Response to referee 1

We thank the anonymous referee for such a detailed review. The insights provided definitely improved the quality of the manuscript.

The referee's primary concern was regarding the hydrologic evaluation of IMERG over Indian basins. We agree that the novelty of this study lies in the hydrologic evaluation. However, the availability of streamflow data for Indian basins for the time period of IMERG data availability (starting from March 2014) is limited. WRIS, the website (http://www.india-wris.nrsc.gov.in) which provides streamflow dataset for India, is not updated and contain data for only a few gaging sites from March 2014 onwards. On going through the WRIS portal again (in January 2017) expecting better streamflow data availability, we found streamflow for the 'Barman' Gaging station in Upper Narmada basin, 'Ashti' gaging site for Wainganga river sub-basin of Lower Godavari from March 2014 apart from the gaging sites in Mahanadi basin that we have already used. We did hydrological evaluation over Wainganga river sub-basin and included the results in the revised manuscript. In case of Upper Narmada basin we found the flow was regulated through a reservoir and in the absence of reservoir discharge data it is extremely difficult to calibrate the model, hence we did not include it.

Another issue was regarding the length of the manuscript along with a large number of figures. We reduced length of the manuscript from 10,133 words, 18 figures, 5 tables to 9141 words, 14 figures and 8 tables.

Title: Slight misplacement of punctuation, I believe this should read: "Does the GPM mission improve the systematic error component in satellite rainfall estimates over TRMM? An evaluation at the pan-India scale"
Title was modified as suggested.

Lines 47-69: Interesting, and I see why this has been included, but this much detail is maybe not required as not all of these example are directly relevant to this study; this paragraph could easily be shortened.
The text was reduced from 302 words to 228 words (lines 49-63).

Lines 75-77: This is almost a repeat of lines 44-46.
The line was removed.

Lines 120 & 142: I would suggest replacing the word "scanty" with "scarce", which is much more widely used and less colloquial.
The word "scanty" was replaced with "scarce".

Section 2.1: While background information (and especially the maps) on the study area is always appreciated, I would recommend condensing section 2.1 - not all of the information is relevant or referred to later in the paper.

The section was condensed from 711 to 612 words. We also incorporated description of Wainganga basin at which additional rainfall runoff exercise was carried out (lines 139-150).

Lines 201-202: This is a repeat of lines 78-79.
The text was removed.

Section 3: Throughout the results section, there are a lot of statements along the lines of "IMERG outperforms TRMM in x out of y basins, but they are similar in z basins" – the authors may be able to reduce the text and number of figures by constructing a table of the number of basins in which IMERG outperforms TRMM, the number in which they are similar, and vice versa, for each skill measure evaluated in the paper. This would also be interesting for the reader to give a quick overview of these numbers without needing to read the entire text and pick them out. Of course, it is still worth discussing these and the regional differences etc. as the authors have done, but this text could be reduced.
The results were summarized in tables 5 and 6.

Lines 279-280: The authors state that the two datasets show similar skills, and immediately then state that IMERG is better in 70% of the basins - this is somewhat of a contradiction.
We modified the line "Both IMERG and TRMM show quite similar skills with correlation values above 0.8, with IMERG showing better correlation in 60 out of 86 basins" to "IMERG shows better correlation in 60 out of 86 basins" (line 263-264).

Section 3.3: Throughout the section on basin-wise bias, the results are difficult to follow. Typically in the literature, a positive bias indicates over-estimation, and a negative bias indicates under-estimation. I would recommend that the authors amend the presentation of the results here to also use this convention, making it more intuitive for the reader and more consistent with the literature. This is simply a case of reversing the sign in the results, i.e. using bias = simulated - observed, instead of bias = observed - simulated.
The bias computation was reversed and the relevant plots and tables were modified accordingly.

Line 352: The authors use the term "increased" bias - it is not clear if this refers to a larger negative or positive bias.
We removed the line as it was too ambiguous.

Line 408: Does section e refer to section 3.5?
We modified the text as section 3.5 (line 376).

Line 543: The term "slightly" is ambiguous - how much worse are they? How much better is the NSE? How much larger the bias?
We included the NSE values in the description (lines 469-472).

Answer to detailed comments:

Lines 99-104: I would like to see more justification of the choice to focus on the basin level, to make it clear what the benefit of this study is over the previous studies the authors have mentioned. The authors state "most" of the previous studies - what about the remaining? How does this study improve on this? Why is the basin scale more useful for water resources and policy makers? It is not clear at the moment why this would be much more useful than the grid-scale analyses.
We specifically focused on basin scale because it is more relevant hydrologically. The results of a basin scale study can be directly used by the watershed managers. Most of the previous studies (as cited in the manuscript) focus on gridscale but we see a gradually changing trend to analysis on basin scale (Bisht et al., 2017; Kneis et al., 2014). It becomes easier to compare the statistical and hydrologic results when the analyses are carried out at a basin scale. Thus, we used basin scale as the reference in this manuscript.

Line 262: Could the authors clarify this statement?
The hydrologic model was calibrated twice, once with IMD as the rainfall forcing and once with TRMM. The model was not calibrated with IMERG as the data period was too short (March 2014 – December 2014). Instead, the two variants of the calibrated model were validated separately using IMERG and TRMM as the rainfall forcings for the year 2014.

Regarding the warmup period, the calibration period was from 2000-2011. The year 2000 was taken as a spinup period and the results for 2000 were excluded while computing calibration statistics.

Lines 270-275: Some of this explanation should be included in the datasets section. It is not clear why this is done like this - why were the TRMM statistics obtained for 2 periods? Also implied here is that IMERG data is only available for March – December 2014, but later in the conclusions the authors state that a longer timeseries is available. This is confusing and should be clarified. If a longer timeseries of IMERG is available, why did the authors choose to use only 2014?
There seems to be a misunderstanding in IMERG timeseries availability. We meant to say that the IMERG is still a very young mission having started in March 2014, and as more data becomes available with time, they will lead to a clearer picture as to how IMERG compares with TRMM.

Lines 309-310: Could the authors expand on what the implications of this result are; why is it worth noting?
The comparison is drawn between the retrospective (1998-2013) and current (2014) time period of TRMM. Over a long period, there is a lot of temporal smoothing which may not be true for a shorter time scale. We pointed it out in the manuscript, it doesn't have any other significance.

Line 354: Surely, in the 20 basins that now exhibit a positive bias which did not before, this is indeed a decay in skill for these basins? Please clarify this statement.
As mentioned in the text, although the number of basins with positive bias increased, it wasn't a fall in skill as the basins with relatively unbiased results (-10% <= Pbias <= 10%) increased. What really happened was some of the more negatively biased basins went to the unbiased category, thus improving the overall skill.

Line 356: What do the authors mean by an increase in the variability of the bias? This is not clear.
We removed the line as it was too ambiguous.

Lines 354-365: The terms "lower" and "higher" when referring to bias are ambiguous; it would be better to refer to "smaller" and "larger" biases. Again, it is not clear in this paragraph whether the authors refer to positive or negative biases. Please also check the rest of the section / paper for further use of these terms.
We replaced the terms "lower" and "higher" biases with "smaller" and "larger" biases throughout the manuscript.

Lines 474-475: What is the reason behind this part of the evaluation? What do the authors aim to gain from this analysis? This may have been mentioned earlier in the paper but is not completely clear and it would be good to see clarification at the start of section 3.5.
We performed a correlation analysis of skill with climatology and topography to understand the systematic biases in satellite products. We reemphasized it in section 3.5 (lines 424-426).

Line 488: Again, the use of "high/low" when referring to bias is confusing.
All instances of high/low bias were changed to large/small bias.

Lines 533-537: This reads as though it should be part of the methodology of the paper, rather than results.
This was included to quickly recap the calibration and validation time durations. We feel this is a good practise as the reader doesn't have to go back in text and he/she can get the relevant information in brief.

Section 3.6: This section is presented in the introduction as a major part of the novelty of this study, but in comparison to the proportion of the paper spent discussing the rainfall results, very little discussion is offered in terms of the hydrology. The implications of the findings are not discussed, and with only one basin used in this experiment, it is not possible to say whether the results would be similar for other basins in India or elsewhere. The aim of this experiment is left unclear and while I think it could be a very interesting part of the study, it seems somewhat unfinished. I would like to see, as the authors state would indeed be interesting, a comparison of these results for other basins in different regions in the study area.

We included hydrologic evaluation over Wainganga basin of Godavari river basin.

Conclusion 1: To which parameter do the authors refer to with the quoted values?
We referred to skill in terms of correlation. We mention it in the revised manuscript (lines 496-498).

Conclusion 5: Use of "higher" bias, as before.
We modified it to "larger" bias.

Conclusion 7: If a longer timeseries of IMERG is available - why was this not used? This should be clarified / justified.
As mentioned before, there seems to be a misunderstanding in IMERG timeseries availability. We meant to say that the IMERG is still a very young mission and as more data becomes available with time, they will lead to a clearer picture as to how IMERG compares with TRMM. We clarified it in our revised manuscript.

Lines 601-604: These statements are somewhat contradictory. The authors state throughout that IMERG outperforms TRMM in various aspects, and here state that there is a reasonable improvement, and also that the improvement is only incremental and not ground-breaking, but also that IMERG is a worthy successor of TRMM. These statements leave the reader somewhat confused as to what the overall conclusion of the study is.
We will modify the text from "In essence, IMERG gives reasonable improvement in rainfall estimates across majority of the Indian basins. However, the improvement was not found to be ground breaking, rather incremental, suggesting that the GPM mission is a worthy successor of the widely acclaimed TRMM mission" to "In essence, IMERG gives reasonable improvement in rainfall estimates across majority of the Indian basins"(lines 528-529).

Line 611: "post forecast data assimilation scheme" - do the authors refer to postprocessing?
We indeed meant postprocessing of streamflows.

Figure 1: Thank you for including this map, this is incredibly helpful for those readers who are not as familiar with the geography of the region. I would recommend splitting Figure 1 into two figures, one containing the two geographical maps (a) and (d), and the second comprising of (b) and (c). Also, the colour scales used for (b) and (c) are confusing - please modify these; the best way to present these would be a colour bar with just one colour for each map, ranging from light to dark with increasing values.
We split the figures as suggested by the referee. We also included map of Wainganga catchment of the Godavari River basin (Fig. 1c)
The reason for selecting multiple colorbar for figure 1 (b) and (c) (now figs. 2a and 2b) is to highlight the spatial heterogeneity in the study area. When we used a simple one colorbar, a lot of information was lost in the contrast (for instance the contrast between low rainfall in Rajasthan and medium rainfall in the Western part of Indo-Gangetic plain in figure 1(b)).

Figures 2.1 and 2.2. Firstly, it is strange to label two separate figures as 2.1 and 2.2 - surely these should be figures 2 and 3. Secondly, what exactly is the precipitation shown here? Is it daily precipitation? Is it averaged over a time period? This should be clarified and included on the axes / in the caption, for both 2.1 and 2.2.
We split the figures 2.1 and 2.2 into two figures (Figs. 3 and 4). The scatterplots show daily precipitation which we mentioned in the figure descriptions.

Figures 3 and 5: These figures are very difficult and confusing to interpret - this data is not continuous (it represents the independent basins, rather than e.g. a continuous time period), and this is not the best way to present it. I would in fact recommend removing figures 3 and 5, and just discussing their results in the text as you have done.
The figures were moved to supplementary material (Figs S1, S2).

Figures 4 and 6, the corresponding spatial maps, are a much clearer way of presenting the data.
Figure 4: I like these maps, it is clear what they show and intuitive to interpret. However, the colours used are very confusing - please amend the colour scale to use just one colour from 0 to 1 (light to dark), and avoid rainbow colours. In the case of (j), (k) and (l) it is not immediately obvious that there is a negative correlation in one or more of the basins and it is hard to spot. So on these maps, two colours should be used – the same as (a-i) for 0 to +1, with white at 0, and a different colour for the negative values. For example, the colour scale the authors have chosen for figure 8 would be perfect for figure 4, with white at 0.
The rationale behind using a rainbow color to represent correlation was to focus on the spatial heterogeneity in correlation values. When we used a single color in the colorbar (ranging from light to dark), most of the spatial features of correlation were lost. For instance, it became really difficult to decipher correlation value of 0.3 from 0.6, which is rather substantial. That’s why we used rainbow color bars instead of a single color bar. In the revised manuscript, fig. 4 is moved to fig. 5.

Figure 6: Again, I like this figure, but the colour scale should be improved. I would recommend again a scale such as that used in figure 8, where 0 is white and the darker the colour, the larger the value. Please note that the colour scale has a big impact on the way the reader interprets the data, and incorrectly used colour scales can be misleading.
We modified the color scale as recommended by the referee (Fig. 6).

Figure 7: Again, the colour scale here is not the best option. For this data, the best would be to use one single colour, from light at 0 to dark at 1. For example, in figures (j-l), at first glance it seems that the blue basins have an opposite result to the red basins, but this is not the case.

Figure 8: While this scale would be perfect for the results shown in figure 4(j-l) and figure 6, it is not the good choice for the data presented in figure 8. As with figure 7, the best option would be one colour from light at 0 to dark at 1.
We opted for the multi color bar to highlight the spatial variability. If there is one colorbar which varies from light to dark, a lot of information is lost as the contrast decreases significantly. For instance, in the case of figure 8, FAR of anything more than 0.5 can be taken as high error, which will be lost if the colorbar had only one color scale. We will use the same color bars in figure 7 and 8 but incorporate the referee's suggestion in other figures.

Figure 9: This graph could be removed and just discussed in the text.
The figure was moved to the supplementary section (Fig. S3).

figures 10 - 17: While I can see why the authors have presented the data in this way, again, there is the issue that this data is not continuous so this type of graph is not really correct, and also this is confusing for the reader. There are also a large number of similar plots here, I would suggest to pick one or two which show the most interesting results to present in the main body of the paper, and move the rest to supplementary material. Most readers would not analyse all the information in all of these figures and would appreciate the highlights, but the interested reader could easily find all the graphs in the supplementary material. This would solve the problem of the overwhelming number of figures included in this paper. Also, I would recommend that the authors display all of these graphs (whether in the main body or the supplementary material) instead as scatter plots of the rainfall/elevation vs. bias/correlation. This would be a much more accurate and easy-to-understand way of displaying the data.
We moved the four figures related to climatology to supplementary and preserved the ones related to topography as they showed more significant results. We couldn't show the scatterplots because the scales are not standardized. If we do a scatterplot of correlation with elevation, correlation varies from -1 to 1 but elevation varies from 0 to 4500m and there is no meaningful 1:1 line to draw any inference. Hence we stuck with the line plots. However, we removed the lines and only kept the points as then it is easier to see if there is a cluster of points behaving in a certain way. The modified plots are Figs. 9-12.

Figure 18: What is "data points"? Is it time on the x axis? Please change this label, and if it is indeed time as I suspect, please display the dates.
We will modify the label to "Number of days since April 1st, 2014.

References:

Bisht, D. S., Chatterjee, C., Raghuwanshi, N. S. and Sridhar, V.: Spatio-temporal trends of rainfall across Indian river basins, Theor. Appl. Climatol., 1–18, doi:10.1007/s00704-017-2095-8, 2017.

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Response to referee 2

We thank the anonymous referee for providing valuable insights into the manuscript.

The referee's primary concern is about the influence of spatial interpolation to obtain gridded precipitation values over India, which in turn was used to obtain basin wise statistics. The gridded product was developed and quality controlled by the India Meteorological Department (IMD) (Pai et al., 2014) and has been extensively used in different statistical and hydrologic evaluations at both basin (Bisht et al., 2017; Kneis et al., 2014) and grid scale (Bisht et al., 2017; Kneis et al., 2014). As requested by the referee, we reported the number of rain gauges used to obtain the gridded precipitation product, their spatial configuration and variation with time in the supplementary section of the manuscript (Figs. S8, S9) and mentioned it in the section on IMD dataset (section 2.2.1). The description is below.

Station related info

Gridded rainfall product of IMD is prepared from station record of rainfall. However, the total number of stations used varies from year to year, the reasons may be attributed to maintenance, cost of operation, data quality, and man power availability. Figure S8 shows the maximum total number of stations used for preparing the high resolution gridded rainfall product during 1998-2014. Decline in the number of station over the period of time is evident form the fig. S8, nevertheless, the IMD gridded rainfall product has been widely used by the researchers in similar studies as discussed in the manuscript. Spatial distribution of rainfall stations during 1998-2014 at 0.25 degree spatial resolution is shown in the fig. S9, to reduce the number of plots maps are shown at 3 year interval during 1998-2014. Comparatively, a high density of rainfall station network can be seen in southern peninsular India. In some cases, the total number of stations in a single grid can go up to 11.

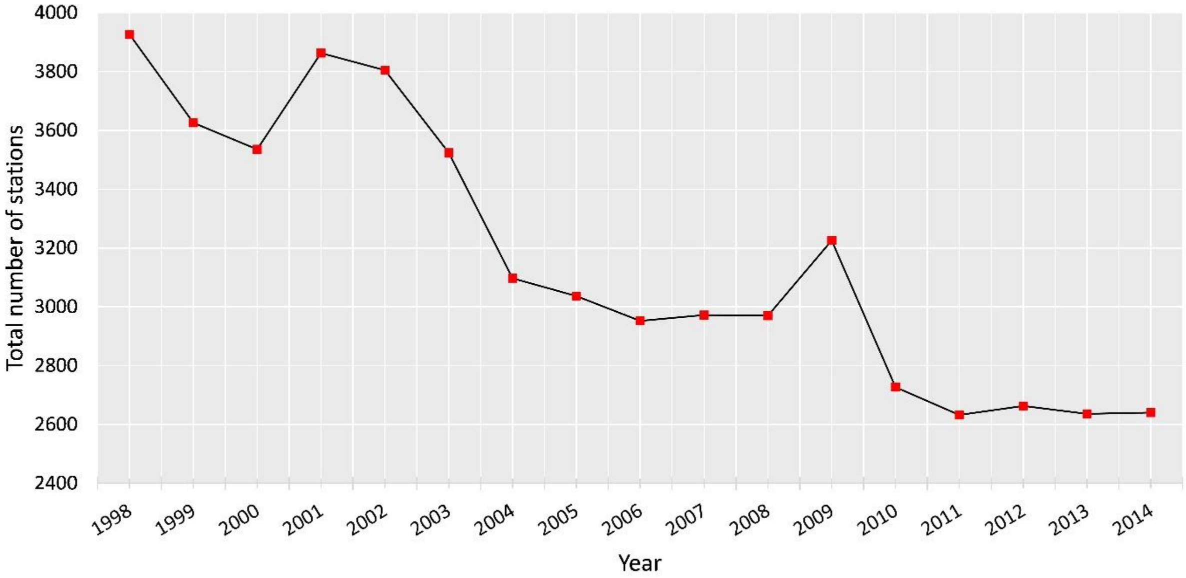

Fig S8. Total maximum number of active rainfall stations across all the grids during 1998-2014

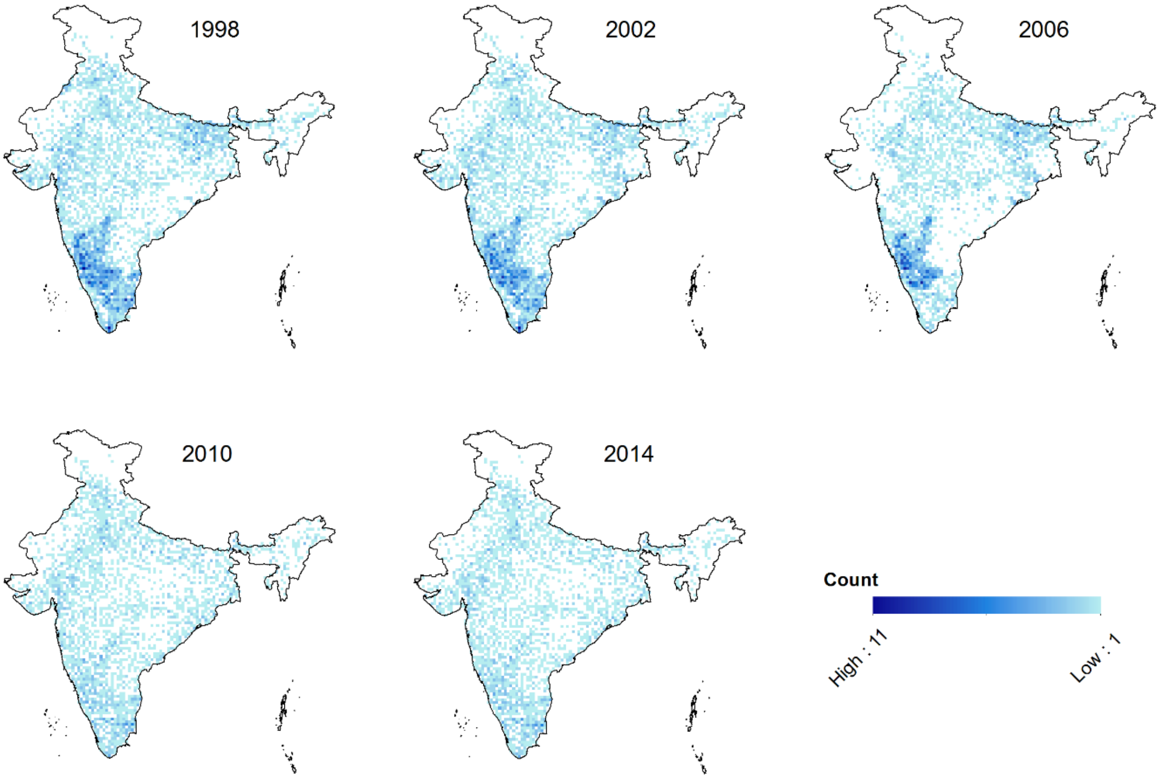

Fig S9. Spatial distribution of rainfall station during 1998, 2002, 2006, 2010, and 2014

References:

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Does the GPM mission improve the systematic error component in satellite rainfall estimates over TRMM?~~,~~ A~~a~~n evaluation at a pan-India scale.~~?~~

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Abstract. Last couple of decades have seen the outburst of a number of satellite based precipitation products with Tropical Rainfall Measuring Mission (TRMM) as the most widely used for hydrologic applications. Transition of TRMM into Global Precipitation Mission (GPM) promises enhanced spatio-temporal resolution along with upgrades in sensors and rainfall estimation techniques. Dependence of systematic error components in rainfall estimates of Integrated Multi-satellitE Retrievals for GPM (IMERG), and their variation with climatology and topography, was evaluated over 86 basins in India for year 2014 and compared with the corresponding (2014) and retrospective (1998-2013) TRMM estimates. IMERG outperformed TRMM for all rainfall intensities across a majority of Indian basins, with significant improvement in low rainfall estimates showing smaller negative biases in 75 out of 86 basins. ~~IMERG increased the inter-basin variability in bias for medium and high rainfall estimates.~~ Low rainfall estimates in TRMM showed a systematic dependence on basin climatology, with significant overprediction in semi-arid basins which gradually improved in the higher rainfall basins. Medium and high rainfall estimates of TRMM exhibited a strong dependence on basin topography, with declining skill in ~~the~~ higher elevation basins. Systematic dependence of error components on basin climatology and topography was reduced in IMERG, especially in terms of topography. Rainfall-runoff modeling using Variable Infiltration Capacity (VIC) model over a flood prone basin (Mahanadi) revealed that improvement in rainfall estimates in IMERG didn't translate into improvement in runoff simulations. More studies are required over basins in different hydro-climatic zones to evaluate the hydrologic significance of IMERG.

