



# Evaluating the Performance of Remotely Sensed Precipitation Estimates against In-Situ Observations during the September 2014 Mega-Flood in the Kashmir Valley

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Received: 17 December 2017 / Revised: 7 July 2018 / Accepted: 27 July 2018 / Published online: 22 October 2018  
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## Abstract

In the present study, 4 gridded satellite precipitation data products for September 2014 flood, IMERG (Integrated Multi-satellitE Retrievals for GPM), GSMaP (Global Satellite Mapping of Precipitation), TRMM-3B42 (Tropical Rainfall Measuring Mission) and INSAT-3D-IMR (INSAT Multispectral Rain), were evaluated against the Indian Meteorological Department rain-gauge data from Sep-1st to Sep-7th 2014. Three evaluation indices; Correlation coefficient (CC), the Relative bias (RB) and the Nash-Sutcliffe coefficient (NSC), were used to evaluate the robustness of satellite precipitation estimates with actual rainfall measurements. IMERG precipitation product has a near perfect positive CC and NSC values of 0.94 and 0.99 respectively; while the CC and NSC values are 0.7 and 0.5 for GSMaP\_Gauge; 0.69 and 0.05 for INSAT-3D-IMR; and 0.9 and 0.8 for TRMM-3B42 respectively. The RB estimates indicate that IMERG, with a bias of 2%, is a best-fit dataset when compared to the surface rain-gauge observations. In contrast, TRMM-3B42, GSMaP and INSAT-3D-IMR have underestimation biases of -31%, -58%, and -86% respectively. Analysis of the indices indicates that IMERG precipitation product performed better than other three satellite precipitation products owing to the closeness of values with surface gauge station data over Kashmir. Owing to scanty observation of rainfall in the region, IMERG has a potential to become a cost effective input data source for designing a flood early warning system (FEWS) for Kashmir. However, it is suggested to evaluate the robustness of different satellite-derived precipitation estimates compared to rain gauge observations by incorporating more extreme events from different mountain regions globally for establishing the best satellite derived precipitation product.

**Keywords** Kashmir Himalaya · September 2014 flood · Satellite-derived rainfall estimates · Surface rain-gauge observations · Nash-Sutcliffe coefficient

## 1 Introduction

Persistent rainfall is usually associated with floods that cause devastating effects both on infrastructure as well as human life besides affecting natural ecosystems. Flood forecasting is very important in topographically complex regions (Romshoo et al. 2012; Tullos et al. 2016), because a heavy rainfall event results into a fast, voluminous stream discharge with a potential to inundate adjacent flood plain (Koriche and Rientjes 2016;

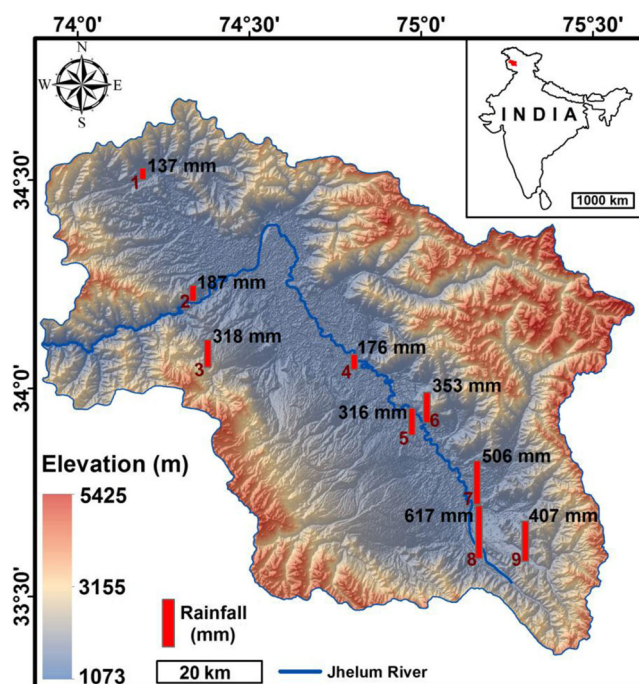
Miao et al. 2016). Accurate estimates of spatial and temporal variations of precipitation are essential for reliable hydrological forecasts (Su et al. 2008; Chang et al. 2010) so that a robust FEWS could be designed (Hong et al. 2007).

