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Indian Summer Monsoon Rainfall Variability on Seasonal to Event Time Scales in TRMM Measurements

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Abstract

An attempt is made here to examine the Indian monsoon rainfall variability on seasonal, inter annual, active-break and rain-event time scales in TRMM 3B42 V7 and IMD gridded data. Inter-comparisons in rainfall composites for the TRMM period, 1998-2015, based on one-to-one data sets prepared on the common grid structure, reveal that all India seasonal mean monsoon rainfall compare well between TRMM and IMD data, however, TRMM is underestimated along the west coast, the extreme north and north-east of India. For the first time, it is shown here that the rainfall contributions of active monsoon spells to all India seasonal monsoon rainfall are at 20.76% and 21.50% in IMD and TRMM data; with the Root Mean Square Error (RMSE) at 19.2 mm day^{-1}. Comparisons in inter annual variability of all India seasonal rainfall between the TRMM and IMD data sets are consistent with the anomalies captured with marginal differences in magnitudes. Inter-comparisons in daily rainfall between IMD and TRMM associated with Medium Rain (MR, 7.5 ≤ rain ≤ 35.4mm day^{-1}), Heavy Rain (HR, 35.5 ≤ rain ≤ 124.4 mm day^{-1}), Very Heavy Rain (VHR, rain ≥ 124.5 mm day^{-1}) categories reveal that the respective RMSEs are at 10.12 mm day^{-1}, 27.47 mm day^{-1} and 61.89 mm day^{-1} for Central India. This analysis is based on 37.4% of good data representing rain-rain data points in both IMD and TRMM data. The RMSE (Root Mean Square Error) between TRMM and IMD data for overlapping VHR category is higher by 12.6% than the average standard deviation over both the data.

Introduction

Over the decades, the rainfall measurements are being made using the instrumentation on the ground and from satellites in space [1-7]. Although the merit of the ground truth measurements is relatively high, Kidd et al., emphasized on the inadequacy in the ground instrumentation coverage of rain gauges and radars globally, and on variations in time and duration of rainfall data availability [2]. On the other hand, satellites do promise growing capability for global measurements of rainfall at high resolutions in space and time, covering remote regions of oceans, forests and irregular terrain. The TRMM (Topical Rain Measuring Mission) satellite, with its mission life until April 2015, provided three dimensional structure of precipitation based on measurements from passive microwave multi frequency TRMM Microwave Imager (TMI), the Ku-band Precipitation Radar (PR) and the Visible and Infrared Radiometer System (VIRS) [8-11]. The latest Global Precipitation Measurement (GPM) mission, a successor to TRMM, launched on February 28, 2014 carried the first space-borne Dual-frequency phased array Precipitation Radar (DPR) operating at Ku and Ka bands (13 GHz and 35 GHz, respectively) and a conical-scanning multichannel (10 GHz-183 GHz) GPM Microwave Imager (GMI) [3, 5]. These missions, TRMM and GPM provided various levels of data products with improved algorithms for scientific analysis and applications after rigorous ground validation, inter-satellite calibration [5, 6, 3]. The Gridded data products released are (1) TRMM 3B42 from JAXA (2) IMERG (Integrated Multi satellite Retrievals for GPM) from NASA), (3) GSMaP (Global Satellite Mapping of Precipitation) from JAXA [11-13]. Here an attempt has been made to examine the Indian summer monsoon variability on seasonal, inter annual, intra seasonal (active and break monsoon) and event (daily) time scales by analyzing TRMM 3B42 V7 data, and to compare with similar analysis of high resolution gridded data released by IMD using measurements from surface instrumentation over the Indian region [12-19].

The ground-based data source for the Indian region is with IMD (India Meteorological Department) with more than 6955 rain gauge stations over India [20-22]. One can refer to Figure 1 given by Pai et al., for IMD rain gauge stations network. The other major source is the establishment by KSNDMC (Karnataka State Natural Disaster Monitoring Centre), Bangalore with 6000 Telemetric Rain Gauge Stations (TRG at every ~25sq. km) in the Karnataka state of India. The Rainfall data is recorded every 15 minutes by KSNDMC [23, 24]. Similar resources are available for other states of India with respective State Government Centers. The ISRO (Indian Space Research Organization) has deployed 1194 AWS (Automated Weather Systems) all over India and hourly rainfall data is available for the period, 2009-2021 (https://www.mosdac.gov.in). The IMD has deployed AWS at 727 locations all over India (https://aws.imd.gov.in).

Parthasarathy et al. constructed All India Rainfall (AIR) (all-India area weighted mean summer monsoon rainfall (JJAS)) for the period, 1901-2014, based on 303 stations over the Indian region. IMD generated daily rainfall data sets gridded at different resolutions using stations data and appropriate interpolation techniques [20-22]. Rajeevan and Bhate, generated gridded daily rainfall dataset at 1° x 1° (0.5° × 0.5°) resolution for the Indian region using 1803 stations with minimum 90% data availability during the analysis period, 1951-2003 (1971-2005) following the interpolation method proposed by Shepard, 1968 [22]. Daily rainfall is accumulated from 8:30am to 8:30am on the following day. Rajeevan, et al, showed that the gridded rainfall data that they generated is better in accurate representation of spatial rainfall variations in comparison with similar global gridded rainfall datasets. The latest data set released by IMD and used here is the daily rainfall data gridded at 0.25° x 0.25° resolution for the period 1901-2015 [20].

On the other hand, attempts were made to realize satellite derived rainfall measurements based on information in cloud features, such as, cloud thickness, cloud albedo, cloud top temperatures, etc., and from rainfall affected cloud features in Visible and IR (Infra-Red) imageries from NOAA, Meteor, FY-1 (Low-Earth orbiting) and Meteosat-5,7, GOMS-1, INSAT-1D, INSAT-2E, FY-2, GMS-5, GOES-10, GOES (Geostationary) satellites. AVHRR (Advanced Very High Resolution Radiometer) were carried onboard NOAA series for measurements in IR and Visible frequencies [25-27]. The transparency of clouds in measurements from High Resolution Infrared Sounder (HIRS) was useful in estimation of the rainfall potential in clouds. While polar orbiting satellites are poor in temporal sampling but are of high spatial resolution, the geostationary satellites provided high temporal, but coarse spatial resolution measurements.

The advent of microwave sensors, Microwave Sounding Unit (MSU), the Advanced Microwave Sounding Unit (AMSU), etc., lead to improved rainfall estimation. Satellite estimation of Rainfall was pursued with Passive microwave radiometry with 19 GHz and 37 GHz channels in ESMR series, SMMR (Scanning Multichannel Microwave Radiometry) at 6.6 GHz, 10.69 GHz, 18.0 GHz, 21.0 GHz and 37.0 GHz frequencies, Special Sensor Microwave/ Imager (SSM/I) at dual polarized frequencies (19.35 GHz, 37.0 GHz and 85.5 GHz) and a vertically polarized channel (22.235 GHz) Defense Meteorological Satellite Program (DMSP) series. One can refer to the extensive review carried out by Kidd, on evolution of satellite instruments technology, the algorithms developed/adopted for rainfall estimation, merits of the rainfall data sets that emerged [28]. Kidd mentioned that the GOES

Precipitation Index (GPI) has been the widely used technique [29-32]. This technique was based on the relationship between cold cloud and rainfall totals and the data from the GARP Atlantic Tropical Experiment (GATE). The passive microwave radiometry was particularly useful in estimating the rainfall over the oceans due to their ability to penetrate clouds, delineate atmospheric liquid water content, perceptible water and rainfall intensity, and to the fact that the precipitation sized particles is the major source of attenuation [33, 34]. A decrease in the signal intensity due to scattering of upwelling surface radiation by precipitation sized particles in higher microwave frequencies improved rainfall estimation particularly over land [35]. Estimation of rainfall using multi-spectral retrievals based on combined infrared and passive microwave rainfall estimation technique lead to global precipitation estimation from satellites, and on validation of the derived precipitation products [2, 12, 13, 36, 37].

