Replies to anonymous referee 1

Assessment of small-scale variability of rainfall and multisatellite precipitation estimates using a meso-rain gauge network measurements from southern peninsular India

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The authors provide a very interesting paper with important contributions to the point to area perspective for rainfall validation using a complex terrain dense gauge network of a Megha-Tropiques test site over Southern India. Data is investigated for different monsoon seasons and compared to satellite MPEs. The topic is of high relevance to the science community.

In my view, this paper is an interesting read, investigates very interesting questions but definitely requires a thorough edit with respect to language and clarity. The points raised below are subdivided into major and minor comments.

We thank the reviewer for his appreciation and positive comments on our manuscript. We revised the manuscript by considering all the suggestions given by the reviewer.

Major Issues:

Comment: The title of the paper reads a little confusing because it contains four imprecisions. First, “multisatellite” should be “multi-satellite”; second, “a network measurements” should either read “network measurements” or “a network”; third, “meso-rain gauge” is not defined to my understanding and should read “mesoscale rain gauge” if this is meant; and fourth “southern peninsular India” contradicts the Abstract where the authors state that the work was done in “southeast peninsular India”. Please be clear and precise on what the title should be about so that it reflects the content of the paper. Would it clarify a little if the term “Southeastern India” is used instead of “Peninsular India”?

As per reviewers’ suggestion, ‘a meso-rain gauge network measurements’ has been changed to ‘measurements from a dense rain gauge network’. Similarly, ‘southeast peninsular India’ to ‘southeast India’ and ‘multisatellite’ to ‘multi-satellite’. The title of the paper now reads as “Assessment of small-scale variability of rainfall and multi-satellite precipitation estimates using measurements from a dense rain gauge network in southeast India”

Comment: It is unclear from reading the abstract what refers to the 50x50 km gauge network, to large-scale Southern India and to stations. Please be very clear on notation, definitions, areas and instruments to not confuse the reader.

The entire paper (not only abstract) is focused on 50 km x 50 km area, in which all our rain gauges are situated. The text has been changed, wherever ambiguity is there to avoid confusion.

Comment: Chapter 3: Does the 45° cone refer to the usual wind direction? Maximum attention should be attributed to data quality according to wind undercatch, orography as well as lower and upper measurement limits of the gauges. Please clarify. There is actually no ground truth, though we all consider an in-situ measurement to show the truth. In reality, this is also far from truth and contains a variety of errors as well that I suggest to elaborate upon. They may a function of wind speed and collection abilities of the gauge. Do the gauges handle extreme precipitation accurately? I know of shipboard high-tech gauges that suffer strongly from overcatch during ITCZ extreme rainfall when compared to disdrometers that are thought to be most accurate, although even they have their limitations. Calibrating three intensities with the lowermost bound at 31.5 mm/h makes me wonder. That is already a substantial amount of rainfall. How accurate are the gauges to detect drizzle and very low precip rates, in the extreme, a few drops, which is a precip minute? This may to a very large extent affect the occurrence of precip measured when compared to satellite data and immediately feeds back to the point to area perspective and beamfilling effects. Your calibration test is performed under ideal conditions, almost lab conditions. How does wind effect these measurements? How is the undercatch and what are the wind speed regimes during the monsoon season? How do extreme precipitation events influence the results? Given that under convective conditions I assume that the rain rate can easily excess 150 mm/h in Southern India. The maximum rain rate recorded by myself was 160 mm/h during an ITCZ thunderstorm event. This usually causes gauges to produce large biases of overcatch while wind speed produces undercatch. Please add information on these issues as they may to a large extent influence the results that you conclude when comparing the MPEs.

While choosing the location several criteria were followed. One of them is the suitability of the location for rainfall measurement, i.e., obstacles should not be within 45° cone (complete azimuth) at the rain gauge location. Wherever possible, locations with more clearance in the direction of wind (predominantly in east-west direction in the study region) have been chosen.

As correctly pointed by the reviewer that none of the measurements are really 100% accurate and each of these instruments have their own sources of error. For instance, the systematic error in rain by the tipping bucket rain gauge is attributed to the winds and its induced turbulence, wetting of inner walls of the gauge, loss of rain water during the tipping and evaporation of the rain water in the gauge (WMO, 2008). The estimated wind-induced error through numerical simulations is found to be in the range of 2%-10% for rainfall and increases with decreasing rain rate and increasing wind speed and fraction of smaller drops (Nespor and Sevruk 1999). The typical surface winds in (at 2 m) the study area are in general weak and rarely exceed 4 m s^{-1} (~2% of total data >4 m s^{-1}). Therefore, the error due to the wind could be within 5% in our measurements (Nespor and Sevruk 1999). The error due to the non-measurement of rain during tipping can be minimized but not eliminated (WMO, 2008). This error is considerable during intense rainfall events. Though the occurrence is less (<1%), a rain rate > 100 mm hr^{-1} is not uncommon in the study area. In fact, this is the reason for using 3 high rain rates for calibration.

The tipping bucket rain gauges are, in general, not ideal for the measurement of drizzle. Drizzle being weak in rain intensity takes finite time to fill the bucket (for instance the gauge used in the present study takes 24 minutes to produce a tip during drizzle with a rain rate of 0.5 mm hr^{-1}). Bigger the bucket, longer the time it takes. Because of this, it is difficult to obtain accurate high-temporal resolution measurements and also the start time of rain. The reduction in the bucket size, on the other hand, will certainly reduce the time to fill the bucket and also produces better resolution data, but increases the error in heavy rain due to the loss of water during the tipping action. As a bargain, a bucket that produces a rain rate of 0.2 mm hr^{-1} has been chosen in the present study.

As per reviewers' suggestion, the major problems in the measurement of rain by tipping bucket rain gauges are highlighted in the revised version of the manuscript.

Comment: Figure 1. The paper would benefit from adding two more geographical maps. There is also space for them as the figure can inset them as a) to d), where c) and d) are the ones already presented. a) should present a geographical map of India maybe including orography showing the two monsoon system areas referred to as SWM and NEM. b) should show the larger geographical domain where the dense gauge network is located. The main reason is that the map presented in the current paper (Figure 1a) version can only be understood by forcing the reader to look at a geographical map on the internet or an atlas finding the lats/lon by him/herself. Please include. The black squares, triangles and dots are not easily separated visually to see the rate dependence on the results. As Figure 1 contains color in any case, I suggest that you additionally use colors for the symbols as well, such as red, blue, black to separate them easily.

As per reviewers' suggestion, two geographical maps were added in the revised version of the manuscript. Figures 1a and 1b now show the rainfall and wind pattern during SWM and NEM, respectively. The monsoon trough region and the region where rain gauges are located are also marked on Figure 1a. Color symbols are used for better visualization and easy interpretation in Figure 1d (in the revised manuscript). The figure is included here for reviewers' reference.

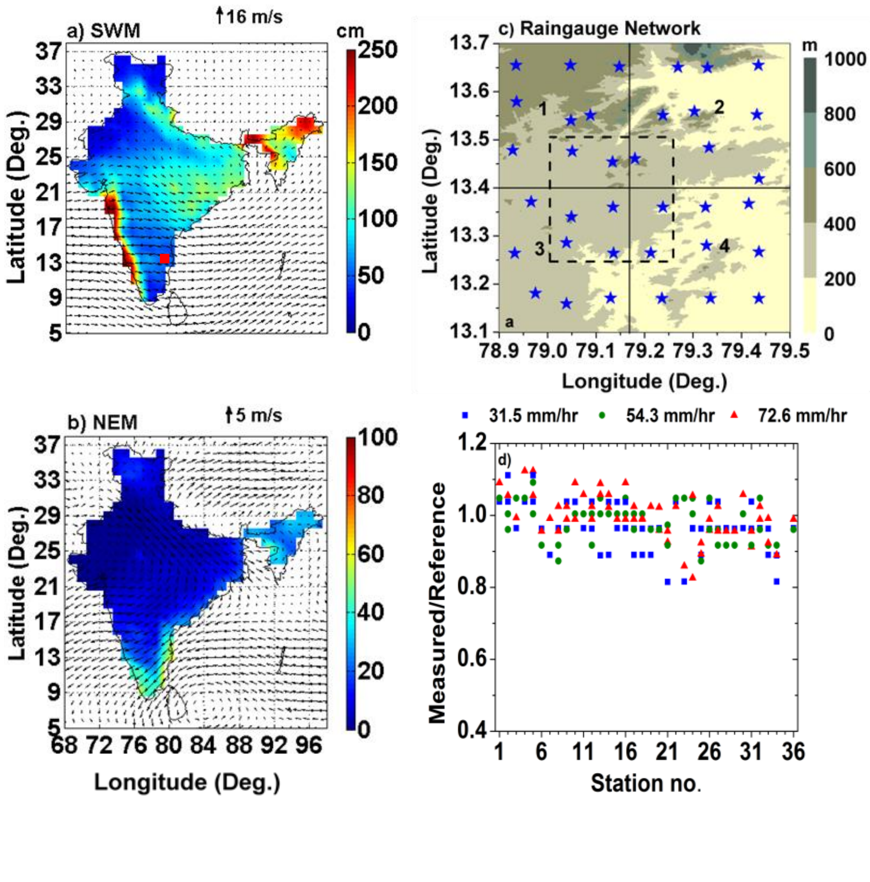

*Figure 1: Spatial distribution of seasonal rainfall (shading) and wind pattern (arrows) on 850 hPa level during **(a)** SWM and **(b)** NEM. Note that the scales are different for SWM and NEM. **(c)** Location of rain gauges in the network. The shading represents the topography (m). The region is divided into 4 quadrants and each quadrant is numbered as 1, 2, 3 and 4. The data in dashed box are used for the evaluation of MPEs. **(b)** The ratio of measured and reference (calibrator – Young 52 260) values at 3 rain rates are shown for each rain gauge location, illustrating the data quality by each gauge.*

Comment: The paper would strongly benefit from an edit by a native speaker. The sentences suffer too often from mixing singular and plural forms, times and wording errors. Please improve this rigorously as this reduces the readability of the paper a lot. I tried to list as many of these errors as possible in the minor issue section. It is, however, too much work to continue this throughout the paper.

Thank you very much correcting the manuscript (partially). We tried our best to minimize the typos and grammatical mistakes in the revised manuscript.

Comment: Page 10395, line 13. The monsoon trough is not introduced to the reader. Please clarify the importance of that also with respect to the region investigated.

The monsoon trough is described briefly and is also shown on Figure 1a to illustrate its location with reference to the study region.

Comment: It is unclear from Figure 2 what's shown here. This is three years of data? Accumulation of 3 years of NE and SW monsoon precip? Average over a season/year/? Please indicate. The gradient of NEM is in the Northeast rather than east-west. Please explain. What makes the Northeast special during the NEM? I assume it's a seasonal average, if not, please make a seasonal average out of it.

The rainfall shown in Figure 2 is the average seasonal rainfall (i.e., average of 3 years seasonal rainfall for SWM and NEM), i.e., average over a season (mm)/year. Though an east-west gradient is present at all latitudes, the maximum gradient is in the northeast direction (as pointed by the reviewer). The text in the revised manuscript has been changed accordingly.

Comment: Page 10398, line 10. Do the cyclones and thunderstorms belong to the SWM and NEM season precipitation are they investigated separately? That is not fully clear to me. Please make clearer.

No. The measurements in the present study include all types of rain (that originated from thunderstorms, cyclones, etc.). We just divided the data into small-scale and large scale based on the criterion discussed in Page 10398, but not segregated based on the source of rainfall.

Comment: The definition of small-scale and large-scale over the 36 gauges area on page 10398, line 14 needs more explanation. Is that definition used/developed by you or used elsewhere as well? If so, could you provide a reference? If it's your definition please explain why you chose this criterion. Your field is 50x50 km in size, so about the size of one passive microwave satellite pixel. Could also a rain rate, or its standard deviation, be used as a criterion. It may matter if the rainfall over the last 2 days and 75% of the gauges was very uniform (large-scale) or varied a lot (small-scale). How large is a typical evening thunder cell in Southern India? I just wonder if the temporal check is sufficient to define convective/stratiform/small to large scale precip. Did you perform a case study analysis e.g. with infrared satellite imagery to check if your categories and definition satisfy your findings?

The criterion used in the paper to identify large and small-scale systems is relative and exclusive for the present data set. Though the horizontal extent of the thunderstorm varies from a few km to 10's of km, the typical size over the study region is ~5 km (Uma and Rao, Mon. Wea. Rev., 2009). Once generated they advect over a few stations before decaying. A slightly large-scale system (with few 10's of km horizontal extent) may produce rainfall over nearly half of the stations. Therefore, we have chosen the spatial criterion in such a way that it avoids these systems to be called as large-scale systems (in our analysis). The temporal condition ensures that the atmosphere is conducive for precipitation, probably unstable due to a large-scale disturbance.

Nevertheless, to avoid confusion, we referred to them as "small-scale/short-lived and large-scale/long-lived" in the revised manuscript.

Comment: I am missing a thorough definition and description of the SW and NE monsoon systems. This should be done in the introduction and include a figure of the geographical areas covered by the monsoons. What is causing them, which flow directions to they take on a map? When cyclones occur? Do cyclones belong to the monsoon system? This would allow the reader to prize the results and findings of this paper in greater detail. Be aware that not all your readers know about the details of the Indian monsoon systems and the cyclone occurrences.

