NOTES AND CORRESPONDENCE

Evaluation of High-Resolution Satellite Precipitation Products over Very Complex Terrain in Ethiopia

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ABSTRACT

This study focuses on the evaluation of 3-hourly, 0.25° × 0.25°, satellite-based precipitation products: the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) 3B42RT, the NOAA/Climate Prediction Center morphing technique (CMORPH), and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN). CMORPH is primarily microwave based, 3B42RT is primarily microwave based when microwave data are available and infrared based when microwave data are not available, and PERSIANN is primarily infrared based. The results show that 1) 3B42RT and CMORPH give similar rainfall fields (in terms of bias, spatial structure, elevation-dependent trend, and distribution function), which are different from PERSIANN rainfall fields; 2) PERSIANN does not show the elevation-dependent trend observed in rain gauge values, 3B42RT, and CMORPH; and 3) PERSIANN considerably underestimates rainfall in high-elevation areas.

1. Introduction

The availability of high-resolution satellite precipitation products has made them very attractive for hydrological applications in regions that have less-dense and less-consistent ground-based measurements. Some of these products are available in (near) real time, making them suitable for flood-forecasting applications. The concept behind these high-resolution satellite precipitation algorithms is to combine information from the more accurate (but infrequent) microwave (MW) with that from the more frequent (but indirect) infrared (IR) to take advantage of the complementary strengths. The combination has been done in a variety of ways. The Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) 3B42RT method (Huffman et al. 2007) uses MW data to calibrate the IR-derived estimates and creates estimates that contain MW-derived rainfall estimates when and where MW data are available and IR estimates where MW data are not available. The Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) method (Sorooshian et al. 2000) uses a neural-network approach to derive relationships between IR and MW data, which are applied to the IR data to generate rainfall estimates. The National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center morphing technique (CMORPH) method (Joyce et al. 2004) uses a tracking approach in which IR data are used only to derive a cloud motion field that is subsequently used to propagate raining pixels. So, only rainfall estimates derived from MW data are used in CMORPH, whereas only rainfall estimates derived from IR are used in PERSIANN. In 3B42RT, rainfall estimates derived from MW are used when MW

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data are available and estimates derived from IR are used when MW are not available. The resolutions of these products are 0.25° and 3-hourly, although finer resolutions are also available for CMORPH and PERSIANN.

Satellite precipitation products can be particularly valuable in mountainous regions, where it is difficult to monitor large areas using a dense rain gauge network. According to Wilheit (1986), even in technologically advanced nations sampling by rain gauges is marginal at best, and in less-advanced regions the gauges are sparsely distributed and often considered to be unreliable. However, the accuracy of satellite products in mountainous regions is poorly understood because of the lack of reliable ground-based observations. Mountainous regions have relatively warm clouds, and the thermal IR thresholds commonly used to discriminate between raining and nonraining clouds could cause the IR rainfall retrieval algorithms to miss light-precipitation events (e.g., Hong et al. 2007) or to underestimate total rainfall (e.g., Bitew and Gebremichael 2010). Clouds over mountainous regions could produce heavy rainfall without much ice aloft, which could lead to rainfall underestimation in passive MW algorithms (Dinku et al. 2010). Cold surface and ice covers over mountaintops could be misclassified as rain clouds in passive MW algorithms, leading to rainfall overestimation. Barros et al. (2006) found that TRMM’s precipitation radar has difficulties in detecting precipitation at high elevations. Therefore rainfall retrieval algorithms that use information from a combination of IR, passive MW, and active MW sensors are subject to all of these error sources in mountainous regions.

