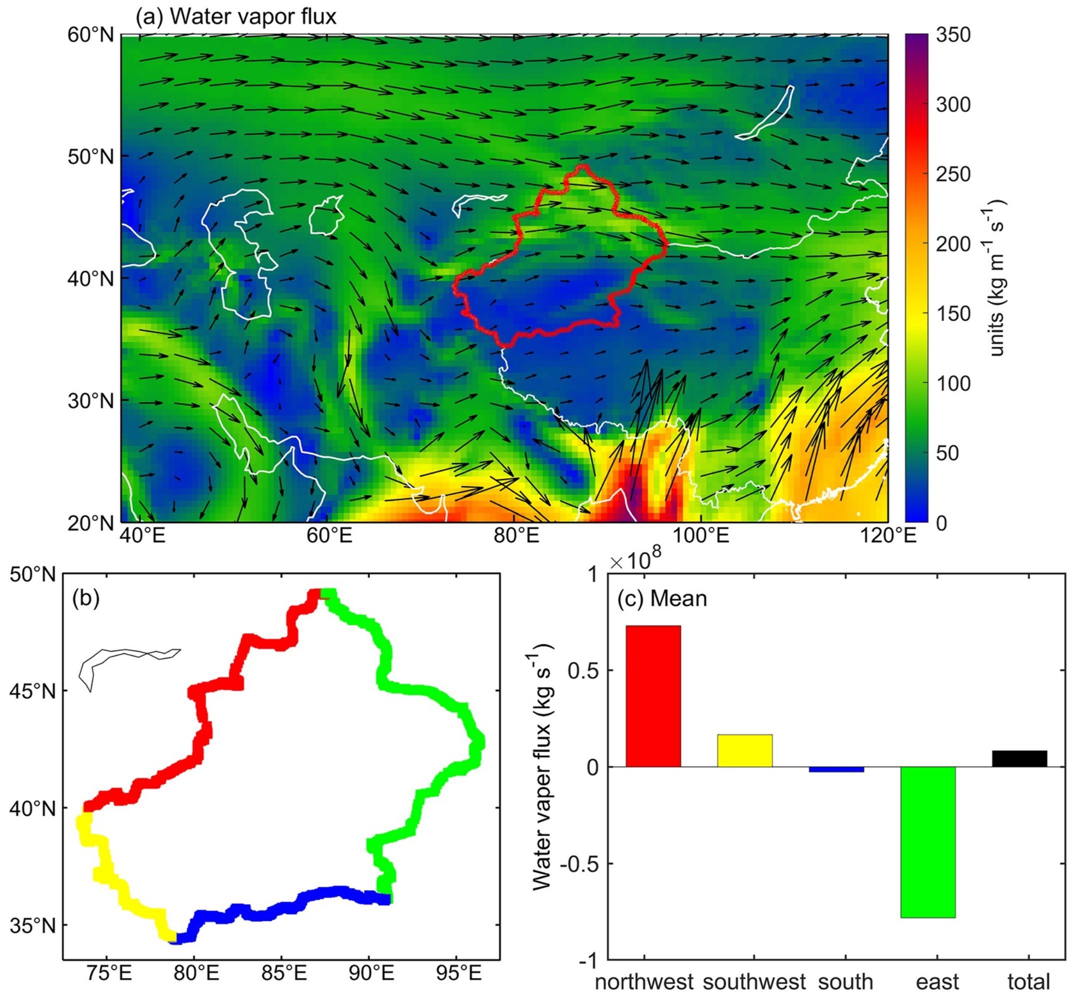


**Figure 7.** (a) Climatology of the vertically integrated water vapor flux (vector) and its magnitude (shading) in the wet season from 1982 to 2020. (b) Xinjiang area defined with four edges, with the northwest, southwest, south, and east boundaries denoted in red, yellow, blue and green, respectively. (c) Climatology of the water vapor fluxes at the four boundaries and in all of Xinjiang. Positive (negative) values indicate inflowing (outflowing) water vapor.

trend (Figure 8d). Thus, together, these fluxes result in a significant increase in the net water vapor inflow to Xinjiang in the wet season, with a trend of $1.82 \times 10^5$ kg s$^{-1}$ yr$^{-1}$. This increased horizontal net water vapor inflow induces the growth of precipitable water, which is beneficial for the formation of increased precipitation caused by the external water cycle.

To explore the reasons for the moisture transport changes observed at the four boundaries, the meridional and zonal wind variations were investigated (Figure 9). Figures 9a–9d demonstrates the spatial climatology distribution and linear zonal wind trends in the wet season. Strong westerlies in the high- and middle-troposphere prevail in Xinjiang. In recent decades, significant weakening of these winds has occurred from the Mediterranean Sea to Balkhash Lake. These weakened westerlies have contributed to the observed decreasing trend of advected water vapor at the northwest boundary of Xinjiang. Conversely, the zonal wind component strengthens from the Iranian Plateau to the Pamir Plateau, and this strengthening is beneficial for the inflow of water vapor at the southwest edge of Xinjiang. The climatology and linear meridional wind trend are displayed in Figures 9e–9h. The results reveal that wind shear occurs between Central Asia and Xinjiang (Figures 9e and 9g). Southerlies prevail in Xinjiang and its southern regions and are responsible for the transport of advected water vapor from the Tibetan Plateau and Arabian Sea to Xinjiang through the south and southwest channels. Yan et al. (2020) noted that the summertime atmospheric water vapor content over the Tibetan Plateau and its southwestern region

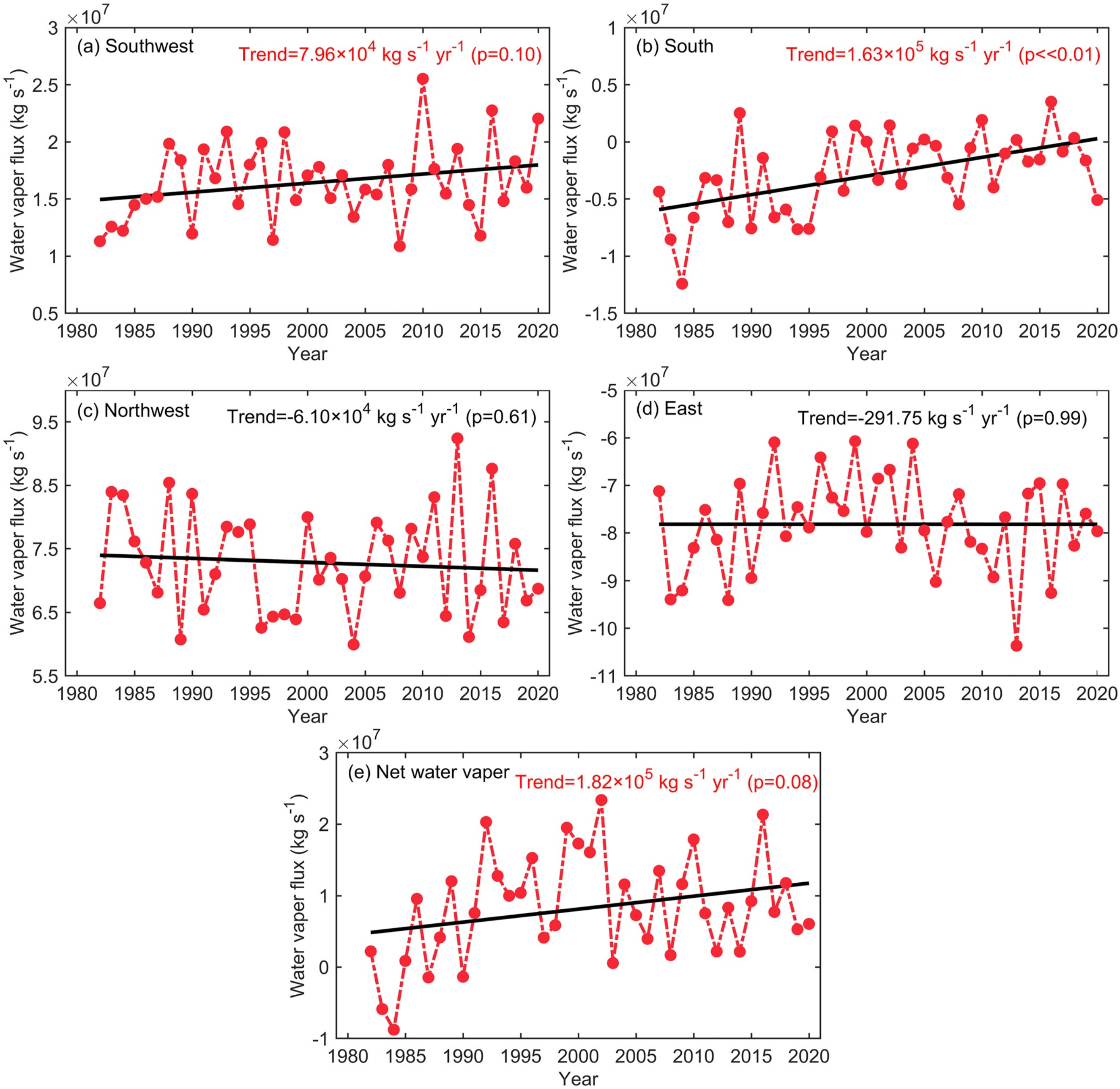


**Figure 8.** Time series of water vapor fluxes at the (a) southwest, (b) south, (c) northwest, (d) east boundaries of the study area and (e) the net water vapor flux in all of Xinjiang in the wet season from 1982 to 2020. Positive (negative) values indicate inflowing (outflowing) water vapor. The black lines indicate the linear trend.

increased significantly over the last 40 years. Thus, the enhanced southerlies (Figures 9f and 9h) can transport more water vapor to the southwest and south boundaries of Xinjiang. Moreover, the strengthening of the south and north winds on both sides of the shear line enhance the cyclonic shear, and this is also conducive to precipitation formation in Xinjiang. The possible cause of the weakening westerlies is the effect of Arctic amplification (Coumou et al., 2018; Liu et al., 2019), and the enhancing southerlies are likely related to northward extension of the surface subtropical high (Archer & Caldeira, 2008; Molnos et al., 2017; Zhang & Zhou, 2015).

