



Comparative analysis of two rainfall retrieval algorithms during extreme rainfall event: a case study on cloudburst, 2010 over Ladakh (Leh), Jammu and Kashmir

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Received: 20 February 2018 / Accepted: 31 July 2019 / Published online: 5 August 2019
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Abstract

Intense rainfall events lead to floods and landslides in the Western Himalayas (WH). These rainfall amounts are considered comparatively moderate over the plains. These events, called ‘cloudbursts,’ are convective triggered followed by orographically locked phenomena producing sudden high-intensity rainfall over a small area. Early warning and prediction of such severe local weather systems is important to mitigate societal impacts arising from the accompanying flash floods, landslides, etc. Due to lack of ground-based observations, cloudbursts over remote and unpopulated hilly areas often go unreported. Present study examines a cloudburst occurred at Ladakh (Leh) in the WH in the early hours of August 5, 2010, using remotely sensed rainfall data from Tropical Rainfall Measuring Mission (TRMM) and Kalpana-1. The storm lasted for 2 days starting from August 3, 2010, followed by flash floods. Rain-band propagation over the region is studied from Kalpana-1 3-hourly rainfall estimates using Indian Satellite (INSAT) multi-spectral rainfall algorithm (IMSRA) and TRMM rainfall estimates using TRMM 3B42 algorithm. Quantitative and qualitative assessment and comparison of these two products is made. It is observed that there is decrease in satellite brightness temperature (BT) during the rainfall event. Initiation of rainfall occurs at about <255 K. Maximum of 16.75 mm/h rainfall is observed over the Jammu and Kashmir at 21 GMT from TRMM 3B42 estimates. In addition, it is observed that Kalpana-1 IMSRA underestimates the rainfall observations with respect to Indian Meteorological Department (IMD) rainfall estimates. Spatial correlation at 5% significant level is evaluated, and similarities in rainfall estimates based on rainfall retrieval algorithms are made during the cloudburst event. Mean and standard deviations depict that TRMM 3B42 and IMD rainfall estimates are closer in terms of spatial signature, but estimates of rainfall from Kalpana-1 underestimate the mean and standard deviation signature. In view of orographic contribution, it has been observed that linear fit is the better than nonlinear with less rainfall bias at 90% confidence bound over the region.

Keywords Western Himalayas · Cloudbursts · Brightness temperature · IMSRA · TRMM 3B42

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1 Introduction

Understanding the rainfall processes and its spatiotemporal variability over the Indian sub-continent is very crucial for a wide range of applications such as: agriculture, water resource management and hydrological purpose. India gets about 80% of total annual rainfall during June–September summer monsoon season. The seasonal migration of the inter-tropical convergence zone (ITCZ), which is a manifestation of a wind reversal process in the monsoon region, plays an important role in the generation and development of the Indian summer monsoon (ISM) (Gadgil 2003). The strength of the monsoon rainfall decreases when it reaches the northern part of the country, particularly Jammu and Kashmir from east to west along its trajectory (Basistha et al. 2007).

1.1 Extreme events and cloud burst

The Western Himalayas (WH) is highly vulnerable to extreme rainfall events (EREs), such as: cloudbursts due to complex orography and elevation-dependent interactions. It leads to fluctuations of weather in the different location of WH which are unpredictable. There is no standard definition of an ERE and/or cloudbursts. As per the Intergovernmental Panel on Climate Change (IPCC 2007), an ERE is defined as the event that is rare within its statistical scale of reference over a particular place and normally rare or rarer than the 90th percentile. As per the IMD, high-intensity rainfall (usually 100 mm/h) within a short duration, over a localized area, is classified as cloudburst events. But this definition reflects rainfall qualitatively and associated dynamics linked to orographic interactions over the WH remain unknown. Cloudbursts and consequent flash floods are the most potential hazards in the Himalayan region (Thayyen et al. 2013). Advance prediction of location and magnitude of such events remain a challenge.

Geographical location of Ladakh extends from the north of the Great Himalayan mountains to the Karakoram mountains and encompasses about 52% area (45,100 Sq. Km) of the state of Jammu and Kashmir (Fig. 1a). It is the second largest district in the country. Elevation of this geographical region ranges from 3300 to 6120 m, and place for different habitants settlements below 3800 m. Zaskar, Ladakh and some parts of the Karakoram range are the most prominent mountain ranges under this location. Several streams (Drass, Zaskar, Suru, Indus, Shyok and Nubra) flow through this region and are often fed by snow and/or glaciers. The geographical region is known as the cold desert due to its cold arid climate. Leh received mean annual precipitation of 115 mm. Inaccessibility of the region and adverse climate conditions limited the population of the Leh district around 1,50,000. Settlements are found close to the water bodies and are susceptible to heavy rain. Figure 1b portrays the regions of the interest, including the different streams originating from the Ladakh range, where massive flood devastation occurred during 4–5 August 2010 as after-effect of multiple cloudbursts.

The cloudbursts are characterized by very-high-intensity rainfall (> 100 mm/h) occurring over short duration under mesoscale weather system and causes devastating flash floods (Das et al. 2006). The Leh cloudburst (August 2010), Manali cloudburst (July 2011), Rudraprayag cloudburst (September 2012) and Kedarnath disaster (June 2013) are few of the major cloudbursts causing great damages to human lives and infrastructure. Thayyen et al. (2013) reported that Leh disaster was noted to be the worst calamity ever occurred in the Ladakh region as it took away about 255 lives and demolished 1749 houses, caused

