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Special Section:
The land-air coupling over Tibetan Plateau and its global climate effects

The Mechanism of Increasing Summer Water Vapor Over the Tibetan Plateau

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Key Points:

- The summer water vapor over Tibetan Plateau (TP) is significantly increasing with a dominant increasing (decreasing) over the western (eastern) TP
- The increasing trend of summer water vapor over TP is dominated by the internal cycle of the water cycle
- The increasing evaporation could strengthen the internal cycle of water cycle over western TP

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Abstract

Rapid warming over the Tibetan Plateau (TP) has been associated with an increasing trend in atmospheric water vapor content, which is critical for recharging the Asian water tower. However, the mechanism associated with the wetting phenomenon remains unclear. Long-term changes in moisture balance and precipitation (PRE) recycling processes are investigated using the ERA5 reanalysis from 1979 to 2019. The increasing trend over TP is mainly due to the summer water vapor trend with significantly increases over the western TP. Based on the moisture balance analysis, it is found that PRE, evaporation, and the convergence of moisture are all increasing over the western TP but decreasing over the eastern TP. Based on the dynamical PRE recycling model, the results suggest that both internal and external cycles contributes to the wetting over TP, with 63.87% and 36.13% contributions respectively. Further analysis found that the atmospheric heating source is also increasing over the western TP, which could shift the moisture transportation from east to west at the southern boundary of TP. The increasing moisture convergence could enhance PRE, and the enhanced latent heating in the mid-atmosphere can further induced moisture convergence, which forms a positive feedback. However, an opposite situation occurred over the eastern TP. The internal and external cycle of the water cycle can stimulate (suppress) each other through PRE over the western (eastern) TP. This mechanism linked the changes in the PRE recycling and atmospheric circulation, and induced the increasing trend over TP in summer.

1. Introduction

The Tibetan Plateau (TP) is one of the highest plateaus globally, with an average altitude of over 4,000 meters, and is known as the Asian water tower. Large amounts of terrestrial water are stored in this "Asian water towers" in glaciers, snow, lakes, and rivers. It's the source of over 12 important Asian rivers, including the Indus, Ganges, Brahmaputra, Yangtze, and Yellow Rivers, which provide essential water resources for more than two billion people (Cuo & Zhang, 2017; Curio & Scherer, 2016; Gao et al., 2018; Immerzeel et al., 2019; Yao et al., 2012). In summer, the humidity in the overlying atmosphere over TP is much higher than its surround regions (X. Xu et al., 2008). X. Xu et al. (2008) proposed that the TP is a global atmospheric "water tower" due to its heating pump affect and found a great relevance with trans-hemispheric transport of water vapor and energy. The water vapor from Indian and Pacific oceans converges over TP and produces precipitation (PRE) to recharge its underlying Asian water tower. However, studies have shown evidences that the water storage in the Asian water tower is decreasing significantly due to the global warming (Immerzeel et al., 2019; Yao et al., 2012, 2019), which may threaten the life of billions of people. The sustainable recharges of the Asian water tower are increasingly recognized as a serious, worldwide public environmental concern. Therefore, many researchers have attempted to explore the variation of the Asian water tower and its risk in the future under climate change (Immerzeel et al., 2010, 2019; Yao et al., 2019). However, the variations of the atmospheric water tower, which is the only source of supply for the Asian water tower, and the mechanisms causing these variations have not been comprehensively investigated, which is critical in understanding the response of the Asian water tower under global warming.

TP is one of the most sensitive regions to climate change (Bibi et al., 2018; Yang et al., 2014). Since the second half of the twentieth century, TP has experienced more significant warming with twice of the global mean warming rate (Duan & Xiao, 2015). The enhanced warming has led to a series of changes in the hydrological cycles, including vegetation greening (W. Zhang et al, 2017; Zhong et al., 2019), glacier degradation, permafrost melting, runoff increasing (Sun et al., 2020) and lake expansion (Song et al., 2014; Yang et al., 2017; G. Zhang et al., 2020). Although the overall terrestrial water storage over TP is decreasing dramatically, the moisture storage in the atmosphere (quantified as total column water vapor (TCWV)) and PRE show increasing trends (Bibi et al., 2018; Sun et al., 2020; Yang et al., 2011; Zhao & Zhou, 2019). For instance, Sun et al. (2020) pointed out that the PRE over the Inner TP (also called the Qiangtang Plateau) has increased since the mid-1990s. How the changes observed in the terrestrial water branch can affect the variation of atmospheric water vapor over TP through evaporation (ET) and PRE remains unclear.

Generally, the atmospheric water vapor comes from local ET within the region (PRE recycling or internal cycle) and externally advected moisture (external cycle) (Dirmeyer & Brubaker, 2007; Dominguez et al., 2019, 2006; Eltahir & Bras, 1996; Gimeno et al., 2012). For a monthly or longer time scale, the atmospheric moisture budget is balanced by PRE, ET, and moisture convergence. The PRE recycling ratio indicates the ratio of the PRE evaporated from local (internal cycle), with the remaining portion coming from remote moisture sources (external cycle). In summer time, solar radiation can efficiently heat the air column over the TP that is of smaller total mass than neighboring regions due to its high altitude, and it can induce large-scale near-surface cyclonic circulation (Wu et al., 2019). As a result, the TP becomes an immensely sensible-heat-driven air pump with large amounts of moisture converging from the surrounding region toward the TP. Therefore, the moisture from outside of TP contributes 70% of total PRE for summertime TP, with the remaining 30% coming from local ET (Hua et al., 2015; Wu et al., 2019; Xu & Gao, 2019). However, the enhanced warming is affecting this balance between the internal and external cycles. For example, the lakes located in the inner TP region have significantly expanded due to the melting of glacier or permafrost (G. Zhang et al., 2020), which could increase the ET and strengthen the internal cycle. On the other hand, the moisture convergence associated with the external cycle can also be affected by the variation of heating source. Such heating can be induced by latent heating (associated with PRE) and greenhouse warming effect, which can trigger positive feedbacks to enhance moisture convergence over TP and therefore rainfall (Duan et al., 2018).

Given the fact of the increasing atmospheric water storage over TP that are of great social-economic relevance, and the possible pathways that can affect moisture storages over TP, the questions we want to address are: What is the dominant mechanism for the wetting of atmospheric water vapor over TP? How do the local recycling and moisture convergence from remote moisture sources contribute to the wetting, and what is the role of atmospheric heating source (AHT)? Answers to these questions are critical for understanding the variations of atmospheric water vapor over TP and predicting future hydrological changes, including glaciers, lakes, and runoffs over TP.

This study aims to understand the mechanism of increasing water vapor over TP by investigating the moisture recycling and transport processes for the years 1979–2019. The rest of this study is arranged as follows. Section 2 describes the data and methodology used in this study, including the Dynamical Recycling Model (DRM) and heating source calculation. Section 3 examines the monthly climatology and trend of atmospheric water vapor over the TP, the variations of moisture budget and recycling processes and their quantified contributions. We further investigate the interaction between the internal and external cycles through the influence of heating source. Section 4 discusses the linkage between those processes, and Section 5 presents a summary of this study.

2. Data

2.1. Reanalysis Data Set and In Situ Data

Lack of in-situ observational data is one of the most important factors limiting research on the TP due to high altitude and complex terrain (B. Wang et al., 2020; Y. Wang et al., 2020). To overcome this difficulty, satellite and reanalysis data sets are widely used in recent studies (e.g., Z. Wang et al., 2017; Zhao & Zhou, 2019), while extra caution should be taken when interpreting reanalysis-based results due to the lack of assimilating observation data over the TP. In this study, we use the ERA5 reanalysis data-set, which is the latest state-of-the-art reanalysis produced by the European Center for Medium-Range Weather Forecasts

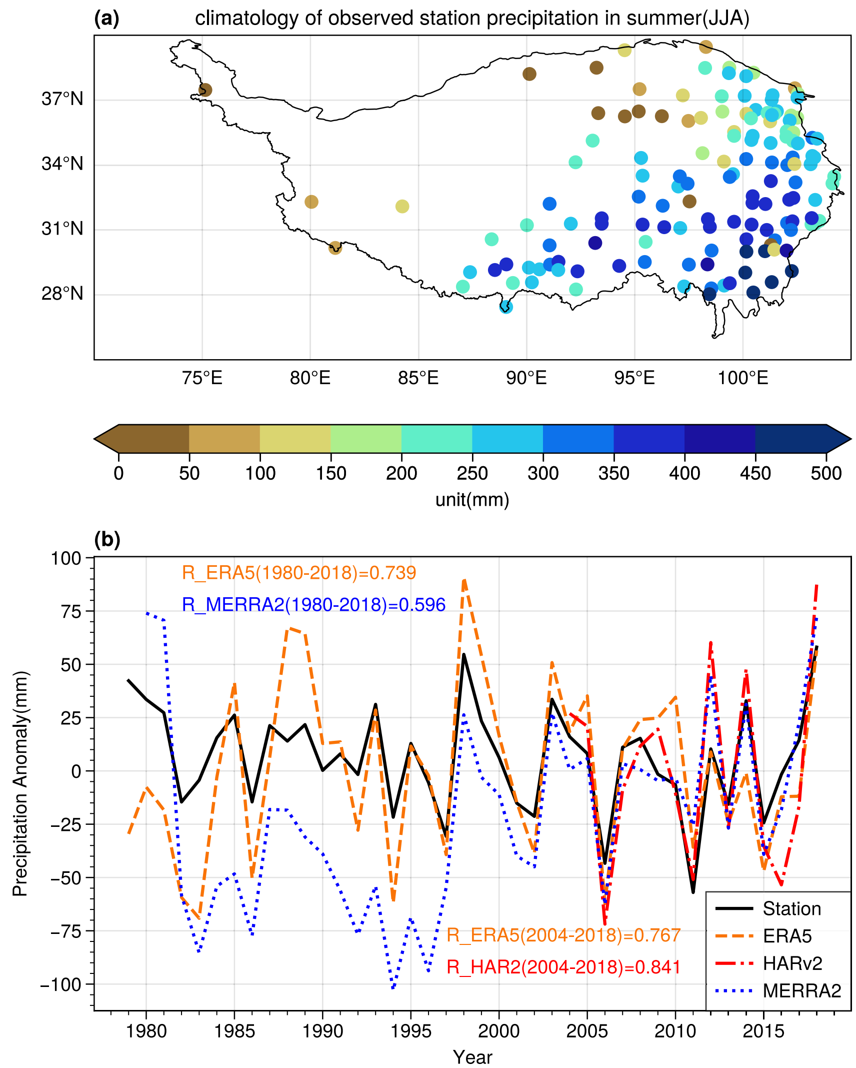

Figure 1. (a) The distribution of the climatology of summer precipitation from CMA stations over TP during 1979–2018. (b) Time series of mean precipitation anomaly over the TP relative to the period of 2004–2018 from different data sets. Reanalysis data sets were first interpolated to the stations by bilinear method. The correlations with station observations are shown as Pearson correlation coefficient and exceed the 95% confidence level. CMA, China Meteorological Administration; TP, Tibetan Plateau.