To seek the underlying mechanism of the increasing precipitation in Xinjiang, we further explored the geopotential height changes at 200 hPa and 500 hPa in the wet season during the 1982–2020 period (Figure 10). Due to atmospheric inflation induced by global warming, the geopotential height has exhibited a rising trend over the

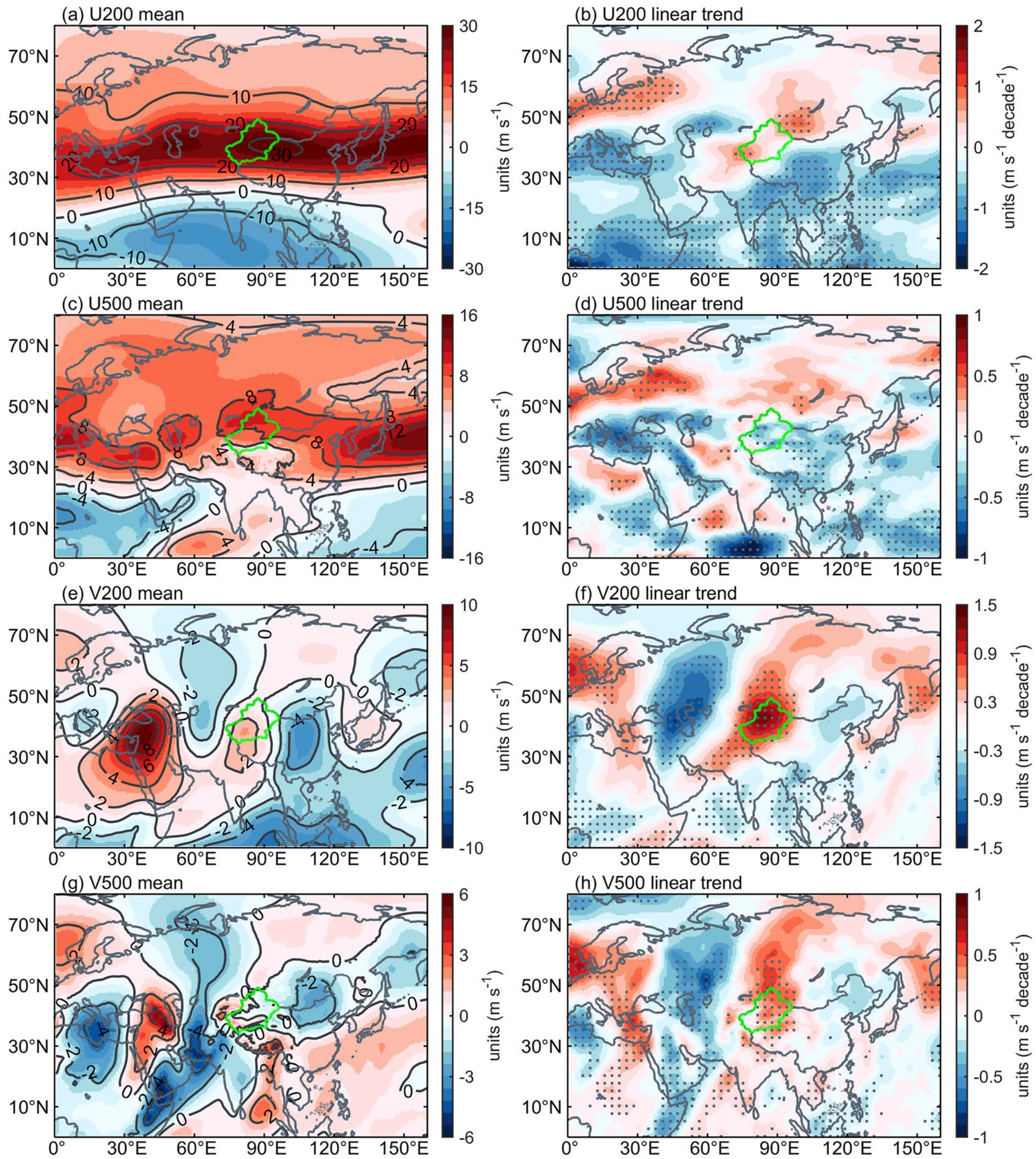


**Figure 9.** Spatial distributions of the (a) climatology and (b) linear trend of the horizontal zonal wind at 200 hPa. Panels (c and d), (e and f), and (g and h) are the same as (a and b) but for the zonal wind at 500 hPa, the meridional wind at 200 hPa, and the meridional wind at 500 hPa, respectively. The black dots indicate statistical significance exceeding the 95% confidence level. The boundary of Xinjiang is depicted by the thick green outline.

entire Northern Hemisphere. We excluded this overall increasing trend by subtracting the zonal average geopotential height. The results indicated that the rising trend is nonuniform and features a zonal wave pattern in the mid-latitude region. This zonal wave pattern is well projected onto the Silk Road pattern (Chowdary et al., 2019), and approximately 50% of these trends are explained by the inter-decadal variations of the Silk Road pattern (Hong & Lu, 2016; P. Wang et al., 2017). The highest anomaly centers were found in Europe and Mongolia, and a relatively weaker center was observed over Central Asia. Influenced by such an anomalous circulation pattern, an abnormal low-pressure trough has developed in Central Asia in the past few decades, and this trough is conducive to the increased precipitation observed in Xinjiang.

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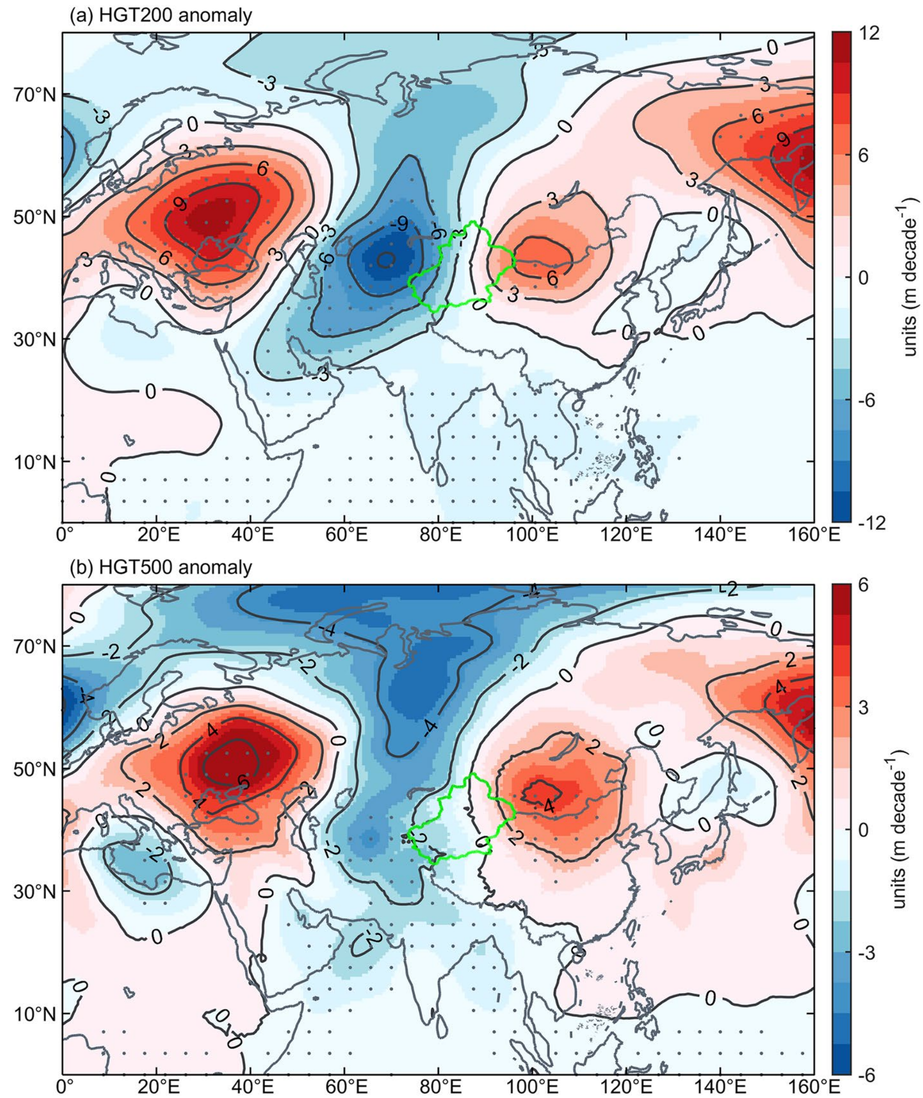


**Figure 10.** Spatial distributions of the anomalous linear trends of the geopotential heights at (a) 200 hPa and (b) 500 hPa in the wet season from 1982 to 2020. The black dots indicate statistical significance exceeding the 90% confidence level. The boundary of Xinjiang is depicted by the thick green outline.

