Interannual Variability of Precipitation Recycle Ratio Over the Tibetan Plateau

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Abstract The water cycle over the Tibetan Plateau (TP) is vital to the regional and downstream climate and ecosystem. Clarifying the water cycle process and its interannual variability mechanism over the TP is important for the climate change adaptation activities. However, our current knowledge about the precipitation recycle ratio over the TP and its interannual variation remains inconclusive. Using the advanced reanalysis data ERA5 of the high resolution and a bulk model method, the water cycle over the TP is estimated in terms of the climatology and interannual variability. The climatic precipitation recycle ratio over the TP in summer is 23%. The reason for the contradictory conclusions between Curio et al. (2015, https://doi.org/10.5194/esd-6-109-2015) and other studies reviewed is analyzed and found to be related to the different definitions of the precipitation recycle ratio associated with the atmospheric water vapor mixture. The interannual variability of the precipitation recycle ratio over the TP in summer is significantly and negatively related with the Niño 3.4 index in the preceding winter. The precipitation recycle ratio decreases to 21.4% due to the more moisture inflow in the El Niño decaying summer. The change in the recycle ratio induced by the preceding El Niño events explains 60% of its interannual variability. The response of precipitation recycle ratio over the TP in summer to the preceding El Niño and La Niña events is asymmetric. Our study is conducive to reach the consensus on the climatic precipitation recycle ratio over the TP and advance our knowledge about its interannual variability mechanism.

1. Introduction

The Tibetan Plateau (referred to as TP hereinafter) is known as the Asian water tower because of its huge storage of glaciers and the TP is the headwaters of many Asian rivers (Immerzeel et al., 2010; T. Yao et al., 2012). The TP can also affect the circulation and the atmospheric moisture transport due to its role of “heat source” (G. Wu et al., 2015; Xu et al., 2008, 2014). The change in water vapor as well as its cycle process over the TP has its own uniqueness and fragility in response to the changing climate system and is vital to the regional and downstream ecosystem (Gao et al., 2014; Gao, Leung, et al., 2015; Gao, Li, et al., 2015; Immerzeel et al., 2010; T. Yao et al., 2012). The TP can also affect the circulation and the atmospheric moisture transport due to its role of “heat source” (G. Wu et al., 2015; Xu et al., 2008, 2014). The change in water vapor as well as its cycle process over the TP has its own uniqueness and fragility in response to the changing climate system and is vital to the regional and downstream ecosystem (Gao et al., 2014; Gao, Leung, et al., 2015; Gao, Li, et al., 2015; Immerzeel et al., 2020; S. Mishra et al., 2020; W. Zhang, Zhou, et al., 2017). Clarifying the water cycle process over the TP and its interannual variability mechanism can advance our knowledge of the change and is important for the climate change adaptation activities.

The precipitation recycle ratio is one important indicator of the water cycle process in the atmosphere, which is defined as the contribution rate of the local evaporation to the total precipitation. Given the importance of the Asian water tower, lots of studies have investigated the precipitation recycle ratio in terms of climatology or longer time scales over the TP, which are summarized in Table 1. According to the definition of the precipitation recycle ratio, these studies can be sorted into two groups: (1) the precipitation recycle ratio is defined as the ratio of climatic local evaporation to the precipitation directly (Curio et al., 2015; referred to as C2015 hereinafter); and (2) the water cycle process is considered more complexly, in which the local evaporation mixes with the external water vapor flux first, then partial evaporation flows out of the TP and the remnant transforms into precipitation. The ratio of the latter part of the evaporation and precipitation is defined as the precipitation recycle ratio (references in Table 1 except for C2015).

As shown in Table 1, under the first definition, the precipitation recycle ratio is more than 63.2% over the TP, which means the local evaporation can sustain more than half of the precipitation over the TP (Table 1 in Curio et al., 2015). Because of the mesoscale systems and convective precipitation, the precipitation is more
sensitive to the local evaporation and the precipitation recycle ratio is higher over the TP than over other areas in China (L. Guo et al., 2018; Hua et al., 2015; Wei & Dirmeyer, 2019). But as summarized in Table 1, although the precipitation is more dependent on local evaporation over the TP, its recycle ratio is no more than 35% under the other definition, which means the precipitation over the TP is still dominated by the external moisture transport (references in Table 1 except for C2015). The climatic precipitation recycle ratio over the TP, or the dominant moisture source of precipitation, remains inconclusive.

