Evaluation of Error in Satellite-Derived Precipitation Estimates over the Himalayan region: A Case study for an Extreme Event in 2013

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ABSTRACT

Conventional tools such as rain-gauge stations and meteorological radars were used to monitor extreme rainfall events in many parts of India. But applications of these measurements to perform hydrological analysis were limited over Indian Himalayas regions because of inaccessibility of areas and lack of homogenous networks of rain-gauge stations. Satellite-based Precipitation Estimates are the alternative options for assessing any hydro-meteorological hazards over Himalayas. In this study, we evaluated three satellite based rainfall products (i.e., TMPA-3B42, Global Satellite Mapping of Precipitation (GSMaP), and NOAA CPC Morphing Technique (CMORPH)) against the rain gauge-based India Meteorological Department (IMD) gridded dataset. The errors in precipitation were assessed especially for an extreme rainfall episode that was witnessed during June 2013 in the Western Himalayas. This event was widely known as Kerdarnath disaster, which has caused widespread flash floods, landslides, and debris flow.

The findings from this comprehensive study suggested that the magnitude of precipitation as well as peak rainfall intensity were underestimated in TMPA-3B42 and CMORPH. However, GSMaP showed dual trends with under- and over-estimations against gauge-based IMD data. Based on the statistical approach on the determination of error statistic metrics, namely, MAE (mean absolute error), NRMSE (normalized root mean square error), PBIAS (percent bias), and NSE (Nash-Sutcliffe efficiency) of respective satellite products, it was confirmed that TMPA-3B42 estimates were more relevant and accurate compared to other two satellite products for this extreme rainfall event. The TMPA-3B42-based precipitation was negatively biased by 18%, while GSMaP was positively biased by 14%. The NSE for TMPA-3B42 were lower (-0.93) compared to other products. Thereby, this study concludes that TMPA-3B42 precipitation can be useful for any hydrological study for extreme rainfall episode in the region, where rain-gauges are sparse or rain-gauge networks are unevenly distributed.

KEY WORDS

TMPA-3B42, Extreme rainfall event, Kerdarnath disaster, percent bias, Nash-Sutcliffe efficiency.

1. INTRODUCTION

So-called the "cloudburst" has no specific meteorological definition and it signifies a sudden rainfall over a geographical area in a short period of time. It is a localized extreme weather event occurred at faster rate and the rainfall rate is ~10 cm/hr. It occurs generally over the orographically dominant regions like Himalayan regions during monsoon season and often caused flash floods. Earlier studies reported that June 2013 extreme rainfall event was a cloudburst event (Das, 2013; Kotal et al., 2014) but it was mainly attributed to multi-day extreme rainfall and snow fall and subsequently outburst of the Chorabari moraine-dammed lake (Rautela, 2013). This major extreme event has caused widespread impacts over the Uttarakhand Himalayas by flash floods, landslides, debris flow, and mudflow. Immense losses in terms of destruction of buildings and properties were reported including the fatalities. The Himalayan region becomes vulnerable to extreme weather events in the recent decades and thus it demands a hydrological based study to analyses various impacts of such events. However, field observations often limited over highly undulated terrain and because of these rain-gauge observations are limited over the Uttarakhand Himalayas.

With the perspectives of increase in recurrence of flash floods followed by severe consequences from glacial lake outburst floods in the Western Himalayas, it demands systematic evaluation of satellite-based rainfall estimates (SBRE) products. To the best of our knowledge, no such study has attempted so far on evaluating the predictability of satellite rainfall products for an extreme rainfall event over Western Himalaya, albeit many studies have analyzed time series dataset of satellite estimates for hydrological applications (Bookhagen and Burbank, 2010; Bharati and Singh 2015). As SBRE rainfall products with high spatial-temporal resolution data are crucial driver for hydrological applications and model development activities, it needs to be evaluated and validated against measurements from rain-gauge stations or existing benchmarked data. Accurate and precise predictions of precipitation have significant implications in hydrological modeling, weather forecasting, and climate change studies. Therefore, it is imperative to know satellite rainfall products in terms of its spatial distribution, magnitude, duration, and peak intensity of the precipitation for an extreme rainfall event.