(ECMWF) (Hersbach et al., 2020). It represents a significant improvement and performs better in capturing the spatial pattern of the annual cycle of TCWV over the TP than other reanalysis data sets (Zhao & Zhou, 2019).

To analyze the water balance in the atmosphere and to explain its changes in recent decades, we used the monthly TCWV, PRE, ET, and vertically integrated moisture divergence (VIMD) from the ERA5 reanalysis data set (Hersbach et al., 2020). The resolution is 0.25 × 0.25 horizontally, with 37 levels in the vertical direction. It covers the period from January 1979 to December 2019. The climatology was calculated from the mean values from 1979 to 2019. To further attribute the increasing of atmospheric vapor over TP to local and remote moisture contributions, we drive the DRM with daily precipitable water, PRE and ET, and hourly specific humidity and wind field.

To evaluate the quality of ERA5 over the TP, other three PRE data sets were used. One is monthly PRE observations during 1979–2018 from the China Meteorological Administration (CMA). There are 143 stations over the TP, which have the continued observations since 1979 as shown in Figure 1a. Second is the annual PRE data from the High Asia Refined analysis version 2(HARv2), which is generated by dynamical downscaling of global ERA5 using the Weather Research and Forecasting (WRF) model (X. Wang et al., 2021). HARv2 covers the period of 2004–2018, and has a high spatial resolution of 10 km. Third is the monthly PRE data from the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA2; Gelaro et al., 2017) produced by NASA's Global Modeling and Assimilation Office. MERRA2 has a spatial resolution of 0.5° × 0.625° in near real-time since from 1980.

2.2. The Analysis of Water Balance Budget

Based on previous studies (Dominguez et al., 2006; Trenberth et al., 2011; Z. Wang et al., 2017), the changes of TCWV is associated with PRE, ET, and moisture convergence through the balance of moisture as shown in below equation:

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

where ω represents TCWV, $-\nabla \cdot Q$ represents moisture convergence, E represents ET, P represents PRE, and res represents the residual term. The non-closure of water moisture is mainly induced by the data assimilation methods in the Reanalysis data set.

2.3. The Description of the DRM

Many methods to quantify moisture contributions from local and remote sources to local PRE exit, including isotopic tracer methods (Kurita & Yamada, 2008; Yang et al., 2006), PRE recycling models (Budyko, 1974; Eltahir & Bras, 1994; Hua et al., 2015; van der Ent et al., 2010; Xu & Gao, 2019) and Lagrangian models (Sodemann et al., 2008; Stohl et al., 2008; Sun & Wang, 2014). Due to the nature of question to investigate long-term variability of the PRE recycling process and the limitations of some methods for such application (e.g., isotopic tracer methods that are often limited to short-term and smaller-scale applications), we use the Dynamic recycling model, which is a semi-Lagrangian analytical model and suitable for long-term studies due to its computational efficiency. DRM is derived from the conservation equation of atmospheric water vapor (Equation 1; see Dominguez et al., 2006 for more details) and can be used to calculate the PRE recycling ratio (the contribution from local evapotranspiration to total PRE) measuring the relative contribution of local water vapor to regional PRE.

The DRM assumes that water vapor from different sources in the atmosphere's vertical direction can mix sufficiently well, which is one of the simplifications used in many PRE recycling models (Goessling & Reick, 2011). Based on this assumption, the ratio of advected to evaporated water vapor in the atmospheric column is equal to the ratio of advected PRE to recycled PRE as shown in Equation 2. Where the subscripts a and m refer to the advected and recycled components, respectively (Dominguez et al., 2006).

$$\frac{P_a}{P_m} = \frac{W_a}{W_m} \text{ or } \frac{P_m}{P} = \frac{W_m}{W}, \tag{2}$$

Using the vertical integration of the conservation of water vapor equation, the recycling equation in grid i could be derived as below (the subscription i is omitted for convenient):

$$\frac{\partial \rho}{\partial t} + \vec{V} \cdot \nabla \rho = \frac{(1-\rho)E}{W}, \tag{3}$$

where E and W indicate ET and precipitable water, respectively. $\vec{V}$ is the water vapor velocity, which is obtained by calculating the average of each layer's wind velocity in the vertical direction weighted by specific humidity. Integrating Equation 3 along the trajectory of water vapor in Lagrangian coordinates derive the local PRE recycling rate $\rho(s)$ as below:

$$\rho(s) = 1 - \exp\left[-\int_{s0}^{s} \left(\frac{E}{W}\right) ds\right], \tag{4}$$

where s_0 is the starting point of the moisture trajectory, and ρ(s) can be approximated by performing a numerical integration along the moisture trajectory. For any given area, the regional PRE recycling rate can be calculated as below:

$$\rho = \frac{P_m}{P} = \frac{\sum_{i=1}^{n} \rho_i P_i \Delta A_i}{\sum_{i=1}^{n} P_i \Delta A_i}, \tag{5}$$

where ΔA_i represents the area of the grid i (Hua et al., 2015, 2016; Dominguez et al., 2006, 2019). Differing from previous analysis models that usually assume negligible storage changes, DRM takes account for the water vapor storage term and thus is suitable for calculating PRE recycling rates on daily time scales. It has been a useful tool for linking weather processes with PRE recycling (Hu & Dominguez, 2015; Martinez & Dominguez, 2014). Therefore, a few recent studies have applied DRM in TP to investigate the PRE recycling ratio (Hua et al., 2015, 2016).

2.4. Heating Source

In the 1950s, Flohn (1957) proposed that the summer TP become a heat source due to the enhanced sensible and latent heating over the high-altitude terrain, and the atmospheric heat source is a physical quantity that reflects the heat budget of the air column. Positive values of heat sources indicate net heat income to the air column. The gained heat needs to be dissipated through dynamic processes such as cold advection and ascending cooling. Yanai et al. (1992) and M. Wang et al. (2011) used the indirect and direct algorithm to verify this conclusion. Here, we used the indirect algorithm proposed by Yanai et al. (1992), the equation is as below:

$$Q_1 = c_p \left(\frac{p}{p_0} \right)^k \left[\frac{\partial \theta}{\partial t} + \vec{V} \cdot \nabla \theta + \omega \frac{\partial \theta}{\partial p} \right], \tag{6}$$

where c_p (=1,005 J/Kg/K) is the constant volume specific heat, p_0 (=1,013.25 hPa) is the sea level pressure, $k = 0.286$, L (=2.5×10^6 J/kg) is the constant associated with latent heat, p is the barometric pressure, θ is the potential temperature, ω is the vertical velocity (hPa / s), ∂t is a partial differentiation of time, and V is a vector of horizontal velocities. Note that we vertically integrate the right-hand terms to obtain Q_1.

3. Results

3.1. The Evaluation of ERA5 Over the TP

The applicability of ERA5 over the TP was evaluated before investigating the increasing trend of water vapor using this data set. Zhao and Zhou (2019) have evaluated the quality of the TCWV over the TP among multiple satellite and reanalysis data sets. They found that ERA reanalysis data set performs well in reproducing the climatology and interannual variability of the water vapor over the TP. To evaluate the PRE, Figure 1 shows the climatology of observed PRE in the stations from the CMA. The PRE from ERA5, HARv2 and MERRA-2 were first interpolated to the stations by using bilinear interpolation method. The time series of annual PRE from four data sets were compared in Figure 1b. Consistent with previous study (Hamm et al., 2020), the climatology of PRE from the ERA5 is much higher than that of the station observations from CMA. However, for the period of 1980–2018, the correlation coefficient between the ERA5 and station observations reach 0.752 with 99% confidence level, which is higher than that between MERRA-2 and station observations. For the period of 2004–2018, the ERA5 has a considerable ability to capture the interannual variability compared with HARv2. Therefore, the PRE in the ERA5 is able to capture the long-term trends and help with identifying climate change features.

3.2. The Long-Term Trend of Summer Water Vapor Over TP

Figure 2 shows the monthly climatology and trends of TCWV over TP, showing evident increasing trends of the atmospheric moisture from 1979 to 2019. The atmospheric water tower was recharged from January to July and was discharged from August to December (Figure 2). Due to the heating pump effect, the

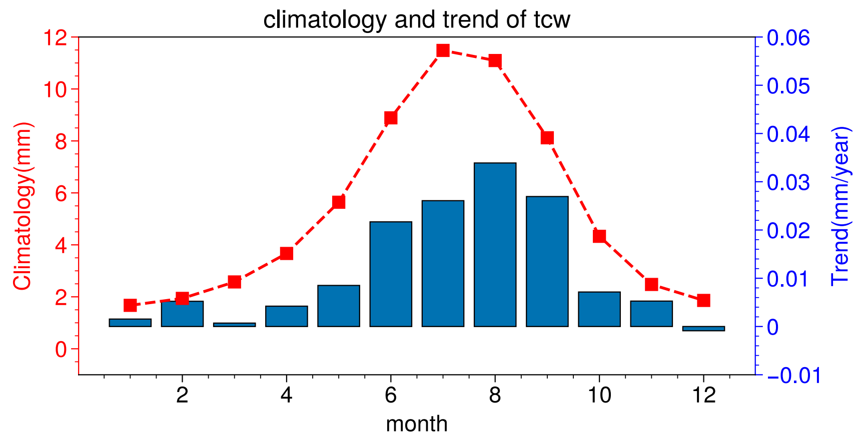

Figure 2. Monthly climatology (lines) and trends (bars) of averaged total column water during 1979–2018.

climatology of TCWV have peak values in summer months, when maximum increasing trends also occur. Comparing the trend of TCWV in summer and winter, the results suggest that the increasing TCWV was mainly caused by the summer recharge period, especially in June–September. Therefore, we focus on the mechanism of increasing TCWV in the summer season. The results from June to September are similar to that from June to August.