First let me clarify a few things to the reviewer. What we mean by SWM and NEM is the two seasons (SWM: June through September and NEM: October through December) during which we get plenty of rainfall (almost 85% of the annual rainfall), but not SWM or NEM monsoon systems. We would like to characterize the rainfall and understand the small-scale variability during these two monsoon seasons. It is explicitly mentioned in the revised manuscript to avoid confusion.

The definition of the seasons exists in the old manuscript (Page 10394, L12 and L15). As suggested by the reviewer, the climatological rainfall and wind pattern during these monsoon systems are included in Figure 1 of the revised manuscript along with a brief description.

Over the study region, cyclones occur during the NEM season, but not during the SWM season. During the SWM season, low pressure systems and depressions form over the head Bay of Bengal and often propagate over central and north India, producing a quasi-permanent low-pressure system over that region, termed as 'monsoon trough region'. The study region is south (and very far) of this monsoon trough region. Some of the above information is included in the revised manuscript for readers' convenience.

Comment: Why are cyclones part of the monsoons? So far I understood that the SW and NE monsoon is investigated, excluding local evening thunderstorms and cyclones because they do not belong to the monsoon system. However, page 10398, line 22 states, that the 75% of the gauges receive >60% of their rainfall from these large-scale systems. Please clearly define your wording! Define large scale vs synoptic scale and which system (e.g. cylones, high/low pressure systems) belong to them. It seems you use the words location / station / gauge as synonyms for gauge. This confuses. Its much better to always use the same word, e.g. gauge. Please clearly define the SW and NE monsoon and what precip types belongs to them. I would expect that a cyclone massively disturbs your monsoon signal by dropping vast rainfall that is not associated with the monsoon system. Please clarify. Maybe I confuse things here, but if so, it calls for writing up things clearer. Maybe define scales to discriminate synoptic/large scale phenomena.

Yes. Cyclones do not belong to the monsoon system. But the prevailing synoptic conditions either enhance or suppress the cyclones. For instance, the large vertical wind shear present during the SWM is detrimental for cyclone intensification. Though other atmospheric parameters (SST, etc.) are conducive for cyclone formation, the low-pressure systems developed over the head Bay of Bengal will intensify only up to depression stage, but not to cyclonic stage. On the other hand, the atmosphere is very conducive for cyclone intensification during the NEM. Most of the low pressure systems form in the south Bay of Bengal (initiated by easterly waves) and intensify to cyclones/severe cyclones while moving northwestward.

Again, we have not excluded the rainfall due to thunderstorms and cyclones from the present analysis. As mentioned above, the rain due to all the systems is included in the present study. We have not segregated the data based on the source of rain (thunderstorm, cyclone, depressions, squall line, mesoscale convective systems, etc.). We just divided the rain caused by large-scale/long-lived (probably covering cyclones/depressions/MCS) and small-scale/short-lived (thunderstorms) systems, based on the criterion described in Page 10398.

Comment: Page 10399, line 17. Does your technical 25 min threshold agree with the meteorology of the showers? If not, this method is not capable as a shower separator. And 0.5 mm/h is already a high value. Most often 0.01 mm/h as a minute value would represent reality. Would it make sense to use a high resolution device such as a disdrometer as to discriminate between showers? Surely you don't want to install 36 disdrometers (which would be great to do in any case) but maybe one to investigate typical durations for showers?

The cumulative rain event rate pdf in Figure 3 looks very interesting. By intuition I would have expected the pdf to be much steeper to saturate at much lower precip rates (e.g. below 1 mm). Is that because you have a lower detection threshold of 0.5 mm/h or because there is few to no low (drizzle) precipitation during the monsoon seasons? In other words, is the pdf explained by the gauge-resolution or the underlying precipitation falling? How would this pdf potentially look like if you had a disdrometer, capable of measuring down to 0.01 mm/h? How does your technical event definition (25 min because of one tip-gauge limitation) influence this graphs result?

I wish to inform the reviewer that we have not omitted the data with rain rates < 0.5 mm hr^{-1}, but omitted the events with accumulated rain less than 0.5 mm/event. As mentioned in the manuscript, the 25 min. threshold used in the present study for separating rain events is based on the typical rain rate of drizzle (0.5 mm hr^{-1}) and rain gauge bucket capacity.

Nevertheless to know the sensitivity of our criterion, 3 years of disdrometric measurements made at Gadanki have been used with different time intervals for separating showers (24, 60 and 120 minutes corresponding to the rain rates of 0.5, 0.2 and 0.1 mm hr^{-1}, respectively). The following figures show the rain duration and rain rate (mm/event) cumulative distributions. As expected, the distribution for duration shifted to longer durations with the increase in time for shower separation. Nevertheless, there is negligible change in rain rate distribution with varying time intervals of shower separation.

Figures also show another curve in each panel depicting the distribution for event duration and rain rates (obtained from disdrometer measurements) without removing any data (i.e., < 0.5 mm/event) (but with 25 min. time as shower separator). As pointed out by the reviewer, the slope of the curve has changed to some extent in such a way that it saturates at lower rain duration and rain rates. But these curves are not significantly different from that the curve used in the present study (i.e., after eliminating data <0.5 mm/event and 25 min. time as shower separator).

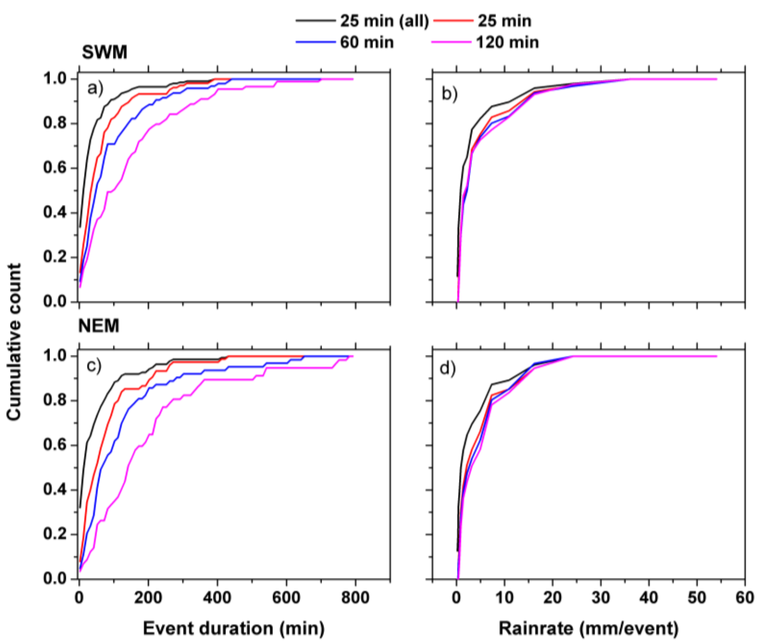

*Figure 2: Cumulative distributions for rain event duration and rain accumulation in the study region for a variety of thresholds for shower separation during **(a)** SWM and **(b)** NEM, depicting the sensitivity of the threshold used in the present study. It also shows cumulative distribution curves for total data (without omitting the events with rain accumulation less than 0.5 mm during the event - black curve).*

Comment: MPE evaluation. Having such a high-res gauge field is great to investigate the MPE at various resolutions as the point-to-area effect probably gets to a fair comparison. However, I wonder about the representation of the low precip rates which are always (probably) the most difficult part to match between surface and aerial measurements. You set a threshold while gridding to 0.5 mm/3h and your gauges resolve 0.5 mm/h at the low end. I assume that reality sees probably most often minutes with rates below 0.5 mm/h. How much is that of an issue for the monsoon systems and hence comparisons. I like to see this at least discussed or mentioned. Chris Kidd often raised that tricky question of "How low you can get" or how low precip rates are in reality. You already show that the MPEs largely underestimate drizzle. In fact I like to raise the question, how large the gauges underestimate the drizzle themselves due to the tip-sampling issue? Underestimation of light rain and overestimation of intense rain is somewhat what I would expect from MPEs and agrees with many findings. It is great to see this with respect to high-res gauge data.

As discussed above, the tipping bucket rain gauges are, in general, not ideal for the measurement of drizzle. Drizzle being weak in rain intensity takes finite time to fill the bucket (for instance the gauge used in the present study takes 24 minutes to produce a tip during drizzle with a rain rate of 0.5 mm hr^{-1}). Bigger the bucket, longer the time it takes. Because of this, it is extremely difficult to obtain accurate high-temporal resolution measurements and also the start time of rain. The optical rain gauges (ORG) are probably the best to capture these light rainfall events, but deploying them in dense networks is a costly proposition.

Therefor the question of "how low you can get?" is a difficult one to answer with rain gauge. The highest resolution that we can get with these rain gauges is 0.2 mm. As mentioned above, instruments like ORG and disdrometer are required to measure low rain rates.

The threshold of 0.5 mm/3hr is employed here to minimize the problems arising due to gridding (as mentioned in the text).

Comment: Is there an indication that the active instrumentation onboard TRMM (PR) outperforms the passive microwave results clearly? Is there an investigation ongoing that uses the GPM active and passive data over your test site?

Though we have used TRMM PR measurements extensively (For ex., Saikranthi et al. 2013, 2014, Sunilkumar et al. 2015), we never compared the active and passive sensors over the study region. Yes, we are evaluating the performances of not only active and passive sensors of GPM, but also the DSD (using dual frequency technique).

Comment: Conclusions point 5. : : :all MPEs severely underestimate the weak and heavy rain. I thought they underestimate the light and tend to overestimate the heavy? See page 10407, line 18, class 8-20 mm.

The text is corrected in the revised version.

Minor Issues and typos:

Page10390 Line 4. Southeast peninsular India contradicts the title “southern peninsular India”. Please clarify on the region. Is the term peninsular really needed? It sounds a little confusing because the India is more a continent, nowadays a subcontinent, rather than a peninsular. The ‘southeastern peninsular India’ has been changed to ‘southeast India’.

The title has been changed to “Assessment of small-scale variability of rainfall and multi-satellite precipitation estimates using measurements from a dense rain gauge network in southeast India”

Line 6. Does “arranged” mean evenly spaced? Figure 1 suggests that they are NOT evenly spaced by 10 km as stated. Please clarify.

They are arranged in a near-square grid, but not exactly separated by 10 km due to other technical and operational problems (security of the instrument, suitable location for the measurement, mobile coverage for data transfer, etc.).

Line 9. The sentence on the seasons is confusing as it states that “two seasons show seasonal differences”. Is it meant that spatio-temporal variability and differences in weather patterns are investigated for two monsoon seasons?

The spatio-temporal variability of rainfall has been examined during the SWM and NEM separately. The word ‘seasonal’ has been dropped from ‘….seasonal differences’ and the word ‘monsoon’ is replaced with ‘rainy’ for better readability.

Line 13. It is unclear to me from the Abstract what is meant by “quadrants”. Does that refer to the investigated 50x50 km gauge network or to entire Southern India area?

Sorry for that. The study area is divided into 4 equal quadrants with each quadrant having 9 gauges. In any case, the above sentence is removed from the abstract.

Line 15: This sentence is confusing. I suggest “The diurnal cycle also exhibits large spatio-temporal variability at all the stations: : :” What is “gauge, what is “station”, what is “network”, what is “quadrant”? Please be very clear terminology. It’s very difficult to follow the storyline of the abstract. Please be aware that the Abstract should be understandable and make appetite to read without knowing the content of the rest of the paper. That’s not the case yet.

The text has been changed as suggested by the reviewer.

Line 19. What is “night-mid”? Why not just saying “between 20 and 02 LT : : :”? Please use 20 LT instead of 20:00 LT.

The text has been changed as suggested by the reviewer.

Line 23. Should read “both monsoon systems or seasons”

Should be ‘monsoon seasons’. The text is corrected.

Line 27. Should read “gauge rainfall data indicate that”. Weak rain should read light rain. Heavy rain should read high rain intensity. Is heavy rain always associated with convective precipitation?

The text has been changed as suggested by the reviewer. Yes. Large rain rates are always associated with convective precipitation (convective precipitation could be due to isolated convective cell or as part of a large scale system, like MCS, cyclone, etc.)

Introduction Line 10. Please include a reference. Precip is among all most important to understand the water and energy cycle regarding observation and modelling. Please include. Line 15. “a high density of gauges” Line 18. Sentence to long. Does microwave radars/images rely to satellite data exclusively? Please clarify. Line 20. Spatio-temporal. Please give a reference for the variability increase in hilly terrain. Line 23. If with “filling” beamfilling is meant please write that.

As per reviewers’ suggestion, all grammatical mistakes have been corrected and references, wherever necessary, have been added in the revised manuscript.

Line 27. The long list of references should be attributed to the list given. So please sort the reference list regarding the topics they deal with (e.g. seasons, aggregation, correlation length). This gives the reader a much better view on the state-of-the-art of research in that field.

