Rainfall estimation from Kalpana-1 satellite data over Indian land and oceanic regions

R. M. Gairola[1,*], Satya Prakash[2], M. T. Bushair[1] and P. K. Pal[1]

[1]Atmospheric and Oceanic Sciences Group, Earth, Ocean, Atmosphere, Planetary Sciences and Applications Area, Space Applications Centre, Indian Space Research Organisation, Ahmedabad 380 015, India

[2]National Centre for Medium Range Weather Forecasting, Earth System Science Organization, Ministry of Earth Sciences, Noida 201 309, India

Rainfall, an integral component of the global water and energy cycle, is one of the critical weather elements. Reliable information of rainfall over India is crucial for food security and sustainable economic growth. The first Indian dedicated meteorological geostationary satellite Kalpana-1 was launched by the Indian Space Research Organisation in late 2002 to study the synoptic weather systems, monsoons and extreme weather events. Various geophysical parameters derived from this satellite measurements are operational and used for a wide range of applications. Two rainfall products, based on distinct algorithms, from this satellite are also available to users. These two algorithms after certain refinements are also applied to the recently launched INSAT-3D satellite measurements to estimate rainfall. In this article, the algorithms used for the development of these Kalpana-1-based rainfall products are summarized. The assessment of these rainfall products against standard multisatellite datasets and *in situ* observations are also outlined. Both the rainfall products are comparable with independent multisatellite datasets and have reasonable agreement with ground-based observations over the Indian land and oceanic regions. Limitations of these rainfall products are also presented; and future scope for further refinement of these products in perspective of upcoming Indian geostationary satellite missions is proposed.

Keywords: Indian monsoon, Kalpana-1 satellite, rainfall estimation, thermal infrared.

RELIABLE information of rainfall over the Indian region is crucial for a wide range of applications including water resource management, agricultural and hydrological purposes. Accurate rainfall estimates are very important in meteorological applications and validation of the weather and climate model outputs for further advancement of the models[1–3]. Ground-based observations from surface rain gauges, weather radars, etc. provide accurate measurement of rainfall. However, inhomogeneous coverage of these observations over the unpopulated regions limits its applicability. On the other hand, the Earth-observation satellites provide comprehensive maps of retrieved rainfall. Geostationary satellites provide cloud-top conditions on a continuous basis and are supposed to be viable sources of information for weather monitoring and dynamical modelling, especially in the tropics[4,5].

Kalpana-1 (originally known as MetSat-1) is the first in the series of exclusive meteorological satellites built by the Indian Space Research Organisation (ISRO). It is the first dedicated geostationary satellite launched by the Polar Satellite Launch Vehicle (PSLV)-C4 on 12 September 2002 for a mission life of 7 years[6]. Interestingly, it is still in operation and positioned at its orbital slot of 74°E. The satellite comprises two payloads, namely a very high resolution radiometer (VHRR) consisting of three wavelength bands and a data relay transponder (DRT) for collection and transmission of meteorological, hydrological and oceanographic data from remote data collection platforms. The VHRR provides the synoptic images of weather systems including severe weather conditions and is used for monitoring the onset and progress of the monsoon. It also provides various geophysical parameters such as cloud cover, sea surface temperature, outgoing longwave radiation, upper tropospheric humidity, cloud motion vectors and quantitative precipitation estimates or rainfall. These products are operational and available at the India Meteorological Department (IMD) and Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC), ISRO.

Two rainfall products, namely, Geostationary Operational Environmental Satellite (GOES) Precipitation Index (GPI) and Indian National Satellite System (INSAT) Multispectral Rainfall Algorithm (IMSRA) are operational among which GPI estimates rainfall at larger spatial and temporal scales[7]; whereas IMSRA is used for rainfall estimation at finer scales[8,9]. These rainfall products are properly validated with other multisatellite rainfall datasets and *in situ* observations over Indian land and oceanic regions and used for various hydro-meteorological applications[10–17]. In this article, the procedures of development of these Kalpana-1-based rainfall products are summarized. Qualitative and quantitative assessment of these products with other global or quasi-global multisatellite rainfall datasets and *in situ* observations are discussed and future scope for the refinement of these algorithms in perspective of future or recently launched Indian satellite missions are also proposed.