The research methods of precipitation recycle ratio can be sorted into three categories: Bulk model (or Analytical model), Euler based model and Lagrange based model. Each kind of the methods has its own advantages and weakness (Gimeno et al., 2012). Bulk model methods, like in Curio et al. (2015) and Brubaker et al. (1993; referred to as B1993 hereinafter), are based on simplified assumptions, which can give the pathway of water vapor transport and the water cycle process in the atmosphere. They have the advantage of simple calculation but are unable to identify the source of the moisture. Euler based methods include water vapor tracer model (Y. Li et al., 2019; C. Zhang, Tang, et al., 2017; Zhang et al., 2019) and atmospheric models with water vapor tracer technology incorporated (Pan et al., 2019), both of which can provide information of moisture sources and water cycle process, but they also have disadvantages of ignoring the vertical shear of the circulation and model dependency. The Lagrange based methods can provide more information about the vertical motion of the particles, but they still suffer from the limited consideration of the cloud process (Chen et al., 2012, 2019; W. Huang et al., 2018; Sun & Wang, 2014; K. Xu et al., 2020; Y. Xu & Gao, 2019; S. Yang et al., 2020).

As introduced above, the contradictory conclusions between Curio et al. (2015) and others studies are related to the different definitions of the precipitation recycle ratio. To clarify the impact of different definitions on precipitation recycle ratio analysis, method B1993 is the optimal choice because both B1993 and C2015 are bulk model methods but they are based on different definitions of precipitation recycle ratio. We therefore hope to find the reason for the contradictory conclusions through comparing results based on the methods of B1993 and C2015. In addition, the above-mentioned methods have been used in lots of studies which mainly focus on the climatic moisture source region of the TP and the long-term trend of the water vapor transport into the TP, however, there is a lack of research on the interannual variability of the precipitation recycle ratio and its mechanism.

In terms of the climatic water vapor source regions of the TP, based on a Lagrange model (FLEXPART), Chen et al. (2012) suggested that the moisture transport to the TP in summer is dominated by a narrow band from the Southern Hemisphere to the Arabian Sea and finally extending to the Indian subcontinent. Water vapor transported from the northwest region and the Bengal Bay is also important. Based on the same model, Chen et al. (2019) divides the TP into four subregions by the point (90°E, 33°N) and analyzes their difference in moisture transport during wet season. The water vapor originated from the nearby region and westerlies domain is important for the northwestern and the northeastern TP and has little subseasonal variation, whereas the moisture over the southeastern and the southwestern TP is dominated by the Indian Summer Monsoon and has corresponding subseasonal variation. Another Lagrangian analysis shows that the land area south of the TP provides 78.7% of the moisture for the wintertime extreme precipitation events over the southeastern TP (W. Huang et al., 2018).

### Table 1

| Reference                        | Period       | Range         | Methods                                           | Recycle ratio   |
|----------------------------------|--------------|---------------|---------------------------------------------------|-----------------|
| Sun and Wang (2014)              | 2000–2009    | Eastern TP    | FLEXPART (Lagrange based)                         | around 10%      |
| Curio et al. (2015)              | 2001–2012    | TP            | Bulk model                                       | 63.2%           |
| C. Zhang, Tang, et al. (2017)    | 1979–2013    | TP            | The modified Water Accounting Model (WAM, Euler based) | 18%             |
| L. Guo et al. (2018)             | 1979–2012    | TP            | Bulk model                                       | 20.83%          |
| Pan et al. (2019)                | 1982–2014    | Northern TP   | CAM5.1 tagging (Euler based)                      | 25.8%           |
| Y. Xu and Gao (2019)             | 1982–2011    | Southeastern TP| QIBT (Lagrange based)                            | 35%             |
| C. Zhang et al. (2019)           | 1979–2016    | TP            | The improved Water Accounting Model (Euler based)  | less than 17%   |

Abbreviation: TP, Tibetan Plateau.
Many studies have analyzed the role of moisture transport change in the precipitation trend over the TP. Based on an Euler tracer model, the increasing precipitation over the central and the western TP during the period of 1979–2013 is found to be related with the increasing moisture influx from the southwest region and the enhanced local supply (C. Zhang, Tang, et al., 2017). For the increasing precipitation over the endorheic TP during the period of 1979–2015, analysis using the same model also shows it is because of the increase in moisture contribution from the Indian Ocean through the western and southern edges in summer (Y. Li et al., 2019). Results from reanalysis data and a Lagrangian tracer model show the water vapor convergence over the TP is enhanced from 1979 to 2018, which is attributed to the increasing contribution rate from the western moisture transport channel (K. Xu et al., 2020). The decreasing precipitation over the southeastern TP during 1982–2011 is attributed to the decrease in the moisture contributed by the Indian Ocean evaporation using a Lagrangian based model (Y. Xu & Gao, 2019). However, using an Euler model, it is found that the drying trend over the southern TP during 1979–2016 is mainly due to the decrease in moisture from the northwest region, although the moisture from the Indian Ocean also decreases. The wetting trend over the northern TP is attributed to the increasing water vapor transport from the southeastern region and the TP itself (C. Zhang et al., 2019). Moisture transport related with large-scale circulation and remote evaporation also contributes to the intensified precipitation events over the TP during the period of 1980–2016 (S. Yang et al., 2020).

