Moisture source assessment and the varying characteristics for the Tibetan Plateau precipitation using TRMM

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Abstract

Precipitation over the west Tibetan Plateau (TP) was always being accused of lacking observations that limits the precipitation moisture attribution and quantitation over the whole TP. By introducing precipitation from the Tropical Rainfall Measuring Mission (TRMM) and other observation-based data, moisture sources for the whole TP and their variations from 1998 to 2018 are explored using an Eulerian model. It is found that the Southwest subregion from TP to the western Indian Ocean is the largest moisture contributor. It contributes around 147.6 ± 13.0 mm yr\(^{-1}\) in water-depth of the TP in climatology, accounting for 31.9 ± 1.9% of the annual precipitation. The TP, the West (TP to Europe), and the Southeast (TP to Indochina Peninsula) follow by contributing 23.6 ± 2.3, 21.8 ± 1.5, and 2.6 ± 0.6%, respectively. Circulations dominate the TP in different seasons. Take spring for example, the westerlies prevail over the TP and the West contributes the most moisture, which accounts for 38.6 ± 2.9% of the spring precipitation. In summer, with the breakout of the Indian monsoon, contribution from the Southwest reaches the highest of 91.1 ± 11.5 mm JJA\(^{-1}\), accounting for 34.6 ± 2.6% of the summer precipitation. The interannual variability (IAV) of the TP precipitation is mainly influenced by the moisture IAVs from the Southwest and the TP, contributing around 36.6% and 31.7%, respectively. Moisture contributed from the Southwest decreases significantly from 1998 to 2018 at a rate of −10.6 mm yr\(^{-1}\) dec\(^{-1}\), but moisture from the local increases significantly at 12.1 mm yr\(^{-1}\) dec\(^{-1}\). Further analyses reveal that the local increase in moisture contribution (and ratio) is primarily due to intensified evaporation of the TP, but the Southwest decrease is mainly caused by reduced moisture transport from the Indian monsoon.

1. Introduction

The Tibetan Plateau (TP), also known as the ‘Third Pole’, exerts great influence on the climate of the surrounding and the northern hemisphere (Ye et al. 1979, Xu et al. 2014). The high elevated landmass (more than 5 km above sea level on average) serves as a large heating source that strengthens and amplifies the Asian monsoons (Duan and Wu 2005, Wang et al. 2012, Zhao et al. 2018). The large landmass also hinders the transport of the westerlies (Wu and Zhang 1998) and blocks the warm humid air in the south from entering into the north (Boos and Kuang 2010). In addition to the crucial role in climate, the giant TP is also birthplace to many large rivers in Asia (Immerzeel et al. 2010, Sun and Wang 2019, Zhang et al. 2020), such as the Yellow River, the Yangtze River, and the Brahmaputra River etc. Since precipitation is a major source of the TP rivers and lakes (Su et al. 2016, Lei and Yang 2017), finding the sources of the TP precipitation is of great importance and has invoked the interest of many scientists.

In early studies, two main moisture transport channels were identified for the TP, i.e. the Indian monsoon channel and the westerlies channel (Sugimoto et al. 2008, Feng and Zhou 2012). Through...
the moisture trajectory analyses with HYSPLIT (Ma et al 2020), more diverse moisture paths were found, but they can still be classified into the two major channels aforementioned. For some regions in the eastern and southern TP, there exits another moisture corridor from the east, which is possibly influenced by the East Asian summer monsoon (EASM) (Ma et al 2020). By adopting an ‘areal source–receptor attribution’ method, Sun and Wang (2014) quantified the moisture contributions from different sources to the eastern TP. The results indicate that moisture released over the eastern TP mostly comes from the Eurasian continent. Although moisture uptake from ocean is considerable, much is lost in route. Recently, similar conclusions are reached that terrestrial originated moisture is dominant for precipitations in the central-western TP (Zhang et al 2017) and the Sanjiangyuan region (Zhang et al 2019b).

It is also being known that the moisture origin over the Plateau is not spatially homogeneous. Based on isotope observations, Yao et al (2013) divided the TP into three climate zones and claimed that moisture in the northern TP is mainly influenced by the westerlies, while moisture from the southern TP is mainly influenced by the monsoons. This viewpoint is supported by Zhang et al (2019a) and Pan et al (2019) through models. Zhang et al (2019a) further gave an estimation that 38.9% of precipitation moisture for the northern TP comes from the westerlies, and 51.4% of precipitation moisture for the southern TP comes from monsoons. Besides, as different circulations influence them, their precipitations display different change trends with a north increase and south decrease pattern in recent decades. The northern and central-western TP precipitation increase can be attributed to more moisture contributions from the TP and the monsoons (Zhang et al 2017, 2019a). Precipitation change in the southern TP is, however, more complicated. Through a further division of the southern TP, Chen et al (2019) found that large differences exist in the sub-seasonal moisture source evolution between the southeastern TP and the southwestern TP, which suggests internal differences within the southern TP.