*For correspondence. (e-mail: rmgairola@sac.isro.gov.in)

Data used

The VHRR sensor onboard Kalpana-1 satellite operates in three wavelength bands, namely visible (VIS, 0.55–0.75 μm), water vapour (WV, 5.70–7.10 μm) and thermal infrared (TIR, 10.50–12.50 μm). In TIR and WV bands, spatial resolution is 8 km; whereas in VIS band, spatial resolution is 2 km. The required level 1 data of TIR and WV bands are obtained from the website at http://www.mosdac.gov.in for rainfall retrieval.

Two multisatellite rainfall products namely, TRMM (Tropical Rainfall Measuring Mission) Multisatellite Precipitation Analysis (TMPA) and Global Precipitation Climatology Project (GPCP) are used for the intercomparison of the Kalpana-1-derived rainfall products. The TMPA is a standard gauge-adjusted rainfall product derived using geostationary infrared (IR) data and microwave (MW) observations[18] available at $0.25° \times 0.25°$ spatial resolution and at different temporal resolutions (three-hourly, daily and monthly). This rainfall product has been developed to take advantage of the rich constellation of satellite-borne precipitation sensors available in a global belt extending from 50°S to 50°N. TMPA is available in both after-real-time and in-real-time, based on calibration by the TRMM combined instrument (TCI) and TRMM Microwave Imager (TMI) precipitation products, respectively. Only the after-real-time product incorporates rain gauge data over land which is called TMPA-3B42/3B43 research monitoring product. This high-resolution rainfall product is the best available multisatellite datasets for the Indian monsoon region[19]. The TMPA-3B42 version 7 (V7) datasets used in this study are obtained from the TRMM website at http://disc2.nascom.nasa.gov/tovas/. Similarly, the GPCP is a global precipitation product which uses precipitation estimates derived from IR data, MW satellite data and surface rain gauge observations[20]. The merging approach of these observations utilizes the higher accuracy of the low-orbit MW measurements to calibrate or adjust the frequent geosynchronous-orbit IR observations. To better understand the potential uses and limitations of satellite IR data in the estimation of large-scale precipitation, the relationship between the observed precipitation and fractional coverage of cold clouds for various combinations of threshold temperatures and temporal and spatial averaging scales has been examined in detail under this project. The daily GPCP version 1.2 product available at $1° \times 1°$ grid cells[21] and monthly GPCP version 2.2 product available at $2.5° \times 2.5°$ grid cells[20] are obtained from the website at http://precip.gsfc.nasa.gov/.

Moreover, high resolution rain gauge derived daily gridded rainfall data developed by IMD[22] are used. This gridded rainfall data are developed using rainfall observations from a dense network of gauge stations over India followed by proper quality-control check. These daily station data are interpolated into a regular grid of 0.5° using a standard Shepard's interpolation method and supposed to be the best available gauge-based gridded rainfall dataset over India.

Large-scale rainfall estimation

For the large-scale rainfall estimation from Kalpana-1 satellite using the GPI method[23], TIR data are used which is an atmospheric window channel. The Kalpana-1 TIR images of 0000, 0300, 0600, …, 2100 UTC, i.e. taken 3-hourly are used[7]. Brightness temperature (Tb) is computed from the grey shade values ranging from 0 to 1023 with the help of associated calibration table. Once the Tbs of all the pixels in a $1° \times 1°$ grid box are known, fractional cloud coverage within a grid box is computed, which is the ratio of the pixels having Tb less than 235 K to the total number of pixels. This gives the measure of the fractional area of the box covered by clouds with tops colder than the threshold. Finally, the 3-hourly rainfall is estimated at $1° \times 1°$ grid box using the following relationship given by Arkin and Meisner[23]

$$R = 3 \text{ mm h}^{-1} \times \text{frac} \times \text{hours}, \tag{1}$$

where R is the rainfall estimate in millimeters, frac is the fractional cloud coverage, and hours indicate the number of hours in the observation period. The daily accumulated rainfall is computed from the accumulation of eight 3-hourly images per day[7]. Similarly, weekly, monthly and seasonal rainfall is computed by the accumulation of daily rainfall.