Figure 3 shows the time series of mean summer TCWV on the TP during 1979–2019 and the distribution of climatology and trend of summer TCWV on the TP during 1979–2019. The results suggest that the

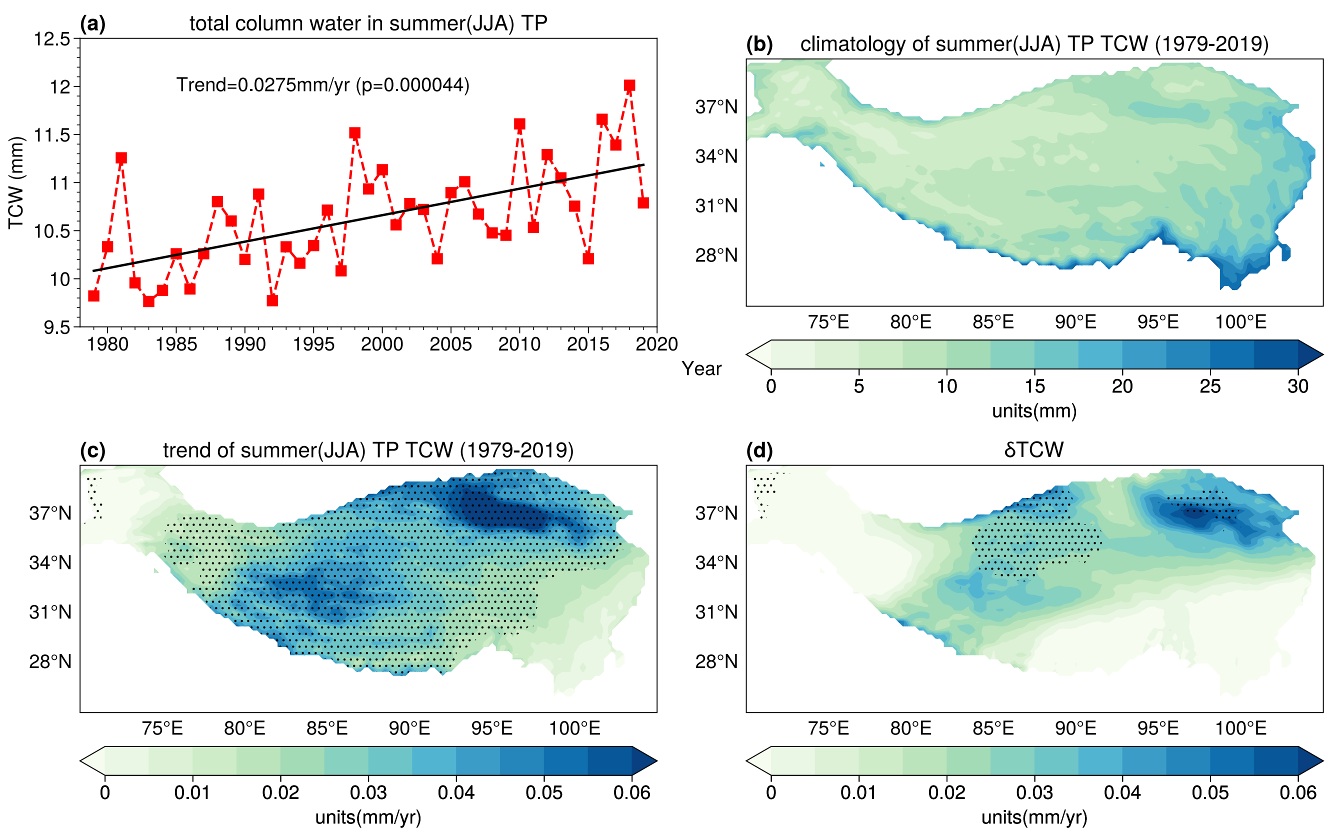

Figure 3. (a) The time series of mean total column water in summer (June–August) on the Tibetan Plateau (TP) during 1979–2019; the distribution of climatology (b) and trend (c) of summer total column water on the TP during 1979–2019; (d) is similar to (c), but for the changes of total column water. The dotted areas indicate statistical significance exceeding 95%.

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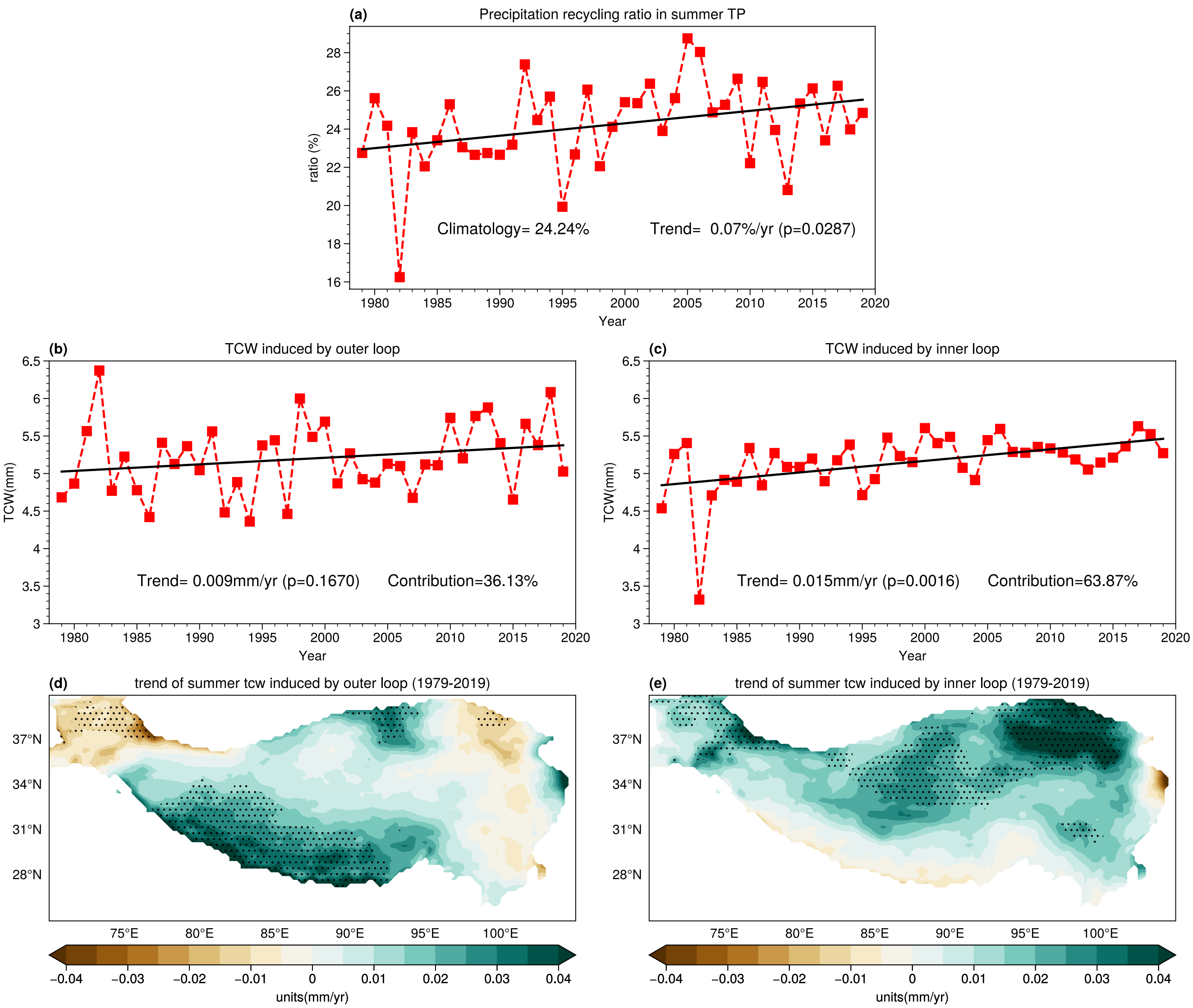

Figure 4. (a) The time series of summer (June–July) precipitation recycling ratio over TP during 1979–2019. The time series of total column water vapor associated with the external (b) and internal (c) cycles of water cycle during 1979–2019. The trend map of TCWV is associated with the external (d) and internal (e) cycles during 1979–2019. * indicates significance at the 90% level. TCWV, total column water vapor.

increasing TCWV in summer is dominated by the increasing trend over the western of TP and Qaidam basin (Figure 3c). Previous studies (Feng & Zhou, 2012; K. Xu et al., 2020) have found that there are two summer moisture transport pathways: One is a southwesterly route from the Arabian Sea and Bay of Bengal to the southeast of the TP by the Indian summer monsoon, and the other is a south branch route from the mid-latitude westerly winds to the south of the TP. Feng and Zhou (2012) suggest that the first route is an essential source of water vapor that influences the interannual variability of summer PRE on the southeastern part of the TP. However, the increasing trend of TCWV is mainly in the western part of the TP and the Qaidam Basin; there is no significant increasing trend in the southeast of TP. To investigate the variation of TCWV in summer, we examine the terms in the moisture balance equation in the next section.

3.3. The Contribution of the Internal and External Cycles to the Trend of TCWV

Given the changes in different terms in the water balance terms, we now examine how these components affect the changes in moisture contributions from local evapotranspiration and remote sources to TP using DRM. We calculate the PRE recycling ratio in summer from 1979 to 2019 from the ERA5 database. Figure 4 shows that the climatology of PRE recycling ratio over TP is 24.24%. Such estimation is consistent with previous studies: Hua et al. (2016) estimated it to be about 25% for the annual mean and approaching 30% in summer by using DRM based on the Japanese 55-years Reanalysis data-set; Gao et al. (2020) used the water tracer method coupled with the WVT-WRF and got a higher estimation (~40%) possibly related with the overestimated summer PRE in their simulation. These demonstrated that DRM can capture the PRE recycling process.