### 3.4. Mechanism of Increasing Precipitation Produced by Internal Moisture

Figure 11 depicts the distributions of the wet-season evapotranspiration climatology and liner trends during the 1982–2020 period in the study area. The results show similar climatology and trends between evapotranspiration and precipitation. The regional mean evapotranspiration in Xinjiang shows a significant increasing trend of 6.06 mm decade$^{-1}$. This increased evapotranspiration causes the specific humidity to increase in the lower troposphere, a crucial source of precipitable water that has a direct effect on increased light precipitation (Song et al., 2017). Moreover, increased evapotranspiration could raise the convective available potential energy, thereby generating increased convective clouds and precipitation (Yao, Chen, Yu, et al., 2020). In addition, water and energy factors jointly affect evapotranspiration, and the former is a major factor affecting evapotranspiration in arid and semiarid areas (Budyko, 1974; Gudmundsson et al., 2016; Lu et al., 2016). Yao et al. (2016) pointed out that evapotranspiration is mainly determined by precipitation rather than potential evapotranspiration in arid and semiarid northwest China. Thus, we calculated the correlation coefficient between wet-season evapotranspiration and precipitation over Xinjiang during the 1982–2020 period (Figure S1 in Supporting Information S1) and found that a positive correlation exists between evapotranspiration and precipitation over all of Xinjiang; and

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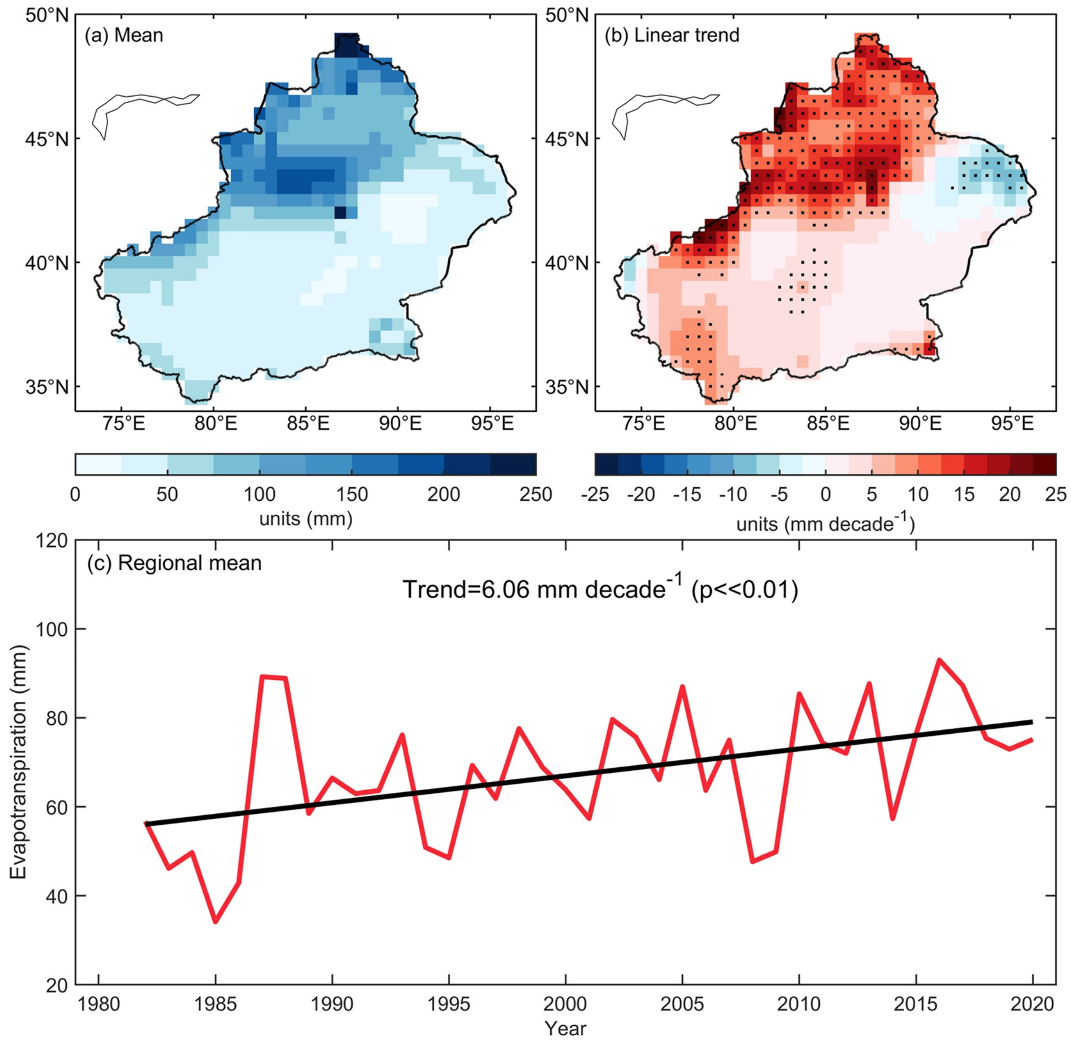


**Figure 11.** Spatial distributions of the (a) climatology and (b) linear trend of evapotranspiration in the wet season from 1982 to 2020 in Xinjiang. (c) Time series of the regional mean evapotranspiration in Xinjiang in the wet season from 1982 to 2020. The black dots indicate statistical significance exceeding the 95% confidence level.

the correlation coefficient between the regional mean evapotranspiration and precipitation time series in Xinjiang reached 0.95 at the 99% confidence level.

In addition to increased precipitation, we explored other causes of this evapotranspiration increase. Underlying surface variations probably also account for this increased evapotranspiration. Seasonal snowmelt from mountains is also critical for the water supply in Xinjiang (Chen et al., 2016), and the increasing meltwater induced by increasing cold-season snowfall and warming has led to increased river runoff, which positively affects evapotranspiration (Bai et al., 2018; Huang & Wen, 2013; Sun et al., 2021; Tao et al., 2011; W. Wang et al., 2020). Oases, as vital components of arid ecosystems, support more than 95% of the population in Xinjiang but cover only 5% of the land area (Jia et al., 2004; Xue et al., 2019). Irrigation farming has developed rapidly over the past century in these oases and this resulted in increased soil moisture, thereby likely resulting in increased surface evapotranspiration (Zhao et al., 2012). In addition, the vegetation greening observed in northwestern China in recent decades also likely contributes to enhanced evapotranspiration by increasing transpiration (Yao et al., 2019; Z. Li, et al., 2016).

Vertical motion is an important dynamic factor that affects precipitation (Rose & Lin, 2003). Figure 12 demonstrates the latitude-pressure vertical cross section of the wet-season climatology and linear vertical velocity

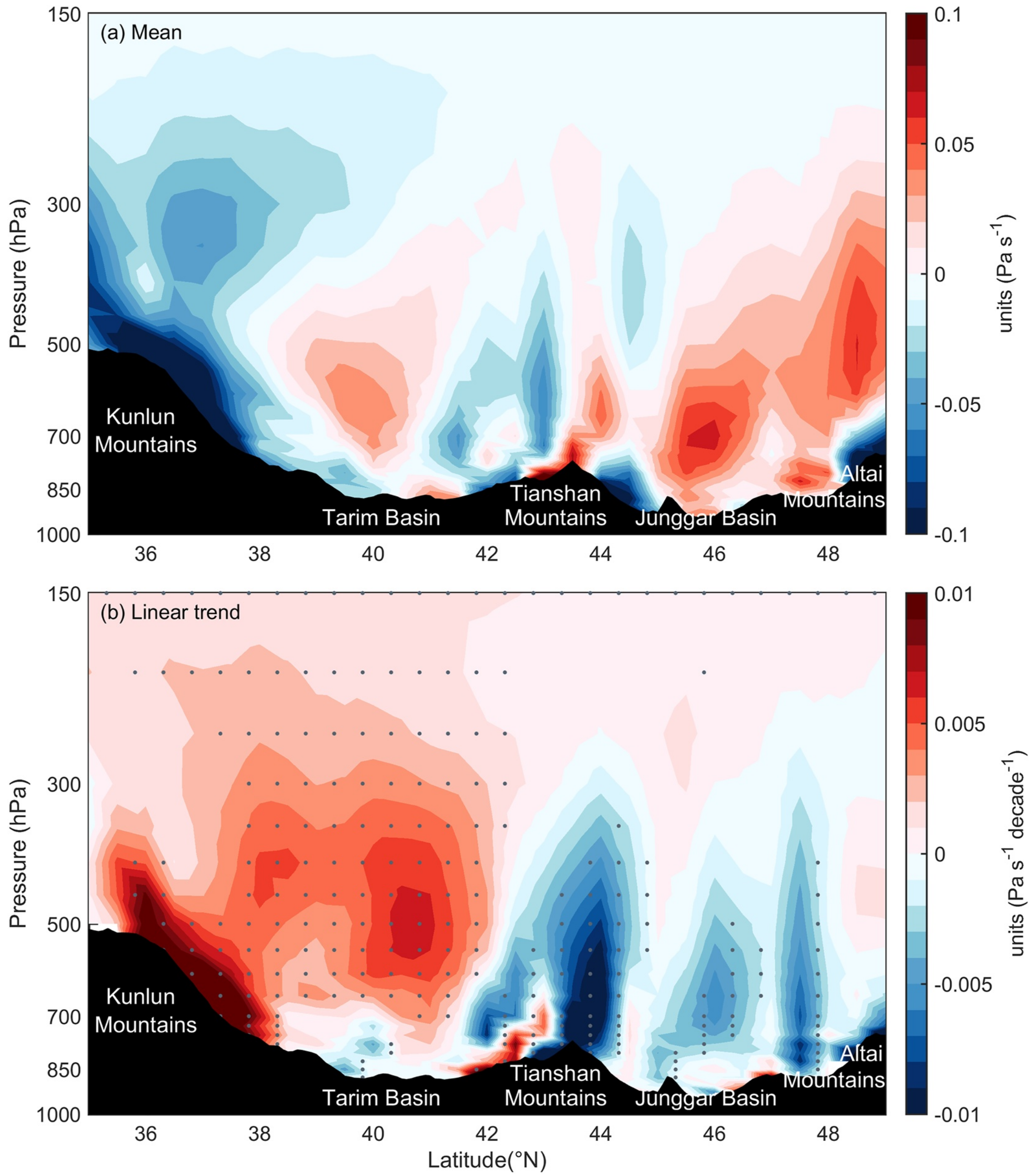


**Figure 12.** Latitude-pressure vertical cross section of the (a) climatology and (b) linear trend of vertical velocity averaged between 70°E and 100°E in Xinjiang in the wet season from 1982 to 2020. The black dots indicate statistical significance exceeding the 95% confidence level.

