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Documentation of multifactorial relationships between precipitation and topography of the Tibetan Plateau using spaceborne precipitation radars

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A R T I C L E I N F O

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A B S T R A C T

Precipitation is one of the most important hydrometeorological components of the Tibetan Plateau (TP). The relationships between precipitation and topography in the TP were investigated using 17 years of Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) data and 2 years of Global Precipitation Measurement (GPM) dual-frequency precipitation radar (DPR) data. First, the retrieval and total errors of the two radars were quantified in the TP using ground-based precipitation datasets. The TRMM PR and GPM DPR both significantly underestimate the precipitation, with total errors up to 40% and 53%, respectively. Then, precipitation of the two radars was corrected prior to effective application. The correction was separately performed for each river basin in the TP by adding total errors. Finally, precipitation–topography relationships were documented using corrected radar data. The main findings on precipitation–topography relationships are: (1) precipitation generally decreases with increasing elevation from 2 to 6 km in the TP. However, the trend is inverse in the Qaidam Basin which is characterized by extremely low precipitation in the interior basin and high precipitation along the windward slopes of surrounding mountains; (2) quantitative relationships between precipitation and elevation can be depicted for most exorheic basins in the TP using exponential fitting. The coefficients of determination for the fitting are higher than 0.9 in six basins; (3) the relationships based on GPM DPR data are less robust due to its fewer samples, whereas the GPM DPR probably resolves the problem of overestimating precipitation in some grid pixels with high elevation, compared to the TRMM PR; (4) three typical mountains (i.e., Himalaya, Hengduan, and Tianshan mountains) exhibit significantly negative correlation between precipitation and elevation. Particularly, there are two bands of precipitation maxima along the southern slopes of the central Himalayas (78°E–88°E), corresponding to the two-step topography, which affects the vegetation distribution. This study provides insights into the precipitation–topography relationships in the TP and its surrounding regions based on data from spaceborne precipitation radars.

1. Introduction

The Tibetan Plateau (TP) with an average elevation > 4000 m and its neighboring regions are known as the Third Pole (Qiu, 2008). As the sources of many major rivers, such as the Indus, Ganges, Brahmaputra, Yangtze, and Yellow, the TP and adjacent mountains are Asia's water towers (Immerzeel et al., 2010). The TP is quite sensitive to climate change; the temperature has significantly increased since the 1950s, particularly in winter (Liu and Chen, 2000). Cryospheric changes of the TP include glacier retreat, snowmelt, and permafrost degradation (Yao et al., 2012a; Chen et al., 2017a, 2017b). The area of most lakes in the TP has expanded between the 1970s and 2010, indicating accelerated glacier melt and/or increased precipitation (Zhang et al., 2014). The security of water resources of rivers fed by snow and ice from the TP is threatened. The Brahmaputra and Indus basins are most susceptible to reductions in water flow (Immerzeel et al., 2010; Long et al., 2017). Accurate observation of the water cycle is a prerequisite to monitor water resource status and climate change impact on the TP. Precipitation is one of the most important components of the water and energy cycles (Yang et al., 2014; Tang et al., 2016a; Chen et al., 2017a, 2017b). Precipitation accounts for 55–60% of the annual runoff in all major rivers originating in the TP, except for the Indus River for which the contribution of both glacier and snow meltwater is extremely important (Zhang et al., 2013).

The topography has a significant impact on precipitation (Daly et al., 1994; Hughes et al., 2009; Kumari et al., 2016). For example,

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windward slopes of mountains tend to receive more precipitation, while leeward slopes receive less, forming the well-known rain shadow (Roe, 2005). Traditionally, rain gauge observations are an important source of data in studies of precipitation–topography relationships. For example, the Precipitation–elevation Regressions on Independent Slopes Model (PRISM) is widely used in distributing point observations to regular grid cells while considering the effects of elevation (Daly et al., 1994, 2002). Precipitation–topography relationships are complex in the TP and its surrounding regions including the Himalaya, Hengduan, and Kunlun mountains (Singh et al., 1995; Yin et al., 2008; Shrestha et al., 2012). Those mountains shape the precipitation characteristics of the TP by blocking water vapor associated with Indian monsoon, Westerlies, and East Asian monsoon (Yao et al., 2012b), leading to sharp decreases in precipitation along the TP boundary.

Reliable ground observations are extremely scarce in the TP (Tang et al., 2016b). Only a few gauges and weather radars are distributed in the eastern TP and there are almost no ground observations in the southern and western parts of the TP (Shen et al., 2014a; Ma et al., 2016). In addition, traditional rain gauges have inherent limitations due to various factors, such as wind-induced undercatch, particularly in the TP (Yang and Ohata, 2001). Furthermore, weather radars also suffer from beam blockage and broadening in mountainous regions (Wen et al., 2016). Multi-satellite precipitation products, such as the Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (IMERG; Huffman et al., 2015), Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA; Huffman et al., 2007), NOAA Climate Prediction Center (CPC) morphing technique (CMORPH; Joyce et al., 2004), and Global Satellite Mapping of Precipitation (GSMaP) project (Ushio et al., 2009), provide valuable precipitation data in remote areas with sparse gauge networks. These multi-satellite products employ as many data sources including infrared and microwave sensors as possible. However, they are also subject to significant uncertainties in the TP due to insufficient gauge adjustment, complex terrain, algorithm defects, and instrument limitations (Tong et al., 2014; Shen et al., 2014a; Ma et al., 2016; Tang et al., 2016a).