During the past four decades, PRE recycling ratio (contribution from TP's evapotranspiration) significantly increased with a trend of 0.07%/yr, which has passed the significance test with 90% confidence level. Further dividing the TCWV into those produced by the external and internal cycle of water cycle, it can be seen that they are both increasing, with trends of 0.00875 mm/yr and 0.01546 mm/yr, respectively (Figures 4b and 4c). Therefore, the increasing trend over TP is mainly contributed by the internal cycle, reaching 63.87%, which is higher than the external cycle (36.13%). Comparing the distribution of their trends, the internal cycle has significant increases over western TP and Qaidam basin, which is consistent with the increasing local ET and PRE (Figure 4c). The increasing TCWV associated with the external cycle mainly occurred in the southern TP, especially to the west of 92°E, which is induced by the strengthening of local moisture convergence and PRE (Figure 4d). The TCWV produced by the external cycle over eastern TP has a decreasing trend, which contributes to the difference of the trend of TCWV between the eastern and western TP. This finding is consistent with that of Xu & Gao (2019), who found that the decreasing ET in the Indian Ocean is responsible for the decreasing PRE over southeastern TP.

3.4. The Variation of Atmospheric Moisture Budget Over TP

To investigate the mechanism of variation of summer TCWV, we examine the variation of PRE, ET, and moisture convergence from the perspective of the atmospheric moisture budget. First, we investigate the trend and climatology of summer PRE on the TP (Figure 5). Based on the climatology distribution, maximum values of summer PRE occurred in the southeastern part of TP and decreases from the southeastern to the northwestern TP (Figure 5b). Consistent with previous studies (Feng & Zhou, 2012; K. Xu et al., 2020), the primary source of moisture on the TP is the Arabian Sea and the Bay of Bengal, which brings warm and wet moisture from the Indian summer monsoon into the southeastern TP. In terms of PRE trends, the mean PRE over TP shows an increasing trend of 0.762 mm/yr ($p < 0.05$), with a significant increasing trend in the western and a decreasing trend in the southeastern part of TP, which is the opposite with the climatology distribution (Figure 5c). Their trends have passed the Student's t-test with 95% confidence.

Consistent with the PRE pattern, ET maximizes in the southeast part of TP. But, we see the most significant increasing trend of ET in the western part of the Plateau (Figure 6). We note that the fluctuation of ET in 2009–2015 with lower-than-climatology values is related to the interdecadal variation of circulation associated with the Atlantic multidecadal oscillation (AMO) (Sun et al., 2020). However, the long-term increasing trend is evident and significant. Under the significant warming over TP, the melting of glaciers and snow cover (G. Zhang et al., 2020), and the expansion of lakes over the inner TP (Yang et al., 2017), contribute to the increasing ET (B. Wang et al., 2020). Besides, the increasing PRE over western TP also contributes to the increased ET. The consistently increasing PRE and ET over western TP suggest that the internal cycle may be strengthening.

We also examine the trend of moisture convergence (Figure 7). The distribution of climatology of moisture convergence is highly consistent with that of PRE, showing maximum values in the southeast boundary. In terms of trends, similar dipole pattern in TCWV and PRE are also found for the trend of moisture convergence: A decreasing trend over the eastern TP and an increasing trend over the western TP. The contrasting trends between the western and eastern TP we find in TWV, PRE and moisture convergence suggest that their hydrological cycle may respond to global warming in a different way.

3.5. The Influence of Heating Source on the Moisture Transportation

The changes of hydrological recycle process is related to the moisture transport. In the following, we further investigate the moisture convergence changes by the variations of water vapor transportation over the TP. Figure 8 shows the climatology and trend of water vapor flux of the TP in four boundaries. From the water

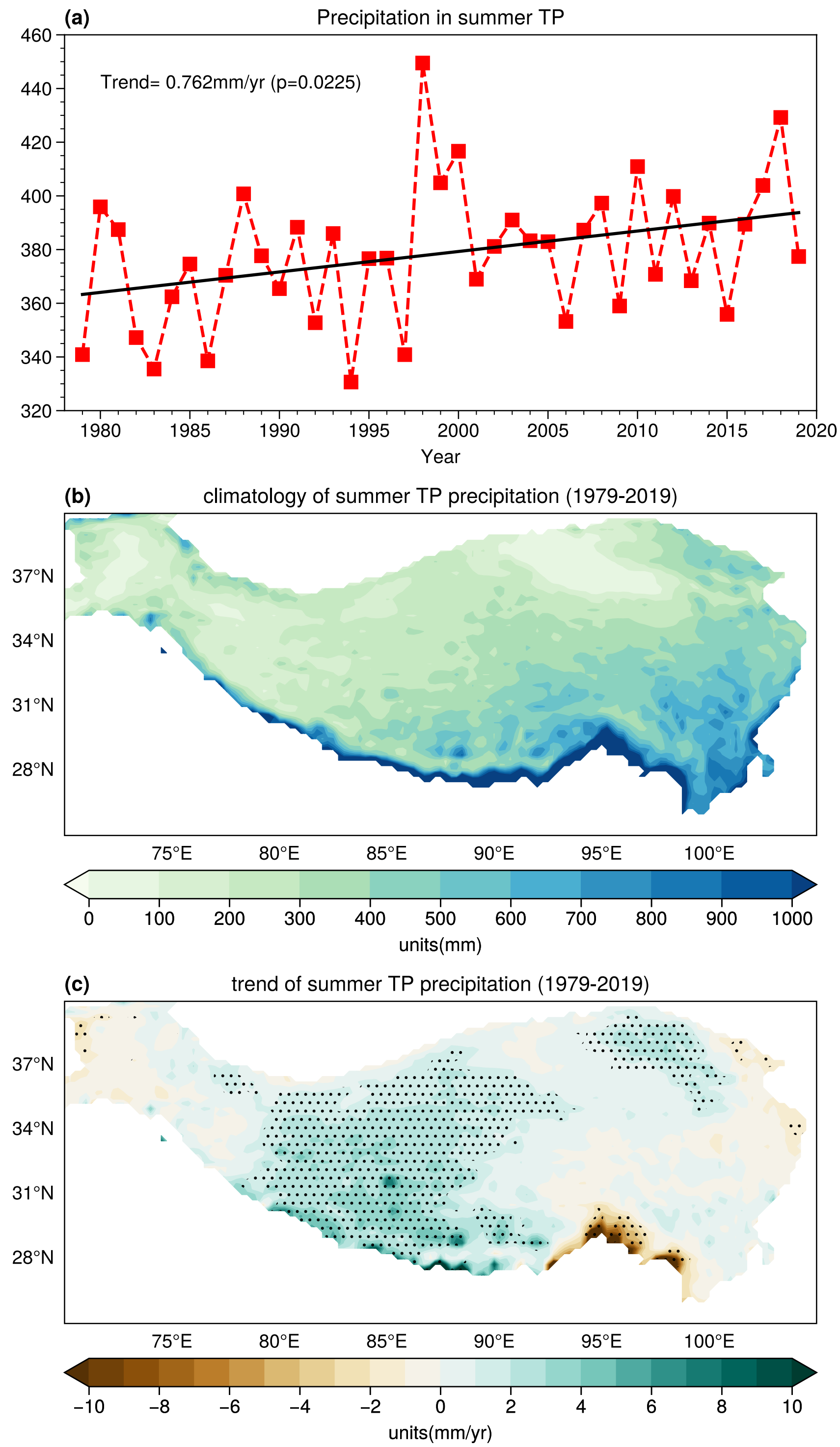

Figure 5. (a) Time series of total precipitation in summer (June and July) on the Tibetan Plateau (TP); the distribution of climatology (b) and trend (c) of summer total precipitation on the TP. The dotted areas indicate statistical significance exceeding 95%.

vapor flux in four directions, the water vapor fluxes in the west and south boundaries are inflow stream, representing inputs of water vapor and primary moisture sources. The water vapor fluxes in the east and north boundaries are outflow streams representing the output channel of water vapor. To understand the changes in water vapor transportation, the interannual variation and trend of water vapor fluxes in four