The references are sorted based on the topic

Page 10392 Line 6. Do you mean “dense gauge networks”? I suggest “moreover” instead of “even” to make the point clearer. Line 8. I would sharpen this point: “This leaves large spatial data gaps in critically important areas due to the unavailability of gauges (e.g.”. Line 9. The timeliness aspect I recommend to split into a second sentence. Line 10. Replace “On the other hand” by However, : : : The high-quality aspect of the data should be mentioned as well. Line 12. Solve the bracket problem () (). Maybe use : : :, e.g. : : :(). Line 13. Satellite remote sensing is capable of measuring near-real time : : : Line 14. : : :including oceans and complex terrain where in-situ precipitation measurements are missing: : : Please provide references for ocean and complex terrain.

As per reviewers’ suggestion, all grammatical mistakes have been corrected and references, wherever necessary, have been added in the revised manuscript.

Please note, that there has been made substantial improvement recently for systematic in-situ oceanic precipitation measurement (rain, snow and mixed-phase) for satellite validation within the OceanRAIN project: Klepp, C., 2015: The Oceanic Shipboard Precipitation Measurement Network for Surface Validation – OceanRAIN. Atmos. Res., Special issue of the International Precipitation Working Group (IPWG), 163, 74-90, doi: 10.1016/j.atmosres.2014.12.014.

I agree with the reviewer that substantial improvements were made recently in the estimation of oceanic rainfall, but most of these measurements are carried out in campaigns aimed to address some scientific problem or validating the output of some satellite/radar. Long-term accurate measurements are limited only to a few locations.

Line 15. Complex terrain is challenging for satellite retrieval to cover, especially for frozen surfaces, snow and light rain. That may not occur in your study area but maybe a reference may be useful to document that, e.g. the work done by Nai-Yu Wang. Line 17. active and passive microwave; multi-satellite Line 23. Please add the MPE references directly behind the data sets. Otherwise it is unclear which reference belong to which data set.

Referencing has been done as suggested by the reviewer.

Line 25. Does "sensor accuracy" point at inter/cross calibration issues? Line 27. Please provide references for these factors. Evaluation should be expanded to validation as well, because you don't want to just intercompare them to see bias but understand their accuracy by validation to ground/surface reference data.

As per reviewers' suggestion, all grammatical mistakes have been corrected and references, wherever necessary, have been added in the revised manuscript.

Page 10393 Line 5. Do you refer to evaluation or validation here?

'evaluation' has been changed to 'validation'

Line 11. Please solve the bracket problem. Do you mean "precisely" when you say "faithfully"? Please clarify.

Bracket problem is resolved and the term 'faithfully' is replaced with 'precisely'

Line 15. Precipitation products Line 17. But reduce Line 18. or when the is aggregated in space and time Line 24. Aghakouchak misspelled with regard to references Line 26. be valid Line 27. vary Line 29. in different climatic regions Page 10394 Line 1. for monthly and seasonal Line 3. However, a detailed study : : : Line. due to the lack of Line 8. ,are to measure and understand Line 10. This is the first paper Line 11. : : : its establishment : : : Line 12. Network doubles here. Better make two sentences. Does "though" mean "although"? Line 15. during the NEM. Also don't use () (). Better use (;) Line 17. of in-situ measured rainfall and performance Line 18. as follows: A description : : : Line 21. during both monsoon seasons Line 24. Results are discussed:

Above grammatical mistakes are corrected as suggested by the reviewer.

Chapter 2 Line 27 and Figure 1. See major issue comment. The reader may not easily be aware with India geography and may miss the larger location setting and monsoon system areas involved. Please add two sub-figures to figure 1 according to major issue and Figure 1 comment.

Figure 1 is modified as per reviewers' suggestion. Two sub-figures are added depicting the spatial variability of rainfall and wind pattern during both monsoon seasons.

Page 10395 Line 4. Highest peak about 1000 m above sea-level. Line 5. In the North of the study region. Line 8. 35% of the annual rainfall Line 9. Please state if the remaining 10% are due to monsoon-unrelated thunderstorms. Phrase “in nature” unneeded Line 10. The stratiform rain fraction Line 12. () () should be (;) Line 13. And is generally not under the Line 19. Does that copious rainfall account for the 10% not attributed to monsoon systems?

Above grammatical mistakes are corrected as suggested by the reviewer. No. Cyclones produce copious rainfall during the NEM. As already mentioned earlier, we have not segregated the rain within the season based on the source of rainfall (thunderstorm, cyclone, MCS, etc.). All the rainfall during the whole season is considered for our analysis. In fact, the remaining 10% of annual rainfall occurs during the premonsoon (March through May).

Chapter 3 Line 20. I suggest Mesoscale rain gauge network because I do not understand the meaning of meso-rain. I assume meso-rain is not what you mean.

The network is meant for understanding mesoscale features. To avoid confusion, we removed the scale. We refer it as dense rain gauge network.

Line 21. The Gadanki gauge network is part of the Megha-Tropiques satellite validation program. I strongly recommend to introduce that in the abstract and introduction as well as this is very interesting to the reader. Line 23. A mesoscale-network Line 24. Centered around Gadanki Line 25. Can you be more precise with the 10 km intergauge distance as Figure 1 suggests that they are not all evenly-spaced at all.

Above grammatical mistakes are corrected as suggested by the reviewer. The premise of network is mentioned in both abstract and introduction. Though we tried to install the gauges with an intergauge spacing of 10 km, several practical problems hampered our efforts. Therefore, you may find some gauges depart slightly from the square grid. Except for one gauge location, the intergauge spacing between the gauge-locations is in the range of 6-12 km.

Line 27. Being an official validation site I suggest you name the gauges officially. Which company built them, which name do they have. Are they all identical? What is mL? Do you mean milliliter’s (ml)?

More information on the gauges are given now in the revised manuscript. Sorry for the typo. It is ‘ml’.

Page 10396 Line 1. The gauges are solar : : :and store : : : data at 1-min resolution : : :on a memory card Line 2. Additionally, the 1-min Line 3. Being should read is : : :in near real-time about every 30-min to a server Line 4. What does GPRS stand for? Utility should read usefulness or importance? Line 6. Each system means each gauge? If so, use gauge pls. Line 8. Does the 45_ cone refer to the usual wind direction? Maximum attention should be attributed to data quality according to wind undercatch and orography. Please clarify. Line 11. “In-situ ground truth”. There is actually no ground truth, though we all consider an in-situ measurement to show the truth. In reality, this is also far from truth and contains a variety of errors as well. They may be linked to wind speed and collection abilities. Do the gauges handle extreme precipitation accurately? I know of shipboard high-tech gauges that suffer strongly from overcatch during ITCZ extreme rainfall when compared to disdrometers that are thought to be most accurate, although even they have their limitations.

Above grammatical mistakes are corrected as suggested by the reviewer. 45° Cone is for all directions. The limitations in the measurement of rainfall with tipping bucket rain gauge are included in the revised manuscript with reference to the study region. The gauges are calibrated at 3 high rain rates (31.5, 54.3 and 72.6 mm h^{-1}) to check their performance at extreme rain rates. Figure 1d (in the revised version) clearly shows that their performance is good.

Line 25. Rectified means recalibrated?

Yes. We do recalibrate after adjusting the leveling screw.

Line 27. These kind of adjustments were required eight times during three years Line 28. How well the gauges estimate Page 10397 Line 1. 31.5 mm/h is already a substantial amount of rainfall. How accurate are the gauges to detect drizzle and very low precip rates? This may to a very large extent affect the occurrence of precip measured when compared to satellite data and immediately feeds back to the point to area perspective and beamfilling effects. This test is performed under ideal conditions, almost lab conditions. How does wind effect these measurements? How do extreme precipitation events influence the results? Given that under convective conditions I assume that the rain rate can easily excess 150 mm/h in Southern India. The maximum rain rate recorded by myself was 160 mm/h during an ITCZ thunderstorm event. This usually causes gauges to produce large biases.

Above grammatical mistakes are corrected as suggested by the reviewer. The limitations in the measurement of rainfall with tipping bucket rain gauge are included in the revised manuscript with reference to the study region. The gauges are calibrated at 3 high rain rates (31.5, 54.3 and 72.6 mm h^{-1}) to check their performance at extreme rain rates. Figure 1d (in the revised version) clearly shows that their performance is good.

As discussed above, the tipping bucket rain gauges are, in general, not ideal for the measurement of drizzle. Drizzle being weak in rain intensity takes finite time to fill the bucket (for instance the gauge used in the present study takes 24 minutes to produce a tip during drizzle with a rain rate of 0.5 mm hr^{-1}). Bigger the bucket, longer the time it takes. Because of this, it is extremely difficult to obtain accurate high-temporal resolution measurements and also the start time of rain. The optical rain gauges (ORG) are probably the best to capture these light rainfall events, but deploying them in dense networks is a costly proposition

Furthermore, I recommend that you introduce a percentage value how accurate your 36 gauges (min/max) and on average perform with respect to the reference of the Young gauge. Please add a reference, why the Young device is allowed to be the reference. Is it a reference by international standard?

The range (min. and max.) of bias measured by 36 rain gauges is included in the manuscript.

Please also name the manufacturer and device name of your identical 36 gauges. I recommend that you introduce your site being part of Megha-Tropiques test program already in the abstract and introduction. That is important information with relevance to your results and findings.

As suggested by the reviewer the name of manufacturer and some text indicating that the network is established as part of Megha-Tropiques validation program is included in the abstract and introduction.

Chapter 4 Line 19. How different its pattern is from the climatology

Figure 1 now contains spatial distribution of climatological rainfall for SWM and NEM. It now becomes easy to compare the present results (from 3 years) with that of climatological patterns.

Line 23. Your sentence on the percentages is not understandable. Do you mean this: The rainfall during the SWM accounts for 55% of the annual rainfall while the NEM contributes 30-35%. Please explain where the remaining 10 to 15% come from. Cyclones and thunderstorms?

Yes. 55% during the SWM, 30-35% during the NEM and the remaining rain during premonsoon (March – May). The rainfall occurring due to cyclones and thunderstorms in respective seasons is already included in the analysis.

Page 10398 Line 1. This demonstrates the difficulty finding your results geographically. Figure 2 shows the max accumulation in the Northeast of the domain while in the text its explained that the southern tip receives most during NEM. If you include a broader area figure with both monsoon types one can much easier grasp the details of your findings. Line 4. In the Northeast sector of your 50x50 km box? Line 7. This becomes clear once I looked it up on a map. Please include as mentioned many times already. You are of course very familiar with your geographical setting. Your readers (and I) are probably not.

Sorry for that. As suggested by the reviewer, Figure 1 is modified. It now contains spatial distribution of the rainfall and wind pattern (at 850 hPa) during SWM and NEM.

Page 10399 Line 3. Towards the west Line 13. As an event with a rain duration: : :rain exceeding 0.5 mm. What is the lowest resolution to define a minute as a precip minute? One tip? That undersamples the occurrence of precip significantly! Please explain. What happens is precip fall but does not reach one tip of the gauge? It's still a precip minute but goes undetected? That biases intercomparison to satellite data.

As discussed above, the tipping bucket rain gauges are, in general, not ideal for the measurement of drizzle. Drizzle being weak in rain intensity takes finite time to fill the bucket (for instance the gauge used in the present study takes 24 minutes to produce a tip during drizzle with a rain rate of 0.5 mm hr^{-1}). Bigger the bucket, longer the time it takes. Because of this, it is extremely difficult to obtain accurate high-temporal resolution measurements and also the start time of rain.

That is why, we have not used 1-min. rain rate for statistics, rather discussed the rain statistics based on the total event (i.e., event duration and accumulated rain during the event, mm/event).

Line 14. The temporal gap Line 15. 25 min. (dot missing) Line 16. Please explain why the 25 min criterion is chosen. How fast do showers in your region move, how large are they? How large are gaps between showers? Please justify. Does your technical 25 min threshold agree with the meteorology of the showers? If not, this method is not capable as a shower separator. And 0.5 mm/h is already a high value. Most often 0.01 mm/h as a minute value would represent reality.

The reason for choosing 25 min. is already given in the manuscript. It is given here again for reviewers' convenience. The 25 min. threshold for the separation of rain events is based on the typical rain rate of drizzle (0.5 mm hr^{-1}) and rain gauge bucket capacity. Assuming that there is no loss of rain water due to evaporation and wetting of inner walls of the gauge, the gauge takes 24 min. for one tip (needs to collect 6.4 ml) during drizzle with a rain rate of 0.5 mm hr^{-1}.

Page 10400 Line 16. Can you pls explain wind shear-cold pool interaction

Mohan (2011) has studied the reason for the mid-night rainfall over southeast India during the active monsoon spell. It has been found from MPEs that there is an eastward propagation of rain bands from the west coast during these spells. Such propagation is not seen during the break spell, in spite of copious rainfall along the west coast. Detailed diagnosis of background parameters, like wind speed and shear, CAPE, depth of westerlies, etc., suggests that the propagation is due to the interaction of wind shear and cold front (strong downdrafts during the decaying stage of thunderstorm). Some of this discussion is included in the revised manuscript.

Page 10401 Line 15. Is the cyclone Neelam part of the monsoon season or excluded from it? As it supplied copious rainfall it strongly influences the monsoon results.

As already mentioned above, all rainfall data within a season are collected irrespective of the source for rainfall.

Line 19. Pls explain the acronym IQR

Sorry for that. It is Interquartile range.

Page 40403 Line 14. Will you explain later why the expectation of the evening peak does not meet the observation of the propagating systems?

