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Satellite derived precipitation estimates over Indian region during southwest monsoons

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ABSTRACT
Quantitative Precipitation Estimates (QPE) derived from Kalpana-1 Satellite and Tropical Rainfall Measuring Mission (TRMM) rainfall have been compared with observed gridded rainfall over six representative regions of India during southwest monsoon 2009 & 2010. The results have shown that no single satellite precipitation estimates are close to the gridded actual rainfall over all the regions in the same year and over the same region in two different types of monsoon, though good correlation coefficients (CC) exist between the satellite precipitation estimates and actual rainfall. While cumulative seasonal TRMM rainfall for June to September is an under-estimation during deficient monsoon year 2009 by about 6 cm, cumulative seasonal QPE is very close to the actual seasonal rainfall. In a normal monsoon year 2010 cumulative seasonal TRMM rainfall was very close to observed seasonal rainfall whereas the difference between the cumulative seasonal QPE and actual rainfall was large.

INTRODUCTION

Accurate estimates of rainfall at small spatial (a few km) and temporal scales (hourly, three-hourly or daily) have many applications in meteorology and hydrology. Using a combination of ground-based radars and dense network of rain gauges, such information are available but only over limited areas. Continuous high temporal resolution satellite data covering a large area are available only from instruments onboard geostationary platforms. The lack of visible data at night has generally restricted geostationary rainfall monitoring technique to the use of IR data alone. Though the satellite IR algorithms benefit from high temporal sampling, the IR radiances eminating from cloud tops have only an indirect relationship with surface rainfall which, in turn, results in weak statistical relationships between rainfall and cloudiness. The most common technique for IR rain estimate counts cloudy pixels within a given area that are colder than a given threshold temperature (e.g. 235 K in cloud indexing method by Arkin et al., 1979). The pixels that are colder than threshold temperature are probably associated with precipitating convective clouds possessing cold high tops. But there are some sources of errors, e.g. high-level cirrus and other non-precipitating clouds often screened in as precipitating with this simple relationship. Arkin et al. (1989) estimated precipitation over Indian region from IR window channel observation of INSAT-1B using simple cloud indexing technique. Bhatt and Nakamura (2005) showed the complex diurnal variability in convection and rainfall around the mountains (Himalayan). Recently, Nath et al. (2008) applied Artificial Neural Network (ANN) approach to improve the quality of INSAT derived Quantitative Precipitation Estimation (QPE) over the Indian region for the summer monsoon. Stephans et al. (2006) presented a critical review of a number of popular methods that have been developed to retrieve cloud and precipitation properties from satellite radiance measurements.

NASA and the Japan Aerospace Exploration Agency (JAXA) collaborated in launching the Tropical Rainfall Measuring Mission (TRMM) satellite in November 1997 to study global rainfall. The major rain sensors for the rainfall measurement onboard TRMM are Precipitation Radar (PR), TRMM Microwave Imager (TMI) and Visible Infrared Scanner (VIRS). Kummerow et al. (2000) have provided a description of the TRMM project and instrument performance.

Precipitation Radar (PR) onboard TRMM gives the three-dimensional structure of rainfall. PR is able to provide significantly more accurate estimation of rain rates but suffers from poor temporal sampling associated with platforms in low earth orbits. Due to the low sampling rate, such instruments are most suitable for the estimation of accumulated rainfall over longer periods. Robert et al. (2007) analyzed the monsoon convection over the Himalayan region using TRMM PR data. Its instantaneous rain estimates could be used to calibrate the IR-brightness temperature (TBs). For this purpose, attempts are being made to integrate IR and microwave (MW) observations. Some such algorithms have been described by Gairola and Krishnamurti (1992), Mitra et al. (2003). An adjusted global precipitation index (AGPI) technique was developed by Adler et al. (1994), in which a correction factor is derived from the comparison of Passive Microwave (PMW) and Global Precipitation Index (GPI) estimates for coincident time slots over some extended periods (e.g. one month). This correction is then applied to all the hourly GPI estimates during that period. Xu et al. (1999) extended this technique to develop the Universally Adjusted GPI (UAGPI) method in which both the monthly IR thresholds and IR conditional rain rate are optimized using coincident PMW and IR data.

There have been a number of efforts to compare and validate TRMM rainfall products with other rainfall measurements. In this study, we compare a high density rain gauge data set over India with two TRMM Level 3 rainfall products: 3B42 which is a calibrated geosynchronous IR rain rate using TRMM estimates and 3B43 which merges satellite data from TRMM, geosynchronous IR, SSM/I, and rain gauges. Because of the high spatial and temporal resolution, 3B42 is the most preferred TRMM product for operational purposes.

DATA USED AND METHOD OF ANALYSIS

Actual Gridded Rainfall data

The Quality controlled and objectively analyzed to 1° lat. x 1° long. grid observed rainfall data from India Meteorological Department (IMD) (Durai et al., 2010; Bhowimik and Das, 2007) have been used here. The objective technique used for rainfall analysis was based on the Cressman (1959) interpolation method. 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 analyzed 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 and TRMM 3B42) over Indian region for monsoons-2009 and 2010.