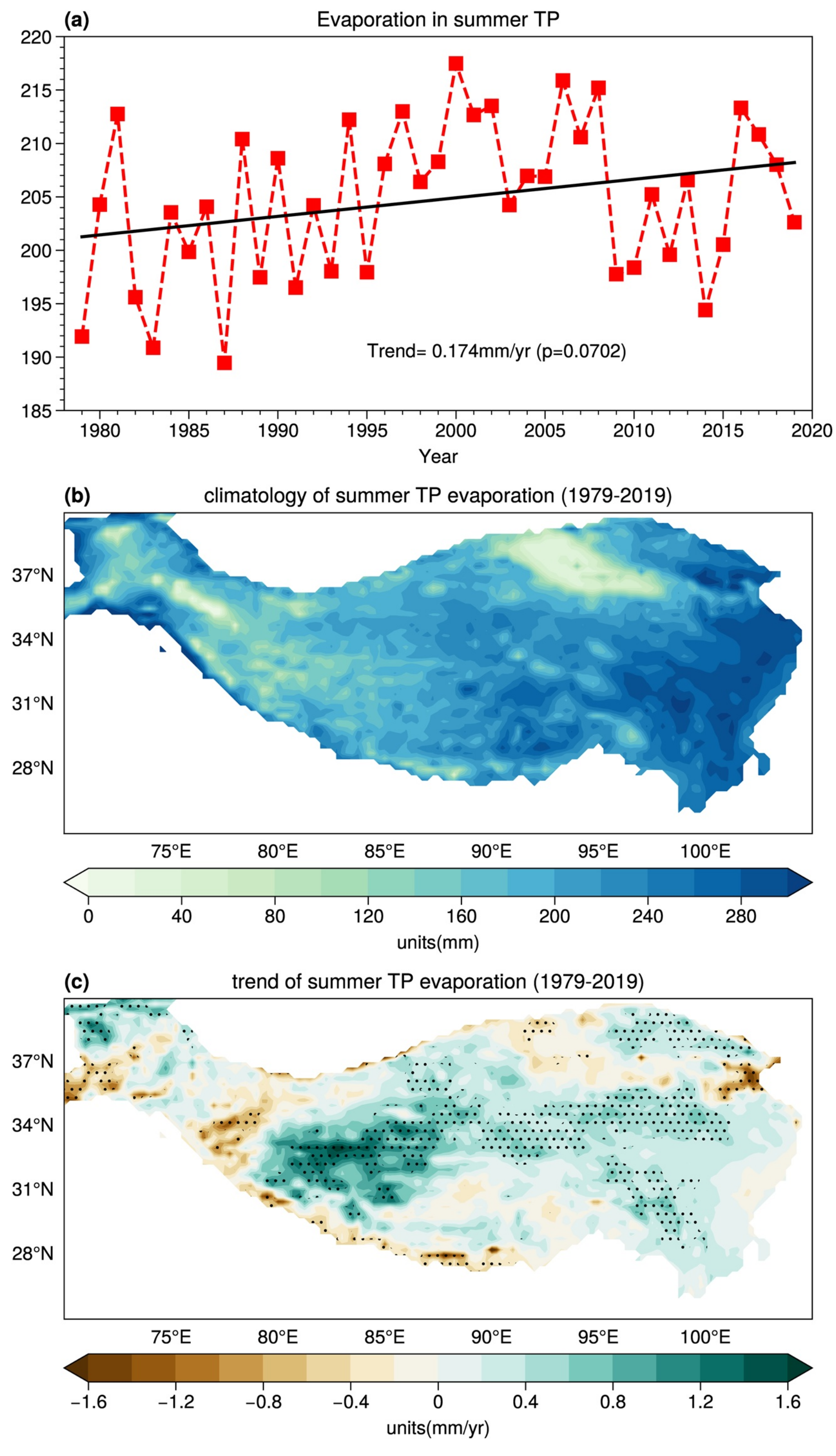

Figure 6. Same as Figure 5, but for evaporation. The dotted areas indicate statistical significance exceeding 95%.

boundaries are investigated in Figures 8b and 8c. The results suggest that the water vapor fluxes in the west and south boundaries do not change significantly. There is a significant decreasing trend in the water vapor flux of the north boundary with interannual fluctuations. However, the water vapor flux in the north boundary did not contribute to the increase of TCWV due to the positive trend. The changes in water vapor flux are most pronounced in the east boundary, showing a clear decreasing trend of outward flow, which

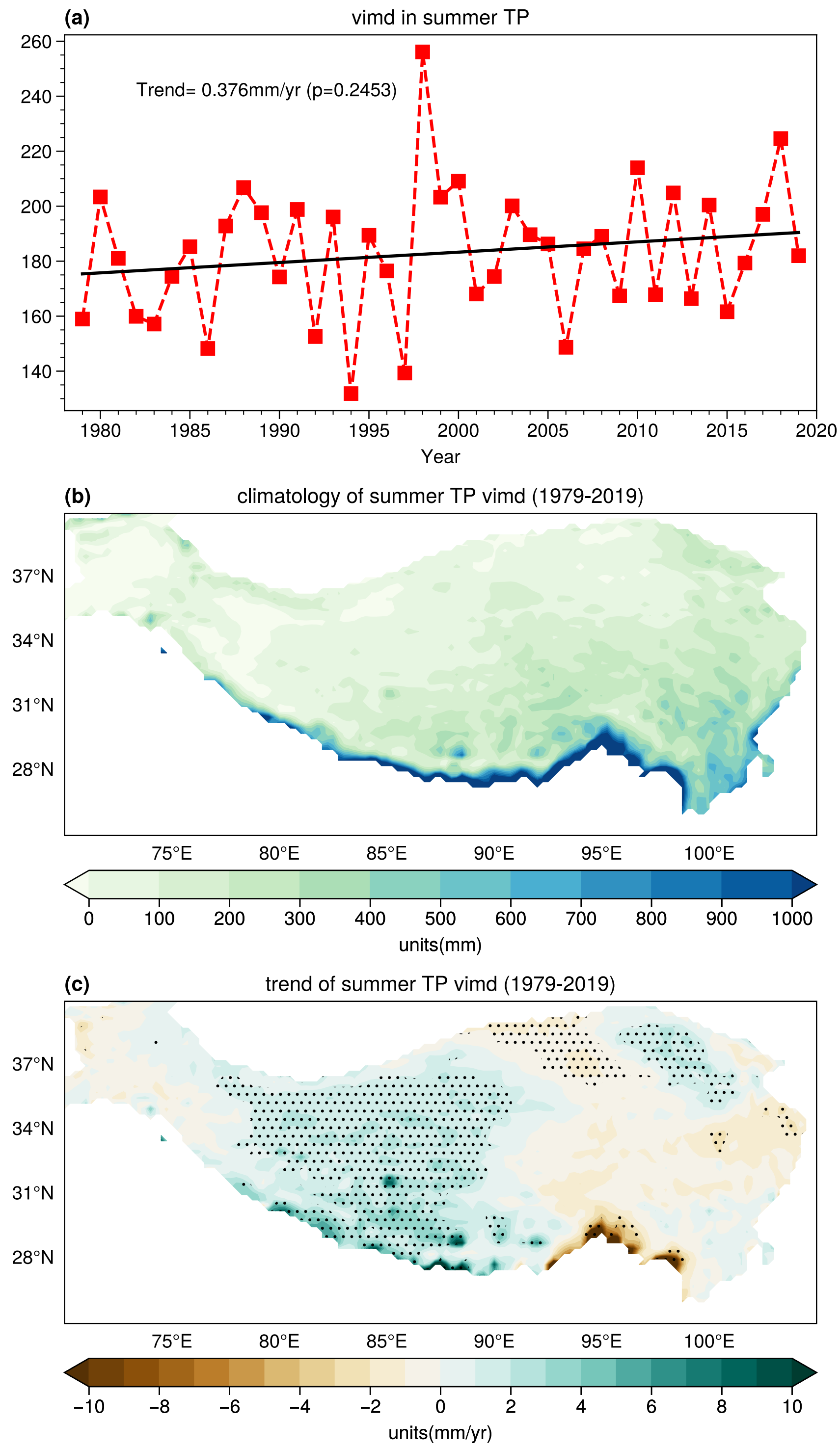

Figure 7. Same as Figure 5, but for vertically integrated moisture divergence (VIMD). Here, the values of VIMD have been multiplied −1 indicating convergence. The dotted areas indicate statistical significance exceeding 95%.

is associated with the decreasing water vapor transport from Indian Ocean (K. Xu et al., 2020). Therefore, the decreasing outflow of moisture from the east, with insignificant changes to the west, south, and north, explains the increase in the summer TCWV and PRE over TP. It is noted that although the higher TCWV is due to the reduction of the moisture fluxes at the eastern boundary, it only demonstrates the increase in

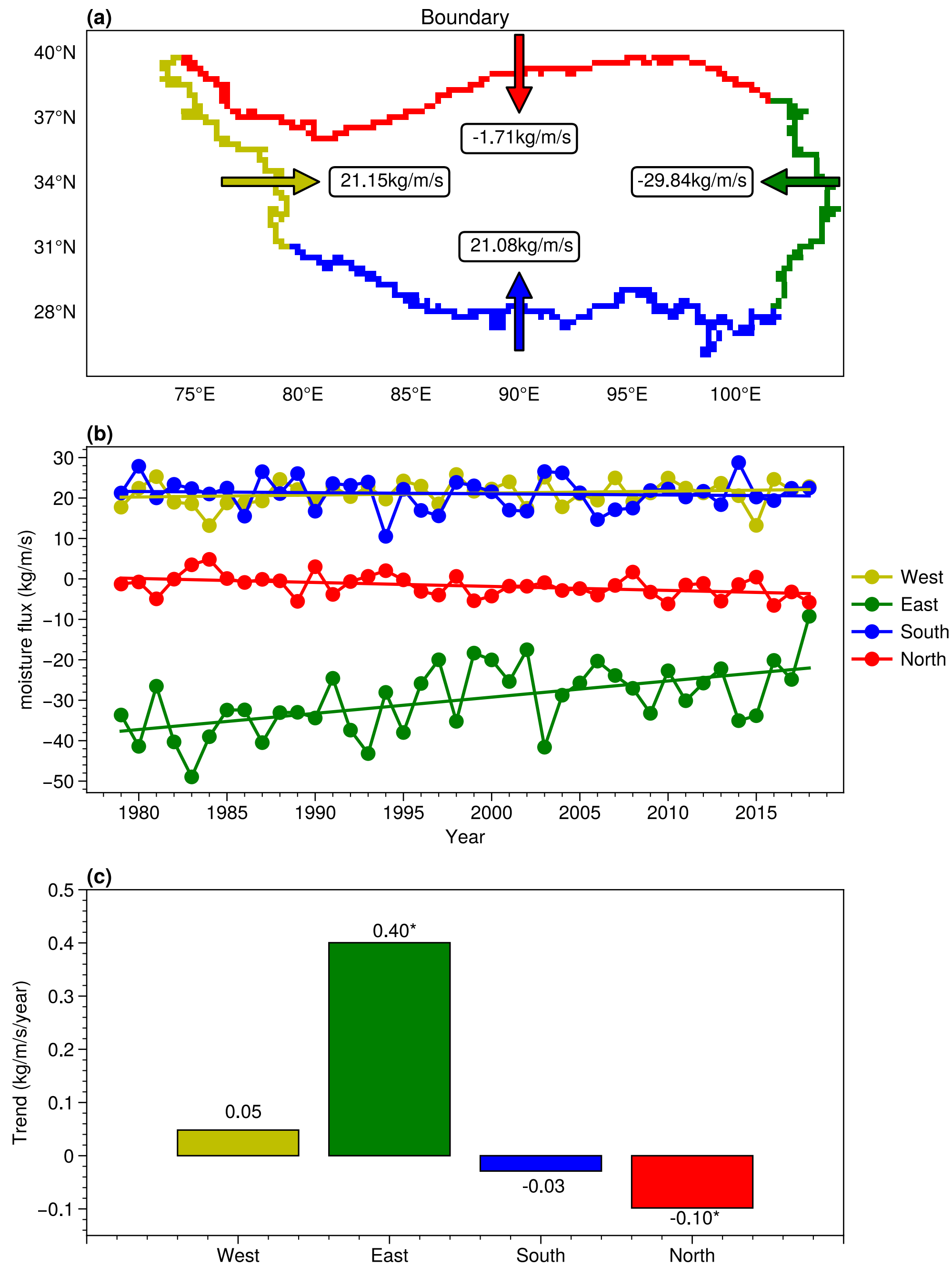

Figure 8. (a) The climatology of vertically integrated summer moisture transport based on the ERA5 data-set for 1979–2019. The arrows and associated values represent the direction and intensity of moisture flux transport at each boundary. Positive (negative) fluxes indicated the inflow (outflow) water vapor flux. The time series (b) and trend (c) of water vapor fluxes in four boundaries of Tibetan Plateau in the summer season.

moisture convergence averaged over TP, which does not contradict the pattern with most wetting trends located at western TP.