As mentioned above, the rainfall due to propagating systems is more than the evening rainfall during the active monsoon spell.

Line 22. Again, I wonder if cyclones are really part of the monsoon? Are they triggered by the monsoon itself or are they seeded from outside the monsoon region? As to my expectation cyclones (like hurricanes) are long-distance wanderers that may travel into the area of the monsoon and get superimposed on the monsoon system and as such do not belong to them. Page 10405 Do cyclones have a strong influence on the decorrelation length?

Cyclones/depressions/low-pressure systems strengthen/weaken during the monsoon seasons. For instance, the large vertical wind shear present during the SWM is detrimental for cyclone intensification. Though other atmospheric parameters (SST, etc.) are conducive for cyclone formation, the low-pressure systems developed over the head Bay of Bengal will intensify only up to depression stage, but not to cyclonic stage. On the other hand, the atmosphere is very conducive for cyclone intensification during the NEM. Most of the low pressure systems form in the south Bay of Bengal (initiated by easterly waves) and intensify to cyclones/severe cyclones while moving northwestward.

The cyclones do alter the decorrelation length. Slightly higher decorrelation length observed during the NEM is mainly due to the dominance of cyclonic rain during this season. Nevertheless, most of the cyclones during the NEM move northwestward and cross the coast (landfall) north of the study region (100's of km away). Though the study region is far from the cyclonic eye in most of the cases, it gets some rainfall due to cyclone (spiral bands).

Page 10406 Line 14. Table 1 gets called here first time. See comment above. Page 10408 Line 16. Is that mention in the introductory statements of the filed site that it's a semi-arid region with significant fraction of virga? Evaporation should say evaporation of falling rain to discriminate from evaporation from the ground.

The text has been changed as suggested by the reviewer.

Figures

Figure 1. What is meso-rain, topography (m). Please note that the stars refer to the individual gauge positions. They do NOT seem to be evenly spaced as introduced in the Abstract. Please note, that the quadrants cover an area of 50x50 km if that is the case. Please add color to 1b as suggested above.

The text has been changed in the revised version as suggested by the reviewer. As mentioned earlier, we tried to establish an evenly spaced rain gauge network. Nevertheless, due to various reasons, like security, suitability of measurements location and availability of mobile network for data transfer, we could not be able to establish such network. In spite of the above problems, the intergauge distance between many stations is maintained as 10 km, wherever possible.

Figure 2. I do not fully understand what's shown here. This is three years of data? Accumulation of 3 years of NE and SW monsoon precip? Seasonal average accumulation? Please indicate.

It is 3 years average of seasonal rainfall.

Figure 3. What is the difference between storm duration and rain duration? : : :four quadrants color coded : : : The term storm is not defined what you mean by that.

It is rain duration and the same term is used throughout the manuscript.

Table 1. Table 1 is called after Table 2. Reverse or call Table 1 already in the introduction where the MPEs are introduced.

Table 1 is introduced in the introduction in the revised version of the manuscript.

Figure 4. I suggest to move the colorbar beneath the figure. Pls indicate in the text that rain accumulation is color-coded in mm.

Figure and figure caption are modified as suggested by the reviewer.

Figure 7. Please indicate, that the black curve is the gauge reference and that the satellite MPEs are color-coded.

Figure caption is modified as suggested by the reviewer.

Replies to Referee 2 comments/suggestions

This paper is focused on presenting results from a dense rain gauge network located in the southern peninsula of India. The study uses three years of rain gauge data from the network to characterize the precipitation variability with the southwest monsoon and northeast monsoon that impacts the region. The authors use these data to evaluate four multi-satellite precipitation estimates (CMORPH, TMPA, GsMAP, and PERSIANN) ability to capture the rainfall characteristics over the dense network.

The paper is well-organized. The authors provide a good supporting background in the introduction, a good overview of the study region and rain gauge network, and provide good supporting discussion of the analysis and results. The evaluation of the satellite precipitation products in the context of the precipitation characteristics is particularly interesting. The results should provide insights on the limitations and possibly what to focus on for improving the satellite precipitation products for monsoon precipitation observed over land.

Overall, I think this is an important contribution to the community, I have few specific comments to improve the manuscript, which are provided below. I recommend a minor revision.

We thank the reviewer for appreciating our work and providing positive comments on our manuscript. All the suggestions given by the reviewer are considered in the revised manuscript.

Specific Comments:
1) Page 10391, line 12: It would be good if the authors could include other references to applications, especially for satellite applications. A good reference to read (and references therein) is: Kucera, P. A., E. E. Ebert, F. J. Turk, V. Levizzani, D. Kirschbaum, F. J. Tapiador, P. Xian, A. Loew, and M. Borsche, 2013: Precipitation from Space: Advancing Earth System Science. Bull. Amer. Meteor. Soc., doi: BAMS-D-11-00171.1.

The above reference is added at the appropriate place in the revised version.

2) Page 10391, lines 20-25: It would be useful to the reader to put the references with the MPE dataset discussed, not at the end of the discussion.

Corrected as suggested by the reviewer.

3) Page 10394, lines 15-19: I think the readers would benefit from further discussion of the impacts of cyclone precipitation on the overall precipitation characteristics in the NEM.

As per reviewers’ suggestion, some more information on cyclonic precipitation during the NEM has been added.

4) Page 10394, line 22: the authors need to describe Megha-Tropiques in more detail and properly reference the project.

As per reviewers' suggestion, more information is given on Megha-Tropiques with relevant references.

5) Page 10394, line 26: the authors need to specify the manufacture and model (and reference) of the tipping bucket rain gauges to allow the reader to compare uncertainties of that type of gauge with other gauges available.

All the above information is furnished in the revised version of the manuscript.

6) Page 10395, line 4: define GPRS.

Sorry for that. GPRS is now defined in the revised manuscript.

7) Page 10412, line 10: I don't find the result that missing rain is found to be significant at higher resolution. Please expand why you find this surprising.

Table 3 clearly shows that the missing rain is significant at higher resolution. 'Surprising' is dropped from the sentence.

8) Figure 1: The authors should place the network map into a large-scale map of India to put in context of the geographical location.

As per reviewers' suggestion, Figure 1 is modified. The spatial distribution of seasonal rainfall and wind pattern during SWM and NEM is now shown in Figure 1 (as 1a and 1b) in the revised manuscript.

Editorial comment: 1) The paper could be improved in terms of readability if it was reviewed by an English editor. The sentence structure made it difficult to understand the context of the discussion without reading it several times. 2) Please make sure all acronyms are defined in the paper.

Sorry for that. We tried out level best to minimize the typos and grammatical mistakes in the revised manuscript. All acronyms are also defined in the revised version.

Assessment of small-scale variability of rainfall and multi-satellite precipitation estimates using ~~a meso-~~measurements from a dense rain gauge network ~~measurements from~~ in southeast ~~rn peninsular~~ India

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Abstract

This paper describes the establishment of a dense rain gauge network and small-scale variability in rain ~~storms~~ events (both in space and time) over a complex hilly terrain in southeast ~~peninsular~~ India. Three years of high-resolution gauge measurements are used to ~~evaluate~~ validate 3-hourly rainfall and sub-daily variations of four widely used multi-satellite precipitation estimates (MPEs). The network, established as part of Megha-Tropiques validation program, consists of 36 rain gauges arranged in a near-square grid area of 50 km x 50 km with an intergauge distance of ~~∼~~6-12~~10~~ km. Morphological features of rainfall in two principal ~~monsoon~~ rainy seasons (southwest monsoon: SWM and northeast monsoon: NEM) show marked ~~seasonal~~ differences. The NEM rainfall exhibits significant spatial variability and most of the rainfall is associated with large-scale/long-lived systems (~~in~~ during wet spells), whereas the contribution from small-scale/short-lived systems is considerable ~~in~~ during the SWM. Rain ~~storms~~ events with longer duration and copious rainfall are seen mostly in the western quadrants (a quadrant is 1/4th of the study region) in SWM and northern quadrants in NEM, indicating complex spatial variability within the study region. The diurnal cycle also exhibits large spatial and seasonal ~~marked spatiotemporal~~ variability with ~~strong diurnal cycle~~larger diurnal amplitudes at all the ~~stations~~ gauge locations (except for 1) during the SWM and smaller and insignificant diurnal ~~cycle~~ amplitudes at many ~~stations~~ gauge locations during the NEM. On average, the diurnal amplitudes

are a factor 2 larger in SWM than in NEM. The 24-hr harmonic explains about 70% of total variance in SWM and only ~30% in NEM. During the SWM, the rainfall peak is observed between ~~The late night-mid night peak~~ (20 ~~-~~and 02 IST (Indian Standard Time)~~)~~ ~~observed during the SWM~~ and is attributed to the propagating systems from the west coast during active monsoon spells. Correlograms with different temporal integrations of rainfall data (1, 3, 12, 24 hr) show an increase in the spatial correlation with temporal integration, but the correlation remains nearly the same after 12 hours of integration in both ~~the~~ monsoon~~s~~ seasons. The 1-hr resolution data shows the steepest reduction in correlation with intergauge distance and the correlation becomes insignificant after ~30 km in both monsoon seasons.

~~Evaluation~~ Validation of high-resolution rainfall estimates from various MPEs against the gauge rainfall data indicate~~s~~ that all MPEs underestimate the ~~weak~~ light and heavy rain. The MPEs exhibit good detection skills of rain at both 3 and 24 hr resolutions, however, considerable improvement is observed at 24-hr resolution. Among the different MPEs investigated, Climate Prediction Centre morphing technique (CMORPH) performs better at 3-hourly resolution in both monsoons. The performance of Tropical Rainfall Measuring Mission (TRMM) multisatellite precipitation analysis (TMPA) is much better at daily resolution than at 3 hourly, as evidenced by better statistical metrics than the other MPEs. All MPEs captured the basic shape of diurnal cycle and the amplitude quite well, but failed to reproduce the weak/insignificant diurnal cycle in NEM.

1. Introduction

Precipitation is ranked among the most variable meteorological parameters in the Earth's climate system. It is also the -most important parameter in the water and energy cycles (Levizzani et al., 2007; Kucera et al., 2013). Understanding and quantification of the variability of precipitation is important not only for management decisions, but also to unravel the underlying processes governing the formation of precipitation and its variability. The density of rain gauges in many operational networks is often too poor to capture the small-scale (both in space and time) variability of rainfall (Habib et al., 2009). Research networks with a high density of gauges, but covering a limited area, are becoming increasingly popular to understand the sub-grid and sub-daily scale variability of rainfall. ~~and also~~ ~~m~~Measurements from such networks are ~~extremely~~ also useful for the validation of precipitation ~~derived~~ estimates from microwave radars and imagers (Krajewski et al., 2003; Habib et al., 2012; Tokay et al., 2014; Dzotsi et al., 2014; Chen et al., 2015). The complexity in small-scale ~~spatio-temporal~~ variability of rainfall increases in hilly terrain (Zangl, 2007 ; Li et al., 2014). The rainfall often becomes inhomogeneous due to topographic influence and at times highly localized, resulting large errors in the retrieved precipitation by passive/active remote sensors due to non-uniform beam-filling of precipitation within the satellite or radar pixel (Tokay and Ozturk, 2012). In order to understand the physical processes responsible for such variability, several studies examined the dependency of rainfall spatial variability (in terms of correlation distance, d_o) on rainfall regimes (Krajewski et al., 2003), seasons, spatial and temporal aggregation of data (Krajewski et al., 2003; Villarini et al., 2008; Luini and Capsoni, 2012; Chen et al., 2015; Prat and Nelson 2015), sample size and extreme rain events (Habib et al., 2001) and geographical features like topography (Li et al., 2014) ~~(Habib et al., 2001; Habib and Krajewski, 2001; Krajewski et al., 2003; Villarini et al., 2008; Luini and Capsoni, 2012; Li et al., 2014~~; ~~Chen et al., 2015; Prat and Nelson 2015)~~. Proper quantification of spatial correlation distance mitigates the uncertainty in the upscaling of rainfall from point-to-areal and also helps in designing rain gauge networks (Bras and Rodriguez-Iturbe, 1993; Villarini et al., 2008).

