Assessment of GPM based Integrated Multi-satellite Retrievals under Diverse Climatic and Topographic Conditions in Pakistan

Muhammad Masood[1*], Abdul Sattar Shakir[2], Habib-ur-Rehman[1]

1. *Centre of Excellence in Water Resources Engineering, UET, Lahore*
2. *Department of Civil Engineering, UET, Lahore*

∗ **Corresponding Author:** Email: chmasoud@gmail.com

Abstract

In this study, assessment of Global Precipitation Measurement Mission's (GPM) Integrated Multi-satellite Retrievals (IMERG) research and IMERG real time was carried out under varying climatic and topographic conditions in Pakistan. A set of evaluating and detective statistical indices were determined. The evaluating indices include Correlation Co-efficient (CC), the BIAS, Relative-BIAS (RBIAS), and Root Mean Square Error (RMSE). The detective tests consist of the Probability of Detection (POD), False Alarm Ratio (FAR), and Critical Success Index (CSI). The assessments were carried out at the grid scale, for the entire study area, and by dividing the study area into five regions based on topography and climatic conditions. Daily accumulated rainfall data, in millimeters, of eighty-two rain gauge stations, for the period from March till December of 2015 were obtained from Pakistan Meteorological Department. For inter-comparison among the satellite based products, TRMM TMPA 3B42 real time was also used. The results showed that the observed co-relation was not significantly high at regional as well as grid scale but the results of BIAS were relatively higher. The value of POD varied from 50 to 100 percent. However, the value of CSI remained up to 30 percent. It was observed that the performance of satellite based products improved in plain areas and areas with sufficient rainfall. However, in high altitude areas, results were not satisfactory due to complex topography and climatic conditions. Inter-comparison of satellite products showed that the performance of IMERG research was better than IMERG real time and TMPA 3B42. However, at mean daily basis, the performance of IMERG real time was better than the other two. The overall performance of IMERG products remained better than 3B42 real time. An inter-comparison between spatial distribution of average daily precipitation of the satellite based estimations and rain gauge values strongly encouraged application and further exploration of satellite based precipitation products.

Key Words: Satellite Precipitation, Assessment, IMERG, TMPA, Pakistan

1. Introduction

Historically rain gauges have been used for measuring rainfall. Now, radar has supplemented rain gauges in technically advanced republics, mainly because of readily access to data. From the last two decades, rainfall radars and gauges have been augmented using satellite based rainfall assessments [1]. The satellite based rainfall estimation techniques provide information on occurrence of rainfall, its quantity, and dissemination over the region. Exploration on assessing precipitation using satellite imageries has increased due to its utilization in distant zones and in the seas [2]. Estimation of precipitation by satellites depend on certain algorithms, based on the observations both, in the Infrared (IR) and Microwave (MW) spectrum for providing amount of precipitation from a number of meteorological satellites [3, 4]. Approaches for the above two spectrums (IR&MW) are significantly different from each other [5-9]. These two spectrums are required, since IR devices on geostationary satellites have the capability of reporting data every 15 minutes, which is required in hydrology for running rainfall runoff models used in flood forecasting. For the MW, the time interval of refreshing the data is longer, as these devices are fitted on polar orbiting satellites.

Estimation of precipitation by satellites is an indirect measurement. There are chances of systematic errors normally called 'BIAS' or uncertainties [10, 11]. Both the types of errors, temporal inaccuracies (±8% to ±12% for each month), and sampling inaccuracies (approximately 30%) can be anticipated in rainfall estimations [12]. Satellite precipitation data needs verification and validation before its application. Such errors can result in incorrect applications if applied without calibration [13]. Many studies have been carried out for the validation of the precipitation around the world, but these studies are region specific [14, 15]. BIAS-adjustment approaches depend on either calculating the difference amid satellite and gauged precipitation where rain gauge values are available [16, 17] or on a blend of numerous satellite based estimations in areas having no rain gauge values [18]. Another practical approach to eliminate uncertainties on a monthly scale or higher is to merge ground based measurements from rain gauges or radar network [19]. Authentication of rainfall approximation using remote sensing has been conducted on many occasions [20]. As these studies are region specific less work have been done in developing countries like Pakistan. Tobin [21] conducted adjustment of satellite precipitation data to facilitate hydrologic modeling to eliminate false alarm or missed bias. Muller [22] did bias adjustment of satellite rainfall data through stochastic modeling. Khan et al [23] evaluated the potential of three high resolution satellite precipitation estimates for monsoon monitoring over Pakistan using validation statistical indices. Cheema and Bastiaanssen [24], calibrated Tropical Rainfall Measurement Mission (TRMM) data for the Indus Basin using regression analysis and geographical differential analysis. Moazami et al [25] conducted the uncertainty analysis of BIAS from satellite rainfall estimates using Copula method.

With the passage of time, more and more development occurred in the field of satellite based precipitation measurement techniques. Resultantly, upgradation of existing and invention of new products took place. A similar development was the launching of Global Precipitation Measurement Mission (GPM) observatory in early 2014, a joint venture of NASA and JAXA. GPM Integrated Multi-satellite Retrievals (IMERG) is a very high resolution precipitation product available in three modes namely, early, late (Real time) that began in March 2014, and final runs (Research) that began in 2015. IMERG is a suite of very high spatial (0.1^o latitude/longitude) and temporal (half-hourly) resolution multi-satellite precipitation product. Real time IMERG is created within a few hours of the satellite observations being collected, and it is supplemented by a higher quality "Research" IMERG that is created several months after the observations are collected. Real time IMERG has two versions: Real time early and Real time Late. Real time IMERG is intended for uses such as disaster monitoring and flood and landslide risk assessment. Research IMERG is intended for meteorological and climatological studies. All such products need assessment and validation prior to application [26, 27]. Tropical Rainfall Measurement Mission (TRMM) launched TRMM Multisatellite Precipitation Analysis (TMPA) in late nineties. It has various precipitation estimation products on various temporal resolutions. TMPA 3B42 real time provided daily accumulated precipitation in millimeters at a spatial frequency of $0.25^o \times 0.25^o$.

In the present study application of GPM based IMERG Real time and Research versions were carried out over climatically and topographically varied regions of Pakistan. The specific objectives of the study were: assessment of uncertainties associated with the selected high resolution satellite precipitation products and offer an insight into the spatiotemporal errors of these datasets.