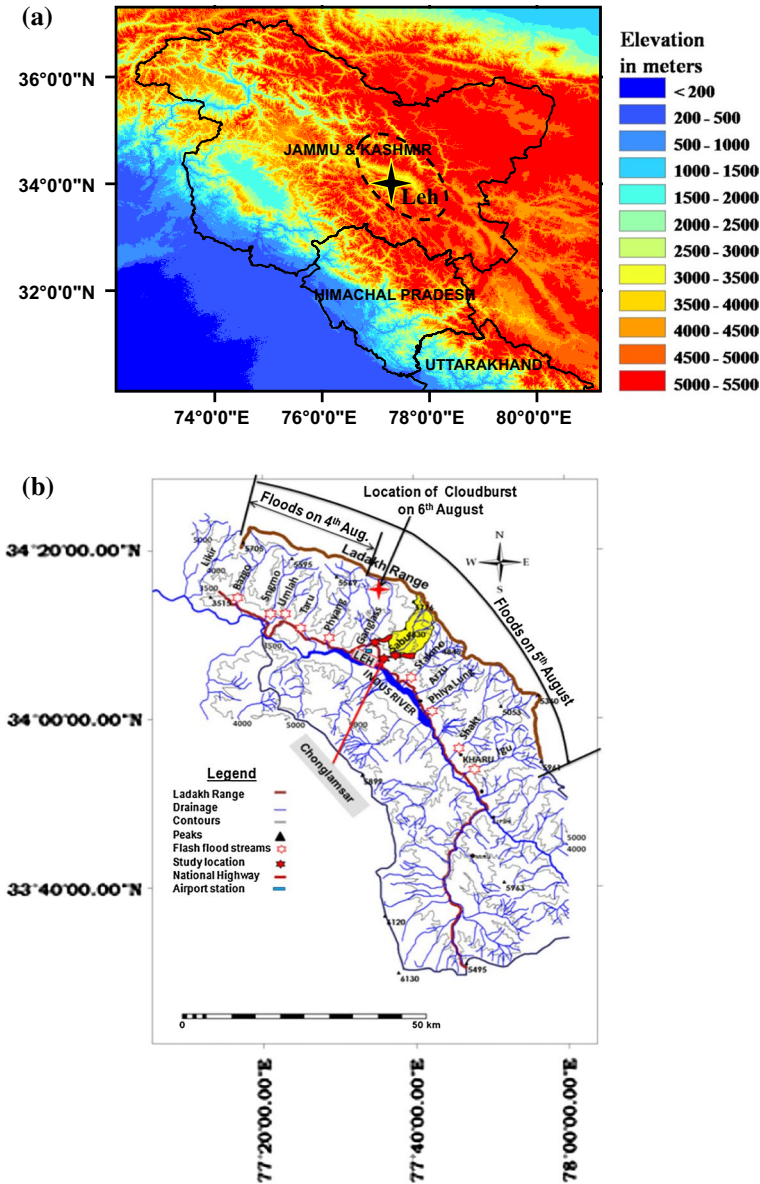


Fig. 1 a Topography of the study region as derived from Shuttle Radar Topography Mission (SRTM~90 m). Color scheme represents variation of elevation in meters. Circle (dashed) area shows the region that received high-intensity rainfall and flash flood due to multiple cloudbursts during August 4–5, 2010. **b** Streams originating from the Ladakh range experienced flash flood on August 4–5, 2010. Streams between Basgo and Phyang experienced flash floods on August 4–5, 2010. *Source:* Thayyen et al. 2013

serious damages to the roads, bridges and settlements within 100-km radius around Leh. The National Highway connecting to Leh was washed off at many places and the roads linked to others places were cut off for many days. Many cloudbursts remain unreported

in the remote and unpopulated places of the Himalayas due to non-availability of weather station and/or undetected due to non-availability of Doppler weather radar. Table 1 shows the list of cloudbursts over Jammu and Kashmir. Studying the Leh cloudburst event (2010), Bhan et al. (2015) proposed monsoon impacts on the Himalayan rain-shadow regions with sufficient energy to create devastating flash floods and topographic elements enhancing rainfall further over the Leh region. Researchers have used different thresholds in order to identify EREs over different locations. The previous study by Francis and Gadgil (2006) over Indian West Coast used 15–20 cm/day as threshold value. For heavy rainfall events over India, Goswami et al. (2006) used 100 mm/day as threshold value, whereas Rajeevan et al. (2008) defined 150 mm/day rainfall as threshold for very heavy rainfall events over India by using IMD-gridded data. Goswami and Ramesh (2007) set 250 mm/day as a rainfall threshold for studying EREs over India excluding the WH. For more details of recent cloudburst events in Indian Himalayan region, Dimri et al. (2017) may be referred to and details on August 4–5, 2010, Leh cloudburst events are discussed in Thayyen et al. (2013). Thus, the present study deliberates on to find out strength and similarity of rainfall retrieval algorithms during the extreme event and to inter-compare the result with IMD and attempts to find out orographic relationship with rainfall and thus not focusing on disaster perspective.

1.2 Role of elevation

Several studies reported that there is a strong connection between elevation and rainfall, as rainfall usually increases with altitude only up to a certain elevation and decreases thereafter (Singh and Kumar 1997; Shrestha et al. 2012). However, elevation alone is not responsible for intense orographic rainfall; as the geometry of topography (slope, aspect, hill-shade, continentality, etc.) and mountain folds play crucial roles in orographic enhancement of rainfall (Smith 1979; Paula and Lettenmaier 1994; Anders et al. 2006). Topographic heterogeneity and land-cover variability limit the mesoscale predictability due to interaction of large-scale motion with underlying orographic boundary (Mann and Kuo 1998).

During the JJAS Warm moisture-laden low-level winds carry air from the Bay of Bengal and the Arabian Sea and after the landfall, the low-level winds interact with the Himalayas and rainfall occurs at different sectors of the Indian Himalayas. Physical interaction between complex Himalayan orography and southwest monsoonal flow further modify vertical column of moisture profile, convective energy, low-level vorticity and upslope moisture convergence which, in turn, modify the rain-bearing clouds. Topographic features further modulate orographic rainfall over different parts of Western Himalayas at different spatiotemporal scale that are poorly understood till now. Previous studies attempt to find out relationship between the Himalayan topography and the Indian summer monsoon (ISM) (Barros et al. 2000; Kriplani et al. 2003; Bookhagen et al. 2005; Anders et al. 2006;

Table 1 List of cloudburst event in Jammu and Kashmir. *Source:* Thayyen et al. 2013; nidm.gov.in

Date of event	Location
June 23–24, 2005	Leh Nalla(Ganglass)
July 31–Aug 1, 2006	Leh Nalla(Ganglass)
Aug 5–6, 2010	Leh
June 8, 2011	Baggar, Doda

Bookhagen and Burbank 2006). Anders et al. (2006) show variation of rainfall (spatial scale ~ 10 km) patterns strongly controlled by the Himalayan topography using TRMM data. Bookhagen and Burbank (2006) attempted to quantify the characteristic elevations and relief at which maximum rainfall occurred by using TRMM data from 1998 to 2005. Typically, violent rain-storms can overcome the orographic barriers and penetrate into arid regions in the northwest Himalayan region at elevation above 3000 m. (Bookhagen et al. 2005). Many studies suggested the mechanism/processes involved in interaction of orography to weather systems and corresponding rainfall over various mountainous region (Barros and Lettenmaier 1994; Pielke 2001; Giorgi et al. 2003; Bookhagen and Strecker 2008; Medina et al. 2010). Few studies used regional climate model (RCM) and downscaled to local-scale models to investigate the orographic role and identify the variation in rainfall (Barros and Lettenmaier 1994; Das et al. 2003; Barros et al. 2006; Dimri and Ganju 2007; Dimri 2009). For comprehensive overview of orographic modification of frontal activity and rainfall pattern including dynamical and microphysical aspects Houze (2012) may be referred to. But no previous study so far is found over WH that relates the elevation with EREs.

