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The Precipitation-Recycling Process Enhanced Extreme Precipitation in Xinjiang, China

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Key Points:

- The mean recycling ratio of extreme precipitation in Xinjiang was 42.3%, with an increasing trend of 2.3% decade^{-1}
- Recycling and external precipitation contributed 49% and 51% to the growing trend of extreme precipitation in Xinjiang, respectively
- The recycling process (external process) dominated the increased extreme precipitation in the Kunlun (Tianshan) Mountains

Supporting Information:

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

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Abstract

The amount, frequency and intensity of extreme precipitation over Xinjiang have increased dramatically under the wetting trend in Northwest China, but long-term trends in the precipitation-recycling process remain largely unexplored. Based on dynamic recycling model and MERRA2 reanalysis, we revealed a mean recycling ratio for extreme precipitation in Xinjiang of 42.3% with a growth rate of 2.3% decade^{-1} during 1982–2019. The increasing trend of extreme precipitation was almost equally attributed to increased recycling precipitation (49%) and external precipitation (51%). The extreme precipitation in Xinjiang exhibited two peak centers, the Tianshan Mountains region (TS) and Kunlun Mountains region (KL), highlighting variations in the water cycle. Specifically, the external cycle predominated the increased extreme precipitation in TS (61%), while the recycling process mainly influenced the increase in KL (67%) due to markedly enhanced evapotranspiration. Moisture source attribution further proved the crucial role of evapotranspiration from Xinjiang and its vicinity in extreme precipitation.

Plain Language Summary

Local evapotranspiration is essential for precipitation over arid and semiarid regions, which can be evaluated via the precipitation recycling process. To date, studies investigating the precipitation-recycling process over Xinjiang have primarily focused on general precipitation, but long-term trends in the precipitation-recycling process during extreme precipitation events remain largely unexplored. In this study, we used a dynamic recycling model and revealed that the recycling process accounted for 42.3% of extreme precipitation in climatology and increased by 2.3% decade^{-1} during 1982–2019. The ascending trend of extreme precipitation over Xinjiang was almost equally attributed to increased recycling precipitation and external precipitation. However, there are regional differences in the dominant factor. Specifically, the Tianshan Mountains region was predominated by the external water cycle, while Kunlun Mountains region was mainly determined by the recycling process. Considering precipitation and evapotranspiration along the moisture trajectory, we further showed that the majority of moisture responsible for extreme precipitation in Xinjiang came from this locality and surrounding area. These findings indicate that the recycling process plays a crucial role in the formation of extreme precipitation in Xinjiang, and a deeper understanding of its changing mechanisms can help reduce the flood risks caused by extreme precipitation.

1. Introduction

Accompanied by global warming, the increase in weather and climate extremes, especially unpredicted extreme precipitation events, seriously threaten human survival and social economics and have attracted much attention from researchers (Chou & Lan, 2012; Ma et al., 2023; Pendergrass, 2018; Yuan et al., 2023). Extreme precipitation is more likely to cause catastrophic disasters in arid and semiarid regions than in other regions, especially secondary disasters (mountain torrents, mudslides and landslides) easily triggered by rainstorms in low vegetation coverage areas (Peng et al., 2015). Xinjiang, located in inner Eurasia and characterized by a typical mountain-basin system (Figure S1 in Supporting Information S1), is one of the driest regions, with an annual precipitation of just 150 mm (Wang et al., 2020), while the arid desert areas in southern Xinjiang experience annual precipitation of even less than 50 mm (Zheng et al., 2017). Noticeably, the total annual precipitation in Xinjiang mainly comes from a few extreme daily precipitation events (Ning et al., 2021). For example, on 31 July 2018, a heavy downpour occurred in southeast Hami, with the maximum 12-hr accumulated rainfall volume reaching 110 mm (Liu et al., 2020). Moreover, an interesting phenomenon has been observed over Xinjiang, where the regional climate has changed from warm-dry to warm-wet conditions, and there has been a concomitant increase in the frequency and intensity of heavy rainfall since the mid-1980s (Shi et al., 2007; Wang et al., 2020;

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Zhang, Lin, et al., 2019). Therefore, it is essential to further deeply explore the changes in extreme precipitation and its related hydrologic cycles to reduce the risks of flood prevention induced by extreme precipitation.

The precipitation recycling process, as a critical part of hydrologic cycles, refers to the formation of precipitation by the condensation of local evaporation and transpiration (Brubaker et al., 1993). The precipitation recycling ratio, denoting the proportion of recycled precipitation to total precipitation, is an essential index linking the atmosphere and land through exchanges between energy and moisture (Dominguez et al., 2006, 2020). Many studies have proven that understanding the precipitation recycling process is crucial for regional climate and hydrologic processes (Baker & Spracklen, 2022; He et al., 2021; Ren et al., 2022). Furthermore, human activities such as deforestation, land utilization and climate change can alter water cycles, which will directly affect the sustainability of ecosystems and human societies on Earth (Baker & Spracklen, 2022; Oki & Kanae, 2006). Arid and semiarid regions are highly susceptible to the effects of global climate change, and as Huang et al. (2012) revealed, the warming trend is particularly amplified in these regions compared to humid areas. Xinjiang and its adjacent areas are rich in glaciers and snow, which have experienced accelerated shrinking and melting by enhanced warming, leading to a greater moisture supply and influencing the precipitation recycling process (J. Yao et al., 2022; T. Yao et al., 2022).