2. Study Area and Data Sets

2.1 Study Area

Pakistan extends approximately from 61^o to 77^o East (longitude) and 23.5^o to 37^o North (latitude) and has varied climate conditions. The altitude varies from sea-level, with arid and warm climate in the south to chilling, snow covered territory towards north holding the snow covered peaks with a height of around 7000 meters (Fig. 1). Because of varied climatic regimes, the precipitation, particularly the rainfall, varies significantly in space and time. Average yearly precipitation ranges approximately from 300 mm to around 1300 mm from south towards the north. In order to record these varied precipitation values, meteorological stations are measuring data in Pakistan. But, the spatiotemporal tenacity of rain-gauge stations in hilly areas is insufficient for precise hydrologic activities (World Meteorological Organization).

2.2 Satellite Based Estimates

IMERG is a multi-satellite precipitation algorithm of the Level 3 by GPM, which is a combination of precipitation estimations from IR-based geosynchronous satellites interpretations, microwave instruments, and rain gauge rainfall data [29]. Presently, IMERG is at its initial phase stated as Day-1 step. Three satellite products were analyzed in this study IMERG Real Time, IMERG Research, and TRMM Multi Satellite Precipitation Analysis (TMPA) 3B42 real time. The GIS version of daily, real time (late) and research (post-real-time) products (version 03D) in the IMERG suite and version seven of TMPA products were used in this study. As the Research version of IMERG is available since March, 2015, the data of all the products from March till December of 2015 were utilized.

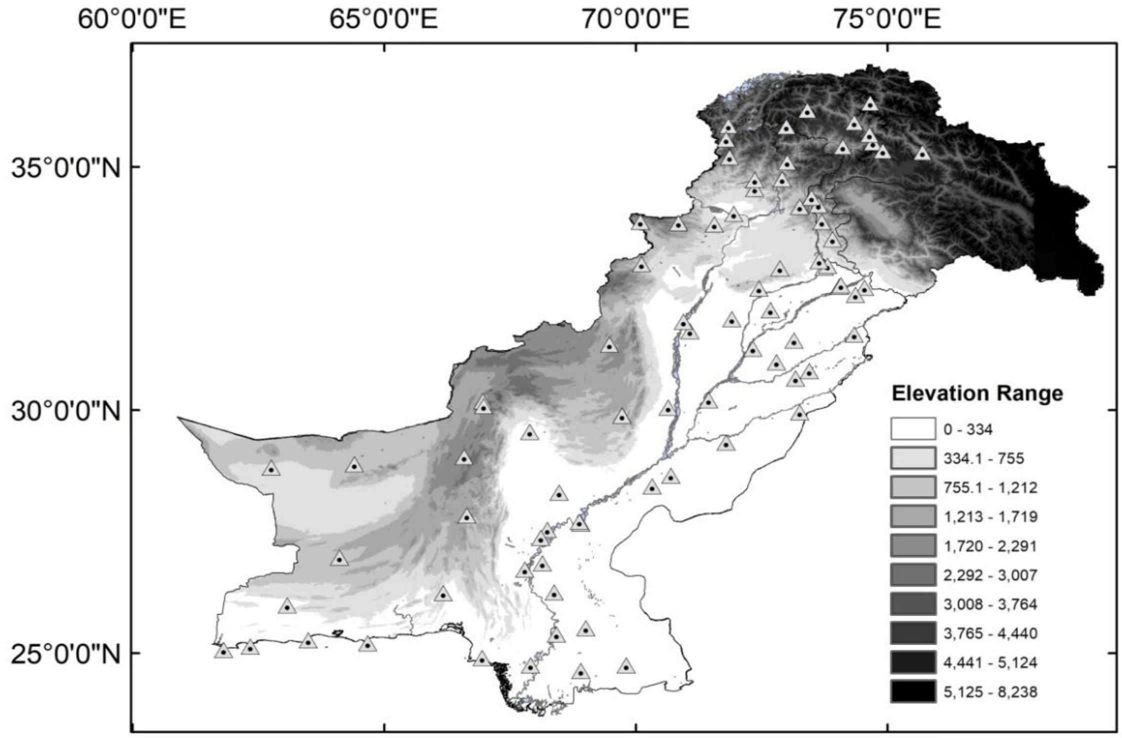

Fig. 1: Elevation (meter) of the study area and spatial distribution of rain gauges

2.3 Rain Gauge Data

Pakistan Meteorological Department (PMD) has established about one hundred weather stations across Pakistan with rainfall gauges. Accumulated rainfall measurements are noted at 8:00 am daily. Salma et al [287] studied the rainfall patterns in various climatic regions of Pakistan based on the analysis of 30 years data. They classified rain gauge stations of Pakistan into five regions as shown in Fig. 2. The description of regions is as under:

Region A

Region A consists of the locations where weather is cold and high peaks. It is located in the north of Pakistan. These places are Muzaffarabad, Said-u-Sharif, Skardu, Astor, Dir, Chilas Chitral, Parachinar, Gilgit, and Kakul etc. These are hill stations mostly situated among 34^o N to 38^o N in the Himalayan, Koh-Hindukash and Kohe-Sufaid regions.

Region B

This region has a mild cold climate and in some area sub foothills, situated around between 31^o to 34 ^{o} North. The locations include Sialkot, Jhelum, Chakwal, Mangla, Islamabad, Bannu, Peshawar, Cherat, D.I.Khan, etc.

Region C

These are hilly places having high altitudes above the mean sea level and extended from 27^o to 32^o North and 64^o to 70^o East. In winter weather is cold and in summer hot. Prominent locations in the region are Zhob, Quetta, Kalat, and Khuzdar. etc.

Region D

This region is the driest and the hottest in the country where highest temperatures are observed in places like Jacobabad. Most of the areas are plains having some deserts such as Thal, Cholistan and Thar. Stations included are Faisal Abad, Multan, D.G. Khan, Khanpur, Bahawalpure, Rohri, and Jacobabad.

Region E

This is a vast region having major cities and seaside municipalities, closer to the Arabian Sea. The coastline part covers a portion of the zone and weather of coastline portion in Baluchistan and in the Sindh province is almost dry to most arid. The places of this region are Nawabshah, Jewani, Karachi, and Hyderabad etc. In the present study, the daily precipitation data of eighty gauging stations situated in the above mentioned regions were obtained from the PMD for the evaluation of the satellite precipitation products.