2 Datasets and methodology

2.1 Satellite remote sensing of rainfall

In WH, there is undulating terrain, and ground-based rain gauges and radar networks are very sparse to get accurate rainfall information. Earth observation satellites can provide information of rainfall over inaccessible remote regions for flood forecasting, weather monitoring, numerical weather prediction application, etc. The meteorological satellite introduced in 1970s and initially interpreted the rainfall intensity from the satellite visible (VIS, based on cloud reflectivity) or infrared (IR, based on cloud top temperature) data (Ebert et al. 2007) and provide crude estimation due to a weak link between cloud top properties and rainfall. A complete overview of satellite's VIS and IR technique is provided by Barrette and Martin (1981). IR-based methods do not represent true interpretation in most of the cases due to high-level cirrus cloud and underestimate warm orographic rains (Dinku et al. 2008; Li 2014). In 1980s, satellite passive microwave (MW) sensors were deployed in polar orbit and gave a better estimation of rainfall than VIS and IR techniques as they are based on either absorption or scattering properties of atmospheric constituents. Precipitation particles are the primary attenuator of upwelling radiation at passive microwave frequencies due to the scattering effect from the ice crystals present in the cloud (Ferraro and Marks 1995). Hence, satellite MW estimates of precipitation are a more direct approach than VIS/IR techniques. But disadvantages include poor spatial and temporal resolution due to diffraction and beam-filling effect of MW sensors (Graves 1993). It gives a better estimation of rainfall over the oceanic region than land due to heterogeneous emission signatures from the land surface (Sumner 1988). The major difficulty in this technique is to separate cloud water from rain water (Kidder and VonderHaar 1995).

The advancement of meteorological satellites and improvements in algorithm for rainfall estimation techniques provides the ample scope to study EREs. TRMM is a joint collaboration between National Aeronautics and Space Administration (NASA) and Japan Aerospace Exploration Agency (JAXA) that first dedicated a meteorological satellite to study rain structure and monitor precipitation distribution from tropical belt to the

subtropical region (NASDA 2001). It is the only satellite, since December 1997, that provides precipitation data (inter-calibrated) at fine spatiotemporal coverage. Latest release of version 7(V7) data offers better precipitation estimates with significantly lower bias even over complex topography (Huffman et al. 2010; Zulkafli et al. 2014).

Indian Space Research Organization (ISRO) launched first meteorological satellite, Kalpana-1, on September 12, 2002 (Kaila et al. 2002) and two of its rainfall products are operational now. The first product is the Geostationary Observational Environmental Satellite (GOES) Precipitation Index (GPI), which uses the thermal infrared (TIR) channel of Kalpana-1 at $1^\circ \times 1^\circ$ spatial resolution for rainfall estimation (Gairola et al. 2010a). Prakash et al. (2011) made a comparative analysis using Kalpana-1-derived rainfall with the multi-satellite rainfall estimates and found that Kalpana-1 rainfall retrieval algorithm performs better over larger spatial and temporal scales and efficiently captures the active and break phases of the ISM. The second product is IMSRA, which was developed for Kalpana-1 and provides more accurate rainfall estimates than TRMM-Precipitation Radar (TRMM-PR) (Prakash et al. 2009). This algorithm uses cloud classification schemes from Water Vapor (WV) channel and TIR and methodology is same as used by Mishra et al. (2010). Potentiality of the IMSRA algorithm is investigated by Prakash et al. (2010). By using summer monsoon data for 2008 and 2009, they observed that synoptic features of the monsoon are well captured and performance of the algorithm is reasonably well over the non-orographic region.

The aim of the present study is to investigate the relative performance of the ongoing operational algorithms over the WH, especially over Jammu and Kashmir and its Ladakh sub-region. Study uses multi-spectral rainfall algorithm, IMSRA from Kalpana-1 and multi-satellite rainfall estimates from TRMM 3B42 to investigate their strength and weakness in rainfall retrieval during August 4–5, 2010, cloudburst over Leh (Thayyen et al. 2013) and results are compared with IMD-gridded rainfall data.

The datasets used in the present study are discussed briefly in this section.

2.1.1 Kalpana-1 data

Very-high-resolution radiometer (VHRR) sensor, which is onboard on Kalpana-1 satellite, operates in three wavelength bands: 0.55–0.75 μm for VIS, 5.70–7.10 μm for WV and 10.50–12.50 μm for TIR of electromagnetic spectrum. Spatial resolution is of 8 km for the TIR and WV bands, whereas 2 km for VIS band. The sensor portrays the synoptic image of a weather system and used for monitoring, propagation and onset of monsoon over the Indian region. Different geophysical parameters, e.g., sea surface temperature, cloud cover, outgoing long-wave radiation and quantitative precipitation estimates of rainfall are obtained from the sensor. Infrared brightness temperature (IRBT) of Kalpana-1 and IMR data at 0.25° resolution is obtained for 2010 summer monsoon months June–September (JJAS) in HDF format from the website link: <http://www.mosdac.gov.in>.

2.1.2 TRMM 3B42 data

TRMM 3B42 is a multi-satellite-based rainfall retrieval algorithm that provides rainfall estimates from geostationary IR and MW observations and is available from January 1998–2015 in gridded format from 50°S to 50°N geographic location at 0.25° spatial resolution at 3-hourly, daily and monthly time scale. Present study utilized 3-hourly combined MW-IR estimates (with gauge adjusted) data from 3B42 algorithm, which provides

precipitation estimates by merging high-resolution IR precipitation and root-mean-square (RMS) precipitation-error estimates (Huffman 2013 and references therein). V7 data are considered as improvement over its previous versions specifically over the Himalayan foot-hill region and highly recommended for research work (Huffman and Bolvin 2014). The research quality data of TRMM 3B42 V7 for 2010 summer monsoon months are downloaded from the website link: <http://disc2.nascom.nasa.gov/tovas/>.

2.1.3 IMD rainfall data

For the validation of the rainfall over Leh, gridded rainfall data ($0.25^\circ \times 0.25^\circ$) from IMD are used in this work. These data are prepared by using 6995 rain gauge stations in India for 1901–2013 (113 years). The spatial distribution of rainfall in heavy rainfall areas and orographic regions is better represented in these data due to the finer spatial resolution and density of the stations (Pai et al. 2013, 2014).