KALPANA-1 Quantitative Precipitation Estimates (K1QPE)

K1QPE were derived at the grid resolution 1° x 1° Lat/Lon for the monsoon seasons 2009 and 2010, following the algorithm described by Arkin et al. (1987). As the algorithm was originally developed for the estimation of large scale precipitation over oceanic areas, extension of the technique to the land areas may give unreasonable estimates over mountainous terrain, where the rainfall is primarily orographic. 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 (Nath et al., 2008) and for INSAT-1B. According to the 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 total number of pixels within the square grid, and h the time in hours. The constant rain rate of 3 mm/h provides the best correlation of the regression relation.

General approach

Neither gauges measurements nor satellite-based estimates are perfect indicators of rainfall. Arkin (1995 & 1996) showed that satellite estimates, they examined, have non negligible biases, when compared with concurrent in situ observations. With gauges, biases are introduced by gauge type, maintenance, and siting as well as by spatial sampling. Xie and Arkin (1995) concluded these are small when compared with the bias in satellite estimates. They also showed that if five or more gauges are available in a 2.5° x 2.5° latitude/longitude grid area, the error in the areal averages from the gauges is about 10% or less. This error is consistent with results obtained by some authors in the context of analyses of African rainfall.

TRMM 3B42

The TRMM and Other-GPI Calibration Rainfall Product algorithm (3B42) uses combined rain structure (2B31) and VIRS calibration (1B01) to adjust IR estimates from geosynchronous IR observations. Global estimates are made by adjusting the GOES Precipitation Index (GPI) to the TRMM estimates. The 3B42 algorithm provides the daily tropical precipitation estimates and also the root mean square (RMS) precipitation error estimates. The output is daily rainfall for 1x1 degree grid boxes within the tropical region from latitude 40N to 40S. To compare the satellite estimated rainfall data (TRMM 3B42 and K1QPE) with observed gridded rainfall data, the following statistical measures use Root Mean Square Error (RMSE) and Correlation Coefficients (CC). These are defined as follows:

Root Mean Square Error

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

and Correlation Coefficients

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

Where N is the total number of samples, i= 1, 2, … N and X is the satellite rainfall estimation and O is the actual observation at the grid. Six representative regions have been selected over the Indian subcontinents which are depicted in Fig. 1. The idea to select these regions is to cover almost entire monsoon core zones.

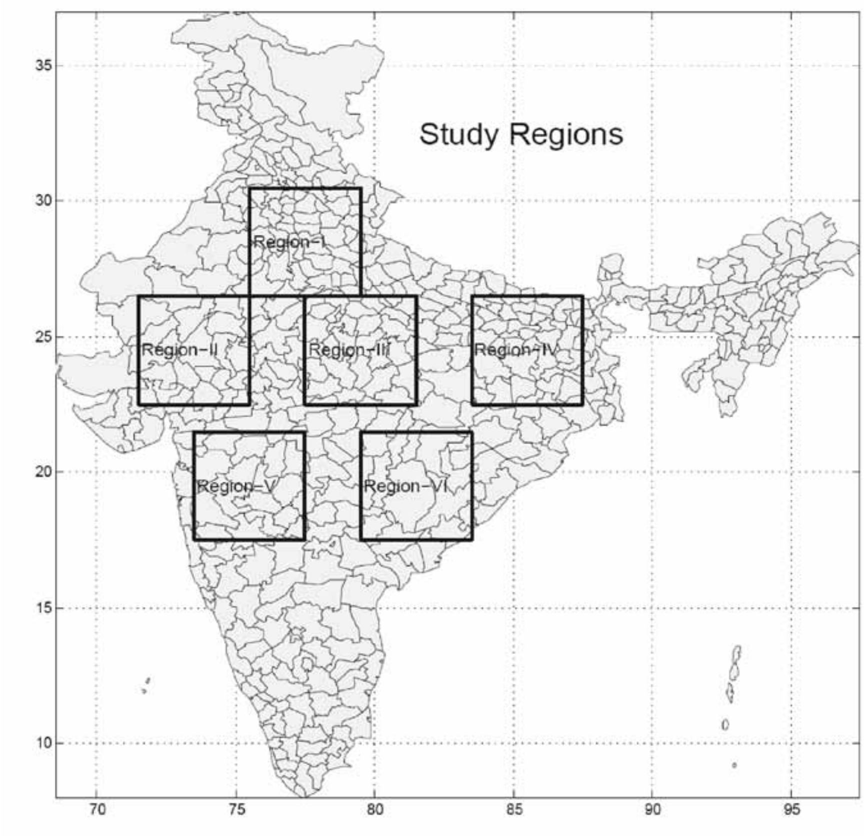

Figure 1. Regions considered in the study; I [75.5-79.5°E, 26.5-30.5°N], II [71.5-75.5°E, 22.5-26.5°N], III [77.5-81.5°E, 22.5-26.5°N], IV [83.5-87.5°E, 22.5-26.5°N], V [73.5-77.5°E, 17.5-21.5°N], VI [79.5-83.5°E, 17.5-21.5°N].