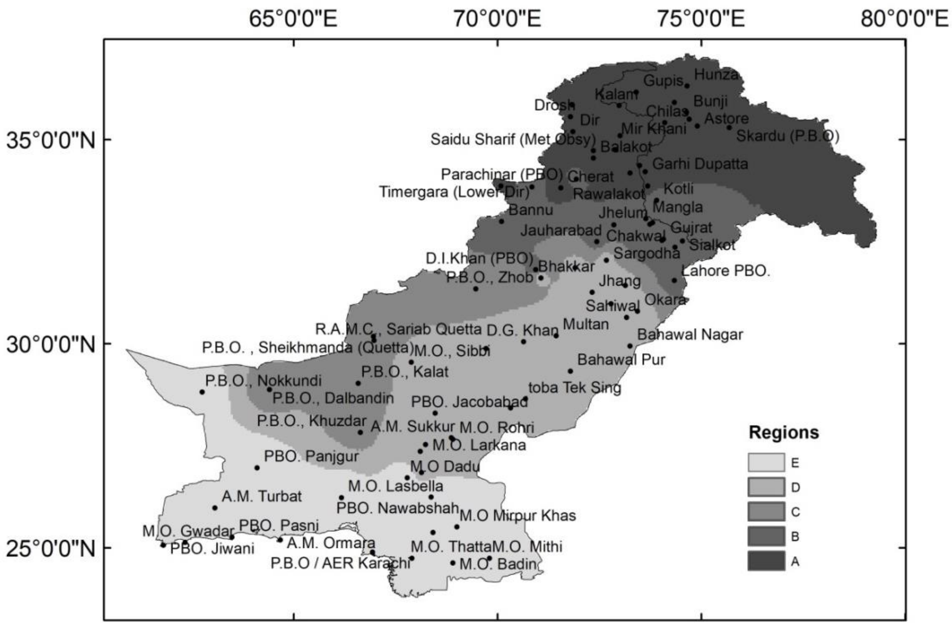

Fig. 2: Classification of rain gauge stations based upon topography and precipitation

3. Methodology

3.1 Assessment

In order to assess the satellite based precipitation products, the tiles of daily precipitation products in '.tif' format were downloaded. To download the GIS version of IMERG Real time and IMERG Research, the following links were utilized respectively ftp://jsimpson.pps.eosdis.nasa.gov/data/imerg/gis/. https://storm.pps.eosdis.nasa.gov/. To obtain Real time TMPA GIS files, the following link was used ftp://trmmopen.gsfc.nasa.gov/pub/gis/.The satellite based precipitation products are continuous retrievals. The daily precipitation tiles having an ending time approximately the same as that of measurement at PMD rain gauges (8:00 am) were selected. The spatial resolution of IMERG product is $0.1^o \times 0.1^o$ and that of TMPA is $0.25^o \times 0.25^o$. However, the rain gauge network of PMD in the study area is limited. In order to enhance the accuracy, the amount of satellite precipitation in the pixel against the exact location (same long. Lat. Value as that of rain gauge) of each rain gauge was extracted using ArcMAp software. The unit of precipitation for rain gauges and all the three satellite products was accumulated rainfall on daily basis in millimeters (mm/day). The satellite products were evaluated on grid (point to point) as well as regional scales.

3.2 Evaluation and Detective Statistics

To evaluate the satellite precipitation as compared to that of rain gauges, following evaluation statistics were used: (a) BIAS, defined as the average difference between satellite estimates and rain gauge data. Its value can be positive or negative. Positive BIAS shows over-estimation whereas negative BIAS shows under-estimation; (b) relative bias (RBias) defines the systematic errors of the satellite based precipitation estimates. Positive and or negative values specify over-estimation and under-estimation of rainfall, respectively; (c) root mean square error (RMSE); it gives more weightage to larger errors as compared to mean absolute error (MAE); (d) correlation coefficient (CC); to assess the agreement between the satellite precipitation and rain gauge values. The detective statistics indices include (a) probability of detection (POD); which demonstrates the ratio of precise identifications of rainfall events by the satellite to the rainfall events perceived by the reference (gauge) data; (b) false alarm ratio (FAR) that indicates the portion of cases in those the satellite detects rainfall while the rain gauge does not; (c) critical success index (CSI); displays generally the portion of rainfall events appropriately identified by the satellite. Statistic indices with their equations and perfect values are given in table 1.P_s stands for the satellite precipitation and P_o represent the gauge data. N represents the sample size (number of days). The 'a' represents hits, the number of days when both the satellite and rain gauge detect precipitation. The 'b' represents false alarm, the number of days when satellite show precipitation but gauge data don't show precipitation. The 'c' represents the misses, the number of days when satellite doesn't show precipitation but gauge record precipitation. The 'd' represent the correct negative, the number of days when both the gauge and satellite report no precipitation. In order to plot results at regional scale IDW interpolation was utilized.

Table 1: Statistical indices used in the comparison and evaluation between the data sources

Statistic indices	Equation	Perfect Value
BIAS	$Bias = \frac{\sum_{i=1}^{N}(P_{Si} - P_{Oi})}{N}$	0
Relative BIAS	$RBias = \frac{\sum_{i=1}^{N}(P_{Si} - P_{Oi})}{\sum_{i=1}^{N} P_{Oi}} \times 100\%$	0
Root Mean Square Error	$RMSE = \left[\frac{\sum_{i=1}^{N}(P_{Si} - P_{Oi})^2}{N}\right]^{1/2}$	0
Correlation Coefficient	$CC = \frac{\sum_{i=1}^{N}(P_{Si} - \bar{P}_S)(P_{Oi} - \bar{P}_O)}{\sqrt{\sum_{i=1}^{N}(P_{Si} - \bar{P}_S)^2}\sqrt{\sum_{i=1}^{N}(P_{Oi} - \bar{P}_O)^2}}$	1
Probability of Detection	$POD = \frac{a}{a+c}$	1
False Alarm Ratio	$FAR = \frac{b}{a+b}$	0
Critical Success Index	$CSI = \frac{a}{a+b+c}$	1

4. Results and Discussion

In order to observe the overall trend, average daily precipitation data of the PMD rain gauges and the three satellites based precipitation products for the period from March to December of 2015 were plotted as shown in Fig. 3.

The results showed a relatively higher resemblance among PMD, IMERG research, and IMERG real time in the relatively flatter areas from the center of the study area towards the southwest regions. However for the hilly areas in the north, where topographic and climatic conditions become complex, the agreement between PMD and IMERG research remain satisfactory but for IMERG real time it got weakened. While 3B42 followed the similar trend but showed significant variation as compared to PMD.

4.1 Grid Scale Evaluation

For the satellite based precipitation products, the pixel/grid having at least one PMD rain gauge was utilized to compute the statistical indices to minimize the error and BIAS induced from interpolation. Box plots of statistical indices over pixels having at least one rain gauge for the selected satellite products at daily scale are shown in Fig.4. Among the applied statistical metrics, BIAS and RBias showed the similar results so only the results of BIAS are shown. The results showed that the values of the first and third quartiles of BIAS were in good agreement with that of PMD data for all the three satellite products.

The under estimation of values (lower limit) is also in the identical range (from -2.5 to-4 mm/day) for the three satellite products.

