MAUSAM, **61**, 3 (July 2010), 317-336

551.501.777 : 551.577

Evaluation of Indian summer monsoon rainfall features using TRMM and KALPANA-1 satellite derived precipitation and rain gauge observation

V. R. DURAI, S. K. ROY BHOWMIK and B. MUKHOPADHYAY

India Meteorological Department, New Delhi – 110 003, India

(*Received 1 April 2009, Modified 10 March 2010*)

e mail : durai.imd@gmail.com

सार – इस शोध पत्र में वर्ष 2006, 2007 और 2008 के ग्रीष्म मॉनसून ऋतु के दौरान वर्तमान समय के सफल उपग्रहों (3 बी 42 आर. टी., 3 बी. 42 वी–6, कल्पना–1) से भारतीय क्षेत्रों के बारे में प्राप्त सूचनाओं को संक्षिप्त और संश्लेषित विवरण प्रस्तुत किया गया है। उपग्रह से प्राप्त आँकड़ों का वर्षामापी प्रेक्षणों के साथ परस्पर तुलना करने से पता चलता है कि टी. आर. एम. एम. 3 बी. 42 वी–6 के उत्पाद ग्रीष्म मानसून की विशेषताओं को सही–सही पकड़ पाए हैं, जैसे कि पश्चिमी घाट के भारी वर्षा वाले उत्तर दक्षिणी भाग में मूसलाधार वर्षा हुई और पूर्व में वृष्टि छाया क्षेत्र बना रहा, देश के पूर्वात्तर भागों के मानसून द्रेाणी के क्षेत्रों में कुछ स्थानों पर भारी वर्षा हुई, पूर्वोत्तर भारत में हिमालय के तराई वाले क्षेत्रों में तथा बंगाल की खाड़ी के उत्तरी भाग में भारी वर्षा हुई। कल्पना–1 और 3 बी. 42 आर. टी. से प्राप्त आँकड़ों से केवल मानसून ऋतु की औसत वर्षा की विस्तृत जानकारी प्राप्त होती है। भारत के पश्चिमी घाट के पर्वतीय क्षेत्र में हुई भारी–वर्षा के आँकड़े वास्तविक समय पर 3 बी 42 आर. टी. और कल्पना–1 से कम आकलित किए गए हैं। टी. आर. एम. एम. 3 बी. 42 वी.–6 से प्राप्त आँकड़ों को जब पूरी ऋतु के आँकड़ों के साथ मिला कर आकलित किया गया तो इसे प्रेक्षित आँकड़ा पैटर्न के करीब पाया गया। हालांकि टी. आर. एम. एम. 3 बी. 42 आर. टी. और कल्पना–1 से प्राप्त आँकड़े देश के अधिकतर भागों में ऋतु के दौरान प्रेक्षित वर्षा आँकड़ों से अपेक्षाकृत कम थे। इन आँकड़ों का एक दूसरे के साथ तुलना करने से पता चलता है कि टी. आर. एम. एम. 3 बी. 42 वी.–6 के आँकड़े पूरे भारत में तथा भारत के समरूपी क्षेत्र में भी दैनिक तथा ऋतु की औसत वर्षा का आकलन करने में अधिक सही स्थिति को दर्शात हैं।

ABSTRACT. The study provides a concise and synthesized documentation of the current level of skill of the satellite (3B42RT, 3B42V-6, KALPANA-1) products over Indian regions based on the data gathered during the summer monsoon seasons of 2006, 2007 and 2008. The inter-comparison of satellite products with the rain gauge observations suggests that the TRMM 3B42V6 product could distinctly capture characteristic features of the summer monsoon, such as north–south oriented belt of heavy rainfall along the Western Ghats with sharp gradient of rainfall between the west coast heavy rain region and the rain shadow region to the east, pockets of heavy rainfall along the location of monsoon trough, over the east central parts of the country, over north-east India, along the foothills of Himalayas and over the north Bay of Bengal. The KALPANA-1 and 3B42RT products reproduce only the broadest features of mean monsoon seasonal rainfall. The near real-time products 3B42RT and KALPANA-1 underestimate the orographic heavy rainfall along the Western Ghats of India. The precipitation estimates from TRMM 3B42V6 product, when accumulated over the whole season, could reproduce the observed pattern. However, the TRMM 3B42RT and KALPANA-1 estimates are comparatively lower than the observed rainfall over most parts of the country during the season. Inter comparison reveals that the TRMM 3B42V6 product showed better skill in estimating the daily and seasonal mean rainfall over all India and also over four homogeneous regions of India.

Key words – TRMM, NWP, 3B42V6, 3B42RT, Rainfall estimate, QPE, Indian summer monsoon, Rainfall estimation skill.

1. Introduction

Accurate estimation of rainfall is crucial for a wide range of applications extending from the real time monitoring and prediction of flood events to initialization and validation of Numerical Weather Prediction (NWP) models. Prior knowledge of the structural characteristics of varying rainfall systems is very essential for real time

TABLE 1

Characteristics of the data sets used in this study

Data Set Name	Spatial resolution	Temporal resolution	Duration
Rain gauge (IMD)	1 × 1 degree (gridded)	Daily (0300 UTC – 0300 UTC)	2006-2008 (June – September)
KALPANA-1	1 × 1 degree	Daily (0000 UTC – 0000 UTC)	2006 -2007 (June -September)
	0.25 × 0.25 degree	Daily (0000 UTC – 0000 UTC)	2008 (June-September)
TRMM 3B42RT	0.25 × 0.25 degree	3 Hourly	2006- 2008 (June-September)
TRMM 3B42 V6	0.25 × 0.25 degree	3 Hourly	2006- 2008(June-September)

monitoring and prediction of flood events. Excess rainfall causes severe flooding, property and lives loss. Extended absence of rainfall lead to droughts, which can devastate crop yields and limits human consumption. India is heavily dependent on rain-fed agriculture, hence excess or insufficient rainfall can be devastating to the national economy and the livelihood of its people. A better understanding of the spatial and temporal rainfall distributions is therefore essential for the Indian economy.

Reliable observations of rainfall data are also important for climate science because precipitation is a major component of the earth's water and energy cycles. These cycles are inherently complex, with interaction between land, ocean, atmosphere and cryosphere. The tropical atmosphere gets three-fourth of its heat energy from the release of latent heat associated with precipitation. Elevated latent heating has strong influence on surface pressure, surface winds in the tropics, evaporation and ocean circulation. Rainfall determines river runoff and modifies sea surface salinity, upper ocean stratification and mixed layer depth. Thus rainfall has very important direct and indirect influence on the distribution of tropical sea surface temperature, atmospheric water vapour, boundary layer moisture convergence, and convection. In order to make progress in the area of dynamical extended range prediction of monsoon rainfall, the first requirement is obtaining observed rainfall data (used in verifying the models) and understanding the processes involved. Finally, the distribution of water vapour and clouds modifies radiative fluxes in the atmosphere, and turbulent exchange of heat and water vapour with land and ocean. Due to the above mentioned reasons, in recent years there has been considerable interest among different scientific groups in the preparation and inter-comparison of gridded rainfall datasets (Huffman *et al*. 1997; Xie and Arkin 1997 and Adler *et al*. 2003)

Rain gauge measurements are usually limited by their spatial coverage. A network of weather radars provides good spatial and temporal coverage. However, the problem of inter-radar calibration and blockage by mountains still limit its capability. Remote sensing techniques using space borne sensors provide an excellent complement to continuous monitoring of rain event both spatially and temporally. The launch of the Tropical Rainfall Measuring Mission (TRMM) satellite in November 1997 jointly by National Aeronautics and Space Administration (NASA) of US and the Japanese Aerospace Exploration Agency (JAXA) provided more than 10 years of quality rainfall data for tropical rainfall study. To improve the TRMM data quality, TRMM products are constantly reprocessed, as new information acquired by TRMM lead to improved algorithms. Recently, the TRMM reprocessing was completed using the Version 6 (V6) algorithms. It is necessary to quantify the biases of the TRMM products relative to gauge measurements that have been used historically to calibrate NWP models. Comparison of India Meteorological Department (IMD) rain gauges with satellite products enables an evaluation of the applicability of satellite rain estimates in India for agricultural and hydrological applications.

There are a number of efforts to compare and validate TRMM rainfall products with other rainfall measurements (Mitra *et al.* 2003, Nicholson *et al.* 2003 a & b). However, these studies are usually limited to comparisons at the monthly scale. For hydrological or agricultural applications, shorter periods, such as daily, five day (pentad) or ten day (decade) rain rates are more appropriate. More recently, comparison of operational rain products at the daily scale have been carried out for the Indian monsoon regions by using GPCP and TRMM (3B42V5 and 3B42V6) data (Rahman and Sengupta 2007). All these rainfall products which they have taken for comparison are post real time research products, available 10 - 15 days after at the end of each month. Since India Meteorological Department is the operational center, there has been growing operational requirement for real time satellite products of improved quality for monitoring and prediction of heavy rainfall events. The comparison study of these real time satellite products over Indian region is lacking. So, it is very important to know the performance skill of the real time satellite products over Indian regions. The main objective of this study is to evaluate/investigate the skill of both near real-time (3B42RT, and KALPANA-1) and post real-time (3B42V6) satellite products over Indian regions during the summer monsoon seasons of 2006, 2007 and 2008.

2. Data sources and methodology

Table 1 shows the data sets and their characteristics used in this study.

2.1. *Rain Gauge dataset (IMD)*

The daily observed (Rain Gauge) rainfall data from the India Meteorological Department (IMD) for the monsoon year of 2006, 2007 and 2008 are quality controlled and objectively analyzed to a 1° × 1° latitude - longitude grid (Roy Bhowmik and Das 2007 and Rajeevan *et al.* 2005). The objective technique used for this rainfall analysis is based on the Cressman interpolation method (Cressman 1959). The Cressman weight function used in the analysis is defined by

$$W_{i,m} = \frac{R^2 - r_{i,m}^2}{R^2 + r_{i,m}^2}$$

Where R is the radius of influence and $r_{i,m}$ is the distance of the station from the grid point. The analysed observed rainfall used for the study is accumulated rainfall in the 24 hours ending 0830 hrs IST (0300 UTC). It is used to validate daily satellite rainfall products (KALPANA-1, 3B42RT & 3B42V6) over Indian land areas for the three consecutive monsoon years of 2006, 2007 and 2008.

2.2. *KALPANA-1 QPE*

The KALPANA-1 is a dedicated Meteorological Satellite, having three channel Very High Resolution Radiometer (VHRR) for cloud imagery in Visible, Infrared and Water Vapour channels and a Data Relay Transponder (DRT). It was launched by India in September, 2002 and is still operational at 74.0° E Longitude. The Quantitative Precipitation Estimation (QPE) from the KALPANA-1 are derived at the grid resolution of 1° × 1° Lat./Long. for the monsoon seasons of 2006 and 2007 and at 0.25° × 0.25° Lat./Long. for 2008, following the algorithm described by Arkin *et al.* (1989). The algorithm was originally developed for estimation of large-scale rainfall distribution over oceanic areas. Extension of the technique to land areas may give unreasonable estimates over mountainous terrain, where the rainfall is primarily orographic and not convective. The detailed description of the method is also given by Rao *et al.* (1989). The approach is identical with the one used to obtain such estimates for GOES (Arkin and Meisgner, 1987) and for INSAT-1B (Kelkar and Rao, 1990). According to this algorithm the rainfall estimates are given by:

$$R = 3 \times f \times h$$

Where R is areal rainfall estimates in mm, f *is* the fraction of IR pixels with temperature less than 235° K and total number of pixels within the square grid, and h is time in hours. The constant rain rate of 3 mm/h provides the best correlation of the regression relation (Richard and Arkin, 1981). Rainfall estimates from the satellite data is based on the hypothesis that the coldest (brightest) clouds in IR (VIS) are associated with the highest rainfall.

2.3. *TRMM 3B42RT and 3B42 Version 6 (V6) products*

The Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA), a new dataset that continues the trend toward routine computation and distribution of finer-scale precipitation estimates. In common with the GPCP products, the TMPA is designed to combine precipitation estimates from various satellite systems, as well as land surface precipitation gauge analyses. The TMPA is computed twice as part of the routine processing for TRMM, first as an experimental best-effort real-time monitoring product (RT) about 9 h after real time, and then as a post-real-time research-quality product (research products) about 10–15 days after the end of each month.