In terms of interannual variability, the precipitation over the TP is negatively correlated with moisture transported by the westerlies and positively correlated with the Indian Summer Monsoon and water vapor from nearby regions (Chen et al., 2019). Results from an atmospheric model incorporated with water vapor tracer technology show there will be more water vapor originated from the tropical Indian Ocean flow into the TP in years with strong TP heating, which is related to the dynamic process (Pan et al., 2019). Little research focuses on the interannual variability of the precipitation recycle ratio over the TP. Using a dynamic recycling model with an analytical moisture trajectory tracking method, Hua et al. (2015) finds that the precipitation recycle ratio over the TP is negatively correlated with the total precipitation but positively correlated with the ratio of the convective precipitation to the large-scale precipitation, in which process the clouds induced radiation plays an important role. In spite of these studies, there is still a lack of research about the impact of the large-scale circulation on the precipitation recycle ratio over the TP in terms of interannual variability, as well as the quantitative assessment of the influence of the mechanism.

In this study, based on the advanced high-resolution reanalysis data ERA5, we aim to answer the following questions: (1) Why do two definitions of the precipitation recycle ratio widely used in previous studies lead to contradictory results when applying to the TP? (2) What kind of processes dominate the interannual variability of precipitation recycle ratio over the TP? By addressing these questions, we hope to reach a consensus on the dominant moisture contribution of the precipitation over the TP and advance our knowledge about its interannual variability mechanism.

The remainder of the manuscript is organized as follows. The data used and method B1993 are introduced in Section 2. In Section 3.1, the rationality of the precipitation recycle ratio definition in C2015 is clarified first, then the estimation of the atmospheric water cycle process over the TP is derived in terms of the climatology. In Section 3.2, we will analyze the interannual variability of the precipitation recycle ratio and its mechanism. Finally, the major results are summarized in Section 4.

2. Data and Methods

2.1. Data

The most advanced reanalysis data ERA5 from the European Centre for Medium Range Weather Forecasts (Hersbach et al., 2019a, 2019b, 2020) is used in the analysis. The monthly data during the period of 1979–2018 is used and the analysis focuses on summer (mean of June, July, and August) unless otherwise specified. ERA5 has the highest horizontal spatial resolution of 0.25 degree among the current reanalysis data sets, allowing us to depict the complex topography of the TP in detail. The anomaly version of the Niño 3.4 index is downloaded from the Climate Prediction Center of NOAA (https://psl.noaa.gov/gcos wgsp/Timeseries/Nino34/). A preceding El Niño (La Niña) event is identified if the average Niño 3.4 index during December in last year to February this year is above 0.5 (below −0.5).
The TP area is defined with 14 edges shown in Figure 2a, which is as the same as in Curio et al. (2015). In this way we can exclude the influence of different study areas and concentrate on the impact of different definitions on precipitation recycle ratio. In addition, the 14 sections of the TP domain defined in Curio et al. (2015) and this study are more elaborate than the usual rectangle definition.

2.2. Methods

The vertically integrated water vapor transport is calculated as:

$$F = - \int_{p_{\text{surf}}}^{p_{\text{top}}} \bar{v}_h q \, dp,$$

(1)

where $q$ is the specific humidity (kg kg$^{-1}$), $\bar{v}_h$ is the horizontal wind (m s$^{-1}$), $p_{\text{top}}$ and $p_{\text{surf}}$ mean the pressure at the top and surface atmosphere, respectively. The change in atmospheric moisture is equal to:

$$\frac{\partial Q}{\partial t} = -\left(\frac{\partial F_u}{\partial x} + \frac{\partial F_v}{\partial y}\right) + E - P,$$

(2)

where $Q$ is the total column water vapor (kg m$^{-2}$), $\frac{\partial F_u}{\partial x}$ and $\frac{\partial F_v}{\partial y}$ is the divergence of the moisture flux (kg m$^{-2}$), $E$ and $P$ are evaporation and precipitation, respectively. In terms of climatology, the change in $Q$ is negligible compared to the terms on the right-hand side of Equation 2, so the atmospheric moisture budget is balanced as:

$$P = -\left(\frac{\partial F_u}{\partial x} + \frac{\partial F_v}{\partial y}\right) + E.$$

(3)

As shown in Table 1 in Curio et al. (2015), the definition of the precipitation recycle ratio in Curio et al. (2015) is simply based on Equation 3. The precipitation recycle ratio derived from method C2015 is:

$$\rho = \frac{E}{P}.$$

(4)

Method B1993 is a more reasonable bulk model method to calculate the precipitation recycle ratio (Brubaker et al., 1993; L. Guo et al., 2018; Trenberth, 1999; J. Yao et al., 2020). As shown in Figure 1, if we take the atmosphere over the TP as a box model, the water vapor in it originates from the external advection ($F_u$ in Figure 1) and the local evaporation ($E$ in Figure 1). After mixing in the atmosphere, partial of the atmospheric moisture transforms into the precipitation ($P$ in Figure 1) and the other flows out of the TP ($F_{\text{out}}$ in Figure 1). In other words, the outflow of the water vapor and the precipitation over the TP both consist of external transported water vapor ($F_{\text{out}, u}$ and $P-a$ in Figure 1) and evaporation moisture ($F_{\text{out}, e}$ and $P-e$ in Figure 1). The precipitation recycle ratio is the ratio of the $P-e$ to $P$.