To date, several studies investigating the precipitation-recycling process over Xinjiang have been carried out. Yao et al. (2020) and Wu et al. (2019) revealed that the annual average precipitation-recycling ratio varied by approximately 10%. Moreover, Zhang et al. (2022) and Wang et al. (2016) indicated that the contribution of recycled moisture to precipitation was 37% and 16% in the wet season over Xinjiang and the large oases of Urumqi, respectively, which have exhibited significantly increasing trends over the last few decades (Yao et al., 2020; Zhang et al., 2022). Regarding extreme precipitation, Yao et al. (2021) and Zhou et al. (2019) explored the sources of moisture related to heavy rainfall in Xinjiang, showing that the moisture from Xinjiang and Central Asia (CA) transported by westerlies are key contributors. Another study further demonstrated that regional moisture plays an important role in the development of extreme precipitation in Xinjiang, with northern Xinjiang experiencing a contribution ratio of 24.5% and southern Xinjiang experiencing a contribution ratio of 30.2% (Hu et al., 2021). Additionally, the strong low-level easterly jet in the Hexi Corridor also contributes to extreme precipitation by bringing in water vapor from eastern China, which could accumulate rapidly and lead to the occurrence of heavy precipitation events (F. Chen et al., 2021; Liu et al., 2020). So far, these works have primarily focused on case study, but the long-term trends in the precipitation-recycling process during extreme precipitation remain largely unexplored. The variability of extreme precipitation poses a greater challenge to the improvement of flood control measures and water resource management policies. Therefore, it is vital to explore the contribution of the recycling process to extreme precipitation and its increasing trend, along with comprehending the effects of climate change activities on the recycling process.

To address the abovementioned knowledge gap, in this study, we used a dynamic recycling model and moisture source attribution method to explore the recycling process of extreme precipitation and quantify the contributions of each moisture source to extreme precipitation in Xinjiang. Additionally, we evaluated the impact of climate factors on the extreme precipitation recycling process to provide an advanced understanding of the physical mechanism of this process.

2. Data and Methodology

2.1. Data

The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA2) is generated by NASA Global Modeling and Assimilation Office based on the Goddard Earth Observation System Model version 5, and offers products that cover a long-term period from 1980 to the present (Gelaro et al., 2017). Previous studies have indicated that MERRA2 outperforms other reanalysis datasets in terms of accurately representing climate characteristics and long-term patterns of water cycles in CA and northwestern China (Jiang et al., 2019; Ren et al., 2022; Zhang et al., 2022). We utilized the observed daily precipitation data from the China Meteorological Agency (CMA) to assess the accuracy of MERRA2 in Xinjiang, which exhibited overall consistency (Figure S2 in Supporting Information S1). The observed daily precipitation data were derived from the surface daily precipitation data set (V3.0) recorded by national operational rain gauges. To calculate the precipitation recycling ratio, 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 Dynamic Recycle Model (DRM). Notably, the data in 1981 were excluded from our study because of the abnormal error possibly attributed from spin-up effects (Reichle et al., 2017; Ren et al., 2022; Zhang et al., 2022).

In addition, the monthly precipitation, evapotranspiration, moisture flux, and runoff from MERRA2 and the normalized difference vegetation index (NDVI) from the Advanced Very High-Resolution Radiometer (Fensholt & Proud, 2012) were utilized to reveal the mechanism of long-term evolution in the precipitation recycling process.

2.2. Extreme Precipitation Threshold Selection

One important aspect of investigating extreme precipitation is determining its threshold, as varying thresholds can produce distinct trends in extreme precipitation and impact its response to global warming (Pendergrass, 2018; Schär et al., 2016). The percentile indices were employed to determine the threshold for extreme precipitation events in this study. Tables S1 and S2 in Supporting Information S1 show the values of the daily precipitation threshold and the corresponding sample sizes for different percentiles in all-day percentiles and wet-day percentiles form MERRA and observations. The threshold value determined by the 99.9th percentile with wet days (>0.1 mm) was 21.9 mm hr^{-1}, which is similar to the fixed threshold defined by the Xinjiang Meteorological Bureau for daily rainstorms (24 mm hr^{-1}). Moreover, its corresponding sample count was better than other thresholds. Thus, the 99.9th percentile with wet days (>0.1 mm) was used to define extreme precipitation in the present study.