The TRMM 3B42RT is as an experimental best-effort real-time monitoring product and 3B42V6 is a post-real-time research-quality product. Both these products are available at the 3-hourly, 0.25° × 0.25° latitude-longitude resolution. The combined microwave, microwave calibrated IR, and merged microwave - IR estimates, which are labelled 3B40RT, 3B41RT and 3B42RT respectively are available from http://precip.gsfc.nasa.gov. The research product system has been developed as the version-6 algorithm for the TRMM operational product 3B42, although that product only provides the final gauge adjusted merged field.

3. Results and discussions

To compare the satellite estimated rainfall products (3B42V6, 3B42RT and KALPANA-1) with observed

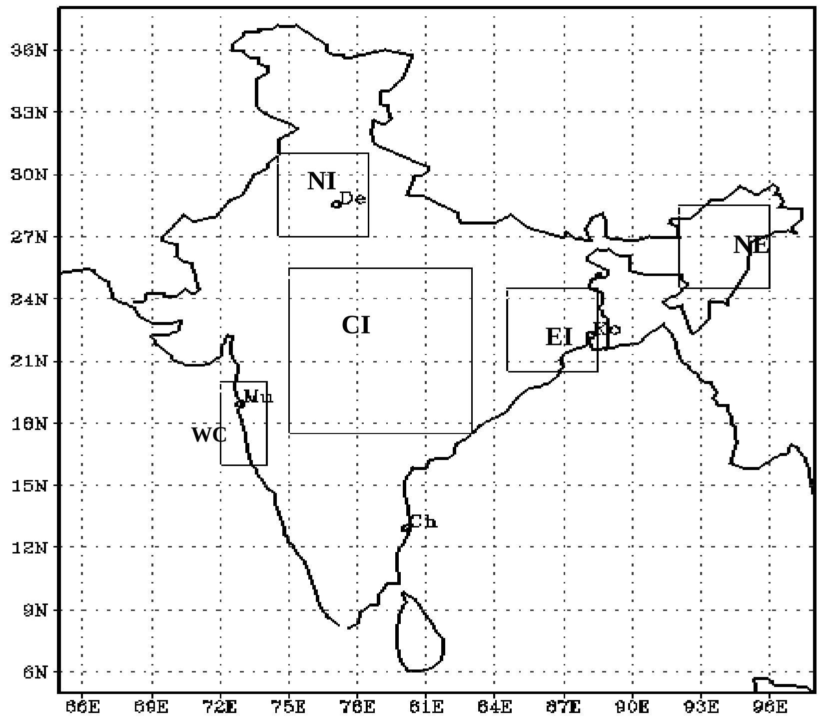


Fig. 1. The region of study. Different regions are shown in outline: NI-North India, CI-Central India, EI-Eastern India, NE-North East India and WC-West Coast of India

Gauge rainfall, the following statistical measures are used- mean error (bias), root mean square Error (RMSE) and correlation coefficient (CC). These are defined as follows:

Mean error (Bias)

$$\text{BIAS} = \frac{1}{N}\sum_{i=1}^{N} \left(X_i - O_i\right)$$

Root mean square error

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(X_i - O_i\right)^2}$$

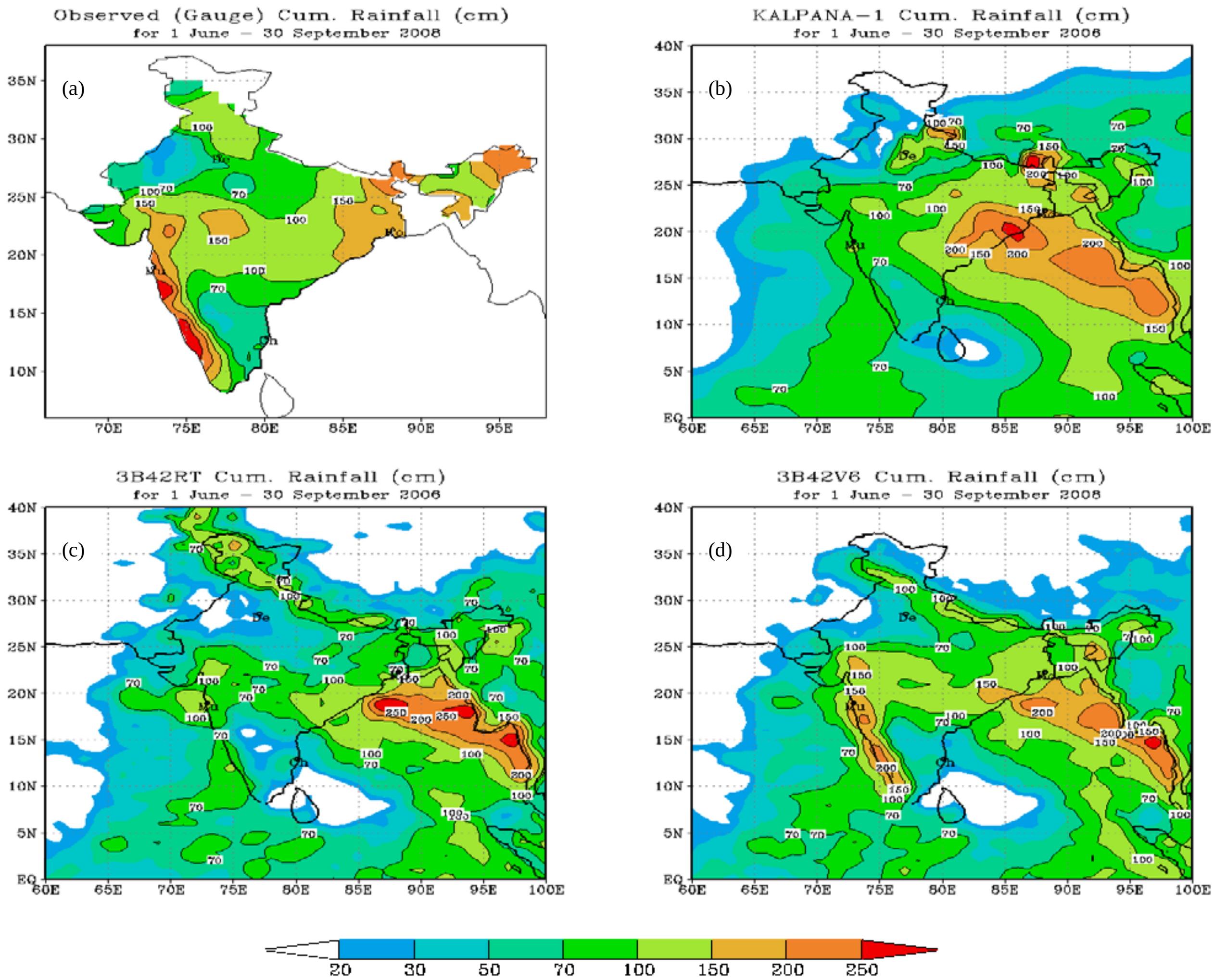
Correlation coefficient

$$\text{CC} = \frac{\sum_{i=1}^{N} \left(X_i - \overline{X}\right)\left(O_i - \overline{O}_i\right)}{\sqrt{\sum_{i=1}^{N} \left(X_i - \overline{X}_i\right)^2 \sum_{i=1}^{N} \left(O_i - \overline{O}_i\right)^2}}$$

Where N is the total number of samples, i = 1, 2… N and X is the satellite rainfall estimation and O is the gauge observation at the grid. The time intervals used for estimating accumulated daily rain by the datasets are different (Table 1). The different regions used for comparison are shown in Fig. 1. Four representative areas over Indian land *i.e.*, North India (NI), Eastern India (EI), North East India (NEI), Central India (CI), and West coast of India (WC) are chosen based on the consideration that daily variability of rain is more or less spatially uniform within each of these regions (Goswami *et al*., 2006).

3.1. *Salient features of Indian summer monsoon during 2006, 2007 and 2008*

The seasonal (summer monsoon) rainfall pattern over India shows that large values of rainfall occur along the west coast and over the north-eastern parts of India where blocking effects of topography induce upward vertical velocity and enhance precipitation at the windward side and suppress precipitation in the lee side (Rao, 1976). The rain shadow due to the Western Ghats spreads over a large area of the Indian peninsula. The states in the northwest and southeast get the least amount of rainfall. The local scale features and passage of synoptic scale monsoon systems further modify this gross picture. There is an increase in daily rainfall at the beginning of the season that is coincident with the onset of the summer monsoon over the southern tip of India, and a

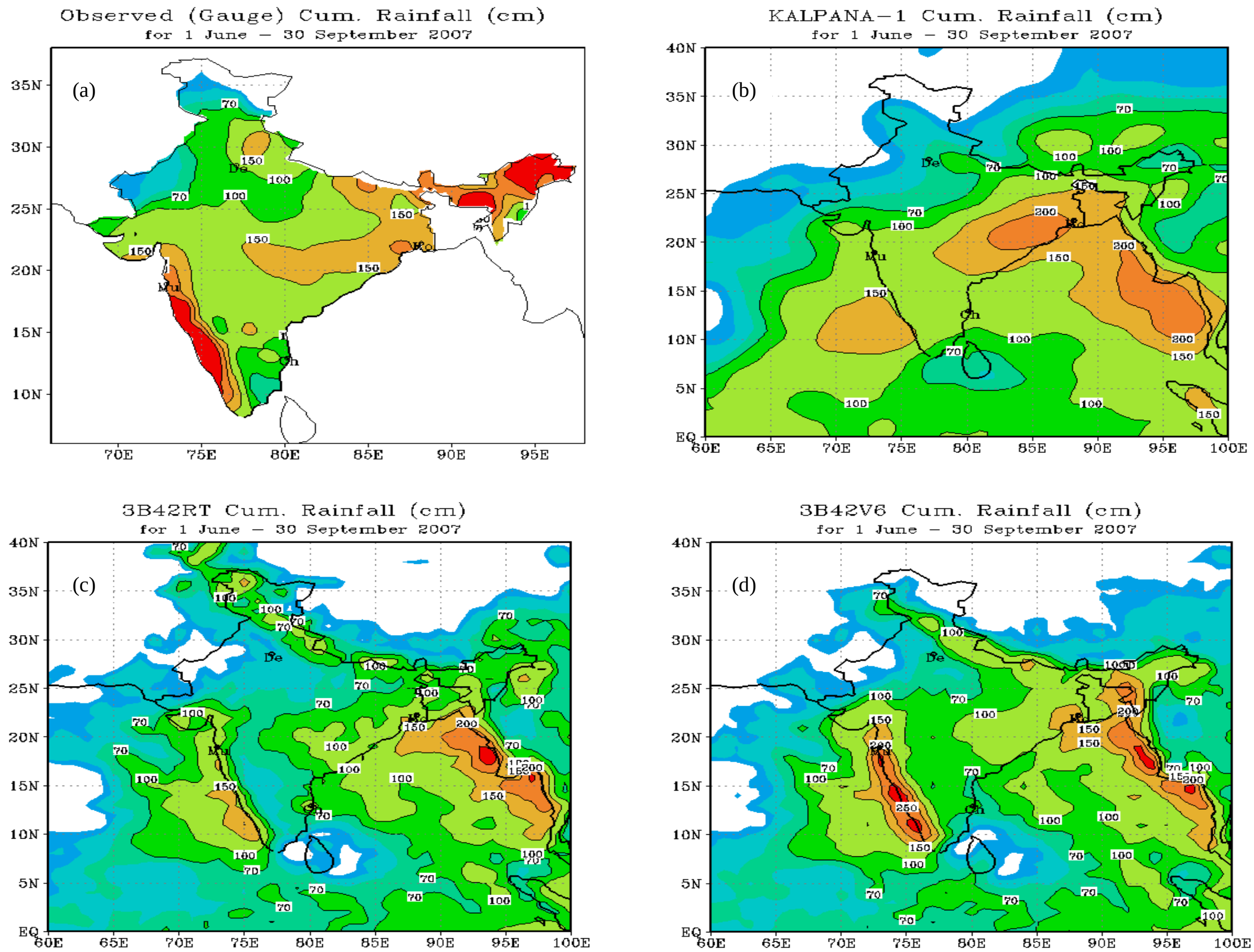


Figs. 2(a-d). Spatial distribution of cumulative rainfall (cm) from (a) Rain gauge observation and (b) KALPANA-1 (c) 3B42RT and (d) 3B42V6 for the period from 1 June to 30 September 2006

gradual increase up to July when the whole of the country is under the influence of the summer monsoon circulation. The rainfall values decrease after August because the monsoon circulation starts withdrawing southward from the west and central parts of the country. The withdrawal process is complete over most of the country, except for the east coast of the extreme south, by the end of September. This general trend is, however, modulated by events of enhanced precipitation activity that are usually associated with one or more synoptic-scale weather systems, like low pressure areas of various intensity or extra tropical influence due to incursions of westerly troughs to the north of the country.