At present, only a few dense research gauge networks are operational worldwide. ~~Even~~ Moreover the gauge locations in operational networks are mostly confined to well-developed and easily accessible locations. This leaves large spatial data gaps in critically important areas due to the unavailability of gauges (over open oceans and remote locations). Further, ~~and/or~~ timely ~~inaccessibility of data~~ dissemination of precipitation data to concerned authorities is another critical issue. ~~On the other hand~~~~However,~~ ~~near~~ Near real-time high-~~resolution~~ quality precipitation measurements are vital for several weather and hydrological forecasting applications, eg., ~~(~~flash flood forecasting and monitoring~~)~~ (Li et al., 2009; Kidd et al., 2009). Satellite remote sensing ~~of precipitation~~ is capable of measuring ~~the only means of obtaining~~ near~~-~~ real ~~-~~time high-resolution (both in space and time) precipitation on a global-scale, including ~~over~~ oceans and ~~hilly~~ complex terrain, where in-situ precipitation measurements are ~~lacking~~missing (Wang et al., 2009). Recently, several merged satellite products have been developed by effective integration of relatively accurate active and passive microwave and high-temporal sampling infrared (IR) measurements. These multi-satellite precipitation estimates (MPEs) are becoming increasingly popular and several such products are now available providing high-resolution precipitation on near-real time. They include, among others, Climate Prediction Centre (CPC) morphing technique (CMORPH; Joyce et al., 2004), TRMM multisatellite precipitation analysis (TMPA; Huffman et al., 2007), Global satellite mapping of precipitation (GSMaP; Kubota et al., 2007; Aonashi et al., 2009) and Precipitation estimation from remotely sensed information using artificial neural networks (PERSIANN; Hsu et al., 1997; Sorooshian et al., 2000) (~~Hsu et al., 1997, Sorooshian et al., 2000; Joyce et al., 2004, Huffman et~~

~~al., 2007~~, ~~Kubota et al., 2007; Aonashi et al., 2009~~). Details of these MPEs, including their spatial and temporal resolutions and input data used to generate them, are given in Table 1. However, several sources of uncertainties, including sensor inaccuracies, retrieval algorithms, not fully understood physical processes and beam-filling factors, limit the accuracy of MPEs (Levizzani et al. 2007). Therefore, ~~evaluation~~ validation of high-resolution MPEs and quantification of their errors are essential before utilizing them further for operational or research applications. Thus far, a great deal of effort has been put into evaluate the MPEs in different climatic conditions (Global - Adler et al., 2001; Turk et al., 2008; Australia, United States of America (USA) and northwestern Europe - Ebert et al., 2007; ~~Turk et al., 2008;~~ Africa and south America - Dinku et al., 2010; India - Prakash et al., 2014; ~~Ghajarnia et al., 2015; Chen et al., 2015;~~ Sunilkumar et al., 2015; Iran - Ghajarnia et al., 2015; China - Chen et al., 2015 and references therein) and seasons (Tian et al., 2007, Kidd et al., 2012; Sunilkumar et al., 2015). Though several studies exist on the evaluation of monthly to seasonal rainfall in the literature, only a few studies focused on ~~evaluating~~ validating the rainfall at daily and sub-daily scales (Sapiano and Arkin, 2009; Sohn et al., 2010; Habib et al., 2012; Kidd et al., 2012; Mehran and Aghakouchak, 2014).

The sub-daily evaluation of five MPEs over the ~~United States~~USA and Pacific Ocean indicates strong performance dependence of MPEs on the region and season, i.e., ~~(~~overestimates warm season rainfall over the ~~United States~~USA and underestimates over tropical Pacific Ocean~~)~~ (Sapiano and Arkin, 2009). They also noted that all MPEs ~~faithfully~~ precisely resolved the diurnal cycle of precipitation. Contrary, ~~On the other hand, the evaluation study by~~ Sohn et al. (2010) ~~over South Korea using a dense rain gauge network shows the~~have noted the underestimation of the amplitude of diurnal cycle by CMORPH, PERSIANN and National

Research Laboratory blended (NRL-blended) precipitation products over South Korea. The observed biases and random errors are found to be large at highest resolution (event and hourly scale), but reduce~~s~~ to smaller values when the evaluations are carried out over the entire study period or when the data are aggregated in space and time ~~time and space~~ (Habib et al., 2012). The performance evaluation of various MPEs and reanalysis precipitation products over northwest Europe reveals a strong seasonal cycle in bias, false alarm ratio and probability of detection (Kidd et al., 2012). A detailed study on the detection capability of intense rainfall by various MPEs using a ~~meso-~~ dense network of rain gauges reveals that none of the high-resolution (3 hr.) MPEs are ideal for detecting intense precipitation rates (Mehran and AghaKouchak, 2014).

The above studies clearly elucidated that the error characteristics obtained for monthly and seasonal scales may not necessarily be valid for high-temporal resolutions, such as sub-daily scale and also the performance of MPEs vary~~ies~~ in different climatic ~~conditions~~regions. It is, therefore, highly essential to perform ~~evaluation studies~~validation independently at finer temporal scales over different climatic regions. As mentioned above, ~~while~~ the evaluation of MPEs ~~at~~ for monthly and seasonal monsoon precipitation was done to some extent over India (Rahman et al., 2009; Uma et al., 2013; Prakash et al., 2014, Sunilkumar et al., 2015). However, a detailed study on the ~~evaluation~~ validation of MPEs at shorter time scales (sub-daily and daily) does not exist due to the lack of suitable measurements. Also, there is no detailed documentation on the small-scale variability of precipitation, discussing the diurnal cycle of precipitation and correlation distance (its dependence on seasons and temporal aggregation of data). The objectives of this paper, therefore, are to quantify and understand the small-scale variability (spatial and temporal) of precipitation over a complex hilly terrain and also to ~~evaluate~~ validate high-resolution MPEs using a dense network of rain gauges established around Gadanki (13.45° N, 79.18° E). This network -has been established as part of Megha-Tropiques (an Indo-French joint satellite mission) validation program (Raju 2013, Roca et al. 2015). This being the first paper on this network, ~~the~~ its establishment and maintenance (stringent calibration procedures adopted) ~~of the network~~ is also discussed briefly. ~~Though~~ Although the southwest monsoon (SWM: June through September) is the main monsoon season for India as a whole, the ~~eastern part of~~ southern part of ~~peninsular~~ India (including the study region) receives significant amount of rainfall in northeast monsoon (NEM: October through December~~) (~~; Rao et al., 2009). The final objective of this paper is, therefore, to understand the seasonal differences in small-scale variability of in-situ measured rainfall and performance of MPEs.

The remainder of this paper is organized as follows~~.~~: A ~~D~~description of the study region including topographical features, seasonal differences and prevailing weather conditions is given in section 2. The establishment and maintenance of the ~~meso-~~rain gauge network is described in section 3. The morphological characteristics of rain during ~~in~~ both ~~the~~ monsoon seasons, including the intensity, duration and small-scale variability are discussed in Section 4. The ~~evaluation~~ validation of MPEs at sub-daily and daily scales is performed in Section 5 using a variety of statistical indices. All the results are summarized in Section 6.

2. Description of study region

The rainfall in India exhibits large and complex spatio-temporal variability governed by a variety of processes, ranging from small-scale convection, orographic lifting and land-sea circulations to gigantic monsoon system. As mentioned above, the SWM season is primary rainy season when considered India as a whole, but the southern parts of India receive considerable rainfall during the NEM (Figures 1a and 1b). The wind pattern (on 850 hPa level shown in Figures 1a and 1b) also changes dramatically from southwesterlies during SWM to northeasterlies during NEM over peninsular India. The daily-gridded 1° x 1° rainfall data generated by India Meteorological Department (Rajeevan et al., 2006) and European Centre for Medium-Range Weather Forecast (ECMWF) - Interim (ERA; Dee et al., 2011) have been used to generate the above figures. Though the conditions in Bay of Bengal, like high seas-surface temperature and cyclonic circulations, favor the formation of low-pressure systems, they do not intensify to the stage of cyclone due to the presence of large vertical wind shear during the SWM. These low-pressure systems and depressions move onto the land along the monsoon trough (a quasi-permanent trough that extends from the head Bay of Bengal to northwest India, covering north and central India) and produce copious rainfall in this region. Contrary, the low-pressure systems formed in the south Bay of Bengal often intensify to cyclonic stage during the NEM. These systems move northwestward and produce rainfall along the eastern coast and southern parts of India.

The study region is centered ~~on~~ around Gadanki, and spreads in an area of 50 km x 50 km in southeastern ~~peninsular~~ India (shown with a box in Figure ~~1a~~1a). The National Atmospheric Research Laboratory (NARL) located at Gadanki is responsible for the establishment and maintenance of the gauge network. The topography in the study region is complex with hillocks distributed randomly on a generally east-west sloped surface (Figure 1c). There is a steep gradient in the north-south direction also due to the Nallamala Hills (highest peak is ~~~~~about ~~1 km~~1000 m above sea-level) in the north~~ern side~~ of the study region. The coast is nearly 100 km away from the center of the study region.

As seen in Figures 1a and 1b, ~~T~~the rainfall in this region ~~is influenced~~occurs primarily ~~by~~ during two monsoon seasons (SWM and NEM), besides intense thunderstorms in May. While 55% of the annual rainfall occurs ~~in~~ during the SWM, the NEM comprises of 35% of the annual rainfall (Rao et al., 2009). Remaining 10% occurs during the premonsoon season (March through May). The rain is predominantly convective ~~in nature~~ during the SWM, whereas the stratiform rain fraction is significant and comparable to that of convective during the NEM (Saikranthi et al., 2014). The rain during the SWM occurs primarily due to evening thunderstorms or propagating mesoscale convective systems ~~(MCS)~~ (Mohan, 2011). This region is far from the monsoon trough and is generally ~~is~~ not under the influence of monsoon depressions and low-pressure systems that produce copious rainfall in central and north India (Houze et al., 2007, Saikranthi et al., 2014). However, the cyclones with varying intensities play a decisive role in altering the spatial distribution of rainfall during the NEM. During the study period (October 2011-September 2014), 3 cyclones and few depressions formed in the Bay-of-Bengal and produced copious rainfall in the study region.

3. ~~Meso~~ A dense rain gauge network around Gadanki

Dense rain gauge networks are an integral part of validation programs. As part of one such satellite validation program - Megha-Tropiques~~, an Indo-French collaborative project,~~(Raju 2013; Roca et al. 2015), NARL has established a ~~meso-~~ dense network of rain gauges in 2011, covering an area of 50 x 50 km^2 centered ~~on~~ around Gadanki. The network consisting of 36 rain gauges ~~with an inter-gauge spacing of ~10 km~~ spreads from 78.9° E to 79.4° E and from 13.1° N to 13.6° E (Figure ~~1a~~1c). Rain gauges employed in the present network are of tipping bucket type with a 20.32 cm diameter orifice, manufactured by Sunrise Technology (Model No. ST-ARS-2011) . Each tip corresponds to 0.2 mm (or 6.4 ml) rainfall. The gauges ~~is~~ are solar-powered and store~~s~~ high-resolution data ~~(~~at 1~~-~~min~~.)~~. resolution at the site ~~in~~ on a memory card, which has the capacity to store 5 years of rainfall data. ~~Also,~~Additionally, the 1-min. data are

~~being~~ transferred ~~on~~ in near real-time (about ~~in~~ every 30 min.~~)~~ to a server located at NARL using general packet radio service (GPRS) technology. The acquisition of near real-time data is ~~of great~~very useful ~~utility~~ not only for research but also to monitor the performance of each ~~system~~gauge. It is possible to reset the gauge, if required, from the central hub (NARL). Several factors were considered while choosing the location for rain gauge installation, like its suitability for rain measurement (no obstacle should be there in a cone of 45°), safety of the instrument, accessibility to the location and coverage of mobile network (required for data transfer). As a result, the inter-gauge spacing is not uniform, rather varied from 6 to 12 km, although majority of them are separated by ~ 10 km (Figure 1c). Although 45° cone for complete azimuth from the rain gauge is ensured, locations with more clearance in the direction of wind (predominantly east-west in the study region), wherever possible, have been preferred for the gauge installation.

The reliability of the assessment of MPEs depends primarily on the availability of accurate in-situ ground truth provided by the rain gauge network. Though in-situ gauge measurements provide better rainfall estimates, they are not error-free. For instance, the systematic errors often noted in tipping bucket rain gauge measurements are attributed to the winds and its induced turbulence, wetting of inner walls of the gauge, loss of rain water during the tipping and evaporation of the rain water in the gauge (WMO, 2008). The estimated wind-induced error through numerical simulations is found to be in the range of 2%-10% for rainfall and increases with decreasing rain rate and increasing wind speed (Nešpor and Sevruk 1999). The measured surface winds (at 2 m) in the study area are in general weak and rarely exceed 4 m s^{-1} (~2% of the total data > 4 m s^{-1}). Therefore, the error due to the wind could be within 5% in our measurements (Nešpor and Sevruk 1999). The error due to the non-measurement of rain during tipping can be minimized but not eliminated (WMO, 2008). This error is considerable during intense rainfall events. To quantify this error, a rain calibrator with 3 high flow rates has been used (discussed in detail later).