RESULTS AND DISCUSSIONS

Correlation Coefficients for daily rainfall

Actual gridded Rainfall vs. Kalpana-1 QPE (K1QPE) The correlation coefficient between K1QPE and actual gridded rainfall has been presented in Fig. 2(a). Good correlations have been observed between actual gridded rainfall and K1QPE during a normal monsoon year 2010. The correlations during a deficit monsoon-2009 are lower over all the six regions. The lowest correlation between K1QPE and ARF was found over Region-I.

Actual gridded Rainfall vs. TRMM Rainfall

The CCs between TRMM rainfall and actual gridded rainfall have been depicted in Fig. 2(b). The correlations are generally higher (except Region-I) during the deficient monsoon year 2009. The CCs between TRMM rainfall and actual rainfall are generally lower during normal monsoon year 2010 as compared to the corresponding CCs between K1QPE and actual rainfall. However, the correlations between TRMM rainfall and actual rainfall are good during deficient monsoon year 2009 as compared to the corresponding CCs between K1QPE and actual rainfall. Some estimates may be better during deficient monsoons whereas some may be better during normal or excess monsoons.

TRMM Rainfall vs. Kalpana-1 QPE

Correlations between K1QPE and TRMM rainfall over different regions during the southwest monsoon seasons (June to September) of 2009 and 2010 have been presented in Fig. 2 (c). Good correlations have been found between QPE and TRMM rainfall during 2009 which was a deficient monsoon year. The CC has been found over Region 2, which is 0.92. The lowest CC has been found over Region-I which is 0.77. The CCs are lower over all the regions during normal monsoon year 2010 as compared to corresponding CCs during deficient monsoon year

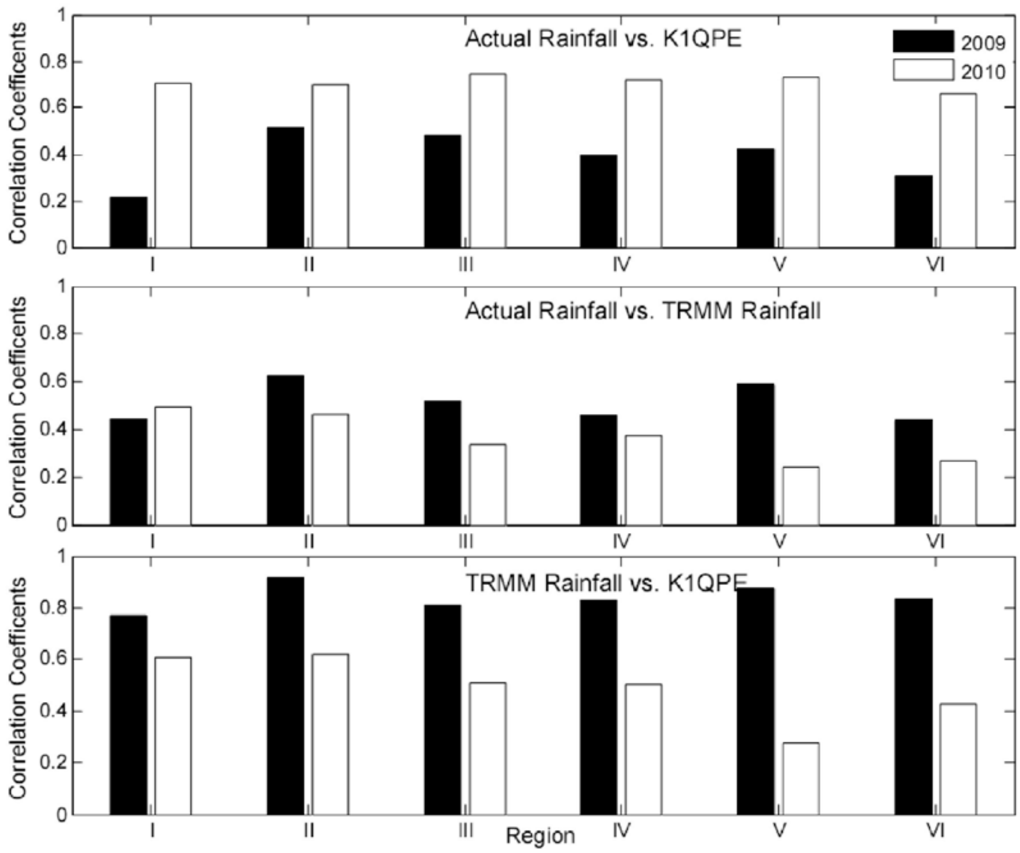

Figure 2. Daily rainfall correlation coefficients (a) Actual rainfall vs. K1QPE, (b) Actual rainfall vs. TRMM rainfall (c) TRMM rainfall vs. K1QPE.