2.3. DRM

The DRM, which provides a measure of the extent to which local water vapor contributes to the overall precipitation in the region, was applied to identify the moisture sources and estimate the precipitation recycling ratio (Dominguez et al., 2006, 2020). The DRM was derived from the conservation equation of atmospheric water vapor:

$$\frac{\partial w}{\partial t} + \nabla \cdot Q = E - P + \text{res}, \tag{1}$$

where w is the atmospheric water content; $-\nabla \cdot Q$ represents moisture convergence, E and P represent evapotranspiration and precipitation, respectively; and res represents the residual term that forces the equation to close and is associated with data assimilation in the reanalysis data set. The specific introduction can be found in Dominguez et al. (2006).

Unlike most recycling models that usually assume negligible atmospheric water content changes, the DRM can model the precipitation-recycling ratio on daily time scales (Brubaker et al., 1993; Dominguez et al., 2006; Schär et al., 1999). Moreover, Xinjiang is mainly situated within the westerlies with weak wind shear in terms of climatology, so DRM is suitable for tracing moisture sources for this region (Ren et al., 2022; Zhang et al., 2022).

2.4. Moisture Source Attribution Method

To quantify the valid contribution from moisture source regions to extreme precipitation over Xinjiang, a "moisture-source attribution" method developed by Sodemann et al. (2008) was adopted in this study. This method considers precipitation and evaporation processes along the trajectory of an air particle and quantifies the contribution of each evaporation location to the precipitation at the target area, which has been widely used in previous studies (Peng et al., 2020; Sun & Wang, 2014, 2015). Similar to the modifications proposed by Ren et al. (2022), we took atmospheric precipitable water for backward tracing and calculated the moisture changes in the air column caused by precipitation or evaporation. The method is specifically described in Method S1 in Supporting Information S1.

3. Results

3.1. Enhanced Extreme Precipitation Recycling Process

Extreme precipitation events in Xinjiang are becoming more common and severe, as demonstrated in Figure S3 in Supporting Information S1. There has been a remarkable increase in amounts, frequencies, intensities, and

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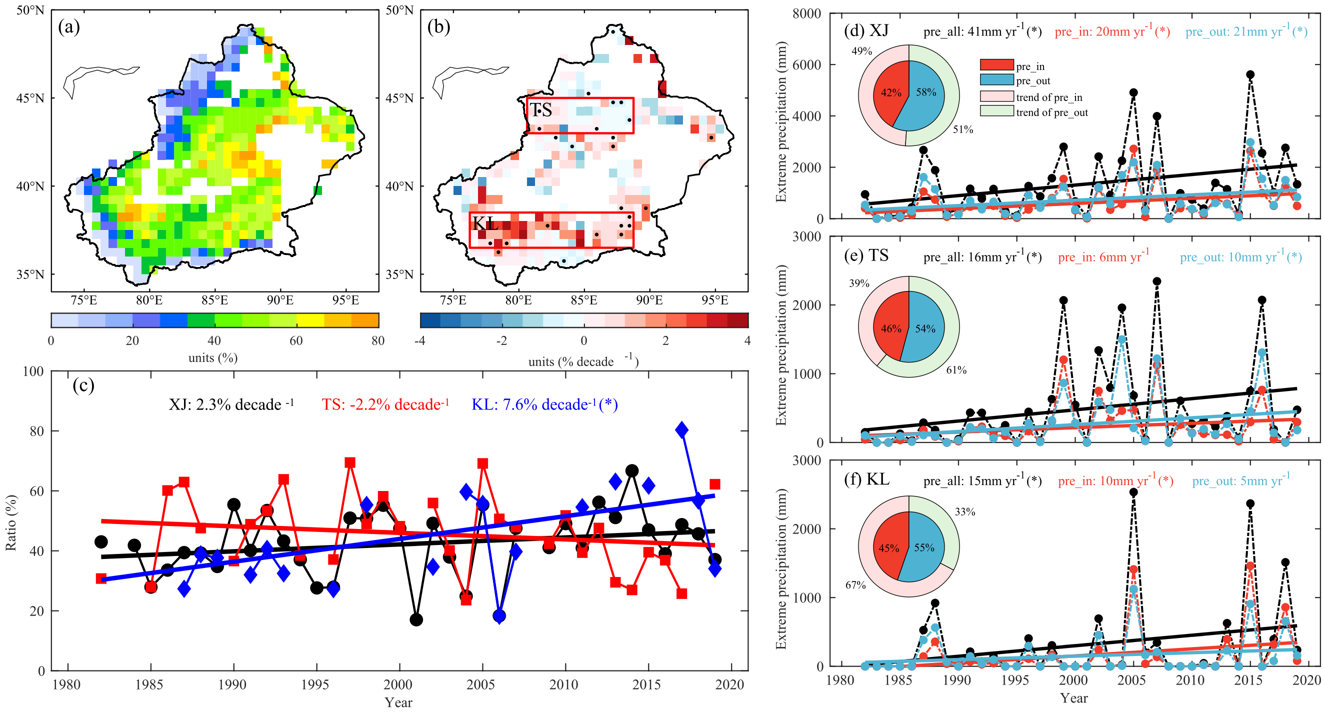

