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Evaluation of remote sensing precipitation estimates over Saudi Arabia

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ABSTRACT

The goal of this study is to evaluate five global high-resolution satellite precipitation products (PERSIANN, PERISANN-CDR, TRMM-RT, TRMM-3B42, and CMORPH) in Saudi Arabia where only 29 rain gauges distributed in various parts of the country record daily rainfall. The satellite data are evaluated on a daily and monthly scale and at a 0.25° x 0.25° spatial resolution from January 2003 to December 2011. The satellite products are further assessed in the western and eastern parts of the country where most of the rain falls during the wet season (November through April). Evaluation of the satellite products at the western and eastern gauges shows that most of the products perform better in estimating rainfall during the wet season but perform poorly at the eastern gauges during the dry season (June to September). PERSIANN-CDR improves rainfall estimates at some locations while PERSIANN performs better at others. TRMM-3B42 exhibits better performance than TRMM-RT at all sites. Overall, in terms of most of the statistical metrics, CMORPH, PERSIANN-CDR and TRMM-3B42 performed better over Saudi Arabia. These results suggest that the satellites using both TIR and PM data for rainfall estimates do not essentially improve rainfall measurements over the satellite using PM data alone.

1. Introduction

Precipitation is the most important element of the local and regional hydrologic cycle (Derin et al., 2016). Accurate estimation of precipitation helps manage the supply and demand of sustainable water resources. Precipitation is also a critical input variable for hydrologic modeling and climate studies which are common tools to assess water-related risks, such as floods/droughts and monitor water resources (Yong et al., 2010; Behrangi et al., 2011). Therefore, availability and accurate estimation of precipitation is crucial for demand management, flood forecasting and drought preparedness.

Precipitation measured in-situ using ground observation network is only reliable and accurate as the amount of rainfall is only known at a point scale. To obtain a more accurate and representative precipitation information, a dense gauge network is required that can capture the spatial and temporal variability of rainfall in an area (Xie and Arkin, 1996). However, in most areas of the world, precipitation observing networks are not only insufficient, but also limited to locations with a larger population and infrastructure (Hong et al., 2007; Behrangi et al., 2011). An alternative to rain gauges are ground-based radars that can provide fairly continuous precipitation coverage in space and time. However, due to beam blockage, radar coverages are not available in high mountainous terrain where orographic precipitation originates (Boushaki et al., 2009; AghaKouchak et al., 2011; Feidas, 2010).

Complementary to ground-based observation and radar networks are satellite-based precipitation products, which offer quasi-global coverage of rainfall measurements over remote areas and oceans (Feidas, 2010; Behrangi et al., 2011). Satellite products can provide rainfall estimates at high spatial (0.25° latitude x 0.25° longitude grid size) and temporal (hourly) resolution (Katiraie-Boroujerdy et al., 2013). These precipitation products are generated by combining passive microwave (PM) and thermal infrared (TIR) reflection data from various on-board satellite sensors. Each satellite product collects reflected electromagnetic radiation at different wavelengths and applies specific algorithms that integrate the reflection data to generate rainfall estimate. In the last four decades, several generations of satellite products have been developed (Novella and Thiaw, 2010) such as the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Network (PERSIANN; Hsu et al., 1997), the Naval Research Laboratory Global Blended-Statistical Precipitation Analysis (NRLgeo; Turk and Miller, 2005), the Climate Prediction Center Morphing Technology (CMORPH; Joyce et al., 2004), the Tropical Rainfall Measurement Mission (TRMM) Multi-sensor Precipitation Analysis (TMPA; Huffman et al., 2007), and the Global Satellite Mapping of Precipitation (GSMap; Ushio and Coauthors, 2009). Various studies have evaluated these and other satellite products at the watershed/regional scale (Behrangi et al., 2011; Su et al., 2008; Dinku et al., 2010; Thiemig et al., 2012; Vernimmen et al., 2012; Sohn et al.,

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2010; Moazami et al., 2016), continental (Adeyewa and Nakamura, 2003; Khan et al., 2007) and at the global scale (Huffman et al., 2007; Tian and Peters-Lidard, 2010).

Depending on the type of radiation data and algorithm used, rainfall estimates from each of the satellite products vary and can overestimate or underestimate in-situ rainfall either spatially or temporally. To reduce the bias in rainfall estimates, rain gauge observation is also used to correct satellite rain estimates. Nonetheless, the bias-adjusted products can also have varying accuracy over different climatic and geographic regions. For example, when Dinku et al. (2010) compared TRMM real time rain estimates with the bias adjusted TRMM product (TRMM-3B42) over the study region Columbia, the authors found TRMM 3B42 shows more bias than the unadjusted product in this tropical country. However, most studies have shown bias-adjustment improves satellites capability of rainfall estimates. Moazami et al. (2016) compared TRMM RT and TRMM 3B42 along with two other satellite products over six regions in Iran and found that TRMM 3B42 performed better than real time TRMM product as well as the other two products over all the six regions. Another study over Iran exhibits bias adjusted adj-PERSIANN product has better performance than the unadjusted PERSIANN product (Katiraie-Boroujerdy et al., 2013). These comparative studies between satellite rainfall estimates concluded that different types of satellites may have varying accuracy and thus result in distinct hydrological applicability in different regions (Jiang et al., 2012). Therefore, satellite products must be validated before its potential usability in hydrologic modeling to assess water resource forecasting and in climate models for forecasting the risks of floods or droughts.