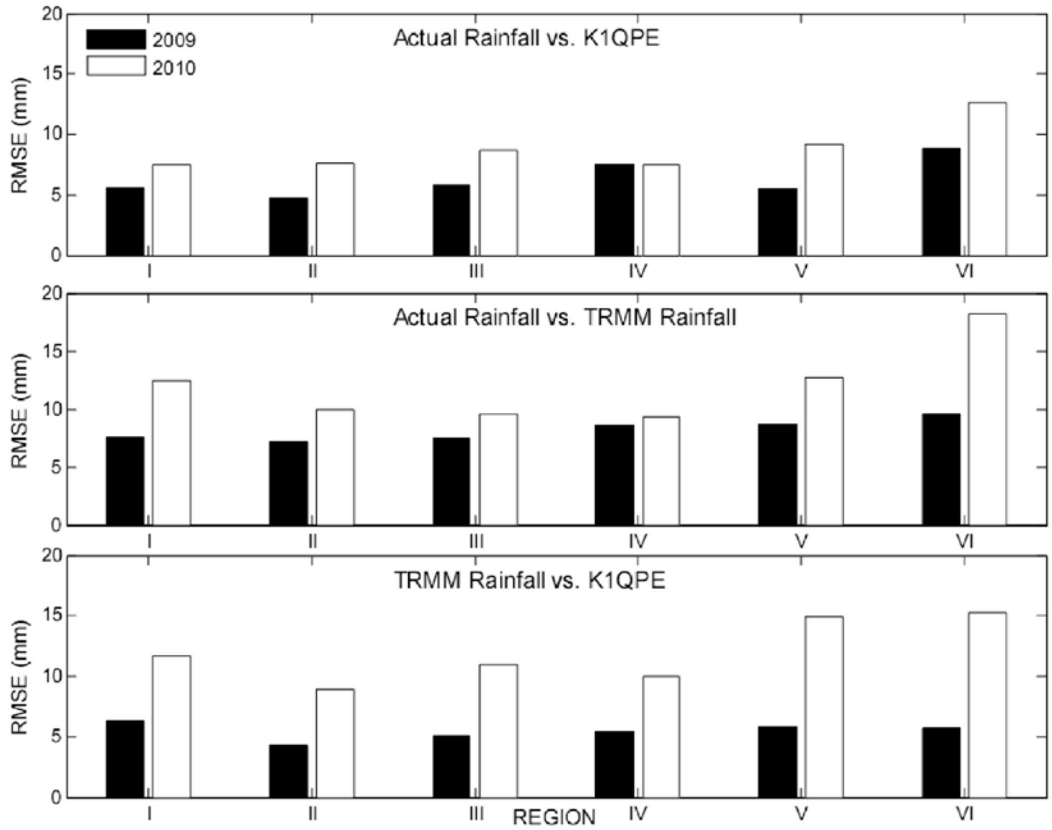

Figure 3. Daily rainfall RMSE (a) Actual rainfall vs. K1QPE, (b) Actual rainfall vs. TRMM rainfall (c) TRMM rainfall vs. K1QPE.

2009. The correlation coefficients over all the regions range from 0.43 to 0.92.

Good CC between actual gridded rainfall and K1QPE in all the six regions, have been observed during 2010 monsoon compared to 2009 monsoon. Very low CC observed (Fig.s 2b, 2c) in Region-I during monsoon 2009, may be due to orographic effect of Himalaya. Actual gridded rainfall vs. TRMM rainfall and TRMM rainfall vs. K1QPE have very good CCs during in monsoon 2009 as compared to 2010 monsoon. This may be possibly due to good CCs during deficient monsoon year compared to normal monsoon year.

Root Mean Square Error for daily rainfall

The Root Mean Square Errors between satellite estimates (RMSE) and actual daily rainfall was more in normal monsoon year 2010 compared to deficient monsoon year 2009.

Weekly rainfall analysis

Weekly rainfall for each case was computed from daily rainfall values. Week one started from 1^{st} June to 7^{th} June and so on and last week has 4 days only i.e. 27^{th} September to 30^{th} September of both the years.

Weekly rainfall time series

It is seen from Fig.. 4(a-b) that weekly TRMM rainfall values were over-estimated compared to actual gridded rainfall in both types of monsoon years 2009 and 2010 over Region-I. The K1QPE values were on higher side of the actual gridded rainfall up to 11^{th} week of deficient monsoon 2009 and under-estimation afterwards except for few weeks. But on the other hand K1QPE values were generally under-estimation in the normal monsoon 2010. In this region we may say that Kalpana-1 satellite was unable to capture heavy rainfall spells