~~On the other hand, the~~ The gauge maintenance can be challenging, especially in remote locations and in extreme weather conditions, for long durations. The rain gauges are carefully calibrated before deploying in the field. Strict maintenance schedules are adhered, which includes 2 regular visits of a qualified technician to all the gauges just before the onset of two principal monsoon seasons, ~~(~~SWM and NEM, ~~)~~ (first visit in May and the second in September) and also to malfunctioning gauges, whenever required, to maintain high-quality data essential for ~~evaluating~~ validating high-resolution MPEs. Three types of checks are performed during each visit, besides monitoring the ~~health~~ performance of sub-systems, time shifts and temporal offsets between gauges (if any, between the clocks of gauge and a standard laptop) and battery output. 1. To check how well rain gauge measures the rain amount, known quantity of water sufficient for 5 tips (5 x 6.4 ml) is poured slowly into the rain gauge and compared with the number of tips recorded by the gauge. 2. To know whether or not each bucket takes the same quantity of rain for tipping, 6.4 ml of water is poured slowly in each bucket. The problem, if any found, is rectified by adjusting the leveling screw. This exercise is repeated till both buckets take the same quantity of water for tipping. Nevertheless, such incidents are rare and ~~this~~these kind of adjustments w~~as~~ere required ~~done only on~~ 8 ~~occasions~~ times during three years. ~~in 3 years.~~ 3. To test how well the gauges estimate~~s~~ different intensities of precipitation, a reference calibrator (Young 52260) with 3 flow rates is employed. The calibrator generates flow rates of 1000, 1500 and 2000 ml hr^{-1}, which corresponds to rain rates of 31.5, 54.3 and 72.6 mm hr^{-1}, respectively, corresponding to a rain gauge with orifice diameter of 20.32 cm (or 8 in.). The calibrator is filled with water (up to the mark recommended by the manufacturer) and the water is released into the gauge along the walls of the orifice. By changing the nozzle, the gauge is allowed to record each flow rate for 5 minutes. The ratios of accumulated rainfall and the estimated rain rate (from calibrator) for each flow rate are estimated. The ratios are estimated at each rain gauge station for all 3 flow rates and are shown in Figure ~~1b~~1d. On average, 90% of gauges show ratio in the range of 0.9 - 1.1 with a mean value nearly equal to 1~~Clearly, the ratios at each station and for each flow rate are nearly equal to 1~~, indicating that the gauges are fairly accurate.

4. Small-scale variability of rain

The small-scale variability of rain distribution in a hilly terrain, such as the present study region, depends on several factors from the horizontal scale of mountains, direction of wind to complex interactions between flow dynamics and cloud microphysics (Zangl, 2007 and references therein) besides the differences in large-scale forcing. This section focuses on the small-scale variability of rain, both in space and time, using 3 years of gauge measurements.

4.1. Morphological features of rain over the study region

To understand the morphological features of rain and also to test ~~whether its pattern during the study period is similar to~~how different its pattern from that of climatology, the spatial distribution of mean seasonal rainfall for SWM and NEM is examined (Figure 2). The mean is taken over 3 years of seasonal rainfall. The rainfall distribution is somewhat uniform during the SWM, while it shows a large gradient towards northeast ~~an east-west gradient~~ during the NEM. The magnitude of seasonal rain is larger in the SWM (~400 mm) ~~than in~~compared to NEM (200-350 mm). The rainfall during the SWM accounts for 55% of the annual rainfall, while the NEM contributes 30-35%, ~~The rainfall in SWM and NEM constitutes ~55% of 30-35% of annual rainfall, respectively~~, consistent with the seasonal rain fractions reported by Rao et al. (2009). In general, the region along the east coast, particularly close to the southern tip of India, receives more rainfall during the NEM, the main monsoon season for that region. However, the rainfall gradually decreases towards west from the East Coast. The present study clearly shows this gradient in seasonal rainfall with rainfall varying by > 100 mm in just 50 km. This east-west gradient is not the same at all latitudes, but is larger towards the north. The highest mountains in the study region lies in that part and are responsible for lifting the moist air from Bay-of-Bengal reaching that region as part of NEM circulation.

The study region receives rainfall due to a variety of processes, starting from small-scale evening thunderstorms to synoptic-scale cyclones. The rainfall occurred during both monsoon seasons is considered for the present study, irrespective of its generating mechanism (thunderstorm, cyclone, etc.). Nevertheless, ~~T~~to know which ~~of these processes~~kind of rain systems (small-scale/short-lived or large-scale/long-lived) contribute more to total rain amount, the data are segregated into two groups as small-scale/short-lived and large-scale/long-lived ~~(wet spell or active spell)~~ and rain fractions associated with those systems are estimated at each ~~station~~ rain gauge location during both monsoon seasons. The system is treated as large-scale/long-lived, if rain occurs over more than 75% of the ~~stations~~ gauge locations for at least 2 days. Remaining rainfall is treated as associated with small-scale/short-lived systems. The number of large-scale/long-lived systems ~~(or spells)~~ and their duration varied from year to year. On average, the number of large-scale/long-lived systems during the SWM and NEM is found to be equal, but their average durations differ (6.9 days for SWM and 4.4 days for NEM). The rain fraction due to large-scale/long-lived systems varies considerably (10 - 15%) from year to year during both the seasons. However, the probability distributions of rain fraction by large-scale/long-lived systems (not shown here), clearly depicts the seasonal variation. The large-scale/long-lived systems contribute more to total rain amount during the NEM with ¾ of locations receive >60% of seasonal rain due to these systems. However, same amount of rain fraction (>60%) by large-scale/long-lived systems is observed only at ½ of the locations during the SWM. Though, the number of rainy days associated with large-scale/long-lived systems (due to longer average duration) is larger ~~in~~ during SWM, but their contribution at many of the locations within the study region is not much. In other words, the small-scale/short-lived systems are also important during the SWM as they produce considerable fraction of total rain amount.

4.2. Regional variability in rain rate and rain duration

Based on the topography and spatial distribution of rainfall, the study region is roughly divided into 4 quadrants (Figure ~~1a~~1c). The division appears arbitrary but intuitive. The rain gauge ~~stations~~ locations towards the west, i.e., regions 1 and 3, are on elevated land and receive nearly equal amount of rainfall in both seasons. The ~~stations~~ locations in region 2 and 4 are on lowland, but the amount of rainfall that they receive varies considerably during the NEM.

To understand the spatial variability within the study region and between the two monsoon seasons, an event-based analysis is performed. As discussed above, the total study region is divided into 4 quadrants in such a way that 9 gauges exist in each quadrant. Rain events at each gauge ~~station~~ location within each quadrant are pooled separately for all 4 quadrants. In the present study, the rain event is defined (for each rain gauge ~~station~~location) as an event ~~having~~ with a rain duration > 5 min. and an accumulated rain ~~of >~~exceeding 0.5 mm. Further, the ~~time~~ temporal gap between any two rain events should not be less than 25 minutes. If rain occurs again within 25 minutes after the first shower, then it is considered as part of the first shower. The 25 min. threshold is chosen as the gauge takes nearly 25 min. for one tip in the presence of drizzle, ~~(~~at 0.5 mm hr^{-1}~~)~~ (assuming rain is continuous and evaporation is negligible). Rain duration and accumulations are estimated from these rain events and their cumulative distributions are shown in Figure 3. Rain event statistics (of event duration and accumulated rainfall) for each quadrant, like mean, maximum and interquartile range (IQR: 75%-25%) and 90th percentile, are presented in Table 2. The 90th percentile is considered for representing the extreme rainfall events. The above statistics are presented for both SWM and NEM to delineate the seasonal differences, if any exist.

During both monsoons, the number of rain events is sufficiently large (> 500) in each quadrant for obtaining robust statistics. The number of events is largest in the 2nd quadrant in both monsoons, a quadrant in which most of the gauges are located near the foot hills of relatively high mountains, suggesting possible influence of mountain flows in enhancing cloud activity in this quadrant. In general, more rain events are observed during the SWM than in NEM in all quadrants. The SWM is a summer monsoon and most of the rainfall in this season is associated with evening convection due to intense heating, mesoscale flows (convection due to mountain and sea-breeze circulations)(Simpson et al., 2007) and propagating systems (Mohan, 2011) (discussed in detail later). Many of them are short-~~-~~lived as can be evidenced from their cumulative distributions (Figure 3). For example, 50% of the events during the SWM have durations < 35 min. compared to ≥ 40 min. in NEM in all quadrants.

A sensitivity analysis has been performed (not shown here) to understand the impact of thresholds used in the present study (25 min. for separating rain events and a rain rate < 0.5 mm/event for omitting the events from the analysis) on distributions for event duration and rain rate (mm/event). Three years (October 2011- September 2014) of impact-type disdrometer data collected at NARL, Gadanki have been used as it provides 1-min. rain rates (Rao et al. 2001).

The distributions for event duration and rain rate have been generated by employing three different temporal intervals for separating rain events, 25, 60 and 120 minutes. As expected, the distributions for rain duration shifted to longer durations with the increase in time for shower separation. Nevertheless, the rain rate distribution remained nearly the same. The impact of omission of data with rain rates < 0.5 mm/event is also found to be negligible.

During the SWM, the statistics of rain events in two western quadrants are different from that of eastern quadrants. It is clear from Figure 3a and Table 2 that both duration of the event and rain accumulation within the event are larger in quadrants 1 and 3 than in 2 and 4. The difference is quite pronounced in the case of extreme rainfall events (i.e., 90^{th} percentile). Over the study region, the long lasting events that produce copious rainfall generally occur during the late night - midnight period ~~in~~ during active monsoon spells. Mohan (2011), using Hovmöller diagram of 3-hourly TMPA rainfall, has shown that these long-lasting rain bands are propagating systems from the west coast ~~and ascribed the propagation to wind shear-cold pool interaction.~~ These systems start propagating from the west coast in the evening and reach the study region, which is nearly 400 km from the west coast (see Figure 1a), around the mid-night. Inspection of background meteorological parameters like low-level wind shear and convective available potential energy (CAPE) reveals that the propagation could be associated with wind shear-cold pool interaction on the down shear regime (Weisman and Rotunno 2004). The intensity of propagating systems gradually diminishes as they move from the west to east. At times, these propagating systems produce rainfall over the ~~stations~~ gauge locations in the western quadrants, but not in eastern quadrants because the rain bands dissipate before reaching the eastern quadrants. This is depicted in pictorial form in Figures 4a and 4b for SWM and NEM, respectively, showing the event duration and rain accumulation as a function of local hour in all quadrants. The number, duration and rain accumulation of events during ~~night late night (~~19 - 04 IST (Indian standard time)~~)~~ ~~are clearly higher~~ in the western quadrants ~~than~~ exceeds those in eastern quadrants. Also, events with longer duration and greater rain accumulation are almost absent during the morning-noon period (08-12 IST) in the western quadrants, while a few such events exist in the eastern quadrants. It is strikingly apparent from Figure 4a that there is a clear diurnal pattern in event duration in all 4 quadrants, though the pattern appears to be smeared in the eastern quadrants. The eastern quadrants, being relatively closer to the coast, may sometimes get rain due to sea-breeze intrusions (Simpson et al., 2007). This coupled with the inability of some propagating systems to reach these quadrants appear to be the reasons for a different diurnal pattern.

Significant regional variability is also observed in rain duration and accumulation during the NEM, wherein the northern quadrants (numbered 1 and 2) experience long lasting events with more rainfall than their counterparts in the southern quadrants (numbered 3 and 4) (Figures 3b and 4b). Almost all the long-lasting events in northern quadrants (1 and 2) produced significant amount of rainfall (> 20 mm), while it is not the case in southern quadrants.~~, where several events having durations > 6 hr. produced a rainfall < 20 mm.~~ The north-south regional differences are distinctly apparent in extreme rainfall cases also (90^{th} percentile) (Table 2). Events ~~of~~ with longest duration and highest rainfall, on the other hand, are seen in the eastern quadrants. For example, the 4^{th} quadrant has 6 events with longer than 10 hours duration with one event producing rainfall continuously for nearly one day (1425 min). This event is associated with a cyclone, ‘Neelam‘, that passed close (~50 km south of Gadanki) to the observational site on 31 November 2012. In fact, this cyclone has produced steady rainfall over several rain gauge ~~stations~~ locations leading to long-lasting events (16 events with duration longer than 6 hours are observed during the passage of Neelam~~ with duration longer than 6 hours~~). This number increased to 53, when events with 3 hours or longer are considered. The observed IQR for rain duration also shows a different pattern during the NEM, where the values in all quadrants are not significantly different from each other. In contrast to the clear diurnal pattern in rain events and duration during the SWM, the NEM does not show any clear signature of diurnal pattern.

4.3. Diurnal variability

Figure 4 clearly demonstrated the diurnal pattern in number of events and duration in both the monsoon seasons. This section further discusses the spatial and seasonal variability in the diurnal cycle of rainfall. The diurnal variation is the fundamental mode of variability in the precipitation time series and the time of occurrence of maximum rainfall depends on several factors, like the underlying surface (land or ocean), mesoscale circulations, topography, etc. (Nesbitt and Zipser, 2003, Janowiak et al., 2005; Yang and Smith, 2006; Kikuchi and Wang, 2008). Since the study region is located in a complex hilly terrain and is about 75-125 km from the coast, several mesoscale circulations triggered by topography and land-sea contrast, besides the propagating systems could alter the rainfall pattern. To better understand these processes ~~in~~ during SWM and NEM, the diurnal variation of rainfall at each ~~station~~ location has been studied during the two monsoon seasons.

The ~~conditional~~ mean hourly rainfall (hourly accumulated rainfall from all the days in a season/number of days) time series at each ~~station~~ gauge location is subjected to harmonic analysis. The amplitude and phase of the diurnal cycle, thus obtained, at each ~~station~~ location is depicted in Figure 5 for both SWM and NEM. The arrow magnitude and direction represent the amplitude and phase (time of maximum rainfall in the form of a 24 hr. clock) of the diurnal cycle, respectively. For instance, the arrow pointing up (0°), right (90°), down (180°) and left (270°) denote, respectively, the rainfall maxima at 00, 06, 12 and 18 IST. The statistical significance of the amplitude is evaluated by using the F-statistic (Anderson, 1971). Statistically insignificant amplitudes are shown with blue arrows. The topography is also shown in the figure (shading) for easy visualization of mountain effects, if any, on the diurnal cycle.

