

Assessment of Kalpana-1 Rainfall Product over Indian Meteorological Sub-Divisions During the Summer Monsoon Season

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Abstract In this paper, Kalpana-1 derived INSAT Multispectral Rainfall Algorithm (IMSRA) rainfall estimates are compared with two multisatellite rainfall products namely, TRMM Multisatellite Precipitation Analysis (TMPA)-3B42 and Global Satellite Mapping of Precipitation (GSMaP), and India Meteorological Department (IMD) surface rain gauge (SRG)-based rainfall at meteorological sub-divisional scale over India. The performance of the summer monsoon rainfall of 2013 over Indian meteorological sub-divisions is assessed at different temporal scales. Comparison of daily accumulated rainfall over India from IMSRA shows a linear correlation of 0.72 with TMPA-3B42 and 0.70 with GSMaP estimates. IMSRA is capable to pick up daily rainfall variability over the monsoon trough region as compared to TMPA-3B42 and GSMaP products, but underestimates moderate to heavy rainfall events. Satellite-derived rainfall maps at meteorological sub-divisional scales are in reasonably good agreement with IMD-SRG based rainfall maps with some exceptions. However, IMSRA performs better than GSMaP product at meteorological sub-divisional scale and comparable with TMPA data. All the satellite-derived rainfall products underestimate

orographic rainfall along the west coast, the Himalayan foothills and over the northeast India and overestimate rainfall over the southeast peninsular India. Overall results suggest that IMSRA estimates have potential for monsoon rainfall monitoring over the Indian meteorological sub-divisions and can be used for various hydro-meteorological applications.

Keywords Indian summer monsoon rainfall · Satellite-derived rainfall products · Meteorological sub-divisions · Surface rain gauges

Introduction

India receives about 80 % of its annual rainfall from the southwest or summer monsoon spanning from June to September which has paramount socio-economic impacts (Gadgil 2003; Gadgil and Srinivasan 2010; Revadekar and Preethi 2010; Prakash et al. 2014). The Indian summer monsoon rainfall (ISMR) exhibits a regionally heterogeneous variability at different time scales such as interannual, seasonal, intraseasonal, etc. (Goswami and Ajayamohan 2001; Gadgil 2003; Krishnamurthy and Shukla 2007). The spatial and temporal variability of ISMR highly influences the agricultural production of India which is supposed to be backbone of the Indian economy. Recently, Revadekar and Preethi (2010) showed the significant impact of extreme monsoon rainfall on food grain yield over India through statistical analysis. Hence, reliable information of ISMR and its variability is crucial for a wide range of applications including agricultural, water resources and hydrological applications. Meteorological satellites provide comprehensive global maps of retrieved rainfall at homogeneous spatial and temporal resolutions which is used for various hydro-meteorological and climatological applications (Tapiador et al. 2012; Kucera et al. 2013).

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The rainfall estimation techniques from the host of meteorological satellites have advanced quite rapidly in the recent decade. With the advent of meteorological satellites, our perceptions about the physics of the Indian monsoon and mechanisms leading to its variability at different time scales have changed dramatically and hence prediction skill of the monsoon is also improved substantially (Srinivasan and Joshi 2007; Gadgil and Srinivasan 2010).

As the geostationary satellites provide frequent updates of the weather systems at high spatial resolution, it is supposed to be viable source of information for the monsoon monitoring. Following the launch of the first Indian dedicated meteorological satellite Kalpana-1 in late 2002 by the Indian Space Research Organisation (ISRO), it is now possible to monitor the onset, progress and performance of ISMR consistently for various applications (Kaila et al. 2002). The recently developed Indian National Satellite System (INSAT) Multispectral Rainfall Algorithm (IMSRA) uses Kalpana-1 satellite data for rainfall estimation at 0.25° latitude \times 0.25° longitude resolution and 3-hourly time interval. This rainfall product takes advantages of high spatial and temporal coverage of Kalpana-1 satellite and accurate rainfall measurements from the first active microwave precipitation radar (PR) onboard the Tropical Rainfall Measuring Mission (TRMM) satellite (Prakash et al. 2009; Gairola et al. 2010a, b). This rainfall product is validated with other standard multisatellite rainfall datasets and in situ observations over the Indian land and oceanic regions and used for various hydro-meteorological applications (Prakash et al. 2010, 2012; Roy et al. 2012; Das et al. 2013; Mahesh et al. 2014; Gairola et al. 2014). Prakash et al. (2010) validated this rainfall product at daily and monthly scales from rain gauges and buoys data over the Indian monsoon region for 2008 and 2009 and reported reasonable agreement of this satellite-based rainfall product with in situ observations, although IMSRA underestimates orographic rainfall along the west coast of India and foothills of the Himalayas. More recently, Roy et al. (2012) independently evaluated this rainfall product with standard multisatellite rainfall estimates for the southwest monsoon season of 2010 and depicted that IMSRA performs reasonably well for short-term rainfall estimation. This rainfall product is operational at the India Meteorological Department (IMD) and Meteorological & Oceanographic Satellite Data Archival Centre (MOSDAC), ISRO for user community.

Moreover, the multisatellite rainfall products take the relative advantages of a rich constellation of precipitation related sensors (both infrared and microwave) aboard the meteorological satellites. TMPA estimates available at 0.25° latitude/longitude (Huffman et al. 2007) and Global Satellite Mapping of Precipitation (GSMaP) available at 0.10° latitude/longitude (Ushio et al. 2009) are among them. TMPA research monitoring product uses additional rain gauge observations over land along with multisatellite rainfall estimates and performs better

than other contemporary multisatellite rainfall products over the Indian monsoon region (Prakash et al. 2014). The retrospective processed version 7 of TMPA performs better than its predecessor and used for various hydrological applications across the globe (Huffman and Bolvin 2013; Tobin and Bennett 2014; Yong et al. 2014; Zulkafli et al. 2014). GSMaP integrates passive microwave radiometer data with infrared measurements based on a Kalman filter model at rather higher spatial and temporal resolutions and is comparable to the other multisatellite products (Ushio et al. 2009).