The precipitation radar, an active microwave sensor, combined with passive microwave sensors on board TRMM measured heavy to moderate rain over the tropical and subtropical oceans [5]. The GPM advanced combined precipitation measurements from several microwave sensors onboard constellation of satellites [3]. In addition to heavy to moderate rain measurement range of TRMM, the GPM sensors included measurements of light-intensity precipitation and falling snow in the middle and high latitudes.

Anagnostou proposed physical basis and mathematical formulation for the new retrieval algorithm for combined measurements from radar-radiometer (PR-TMI) onboard TRMM for estimation of rainfall over land [38]. They also discussed the passive microwave (TMI and SSM/I) rain estimation techniques for land. Iguchi et al., described the criticality to be dealt with attenuation correction, drop size distribution model selection and on the non-uniform beam-filling effect correction in the algorithm for rainfall rate estimation [34]. Major inference noted by Iguchi et al., that the models for drop size distribution applicable for convective rain over ocean are not consistent over land [39].

Various gridded data sets, such as, the GPCP (The Global Precipitation Climatology Project) combined precipitation data set, the CMAP (CPC Merged Analysis of Precipitation) data set, the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN), CMORPH products, TRMM 3B42, IMERG and GSMaP are being produced systematically and released [12-18, 37, 40-44] . Skofronick-Jackson et al., mentioned that reprocessing of various level products is carried out back to the beginning of TRMM (in 1998) to establish a long and consistent record of precipitation [3].

Several studies tried to evaluate these gridded data products against the ground truth and model simulations [45-55]. Rao et al., compared TRMM 3B42 rainfall measurements against the ground truth measurements from AWS (Automated Weather Systems) for the Indian Southern Peninsular region at three representative locations, namely, Bangalore (12.54 m, 77.22 m, 741 m Elevation a.m.s.l.), Chennai (12.55 m, 77.30 m, 6.4m Elevation a.m.s.l.), Cochin (10.04 m, 76.32 m, 38 m Elevation a.m.s.l.) for the period, Jan-Dec 2008 and inferred that the RMSE is as high as one standard deviation based on an overall ~89% of one to one data points in TRMM and AWS [45] Based on comparisons over a decade-long (2001-2010) with daily rain gauge dataset. Xue et al., showed that 3B42V7 improved upon the, underestimation in 3B42V6 both for the whole basin and for a grid cell with high-density gauges [50]. Chen, et al., examined the similarities and differences of spatial error structures of surface precipitation in 3B42V6 and 3B42V7, in comparison with the China Meteorological Administration's national daily precipitation analysis during June 2008-May 2011 [51]. They showed that 3B42V7 improved upon 3B42V6 over China in terms of daily mean precipitation. Mitra et al. merged TRMM Multi-satellite Precipitation Analysis (TMPA) satellite estimates with the India Meteorological Department (IMD) rain gauge values for the Indian monsoon region and prepared daily merged satellite data product (NMSG) at 1° latitude longitude resolution [56]. They showed that incorporation of IMD gauge data enhanced the value of the satellite information and corrected the mean biases of the TMPA values. Nair et al., carried out validation of 3B42-V6 data against observations from a high density rain gauge network over the Indian Western Ghats to show that the satellite rainfall estimates over the state are most accurate over regions of moderate rainfall and mainly inaccurate in regions of sharp rainfall gradient [57]. They inferred that the west- east rainfall gradient along the west coast is captured, but the orographic effect, that is, the rainfall maxima observed over the Western Ghats (as captured by the rain-gauge) is not reflected in 3B42-V6. However, the daily rainfall inter-comparisons indicate the ability of the 3B42-V6 estimates to detect the wet and dry phases of monsoon over most parts of the state.

Prakash, et al., evaluated and showed that IMERG precipitation is better with the systematic error lower by about 14% over the Bay of Bengal than the Arabian Sea against hourly observations from moored buoy over the north Indian Ocean during March 2014-December 2015 [48]. IMERG showed an improvement over the TMPA at a daily scale over the north Indian Ocean. Prakash et al., evaluated TMPA-RT and TMPA-V7 data against gridded gauge based data over India at daily scale for a 13-year (2001-2013) period. TMPA showed an over estimation of rainfall over most parts of the country except over the orographic regions. They attributed larger random error in TMPA-RT than TMPA-V7 to difference in calibration methods in development of data [49]. Shige, et al, made remarkable inferences that maximum in rainfall occurred upslope of the Western Ghats in rainfall measurements from Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR), unlike the previous studies identifying off shore locations of rainfall maxima [47].

The primary objective of this study is to make an assessment of how best the observed features of Indian monsoon rainfall are captured in TRMM V7 rainfall products. The Indian land region and the surrounding seas experience the summer monsoon with the surface wind blowing south-westerly in the months of Jun to Sep every year [58-60]. The Southwest or summer monsoon is the chief rainy season for India, during when the country receives 75% of the annual rainfall.

The mean precipitation structure of the south Asian monsoon is spatially complex with maximum precipitation observed over the oceans and not over the land regions [61]. The broad precipitation maximum extends eastward from 70°E to the northwest tropical Pacific Ocean including strong local maxima to the west of the Western Ghats mountain range of India and over the eastern tropical Indian Ocean and the Bay of Bengal (BoB). It is observed that the strongest large-scale global maximum in precipitation is located over the Bay of Bengal. Several studies examined variations in orography associated rainfall during the summer monsoon season over India [41]. Hoyos et al., also noted that the Burma mountain range play an important role in enhancing the rainfall considerably in the northeast corner of the Bay, explaining much of the observed summer maximum oriented parallel to the mountains [61]. Similar interplay occurs to the west of the Ghat thus indicating that the rainfall activity associated with sharp mountain ranges needs to be well simulated in monsoon simulation models. Kumar et al, observed that although, both the Myanmar range of mountains and the Western Ghats are characterized by very similar orographic features and even when the amount of rain in June-July months is almost same in the two regions, there are significant differences in frequency of occurrence of precipitating clouds [62]. They inferred that, during the monsoon season, low and moderate rains contribute more to the total rain in the Myanmar Coast while heavy rains contribute more to the total rain in the Western Ghats. Western Ghats also gets more intense rains but less frequently [49]. Thus, it is very important to establish how good the satellites capture orographic rain and characterize the regions for precipitation occurrence on inter annual time scales [50].

Indian summer monsoon rainfall exhibits distinct temporal variability as well, particularly, on decadal, inter annual, intra seasonal (30-50 days and bi-weekly), super-synoptic time scales of active and break, synoptic time scales (Lows, Depressions, Cyclones) Webster et al., and the references therein) [60]. Recently, the Indian monsoon variability has been viewed to be significantly modulated with extreme rain and moderate rain events [60, 63-66].

The Indian Seas, the Bay of Bengal and the Arabian Sea, are crucial in influencing in a variety of ways the precipitation variations of summer and winter monsoons. Thus, the high resolution satellite data sets in space and time provide unique opportunity to understand vagaries of summer monsoon over land and oceans in time and space. The motivation for this study is to examine the feasibility of TRMM data usage for both the Indian land and sea regions in view of the limitation with the gridded data availability only for the Indian land region. The idea is to verify the precipitation features observed for the Indian land region in TRMM V7 data against the IMD gridded data, and thereby review the possibility of extending the applicability of TRMM data to Indian seas.

Here an attempt has been made to carry out inter-comparisons in summer monsoon rainfall climatology on seasonal to event (day) time scales in TRMM and IMD data sets for the Indian land region. Rainfall climatology is constructed for various time scales of monsoon variability, namely, the inter annual, the active and the break cycles, and over event time scales.