Like the Equation 3, the precipitation originated from external moisture advection ($P_a$) is balanced as:

$$P_a = -\left(\frac{\partial F_{u, a}}{\partial x} + \frac{\partial F_{v, a}}{\partial y}\right).$$

(5)

where the term on the right-hand side is the convergence of the external moisture advected.
The method B1993 is mainly based on three assumptions as follows: (1) The change in the storage of the atmospheric water vapor is small enough to be ignored comparing with the moisture flux at the sufficiently long timescales (like monthly in this study), shown as the Equation 3; (2) The water vapor from the local evaporation and the external transport is well mixed in the atmosphere; and (3) Precipitation, evaporation and Pa are constant within the region of interest.

Based on the third assumption and the Gauss divergence theorem, Equations 3 and 5 can be written as:

\[(P - E)A = F^{in} - F^{out},\]  \hspace{1cm} (6)

\[P_aA = F^{in} - F^{out},\]  \hspace{1cm} (7)

where \(A\) is the area of the region, \(F^{in}\) and \(F^{out}\) are the inflow and outflow the atmospheric water vapor, respectively. \(F^{out}\) is the outflow of the advected external moisture. As shown in Equations 6 and 7, \(F^{out}\) and \(F^{out}_{a}\) are linearly related with \(F^{in}\), so the mean moisture flux in the atmosphere can be represented as the arithmetic average of the inflow and outflow:

\[\bar{F} = \frac{F^{in} + F^{out}}{2} = \frac{F^{in}}{2} + \frac{(E - P)A}{2},\]  \hspace{1cm} (8)

\[\bar{F}_a = \frac{F^{in} + F^{out}_{a}}{2} = \frac{F^{in}}{2} - \frac{P_aA}{2}.\]  \hspace{1cm} (9)

According to the second assumption, the ratio of the evaporated water vapor and the advected water vapor is equal in both precipitation and the atmospheric moisture flux:

\[\frac{P_a}{P} = \frac{\bar{F}_a}{\bar{F}}.\]  \hspace{1cm} (10)

Applying Equations 8 and 9 to the Equation 10, the contribution of external moisture advection to the precipitation can be derived as:

\[\frac{P_a}{P} = \frac{2F^{in}}{2F^{in} + EA}.\]  \hspace{1cm} (11)

Therefore the precipitation recycle ratio is obtained as:

\[\rho = \frac{EA}{EA + 2F^{in}}.\]  \hspace{1cm} (12)

where \(E\) is the regionally averaged evaporation (kg m\(^{-2}\) s\(^{-1}\)), \(A\) is the size of the study area (m\(^2\)), \(F^{in}\) is the vertically integrated water vapor transported into the study area (kg s\(^{-1}\)). For other details of the bulk model method B1993, please see Brubaker et al. (1993) and L. Guo et al. (2018).

As mentioned above, the precipitation recycle ratio defined in C2015 is the ratio of the climatic total evaporation and the precipitation, which has limited consideration of the evaporation and advected water vapor mixture process. In other words, it neglects the evaporation-contributed part in the water vapor outflow (\(F^{out}_{e}\) in Figure 1). For this reason, we will calculate the evaporation-contributed part in the water vapor outflow using method B1993 and thereby clarify the rationality of the C2015 definition of the precipitation recycle ratio.

3. Results

3.1. Climatic Atmospheric Water Cycle Over the TP and Evaluation of Definition in C2015

The pattern of vertically integrated water vapor transport over the TP in summer is shown in Figure 2. The same as many previous studies (Feng & Zhou, 2012; Lin et al., 2018; K. Yang et al., 2014; T. Yao et al., 2013; W. Zhang, Zhou, et al., 2017), the moisture transport over the TP is dominated by the Indian Summer Mon-
soon (ISM) and the westerlies in terms of the climatology (Figure 2a). The water vapor brought by the ISM flows into the TP mainly through the southeast edges (edges 4 and 6), especially the Yarlung Zangbo Grand Canyon. The water vapor also can flow into the TP through the west edges (edges 2 and 3) brought by the westerly. Inflow through the edge 2 is more outstanding because of the longer edge length. As a result of the lower altitude of the Qaidam Basin, the column water vapor inflow through the north edge 9 is comparable with the south and west edges (Figure 2b).