Keywords: GPM, IMERG, TRMM, VIC, climatology, topography

1 Introduction

The developing part of the world suffers from acute data shortage, both in terms of quality and quantity. A recent commentary from Mujumdar (2015) provided insights into the problems faced by the Indian hydrologic community due to the lack of willingness of the relevant governmental bodies to openly share meteorologic and hydrologic data and its meta data to the research community. With the threats of climate changing looming large, high quality precipitation products (in terms of accuracy, spatial and temporal resolution) are the need of the hour. Satellite precipitation products offer a viable alternative to gauge based rainfall estimates.

A number of satellite based precipitation estimates have cropped up in the past two decades, the famous ones being Climate Prediction Center morphing technique (CMORPH), Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN), PERSIANN Climate Data Record (PERSIANN-CDR), Tropical Rainfall Measuring Mission (TRMM), Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) and National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC). A number of studies over the past decade have evaluated the hydrologic application of these datasets over regions with varied topography and climatology.

Artan et al. (2007) found reasonable streamflow simulations using CPC~~used CPC to drive a hydrologic model~~ over four basins ~~with varied hydro-climatic and physiographic conditions~~ in Africa and South-east Asia ~~and reported similar rainfall-runoff performance on calibration using gauge and satellite rainfall estimates~~ while~~.~~ Collischonn et al. (2008) found similar results using ~~also reported reasonable streamflow simulations using~~ TRMM ~~estimates~~ over ~~an~~ Amazon River basin. Akhtar et al. (2009) used ~~multiple artificial~~ neural networks ~~(ANN)~~ to forecast discharges at varying lead times using TRMM 3B42V6 precipitation estimates. Wu et al. (2012) used TRMM 3B42V6 estimates to develop a real-time flood monitoring system and concluded that the probability of detection (POD) improved with longer flood durations and larger affected areas. Kneis et al. (2014) evaluated TRMM 3B42-V7 and its real-time counterpart TRMM 3B42-V7RT over Mahanadi River basin in India and found the research product (3B42) to be superior to the real-time alternative (3B42RT) ~~in terms of both the statistical and hydrologic components~~. Peng et al. (2014) found a systematic dependence of TRMM estimates on climatology in North-West China, characterizing the wetter regions better than the drier ones ~~conditions. They also reported promising results in the streamflow simulations at ungauged basin in arid and semi-arid regions~~. Bajracharya et al. (2014) used CPC to drive a hydrologic model over Bagmati basin in Nepal and reported that the incorporation of local rain gauge data ~~in addition to CPC~~ tremendously benefited the streamflow simulations. Shah and Mishra (2015) explored ~~the~~ uncertainty in the estimates of multiple satellite rainfall products over major Indian basins ~~and investigated the influence of bias in the satellite rainfall products on flood simulation over Mahanadi River basin in India~~. Most of the studies which evaluated multiple satellite precipitation estimates have reported TRMM to give the best estimate over the Tropical part of the world (Gao and Liu, 2013; Prakash et al., 2016b; Zhu et al., 2016).

Tropical Rainfall Measuring Mission (TRMM) satellite was launched in late 1997 and provides high resolution (0.25° x 0.25°) quasi-global (50° N-S) rainfall estimates (Huffman et al., 2007). The TRMM mission is a joint mission between the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration (JAXA) Agency to study rainfall for weather and climate research. The TRMM satellite produced 17 years of valuable precipitation data over the Tropics. ~~In the last decade, a number of studies have evaluated Tropical Rainfall Measuring Mission (TRMM) Multi-Resolution Analysis (TMPA) product over different topographies and climatologies.~~

Owing to the tremendous success of TMPA mission, Global Precipitation Measurement (GPM) was launched on February 27, 2014 (Liu, 2016). The GPM sensors carry first spaceborne dual-frequency phased array precipitation radar (DPR) operating at Ku (13 GHz) and Ka (35 GHz) bands and a canonical-scanning multichannel (10-183 GHz) microwave imager (GMI) (Hou et al., 2014). The improved sensitivity of Ku and Ka bands allow for improved detection of low precipitation rates (<0.5 mm/h) and falling snow.

A few preliminary assessments of GPM over India and China (Prakash et al., 2016a, 2016b; Tang et al., 2016a) suggest an improvement over TMPA. For 2014 monsoon (Prakash et al., 2016b) reported that Integrated Multi-satellitE Retrievals for GPM (IMERG), which is a level three multi-satellite precipitation algorithm of GPM (Hou et al., 2014), outperformed TMPA in extreme rainfall detection along the Himalayan foothills in North India and over North Western India, with slightly reduced false alarms. Tang et al. (2016a) found that IMERG outperformed TMPA in almost all the indices for every sub-region of mainland China at 3-hourly and daily temporal resolutions. They also reported that IMERG reproduced probability density functions more accurately at various precipitation intensities and better represented the precipitation diurnal cycles. In another work by Prakash et al. (2016a), IMERG was compared with Global Satellite Mapping of Precipitation (GSMaP) V6 and TMPA 3B42V7 for the 2014 monsoon over India. It was found that IMERG estimates represented the mean monsoon rainfall and its variability more realistically, with fewer missed and false precipitation bias and improvements in the precipitation distribution over low rainfall rates.

Most of the previous studies that compared satellite and reanalysis precipitation products for pan-India focused at a grid scale, rather than a basin scale (Prakash et al., 2015, 2016a, 2016b). We focused at a basin scale as it is more relevant in terms of water resources assessment for policy makers. ~~Also, i~~It provides a clear signal of the utility of the satellite precipitation products at the required spatial resolution for water managers working at a basin scale. Also, at a basin scale, the statistical and hydrologic results are more complementary (Bisht et al., 2017; Kneis et al., 2014).

In this study, we comprehensively evaluated TRMM 3B42 from 1998-2013 over 86 basins in India and explored systematic biases due to climatology and topography. We then compared TRMM 3B42 precipitation estimates with IMERG for 2014 and explored if the systematic biases were reduced in IMERG, and whether IMERG was able to better capture the low rainfall magnitudes. Finally, we used a macroscale hydrologic model (Variable Infiltration Capacity (VIC)) to evaluate TRMM and IMERG over a flood prone basin in Eastern India (Mahanadi River basin) for the year 2014.

2 Description of the study area, datasets used and methodology

2.1 Study area

~~The study was conducted over India at a basin scale (Fig. 1a).~~ Water Resources Information System of India (India-WRIS) delineates India into multiple sub-basins ~~divides India into 91 major basins~~ (Fig. 1a) (India, 2014). In this study, 86 basins were used, with the five excluded basins located in the Jammu and Kashmir region of Northern India (details included in Supplementary table 1). Also, the Lakshadweep islands (located off the Indian West coast in the Arabian Sea) and the Andaman and Nicobar islands (located in the Bay of Bengal) were excluded from the analysis due to ~~scanty~~ scarce rain-gauge monitoring network.

Most of India experiences a tropical monsoon type of climate receiving an average annual rainfall of around 1100 mm/year, of which about 70-80% is concentrated during the monsoon season (June – September). Fig. 2a~~1b~~ shows the spatial distribution of rainfall (details in supplementary table 1), calculated using India Meteorological Department (IMD) gridded precipitation dataset (computed using 31 years (1980-2010) of rainfall time series) over India. The Western Ghats (located on the Indian West coast) and the North-Eastern basins receive the highest rainfall, with ~~the~~ magnitudes going ~~as high as~~up to 3000 mm/year. The Western Ghats receive orographic rainfall due to ~~the~~ steep topographic gradient that exist from the West to the East, making the Eastern part ~~of the mountains~~ a leeward area where rainfall is mainly associated with the passage of lows and depressions developed in the Bay of Bengal (Prakash et al., 2016a). Details of the orographic features of rainfall over Western Ghats can be found in Tawde and Singh (2015). The high rainfall in the North-Eastern part of India is associated with orographic control and multi-scale interactions of monsoon flow (Prakash et al., 2016a). Basins in the Indo-Gangetic plain and on the East coast receive above average rainfall of around 1400 mm/year, governed by the tropical monsoons. ~~The hilly tracts of Jammu and Kashmir situated in North-most part of India receive an annual average rainfall of around 1000 mm/year.~~ The North-west basins, associated with semi-arid type of climate, receive low annual rainfall ranging from 300-400 mm/year. ~~The basin-wise rainfall is provided in Supplementary table 1.~~

Fig. 2b~~1c~~ shows the spatial distribution of the basin-wise elevation above mean sea level (m.s.l) (details in supplementary table 1). The Northern tract of Jammu and Kashmir comprises the basins with highest elevations, in between 2500 m to 5000 m above m.s.l. These basins ~~also~~ suffer from ~~scanty~~ scarce rain monitoring networks, due to which five of these high elevation basins have been ignored in the analysis ~~(details in Supplementary table 1)~~. High Pitch Mountains are also found in the North-Eastern basins where basin-wise elevation goes as high as 1400 m above m.s.l. The Western Ghats are characterized by a ~~very~~ sharp topographic gradient with the elevations increasing from around 200 m on the West coast to above 600 m above m.s.l as we move east. This transition results in heavy orographic rainfall on the West coast and leads to the sharp rainfall contrast on the leeward side of the Western Ghat~~-~~s ~~Mountains~~. ~~The Indo-Gangetic plain and the Eastern basins are mostly plateau areas, with basin elevation lying in between 200-400 m above m.s.l. The semi-arid North-Western basins are also characterized by plateau land (elevation between 200-300 m above m.s.l). The basin-wise elevation is provided in Supplementary table 1.~~

~~The r~~Rainfall-runoff modeling~~ exercise~~ was done~~ carried out~~ in Hirakud catchment of the Mahanadi River basin (MRB) and Wainganga catchment of Godavari River basin. ~~the Hirakud catchment of the Mahanadi River basin (MRB), located on the Eastern coast of India.~~ MRB, situated on the Eastern coast of India, is one of the largest Indian basins draining an area of 1,41,000 km^2~~, mostly flowing through the states of Chattisgarh and Odisha~~. It is prone to frequent flooding at the downstream, with five major flood events in the first decade of the 21st century (Jena et al., 2014). On the upstream of the MRB is a multi-purpose dam (Hirakud) which encompasses catchment area of around 85,200 km^2 ~~and spans between 19.5° and 23.8° N latitudes and 80° to 84° E longitudes~~ (Fig. 1b~~d~~). Hirakud dam started its operations in 1957 and its upstream does not include any major dam, although a number of small scale irrigation reservoirs are operational during the monsoon. Agricultural, forest and shrub land account for around 55%, 35% and 7% of the total basin coverage respectively (Kneis et al., 2014). Wainganga river basin, the largest sub-basin of Godavari basin (located in Peninsular India) drains a total of 51,422 km2 area. ~~The~~ Both the ~~area~~ basins receive~~s~~ ~~experiences a tropical monsoon type of climate, with an~~ annual rainfall of around 1500 mm. ~~Agricultural, forest and shrub land account for around 55%, 35% and 7% of the total basin coverage respectively (Kneis et al., 2014).~~

2.2 Datasets used

IMD gridded rainfall dataset was used as the reference product and Tropical Rainfall Measuring Mission (TRMM) and Integrated Multi-satellitE Retrievals for GPM (IMERG) were compared against IMD. A brief summary of the datasets is given in Table 1. A brief introduction to the three rainfall datasets is given below.

2.2.1 Gridded IMD and streamflow dataset

IMD gridded precipitation dataset provides daily rainfall estimates over the Indian landmass from 1901-2014 at a spatial resolution of 0.25° x 0.25°. It has been developed using a dense network of rain gauges consisting of 6955 stations and is known to reasonably capture the heavy orographic rainfall in the Western Ghats, the Northeast and the low rainfall on the leeward side of the Western Ghats. Details about the number of stations used to make the gridded product are discussed in the supplementary material. For a detailed discussion on the evolution of IMD gridded dataset, refer to Pai et al. (2014).

It is to be noted that IMD measures rainfall accumulation at 8:30 AM Indian Standard time (IST) or (3:00 AM UTC). The accumulated rainfall for the previous day is provided as the rainfall estimate for current day. For instance, IMD rainfall estimate at a gauging station for September 14th, 2014 refers to the rainfall accumulation from 8:30 AM IST (3:00 AM UTC) on September 13th, 2014 to 8:30 AM IST (3:00 AM UTC) on September 14th, 2014. Both TRMM and IMERG precipitation estimates were converted to IMD timescale.

The gridded daily minimum and maximum temperature was obtained from IMD at a spatial resolution of 1° x 1° (Srivastava et al., 2009). Daily wind speed data was obtained from coupled National Centers for Environmental Prediction (NCEP) and Climate Forecast System Reanalysis (CFSR) at a spatial resolution of 0.5° x 0.5°. Daily discharge data at the inflow site of the Hirakud reservoir was obtained from the State Water Resources Department (Odisha), Hirakud Dam Project, Burla, Sambalpur. Daily discharge data at Wainganga basin was obtained through WRIS-website (http://www.india-wris.nrsc.gov.in/wris.html).

2.2.2 Tropical Rainfall Measuring Mission (TRMM)

In order to provide high resolution precipitation dataset in real-time, the TRMM satellite was launched in late 1997 and it provides 3-hourly rainfall estimates from 1998 to the current date at a quasi-global coverage (50° N-S) at a spatial resolution of 0.25° x 0.25° (Huffman et al., 2007). Two variants of TRMM multi-satellite precipitation analysis (TMPA) are available, a real time product which is available at 3-6 hours latency and the research product which is available at 2-months latency. TRMM research product makes use of rain gauge stations from Global Precipitation Climatology Centre (GPCC) to post-process the TRMM estimates, details of which can be found in Huffman et al. (2007). We used TRMM research product in this study (henceforth mentioned as TRMM).

2.2.3 Integrated Multi-SatellitE Retrievals for GPM (IMERG)

~~Due to the great success of TMPA mission, Global Precipitation Measurement (GPM) was launched on February 27, 2014 (Liu, 2016).~~ IMERG is the day-1 multi-satellite precipitation algorithm for GPM which combines data from TMPA, PERSIANN, CMORPH and NASA PPS (Precipitation Processing System). For a detailed understanding of the retrieval algorithm of IMERG, refer to (Huffman et al., 2014; Liu, 2016).

The major advancement in GPM satellite is the improved sensitivity of sensors leading to improved detection of low precipitation rates (<0.5 mm/h) and falling snow, a known shortcoming of TRMM. IMERG is available in 3 variants, (a) Early run (latency ~ 6 hours), (b) Late run (latency ~ 18 hours) and (c) Final run (latency ~ 4 months) (Liu, 2016). Each product is available at half-hourly temporal and 0.1° x 0.1° spatial resolution. The spatial coverage is 60° N-S which is planned to be extended to 90° N-S in the near future. We used the Final run product in our analysis.

2.3 VIC Hydrological Model

VIC is a macroscale semi-distributed hydrological model which uses a grid-based approach to quantify different hydro-meteorological processes by solving water balance and energy flux equations, specifically designed to represent the surface energy and hydrologic fluxes at varying scales (Liang et al., 1994, 1996). VIC uses multiple soil layers with variable infiltration, non-linear baseflow and addresses the sub-grid scale variability in vegetation. A stand-alone routing model (Lohmann et al., 1996) is used to generate runoff and baseflow at the outlet of each grid cell, assuming linear and time-invariant runoff transport. The land surface parameterization (LSP) of VIC is coupled with a routing scheme in which the drainage system is conceptualized by connected-stem rivers at a grid scale. The routing model extends the FDTF-ERUHDIT (First Differenced Transfer Function-Excess Rainfall and Unit Hydrograph by a Deconvolution Iterative Technique) approach (Duband et al., 1993) with a time scale separation and liberalized Saint-Venant equation type river routing model. The model assumes runoff transport process to be linear, stable and time invariant.

VIC has been successfully used in a number of global and local hydrologic studies (Hamlet and Lettenmaier, 1999; Shah and Mishra, 2016; Tong et al., 2014; Wu et al., 2014; Yong et al., 2012). A recent commentary on the need for process-based evaluation of large-scale hyper-resolution models by Melsen et al. (2016) provides interesting insights into the use of VIC at different spatial scales and why we shouldn’t just decrease the grid size (hence increasing the spatial resolution of model) without considering the dominant processes at that scale. In lines with the discussions in Melsen et al. (2016), VIC was run at a grid size of 0.5° x 0.5° for Hirakud basin and at 0.25° x 0.25° for Wainganga basin.

2.4 Methodology

All the analysis was performed at a basin scale. Basin-wise mean areal rainfall was calculated for all the three rainfall products (IMD, TRMM and IMERG) using Thiessen Polygon method for their respective periods of availability.

In order to statistically evaluate the precipitation products, two skill measures were used (Pearson correlation (R) and percentage bias (Pbias/bias)) along with two threshold statistics (probability of detection (POD) and false alarm ratio (FAR)). Table 2 shows the contingency table and Table 3 provides a summary of the statistical indices.

All the statistical inferences were drawn for the overall time series, and then separately for the different rainfall regimes. Table 4 shows the criterion to segregate the rainfall time series into different components. For computing POD and FAR for different rainfall regime, a threshold is required. The 25th percentile value was selected as the threshold for low rainfall regime, 50th percentile for medium regime, 75th percentile for high rainfall regime and 95th percentile for very high rainfall regime. The statistical indices were calculated basin-wise.

In order to identify systematic bias in the satellite products, one meteorologic index (long term basin mean annual rainfall) and one topographic index (basin mean elevation) was computed for the 86 basins. The long term mean annual rainfall was computed using IMD gridded dataset from 1980 – 2010 (31 years). Basin mean digital elevation model (DEM) was extracted from Shuttle Radar Topography Mission (SRTM) DEM and mean elevation was obtained on a basin-wise scale.

Due to the limited availability of IMERG data (starting from 2014), calibration of VIC was done using an approach similar to the one used by Tang et al. (2016b). First, VIC was calibrated (2000-2011) and validated (2011-2014) using gridded IMD precipitation time series. VIC was then calibrated (2000-2011) and validated (2011-2014) with TRMM precipitation time series. Further, both the IMD and TRMM calibrated models were validated with IMERG and TRMM for the year 2014 (from April 1, 2014 to December 31st, 2014). The year 2000 was used as a warm up period for the model.

In line with the recent discussion by McCuen (2016) on the correct usage of statistical and graphical indices to evaluate model calibration and validation, four statistical parameters (Nash Sutcliffe efficiency (NSE), Percentage bias (Pbias), coefficient of determination (R^2) ~~along with its significance probability (p-value)~~ and root mean squared error (RMSE)) were used to evaluate the runoff simulations from VIC. Table 3 provides a summary of these indices.

3 Results

All the TRMM statistics were obtained for two distinct periods (1998-2013 and 2014). For the year 2014, the IMERG precipitation estimates were available from March 12, 2014. Therefore, the TRMM statistics for the year 2014 were obtained from March 12, 2014 to December 31, 2014. Henceforth, for the sake of convenience, statistics of TRMM-R refers to the time period 1998-2013, statistics of TRMM and IMERG refers to the time period March 12, 2014 to December 31, 2014.