The Kalpana-1 rainfall product utilizing this algorithm was intercompared with TMPA-3B42 rainfall product over the Indian region for the southwest monsoon seasons of 2006, 2007 and 2008 by Durai *et al.*[14]. As India receives about 80% of its annual rainfall from the southwest monsoon, the performance analyses are focused on this season. Their study showed that the Kalpana-1 rainfall product is able to capture broad-scale monsoon rainfall features reasonably well. In another study by Prakash *et al.*[12], this rainfall product is evaluated at weekly, monthly and seasonal scales for the southwest monsoon season of 2009. They showed that the rainfall estimates from this algorithm captures well active and break spells of monsoon when compared with GPCP dataset. One such example of the capability of this rainfall product to reproduce the active and break spells of the monsoon is shown in Figure 1. The Kalpana-1-derived weekly accumulated rainfall is compared with the multisatellite GPCP datasets for 16–22 July 2009 (active spell) and 30 July to 5 August 2009 (break spell) over the Indian region. Both the rainfall datasets show similar features over the Indian region. Prakash *et al.*[12] also evaluated Kalpana-1 rainfall product quantitatively against multisatellite and gauge-based datasets for the monsoon season of 2009 at

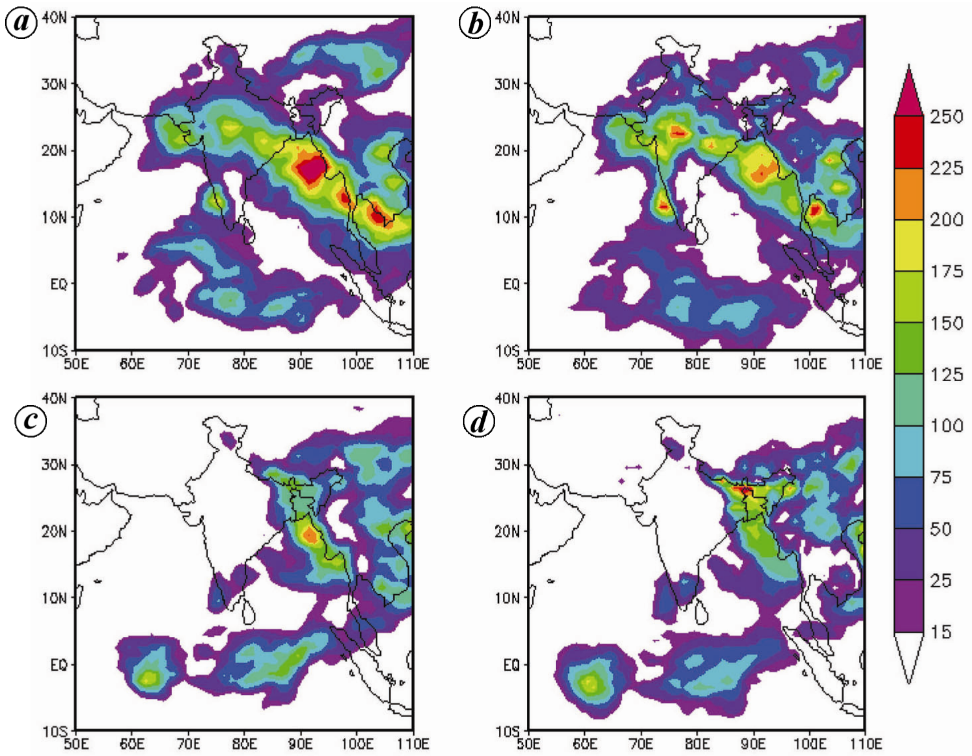

Figure 1. Weekly accumulated rainfall (mm) from (***a***, ***c***) Kalpana-1 GPI and (***b***, ***d***) GPCP datasets for the period (***a***, ***b***) 16–22 July 2009 and (***c***, ***d***) 30 July–5 August 2009.

monthly and seasonal scales. They showed that the Kalpana-1-derived rainfall is in good agreement with GPCP dataset, but it underestimates orographic rainfall as compared to gauge-based dataset. However, the error in Kalpana-1-derived rainfall is about 50% as compared to both the independent rainfall observations at seasonal time scale.

