Atmospheric moisture transport *versus* precipitation across the Tibetan Plateau: a mini-review and current challenges

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The Revised Manuscript Submitted to *Atmospheric Research*

March, 2018

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Abstract

The Tibetan Plateau (TP), being an average of surpassing 4000 *m* above sea level and around 2.5 x 10^6 km^2, is the highest and largest plateau in the world and also called as the "Third Pole". Due to its elevated land surface and complex terrain, the TP is subjected to combined regulations of multiple climate systems and associated large-scale atmospheric circulations. In this paper, we comprehensively review the recent studies of atmospheric moisture transport *versus* precipitation across the TP, with the attempt to link the two, which did not receive much attention previously. This review focuses on the atmospheric moisture transport and associated circulation patterns in this region, widely adopted approaches to identify the atmospheric moisture transport, qualitative and quantitative analyses for the role of water vapor transport on the precipitation, as well as the internal physical mechanism between atmospheric moisture transport and precipitation over the TP. Moreover, directions of future research are discussed based on the following aspects, which include 1) proposing an integrated statistical-physical framework for demonstrating the influence of atmospheric moisture transport and associated circulation patterns on the precipitation, especially the extremes, in the high-cold mountainous region; 2) quantifying the contribution of atmospheric water vapor from the surrounding sources as well as the local moisture recycling on the TP's precipitation; 3) providing higher quality data for atmospheric water vapor and precipitation; 4) emphasizing on the physical mechanism sustaining the atmospheric moisture transport as well as its potential influence on the extreme precipitation, including amount, frequency, intensity and duration. It is expected

that this review will be beneficial for exploring the linkage between atmospheric moisture transport *versus* precipitation across the TP.

Key words: atmospheric moisture transport; precipitation; mini-review and challenges; qualitative and quantitative analyses; Tibetan Plateau;

1. Introduction

The Tibetan Plateau (TP), with an average elevation of more than 4000 *m* above sea level (*a.s.l.*), is the highest and largest plateau around the world. Give the significance of climate change, the TP, accompanied with Antarctic and Arctic, is currently attracting increased attention by the academic community (Qiu, 2008). Due to its unique terrain and specific underlying surfaces, the TP is subjected to combined regulations by multiple climatic systems, where the circulation patterns are featured primarily by the Indian monsoon in summer and the mid-latitude Westerlies in winter, as well as the East Asian monsoon affecting the eastern margin, e.g. Mount Gongga and eastern Qilian mountains (Yao et al., 2012). Also, the TP is the source region of several major rivers in the Asian continent and recognized as the "Asia's water tower", providing water for more than 1/3 of the world's population over China and India (Xu et al., 2008; Yao et al., 2012). Thus, an understanding of the nature and intensity of the hydrological cycle over the TP and of its development over time is a topic of crucial importance. In particular, precipitation, being a critical component of the water cycle, is one of the most emerging challenges faced by scientists over the TP due to the lack of reliable high-quality data set. (Gimeno et al., 2012; Ma et al., 2015; Wang et al., 2017a).

Wang et al. (2017a) reviewed the changes of the TP's precipitation over the past decades from the perspectives of observations and simulations. Overall, the precipitation exhibits an increasing trend with moderate variability since 1960s in the TP. Spatially, the precipitation shows a decreasing trend from southeast to northwest. It also has a strong seasonality-primarily occurs in summer (from June to August), accounting for nearly 70% of the annual total amounts (Ma et al., 2016; Tong et al., 2014). As the TP is a stronger heat source for the atmosphere in summer, the convective activity is frequent at the sub-daily scale, especially in the late afternoon. Thus, diurnal variation is significant for the precipitation in this region, in particular over the hilly areas (Maussion et al., 2014; Xu et al., 2014). Moreover, the rainfall peak often occurs over the large lakes in the morning but the time of peak rain rate is delayed as the lake size increases (Singh and Nakamura, 2009). Thanks to the availability of more satellite products, *in-situ* observations, and reanalysis simulations, more studies have been done recently to investigate the precipitation variabilities and trends in the TP (Gao and Liu, 2013; Ma et al., 2016; Ma et al., 2015; Maussion et al., 2014; Shen et al., 2014; Tong et al., 2014; You et al., 2015).

The precipitation over the TP is significantly influenced by the variations of the large-scale atmospheric circulations and associated local moisture recycling (Chen et al., 2012; Curio et al., 2015; Xu et al., 2014). The local moisture recycling provides higher atmospheric water vapor needed for the precipitation amounts than that from the outside of the TP (Curio et al., 2015). But the remote moisture transports, which are driven by the large-scale atmospheric circulations, primarily influence the variability of summer precipitation over the TP (Feng and Zhou, 2012; Wang et al., 2017b). Given the projected global warming in the future, the atmospheric water vapor holding capacity is expected to increase with elevated temperature, potentially causing changes of precipitation features in terms of intensity and/or frequency (Xu et al., 2008). Thus, more attentions are paid to explore the role of atmospheric moisture transport on the precipitation as well as its internal physical mechanisms across the TP in recent years (Cannon et al., 2016; Curio et al., 2015; Dong et al., 2016; Feng and Zhou, 2012; Wang et al., 2017b; Xu et al., 2008; Zhang et al., 2017). Various studies have been done in other regions, exemplified by the North and South America, the Europe and the Southeast China (Gershunov et al., 2017; Gimeno et al., 2010; Gimeno et al., 2014; Gimeno et al., 2012; Hecht and Cordeira, 2017; Lamjiri et al., 2017; Lavers and Villarini, 2013; Lu and Hao, 2017; Lu and Lall, 2017; Lu et al., 2013; van der Ent et al., 2010).

In summary, recent studies have deepen our understanding on the origin and evolution of the precipitation in the TP, ranging from some early-stage qualitative assessment to subsequently more integrated quantitative analysis. And related topics have been explored in other regions of the world, providing a good foundation for our investigation in the TP. However, a thorough review and a comprehensive summary is urgent to advance the knowledge of the role of atmospheric moisture transport and associated circulation patterns on the TP's precipitation, especially given the recent trend of the increasing extreme hydrometeorological events in this high-elevated region (Donat et al., 2016; Ingram, 2016; Kang et al., 2010; You et al., 2008).

