Atmospheric Research 209 (2018) 50–58

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Invited review article

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

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ARTICLE INFO

Keywords:
Atmospheric moisture transport
Precipitation
Mini-review and challenges
Qualitative and quantitative analyses
Tibetan Plateau

ABSTRACT

The Tibetan Plateau (TP), being an average of surpassing 4000 m above sea level and around $2.5 \times 10^6\,km^2$, 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.

1. Introduction

The Tibetan Plateau (TP), with an average elevation of > 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 > 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),

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https://doi.org/10.1016/j.atmosres.2018.03.015
Received 12 January 2018; Received in revised form 12 March 2018; Accepted 20 March 2018
Available online 26 March 2018
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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 (Sections 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 (Fig. 1). At any time, three-to-five typically major

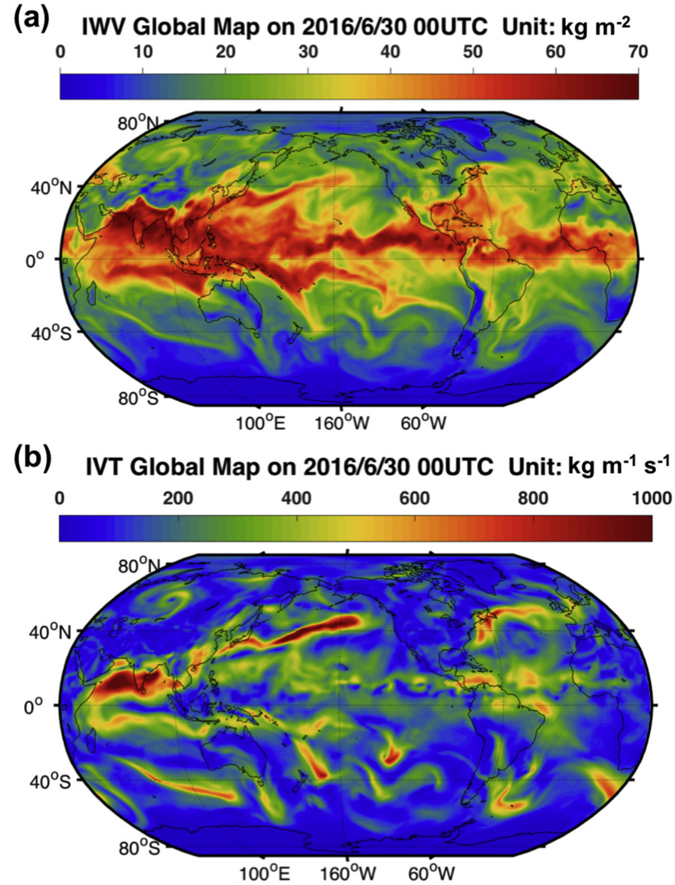

Fig. 1. A general distribution of (a) composite Integrated Water Vapor (IWV) and (b) vertically horizontal water vapor transport fluxes (IVT) showing the atmospheric moisture transport on Jun 30th 2016 across the globe.

conduits exist in each hemisphere, and each belt with the length > 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”) (Fig. 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

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