4.2 National and Regional Scale Evaluation

The three selected satellite products were also compared at national and regional levels. The study area was divided into five regions based on climatic conditions and rainfall. Fig. 5 shows spatial distribution of statistical indices BIAS, RMSE and CC. For IMERG research the value of BIAS varied from1.99 to -3.72. In the plain areas, starting from lower parts of region C and D. The value of BIAS varied from 0.16 to 0.44 and towards region E its value varied from -0.11 to 0.15.

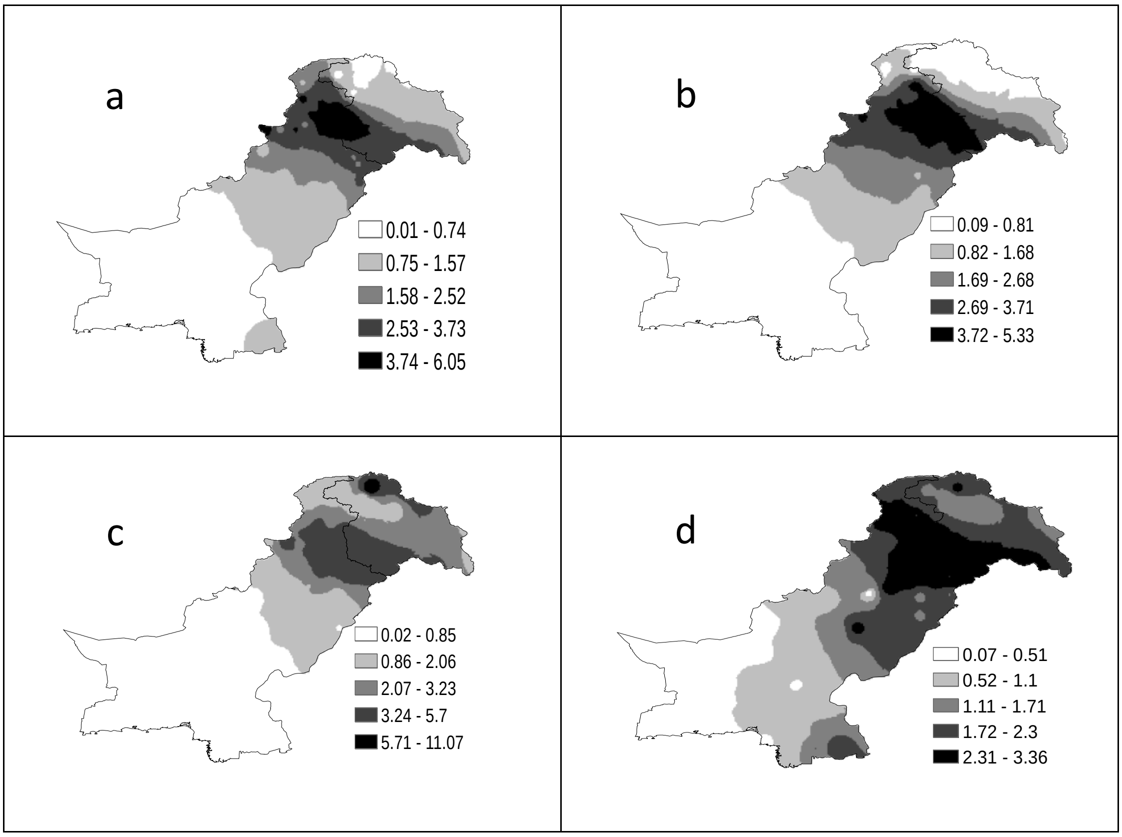

Fig. 3: Spatial distribution of average daily rainfall (mm) for the period of March-December 2015, from (a) gauge observation and three satellite products (b) IMERG Research, (c) IMERG Real Time, and (d) 3B42

It showed relatively higher under estimation and over estimation in high altitude areas having complex topography and climatic conditions. The BIAS value of IMERG Real time varied from 7.21 to -3.23 with trends identical to IMERG research. In plain areas of region C, D, and E its value ranged from -0.15 to 0.25. In high altitude areas it also showed a trend with higher values of under and overestimation. For 3B42, the value of BIAS varied from -3.97 to 25.97 showing overall trend like that of IMERG. But its level of accuracy was less than IMERG showing lowest values from-0.41 to 0.28 in western parts of the region E. The spatial distribution of interpolated values of RMSE for IMERG research varied from 1.71 to 20.43, which is not satisfactory.

The higher deviation from ideal value was observed in hilly areas while it improved in plain areas towards south. For IMERG real time, a similar trend in RMSE interpolated values was observed with some improved accuracy from central (region D) towards southwest (region E). The 3B42 showed some higher values of RMSE at selected locations. However, the overall results were relatively satisfactory. The results of CC for IMERG research showed variation from -0.06 to 0.4. These results were scattered and did not show any regional trend but showed some higher correlation at some locations in plain areas of regions D and E. Results of CC for IMERG Real time were Similar that of IMERG Research (-0.04 0.7) with some better performance in plain areas. For 3B42 the values of CC ranged from -0.02-0.2 for most of the areas. However in coastal area at certain sites the value ranged from 0.5 to 1.

The results of POD, FAR and CSI to describe the likelihood of satellite based products to estimate precipitation are shown in Fig 6. The value of POD for IMERG research varied from 0.1 to 0.52. In central regions B and D and in some coastal areas it was detected to be more that 50 percent of the rainfall events. The POD range of IMERG Real time was better than IMERG research. Its percentage of detection improved and ranged from 50 to 100% in lower parts of region B, region D, and in coastal areas. Its performance remained poor in high altitude areas of region A and C. POD of 3B42 remained below 50% across most of the study area with some relatively higher results at selected areas. On the basis of FAR value the efficiency of satellite products improved from IMERG research toward 3B42 through IMERG real time. The value of FAR ranged from 0.43 to 1 for IMERG research, 0.2 to 1 for IMERG real time and 0.16 to 1 for 3B42 respectively. A mixed trend was observed for IMERG products but 3B42 gave an improving trend towards south and coastal areas. The CSI for IMERG products showed similar trends with values ranging from 0 to 0.37 for IMERG research and 0 to 0.5 for IMERG real time. The CSI had improved results in the lower parts of region A and region B. For 3B42 the overall index value remained lower than IMERG but at some coastal areas it gave relatively higher values.