The 2006 summer monsoon was a normal monsoon year with the seasonal rainfall of 100% of the long term average normal (IMD, 2007). The rainfall was unevenly distributed in space and time. Monsoon advanced over Kerala (extreme south-east state of India) on 26 May, almost a week prior to the normal date. The monsoon covered the entire country on 24 July, about 9 days later than normal date of 15 July. Withdrawal of monsoon from northwest India took place on 21 September, 20 days later than normal date of 1 September. During the season as many as 16 low pressure systems formed and out of them 8 systems were depression. One depression formed in July, 4 depressions in August and 3 depressions in September. Most of them had long track across the central mostly in west/northwest direction.

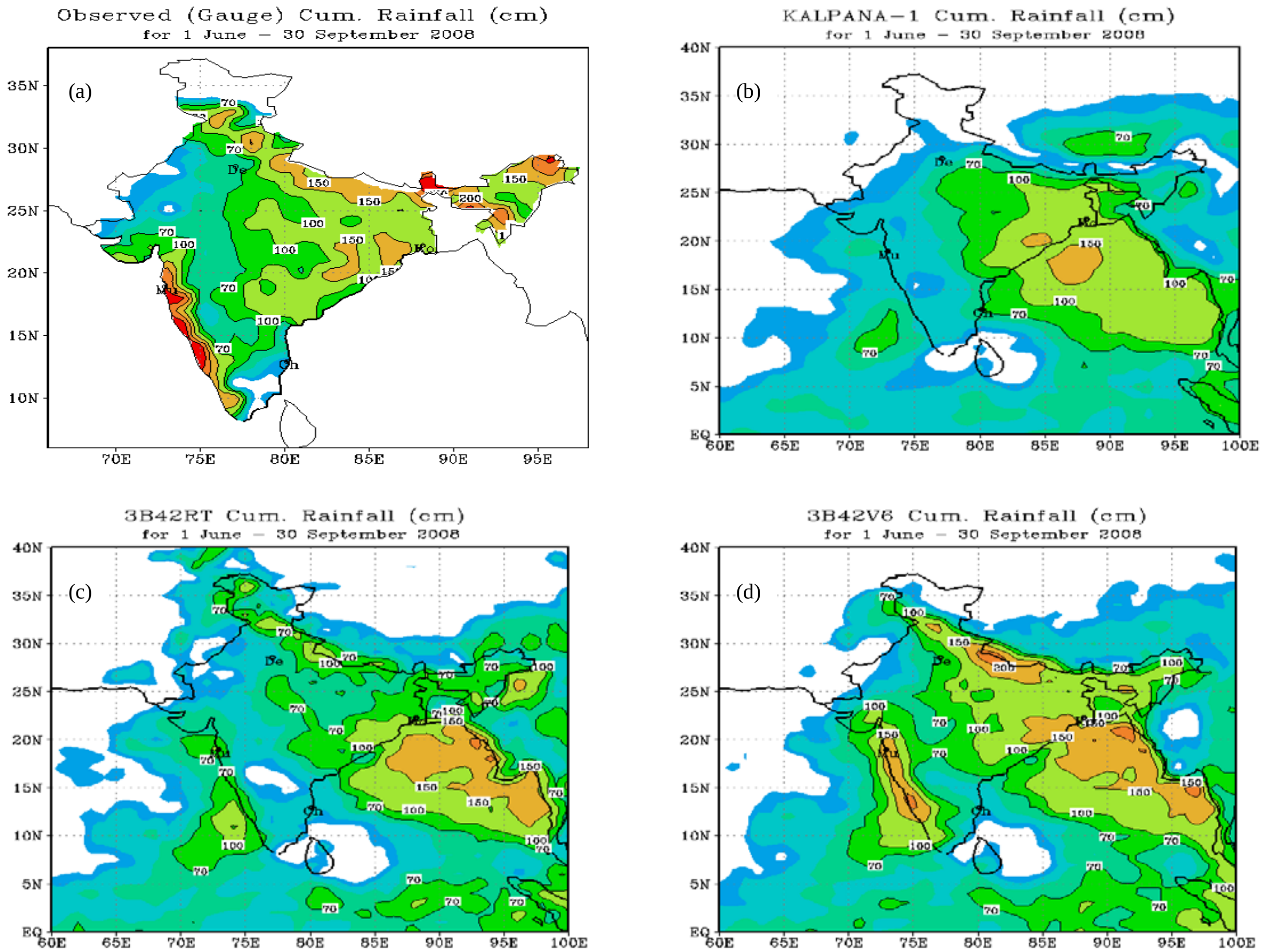
For monsoon 2007, the total rainfall for the whole of the country was 105% of the long term average normal



Figs. 3(a-d). Same as Figs. 2(a-d) but for the year 2007

(IMD, 2008). Onset of monsoon over Kerala, extreme southwest state of India was on 28 May, 4 days in advance of the normal date of onset over Kerala. Further advancement of monsoon took place from 8 June onward after a hiatus of 9 days. It covered the northeastern states by 10 June, peninsular India and central India by 25 June and subsequently the entire country on 4 July, nearly 11 days ahead of the normal schedule. The southwest monsoon started withdrawing from northwest parts of the country on 30 September against the normal date of withdrawal of 15 September.

In the monsoon season of 2008, the cumulative seasonal rainfall for the country as a whole was near normal and it was 98% of its long period average (IMD, 2009). The monsoon set in over Kerala on 31 May, one day prior to the normal date. Further, advance took place quite rapidly mainly due to a depression (5 - 6 June) over the east central Arabian Sea and a well marked low pressure area (9 - 11 June) over Saurashtra & Kutch and neighborhood. By 16 June, southwest monsoon had covered most parts of the country except for some parts of Rajasthan. The rapid advance of monsoon could be attributed to the interaction of the monsoon circulation with mid-latitude westerly system. Subsequently, there was a hiatus in the further advance due to the weakening of the monsoon current for 23 days from 17 June to 09 July. The monsoon covered the entire country by 10 July, against normal date of 15 July. There was a delay in the commencement of withdrawal of southwest monsoon from extreme west Rajasthan. The southwest monsoon withdrew from entire Jammu & Kashmir, Himachal Pradesh, Punjab, Haryana, Chandigarh & Delhi, west Rajasthan, most parts of Uttarakhand, west Uttar Pradesh

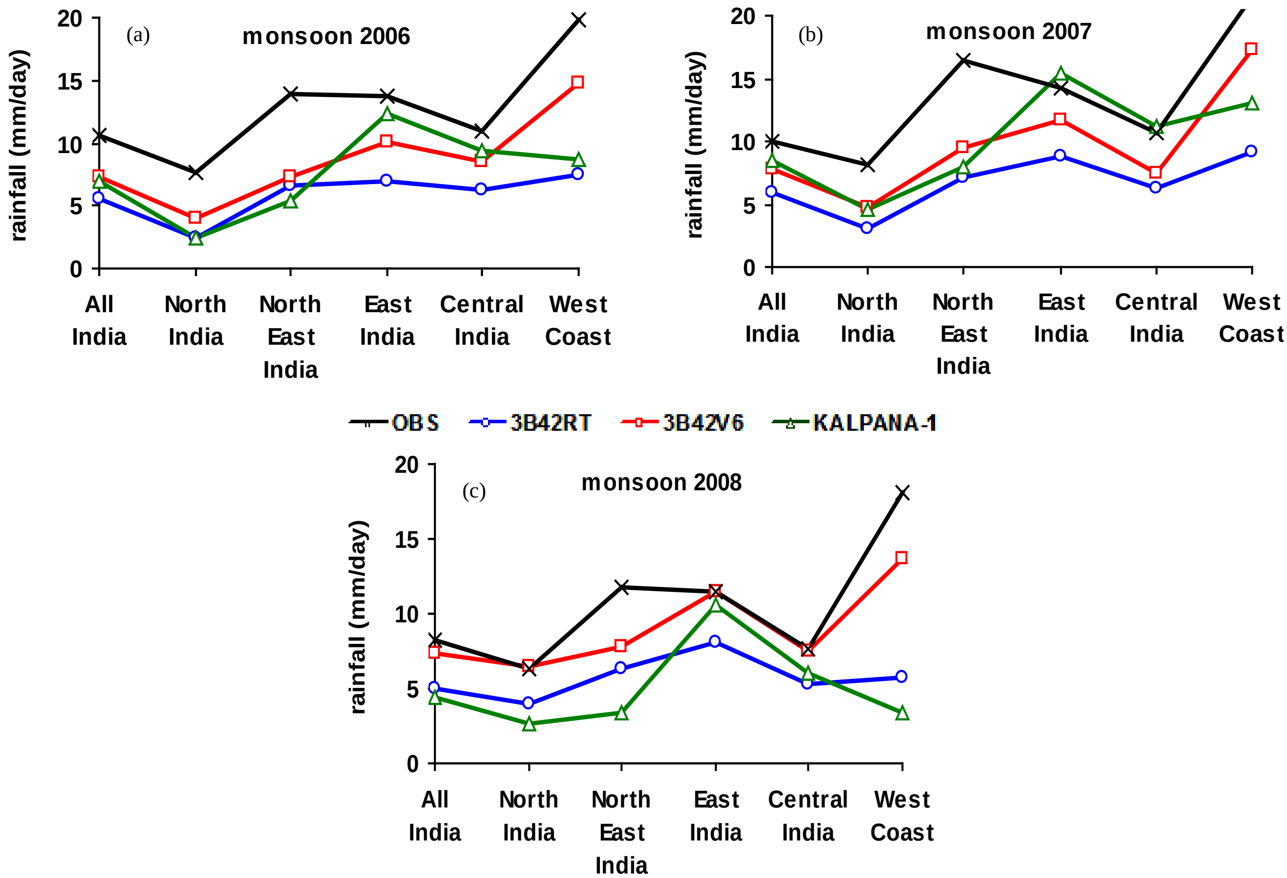


Figs. 4(a-d). Same as Figs. 2(a-d) but for the year 2008

and east Rajasthan, some parts of north Gujarat State and north Arabian Sea on 29th September. The normal date of withdrawal of southwest monsoon from west Rajasthan is 1 September. The delay was mainly due to the presence of systems in westerlies over northwest India interacting with the monsoon circulation (Kalsi *et al*., 1980).

3.2. *Spatial distribution of Gauge observed and satellite estimated rainfall over India*

The spatial distribution of cumulative seasonal (June-September; JJAS) rainfall over India from Rain Gauge (IMD) and satellite products (KALPANA-1, 3B42-RT and 3B42V6) for the monsoon year of 2006, 2007 and 2008 are shown in Figs. 2(a-d), Figs. 3(a-d) and Figs. 4 (a-d) respectively. The observed seasonal total rainfall (IMD) distribution for 2006 [Fig. 2(a)] shows a north-south oriented belt of heavy rainfall along the west coast between latitude 8° N and 20° N with two peaks (> 250 cm) centered near Lat. 13° N and Lat. 17° N. The sharp gradient of rainfall between the west coast heavy rain region and the rain shadow region to the east is brought out realistically in the observed rainfall. Two heavy rainfall pockets (>200 cm) one over the Gangetic plains and another over the extreme northeastern parts of the country are observed. The KALPANA-1 [Fig. 2(b)] and 3B42RT [Fig. 2(c)] products do not show the observed high rainfall over the west coast and the northeast of India. The high rainfall over both of these west coast and north east of India is attributed to orography; it is captured by seasonal TRMM PR measurements and SSM/I data (Xie *et al.*, 2006). The 3B42-V6 [Fig. 2(d)] product captures the pattern of orographic rain seen in the IMD data, but underestimates the rainfall amount. A possible reason for under estimation of satellite derived orographic rainfall by INSAT KALPANA-1 is partly due to the maximum