Using the method B1993, the climatic atmospheric water cycle over the TP in summer is estimated in Figure 1, as well as the interannual variability, which will be further analyzed in Section 3.2. The climatic total precipitation on the TP is $8.36 \times 10^7$ kg s$^{-1}$ (with the interannual variability of $0.75 \times 10^7$ kg s$^{-1}$) and the precipitation recycle ratio is 22.6% (with the interannual variability of 2.0%), which means 77.4% of the total precipitation is contributed by the external moisture advection and only 22.6% is recycled from the local evaporation. The external water vapor transport dominates the precipitation over the TP. The climatic total evaporation on the TP in summer is $5.24 \times 10^7$ kg s$^{-1}$ (with the interannual variability of $0.12 \times 10^7$ kg s$^{-1}$ of the interannual variability) is transported out of the TP after the water vapor mixture in the atmosphere. It implies the ratio of the climatic total evaporation to the precipitation cannot be regard-

![Figure 2. The climatology of the water vapor transport over the TP during the period of 1979–2018 in summer (JJA mean). (a) The vertically integrated water vapor flux (vector) and its magnitude (shading) over the TP, units: $10^7$ kg m$^{-1}$ s$^{-1}$. The 14 edges of the TP are the same as that in C2015. (b) The column water vapor inflow integrated along each edge, units: kg s$^{-1}$. TP, Tibetan Plateau.](image-url)
ed as the contribution of the evaporation to the precipitation directly. The external moisture inflow to the TP is 9.05 × 10^7 kg s^{-1} (0.89 × 10^7 kg s^{-1} of the interannual variability), most of which transforms into the precipitation (6.48 × 10^7 kg s^{-1} of the climatology and 0.65 × 10^7 kg s^{-1} of the interannual variability) and the other flows out of the TP (2.58 × 10^7 kg s^{-1} of the climatology and 0.57 × 10^7 kg s^{-1} of the interannual variability). The total outflow of the water vapor over the TP is 5.94 × 10^7 kg s^{-1} in terms of the climatology and 0.61 × 10^7 kg s^{-1} of the interannual variability.

Why is the climatic precipitation recycle ratio estimated in C2015 much higher than 23%? Given that more than half of the outflow originates from the evaporation, the definition of the precipitation recycle ratio in C2015 will underestimate the net flux of the external moisture, as well as its contribution to the precipitation. In order to verify it and clarify the rationality of the definition in C2015, we use the ratio between the external and local moisture in the total outflow to modify the results of C2015 and see the difference.

As shown in Table 2, only 46.1% of the outflow over the TP is originated from the external inflow in summer (Out-a in B1993 column). Because the definition in C2015 leaves the evaporation-contributed outflow out of consideration, the total outflow is regarded as fully rooting in the external inflow (66.23 kg m^{-1} month^{-1}, original F_{out} in C2015 column). This value should be modified to 30.51 kg m^{-1} month^{-1} according to the ratio between the external and local moisture in the total outflow (modified F_{out} in C2015 column). After the modification, external moisture net flux over the TP (F_{net}) increases from 40.76 kg m^{-1} month^{-1} to 76.48 kg m^{-1} month^{-1}, as well as its contribution to the precipitation (P-a).

The original precipitation recycle ratio under the definition in C2015 is 58.7%, changing to 22.6% after the modification. Hence attentions should be paid to the definition of precipitation recycle ratio in the research community. As the moisture mixture process is important and should not be ignored, the definition in B1993 instead of C2015 is recommended in calculating the precipitation recycle ratio.

### 3.2. Interannual Variability of Precipitation Recycle Ratio over the TP

We use the empirical orthogonal function analysis method to identify the leading interannual variability mode of summer precipitation over the TP. The first mode explains 20.21% of total variance and exhibits a dipole mode between the southeastern TP and the central and northern India (Figure 3). When the summer precipitation on the central and northern India decreases, there is more precipitation on the TP (especially the southeastern TP) than normal, as well as on the southern India. While the pattern has been reported in previous studies (Jiang et al., 2016; Jiang & Ting, 2017, 2019), how such kinds of interannual variability mode affect the precipitation recycle ratio and the atmospheric water cycle over the TP remains unknown.