Figure 1. The recycling progress of extreme precipitation in Xinjiang. The distributions of (a) climatology and (b) linear trends of the extreme precipitation recycling ratio during the period of 1982–2019 in Xinjiang. (c) The time series of the regional extreme precipitation recycling ratio in Xinjiang (XJ), TS and KL during 1982–2019. The black dots in (b) indicate statistical significance exceeding the 90% confidence level. The two rectangles in (b) are marked as TS (80.5°–88.5°E, 43.0°–45.0°N) and KL (76.0°–88.5°E, 36.5°–38.5°N), representing the Tianshan Mountains and Kunlun Mountains, respectively. (d) The time series of extreme precipitation (black line) and precipitation associated with the external (blue line) and internal (red line) cycles during 1982–2019 in XJ. The inner pie in (d) represents fractional contributions of climatological precipitation associated with the external and internal cycles to total extreme precipitation, while the outer pie represents contributions of the linear trend of precipitation associated with the external and internal cycles to the trend of total extreme precipitation. (e and f) are the same as (d) but for TS and KL, respectively. The asterisk in parentheses (*) indicates that the statistical significance exceeds the 90% confidence level.

proportions of extreme precipitation to total precipitation. The highest amounts of extreme precipitation were observed in the Tianshan Mountains region and Kunlun Mountains region (abbreviated to TS and KL, respectively). The extreme precipitation in TS exhibited high frequency and relatively weak intensity, while extreme precipitation in KL presented low frequency and stronger intensity. In particular, the proportion of extreme precipitation in KL was maximum, which highlighted the distinctive precipitation features in this region. Thus, the recycling processes of extreme precipitation in typical areas, that is, TS and KL, and throughout Xinjiang were explored.

Figure 1 illustrates the spatiotemporal variations in the extreme precipitation recycling process in Xinjiang from 1982 to 2019. The precipitation-recycling ratio generally increased from the west to the east in most regions of Xinjiang, which was mainly due to the prevailing westerlies in the mid-latitude region. A high center was located around the Yanqi Basin, with a value of more than 70%. Due to the three-sided barrier by mountains and the funnel-shaped terrain opening to the east in the Tarim Basin, external water vapor advected by westerlies below 700 hPa finds it challenging to enter the basin, resulting in a high recycling ratio in the basin's western region (C. Chen et al., 2021; F. Chen et al., 2021; Huang et al., 2015). The climatic mean recycling ratio of extreme precipitation in Xinjiang was 42.3% with an increasing trend of 2.3% decade^{-1}, implying that the recycling process of extreme precipitation was enhanced. The recycling processes in TS and KL were calculated separately, with climatological recycling ratios of 45.8% and 44.7%, respectively. TS showed a slightly decreasing trend, with a rate of 2.2% decade^{-1}, whereas KL exhibited a significantly increasing trend, with a rate of 7.6% decade^{-1}. Furthermore, we explored the impacts of internal and external water cycles on the overall trend of extreme precipitation. Total extreme precipitation was divided into recycling precipitation and precipitation induced by the external water cycle. Based on our estimates, both recycling precipitation and external cycle precipitation have significantly increased across Xinjiang, which roughly equally contributed to the growth trend of extreme precipitation, accounting for 49% and 51%, respectively. Although the external precipitation and