trends during the 1982–2020 period. The results reveal that the vertical velocity features ascending movement in mountainous areas (from south to north: the Kunlun Mountains, Tianshan Mountains, and Altai Mountains) and descending movement in basin areas (from south to north: the Tarim Basin and Junggar Basin), thus forming two meridional secondary circulation patterns in South Xinjiang and North Xinjiang (Figure 12a). In the lower and middle troposphere, we noticed an increasing ascending motion trend above the Tianshan Mountains, North Xinjiang and the oases at the foothills of the Kunlun Mountains (Figure 12b). In addition, regional mean vertical motion was significantly enhanced in the lower troposphere (Figure S2 in Supporting Information S1). Previous studies have indicated that both the tropopause and the boundary layer exhibit obvious increases and that the increasing height of the boundary layer is related to the extent of surface warming (Lin et al., 2017; Lorenz & DeWeaver, 2007; Meng et al., 2021). Furthermore, Zhao et al. (2012) indicated that the increased soil moisture

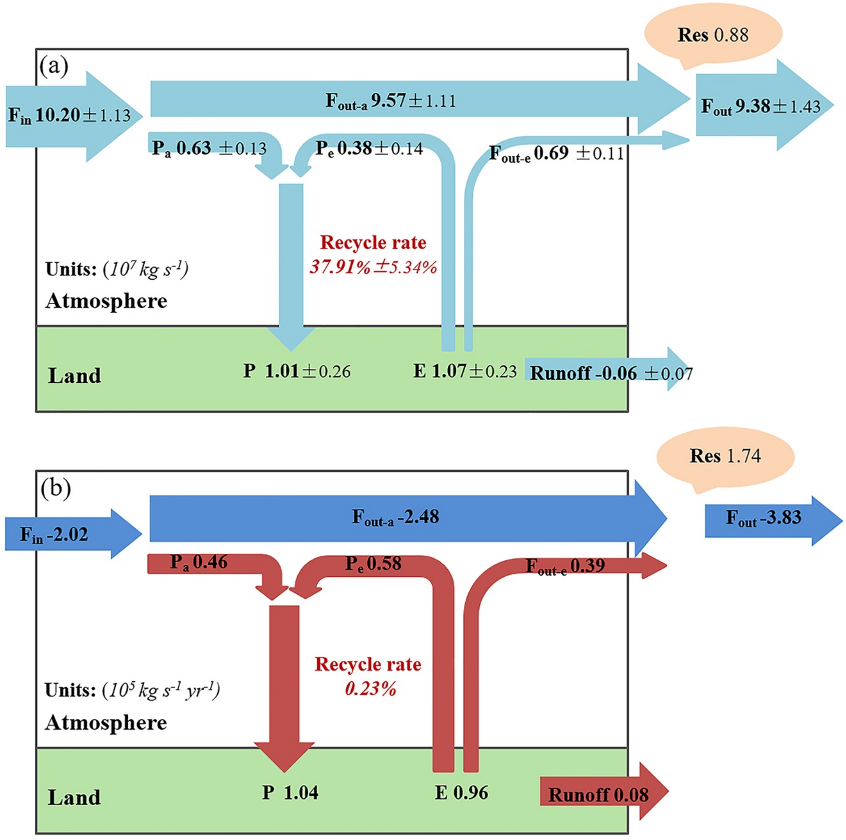


**Figure 13.** Schematic diagram of the atmospheric water cycle in the wet season in Xinjiang: the (a) climatology and (b) linear trend during the 1982–2020 period. *P* and *E* are precipitation and evapotranspiration, respectively. $F_{in}$ and $F_{out}$ represent the horizontal moisture into the region and out of the region, respectively. $P_a$ is the precipitation produced by external water vapor. $P_e$ is the precipitation produced by internal water vapor. $F_{out\text{-}e}$ is the outflowing water vapor contributed by regional evapotranspiration. $F_{out\text{-}a}$ is the outflowing water vapor contributed by a part of the horizontal moisture inflowing into the region. *Runoff* is the difference between precipitation and evapotranspiration. *Res* represents the residual term, which is mainly induced by the data assimilation methods in the Modern Era Retrospective analysis for Research and Application version 2 reanalysis data set.

resulted in increased evapotranspiration and surface cooling, followed by asymmetrical surface warming, which altered the regional wind fields and enhanced the ascending motion in the low troposphere.

### 3.5. Water Budget in Xinjiang

Using the DRM and Equation 1, the climatological patterns and trends of the wet-season atmospheric water cycles over Xinjiang during the 1982–2020 period were estimated, as indicated in Figure 13. In the local atmospheric moisture pattern over Xinjiang, water vapor can only be exchanged with the outside environment through advection transport ($F_{in}$ and $F_{out}$) or vertical transport from the ground (*P* and *E*). The precipitation climatology was $1.01 \times 10^7$ kg s$^{-1}$, consisting of two components, one of which was induced by evapotranspiration ($P_e$, $0.38 \times 10^7$ kg s$^{-1}$) and the other of which was produced by advected moisture ($P_a$, $0.63 \times 10^7$ kg s$^{-1}$). This finding indicates that the total precipitation is dominated by externally advected moisture at a contribution rate of 62.1%. The total external moisture inflow into Xinjiang was found to be $10.20 \times 10^7$ kg s$^{-1}$ ($F_{in}$), and the vast majority of this moisture flowed out of Xinjiang ($F_{out\text{-}a}$, $9.57 \times 10^7$ kg s$^{-1}$), while only a small portion was transformed into precipitation over Xinjiang ($P_a$). The total evapotranspiration over Xinjiang was $1.07 \times 10^7$ kg s$^{-1}$, and more than half of this evapotranspired moisture was transported out of Xinjiang ($F_{out\text{-}e}$, $0.69 \times 10^7$ kg s$^{-1}$). The total water vapor which was transported out of Xinjiang was $9.38 \times 10^7$ kg s$^{-1}$. A residual term exists in the atmospheric water cycling process, and the nonclosure of the water cycle was mainly induced by the data assimilation methods in the reanalysis data set (Dominguez et al., 2006; Reichle et al., 2017).

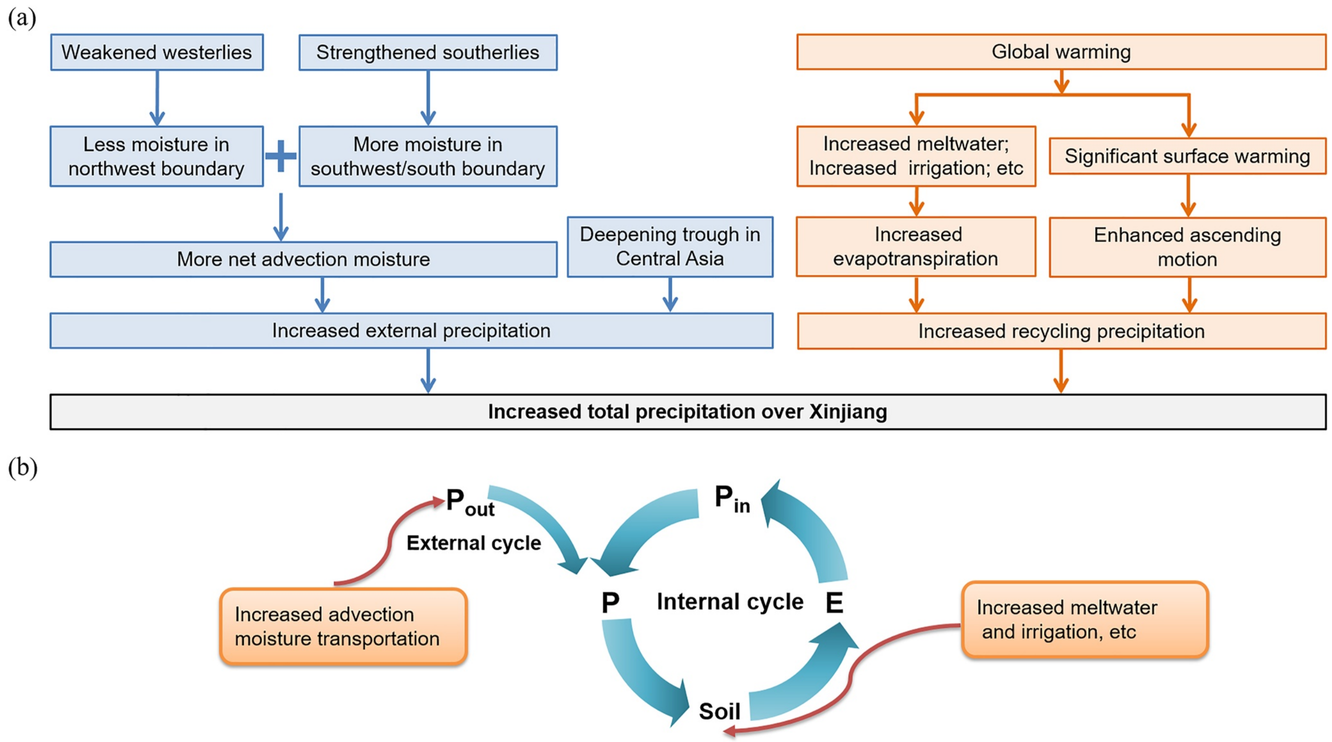


**Figure 14.** (a) Conceptual framework of the atmospheric water cycle changes observed during the last few decades in Xinjiang. (b) Schematic illustration of the relationship between the internal and external water cycles over Xinjiang.