Data

The primary data set analyzed here is the latest version 7 (V7) of TMPA products, namely, TRMM 3B42 V7 rain rates (mm hr^{-1}) for the period, 1998-2015 made available by Huffman et al., at spatial resolution of 0.25 X 0.25 every 3 hours. The IMERG (Integrated Multi satellite Retrievals for GPM) rainfall product, equivalent to TMPA, retrieved from GPM comprising international constellation of satellites is being updated continuously [49]. Liu 2016 compared IMERG Final Run monthly product with the TMPA monthly product (3B43) during 2014-2015 to show that the systematic differences are much smaller over land compared to those over ocean because of the similar gauge adjustment used in the two monthly products. In the present study, we present results based on TRMM 3B42 V7 data for the Indian land region [67].

The second data set is the All India Rainfall (AIR), area-weighted mean summer monsoon rainfall (JJAS), estimated by using rainfall measurements for 303 stations all over the Indian land region for the period, 1901-2014 [25]. The third data set is the IMD gridded daily rainfall made available at 0.25° X 0.25° resolutions in space for the period, 1901-2015 (115 years) [20-22]. IMD gridded data is based on 1803 stations with minimum 90% data availability during the analysis period. On an average, 1600 stations data were available for the entire period.

In order to carry out inter-comparisons in rainfall climatology, one-to-one data sets of TRMM 3B42 and IMD are prepared on a common grid structure in space. In their original forms at native resolution, TRMM grid points are not overlapping on IMD grid points. A few steps are followed to create one-to-one TRMM and IMD data sets as described in Appendix. First of all, TRMM grid points are sorted out within the IMD data boundary. Then, for each data point on TRMM grid, diagonally opposite data point on the IMD grid is considered as corresponding data point for preparing one-to-one time series. The end points are automatically taken care as TRMM grid points precede IMD end points location wise.

Monsoon Variability on Various Time and Spatial Scales based on IMD Gridded Data

Monsoon rainfall variability on inter annual time scale is constructed here for 114 years for the period, 1901-2014 based on one-to-one IMD gridded data set prepared (on the common grid structure) as described in Appendix. Monsoon rainfall climatology is also constructed here on seasonal scale for the Indian region and rainfall composites over the periods of active and break cycles.

Figure 1 describe the inter annual variability in All India Monsoon (JJAS) Rainfall (Area weighted mean summer monsoon rainfall) constructed by Parthasarathy et al., for the period, 1901-2014 [25]. Rainfall anomaly normalized with inter annual standard deviation is plotted on y-axis in figure 1. The mean summer monsoon rainfall over the period, 1901-2014, is 88.61cm and the corresponding standard deviation is 8.64 cm. One can observe severe drought years of 1972, 1977, 1979, 2002 and 2009 associated with large negative rainfall anomalies (~2 standard deviations); the good monsoon year 1988 associated with large positive rainfall anomaly on the contrary.

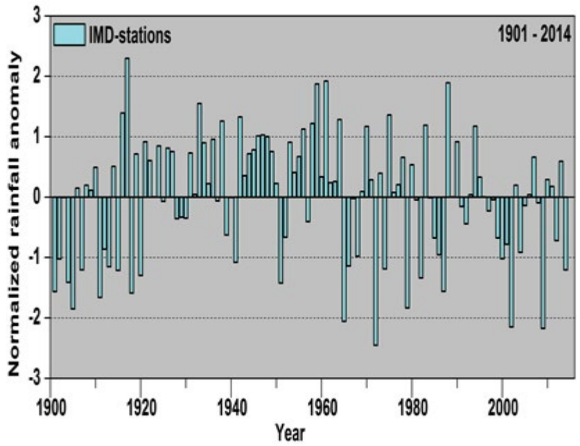

Figure 1. Inter annual variability in all India Summer monsoons (JJAS) rainfall during 1901-2014. Rainfall anomaly normalized with inter annual Standard deviation is plotted on y-axis. The mean summer monsoon rainfall is 88.61 cm and the corresponding standard deviation is 8.64 cm.

Figure 2a describes the spatial distribution of the climatological mean summer monsoon rainfall (mm day^{-1}) for the period 1901-2015 for the Indian land region based on one-to-one IMD gridded data set (Appendix) and Figure 2b, the corresponding standard deviation in rainfall. A large homogeneous region can be observed over central India in both the mean seasonal rainfall and standard deviation in Figures 2a and 2b.

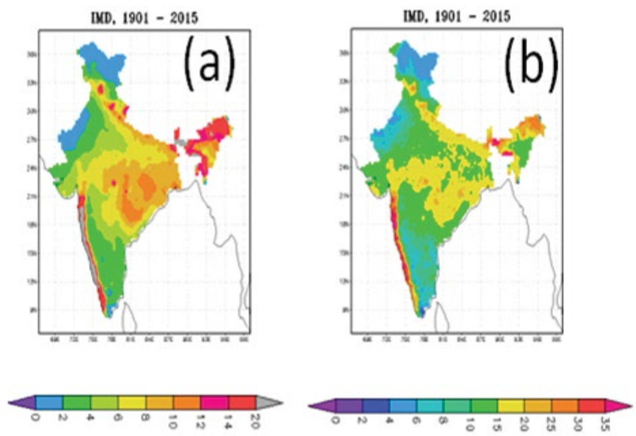

Figure 2. a) The Climatological mean summer monsoon rainfall (mm day^{-1}) b) the corresponding standard deviation in rainfall (mm day^{-1}) based on one-to-one data sets of IMD for the period 1901-2015.

Heaviest rain occurrence is observed over the upslope of the Western Ghats of India and as well over the north-eastern Indian region; however, with anomalous rainfall larger than the mean rainfall (Figures 2a and 2b) in both the regions. Also, the north-western and northernmost parts of India and a large part of southern peninsula are observed to be rain deficit regions. The foothills of Himalayas are as intense in rainfall occurrence as the central parts of India during the monsoon season.

Figures 3a and 3b describe the climatological distribution of the mean summer monsoon rainfall (mm day^{-1}) respectively for the active and the break spells during 1901-2015 based on one-to-one IMD gridded data set (Appendix). The periods of active and break spells considered here are from the reports published every year by IMD at the end of the summer monsoon season. During breaks, rainfall occurrence is scanty over the entire Indian region except over the slopes of the western Ghats, foothills of the Himalayas and the north-eastern parts of India (Figure 3b); whereas during the active spells, heaviest rainfall occurrence is over the upslope of the Western Ghats (Figure 3a). Rainfall distribution is homogeneous over large parts of central India during the active spells. The north-western and northernmost parts of India and a large part of southern peninsula are rain deficit regions even during the active spells.

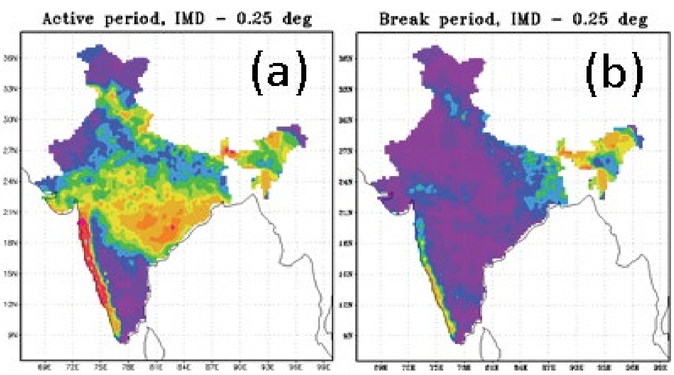

Figure 3. The climatological mean summer monsoon rainfall (mm day^{-1}) (averaged over) for a) the active b) the break spells in IMD gridded data for the period 1901-2015.

Result and Discussion

Inter-Comparisons in rainfall climatology between IMD and TRMM in space and time

All inter-comparisons in rainfall climatology presented in this section are based on the one-to-one IMD and TRMM data sets prepared on the common grid structure (Appendix).