2.1.4 SRTM elevation

The present study uses Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) of spatial resolution ~ 90 m to investigate the orographic relationship with rainfall over Jammu and Kashmir. Geo-Tiff format data (version 4) are downloaded from the link: <http://www.cgiar-csi.org/>. Jarvis et al. (2004) suggested that in terms of accuracy, quality and usability, SRTM provides more accurate measurements of elevation and other topographic derivatives as compared to coarser resolution digital elevation models.

2.2 Methodology

To understand the relationship between IRBT and rain-rate over the WH region, IRBT collocated with IMSRA rainfall estimates (IMR) is extracted for 2010 JJAS.

For the comparative assessments, study uses three rainfall products: two derived from satellites, i.e., IMR and TRMM 3B42 and the third high-resolution IMD-gridded data used for validation. Rain rates are derived from 3-hourly accumulated rainfall estimates from Kalpana-1 IMR. 3-hourly observations from these two satellites are studied and propagation of rain-band is analyzed. Spatial distribution of rainfall is studied in order to compare the spatial and areal coverage of rain-bearing band during August 4–5, 2010. Quantitative and qualitative assessments are made between two satellites observations to find out which one captures rainfall better. Using the observation, spatial correlations are evaluated and level of significance of the correlation is mapped to locate whether the two satellites are in good agreements with probability value of ≤ 0.05 at 5% significance level.

Spatial pattern of rainfall and its variability provides crucial information about the contribution of meteorological and topographical factors. As the weather often fluctuates over the different sub-regions of the WH, it is necessary to evaluate the degree of change in rainfall estimations between two satellites. The degree of correlation between two satellites suggests similarities, i.e., how closely they estimate rainfall intensity. Regional patterns of 3-hourly rainfall from two platform are studied by means of lag-zero cross-correlation. The output of this technique is better over areas with similarities than that by original rainfall. This process reflects incidence of rainfall relevant with spatial dependencies.

Mean and standard deviation of rainfall estimates from all three products for JJAS2010 and seasonal contribution in terms of percentage of total rainfall capture are evaluated to compare relative performances.

For orographic relationship with satellite rainfall estimates, SRTM DEM ~90 m is used. As satellite data are available at 0.25 spatial resolution, elevation pixels are re-sampled to $0.25^\circ \times 0.25^\circ$ using nearest neighbor approach. Both linear and nonlinear trends are fitted with 90% confidence level to understand which fit better over the WH. The study uses Pearson correlation coefficient, root mean square error (RMSE) to evaluate degree of association in rainfall estimates from two datasets during cloudburst. Correlation coefficient by Pearson's method evaluates the degree of linear association between the two datasets but did not consider the magnitude of errors (Ebert et al. 2007). RMSE factor indicates the magnitude of the errors in estimation.

3 Results and discussion

Kalpana-1-based rainfall estimate (IMR) is used for monitoring the rainfall during cloudburst August 3–5, 2010, over Jammu and Kashmir. Figure 2a–f shows the propagation of rain-band as estimated from Kalpana-1 IMR during 3–5 Aug cloudburst when heavy precipitation occurred over Leh, Jammu and Kashmir. Rainfall features over Leh and adjacent regions associated with the convective activity are clearly shown. Figure 2g–l shows the corresponding satellite IRBT. Spatial pattern of rainfall depicts that the zone of heavy rainfall area is associated with lower IRBT which is quite expected as colder cloud tops (CT) are mostly related to higher rainfall amount for convective clouds (Liu 2003). Lower temperature in IRBT is a signature of higher CT with greater thickness leading to larger probability of rain (Punay and Perez 2014). Variation of rainfall with IRBT is shown in Fig. 3a. It is observed that when Kalpana-1 IMR rainfall estimates is about 25 mm during August 4, 2010, at 20 GMT, there is a significant drop in IRBT of about 195 K. Figure 3b shows changes in rain-rate over the study region with IRBT. It is clear from the analysis that rainfall process initiates at IRBT <255 K. The rain-rate vs. IRBT curve shows nonlinearity.

3.1 Qualitative and quantitative analysis

For the assessment of Kalpana-1 IMSRA, study uses TRMM 3B42 algorithm estimates and high-resolution gridded rainfall dataset from IMD, where all three rainfall products are at 0.25° spatial resolution.

Spatial signature of rainfall estimates between IMR, Fig. 4, and TRMM 3B42, Fig. 5, is analyzed first. Two rain-bands coming from opposite directions (one from southeast another from northwest) are observed on August 4, 2010, at 21 GMT which merged over Leh and adjacent region during August 5, 2010, at 00 GMT. Then event moved further northward and at 00 GMT and 03 GMT on August 5, 2010, and rainfall estimates from Kalpana-1 IMR are 1.65 mm/h and 0.45 mm/h, respectively, and from TRMM 3B42 estimates 3.5 mm/h and 0.96 mm/h, respectively. During 03–12 GMT very light rain of about 2 mm/h is observed. After 12 GMT two rain-bands further intensified over sub-region of Leh during 15 GMT and merged over Leh at 18 GMT leading to heavy rainfall and quantitative analysis shows 4.85 mm/h and 10.2 mm/h rainfall estimates from Kalpana-1 IMR and TRMM 3B42, respectively. It is further intensified during 18–21 GMT over Leh. After 21 GMT rain-bearing cloud moved toward western part of the Jammu and Kashmir. Figure 6a