Kashmir valley, located in Indian Himalaya (Fig. 1), witnessed one of the worst floods during the first week of September 2014, caused by the continuous seven day heavy rainfall. Although precipitation measured from surface rain gauges provides a direct physical measurement (point data) with longer records but these measurements are seldom realistic in representing the variations in space (Wang and Lin 2015), especially in mountainous areas where rain gauges are often scanty (Romshoo and Rashid 2010). Precipitation measured using rain gauges is not always adequate for hydrological research and modeling, particularly in runoff simulations for mountain regions (Yang and Luo 2014). Keeping in view the limitations of rain gauge observations, satellite-

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**Fig. 1** Spatial distribution of surface rain-gauge stations and cumulative rainfall recorded by IMD-AWS stations during September 2014 flood (1–7 September 2014) over Kashmir valley. 1: Kupwara; 2: Baramulla; 3: Gulmarg; 4: Srinagar; 5: Malangpura; 6: Awantipur; 7: Anantnag; 8: Qazigund; 9: Kokernag

derived precipitation estimates are the only credible source of information pertaining to spatio-temporal variations of precipitation. Satellite-derived rainfall products provide an opportunity for developing a robust FEWS besides overcoming the problem of sparse and unevenly distributed rain gauge observations (Sandeep and Stordal 2013; Toté et al. 2015). In topographically complex areas with a limited gauge network, as in the Himalayan region, satellite-based rainfall estimation can provide information on rainfall occurrence, amount and distribution (Hong et al. 2007; Anagnostou et al. 2010).

In recent years, satellite precipitation products have been developing rapidly and have made great contributions towards improving the understanding of the various hydrological processes (Li et al. 2012; Samaniego et al. 2012). Currently there are several high-resolution satellite precipitation products including TRMM (tropical rainfall measuring mission) multi-satellite precipitation analysis (TMPA), GSMAP (the Global Satellite Mapping of Precipitation), INSAT-3D-IMR product and IMERG (Integrated Multi-satellite Retrievals for GPM). All of them are currently available as gridded datasets both near-real time and post-real time. Such gridded precipitation datasets along with the use of physically-based distributed hydrological models provide an opportunity to develop near-real time flood forecasts and other water resource management applications in data sparse regions (Shrestha et al. 2008). Like any other remotely sensed data, satellite-derived rainfall estimates have uncertainties (Michaelides et al. 2009).

Quantifying these uncertainties is very critical for evaluating the performance of such gridded remotely sensed precipitation products. It is, therefore, essential to evaluate the performance of the satellite-derived precipitation estimates by comparing them with in-situ observations (Nair et al. 2009; Chen et al. 2013). Such evaluations can help to find the most appropriate and accurate satellite precipitation product that could be relied upon for effectively simulating various land surface processes in mountainous regions.

Several researchers have examined the quality of satellite-derived precipitation datasets, by evaluating these products with observations from rain gauge stations. Most of such studies suggest that TRMM-3B42 shows better performance than other satellite precipitation products (Krakauer et al. 2013; Prakash et al. 2014). Gairola et al. (2014) evaluated the IMSRA-Insat Multi-Spectral Rainfall Algorithm (also used in INSAT-3D-IMR product) to derive precipitation estimates, which shows a significant improvement over the GPI (Global Precipitation Index), but underestimates orographic rainfall. Shrestha et al. (2011) validated GSMaP\_MVK+ (Global Satellite Mapping of Precipitation) satellite rainfall products with rain gauge measurements over the Nepal Himalaya and reported that the performance of GSMaP deteriorates with an increase in altitude while its performance is better in a flatter terrain. Liu (2016) characterized the differences between the newly launched Integrated Multi-satellite Retrievals for GPM (IMERG) and TRMM-TMPA and found that IMERG product comprehensively captures the major heavy precipitation regions in the Northern and Southern Hemispheres compared to TRMM-TMPA.

Keeping these intricacies of satellite-derived precipitation estimates in view; this research work evaluated the performance of four high resolution satellite-based precipitation products with IMD/AWS observatory data during the first week of September 2014, a mega-flood event over Kashmir valley (Bhatt et al. 2017).

## 2 Materials and Methods

### 2.1 Study Area

Kashmir valley is a deep, asymmetric basin lying between the Greater Himalayan mountain range to the north-east and the Pir Panjal mountain range to the south-west in the Indian state of Jammu and Kashmir. The basin is asymmetric owing to the fact that Jhelum River draining Kashmir is tilted towards the right with respect to its flow (Dar et al. 2014). The basin extends from longitudes 73°40'–75°40' E and latitudes 33°20'–34°40' N, and experiences temperate climate (Bagnolus and Meher-Homji 1959) characterized by annual precipitation of ~750 mm, derived partially from the summer monsoon and mostly from the western disturbances during

winter (Ray et al. 2015). The mean summer and winter temperatures vary between 5 °C and 25 °C at Srinagar (Romshoo et al. 2018a) and decrease along the altitudinal gradient towards mountain fronts (Rashid et al. 2015; Rashid et al. 2017). The elevation of the basin ranges from 1073 to 5236 m a.m.s.l. Kashmir valley has had a long history of flooding. The valley has witnessed heavy casualties and loss of property due to flooding (Singh and Kumar 2013). The valley has witnessed significant flooding during 855 AD, 1841, 1893, 1903, 1929, 1948, 1950, 1957, 1959, 1992, 1996, 2004, 2006 and 2014. During 2014, Kashmir valley witnessed one of the worst flood situations in the last six decades (Romshoo et al. 2018b). Kashmir valley is a topographically complex region (Rashid et al. 2016) and the rainfall gauge stations located here are very sparsely distributed only in low altitudes ranging from 1590 to 2890 m a.m.s.l. (Fig. 1), which is a major impediment in forecasting floods and other land surface processes (Romshoo et al. 2012).