In the semiarid and highly mountainous region of Mexico, Hong et al. (2007) compared the PERSIANN Cloud Classification System (PERSIANN-CCS; a variant of PERSIANN) with the North American Monsoon Experiment Event Rain Gauge Network (see Gochis et al. 2003; Gebremichael et al. 2007) for summer 2004. They reported that elevation-dependent biases exist in PERSIANN-CCS products that are characterized by an underestimate in the occurrence of light precipitation at high elevations and an overestimate in the occurrence of precipitation at low elevations and that there is an overall positive bias in PERSIANN-CCS products. In the Tibetan Plateau, Yin et al. (2008) compared TMPA 3B42, version 5 (an earlier version of the research TMPA 3B42 algorithm), with rain gauge observations and reported that 3B42, version 5, overestimated rainfall in this mountainous region. In the mountainous western region of the United States, Gottschalck et al. (2005) found that 3B42RT and PERSIANN-CCS overestimated precipitation. Dinku et al. (2010) selected a large area in Ethiopia (latitude of 7°–10°N and longitude of 35°–40°E), which consists of both mountainous and flat regions, and compared 3B42RT and CMORPH precipitation estimates with operational rain gauge observations. They reported lumped statistics for the region comparing satellite precipitation products and rain gauge observations: correlation coefficients of 0.46 for 3B42RT and 0.60 for CMORPH, and bias ratios of 1.13 for 3B42RT and 1.11 for CMORPH.

The above studies in northern Mexico, the Tibetan Plateau, western United States, and a region in Ethiopia indicate overestimation of satellite precipitation products. However, deploying an unprecedented high-density rain gauge network over a small mountainous region (<25 km²) in Ethiopia, Bitew and Gebremichael (2010) reported underestimation of rainfall (particularly for the large events that cause flooding) by PERSIANN and CMORPH. It becomes clear from this that further validation studies in different mountainous regions of the world are important to explore and address the limitations in the satellite precipitation algorithms. It is also clear that the validation results need to be stratified by elevation in mountainous regions. Motivated by this, our study provides an elevation-dependent comparison of 3B42RT, CMORPH, PERSIANN, and rain gauges in a large river basin in Ethiopia that is characterized by a large range of elevation differences.

2. Study region and data

a. Study region

The Awash River basin, with an area of 110 000 km², is located in the northeastern part of Ethiopia. The basin exhibits dramatic variation in elevation, ranging from 240 to 3400 m, making it suitable to examine satellite precipitation products over different elevation ranges (Fig. 1). Hosting 11 million people and accounting for 70% of the nation’s irrigated agriculture, Awash is economically the most important river basin in Ethiopia. However, Awash floods frequently, taking a big toll on the vulnerable population living along the river. For example, according to the NOAA State of the Climate Global Hazards Monthly Report for August 2005 (available online at http://www.ncdc.noaa.gov/sotc/?report=hazards&year=2005&month=8&submitted=Get+Report; verified in September 2009), 7500 people were forced out of their homes as the Awash River rose above the flood stage and at least 5000 ha of agricultural land were submerged just in August of 2005. The need for evaluating and improving the accuracy of satellite precipitation products in African basins like Awash cannot be overemphasized given the fact that these basins can benefit the most from satellite precipitation products for the following reasons: 1) satellite precipitation estimates are and will probably be the
only available information on rainfall in the mountainous regions of Africa, 2) African societies are the most vulnerable to precipitation-related hazards (e.g., the average number of casualties per flood event is about 50 in developed countries, whereas it is about 1300 in Africa), and 3) many major development challenges in Africa, such as food security and floods, are inherently linked to precipitation.

b. Data and method

We examined three satellite rainfall products: 3B42RT, CMORPH, and PERSIANN. The products have 3-hourly and 0.25° × 0.25° resolution. CMORPH and PERSIANN

FIG. 1. (a) Relief map of northeastern Africa; the inset box shows the Awash River basin and its neighborhood. (b) The Awash River basin (110 000 km²) and its elevation derived from a 30-m digital elevation map.