The paper is organized as follows. Section 2 describes recent research progress of atmospheric water vapor and its link with precipitation across the TP, from the atmospheric moisture transport and associated circulation patterns (Section 2.1), to the widely adopted approaches for prominent moisture transport detection

(Section 2.2), then followed by some analysis of their roles in the TP precipitation (Section 2.3 & 2.4) and the governing physical mechanism (Section 2.5). Further challenges and prospects are discussed in Section 3. The conclusion is summarized in Section 4 at the end.

2. Recent processes of atmospheric moisture transport *versus* precipitation across the TP

2.1 Atmospheric moisture transport and associated circulation patterns in a changing climate

The upper-level atmospheric moisture transport plays an important role in the entire global natural and climate environment (Waliser et al., 2012). Filamentary structure is a common feature for the atmospheric moisture transport (Figure 1). At any time, three-to-five typically major conduits exist in each hemisphere, and each belt with the length more than 2000 km and width ranging from 500 to 1000 km carries large amounts of moisture across the mid-latitudes (Zhu and Newell, 1994; Zhu and Newell, 1998). A great number of convey belts are observed in the north-eastern Pacific, and about 15 land-falling convey belts per year are counted in California over longer periods and 8-10 consistent winter filaments affect winter floods in Britain (Hecht and Cordeira, 2017; Lavers and Villarini, 2013; Lavers et al., 2012; Neiman et al., 2008; Waliser et al., 2012). Other major global moisture sources in the tropical Atlantic oceanic areas are found to be linked with extreme precipitation in the Northeastern United States, the Southeastern China and the Western Europe (Lu and Hao, 2017; Lu and Lall, 2017; Lu et al., 2013). Thus, enhanced atmospheric moisture transports clearly contribute to the occurrence of hydrological extremes in many regions over the globe.

As the Asia's water tower, there are four primary climate systems regulating the moisture transport to the TP, including the Indian monsoon system, the mid-latitude Westerlies, the East Asian monsoon system and the local moisture recycling (also termed as "Tibetan Plateau monsoon") (Figure 2) (Bolch et al., 2012; Duan et al., 2011; Tang and Reiter, 1984; Tian et al., 2007; Xu et al., 2008; Yao et al., 2012). The elevated topography of the TP is taken as a barrier to the mid-latitude Westerlies and also enhances the Indian monsoon through its dynamical and thermal driving forces, thus contribute to the large-scale atmospheric circulations. Since there is a strong contrast of thermal property between land and ocean, a seasonally cross-south-north hemispherical monsoonal circulation exists in the earth. In summer, the TP serves as a strong "dynamic pump" and continuously attracts moist air from the surrounding oceans through deep canyons in the southern and western boundaries, even if their western boundary is further east (Feng and Zhou, 2012; Xu et al., 2008). The water vapor entering the TP through the eastern part of the southern margin is from the Indian monsoon air masses, while that through the western margin originates from the mid-latitude Westerlies. Revealed from the oxygen isotopes in precipitation, Tian et al. (2001) showed that the atmospheric moisture transport trajectories originate from the Arabian Sea to Indian continent, then to the Bay of Bengal, and finally arrive at the TP in summer. Based on the numerical experiments, Sugimoto et al. (2006) demonstrated that the process of water vapor transport into the TP contains multiple steps: the Westerlies carry the water vapor to the southern foot of the Himalayas at 1500 *m a.s.l.* in the afternoon, and then upslope winds in the southern slopes of the Himalayas convey the moist air mass to the plateau level.

Since the TP is a strong heat source in summer, the local moisture recycling forced by the thermal effect impacts the summer rainfall associated with atmospheric circulations in the internal TP (Duan et al., 2011; Kurita and Yamada, 2008). However, the thermal forcing may not be the primary factor for regulating the TP's precipitation variability. Wang et al. (2017b) found that remote moisture transport controls the variability of summer precipitation over the southern TP. There is also a persistent anticyclone over the Arabian Sea along the Somalia coast in winter, which takes more water vapor into the subtropical jet. The further moistened Westerlies jet continues to transport water vapor into the TP (Xu et al., 2008).

2.2 Several approaches to identify atmospheric moisture transport

Several features of the moisture transport, such as water vapor content, wind speed and the shape of intensive moisture fluxes, etc., influence the precipitation, especially for extreme rainfall. (Gimeno et al., 2014; Gimeno et al., 2012; Knippertz et al., 2013; Waliser et al., 2012). To clarify how atmospheric moisture transport influences the precipitation variability, the distribution and movement of water vapor need to be quantified first using satellite retrievals and/or ground-based observations.

There are four widely adopted approaches to retrieve the characteristics of atmospheric moisture transport, which are 1) using the vertically integrated water vapor transport fluxes (IVT) between the surface pressure and the pressure limit at the highest altitude of reliable radiosonde measurements (Zhu and Newell, 1998), 2) calculating the distribution of Integrated Water Vapor (IWV) from multi-sources/sensors or reanalysis model simulations (Dettinger et al., 2011; Neiman et al., 2008; Ralph et al., 2004), 3) estimating the Tropical Moisture Exports (TMEs) using the Lagrangian analysis on the basis of several-day forward trajectories starting from tropical lower troposphere (Knippertz and Wernli, 2010; Knippertz et al., 2013), 4) analyzing the stable oxygen isotope in precipitation which can be obtained from either field observations or isotopic atmospheric circulation models (Tian et al., 2007; Yao et al., 2013).