3.1 Scatterplots

Fig. 3~~2.1~~ shows the scatterplot of IMERG and TRMM with respect to IMD precipitation combining data from all the 86 basins for the year 2014. ~~Both IMERG and TRMM show quite similar skills with correlation values above 0.8, with~~ IMERG shows~~ing~~ better correlation in 60 out of 86 basins. On looking at the scatterplots for individual basins (Fig. 4~~2.2~~), IMERG tends to be better correlated to IMD than TRMM. It can be seen that the correlation values go as high as 0.96 for IMERG (and 0.94 for TRMM) with a very uniform spread across the 1:1 line for the five best basins (Figs. 4~~2.2~~a–e) (decided on the basis of correlation of IMERG with IMD in 2014). These basins are situated in the flat Deccan Plateau belt in South-central India (mostly concentrated in Tapi and Godavari basins). For the other five basins (Figs. 4~~2.2~~f–j), the poor correlation is due to the gross overestimation of IMERG/TRMM over IMD. Four of these five basins are situated in the high elevation basins in Northern India, which hints at a systematic dependence of IMERG/TRMM estimates with elevation. This is explored in detail in section 3.5~~e~~.

3.2 Basin-wise correlation

Basin-wise correlation was computed for retrospective analysis of TRMM-R and to compare TRMM and IMERG rainfall estimates for the year 2014. Table 5 provides the summary of the number of basins where IMERG/TRMM has a higher correlation. IMERG gives ~~slightly~~ better rainfall estimates in majority of basins for all rainfall regime.~~Fig. 3 suggests that IMERG gives slightly better rainfall estimate than TRMM for all rainfall regimes (with IMERG showing higher correlation for the year 2014 for 60, 52, 52 and 55 out of 86 basins for overall, low, medium and high rainfall regimes). IMERG shows a correlation coefficient higher than 0.8 (for overall time series) for 73 out of 86 basins, compared to 68 basins for TRMM and higher than 0.9 for 20 basins compared to 13 for TRMM.~~ The decomposition of the overall time series into different rainfall regime reduces the correlation, which can be attributed to temporal smoothening in longer time series.

The spatial maps (Fig. 5~~4~~) provide an illustration of the slight improvement of IMERG over TRMM with spatially coherent patterns. ~~In general, both TRMM and IMERG show high basin-wise correlation values for the overall time series.~~ In the overall spatial maps (Figs. 5~~4~~b–c), for the year 2014, TRMM and IMERG show similar skill, with IMERG capturing the rainfall slightly better in Central and Southern India. Both show similar skill in the high rainfall areas of the Western Ghats and the North Eastern basins. IMERG gives slightly better estimates in the high elevation basins in North India. There is no significant improvement in the basins located on the Eastern coast (like the Mahanadi river basin). TRMM provides slightly better estimates of rainfall in the semi-arid basins located in the North Western states of India (Rajasthan). It is to be noted that TRMM statistics for 2014 are much better than its retrospective statistics (TRMM-R) with spatial coherent trends.

The low rainfall estimates (Figs. ~~4~~5d–f) over the semi-arid North Western basins are slightly better for TRMM compared to IMERG. IMERG captures low rainfall better over the Indo-Gangetic plain. Both IMERG and TRMM show similar trends over the Western Ghats, North-Eastern basins, Eastern coast and over the Deccan Plateau. IMERG doesn’t capture the low rainfall regime over the Upper Indus basin (in Northern India) and over the upper Bhima and the upper Godavari basin (in the Deccan plateau belt).

The medium rainfall estimates (Figs. 5~~4~~g–i) are best represented in Central India and over the Deccan Plateau by TRMM and IMERG. Both show similar statistics over the Western Ghats and basins in North-Eastern and Eastern coast of India. TRMM slightly outperforms IMERG in the North-Western basin of Rajasthan, a trend also found in the low rainfall regime. IMERG doesn’t capture the medium rainfall trends over the Upper Indus basin (in Northern India). In general, TRMM-R medium rainfall estimates are best correlated in the semi-arid region of Rajasthan (North-Western basins) and in Central India. There is not much variability in the correlation of medium rainfall trends of TRMM-R, with correlation coefficient mostly around 0.5 for entire India, except for the high elevation Upper Indus basin.

The high rainfall estimates (Figs. 5~~4~~j–k) show highest correlation in the Deccan Plateau belt, higher elevation basins in Northern India, the Western Ghats and the East coast basins (except for the Southern-most basin) for TRMM and IMERG. High rainfall estimates of TRMM are better correlated than IMERG in the North-Eastern basins of Brahmaputra and Barak and the North-Western basins of Rajasthan. Both show similar correlation over the high elevation basins in the North and over the Western Ghats. IMERG outperforms TRMM in the rain-shadow area of the Western Ghats and in the South-Eastern basins of Pennar and Cauvery. Retrospective maps of TRMM-R (Fig. 5~~4~~j) suggest that high rainfall is adequately captured in the Indo-Gangetic plain, Western Ghats, North-Western basins of Rajasthan, South-Eastern basins of Pennar and Cauvery and the Eastern coast basins of Central India. However, TRMM gives very low correlation values for the rain-shadow belt of the Western Ghats, suggesting that it doesn't capture the steep orographic gradient. The high rainfall estimates of TRMM-R give modest correlation in the North-Eastern basins, high elevation basins in Northern India and the West most basins of the South (Varrar and Periyar).

3.3 Basin-wise bias

Basin-wise bias was computed for retrospective analysis of TRMM-R and to compare TRMM and IMERG rainfall estimates for the year 2014. ~~Although, IMERG tends to give slightly better correlation on a basin-wise scale (Fig. 3a), Fig. 5a suggests that it also enhances the bias in the product. The b~~Bias~~ plot~~ for ~~the ~~low rainfall regime (Fig. S2~~5~~b) suggests that TRMM is more positively~~ negatively~~ biased than IMERG for 75 out of 86 basins implying~~s. Negative bias indicates~~ overestimation, which is a known problem with TRMM as its sensors cannot detect very low rainfall magnitudes (<0.5 mm/hour) (Hou et al., 2014). If it detects a low intensity storm, it is most likely to overestimate (~~it which can be clearly seen in ~~Fig. S2~~5~~b). ~~IMERG tends to give a better estimate of low rainfall magnitudes with smaller negative biases for 75 out of 86 basins~~This seems to have improved in the IMERG product, due to the sensor improvements in the GPM mission (Huffman et al., 2014). ~~For the medium rainfall magnitudes, IMERG slightly increased the bias in the majority of basins (63 out of 86). In TRMM, there were 18 basins which showed positive bias which was increased to 38 in IMERG~~ The number of unbiased basins (-10% <=bias <= 10%) increased from~~. However, this is not to be misunderstood as a decay in skill as in TRMM there were~~ 28 in TRMM to 37 in IMERG basins~~ which were relatively unbiased (-10% <=bias <= 10%) which was increased to 37 in IMERG. IMERG tends to increase the variability of bias in the high rainfall regime (Fig. 5d)~~. ~~For the high rainfall estimates, TRMM has 57 basins whose bias lies between -20% to +20% which is decreased to 52 in IMERG. In TRMM, 57 basins showed positive bias (implying underprediction) which was reduced to 48 basins in IMERG. This suggests a reduction in systematic underprediction, although with greater variability in bias in IMERG for the high rainfall regime.~~

The spatial maps for the overall rainfall time series (Figs. 6a-c) suggests similar bias patterns in TRMM and IMERG with spatial coherent trends throughout most of India. IMERG gives slightly ~~lower~~ smaller bias (closer to zero) over the high elevation basins of North India (Upper Indus basin) and slightly larger ~~higher~~ bias (more negative) over the North Eastern basins (of Brahmaputra and Barak) and the West flowing rivers of Kutch on the Western coast in the state of Gujarat. IMERG and TRMM give~~s a~~ large positive ~~negative~~ biases (overprediction) over Upper and Middle Godavari basin (in Deccan Plateau belt) which suggests that the sharp topographic gradient is not well captured. Retrospective maps of TRMM-R suggest ~~an~~ underestimation over high elevation basins in Northern India (Indus, Jhelum and Chenab basins). However, TRMM captures the heavy precipitation on the Western Ghats well with ~~very~~ low biases.

The low rainfall spatial maps (Figs. 6d–f) show ~~the~~ large overprediction (positive ~~negative~~ bias) by TRMM (1998-2013 and 2014) which is improved in IMERG. The improvement is most prominent in the North Eastern basins (of Brahmaputra and Barak), Central India (Mahi, Chambal and the Indo-Gangetic plain), rain-shadow area of the Western Ghats and the South-Eastern coast. IMERG shows gross overprediction over Luni basin (near the Western coast of Rajasthan). Retrospective TRMM-R maps for low rainfall regime (Fig. 6d) show that the low rainfall was best captured in high rainfall areas of the Western Ghats, the Indo-Gangetic plain and the Eastern coastal basins, which is not very surprising as TRMM doesn't detect low rainfall magnitudes very well, thus suffering from overprediction in arid and semi-arid basins. Improvement in the low rainfall sensors in IMERG has improved low rainfall estimates, but it still suffers from gross overprediction in semi-arid areas (as evident in the semi-arid basins in North-West India (Fig. 6f)).

The medium rainfall spatial maps (Figs. 6g–i) suggest ~~very~~ similar spatial bias pattern in TRMM and IMERG~~, with low biases in most of the basins~~. Both TRMM and IMERG suffer from underprediction (negative ~~positive~~ bias) in the high elevation Northern basins (of Indus and Jhelum), although IMERG seem to be less biased than TRMM. Both show similar trends in the Western Ghats, with ~~very~~ low bias. However, both the products show large positive ~~negative~~ bias (overprediction) in the Middle Godavari basin, unable to capture the sharp topographic gradient in the region. IMERG slightly overpredicts rainfall in the North Eastern basins (of Brahmaputra and Barak). The retrospective TRMM maps for medium rainfall (Fig. 6g) show low ~~almost constant~~ bias ~~(almost unbiased)~~ over entire India, except over the Western Ghats (~~slightly positive bias (~~slight underprediction)~~)~~ and high elevation Northern basins of Indus and Jhelum (~~positive bias (~~strong underprediction)~~)~~.

The high rainfall spatial maps (Figs. 6j–l) suggest similar spatial pattern in TRMM and IMERG, with slight negative bias over majority of the basins. The high rainfall in the Western Ghats is well represented in TRMM and IMERG, however with strong overprediction in the leeward side of the Western Ghats, suggesting that IMERG is unable to capture the sharp topographic gradients. IMERG shows ~~slightly greater bias (implying ~~greater underprediction~~)~~ in the high rainfall areas of the North Eastern basins than TRMM, however~~.~~ ~~IMERG ~~giving~~es a~~ better estimates ~~(still underpredicts) ~~in the high elevation basins in Northern India. Both IMERG and TRMM give similar bias pattern in the Indo-Gangetic plain and the semi-arid areas of the North-West. The retrospective TRMM-R map ~~for ~~of high rainfall (Fig. 6j) suggests spatially homogeneous trends throughout India~~s that TRMM slightly overpredicts high rainfall in majority of India (Indo-Gangetic plain, Deccan Plateau, rain-shadow area of the Western Ghats)~~. However, it suffers from gross underestimation in the high elevation basins of Northern India (Indus, Jhelum and Chenab). It is clearly observed that the high elevation basins are an outlier in most of the analysis.~~;~~ A~~a~~ systematic dependence of bias with elevation may be an underlying trend which is further explored in section *3.5*~~*e*~~.

3.4 Threshold statistics

~~Basin-wise POD and FAR was computed for retrospective analysis of TRMM-R and for the comparison of TRMM with IMERG (Figs. 7 and 8). Four rainfall thresholds were chosen, representative of different rainfall regimes (low threshold: 25 percentile, medium threshold: 50 percentile, high threshold: 75 percentile and very high threshold: 95 percentile).~~ Increasing rainfall threshold leads to deteriorating trends in POD and FAR across majority of the basins, with decreasing POD and increasing FAR.

Table 6 summarizes the number of basins in which IMERG/TRMM gives higher/lower threshold statistics, including the basins in which they show similar results. ~~For ~~At~~the~~ low rainfall threshold, IMERG shows~~ gives higher POD than TRMM for 62 basins, with the~~ major improvement in POD in the Western region of Gujarat (Luni, Bhadar and Setrunji basins) (Figs. 7b,c). ~~There is less spatial variability in POD for both TRMM and IMERG at low rainfall threshold with POD above 0.9 for 75 basins for IMERG and 63 basins for TRMM. ~~The average POD (low rainfall threshold) across basins is 0.95 for IMERG and 0.91

for TRMM. ~~For the~~At medium rainfall threshold, ~~IMERG outperforms TRMM in 39 basins with TRMM giving a higher POD in 37 basins; both the products give similar POD in 10 basins. The~~ average POD ~~(medium rainfall threshold)~~ across basins is 0.87 for both IMERG and TRMM. Notably, IMERG gives lower POD (medium rainfall threshold) in two~~2~~ (Barak and Brahmaputra lower sub-basin) out of the three~~3~~ North-Eastern basins, and higher POD (medium rainfall threshold) in the semi-arid basins of Rajasthan and Gujarat (Luni, Bhadar and Setrunji basins) (Figs. 7e,f). At ~~For the~~ high rainfall threshold, ~~TRMM outperforms IMERG in 45 basins with IMERG giving a higher POD in 32 basins, both the products give similar POD in 9 basins. The~~ average POD ~~(high rainfall threshold)~~ across basins is 0.76 for IMERG and 0.77 for TRMM. There is notable fall in performance in all the ~~3~~three North-Western basins. IMERG gives slightly higher POD (high rainfall threshold) in the high elevation Northern basins (Upper Indus and Jhelum basins) (Figs. 7h,i). At ~~For the~~ very high rainfall threshold, ~~IMERG outperforms TRMM in 44 basins with TRMM giving a higher POD in 27 basins; both the products give similar POD in 15 basins. The~~ average POD ~~(very high rainfall threshold)~~ across basins is 0.72 for IMERG and 0.7 for TRMM. At very high rainfall threshold, it's clear that POD of IMERG is worse for all the ~~3~~three North-Eastern basins and over the semi-arid basins of Rajasthan and Gujarat (Figs. 7k,i). There is slight improvement in POD values for the high elevation Northern basins (Chenab, Ravi, Beas and Satulaj basins).

At low rainfall threshold, ~~TRMM gives higher FAR than IMERG in 42 basins with IMERG giving a higher FAR in 40 basins; both the products give similar FAR in 4 basins.~~ t~~T~~he average FAR ~~(low rainfall threshold)~~ across basins is 0.24 for TRMM and 0.22 for IMERG. ~~For the~~At medium rainfall threshold, ~~IMERG outperforms TRMM (with lower FAR) in 53 basins with TRMM giving lower FAR in 26 basins; both the products give similar FAR in 7 basins. The~~ average FAR ~~(medium rainfall threshold)~~ across basins is 0.22 for TRMM and 0.19 for IMERG. Notably, IMERG outperforms TRMM at low and medium rainfall thresholds giving lower FAR in the Western basins of Gujarat (Luni and Setrunji basins) (Figs. 8b,c,e,f). ~~For the~~At high rainfall threshold, ~~IMERG outperforms TRMM in 67 basins (lower FAR) with TRMM giving a lower FAR in 15 basins; both the products give similar FAR in 4 basins. The~~ average FAR ~~(high rainfall threshold)~~ across basins is 0.18 for IMERG and 0.22 for TRMM. Slightly reduced FAR are seen in Central India (Yamuna and Chambal basins) and the North-Eastern basins (Brahmaputra basin) in IMERG at high rainfall threshold (Figs. 8h,i). ~~For the~~At very high rainfall threshold, ~~IMERG outperforms~~

~~TRMM in 64 basins (lower FAR) with TRMM giving a lower FAR in 17 basins; both the products give similar FAR in 5 basins. The~~ average FAR ~~(very high rainfall threshold)~~ across basins is 0.33 for IMERG and 0.41 for TRMM. There are notably fewer false alarms in IMERG estimates over the Northern, North-Eastern basins and the Western Ghats at very high thresholds. Both products give similar FAR (very high threshold) along the Eastern coast and Deccan Plateau basins.

POD for TRMM-R suggests decreasing POD and increasing FAR with increasing rainfall threshold (Figs. 7a,d,g,j, Figs. 8a,d,g,j). The average POD across basins is 0.89, 0.85, 0.77 and 0.66 for low, medium, high and very high rainfall thresholds, respectively. The respective FAR values are 0.26, 0.22, 0.21 and 0.43. At high and very high threshold, POD drops significantly over the high elevation Northern basins and high rainfall North-Eastern basins and the Western Ghats) (Figs. 7g,j). High FAR is recorded in the basins in Gujarat (Luni and Setrunji) and Central India (Bhadar and Chambal) at low and medium rainfall threshold (Figs. 8a,d) suggesting TRMM creates a lot of false alarms at low and medium rainfall magnitudes. There is a sharp contrast between FAR at high and very high thresholds, with low FAR at high rainfall threshold (75 percentile) and high FAR at very high threshold (95 percentile) (Figs. 8g,j). This suggests that TRMM-R creates a lot of false alarms at very high rainfall thresholds, especially in the North-Eastern, Northern and extreme Southern basins (Fig 8j).

3.5 Systematic error in satellite estimates as a function of annual rainfall and mean elevation

The satellite precipitation estimates were evaluated against a climatologic parameter (long term annual rainfall of basin) and a topographic parameter (basin mean elevation), to investigate if there was any systematic variation in errors with climatology or topography. ~~Fig. 9 describes the relationship between mean annual precipitation and mean elevation by considering the point values for 86 basins. It was found that t~~There is no ~~is no~~ systematic dependence between the climatologic and topographic parameter (R = 0.07, Fig S3) and they can be considered as independent (implying minimal interference).

~~TRMM-R rainfall estimates exhibited strong systematic dependence of bias and correlation with basin wise mean rainfall at low and medium rainfall estimates (Figs. 10 and 11). At low rainfall regime, TRMM-R estimates for basins experiencing low annual rainfall were found to be strongly negatively biased (Fig. 10b), implying significant overprediction.~~

~~The bias values improved drastically for basins experiencing higher annual rainfall. This is also reflected in the correlation plots (Fig. 11b), where a positive correlation between basin-wise correlation and annual rainfall (R = 0.3) implies improved estimates of low rainfall at basins which experience high annual rainfall. At the medium rainfall regime, TRMM-R estimates showed higher bias (implying underprediction) and lower correlation (reduced skill) in basins receiving higher annual rainfall, with a sharp drop in correlation for heavy rainfall basins (Figs. 10c and 11c). At high rainfall regime, the systematic bias was reduced, both in terms of percent bias and correlation, implying that there is no significant difference in TRMM-R estimates of high rainfall, in basins receiving low/high annual rainfall.~~

~~For the year 2014, both IMERG and TRMM showed increasing bias as a function of increasing annual rainfall for all the rainfall regimes (Fig. 12), with the systematic dependence strongly reduced in IMERG estimates for the medium rainfall regime. For the low rainfall regime, bias and correlation values improve for basins receiving higher rainfall (Figs. 12b and 13b). TRMM and IMERG showed similar systematic dependence on annual rainfall at low rainfall regime, with correlation values between basin wise correlation and annual rainfall equal to 0.38 and 0.39 for TRMM and IMERG, respectively. For the medium rainfall regime, both IMERG and TRMM showed increasing bias with increasing annual basin-wise rainfall (Fig. 12c). However, there was a strong reduction in the systematic bias component in IMERG, with correlation between basin-wise bias and rainfall decreasing from 0.43 (for TRMM) to 0.3 (for IMERG). At medium rainfall, a substantial skill was lost in terms of decreasing correlation for basins receiving high rainfall (Fig. 13c). This systematic dependence wasn’t reduced in IMERG estimates, with correlation values between basin-wise correlation and rainfall as -0.45 for TRMM and -0.44 for IMERG. At high rainfall regime, bias was higher for basins which received more rainfall, implying greater underprediction in basins with heavy rainfall magnitude (Fig. 12d). This systematic bias wasn’t reduced in IMERG estimates. No systematic dependence was found in the correlation of IMERG/TRMM estimates with basin-wise rainfall (Fig. 13d).~~

TRMM-R rainfall estimates exhibited very strong dependence on mean basin elevation, with decreasing skill (~~higher~~ larger bias and lower correlation) in basins with high mean elevation (Figs. 9~~14~~ and 10~~5~~). ~~For the low rainfall regime, a correlation coefficient (between basin-wise bias and elevation) of (-0.08) (Fig. 14b) may suggest that there is no systematic dependence between elevation and bias.~~ For medium and high rainfall regimes (Figs. 9~~14~~c, d), bias values were highly~~very~~ negative~~increase drastically~~ for high elevation basins (especially for basins with mean elevation > 2000 m), implying underprediction~~ at higher elevations~~. The corresponding correlation values (Figs. 1~~5~~0c, d) also suggested reduced skill at high~~er~~ elevation basins.