To address aforementioned issues, the main objective of this comprehensive study was to evaluate the capacity of three SBRE rainfall products against the IMD gridded gauge-based dataset during an extreme rainfall event and to determine their appropriateness as an additional option to conventional tools (i.e., rain gauged) for use in hydrological predictions and applications. In particular, we evaluated three SBRE products, namely, TMPA-3B42, Global Satellite Mapping of Precipitation (GSMaP), and NOAA CPC Morphing Technique (CMORPH).

2. DATA AND METHODS

2.1 Study region

The study area is the Uttarakhand state (Northern part of India) which is part of the Western Himalayas regions and situated in the upper Ganga river basin. The entire state has 40 rain-gauge stations that often limit the hydrological studies over this complex topography. Prominent physiographic features comprise Siwaliks (Sub-Himalayan region) and Himalayan region with undulated topography that consists of snow clad mountain peaks, scatter crests, deep valleys, and glaciers. The Chorabari glacier is medium size glacier (3900–6420 m) situated near Kedarnath covering an approximate area of 6.6 km^2. This Lake was suddenly collapsed during June 2013 ensuing flash floods in Saraswati River and Mandakini River and the rivers changed their respective courses and further sedimentation has been settled up to 6 m. The Kedarnath town (30° 44' 6.7” N and 79° 04' 1” E) is located 2 km downstream from the Chorabari Lake and this region had witnessed the major devastation during June 2013.

2.2 Data Used

TMPA 3B42 rainfall data:

Rainfall obtained from satellite radar sensor is the only option for monitoring unprecedented any extreme weather events. Microwave based satellite data from Tropical Rainfall Measuring Mission (TRMM) provides a real-time measurement of hourly rainfall over the globe. It is using the Precipitation Radar (PR) sensor and operates at 13.8 GHz to provide information on intensity and distribution of the rain at 0.25° spatial resolution (Huffman 1997). Using the TRMM data, here we demonstrate the capability of Satellite Based Rainfall Estimates (SBRE) for hydrological analysis of extreme rainfall event over the Uttarakhand Himalayas. Specifically, we used TRMM daily precipitation product called 3B42 (v7) to capture information about rainstorms during June 2013.

CMORPH rainfall data:

The CMORPH data were available at native spatial resolution of 0.25° latitude and longitude and detailed information. Here, we employed a temporal resolution of 3-hourly data. They were summed to daily data to analyze rainfall magnitude during an extreme rainfall event during June 2013 and to compare with other satellite rainfall products. The variable used for this study was '*CMORPH precipitation estimate*'. The data were obtained from the Research Data Archive (Climate Prediction Centre, NOAA) managed by the Computational and Information Systems Laboratory.

GSMaP rainfall data:

The JAXA Global Rainfall Watch provides the Global Satellite Mapping of Precipitation (GSMaP) rainfall products. Here, we employed GSMaP of daily averaged gauge-calibrated rainfall product (the GSMaP_Gauge) which was derived from various sensors at 0.1° latitude and longitude grid (Ushio, et al., 2013). The daily dataset obtained from the JAXA Global Rainfall Watch (http://sharaku.eorc.jaxa.jp/GSMaP) and used to compare with other satellite rainfall products.

IMD rainfall data

The India Meteorological Department (IMD) rainfall data were available at the National Data Center (NDC), Pune. The National Climate Centre constructed gridded rainfall data with a spatial resolution of 0.25° latitude and longitude grid and they are interpolated from the 7000 rain-gauge stations. This is the latest dataset for India developed by IMD and detailed description and quality control were mentioned in Pai et al. (2014).

Hydrological data

The hydrological methods used were the mass curve and hyetograph for identifying the number of storms and timing of storms. Hydro-meteorological data used were observed daily discharge rate and daily rainfall and these data were obtained from Wadia Institute of Himalayan Geology (WIHG) to analyze runoff pattern during this extreme events (Dobhal et al., 2013).