## 2.2 Satellite-Based Precipitation Products

In the present study, we used four high-resolution satellite precipitation products: TRMM 3B42, GSMaP\_Gauge, INSAT3D-IMR, and IMERG-GPM for finding an appropriate dataset which has the better capability of estimating precipitation by comparing with the gauge observations over mountainous terrain of Kashmir, north-west Himalaya. Details of these satellite precipitation products are provided in Table 1.

The TRMM-3B42 (version 7) three-hourly, daily product with a spatial resolution of 0.25° and available globally from the belt extending from 50°S-50°N, is produced by the TRMM project at the National Aeronautics and Space Administration (Huffman et al. 2010). TRMM-3B42 product used in this study is one type of the TMPA (TRMM Multi-Satellite Precipitation Analysis) product corrected by using Global Precipitation Climatology Center (GPCC) full gauge analysis (version 4) and the GPCC monitoring gauge analysis. The TRMM products are developed in four stages: (1) the microwave precipitation estimates are calibrated and combined; (2) infrared precipitation estimates are created using the calibrated microwave precipitation; (3) the microwave and IR estimates are combined; and (4) rescaling to monthly data is applied (Qin et al. 2014). Each precipitation field is best interpreted as the precipitation rate effective at the nominal observation time (Negri et al. 2002; Huffman et al. 2010). The Version 7 TRMM 3B42 products can be freely downloaded from <https://pmm.nasa.gov/data-access/downloads/trmm>.

The Global Satellite Mapping of Precipitation (GSMaP) project is sponsored by Core Research for Evolutional Science and Technology (CREST) of the Japan Science and Technology Agency (JST) during 2002–2007. GSMaP project developed by the JAXA Precipitation Measuring Mission

**Table 1** Details of precipitation products used in this study

Satellite Precipitation Products	TRMM-3B42	GSMaP_Gauge	INSAT3D-IMR	IMERG(GPM)
Spatial Resolution	0.25°	0.1°	0.1°	0.1°
Temporal Resolution	Daily	Daily	Daily	Half-Hourly
Calibrated with Gauge Observations	Yes (GPCC)	Yes (CPC NOAA)	No	Yes (GPCC, CPC NOAA)
Geographic coverage	50° N-50°S	60°N-60°S	40° N-40°S	60°N-60°S
Availability	January 1998 to present	March 2002 to present	June 2014 to present	March 2014 to present
Distributing agency	NASA	JAXA	ISRO	NASA
Download Link	<a href="https://pmm.nasa.gov/data-access/downloads/trmm">https://pmm.nasa.gov/data-access/downloads/trmm</a>	<a href="http://sharaku.eorc.jaxa.jp/GSMaP/index.htm">http://sharaku.eorc.jaxa.jp/GSMaP/index.htm</a>	<a href="http://www.mosdac.gov.in/content/insat-3d">http://www.mosdac.gov.in/content/insat-3d</a>	<a href="http://pmm.nasa.gov/data-access/downloads/gpm">http://pmm.nasa.gov/data-access/downloads/gpm</a>



(PMM) Science Team (Okamoto et al. 2005) and its gauge-calibrated rainfall algorithm (GSMaP\_Gauge) product having spatial resolution of  $0.1^\circ$  and temporal resolution of one hour has been used in this study. The gauge-calibrated rainfall algorithm in GSMaP\_Gauge adjusts the GSMaP\_MVK (Moving Vector with Kalman Filter) estimates with global gauge analysis data (CPC Unified Gauge-Based Analysis of Global Daily Precipitation) supplied by NOAA (National Oceanic and Atmospheric Administration). Further details regarding GSMaP\_MVK algorithm can be found in Ushio et al. (2009) and the datasets are available from <http://sharaku.eorc.jaxa.jp/GSMaP/index.htm>.

INSAT-3DIMG\_L3G\_IMR\_DLY is a daily IMR data product obtained through IMAGER sensor of INSAT-3D satellite launched on 26th July, 2013 and available at a spatial resolution of  $0.1^\circ$  covering Indian region. The required INSAT-3D IMR daily product used in this study have been obtained from <http://www.mosdac.gov.in/content/insat-3d>. This data product is generated using INSAT Multi Spectral Rainfall Algorithm (IMSRA). IMSRA estimates precipitation based on non-linear power law relationship established between INSAT-3D IR (infrared), WV (water-vapor) brightness temperatures and TRMM-PR surface rainfall rate at  $0.25^\circ$  grids (Mishra et al. 2009; Gairola et al. 2014).