For the year 2014, ~~except at low rainfall magnitude, bias increases with mean basin elevation for TRMM and IMERG rainfall estimates (Fig. 16). T~~the~~is~~ systematic dependence of bias on basin elevation~~ is~~ improved in IMERG estimates, with ~~the ~~correlation between basin-wise bias and elevation reducing from -0.43~~ 0.43~~ to -0.32 for medium rainfall ~~regime~~ intensity (Fig. 11~~6~~c) and from -0.31 to -0.08 for high rainfall intensity~~ regime~~ (Fig. 11~~6~~d). The same was not ~~seen~~observed in~~ It's interesting to note that the same is not seen for~~ the correlation plots (Fig. 12~~7~~). At low~~ For the low~~ rainfall intensity~~ regime~~ (Fig. 12~~7~~b), IMERG estimates exhibited stronger systematic relationship between basin-wise correlation and elevation, with strongly decreasing correlation with elevation than TRMM. At medium rainfall intensity (Fig. 12~~7~~c), both TRMM and IMERG showed decreasing skill with increasing elevation. This systematic dependence was~~ is again~~ stronger in IMERG than TRMM, as reflected in the higher negative correlation between basin-wise correlation and elevation in medium rainfall IMERG estimates (Fig. 1~~7~~2c).~~ For the high rainfall intensity (Fig. 17d), both IMERG and TRMM do not show any systematic dependence of skill with elevation.~~

The same analysis was repeated against mean annual precipitation (Figs. S4-S7) wherein~~. The~~ systematic error dependence was found to be smaller~~ than in elevation~~. TRMM-R rainfall estimates exhibited systematic dependence of bias and correlation with basin wise mean annual rainfall ~~at~~for low and medium rainfall estimates (Fig. S4 and S5). At low rainfall intensity, TRMM-R estimates for basins experiencing low annual rainfall were found to be strongly positively biased (Fig~~s~~. S4b), implying significant over~~prediction-~~estimation. For the year 2014, systematic dependence of bias was reduced in IMERG at medium rainfall intensities (Fig. S6c, correlation ~~down~~improved from -0.43 in TRMM to -0.3 for IMERG). A substantial skill was lost in terms of decreasing correlation for basins receiving high rainfall in both TRMM and IMERG estimates (Fig. S7c). At high rainfall intensities, bias was more negative (implying underprediction) in basins which received more rainfall in both IMERG and TRMM (Fig. S6d).

3.6 Rainfall-runoff modeling

Rainfall-runoff modeling was carried out over Hirakud catchment of Mahanadi River basin and Wainganga catchment of Godavari River basin, with the calibration and validation periods as 2000-2011 and 2012-2014, respectively. VIC was first calibrated with IMD gridded precipitation and then with TRMM3B42 V7. The two calibrated models were then forced with TRMM and IMERG precipitation ~~forcing~~ for the year 2014 (April – December). Tables 7~~5~~ and 8 show~~s~~ the model performances.

~~VIC was successfully calibrated using IMD (NSE = 0.83 for calibration and 0.86 for validation) and TRMM for both Hirakud and Wainganga basins(NSE = 0.72 for calibration and 0.73 for validation).~~ The IMD calibrated model showed better simulations compared to the TRMM calibrated model, with higher NSE, coefficient of determination and ~~lower~~ smaller bias and RMSE in both Wainganga and Hirakud basins. TRMM calibrated model showed ~~slight~~ overprediction (~~negative~~ positive bias) in Hirakud basin, but was relatively unbiased in Wainganga basin (-10 <= Pbias <= 10) (Tables 7, 8~~5~~).

The IMERG simulations with IMD and TRMM calibrated models were slightly inferior in comparison with TRMM simulations for 2014 (NSE = 0.64 for IMERG and 0.72~~3~~ for TRMM in IMD calibration; NSE = 0.7 for IMERG and 0.72 for TRMM in TRMM calibration) (Table 7~~5~~, Fig. 13~~8~~) for Hirakud. However, the IMERG simulations gave similar results as TRMM in Wainganga basin when calibrated using IMD data, but inferior results when calibrated with TRMM data (NSE = 0.61 for IMERG and 0.72 for TRMM) (Table 8, Fig. 14). In case of Hirakud basin, IMERG simulations gave higher NSE when calibrated with TRMM data. However, in the case of Wainganga basin, IMERG gave higher NSE when calibrated with IMD data. ~~The IMERG simulations with TRMM calibrated model reported higher NSE and coefficient of determination, with lower smaller bias and RMSE, which might be due to the fact that TRMM and IMERG are both satellite products and exhibit similar spatio-temporal trends.~~ The high negative bias in IMERG simulations (with IMD and TRMM calibrated models) showed significant overprediction compared to TRMM.

Both TRMM and IMERG underestimated the magnitude of the two major ~~high~~ peaks (flow > 15000 m^3/s) in Hirakud and Wainganga basin in 2014 (Figs. 13, 14). However, the phase was well captured by both IMERG and TRMM in the two basins. ~~Apart from the two major peaks,~~ IMERG overestimated low flows for the majority of ~~the~~ time in both IMD and TRMM calibrated VIC model for both the basins ~~(hence the negative bias value)~~, and thus was inferior in performance to TRMM. This suggests that the use of an appropriate postprocessor (in form of real-time error updation) could tremendously benefit the flow simulations, which might be an interesting study for the future.

4 Conclusions

TRMM 3B42 and IMERG precipitation estimates were comprehensively evaluated over 86 basins in India. TRMM 3B42 was analysed for two distinct time periods, the retrospective analysis was carried out from 1998-2013 and the current estimates were compared with IMERG for the year 2014 (March 12th 2014 – December 31st 2014). The systematic biases in both the estimates were explored with respect to a climatologic parameter (basin mean annual rainfall) and a topographic parameter (basin mean elevation). Finally, TRMM and IMERG were hydrologically evaluated by carrying out rainfall-runoff modeling over Hirakud catchment of Mahanadi River basin and Wainganga catchment of Godavari River basin~~, a flood prone basin in Eastern India~~. The results of the study are summarized as:

1. IMERG rainfall estimates were found to be better than TRMM at all rainfall intensities, in terms of correlation. IMERG outperformed TRMM in 60, 52, 52 and 55 out of 86 basins for overall, low, medium and high rainfall regimes.
2. IMERG gave better estimates of low rainfall magnitudes with smaller ~~negative~~ biases in 75 out of the 86 basins analysed, which suggests that the sensor improvement in IMERG satellite translated into better low rainfall estimation. IMERG captured the low rainfall magnitudes better over the Indo-Gangetic plain, North Eastern basins of Brahmaputra and Barak, Central India (Mahi, Chambal and the Indo-Gangetic plain) and the rain shadow area of the Western Ghats. However, for the semi-arid North Western basins, TRMM low rainfall estimates outperformed IMERG.
3. The high rainfall estimates of IMERG outperformed TRMM in the rain-shadow area of the Western Ghats, the high elevation basins of the North and the South-Eastern basins of Pennar and Cauvery. However, TRMM did a better job in the North-Eastern basins of Brahmaputra and Barak and the North-Western basins of Rajasthan. ~~Interestingly, IMERG reduced the systematic underprediction over TRMM although with greater variability in bias at high rainfall intensity.~~
4. Increasing rainfall thresholds lead to deteriorating trends in POD and FAR across majority of basins, with decreasing POD and increasing FAR.
5. The skill of TRMM-R medium rainfall estimates (in terms of Pbias and correlation) was found to exhibit strong systematic dependence on annual rainfall (climatologic

parameter), with ~~higher~~ larger bias and lower correlation in basins which received higher annual rainfall. This systematic dependence was reduced significantly in IMERG estimates. However, no such improvement was found at low and high rainfall intensities.

6. A very strong deteriorating skill (increasing bias and decreasing correlation) was found in TRMM-R rainfall estimates at all intensities in the high elevation basins. This systematic dependence was strongly reduced in IMERG estimates at all rainfall intensities, suggesting IMERG captures the rainfall trends better with respect to topography.
7. Rainfall runoff modeling using VIC model over ~~Hirakud catchment of the~~ Mahanadi and Wainganga River basins ~~River basin~~ gave better results with TRMM as input forcing, rather than IMERG. Both TRMM and IMERG captured the phase of the peak flows, however both underreported the magnitudes. Low flows were grossly over predicted by IMERG, which led to overall poor performance with IMERG. As GPM is still a young mission, with time a longer timeseries ~~As longer timeseries~~ of IMERG will~~is available, it may~~ help in model ~~performance~~ evaluation as IMERG can be used to directly calibrate the model, hence capturing the fine details in the product.

In essence, IMERG gives reasonable improvement in rainfall estimates across majority of the Indian basins. ~~However, the improvement was not found to be ground breaking, rather incremental, suggesting that the GPM mission is a worthy successor of the widely acclaimed TRMM mission.~~ The most notable improvement in IMERG is the reduction in systematic error dependence on topography (basin mean elevation), which suggests improvements in the assimilation of satellite observations. The improved sensitivity of Ku and Ka bands in GPM satellite resulted in improvement in detection of low rainfall magnitudes. The expected improvement in IMERG in snow detection could not be verified in this study as India is mostly a tropical country which receives very less snow. The constant overestimation of low flow magnitudes in the rainfall-runoff exercise suggest that IMERG may benefit from a post forecast data assimilation scheme, which is a worthy topic for further research.

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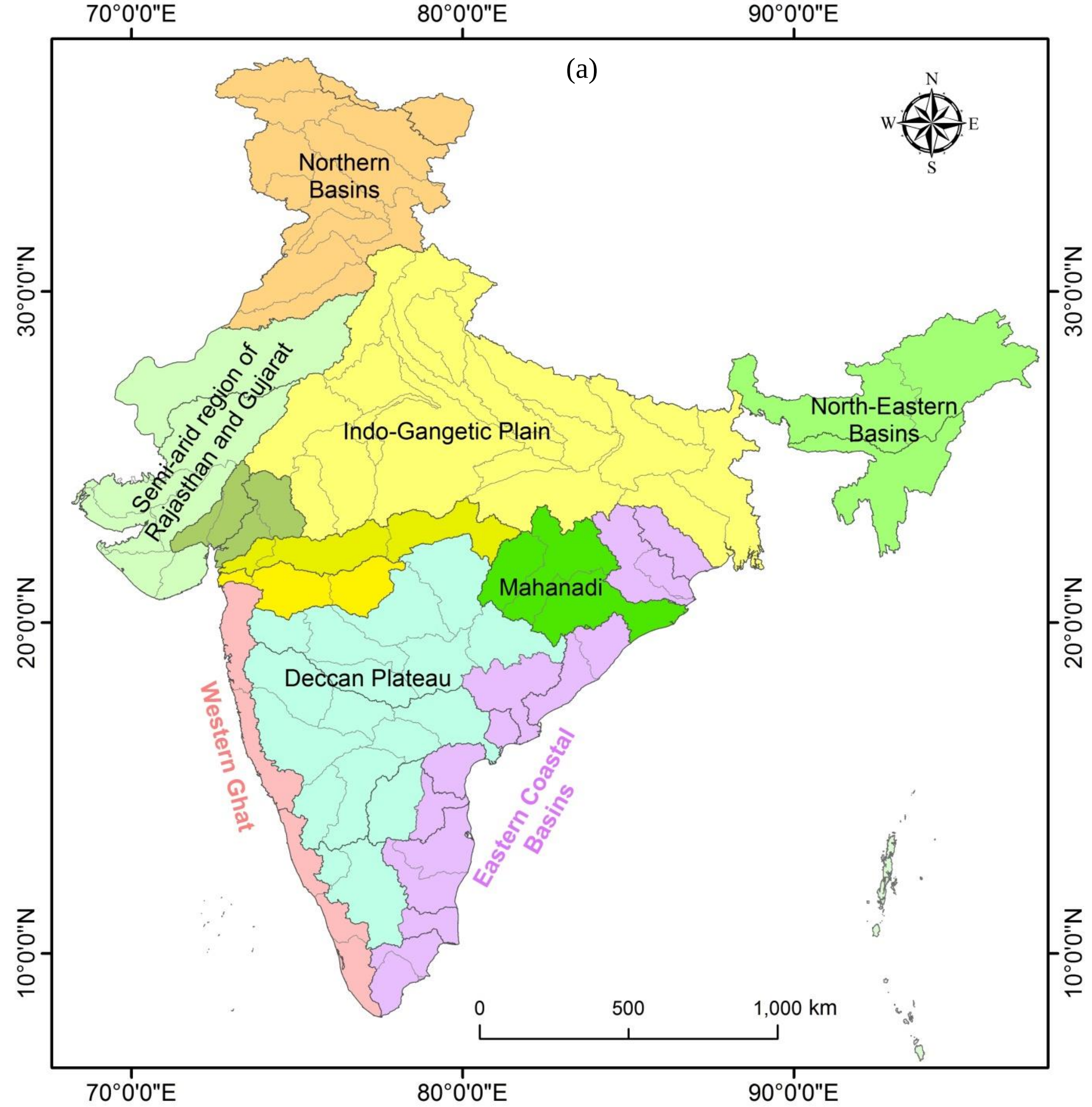
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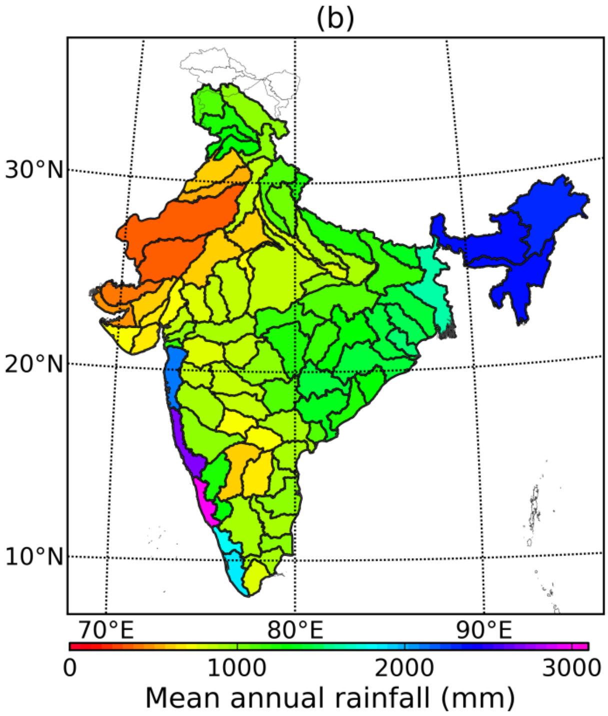
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Mean annual rainfall (mm)
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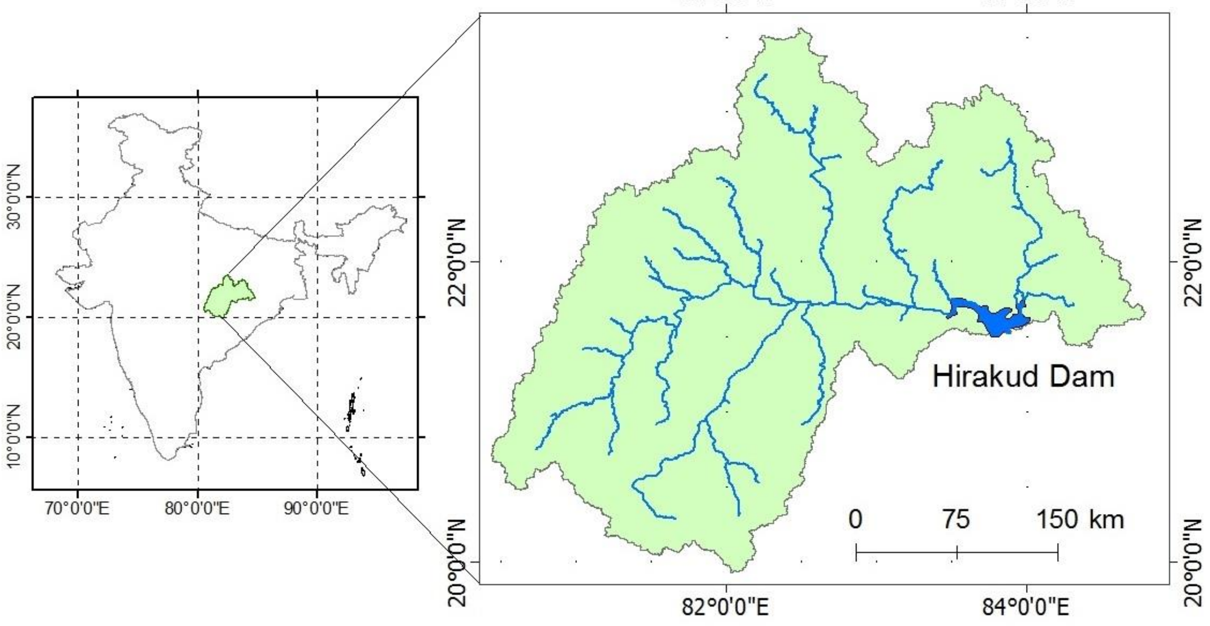
Mean elevation (m)

(b~~d~~


82°0'0"E
84°0'0"E
22°0'0"N
20°0'0"N
Hirakud Dam
0
75
150 km
30°0'0"N
20°0'0"N
10°0'0"N
70°0'0"E
80°0'0"E
90°0'0"E

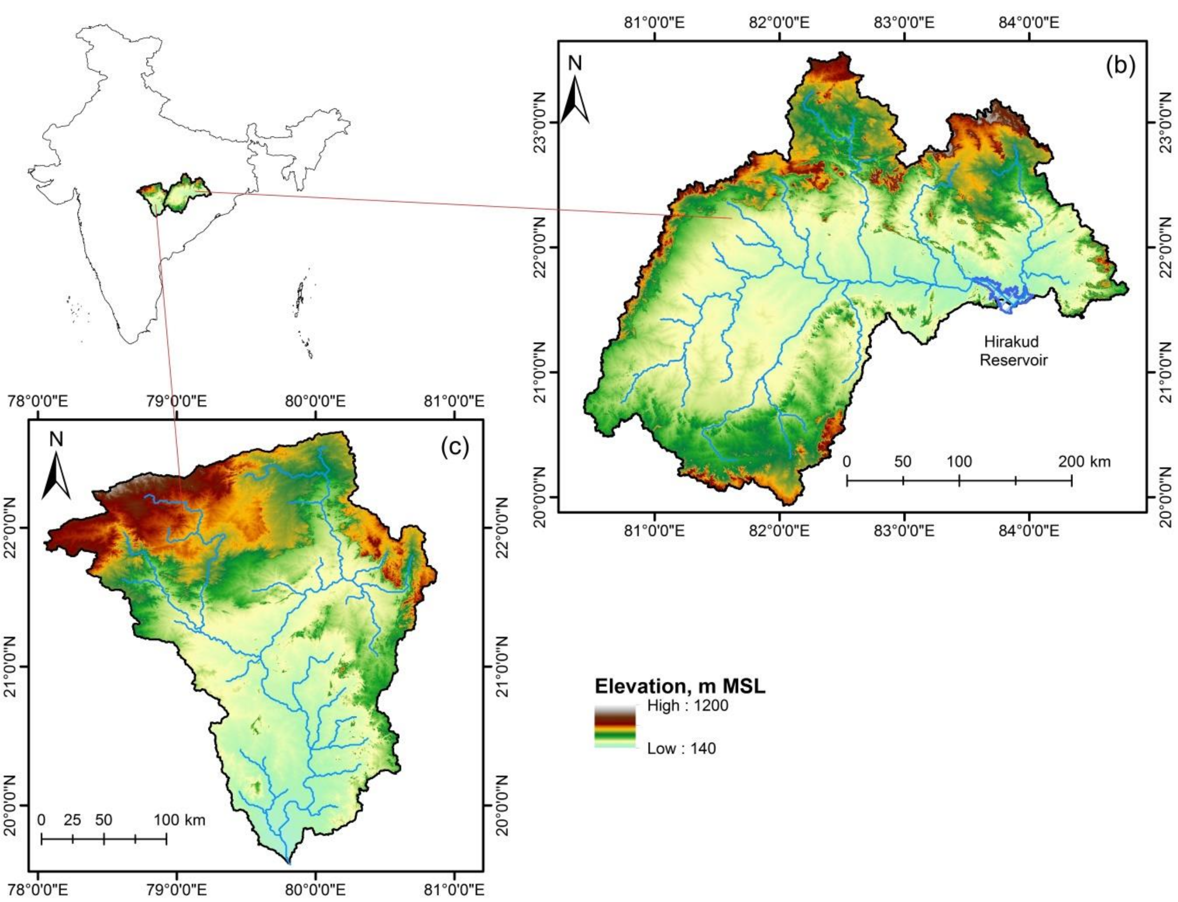
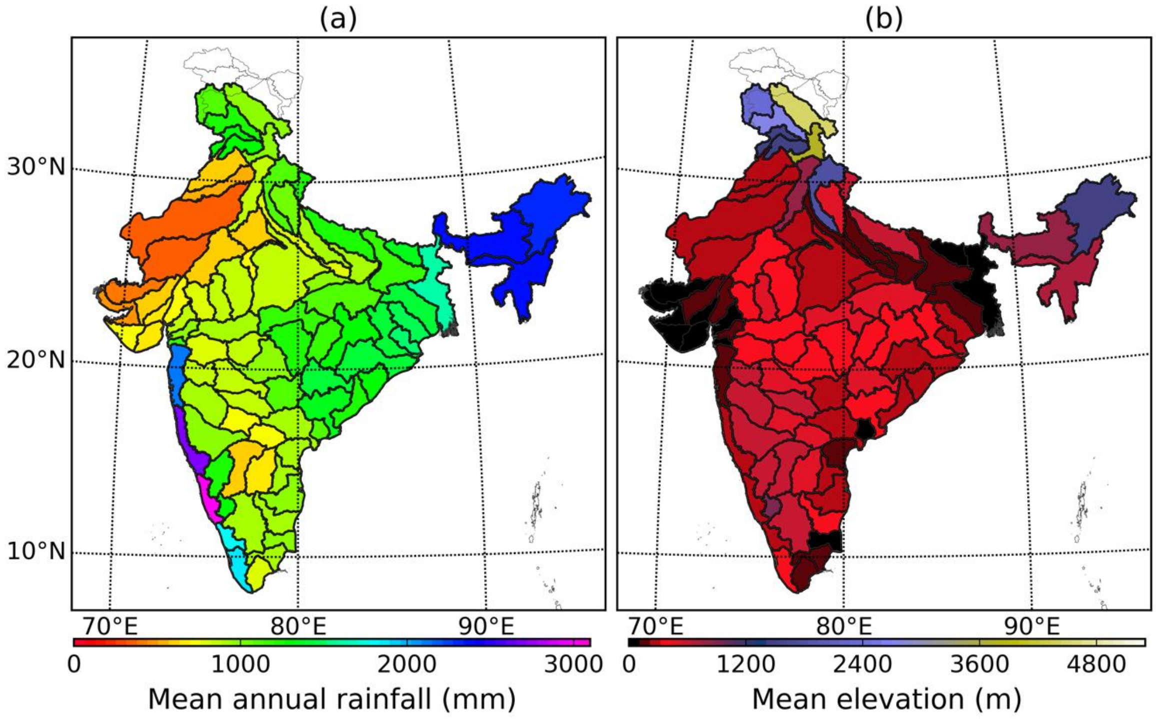


Figure 1(a). Map of the major basins in India, map of (b) Hirakud catchment of the Mahanadi River basin and (c) Waingaga catchment of the Godavari River basin.