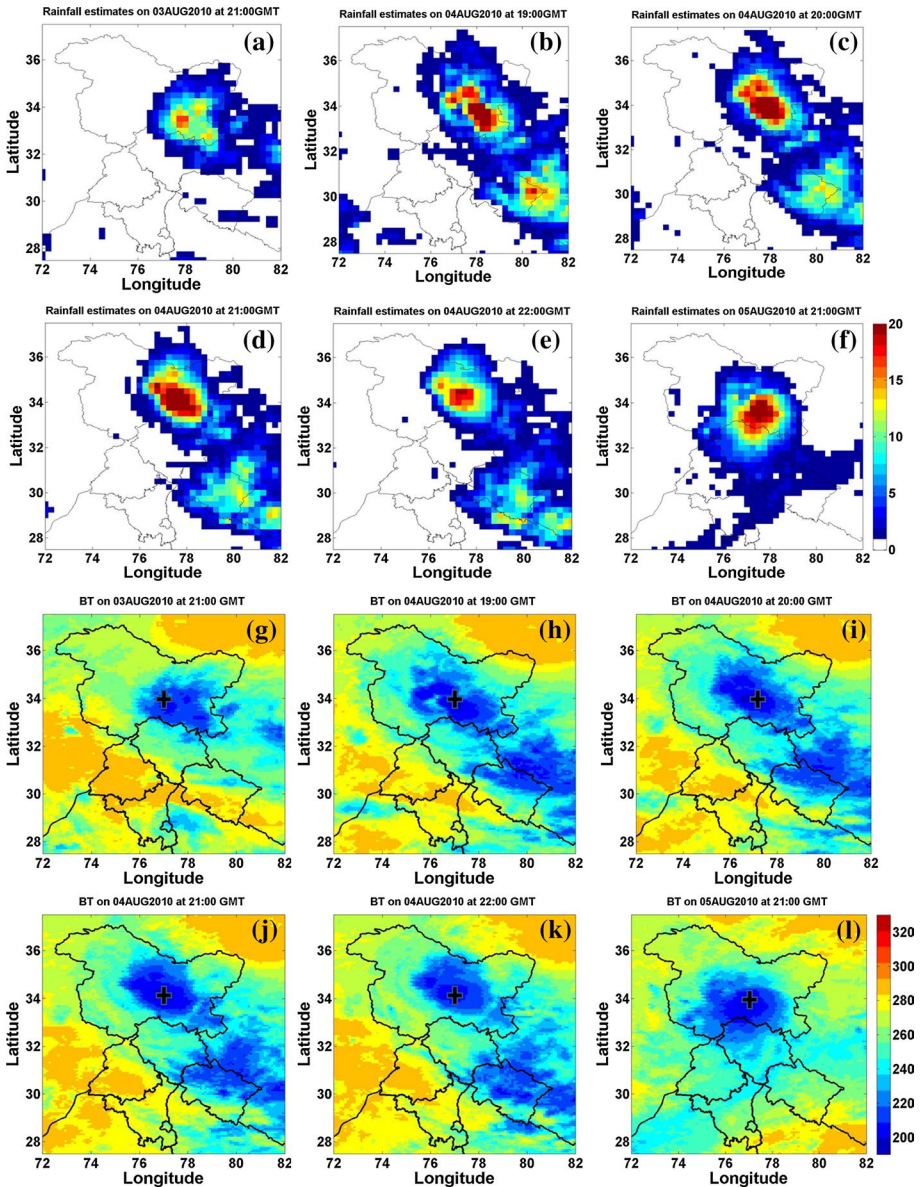


Fig. 2 a–f Rainfall estimates from Kalpana-1 and corresponding satellite estimates of brightness temperature. g–i Color bar represents rainfall in mm and brightness temperature in Kelvin

depicts quantitative rainfall assessment over Leh during the event using these two algorithms. It is observed that in terms of rainfall intensity TRMM 3B42 captured more rainfall than Kalpana-1 IMR over this region. Figure 6b represents the strength of the two algorithms during the Leh cloudburst, where it depicts that rainfall estimates by TRMM 3B42 underestimates Kalpana-1 IMSRA rainfall estimates. Though, correlation and RMSE factors are 0.91 and 0.93, respectively, between two rainfall estimate algorithms, see Table 2.

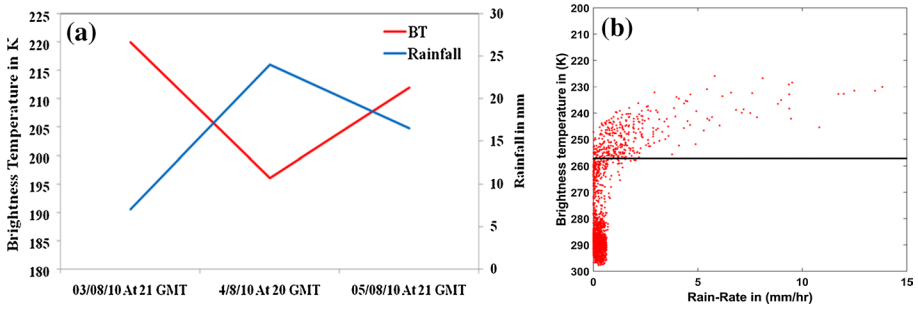


Fig. 3 a Variation of rainfall with satellite infrared brightness temperature (IRBT) during cloudburst over Leh. b Rain-rate versus IRBT estimates over the WH during June–September 2010

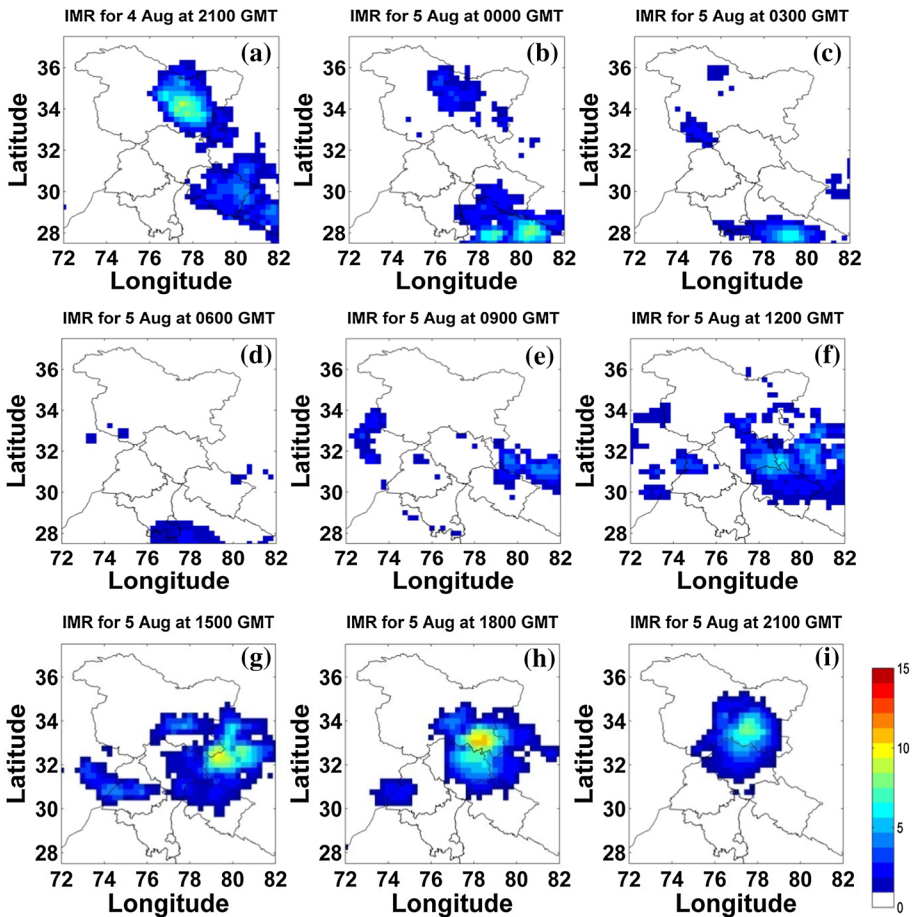


Fig. 4 The rainfall estimates from Kalpana-1 IMR for August 4–5, 2010, and color bar indicates rainfall in mm/h. Over Jammu and Kashmir maximum of 11 mm/h rainfall is observed on August 5, 2010, at 1800 GMT (h)