In order to refine the large-scale rainfall estimates from Kalpana-1 data, Mishra *et al.*[24] proposed the use of additional moisture correction factor derived using the precipitable water and relative humidity products from the numerical model outputs along with the GPI-based rainfall. This new improved rainfall algorithm is termed as modified GPI (MGPI). It is based on the fact that rainfall retrieved from the cloud-top information is underestimated (overestimated) under moist (dry) environmental conditions[25]. The performance of MGPI product was also demonstrated by Mishra *et al.*[24] for the southwest monsoon season with multisatellite and ground-based observations and they suggested that MGPI is superior to GPI estimates. The accumulated rainfall for the peak monsoon months of July and August 2009 from Kalpana-1 GPI, MGPI and GPCP datasets are shown in Figure 2. The underestimation of rainfall by GPI technique along the west coast of India is considerably improved by the MGPI technique, as compared to GPCP dataset. However, the high rainfall regions of the Bay of Bengal and surrounding regions show an overestimation of rainfall from MGPI. This may be due to the fact that the moisture content is generally high over these regions during the monsoon season which in turn increases the rainfall amount. Another limitation of this method is that it can only change the rainfall amount from GPI estimates based on moisture content, but it is unable to change the rainfall areas as MGPI is a product of GPI rainfall estimates and moisture correction factor. Hence, direct use of moisture correction factor over the entire study region is not sufficient and produces misleading results which needs to be addressed further. The development of regional coefficients based on Kalpana-1 TIR Tbs and TRMM–precipitation radar (PR) surface rainfall estimates would essentially improve the performance of GPI rainfall estimates.

Small-scale rainfall estimation

The IMSRA technique is the combination of the IR and MW measurements which benefits from the relative accuracy of the MW-based estimates and the relatively low sampling errors of the TIR-based estimates[8,9]. This algorithm is developed for the small-scale rainfall estimation over the Indian region. The development of this algorithm includes two major steps: (a) classification of rain-bearing clouds using proper cloud classification scheme utilizing Kalpana-1 TIR and WV Tbs and (b) collocation of Kalpana-1 IR Tbs with TRMM-PR surface rainfall rate

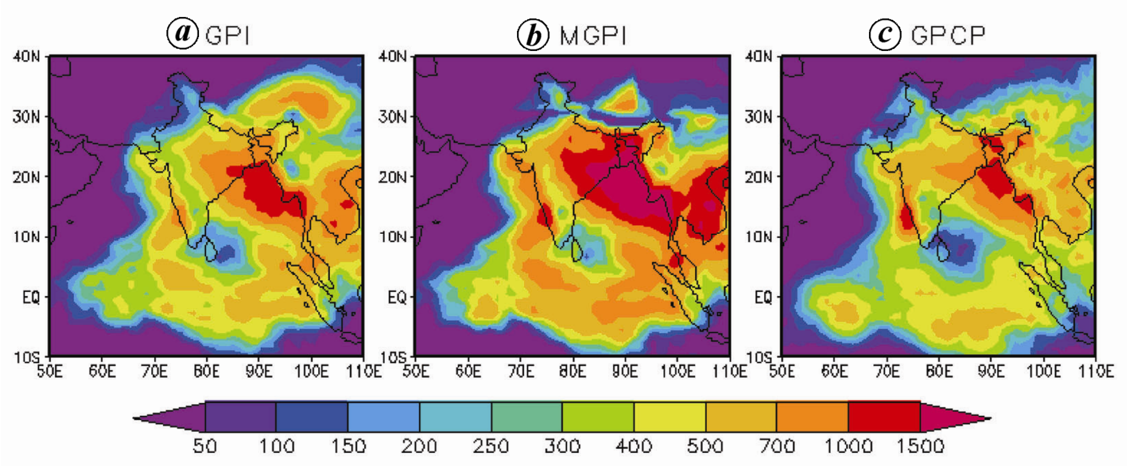

Figure 2. July–August accumulated rainfall (mm) for 2009 from (***a***) Kalpana-1 GPI; (***b***) MGPI and (***c***) GPCP datasets.