Despite the progress made so far, the moisture sources of the TP are still in a lack of an accurate estimation. The reasons vary with different methods. For studies that apply general circulation model (GCM) (e.g. Pan et al 2019), the GCM generally overestimates the precipitation over the TP, causing large uncertainties in attributing the precipitation moisture. For studies that apply the Lagrangian moisture diagnostics, the tracked moisture is released moisture in the air, which does not match well with the observational ground precipitation (e.g. figure 10(a) in Chen et al (2019)). For studies that apply the Eulerian model (e.g. Zhang et al 2017), the input of precipitation is mandatory, but the precipitation gauges on the west TP are extremely sparse, which limits the applicability of the gauge-based precipitation at the TP scale. Fortunately, with the rise of the satellite era, more sensors are being designed to collect precipitation data, such as the Tropical Rainfall Measuring Mission (TRMM). The TRMM Multisatellite Precipitation Analysis (Huffman et al 2007), which has already been widely applied (e.g. Chen et al 2013, Zhang and Tang 2015), provides a unique opportunity to explore precipitation over sparsely gauged or ungauged regions. As a reliable precipitation dataset is a prerequisite for accurate assessment of the precipitation origins, the application of TRMM over the TP can be significant in unveiling the moisture sources for the whole TP for the first time. Based on the moisture traceback from 1998 to 2018, the moisture contribution, the interannual variability (IAV), the changing trend, and the seasonal variation of the sources are all explored, respectively.

2. Dada, model, and methods

2.1. Data and study area

The primary data include precipitation, evaporation, and atmospheric data. They serve as model input for moisture tracking. For precipitation, the gauge-calibrated TRMM research product 3B43 (V7) is chosen, which covers the latitude of 50°N–S at 0.25° × 0.25° grids monthly from 1998 to 2018. For evaporation over the land, the 3 h 1° gridded evaporation product from the community land model (CLM) in the Global Land Data Assimilation System (GLDAS; Rodell et al 2004) is chosen. The CLM is a physically-based model that is subject to vigorous evaluation. The forcing data, including precipitation, temperature, radiation, etc, are observational. In general, GLDAS outperforms other reanalyses on surface variables (Wang and Zeng 2012, Gao et al 2014). Over the ocean, the monthly 1° gridded evaporation from the Objectively Analyzed Air–Sea Fluxes (OAFlux, Yu and Weller 2007) is adopted. OAFlux has assimilated satellite data since 1985. According to Trenberth et al (2011), OAFlux evaporation agrees well with in situ buoy data and appears to be best among the available products. In addition to these observation-based data, the 3 h 1° gridded evaporation and precipitation fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim (ERA-I hereafter; Dee et al 2011) are also applied. Precipitation and evaporation from ERA-I are pure model output (Dominguez et al 2006), which are used for comparison.

For the atmospheric data, the reanalysis of ERA-I at 1° × 1° grids is chosen because it has a better performance concerning the atmospheric water budget among the available reanalyses (Trenberth et al 2011, Lorenz and Kunstmann 2012). ERA-I provides a variety of atmospheric data, including 6 hourly model-level zonal winds, meridional winds, and specific humidity; 6 hourly surface pressures; and
a set of vertically integrated moisture and flux variables (vertically integrated water and vertically integrated northward/eastward water fluxes in the forms of vapor, liquid, and ice).

The geographic location of the TP is shown in figure 1(a) (Zhang et al. 2014). The topographic height data are provided by the Global Land One-km Base Elevation Project (GLOBE). With TRMM, the TP precipitation is around 462.7 ± 24.4 mm yr⁻¹ from 1998 to 2018. With ERA-I, this value is extremely large as 813.3 ± 50.7 mm yr⁻¹ (figure 1(b)). The ERA-I series also shows a strong declined trend, while there is no obvious trend for TRMM. The two series show similar variabilities with the correlation parameter between the two linearly detrended series being 0.69 at the 0.01 significant level, implying that the precipitation variability of ERA-I is somewhat reliable.