The Integrated Multi-satellitE Retrievals for GPM (IMERG) is a gridded precipitation product that estimates precipitation measurements from a network of satellites in the GPM (Global Precipitation Measurement) constellation (Huffman et al. 2015). IMERG is a unified U.S. Multi-satellite algorithm, based on components from three prior multi-satellite algorithms from NASA (TMPA, NOAA-CPC: Climate Prediction Center Morphing–Kalman Filter; CMORPH-KF; and PERSIANN-CCS: University of California Irvine Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks Cloud Classification System). The input precipitation estimates computed from the various satellite passive microwave sensors are inter-calibrated to the GPM Combined Instrument product (because it is presumed to be the best snapshot GPM estimate), then “morphed” and combined with microwave precipitation-calibrated geo-IR fields, and adjusted with monthly surface precipitation gauge analysis data (where available) to provide half-hourly and monthly precipitation estimates on a  $0.1^\circ$  grid over the domain  $60^\circ\text{N-S}$  (Huffman et al. 2014). Precipitation phase is diagnosed using analyses of surface temperature, humidity, and pressure. The current period of record is mid-March 2014 to the present (delayed by about 3 months). The version-3 IMERG product used in this study is available at a half hourly temporal resolution and can be downloaded from <http://pmm.nasa.gov/data-access/downloads/gpm>.

## 2.3 Rain Gauge Data

For the evaluation of satellite precipitation products over Kashmir valley during September 2014 flood, rain gauge data from the nine fully functional Automatic Weather Stations (AWS) of Indian Meteorological Department (IMD) were used as reference data. The details of the sensor characteristics of IMD-AWS are provided at [https://www.wmo.int/pages/prog/www/IMOP/publications/IOM-104\\_TECO-2010/P1\\_36\\_Ranalkar\\_India.pdf](https://www.wmo.int/pages/prog/www/IMOP/publications/IOM-104_TECO-2010/P1_36_Ranalkar_India.pdf). The sensors are calibrated annually following the BIS protocol - 4849 1992 (<https://archive.org/details/gov.in.is.4849.1992>). Although the AWS from IMD provides hourly precipitation data, the accumulated precipitation over 24 h period is collected each day at 8:30 AM IST (3:00 GMT) and distributed to users. These data served as validation for 4 different high resolution remotely sensed precipitation estimates.

## 2.4 Evaluation Method

Since the satellite-based precipitation products are available at  $0.1^\circ$  (GSMaP, IMERG and INSAT-3D-IMR) and  $0.25^\circ$  (in case of TRMM-3B42), the reference IMD-AWS point gauge data were interpolated for comparison at same spatial resolution using kriging interpolation keeping into consideration the robustness of kriging interpolation algorithm than the other methods (Creutin and Obled 1982; Tabios and Salas 1985; Borga and Vizzaccaro 1997). The comparisons were carried out by pixel-to-pixel between gridded remote sensing precipitation products and interpolated rain gauge data.

In order to quantitatively evaluate the variability shown by the various satellite precipitation products against the surface rain gauge observations, three statistical validation indices - Correlation coefficient-CC (Pearson and Lee 1896), Relative bias-RB (Gumindoga et al. 2016) and the Nash-Sutcliffe coefficient-NSC (Nash and Sutcliffe 1970) were used. The CC was used to reflect the degree of correlation between satellite precipitation and in-situ precipitation estimates. A CC value of +1 indicates a perfect positive fit, -1 indicates perfect negative fit while 0 indicates no correlation. The relative bias (RB) is used to assess the systematic bias of satellite precipitation; a negative bias (RB) indicates underestimation by satellite precipitation while a positive bias indicates overestimation. The performance was characterized into three basic types: underestimation (bias  $<-10\%$ ), overestimation (bias  $>10\%$ ), and approximately equal (bias range from  $-10\%$  to  $10\%$ ) (Brown 2006). The Nash-Sutcliffe coefficient, also known as the coefficient of efficiency, indicating the skill of the estimates relative to a reference (in this case the gauge data) was used to measure the consistency of the satellite-derived precipitation and gauge observations both in amount and temporal distribution (Dinku et al. 2007; Jiang et al. 2010). Its values vary from minus  $\infty$  to 1, with 1 being the perfect skill.

The values of CC, RB and NSC were calculated using eqs. 1, 2 and 3 respectively mentioned hereunder:

$$CC = \frac{\sum_{i=1}^n (G_i - \bar{G})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^n (G_i - \bar{G})^2} \sqrt{\sum_{i=1}^n (S_i - \bar{S})^2}} \quad (1)$$

$$RB = \frac{\sum_{i=1}^n (S_i - G_i)}{\sum_{i=1}^n G_i} \times 100 \quad (2)$$

$$NSC = 1 - \frac{\sum_{i=1}^n (S_i - G_i)^2}{\sum_{i=1}^n (G_i - \bar{G})^2} \quad (3)$$

where  $n$  is the total number of the rain gauge data or satellite precipitation data;  $S_i$  and  $G_i$  are the  $i$ th values of the satellite precipitation data and rain gauge observations, and  $\bar{G}$  and  $\bar{S}$  are the average gauge and satellite rainfall estimates.