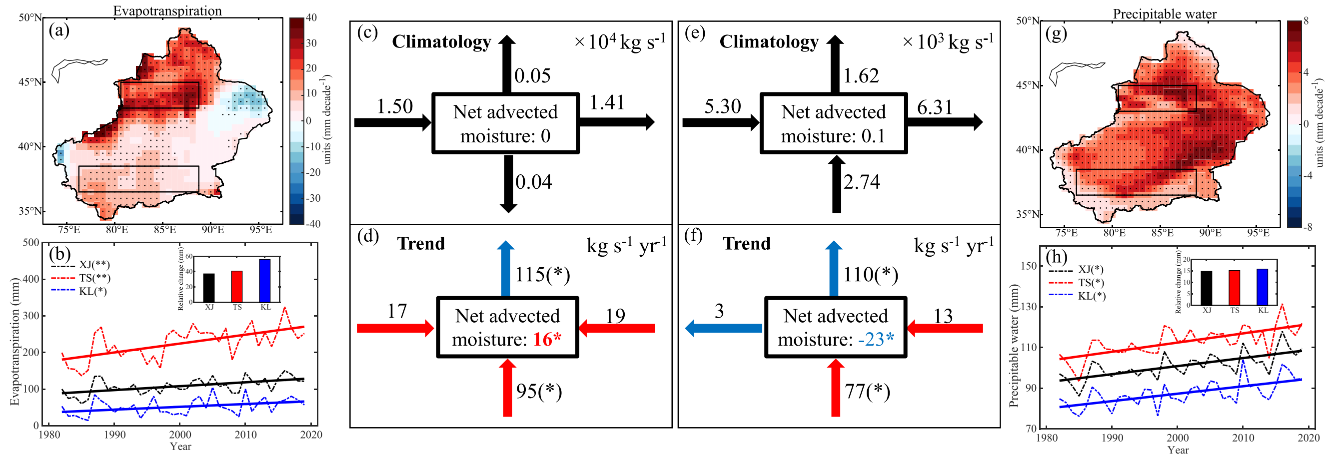

Figure 2. The mechanism of changing water cycles of extreme precipitation. (a) The spatial distribution of the linear trend of evapotranspiration during 1982–2019 in Xinjiang. (b) The time series of regional evapotranspiration in XJ, TS, and KL during 1982–2019. The bar in (b) indicates relative changes in evapotranspiration in different regions. (c) The climatology and (d) linear trend of the vertically integrated water vapor flux at the four boundaries for TS during 1982–2019. The arrows indicate the direction of water vapor flux in (c), and red (blue) arrows indicate the water vapor inflow (outflow) in (d). (e and f) are the same as (c and d) but for KL. (g and h) are the same as (a and b) but for precipitable water. The black dots indicate the statistical significance exceeding the 90% confidence level in (a and g). The asterisk (*) and double asterisk (**) in parentheses represent that statistical significance exceeds the 90% and 95% confidence levels, respectively.

recycling precipitation exhibited consistent long-term growth evolution in both TS and KL, their contributions to the total extreme precipitation in TS and KL were quite opposite. The external precipitation in TS dominated the increasing extreme precipitation, with a contribution factor of 61%, while the recycling precipitation in KL determined the trend with 67%.

3.2. Mechanism of an Enhanced Precipitation-Recycling Process

Figure 2 demonstrates the changes in internal moisture (evapotranspiration), external advection moisture (vertically integrated water vapor flux) and precipitable water (composed of internal and external moisture). The evapotranspiration in Xinjiang, TS, and KL presented significant growth with relative increases of approximately 37%, 41%, and 56%, respectively, over the last few decades. Dominated by the westerlies, the moisture advected to the TS primarily inflowed through its western boundary and outflowed through the eastern boundary, with negligible moisture transportation along the northern and southern boundaries. In contrast, the moisture afflux in KL was transported from both the western and southern boundaries, affected by the westerly circulation and meridional wind, with predominant moisture outflow through the eastern boundary. It is worth noting that the northern/southern boundaries have undergone more pronounced changes than the eastern/western boundaries, indicating an enhancement of meridional moisture transportation. This may be related to changed global atmospheric circulation and intensified meridional wind over CA (Wang et al., 2022; Zhang et al., 2022; Zhang & Zhou, 2015). In terms of net moisture transportation, there was an increase in TS at a rate of 16 $kg^{-1}\ s^{-1}\ yr^{-1}$, whereas net moisture transportation experienced a decrease in KL at a rate of 23 $kg^{-1}\ s^{-1}\ yr^{-1}$. Therefore, the precipitable water in Xinjiang exhibited a remarkable growth trend as a synergetic result of evapotranspiration and external advection moisture. Their relative changes were comparable in TS, KL and Xinjiang, with increases of 15%, 16%, and 15%, respectively. Notably, the increase in precipitable water over KL was exclusively attributed to the contribution of evapotranspiration, which greatly enhanced the recycling process. For TS, both external moisture and internal evapotranspiration contribute positively to the increased precipitation. However, the deepening of the Central Asian trough facilitates the intensification of upward motion and guides more water vapor transport into TS (Ma et al., 2021; Zhang et al., 2022). Furthermore, the increase in evapotranspiration over TS is relatively limited compared to KL. Those provided evidence that the increasing extreme precipitation in TS is predominately driven by external moisture. In conclusion, the changes in evapotranspiration and external advection moisture provided a reasonable and direct explanation for the differences in the recycling process of extreme precipitation between TS and KL.

We conducted further analyses on the underlying mechanism influencing evapotranspiration, which is a crucial factor affecting the recycling process in arid and semiarid areas (Figure 4; Figure S4 and Table S3 in Supporting Information S1). Precipitation and evapotranspiration were highly correlated in both time and space, especially in KL, where the correlation coefficient reached 0.99. Nevertheless, the correlation between evapotranspiration and temperature was very low. This was consistent with previous studies that indicated that evapotranspiration is controlled by water rather than energy in arid and semiarid areas (Roderick et al., 2014; Yue et al., 2019; Zhang, Yang, et al., 2019). Although evapotranspiration is not deficient in energy, increased temperature can indirectly affect evapotranspiration resulting from an increase in runoff due to accelerating snow and ice melting. On the other hand, there were significantly positive correlations between evapotranspiration and both runoff and NDVI because increased precipitation not only directly affected evapotranspiration but also indirectly affected it by increasing runoff and improving vegetation coverage. Apart from the greening induced by climate change, the fertilization effect caused by the increase of CO_2 has also played a positive role in enhancement of vegetation growth, enhancing transpiration sequentially (Piao et al., 2019; Zhu et al., 2016). It is notable to mention that the factors of precipitation, runoff, and NDVI experienced more pronounced increases in KL compared to TS, which ultimately led to a higher relative change of evapotranspiration in KL despite its comparatively arid and barren environment. In summary, increased evapotranspiration and precipitation indicated that water exchange between the atmosphere and land has enhanced, which favors more extreme precipitation.