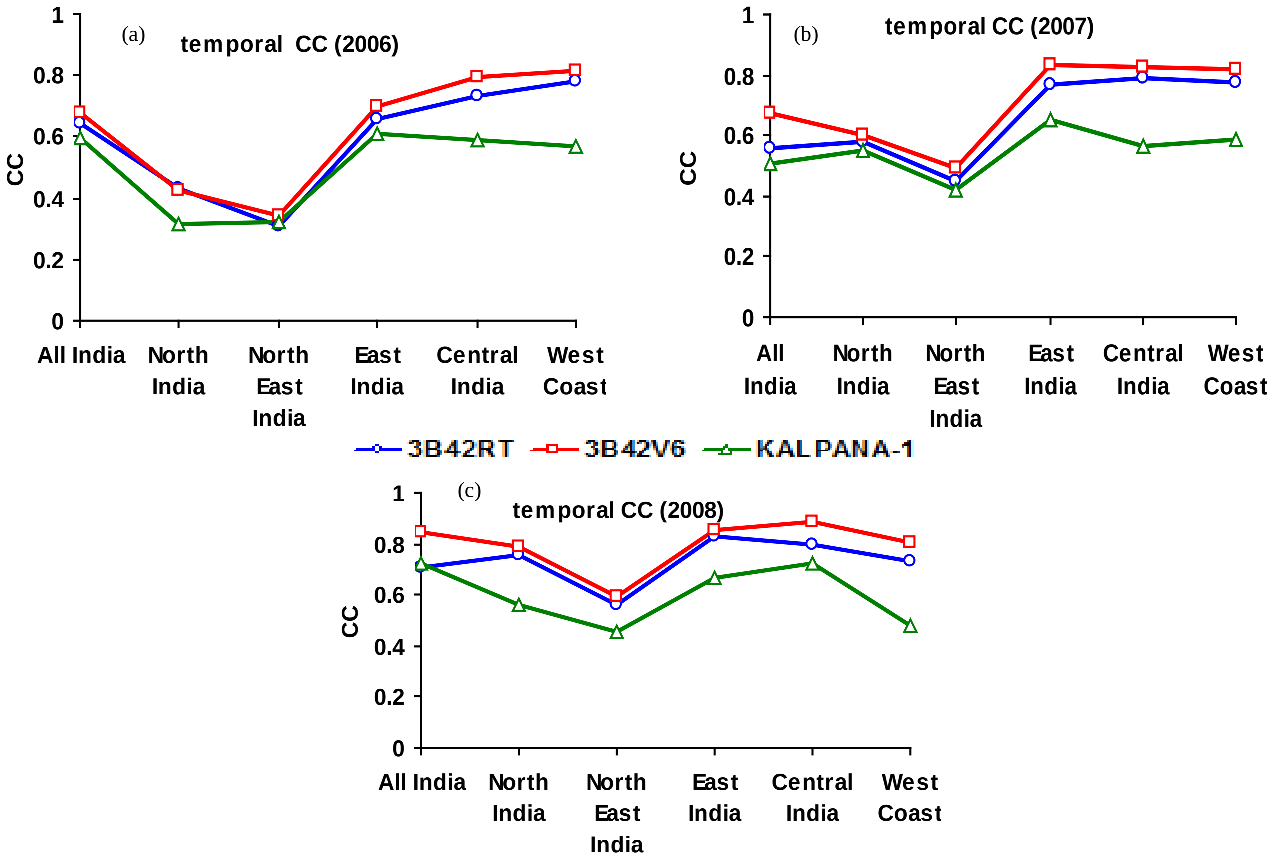


Figs. 5(a-c). Area weighted seasonal (Jun-Sep) rain rate (mm/day) from Rain Gauge (IMD) and Satellite products (KALPANA-1, 3B42RT and 3B42V6) over All India, North India, North East India, East India, Central India and West coast of India for the summer monsoon of (a) 2006; (b) 2007 and (c) 2008

rainfall rate constant 72 mm/day which is unrealistically low in the context of intense Mesoscale convective orographic rainfall. Large errors of orographic rainfall by TRMM may be closely related to issues of hydrometeors vertical profile in the Passive Microwave retrievals. The Passive Microwave scattering associated with ice particles above the freezing level is relatively weak in the orographic rainfall, and retrieval using high frequency channel may be regarded as small [Takuji *et al*. (2009)].

During the year 2007, the observed seasonal total rainfall (IMD) distribution [Fig. 3(a)] shows a continuous north-south oriented orographic heavy rainfall along the west coast with a peak value of more than 250 cm. The heavy rainfall region over north east India shows a peak of 250 cm. We find another region with a maximum of 150 cm of rainfall over the Gangetic plains and south of the axis of the normal position of the monsoon trough. The west coast rainfall amount in the KALPANA-1 [Fig. 3(b)] and 3B42RT [Fig. 3(c)] are only 100 to 150 cm. Compared to the IMD observed rainfall [Fig. 3(a)], both the KALPANA-1 and 3B42RT products underestimate the rainfall over the west coast of India. The observed heavy rainfall [Fig. 3(a)] pockets (>200 cm) over the extreme northeastern parts of the country are not seen in all the three satellite products. Like in the year 2006, the 3B42-V6 [Fig. 3(d)] product captures the pattern of orographic rain seen in the IMD gauge data [Fig. 3(a)] in 2007 also, but consistently underestimates the rainfall amount. This (3B42-V6) product also underestimates rain over the Gangetic plains Fig. 3(d).

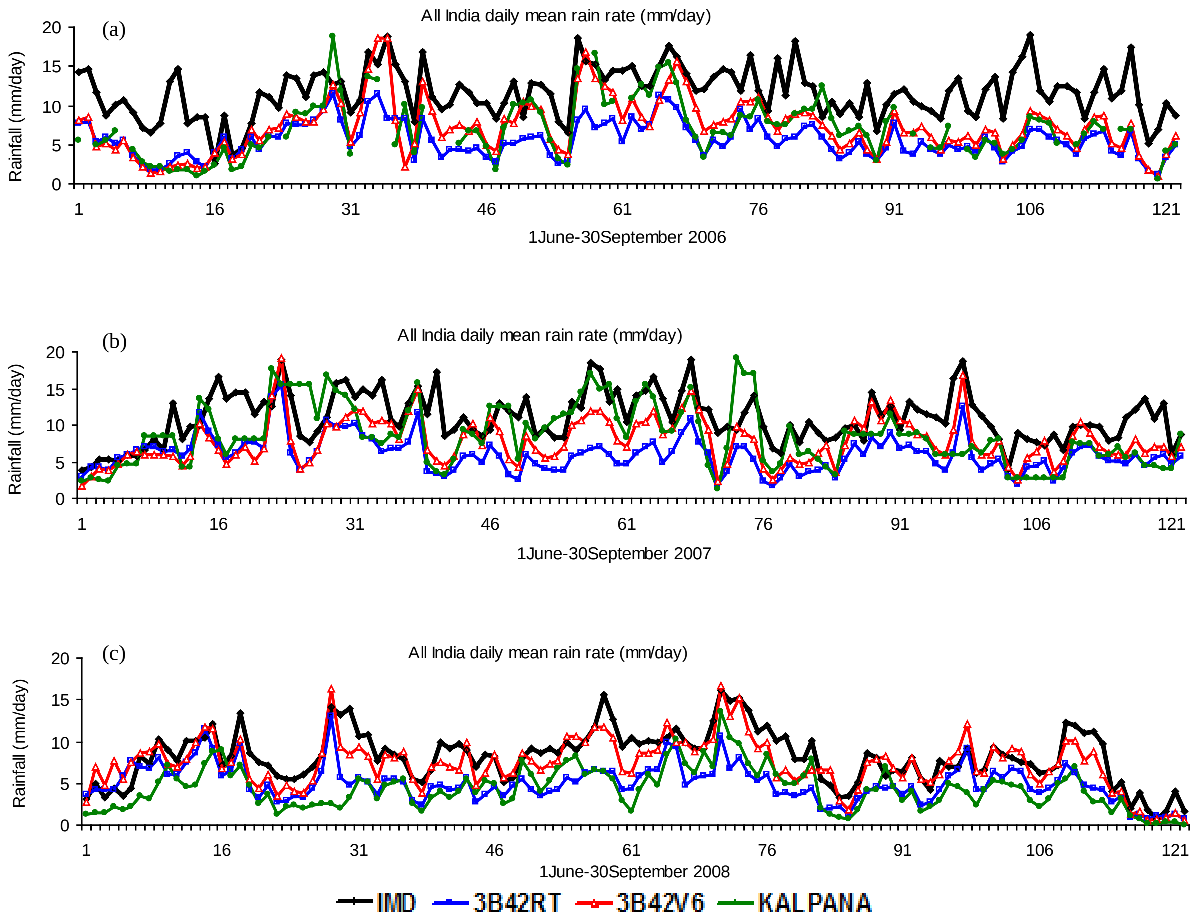
Like other previous years, in 2008, the large seasonal total precipitation due to topographical forcing over the west coast (>250 cm) and the north eastern parts of the country (200-250 cm) are seen in the rain gauge (IMD) seasonal total precipitation [Fig. 4(a)]. Another region of large precipitation (IMD 1981) in the eastern part of the



Figs. 6(a-c). Correlation coefficient between domain mean observed Rain Gauge rainfall (IMD) and Satellite products (KALPANA-1, 3B42RT and 3B42V6) over All India ,North India, North East India, East India, Central India and West coast of India for the summer monsoon of (a) 2006 ; (b) 2007 and (c) 2008

country to the south of the seasonal average location of the eastern part of the monsoon trough is observed with a peak of 150 cm. In contrast to the other two regions, the large seasonal total precipitation over the eastern part of the country particularly over coastal Orissa and adjoining Gangetic West Bengal (GWB) regions is not topographical forcing, but is due to dynamical forcing produced by the generation of cyclonic circulations near the eastern end of the monsoon trough dipping into the Bay of Bengal (Rao 1976). In the IMD rain gauge [Fig. 4(a)] observations, we get another region of maximum rainfall (more than 150 cm) along the foothills of the Himalayas mountain range. Contours in both the 3B42RT [Fig. 4(c)] and 3B42V6 [Fig. 4(d)] products indicate a region of high rainfall in that area, but the area of coverage and values are lower as compared to the observed value. This realistic rainfall is not seen in the KALPANA-1 [Fig. 4(b)] product. The sharp gradient of rainfall between the west coast heavy rainfall and the rain shadow region to the east, which is normally expected, is noticed in the observed [Fig. 4(a)] as well as the satellite estimated products [Figs. 4(b-d)]. The region of scanty precipitation over the desert to the west of the country and over south east peninsular India (southern part of Tamilnadu) with the seasonal accumulated precipitation of less than 20 cm are also noticed in both observed [Fig. 4(a)] and satellite estimated products [Figs. 4(b-d)].

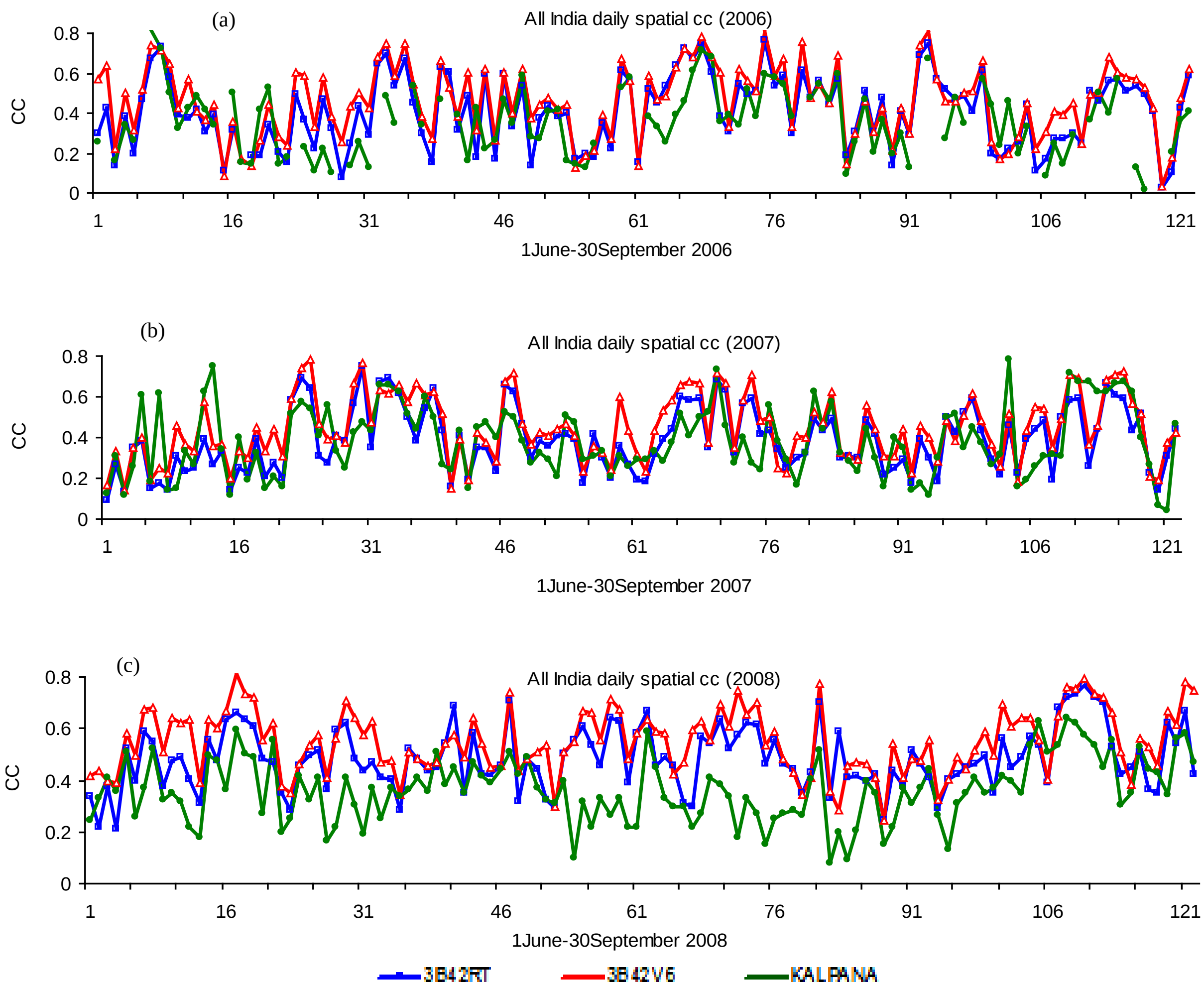
The inter-comparison of satellite products with the rain gauge observations suggests that the TRMM 3B42V6 product could distinctly capture characteristic features of the summer monsoon such as north–south oriented belt of heavy rainfall along the Western Ghats with sharp gradient of rainfall between the west coast heavy rain region and the rain shadow region to the east, pockets of heavy rainfall along the location of monsoon trough, over the east central parts of the country, over north-east India, along the foothills of Himalayas and over the north Bay of Bengal. However, the near real-time products KALPANA-1 [Figs. 2(b), 3(b) & 4(b)] and 3B42RT [Figs. 2(c), 3(c) & 4(c)] underestimate the orographic heavy rainfall along the Western Ghats of India.