In this paper, the performance of ISMR is assessed at meteorological sub-divisional scale for the summer monsoon of 2013 using three satellite-derived products namely, IMSRA, TMPA and GSMaP. Rainfall at meteorological sub-divisions from satellite-derived products is computed using the Geographic Information System (GIS) tools. Recently, Mahesh et al. (2014) generated rainfall maps for 2009 at different meteorological sub-divisions using Kalpana-1 IMSRA data and suggested that IMSRA technique can act as a complementary tool for the monsoon monitoring. Since IMSRA is developed for Indian monsoon region and uses Kalpana-1 measurements, rainfall estimates from this algorithm is compared with independent multisatellite rainfall products at meteorological sub-divisional scale. The satellite-derived rainfall is also compared with gauge-based rainfall maps produced by the IMD to assess the capability of each rainfall estimate. The southwest monsoon 2013 was unique in many ways. The onset over the Kerala state took place at its normal date of 1st June, but the advance of monsoon was very fast and it covered the entire country by 16th June which was about a month earlier than its normal date of 15th July (IMD 2013; Srivastava et al. 2014). During this season, 2 depressions and 16 low pressure areas formed and no typical break condition developed. Even if the seasonal rainfall for the country as a whole was normal, it showed a large spatial and temporal variability. The east and northeast India received below normal rainfall and three out of the four geographical regions (central India, northwest India and south peninsula) received above normal rainfall (IMD 2013).

Data and Methods

Kalpana-1 Data

The very high resolution radiometer (VHRR) onboard the Kalpana-1 satellite operates in three wavelength bands namely visible (VIS; $0.55\text{--}0.75\ \mu\text{m}$), water vapour (WV; $5.70\text{--}7.10\ \mu\text{m}$) and thermal infrared (TIR; $10.50\text{--}12.50\ \mu\text{m}$). In WV and TIR bands, the spatial resolution is 8 km where as in VIS band spatial resolution is 2 km. More specifics of the Kalpana-1 satellite are given by Kaila et al. (2002). For rainfall estimation from IMSRA, TIR channel data of Kalpana-1 are

used. IMSRA is developed after a proper cloud classification using TIR and WV channels data and calibration with near-simultaneous TRMM-PR data, similar to Mishra et al. (2010) used for rainfall estimation from Meteosat measurements over the Indian region (Prakash et al. 2009; Gairola et al. 2010a, b). The detailed description of this algorithm and its validation is outline by Gairola et al. (2014). Daily IMSRA product for the entire monsoon period of 2013 is obtained from the website at <http://www.mosdac.gov.in/>.

GSMaP Data

The GSMaP project was established by the Japan Science and Technology Agency (JST) in 2002 to produce global precipitation products with high resolution and precision from multisatellite measurements. The GSMaP_MVK estimates are developed by integrating the data from microwave radiometers and infrared radiometers. It uses a Kalman filter to update the rainfall rate after propagating the rain pixels along the atmospheric motion vector derived from the successive infrared images (Ushio et al. 2009). This rainfall product is properly validated with independent in situ observations and found to be comparable with other contemporary multisatellite products. The near-real time (NRT) daily rain rate product is used for the southwest monsoon season of 2013.

TMPA-3B42 Data

Another satellite-derived rainfall product used in the study is the TMPA-3B42 which is a standard merged infrared and microwave rainfall product developed to take the advantage of rich constellation of satellite-borne precipitation sensors. In this algorithm, the available passive microwave and infrared estimates are combined by calibrating the infrared measurements, however the microwave estimates are taken as preferentially and remaining empty grids are filled with infrared estimates (Huffman et al. 2007, 2010). TMPA is available in both near-real-time and delayed-time modes, based on calibration by the TRMM Microwave Imager precipitation and TRMM combined instrument products, respectively. The research monitoring TMPA-3B42 version 7 daily rainfall data for the summer monsoon period of 2013 is obtained from the website at <http://disc2.nascom.nasa.gov/tovas>. Detailed description of this rainfall product can be found in Huffman and Bolvin (2013).

Gauge-Based Rainfall Maps

For the validation of the satellite-derived rainfall products over the Indian meteorological sub-divisions, gauge-based rainfall maps developed by IMD are used. IMD uses a large network of surface rain gauge (SRG) stations across

the country to calculate all-India rainfall at different spatiotemporal scales and also generates meteorological sub-divisions wise rainfall maps for the assessment of progress and performance of monsoon over India. IMD has categorized the Indian sub-continent into 36 different meteorological sub-divisions based on their climatic and geographic features (Parthasarathy et al. 1987). The SRG-based near real-time weekly, monthly and seasonal rainfall maps (Srivastava et al. 2014) are obtained from the IMD website at <http://www.imd.gov.in>.

Methodology

IMSRA and TMPA daily rainfall products are available at 0.25° latitude/longitude resolution whereas GSMaP rainfall is available at 0.10° latitude/longitude. For the comparison of IMSRA with TMPA and GSMaP products at daily scale, GSMaP daily rainfall data set is re-sampled in 0.25° latitude/longitude grids using linear averaging method. Since satellite-derived rainfall products are available over land as well as oceanic regions and IMD SRG-based rainfall maps are available only over the mainland of India, rainfall over Indian land is extracted from the satellite products through overlay analysis in the GIS. Political boundary of India and meteorological sub-divisions has been spatially digitized with reference to IMD maps. Daily rainfall estimates are accumulated for a given week, month or season to find the weekly, monthly or seasonal rainfall, respectively. Finally, the meteorological sub-division wise rainfall is computed by area-weighted average using GIS tool for the comparison with gauge-derived rainfall maps. The procedure for the computation of meteorological scale rainfall using satellite-based data sets is similar to the method used by IMD using SRG observations (Parthasarathy et al. 1987). The normal rainfall given by IMD is used as reference for satellite-based rainfall data to compute departure due to non-availability of long-term data from these products. The IMD criteria are adopted for the classifications of excess (20 % or more), normal (−19 to 19 %), deficient (−20 to −59 %) and scanty (−60 to −99 %) rainfall from the satellite-based rainfall products over the meteorological sub-divisions.