3.3. Moisture Source Quantitative Attribution

We then analyzed the cluster results of backward trajectories associated with extreme precipitation events in TS and KL (Figures 3a and 3b; Figures S5 and S6 in Supporting Information S1). There were four moisture transport channels for TS (Figure 3a). The primary route was the short-range western channel (in blue), which originates from CA and accounted for more than half of moisture transportation (51%). The long-range western channel (in purple) was the second most significant route, originating from the Black Sea and contributing 35% to moisture transportation. The other two moisture transport conduits were from the North Atlantic (7%) and East Asia (EA) (6%). For KL, extreme precipitation was fueled by the moisture influx through three main channels (Figure 3b). The northwest (in blue) and southwest channels (in red) were the main transport pathways, which originated from the Pamir Plateau and Western Siberia, accounting for 44% and 40% of the total moisture transportation, respectively. The third was the western pathway (in green), which originated from the Mediterranean region (MR) and accounted for 16%. In summary, extreme precipitation events have several significantly concentrated channels for water vapor transport. Conversely, the moisture back-trajectory for all precipitation performs wide distribution and long-range transportation compared to extreme precipitation (Figure S7 in Supporting Information S1).

The backward trajectories of moisture transportation could adequately reflect the moisture pathways and source regions, but they could not describe the valid contribution of each moisture source to extreme precipitation because of the varying moisture in the trajectory from the origin to the target area resulting from evaporation or precipitation. Thus, the quantitative contributions of evapotranspiration along trajectories to extreme precipitation in TS and KL are also depicted in Figures 3c, 3d, and 3g. The moisture contributed to the target area was mostly from Xinjiang and its vicinity (XJV), CA, North Atlantic (NAO), Northern Europe, Northern Asia (NA), the MR, EA, and Northern Indian Ocean (NI). For TS, the moisture from XJV contributed the most, with 64%, followed by CA (17%). The contributions from MR, NE, NA, and EA were all approximately 2%, while the contributions from NAO and NI were less than 1%. For KL, XJV had the highest water vapor uptake (71%), and ranking second was CA (18%), which mainly covered from the Pamir Plateau to the upstream Indus River. NI contributed 2%, while other regions contributed less than 1%. Figures 3e, 3f, and 3h showed the contribution of moisture sources to all precipitation and the difference of moisture contribution from major sources between extreme precipitation and climatology. It is observed that apart from XJV and CA, other remote moisture sources also make contributions to all precipitation, although these contributions are relatively small. Moreover, XJV exhibited a significantly higher contribution to extreme precipitation than all precipitation both in TS and KL. This indicated that long-range transport of moisture contribution to extreme precipitation in Xinjiang was limited due to precipitation depletion and evapotranspiration supplementation. The evapotranspiration occurring in Xinjiang and its adjacent areas was the primary factor contributing to the formation of extreme precipitation events. In this study, the total amount of contribution from determined moisture source regions to extreme precipitation in the target area was approximately 90%. The remaining 10% of moisture has not been identified and is either present in the air column before the earliest uptake ($t > 10$ days), or its uptake is too small to be included in the calculation (Sodemann et al., 2008).