The terms ($F_{in}$, $F_{out}$, and $F_{out\text{-}a}$) associated with advected moisture showed decreasing trends, indicating that horizontal moisture movement has decelerated. This deceleration of horizontal water vapor transport is related to the weakening of westerlies caused by altered atmospheric circulations (Figures 8 and 9). Moreover, as the atmosphere warms, the water-holding capacity of the atmosphere is enhanced and atmospheric circulation weakens; thus, water can remain in the atmosphere longer (Trenberth, 1999b; Trenberth, 2011). This process may be closely related to the deceleration of moisture advection (Dee et al., 2018; Ma et al., 2012; Pendergrass & Gerber, 2016) and needs to be further verified. However, the analyzed terms ($P$, $E$, $P_e$, $P_a$, and $F_{out\text{-}e}$) exhibit ascending trends, indicating that the water exchanges between the atmosphere and land have been enhanced. As shown in Figures 10 and 12, dynamic conditions become more favorable for the formation of precipitation from advection and evapotranspiration moisture in Xinjiang. Moreover, a positive feedback effect was found between precipitation and evapotranspiration (Figure 14b). Increasing precipitation led to increasing soil moisture, which enhanced evapotranspiration and further induced increased precipitation. In addition, the increasing precipitation trend was larger than that of evapotranspiration, thus allowing the soil moisture and surface runoff to be recharged in the wet season and further contributing to wetting in Xinjiang.

## 4. Conclusions and Discussions

From 1982 to 2020, Xinjiang experienced a wetting trend with 6.4 mm decade$^{-1}$ in the wet season. In this study, the contributions of the precipitation-recycling process to this wetting trend were investigated using a DRM and the MERRA2 reanalysis product. The results show that the precipitation-recycling process contributed approximately 40% to wet-season precipitation climatology in Xinjiang, while externally advected moisture accounted for 60%. This finding implies that the mean precipitation is dominated by externally advected moisture rather than by internal evapotranspiration. It is worth noting that the precipitation-recycling ratio has increased with a trend of 2.29% decade$^{-1}$ in recent decades, and the recycled precipitation has accounted for 55.55% of the total precipitation increase recorded in Xinjiang, thus exceeds the precipitation contribution produced by externally advected moisture (44.45%).

In the wet season, Xinjiang is a moisture sink. In recent decades, weakening zonal winds have led to a decreasing trend of advected inflowing water at the northwest edge of the study area, while strengthening meridional winds caused more moisture to inflow at the southwest and south edges (Figure 14a). As a whole, the net water vapor budget in Xinjiang increased significantly throughout the study period. In addition, an abnormal low-pressure trough developed in Central Asia over the last few decades. All these circumstances are conducive to increased external-cycle precipitation (Figure 14a).

The increasing contribution of recycled precipitation can mainly be attributed to evapotranspiration, which was observed in this work to be significantly enhanced, with a trend of 6.06 mm decade$^{-1}$. The increasing atmospheric water contents caused by enhanced evapotranspiration directly affect precipitation and may improve the convective available potential energy, thereby favoring convective movement conducive to increased cloud cover and precipitation. In turn, precipitation is the most important factor affecting evapotranspiration, and a positive feedback effect exists between them (Figure 14b). Apart from precipitation, variations in the underlying surface, such as increasing meltwater and irrigation, have also likely contributed to enhanced evapotranspiration. In summary, the increased precipitation caused by both the increased net transport of advected moisture and increased evapotranspiration enhanced the precipitation-recycling process over Xinjiang in the wet season in the context of global warming (Figure 14b).

In this study, we quantitatively revealed the separate contributions of local and remote moisture to the wetting trend in Xinjiang while acknowledging that the results are focused mainly on the direct reasons responsible for the precipitation-recycling process changes. The profound drivers of the enhanced recycling process and whether the wetting phenomenon is a long-term trend or a multidecadal change are unclear. Previous studies have indicated that human activities and global warming are important drivers of water cycles in meltwater-dominated regions (Barnett et al., 2005; Liu et al., 2017). The increased meltwater from glaciers and snow, increased runoff and increased irrigation-based agriculture have accelerated the water cycles and increased precipitation in Xinjiang (Liu et al., 2017; Shen et al., 2020; Shi et al., 2006).

On the other hand, previous studies have indicated that Xinjiang precipitation is influenced by the Silk Road pattern (SRP), the Atlantic Multidecadal Oscillation (AMO), El Niño-Southern Oscillation (ENSO), Indian Summer Monsoon (ISM), and East Asian Summer Monsoon (EASM), etc. (Lu et al., 2019; Zhou et al., 2014). J. Zhang et al. (2018) indicated that the enhancement of Eurasian forced waves, such as the Eurasian teleconnection pattern and Silk Road pattern, are closely related to the consecutive dry days in Xinjiang. Moreover, the AMO may modulate the interdecadal variations in the Silk Road pattern (Huang, Chen, et al., 2015; Jiang et al., 2021) and subsequently alter the westerly jet and Xinjiang precipitation (Hong et al., 2017; Jiang et al., 2021; Tan & Shao, 2017; Tao et al., 2021; Wang et al., 2021). The ENSO may affect precipitation in Xinjiang by inducing the extension and movement of the South Asia High and the subtropical jet and causing a low-pressure anomaly to form over Central Asia (Apurv et al., 2019; Chang et al., 2018; Chen et al., 2018; Hu et al., 2017; Lu et al., 2019). In addition, the ISM and EASM also play important roles in the wetting trend over Xinjiang (Chang et al., 2018; Zhong et al., 2017). The Silk Road pattern and anomalous ISM jointly influence precipitation in Xinjiang (Huang, Chen, et al., 2015). The weakened EASM, alongside the westward extension of the western Pacific subtropical high and abnormal Mongolian anti-cyclonic activities, promotes increased water moisture transport from the Indian Ocean and the Pacific to Xinjiang (B. Li, et al., 2016; Chen et al., 2020, 2021). Both human activities and natural factors may affect the wetting phenomenon observed in Xinjiang; therefore, further studies are needed to quantify the contributions of these factors to the observed precipitation changes.

## Data Availability Statement

MERRA2 reanalysis data are available from https://disc.gsfc.nasa.gov/datasets?project=MERRA-2. ERA5 reanalysis data are available from https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=form. GLEAM evapotranspiration data are available from the GLEAM homepage: https://www.gleam.eu/. The observed precipitation and temperature data provided by the China Meteorological Agency: http://data.cma.cn/data/cdcdetail/dataCode/A.0012.0001.html. Figures in this manuscript were made with MATLAB version 2020a and this software is available from www.mathworks.com/ (The Math Works, Inc., 2020).

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## References

An, Z., Colman, S., & Zhou, W. (2012). Interplay between the Westerlies and Asian monsoon recorded in Lake Qinghai sediments since 32 ka. *Scientific Reports*, *2*, 619. https://doi.org/10.1038/srep00619

Apurv, T., Xu, Y. P., Wang, Z., & Cai, X. (2019). Multidecadal changes in meteorological drought severity and their drivers in mainland China. *Journal of Geophysical Research: Atmospheres*, *124*(23), 12937–12952. https://doi.org/10.1029/2019jd031317

Archer, C. L., & Caldeira, K. (2008). Historical trends in the jet streams. *Geophysical Research Letters*, *35*(8). https://doi.org/10.1029/2008GL033614

Bai, J., Li, J., Shi, H., Liu, T., & Zhong, R. (2018). Snowmelt water alters the regime of runoff in the arid region of northwest China. *Water*, *10*(7), 902. https://doi.org/10.3390/w10070902

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, *438*(7066), 303–309. https://doi.org/10.1038/nature04141

Bretherton, C. S., Peters, M. E., & Back, L. E. (2004). Relationships between water vapor path and precipitation over the tropical oceans. *Journal of Climate*, *17*(7), 1517–1528. https://doi.org/10.1175/1520-0442(2004)017<1517:rbwvpa>2.0.co;2

Brubaker, K. L., Entekhabi, D., & Eagleson, P. S. (1993). Estimation of continental precipitation recycling. *Journal of Climate*, *6*(6), 1077–1089. https://doi.org/10.1175/1520-0442(1993)006<1077:eocpr>2.0.co;2

Budyko, M. I. (1974). *Climate and life*. Academic press.