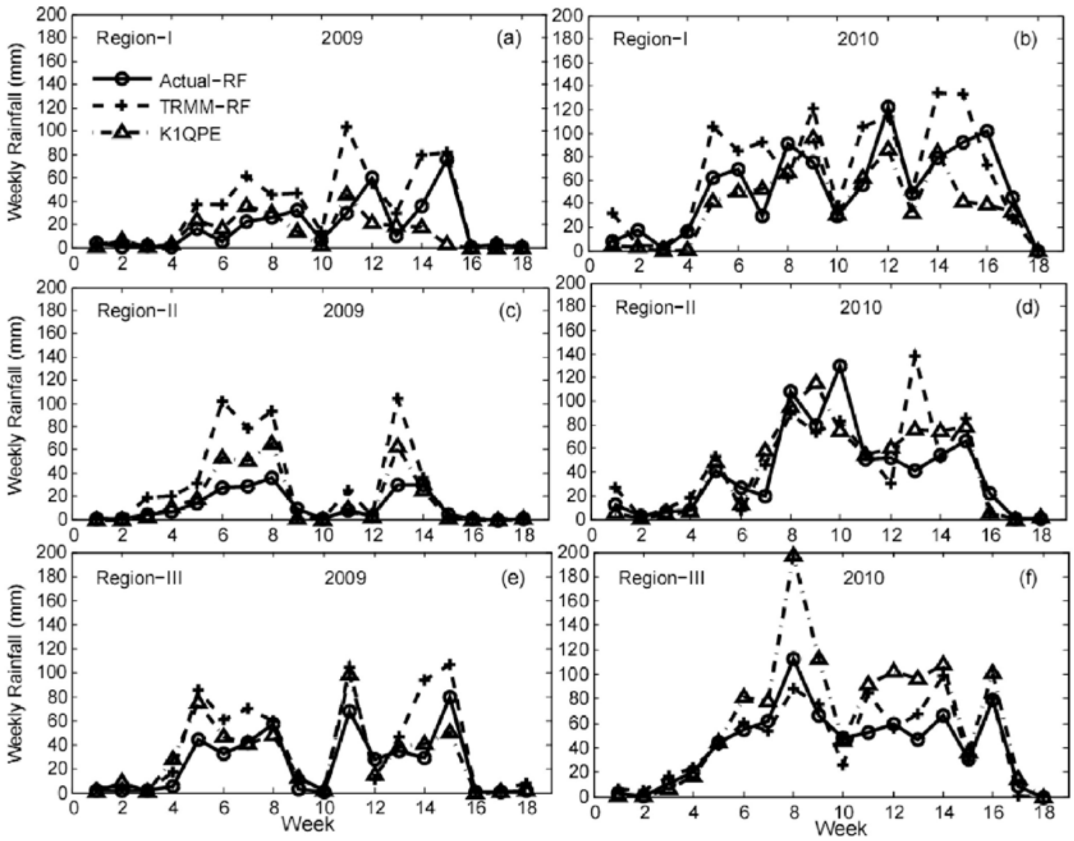

Figure 4a-f. Weekly rainfall time series (a-l) Actual rainfall, TRMM rainfall and K1QPE.

which TRMM did. Over Region-II as brought out by Fig. 4(c-d) TRMM rainfall and K1QPE both were clearly over-estimations during the deficient monsoon 2009. On the other hand this was not the case in normal monsoon 2010 when the TRMM and Kalpana-1 estimates were close to actual rainfall and mixed kind of variations were observed afterwards. Fig. 4(e-f) shows that the K1QPE and TRMM rainfall were generally on higher side except a few exceptions with respect to actual gridded rainfall in the deficient monsoon 2009. But on the other hand in normal monsoon 2010 very close to actual gridded rainfall up to the 5th week was observed. K1QPE was an over-estimation afterwards in rest of the weeks.

In the Region-IV Fig. 4(g-h), mixed kind of variations was observed in K1QPE and TRMM rainfall with respect to actual gridded rainfall in the deficient monsoon 2009. Good resemblance was observed between TRMM rainfall and actual gridded rainfall during monsoon 2009. But in the normal monsoon 2010, the K1QPE was generally an over-estimation to the actual gridded rainfall and TRMM rainfall. Barring few exceptions TRMM rainfall was in good agreement with the actual gridded rainfall. For this region (East India) we may say that TRMM precipitation product was better than Kalpana-1 QPE. In the Region-V Fig. 4(i-j), apart from a few exceptions TRMM rainfall generally in over-estimation compared to the K1QPE and actual gridded rainfall during deficient monsoon 2009. On the other hand K1QPE was in good agreement with the actual gridded rainfall. In case of normal monsoon 2010 mixed kind of variations were observed among the K1QPE, TRMM rainfall and actual gridded rainfall. Over Region-VI (Fig. 4(k-l)), apart from a few exceptions both K1QPE and TRMM rainfall were higher as compared to actual gridded rainfall in deficient monsoon year 2009. On the other hand K1QPE was close to actual gridded rainfall during normal monsoon 2010. We may say that for