Results and Discussions

As IMSRA is based on region-specific algorithm and uses infrared only measurements for rainfall estimation, this rainfall estimate is compared with multisatellite GSMaP and TMPA rainfall products at meteorological sub-divisional scale over India. The comparison is done at different temporal scales for the entire monsoon season of 2013.

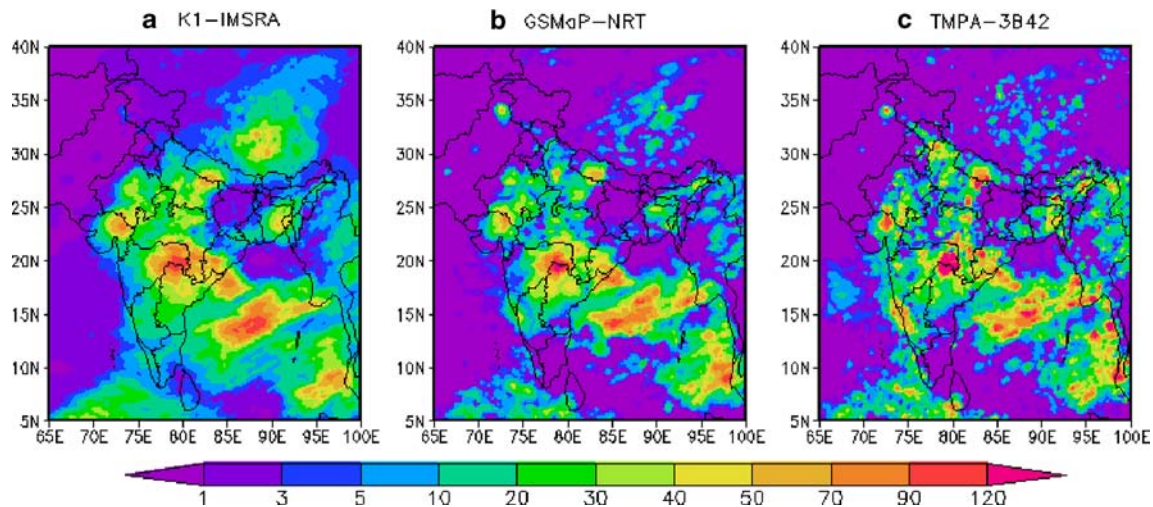


Fig. 1 Spatial distributions of daily accumulated rainfall (mm) from **a** Kalpana-1 IMSRA, **b** GSMaP-NRT and **c** TMPA-3B42 data sets for 22 July 2013

Assessment of ISMR at Daily Time Scale

In this section, Kalpana-1 derived IMSRA estimate is compared with GSMaP and TMPA rainfall products at daily scale. One example of daily accumulated rainfall over the Indian monsoon region for 22 July, 2013 is shown in Fig. 1. The monsoon was active over the entire country during this period. All the three rainfall products show similar rainfall features over the land and oceanic regions qualitatively. Widespread rainfall over the central India, western India and along the Himalayan foothills and over the Bay of Bengal is captured well by the satellite-derived rainfall products. However, there are some differences in magnitude between these rainfall products.

For the quantitative comparison, daily accumulated rainfall from 01 June to 30 September over the Indian monsoon region is used. Figure 2 shows the density scatter plots comparing IMSRA with GSMaP and TMPA estimates. The linear correlation of 0.70 and 0.72 are observed with GSMaP and TMPA estimates, respectively. The positive biases in IMSRA as compared to GSMaP and TMPA show that IMSRA overestimates ISMR. It is mainly due to overestimation of daily rainfall below 10 mm by IMSRA estimates. In general, IMSRA is comparable with both the global multisatellite rainfall products which are commensurable with the earlier studies. The daily rainfall from these satellite-based products is also compared over the monsoon trough region bounded by 20°N–25°N and 75°E–85°E. This region receives reasonably good amount of monsoon rainfall associated with the passage of