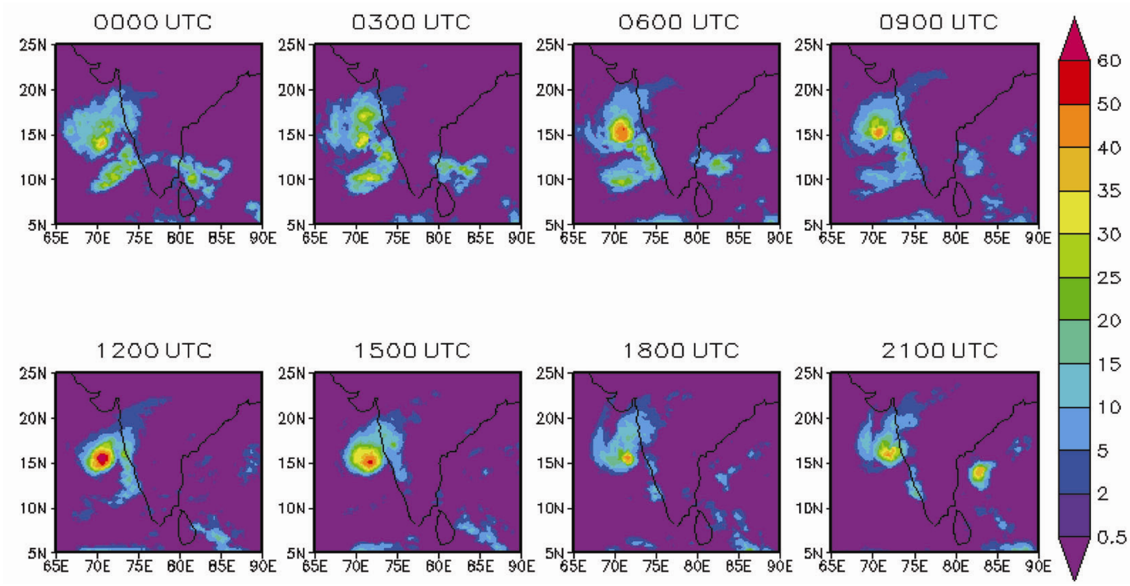

Figure 3. Three-hourly accumulated rainfall (mm) for 10 November 2009 from Kalpana-1 IMSRA for Phyan cyclone.

and establishment of a regression relation between them. The procedure of the development of this algorithm is similar to the algorithm developed by Mishra *et al.*[26] for the study of intense rainfall events using Kalpana-1 and PR measurements and Mishra *et al.*[27] for small-scale rainfall estimation over the Indian region by the combined use of Meteosat and PR data. The cloud classification is carried out using TIR and WV bands to identify the thin cirrus, deep convective and highly deep convective clouds following Roca *et al.*[28]. In the second step, TIR Tbs with the PR surface rainfall are collocated within 15 min of difference and the two measurements have nearly identical spatial resolution (~5–8 km). The present algorithm computes 3-hourly rainfall rates (e.g., at 0000, 0300, 0600, …, 2100 UTC) at 0.25° latitude × 0.25° longitude resolution based on the non-linear power law relation given in eq. (2) between the collocated and near simultaneous TIR-Tbs and PR rainfall rates after applying the above-mentioned cloud classification scheme

$$R = a \times \exp(-(\mathrm{Tb} - b)/c), \qquad (2)$$

where a, b, c are constants, R is rain rate in mm h^{-1} and Tb is the cloud top temperature in Kelvin. The daily accumulated rainfall is computed from the accumulation of eight 3-hourly images per day[8,9].

This Kalpana-1-based rainfall estimate is successfully used for rainfall monitoring during the monsoon and severe weather conditions. Rainfall during the Phet cyclone was monitored using this algorithm and the results were compared with other standard rainfall observations[11]. Figure 3 shows the three-hourly rainfall from

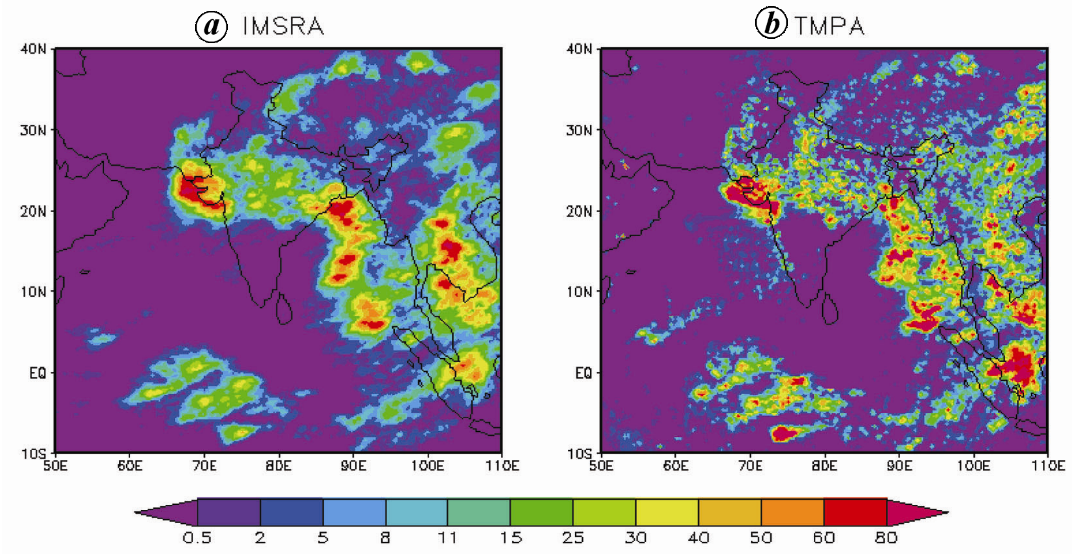

Figure 4. Daily accumulated rainfall (mm) from (***a***) Kalpana-1 IMSRA and (***b***) TMPA-3B42V7 datasets for 1 August 2010.