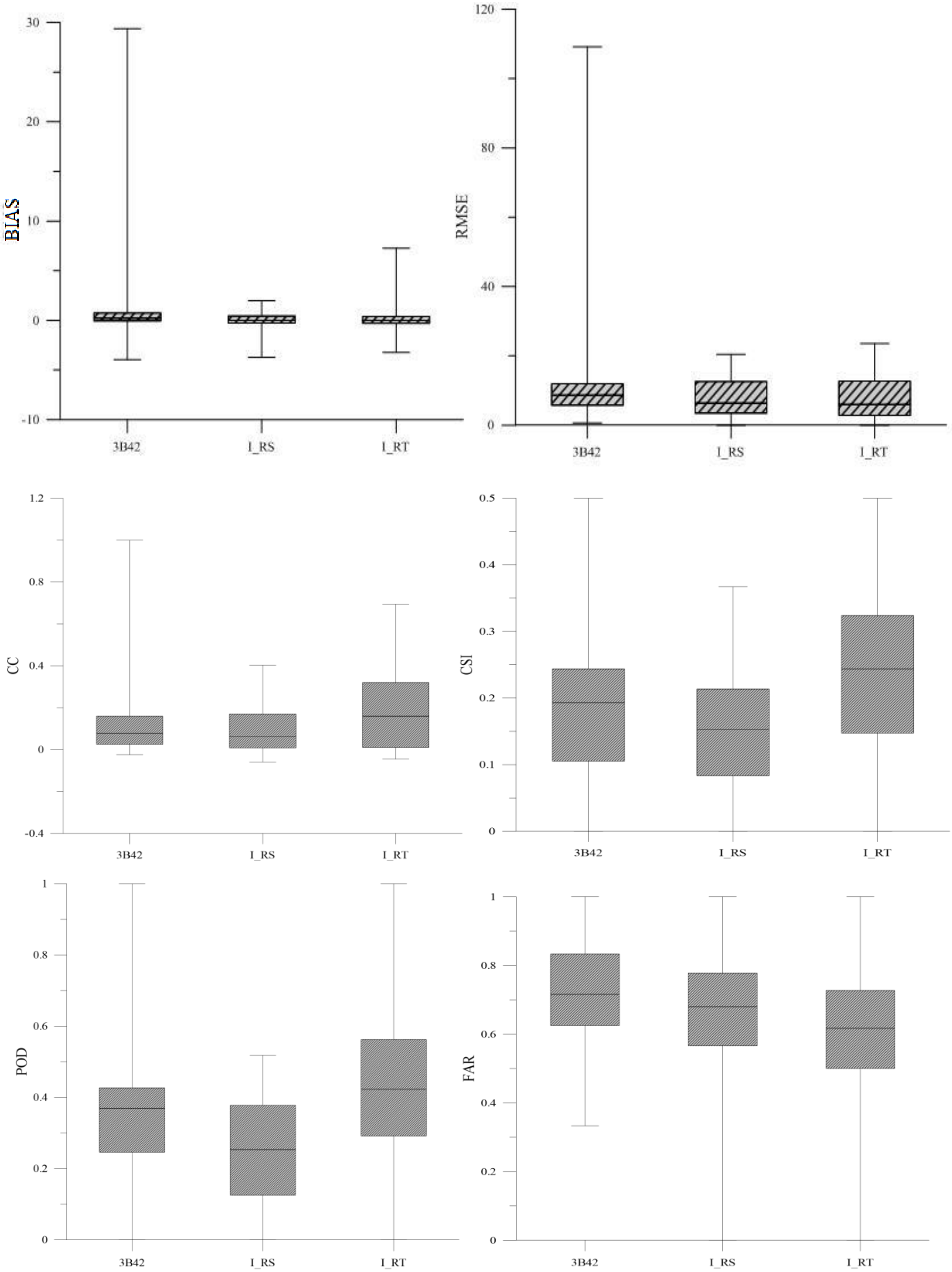

Fig. 4: Box plots of metrics at grid scale for IMERG research, IMERG real time and 3B42

To further illustrate the rainfall evaluation and detection limitations from the selected satellite based algorithms, the daily averaged values of evaluation statistic (BIAS, RMSE, CC) and detection statistical indices (i.e., POD, FAR, CSI) were plotted for the entire study area and the five regions, as shown in Fig 7. The results of BIAS showed that IMERG Research gave the best results with BIAS value of -0.041. IMERG real time and 3B42 showed 0.14 and 0.40, respectively. The results of IMERG products showed close approximation with that of gauge data on daily averaged results, however, 3B42 showed some overestimation. On regional basis, the results (Fig 7) were not relatively higher for region A and B. The three products underestimated the precipitation for region A and overestimated for the region B. The performance of IMERG real time with reference to BIAS was higher in region A and relatively higher in region B as compared to the other two satellite products. For the remaining three regions, the BIAS value was lower than the regions A and B. The values of IMERG products varied from 9 to 24% with IMERG research being more precise. The BIAS of 3B42 also improved for these regions with variation ranging from 6 to 34% for the regions C, D and E. The results of RMSE were not relatively higher for the entire study area as well for A and B regions. However, its value improved in regions C, D, and E as shown in Fig 7. Regarding inter-comparison among the satellite products, the performance of IMERG research was better over entire region and in high altitude regions A and B. While in other three regions, IMERG real time performed better.

Overall performances of IMERG products remained better than 3B42. In case of CC, the overall performance was relatively low. Its value ranged from 0.1 to 0.35 with reference to PMD gauge data. But, an inter-comparison among the satellite products showed that the IMERG real time showed a better correlation not only over entire study area but also on regional basis. Regarding the performance of detection statistics, the results of POD against the PMD gauge data ranged from 0.25 to 0.55 in the entire study area and across the regions. IMERG real time showed better values of POD ranging from 0.45 to 0.55. The POD value of 3B42 ranged from 0.27 to 0.37. IMERG research could not perform better. It might be because the number and data availability from rain gauges for further correction may be limited.

FAR results were not satisfactory. The values of three satellite products ranged from 0.6 to 0.8. No significant difference was observed among the results of the entire study area and in the regional analyses. However, for inter-comparison among the selected satellite products, IMERG real time was better. CSI, a combination of characteristics of POD and FAR, was therefore, a relatively balanced score. The value of CSI varied from 0.10 to 0.30. The IMERG real time showed better results for the entire study area as well as on the regional basis. Its value varied from 0.18 to 0.30. Its performance remained identical for the entire study area and for the five regions except region C, where elevation is a moderately higher and weather is relatively dry.

5. Conclusions

In this study, a preliminary assessment of the GPM IMERG was carried out. For inter-comparison among satellite products, TRMM TMPA 3B42 was utilized. Spatial distribution of mean daily precipitation demonstrated a promising resemblance among the rain gauge data and the IMERG real time and IMERG research products. However, some contrasts were observed in high altitude areas. While for TRMM 3B42, this contrast was further widened. A set of evaluating and detecting statistical test was applied at the grid, to the entire study area, and on the regions. The value of BIAS remained encouraging on the grid and across the regions. However, at some location higher underestimation or overestimation of precipitation was observed. The values of CC and RMSE were also lower. Regarding the values of the evaluating statistics, the results of probability of detection were favorable, however the values of false alarm ratio was not quite satisfactory. CSI showed better values than FAR but still require improvement. During the analysis it was noted that temporal frequency of rain gauge data and the satellite data widely varied. Results can be improved further if rain gauge data on the same temporal frequency as that of satellite precipitation products are available.