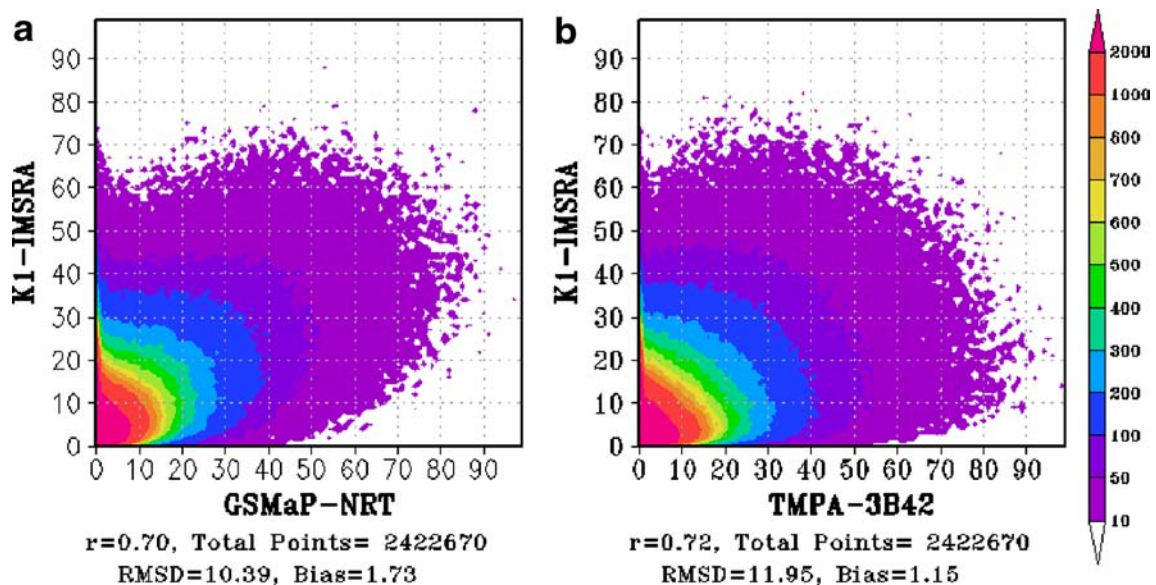


Fig. 2 Density scatter plots of daily accumulated rainfall (mm) over the Indian monsoon region from **a** IMSRA and GSMaP-NRT **b** IMSRA and TMPA-3B42 for 01 June to 30 September 2013. Correlation coefficient

(r), total number of matches, root-mean-square difference (RMSD) and bias are also given at the bottom of each plot

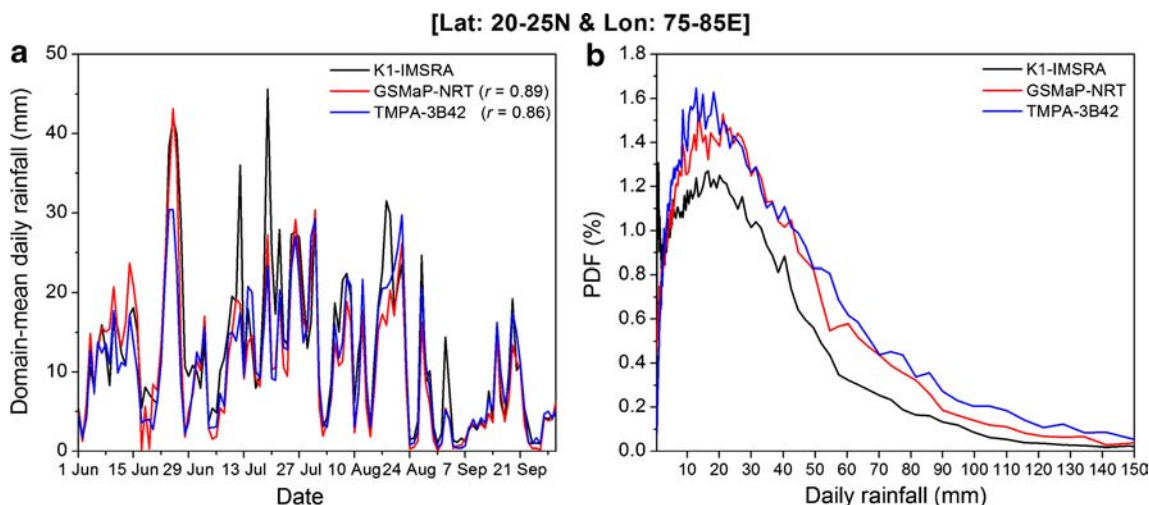


Fig. 3 **a** Time-series of domain-mean daily rainfall (mm) over the monsoon trough region from Kalpana-1 IMSRA, GSMaP-NRT and TMPA-3B42 data sets. Correlation coefficient (r) with respect to

IMSRA is also given. **b** Probability distribution function (%) of daily rainfall over the monsoon trough region from IMSRA, GSMaP-NRT, and TMPA-3B42 data sets for JJAS 2013

lows and depressions originated in the Bay of Bengal (Goswami and Ajayamohan 2001; Gadgil 2003). Figure 3(a) shows the time-series of daily domain-mean rainfall over the monsoon trough region from IMSRA, GSMaP and TMPA products, which shows that the daily rainfall variability over this region is comparable among these products. IMSRA shows a linear correlation of 0.89 and 0.86 with GSMaP and TMPA products, respectively. The probability distribution function of daily rainfall over this region is also examined from these three rainfall products which are shown in Fig. 3(b). It can be seen that even though IMSRA well

captures daily rainfall frequency qualitatively, it underestimates moderate to heavy rainfall (more than 10 mm day⁻¹) and overestimates light rainfall (less than 2 mm day⁻¹) as compared to GSMaP and TMPA products.

Assessment of ISMR at Weekly Time Scale

In this section, Kalpana-1 derived IMSRA rainfall is compared with GSMaP, TMPA and IMD SRG-based rainfall data at weekly scale over the meteorological sub-divisions. Figure 4(a) and (b) present the scatter plots of weekly