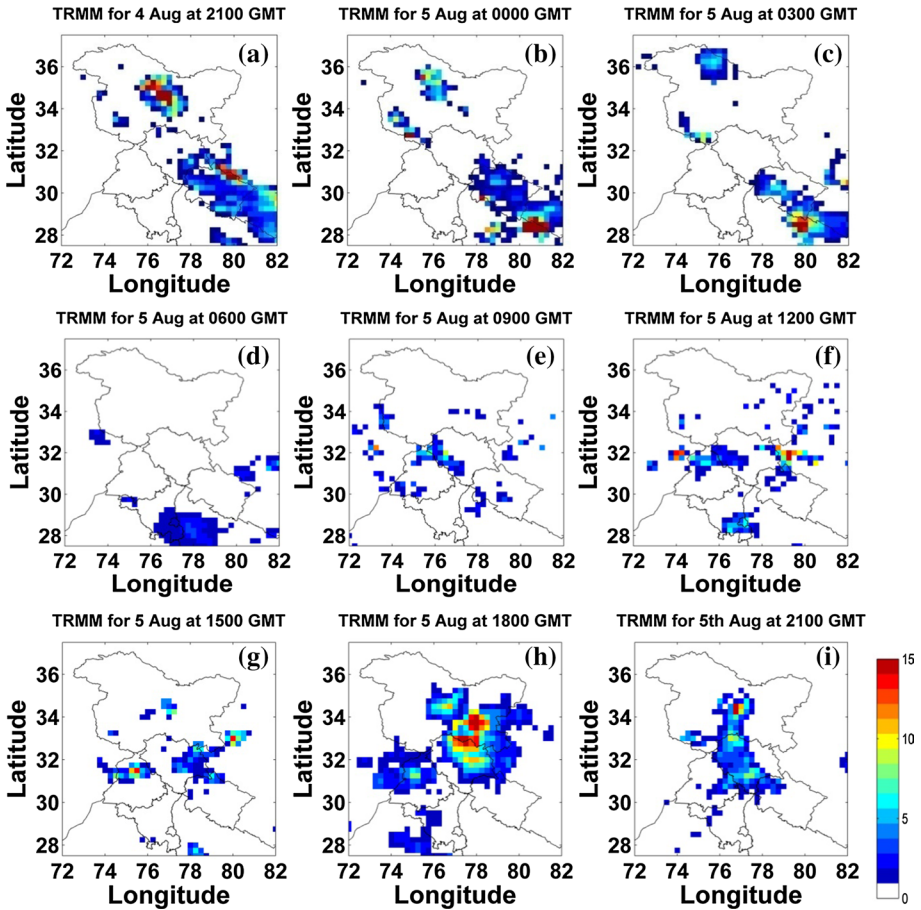


Fig. 5 The rainfall estimates from TRMM 3B42 for August 4–5, 2010, and color bar indicates rainfall in mm/h. Maximum of about 17 mm/h rainfall is observed over the Jammu and Kashmir at 1800 GMT (h)

Spatial correlation between two satellite rainfall estimates is shown in Fig. 6c, which shows positive correlations over central and southern part of Jammu and Kashmir. Negative correlation is observed in eastern part of Leh. Over some parts of central and west central part of the Northwest India both the data sets are in good agreement with each other. The zone where agreement from two independent platforms is more correlated with significant $p < 0.05$ is shown in Fig. 6d. Over Leh, it shows good agreement as per the observations.

Mean rainfall intensities during the cloudburst event are estimated from both the platform and are shown in Fig. 7a. Pixel-to-pixel correlated part of rainfall intensity is filtered out, which is shown in Fig. 7b. Correlated rainfall intensity between TRMM 3B42 and IMSRA estimates during the cloudburst is shown in Fig. 7(c), which is a good measure of degree of similarity in rainfall intensity estimates between IMSRA and TRMM 3B42.

For the validation point of view study used high-resolution IMD-gridded data as there is no meteorological stations available during that period which can provide the in situ measurements during the episodes. But it is clear from Fig. 8 that during the event it underestimates rainfall signature over Leh region. Daily observation from August 3 to 5,