Burde, G. I., & Zangvil, A. (2001a). The estimation of regional precipitation recycling. Part I: Review of recycling models. *Journal of Climate*, *14*(12), 2497–2508. https://doi.org/10.1175/1520-0442(2001)014<2497:teorpr>2.0.co;2

Burde, G. I., & Zangvil, A. (2001b). The estimation of regional precipitation recycling. Part II: A new recycling model. *Journal of Climate*, *14*(12), 2509–2527. https://doi.org/10.1175/1520-0442(2001)014<2509:teorpr>2.0.co;2

Chang, X., Wang, B., Yan, Y., Hao, Y., & Zhang, M. (2018). Characterizing effects of monsoons and climate teleconnections on precipitation in China using wavelet coherence and global coherence. *Climate Dynamics*, *52*(9–10), 5213–5228. https://doi.org/10.1007/s00382-018-4439-1

Chen, C., Zhang, X., Lu, H., Jin, L., Du, Y., & Chen, F. (2020). Increasing summer precipitation in arid Central Asia linked to the weakening of the East Asian summer monsoon in the recent decades. *International Journal of Climatology*, *41*(2), 1024–1038. https://doi.org/10.1002/joc.6727

Chen, F., Chen, J., & Huang, W. (2021). Weakened East Asian summer monsoon triggers increased precipitation in Northwest China. *Science China Earth Sciences*, *64*(5), 835–837. https://doi.org/10.1007/s11430-020-9731-7

Chen, F., Chen, J., Huang, W., Chen, S., Huang, X., Jin, L., et al. (2019). Westerlies Asia and monsoonal Asia: Spatiotemporal differences in climate change and possible mechanisms on decadal to sub-orbital timescales. *Earth-Science Reviews*, *192*, 337–354. https://doi.org/10.1016/j.earscirev.2019.03.005

Chen, X., Wang, S., Hu, Z., Zhou, Q., & Hu, Q. (2018). Spatiotemporal characteristics of seasonal precipitation and their relationships with ENSO in Central Asia during 1901–2013. *Journal of Geographical Sciences*, *28*(9), 1341–1368. https://doi.org/10.1007/s11442-018-1529-2

Chen, Y., Li, B., Fan, Y., Sun, C., & Fang, G. (2019). Hydrological and water cycle processes of inland river basins in the arid region of Northwest China. *Journal of Arid Land*, *11*(2), 161–179. https://doi.org/10.1007/s40333-019-0050-5

Chen, Y., Li, W., Deng, H., Fang, G., & Li, Z. (2016). Changes in central Asia's water tower: Past, present and future. *Scientific Reports*, *6*, 35458. https://doi.org/10.1038/srep35458

Chowdary, J. S., Hu, K., Srinivas, G., Kosaka, Y., Wang, L., & Rao, K.(2019). The Eurasian jet streams as conduits for east Asian monsoon variability. *Current Climate Change Reports*, *5*(3), 233–244. https://doi.org/10.1007/s40641-019-00134-x

Coumou, D., Di Capua, G., Vavrus, S., Wang, L., & Wang, S. (2018). The influence of Arctic amplification on mid-latitude summer circulation. *Nature Communications*, *9*(1), 2959. https://doi.org/10.1038/s41467-018-05256-8

Dai, A., Fung, I. Y., & Del Genio, A. D. (1997). Surface observed global land precipitation variations during 1900–88. *Journal of Climate*, *10*, 2943–2962. https://doi.org/10.1175/1520-0442(1997)010<2943:soglpv>2.0.co;2

Dai, A. G., Wang, J. H., Thorne, P. W., Parker, D. E., Haimberger, L., & Wang, X. L. L. (2011). A new approach to homogenize daily radiosonde humidity data. *Journal of Climate*, *24*, 965–991. https://doi.org/10.1175/2010JCLI3816.1

Dee, S. G., Nusbaumer, J., Bailey, A., Russell, J. M., Lee, J.-E., Konecky, B., et al. (2018). Tracking the strength of the Walker circulation with stable isotopes in water vapor. *Journal of Geophysical Research: Atmospheres*, *123*(14), 7254–7270. https://doi.org/10.1029/2017jd027915

Dirmeyer, P. A., & Brubaker, K. L. (2007). Characterization of the global hydrologic cycle from a back-trajectory analysis of atmospheric water vapor. *Journal of Hydrometeorology*, *8*(1), 20–37. https://doi.org/10.1175/jhm557.1

Dolman, A. J., & Bisselink, B. (2008). Precipitation recycling: Moisture sources over Europe using ERA-40 data. *Journal of Hydrometeorology*, *9*(5), 1073–1083. https://doi.org/10.1175/2008JHM962.1

Dominguez, F., Hu, H., & Martinez, J. A. (2020). Two-layer dynamic recycling model (2L-DRM): Learning from moisture tracking models of different complexity. *Journal of Hydrometeorology*, *21*(1), 3–16. https://doi.org/10.1175/jhm-d-19-0101.1

Dominguez, F., Kumar, P., Liang, X. Z., & Ting, M. (2006). Impact of atmospheric moisture storage on precipitation recycling. *Journal of Climate*, *19*(8), 1513–1530. https://doi.org/10.1175/jcli3691.1

Dong, W., Lin, Y., Wright, J. S., Xie, Y., Xu, F., Xu, W., et al. (2017). Indian monsoon low-pressure systems feed up-and-over moisture transport to the southwestern Tibetan plateau. *Journal of Geophysical Research: Atmospheres*, *122*(22), 12140–12151. https://doi.org/10.1002/2017jd027296

Eltahir, E. A. B., & Bras, R. L. (1994). Precipitation recycling in the Amazon basin. *Quarterly Journal of the Royal Meteorological Society*, *120*(518), 861–880. https://doi.org/10.1002/qj.49712051806

Eltahir, E. A. B., & Bras, R. L. (1996). Precipitation recycling. *Reviews of Geophysics*, *34*(3), 367–378. https://doi.org/10.1029/96rg01927

Gelaro, R., McCarty, W., Suarez, M. J., Todling, R., Molod, A., Takacs, L., et al. (2017). The modern-Era Retrospective analysis for research and applications, version 2 (MERRA-2). Journal of Climate, *30*(13), 5419–5454. https://doi.org/10.1175/jcli-d-16-0758.1

Goessling, H. F., & Reick, C. H. (2011). What do moisture recycling estimates tell us? Exploring the extreme case of non-evaporating continents. *Hydrology and Earth System Sciences*, *15*(10), 3217–3235. https://doi.org/10.5194/hess-15-3217-2011

Gudmundsson, L., Greve, P., & Seneviratne, S. I. (2016). The sensitivity of water availability to changes in the aridity index and other factors-A probabilistic analysis in the Budyko space. *Geophysical Research Letters*, *43*(13), 6985–6994. https://doi.org/10.1002/2016gl069763

Guo, Y., & Wang, C. (2014). Trends in precipitation recycling over the Qinghai–Xizang Plateau in last decades. *Journal of Hydrology*, *517*, 826–835. https://doi.org/10.1016/j.jhydrol.2014.06.006

He, Y., Tian, W., Huang, J., Wang, G., Ren, Y., Yan, H., et al. (2021). The mechanism of increasing summer water vapor over the Tibetan plateau. *Journal of Geophysical Research: Atmospheres*, *126*(10). https://doi.org/10.1029/2020jd034166

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horanyi, A., Munoz-sabater, L., et al. (2020). The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hong, X., & Lu, R. (2016). The meridional displacement of the summer Asian jet, silk road pattern, and tropical SST anomalies. *Journal of Climate*, *29*(10), 3753–3766. https://doi.org/10.1175/JCLI-D-15-0541.1

Hong, X., Lu, R., & Li, S. (2017). Amplified summer warming in Europe–West Asia and Northeast Asia after the mid-1990s. *Environmental Research Letters*, *12*(9). https://doi.org/10.1088/1748-9326/aa7909

Hu, Z., Zhou, Q., Chen, X., Cheng, Q., Wang, S., & Li, J. (2017). Variations and changes of annual precipitation in Central Asia over the last century. *International Journal of Climatology*, *37*, 157–170. https://doi.org/10.1002/joc.4988

Hua, L., Zhong, L., & Ke, Z. (2016). Precipitation recycling and soil-precipitation interaction across the arid and semi-arid regions of China. *International Journal of Climatology*, *36*(11), 3708–3722. https://doi.org/10.1002/joc.4586

Huang, G., & Wen, G. (2013). Spatial and temporal variations of light rain events over China and the mid-high latitudes of the Northern Hemisphere. *Chinese Science Bulletin*, *58*(12), 1402–1411. https://doi.org/10.1007/s11434-012-5593-1

Huang, W., Chang, S. Q., Xie, C. L., & Zhang, Z. P. (2017). Moisture sources of extreme summer precipitation events in North Xinjiang and their relationship with atmospheric circulation. *Advances in Climate Change Research*, *8*(1), 12–17. https://doi.org/10.1016/j.accre.2017.02.001

Huang, W., Chen, J., Zhang, X., Feng, S., & Chen, F. (2015). Definition of the core zone of the "westerlies-dominated climatic regime", and its controlling factors during the instrumental period. *Science China Earth Sciences*, *58*(5), 676–684. https://doi.org/10.1007/s11430-015-5057-y

Huang, W., Feng, S., Chen, J., & Chen, F. (2015). Physical mechanisms of summer precipitation variations in the Tarim Basin in northwestern China. *Journal of Climate*, *28*(9), 3579–3591. https://doi.org/10.1175/jcli-d-14-00395.1

Jia, B., Zhang, Z., Ci, L., Ren, Y., Pan, B., & Zhang, Z. (2004). Oasis land-use dynamics and its influence on the oasis environment in Xinjiang, China. *Journal of Arid Environments*, *56*(1), 11–26. https://doi.org/10.1016/s0140-1963(03)00002-8

Jiang, J., Zhou, T., Chen, X., & Wu, B. (2021). Central Asian precipitation shaped by the tropical Pacific decadal variability and the Atlantic multidecadal variability. *Journal of Climate*, *34*(18), 7541–7553. https://doi.org/10.1175/jcli-d-20-0905.1