Given the fact that the moisture convergence over the eastern TP has a slightly decreasing trend, the increasing water vapor flux on the east boundary is possibly induced by the decrease in water vapor, which is related with water vapor transportation. Therefore, we investigate the trend of water vapor flux at the southern boundary of TP along longitude (Figure 9a). The results show that the trend of water vapor flux on the south boundary is found to be positive to the west of 92°E and be negative to the east of 92°E.

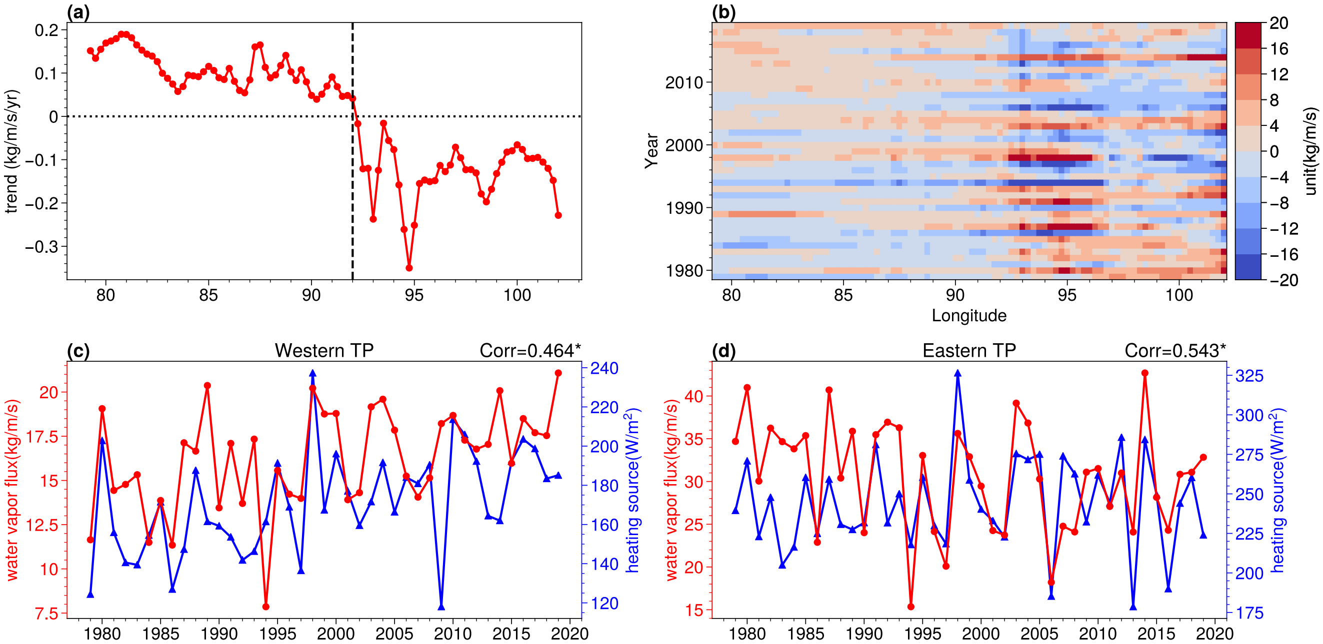

Figure 9. (a) The distribution of trend of water vapor flux at the southern boundary of Tibetan Plateau (TP) along longitude; (b) time-longitude evolution of the water vapor flux at the southern boundary of TP. (c) Time series of the water vapor flux on the west of 92°E at the southern boundary (red line) and heating source over western TP (blue line) in summer. (d) Time series of the water vapor flux on the east of 92°E at the southern boundary (red line) and heating source over eastern TP (blue line) in summer. The numbers located in the right corner is the correlation coefficients between water flux and heating source over western and eastern TP. The star (*) indicates the correlation coefficients are significant at the 0.05 level.

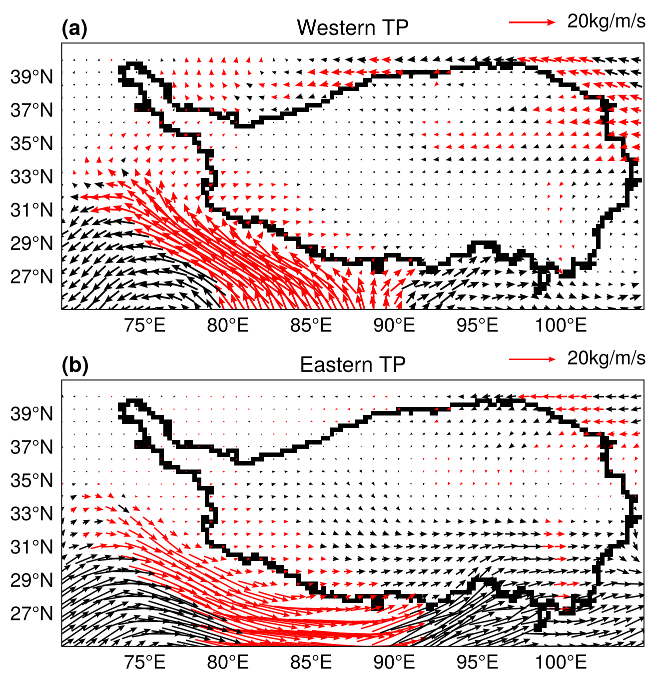

Figure 10. Regression patterns of vertically integrated moisture transport against the averaged heating source over western TP (a) and eastern TP (b). The red vectors indicate the statistical significance at the 95% confidence level. The units are kg/m/s. The bold black lines denote the topographic height of 2,500 m. TP, Tibetan Plateau.

Figure 9b shows the time-longitude evolution of the water vapor flux at the southern boundary of TP. To the west of longitude 92°E, there is a gradual increase from negative to positive, while to the east, there is a corresponding decreasing trend (Figure 9b). These results suggest that the water vapor transportation at the southern boundary has weakened in the east and strengthened in the west. To investigate the influence of the variation of heating source on the shift of water vapor transportation, we analyzed their relationship between the water vapor flux and the heating source over the eastern and western TP. The result suggests that they have a significant relationship, with their correlation coefficients of 0.464 and 0.543, respectively (Figures 9c and 9d). To further confirm the above analysis, Figure 10 shows the regression patterns of moisture transport against the eastern and western TP heating source. Similarly, the water vapor flux to the west of longitude 92°E is mainly influenced by the western heating source, whereas the eastern heating source dominates the water vapor flux to the east. Therefore, the contrast changes of heating sources between the west and east TP induce a westward shift of water vapor transportation from the Indian Ocean and then reduce the water vapor flux at the east boundary.

With the significant warming in the TP in recent decades, along with the increasing trend of PRE and water vapor convergence in the west and a decreasing trend in the east, what is the role of heating source in inducing these changes? To answer this question, we investigate the AHT over TP (Figure 11). During 1979–2019, the AHT over TP shows a significant increasing trend with 0.648 $W/m^2/yr$. In climatology, the AHT's maximum values occur in the eastern TP, which is consistent with PRE and moisture convergence (Figures 11b). However, there is a significant strengthening

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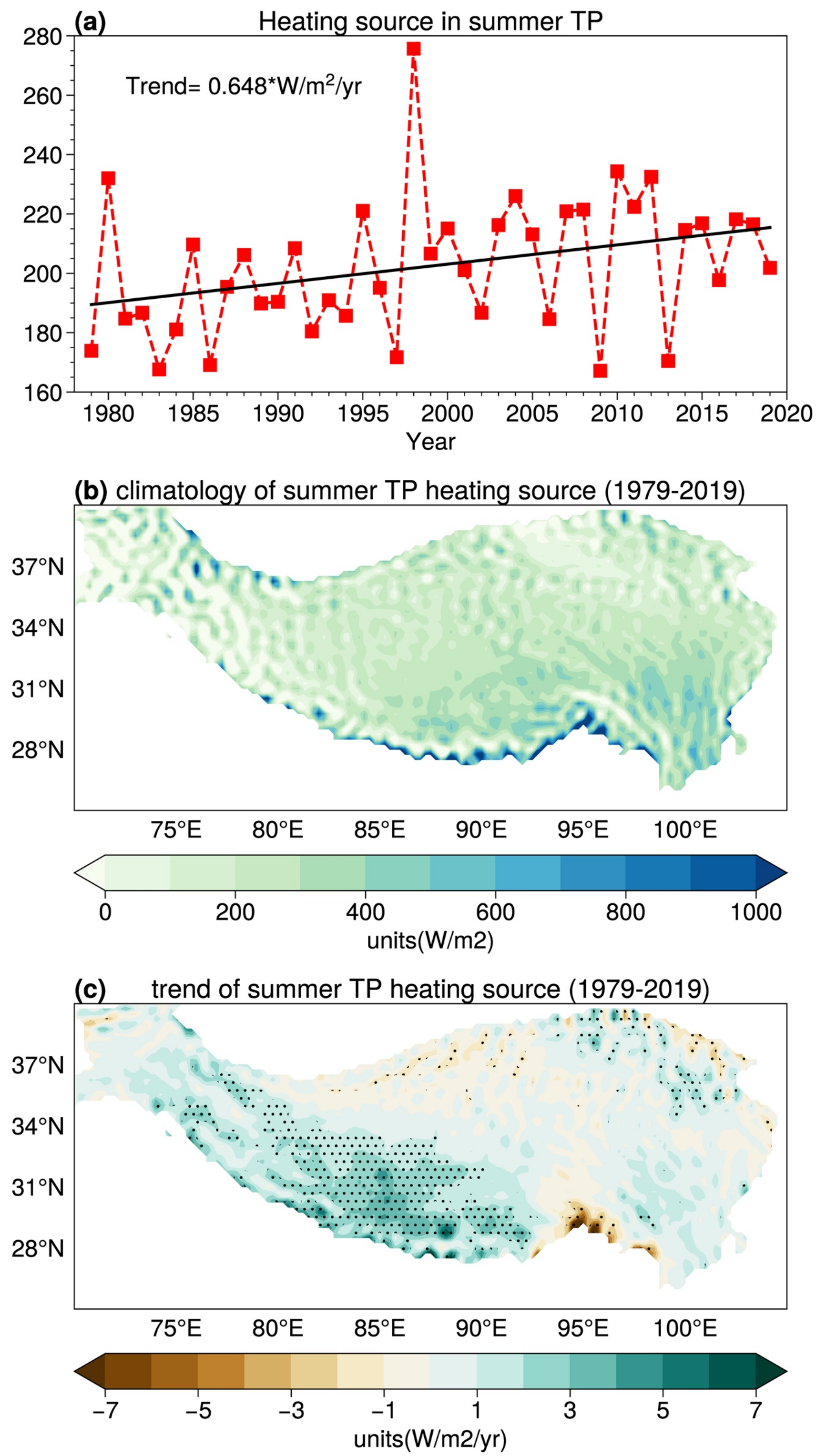

Figure 11. Same as Figure 5, but for the heating source.