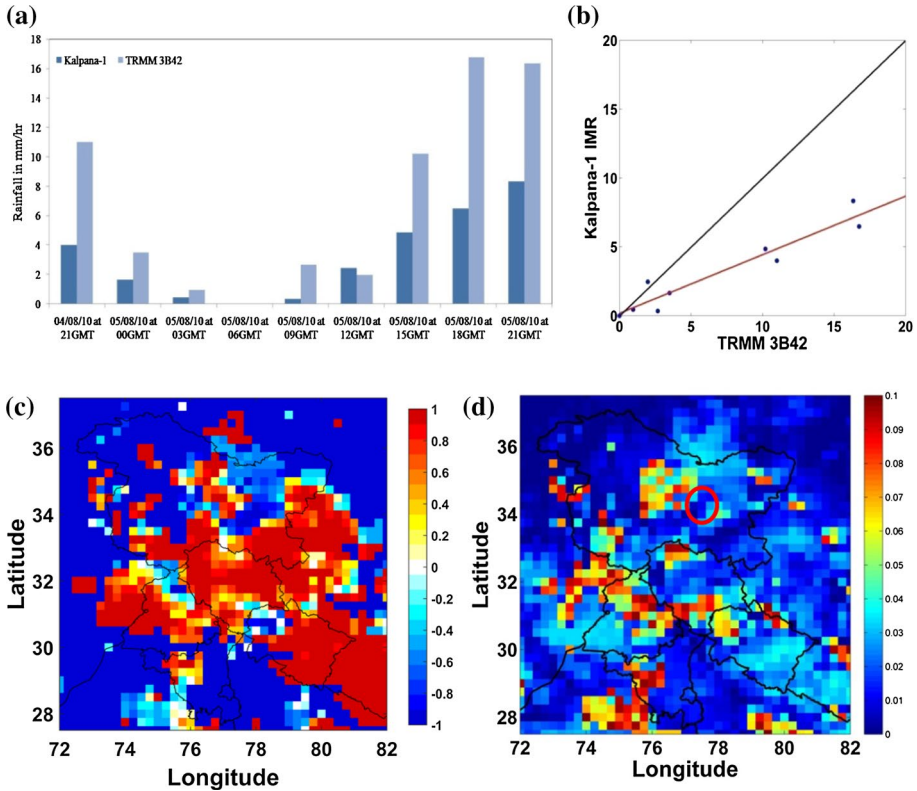


Fig. 6 **a** Rainfall estimates from Kalpana-1 IMR and TRMM 3B42 product during August 4–5, 2010, over Leh **b** shows 3B42 versus IMR rainfall estimates for the same. Black line represents diagonal and red line is the trend. Rainfall estimates in mm/h **c** shows spatial correlation between TRMM 3B42 and Kalpana-1 IMSRA **d** shows significant level of spatial correlation with 5% significances

Table 2 TRMM 3B42 versus IMSRA algorithm estimates

Slope	Intercept	Correlation	RMSE	Observations
0.43	0.18	0.91	0.93	9

2010, indicates rainfall below 5 mm/day. Overall seasonal rainfall pattern for 2010 summer monsoon months is shown in Fig. 9. Figure 9a–c shows mean rainfall estimates from Kalpana-1 IMR, TRMM 3B42 and IMD, respectively, where Fig. 9d–f represents the corresponding standard deviation from the mean rainfall estimates. Over the WH (Jammu and Kashmir, Himachal Pradesh and Uttarakhand) mean JJAS rainfall estimated from IMR is less than 10 mm/day and standard deviation ranges from about 1–5 mm/day from mean rainfall capture. Mean JJAS rainfall estimates from TRMM 3B42 is 5–15 mm/day over the region and standard deviation ranges from about 6–25 mm/day from mean rainfall estimates, whereas IMD shows 5–20 mm/day mean rainfall estimates with standard deviation of about 5–30 mm/day encompassing WH.

Seasonal contribution of rainfall estimates from all three platforms is shown in Table 3. It has been observed that rainfall estimates from IMSRA and IMD shows much closer

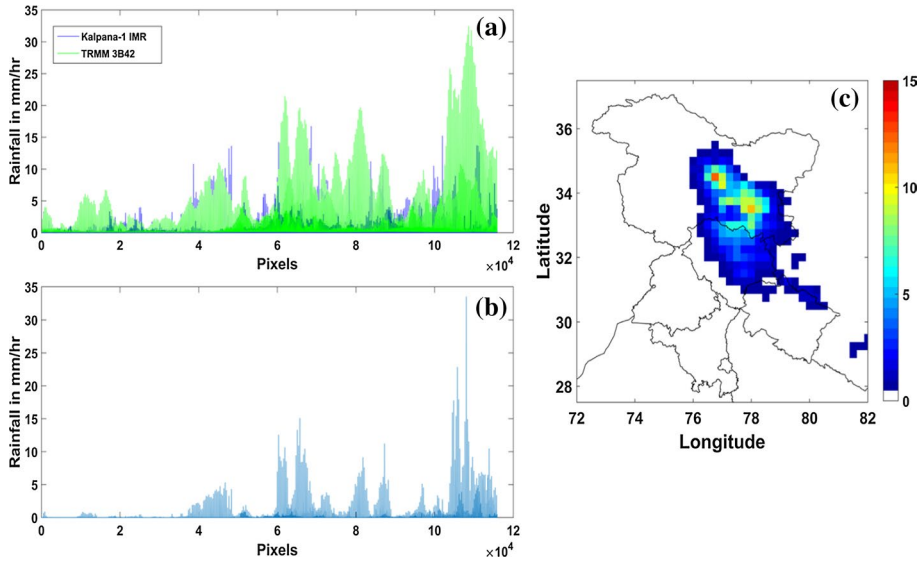


Fig. 7 **a** represents the mean rainfall intensity from two independent platform during August 4–5, 2010. Blue line represents rainfall intensity from Kalpana-1 IMSRA estimates and green line for TRMM 3B42 from each pixels **b** shows correlated rainfall intensity between TRMM 3B42 and Kalpana-1 IMR estimates and **c** shows the spatial distribution of correlated rainfall intensity between two platforms in mm/h

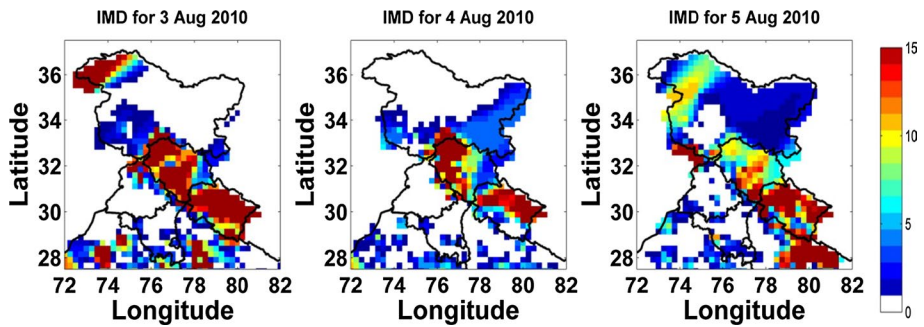


Fig. 8 IMD rainfall estimates for August 3–5, 2010. The color bar indicates rainfall in mm/day

estimation in terms of percentage of total rainfall capture for June, where there is overestimation from TRMM 3B42 estimates. Percentage of rainfall estimates from IMSRA and TRMM 3B42 shows much closer result with respect to IMD for July. Rainfall estimates from IMSRA shows maximum of 36% total rainfall for August where, TRMM 3B42 and IMD contributed 26% and 44%, respectively. For September, TRMM 3B42 and IMSRA show closer estimates, whereas IMD depicts 16% of total rainfall estimates.