2.2. WAM-2layers and experiment design
The Water Accounting Model-2layers (WAM-2layers) is an Eulerian model of moisture recycling that tracks moisture either forward or backward in time to quantify moisture source-sink relations (van der Ent et al. 2013, 2014). WAM-2layers is an updated version of WAM (van der Ent et al. 2010), which has deficits in moisture attribution over regions with strong wind shear in the vertical. WAM-2layers basically resolves this problem by dividing the vertical into two layers. This model has since been applied in many studies (e.g. van der Ent et al. 2017, Keys et al. 2017, Guo et al. 2019). Compared with some Lagrangian models such as FLEXPART and HYSLIP (e.g. Sodemann et al. 2008, Sun and Wang 2014, Chu et al. 2017), one major difference is that WAM-2layers tracks the moisture of real precipitation fallen on the ground, while the Lagrangian methods track the moisture released in the air, which is not the actual precipitation observed on the ground (Huang and Cui 2015, Chen et al. 2019). Besides, WAM-2layers is able to keep the ‘tagged water’ conserved (Zhang et al. 2017). In other words, all the precipitated moisture can be tracked back to the evaporative sources. These features make WAM-2layers more suitable for ground-precipitation-based research. The tracking algorithm is introduced in the supplementary material.

Two groups of experiments are performed. The first group is entirely based on the ERA-I data, referred to as ERA-Suite. The advantage of this suite is that the inner water cycle within ERA-I is more self-consistent. The second group is based on observation-constrained data, i.e. the atmospheric data of ERA-I and surface fluxes of TRMM precipitation and GLDAS/OAFlux evaporation. Compared with observations, ERA-I precipitation over the TP is far too abundant (Tong et al. 2014; figure 1(b)). Thus, the first group is regarded as supplementary. Limited use is made of it such as providing the variabilities and uncertainties. The second group is primary and more preferred. It is also referred to as the observation group. The data processing details for the two groups are put in the supplementary material.

2.3. Variability contribution index
The index proposed by Ahlstrom et al. (2015) is applied to evaluate the variability contribution of the annual and seasonal moisture from different sub-regions to the annual precipitation of the TP. It is expressed as

\[ f_j = \frac{\sum x_{jt} |X_t|}{\sum |X_t|} \]

where \( x_{jt} \) is the moisture anomaly (departure from a long-term trend) for subregion \( j \) at time \( t \) (in years), and \( X_t \) is the TP precipitation anomaly (\( X_t = \Sigma x_{jt} \)). \( f_j \) can be referred to as the average relative anomaly \( x_{jt}/X_t \) for subregion \( j \), weighted with the absolute precipitation anomaly \( |X_t| \). Subregions with higher and positive scores are considered as contributing more in governing the TP IAV, as opposed to subregions with smaller or negative scores. It enables a comparison of their relative importance in governing the IAV (Ahlstrom et al. 2015).

Besides, the results are generally attached with one standard deviation to indicate the uncertainty.

3. Results

3.1. Annual moisture contribution
The annual moisture contribution (figure 2) indicate that influence from the west is long and wide. The contribution intensity from the west tends to be mild but extended. The contribution from the southwest is substantial and intense. Moisture from the west is mainly transported by the westerlies, while moisture from the Southwest is basically transported by the Indian monsoon. The circulation turning along the east coast of Africa leaves a long tail of moisture trace over the western Indian Ocean. In contrast, the contribution from the southeast is narrow and short in distance. This region is seated downwind of both the Indian monsoon and the westerlies. Moisture downwind is hard to influence the upwind region directly. However, in summer, when the EASM forms, moisture there has a chance to be transported upwind to the Plateau by the EASM. It is also worth noting, sources from the north barely have any influence on the TP.

Moisture distribution generally follows the rule that the nearer of the source in the upwind, the more it contributes. Within the target region, the core of moisture contribution is seated along the south side of the TP. This area is humid as opposed to the dry north (Yao et al. 2013). The humid area produces more evaporation. The more it evaporates, the more it is recycled. Besides, moisture evaporated from the south is more likely to be recycled as local
precipitation as it stays longer in the Plateau along with the southwesterly flux, while moisture from the north is quickly transported outside. These spatial features are generally consistent with those using ERA-Suite.