Figures 2a and 4a describe the rainfall climatology constructed for the Indian region using one-to-one IMD (Figure 2a) and TRMM (Figure 4a)) data sets for the respective periods of 1901-2015 and 1998-2015. Inter-comparisons indicate that the seasonal mean monsoon rainfall for all India is comparable with the mean values at 85.6 cm and 86.9 cm respectively. Prakash et al., also concluded that both TMPA-V7 and RT data sets represent the mean seasonal rainfall characteristics reasonably well [25]. Although both the climatological mean summer monsoon rainfall (Figure 4a) and the corresponding standard deviations (Figure 4b) are underestimated over the Western Ghats in TRMM data, it is striking to note that the heaviest rainfall occurs over upslope of the Western Ghats. This finding that rainfall maxima occurrence is over upslope of the Western Ghats is consistent with the findings of Shige et al., which is based on Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) data. In the past studies based on various satellite data [57, 61-62, 68-71], the rainfall maxima occurrence was observed over offshore locations in the rainfall climatology, unlike the findings of Shige et al,. The rainfall underestimation is also noted here in extreme north and northeastern parts of India. Rainfall distribution is homogeneous over large parts of central India in both the mean and standard deviation [47].

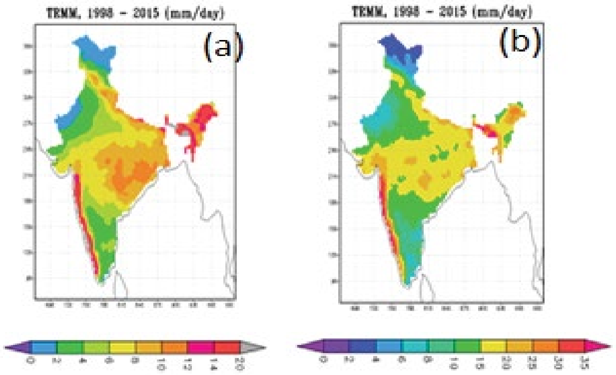

Figure 4. a) The Climatological mean summer monsoon rainfall (mm day^{-1}) (left panel) b) the corresponding standard deviation in rainfall (mm day^{-1}) (right panel) based on one-to-one data sets TRMM for the respective periods of 1998-2015.

Underestimation of rainfall over the Western Ghats observed here in TRMM 3B42 data is also consistent with the findings of Nair et al., Inter-comparisons in their analysis by Nair et al., revealed that the orographic effect is not reflected in TRMM 3B42 V6 data in capturing the rainfall maxima (observed by the rain-gauges) over Maharashtra region of the Western Ghats during monsoon seasons of 1998-2004, although the west- east rainfall gradient along the west coast is well captured [57]. Prakash et al. showed larger systematic error over the mountainous regions of northeast India in both the TMPA RT and V7 products based on evaluation against gridded gauge-based data at daily scale during the monsoon seasons of 2001-2013 [49]. They attribute difference in calibration methods adopted for the development of the data sets could be the possible reason for the larger random error.

Climatological mean seasonal rainfall and standard deviation based on five data sets

Comparisons in climatological seasonal mean rainfall distributions are presented here between four data sets constructed for all India and central India using TRMM and IMD data at native resolutions. The central India is considered here for comparisons as it is the chief seat of monsoon convection. The first data set used here, 'IMD-Stations-AIR', is the All India Rainfall (AIR) (all-India area-weighted mean summer monsoon rainfall (JJAS)) given by Parthasarathy et al., the Indian region for the period 1901-2014. The second data set, IMD-Daily 0.25 degree-AIR, is the All India Rainfall constructed with one-to-one IMD data gridded at 0.25 × 0.25 resolution; the third data set, IMD-Daily-0.25 degree-CI, is similarly constructed for the central India (74.5E - 86.5E: 16.5N-26.5N); the fourth and the fifth data sets, TRMM-0.25 degree-AIR and TRMM-0.25 degree-CI, are constructed respectively for all India and the central India using one-to-one TRMM data at native resolution [25].

Figure 5 describes comparisons between the five data sets in climatological seasonal mean rainfall and in the corresponding standard deviations. The 2nd (4th) and the 3rd (5th) vertical bars show comparisons for all India (Central India). The climatological seasonal mean rainfall for all India (central India) computed using the five data sets are in range 85.6 cm -88.6 cm (91.5 cm-94.9 cm) and the corresponding standard deviations in the range, 7.9 cm-8.6 cm (9.9 cm-10.1 cm). Hence, the comparisons are quite good.

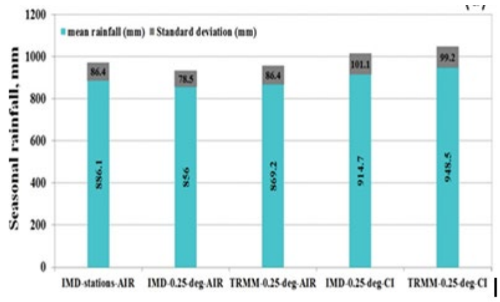

Figure 5. Comparisons in Climatological seasonal mean rainfall and the corresponding standard deviations.

Year to year variations in seasonal mean rainfall for all India and central India

Comparisons in year to year variations of seasonal mean monsoon rainfall for 18 years (1998-2015) of TRMM period between the five data sets, IMD-Stations-AIR, IMD-Daily-0.25 degree-AIR, IMD-Daily-0.25 degree-CI, TRMM-0.25 degree-AIR and TRMM-0.25 degree-CI are presented in Figure 6. Seasonal rainfall shows low mean values in all the five data sets during the five drought years, 2002, 2004, 2009, 2014, and 2015. No flood years are reported during the TRMM period.

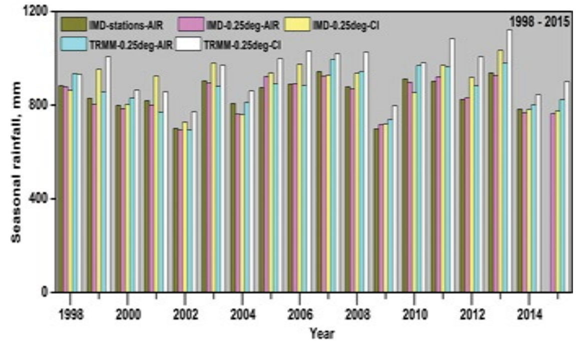

Figure 6. Comparisons in annual seasonal Mean rainfall for all India and central India between the five data sets during 1998-2015.

Inter-comparisons in Monsoon variability between IMD and TRMM on Various Time and Spatial Scale

Inter-comparisons in inter annual variability in seasonal mean monsoon rainfall for all India and central India

The inter-comparisons between the data sets described in Figure 7 are good in capturing the negative and positive rainfall anomalies. Except for the largest discrepancy in the year 1999, the differences in magnitudes are marginal between the three data sets, IMD-Stations-AIR, IMD-Daily-0.25 degree-AIR; IMD-Daily-0.25 degree-CI is noteworthy. This indicates the consistency between IMD gridded rainfall data and IMD stations data for all India monsoon rainfall during the entire period, 1951-2015. Both for all India and central India, TRMM is consistent with IMD, particularly the agreement during the severe drought years of 2002, 2009 and 2014 is quite good between the data sets with negative rainfall anomalies overlapping; and similarly, for the good monsoon year, 1988 with the positive rainfall anomalies overlapping. TRMM has captured well a bunch of negative rainfall anomalies during 1999-2002. TRMM significantly overestimated for the years, 2007, 2010, 2011 and 2012.

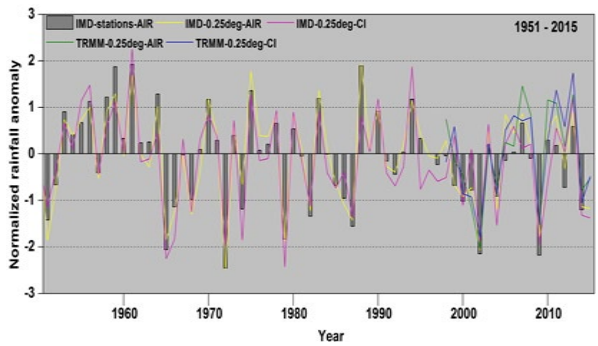

Figure 7. Inter annual Variability in All India Monsoon (JJAS) Rainfall for all India and central India in five data sets, IMD-Stations-AIR, IMD-Daily-0.25 degree-AIR, TRMM-0.25 degree-AIR, IMD-Daily-0.25 degree-CI, and TRMM-0.25 degree-CI for the respective data periods. Rainfall anomaly normalized with respective standard deviation is plotted in y-axis.