This study aims to evaluate satellite rainfall estimates over Saudi Arabia which has only limited number of rainfall gauges and therefore satellite precipitation can complement the country's sparse precipitation gauge network by providing a spatio-temporal distribution of rainfall patterns. In recent years, several flash floods (November 2009; December 2010; January 2011) have caused extensive loss to human life and infrastructure in Saudi Arabia (Al-Khalaf and Basset, 2013; Almazroui, 2013; Haggag and El-Badry, 2013; Youssef et al., 2016; Deng et al., 2015). These intense rainfall events occurring in areas with dry soils with limited infiltration capacity have generated fast flowing surface runoff (Deng et al., 2015). Although no streams exist within the country, numerous high density wadis (riverine) found in the western part of Saudi Arabia (Nouh, 2006), quickly turn into raging rivers after high-intensity, short duration storms, thus causing flash flooding (Almazroui, 2011b; de Vries et al., 2016). To understand and investigate potential atmospheric dynamics of these extreme climates, studies have examined statistical trends in observation data (e.g., AlSarmi and Washington, 2011, 2014; Donat et al., 2014) and applied regional climate models (e.g., Deng et al., 2015; Almazroui, 2011a,b). These studies suggest that the robust evaluations of these extreme events are not possible due to the lack of sufficient spatial and temporal coverage of gauge data (Deng et al., 2015). Therefore, satellite data with higher accuracy can provide spatially and temporally continuous dataset that can allow detailed climatological assessment of the region. The satellite data can also provide climate forcing data for various hydrological and climate models (Yesubabu et al., 2016) and thus help decision makers adopt appropriate engineering practices for impact mitigation and adaptation.

Given the need to assess satellite data over Saudi Arabia, a recent study by Kheimi and Gutub (2015) has evaluated four satellite precipitation products against the rainfall gauge data in the country. They have found that all the selected satellite products overestimate the rainfall of the country but the gauge adjusted product TRMM 3B42 has shown better performance at the monthly scale than the other three unadjusted near real-time products – PERSIANN, CMORPH, and GSMap_MVK. This result is consistent with other studies that show that the gauge adjusted products often have better prediction skills in comparison to unadjusted near real-time satellite products (e.g., Dinku et al., 2010; Behrangi et al., 2011; Katiraie-Boroujerdy et al., 2013; Moazami et al., 2016). Kheimi and Gutub (2015) study focused on the overall performance of the satellite based precipitation estimates over the entire country. However, within a country there can be different topographical and climate settings which can influence the accuracy of the satellite rainfall estimates (Moazami et al., 2016) and a thorough investigation of satellite rainfall estimates in a range of settings can provide more insight on the optimal satellite precipitation product for the country.

Therefore, the purpose of this study is to evaluate detailed performance of five widely used satellite precipitation products in different regions and climates of Saudi Arabia where semi-arid to arid climate influences country's precipitation pattern. The selected precipitation products are – (1) PERSIANN (Hsu et al., 1997; Sorooshian et al., 2000), (2) PERSIANN-Climate Data Record (PERSIANN-CDR: Ashouri et al., 2015), (3) TRMM TMPA RT (v7) (Huffman et al., 2007), (4) TRMM 3B42 (v7) (Huffman et al., 2010), and (5) CMORPH (Joyce et al., 2004). TRMM RT and PERSIANN – the two near real-time precipitation products are based on passive microwave (PM) and thermal infrared (TIR) observations. Their gauge-adjusted precipitation products are TRMM 3B42 and PERSIANN-CDR and are bias-corrected using gauge observations. CMORPH applies high sampling frequency of TIR data to derive cloud motion; however, they exclusively use passive microwave observations (PM) for rainfall estimates. The goal of this study is to also compare the performance of the satellite estimates based on both PM and TIR data to the product that only uses PM data.

The description of the study area and satellite precipitation products is discussed in section 2, the evaluation methodology is explained in section 3, the validation results are presented in section 4, and the conclusion of this study is discussed in section 5.

2. Study region and data sets

2.1. Study region and gauge data

Saudi Arabia bounded within 30°W-57°W and 12°N–35°N, is the fifth largest country in Asia and constitutes most of the Arabian Peninsula with its 2,150,000 km^2 area. The country is surrounded by the Red Sea in the west and the Persian Gulf to the east and both bodies of water are considered the primary source of water vapor in the country (Al-Ahmadi and Al-Ahmadi, 2013) (Fig. 1). Topography varies from relatively flat terrain in the east to mountain ranges rising from the central part of the country to the west (El Kenawy and McCabe, 2016). The highest mountain within Saudi Arabia lies along the west coast where the elevation rises to 2990 m influencing temperature and rainfall patterns in the southwest region. The influence of topography causes a semi-arid climate in the southwest region, while the rest of the country has a hot and dry desert climate (Koppen, 1936). The country's rainfall has high spatial and temporal variability. Southwest and eastern regions receive more rainfall than the rest of the country (Fig. 2a). At these two regions, maritime and continental air mass originating during different times of the year condenses because of the higher mountain slopes causing occasional local rainfall events throughout the year (Almazroui, 2011a; Al-Ahmadi and Al-Ahmadi, 2013; El Kenawy and McCabe, 2016). In other regions, rain primarily falls between November and April.

Rainfall is recorded at a sparse network of rain gauges (only 29 gauges operated and maintained by the PME) distributed mainly in the western, northern, and the eastern part of the country (Fig. 1), which are located at a wide elevation range from 7 m to 2093 m. Fig. 2a show spatial distribution over the country, while Fig. 2b reports the long-term mean annual precipitation average over 30-years (1979-2009) at each rain gauge along with mean rainfall of 93.5 mm across the gauges (dash line) (Almazroui et al., 2012). The location of the rain gauges where the mean annual precipitation is more than the country's 30-years average annual rainfall (93.5 mm) are shown in Fig. 2c (in circles). Table 1 shows the locations, elevation of the 29 rain gauges along with the 30-years