FIG. 2. The 5-yr (2003–07) mean annual rainfall at 0.25° spatial resolution over the Awash River basin derived from (a) 3B42RT, (b) CMORPH, and (c) PERSIANN. Circles indicate the corresponding rain gauge values.
have been available since 2003, and 3B42RT has been available since 2003. There are also 12 rain gauge stations across Awash. We obtained quality-controlled rain gauge data from the National Meteorological Agency of Ethiopia. Our method consists of intercomparisons of satellite rainfall products from daily to mean annual time scales, and comparison of these products with rain gauge observations at mean annual time scale. The low density of the rain gauge network did not allow us to quantify the random errors in satellite rainfall estimates. However, by averaging the rain gauge observations over a 5-yr period and examining the relationship between mean annual rainfall and elevation, we were able to assess in qualitative terms the overall performance behavior of satellite rainfall products with respect to elevation. We acknowledge that, in addition to elevation, there may be other local and mesoscale mechanisms that explain part of the differences between satellite estimates and gauge observations; however, our focus in this study is on elevation, mainly because of data limitation.

3. Results and discussion

a. Comparisons at mean annual time scale

In Fig. 2, we present a spatial map of the 5-yr (2003–07) mean annual rainfall at 0.25° spatial resolution, derived from each satellite product. The 3B42RT estimates show that the region exhibits tremendous spatial variability in the mean annual rainfall, ranging from 230 to 1230 mm yr$^{-1}$. The corresponding range of variability is from 240 to 1060 mm yr$^{-1}$ for CMORPH and from 200 to 610 mm yr$^{-1}$ for PERSIANN. So, PERSIANN gives a smaller range of variability and underestimates the large rainfall accumulations in comparison with 3B42RT and CMORPH. The 3B42RT estimates show that the rainfall pattern is controlled by topography: high-elevation areas receive more rain than do low-elevation areas. The linear correlation for the spatial mean annual rainfall is 0.97 between CMORPH and 3B42RT, 0.73 between PERSIANN and 3B42RT, and 0.77 between PERSIANN and CMORPH. This indicates that, while there is a good agreement between 3B42RT and CMORPH in terms of the spatial pattern of mean annual rainfall, PERSIANN gives a slightly different spatial structure relative to both 3B42RT and CMORPH. Superimposed in Fig. 2 are the corresponding mean annual rainfall amounts derived from rain gauges at each location. The satellite estimates and rain gauge measurements agree in the spatial distribution of rainfall: high-elevation areas receive large rainfall accumulations.

Let us now investigate how the satellite precipitation products depict the elevation-dependent trends in precipitation. Figure 3 shows the scatterplot of mean annual rainfall estimates against topographic elevation. The elevation-dependent trends are constructed by connecting precipitation values averaged across each successive 100-m-elevation bin. To look at a large range of elevation difference, we also included data points that

![Fig. 3. The 5-yr mean annual rainfall derived from satellite products as a function of elevation. Each point represents the 0.25° grid; trends connect the precipitation values averaged across each successive 100-m-elevation bin.](image-url)
fall outside of Awash but inside the inset box shown in Fig. 1a. In the 50–1000-m-elevation range, all products show that precipitation amount increases with elevation at steep slope, notwithstanding the wiggles in the trend that resulted from sample size differences. In the 1000–2000-m-elevation range, precipitation increases with elevation; however, its slope varies for different products: 3B42RT and CMORPH give steep slopes while PERSIANN gives milder slope, resulting in PERSIANN giving smaller precipitation estimates at higher elevations.

In the 2000–3000-m-elevation range, precipitation remains constant regardless of elevation; however, PERSIANN gives substantially smaller precipitation than do 3B42RT and CMORPH. The picture that emerges from this analysis is that the performance of satellite precipitation products depends on elevation. In the low-elevation areas (<1000 m), the three satellite precipitation products have similar performances. In the high-elevation areas (>1400 m), PERSIANN gives considerably lower rainfall in comparison with both 3B42RT and CMORPH.

Fig. 4. Similar to Fig. 3, but for rain gauge rainfall measurements and satellite rainfall estimates only at pixels that contain the rain gauges.