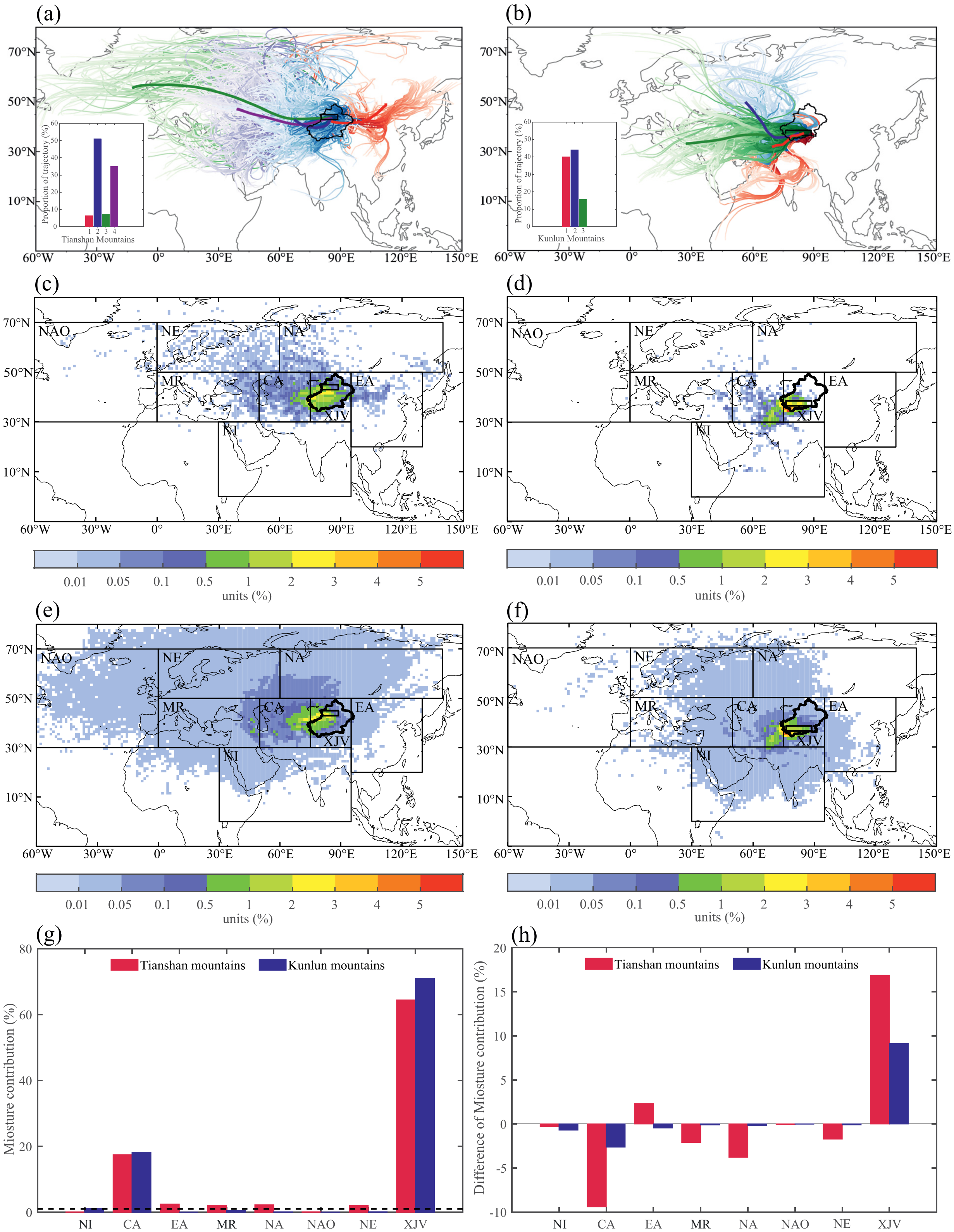
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
Tianshan Mountains
Kunlun Mountains
Proportion of trajectory (%)
NAO
NE
NA
MR
CA
EA
XJV
NI
units (%)
0.01
0.05
0.1
0.5
1
2
3
4
5
Tianshan mountains
Kunlun mountains
Miosture contribution (%)
Difference of Miosture contribution (%)

Figure 3.

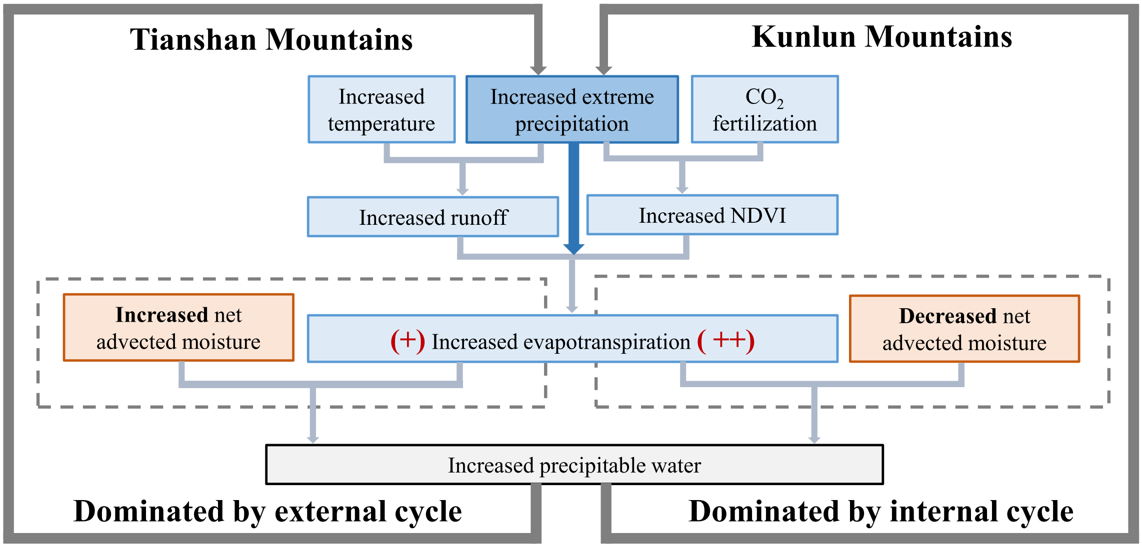

Figure 4. Schematic diagram of the differences in the recycling process of the increased extreme precipitation between TS and KL.