Figs. 7(a-c). Time series of All-India area weighted rainfall (mm/day) from rain gauge (IMD) and satellite products (KALPANA-1, 3B42RT and 3B42V6) for the period from 1 June -30 September of year (a) 2006,(b) 2007 and (c) 2008

The observed and satellite estimated seasonal mean rain rate (mm/day) over all India and four representative areas over Indian land *i.e*., North India (NI), Eastern India (EI), North East India (NEI), Central India (CI), and West coast of India (WC) for the monsoon year of 2006,2007 and 2008 is plotted in Figs. 5 (a-c). It shows that all the satellite products underestimate the observed (IMD) seasonal mean rain rate in all the three years and in all the four areas of study. The KALPNA-1 rainfall estimates over East India and central India box are close to the observed rainfall (IMD) during all the three years. The rainfall due to orographic effect over north east and west coast of India are underestimated by all the satellite products in all the years of study, but the estimation by 3B42V6 product is better as compared to 3B42RT and KALPANA-1 data in terms of spatial pattern and magnitude to capture monsoon features like heavy rainfall belt along the west coast and over the monsoon trough region.

The correlation coefficient (cc) between daily domain mean observed and satellite estimated precipitation over all India and four representative regions for the monsoon years of 2006, 2007 and 2008 is shown in Figs. 6 (a-c). The correlation coefficient between trends in the satellite estimation and observation is a measure of the phase relationship between them. From Fig. 6(a), it is seen that the domain mean (cc) for all satellite products are consistent with each other in all the 3 years (2006-2008). The 3B42V6 has higher (cc) as compared to other two products (3B42RT and KALPANA-1) over four homogeneous domains (North India, Eastern India, North East India, Central India, and West coast of India) of study during the monsoon periods (2006-2008). All the products show lower (cc) over North East India in all 3 years. The lower (cc) over North East India shows that the difference in predicted and observed daily mean rainfall over this region is more as compared to other regions. In general, the values of correlation coefficient for all the



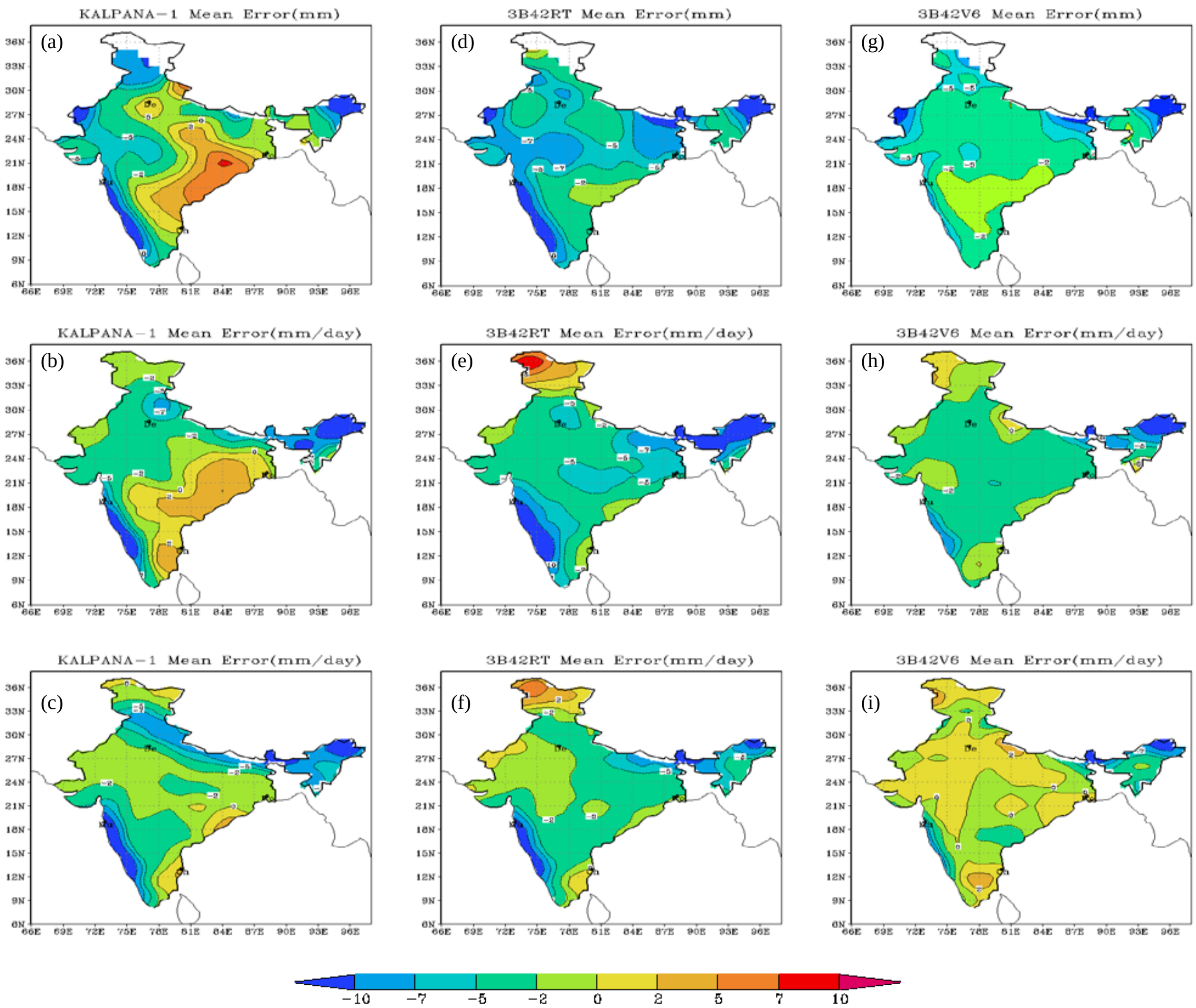
Figs. 8(a-c). Time series of daily spatial correlation coefficient between rain gauge and satellite products (KALPANA-1, 3B42RT and 3B42V6) for the period from 1 June -30 September of year (a) 2006, (b) 2007 and (c) 2008

satellite products are greater than 0.50 over all the four domains, except in 2006 [Fig. 6(a)] over NE India.

3.3. *Temporal distribution of Gauge observed and satellite estimated rainfall over Indian land areas*

In order to examine how the satellite based rainfall estimation products capture time variability, we computed the daily area weighted all India observed (IMD) and satellite (3B42RT, 3B42V6 and KALPANA-1) estimated precipitation (mm/day) for the summer monsoon season (Jun-sep) of 2006 [Fig. 7(a)], 2007 [Fig. 7(b)] and 2008 [Fig. 7(c)]. The satellites estimated mean rain rate (mm/day) during monsoon 2006 [Fig. 7(a)] are in phase with observed rain gauge (IMD) rainfall, indicating a consistency in the satellite estimation. The seasonal (Jun-Sep) mean rain rates from rain gauge (IMD), KALPANA-1, 3B42RT and 3B42-V6 for the monsoon 2006 are 10.7, 7.0, 5.6 and 7.3 mm/day respectively. The correlation between the mean observed rainfall from rain gauge (IMD) and KALPANA-1, 3B42RT and 3B42-V6 products are 0.6, 0.65 and 0.68. The 3B42V6 and KALPANA-1 show low biases compared to 3B42RT product.

Fig. 7(b) shows the time series of mean rain rate (mm/day) during monsoon season of 2007 for rain gauge and satellites estimates. The seasonal mean rain rates for the monsoon 2007 from rain gauge (IMD), KALPANA-1, 3B42RT and 3B42-V6 are 10.1, 8.6, 6.0 and 7.8 mm/day respectively and the correlation for KALPANA-1, 3B42RT and 3B42-V6 products in monsoon 2007 are 0.51, 0.56 and 0.69. The bias for 3B42V6 and KALPANA-1 are 2.6 and 1.6 mm/day. It show low biases

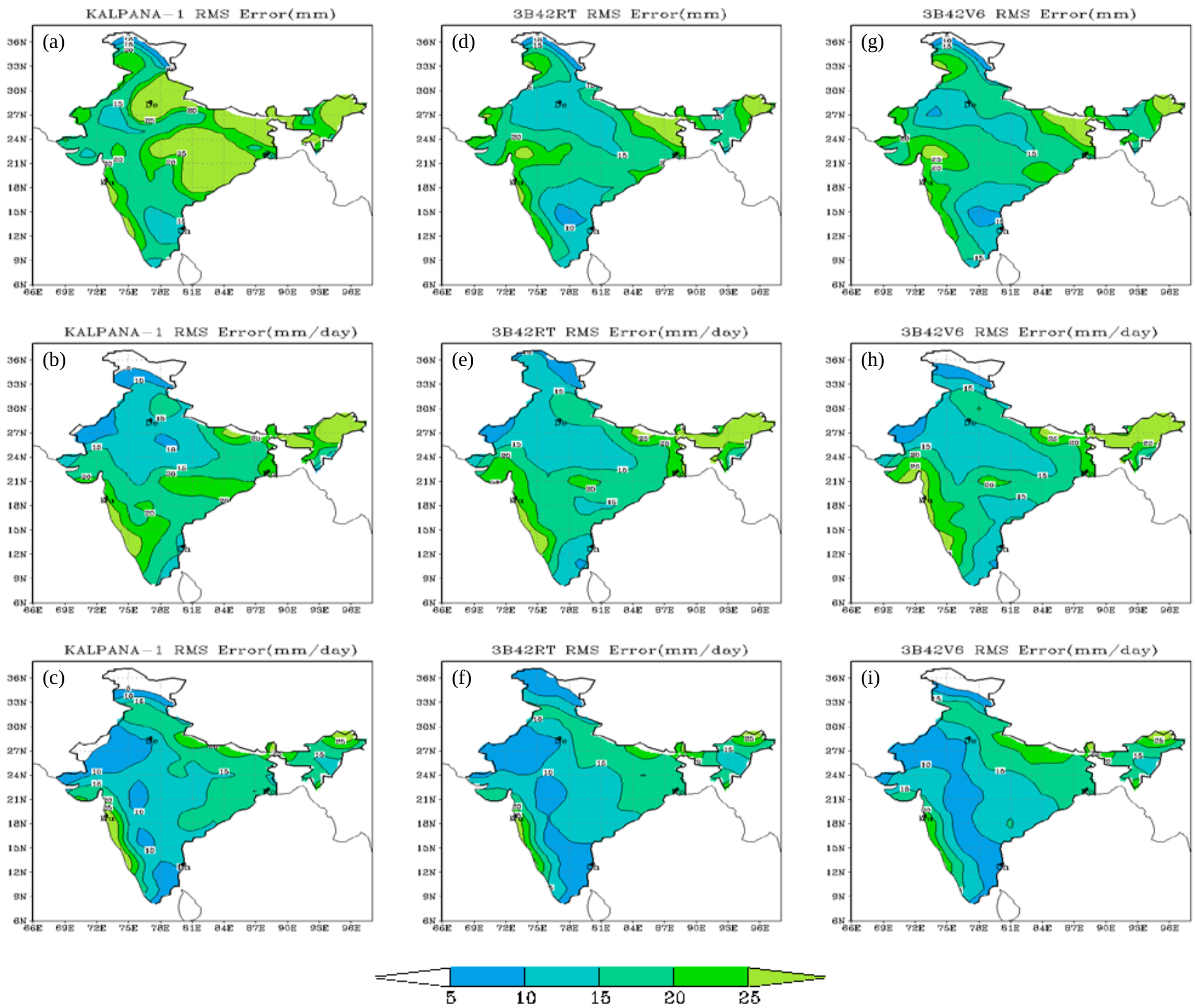


Figs. 9(a-i). Spatial distribution of mean Error (Satellite – Gauge) rainfall (mm/day) from (a-c) KALPANA-1; (d-f) 3B42RT and (g-i) 3B42V6 for the period from 1 June to 30 September of 2006, 2007 and 2008

in 2007 as compared to 2006. During the active monsoon period, KALPANA-1 estimates are close to rain gauge (IMD) measurement.