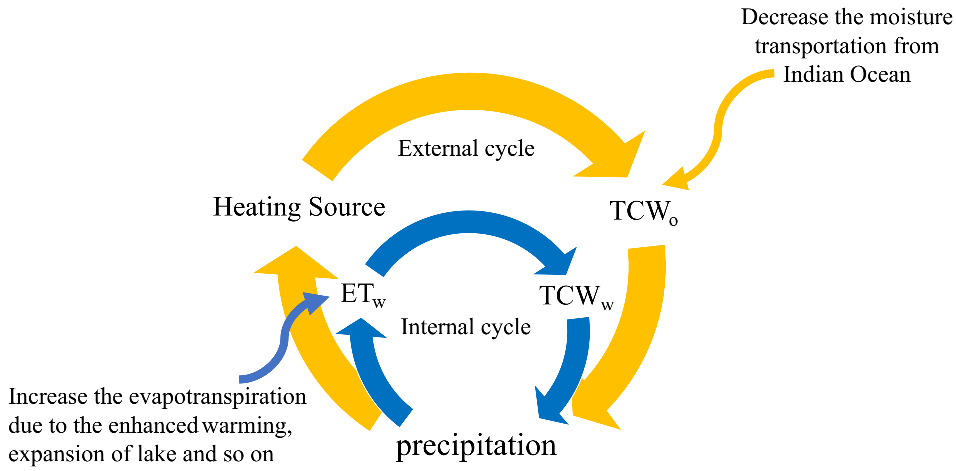

Figure 12. Schematic illustration of the couple between the internal and external cycle of water cycle on the Tibetan Plateau. Subscript *w* and *o* represent the water vapor that evaporates within the region and outside the region, respectively.

trend in the western TP in terms of trends and no significant strengthening or even a decrease trend in the eastern TP, especially in the Brahmaputra river (Figures 11c). Atmospheric heat sources can reflect the energy budget of the air column and have an essential effect on PRE, ET, and moisture convergence by altering the transportation of water vapor. The most pronounced trend in reducing heat sources may be induced by a decrease in the latent heating release from PRE, which is associated with water vapor transportation from the Indian Ocean.

4. Discussion

4.1. The Linkage Between the Shift of Water Vapor Transportation and the Precipitation Recycling Process

We have demonstrated that the increasing trend of TCWV is mainly caused by the increasing trend over the western TP in summer, which is mainly associated with the strengthening of the internal cycle (i.e., PRE recycling). The following provides a preliminary physical picture on how the PRE recycling affects the increasing (decreasing) trend of TCWV over the western (eastern) TP.

The mechanism explaining the changes in the internal and external cycle has been summarized as the schematic diagram (Figure 12). For the western TP, the enhanced warming and the expansion of lakes induced by the glacier's melting could significantly enhance the internal cycle of water cycle by increasing the ET and then the PRE. The latent heating from PRE caused by the internal cycle can also enhance the external cycle by increasing the heating source and moisture convergence. Therefore, the hydrological cycle over the western TP is accelerating, driven by the enhanced warming and the expansion of lakes. For the eastern TP, the external cycle of the hydrological cycle is decelerating under global warming. In response to the increasing heating source over the western TP, the original water vapor transportation in the eastern TP weakens, especially over the Brahmaputra river. When the Indian Ocean's moisture transportation decreases, the heating source would also decrease due to weakened latent heating from PRE, then the external cycle decelerates. The decreasing PRE induced by the weakened external cycle can then reduce the ET and weaken the internal cycle. The interaction between the internal and external cycles of atmospheric moisture could induce positive feedbacks to enhance the hydrological cycle's response to rapid warming over TP. The resultant changes in PRE have induced increasing heating source over the western TP and decreasing heating source over the eastern TP, which could shift the water vapor transportation at the southern boundary of TP. Therefore, the changes in water vapor transportation can also contribute to the increasing trend over TP. It should be pointed out that water vapor could transport from the Arabian Sea to the Inner TP. Dong et al. (2016) proposed that water vapor was first lifted to the mid-troposphere by enhanced convection over the Indian subcontinent and was then advected into the Inner TP by enhanced southwest winds. However, the shift of water vapor transportation has a considerable uncertainty due to the reanalysis data set's quality. Therefore, additional work will be required to investigate this phenomenon.

4.2. Driver of the Long-Term Trend of the Precipitation Recycling Process

The above mechanism explains the contrast responses of PRE recycling to global warming over the western and eastern TP; however, their drivers were different. The increased ET triggered the strengthening internal cycle of water cycle over western TP due to the enhanced warming, the expansion of lakes and so on. Sun et al. (2020) found that the lake's expansion is mainly induced by PRE, which is significantly correlated with the AMO on interdecadal time scales. They point out that the AMO during the positive phase could induce an anomalous anticyclone to the east of the Inner TP, weakening the westerly winds and traps water vapor. However, the mechanism they proposed may not explain the long-term increasing trend over TP. The long-term trend of PRE over TP is possibly related to the rapid warming, although the interannual and decadal variation of summer PRE was significantly correlated with north Atlantic oscillation (Z. Wang et al., 2017) and AMO (Sun et al., 2020). On the other hand, the decelerated external moisture cycle over the eastern TP was caused by the decreased water vapor transportation from the Indian Ocean. This phenomenon was not only associated with the increasing heating source over western TP, but it was also influenced by the variation of ET over the Indian Ocean (Xu & Gao, 2019).

5. Conclusions

The increasing trend of TCWV over TP has an important effect on the Asian water tower; however, its mechanism remains unclear. Based on the ERA5 reanalysis data set from the ECMWF, the variation of summer TCWV over TP and its mechanism was investigated. We found that the annual TCWV shows a significant increasing trend, which is mainly contributed by the summer season, especially from June to August. Further investigation suggests that summer TCWV shows contrast changes between the western and eastern TP. PRE, ET, and moisture convergence all show increasing trends in the western TP but decreasing trends in the eastern TP. These changes are associated with the response of the hydrological cycle's internal and external cycle (i.e., local recycling and moisture convergence) to the enhanced warming over TP. Based on the DRM simulation, the TCWV contributed by the external cycle is increasing in the western and decreasing in the eastern, which is consistent with the analysis of terms in the water-balance equation. However, the TCWV associated with the internal cycle increases over the western and eastern TP due to the increasing local ET. The result suggests that the increasing trend of summer TCWV is contributed by the internal cycle (63.87%) and external cycle (36.13%). The PRE recycling process accelerated (decelerated) over the western (eastern) TP, which is mainly related to the heating source. Due to the increased heating source over the western TP, the water vapor transportation from the Indian Ocean also shift to the west of longitude 92°E.

However, it is a fact that the ERA5 reanalysis data-set overestimates the PRE and wind speed in summer due to the influence of complex terrain (Z. Wang et al., 2017). The simulation could significantly reduce the error of wind speed and PRE when the resolution reach 3 km (Y. Wang, et al., 2020). However, the cost of simulation with high resolution is too expensive to simulate the long-term hydrological variation over TP. Therefore, the response of the internal and external cycles of the hydrological cycle to global warming over TP remains uncertain based on the reanalysis data set and additional verifications in the model simulations are needed in the future.

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Data Availability Statement

The ERA5 data are available from https://cds.climate.copernicus.eu.

References

Bibi, S., Wang, L., Li, X., Zhou, J., Chen, D., & Yao, T. (2018). Climatic and associated cryospheric, biospheric, and hydrological changes on the Tibetan Plateau: A review. *International Journal of Climatology*, *38*, e1–e17. https://doi.org/10.1002/joc.5411

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

Cuo, L., & Zhang, Y. (2017). Spatial patterns of wet season precipitation vertical gradients on the Tibetan Plateau and the surroundings. *Scientific Reports*, *7*(1), 5057. https://doi.org/10.1038/s41598-017-05345-6

Curio, J., & Scherer, D. (2016). Seasonality and spatial variability of dynamic precipitation controls on the Tibetan Plateau. *Earth System Dynamics*, *7*(3), 767–782. https://doi.org/10.5194/esd-7-767-2016

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

Dominguez, F., Hu, H., & Martinez, J. A. (2019). 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., Ming, Y., Xie, Y., Wang, B., et al. (2016). Summer rainfall over the southwestern Tibetan Plateau controlled by deep convection over the Indian subcontinent. *Nature Communications*, *7*, 1–9. https://doi.org/10.1038/ncomms10925

Duan, A., Liu, S., Zhao, Y., Gao, K., & Hu, W. (2018). Atmospheric heat source/sink dataset over the Tibetan Plateau based on satellite and routine meteorological observations. *Big Earth Data*, *2*(2), 179–189. https://doi.org/10.1080/20964471.2018.1514143

Duan, A., & Xiao, Z. (2015). Does the climate warming hiatus exist over the Tibetan Plateau? *Scientific Reports*, *5*(1), 13711. https://doi.org/10.1038/srep13711

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

Feng, L., & Zhou, T. (2012). Water vapor transport for summer precipitation over the Tibetan Plateau: Multidata set analysis. *Journal of Geophysical Research*, *117*(D20), D20114. https://doi.org/10.1029/2011jd017012