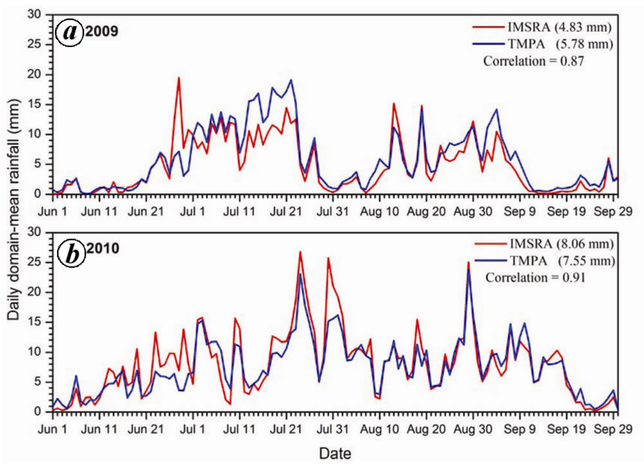

Figure 5. Time-series of domain-mean daily accumulated rainfall (mm) over the core monsoon region from Kalpana-1 IMSRA and TMPA-3B42V7 datasets for the southwest monsoon period of (***a***) 2009 and (***b***) 2010. Mean seasonal rainfall values (in parentheses) and correlation coefficient between both the datasets are also given.

IMSRA estimates for 10 November 2009 during the Phyan cyclone. Rainfall features over the eastern Arabian Sea and adjoining regions associated with the cyclonic activity are clearly shown which appears to be realistic. Moreover, the daily accumulated rainfall from Kalpana-1 and TMPA-3B42 for 1 August 2010 (Figure 4) shows that the IMSRA is able to capture the rainfall areas well qualitatively. However, there are some differences in magnitude between both the rainfall products. The daily rainfall averaged over the core monsoon region bounded by 18°N–28°N and 65°E–88°E during the monsoon seasons of 2009 and 2010 (Figure 5) shows the contrasting behaviours of the monsoon from both the rainfall datasets namely, Kalpana-1 IMSRA and TMPA-3B42. The monsoon season 2009 was anomalously deficient, whereas 2010 was a normal monsoon year. The correlation coefficient between daily domain-mean rainfall derived from IMSRA and TMPA-3B42 products is 0.87 during 2009 and 0.91 during 2010. These results convincingly show that both the rainfall products are in good agreement with each other.

In order to assess the potential of IMSRA, rainfall estimates from this algorithm are evaluated with multisatellite TMPA and GPCP products and rain gauge observations for the southwest monsoon seasons of 2008 and 2009 at daily and monthly scales[10]. They showed that rainfall estimates from IMSRA are comparable with multisatellite products. It has reasonably good agreement with gauge observations over the Indian land and oceanic regions. This rainfall product is also independently validated by Roy *et al.*[15] and they showed that IMSRA performs better than GPI estimates and has potential for small-scale rainfall retrieval. This operational rainfall product is used for the monsoon rainfall monitoring at meteorological sub-divisional scale[17], numerical model output verification[13,16], etc. The rainfall product from IMSRA is further downscaled at pixel scale (~8 km) and hourly rainfall rate is estimated to pick up the fine features of the monsoon systems[29]. One example of pixel-scale rainfall estimation from Kalpana-1 IMSRA is shown in Figure 6. Higher rainfall is associated with regions having lower Tbs in TIR channel, as expected. Fairly good amount of rainfall over Rajasthan, eastern parts of India, and equatorial Indian Ocean and heavy rainfall over the north Bay of Bengal is observed from this algorithm which is commensurable with the Kalpana-1 TIR Tbs. However, IMSRA underestimates orographic rainfall along the west coast of India and over the Himalayan foothills as expected from the IR-based rainfall estimates[10,20].