Keys et al. (2014) proposed a concept of ‘precipitationshed’, i.e. atmospheric watershed, where the target’s precipitation is basically originated from within. Following this idea, this study set a threshold of 5.0 mm yr$^{-1}$ and extracted grids with higher moisture contributions that contribute around 80.0% of the TP precipitation. This watershed scope is robust in the control experiment, as it contributes around 82.3% of the TP precipitation using ERA-Suite. To further quantify the contribution from different sources, the precipitationshed is divided into four subregions.
Figure 2. Annual moisture contribution (mm yr$^{-1}$) with (a) observation data and (b) ERA-Suite. The brown line marks out the 'precipitationshed' that contributes around 80% of the annual precipitation. (c) Further division of the precipitationshed into four subregions, i.e. the West, Southwest (SW), TP, and Southeast (SE).

Moisture contribution series (figure 3(a)) indicate that the Southwest contributes the most of about 147.6 ± 13.0 mm yr$^{-1}$ (in water-depth of the TP). The TP, the West, and the Southeast follow by contributing 109.5 ± 13.1, 100.6 ± 7.5, and 12.3 ± 2.8 mm yr$^{-1}$, and accounting for 31.9 ± 1.9, 23.6 ± 2.3, 21.8 ± 1.5, and 2.6 ± 0.6%, respectively, of the annual precipitation. There are some quantitative evaluations on the sources for some particular regions over the TP, such as the northern TP (Zhang et al 2019a) and the Sanjiangyuan Region (Zhang Y et al 2019). The results differ in the largest moisture source. This is not hard to comprehend as they are influenced by different climates. For the northern TP where the westerlies prevail, the westerlies are the main moisture source. For the southern TP, the monsoon dominates and provides the most...
moisture. As the TP precipitation decreases rapidly from south to north (figure S1 (available online at https://stacks.iop.org/ERL/15/104003/mmedia)), precipitation in the south weighs much larger than that in the north. When the TP is put as a whole, it is no wonder that the largest source is still the monsoon region, i.e. the Southwest representing the Indian monsoon.

There are no apparent trends in moisture contributions from the West and Southeast. Moisture contributed from the Southwest decreases significantly at a rate of $-10.6 \text{ mm yr}^{-1} \text{ dec}^{-1}$, while moisture contributed from the local increases significantly at $12.1 \text{ mm yr}^{-1} \text{ dec}^{-1}$. The two items offset the moisture change trend, resulting in a weak trend in the precipitation. Since the ERA-I precipitation trend differs too much from TRMM, the moisture trend using ERA-Suite is not analyzed. For the TP precipitation IAV, the Southwest and the TP contribute the most, which account for 36.6% and 31.7%, respectively. The West makes a unparalleled contribution of 17.3% in comparison with the TP. The Southwest contributes only 2.9%. The results are generally consistent with those using ERA-Suite.

The Southwest, TP, West, and Southeast contribute 31.8%, 21.0%, 19.0%, and 2.4%, respectively, of the precipitation IAV.

### 3.2. Seasonal moisture contribution

As circulations affect the TP differently in different periods of the year, it is necessary to explore the seasonal change in moisture contribution. As winter precipitation in the TP accounts for only 4.3% of the annual precipitation, it is thus omitted for analysis. The seasonal change in moisture contribution for the TP precipitation is shown in figure 4. Moisture varies remarkably with seasons. In spring, moisture for the precipitation mainly comes from the west by the westerlies. The West contributes around $38.6 \pm 2.9\%$ of the spring precipitation. In summer, both the contributions from the west and south are strengthened. Moisture from the south bursts due to the breakout of the Indian monsoon. Contribution from the Southwest reaches the highest among the subregions in all seasons, which is $91.1 \pm 11.5 \text{ mm JJA}^{-1}$ accounting for $34.6 \pm 2.6\%$ of the summer precipitation. The EASM also acts
actively as contributing more moisture from the southeast. In autumn, moisture contributed from the west weakens substantially, while the precipitation moisture comes mainly from the south with the Southwest contributing $23.9 \pm 3.0\%$ of the autumn precipitation.

Moisture from the subregions varies with seasons, so does the moisture IAV from 1998 to 2018. To be more specific about the seasonal contributions in the annual precipitation IAV, the subregions’ moisture IAV is deposited at the seasonal scale. Moisture from the Southeast explains only 2.9% (2.4% with ERA-Suite) of the precipitation IAV, and it is not considered. As a result, figure 5 shows the variability contributions from the West, Southwest, and the TP in spring, summer, and autumn. In general, the sources explain the variability most in summer except for the West, where there is no distinct difference between spring and summer. The Southwest in summer contributes the most of 27.5%, followed by the TP of 22.1%. The results with ERA-Suite also indicate that the Southwest and TP in summer are the largest two in contributing to the precipitation IAV among the sources in different seasons.