Spaceborne precipitation radars, such as the precipitation radar (PR) onboard the TRMM satellite and the Dual-frequency Precipitation Radar (DPR) onboard the Global Precipitation Measurement (GPM) Core Observatory, provide the most direct precipitation estimates for the Earth from space. The TRMM PR (Ku band), launched on November 27, 1997, is the world's first spaceborne precipitation radar. During its 17-year operation, the TRMM PR has substantially improved our knowledge of tropical and subtropical precipitation. The TRMM satellite re-entered the Earth's atmosphere in June 2015. As the successor of the TRMM PR, the GPM DPR (Ku and Ka bands) is the first dual-frequency spaceborne precipitation radar. It was launched on February 27, 2014. Compared with the TRMM PR, the GPM DPR is more sensitive to light precipitation and snowfall at middle and high latitudes (i.e., > 30°, Hou et al., 2014; Hamada and Takayabu, 2016; Tang et al., 2017). In addition, the GPM DPR expands the spatial coverage of the TRMM PR from 37°N–S to 66°N–S. As Level-2 products of the TRMM and GPM projects, the PR and DPR are data sources of Level-3 products (TMPA and IMERG) that are widely used in the hydrological and hydrometeorological communities. In combination with microwave radiometers (passive microwave) that are also onboard the TRMM and GPM satellites, the PR and DPR (active microwave) play an important role for the calibration standard of Level-3 products due to their high data quality (Huffman et al., 2015). The utility of Level-2 products has yet to be fully explored, in contrast to Level-3 products.

Benefiting from the high accuracy and fine spatial resolution, spaceborne radar data have been employed in various precipitation-related studies (Fu et al., 2006; Houze et al., 2007; Biasutti et al., 2012) including those focusing on precipitation–topography relationships (Bookhagen and Burbank, 2006; Shrestha et al., 2012). As the highest mountain range in the world, the Himalaya Mountains have received considerable attention. For example, there are two significant precipitation peaks along the southern Himalayan slope, which are due to a two-step topography (Bookhagen and Burbank, 2006; Yatagai and Kawamoto, 2008; Shrestha et al., 2012). However, the macroscopic precipitation–topography relationships across the TP, which are critical to understanding hydrologic and atmospheric systems, remain largely unknown. In addition, due to the TP's unique topography and climate, systematic errors caused by insufficient sampling and retrieval algorithms (Fisher, 2007) are nonnegligible but poorly considered in previous precipitation–topography studies.

Therefore, the objectives of this study are to: (1) correct TRMM PR and GPM DPR errors using ground observations; and (2) document the relationships between precipitation and topography across the entire TP using corrected TRMM PR and GPM DPR precipitation estimates. The long time series of TRMM PR data (17 years) is valuable in achieving conclusive precipitation–topography relationships in regions south of 37°N. Meanwhile, the latest GPM DPR (2 years) provides preliminary insights into the precipitation variation depending on topography beyond the TRMM region north of 37°N.

2. Study area, datasets, and methods

2.1. Study area

The TP boundary is defined by the 2500 m contour line using the National Aeronautics and Space Administration (NASA) Shuttle Radar Topographic Mission (SRTM) 90 m DEM (Zhang et al., 2014), as shown in Fig. 1a. Along the boundary, the topography is characterized by marked variations and the relief is much larger than that of the inner TP (Fig. 1b). The distribution of national rain gauges in China, provided by the China Meteorological Administration (CMA), is shown in Fig. 1c. Most gauges are located in low-elevation regions because of technical and economic reasons. The sparse and uneven gauge distribution poses a challenge to the study of precipitation–topography relationships in the TP, necessitating remote sensing techniques. We further investigated the precipitation–topography relationships of three typical mountain ranges (Fig. 1d), that is, the Himalayas as the world's highest mountains, Hengduan as the widest N–S mountain range in China with many important transboundary and domestic rivers (e.g., the Mekong, Salween, and Jinsha rivers), and Tianshan as the highest mountain in the study region not part of the TP.

2.2. Datasets

Table 1 shows the basic information regarding the satellite products and ground data involved in this study. Detailed descriptions are given below.

2.2.1. TRMM PR

The Level-2 TRMM product 2A25 (version 7) from January 1998 to March 2015 (Iguchi et al., 2000; Iguchi et al., 2009) was used, covering the whole operation period of the TRMM PR. The 2A25 dataset provides near-surface precipitation estimates, corresponding to the range bin closest to the surface that is free of the impact of ground clutter.

The TRMM satellite experienced two orbit adjustments during its operation. The first adjustment was made in August 2001, when the orbit was boosted from 350 to 402.5 km. The data differences before and after the boost are insignificant and can be neglected (Shrestha et al., 2012). The second adjustment was made from October 8, 2014 to February 12, 2015, during which the TRMM satellite descended to 350 km. Therefore, 2A25 data are missing during this period. In spite of orbit adjustments, the TRMM PR data series are generally continuous and consistent. However, the spatial coverage of the PR ranges between 37°S–N and only the southern part of the TP is covered.

2.2.2. GPM DPR

The Level-2 GPM product 2ADPR (version 04A) from April 2014 to