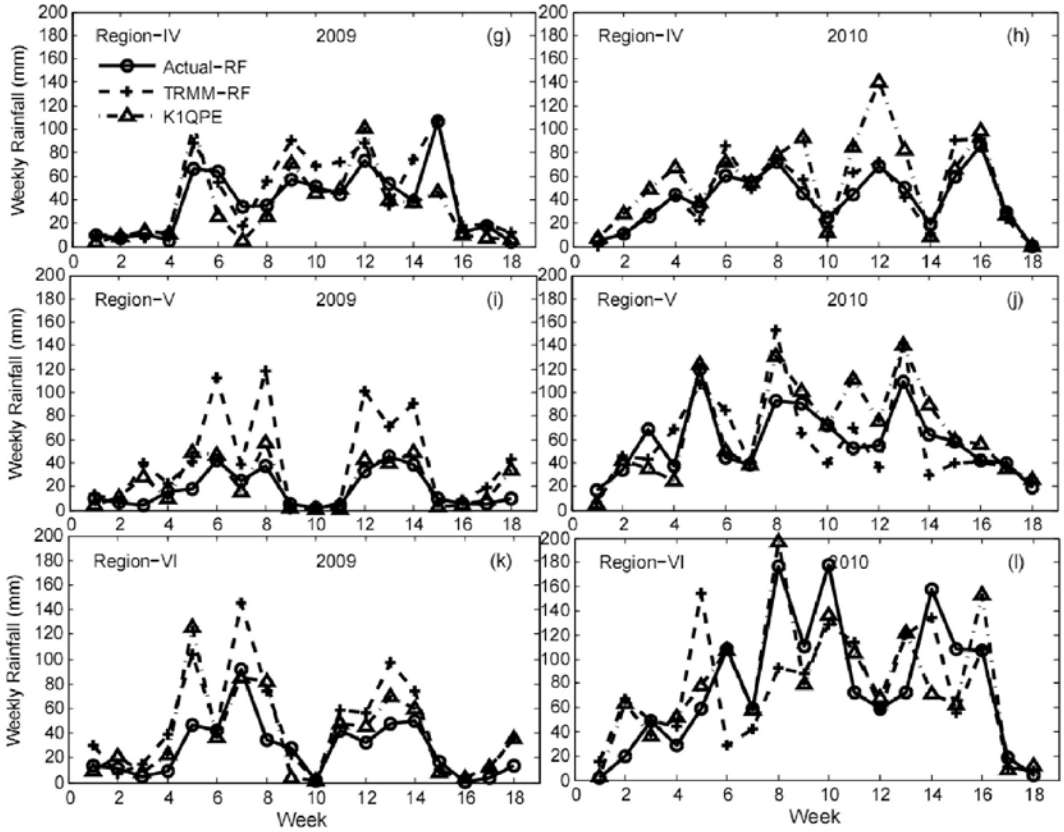

Figure 4g-l. Weekly rainfall time series (a-l) Actual rainfall, TRMM rainfall and K1QPE.

this region TRMM also was unable to capture heavy rainfall spells.

Weekly rainfall correlation coefficients

The weekly correlations were generally higher (except Region-I) during the deficient monsoon year 2009. It is interesting to note that the CCs between TRMM rainfall and actual rainfall are generally lower during normal monsoon year 2010, as compared to the corresponding CCs between K1QPE and actual rainfall. However, the correlations between TRMM rainfall and actual rainfall were good during deficient monsoon year 2009, as compared to the corresponding CCs between K1QPE and actual gridded rainfall. Therefore, usefulness of a particular satellite precipitation estimate over the Indian subcontinent seems to depend upon the type of monsoon. Some estimates may be better during deficient monsoons whereas some may be better during normal or excess monsoons.

Weekly rainfall root mean square error

Except for few regions (Fig. 6a) weekly RMSE were more than 20 mm during monsoons 2009 and 2010. Actual gridded rainfall vs. TRMM rainfall indicates highest and lowest RMSE of about 45mm and 12 mm respectively over Region-VI and Region-IV. Actual gridded rainfall vs. K1QPE (Fig 6b) shows higher RMSE in normal monsoon 2010 compared to the deficient monsoon 2009, over all regions. K1QPE vs. TRMM rainfall RMSEs (Fig. 6c) observed were comparable during normal and deficient monsoons, except for Regions-III & VI.

Accumulated Monthly Rainfall

It is seen from Fig. 7(a-b) that in the month of June the TRMM rainfall was slightly lower compared to the actual gridded rainfall during deficient monsoon 2009. Mixed kind of results was observed during normal monsoon 2010. On the other hand, monthly