Figure 4. Seasonal moisture contribution (left) and the summarized statistics (right). They are for (a) spring, (b) summer and (c) autumn, respectively.
4. Discussion

4.1. Validation of TRMM

The TRMM 3 h precipitation product of 3B42 (V6) was once evaluated over the TP (Tong et al. 2014). They found that 3B42 was among the best estimates over the TP basins, just slightly worse than the gauged-based products. The 3B43 (V7), which is the monthly sum of 3B42 (V7), is applied in this study. To be more cautious about its applicability over the Plateau, a comparison is made between TRMM-3B43 and a gauge-based precipitation dataset by the China Meteorological Administration (CMA, Zhao et al. 2014). The CMA precipitation is monthly at 0.5° × 0.5° grids, which is available from 1961 to 2017. The precipitation stations are densely distributed in the east while they drop to nearly none in the west (figure 6(a)). Thus, the east part of the TP (ETP) is chosen for comparison over the overlapped period of 1998–2017. The ETP precipitations are 676.6 ± 40.4 for TRMM and 729.8 ± 56.4 mm yr⁻¹ for CMA. The TRMM precipitation is a little smaller, which accounts for 92.9 ± 2.9% of the CMA precipitation. In light of that there are also biases in gauge measurement due to losses from wind or others (Goodison et al. 1998), a difference between two gauge-based precipitation products of over 10% would be common depending on whether gauge corrected (Adam and Lettenmaier 2003, Tong et al. 2014). As a satellite product that the difference from the ground observation is less than 10%, it is better than average. In addition, the correlation coefficient of the two series (figure 6(b)) is 0.92, which further demonstrates TRMM’s excellent performance. If TRMM performs well over the gauged TP, it is inferred that it also does well over the ungauged TP due to similar retrieval and calibration algorithm.

4.2. Increased precipitation recycling ratio

The precipitation recycling ratio is defined as the contribution of local evaporation to local precipitation (Brubaker et al. 1993, Eltahir and Bras 1996). It is an important indicator that measures the potential of interactions between land surface processes and atmospheric processes (Goessling and Reick 2011). During the study period, the ratio shows a strong increasing trend (figure 7(a)), indicative of a strengthened role of local moisture. The recycling ratio is expressed as \( r = \frac{P_{\text{loc}}}{P} \), where \( P_{\text{loc}} \) is recycled precipitation, i.e. local moisture contribution from evaporation. When \( P \) keeps stable, the increased \( r \) must be caused by the increased \( P_{\text{loc}} \). The recycled precipitation shows an increasing trend of 12.1 mm yr⁻¹ dec⁻¹ at the 0.01 significant level (figure 7(b)). If precipitation keeps steady, the increased local contribution may be due to intensified local evaporation, i.e. the more it evaporates, the more it contributes. The evaporation series from GLDAS as presented in figure 7(b) indeed shows a significant increasing trend. However, is this increasing trend reliable? Under global warming, the temperature over the TP increases more rapidly due to the high elevation effect (Pan and Li 1996, Yang et al. 2014). More glaciers and snow are being melted and retreated, thus releasing more liquid water. (Li et al.
Figure 6. (a) The East TP as cut by a dashed black line. Blue dots represent the 0.5° grids with at least one precipitation gauge over the TP. (b) The precipitation series of TRMM and CMA during 1998–2017.

The lake areas are being expanded with the potential to evaporate more (Song et al 2014, Lei and Yang 2017). Besides, due to more water and proper temperature, the TP is becoming ‘greener’ (Zhong et al 2019, Li et al 2019). All these evidences support an increased evaporation/evapotranspiration over the TP, just as the GLDAS evaporation series reflects.

4.3. Decreased moisture contribution from the Southwest

A significant decreasing trend in moisture contributed from the Southwest is observed during the study period (figure 3(a)). To further explore the decrease, the annual trend is deposed into seasonal. From spring to autumn, moisture from the Southwest decreases at rates of \(-2.4\), \(-7.2\), and \(-1.5\) mm yr\(^{-1}\) dec\(^{-1}\), respectively. Moisture decrease in summer accounts for a major part of the annual decrease of 67.9%. Thus, a specific focus is put on the moisture change in summer. As precipitation during the study period remains stable, the reduced moisture contribution from the Southwest is probably caused by the weakened moisture transport by the Indian monsoon. To prove this, an index is constructed as the moisture transported from the Southwest into TP at the adjacent boundary. The standardized moisture transport index is shown in figure 8 along with the standardized moisture contribution from the Southwest. The transport index shows similar fluctuations with that of the moisture contribution. The correlation parameter of the two linearly detrended series is 66.6% at the 0.01 significant level. Besides, the index decreases as the Southwest moisture contribution at the 0.1 significant level. It is worth noting that moisture transport is not the only factor that guarantees precipitation. Other factors such as coupling with the local system, air uplifting, are also indispensable for precipitation (Gustafsson et al 2010). Thus, the moisture transport index cannot be in a full linear relationship with the contributed precipitation. That said, the reduction in moisture transport is considered to be the main reason for the decreased moisture contribution from the Southwest.