The time series of rain gauge (IMD), KALPANA-1, 3B42RT and 3B42-V6 rain rates for the monsoon 2008 is shown in Fig. 7(c). There are good agreements between these products. The daily average rain rate (mm/day) for rain gauge(IMD), KALPANA-1, 3B42RT and 3B42-V6 are 8.2, 4.6,5.0 and 7.3 mm/day respectively.The correlation between rain gauge (IMD) and KALPANA-1, 3B42RT and 3B42-V6 products are 0.71, 0.72 and 0.81 respectively for 2008 monsoon. The bias for KALPANA-1 and 3B42RT are 3.9 and 3.3 mm/day. The 3B42V6 product show better correspondence to rain gauge observation in 2008. The bias for 3B42V6 is -0.8 mm/day, a low negative bias compared to 3B42RT (-3.3 mm/day) and KALPANA-1 (-3.8 mm/day).

The phase of all the satellite estimated rainfall [Figs. 7(a-c)] is in general agreement with the observed phase of the day-to-day variations for most of the 122 days in the three monsoon seasons of 2006, 2007 and 2008, indicating the possibility of predicting the all India average rainfall using satellite products. All the satellite products underestimate the observed (IMD) rain gauge measurement throughout most of the 122 days in the seasons. The satellite based products capture time variability of the all India average rainfall. Heavy rainfall events are in general underestimated in 3B42RT and



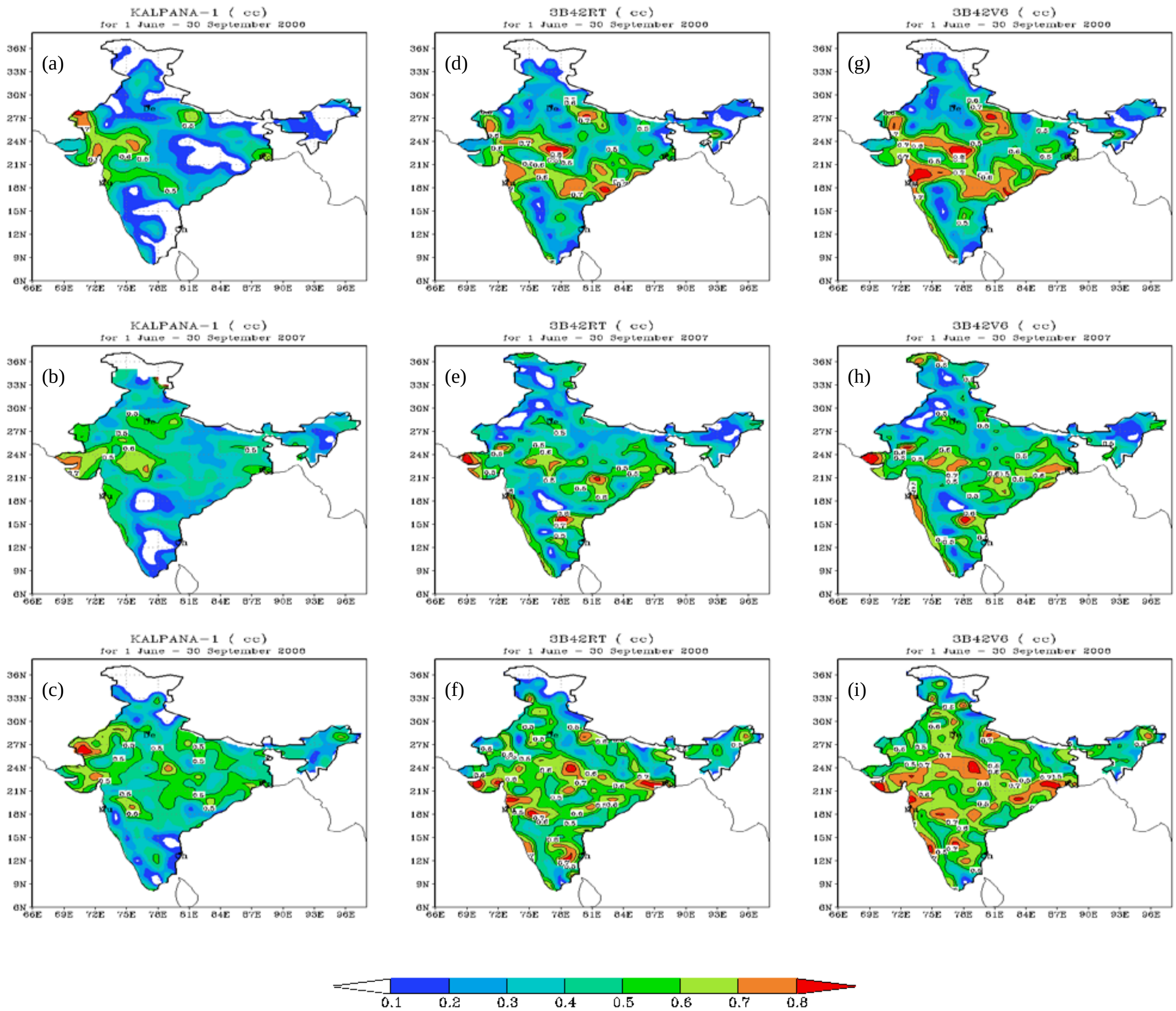
Figs. 10(a-i). Spatial distributions of Root Mean Square Error rainfall (mm/day) from (a-c) KALPANA-1 (d-f) 3B42RT and (g-i) 3B42V6 for the period from 1 June to 30 September of 2006, 2007 and 2008

KALPANA-1 data. The major active spells are picked up by 3B42V6 in all three years (2006-2008) of study and KALAPANA-1 data in 2006 and 2007 but 3B42RT tends to underestimate peak rainfall during active monsoon periods. These results suggest that among the three satellite products, 3B42-V6 product may be the most suitable for study of variability on daily and longer time scales.

The time series of daily spatial correlation coefficient between rain gauge observation and the satellite products (KALPANA-1, 3B42RT and 3B42V6) over Indian land areas computed for the monsoon season of 2006, 2007 and 2008 is shown in Figs. 8 (a-c). Spatial correlation is computed from 313 grid boxes over Indian land areas. For almost every day during monsoon 2008, the 3B42V6 perform better as compared to other satellite products. The inter-comparison of daily spatial correlation coefficient (cc) of satellite products over all India is more consistent with the daily rainfall time series shown in Figs. 7 (a-c).

3.4. *Evaluation skill of the satellite products*

We now present and discuss the results of some computations of Mean Error, Root mean square Error and correlation coefficient based on the satellite products for monsoon season of 2006, 2007 and 2008. The purpose of



Figs. 11(a-i). Spatial distributions of correlation coefficient between Gauge observation and Satellite Estimation from (a-c) KALPANA-1; (d-f) 3B42RT and (g-i) 3B42V6 for the period from 1 June to 30 September of 2006, 2007 and 2008

these calculations is to evaluate the performance and examine the relationship between these measures of skill in a realistic context. We have used the IMD grid to mask out oceanic regions from the satellite products for computing the error statistics.

(*i*) *Spatial distribution of seasonal mean Error*

In order to quantify the difference between the observed (IMD) and satellite estimated rainfall over land areas of the Indian region, spatial distributions of mean error (satellite-Gauge) for monsoon 2006, 2007 and 2008 are shown in Figs. 9(a-i). The KALPANA-1 shows considerable underestimation of orographic rainfall (>10 mm/day) along the west coast of India and over north east India and slight underestimation of orographic rainfall (2-5 mm/day) along the foothills of Himalayas during monsoon seasons of 2006, 2007 and 2008 [Figs. 9(a-c)], whereas it shows excessive rainfall over east central parts of the country, over the domain of south-eastern end of monsoon trough. The excessive rainfall (overestimation) over east central parts of the country in 2006 [Fig. 9(a)] is high and is in the order of 5-7 mm/day, while in 2007 [Fig. 9(b)], it reduced to 2-5 mm/day. Both the area and magnitude of error are further reduced considerably in 2008 [Fig. 9(c)]. No appreciable difference is noticed between observed (IMD) and satellite estimated rainfall over the rest of the country.

The 3B42RT [Figs. 9(d-f)] product underestimates the rainfall over the entire Indian land areas in all three years (2006, 2007 and 2008) of study. The underestimation of orographic rainfall along the west coast of India and over north east India is very high in 3B42RT. It also underestimates the rainfall over the Gangetic plains and to the south of the normal position of the monsoon trough in 2006 and 2008. From Figs. 9 (d-f), it shows that the estimation by 3B42RT is improved considerably from 2006 to 2008. Like 3B42RT product, the 3B42V6 [Figs. 9 (g-i)] product also underestimates the rainfall over the entire Indian land areas in 2006 and 2007, but the underestimation of orographic rainfall along the west coast of India and over north east India is less as compared to KALPANA-1 and 3B42RT products. The spatial distribution of errors (3B42V6) is more or less uniform over wide areas in 2006 and 2007. The mean error for 3B42V6 in 2008 shows positive error(overestimation) over northern part and negative errors (under estimation) over southern parts of the country. But the mean error in 2008 is within the range of ±2 mm/day over Indian land areas.