2.3 METHODS

In this study, we used three satellite based rainfall products, namely, TMPA-3B42, Global Satellite Mapping of Precipitation (GSMaP), and NOAA CPC Morphing Technique (CMORPH)) and compared against the rain gauge-based India Meteorological Department (IMD) gridded dataset. The detailed methodology has been described below.

IMD gauge-based dataset of 0.25° latitude and longitude grid were used. Both TMPA-3B42 and CMORPH data were available at 0.25° latitude and longitude resolution and the binary format of these products including IMD dataset were converted to raster format using the "raster" package in R (Hijmans, et al. 2016). The GSMaP data were obtained at 0.1° latitude and longitude resolution. The dataset, namely, IMD, TMPA, and CMORPH with 0.25° latitude and longitude resolution were resampled to 0.1° resolution based on the nearest neighborhood method. The resampled data were further subjected to smoothening function that uses a matrix of weights (window of 3 by 3 matrix) for the neighborhood of the focal cells. The aforementioned steps were performed using the R package "raster and all maps were generated using this package.

The SBRE products and gridded IMD gauge data were compared using various quantitative statistical indicators, namely, MAE (Mean Absolute Error), NRMSE (Normalized root mean square error), PBIAS (Percent Bias), and NSE (Nash-Sutcliffe efficiency), as described in Eqs (1-4) below:

$$MAE = \frac{1}{N}\sum_{t=1}^{N} SAT_i - G_i \qquad (1)$$

$$NRMSE = \frac{\sqrt{\frac{1}{N}\sum_{t=1}^{N}(SAT_i - G_i)^2}}{\bar{G}}\ 100 \tag{2}$$

$$PBIAS = \frac{\sum_{t=1}^{N}(SAT_i - G_i)}{\sum_{t=1}^{N} G_i}\ 100 \tag{3}$$

$$NSE = 1 - \frac{\sum_{t=1}^{N}(SAT_i - G_i)^2}{\sum_{t=1}^{N}(SAT_i - \overline{G_i})^2} \tag{4}$$

where, G= gauge (IMD), $\bar{G}$= average of Gauge, SAT = Satellite data (i.e. TMPA-3B42, GSMaP, CMORPH), and N= number of data pairs. The MAE is in mm, NRMSE and PBIAS are in %, while NSE is dimensionless. The NRMSE gives the standard deviation of the satellite estimates error, and a smaller value indicates higher accuracy in satellite estimation. The positive values of PBIAS indicate overestimation by satellite data, whereas negative values of PBIAS indicate underestimation. The NSE is a normalized statistic and its values range from -∞ to 1 and close to 1 means the more accurate satellite estimates.

3. RESULTS AND DISCUSSIONS

3.1 Spatial pattern of precipitation products and IMD dataset

The utilization of SBRE rainfall products for evaluation of rainfall pattern for an extreme rainfall event like Kedarnath disaster over the Uttarakhand during June 2013 has been performed. Figure **1** depicts the spatial distribution of accumulated precipitation during 15 to 18 June over the state of Uttarakhand (Figure **1a, b, c, and d**). We compared three SBRE rainfall products such as GSMaP, TMPA, and CMORPH with the IMD (interpolated observations). These maps show that the pattern of precipitation from the IMD was widespread. These regions were observed with precipitation >200 mm and even some districts (i.e. Dehradun, Uttarkashi, Tehri Garhwal, Naini Tal) have witnessed precipitation as 350 mm. The Kedarnath located near the Chorabari Lake wherein IMD recorded precipitation as 232 mm. As compared to IMD, the satellite estimates were 225, 212, and 151 mm for GSMaP, TMPA, and CMORPH, respectively. So, for a single grid-point (i.e., Kedarnath) the satellite estimates showed negative precipitation biases with PBIAS as -3.0, -8.6, and -35 for GSMaP, TMPA, and CMORPH, respectively. Based on visual interpretation, TMPA showed that precipitation was well distributed over the state as compared to IMD. But, the magnitude of precipitation differs with respect to IMD, whereas GSMaP showed both under and overestimation of precipitation irrespective of surface elevation. However, CMORPH precipitation was underestimated considerably across many grid-points as the product was not calibrated against the rain gauge data.