The IVT is calculated from the water vapor mixing ratios, i.e., the specific humidity (q, unit: kg/kg) and the zonal and meridional wind components (u and v, respectively, unit: m/s) for the troposphere, i.e., from the surface (1000 hPa) or all mandatory-level pressure surfaces (p_0) up to the pressure limit at the highest altitude of reliable radiosonde measurements (300 hPa). The product components $q \times u \times dp/g$ and $q \times v \times dp/g$ at each grid point were summed vertically from the surface to 300 hPa and then combined into a horizontal transport vector, with units of $kg\ m^{-1}\ s^{-1}$ below (Neiman et al., 2008; Zhu and Newell, 1998).

$$\mathrm{IVT} = \sqrt{\left(\frac{1}{g}\int_{p_0}^{300} qudp\right)^2 + \left(\frac{1}{g}\int_{p_0}^{300} qvdp\right)^2} \quad (1)$$

Since there is not a universal threshold for the identification of atmospheric rivers or deeper corridors with concentrated water vapor transports from the aforementioned literatures, the percentiles of the IVT distribution instead of a single value is preferred for different regions (Lavers et al., 2012). The detection approach is typically on the basis of a zonal threshold (Zhu and Newell, 1998), or a zonal and meridional threshold (Jiang and Deng, 2011). For instance, Lavers and Villarini (2013) used the 85th percentile of the IVT in each latitude bin as the threshold for identifying the atmospheric rivers in the pan-European region. In addition to the IVT threshold, some features, including time step, search region, latitudinal movement and time interval of the IVT maximum, are also considered. Further details and discussion of this method can be found in Lavers and Villarini (2013); Lavers et al. (2012); Zhu and Newell (1998).

It is well known that a key contributor to the advection of water vapor is the low-level jet, also referred to as the "warm conveyor belt". Since there is a close correlation between horizontal water vapor flux and the horizontal distribution of integrated water vapor (IWV) at each grid point, the IWV is considered as a proxy to characterize narrow features describing most of the instantaneous meridional water vapor transport at mid-latitudes (Schluessel and Emery, 1990). Ralph et al. (2004) indicated that 75% of the observed fluxes through a 1000 *km* cross-front baseline includes a 565 *km* width zone roughly 4 *km* depth, and the meridional water vapor flus is 1.5 x 10^8 *kg/s*. The IWV takes into account the density of liquid water, which expressed in *kg/m²* and also labeled as *mm* of total precipitable water. It is the vertically integrated total mass of water vapor *per* unit area for a column of atmosphere. The IWV formula is given below:

$$\text{IWV} = \int_{z=0}^{z} \rho_v(z)dz \tag{2}$$

where *z* refers to the column of atmosphere water vapor, and ρ_v is absolute humidity, the same as the water vapor density. However, not all the water vapor is actually precipitable. Gimeno et al. (2014) presented an approach of applying the criteria on the IWV, e.g., in terms of the areas greater than 2 *cm*, narrower than 1000 *km*, and longer than around 2000 *km*, as well as the wind speed in the lowest 2 *km* greater than 12.5 *m/s*. However, the above characteristics are summarized in the North American west coast, and they should be carefully redefined in other regions, such as the TP. Because of the strong water vapor absorption near 22*GHz* in the microwave range, the IWV can be retrieved using the classical radiative transfer model and careful instrument intercalibration from microwave sensor, such as SSM/I, SSMIS, TMI, AMSR-E, WindSat, AMSR2, GMI (Hou et al., 2014; Neiman et al., 2008; Ralph et al., 2004; Schluessel and Emery, 1990). Because of frequent blockage by the rainfall, the vertical wind profile is difficult to quantify from the current satellite estimates. Thus, it is challenging for the IWV to quantify as a proxy for the identification of atmospheric moisture structures.

The Lagrangian method is also developed to quantify the contribution of the atmospheric moisture transport to the precipitation coupled with air parcels by backward or forward trajectories. It is recommended by Knippertz and Wernli (2010) to propose an objective climatology of TMEs from more than 1.25 billion trajectories using the reanalysis data sets. The trajectories are calculated with the Lagrangian Analysis Tool (LAGRANTO), which is widely used in the atmospheric sciences, for instance to identify flow structures in extratropical cyclones and long-range transport pathways of moisture and trace substances (Sprenger and Wernli, 2015; Werner and Davies, 1997; Wernli, 1997). The identification process of TMEs includes three steps: 1) to define the moisture source in the tropics between 0 and 20°N, and between 1000 *hPa* and 490 *hPa*, since about 90% of all the water vapor is concentrated below the level of 490 *hPa*. However, it is noted that these trajectories might be not appropriate in regions of active tropical convection (Knippertz and Wernli, 2010); 2) to quantify the poleward circulation, where only the trajectories crossed the 20°N are considered for another six days, and if they have reached

35°N within this period, they are retained. The average meridional wind speed must exceed 2.85 *m/s*; 3) to diagnose the significant moisture transport into the extratropics, and only retain those trajectories that have moisture flux exceeding 100 $g\ kg^{-1} m\ s^{-1}$ in the north of 35°N. In general, the number of trajectories varies nonlinearly with the selected threshold. Such a flux for the threshold of 100 $g\ kg^{-1} m\ s^{-1}$ is more feasible for "fast" or "robust" trajectory events with meaningful statistics test (Knippertz and Wernli, 2010). However, this approach does not quantify the uptake of water vapor along the track. In addition, the influence of ocean evaporation along the subtropical area on TMEs trajectories is not specially involved (Knippertz et al., 2013). Trajectory analysis of air parcels has gained a lot popularity for the past two decades. Many trajectory analysis tools are developed for computing backward and forward trajectories using reanalysis data sets. These tools include FLEXTRA (Stohl, 1998), the NASA Goddard trajectory model (Schoeberl and Newman, 1995), the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) (Draxler and Hess, 1998; Stein et al., 2015), and the UGAMP offline trajectory model (Methven, 1997). Moreover, the space-time statistical analysis on the trajectory products have shown its contribution to better understanding of the linkage between enhanced moisture transport and extremes, especially in the mid-latitudes (Lu and Hao, 2017; Lu and Lall, 2017; Lu et al., 2013; Najibi et al., 2017)