### 3 Results

The rainfall data from IMD-AWS gauge observations for the first week of September 2014 shows that Qazigund, Kokernag, Anantnag, Awantipur and Gulmarg received very heavy rainfall whereas stations like Srinagar and Kupwara experienced relatively lower rainfall (Fig. 1). It is pertinent to mention that IMD describes rainfall events with 64–124 mm rainfall in a span of 24 h as heavy rainfall. As and when the rainfall exceeds 124 mm within 24 h period, it is considered a very heavy rainfall (<http://imd.gov.in/section/nhac/termglossary.pdf>). Table 2 represents the daily rainfall data recorded by IMD-AWS gauge observations for the first week of September 2014 flood. However the valley received heavy to very heavy rainfall (64–181 mm per day) between 4th and 6th September. The interpolated gauge data of heavy

rainfall days of 2014 flood event as well as seven day accumulated rainfall amounts obtained from IMD-AWS in-situ observations were used to evaluate the performance of satellite-based precipitation products over Kashmir valley during the September 2014 flood event.

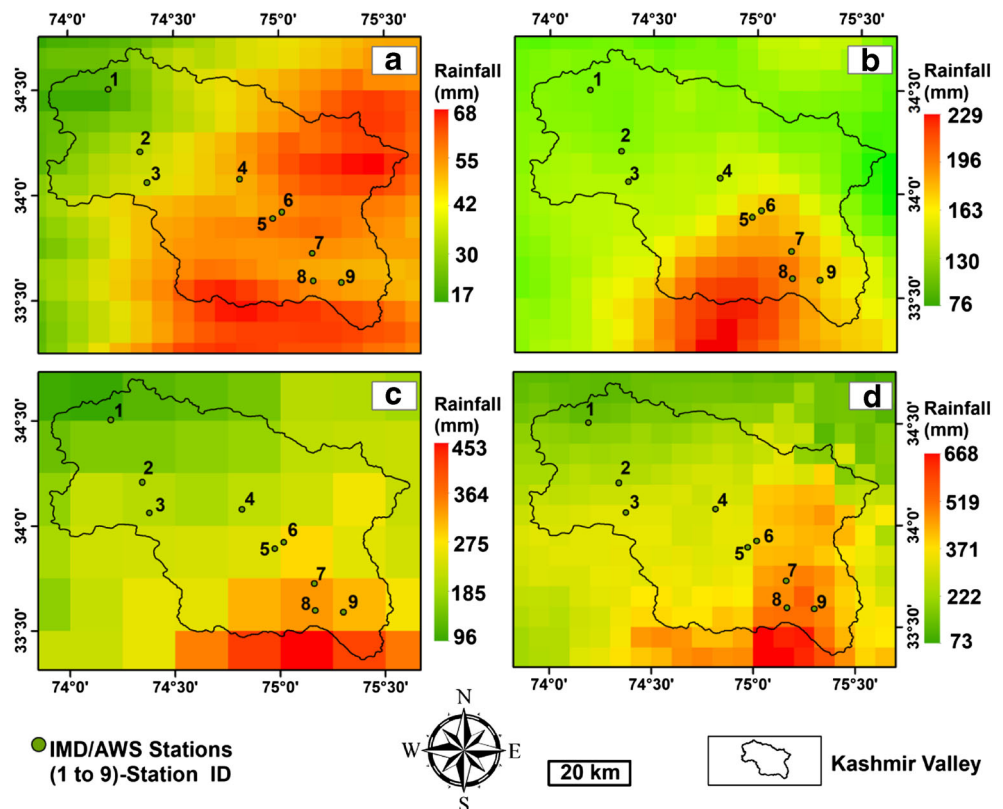
Both daily (very high rainfall precipitation days) and seven-day accumulated precipitation estimates (Fig. 2) from satellite-derived precipitation products during the first week of September 2014 flood event over Kashmir valley and their comparison with ground observations are shown in Figs. 3 and Fig. 4 respectively. Based on these data, IMERG product agreed well with gauge observations and captured high magnitude rainfall values compared to other satellite-derived precipitation products. The accumulated IMERG estimates revealed that Qazigund received 525 mm followed by Kokernag (463 mm), Anantnag (434 mm) and Malangpura (347 mm) while the interpolated gauge observation at these stations recorded 590 mm, 495 mm, 470 mm and 337 mm respectively indicating the closest match of IMERG estimates with surface rain gauge observations. INSAT-3D-IMR shows higher underestimation compared to all the gauge stations and other satellite products used in this research. It has not produced any value greater than 68 mm (Fig. 2a) during the flood event and was also unable to capture high magnitude rainfall values during high intensity rainfall days. GSMaP product showed the similar trend but exhibits lesser underestimation over stations 1, 2, and 4 as compared to INSAT-3D-IMR product. While TRMM precipitation product showed reduced underestimation over stations 1, 2 and 4 that received minimum rainfall, it exhibited higher underestimation over stations 3, 5, 6, 7, 8, and 9 that received maximum amount of rainfall during the flood event.