Visual comparison of satellite estimates indicates that the NOAA CPC product CMORPH was underestimated over all districts of Uttarakhand state except few districts, namely, Uttarkashi, Dehradun, and Tehri Garhwal. By contrast, rain gauge calibrated satellite estimates of GSMaP and TMPA were well comparable with the reference IMD-gauge data, although few regions exhibited dissimilarity. Notably, precipitation of GSMaP was overestimated over Northern districts (Uttarkashi, Dehradun, Haridwar, and Tehri Garhwal) of Uttarakhand as compared to IMD, while Southern and Eastern districts of Uttarakhand state (Almora, Naini Tal, Champawat, Chamoli, Pithoragarh, Bageshwar) were underestimated.

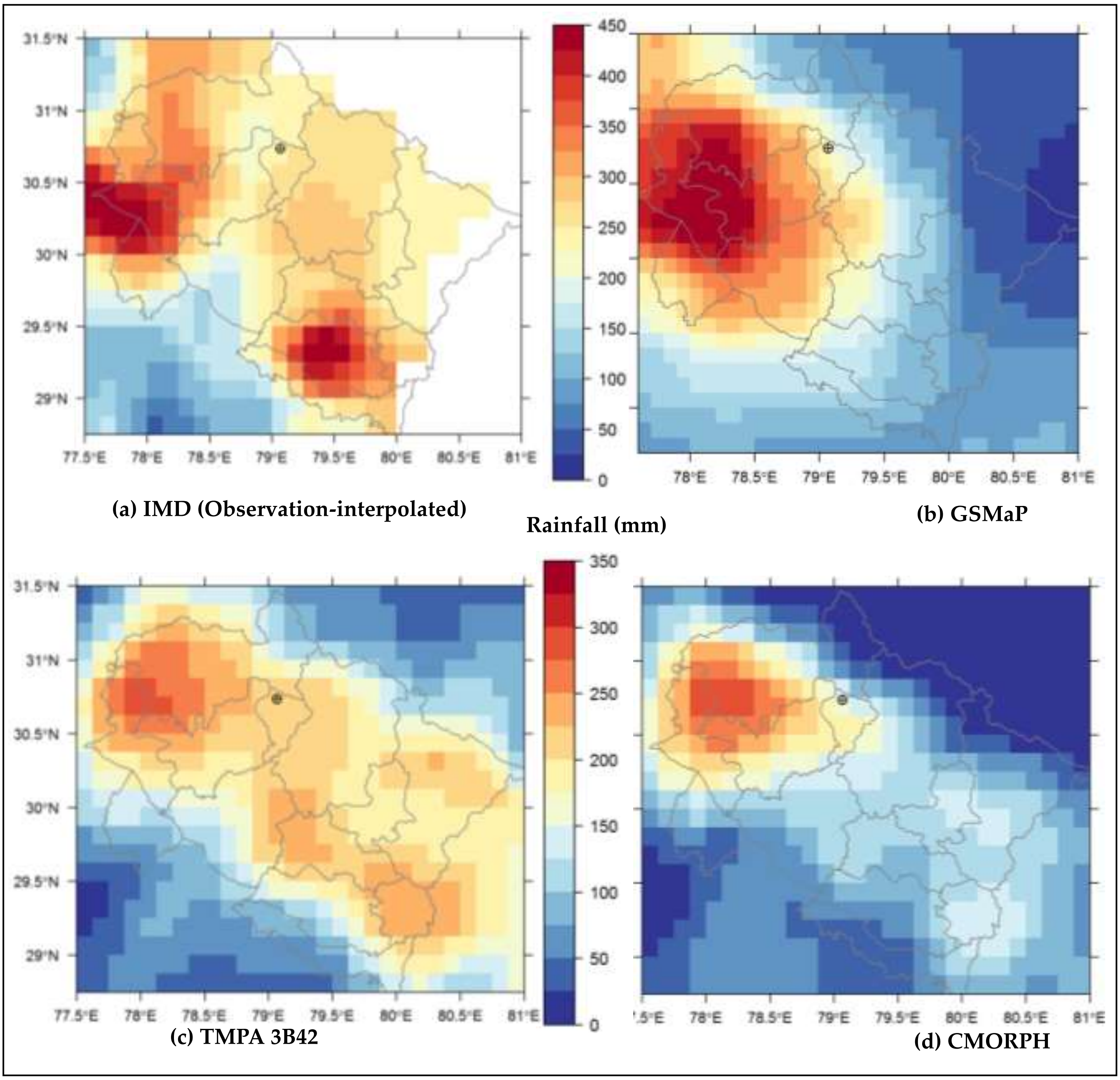

Figure 1. Spatial patterns of accumulated daily precipitation (mm): (a) IMD (observation-interpolated); (b) GSMaP; (c) TMPA 3B42; and (d) CMORPH during peak storm during 15-18 June 2013 over Uttarakhand state. The circular plus symbol denotes location of Kedarnath.

By comparing all three rainfall products with IMD data, we didn’t find any distinct differences of under estimation and overestimation of precipitation with respect to surface elevation. Notably, the spatial extent of precipitation of TMPA-3B42 was well distributed across all the districts of Uttarakhand as compared to the GSMaP and CMORPH, albeit its magnitude was lower than IMD-gauge based precipitation. We described the quantitative evaluation of satellite-based estimates with gauge-based rainfall using the standard statistical metrics as described in Table 1.

Table 1. Results of statistical error parameters to compare satellite-based rainfall products with gauge-data (IMD).

Parameters	TMPA-3B42 (v7)	GSMaP	CMORPH
PBIAS (%)	-18.2	14.4	-29.0
MAE(mm)	52.7	71.8	82.5
NRMSE(%)	21.5	28.0	33.0
NSE	-0.93	-2.25	-3.52