4. Conclusion

Using MERRA2, the DRM and a moisture source attribution method, we evaluated the impact of the precipitation-recycling process on extreme rainfall and quantified the contributions of each moisture source region to extreme precipitation in Xinjiang. The results indicate that the recycling process accounts for 42.3% of extreme precipitation and is increasing by 2.3% decade^{-1}. Both recycling precipitation and external precipitation have significantly increased throughout Xinjiang, contributing almost equally to the growing trend of extreme precipitation by 49% and 51%, respectively, which implies that enhanced recycling process plays a vital role in the observed rise in extreme precipitation. There are differences in the factors contributing to the increase in extreme precipitation between TS and KL, and the mechanism is shown in Figure 4. For TS, increased extreme precipitation is mainly caused by external water cycles (61%), which is induced by a significant increase in net external moisture transportation. In contrast, the increased extreme precipitation for KL is primarily driven by the recycling process (67%). The KL experienced less net external moisture, but more local evapotranspiration due to precipitation, runoff and vegetation growth, which enhanced the regional recycling process. Moreover, considering precipitation and evapotranspiration along the moisture trajectory, this study revealed that most of the moisture responsible for extreme precipitation in Xinjiang comes from XJV and CA. In summary, the interaction between the atmosphere and land has enhanced over Xinjiang, and the regional recycling process plays a crucial role in the formation of extreme precipitation in arid and semiarid areas, which should be given more attention.

5. Discussion

This study only discussed the qualitative relationships between temperature, precipitation, runoff, vegetation and evapotranspiration and did not analyze their quantitative contributions. Additionally, irrigated farming has been developing rapidly in recent decades, and the wetting and warming of Xinjiang have also generated increases in lake water levels, which could exert a significant influence on the water cycles in Xinjiang (Yao et al., 2019; T. Yao et al., 2022; Zhao et al., 2012). On the other hand, we only analyzed the recycling process of extreme precipitation in terms of the water factor and quantitatively highlighted the crucial role of evapotranspiration. The atmospheric circulations indicate that an anomalous cyclone over CA and anomalous anticyclones near Lake Baikal

Figure 3. The trajectory clusters and moisture-source contributions for extreme precipitation in TS and KL. 10days back-trajectory clusters of extreme precipitation for (a) TS and (b) KL, and the bottom-left corners represent the proportion of each trajectory cluster. The spatial patterns of contributions from moisture sources to (c, d) extreme precipitation during 1982–2019 and to (e, f) all precipitation (≥0.1 mm) during 2010–2019 for (c, e) TS and (d, f) KL. (g) The total contributions from major moisture sources regions to extreme precipitation in TS and KL during 1982–2019. (h) The difference of contribution from major moisture sources between extreme precipitation and all precipitation. The black boxes in (c–f) represent the defined geographic regions: North Atlantic Ocean (NAO: 60°W–0°, 30°–70°N), Northern Europe (NE: 0°–60°E, 50°–70°N), Northern Asia (NA: 60°–140°E, 50°–70°E), the Mediterranean region (MR: 0°–50°N, 30°–50°N), Central Asia (CA: 55°–75°E, 30°–50°N), Xinjiang and its vicinity (XJV: 75°–95°E, 30°–50°N), Eastern Asia (EA: 95°–130°E, 20°–50°N), and Northern Indian Ocean (NI: 30°–95°E, 0°–30°N).

and eastern Europe are responsible for extreme precipitation in Xinjiang (Figure S8 in Supporting Information S1). Ma et al. (2021) investigated the variability and mechanisms of extreme precipitation in eastern CA from a multiscale synergy perspective, which showed that increased high-latitude North Atlantic SST via adjusting the quasi-stationary wave train guided the cyclonic anomaly in CA, deepened the Lake Balkhash trough. Meanwhile, mesoscale vortices observed by satellite were stimulated and strengthened in front of the trough. However, how the convection trigger and water vapor converges rapidly during extreme precipitation are still unclear and need to be further studied. Moreover, compared to TS, KL experienced a more pronounced change in the precipitation recycling process. In consideration of wind shear and steep terrain in Tarim Basin, two layer-DRM considering strong wind shear and higher resolution data from numerical modes are necessary to investigate water cycles more accurately in the basin subsequently (Dominguez et al., 2016, 2020; Van et al., 2013).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

MERRA2 reanalysis data are available from https://disc.gsfc.nasa.gov/datasets?project=MERRA-2. The GIMMS NDVI dataset (NDVI3.1g) can be found at https://climatedataguide.ucar.edu/climate-data/ndvi-normalized-difference-vegetation-index-3rd-generation-nasagfsc-gimms. The observed daily precipitation provided by the China Meteorological Agency: http://data.cma.cn/data/cdcdetail/dataCode/A.0012.0001.html. Due to the data policy in China, these data records are not available via a website for public download. However, anyone could contact the China Meteorological Data Service Center (http://data.cma.cn/en) or the China Meteorological Administration (CMA) (http://www.cma.gov.cn/en2014/aboutcma/contactus/) for detailed information on data acquisition.

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