Inter-comparisons in rainfall composites between active and break phases of the Indian summer monsoon

An effort is made here to construct climatological rainfall distribution across the Indian region over the active and break spells in TRMM rainfall measurements and compare with that based on IMD observations. Also, contrasting variations in rainfall composites between the active and break spells and between the data sets are presented here.

As proposed by Rao et al., active and break monsoon spells are extracted here with the criteria applied on IR Brightness Temperatures (IRBRT) averaged over the central Indian region [75°E-85°E:15°N-25°N]. The criterion constrains area averaged IRBRT to be < (>) 270K almost continuously for a minimum of four days and above during an active (break) phase [71]. Figure 8 describes periods of Active (magenta) and Break (green) monsoon spells corresponding to IR Brightness temperatures <270K and >270K respectively during June-September months in the years 2006-2011. Active and break monsoon spells thus identified during 2006 to 2011 are listed in Table 1. Total number of active and break days are respectively 114 and 115 with the duration of Break (Active) periods in range, 4-17 (4-10) days.

Table 1. List of active and break spells of the Indian summer monsoon identified during the years 2006-2011.

Year	Active period (Days)	Break period (Days)
2006	27 Jun - 4 Jul (8)	5 Jun - 17 Jun (13)
	19 Jul - 23 Jul (5)	9 Jul - 13 Jul (5)
	26 Jul - 29 Jul (4)	6 Sep - 10 Sep (5)
	2 Aug - 8 Aug (7)	-
2007	25 Jun - 1 Jul (7)	9 Jul - 12 Jul (4)
	24 Jul - 29 Jul (6)	-
2008	16 Jun - 19 Jun (4)	22 Sep - 30 Sep (9)
	22 Jul - 28 Jul (7)	-
	1Aug - 10 Aug (10)	-
2009	12 Jul - 16 Jul (5)	1 Jun-12 Jun (12)
	19 Jul - 22 Jul (4)	23 Jul -26 Jul (4)
	31 Jul - 3 Sep (4)	28 Jul - 9 Aug (13)
	-	10 Sep - 26 Sep (17)
2010	30 Jun - 4 Jul (5)	1 Jun - 10 Jun (10)
	20 Jul - 26 Jul (7)	7 Aug - 10 Aug (4)
	27 Jul - 3 Aug (8)	25 Sep - 30 Sep (6)
	11 Aug - 17 Aug (7)	-
2011	25 Jun - 29 Aug (5)	18 Sep - 30 Sep (13)
	12 Jul - 17 Jul (6)	-
	23 Aug - 27 Aug (5)	-

The seasonal rainfall during the summer monsoon for the years 2006-2012 are respectively at 102%, 106%, 98%, -25%, 102%, 102% and 93% of its Long Period Average (LPA) (http://www.tropmet.res.in/~kolli/mol/). The years 2006, 2007, 2010 and 2011 are normal monsoon years, whereas, 2008 and 2012 are near-normal years. The year 2009 was the worst drought year till then. In the year 2009, the break periods occurred in all the three months of June, July and August as shown in Figure 8. In the years, 2008 and 2011, no break periods occurred during the primary monsoon months of July and August. In 2007, only one short break spell of 4 days occurred in July (Figure 8).

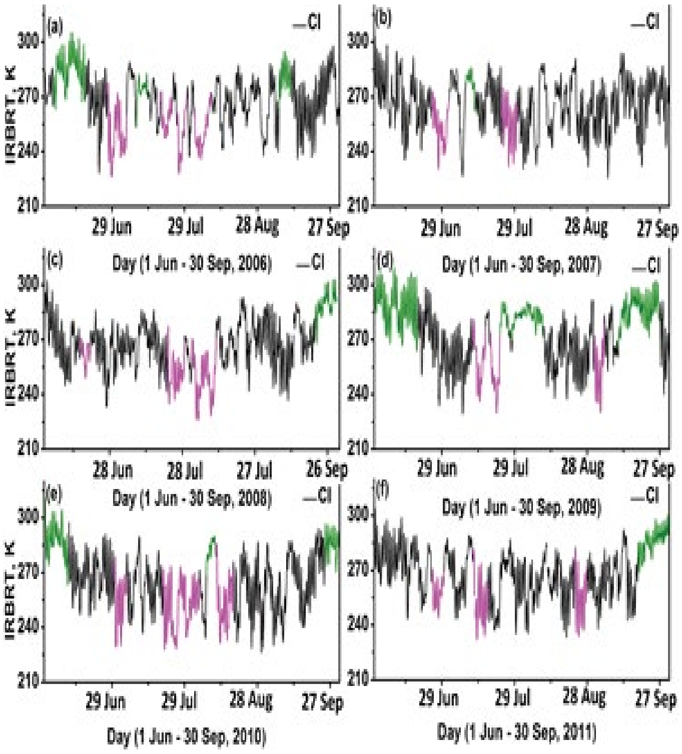

Figure 8. Active (magenta) and Break (green) spells corresponding to IR brightness temperatures <270 K and >270 K respectively during June-September months in the years a) 2006 b) 2007 c) 2008 d) 2009 e) 2010 f) 2011.

Rainfall composites averaged over all active and break monsoon spells

Rainfall composites (mm day^{-1}) constructed by averaging over all active monsoon spells and break monsoon spells during 2006-2011 (listed in Table 1) for the Indian region in TRMM- 0.25 degree data are plotted in Figures 9a and 9b respectively. Region-wise rainfall distribution features in composites for active and break spells for the land region in TRMM data are similar to the features observed in IMD data (Figure 3a and 3b), both in pattern and intensity, however with significant differences in magnitude. That is, the rainfall occurrence over the Western Ghats is significantly underestimated in TRMM. However, large part of central India and north eastern India compare in spatial and intensity-wise rainfall distribution in TRMM and IMD data. Also, the contrasts in rainfall distribution in composites observed between active and break spalls in TRMM data (Figures 9a and 9b) are similar to the contrasts in rainfall in IMD data. TRMM describes a vast rain intense region over the Bay of Bengal extending to coastal regions of Myanmar Arakan Yoma.

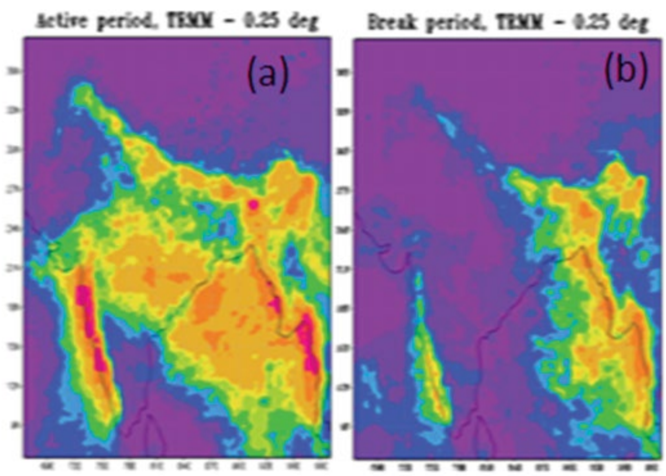

Figure 9. The Climatological Mean Summer Monsoon Rainfall (mm day^{-1}) a) active spells for the land region in TRMM data (left panel) b) break spells for the land region in TRMM data (right panel) for the period 1998-2015.