The isotopic composition of precipitation, e.g., observed and modelled stable oxygen isotope ratios ($\delta^{18}O$), is another approach to identify the sources and pathways of water vapor (Cai and Tian, 2016; Guo et al., 2017; Yao et al., 2013). For example, Figure 3 displays the precipitation $\delta^{18}O$ monitoring network and associated schematic framework of the main moisture processes over the TP. The water isotope samples are collected at the field sites using a specifically designed container to avoid the danger of sample re-evaporation (Groning et al., 2012). The samples are then analyzed using the Liquid Water Isotope Analyzer (e.g., Picarro-2130i) in the Lab (Guo et al., 2017). Moreover, three widely used isotopic Atmospheric General Circulation Models (AGCMs-iso), i.e., LMDZ-iso, REMO5-iso, and ECHAM5-wiso, provide the gridded water stable isotopes with high spatial resolution and gain substantial new insights into the moisture transport (Hoffmann et al., 1998; Risi et al., 2010; Sturm et al., 2005). However, the AGCMs-iso are not capable of simulating the observed rapid and large variations of the water isotope signals. Note that the integrations between the explicit samples of precipitation isotopes and the simulations of the state-of-the-art AGCMs-iso enable us to deeply understand the moisture transports.

2.3 Qualitative analysis for the role of atmospheric moisture transport on precipitation in the TP

The TP's precipitation generally shows a slightly increasing trend in the past decades under the warming climate (Kang et al., 2010; Ma et al., 2018b). Xu et al. (2008) reported a positive correlation between atmospheric moisture content and precipitation during the past 50 years over the TP. According to the classical Clausius-Clapeyron equation (Trenberth, 2011), the increasing temperature leads to higher capacity of atmospheric moisture, and thus very likely results in more precipitation. The large-scale atmospheric circulations dominate the water vapor transport and thus regulate the interannual variability of summer precipitation across the TP (Chen et al., 2012; Liu and Yin, 2001; Xu et al., 2008). Also, a seesaw structure with regard to the interannual variability of summer precipitation is identified between the southern and northern TP. It is closely associated with the North Atlantic Oscillation [NAO] (Liu and Yin, 2001).

The TP, especially in the mountainous regions, has strong local precipitation systems in summer (Gou et al., 2018), and locally recycled moisture also plays a crucial role in the precipitation associated regional circulation. For instance, the local recycling ratio, which is the contribution of locally evapotranspirated water in the boundary layer, increases from 30% to 80% as the regional circulation type of rainfall occurs (Kurita and Yamada, 2008). Chow and Chan (2008) proposed that the local forcing indices, such as strong solar radiation and complex terrains, might dominate the summer rainfall patterns at the diurnal scale in the TP. The diurnal cycle of summer rainfall is more associated with a robust diurnal cycle of the atmospheric system around the southern TP, where a strong daytime wind accompanied with increasing humidity prevails in the deep valleys (Ueno et al., 2008). The southeasterly wind carries out favorable moisture for the midnight and early morning rainfall (Bhatt and Nakamura, 2006). In addition, the cyclonic circulation over the Indian subcontinent hampers parts of water vapor intrusion into the TP (Sugimoto et al., 2006). However, the internal physical mechanism needs further verifying with plenty of field observations.

The dominant origin of the moisture contributing to the TP is a narrowly tropical-subtropical belt from the Indian subcontinent to the southern Hemisphere. Another two sources are identified in the northwestern part of the TP and the Bay of Bengal (Chen et al., 2012). The water vapor from the Bay of Bengal moves through the Brahmaputra channel and plays a significant role on the precipitation characteristics in the southeastern TP (Maussion et al., 2014). While the southwest is more influenced by the water vapor from northern Indian subcontinent (Dong et al., 2016). The shifting moisture origin between Bay of Bengal and southern Indian Ocean influences the precipitation patterns in the southern TP, with an abrupt decrease in May and most depletion in August in terms of precipitation $\delta^{18}O$ (Yao et al., 2013).

2.4 Quantitative analysis for the contribution of atmospheric moisture transport to precipitation in the TP

The contributions to the precipitation variability in the TP by the local moisture recycling and the remotely water vapor transport are comparable (Xu et al., 2014). A growing number of studies have been not only focused on identifying water vapor origins but also quantifying their contributions to the precipitation in the TP (Curio et al., 2015; Feng and Zhou, 2012; Wang et al., 2017b; Zhang et al., 2017).

Feng and Zhou (2012) initially examined the various sources of atmospheric water vapor for summer precipitation over the southeastern TP during 1979-2002 using multiple reanalysis data. To quantitatively reveal the vertical distribution of moisture transport, they divide the whole air column into lower (1000-700 *hPa*), middle (700-400 *hPa*), and upper (400-300 *hPa*) layers across the four borders of the TP. Overall, the moisture from the southern edge, which comes from the Indian Ocean and the Bay of Bengal, dominates the summer precipitation in the southeastern TP. Around 32% of the water vapor comes from the western part along the southern margin of the TP. As for the interannual variability of summer precipitation in the southeastern TP, it is dominated by the anomalous anticyclone at the Bay of Bengal and the northern Indian subcontinent. An excessive rainfall anomaly of 1 *mm/day* in this region is associated with an anomalous water vapor input of 138 $kg\ m^{-1}\ s^{-1}$ and 104 $kg\ m^{-1}\ s^{-1}$ from the western and southern margins of TP, respectively (Feng and Zhou, 2012).

Although a first step has attempted to quantify the water vapor's contribution on the precipitation of the TP, the question arises of whether the high-resolution data sets lead to an improvement on the atmospheric moisture quantitation. Later, Curio et al. (2015) critically quantified the atmospheric moisture transport towards the TP based on a new data set, i.e., the 12-year High Asia Refined analysis (HAR), which better describes the complex topography of the TP. They concluded that 36.8±6.3% of the contributing atmospheric moisture comes from outside of the TP, while local moisture recycling accounts for the remaining 63.2%. The mid-latitude Westerlies contribute higher for the moisture transport in summer than previously assumed. It shows that the Westerlies are not fully blocked by the TP and parts of the moisture are redirected to the north/south.