5. Summary and conclusion

Moisture sources for precipitation over the whole TP are identified and assessed by WAM2layers using the TRMM precipitation and other observation-based
data. Through comparison with the control experiment, these findings are considered to be important.

(a) The Southwest subregion is the largest moisture contributor to the TP, which contributes around 147.6 ± 13.0 mm yr⁻¹ in water-depth of the TP in climatology, followed by the TP, the West, and the Southeast, contributing 109.5 ± 13.1, 100.6 ± 7.5, and 12.3 ± 2.8 mm yr⁻¹, respectively. They account for 31.9 ± 1.9, 23.6 ± 2.3, 21.8 ± 1.5, and 2.6 ± 0.6%, respectively, of the annual precipitation. Circulations dominate the TP and the precipitation according to the seasons. In spring, the westerlies prevail over the TP and the West subregion contributes the most moisture among the subregions, which accounts for 38.6 ± 2.9% of the spring precipitation. In summer, the contribution from the Southwest amplifies due to the burst out of the Indian monsoon, which equals 91.1 ± 11.5 mm JJA⁻¹, and accounts for 34.6 ± 2.6% of the summer precipitation. In autumn, the Southwest contributes the most moisture that accounts for 23.9 ± 3.0% of the autumn precipitation.

(b) Moisture IAVs from the Southwest and the TP contribute the most to the TP precipitation IAV, which accounts for 36.6% and 31.7%, respectively. The West, as a comparative source as the TP, contributes only 17.3%. At seasonal scale, the Southwest in summer contributes the most of 27.5%, followed by the TP of 22.1%. The results are consistent with those using EAR-Suite, which demonstrate the major roles of the Southwest and the TP in influencing the precipitation IAV of the TP and especially in summer.

(c) Moisture contributed from the Southwest decreases significantly from 1998 to 2018 at
a rate of $-10.6 \text{ mm yr}^{-1} \text{ dec}^{-1}$, while moisture contributed from the local increases significantly at $12.1 \text{ mm yr}^{-1} \text{ dec}^{-1}$. The two major sources counteract each other to result in a trivial trend in annual precipitation. Further analyses reveal that the local increase in moisture contribution and recycling ratio are mainly caused by intensified evaporation of the TP. The decrease in moisture contribution from the Southwest is mainly caused by decreased moisture transport from the Indian monsoon in summer.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the author.

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References

Adam J C and Lettenmaier D P 2003 Adjustment of global gridded precipitation for systematic bias J. Geophys. Res. 108 4257

Ahlistrom A et al 2015 The dominant role of semi-arid ecosystems in the trend and variability of the land CO2 sink Science 348 895–9

Boos W and Kuang Z 2010 Dominant control of the South Asian monsoon by orographic insulation versus plateau heating Nature 463 218–22

Brubaker K L, Entebah D and Eagleson P S 1993 Estimation of continental precipitation recycling J. Clim. 6 1077–89

Chen B et al 2019 Identifying and contrasting the sources of the water vapor reaching the subregions of the Tibetan Plateau during the wet season Clim. Dyn. 53 6891–907

Chen S et al 2013 Evaluation of the successive V6 and V7 TRMM multisatellite precipitation analysis over the continental United States Water Resour. Res. 49 8174–86

Chu Q, Wang Q and Feng G 2017 Determination of the major moisture sources of cumulative effect of torrential rain events during the pre-flood season over South China using a Lagrangian particle model J. Geophys. Res. Atmos. 122 8369–82

Dee D P et al 2011 The ERA-Interim reanalysis: configuration and performance of the data assimilation system Q. J. R. Meteorol. Soc. 137 553–97

Dominguez F, Kumar P, Liang X and Ting M 2006 Impact of atmospheric moisture storage on precipitation recycling J. Clim. 19 1513–30

Duan A M and Wu G X 2005 Role of the Tibetan Plateau thermal forcing in the summer climate patterns over subtropical Asia Clim. Dyn. 24 793–807