~~**Figure 1.(a)** Map of the major basins in India, spatial distribution of **(b)** long term average annual rainfall (calculated from IMD gridded rainfall dataset from years 1980-2010), **(c)** average elevation above mean sea level (calculated using SRTM DEM) over 86 major basins in India and (bd) map of Hirakud dam catchment of the Mahanadi River basin in Eastern India.~~



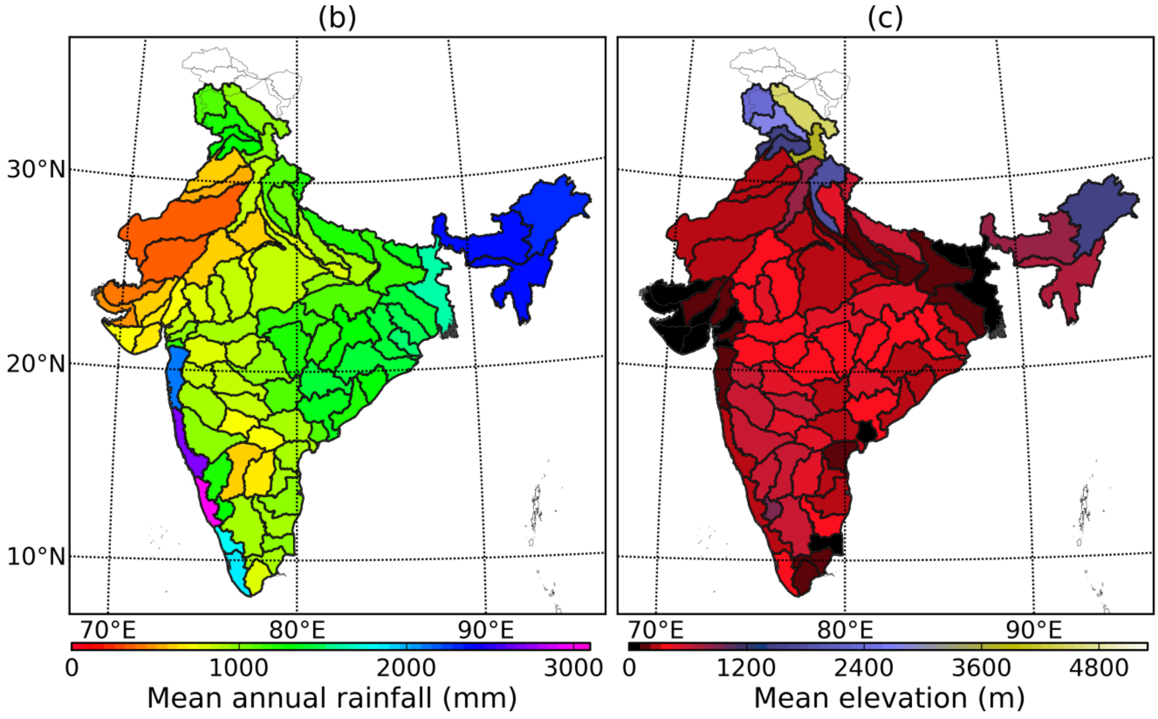


Figure 2. Spatial distribution of (a) long term average annual rainfall (calculated from IMD gridded rainfall dataset from years 1980-2010), and (b) average elevation above mean sea level (calculated using SRTM DEM) over 86 major basins in India.

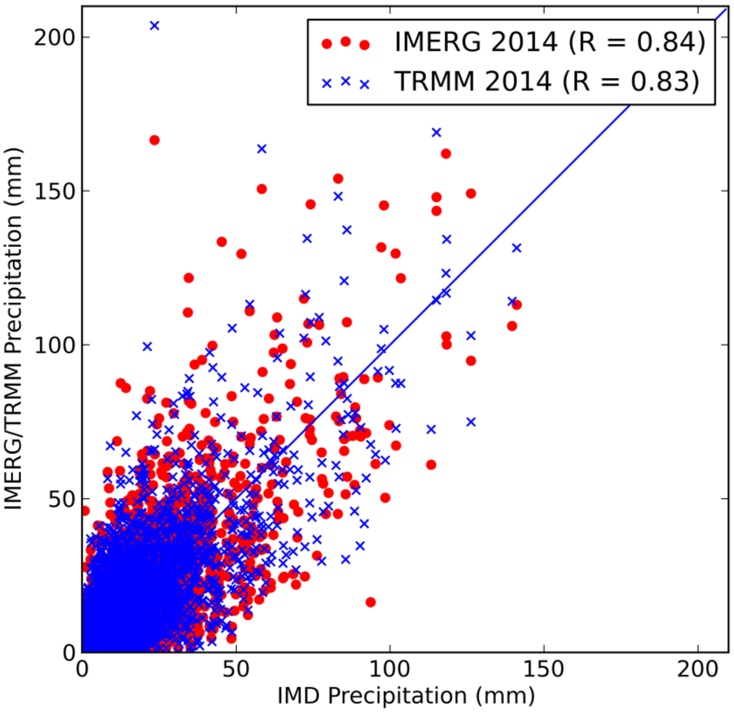


Figure 3.~~2.1~~ Scatterplot of satellite precipitation products (TRMM and IMERG) vs observed rainfall (IMD) computed over 86 major basins in India (based on daily precipitation data from March 12, 2014 to December 31, 2014).

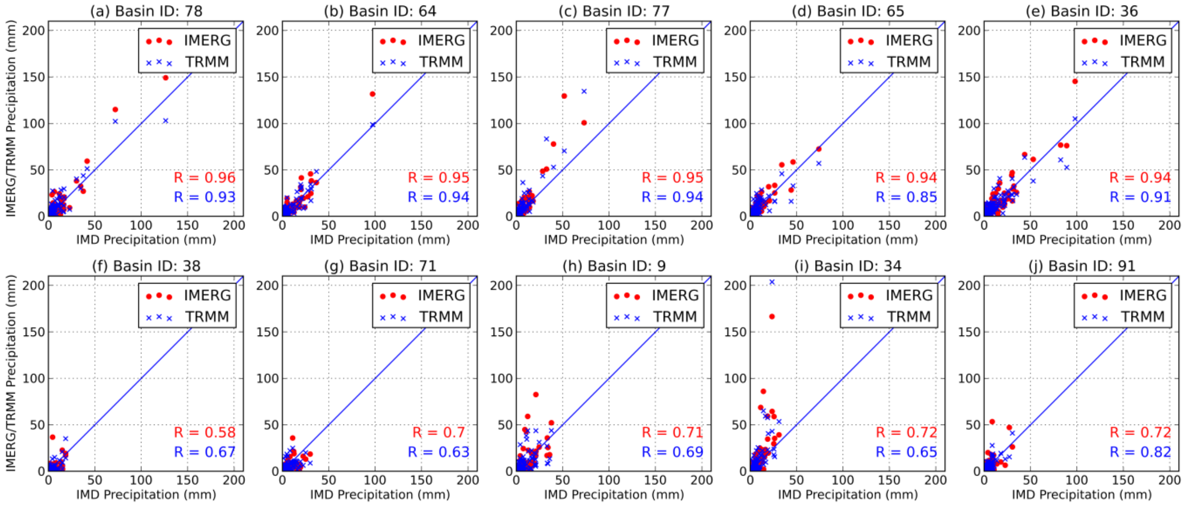
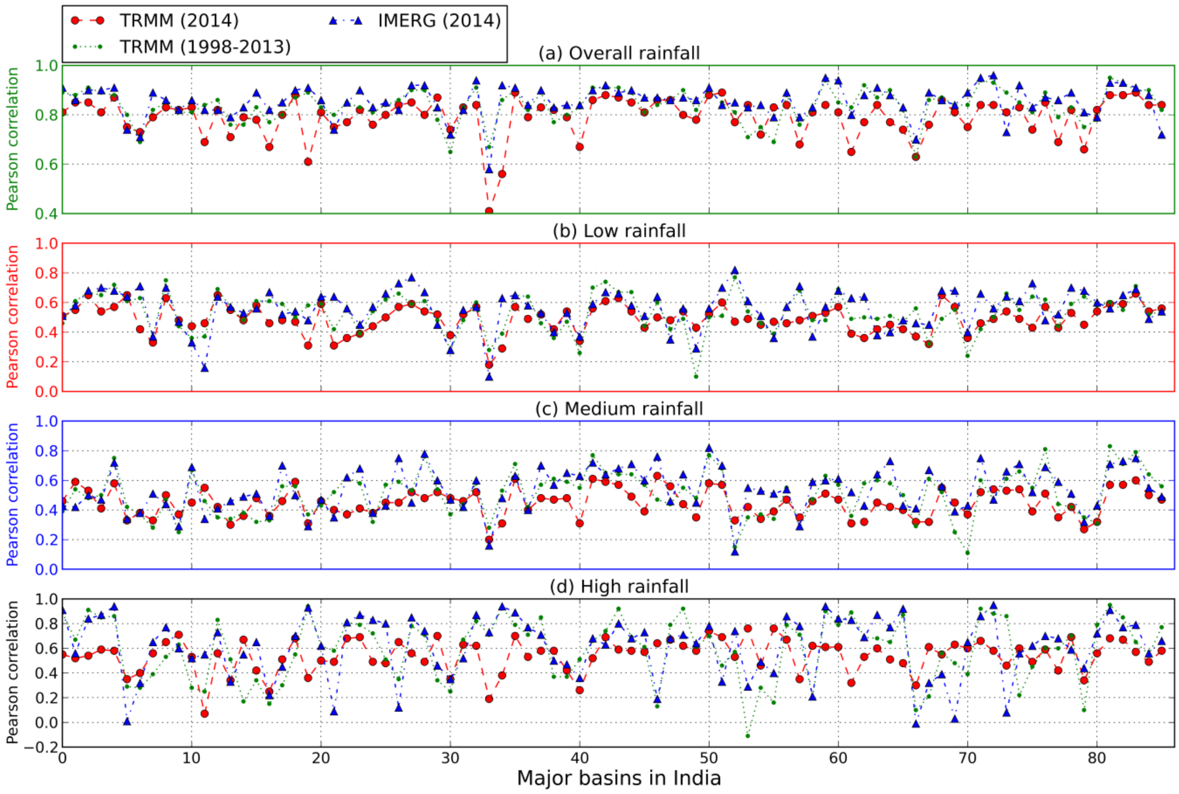


Figure 4~~2.2~~. Scatterplot of satellite precipitation products (TRMM and IMERG) vs observed rainfall (IMD) for **(a)** – **(e)** five best basins in terms of correlation of IMERG with IMD (arranged in descending order) and **(f)** – **(j)** five worse basins in terms of correlation of IMERG with IMD (arranged in ascending order) (based on daily precipitation data from March 12, 2014 to December 31, 2014).



~~**Figure 3.** Correlation of TRMM (1998-2013), TRMM (2014) and IMERG (2014) over 86 major basins in India for **(a)** overall time series and over **(b)** low, **(c)** medium and **(d)** high rainfall regime.~~

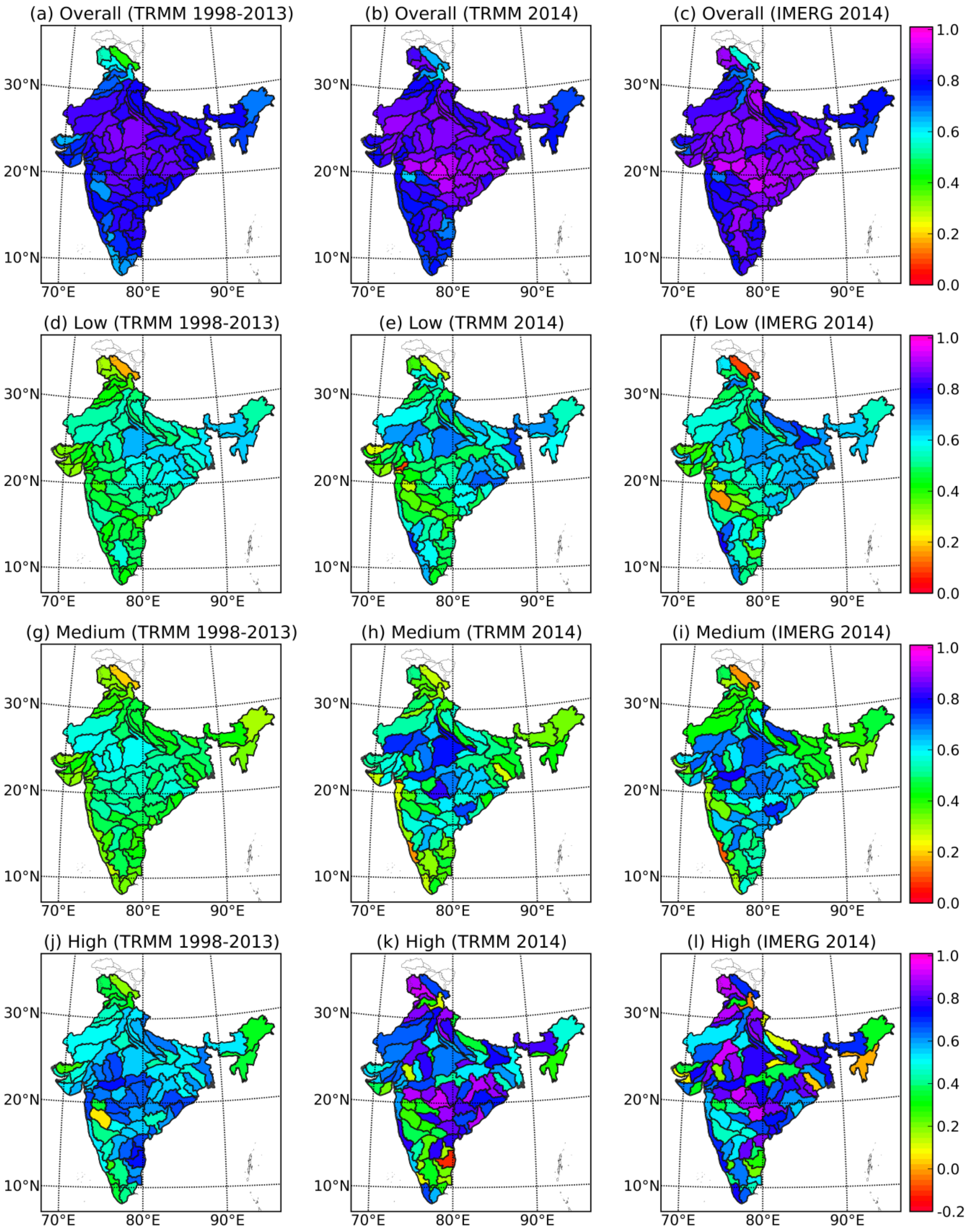
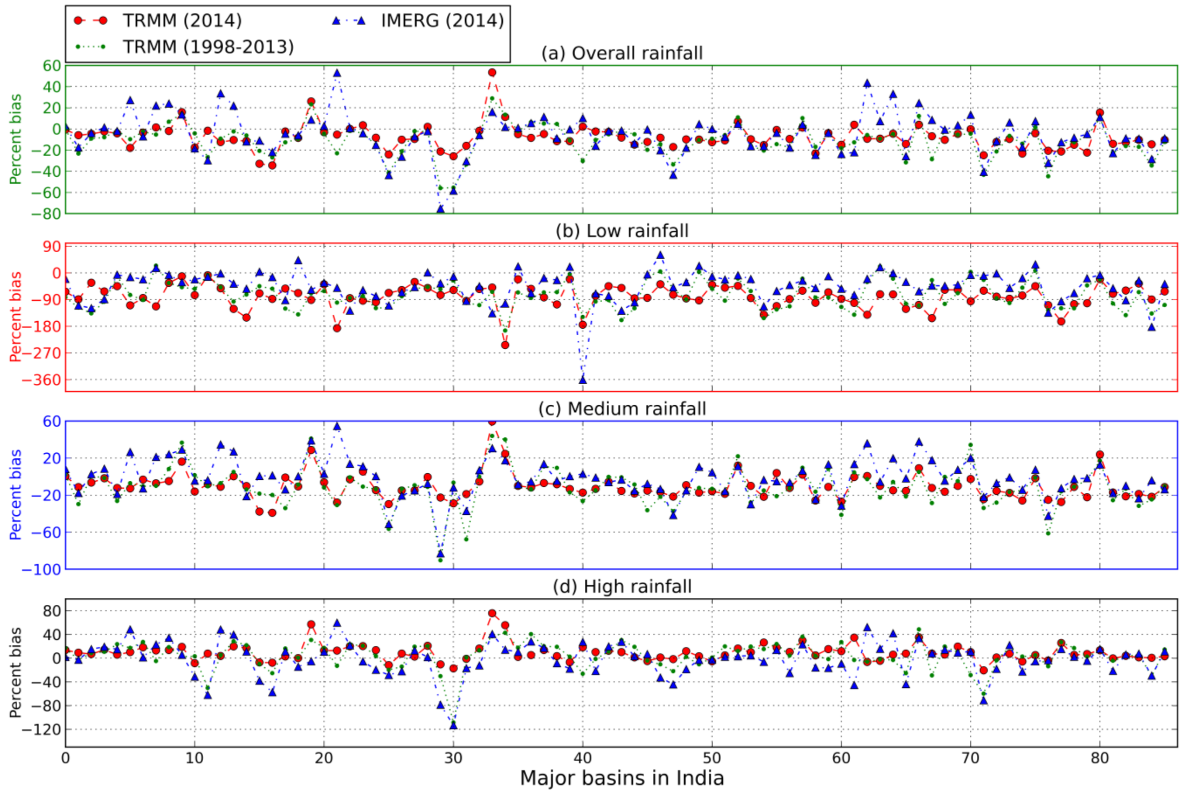
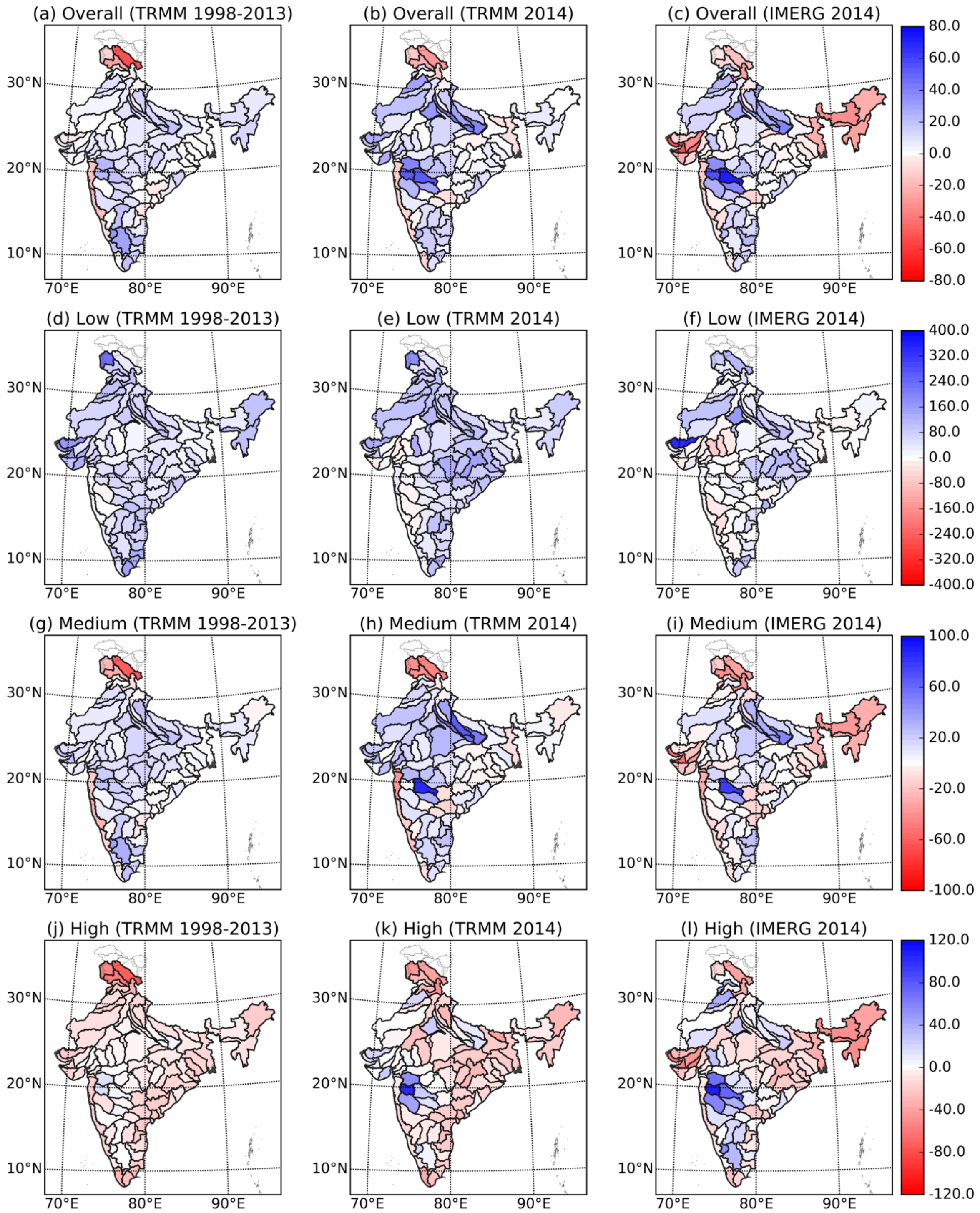


Figure ~~5~~4. Spatial representation of correlation of TRMM (1998-2013), TRMM (2014) and IMERG (2014) over 86 major basins in India for **(a)** – **(c)** overall time series, **(d)** – **(f)** low, **(g)** – **(i)** medium and **(j)** – **(l)** high rainfall regime.