Rainfall statistics are constructed by averaging over all active monsoons and break monsoon spells during 2006-2011 (listed in Table 1) for the Indian region in IMD-0.25 degree and TRMM-0.25 degree data. Mean rainfall in IMD and TRMM data sets over all the active periods are respectively at 9.5 mm ± 19.4 mm day^{-1} and 10.4 mm ± 20.5 mm day^{-1}

for All India; 11.6 mm ± 21.5 mm day^{-1} and 12.6 mm ± 22.1 mm day^{-1} for Central India (Table 2). This indicates that the overall rainfall contribution in both IMD and TRMM data sets are comparing very well during the active periods of the Indian Summer Monsoon with corresponding RMSE (Root Mean Square Difference) at 19.8 mm day^{-1} (Table 2).

Table 2. Rainfall statistics for Active and Break periods during 2006-2011.

All India Region			
Monsoon activity	IMD mean ± std (mm day^{-1})	TRMM mean ± std (mm day^{-1})	RMSE (mm day^{-1})
Active period	9.5 ± 19.4	10.4 ± 20.5	19.2
Break period	3.9 ± 12.1	4.0 ± 13.0	12.3
Central India Region			
Active period	11.6 ± 21.5	12.6 ± 22.1	20.3
Break Period	2.9 ± 10.3	2.8 ± 10.6	9.1

Table 3 describes comparisons in rainfall accumulated over active and break spells for each year during 2006-2011 between TRMM and IMD data for all India and central India. The first two rows describe the number of active and break days in each year during 2006-2011. The third and fourth rows describe the accumulated rainfall for all India over all active and break days respectively for years 2006, 2007, 2008, 2009, 2010 and 2011; the 5th and 6th rows for central India. The year-wise comparisons for active and break spells are extremely good between TRMM and IMD for both all India and central India.

Table 3. Yearly Rainfall accumulated over Active and Break periods during 2006-2011.

Year	Data set	2006	2007	2008	2009	2010	2011
Number of active days (114)	Merged IRBRT	24	13	21	13	27	16
Number of break days (115)		23	4	9	46	20	13
Accumulated Rainfall over active days for All India Rainfall (mm)	IMD	255.2	123.9	195	111.3	161.4	143.8
	TRMM	266.1	121	217.4	117.4	293	166.4
Accumulated Rainfall over break days for All India Rainfall (mm)	IMD	115	30.4	20.8	167.2	69.6	42.7
	TRMM	113.8	30.5	20.6	167.9	83.9	45.7
Accumulated Rainfall over active days for Central India (mm)	IMD	334	138.5	253.4	153.2	278.1	161.4
	TRMM	346.3	130.9	270.4	160.5	331.9	199.3
Accumulated Rainfall over break days for Central India (mm)	IMD	89.5	23.7	17.3	101.3	37.9	60.7
	TRMM	86.8	19.2	17.2	97.9	42.8	57.5

Figures 10a and 10b describe the spatial variations in rainfall difference (mm day^{-1}) between the active and break monsoon spells respectively in IMD and TRMM data. The coastal region along the western India and large part of the central India are the prominent regions of rainfall excess during the active monsoon spells over the break spells; whereas the northeastern and southern peninsular regions are regions of significant rainfall deficiency. That is the regional features indicating excess rain over western coast and central parts of India, and deficit over southern peninsula and north-eastern parts of India in rainfall composite for active spells are well captured in both the data sets of TRMM and IMD although discrepancies in intensity are observed.

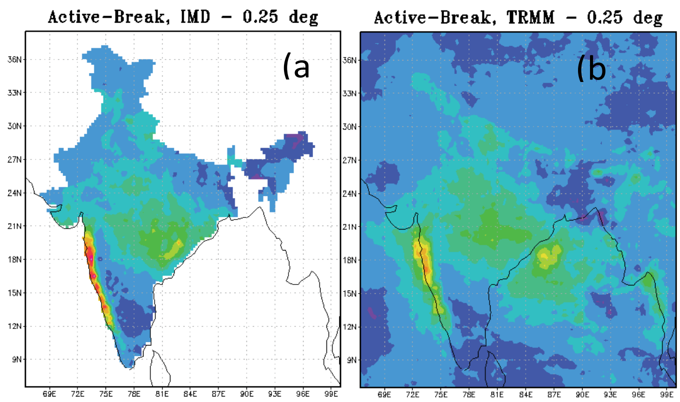

Figure10. Rainfall difference (mm day^{-1}) between Active and Break spells in a) IMD data b) TRMM data

Figures 11a and 11b describe the rainfall excess in IMD measurements over the TRMM for the active and break spells. Note that in Figure 11a, rainfall in TRMM is significantly underestimated in the west coast of India; and is overestimated in immediate region parallel to the west coast and in Central India (CI). During break spells, large differences are seen in the northeastern India. Thus the present findings based on TRMM 3B V7 are consistent with the inferences of Nair et al, that 3B42-V6 is capable of detecting the wet and dry phases of monsoon over most parts of the state although the rainfall amounts estimated by the satellite product were sometimes under-estimated or over-estimated and that TRMM 3B42-V6 demonstrates tremendous potential to be used for intra seasonal studies [57].

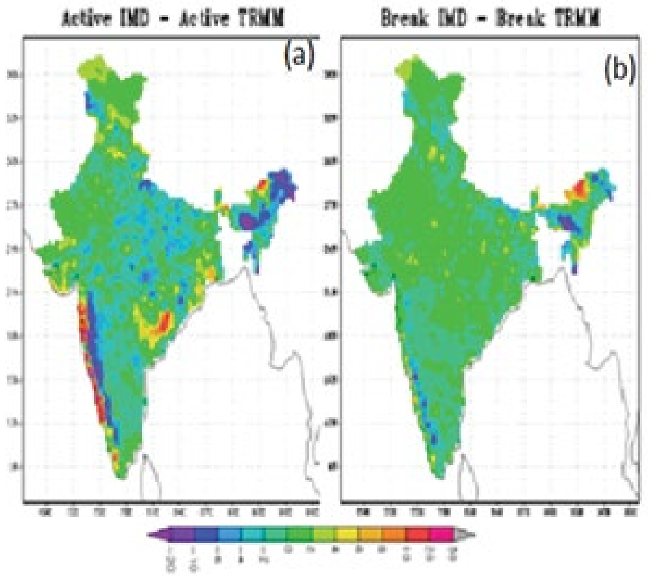

Figure 11. Rainfall difference (mm day^{-1}) between IMD and TRMM data sets for a) active spells b) break spells.

Contribution of Active and Break Spells to the All India Seasonal Summer Monsoon Rainfall in IMD and TRMM Data Sets

In an extensive review, Palmer and Anderson, confirm that the Indian monsoon rainfall is less predictable on seasonal scale and this they attribute to intra seasonal oscillations associated with 30-50 days and active and break monsoon phases [72]. Based on an observational analysis Goswami and Mohan, Showed that predictability of Indian monsoon climate deteorates due to relatively large internal variability associated with the intra seasonal oscillation and reduced contribution by boundary forcing [73]. It has been shown by Ferranti and Goswami et al., that intra seasonal oscillations play crucial role in explaining the monsoon variability on both inter annual and synoptic time scales [74, 75]. The intensity and duration of active and break spells explain differences in the seasonal rainfall between good and bad monsoon years [76-77]. In fact the monsoon variability over these different time scales is interconnected and influences each other. Here an attempt is made to estimate rainfall contributed by active and break monsoon spells to all India seasonal Monsoon.

Figures 12a and 12b describes percentage of rainfall accounted by active and break monsoon spells during 2006-2011 to Seasonal Monsoon (JJAS) of all India (top panel) and central India (bottom panel). The agreement between TRMM and IMD data in year-wise contribution to seasonal rainfall is striking, irrespective of whether it is active or breaks monsoon condition, for both all India and central India.