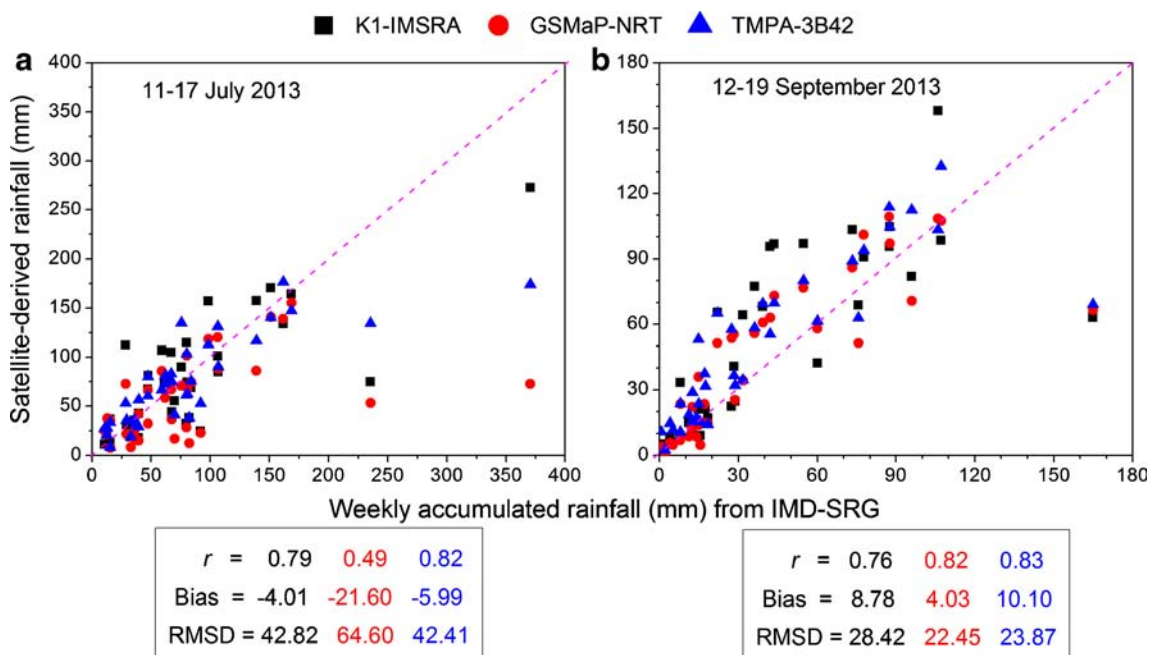


Fig. 4 Scatter plots of weekly accumulated rainfall (mm) from three satellite-derived rainfall products against IMD-SRG based rainfall data set at meteorological sub-divisional scale for (a) 11–17 July 2013, and (b)

12–19 September 2013. Correlation coefficient (r), bias and RMSD with respect to IMD-SRG based rainfall are also given at the bottom of each plot

accumulated rainfall averaged over each meteorological sub-division using IMSRA, GSMaP and TMPA with respect to IMD-SRG for 11–17 July 2013 and 12–19 September 2013, respectively. During 11–17 July, the monsoon was active over central and southern parts of India (IMD 2013). The IMD-SRG showed 13 meteorological sub-divisions received excess rain and 8 sub-divisions received normal rainfall. IMSRA, GSMaP and TMPA showed 14, 13 and 15 sub-divisions, respectively with excess rainfall and 6 sub-divisions with normal rainfall by each estimate. All the three satellite-based rainfall estimates substantially underestimate rainfall over Coastal Karnataka, and Konkan & Goa sub-divisions. GSMaP shows the least correlation of 0.49 and the greatest magnitude

of bias and root-mean-square difference (RMSD) as compared to IMD-SRG based estimates. IMSRA and TMPA show reasonably high correlation and lower bias as compared to IMD-SRG based estimates. During 12–19 September 2013, the monsoon was about to withdraw from India. Southern India received good amount of rainfall during this period (IMD 2013; Srivastava et al. 2014). IMD-SRG showed 11 sub-divisions received excess rainfall whereas 13 sub-divisions received scanty rainfall. IMSRA and GSMaP showed 15 and 12 sub-divisions, respectively with excess rainfall and 10 sub-divisions by both products with scanty rainfall. TMPA showed 12 sub-divisions with excess rainfall but only 6 sub-divisions with scanty rainfall. Similarly, TMPA showed 11