Wang et al. (2017b) investigated the relative contribution of remote moisture transport and local surface evaporation to the summer rainfall variability over the southern TP. The averaged moisture flux and local surface evaporation in summer are 4.16 *mm/d* and 2.79 *mm/d* from 1980 to 2010, respectively, which is consistent with the observed average summer rainfall rate of *7.17* mm/d. That's to say, local moisture recycling amounts to around 40% to the total summer rainfall over the southern TP. The remote moisture transport regulates the interannual variability in the summer rainfall in this region, since the mean anomaly of local surface evaporation is merely 0.07 *mm/d*. For the remote moisture sources, the southern and western boundaries are two incoming channels with moisture fluxes of 1991.47 $kg\ m^{-1}\ s^{-1}$ and 160.13 $kg\ m^{-1}\ s^{-1}$, respectively. Both of the northern and eastern boundaries are export channels with regard to the moisture fluxes in terms of 267.77 $kg\ m^{-1}\ s^{-1}$ and 381.97 $kg\ m^{-1}\ s^{-1}$, respectively. Although most external moisture comes cross the southern edge, it serves as a secondary contribution to the variation of the summer rainfall in the southern TP. Because most of the moisture is directly converted into precipitation during the elevating process over the steep southern slope of the TP (Lin et al., 2018; Wang et al., 2017b), the water vapor from the western margin mainly regulates the summer rainfall variability in spite of its relatively weaker total contribution.

The TP shows an overall wetting trend especially in the west-central TP during the past decades. By using the modified Water Accounting Model, the changes in the moisture sources of the precipitation in the west-central TP are quantitatively investigated (Zhang et al., 2017). On average, the land and ocean contribute > 69% and > 21% of the water vapor supply to the total precipitation in the targeted area, respectively, while the local moisture recycling contributes around 18% of the total precipitation. As for the recent increase of precipitation in the west-central TP, the enhanced water vapor transport from the Indian Ocean in July and September and the intensified local moisture recycling might be the dominating cause (Zhang et al., 2017).

The quantitative analysis of atmospheric water transport from different areas towards the TP relies on the calculation of the moisture budget through the cross sections following the border of the TP. Given the accuracy of the data sources, the position of the cross sections used to calculate the moisture budget, and the vertical resolution of the data sets, as well as the reanalysis model structures, some biases of the results might be introduced. Thus, the exploration of quantifying the contribution of atmospheric moisture transport to the precipitation in the TP is still on its early stage given the current progress and findings.

2.5 Physical mechanism between atmospheric moisture transport and precipitation in the TP

The physical mechanism explaining the roles of water vapor transport and the associated synoptic-scale circulation patterns in the TP's precipitation is complicated (Feng and Zhou, 2012) and needs further diagnostic analysis. The governing system is influenced by the Indian monsoon systems, the mid-latitude Westerlies and the elevated heating of the plateau. The climate teleconnections, including the NAO, the Indian Ocean Dipole (IOD) mode, and EI Nino-Southern Oscillation, have an additional effect on the climate monsoon systems at different timescales (Cherchi and Navarra, 2012; Liu et al., 2015), and in turn take a far-reaching influence on the atmospheric moisture transport across the TP (Lin et al., 2016; Wang et al., 2017b).

The TP is a persistent pool of water vapor maximum in the 500-300 *hPa* atmosphere layer, which is named as an "air pump" (Xu et al., 2008). There is a strong thermal contrast between the TP and its surrounding oceans, and the water vapor from the low-latitude oceans moves toward the elevated plateau by this air pump (Wu et al., 2012). The convergence of the warm-moist air lifts along the plateau's slope and diverges at the top height. Because the sucking and pumping effects in the southern TP contribute most of the moisture ascent and convergence in the monsoon season, heavy rainfall event is frequent across the Himalayas (Wu et al., 2007). Xu et al. (2014) proposed that a two-ladders of "CISK-like mechanism" (conditional instability of the second kind) forces water vapor flows climbing up the southern slope of Himalayas (Figure 4). The thermodynamic processes depict a coupling of two CISK type systems, both with convergence at low level and divergence at upper level. But the coupled system is horizontally contiguous and vertically staggered. The diverged flow drives the convergence at the low-pressure center in the TP, provides the local convection system with warm-moist air, and consequently results in precipitation over the TP.

Based on several lines of evidences based on satellite and in-situ observations, numerical sensitivity simulations, and water vapor trajectories, Dong et al. (2016) found that the pathway of moisture transport is "up-and-over" rather than by "upslope" flow along the southern Himalayas (Figure 5). The hydrometers and moist air parcels are lifted by convective storms over the Indian subcontinent and the foothills of Himalayas, and subsequently swept along the southern edge by the mid-tropospheric circulation. The "up-and-over" moisture transport accounts for ~23% of the summertime and contributes to half of the total summer rainfall in the southwestern TP.

3 Research challenges and prospects

The study on the atmospheric moisture transport and its linkage with the precipitation over the TP has achieved great progress for the past decades. However, more attention is suggested to devote in the following aspects:

After reviewing the leading studies on the atmospheric moisture transport *versus* precipitation in the TP, the majority focused on the diagnosis of atmospheric moisture budget and its impact on the precipitation variability in summer, or warm period. Overall, the water vapor from the southern and western boundaries regulates the yearly variability of summer precipitation in the TP. Considered that snowfall or snow-melting process has significant influence on the water resources, as well as the thermal regimes of frozen ground over the TP (Kang et al., 2010; Yang et al., 2014; Zhang and Ma, 2018), more attention is needed for the atmospheric moisture budget in winter or cold-season. First of all, the physical mechanism for the precipitation variability in winter over the TP is unclear. Some studies have explored the close linkage between the atmospheric moisture transport and precipitation variability in the TP on daily to longer time scales. The sub-daily or hourly scale has not been examined in this region. But such timescale is of great importance for the featured hourly storms and instantaneous floods in the TP. A deeper understanding of extreme rainfall events, such as occurrence, amount, duration, and frequency, is also necessary and would be beneficial to the hazardous floods in the TP under the changing climate. More evidences have suggested the dominating role of the local moisture recycling in the summer precipitation in the TP (Curio et al., 2015; Sugimoto et al., 2006). But the role of local moisture recycling on the extreme rainfall remains unknown. Thus, how to develop an integrated physical and statistical framework for the TP concerning the influence of atmospheric moisture transport and the associated circulation patterns on the precipitation variability with respect to the various aspects mentioned above is an urgent task.