The quantitative error statistics were shown in the Table **1**, wherein PBIAS suggests that both positive (GSMaP) and negative (TMPA-3B42 and CMORPH) bias of satellite estimates. Both MAE and NRMSE showed that the errors increased from TMPA to CMORPH. The NRMSE values were 21.5%, 28%, and 33% for TMPA-3B42, GSMAP, and CMORPH, respectively. The TMPA-3B42 satellite estimates showed smaller NRMSE value than the others, suggesting better performance over GSMaP and CMORPH. The NSE indicator showed that TMPA was more closure towards zero than the others. Among three satellite rainfall products used in this study, we confirm that TMPA-3B42 performed better than other products.

4. CONCLUSIONS

The SBRE rainfall products of having diverse spatial and temporal resolutions became crucial for a broad variety of hydrological applications covering regional scale to global scale studies. Especially, it was useful in data spare regions, rugged terrain conditions, and regions with limited *in-situ* observational network (Shrestha, et al., 2008). Our results suggested that the extreme rainfall events resembled cloudburst type of event can be detected using the hourly or daily satellite-based rainfall products from TMPA-3B42, GSMaP, and CMORPH over highly heterogeneous topography and inaccessible areas with lower rain-gauge networks. However, it needs good understanding on the differences in magnitude of satellite based rainfall against the observational setup.

We found that among the three SBRE rainfall products, the accumulated precipitation estimated by CMORPH was underestimated considerably as this product was not gauge calibrated. The error statistics such as PBIAS, MAE, NRMSE, and NSE for CMORPH were also higher compared to both TMPA and GSMaP (Table **1**). The gauge-calibrated products such as GSMaP and TMPA have performed better against IMD gauge-based data especially over Northern districts of the state.

Overall, the error statistics indicator showed that TMPA-3B42 performed better against reference IMD data. The underestimation of TMPA based rainfall over the Mandakini valley was also reported by Mishra and Srinivasan (2013) and Bharti et al. (2016). The algorithms used for these satellite rainfall products lack regional factors and orographic settings for precipitation estimation and apparently, the rainfall biases were observed over this highly complex Himalayan region.

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