Clearly, the rainfall shows distinctly different diurnal cycles ~~in~~ during SWM and NEM. Except for one ~~station~~location, the diurnal cycle is significant with large amplitudes at all locations ~~stations~~ during the SWM. Though the diurnal cycle is insignificant at one location ~~station~~ (station numbered 10), the seasonal rainfall at this location~~station~~ doesn't show any anomalous behavior (the seasonal rainfall at this location~~station~~ is nearly equal to that of its surrounding locations~~stations~~). On the other hand, the diurnal cycle is insignificant at several locations ~~locations~~ (15) during the NEM. Even ~~at~~ those locations~~stations, where~~ at which the diurnal variation is significant, the amplitudes are smaller than those observed ~~in~~during SWM. For instance, during the SWM, 17 locations~~stations~~ show diurnal amplitudes larger than the largest diurnal amplitude in NEM. On average, the diurnal amplitudes are larger by a factor of ~ 2 in SWM ~~are larger~~ than ~~that~~ in NEM~~ by a factor of ~2~~.

The diurnal cycle also exhibits spatial variability during both monsoon seasons. The diurnal cycle is stronger in ~~the~~ western quadrants of the study region during the SWM, as evidenced by the large diurnal amplitudes. Though several rain events occur during the afternoon - evening period (~40% of total events occur during 14 - 19 IST), most of them are short~~-~~lived and contribute only 30% to the seasonal rainfall. On the other hand, 50% of total events occur during ~~the late night-midnight period~~20 - 00 IST, but they occupy ~60% of seasonal rain amount (Figure 4). Among 4 quadrants, the rain fraction by events occurring during ~~the late night-mid~~

~~night hours~~ 20-00 IST is highest in western quadrants (1 and 3, wherein ~~the rain fraction~~it exceeds 62 - 67%). The diurnal cycle shows a broad peak during ~~the late night-mid night (~~~20 - ~~12~~ 00 IST~~)~~ at all the ~~stations~~ locations with maxima at 21 IST. One would expect an evening peak in the diurnal cycle of rainfall over the land, ~~where~~ when the convective instability induced by solar heating ~~during the day~~ increases, resulting cloud formation and precipitation. However, the diurnal cycle in rainfall in the study region peaks much later and this peak is primarily associated with the propagating systems (Mohan, 2011).

During the NEM, except for 6 ~~stations~~ locations that show an evening peak (16-18 IST) in the diurnal cycle, all other ~~stations~~ locations (30) depict a broad peak during ~~the evening-late night~~ ~~(~~18 - 22 IST~~)~~. In this season, the rainfall is governed by a variety of processes, like depressions/cyclones originated in adjoining Bay-of-Bengal, small-scale evening thunderstorms, advection of ~~morning-time~~nocturnal precipitating systems from Bay-of-Bengal, mountain-induced rainfall (either by lifting the moist air reaching the study region with the synoptic flow or by generating convergence zones for convection during the night). These processes generate rainfall that either doesn't show any diurnal cycle (like cyclones) or peaks at different timings (solar heating-induced convection peaks ~~in~~ during the evening, rainfall due to advection from Bay-of-Bengal in the morning, mountain-induced rainfall during the night), producing a weaker (in some cases insignificant) diurnal cycle of rainfall. The spatial variability in the diurnal cycle is also considerable with majority of the ~~stations~~ locations in the eastern quadrants showing significant diurnal cycle. ~~, while it~~Contrary, the diurnal cycle is insignificant at several ~~stations~~ locations in the western quadrants.

The present study mainly focuses only on the first harmonic (24 hr. component) of the diurnal variation, as it is regarded as the dominant mode by earlier studies elsewhere. To examine this issue and also to quantify how much variance the 24-hr component explains in the total variance, both total variance and variance due to 24-hr harmonic are estimated. Figure 5c shows the contribution of 24-hr harmonic to the total variance at each rain gauge location during SWM and NEM seasons. It is clearly evident from Figure 5c that the 24-hr component is the dominant mode in the diurnal variation of rainfall during the SWM. It explains 40-90% of the total variance of the diurnal cycle at different locations with an average contribution of ~70%. Only one station (No. 10), where the diurnal cycle is insignificant (Figure 5a), shows less contribution ~~from~~ to the diurnal ~~cycle~~variance. On the other hand, the contribution of 24-hr harmonic to the total variance is mere ~30% (on average) during the NEM, indicating that other high frequency modes might be important during the NEM. Also, the diurnal component contributes < 20% to ~~its~~ the total variance at several locations (1/3 of total number of ~~stations~~locations). As discussed above, several processes including the evening convection, early morning rain due to oceanic clouds, wide spread and continuous cyclonic rain weaken~~s~~ the diurnal cycle during the NEM.

4.4 Spatial correlation

To understand the similarities and differences in spatial coherence of rainfall between the two monsoon seasons, correlation analysis is performed. Earlier studies have shown the usefulness of such analysis in gauge-satellite comparisons, hydrological and meteorological modelling and setting-up gauge networks (Habib et al., 2001; Krajewski et al., 2003; Ciach and Krajewski, 2006; Villarini et al., 2008; Liechti et al., 2012; Luini and Capsoni, 2012; Mandapaka and Qin, 2013, Li et al., 2014, Chen et al., 2015). Spearman correlation coefficients have been computed between each pair of rain gauge ~~stations~~ locations for different rain accumulation periods. In the present study, 4 accumulation periods are considered (1, 3, 12 and 24 hr.) to understand the spatial correlation structure on varying rain accumulation periods (temporal scales).

The spatial correlation of rainfall between different rain gauge ~~stations~~ locations at different rain accumulation periods (1, 3, 12 and 24 hr.) is plotted as a function of gauge distance in Figure 6 (a for SWM and b for NEM). The spatial correlation distance is obtained by fitting a modified exponential model on the data samples in correlograms (intergauge correlation coefficient vs. intergauge distance), as given by Ciach and Krajewski (2006),

$$\rho(d) = \rho_0 \, exp\left[-\left({}^{d}/_{d_0}\right)^{s_0}\right] \qquad (1)$$

where $\rho_0$is the nugget parameter signifying the local decorrelation (caused by random instrumental errors), d is the distance between the pair of gauges (varies from ~~4.2~~6 to 73.5 km in the present study), d_0 is the correlation distance (or scale parameter) and s_0 is the shape parameter. The integration time, d_0 and s_0 are also depicted on the figure for ease of comparison.

It is clearly evident from Figure 6 that the correlation decreases with increasing gauge distance and increases with the accumulation time, consistent with earlier studies (Krajewski et al., 2003; Villarini et al., 2008; Luini and Capsoni, 2012; Li et al., 2014). The steepest decrease of correlation is observed with 1 hr. integrated rain, which shows insignificant correlation (<0.2) after ~30 km. Further, the spatial correlation (in terms of correlation distance and slope) varies rapidly with time scales up to 3 hours, but remains nearly the same for rain accumulations of 12 and 24 hr. The correlograms for all rain accumulations show large scatter around the model curve even at shorter gauge distances. The large scatter indicates that the rainfall in the study region is quite variable both in space and time. Because of this large variability even at shorter distances, the nugget parameter shows values in the range of 0.8-0.95 (for different accumulations). These features are observed ~~in~~ during both monsoon seasons, albeit with differing slopes and correlation distances. The correlation characteristics exhibit some seasonal variation for all rain accumulations, as evidenced by different correlation distance and slope values during SWM and NEM. The correlation distances (slope) during the NEM are found to be larger than in SWM, indicating higher spatial correlation of rainfall ~~in~~ during NEM. The observation of weaker correlation ~~in~~ during SWM than in NEM is consistent and analogous to earlier reports that show smaller correlation distances during summer than in winter (Baigorria et al., 2007; Dzotsi et al., 2014; Li et al., 2014). Weak correlation in summer is attributed to the large spatial variability of rainfall due to highly localized and short-lived convective systems (Krajewski et al., 2003; Dzotsi et al., 2014; Li et al., 2014). It indeed is true that such systems occur frequently during the SWM over the study region (Figures 3 and 4).

5. ~~Evaluation~~ Validation of high-resolution MPEs

As mentioned in Section 1, several evaluation studies exist in the literature focusing on the assessment of seasonal rainfall over India (Uma et al., 2013; Prakash et al., 2014; Sunilkumar et al., 2015), but none of them dealt with high-resolution (temporal) measurements. This aspect has been studied in detail in this section, in which the focus is primarily on the ~~evaluation~~ validation of high-resolution MPEs using a variety of metrics and statistical distributions ~~of MPEs~~ and also on the diurnal cycle of rainfall. As seen in Table 1, MPEs provide precipitation information ~~on precipitation~~ with different temporal and spatial resolutions. For proper assessment of MPEs, they need to be uniform and should match with the reference. First, all MPEs are temporally integrated for 3 hours and then remapped onto 0.25° x 0.25°. The study region, therefore, will have 4 satellite grid points. Among them, one grid point is chosen (for the ~~evaluation~~validation) (13.375° N, 79.125 E) in such a way that the grid point is close to the center of the network and the rainfall and terrain are somewhat homogeneous around that grid (dashed box covering a region of 0.25° x 0.25° in Figure 1c). Moreover, the diurnal cycle at all ~~stations~~ locations (9 in number) within the selected region is somewhat similar. The intergauge spacing within the selected region is in the range of 6-12 km, which is much smaller than d_0 of 3-hourly rainfall in this area (Figure 6). It is known from earlier studies that the density of operational gauges is often too small to resolve the rainfall variations at smaller scales (Habib et al. 2009). However, the 6-12 km inter~~-~~gauge distance employed here is almost equal to the highest resolution given by MPEs (i.e., 8 km by CMORPH) and therefore they can serve as a reference for ~~evaluating~~ validating high-resolution MPEs. However, to match the resolution of other MPEs (0.25° x 0.25°), the rainfall data at the selected grid is obtained by interpolating (using inverse distance weighting) the data at all the ~~stations~~ locations within the selected region. Further, to discard the rain data arising due to the gridding, a rain threshold of 0.5 mm per 3 hr. is used as a lower threshold to discriminate the rain from no rain.

The ~~evaluation~~ validation of rain rates generated by MPEs is performed in a statistical way by comparing the cumulative distributions of 3-hr rain rates ~~for~~ by MPEs with ~~that for~~ rain gauge network (Figure 7). Note that the frequency bins of cumulative distribution are taken for logarithmic values of 3-hr rain rates. Figure 7 clearly shows that all MPEs severely underestimate the drizzle rain having rain rates less than 0.8 mm 3hr^{-1}. Although the underestimation at low rain rates is seen ~~in~~ during both monsoon seasons, ~~but~~ it is severe in NEM. Later it will be shown that this underestimation is partly due to MPEs inability to detect the light rain and partly due to the underestimation of rain rates in light rain (to values < 0.5 mm 3hr^{-1}, the threshold used to detect the rain). Among different data sets, the underestimation is severe in the case of TMPA, but is less in PERSIANN. While the distributions for MPEs and reference show a very good agreement for rain rates 1 - 8 mm 3hr^{-1}, but all MPEs overestimate rain rates during the moderate-heavy rain (8 - 20 mm 3hr^{-1}). The PERSIANN hardly shows rain rates greater than 25 mm $3hr^{-1}$. Nevertheless, the number of samples in higher rain rate bins is quite small and need to be dealt carefully.

All MPEs are~~, then, evaluated~~ validated for their detection capabilities and also for quantifying the root mean square error (RMSE) at two temporal resolutions (3-hr and 24-hr). While 3-hr corresponds to the highest temporal resolution that most of MPEs provide, the 24-hr rain accumulation is the commonly used temporal integration in such evaluation studies (Ebert et al., 2007; Habib et al., 2012; Sunilkumar et al., 2015 and references therein). Table 3 shows ~~evaluation~~ validation statistics in terms of detection metrics (in %) (Probability of detection (POD~~) (i.e.,~~- both reference and MPEs detect the rain correctly), false alarm ratio (FAR~~) (~~- MPEs detect the rain wrongly), misses (missing rain~~) (~~- MPEs fail to detect the rain)), and accuracy metrics (correlation coefficient and RMSE~~) (~~; Ebert et al., 2007; Sunilkumar et al., 2015 for formulae). The detection metrics clearly show marked differences between the seasons and also between MPEs within the season. All MPEs exhibit good detection skills of rain at 3- and 24-hr temporal resolutions, however, the 24-hr accumulation provides relatively better statistics (higher POD ~~in~~ during both seasons). Although the detection skills of all MPEs improve~~s~~ with higher temporal accumulation, the degree of improvement varied from season to season and also between different data sets. It varied by ~20-65% during the SWM, but the improvement is only marginal for 3 data sets ~~in~~ during NEM (<20%, but only TMPA shows considerable improvement in POD with longer rain accumulation).