Figure 5 presents scatter plots for satellite precipitation products against rain gauge observations and infers that INSAT-3D-IMR, GSMaP, and TRMM underestimate precipitation by –86%, –58%, and –31% with CC and NSC values of 0.69, 0.05; 0.70, 0.50; and 0.90, 0.87 respectively. The IMERG values showed negligible underestimation of 2% and produced better CC (0.94) and NSC (0.99).

**Table 2** Daily rainfall (in mm) recorded by IMD-AWS stations during first week of September 2014 flood event

Station ID	01/09/2014	02/09/2014	03/09/2014	4/09/2014	05/09/2014	06/09/2014	07/09/2014
1	2	2	5	48	74	16	1
2	2	0	16	70	93	30	7
3	1	0	24	97	113	36	11
4	12	0	22	57	67	18	25
5	5	1	41	64	119	68	36
6	5	1	41	64	119	68	36
7	8	7	52	150	153	80	42
8	7	8	68	148	181	101	43
9	1	10	64	122	155	89	43

**Fig. 2** Seven day accumulated precipitation map estimated by satellite-based precipitation products over Kashmir valley during September 2014 flood. **a** INSAT-3D IMR product **b** GSMaP\_Gauge product, **c** TRMM-3B42 product, and **d** IMERG-GPM product



## 4 Discussion

The valley of Kashmir experienced heavy rains that began on 1st September 2014 which continued for a week that led to unprecedented widespread flooding across the valley. The banks of Jhelum and several other streams were overflowing causing loss of life leading to death of 277 people (Mishra 2015) and economic damage amounting to INR 1 trillion (World Bank 2015). The mid latitude westerlies lying over the Kashmir valley and low-pressure system that originated from the Bay of Bengal interacted at Qazigund in Pir Panjal region of Kashmir valley as a result of which a massive downpour occurred over southward side of Kashmir valley (Kumar and Acharya 2016). Rainfall data obtained from satellite precipitation products as well as gauge stations revealed that South Kashmir has experienced the maximum amount of rainfall during the September, 2014 deluge giving credence to the analogy put forth by Kumar and Acharya (2016) that two weather systems interacted over Pir Panjal mountain range.

IMERG-GPM is the only satellite precipitation product that performed well during September 2014 flood and has been able to capture heavy precipitation accurately (Figs. 2, 3, and 4). The scatter plots showing the comparison of satellite derived precipitation estimates with rain gauge observations (Fig. 5) also are indicative of the fact that IMERG has scored higher values of CC and NSC compared to the other satellite precipitation products used in the research.

IMERG showed insignificant bias as indicated by RB values. The reason behind the robust precipitation estimates of IMERG product with the IMD-AWS data and higher accuracy could be due to its highest temporal resolution (half-hourly) compared to other satellite derived precipitation products (Huffman 2015) used in this study. Moreover, relative to TRMM and other satellite precipitation products used in this study, GPM (Global Precipitation Measurement) mission producing IMERG product has been introduced with newly sensor-like dual-frequency precipitation radar, a conical-scanning multi-channel GPM Microwave Imager (Huffman et al. 2015; Prakash et al. 2016a; Asong et al. 2017) and updated calibration algorithms (Huffman et al. 2014) that have undoubtedly improved its accuracy. This has been also confirmed by Sharifi et al. (2016) who suggested that IMERG product for heavy precipitation is superior to the other products like ERA-Interim and TMPA-3B42 and that it could be used in future for hydrological forecasts.

After IMERG, TRMM product yields higher values of CC and NSC in comparison to GSMaP\_Gauge and INSAT-3D-IMR products, but compared to gauge observational rainfall data it is showing an underestimation indicated by RB bias of  $-30\%$  during first week of September 2014 extreme precipitation event. It is pertinent to mention that although TRMM is capable of capturing high extremes (Fig. 2-c and Fig. 4) over stations located towards the high altitude regions of Kashmir valley but it usually underestimates