Jiang, J., Zhou, T., & Zhang, W. (2019). Evaluation of satellite and reanalysis precipitable water vapor data sets against radiosonde observations in central Asia. *Earth and Space Science*, *6*(7), 1129–1148. https://doi.org/10.1029/2019ea000654

Kumar, P., & Dominguez, F. (2008). Precipitation recycling variability and Ecoclimatological stability—a study using NARR data. Part I: Central U.S. Plains Ecoregion. *Journal of Climate*, *21*(20), 5165–5186. https://doi.org/10.1175/2008JCLI1756.1

Li, B., Chen, Y., Chen, Z., Xiong, H., & Lian, L. (2016). Why does precipitation in northwest China show a significant increasing trend from 1960 to 2010? *Atmospheric Research*, *167*, 275–284. https://doi.org/10.1016/j.atmosres.2015.08.017

Li, C., Zhao, T., Shi, C., & Liu, Z. (2021). Assessment of precipitation from the CRA40 dataset and new generation reanalysis datasets in the global domain. *International Journal of Climatology*, *41*(11), 5243–5263. https://doi.org/10.1002/joc.7127

Li, J., & Si, R. (2018). Spatiotemporal distribution of precipitation recycling across the arid regions of Asia and Africa. *Journal of Geoscience and Environment Protection*, *06*(09), 195–206. https://doi.org/10.4236/gep.2018.69015

Li, Z., Chen, Y., Wang, Y., & Fang, G. (2016). Dynamic changes in terrestrial net primary production and their effects on evapotranspiration. *Hydrology and Earth System Sciences*, *20*(6), 2169–2178. https://doi.org/10.5194/hess-20-2169-2016

Lin, P., Paynter, D., Ming, Y., & Ramaswamy, V. (2017). Changes of the tropical tropopause layer under global warming. *Journal of Climate*, *30*(4), 1245–1258. https://doi.org/10.1175/jcli-d-16-0457.1

Liu, J., Wu, D., Liu, G., Mao, R., Chen, S., Ji, M., et al. (2019). Impact of Arctic amplification on declining spring dust events in East Asia. *Climate Dynamics*, *54*(3–4), 1913–1935. https://doi.org/10.1007/s00382-019-05094-4

Liu, S., Ding, Y., Shangguan, D., Zhang, Y., Li, J., Han, H., et al. (2017). Glacier retreat as a result of climate warming and increased precipitation in the Tarim river basin, northwest China. *Annals of Glaciology*, *43*, 91–96. https://doi.org/10.3189/172756406781812168

Lorenz, D. J., & DeWeaver, E. T. (2007). Tropopause height and zonal wind response to global warming in the IPCC scenario integrations. *Journal of Geophysical Research*, *112*(D10). https://doi.org/10.1029/2006jd008087

Lu, B., Li, H., Wu, J., Zhang, T., Liu, J., Bao, L., et al. (2019). Impact of El Niño and southern oscillation on the summer precipitation over northwest China. *Atmospheric Science Letters*, *20*(8). https://doi.org/10.1002/asl.928

Lu, R. Y., Oh, J. H., & Kim, B. J. (2016). A teleconnection pattern in upper-level meridional wind over the North African and Eurasian continent in summer. *Tellus A: Dynamic Meteorology and Oceanography*, *54*(1), 44–55. https://doi.org/10.3402/tellusa.v54i1.12122

Ma, J., Xie, S. P., & Kosaka, Y. (2012). Mechanisms for tropical tropospheric circulation change in response to global warming. *Journal of Climate*, *25*(8), 2979–2994. https://doi.org/10.1175/jcli-d-11-00048.1

MARengo, J. A. (2006). On the hydrological cycle of the Amazon basin: A historical review and current state-of-the-art. *Revista brasileira de meteorologia*, *21*(3), 1–19. Retrieved from https://clivar.org/sites/default/files/documents/vamos/LBA002-2006_JAMarengo.pdf

Martens, B., Miralles, D. G., Lievens, H., Schalie, R., De Jeu, R. A. M., Fernández-Prieto, D., et al. (2017). GLEAMv3: Satellite-based land evaporation and root-zone soil moisture. Geoscientific Model Development, *10*(5), 1903–1925. https://doi.org/10.5194/gmd-10-1903-2017

Meng, L., Liu, J., Tarasick, D. W., Randel, W. J., Steiner, A. K., Wilhelmsen, H., et al. (2021). Continuous rise of the tropopause in the northern hemisphere over 1980-2020. *Science Advances*, *7*(45), eabi8065. https://doi.org/10.1126/sciadv.abi8065

Molnos, S., Mamdouh, T., Petri, S., Nocke, T., Weinkauf, T., & Coumou, D. (2017). A network-based detection scheme for the jet stream core. *Earth System Dynamics*, *8*(1), 75–89. https://doi.org/10.5194/esd-8-75-2017

Muller, C. J., Back, L. E., O'Gorman, P. A., & Emanuel, K. A. (2009). A model for the relationship between tropical precipitation and column water vapor. *Geophysical Research Letters*, *36*(16). https://doi.org/10.1029/2009gl039667

Numaguti, A. (1999). Origin and recycling processes of precipitating water over the Eurasian continent: Experiments using an atmospheric general circulation model. *Journal of Geophysical Research*, *104*(D2), 1957–1972. https://doi.org/10.1029/1998jd200026

Pan, C., Zhu, B., Gao, J., Kang, H., & Zhu, T. (2018). Quantitative identification of moisture sources over the Tibetan Plateau and the relationship between thermal forcing and moisture transport. *Climate Dynamics*, *52*(1–2), 181–196. https://doi.org/10.1007/s00382-018-4130-6

Pendergrass, A. G., & Gerber, E. P. (2016). The rain is askew: Two idealized models relating vertical velocity and precipitation distributions in a warming world. *Journal of Climate*, *29*(18), 6445–6462. https://doi.org/10.1175/JCLI-D-16-0097.1

Peng, D., & Zhou, T. (2017). Why was the arid and semiarid northwest China getting wetter in the recent decades? *Journal of Geophysical Research: Atmospheres*, *122*(17), 9060–9075. https://doi.org/10.1002/2016jd026424

Reichle, R. H., Liu, Q., Koster, R. D., Draper, C. S., Mahanama, S. P. P., & Partyka, G. S. (2017). Land surface precipitation in MERRA-2. *Journal of Climate*, *30*(5), 1643–1664. https://doi.org/10.1175/jcli-d-16-0570.1

Ren, Y., Yu, H., LIu, C., He, Y., Huang, J., Zhang, L., et al. (2021). Attribution of dry and wet climatic changes over Central Asia. *Journal of Climate*, *35*(5), 1399–1421. https://doi.org/10.1175/JCLI-D-21-0329.1

Rose, B. E. J., & Lin, C. A. (2003). Precipitation from vertical motion: A statistical diagnostic scheme. *International Journal of Climatology*, *23*(8), 903–919. https://doi.org/10.1002/joc.919

Schär, C., Lüthi, D., Beyerle, U., & Heise, E. (1999). The soil–precipitation feedback: A process study with a regional climate model. *Journal of Climate*, *12*(3), 722–741. https://doi.org/10.1175/1520-0442(1999)012<0722:TSPFAP>2.0.CO;2

Shen, Y. J., Shen, Y., Guo, Y., Zhang, Y., Pei, H., & Brenning, A. (2020). Review of historical and projected future climatic and hydrological changes in mountainous semiarid Xinjiang (northwestern China), central Asia. *Catena*, *187*, 104343. https://doi.org/10.1016/j.catena.2019.104343

Shi, Y., Shen, Y., Kang, E., Li, D., Ding, Y., Zhang, G., & Hu, R. (2006). Recent and future climate change in northwest China. *Climatic Change*, *80*(3–4), 379–393. https://doi.org/10.1007/s10584-006-9121-7

Song, S., Ding, J., Zong, Z., Yang, A., & Luo, G. (2017). Possible causes for spatial and temporal variation of warm season precipitation in Xinjiang from 1960–2014. *Atmosphere*, *8*(12), 20. https://doi.org/10.3390/atmos8010020

Sun, B., & Wang, H. (2014). Moisture sources of semiarid grassland in China using the Lagrangian particle model FLEXPART. *Journal of Climate*, *27*(6), 2457–2474. https://doi.org/10.1175/jcli-d-13-00517.1

Sun, B., Wang, H., Wu, B., Xu, M., Zhou, B., Li, H., & Wang, T. (2021). Dynamic control of the dominant modes of interannual variability of snowfall frequency in China. *Journal of Climate*, *34*(7), 2777–2790. https://doi.org/10.1175/jcli-d-20-0705.1

Tan, X., & Shao, D. (2017). Precipitation trends and teleconnections identified using quantile regressions over Xinjiang, China. *International Journal of Climatology*, *37*(3), 1510–1525. https://doi.org/10.1002/joc.4794

Tao, H., Gemmer, M., Bai, Y., Su, B., & Mao, W. (2011). Trends of streamflow in the Tarim River Basin during the past 50years: Human impact or climate change? *Journal of Hydrology*, *400*(1–2), 1–9. https://doi.org/10.1016/j.jhydrol.2011.01.016

Tao, W., Huang, G., Dong, D., Wang, P., Yu, T., & Gong, H. (2021). Dominant modes of interannual variability in precipitation over the Hengduan Mountains during rainy seasons. *International Journal of Climatology*, *41*(4), 2795–2809. https://doi.org/10.1002/joc.6990

The Math Works, Inc. (2020). MATLAB (Version 2020a). [Software] Retrieved from www.mathworks.com/

Trenberth, K. E. (1999b). *Conceptual framework for changes of extremes of the hydrological cycle with climate change, Weather and climate extremes* (pp. 327–339). Springer. https://doi.org/10.1007/978-94-015-9265-9_18