The precipitation recycle ratio over the TP has the significant negative correlation with the principal component (PC) series (r = −0.68, p < 0.01; Figure 4a). When the normalized PC is larger than 0.5 (referred to as wet years hereinafter), there is more moisture inflow to the TP, especially through the southern edges (Figure 4b). In the meantime, the evaporation on the TP is below the normal, which results from the lower

### Table 2

|                | B1993 | C2015 |
|----------------|-------|-------|
| mm month^{-1}  |       |       |
| E              | 61.98 | 106.99|
| P              | 77.4% | 46.1% |
| P-a            | 46.1% |       |
| Out-a          |       |       |
| P              | −66.23| −30.51|
| F_{in}         | Original
| F_{out}        | Modified
| P              | Original
| P-a            | Modified
| F_{net}        | Original
| P-a            | Modified

Notes. Italics are results from B1993 definition and the Romans are from C2015 definition. The meanings of the abbreviations are: E for evaporation (mm month^{-1}); F_{in} for all inflow of the water vapor advection (kg m^{-2} month^{-1}); P-a for the ratio of the precipitation contributed by the advection; Out-a for the ratio of the outflow contributed by the advection; P for precipitation (mm month^{-1}); F_{out} for the outflow through all edges (kg m^{-1} month^{-1}), of which the original value includes the contribution of both external advection and local evaporation, while the modified value only includes the external-moisture contributed part; F_{net} for the sum of F_{in} and the corresponding F_{out} (kg m^{-2} month^{-1}), of which the original value is the total moisture convergence in the atmosphere and the modified value is the net flux of the external moisture advection; P-a for the ratio of the precipitation contributed by the advection.
surface temperature and wetter atmosphere after the precipitation (Y. Guo & Wang, 2014; Hua et al., 2015). Because of the joint impact of the higher moisture inflow and the less local evaporation, the precipitation recycle ratio over the TP decreases.

To find the reason for the difference in the moisture inflow between the wet years (PC > 0.5, more moisture inflow to the TP) and the dry years (PC < −0.5, less moisture inflow to the TP) of the TP, the patterns of the column water vapor transport and geopotential in lower troposphere anomalies are shown in Figure 5. In the wet years of the TP (more precipitation on the southeastern TP but less on the central and northern India), there is an anomalous anticyclone over the central and northern India. The dry anomaly and the high geopotential anomaly in the low level of the troposphere suppress the precipitation over the central and norther India. While in the meantime, the westerly anomalies along the north flank of the anomalous anticyclone bring more water vapor into the TP and increase the precipitation on the southeastern TP (Figure 5a). In the dry years, there is an anomalous cyclone over the northern Bengal Bay with easterly anomalies over the TP, which reduces the water vapor transport into the TP (Figure 5b).

Figure 3. The interannual variability of the summer precipitation on the TP and the India Peninsula. (a) The leading mode of the empirical orthogonal function (EOF) of the 9-year high-pass filtered precipitation. (b) The standardized principal component (PC) series. TP, Tibetan Plateau.
The atmospheric water cycle over the TP in wet years (PC > 0.5, more moisture inflow to the TP) and dry years (PC < −0.5, less moisture inflow to the TP) is shown in Figure 6. In the wet years, because of the influence of the anomalous anticyclone mentioned above, the moisture inflow (9.67 × 10^7 kg s^{-1}) over the TP is more than the climatology (9.05 × 10^7 kg s^{-1} in Figure 1b), indicating an increase of 7%. The change in the evaporation over the TP, especially the eastern TP, is dominated by the net radiation received by the land surface at the interannual time scale (Hua et al., 2015). Because of the increasing water vapor inflow and precipitation in wet years, there will be more clouds and less downward shortwave radiation over the TP. As a result, the total evaporation and the precipitation recycle ratio in wet years is less than the climatology. Only 21% of the precipitation over the TP is contributed by the local evaporation in the wet years (Figure 6a). In the dry years, the external water vapor inflow and the total precipitation decrease, but the local evaporation increases (Figure 6b). As a result, the precipitation recycle ratio over the TP increases to 25% in the dry years. The precipitation in dry years is more dependent on the local water cycle process than in the wet years over the TP.