Currently, the analysis data from either satellite retrieval, reanalysis model simulation or field *in-situ* observation are not sufficient to capture complex terrains of the TP, higher spatial resolution products are in great demand to improve the understanding of the moisture transport and assist further quantitative analysis on its linkage/contribution with/to precipitation variability in the TP. For instance, Lin et al. (2018) investigated the spatial resolution dependency of simulated moisture transport through the central Himalayas and its further influence on precipitation bias over the TP. Moreover, the ground-based monitoring network is sparse in the TP, especially in the west, which induces higher uncertainty for the precipitation patterns (Ma et al., 2015). Maussion et al. (2014) demonstrate the contribution of using the dynamical downscaling approach to produce a better product. We have developed ensemble precipitation data sets with higher quality at daily and 0.25° scales from 2001 to 2015 over the TP (Ma et al., 2018a; Ma et al., 2018b), but more efforts need to be done to provide more reliable data sets for our planned work in this region.

Conventional "upslope" route is the mainstream hypothesis for the atmospheric moisture transport through the Himalayas and thus into the southern TP (Xu et al., 2014). Recently, a new "up-and-over" scheme for the atmospheric moisture transport was proposed and evidenced in the southwestern TP (Dong et al., 2016). Sensitivity simulations showed that the "upslope" and "up-and-over" routes coexist in the moisture transport processes, where the "upslope" moisture transport is frequent but inefficient, the "up-and-over" transport is more efficient but less frequent (Dong et al., 2016). However, the detailed moisture transport (e.g., the transient eddies) is not yet being well described. And the question of how to quantifying the relative contribution of the two modes along the southern slope of Himalayas remains unanswered.

The applicable prospect of this review study potentially links the current leading "Sky-River" project in the Three-River Headwaters region, which is regarded as the prominent water resources management program in mainland China (Wang et al., 2016). One of the great challenge is conducting trans-regional water diversion from the atmospheric rivers at the optimal moment. The artificial precipitation experiment is more empirical and lack of reasonable evaluation and guidance. If the atmospheric moisture transport conditional on the precipitation patterns, especially the extreme rainfall events, were explicitly illustrated, it would be beneficial for the artificial rainfall experiment and thus contributed to this enormous project. In summary, the endeavor for understanding the role of the atmospheric moisture transport and the associated circulation patterns on the precipitation variability in the TP is significantly valuable for the scientific community.

4 Concluding summary

The TP is the highest and one of the most active centers in the global water cycle. Recent processes and challenges regarding the atmospheric moisture transport *versus* precipitation variability across the TP are comprehensively reviewed in this paper.

The TP serves as a strong "dynamic pump" and continuously attracts moist air from the surrounding oceans under the large-scale atmospheric circulations. More specifically, the warm-moist air continuously elevates along the southern slope of the Himalayas, where the conventional "upslope" and new-finding "up-and-over" schemes coexist to force the water vapor transport. Although four approaches (i.e., IWV, IVT, TMEs, and water isotopes) are widely adopted for the identification of atmospheric moisture transport, it is not easy to quantify the role of atmospheric moisture transport on the precipitation in the TP. Based on the moisture budget method, local moisture recycling has larger contribution to the TP's precipitation than that from the remote moisture transport. Overall, the water vapor from the outside is mainly from the southern and western borders, which are driven by the Indian monsoon and the Westerlies, respectively. The water vapor from the western boundary primarily influences the variability of summer rainfall in the southern TP, in spite of weaker amounts than that from the southern boundary.

Quantitative identification for the atmosphere moisture sources using the integrated trajectory approach is the next step for exploring the extreme precipitation in the TP. More importantly, a statistical-physical framework aimed to explore the influence of atmospheric moisture transport and associated large-scale circulation patterns on the TP's precipitation should be proposed in advance. Also, it is necessary to develop the atmospheric moisture and precipitation data sets with high accuracy in order to perform the above analysis.

Acknowledgements

This work is financially supported by the National Natural Science Foundation of China (Nos. 41601065, 91437214, and 51709051) and the Hong Kong Research Grants Council funded project (No. 26200017). Y. Ma is partially supported through The Hong Kong University of Science and Technology (HKUST) Post-Doctoral Fellowship (PDF) Matching Fund 2017. M. Lu and M. Pan are partially supported by the HKUST funds (Nos. Z0488, R9392 and IGN16EG06). We would like to thank the Editor and two anonymous reviewers for their thoughtful comments.