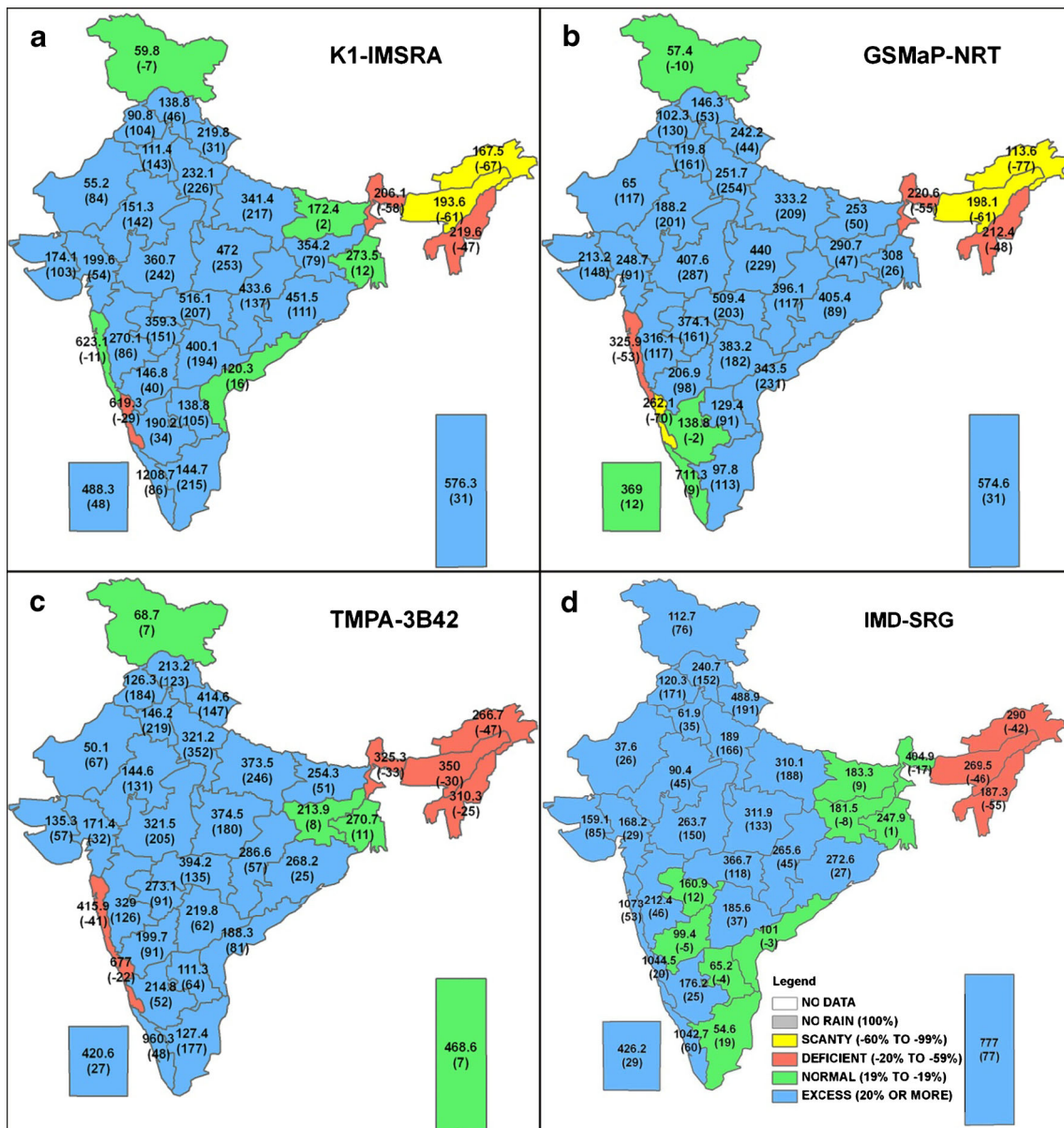


Fig. 5 Meteorological sub-divisional scale monthly accumulated rainfall (mm) and its departure from the normal (given in parentheses) using a Kalpana-1 IMSRA, b GSMaP-NRT, c TMPA-3B42 and d IMD-SRG data sets for June 2013

sub-divisions with normal rainfall whereas it was 6 in IMD-SRG. All the three satellite-based rainfall estimates notably underestimates rainfall over Kerala sub-division as compared to IMD-SRG based estimates. The complex orographic rainfall caused by ambient atmospheric conditions (Houze 2012) might be one of the possible reasons behind underestimation of rainfall from satellite-based estimates along west coast of India. IMSRA shows comparable error statistics with GSMaP and TMPA when evaluated against IMD-SRG based estimates at meteorological sub-divisional scale.

Assessment of ISMR at Monthly Time Scale

In this section, the three satellite-derived rainfall estimates are compared with IMD-SRG based rainfall maps at monthly scale over the meteorological sub-divisions. The monthly rainfall maps from the four rainfall products for the month of June are shown in Fig. 5. The country received about 34 % more than normal rainfall during this month as per IMD-SRG based estimates. The catastrophic heavy rainfall over Uttarakhand state during 16–18 June also occurred in this month (Mishra and Srinivasan 2013; Kotal et al. 2014). Only three sub-divisions of the northeast India received deficient rainfall. The three satellite-derived rainfall estimates shows reasonably good agreement over the central India, but shows an overestimation over the southeast India and underestimation over Jammu & Kashmir region, along the west coast of India. The uneven density of gauges over the northern hilly

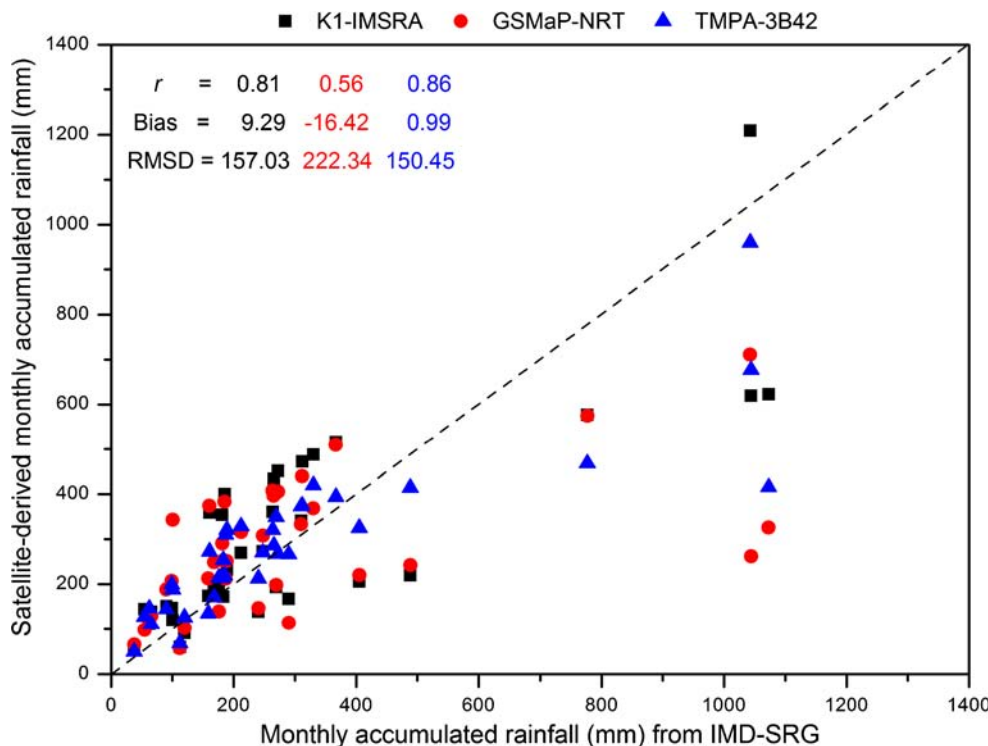
regions and mountainous west coast might also cause uncertainty in IMD-SRG based estimates.