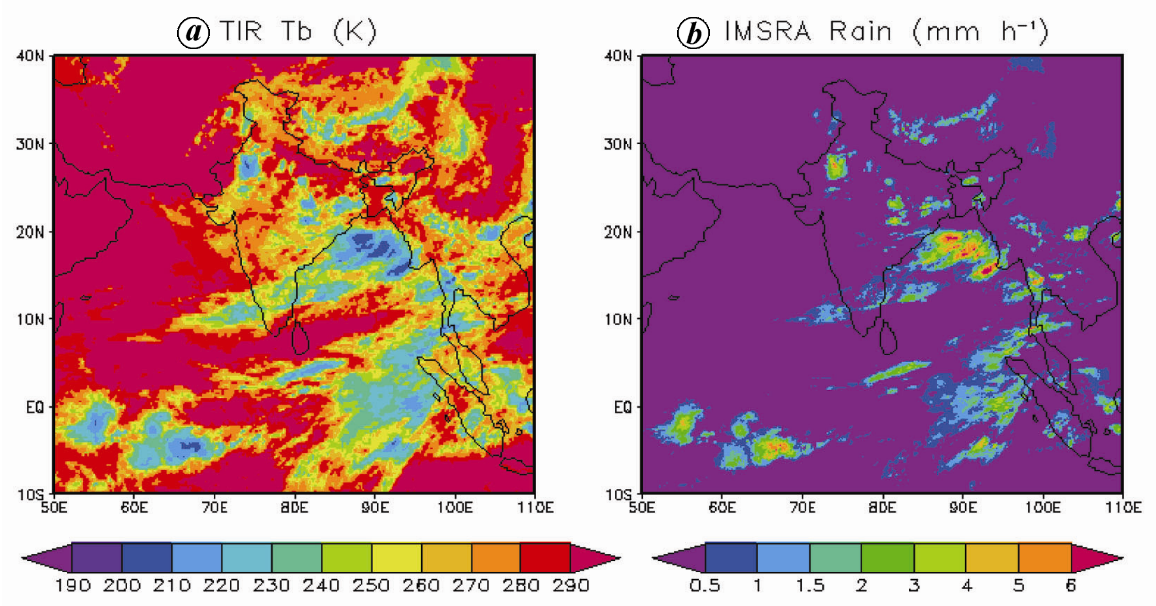

Figure 6. Spatial distributions of pixel-scale Kalpana-1; (***a***) TIR Tbs (K) and (***b***) IMSRA rainfall (mm h^{-1}) for 09 July 2008 at 0900 UTC.

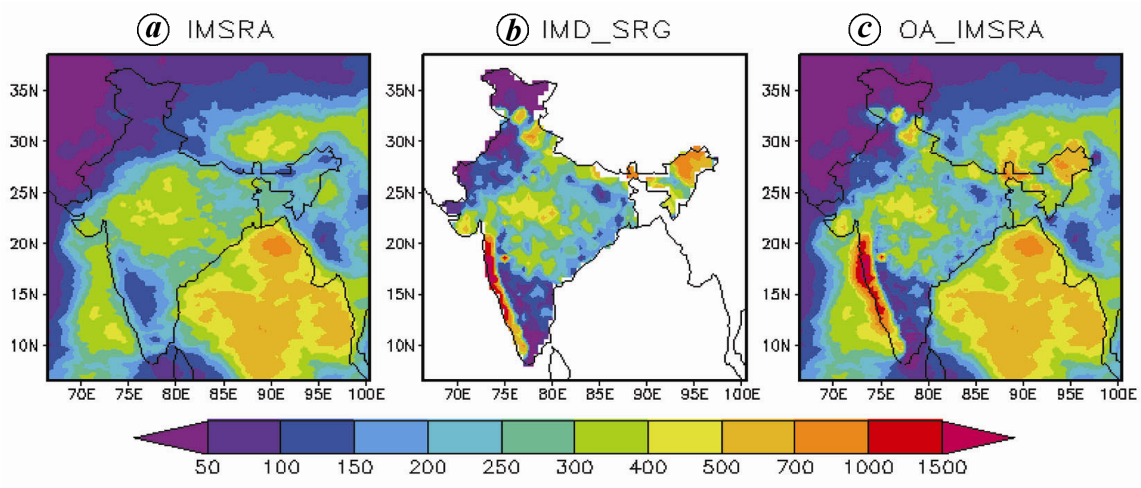

Figure 7. Spatial distributions of monthly accumulated rainfall (mm) from (***a***) IMSRA, (***b***) IMD surface rain gauges and (c) objectively analysed IMSRA for July 2011.