Flohn, H. (1957). Large-scale aspects of the "Summer Monsoon" in south and east Asia. *Journal of the Meteorological Society of Japan*, *35A*, 180–186. https://doi.org/10.2151/jmsj1923.35A.0_180

Gao, Y., Chen, F., Lettenmaier, D. P., Xu, J., Xiao, L., & Li, X. (2018). Does elevation-dependent warming hold true above 5000 m elevation? Lessons from the Tibetan Plateau. *npj Climate and Atmospheric Science*, *1*(1), 19. https://doi.org/10.1038/s41612-018-0030-z

Gao, Y., Chen, F., Miguez-Macho, G., & Li, X. (2020). Understanding precipitation recycling over the Tibetan Plateau using tracer analysis with WRF. *Climate Dynamics*, *55*, 2921–2937. https://doi.org/10.1007/s00382-020-05426-9

Gelaro, R., McCarty, W., Suárez, 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*(14), 5419–5454. https://doi.org/10.1175/jcli-d-16-0758.1

Gimeno, L., Stohl, A., Trigo, R. M., Dominguez, F., Yoshimura, K., Yu, L., et al. (2012). Oceanic and terrestrial sources of continental precipitation. *Reviews of Geophysics*, *50*(4), RG4003. https://doi.org/10.1029/2012RG000389

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

Hamm, A., Arndt, A., Kolbe, C., Wang, X., Thies, B., Boyko, O., et al. (2020). Intercomparison of gridded precipitation datasets over a sub-region of the central Himalaya and the Southwestern Tibetan Plateau. *Water*, *12*(11), 3271. https://doi.org/10.3390/w12113271

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

Hu, H., & Dominguez, F. (2015). Evaluation of oceanic and terrestrial sources of moisture for the North American monsoon using numerical models and precipitation stable isotopes. *Journal of Hydrometeorology*, *16*(1), 19–35. https://doi.org/10.1175/JHM-D-14-0073.1

Hua, L., Zhong, L., & Ke, Z. (2015). Characteristics of the precipitation recycling ratio and its relationship with regional precipitation in China. *Theoretical and Applied Climatology*, *127*(3–4), 513–531. https://doi.org/10.1007/s00704-015-1645-1

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

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., et al. (2019). Importance and vulnerability of the world's water towers. *Nature*, *577*(7790), 364–369. https://doi.org/10.1038/s41586019-1822-y10.1038/s41586-019-1822-y

Immerzeel, W. W., van Beek, L. P. H., & Bierkens, M. F. P. (2010). Climate Change will affect the Asian water towers. *Science*, *328*(5984), 1382–1385. https://doi.org/10.1126/science.1183188

Kurita, N., & Yamada, H. (2008). The role of local moisture recycling evaluated using stable isotope data from over the middle of the Tibetan Plateau during the monsoon season. *Journal of Hydrometeorology*, *9*(4), 760–775. https://doi.org/10.1175/2007JHM945.1

Martinez, J. A., & Dominguez, F. (2014). Sources of atmospheric moisture for the La Plata river basin. *Journal of Climate*, *27*(17), 6737–6753. https://doi.org/10.1175/JCLI-D-14-00022.1

Sodemann, H., Schwierz, C., & Wernli, H. (2008). Interannual variability of Greenland winter precipitation sources: Lagrangian moisture diagnostic and north Atlantic Oscillation influence. *Journal of Geophysical Research*, *113*(3), 1–17. https://doi.org/10.1029/2007JD008503

Song, C., Huang, B., Richards, K., Ke, L., & Hien Phan, V. (2014). Accelerated lake expansion on the Tibetan Plateau in the 2000s: Induced by glacial melting or other processes? *Water Resources Research*, *50*(4), 3170–3186. https://doi.org/10.1002/2013wr014724

Stohl, A., Forster, C., & Sodemann, H. (2008). Remote sources of water vapor forming precipitation on the Norwegian west coast at 60°N-a tale of hurricanes and an atmospheric river. *Journal of Geophysical Research*, *113*(5), 1–13. https://doi.org/10.1029/2007JD009006

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, J., Yang, K., Guo, W., Wang, Y., He, J., & Lu, H. (2020). Why has the inner Tibetan Plateau become wetter since the Mid-1990s? *Journal of Climate*, *33*(19), 8507–8522. https://doi.org/10.1175/jcli-d-19-0471.1

Trenberth, K. E., Fasullo, J. T., & Mackaro, J. (2011). Atmospheric moisture transports from ocean to land and global energy flows in reanalyses. *Journal of Climate*, *24*(18), 4907–4924. https://doi.org/10.1175/2011jcli4171.1

van der Ent, R. J., Savenije, H. H. G., Schaefli, B., & Steele-Dunne, S. C. (2010). Origin and fate of atmospheric moisture over continents. *Water Resources Research*, *46*(9). https://doi.org/10.1029/2010WR009127

Wang, B., Ma, Y., Su, Z., Wang, Y., & Ma, W. (2020). Quantifying the evaporation amounts of 75 high-elevation large dimictic lakes on the Tibetan Plateau. *Science Advances*, *6*(26), eaay8558. https://doi.org/10.1126/sciadv.aay8558

Wang, M., Zhou, S., & Duan, A. (2011). Trend in the atmospheric heat source over the central and eastern Tibetan Plateau during recent decades: Comparison of observations and reanalysis data. *Chinese Science Bulletin*, *57*(5), 548–557. https://doi.org/10.1007/s11434-011-4838-8

Wang, X., Tolksdorf, V., Otto, M., & Scherer, D. (2021). WRF-based dynamical downscaling of ERA5 reanalysis data for High Mountain Asia: Towards a new version of the High Asia refined analysis. *International Journal of Climatology*, *41*, 743–762. https://doi.org/10.1002/joc.6686

Wang, Y., Yang, K., Zhou, X., Chen, D., Lu, H., Ouyang, L., et al. (2020). Synergy of orographic drag parameterization and high resolution greatly reduces biases of WRF-simulated precipitation in central Himalaya. *Climate Dynamics*, *54*(3–4), 1729–1740. https://doi.org/10.1007/s00382-019-05080-w

Wang, Z., Duan, A., Yang, S., & Ullah, K. (2017). Atmospheric moisture budget and its regulation on the variability of summer precipitation over the Tibetan Plateau. *Journal of Geophysical Research: Atmospheres*, *122*(2), 614–630. https://doi.org/10.1002/2016jd025515

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

Xu, K., Zhong, L., Ma, Y., Zou, M., & Huang, Z. (2020). A study on the water vapor transport trend and water vapor source of the Tibetan Plateau. *Theoretical and Applied Climatology*, *140*(3–4), 1031–1042. https://doi.org/10.1007/s00704-020-03142-2

Xu, X., Lu, C., Shi, X., & Gao, S. (2008). World water tower: An atmospheric perspective. *Geophysical Research Letters*, *35*(20), L20815. https://doi.org/10.1029/2008gl035867

Xu, Y., & Gao, Y. (2019). Quantification of evaporative sources of precipitation and its changes in the southeastern Tibetan Plateau and middle Yangtze River Basin. *Atmosphere*, *10*(8), 428. https://doi.org/10.3390/atmos10080428

Yanai, M., Li, C., & Song, Z. (1992). Seasonal heating of the Tibetan plateau and its effects on the evolution of the Asian Summer Monsoon. *Journal of the Meteorological Society of Japan*, *70*(1B), 319–351. https://doi.org/10.2151/jmsj1965.70.1b_319

Yang, K., Lu, H., Yue, S., Zhang, G., Lei, Y., La, Z., & Wang, W. (2017). Quantifying recent precipitation change and predicting lake expansion in the Inner Tibetan Plateau. *Climatic Change*, *147*(1–2), 149–163. https://doi.org/10.1007/s10584-017-2127-5

Yang, K., Wu, H., Qin, J., Lin, C., Tang, W., & Chen, Y. (2014). Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: A review. *Global and Planetary Change*, *112*, 79–91. https://doi.org/10.1016/j.gloplacha.2013.12.001

Yang, K., Ye, B., Zhou, D., Wu, B., Foken, T., Qin, J., & Zhou, Z. (2011). Response of hydrological cycle to recent climate changes in the Tibetan Plateau. *Climatic Change*, *109*(3–4), 517–534. https://doi.org/10.1007/s10584-011-0099-4

Yang, M., Yao, T., Wang, H., Tian, L., & Gou, X. (2006). Estimating the criterion for determining water vapour sources of summer precipitation on the northern Tibetan Plateau. *Hydrological Processes*, *20*(3), 505–513. https://doi.org/10.1002/hyp.5918

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., et al. (2012). Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change*, *2*(9), 663–667. https://doi.org/10.1038/nclimate1580

Yao, T., Xue, Y., Chen, D., Chen, F., Thompson, L., Cui, P., et al. (2019). Recent third pole's rapid warming accompanies cryospheric melt and water cycle intensification and interactions between monsoon and environment: Multidisciplinary approach with observations, modeling, and analysis. *Bulletin of the American Meteorological Society*, *100*(3), 423–444. https://doi.org/10.1175/bams-d-17-0057.1

Zhang, G., Yao, T., Xie, H., Yang, K., Zhu, L., Shum, C. K., et al. (2020). Response of Tibetan Plateau lakes to climate change: Trends, patterns, and mechanisms. *Earth-Science Reviews*, *208*, 103269. https://doi.org/10.1016/j.earscirev.2020.103269

Zhang, W., Zhou, T., & Zhang, L. (2017). Wetting and greening Tibetan Plateau in early summer in recent decades. *Journal of Geophysical Research: Atmospheres*, *122*(11), 5808–5822. https://doi.org/10.1002/2017jd026468

Zhao, Y., & Zhou, T. (2019). Asian water tower evinced in total column water vapor: A comparison among multiple satellite and reanalysis data sets. *Climate Dynamics*, *54*(1–2), 231–245. https://doi.org/10.1007/s00382-019-04999-4

Zhong, L., Ma, Y., Xue, Y., & Piao, S. (2019). Climate change trends and impacts on vegetation greening over the Tibetan Plateau. *Journal of Geophysical Research: Atmospheres*, *124*(14), 7540–7552. https://doi.org/10.1029/2019jd030481