~~**Figure 5.** Percentage bias of TRMM (1998-2013), TRMM (2014) and IMERG (2014) over 86 major basins in India for **(a)** overall time series and over **(b)** low, **(c)** medium and **(d)** high rainfall regime.~~


(a) Overall (TRMM 1998-2013)
(b) Overall (TRMM 2014)
(c) Overall (IMERG 2014)
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
(d) Low (TRMM 1998-2013)
(e) Low (TRMM 2014)
(f) Low (IMERG 2014)
400.0
320.0
240.0
160.0
80.0
0.0
-80.0
-160.0
-240.0
-320.0
-400.0
(g) Medium (TRMM 1998-2013)
(h) Medium (TRMM 2014)
(i) Medium (IMERG 2014)
100.0
60.0
20.0
-20.0
-60.0
-100.0
(j) High (TRMM 1998-2013)
(k) High (TRMM 2014)
(l) High (IMERG 2014)
120.0
80.0
40.0
0.0
-40.0
-80.0
-120.0
30°N
20°N
10°N
70°E
80°E
90°E

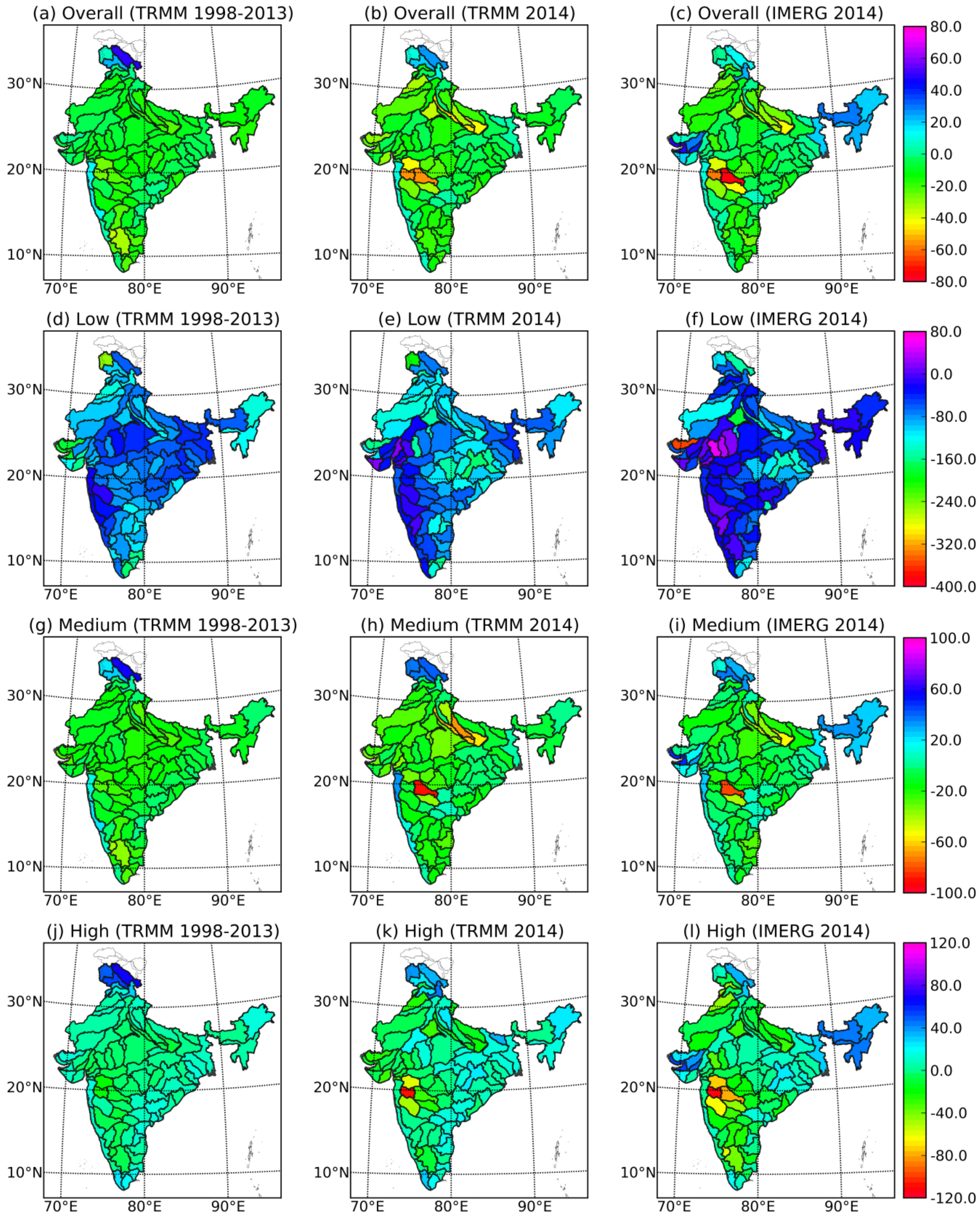


Figure 6. Spatial representation of percentage bias of TRMM (1998-2013), TRMM (2014) and IMERG (2014) over 86 major basins in India for **(a)** – **(c)** overall time series and over **(d)** – **(f)** low, **(g)** – **(i)** medium and **(j)** – **(l)** high rainfall regime.

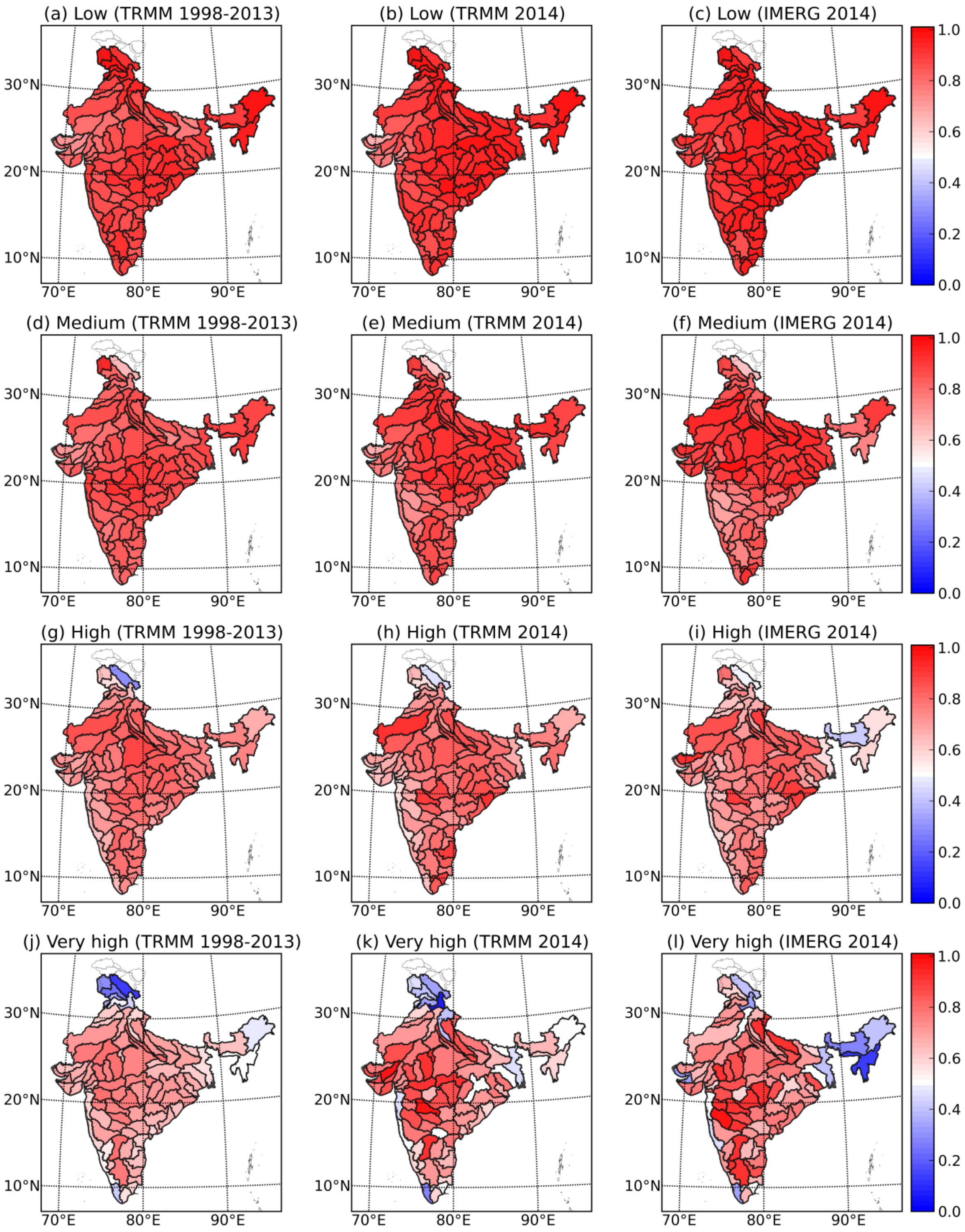


Figure 7. Spatial representation of probability of detection (POD) for **(a)** – **(c)** low (25 percentile), **(d)** – **(f)** medium (50 percentile), **(g)** – **(i)** high (75 percentile) and **(j)** – **(l)** very high (95 percentile) rainfall threshold for TRMM (1998-2013), TRMM (2014) and IMERG (2014) rainfall estimates over 86 major basins in India.

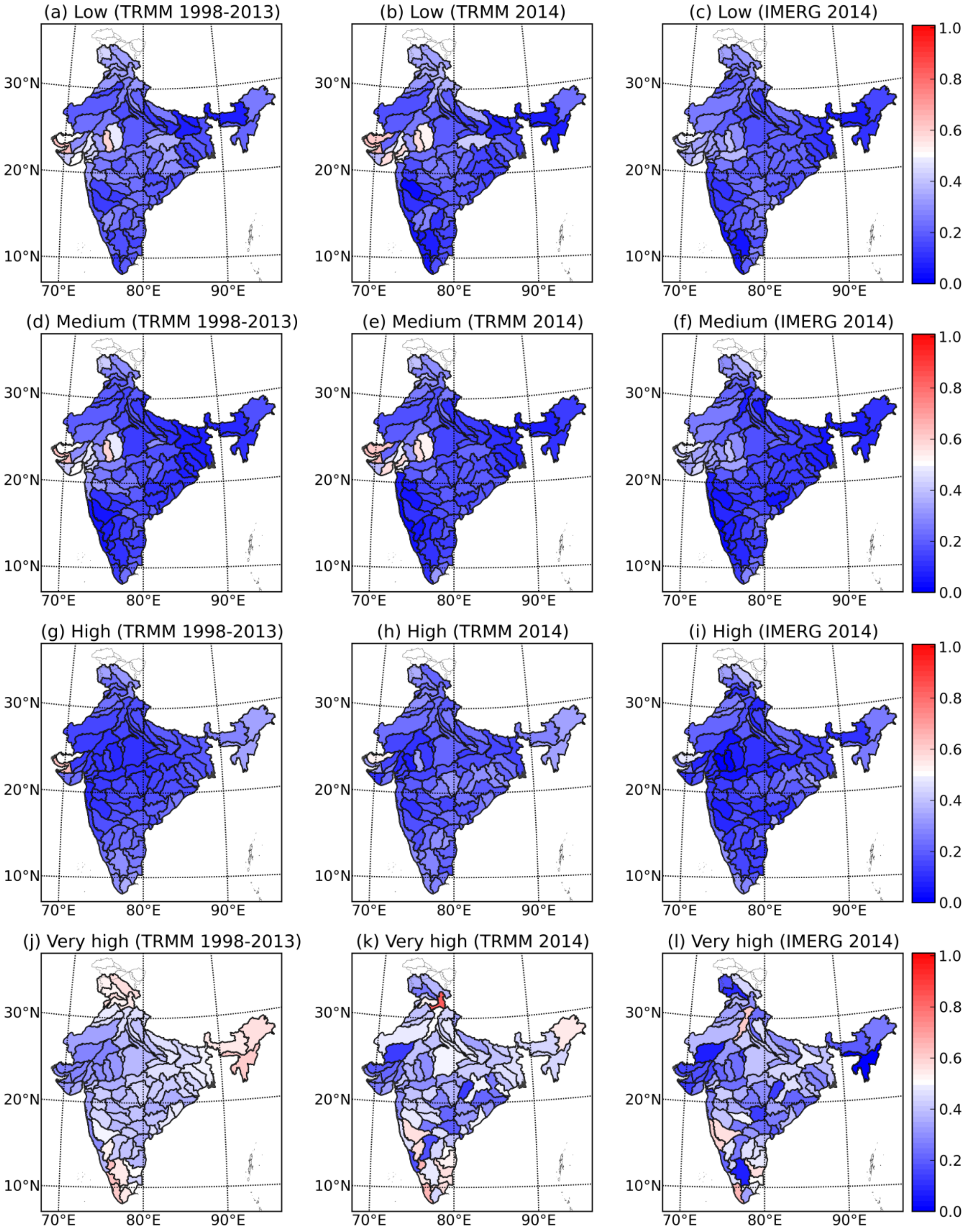
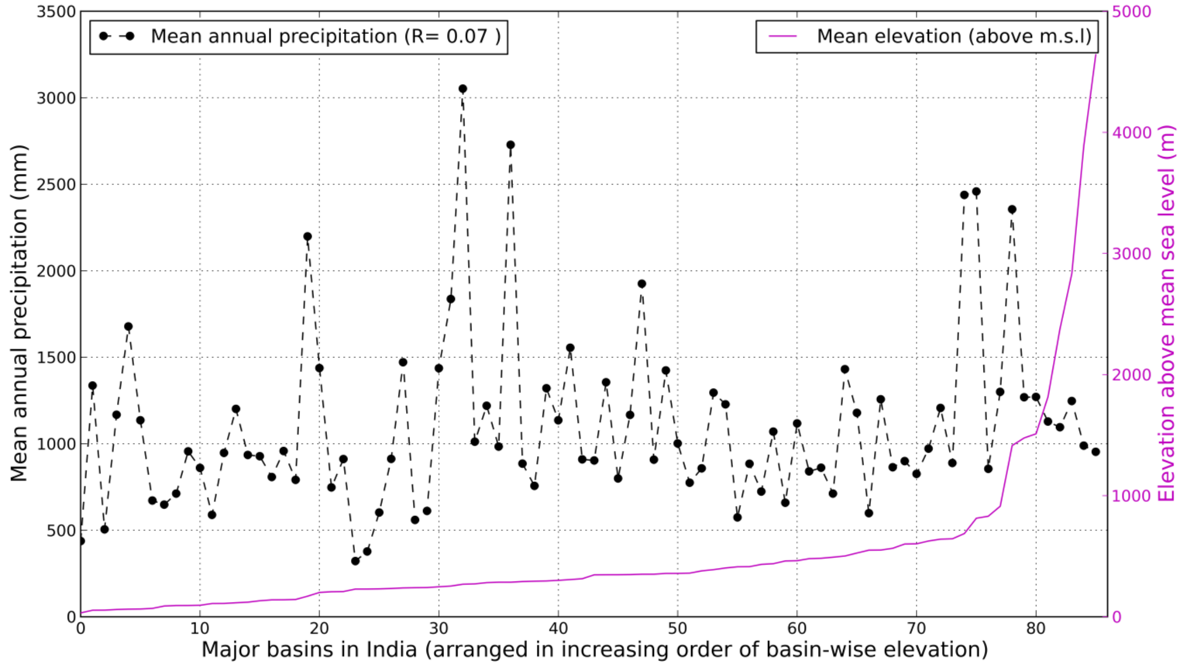
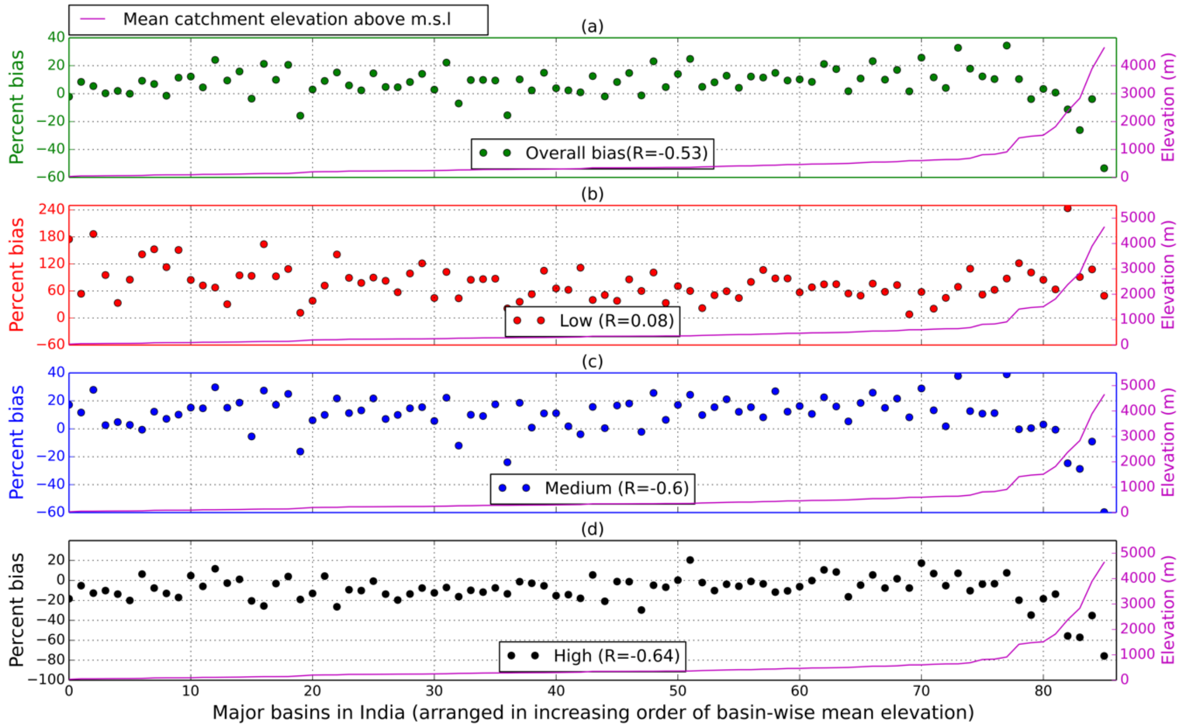
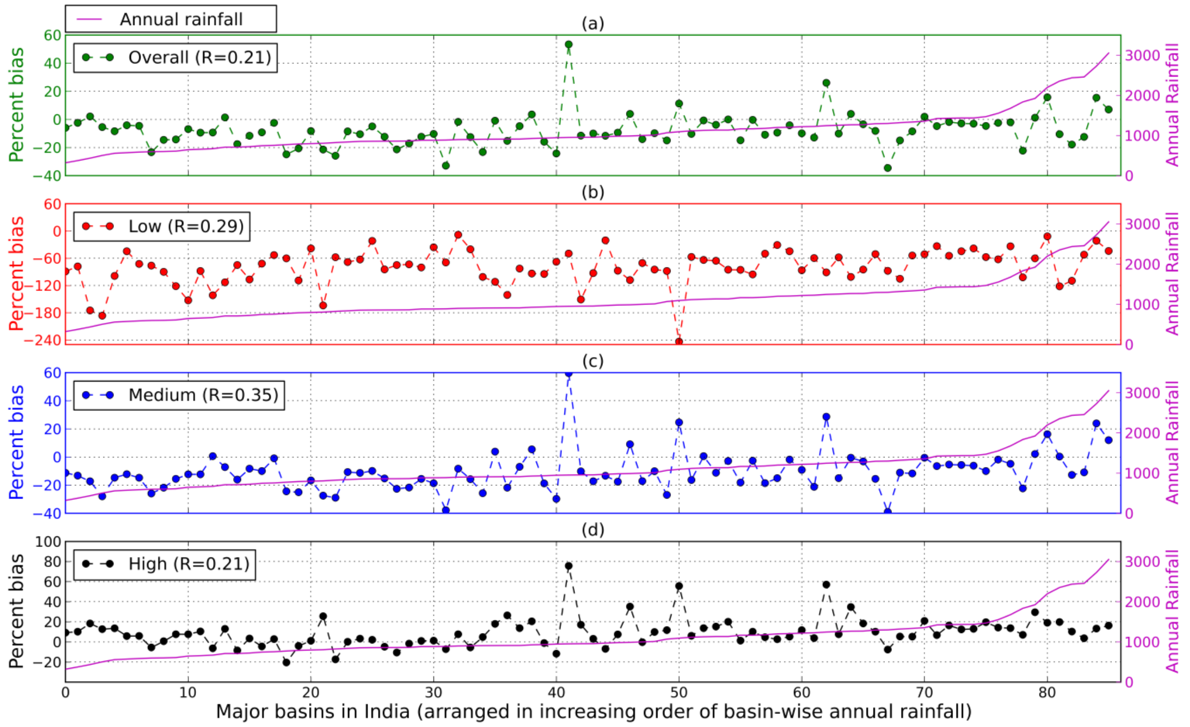


Figure 8. Spatial representation of false alarm ratio (FAR) for **(a)** – **(c)** low (25 percentile), **(d)** – **(f)** medium (50 percentile), **(g)** – **(i)** high (75 percentile) and **(j)** – **(l)** very high (95 percentile) rainfall threshold for TRMM (1998-2013), TRMM (2014) and IMERG (2014) rainfall estimates over 86 major basins in India.