To find the reason for the anomalous anticyclone over the northern Bengal Bay in the wet years of the TP, the patterns of the regression coefficients between the PC series and the global sea surface temperature (SST), precipitation and low-level horizontal winds are shown in Figure 7. The leading mode of the interannual variability of the summer precipitation on the TP and India is related to the El Niño events in the preceding winter (Figure 7a). In the post-El Niño summers, the most dominant anomaly in the atmosphere is the large-scale anomalous anticyclone spanning from the tropical Northwest Pacific to the North Indian Ocean, which is induced by the interbasin ocean–atmosphere interaction called Indo-western Pacific Ocean capacitor effect (Kosaka et al., 2013; B. Wu et al., 2009; Xie et al., 2009; J. Yang et al., 2007; also see T. Li et al., 2017; Xie et al., 2016 for reviews). During the mature phase of El Niño, the Walker Circulation is weakened and an anomalous anticyclone is forced over the southeast Indian Ocean because of the increased SST.
at the tropical central and eastern Pacific Ocean (Figure 7a). The anomalous anticyclone forces westward
downwelling Rossby waves in the Indian Ocean, which deepens the thermocline and causes the ocean to
warm. The warm south Indian Ocean induces winds anomalies from north to south of the equator, which
turn northeasterly over the north Indian Ocean due to the Coriolis effect (Figure 7b). Under the background
of southwesterly monsoon in spring and summer, the anomalous northeasterly over the north Indian Ocean
weakens local surface winds and evaporation, warming the north Indian Ocean second (Figure 7c). Finally,
a tropospheric Kelvin wave is excited and propagates to the western Pacific, forcing the anomalous anticy-
cclone spanning from the tropical Northwest Pacific to the North Indian Ocean (Figure 7d). The anomalous
anticyclone has an extensive influence on the Asian summer monsoon (Figure 7d). Coupled with cooling
sea surface temperature, the anomalous anticyclone over the tropical Northwest Pacific excites the merid-
ional precipitation and low-level tropospheric circulation anomalies over the East Asia, which is called as
Pacific-Japan (PJ) pattern or East Asia-Pacific (EAP) pattern and affects the East Asian summer monsoon
(R. H. Huang & Sun, 1992; Kosaka & Nakamura, 2010; Lu et al., 2006; Nitta, 1987). The anomalous anticy-
cclone over the Bengal Bay also affects the precipitation over the India and the TP (Feng & Zhou, 2012; L.
Guo et al., 2018; Jiang & Ting, 2017; V. Mishra et al., 2012). In our study, the Bengal Bay anticyclonic anom-
aly is demonstrated to have an influence on the precipitation recycle ratio over the TP, because of its impact
on the moisture transport through the southern edges of the TP.

Figure 5. Moisture and geopotential anomalies. (a) The column moisture flux (vector, units: kg m⁻¹ s⁻¹) and specific humidity (shading, units: kg kg⁻¹)
anomalies in years of PC larger than 0.5. (b) The same as (a) but for years of PC less than −0.5. (c) The difference between (a) and (b). Only the moisture flux
anomalies significant at the level of 0.1 are shown. (d) The composite difference in geopotential anomalies between the years of PC larger than 0.5 and less than
−0.5, units: m² s⁻². Dots mean the difference is significant at the level of 0.1. PC, principal component.
There is also a positive feedback process between the precipitation over the TP and the external moisture transported into it. On the one hand, precipitation increases with more water vapor transported into the TP (Figure 6a), and on another hand, the increased precipitation can strengthen the diabatic heating over the TP, which in turn affects the formation of the anomalous anticyclone over the Bengal Bay (Jiang & Ting, 2017), further increasing the external moisture transport and reducing the precipitation recycle ratio over the TP. Evidence shows that the contribution of the moisture originated from the tropical Indian Ocean to the TP precipitation will increase in years with strong TP heating (Pan et al., 2019).

To reveal the relationship between the summer precipitation recycle ratio over the TP and the ENSO events, time series of the precipitation recycle ratio and preceding Niño 3.4 index are shown in Figure 8a. The
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summer precipitation recycle ratio over the TP is significantly and negatively correlated with the Niño 3.4 index in the proceeding winter ($r = -0.38$, $p < 0.05$). The standard deviation of the precipitation recycle ratio is 2%, equally to 8.8% of its climatic mean value. The minimum recycle ratio (19%, decreased 15% of the climatic value) appears in the summer of 1998, as the result of the extreme El Niño event in the preceding winter, while the maximum recycle ratio (27%, increased 21% of the climatic value) appears in the summer of 1997, as the result of an La Niña event in preceding winter. The moisture transport anomalies patterns indicate the response of the water vapor flux to the preceding El Niño and La Niña events is asymmetric.

Figure 7. The role of the global sea surface temperature (SST). (a–c) The patterns of the regression coefficients between the global SST (shading) and horizontal winds at 850 hPa (vector) of the preceding winter to the simultaneous summer and the PC series. (d) The pattern of the regression coefficients between the PC series and the global precipitation (shading) and horizontal winds in 850 hPa (vector) of the simultaneous summer. Only the coefficients significant at the level of 0.1 are shown. PC, principal component.
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In El Niño decaying summers, there is a large-scale anticyclone spanning over Indo-Pacific Ocean, of which the Bengal Bay part induces westerly anomalies over the TP and transports more water vapor. However, in the La Niña decaying summers, there are cyclonic anomalies over the Northwest Pacific. The response of the atmospheric circulation is weaker than its counterpart in El Niño decaying summers, so the change in moisture transport over the TP is not significant. The asymmetric response of the atmospheric circulation to different phases of ENSO in their mature winter as well as decaying summer has been noted (Tao et al., 2016; B. Wu et al., 2010). The anomalous cyclone over Northwest Pacific in La Niña decaying summer, which is modulated by the cooling equatorial central and eastern Pacific, is found to be weaker and shift northwestward comparing to the anticyclone in El Niño decaying summer (Tao et al., 2016; B. Wu et al., 2010).

