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Evaluation of satellite precipitation retrievals and their potential utilities in hydrologic modeling over the Tibetan Plateau

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SUMMARY

In this study, we evaluate four widely used global high-resolution satellite precipitation products against gauge observations over the Tibetan Plateau (TP). We also investigate the capability of the satellite products in streamflow simulations using the VIC hydrological model. Results show that the 3B42 and CMORPH perform better than the 3B42RT and PERSIANN at both plateau and basin scales. The 3B42RT and PERSIANN considerably overestimate the gauge precipitation estimates almost over the entire plateau, and the PERSIANN fail to capture the spatial and temporal pattern of the gauge precipitation estimates. For different satellite estimates, the error sources are systematically different for various seasons. For the 3B42, the miss bias is the main problem. The CMORPH exhibits obvious negative hit bias and miss bias in the rainy season and false-rain bias in the non-rainy season. The total bias in the 3B42RT and PERSIANN mainly attribute to positive hit bias in the rainy season and false-rain bias in the non-rainy season. The 3B42RT and PERSIANN show little capability for streamflow simulations over the TP, while the CMORPH exhibits an encouraging potential for hydrological applications in this regions in spite of the general underestimates. The 3B42 shows comparable performance to the CMA (China Meteorological Administration) data in both monthly and daily streamflow simulations mostly due to the monthly gauge adjustment involved in it.

1. Introduction

Precipitation is the most important atmospheric input to the terrestrial hydrologic system, and its variability is a critical component of both hydrological processes and energy cycles. Precipitation measurements provide essential information about the global water cycle and the distribution of the Earth's latent heating, which has direct effects on the planetary circulation of the atmosphere (Ebert et al., 2007). Gauge observation is the traditional approach to obtain precipitation information; however gauge networks are unfortunately sparse or nonexistent in many remote parts of the world. This is especially true in the Tibetan Plateau (TP), which is the highest and most extensive plateau in the world (Liu and Chen, 2000). Due to the high elevation, complex terrain, severe weather, and the inaccessibility, direct meteorological observations do not exist over large portions of the TP, especially in the western part of the plateau (Tong et al., 2014).

Precipitation products derived from satellite observations have reached a good level of maturity over the last decade (Kidd and Levizzani, 2011). Various satellite rainfall products with different temporal and spatial resolutions are available (Adler et al., 2003; Huffman et al., 2001; Joyce et al., 2004; Turk and Miller, 2005; Xie et al., 2003). Satellite-based estimates have become very important sources for precipitation information, particularly in regions where the gauge distribution is very sparse. However, satellite precipitation estimates are subject to a variety of errors and uncertainties, such as gaps in revisit times, poor direct relationship between remotely sensed signals and rainfall rate, and atmospheric effects that modify the radiation field. Because of these issues, a thorough validation is necessary (Bitew and Gebremichael, 2011a, 2011b).

There are 2 types of validation efforts of satellite precipitation products: (1) direct comparison of the satellite estimates to the precipitation gauge data and ground-based radar estimates; and (2) evaluation of satellite precipitation estimates based on their predictive ability of streamflow in a hydrological modeling framework (Bitew and Gebremichael, 2011b). Some global and regional validations have been reported for different satellite products (Adler et al., 2001; Bowman et al., 2003; Brown, 2006; Chokngamwong and

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Chiu, 2008; Dinku et al., 2007, 2008; Ebert et al., 2007; Gebremichael et al., 2005; Hirpa et al., 2010; Hong et al., 2007; Xie and Arkin, 1995). However, there has been very few validation activities over the TP – a region with very complex topography and high elevation. Yin et al. (2008) compared SSM/I and the Tropical Rainfall Measuring Mission (TRMM) 3B42 version 5 estimates with rain gauge observations, and reported that SSM/I underestimated while 3B42 version 5 overestimated gauge estimates in this mountainous region. Barros et al. (2000) evaluated the skill of TRMM sensors in detecting rain-producing weather systems, and compared TRMM-derived precipitation with ground observations in middle Himalayas. TRMM-derived precipitation showed better detection of rain at low altitudes as compared with high elevation stations. The diurnal patterns of summertime precipitation over the TP were investigated using the TRMM multi-satellite precipitation analysis product (Bai et al., 2008). It was shown that the TRMM product can approximately capture the daily evolution observed from the surface stations, although the intensity is somewhat underestimated, probably because of the sparse meteorological sites which cannot adequately depict the spatial distributions over the complex mountainous region. Gao and Liu (2013) evaluated four high-resolution satellite products over the TP. The results show that satellite products have better agreement with the gauge measurements over the humid regions than over arid regions, and generally tend to overestimate light rainfall (0–10 mm) and underestimate moderate and heavy rainfall (>10 mm).