In order to further refine this algorithm, Mahesh *et al.*[30] developed a separate regression equation between Kalpana-1 cloud-top temperature and PR rainfall for orographic regions and introduced an additional cooling index based on two consecutive Kalpana-1 TIR images. To assess the capability of this experimental modified algorithm, they carried out a preliminary evaluation with other independent rainfall observations for the monsoon season of 2010 and showed that the new algorithm improves rainfall estimates by about 30% as compared to the existing IMSRA rainfall estimates. However, a rigorous validation with more years of datasets is required and needs further extension for all the seasons as it is presently developed for the southwest monsoon season.

Furthermore, the merging of Kalpana-1-derived rainfall estimates with *in situ* observations would provide optimal rainfall estimates. The potential of merging of satellite-retrieved rainfall with rain gauge observations over the Indian monsoon region is also reported by Mitra *et al.*[31]. They used near-real time TMPA-3B42 rainfall product for the development of daily gridded merged rainfall analysis. Gairola *et al.*[32] demonstrated the potential of merging IMSRA estimates with gauge observations over the Gujarat state region. They used successive correction method for the objective analysis which performs reasonably well for rainfall estimates[31,33,34] and showed that the merged product benefits from high spatial coverage of the satellite measurements and accurate rainfall from gauge observations. Figure 7 shows the impact of merging gauge data with Kalpana-1-retrieved rainfall at monthly scale for July 2011. We have experimentally used daily gridded gauge-based rainfall data over India[22] and accumulated both the datasets (satellite and gauge) at monthly scale for merging because gauge-based data accumulates rainfall at 0300 UTC which is different from the satellite-retrieved rainfall accumulation convention. Moreover, the gridded gauge-based rainfall data is treated as point observation in this study for demonstrating the impact of merging. Underestimation of rainfall over the west coast of India and along the foothills of the Himalayas by IMSRA improve noticeably after merging. Demarcation of high rainfall over the foothills of the Himalayas and the monsoon trough improves considerably. Overall, the results show that the synergistic use of ground-based observations and Kalpana-1-retrieved rainfall has large potential for accurate rainfall estimation over the Indian monsoon region.

Conclusions and future scope

In this study, we have presented an overview of algorithms used for rainfall estimation operationally from the Kalpana-1 satellite data for the Indian land and oceanic regions. Two algorithms namely, GPI and IMSRA are used for rainfall estimation. Evaluation of both the rainfall products with independent multisatellite and ground-based observations is also presented. GPI is suitable for large-scale rainfall estimation and able to capture the intraseasonal variability (active and break spells) of the southwest monsoon as compared to GPCP datasets. Rainfall estimates from this algorithm are in good agreement with GPCP and gauge-based observations quantitatively, when compared at monthly and seasonal scales. At the same time, IMSRA is capable of rainfall estimation at finer scale. It captures the onset and progress of the monsoon and extreme weather conditions such as tropical cyclones reasonably well. This rainfall product is used for various applications by the users. Evaluation of IMSRA against independent rainfall datasets showed that this algorithm has potential for small-scale rainfall retrieval, even though it underestimates orographic rainfall along the west coast of India and the Himalayan foothills. Nevertheless, these two algorithms after certain fine-tunings such as histogram matching, etc. are also applied to the recently launched INSAT-3D satellite measurements to estimate rainfall. INSAT-3D has further advantages of having together six spectral channels in VHRR that produces images in the visible (VIS; 0.55–0.75 μm), shortwave infrared (SWIR; 1.55–1.70 μm), midwave infrared (MWIR; 3.80–4.00 μm), water vapour (WV; 6.50–7.10 μm) and thermal infrared (TIR–1 and 2; 10.20–11.30 μm and 11.5–12.5 μm) parts of the spectrum. The additional SWIR and MWIR channels of INSAT-3D would enable better land–cloud discrimination and detection of surface features such as snow. This will allow further exploration of certain microphysical properties of the clouds and will help in improving the IMSRA rainfall estimates.

For further refinement of the GPI algorithm, the development of regional coefficient would provide more accurate rainfall estimates. The direct use of moisture correction factor needs further investigation to obtain more appropriate parameters to improve the large-scale rainfall estimates. The use of separate regression equation for orographic regions along with cooling index would essentially improve the quality of IMSRA rainfall product. Moreover, the synergistic use of ground-based observations and satellite-based rainfall estimates would certainly provide optimal rainfall estimates.

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