The results of the regional analysis showed that the satellite based products behaved well in agreement with rain gauges in relatively plain areas and in areas having sufficient rainfall. In high altitude areas the performance remained low due to complex topography and climatic conditions. In the present study already defined regions were used. This regionalization needs further consideration keeping in view the application of satellite based precipitation products.

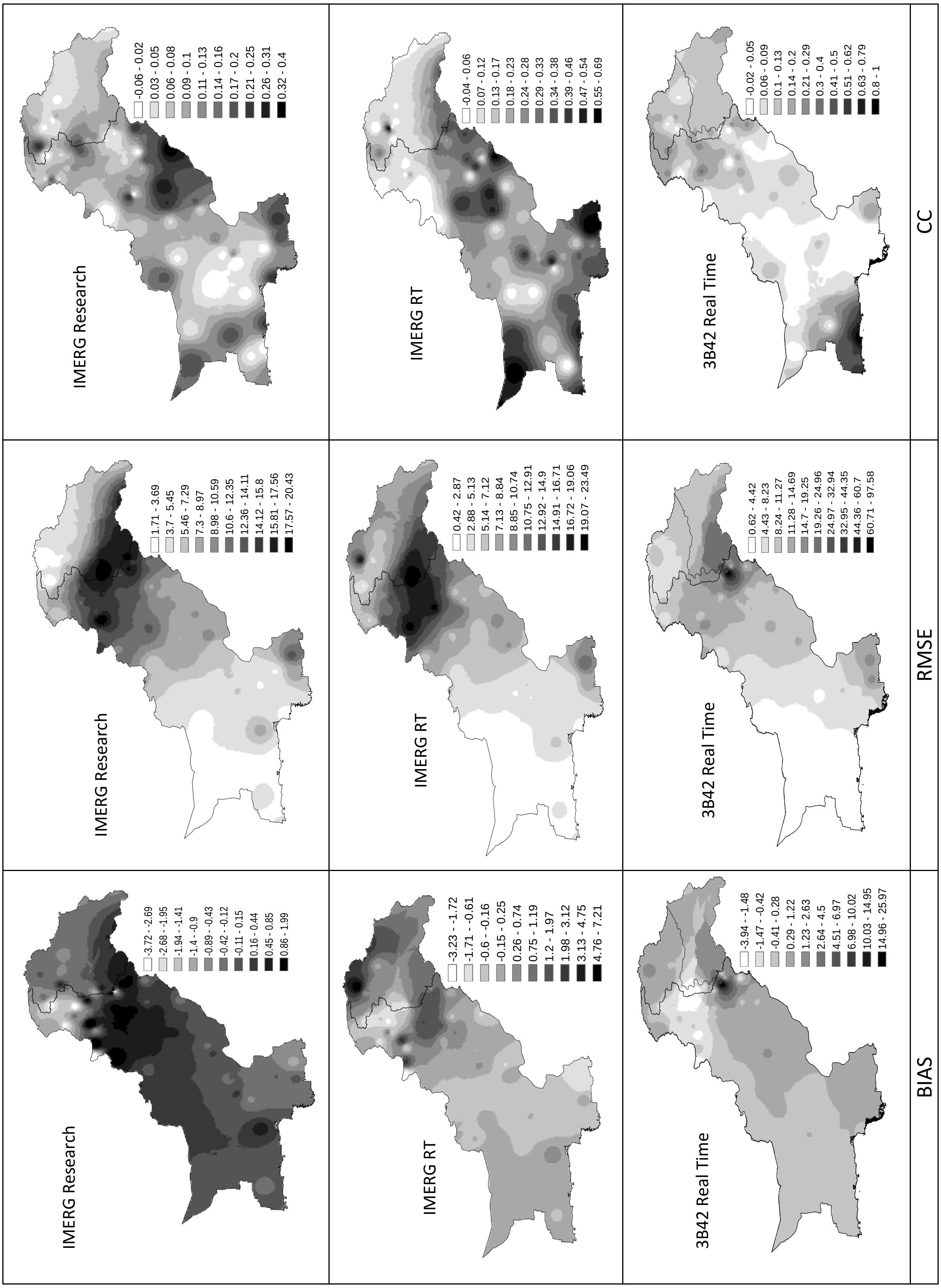

Fig. 5: Spatial distribution of evaluating statistical indices BIAS, RMSE and CC for the selected satellite precipitation products