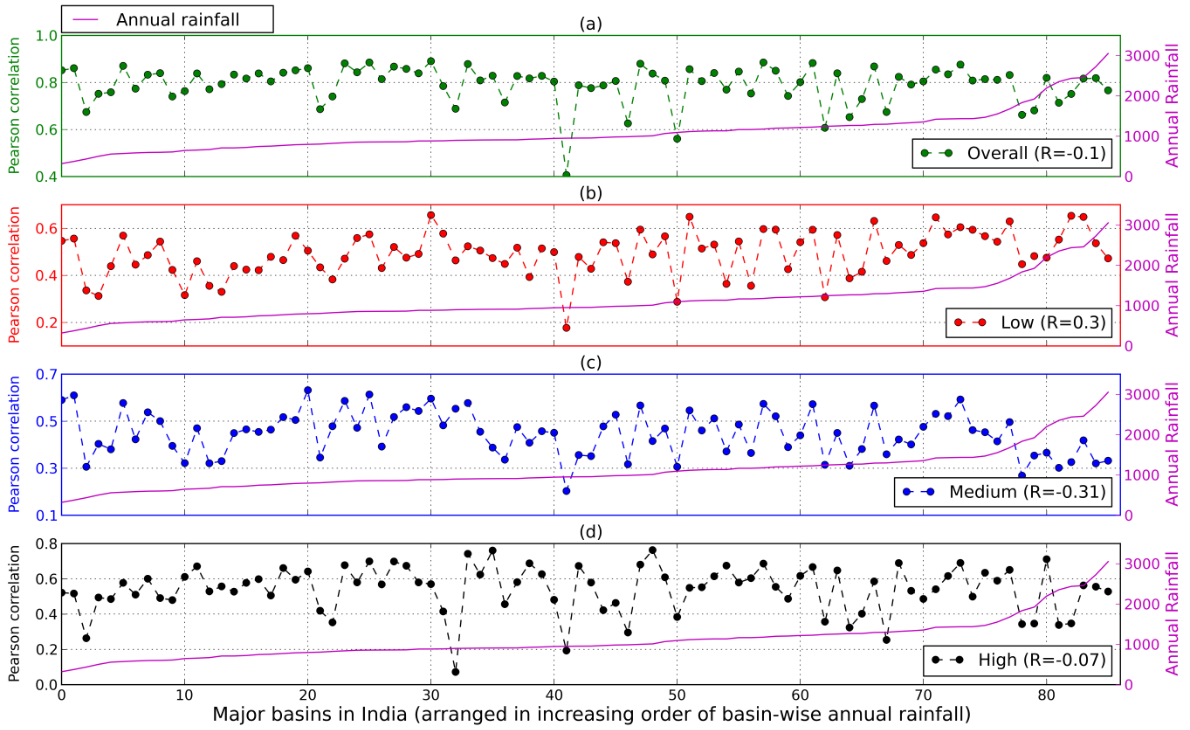




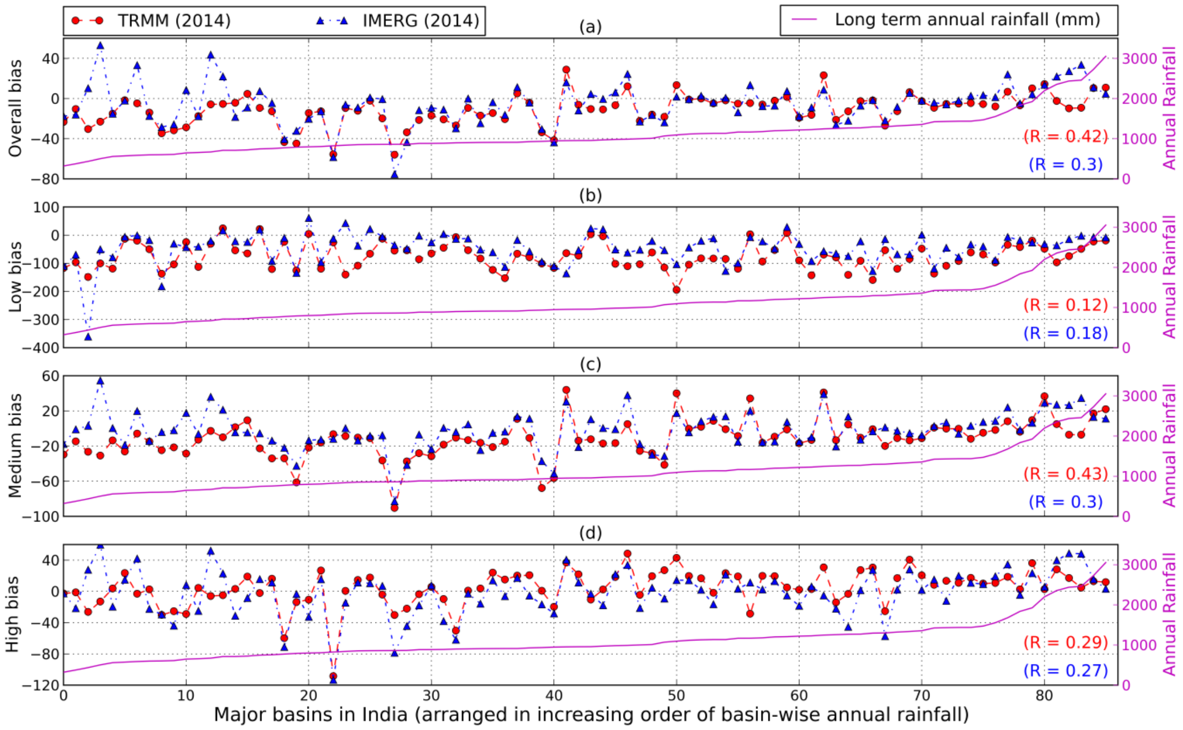
~~**Figure 9.** Graphical representation of long term average annual rainfall (calculated from IMD gridded rainfall dataset from years 1980-2010) and average elevation above mean sea level for 86 major basins in India (arranged in increasing order of their mean elevation).~~



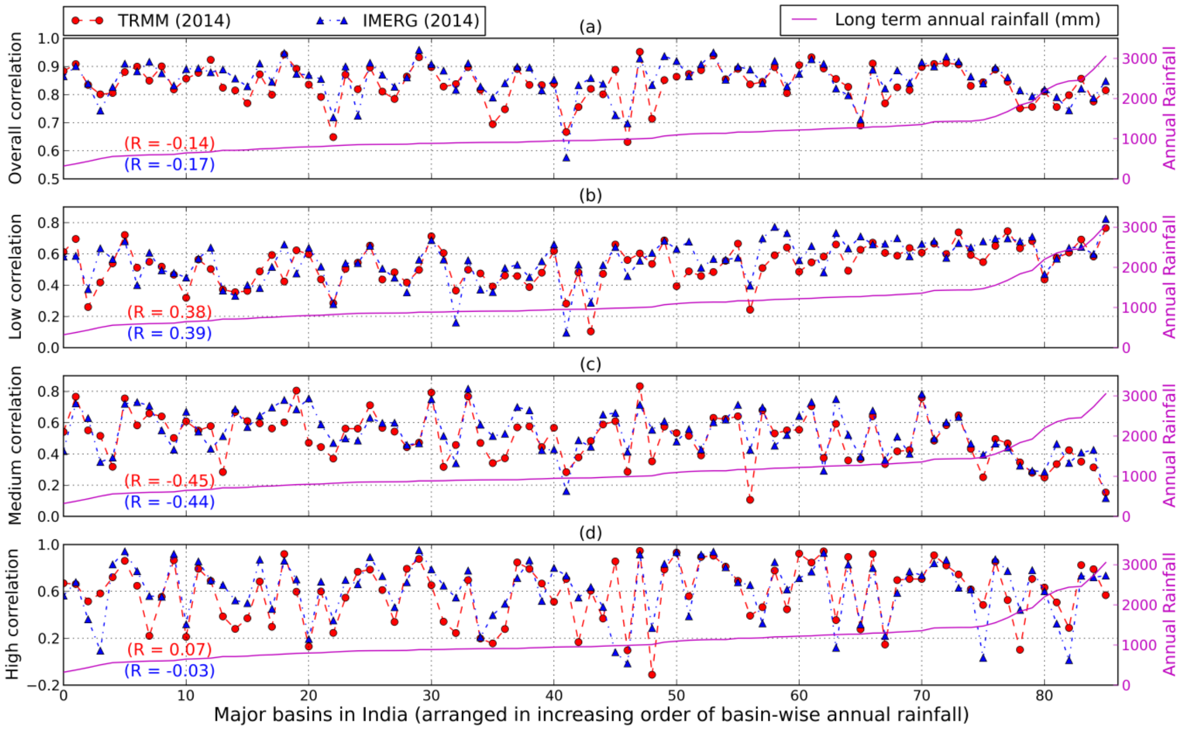
~~**Figure 10.** Graphical representation of percentage bias of TRMM (1998-2013) arranged in the increasing order of basin-wise average annual rainfall for **(a)** overall time series and over **(b)** low, **(c)** medium and **(d)** high rainfall regime for 86 major basins in India.~~



~~**Figure 11.** Graphical representation of correlation of TRMM (1998-2013) arranged in the increasing order of basin-wise average annual rainfall for **(a)** overall time series and over **(b)** low, **(c)** medium and **(d)** high rainfall regime for 86 major basins in India.~~



~~**Figure 12.** Graphical representation of percentage bias of IMERG (2014) and TRMM (2014) arranged in the increasing order of basin-wise average annual rainfall for **(a)** overall time series and over **(b)** low, **(c)** medium and **(d)** high rainfall regime for 86 major basins in India.~~



~~**Figure 13.** Graphical representation of correlation of IMERG (2014) and TRMM (2014) arranged in the increasing order of basin-wise average annual rainfall for **(a)** overall time series and over **(b)** low, **(c)** medium and **(d)** high rainfall regime for 86 major basins in India.~~

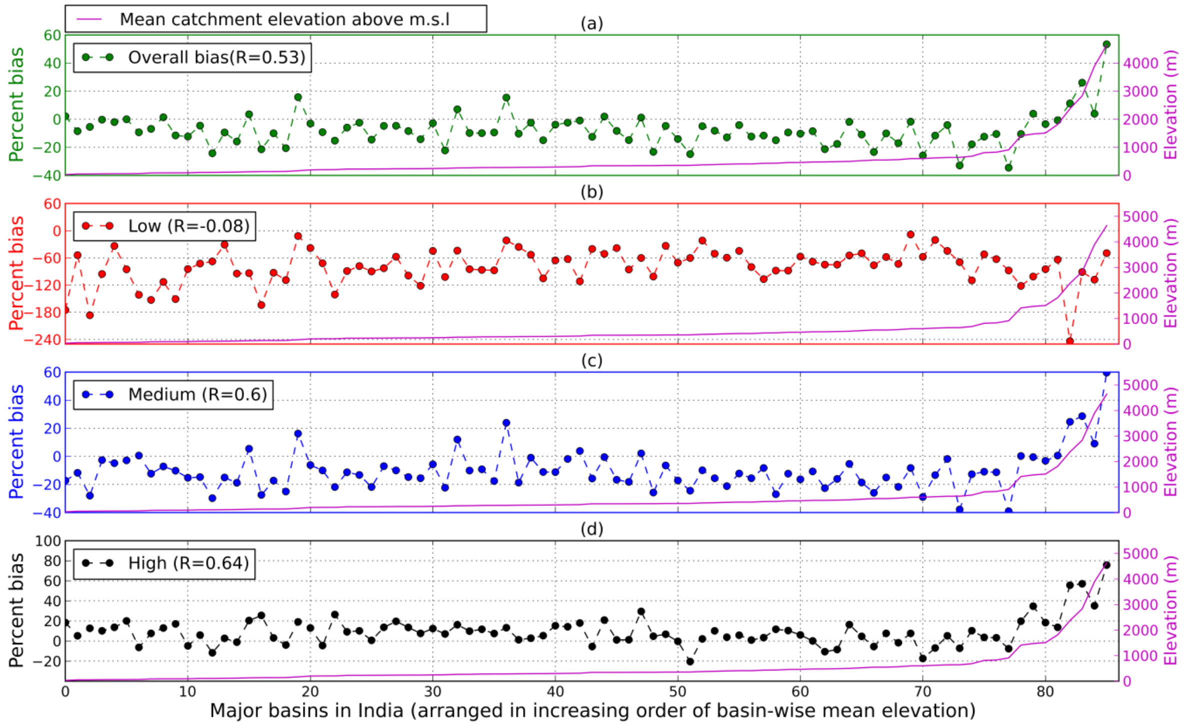
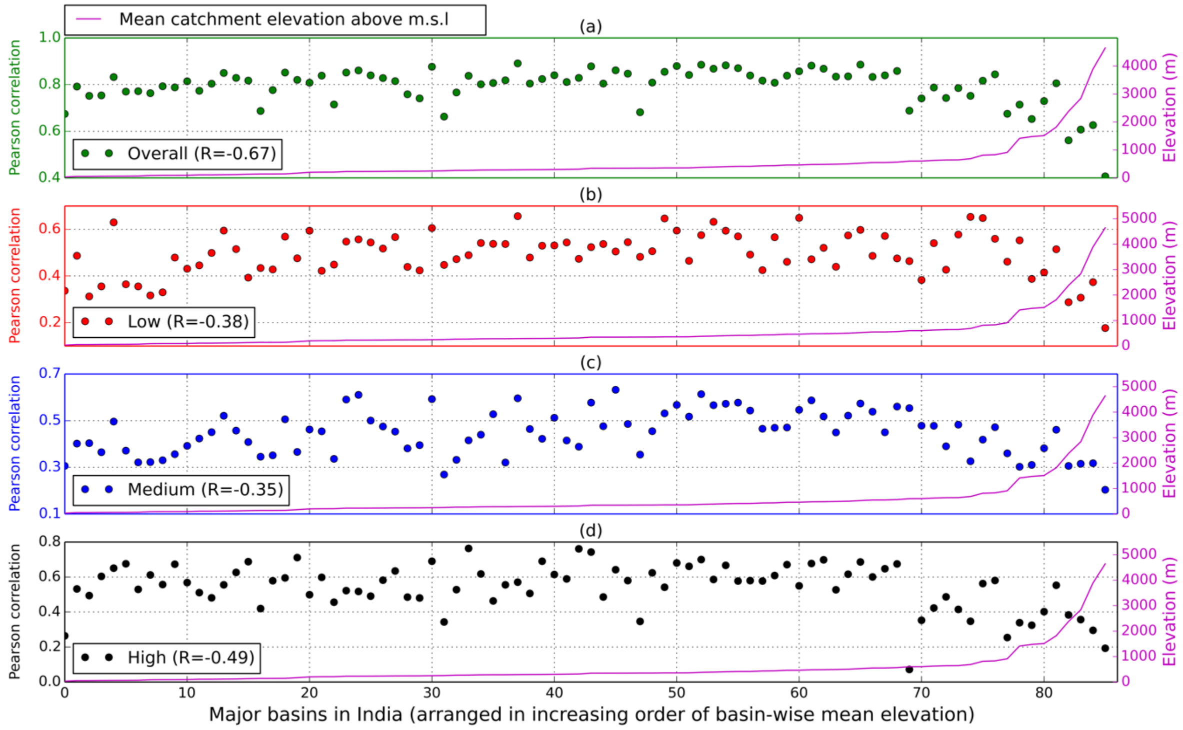


Figure ~~14~~9. Graphical representation of percentage bias of TRMM (1998-2013) arranged in the increasing order of basin-wise average elevation over mean sea level for **(a)** overall time series and over **(b)** low, **(c)** medium and **(d)** high rainfall regime for 86 major basins in India.



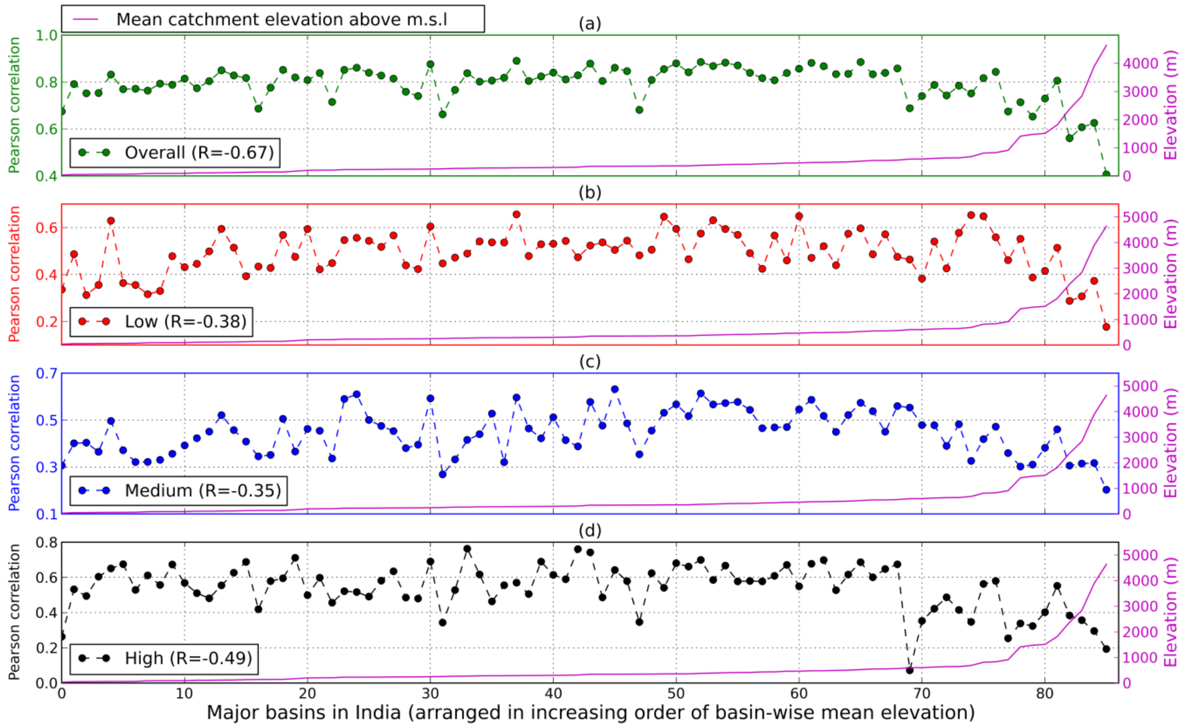
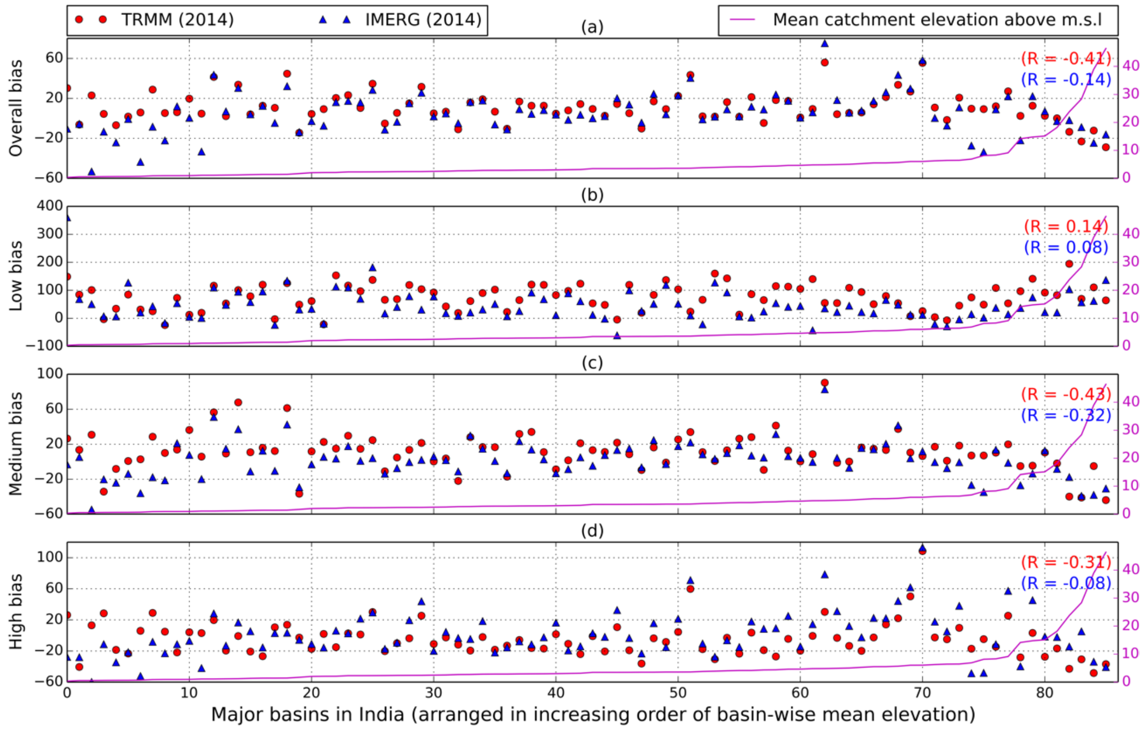


Figure 10~~5~~. Graphical representation of correlation of TRMM (1998-2013) arranged in the increasing order of basin-wise average elevation over mean sea level for **(a)** overall time series and over **(b)** low, **(c)** medium and **(d)** high rainfall regime for 86 major basins in India.