Figure 6 presents the scatter plot of monthly accumulated rainfall for the month of June from three satellite-derived rainfall products against IMD-SRG based estimates. IMSRA and TMPA show higher correlation and smaller bias and RMSD than GSMaP estimates. GSMaP shows an underestimation of rainfall as compared to IMD-SRG based estimates. Better performance of TMPA data than GSMaP is possibly due to incorporation of rain gauge observations in TMPA research monitoring rainfall product (Prakash et al. 2014; Tobin and Bennett 2014; Yong et al. 2014; Zulkafli et al. 2014). The underestimation of orographic rainfall by the three satellite-based products over the meteorological sub-divisions situated along the west coast of India like Konkan & Goa, and Coastal Karnataka can also be seen. This analysis suggests that IMSRA performs reasonably well in the estimation of rainfall at meteorological sub-divisional scale except over the orographic regions.

Assessment of ISMR at Seasonal Time Scale

In this section, the three satellite-derived rainfall estimates are compared with IMD-SRG based rainfall estimates at seasonal scale over the Indian meteorological sub-divisions. Figure 7 illustrates the seasonal monsoon rainfall maps over the meteorological sub-division of India from IMSRA, GSMaP,

Fig. 6 Scatter plot of monthly accumulated rainfall (mm) from three satellite-derived rainfall products against IMD-SRG based rainfall data set at meteorological sub-divisional scale for June 2013. Correlation coefficient (*r*), bias and RMSD with respect to IMD-SRG based rainfall are also given