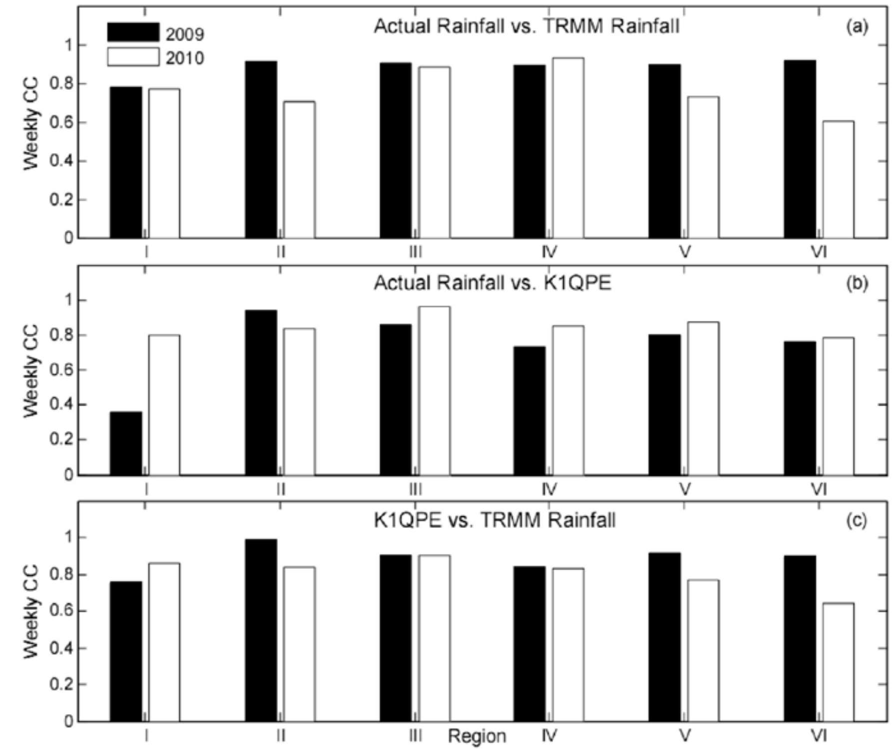

Figure 5. Weekly correlation coefficients (a) Actual Rainfall vs. TRMM Rainfall (b) Actual Rainfall vs. K1QPE (c) K1QPE vs. TRMM Rainfall

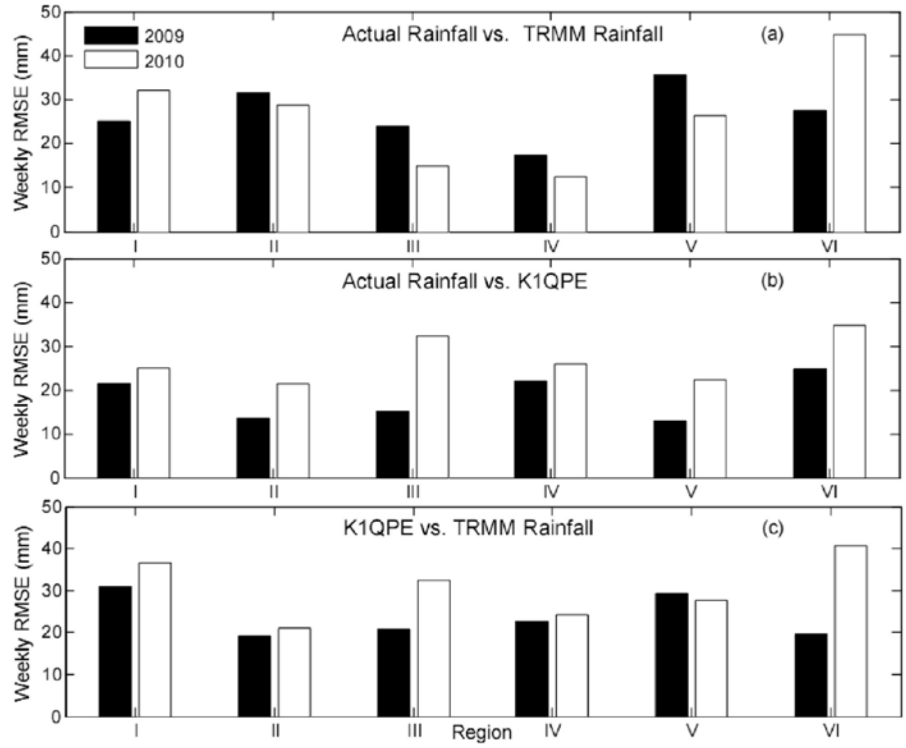

Figure 6. Weekly RMSE (mm) (a) Actual Rainfall vs. TRMM Rainfall (b) Actual Rainfall vs. K1QPE (c) K1QPE vs. TRMM Rainfall