Eltahir E A B and Bras R L 1996 Precipitation recycling Rev. Geophys. 34 367–78

Feng L and Zhou T 2012 Water vapor transport for summer precipitation over the Tibetan Plateau: multidata set analysis J. Geophys. Res. 117 D20114

Gao Y, Lan C and Zhang Y 2014 Changes in moisture flux over the Tibetan Plateau during 1979–2011 and possible mechanisms J. Clim. 27 1876–93

Goessling H and Reick C 2011 What do moisture recycling estimates tell us? Exploring the extreme case of non-evaporating continents Hydrol. Earth Syst. Sci. 15 3217–35

Goodison B E, Louie P Y T and Yang D 1998 WMO solid precipitation measurement intercomparison, final report. World Meteorological Organization Tech. Doc. WMO TD-872, 212
Guo L, van der Ent R J, Klingaman N P, Demory M, Vidale P L, Turner A G, Stephan C C and Chevuturi A 2019 Moisture sources for East Asian precipitation: mean seasonal cycle and interannual variability J. Hydrometeor 20 657–72
Gustafsson M, Rayner D and Chen D 2010 Extreme rainfall events in southern Sweden: where does the moisture come from? Tellus A 62 605–16
Huang Y and Cai X 2015 Moisture sources of an extreme precipitation event in Sichuan, China, based on the Lagrangian method Atmos. Sci. Lett. 16 177–83
Huffman G J et al 2007 The TRMM Multisatellite Precipitation Analysis (TMPA): quasi-global, multiyear, combined-sensor precipitation estimates at fine scales J. Hydrometeor 8 38–55
Immerzeel W W, van Beek L P H and Bierkens M 2012 The hydrological cycle in three major upstream river basins in the Tibetan Plateau: where is the moisture from? Atmos. Res. 112 213–26
Keys P W, Barnes E A, van der Ent L G J and Gordon L J 2014 Variability of moisture recycling using a precipitation sheds framework Hydrol. Earth Syst. Sci. 18 3937–50
Keys P W, Wang-Erlandsson L, Gordon L J, Galaz V and Ebbesson L J 2017 Approaching moisture recycling governance Glob. Environ. Change 45 15–23
Lei Y and Yang K 2017 The cause of rapid lake expansion in the Tibetan Plateau: climate warming or warming? WIREs. Water 7 3170–86
Li H, Liu L, Liu X, Li X and Xu Z 2019 Greening implication inferred from vegetation dynamics interacted with climate change and human activities over the Southeast Qinghai–Tibet Plateau Remote Sens. 11 2421
Lorenz C and Kunstmann H 2012 The hydrological cycle in three state-of-the-art reanalyses: intercomparison and performance analysis J. Hydrometeor 13 1397–420
Ma Y, Lu M, Bracken C and Chen H 2020 Spatially coherent clusters of summer precipitation extremes in the Tibetan Plateau: where is the moisture from? Atmos. Res. 237 104841
Pan B and Li J 1996 Qinghai-Tibetan Plateau: a driver and amplifier of the global climactic change J. Lanzhou Univ. (Nat. Sci.) 32 108–15 (in Chinese)
Pan C et al 2019 Quantitative identification of moisture sources over the Tibetan Plateau and the relationship between thermal forcing and moisture transport Clim. Dyn. 52 181–96
Rodell M et al 2004 The global land data assimilation system Bull. Am. Meteorol. Soc. 85 381–94
Sodemann H, Schwierz C and Wernli H 2008 Interannual variability of Greenland winter precipitation sources: lagrangian moisture diagnostic and North Atlantic Oscillation influence J. Geophys. Res. 113 D03107
Song C, Huang B, Richards K, Ke L and Hien Phan V 2014 Accelerated lake expansion on the Tibetan Plateau in the 2000s: induced by glacial melting or other processes? Water Resour. Res. 50 3170–86
Su F, Zhang L, Ou T, Chen D, Yao T, Tong K and Qi Y 2016 Hydrological response to future climate changes for the major upstream river basins in the Tibetan Plateau Glob. Planet. Change 136 82–95
Sugimoto S, Ueno K and Sha W 2008 Transportation of water vapor into the Tibetan Plateau in the case of a passing synoptic-scale trough J. Meteorol. Soc. Japan 86 935–49
Sun B and Wang H 2019 Enhanced connections between summer precipitation over the Three-River-Source region of China and the global climate system Clim. Dyn. 52 3471–88