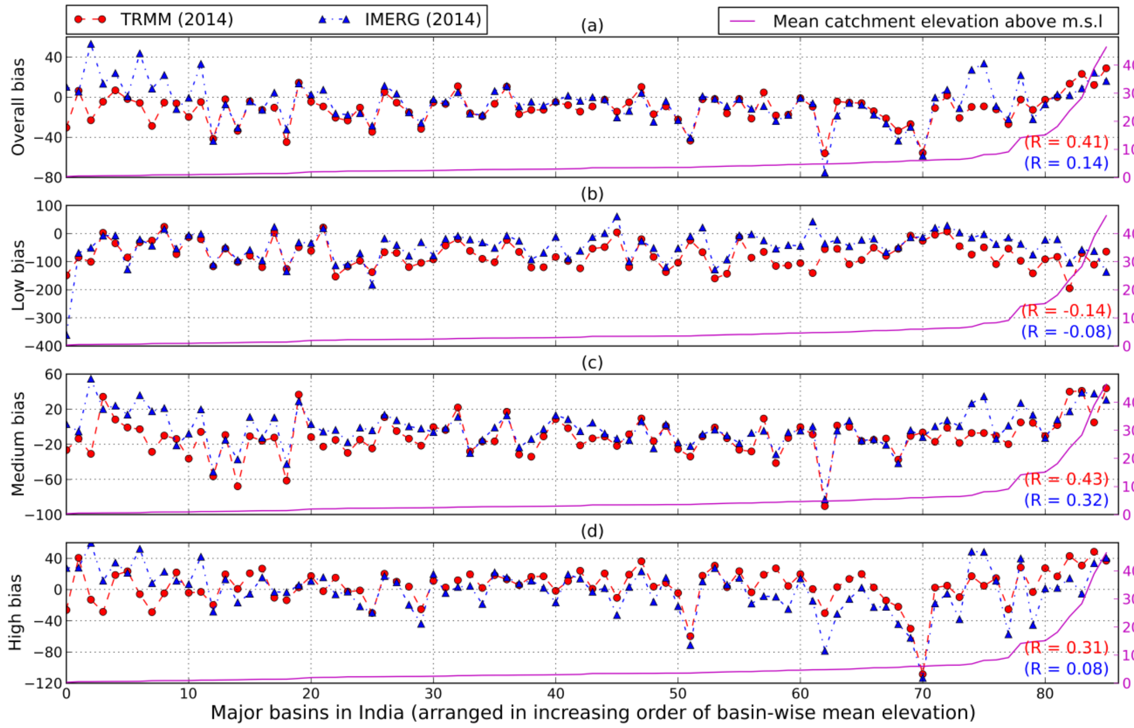
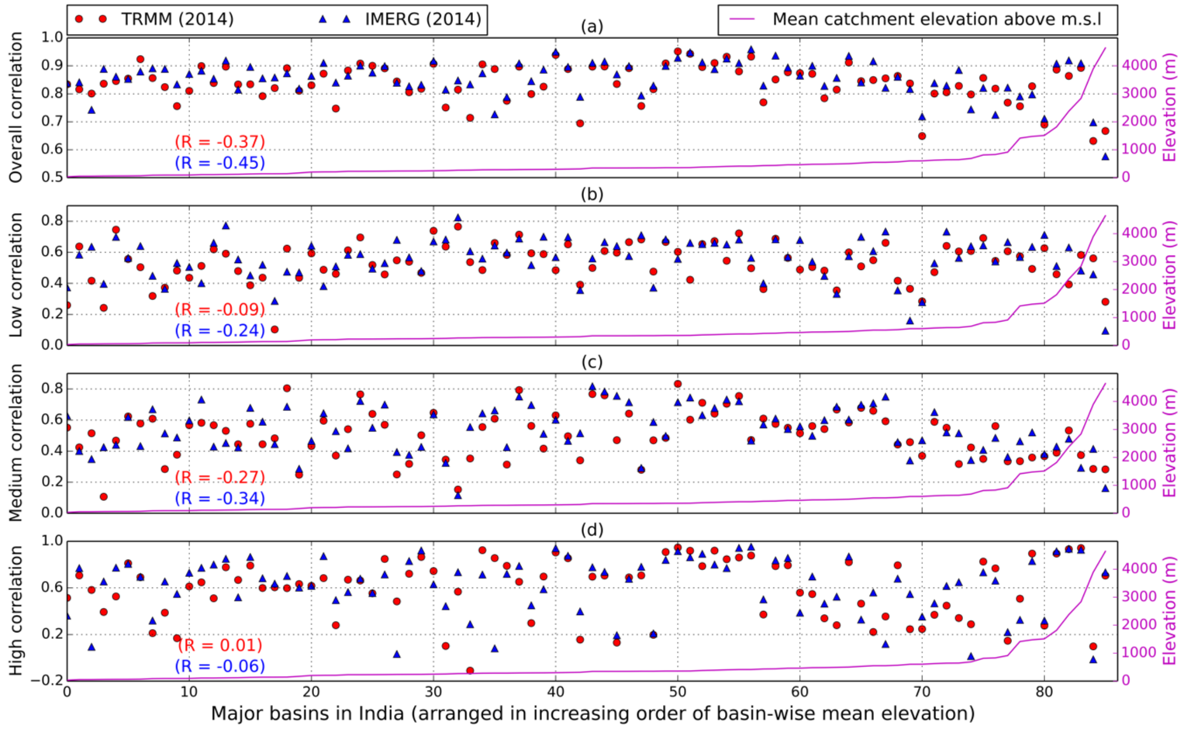


Figure 1~~6~~1. Graphical representation of percentage bias of IMERG (2014) and TRMM (2014) arranged in the increasing order of basin-wise average elevation over mean sea level for **(a)** overall time series and over **(b)** low, **(c)** medium and **(d)** high rainfall regime for 86 major basins in India.



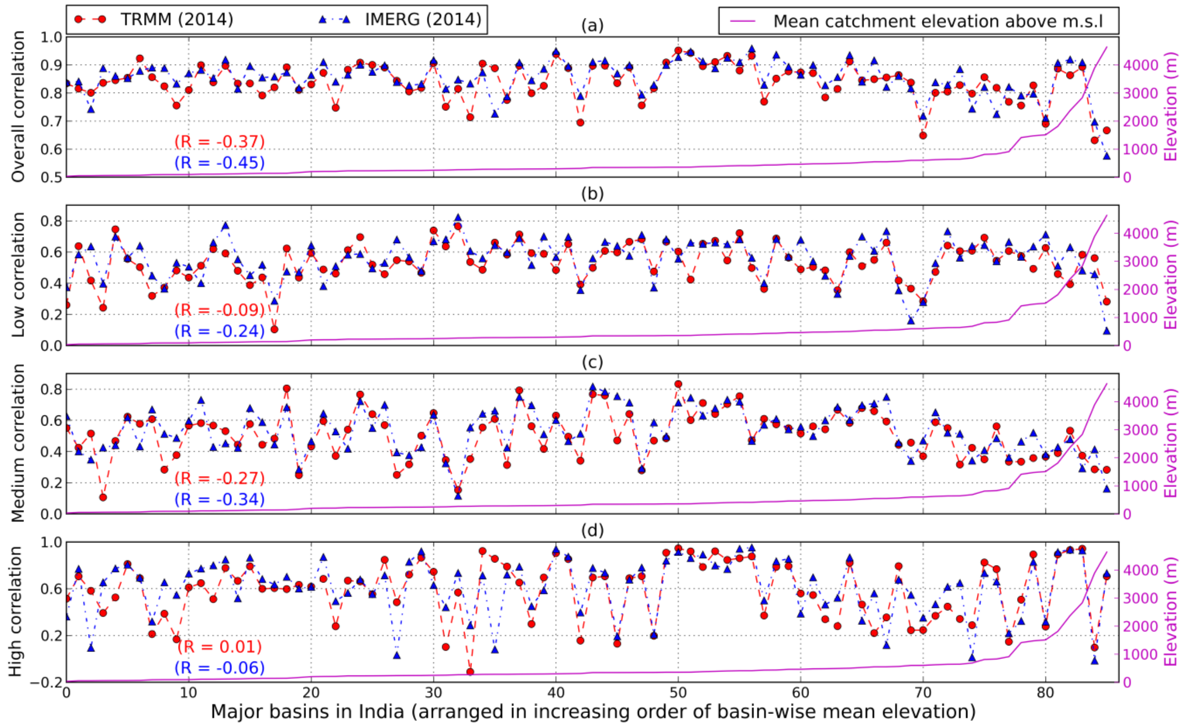


Figure 12~~7~~. Graphical representation of correlation of IMERG (2014) and TRMM (2014) arranged in the increasing order of basin-wise average elevation over mean sea level for **(a)** overall time series and over **(b)** low, **(c)** medium and **(d)** high rainfall regime for 86 major basins in India.

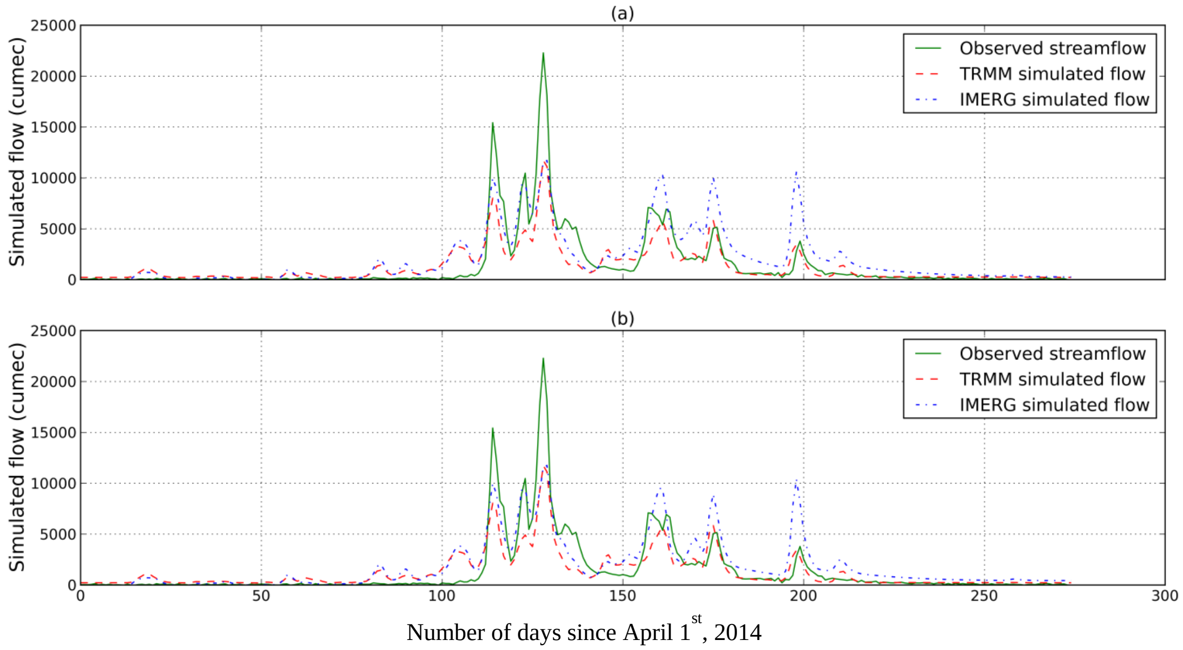


Figure 13~~8~~. Hydrographs for TRMM and IMERG simulations (April 1, 2014 – December 31, 2014) with **(a)** IMD and **(b)** TRMM calibrated VIC model for Hirakud basin.

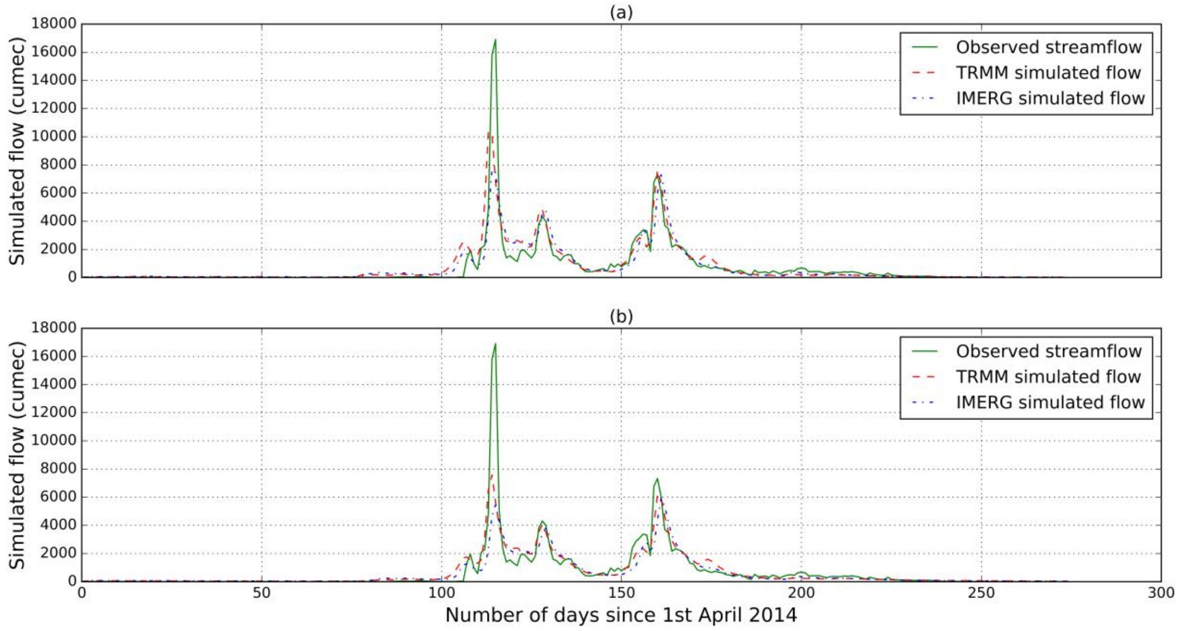


Figure 14. Hydrographs for TRMM and IMERG simulations (April 1, 2014 – December 31, 2014) with **(a)** IMD and **(b)** TRMM calibrated VIC model for Wainganga basin.

Table 1. Summary of the precipitation datasets used.

Product name	**Spatial resolution**	**Temporal resolution**	**Spatial coverage**	**Temporal coverage**	**Period used in this study**
IMD Gridded Rainfall	0.25° x 0.25°	Daily	Indian landmass	1901-2014	1998-2013, 12th March, 2014 – 31st December 2014
TRMM Research product	0.25° x 0.25°	3-hourly	50° N-S	1998-present	1998-2013, 12th March, 2014 – 31st December 2014
IMERG Final Run	0.1° x 0.1°	Half-hourly	60° N-S	12th March, 2014 - present	12th March, 2014 – 31st December 2014

Table 2. Contingency table used to calculate probability of detection (POD) and false alarm ratio (FAR) at a given rainfall threshold.

		Simulated	
		> Threshold	<= Threshold
Observed	> Threshold	HIT	MISS
	<= Threshold	FALSE	NEGATIVE

Table 3. Summary of different statistical indices used to evaluate the satellite precipitation products.

Index	**Formula**	**Best value**	**Worst value**
Pearson correlation (R)	$\frac{\sum(X-\bar{X})(Y-\bar{Y})}{\sqrt{\sum(X-\bar{X})^2}\sqrt{\sum(Y-\bar{Y})^2}}$	1	0
Percentage bias (Pbias)	$\frac{\sum(Y\cancel{X}-X\cancel{Y})}{\sum X} * 100$	0	+∞ / - ∞
Probability of detection (POD)	$\frac{HIT}{HIT+MISS}$	1	0
False alarm ratio (FAR)	$\frac{FALSE}{HIT+FALSE}$	0	1
Nash Sutcliffe efficiency (NSE)	$1-\frac{\sum(X-Y)^2}{\sum(X-\bar{X})^2}$	1	- ∞ (negative value means that mean is a better estimator

			than the model).
Root mean squared error (RMSE)	$\sqrt{\frac{\sum(X-Y)^2}{n}}$	0	+∞

$(X = Observed, \bar{X} = Observed\ mean, Y = Simulated, \bar{Y} = Simulated\ mean, n = Data\ points)$

Table 4. Segregation of overall rainfall time series into low, medium and high rainfall time series (R = Rainfall, μ = Mean of rainfall, σ = Standard deviation of rainfall).

Rainfall regime	**Criterion**
Low	R < μ
Medium	R >= μ and R <= μ + 2σ
High	R > μ + 2σ

Table 5. Comparison of the IMERG and TRMM based on the number of basins in which the satellite products show higher/lower correlation based on the year 2014 (R: pearson correlation)

Expression	**IMERG**	**TRMM**
R > 0.8	73	68
R > 0.9	20	13
Higher R	60	26
Higher R (low rainfall regime)	52	34
Higher R (medium rainfall regime)	52	34
Higher R (high rainfall regime)	55	31

Table 6. Comparison of the IMERG and TRMM based on the number of basins in which the satellite products show higher/lower POD/FAR based on the year 2014. The third column gives the number of basins in which IMERG/TRMM gives similar POD/FAR. (Low, medium, high and very high threshold: 25, 50, 75, 95 percentile respectively)

Expression	**IMERG**	**TRMM**	**Similar**
Higher POD (low rainfall threshold)	62	24	0
Higher POD (medium rainfall threshold)	39	37	10
Higher POD (high rainfall threshold)	32	45	9
Higher POD (very high rainfall threshold)	44	27	15
Lower FAR (low rainfall threshold)	42	40	4
Lower FAR (medium rainfall threshold)	53	26	7
Lower FAR (high rainfall threshold)	67	15	4
Lower FAR (very high rainfall threshold)	64	17	5

Table 7~~5~~. Performance statistics for rainfall-runoff modeling using VIC for Hirakud catchment of Mahanadi River basin ~~in India~~.

	Time period	**NSE**	**R^2 ~~(p-value)~~**	**P-bias**	**RMSE (m^3/s)**
IMD calibration	2000-2011	0.83	0.84 ~~(0.01)~~	-16.78	919.88
IMD validation	2012-2014	0.86	0.88 ~~(0.01)~~	-3.91	823.58
TRMM calibration	2000-2011	0.72	0.74 ~~(0.01)~~	-18.2	1160.94
TRMM validation	2012-2014	0.73	0.74 ~~(0.01)~~	-14	1128.15
TRMM (IMD calibration)	2014	0.72	0.82 ~~(0.01)~~	-9.41	1591.09
IMERG (IMD calibration)	2014	0.64	0.68 ~~(0.01)~~	-41.4	1786.22
TRMM (TRMM calibration)	2014	0.72	0.82 ~~(0.01)~~	-9.24	1588.86
IMERG (TRMM calibration)	2014	0.7	0.72 ~~(0.01)~~	-31.32	1641.82

Table 8. Performance statistics for rainfall-runoff modeling using VIC for Wainganga River basin.

	Time period	**NSE**	**R^2 (p-value)**	**P-bias**	**RMSE (m^3/s)**
IMD calibration	2000-2011	0.81	0.81	9.18	740.49
IMD validation	2012-2014	0.87	0.88	-10.8	852.9
TRMM calibration	2000-2011	0.7	0.71	15.66	931.65
TRMM validation	2012-2014	0.83	0.83	5.93	973.41
TRMM (IMD calibration)	2014	0.74	0.74	8.70	883.19
IMERG (IMD calibration)	2014	0.74	0.76	-0.52	883.59
TRMM (TRMM calibration)	2014	0.72	0.75	-2.70	922.04
IMERG (TRMM calibration)	2014	0.61	0.66	-12.10	1082.34