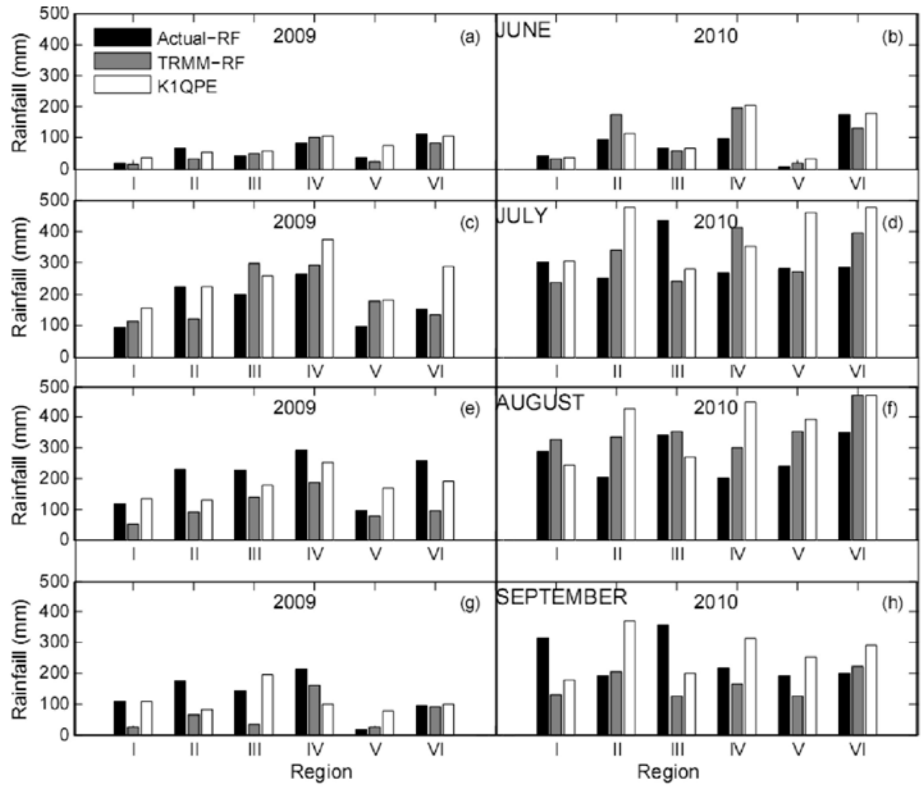

Figure 7. Monthly cumulative rainfall (a-h) Actual rainfall, TRMM rainfall and K1QPE during monsoon seasons 2009 and 2010.

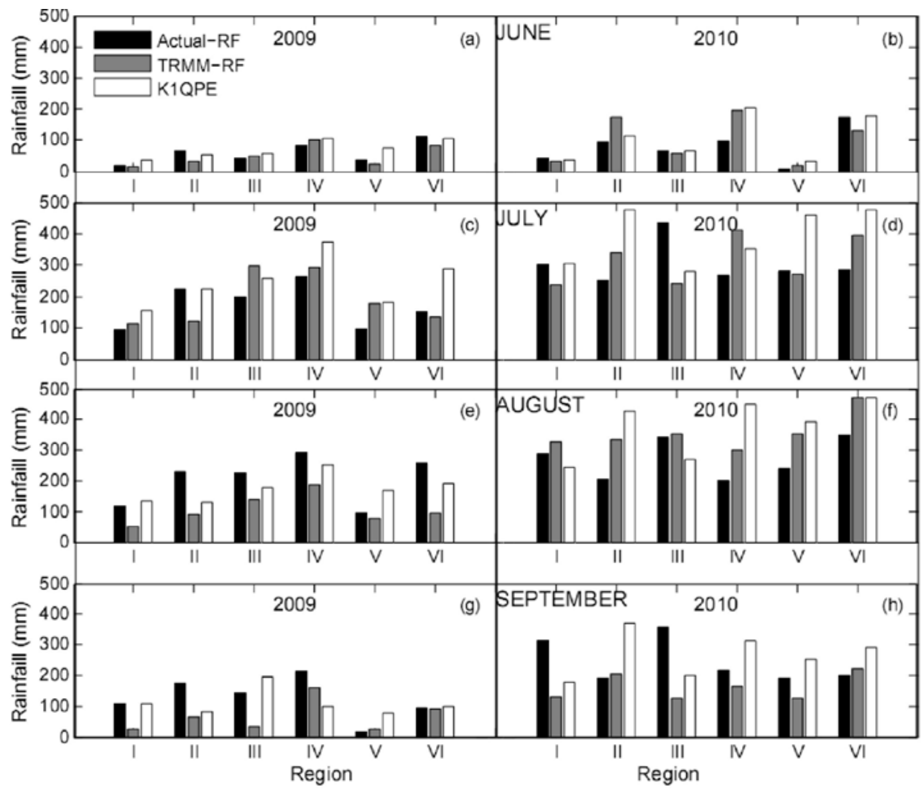

Figure 8. Seasonal cumulative rainfall (a-b) Actual rainfall, TRMM rainfall and K1QPE.

K1QPE for June was generally an over-estimation to the actual gridded rainfall, during 2009 and 2010. Fig. 7(c-d) shows mixed variations in TRMM rainfall and K1QPE during July. In August (Fig. 7(e-f)) both the TRMM rainfall and K1QPE were under-estimation to the actual gridded rainfall, during deficient monsoon 2009 and over-estimation during normal monsoon 2010. Fig. 7(g-h) shows that the TRMM rainfall was generally under-estimation, except to the actual gridded rainfall in monsoons 2009 and 2010.

Seasonal accumulated rainfall

Fig. 8(a-b) shows that the cumulative seasonal TRMM rainfall was under-estimation during deficient monsoon 2009 and an over-estimation in normal monsoon 2010, barring few exceptions with respect to the actual gridded rainfall. On the other hand, the K1QPE was close to the actual gridded rainfall during deficient monsoon 2009, and generally an over-estimation in normal monsoon 2010.

CONCLUSIONS

Usefulness of a particular satellite precipitation estimate over the Indian subcontinent seems to depend upon the type of monsoon.

The Root Mean Square Errors between satellite estimates (RMSE) and actual daily rainfall was more in normal monsoon year 2010 compared to deficient monsoon year 2009.

Correlations between K1QPE and TRMM rainfall were better during deficient monsoon 2009 as compared to during normal monsoon 2010.

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