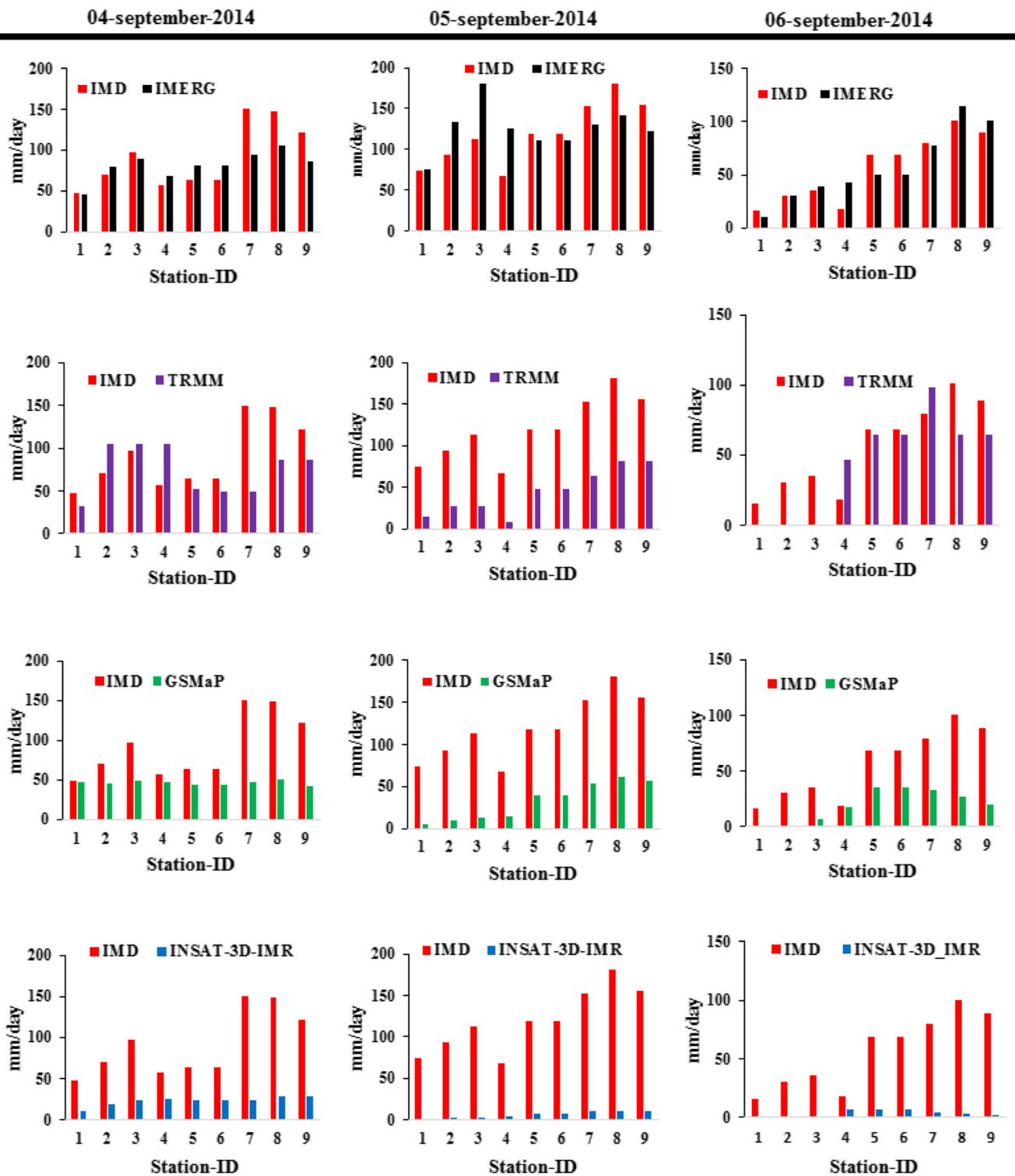


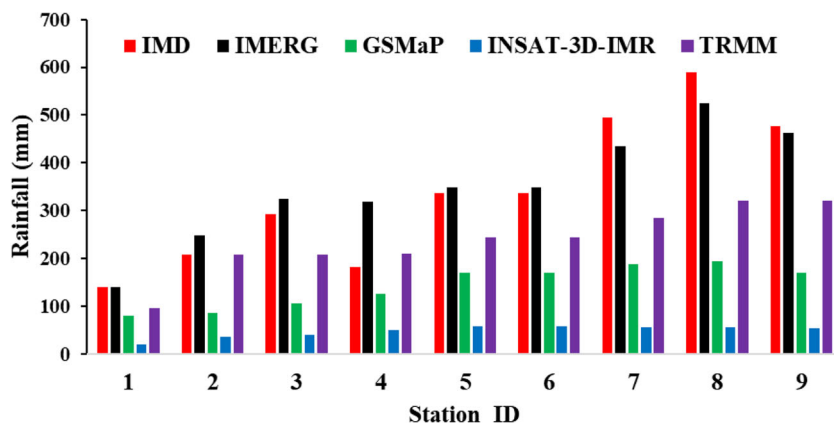
Fig. 3 Comparison of satellite-derived precipitation estimates with rain gauge observations for heavy rainfall days of 4th, 5th and 6th September, 2014

the rainfall amount, which has also been reported by Mantas et al. (2014) and Zulkafli et al. (2014).

It is clear from Fig. 2-a,b and Fig. 3 that both INSAT-3D-IMR and GSMaP were unable to accurately capture the high intensity rainfall during the September 2014 flood event.