Sun B and Wang H 2014 Moisture sources of Semiarid Grassland in China using the Lagrangian particle model FLEXPART J. Clim. 27 2457–74
Tong K, Su F, Yang D, Zhang L and Hao Z 2014 Tibetan Plateau precipitation as depicted by gauge observations, reanalyses and satellite retrievals Int. J. Climatol. 34 265–85
Trenberth K E, Fasullo J T and Mackaro J 2011 Atmospheric moisture transports from ocean to land and global energy flows in reanalyses J. Clim. 24 4907–24
van der Ent R J, Savenije H H G, Schaefl B and Steele-Dunne S C 2010 Origin and fate of atmospheric moisture over continents Water Resour. Res. 46 W09525
van der Ent R J, Tuinenburg O A, Knoche H R, Kunstmann H and Savenije H H G 2013 Should we use a simple or complex model for moisture recycling and atmospheric moisture tracking? Hydrol. Earth Syst. Sci. 17 4869–84
van der Ent R J and Tuinenburg O A 2017 The residence time of water in the atmosphere revisited Hydrol. Earth Syst. Sci. 21 779–90
van der Ent R J, Wang-Erlandsson L, Keys P W and Savenije H H G 2014 Contrasting roles of interception and transpiration in the hydrological cycle – part 2: moisture recycling Earth Syst. Dynam. 5 281–326
Wang A and Zeng X 2012 Evaluation of multi-reanalysis products with in situ observations over the Tibetan Plateau J. Geophys. Res. 117 D05102
Wang M R, Zhou S W and Duan A M 2012 Trend in the atmospheric heat source over the central and eastern Tibetan Plateau during recent decades: comparison of observations and reanalysis data Chin. Sci. Bull. 57
Wu G X and Zhang Y S 1998 Tibetan Plateau forcing and timing of the monsoon onset over South Asia and South China Sea Mon. Weather Rev. 126 913–27
Xu X, Zhao T, Lu C, Guo Y, Chen B, Liu R, Li Y and Shi X 2014 An important mechanism sustaining the atmospheric ‘water tower’ over the Tibetan Plateau Atmos. Chem. Phys. 14 11 287–11 295
Yang K, Wu H, Qin J, Lin C, Tang W and Chen Y 2014 Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: a review Glob. Planet. Change 112 79–91
Yao T D et al 2013 A review of climatic controls on δ18O in precipitation over the Tibetan Plateau observations and simulations Rev. Geophys. 51 525–48
Ye D Z et al 1979 Qinghai-Xizang Plateau Meteorology (Beijing: Science Press 278) (in Chinese)
Yu L S and Weller R A 2007 Objectively analyzed air–sea heat fluxes for the global ice-free oceans (1981–2005) Bull. Am. Meteorol. Soc. 88 527–39
Zhang C, Tang Q and Chen D 2017 Recent changes in the moisture source of precipitation over the Tibetan Plateau J. Clim. 30 1807–19
Zhang C, Tang Q, Chen D, van der Ent R J, Liu X, Li W and Haile G G 2019a Moisture source changes contributed to different precipitation changes over the Northern and Southern Tibetan Plateau J. Hydrometeor 20 217–29
Zhang H, Zhang L, Li J, An R D and Deng Y 2020 Monitoring the spatial-temporal terrestrial water storage changes in the Yarlung Zangbo River Basin by applying the P-LSA and EOF methods to GRACE data Sci. Total Environ. 713 136274
Zhong X and Tang Q 2015 Combining satellite precipitation and long-term ground observations for hydrological monitoring in China J. Geophys. Res. Atmos. 120 6426–43
Zhong Y, Huang W and Zhong D 2019b Major moisture pathways and their importance to rainy season precipitation over the Sanjiangyuan region of the Tibetan Plateau J. Clim. 32 6837–57
Zhong Y, Li B and Zheng D 2014 Datasets of the boundary and interannual variability of Greenland winter precipitation sources for East Asian precipitation: mean seasonal cycle and interannual variability J. Hydrometeor 20 657–72
Zhao P et al 2018 The third atmospheric scientific experiment for understanding the earth–atmosphere coupled system over the Tibetan Plateau and its effects Bull. Am. Meteorol. Soc. 99 757–74
Zhao Y, Zhu J and Xu Y 2014 Establishment and assessment of the grid precipitation datasets in China for recent 50 years J. Meteorol. Sci. 34 414–20 (in Chinese)
Zhong L, Ma Y, Xue Y and Piao S 2019 Climate change trends and impacts on vegetation greening over the Tibetan Plateau J. Geophys. Res. Atmos. 124 7540–52