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Figure Captions

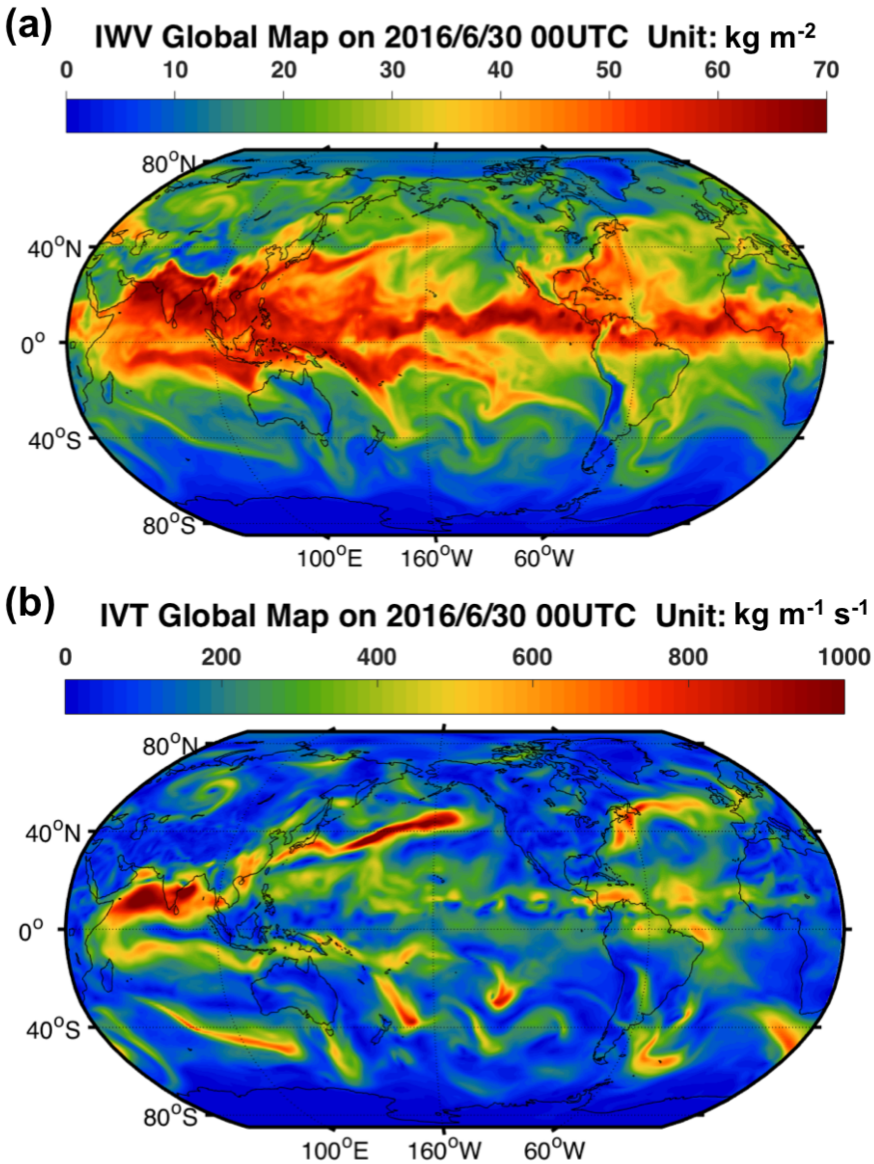
Figure 1 A general distribution of (a) composite Integrated Water Vapor (IWV) and (b) vertically horizontal water vapor transport fluxes (IVT) showing the atmospheric moisture transport on Jun 30th 2016 across the globe.

Figure 2 Sketch map of several climate systems that regulates the atmospheric moisture entering the Tibetan Plateau, where the green arrays stand for the Indian monsoon system, the grey arrays stand for the mid-latitude Westerlies, the black arrays stand for the East Asian monsoon system, and the red dotted ellipse stand for the local moisture recycling, also termed as Tibetan Plateau monsoon. The background map shows the mean value of composite Integrated Water Vapor (IWV) and wind direction at 500 *hPa* in the summer of 2016 around the TP.

Figure 3 (a) The precipitation $\delta^{18}O$ monitoring network over the Tibetan Plateau (TP). Red triangles depict locations of $\delta^{18}O$ monitoring stations, where Up triangles stand for the Global Network of Isotopes in Precipitation (GNIP) stations and down triangles stand for the Tibetan Network for Isotopes in Precipitation (TNIP) stations; Open circles show ice core sites. (b) Schematic framework of the main processes affecting precipitation $\delta^{18}O$ over the TP. (Cited from Yao et al. (2013))

Figure 4 A diagram of the summary on two ladders of CISK-like processes with two couplings of heat source Q1 and moisture sink Q2 over the southern slopes of TP as well as primary platform in driving atmospheric moisture flows climbing up towards the plateau. (Cited from Xu et al. (2014))

Figure 5 A schematic of the "up-and-over" atmospheric moisture transport from central-eastern India towards the periphery of the southwestern Tibetan Plateau (SWTP) (Cited from Dong et al. (2016))



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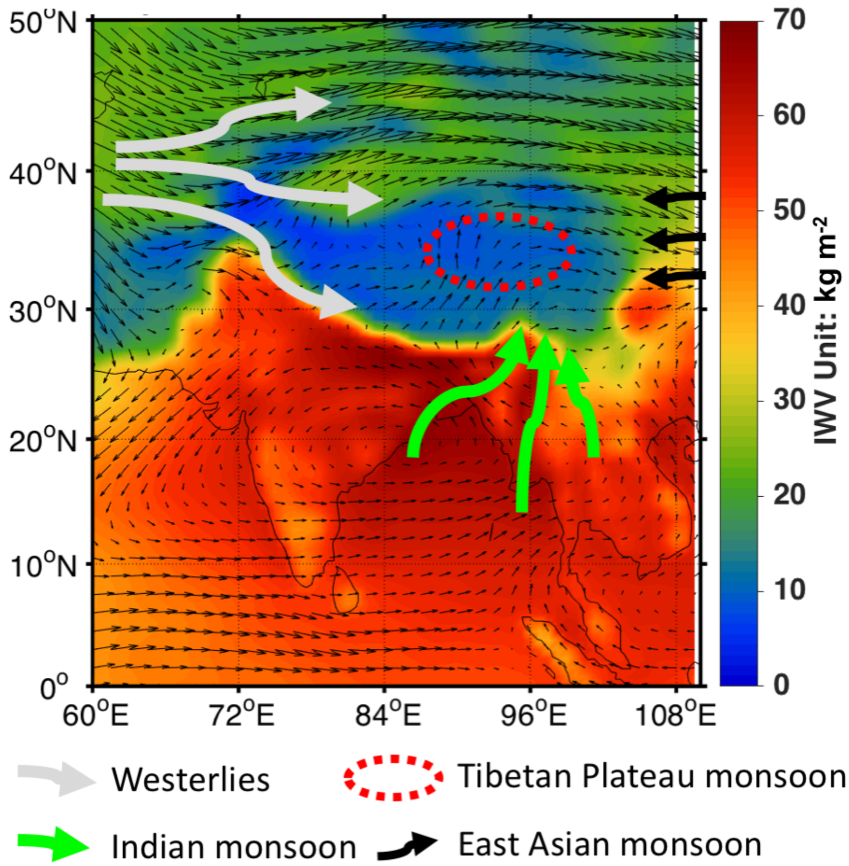