(*ii*) *Spatial distribution of Root Mean Square Error*

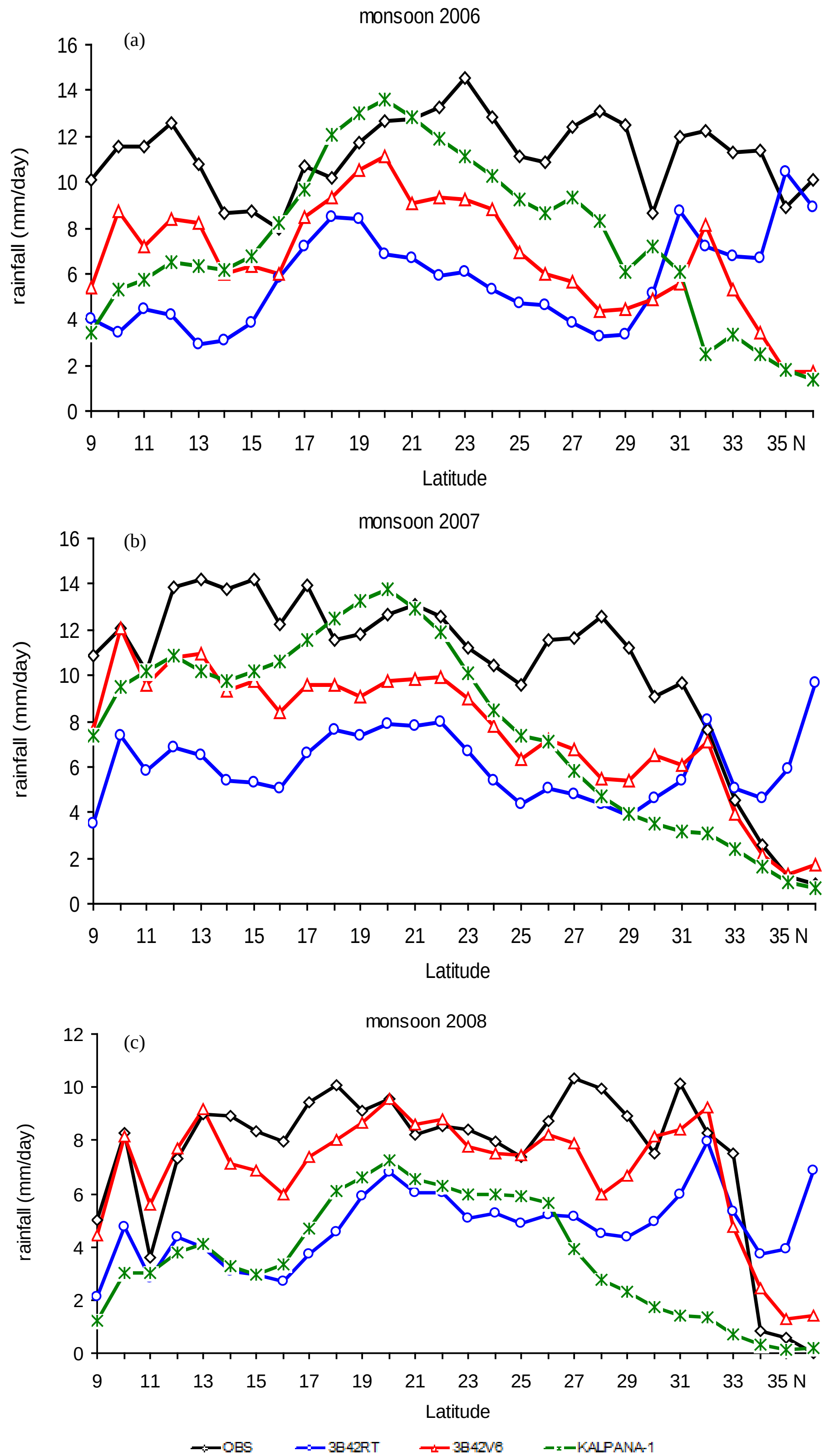
The spatial distributions of root mean square error (RMSE) for KALPANA-1,3B42RT and 3B42V6 for monsoon 2006, 2007 and 2008 is shown in Figs. 10 (a-i). The RMSE for KALPANA-1 [Figs. 10(a-c)] ranges between 20 and 30 mm/day along the west coast, eastern part of monsoon trough, over north east India and over few pockets along the foothills of the Himalayas. The RMSE decreases over the remaining parts of the country and remains within a reasonably small range. The RMSE of both 3B42RT [Figs. 10(d-f)] and 3B42V6 [Figs. 10(g-i)] have a magnitude between 10 and 20 mm/day over the country in 2006 and 2007 and between 5-15 mm/day in 2008, except along the west coast and over the north-eastern parts of the country where the magnitude of rmse exceeds 25 mm/day. The inter comparison of satellite (KALPANA-1,3B42RT and 3B42V6) products shows that the errors are of a more systematic type.

(*iii*) *Spatial distribution of Correlation Co-efficient*

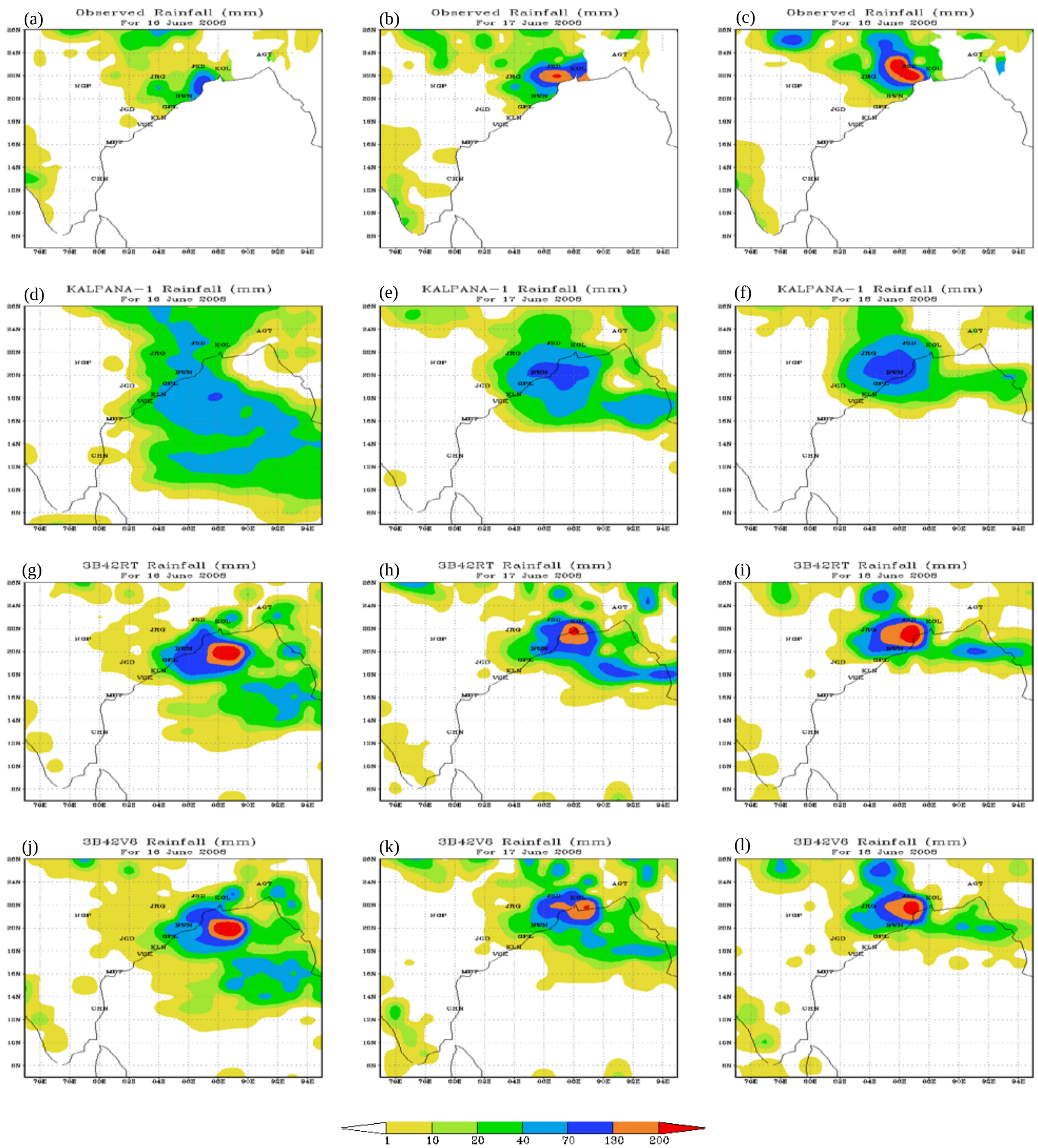
The correlation coefficient (cc) between the observed and the satellite products (KALPANA-1,3B42RT and 3B42V6) over Indian land areas for monsoon 2006, 2007 and 2008 is shown in Figs. 11 (a-i). The magnitude of (cc) for KALPANA-1 in 2006 [Fig. 11(a)] lies between 0.2 and 0.4, while over large parts of west central and adjoining north west India, the magnitude of (cc) exceeds 0.6. Within this area there are regions where the magnitude of (cc) exceeds 0.7. The spatial pattern of (cc) for KALPANA-1 in 2007 [Fig. 11(b)] is similar to that in 2006, except in pockets near the west coast where the (cc) values still exceed 0.6. Both the magnitude and spatial distribution of (cc) increases significantly in 2008 [Fig. 11(c)], with higher (cc) of more than 0.6 has been observed over many parts of Gangetic West Bengal, central and parts of north west India. For the 3B42RT product, the higher (cc) is observed over central India in 2006 [Fig. 11(d)] and it spreads southward and along the west coast in 2007 [Fig. 11(e)], while it improved significantly with higher (cc) exceeding 0.6 over many parts of the country in 2008 [Fig. 11(f)]. The spatial pattern of (cc) for 3B42V6 [Figs. 11 (g-i)] is similar to 3B42RT product with exceptional higher magnitude of (cc) over west cost of India. The inter-comparison clearly indicates that the post real time research product 3B42V6 could take advantage of rain gauge observations over land areas where performance of satellite estimates is poor, particularly for orographic rainfall. This indicates that the trend in estimation of precipitation in the 3B42V6 product is in good phase relationship with the observed trend over a large part of the country. Note that the 3B42V6 estimates are very close to the observed values in all statistics over the entire period of study. The skill of the product is dependent on the spatial coverage of the rainfall, *i.e.*, it is easier to estimate with reasonable accuracy over a large area than a small one, and when the rainfall is widespread rather than localized.

(*iv*) *Meridional transects of mean rainfall*

Figs. 12 (a-c) shows latitudinal transects of seasonal rainfall (mm/day) based on rain gauge (IMD) and satellite products (KALPANA-1, 3B42RT and 3B42V6) for the summer monsoon of 2006, 2007 and 2008. These were calculated for a longitudinal band covering Indian land area from 70E to 100E, using, for each dataset, the grid boxes or Rain Gauge stations within this area. The agreement between 3B42V6 and the reference rain-gauge (IMD) data is good for the season as a whole in 2006 and 2007, while it is excellent for 2008. The comparisons in Figs. 12(a-c) thus suggest that the latitudinal transects of seasonal mean rainfall is in good linear relationship with little bias, but the seasonal estimates for 3B42V6 in 2008 is superior to the other satellite products in all latitudes. The performance of 3B42RT in 2006 and 2007 is similar to that of 3B42V6, although there is some tendency for underestimation. The 3B42RT continuously underestimate with respect to the observed rainfall (gauge) in all the 3 monsoon seasons (2006-2008). The over estimation rainfall by KALPANA-1 product over Eastern part of country during monsoon 2006 and 2007 are reflected in Figs. 12 (a&b). The results are consistent with those in Figs. 2-4 of the seasonal cumulative rainfall. 3B42RT and KALPANA-1 perform poorly, with 3B42RT markedly underestimating seasonal rainfall nearly everywhere and



Figs. 12(a-c). Latitudinal transect of seasonal rain rate (mm/day) based on Rain Gauge (IMD) and Satellite products (KALPANA-1, 3B42RT and 3B42V6) during the summer monsoon season of (a) 2006, (b) 2007 and (c) 2008



Figs. 13 (a-l). (a-c) Observed (top panel) and corresponding satellite estimated rainfall from (d-f) KALPANA-1(second panel); (g-i) 3B42RT (third panel) and (j-l) 3B42V6 (bottom panel) for 16, 17 and 18th June 2008

KALPANA-1 underestimating rainfall north of approximately 28° N and south of approximately 15° N. For monsoon 2008 [Fig. 12(c)], 3B42RT and KALPNA-1 underestimate rainfall nearly everywhere along the latitudes and its estimated values are also matching with each other up to latitudes south of 28° N.