Values of evaluation indices like RB, CC, and NSC with gauge are also lowest compared to TRMM and IMERG products (Fig. 5). Poor performance of INSAT-3D-IMR could be attributed to that fact that IR data used in INSAT-3D-IMR product has difficulties in capturing precipitation information

**Fig. 4** Comparison between satellite-based precipitation products and interpolated IMD-AWS gauge station data during first week of September 2014 flood

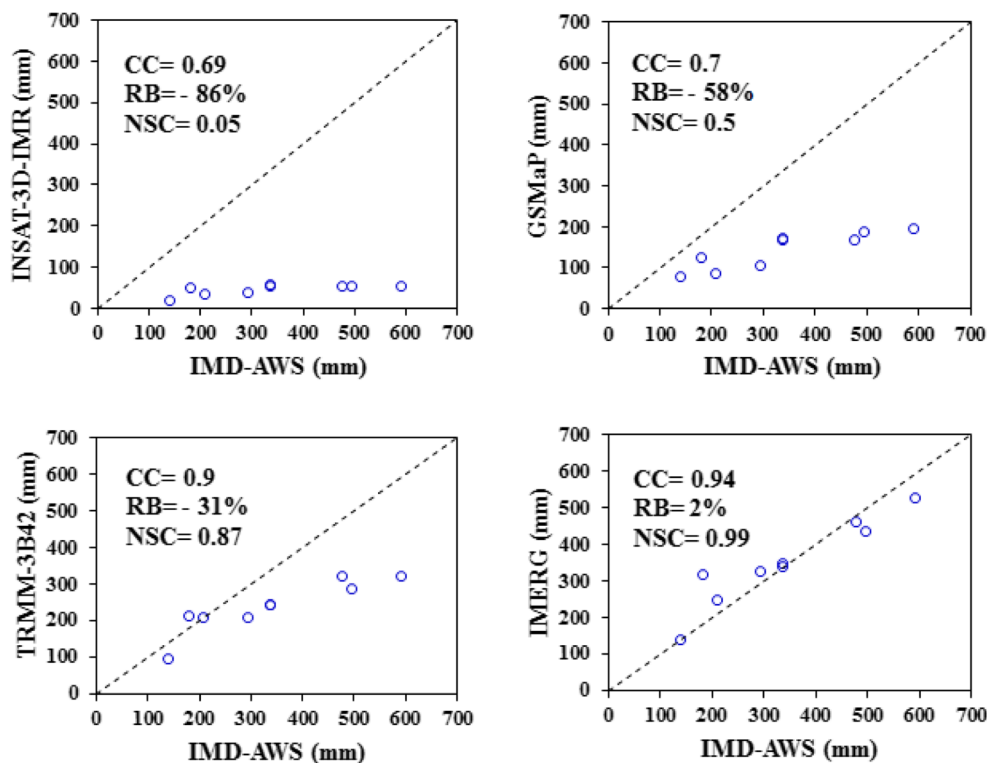


owing to non-penetrability of IR emissions through clouds (Hirpa et al. 2010; Kalinga and Gan 2010). As such only cloud top brightness is measured resulting in an indirect relationship with surface rainfall which enhances the uncertainty in the retrieval of precipitation estimates (Richard and Arkin 1981). In comparison to INSAT-3D-IMR, GSMaP performs better and underestimated precipitation by  $-56\%$  during the flood event. GSMaP suffers higher underestimation over some stations that include 3, 5, 6, 7, 8 and 9 as these are located towards mountain fronts between the altitudes ranging from 1650 to 2890 m a.m.s.l. Pertinently GSMaP precipitation product over complex orographic regions has been demonstrated to exhibit poor rainfall detection (Maggioni et al. 2016; Prakash et al. 2016b).

### 5 Conclusions

This study compared four satellite-derived precipitation products, INSAT-3D-IMR, GSMaP\_Gauge, TRMM-3B42 and IMERG-GPM against the surface rain gauge observations over Kashmir valley during the September, 2014 extreme precipitation event. From the three evaluation indices used in this study, it is inferred that IMERG product produces the best values of CC (0.94), NSC (0.99), and RB (2%) indicating its near-perfect fit with the in-situ observations over Kashmir valley. This is substantiated by the fact that IMERG precipitation estimates are closest to IMD-AWS rain gauge observations compared to other products. The higher spatial and temporal resolution, besides sensor improvement, enhances the

**Fig. 5** Scatter plots with evaluation indices between satellite-based precipitation estimates and rainfall gauge observations





potential of IMERG estimated precipitation, to be used in FEWS. Although TRMM 3B42 performs better than INSAT-3D-IMR and GSMaP\_Gauge, it showed underestimation in precipitation when compared to both the rain gauge and IMERG estimates over Kashmir valley during September-2014 flood. Both INSAT-3D-IMR and GSMaP\_Gauge products performed poorly in capturing rainfall during September 2014 Kashmir flood. The present research effort quantified the robustness of various satellite derived precipitation products with rain gauge observations for a single flood event over Kashmir region. It is, therefore, suggested to assess the reliability of satellite-derived precipitation products more conclusively by comparing them with rain gauge observations across different mountain regions.

**Acknowledgements** The authors express gratitude to the two anonymous reviewers for their valuable comments and suggestions on the earlier version of the manuscript that greatly improved the content and structure of this manuscript. The authors express gratitude to IMD for providing the AWS data of the September 2014 flood event. We are also thankful to NASA, JAXA and ISRO for the free distribution of satellite-based precipitation estimates.

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