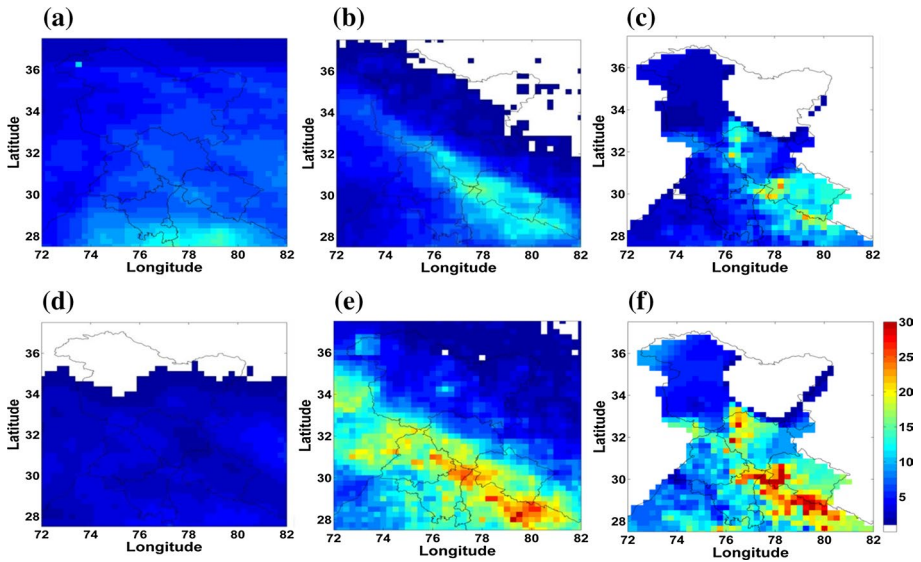


Fig. 9 Mean and standard deviation of JJAS rainfall for year 2010. **a–c** represent estimation of mean rainfall from Kalpana-1 IMR, TRMM 3B42 and IMD, respectively, where **d–f** represents standard deviation of rainfall for the same. The color bar indicates rainfall in mm/day

Table 3 Seasonal contribution of rainfall estimates for 2010 summer monsoon months (JJAS)

Observation	June (%)	July (%)	August (%)	September (%)
IMSRA	15	25	36	24
TRMM 3B42	24	28	26	22
IMD	11	29	44	16

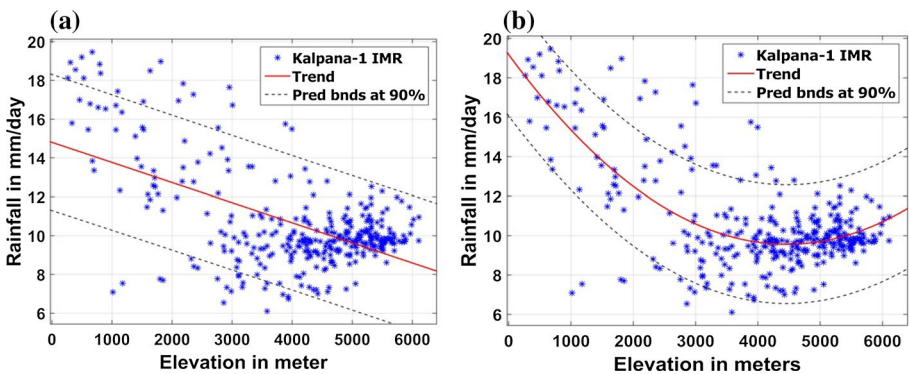


Fig. 10 Elevation versus rainfall for Jammu and Kashmir. **a** and **b** shows linear and nonlinear trend of rainfall with elevation, respectively, at 90% confidence level. Red line indicates the trend

Table 4 Orographic relationship with satellite rainfall estimates over Jammu and Kashmir

Fitting	Slope	Intercepts	Correlations	RMSE	Sample size
Linear	-0.001035	14.8	0.32	2.098	346
Nonlinear	4.827×10^{-7} -0.004309	19.18	0.49	1.821	346

3.2 Orographic relationship with rainfall

In addition, study also investigates orographic relationship with satellite rainfall estimates over Jammu and Kashmir by using the rainy conditions over the study region during JJAS 2010. Figure 10 shows the orographic relationship with rainfall for Jammu and Kashmir. Both linear and nonlinear trend of rainfall with elevation are shown in Fig. 10a and b, respectively. Table 4 indicates our observation based on orographic rainfall analysis. Correlation factor increases from 0.32 to 0.49 when we select mode of operation from linear to nonlinear. As compared to linear mode, RMSE factor also improved in nonlinear relationship but in both the cases there are heavy rainfall bias associated with elevation pixels. Present study attempts to investigate how rainfall pattern changes over the region with elevation and what could be the best possible fit. But we observed that there is heavy rainfall bias in Kalpana-1 IMR. Thus, we limited our study up to this level only.

4 Conclusions

Drop in IRBT and its spatial distribution shows a good signature of rainfall area, but it could be more accurate if satellite microwave brightness temperature is introduced. Study suggests that region-specific microwave-based algorithm could perform better than IR-based techniques in rainfall estimation as scattering method is implemented there. Our study shows TRMM 3B42 rainfall estimates underestimate Kalpana-1 IMR rainfall estimates over the region and IMD rainfall is also unable to capture the rainfall signature over the location during the events which is regarded as a benchmark data in validation of rainfall estimates for India. Mean and standard deviation of rainfall distribution depicts that IMSRA performs poor with respect to IMD while TRMM 3B42 is much closer though it has rainfall bias over the Himalayan foothill region. Spatial correlation between IMSRA and TRMM 3B42 rainfall estimates shows good agreement of rainfall estimation over some parts of WH but high p -values ($p > 0.05$) are also present over some regions where no agreement is possible. Correlated rainfall intensity represents overall similarity between two rainfall retrieval algorithm during the cloudburst over Leh. Along with Dimri et al. (2017) present study also proposed to revised and reassessed the definition of cloudburst based on the rainfall threshold according to regional differentiation. Seasonal contribution of rainfall estimates shows that in July and September TRMM 3B42 and Kalpana-1 IMR rainfall estimates are much closer in terms of percentage of total rainfall captured. Further refinements of the Kalpana-1 algorithm could better estimate the rainfall over such complex terrain. Study also suggests that inclusion of orographic factors in the rainfall retrieval algorithm may provide better result. Improvement of algorithm is necessary for future prospective as the same algorithm is used in INSAT-3D, which is now operational by ISRO.

Acknowledgements The present work is a part of NMHS Project and authors thankfully acknowledge the support and encouragement provided by MOEF&CC. We convey thanks to the MOSDAC data portal for providing the Indian Meteorological Satellite Data, NASA for the TRMM3B42 data and Indian Meteorological Department for providing high-resolution gridded rainfall data for research purpose.

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