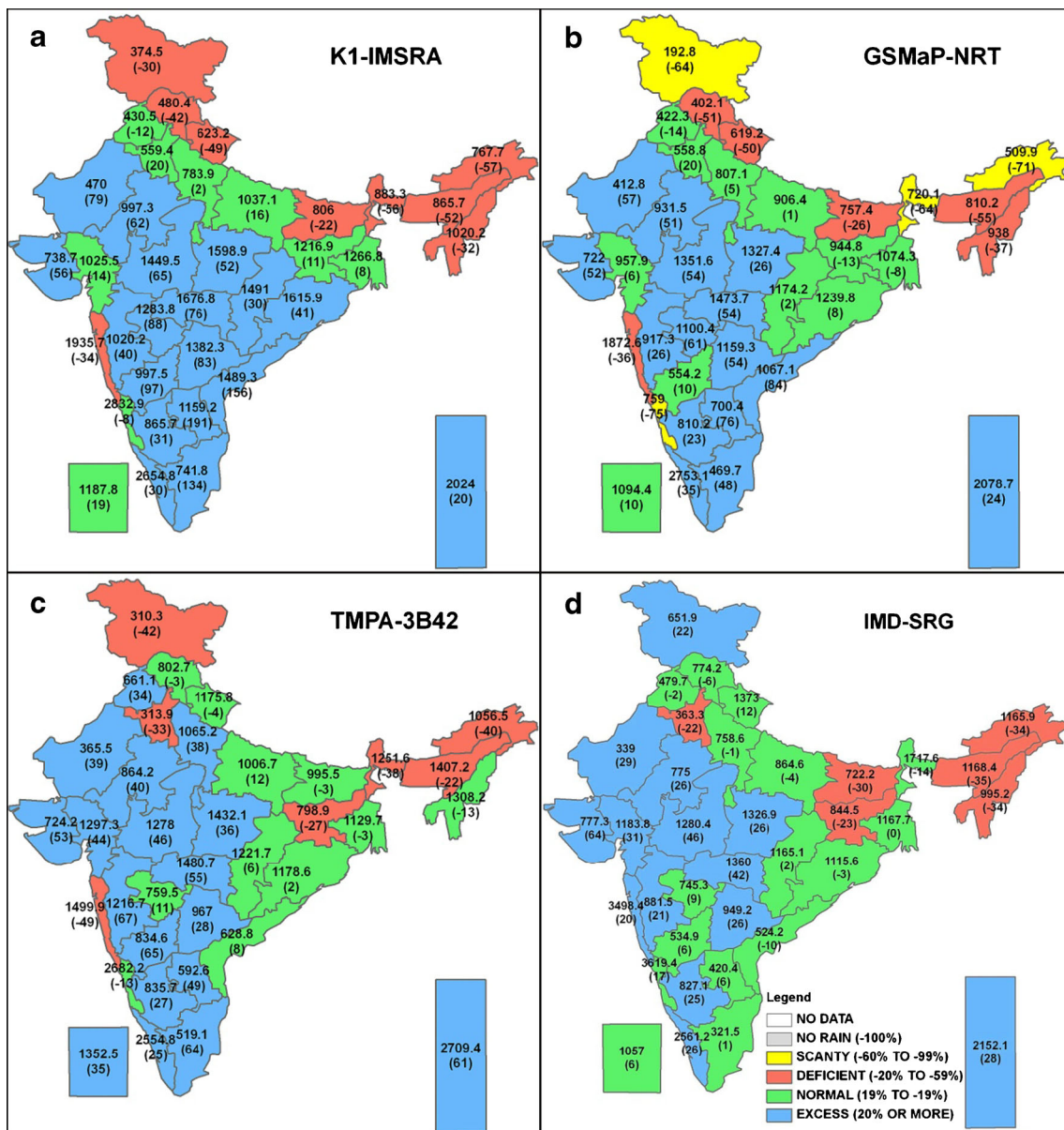


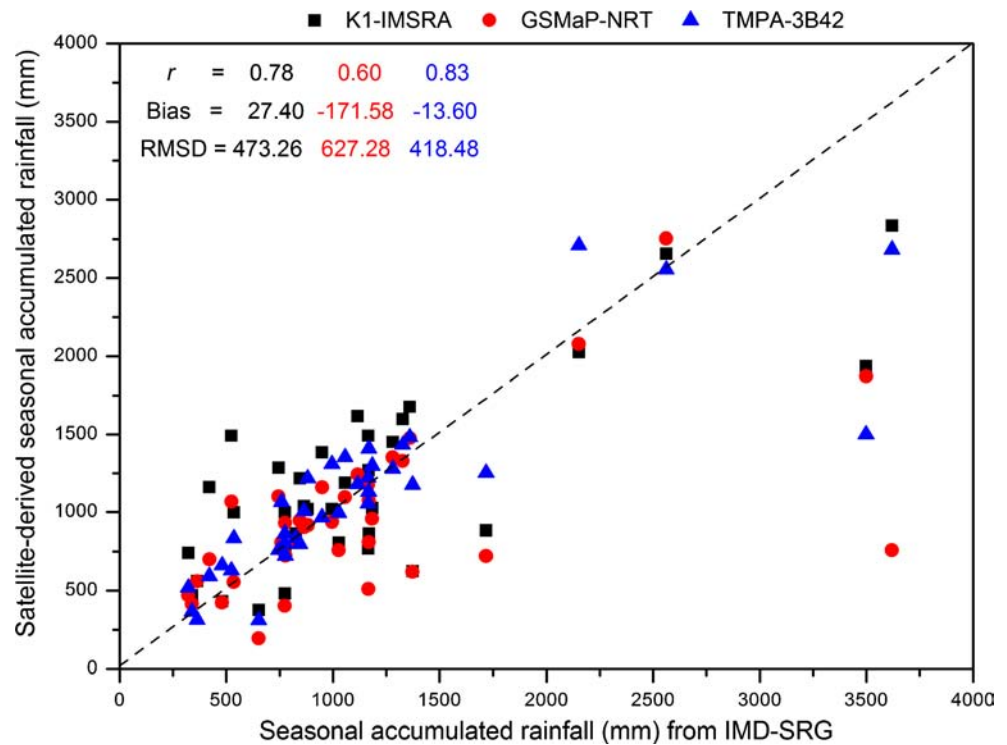
Fig. 7 Meteorological sub-divisional scale seasonal JJAS accumulated rainfall (mm) and its departure from the normal (given in parentheses) using a Kalpana-1 IMSRA, b GSMaP-NRT, c TMPA-3B42 and d IMD-SRG data sets for the southwest monsoon of 2013

TMPA and IMD-SRG products. The seasonal rainfall over India was recorded as 6 % more than normal using IMD-SRG based estimates. Most of the sub-divisions got normal or excess rainfall during this season. From IMD-SRG out of 36 sub-divisions, 15 sub-divisions received excess rainfall and 15 received normal rainfall whereas 6 sub-divisions received deficient rainfall. IMSRA indicates that 18 sub-divisions received excess rainfall, 9 sub-divisions received normal rainfall and other 9 sub-divisions as deficient. The Himalayan region and Western Ghats regions show dissimilarities from IMD-SRG due to underestimations of orographic rainfall, whereas the seasonal rainfall of northeast India from IMSRA matches well with IMD-SRG. TRMM-3B42 and GSMaP also shows

nearly same pattern over the country. IMD-SRG, IMSRA and TRMM-3B42 report no scanty regions during this season but GSMaP product shows four sub-divisions as scanty. The satellite-derived rainfall products show overestimation over the southeast peninsular India and underestimation over the mountainous regions.

The scatter plot of seasonal rainfall averaged over each meteorological sub-division from the three satellite-based rainfall products against IMD-SRG based estimates is shown in Fig. 8. GSMaP shows the smallest correlation of 0.60 and the largest RMSD of 627 mm. This rainfall product largely underestimates monsoon rainfall over the Indian meteorological sub-divisions. Higher correlation and lower bias from

Fig. 8 Scatter plot of seasonal JJAS accumulated rainfall (mm) from three satellite-derived rainfall products against IMD-SRG based rainfall data set at meteorological sub-divisional scale for the summer monsoon of 2013. Correlation coefficient (r), bias and RMSD with respect to IMD-SRG based rainfall are also given



IMSRA and TMPA data sets with respect to IMD-SRG based estimates clearly shows the potential of Kalpana-1 derived rainfall product for monsoon monitoring at meteorological sub-divisional scale. Furthermore, it is recently shown that the combined use of IMSRA and rain gauge observations provides better rainfall estimates over the Indian monsoon region (Gairola et al. 2015). Thus, the merged satellite-gauge rainfall product would provide better rainfall estimates at meteorological sub-divisional scale.

Conclusion

Kalpana-1 derived IMSRA rainfall was compared with two independent multisatellite products and IMD-SRG based estimates. The progress of the ISMR of 2013 was assessed by these rainfall products over meteorological sub-divisions and at different temporal scales. The qualitative as well as quantitative comparison between IMSRA and other two satellite-based products showed that IMSRA is able to capture rainfall over the Indian region. IMSRA is also able to capture daily rainfall variability over the monsoon trough region, but underestimates heavy rainfall and overestimates light rainfall. The rainfall at meteorological sub-divisional scale from these satellite-derived products was also compared with IMD-SRG based observations. IMSRA and TMPA data sets perform better than GSMaP product at meteorological sub-divisional scale over India. Even though IMSRA and TMPA were in reasonably good agreement with IMD-SRG based

rainfall maps, satellite-derived rainfall products underestimate orographic rainfall along the west coast and overestimate over the southeast peninsular India. Results suggest that the IMSRA is suitable for rainfall estimation over India with possible augmentation of separate method for rainfall estimation along orographic regions. This methodology can be further applied to the recently launched INSAT-3D satellite data. Nevertheless, the synergistic use of satellite-based rainfall estimates and ground-based observations would essentially provide better rainfall estimates at meteorological sub-divisional scale for Indian monsoon rainfall monitoring and other applications.

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