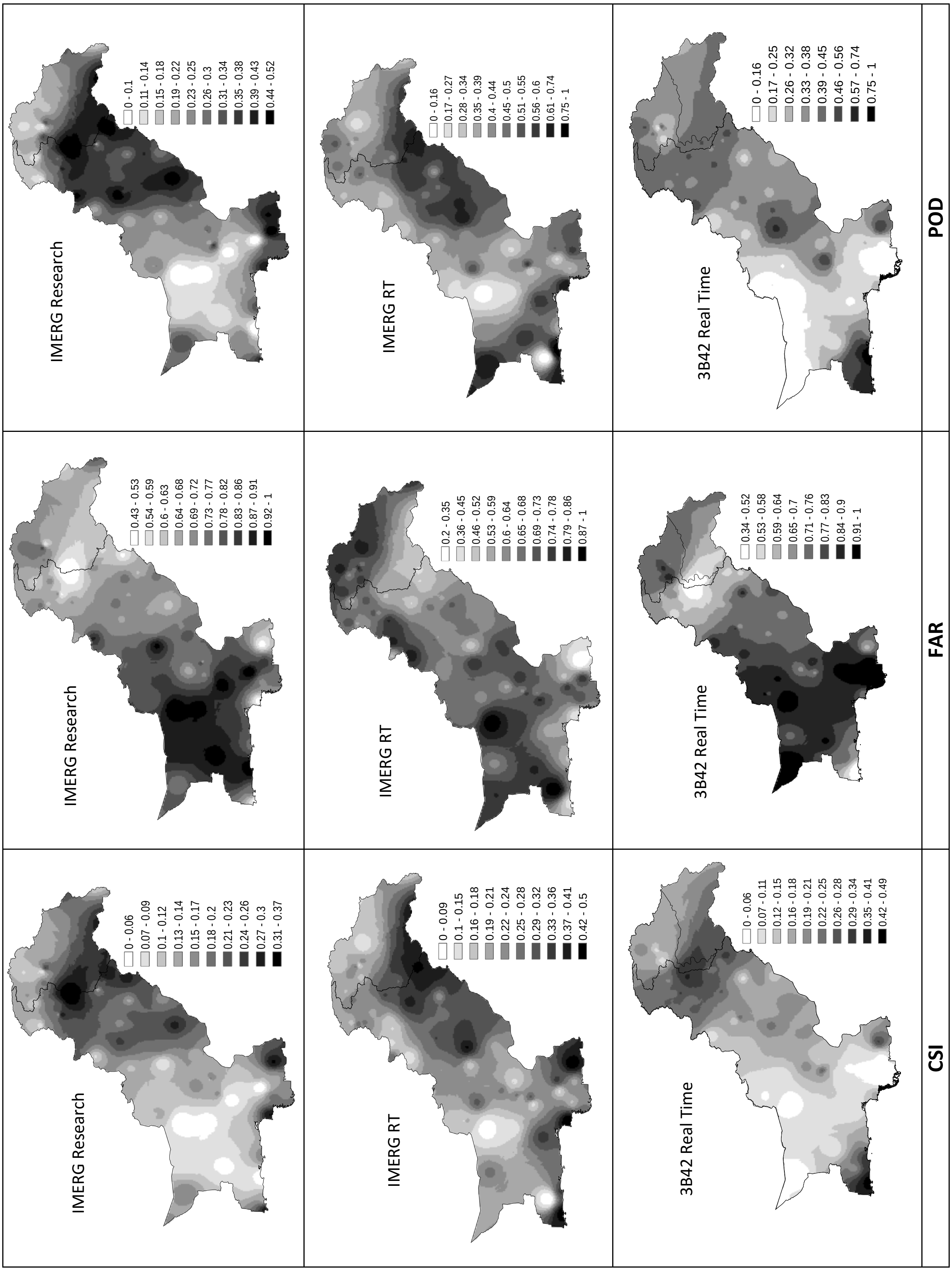

Fig. 6: Spatial distribution of detecting statistical indices POD, FAR and CSI for the selected satellite precipitation products

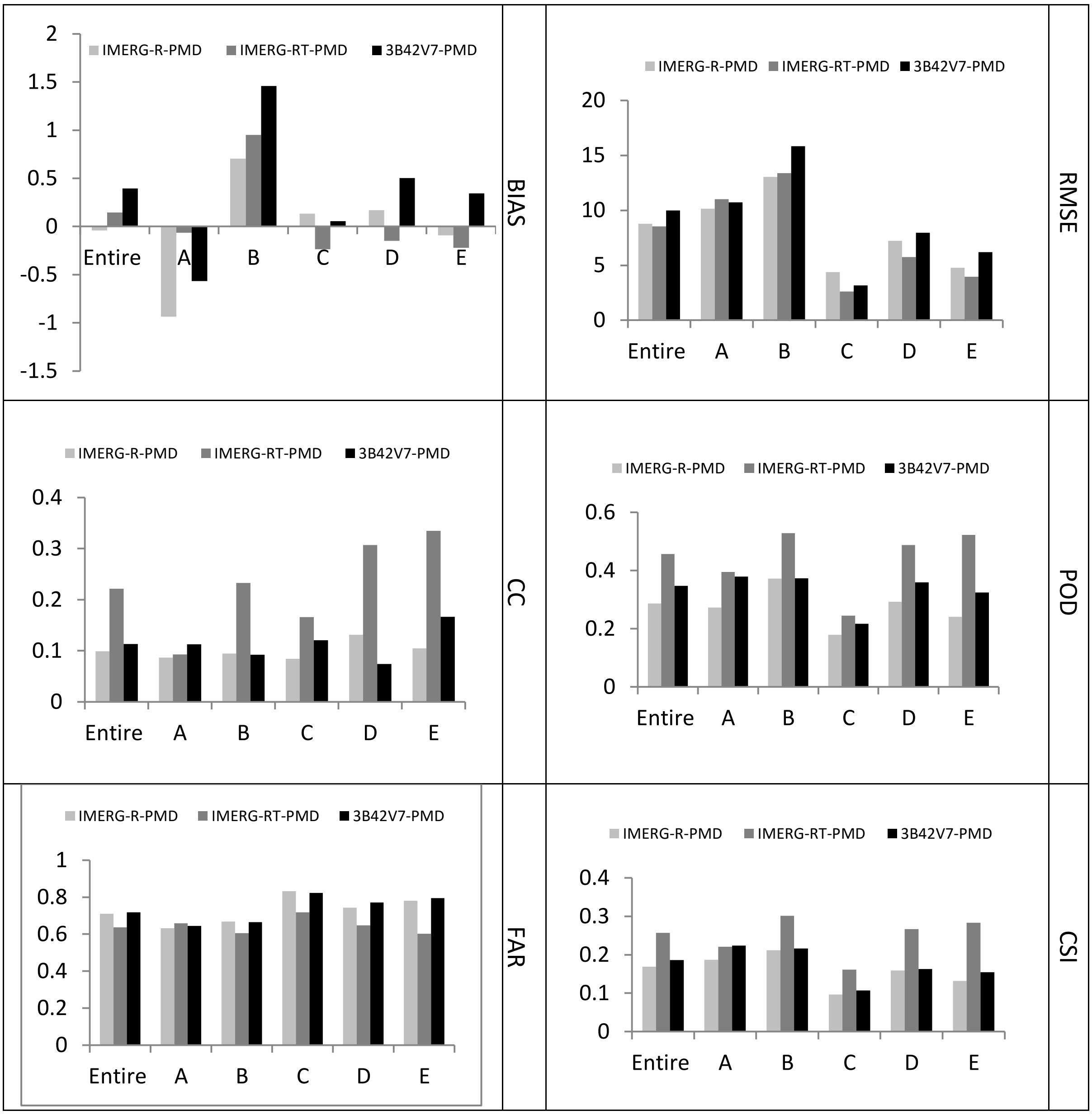

Fig. 7: Evaluating and Detecting statistical indices on mean daily basis for the IMERG research, IMERG real time and 3B42

An inter comparison among IMERG and 3B42 showed that the overall performance of both the IMERG products remained better than 3B42. The results were encouraging but needs further studies for improvement keeping in view precipitation intensities and patterns.

6. REFRENCES

[1] Michaelides, S., Levizzani, V., Anagnostou, E.N., Bauer, P., Kasparis, T., Lane, J.E. (2009). Precipitation: measurement, remote sensing, climatology and modeling. *Atmospheric Research*. Res. 94, 512–533.

[2] Kidd, C., Huffman, G. (2011). Global precipitation measurement. *Meteorological Applications*, 18 (3), 334–353.