Some work has been done to evaluate the suitability of satellite products as input to hydrologic models in different regions of the world. Yilmaz et al. (2005) investigated the PERSIANN in streamflow forecasting with a lumped hydrologic model over several medium-size basins in the southeastern United States. Results indicate that the accuracy of model simulations depended on the bias in the precipitation estimates and the size of watersheds. The PERSIANN-based model simulation had a better quality when the model was calibrated with satellite data rather than with rain gauge data. Artan et al. (2007) and Bitew et al. (2012) got similar results with Yilmaz et al. (2005) that improved the performance of remotely sensed precipitation data in hydrologic modeling when the hydrologic model was calibrated with satellite data in the sub-basins of Mekong, Nile Rivers, and a small mountainous watershed in Ethiopia, respectively. Su et al. (2008) investigated the feasibility of TRMM Multi-satellite Precipitation Analysis (TMPA) data (3B42 V6) for hydrologic predictions in the La Plata basin. They concluded that satellite precipitation has the potential for hydrologic forecasting although satellite-based estimates tended to overestimate peak flows. Their extended work (Su et al., 2011) indicates that the relative accuracy and the hydrologic performance of TMPA-RT-based streamflow simulations generally improved after February 2005 and suggests considerable potential for hydrologic prediction using purely satellite-derived precipitation estimates in parts of the globe with sparse in-situ observations. The results obtained by Yong et al. (2012) in a high latitude basin (Laohahe basin, China) also demonstrated an increasing potential in the use of TMPA-RT in hydrologic streamflow simulations over its three algorithm upgrade periods.

Unfortunately, over the TP, there is little evaluation work focusing on the hydrological modeling with satellite precipitation products. In this study, we compare four widely used global high-resolution satellite precipitation products (3B42 V7, 3B42 V7-RT, CMORPH, and PERSIANN) with gauge observations from the China Meteorological Administration (CMA), and use those satellite products as inputs for streamflow simulations to a hydrological modeling framework. The results of this study will provide insights on the level of estimation error in each satellite product and the implications for streamflow forecast in the TP. The specific purposes of this work are to: (1) evaluate the performance of satellite precipitation retrievals over the TP; and (2) assess the capability and limitation of satellite products as input to a hydrological model for streamflow simulation in the large watersheds in the TP.

2. Study region

The TP is known as the Third Pole (Qiu, 2008) located in central Asia with a mean elevation of more than 4000 m above sea level and an area of about 2.5 million km^2. It is bordered on the south by Myanmar, Bhutan and Nepal and by India and Pakistan on the western side. Since all the available precipitation gauge stations are within China, in this work, our study area is limited to the plateau within China between latitudes 26°53′49″–40°39′34″north and longitude 73°23′56″–105°6′21″east (Fig. 1), covering the entire Tibet autonomous region and Qinghai province, and a small portion of the western Sichuan, southwestern Gansu, southern Xinjiang, and northern Yunnan.

The TP is influenced by various dynamical climate systems. In summer, abundant moisture supply is brought to the TP from the Arabian Sea and the Bay of Bengal by the Indian summer monsoon and from the South China Sea and the western Pacific by the East Asian summer monsoon. The mid-latitude westerlies also supply the northern part of the TP with moisture mostly originated from the North Atlantic (Zhu et al., 2011). In winter, the zonal orientation of the Himalayas blocks the synoptic scale exchanges of warm tropical air with cold polar air centered near Siberia; the only avenue of air exchange is east of the Himalayas over Southeast Asia. Thus, in the summer months, the south-east monsoon produces heavy precipitation; while westerlies winds bring winter precipitation (Rees and Collins, 2006).

In this study, the source regions of the Yellow (Upper Yellow) and Yangtze (Upper Yangtze) River basins (Fig. 1) have been selected for hydrologic evaluation of satellite precipitation products. The drainage areas of Upper Yellow (upstream of Tangnaihai) and Upper Yangtze (upstream of Zhimenda) are 121,972 km^2 and 137,704 km^2, respectively. The elevation ranges from 2728 to 5969 m above sea level for the Upper Yellow, and 3804 to 5959 m for the Upper Yangtze. One reason to choose these two basins for hydrologic evaluation is the availability of the most recent streamflow records at the basin outlets (Table 1). Another reason is that monsoon precipitation plays a dominant role in runoff generation over the Upper Yellow and Upper Yangtze, with more than 80% of annual precipitation or runoff over May–October (Zhang et al., 2013), allowing us to evaluate how the errors in satellite precipitation input affect the streamflow processes and simulations.

3. Data and method

3.1. Satellite retrievals and CMA precipitation data

Satellite-based instruments have been designed to collect observations mainly at thermal infrared (IR) and passive microwave (MW) wavelengths that can be used to estimate rainfall rates. MW imagers and sounders have a direct physical connection to the hydrometeor profiles above the surface, but suffer from poor temporal sampling. In contrast, geo-infrared data provide excellent time-space coverage; however, their relationship to precipitation is indirect. The concept behind the high-resolution satellite rainfall algorithms is to combine information from the more accurate (but infrequent) MW with the more frequent (but indirect) IR to take advantage of the complementary strengths. The combination has been done in a variety of ways, leading to several satellite products.