TABLE 2

Bias between rain gauge and satellite products

	2006			2007			2008		
BIAS (mm/day)	3B42RT	3B42V6	KALPANA	3B42RT	3B42V6	KALPANA	3B42RT	3B42V6	KALPANA
All India	-5.1	-3.4	-3.7	-4.1	-2.3	-1.6	-3.3	-0.8	-3.8
North India	-5.9	-4.2	-5.7	-5.1	-3.5	-4.5	-2.5	0.13	-3.8
North East India	-7.3	-6.8	-8.7	-9.4	-7	-9.2	-5.5	-4.0	-8.3
East India	-6.9	-3.8	-1.4	-5.6	-2.8	2.1	-3.4	-0.1	-0.9
Central India	-4.7	-2.5	-1.6	-4.5	-3.2	-0.1	-2.4	-0.2	-1.7
West Coast	-12.4	-5	-11.1	-12.3	-4.3	-10.6	-12.5	-4.4	-14.8

TABLE 3

Root mean square error (RMSE) between rain gauge and satellite products

	2006			2007			2008		
RMSE (mm/day)	3B42RT	3B42V6	KALPANA	3B42RT	3B42V6	KALPANA	3B42RT	3B42V6	KALPANA
All India	6.6	5.2	5.4	6	4.3	4.7	3.3	1.4	3.8
North India	8.6	8.6	9.4	8.6	7.7	7.8	5.0	4.8	6.8
North East India	13.1	12.7	13.5	15.6	14	15.2	9.9	7.1	11.3
East India	10.4	8.8	9	10.9	8.4	13.2	7.7	6.2	9.7
Central India	6.7	5.4	6.6	6.4	5.2	7.3	4.1	2.2	4.5
West Coast	20.2	15	19.2	20.1	15.1	22.2	20.6	13.8	24.7

(*v*) *Case study; Monsoon depression of 16-18 June 2008*

A low-pressure area formed over the North Bay of Bengal at 0300 UTC of 15 June 2008. The system concentrated into a depression and lay centered at 0300 UTC of 16 June near Lat. 21.5° N Long. 90° E. The system continued to move in a northwesterly direction till 17 June morning and then moved slightly west-northwest wards. It further moved in a north-westerly direction till 18th morning before it weakened into a low pressure area. An inter-comparison of rainfall estimations by these satellite products (KALPNA-1, 3B42RT and 3B42V6) against observed rainfall of 16, 17 and 18 June 2008 is shown in Figs. 13 (a-i). On 16th June, the heavy rainfall occurred over the sea near Lat. 20° N, Long. 88 °E. It was captured by all the satellite products, but the estimation by KALPANA-1 [Fig. 13(d)] was only 70-130 mm against >200 mm by both the TRMM (3B42RT and 3B42V6) products [Figs. 13 (g-l)]. The observed rainfall for 17th June [Fig. 13 (b)] shows a patch of heavy rainfall over the Head Bay of Bengal to the south of Calcutta with a peak of order 200 mm in association with this depression. The 3B42RT and 3B42V6 could capture the heavy rainfall area and amount with slight shift in location, but KALPANA-1 failed to capture the correct location and amount of the heaviest rainfall in association with the depression. KALPANA-1 showed heavy rainfall in the order of 70-130 mm over Orissa coast to the south of the actual observed positions on 17th June. The heavy rainfall patch moved slightly northwestwards on 18th due to the movement of the system. The rainfall estimation for 18 June reveals that both the 3B42RT [Fig. 13 (i)] and 3B42V6 [Fig. 13 (l)] products could capture the magnitude and location of heavy rainfall in a more realistic way. KALPANA-1 [Fig. 13(f)] continuously shows some mismatch in capturing the location and magnitude of heavy rainfall in association with the depression. The inter-comparison of rainfall estimation for 16-18 June 2008 shows that the TRMM near real time product 3B42RT and post real time research quality product 3B42V6 could capture the magnitude and location of heavy rainfall in a more better and a realistic way in all three days. The limitation of KALPANA-1 is that it cannot produce more than 72 mm rainfall in 24 hours, due to the limitation of rainfall algorithm used, which is not true in the case of monsoon depression or other intense synoptic systems. So, it always under-estimates the rainfall when it becomes more than 72 mm in a day.

(*vi*) *Error statistics*

Error statistics are calculated by comparing rainfall estimates from satellites (KALPANA-1, 3B42RT and 3B42V6) at individual grid boxes and by using the IMD gauge rainfall as a reference. The analysis is based on the grid box domains shown in Fig. 1. For all the satellite products, bias and rms errors are calculated relative to the observed gauge dataset. The average of the errors over a long period of time is a measure of the systematic part of the error, while root-mean-square error (rmse) is a measure of the random component of the error in the satellite estimation. The TRMM (3B42RT and 3B42V6) and KALPANA-1 rainfall products contain both random errors and systematic errors (the biases). The results of bias and rms error are presented in Table 2 and Table 3 respectively. For both 3B42RT and 3B42V6, the bias (Table 2) is relatively small and it is less than 1mm/day for 3B42V6 over all India in 2008, but it is little higher (2-3 mm/day) in 2006 and 2007. The error value (bias) of 3B42V6 is consistently lower than the 3B42RT and KALPANA-1 and hence shows lower biases. The bias over all India indicates that the systematic error is relatively small for 3B42V6 product. The regional biases are higher for west coast of India and North East India, because these two regions come under the orographic effect. For the season as a whole the performances of the 3B42V6 product is better and 3B42RT and KALPANA-1 are roughly equal. The rms errors (Table 3) do not vary much from year to year and the values for individual years are more or less uniform over Indian land areas during the monsoon seasons of 2006, 2007 and 2008. This number can be interpreted as the likely range over which the values at individual regional domains differ from gauge-estimated rainfall. It can be large even when the bias is relatively small, indicating that the errors are mainly random. Two features are apparent in the results. The first is the much greater error in the KALPANA-1 satellite product than in the TRMM 3B42RT and 3B42V6 products. The second is that for the 3B42R6 and 3B42V6 products, the bias (Table 2) and RMS (Table 3) error do not vary much from year to year and the values for individual years are similar. This is not the case for the KALPANA-1 product.

4. Conclusions

Daily satellite-based rainfall from KALPANA-1 and the TRMM near real-time product 3B42RT and merged post real-time product 3B42V6 have been validated against daily gridded data from rain gauges by the India Meteorological Department, for the summer monsoon seasons of 2006, 2007 and 2008. The inter-comparison of satellite products with the rain gauge observations suggests that the TRMM 3B42V6 products could distinctly capture characteristic features of the summer monsoon rainfall. The KALPNA-1 and 3B42RT products reproduce only the broadest features of mean monsoon seasonal rainfall over India. If one looks at the shape and size of high and low rainfall regions in any detail, KALPANA-1 and 3B42RT may be considered inadequate representations. However, the patterns of 3B42-V6 mean monsoon rainfall, including those related to orography (Xie *et al*., 2006), are reasonably close to the observed patterns from IMD rain gauge data [Figs. 2 (a-d)]. This may be because of the use of TRMM precipitation radar (PR) data in 3B42-V6. All satellite products underestimate seasonal mean all-India rainfall [Figs. 5 (a-c)]. The seasonal mean rainfall over the Central India and East India boxes are close to rain gauge values. The daily all India mean rainfall of both 3B42-V6 and 3B42RT products are close to the rain gauge values [Figs. 7 (a-c)] in most of the days. The daily all India mean rainfall variability in the satellite products has the right phase but the amplitude is generally underestimated, because of the underestimation of rainfall in the satellite products over orographic regions give rise to the underestimation of all India mean rainfall. The spatial distribution of daily mean error is reasonably less for 3B42V6 data, except over north East India and along the west coast of India. KALAPNA-1 overestimates rainfall (positive bias) over the Gangetic plains and parts of east Central India [Figs. 9 (a-i)]. At individual grid points, the RMS error between daily satellite and gauge rain can be high [Figs. 10 (a-i); Table 3], but over larger regions the agreement is better. The case studies illustrated show that the TRMM near real time product 3B42RT and post real time research quality product 3B42V6 could capture the magnitude and location of heavy rainfall in a more better and a realistic way in all three days during monsoon depression. In the KALPANA-1 estimation, the heavy rainfall amount is limited to 72 mm per day due to its algorithm, so it always under-estimate the rainfall when it become more than 72 mm in a day. This study with data of three seasons shows sufficiently promising results for operational applications. Availability of these real-time satellite products (KALPANA-1 and 3B42RT) is expected to benefit various user communities involved with the task of monitoring and prediction of monsoon activity and flood events. The daily satellite estimate, particularly the research product 3B42-V6, has greater potential for the study of rainfall variability on synoptic to inter annual time scales over the Indian monsoon region.

Acknowledgements

Authors are grateful to the Director General of Meteorology, India Meteorological Department for providing all facilities to carry out this operational research work. Authors acknowledge the use of TRMM Products of NASA, USA in this work

References

Adler, R. F., Huffman, G. J. and Co-authors, 2003, "The version 2 Global Precipitation Climatology Project (GPCP) Monthly precipitation analysis (1979-present)", *J. Hydrometeorology*, **4**, 1147-1167.

Arkin, P. A. and Meisner, 1987, "The relationship between large-scale convective rainfall and cold cloud over the western hemisphere during 1982-84", *Mon. Wea. Rev.*, **115**, 51-74.

Arkin, P. A., Rao, A. V. R. K. and Kelkar, R. R., 1989, "Largescale precipitation and out-going long-wave radiation from INSAT-1B during 1986 southwest Monsoon season", *J. Climate*, **2**, 619-628.

Cressman, G. P., 1959, "An operational objective analysis system", *Mon. Wea. Rev.*, **87**, 367-374.

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoosudanan, M. S. and Xavier, P. K., 2006, "Increasing trend of extreme rain events over India in a warming environment", *Science*, **314**, 1442-1445.

Huffman, G. J., Adler, R. F., Arkin, P., Chang, A., Ferraro, R., Gruber, A., Janowiak, J., McNab, A., Rudolf, B. and Schneider, U., 1997, "The Global Precipitation Climatology Project (GPCP) combined precipitation dataset", *Bull. Amer. Meteor. Soc.*, **78**, 5-20.

IMD, 1981, "Part A, Rainfall", Climatological Atlas of India, Office of the DDG, p63.

IMD, 2007, "Monsoon 2006", A Report - Met Monograph No: Synoptic Meteorology: **4**/2006.

IMD, 2008, "Monsoon 2007", A Report - Met Monograph No: Synoptic Meteorology: **6**/2008.

IMD, 2009, "Monsoon 2008", A Report - Met Monograph No: Synoptic Meteorology: **6**/2009.

Kalsi, S. R., 1980, "On some aspects of interaction between middle latitude Westerlies and Monsoon Circulation", *Mausam*, **31**, 305-308.

Kelkar, R. R. and Rao, A. V. R. K., 1990, "Inter-annual variability of monsoon rainfall as estimated from INSAT-1B Data", *Mausam*, **41,** 183-188.

Mitra, A. K., Gupta, M. D., Singh, S.V. and Krishnamurti, T. N., 2003, "Daily rainfall for the indian monsoon region from merged satellite and rain gauge values: Large-scale analysis from real-time data", *J. Hydrometeor.*, **4**, 769-781.

Nicholson, S. E., Some, B., McCollum, J., Nelkin, E., Klotter, D., Berte, Y., Diallo, B. M., Gaye, I., Kpabeba, G., Ndiaye, O., Noukpozounkou, J. N., Tanu, M. M., Thiam, A., Toure, A.A. and Traore, A. K., 2003a, "Validation of TRMM and Other Rainfall Estimates with a High-Density Gauge Dataset for West Africa. Part I: Validation of GPCC Rainfall Product and Pre-TRMM Satellite and Blended Products", *J. Appl. Meteor.*, **42**, 1337-1354.

Nicholson, S. E., Some, B., McCollum, J., Nelkin, E., Klotter, D., Berte, Y., Diallo, B. M., Gaye, I., Kpabeba, G., Ndiaye, O., Noukpozounkou, J. N., Tanu, M. M., Thiam, A., Toure, A. A. and Traore, A. K. 2003b, "Validation of TRMM and Other Rainfall Estimates with a High-Density Gauge Dataset for West Africa. Part II: Validation of TRMM Rainfall Products", *J. Appl. Meteor.*, **42**, 1355-1368.

Rao, A. V. R. K., Kelkar, R. R. and Arkin, P. A., 1989, "Estimation of Precipitation and outgoing long wave radiation from INSAT-1B radiance data", *Mausam*, **40**, 123-130.

Rao, Y. P., 1976, "Southwest monsoon, India Meteorological Department", Meteorological Monograph on Synoptic Meteorology, No. **11**-1976, Delhi, p337.

Rahman, H. and D. Sengupta, 2007, "Preliminary comparison of daily rainfall from satellites and Indian gauge data", Tech. Rep. 2007AS1, 26pp, Indian Institute of Science, Bangalore, India;

Rajeevan, M., Bhate, J., Kale, J. D. and Lal, B., 2005, "Development of a high resolution daily gridded rainfall data for Indian region", Met. Monograph Climatology No. **22**/2005, India Meteorological Department, Pune, p26.

Richard, F. and Arkin, P. A., 1981, "On the relationship between satellite observed cloud cover and Precipitation", *Mon. Wea. Rev.*, **109**, 1081-1093.

Roy Bhowmik, S. K. and Das Ananda, K., 2007, "Rainfall analysis for Indian monsoon region using the merged rain gauge observations and satellite estimates : Evaluation of monsoon rainfall features", *J. Earth Syst. Sci.*, **116**, 3, 187-198.

Takuji, K., Tomoo. U., Shoichi, S., Satoshi, K., Misako, K. and Ken'ichi, O., 2009, "Verification of high resolution satellite based rainfall estimates around Japan using gauge calibrated ground radar dataset", *Journal of Met. Soc. Japan*, **87A**, 203-222.

Xie, P. and Arkin, P. A., 1997, "Global Precipitation: A 17-year monthly analysis based on observations", satellite estimates, and numerical model outputs. *Bull. Amer. Meteor. Soc.*, **78**, 2539-2558.

Xie, S. P., Xu, H., Saji, N. H. and Wang, Y., 2006, "Role of Narrow Mountains in Large-Scale Organization of Asian Monsoon Convection", *Jour. of Climate*, **19**, 3420-3429.