The atmospheric water cycle and its changes with ENSO events over the TP in summer are summarized in Figure 9. In the El Niño decaying summer, because of the westerly anomalies along the north flank of the Bengal Bay anticyclone, the moisture inflow to the TP increases by 5.9%. As a result, the precipitation recycle ratio decreases to 21.4%. Considering that the interannual variability of the recycle ratio over the TP is 2.0%, the change related to El Niño decay explains 60% of the total variability of precipitation recycle ratio at interannual scale. In the La Niña decaying summer, the moisture inflow to the TP decreases by 1.7% and the precipitation recycle ratio increases to 23.1%. However, as mentioned before, due to the weaker response of the atmospheric circulation over Indo-Northwest Pacific Ocean in the La Niña decaying summer, these changes are not significant ($p > 0.1$).

Figure 9. The schematic diagram of the atmospheric water cycle and its changes with ENSO events over the TP in summer, units: 10$^7$ kg s$^{-1}$. The black fonts represent the climatic mean value and interannual variability. The red (blue) fonts represent the average value in El Niño (La Niña) decaying summers. Slant fonts denote that changes are significant at the level of 0.1.

(Figures 8b and 8c). In El Niño decaying summers, there is a large-scale anticyclone spanning over Indo-Pacific Ocean, of which the Bengal Bay part induces westerly anomalies over the TP and transports more water vapor. However, in the La Niña decaying summers, there are cyclonic anomalies over the Northwest Pacific. The response of the atmospheric circulation is weaker than its counterpart in El Niño decaying summers, so the change in moisture transport over the TP is not significant. The asymmetric response of the atmospheric circulation to different phases of ENSO in their mature winter as well as decaying summer has been noted (Tao et al., 2016; B. Wu et al., 2010). The anomalous cyclone over Northwest Pacific in La Niña decaying summer, which is modulated by the cooling equatorial central and eastern Pacific, is found to be weaker and shift northwestward comparing to the anticyclone in El Niño decaying summer (Tao et al., 2016; B. Wu et al., 2010).

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Figure 8. The response of the precipitation recycle ratio over the TP in El Niño and La Niña decaying summers. (a) Time series of the summer precipitation recycle ratio over the TP (% black line, right axis with the average value in the middle) and Niño3.4 index in the preceding winter (bar, left axis). The upward and downward triangles denote the maximum and minimum recycle ratio respectively. (b) Column moisture flux (vector, units: kg m$^{-1}$ s$^{-1}$) and specific humidity (shading, units: kg kg$^{-1}$) anomalies in El Niño decaying summers. (c) The same as (b) but for La Niña decaying summers. Only the moisture flux anomalies significant at the level of 0.1 are shown. TP. Tibetan Plateau.
4. Conclusions

Using the advanced reanalysis data ERA5 of the high resolution, we estimate the climatic atmospheric water cycle over the TP in summer and analyze the reason for the contradictory conclusions of previous studies on the precipitation recycle ratio over the TP. The interannual variability of precipitation recycle ratio over the TP is analyzed. The major findings are summarized below.

(1) In terms of the climatology, the total precipitation on the TP is $8.36 \times 10^7$ kg s$^{-1}$ and the precipitation recycle ratio is 23% in summer. The definition of the precipitation recycle ratio in B1993 instead of C2015 is recommended, since the former reasonably considers the water vapor mixture processes, thus avoids the underestimation of the net moisture flux and its contribution to the precipitation and the overestimation of the precipitation recycle ratio as the C2015.

(2) The interannual variability of the precipitation recycle ratio over the TP in summer is significantly and negatively related with the Niño 3.4 index in the preceding winter ($r = -0.38$, $p < 0.05$). In the El Niño decaying summers, the large-scale anomalous anticyclone spans over the Indo-Northwest Pacific and the westerly anomalies along the north flank of the anticyclone transport more moisture into the TP, which decreases the precipitation recycle ratio over the TP to 21.4%. The change of the recycle ratio induced by the preceding El Niño events explains 60% of its interannual variability.

(3) The response of precipitation recycle ratio over the TP in summer to the preceding El Niño and La Niña events is asymmetric. In La Niña decaying summers, the precipitation recycle ratio increases to 23.1% due to the less moisture inflow. Nevertheless, the changes are not significant because of the weaker response of the atmosphere over Indo-Pacific Ocean in La Niña decaying summers than its counterpart in El Niño decaying summers.

Data Availability Statement

ERA5 data is provided by the European Centre for Medium-Range Weather Forecasts (ECMWF, http://www.ecmwf.int/). It can be obtained from the Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/home) and Hersbach et al. (2019a, 2019b). Considerable gratitude is owed to the related reanalysis working team.

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