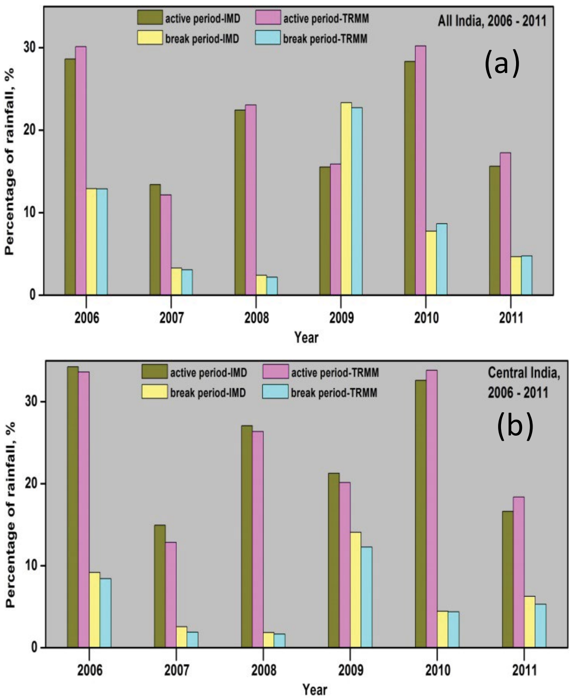

Figure 12. Percentages of Seasonal summer monsoon (JJAS) rainfall accounted by active and break monsoon spells for a) all India (top panel) b) central India (bottom panel) during 2006-2011.

Also, it is noteworthy that the active spells contribution to seasonal rainfall does not exceed 35% for both all India and central India; and the rainfall deficit due to break spells is less than ~12% except in the year 2009. It is striking to note that overall contributions of active monsoon spells to All India (Central India) seasonal summer monsoon rainfall in IMD and TRMM data sets compare extremely well with the respective numbers being 20.76% (24.50%) and 21.50% (24.24%) (Table 4).

Table 4. Percentages of seasonal summer monsoon (JJAS) rainfall accounted by active and break monsoon spells for all India (top panel) and central India (bottom panel) during 2006-2011.

Monsoon Activity	Percentage of seasonal monsoon rainfall (JJAS) accounted by active and break spells for all India region during 2006-2011	
	IMD-0.25 deg	TRMM-0.25 deg
Active spells	20.76%	21.50%
Break spells	8.54%	8.42%
Monsoon Activity	**Percentage of seasonal monsoon rainfall (JJAS) accounted by active and break spells for central India region during 2006-2011**	
	IMD-0.25 deg	**TRMM-0.25 deg**
Active spells	24.50%	24.24%
Break spells	6.14%	5.41%

Inter-Comparisons in Rainfall on Event (Daily) Time Scale between TRMM 3B42 V7 and IMD Gridded Data

Daily rainfall in TRMM data is constructed as accumulated rainfall from 3 GMT to 3 GMT on the next day. Further, TRMM and IMD daily rainfall data are scrutinized for good and bad data by segregating in to three categories, namely, 1. Bad data showing mismatch in data, that means rain in IMD data showing no-rain in corresponding TRMM data (no rain (IMD)-rain (TRMM)), 2. Good data, (i) showing no rainfall at the corresponding data points in both IMD and TRMM (No rain-No rain data) data sets and (ii) showing non-zero rainfall at the corresponding data points in both IMD and TRMM (Rain-Rain) data. The bad data turns out to be 28.2%, the No rain-No rain data, 34.4% and the Rain-Rain data, 37.4%. Thus 37.4% of one-to-one rainfall (Rain-Rain) data set is chosen for further analysis. Bin-wise distribution of rainfall in one-to-one data is described in Figures 13a and 13b. It may be noted in figure 13 that percentage of bin-wise rainfall distribution in both the data sets is similar in pattern.

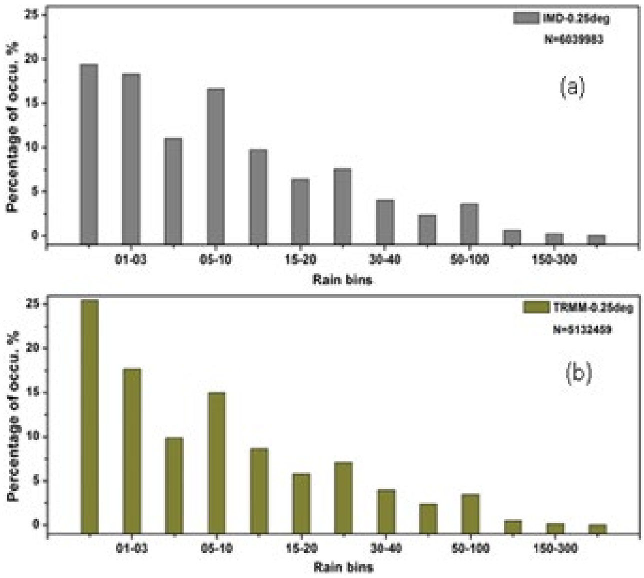

Figure 13. Bin-wise distribution of rainfall in one-to-one a) IMD (top panel) b) TRMM (bottom panel) data sets.

Inter-comparisons in rain events composites for all India and central India

Here, the rain events are constructed as Light Rain events (LR), Moderate Rain events (MR), Heavy Rain events (HR) and Very Heavy Rain events (VHR) for all India and Central India using one-to-one rainfall (Rain-Rain) data set as Segregrated in the previous section. The rainfall variations in these LR, MR, HR and VHR event categories are respectively in ranges, $0.1 \le$ rain ≤ 7.4 mm day^{-1}, $7.5 \le$ rain ≤ 35.4 mm day^{-1}, $35.5 \le$ rain ≤ 124.4 mm day^{-1} and rain ≥ 124.5 mm day^{-1}. These ranges of rainfall variations for the four rain event categories are based on IMD definition. The percentages of rain event occurrence in these four categories are estimated in one-to-one rainfall data sets of IMD and TRMM (3803176 data points) and are listed in Table 4. Table 5 revealed striking comparisons in percentages of rain event occurrence between the TRMM and IMD data sets in all categories for both all India and central India with LR & MR events occurrences in range of 39.2% to 49.5%, HR events in 10.0% to 13.4% and VHR events in 0.5% to 0.7%.

Table 5. Percentages of rain event occurrence for All India and Central India.

IMD Rain Category	% of Rain Event occurrences for all India		% of Rain Event occurrences for central India	
	IMD	TRMM	IMD	TRMM
Light Rain (LR) $0.1 \le$ rain ≤ 7.4 (mm day^{-1})	49.50%	42.50%	-	-
Moderate Rain (MR) $7.5 \le$ rain ≤ 35.4 (mm day^{-1})	39.20%	41.60%	41.40%	44.50%
Heavy Rain (HR) $35.5 \le$ rain ≤ 124.4 (mm day^{-1})	10.30%	13.30%	10.00%	13.40%
Very Heavy Rain (VHR) rain ≥ 124.5 (mm day^{-1})	0.60%	0.70%	0.50%	0.50%

Table 6 presents the comparison statistics in TRMM data for both the overlapping and non-overlapping rain event categories of IMD (1st column). Overlapping rain event category means, for instance, the data point in IMD data set representing LR event category will have corresponding TRMM data point representing LR event category only. Thus overlapping LR-LR rain event category represents Light Rain in both IMD and TRMM data set; similarly, overlapping MR-MR rain event category represents Moderate Rain in both IMD and TRMM data set, overlapping HR-HR rain event category, the Heavy Rain and overlapping VHR-VHR rain event category, the Very Heavy Rain. Non-overlapping rain event categories, LR-MR, LR-HR and LR-VHR means, data points in IMD data set representing LR event category not corresponding to a TRMM data point not representing LR event category, but represents MR, HR or VHR other than LR rain event category. The 2nd and 3rd columns represent the total number of points and % of data points in respective category. The 4th and 5th, columns represent the mean rainfall over the category listed in

1st column and the corresponding standard deviations based on IMD and TRMM data; the last three columns represent the corresponding RMSE, Correlation coefficient (R) and the Bias.