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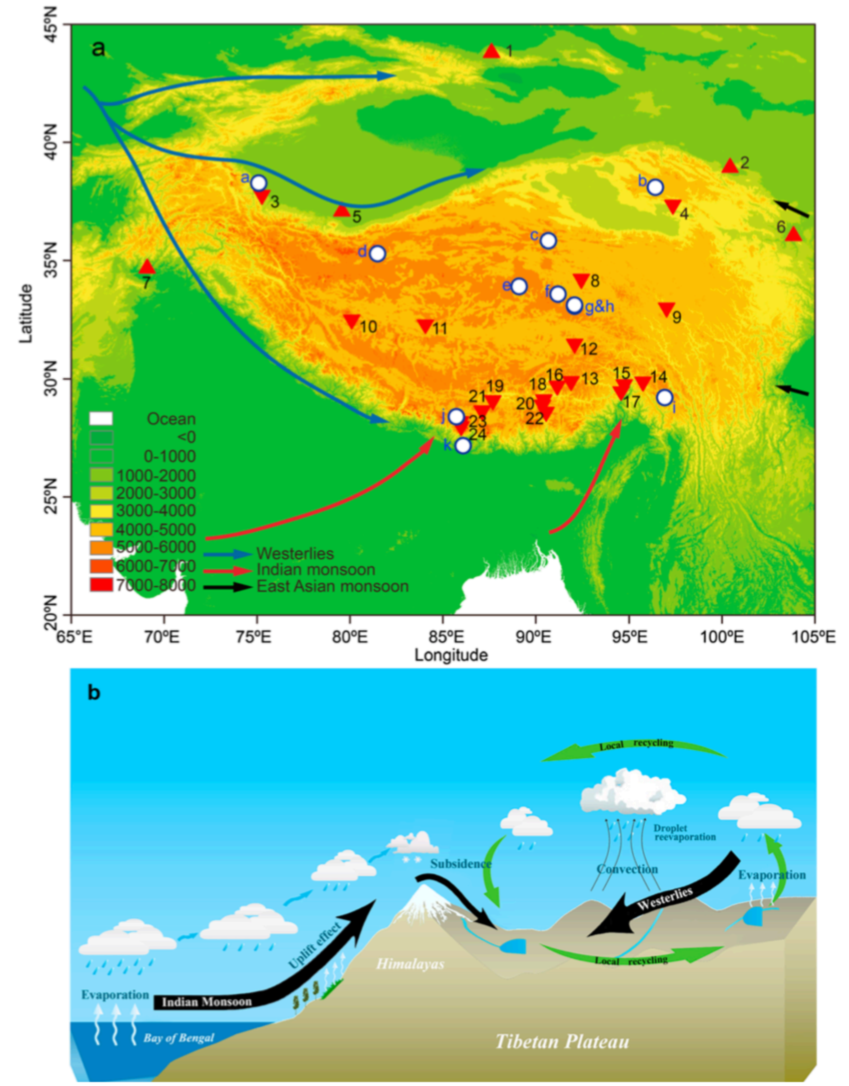

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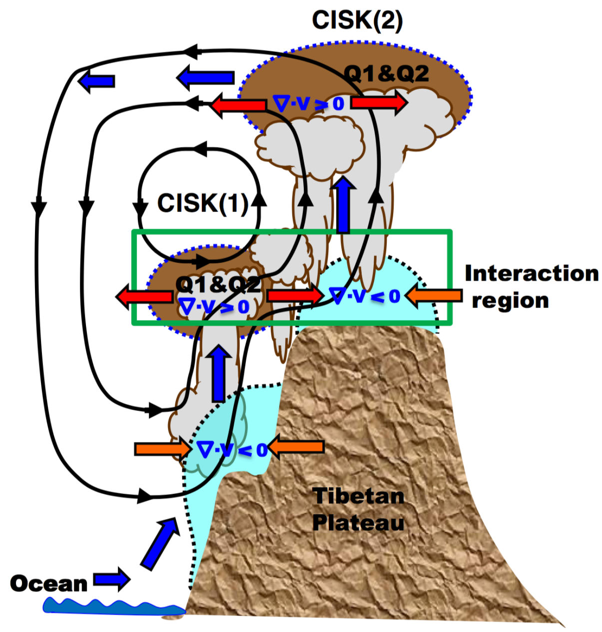

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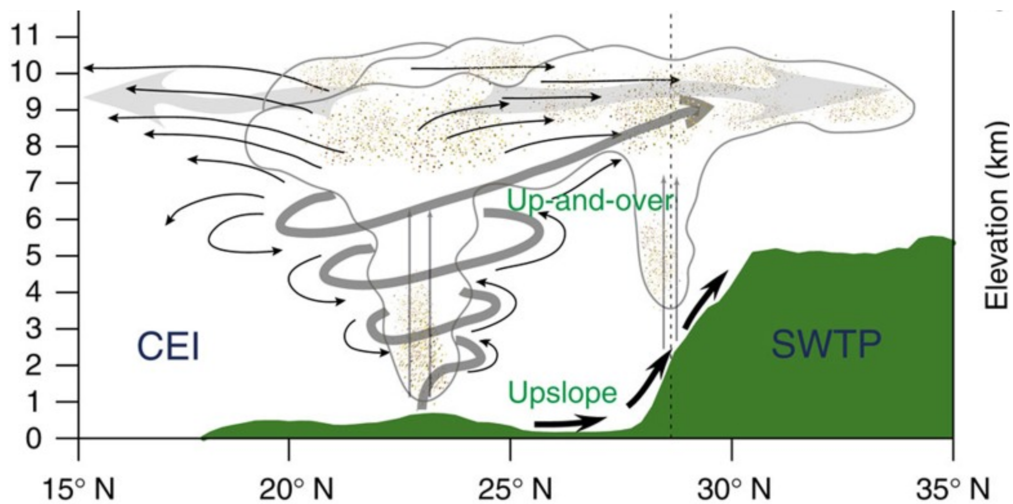

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