Fig. 5. Time series of spatial correlation (calculated at the daily time scale within the two rainy seasons, March–May and June–September) over the Awash River basin between pairs of satellite precipitation products. The time series is displayed as a 14-day running mean to improve clarity.
Overall, 3B42RT and CMORPH give similar values, with 3B42RT giving slightly higher values relative to CMORPH in the high-elevation areas, and vice versa in the low-elevation area.

Figure 4 presents a similar scatterplot of mean annual rainfall versus elevation, but using rain gauge rainfall measurements and satellite rainfall estimates only at pixels that contain the rain gauges. The gauge-measured rainfall clearly increases with elevation, across the entire range of elevations used. 3B42RT and CMORPH also show an increasing trend with elevation, although with large variation. However, PERSIANN does not show a trend in the high-elevation areas (1400–2400 m). PERSIANN also gives much lower values than the gauge-measured rainfall in the high-elevation areas. We acknowledge that comparison of gauge-measured point rainfall with gridded (0.25° × 0.25°) satellite rainfall estimates could introduce errors in this comparison. However, we have used a coarse time scale (5 yr) in this comparison, which should minimize the
spatial-representativeness (over an area of 0.25° × 0.25°) errors in rain gauge values.

**b. Comparisons at daily time scale**

At the daily time scale, we only present the intercomparison of satellite rainfall products. Figure 5 presents a time series of spatial correlation (computed daily over Awash) between pairs of satellite precipitation products. The correlation between 3B42RT and CMORPH improves after 2005 and does not in general show a clear dependence on season. The correlation between PERSIANN and any of the other products shows large fluctuations in time and tends to increase in the summer rainy season. Overall, the correlation between 3B42RT and CMORPH is mostly higher than the correlation between PERSIANN and any of the other products. This shows that, in comparison with PERSIANN, CMORPH and 3B42RT have closer spatial structure of rainfall estimates.

A very important property of satellite precipitation products for the Awash River basin is how they represent the distribution of precipitation—in particular, the extreme wet events. Figure 6 presents the distribution of daily 0.25° × 0.25° precipitation derived from each satellite product. At the upper tail of the distribution (>25 mm day⁻¹), 3B42RT gives the largest number of extreme wet events and PERSIANN gives the smallest number of extreme wet events. This indicates that PERSIANN consistently underestimates extreme wet events in comparison with 3B42RT and CMORPH.

**4. Conclusions**

We assessed the performance of three high-resolution satellite rainfall products (TMPA 3B42RT, CMORPH, and PERSIANN) across a large river basin in Ethiopia that has a large range of elevations, ranging from 240 to 3400 m. Our method consists of intercomparison of the satellite rainfall estimates as a function of elevation and comparison of the satellite estimates with rainfall measurements from 12 rain gauge stations at different elevations. Our key findings can be summarized as follows:

1) 3B42RT and CMORPH give similar rainfall fields (in terms of bias, spatial structure, elevation-dependent trend, and distribution function), which are different from PERSIANN rainfall fields.

2) PERSIANN does not show the elevation-dependent trend observed in rain gauge values, 3B42RT, and CMORPH.

3) PERSIANN considerably underestimates rainfall in high-elevation areas.

The main difference between PERSIANN and 3B42RT/CMORPH lies in the major satellite band used. CMORPH is primarily MW based, 3B42RT is primarily MW based when MW data are available and IR based when MW data are not available, and PERSIANN is only IR based. Our study, in agreement with other similar studies in different regions of the world, clearly reveals that IR-based rainfall algorithms have major limitations in reproducing rainfall fields in mountainous regions of East Africa. Therefore, additional information, such as relative humidity (e.g., Janowiak et al. 2004) and/or rain gauge data at different elevations (e.g., Thorne et al. 2001), may be needed to improve the accuracy of rainfall estimates from IR-based algorithms.

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