Table 6. Statistics in TRMM data for the overlapping and non overlapping Rain category for the Central India region.

IMD rain category	N	% of data points	IMD mean ± std (mm/day)	TRMM mean ± std (mm/day)	RMSE (mm/day)	R	BIAS (mm/day)
LR- LR	432265	25.89	2.64 ± 2.07	3.15 ± 2.01	2.82	0.08	-0.51
LR-MR	303939	18.2	3.17 ± 2.14	16.09 ± 7.12	14.83	0.07	-12.92
LR-HR	43077	2.58	3.57 ± 2.15	52.21 ± 16.29	51.32	0.02	-48.64
LR-VHR	476	0.03	3.80 ± 2.13	149.02 ± 23.65	147.13	0.03	-145.22
MR-LR	216221	12.95	15.49 ± 6.84	3.62 ± 2.05	13.8	0.06	11.87
MR-MR	358453	21.47	17.41 ± 7.43	18.11 ± 7.63	10.12	0.1	-0.7
MR-HR	108526	6.5	19.64 ± 7.86	54.88 ± 17.93	40.07	0.07	-35.23
MR-VHR	1812	0.11	21.67 ± 7.98	150.89 ± 26.46	132.14	0	-129.22
HR-LR	20278	1.21	50.33 ± 15.27	3.92 ± 2.05	48.89	0.02	46.41
HR-MR	75494	4.52	53.04 ± 17.04	20.69 ± 7.92	37.08	0.09	32.35
HR-HR	66621	3.99	60.66 ± 21.53	60.95 ± 21.08	27.47	0.17	-0.3
HR-VHR	3417	0.2	72.57 ± 24.60	157.06 ± 33.49	93.63	0.06	-84.49
VHR-LR	217	0.01	173.19± 59.64	3.85 ± 2.16	179.48	0.03	169.34
VHR-MR	1412	0.08	159.91± 42.23	22.55 ± 7.97	143.93	-0.01	137.35
VHR-HR	5308	0.32	164.87± 39.94	75.50 ± 24.56	99.88	0.11	89.36
VHR-VHR	1555	0.09	181.12± 51.94	166.74 ± 37.67	61.89	0.13	14.38

Table 6, rows 1, 6, 11 and 16 present the statistics in TRMM data respectively for the overlapping rain event categories of light rain (LR-LR), moderate rain (MR-MR), heavy rain (HR-HR) and very heavy rain (VHR-VHR). Mean rainfall and standard deviations are comparable between TRMM and IMD for the three LR-LR, MR-MR and HR-HR categories. However, the RMSEs for HR-HR and VHR-VHR overlapping categories are quite large. The RMSE for LR-LR category at 2.82 mm day^{-1} is comparable to the mean and the standard deviations in rainfall; whereas, the RMSEs are ~57.0% of the mean rainfall over both the data and higher by ~34.3% than the mean standard deviation for MR-MR category.

For HR-HR and VHR-VHR categories, the RMSEs are respectively 45.2% and 35.6% of the mean rainfall over both data and higher than the respective mean standard deviations by 28.9% and 12.6%. The limitation with this rain event categories definition is that they are not governed by the duration of the rain events, instead they are considered to be of fixed duration of 24 hrs.

One can observe that significant percentage of data falls in non-overlapping categories of LR-MR (2nd row), that is, significant data in IMD LR category are corresponding to MR category in TRMM, obviously associated with large mean rainfall (16.09 mm day^{-1}), RMSE (14.83 mm day^{-1}) and Bias (12.92 mm day^{-1}). Similarly, with the non-overlapping categories of MR-LR (5th row), HR-MR (10th row), VHR-HR (15th row). However, it is to be noted that this analysis is on daily rainfall data, not on the event rainfall over the duration of the event. Results from an analysis on event rainfall over the precise duration of the event will be presented in a subsequent paper.

Conclusion

Monsoon rainfall climatology and monsoon variability on Seasonal, Inter annual, Active-break cycles and daily time scales are constructed in TRMM (Tropical Rain Measuring Mission) 3B42V7 and IMD (India Meteorological Department) data, both gridded at 0.25° × 0.25°, for the TRMM period 1998-2015. All the inter-comparisons in rainfall variations and composites between IMD and TRMM discussed in the present study are based on one-to-one data sets prepared on the common grid structure (Appendix). The Mean summer monsoon rainfall based on IMD data over the period 1901- 2014 is 88.6 cm with the corresponding standard deviation at 8.64 cm. All India seasonal mean monsoon rainfall in IMD and TRMM data sets are comparable, however, in certain regions along the west coast, the extreme north and north-east India, the seasonal rainfall is underestimated in TRMM data.

Inter annual variability in seasonal monsoon rainfall for all India and central India are examined by constructing various data sets, namely, all India daily Rainfall data set using the IMD gridded data at 0.25 × 0.25 resolution; similarly, the central India (74.5E-86.5E: 16.5N-26.5 N) daily Rainfall data set using the IMD gridded data at 0.25 × 0.25 resolution; all India and central India daily rainfall data sets using TRMM data at native resolution. The Inter annual variability in all these data sets is comparable with the negative and positive rainfall anomalies captured, however with marginal differences in magnitudes. The agreement, for instance, for the severe drought years of 1972, 2002 and 2009 is good with negative rainfall anomalies overlapping between the data sets; and similarly, with the positive rainfall anomalies overlapping in the good monsoon year, 1988.

Comparisons in rainfall composites between TRMM and IMD data are carried out for the active and break cycles of the Indian summer monsoons with the active/break monsoon spells extracted using the criteria of Rao et al. The criterion for active (break) spell is that the area averaged IR brightness temperature for the central India region (75°E - 85°E: 15°N - 25°N) is < (>) 270K almost continuously for a minimum of four days and above. Total number of active and break days during 2006-2011 are respectively at 114 and 115 with the duration of break (active) periods in range, 4-17 (4-10) days. It is striking to note that overall contributions of active and break monsoon cycles to all India (central India) seasonal monsoon rainfall are comparing extremely well between IMD and TRMM data sets with the respective numbers being 20.76% (24.50%) in IMD data and 21.50% (24.24%) in TRMM data; however, the respective RMSEs (Root Mean Square Differences) are at 19.76 mm day^{-1} and 10.7 mm day^{-1}.

Rain events of the monsoon season are extracted as Moderate Rain events (MR, 7.5≤mrain ≤ 35.4 (mm day^{-1})), Heavy Rain events (HR, 35.5 ≤ rain ≤ 124.4 (mm day^{-1})), Very Heavy Rain events (VHR, rain ≥ 124.5 (mm day^{-1})) and Light Rain events (LR, 0.1 ≤ rain ≤ 7.4 (mm day^{-1})) based on IMD definition. LR, MR, HR, VHR rain events are extracted in 37.4% of good data representing rain–rain data points in both TRMM and IMD data sets. The respective Root Mean Square Errors (RMSE) are at 2.82 mm day^{-1}, 10.12 mm day^{-1}, 27.47 mm day^{-1} and 61.89 mm day^{-1} for the central India region. The RMSE for the overlapping rain events in IMD and TRMM, called as LR-LR category, being 2.8 mm day^{-1}, is comparable to the mean and the standard deviations in rainfall in both the data sets; whereas, the RMSE is ~57.0% of the mean rainfall over both data for MR-MR overlapping rainfall category and higher by ~34.3% than the mean standard deviation. For HR-HR and VHR-VHR categories, the RMSEs are respectively 45.2% and 35.6% of the mean rainfall over both data and higher by 28.9% and 12.6% than the respective mean standard deviations. Here, the point to be noted is that, although the ranges of IMD rain categories are meaningfully representing the rainfall variations, there is no constraint on duration of rain events for these categories. The RMSEs may significantly reduce if rain event durations are considered for all categories. The results on inter-comparisons of rain events considering the precise durations of rain events will be presented in a subsequent paper.

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