Trenberth, K. E. (1999a). Atmospheric moisture recycling: Role of advection and local evaporation. *Journal of Climate*, *12*(5), 1368–1381. https://doi.org/10.1175/1520-0442(1999)012<1368:amrroa>2.0.co;2

Trenberth, K. E. (2011). Changes in precipitation with climate change. *Climate Research*, *47*(1), 123–138. https://doi.org/10.3354/cr00953

Wang, B., Zhang, M., Wei, J., Wang, S., Li, S., Ma, Q., et al. (2013). Changes in extreme events of temperature and precipitation over Xinjiang, northwest China, during 1960–2009. *Quaternary International*, *298*, 141–151. https://doi.org/10.1016/j.quaint.2012.09.010

Wang, L., Dong, Y., Han, D., & Xu, Z. (2019). Stable isotopic compositions in precipitation over wet island in Central Asia. *Journal of Hydrology*, *573*, 581–591. https://doi.org/10.1016/j.jhydrol.2019.04.005

Wang, L., Xu, P., Chen, W., & Liu, Y. (2017). Interdecadal variations of the silk road pattern. *Journal of Climate*, *30*(24), 9915–9932. https://doi.org/10.1175/JCLI-D-17-0340.1

Wang, L., Xu, P., & Chowdary, J. S. (2021). *Teleconnection along the Asian jet stream and its association with the Asian summer monsoon, Indian summer monsoon variability* (pp. 287–298). Elsevier. https://doi.org/10.1016/b978-0-12-822402-1.00009-0

Wang, L., Zhang, M., Wang, S., Argiriou, A., Wang, G., Salamalikis, V., et al. (2020). Stable isotope signatures and moisture transport of a typical heavy precipitation case in the southern tianshan mountains. *Chinese Geographical Science*, *30*(1), 180–188. https://doi.org/10.1007/s11769-019-1091-6

Wang, P., Wang, B., Cheng, H., Fasullo, J., Guo, Z.-T., Kiefer, T., & Liu, Z. (2017). The global monsoon across time scales: Mechanisms and outstanding issues. *Earth Science Review*, *174*, 84–121. https://doi.org/10.1016/j.earscirev.2017.07.006

Wang, S., Zhang, M., Che, Y., Chen, F., & Qiang, F. (2016). Contribution of recycled moisture to precipitation in oases of arid central Asia: A stable isotope approach. *Water Resources Research*, *52*(4), 3246–3257. https://doi.org/10.1002/2015wr018135

Wang, S., Zhang, Q., Yue, P., & Wang, J. (2020). Effects of evapotranspiration and precipitation on dryness/wetness changes in China. *Theoretical and Applied Climatology*, *142*(3–4), 1027–1038. https://doi.org/10.1007/s00704-020-03336-8

Wang, W., Li, H., Wang, J., & Hao, X. (2020). Water vapor from Western Eurasia promotes precipitation during the snow season in northern Xinjiang, a typical arid region in central Asia. *Water*, *12*(1), 141. https://doi.org/10.3390/w12010141

Wu, P., Ding, Y., Liu, Y., & Li, X. (2019). The characteristics of moisture recycling and its impact on regional precipitation against the background of climate warming over Northwest China. *International Journal of Climatology*, *39*(14), 5241–5255. https://doi.org/10.1002/joc.6136

Wu, Z., Zhang, H., Krause, C. M., & Cobb, N. S. (2010). Climate change and human activities: A case study in Xinjiang, China. *Climatic Change*, *99*(3–4), 457–472. https://doi.org/10.1007/s10584-009-9760-6

Xue, J., Gui, D., Lei, J., Sun, H., Zeng, F., Mao, D., et al. (2019). Oasification: An unable evasive process in fighting against desertification for the sustainable development of arid and semiarid regions of China. *Catena*, *179*, 197–209. https://doi.org/10.1016/j.catena.2019.03.029

Xun, X., Hu, Z., & Ma, Y. (2012). The dynamic plateau monsoon index and its association with general circulation anomalies. *Advances in Atmospheric Sciences*, *29*(6), 1249–1263. https://doi.org/10.1007/s00376-012-1125-9

Yan, H., Huang, J., He, Y., Liu, Y., Wang, T., & Li, J. (2020). Atmospheric water vapor budget and its long-term trend over the Tibetan plateau. *Journal of Geophysical Research: Atmospheres*, *125*(23). https://doi.org/10.1029/2020jd033297

Yao, J., Chen, Y., Yu, X., Zhao, Y., Guan, X., & Yang, L. (2020). Evaluation of multiple gridded precipitation datasets for the arid region of northwestern China. *Atmospheric Research*, *236*, 104818. https://doi.org/10.1016/j.atmosres.2019.104818

Yao, J., Chen, Y., Zhao, Y., Guan, X., Mao, W., & Yang, L. (2020). Climatic and associated atmospheric water cycle changes over the Xinjiang, China. *Journal of Hydrology*, *585*, 124823. https://doi.org/10.1016/j.jhydrol.2020.124823

Yao, J., Hu, W., Chen, Y., Huo, W., Zhao, Y., Mao, W., & Yang, Q. (2019). Hydro-climatic changes and their impacts on vegetation in Xinjiang, Central Asia. *The Science of the Total Environment*, *660*, 724–732. https://doi.org/10.1016/j.scitotenv.2019.01.084

Yao, J., Mao, W., Yang, Q., Xu, X., & Liu, Z. (2016). Annual actual evapotranspiration in inland river catchments of China based on the Budyko framework. *Stochastic Environmental Research and Risk Assessment*, *31*(6), 1409–1421. https://doi.org/10.1007/s00477-016-1271-1

Yao, S., Jiang, D., & Zhang, Z. (2021). Moisture sources of heavy precipitation in Xinjiang characterized by meteorological patterns. *Journal of Hydrometeorology*, *22*(8), 2213–2225. https://doi.org/10.1175/jhm-d-20-0236.1

Zhang, J., Chen, H., & Zhang, Q. (2018). Extreme drought in the recent two decades in northern China resulting from Eurasian warming. *Climate Dynamics*, *52*(5–6), 2885–2902. https://doi.org/10.1007/s00382-018-4312-2

Zhang, L., & Zhou, T. (2015). Drought over East Asia: A review. *Journal of Climate*, *28*(8), 3375–3399. https://doi.org/10.1175/JCLI-D-14-00259.1

Zhang, Q., Lin, J., Liu, W., & Han, L. (2019). Precipitation seesaw phenomenon and its formation mechanism in the eastern and western parts of Northwest China during the flood season. *Science China Earth Sciences*, *62*(12), 2083–2098. https://doi.org/10.1007/s11430-018-9357-y

Zhang, Q., Singh, V. P., Li, J., Jiang, F., & Bai, Y. (2012). Spatio-temporal variations of precipitation extremes in Xinjiang, China. *Journal of Hydrology*, *434*, 7–18. https://doi.org/10.1016/j.jhydrol.2012.02.038

Zhang, Q., Yang, Z., Hao, X., & Yue, P. (2018). Conversion features of evapotranspiration responding to climate warming in transitional climate regions in northern China. *Climate Dynamics*, *52*(7–8), 3891–3903. https://doi.org/10.1007/s00382-018-4364-3

Zhao, W. Y., Chen, Y. N., Li, J. L., & Jia, G. S. (2010). Periodicity of plant yield and its response to precipitation in the steppe desert of the Tianshan Mountains region. *Journal of Arid Environments*, *74*(4), 445–449. https://doi.org/10.1016/j.jaridenv.2009.09.022

Zhao, Y., Fang, Y., Cui, C., & Huang, A. (2012). Effects of irrigation on precipitation in the arid regions of Xinjiang, China. *Journal of Arid Land*, *4*(2), 132–139. https://doi.org/10.3724/sp.j.1227.2012.00132

Zhao, Y., Yu, X., Yao, J., Dong, X., & Li, H. (2019). The concurrent effects of the South Asian monsoon and the plateau monsoon over the Tibetan Plateau on summer rainfall in the Tarim Basin of China. *International Journal of Climatology*, *39*(1), 74–88. https://doi.org/10.1002/joc.5783

Zhao, Y., & Zhou, T. (2021). Interannual variability of precipitation recycle ratio over the Tibetan plateau. *Journal of Geophysical Research: Atmospheres*, *126*(2). https://doi.org/10.1029/2020jd033733

Zheng, Z., Ma, Z., Li, M., & Xia, J. (2016). Regional water budgets and hydroclimatic trend variations in Xinjiang from 1951 to 2000. *Climatic Change*, *144*(3), 447–460. https://doi.org/10.1007/s10584-016-1842-7

Zhong, Y., Wang, B., Zou, C. B., Hu, B. X., Liu, Y., & Hao, Y. (2017). On the teleconnection patterns to precipitation in the eastern Tianshan Mountains, China. *Climate Dynamics*, *49*(9–10), 3123–3139. https://doi.org/10.1007/s00382-016-3500-1

Zhou, Y., Huang, A., Zhao, Y., & Yang, Q. (2014). Influence of the sea surface temperature anomaly over the Indian Ocean in March on the summer rainfall in Xinjiang. *Theoretical and Applied Climatology*, *119*(3–4), 781–789. https://doi.org/10.1007/s00704-014-1149-4

Zhou, Y. S., Xie, Z. M., & Liu, X. (2019). An analysis of moisture sources of torrential rainfall events over Xinjiang, China. *Journal of Hydrometeorology*, *20*(10), 2109–2122. https://doi.org/10.1175/jhm-d-19-0010.1