[3] Di Michele, S., Marzano, F.S., Mugnai, A., Tassa, A., Poiares Baptista, J.P.V. (2003). Physically-based statistical integration of TRMM microwave measurements for precipitation profiling. *Radio Science, 38*(4), 8072–8088.

[4] Kidd, C., Kniveton, D.R., Todd, M.C., Bellerby, T.J. (2003). Satellite rainfall estimation using combined passive microwave and infrared algorithms. *Journal of Hydrometeorology*. *4*(6), 1088–1104.

[5] Adler, R.F., Negri, A.J. (1988). A satellite infrared technique to estimate tropical convective and stratiform rainfall. *Journal of Applied Meteorology, 27*(1), 30–51. http://dx.doi.org/10.1175/1520-0450(1988) 02760030:ASITTEP2.0.CO;2.

[6] Joyce, R.J., Janowiak, J.E., Arkin, P.A., Xie, P. (2004). CMORPH: a method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *Journal of Hydrometeorology*. 5(3), 487–503.

[7] Lensky, I., & Rosenfeld, D. (2003). A Night-Rain Delineation Algorithm for Infrared Satellite Data Based on Microphysical Considerations. *Journal Of Applied Meteorology*, *42*(9), 1218-1226.

[8] Kummerow, C., Olson, W., & Giglio, L. (1996). A simplified scheme for obtaining precipitation and vertical hydrometeor profiles from passive microwave sensors. *IEEE Transactions On Geoscience And Remote Sensing*, *34*(5), 1213-1232.

[9] Panegrossi, G., Dietrich, S., Marzano, F., Mugnai, A., Smith, E., & Xiang, X. et al. (1998). Use of Cloud Model Microphysics for Passive Microwave-Based Precipitation Retrieval: Significance of Consistency between Model and Measurement Manifolds. *Journal Of The Atmospheric Sciences*, *55*(9), 1644-1673.

[10] Hong, Y., Hsu, K., Moradkhani, H., & Sorooshian, S. (2006). Uncertainty quantification of satellite precipitation estimation and Monte Carlo assessment of the error propagation into hydrologic response. *Water Resources Research*, *42*(8).

[11] Hossain, F., Anagnostou, E., & Bagtzoglou, A. (2006). On Latin Hypercube sampling for efficient uncertainty estimation of satellite rainfall observations in flood prediction. *Computers & Geosciences*, *32*(6), 776-792.

[12] Franchito, S.H., Rao, V.B., Vasques, A.C., Santo, C.M.E. and Conforte, J.C. (2009). Validation of TRMMprecipitation radar monthly rainfall estimates over Brazil. *Journal of Geophysical Research,* 114, D02105, doi:10.1029/2007JD009580.

[13] Aghakouchak, A., Nasrollahi, N. and Habib, E. (2009). Accounting for uncertainties of the TRMM satellite estimates. *Remote Sensing*, 1, pp. 606–619.

[14] Gebremichael,M., Anagnostou, E.N. and Bitew, M.M. (2010). Critical steps for continuing advancement of satellite rainfall applications for surface hydrology in the Nile river basin. Journal of *The American Water Resources Association, 46*(2), 361-366.

[15] Moazami, S., Golian, S., Hong, Y., Sheng,S. Reza, M. (2016). Comprehensive evaluation of four high-resolution satellite precipitation products under diverse climate conditions in Iran" *HYDROLOGICAL SCIENCES JOURNAL*, VOL. 61, NO. 2, 420–440.

[16] Chokngamwong, R. and Chiu, L. (2006). TRMM and Thailand daily gauge rainfall comparison. In The 86th AMS Annual Meeting, 29, Atlanta, GA (Boston, MA: American Meteorological Society), P1.2.

[17] Dinku, T., Ceccato, P., Grover-Kopec, E., Lemma, M., Connor, S., & Ropelewski, C. (2007). Validation of satellite rainfall products over East Africa's complex topography, *International Journal Of Remote Sensing*, *28*(7), 1503-1526.

[18] Boushaki, F. I., K. Hsu, S. Sorooshian, G. Park, S. Mahani, and W. Shi. (2009). Bias Adjustment of Satellite Precipitation Estimation Using Ground-Based Measurement: A Case Study Evaluation over the Southwestern United States. *Journal of Hydrometeorol*ogy, *10*(5)**,** 1231–1242.

[19] Huffman, G.J., Adler, R.F., Bolvin, D.T., GU, G., Nelkin, E.J., Bowman, K.P., Hong, Y., Stocker, E.F. and Wolff, D.B. (2007). The TRMM multi satellite precipitation analysis (TMPA): quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *Journal of Hydrometeorology*, *8*(1), 38–55.

[20] Habib, E., Larson, B.F., Graschel, J. (2009). Validation of NEXRAD multisensory precipitation estimates using an experimental dense rain gauge network in south Louisiana. *Journal Of Hydrology*, *373*(3-4), 463-478.

[21] Tobin, K.J. and Bennett, M.E. (2010). Adjusting satellite precipitation data to facilitate hydrologic modeling. *Journal of Hydrometeorology*, 11, pp. 966–978.

[22] Muller, M. F., Thompson, S. E. (2013). Bias adjustment of satellite rainfall data through

stochastic modeling: Methods development and application to Nepal. *Advances in Water Resources*, *60*, 121–134.

[23] Khan, S. I., Y. Hong, J. J. Gourley, M.U. Khattak, B. Yong, Vergara H. J. (2014). Evaluation of Three High-Resolution Satellite Precipitation Estimates: Potential for Monsoon Monitoring over Pakistan. *Advances in Space Research*. *54*(4), 670-684.

[24] Cheema, M. J. M., and W. G. Bastiaanssen. (2012). Local calibration of remotely sensed rainfall from the TRMM satellite for different periods and spatial scales in the Indus Basin. *International Journal Of Remote Sensing*, *33*(8), 2603-2627.

[25] Moazami, S., Golian , S, Kavianpour., M, R., Hong, Y. (2014). Uncertainty analysis of bias from satellite rainfall estimates using coupla method *Atmospheric Research*, *137*, 145-166.

[26] Prakash, S,. Mitra A, AghaKouchak A. (2018). A preliminary assessment of GPM-based multi-satellite precipitation estimates over a monsoon dominated region. *Journal of Hydrology*. 556, 865-876.

[27] Tang, G., Yingzhao, M., Long, D., Zhong, L., Hong, Y. (2016). Evaluation of GPM Day-1 IMERG and TMPA Version-7 legacy products over Mainland China at multiple spatiotemporal scale. *Journal of Hydrology*. *533* (2016),152–167.

[28] Salma, S., S, Rehman., M, A, Shah. (2012). Rainfall Trends in Different Climate Zones of Pakistan. *Pakistan Journal Of Meteorology*, *9*(17),37-47.