The FAR values ~~evaluated~~ validated at 3-hr accumulation are quite small and show large seasonal differences. Examination of data reveals that these small values are due to the large number of non-rainy data points in the reference data (it appears in the denominator). Nevertheless, the FAR values increase with temporal accumulation and are nearly comparable with those available in the literature (Sunilkumar et al., 2015). The study region being a semi-arid region with dry atmospheric conditions, evaporation of falling rain is found to be significant with higher fraction of virga rain (predominant ~~in~~ during SWM) (~~Rao et al., 2009~~Radhakrishna et al. 2008; Saikranthi et al., 2014). Since MPEs depend mostly on cloud top temperature or ice scattering signature for deriving rainfall over the land, significant evaporation of falling rain and higher fraction of virga rain results larger FAR values (Sunilkumar et al., 2015). For the same reason, the missing rain is expected to be less. Contrary, the missing rain is found to be quite high in both monsoon seasons, particularly with 3-hr rain accumulation data. Although with 24-hr accumulation, the fraction of missing rain ~~has~~ reduced considerably during the SWM, but not in NEM. Interestingly, the observed percentage of missing rain is comparable to that obtained by Sunilkumar et al. (2015) ~~in the southeast peninsular India~~ using an independent data set as the reference (1° x 1° gridded operational rainfall data set). The reasons for higher fraction of missing rain ~~in~~ during NEM even with longer time integration are not immediately obvious. Several possibilities exist for the observed large fraction of missing rain ~~in~~ during NEM, like higher occurrence of weaker rain, the underestimation of weak rain (0.5-1 mm $3hr^{-1}$) by MPEs, higher occurrence of shallow rain ~~in NEM~~. The data are examined for the existence of such ~~data~~ instances in both the seasons. The occurrence percentage of weak rain with rain rates 0.5-1 mm $3hr^{-1}$ is found to be high (~35%) and nearly equal in both monsoon seasons, indicating that it may not be the real cause. The second aspect, the underestimation of rain rates by MPEs, could be a decisive factor, particularly in the presence of considerable fraction of weaker rain. If the underestimation of MPEs is such that the 3-hr rain accumulation by MPEs is <0.5 mm hr^{-1}, then the algorithm considers it as missing rain. Such cases, indeed, exist in the data and are more frequent during the NEM than in SWM, but certainly they are not enough to explain the higher missing rain in NEM. Even if we include them as rain, the missing rain reduces only by 5%. The third aspect is higher occurrence of shallow rain. Earlier studies have shown that the rain top height is indeed low with higher occurrence of shallow rain ~~in~~ during NEM in the study region (Saikranthi et al., 2014). It is also known from earlier studies that most of MPEs suffer in identifying the shallow rain, particularly in the vicinity of mountains (Sunilkumar et al. 2015). Therefore any of the above and or all could be the reasons for the higher occurrence of missing rain ~~in~~ during NEM.

The correlation of rainfall between MPEs and reference is quite weak and insignificant at 3 hr accumulation, but improved considerably and is significant at 24-hr rain accumulation. The correlation coefficient does not show any clear seasonal difference. On the other hand, the RMSE clearly shows seasonal differences with smaller values in SWM than in NEM. Overestimation of heavy rain coupled with higher fraction of missing rain and lower fraction of POD are contributing considerably to higher RMSE in NEM. The RMSE increases with the integration time in both monsoon seasons and the daily~~-~~RMSEs are comparable in magnitude with those available in the literature (Sunilkumar et al. 2015).

Among different MPEs, ~~the~~ PERSIANN appears to overdetect the rain as evidenced by larger POD and FAR and smaller missing values. However, because of its inability to detect very heavy rain (> 25 mm hr^{-1}, not shown as a separate figure but can be seen from Figure 7 ~~(but with 3 hour rain accumulation)~~) and overdetection of rain, PERSIANN produces weak correlation with the reference and large RMSE. This feature is more prominently observed during the SWM. On the other hand, TMPA performs poorly at 3-hr resolution with higher (smaller) values of misses, FAR and RMSE (POD ~~and correlation coefficient~~) when compared to other MPEs. However, TMPA improves tremendously and provides much better precipitation estimates at longer temporal integration in both the monsoon seasons~~, probably due to gauge adjustment that corrects the overall bias~~. Examination of detection and accuracy metrics in Table 3 reveals that CMORPH-derived precipitation estimates are the best among all MPEs at 3-hr resolution.

~~Evaluation~~ Validation of the diurnal cycle of rainfall could be more intriguing, ~~because~~as it is not only poorly represented by numerical models (Betts and Jakob, 2002; Nesbitt and Zipser, 2003), but also distinctly different in different seasons over the study region (Figures 4 - 6). Figure 8 shows the comparison of diurnal cycle (with 3-hr unconditional rain rate) obtained by MPEs and reference in both ~~the~~ monsoon seasons. Clearly the diurnal cycle is quite strong during the SWM and all MPEs captured the basic shape of the cycle, with nocturnal maximum and morning-noon minimum, quite well. However, all MPEs overestimate the rainfall rate, albeit with different magnitudes, almost throughout the day. The overestimation is severe (as high as a factor of 5) in the case of PERSIANN, while others show relatively small overestimations. While the amplitude of the diurnal cycle by all MPEs is nearly equal, the phase is different for different MPEs. The reference data set peaks at 15 UT (universal time = IST - 05.30), which is equivalent to 20.30 IST. All MPEs capture the peak with a time lag/lead. While PERSIANN peaks 3 hours prior to the reference-peak time, others peak 3-6 hours later. It is known from earlier studies that MPEs that depend heavily on IR data shows a lagged diurnal cycle due to the lag between the detection of clouds and the occurrence of rainfall at the surface (Sorooshian et al., 2002; Janowiak et al., 2005). Though all MPEs considered here use microwave data, IR contribution appears to dominate the final rainfall product, at least in the case of PERSIANN. On the other hand, MPEs fail to reproduce the weak/insignificant diurnal cycle during the NEM. All MPEs show significant diurnal cycle, albeit with smaller amplitude than in SWM, with a broad peak centered on 15 UT. Except during the evening - midnight, the rain rates derived by MPEs and the reference agree fairly well. The overestimation of seasonal rainfall is also probably due to the overestimation of rain intensity during the evening-midnight period. The overestimation is severe in the case of PERSIANN, similar to that of in SWM.

6. Conclusions

This paper describes the establishment of a dense rain gauge network, its geometric configuration and the quality assurance tests employed to generate high-quality and high-resolution rainfall data. The network consists of 36 rain gauges with an inter-gauge distance of 6-12 km spread over an area of 50 km x 50 km, which makes the network much denser than the operational networks in India. The locations have been chosen to have a near uniform distribution and considering several practical issues, like accessibility by road, mobile coverage for data transfer and security. The high-resolution rainfall measurements have been used to understand the small-scale variability (in space and time) in rain storms and also for ~~evaluating~~ validating 4 widely used MPEs. A suite of statistical error metrics (detection and accuracy) are employed for this purpose. Important results of the analysis are summarized below.

1) Morphological features of rainfall (like spatial distribution and seasonal rain fraction) are consistent with earlier reports. Though the number of large-scale/long-lived systems (active monsoon spells) is equal in both the seasons, the average duration of each spell is larger ~~in~~ during the SWM (6.9 days) than in NEM (4.4 days). These large-scale systems contribute more than 60% of seasonal rainfall in NEM at ¾ of the ~~stations~~ locations in the network, whereas the contribution from small-scale/short-lived systems is found to be significant ~~in~~ during the SWM (almost equal to that of large-scale systems). Majority of these large-scale/lon-lived systems are due to the passage of cyclones ~~in~~ during NEM and due to propagating systems from the west coast during the active monsoon spell in SWM.

2) The cumulative distributions for rain ~~storm~~ duration and intensity (rain accumulation within the storm) show~~s~~ regional differences. These regional differences are more pronounced in the 90th~~%~~ percentile of storm duration and accumulations. The western quadrants experience longer rain duration ~~storms~~ events with more rain accumulation~~s~~ in SWM. On the other hand, such ~~systems~~ events ~~occur~~ are seen more frequently in northern quadrants ~~in~~ during NEM. While the number ~~of rain events~~ and duration of events clearly show a diurnal pattern ~~in~~ during the SWM, such pattern is absent in NEM.

3) The diurnal cycle exhibits marked seasonal and spatial differences within the study region. The diurnal amplitudes are significant and large during the SWM, while they are insignificant at many locations and also small during the NEM. On average, the diurnal amplitudes are larger ~~in~~ during SWM than that in NEM by a factor of ~2. Further, the diurnal cycle explains 70% of total variance in SWM, but only 30% in NEM. Large diurnal amplitudes are found in western quadrants during the SWM and in eastern quadrants in NEM. The propagating systems in SWM appear to be responsible for the observed late night-mid night peak. During the NEM, ~~On the other hand,~~ the rainfall occurs ~~in NEM~~ due to a variety of processes that either do not have any diurnal cycle or peak at different timings of the day, making the diurnal cycle weak and/or insignificant.

4) A modified exponential function has been fitted to paired correlations in both seasons for different temporal rainfall accumulations. Clearly, the correlation increases with increasing integration period up to 12 hr. ~~integration, however~~However, not much improvement is seen in the correlation with further integration. The correlation falls rapidly when the high-resolution data (1 hr.) are employed for the analysis in both monsoon seasons with correlation becoming insignificant after an intergauge distance of

~30 km. Some seasonal differences are seen in the correlation distance, but the differences are not pronounced. The scatter in the correlograms is wide spread along the fitted exponential curve for all accumulation periods in both monsoon seasons, signifying the complex variability of rainfall within the study region.

5) Comparison of cumulative distributions for MPEs and reference indicates that all MPEs severely underestimate the weak ~~and heavy~~ rain. The MPEs exhibit good detection skills of rain at both 3-hr and 24-hr resolutions, though considerable improvement is seen with 24-hr resolution data. The FAR values ~~evaluated~~ validated at 24-hr resolution are nearly equal with those obtained in earlier studies with a different independent dataset (Sunilkumar et al., 2015), indicating the consistency with different datasets. ~~Surprisingly,~~ ~~t~~The missing rain is found to be significant at higher resolution in both monsoon seasons. Though the occurrence of missing rain reduced considerably in the SWM at 24-hr resolution, such reduction is absent in NEM. Possible causes (underestimation of weaker rain and predominance of shallow rain) for the higher occurrence in NEM are examined. Among various MPEs, the performance of TMPA is found to be poor at 3-hr resolution, but improves tremendously with 24-hr integrated data. CMORPH produces best 3-hr resolution precipitation products in both monsoon seasons, as evidenced by better accuracy and detection metrics (Table 3).

6) All MPEs captured the basic shape of the diurnal cycle and the amplitude quite well ~~in~~ during SWM, but they overestimate the rainfall throughout the day. They fail to reproduce the insignificant diurnal cycle ~~in~~ during NEM, rather MPEs show a significant diurnal cycle in NEM, albeit with a relatively smaller amplitude.

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Figure captions

~~Figure 1: a) Location of rain gauges (indicated with stars) in the meso-rain gauge network. The shading represents the topography (m). The region is divided into 4 quadrants and each quadrant is numbered as 1, 2, 3 and 4. The data in dashed box are used for the evaluation of MPEs. b) The ratio of measured and reference (calibrator – Young 52260) values at 3 rain rates are shown for each rain gauge location, illustrating the data quality by each gauge.~~

Figure 1: Spatial distribution of mean seasonal rainfall (shading) and wind pattern (arrows) on 850 hPa level during (a) SWM and (b) NEM. Note that the scales are different for SWM and NEM. The black solid contour line covering the north and central India indicates the monsoon trough. The red colored square box in Figure (a) indicates the region of rain gauges. (c) Location of rain gauges in the network (indicated with stars). The shading represents the topography (m). The region is divided into 4 quadrants and each quadrant is numbered as 1, 2, 3 and 4. The data in dashed box are used for the evaluation of MPEs. (d~~b~~) The ratio of measured and reference (calibrator – Young 52 260) values at 3 rain rates are shown for each rain gauge location, illustrating the data quality by each gauge.

Figure 2: Spatial distribution of average seasonal rainfall ~~during~~ for (a) SWM and (b) NEM. Also overlaid is the location of rain gauges.

Figure 3: Cumulative distributions for ~~storm rain~~event duration and rain accumulation within the event ~~of storms~~ in 4 quadrants (color-coded) of the study region during (a) SWM and (b) NEM, depicting the regional variability in rain ~~storms~~events.

Figure 4: Diurnal variation of ~~storm~~ event duration and rain accumulation in 4 quadrants of the study region during (a) SWM and (b) NEM. Accumulated rain (in mm) is shown in the color bar.

Figure 5: Diurnal variation of ~~conditional~~ rainfall at all rain gauge locations during (a) SWM and (b) NEM. The vector length and pointing arrows indicate the amplitude and phase (peak rainfall hour), respectively, of the first harmonic. The shading and blue arrows indicate, respectively, topography and insignificant diurnal amplitudes. c) Percentage contribution of variance by first harmonic to the total variance at each rain gauge location during both monsoons.

Figure 6: Correlograms (correlation coefficient vs. intergauge distance) for 1 hr, 3 hr, 12 hr and 24 hr rain accumulations during (a) SWM and (b) NEM. The red curve indicates the fitted modified exponential function to the data. The accumulation period, slope of the curve and spatial correlation distance are also shown in each plot.

Figure 7: Cumulative distributions of rain rate (mm/3hr) for various MPEs (color-coded) and rain gauge network at (13.375° N, 79.125° E) (black curve) during (a) SWM and (b) NEM.

Figure 8: Comparison of diurnal variation of rainfall obtained by various MPEs and reference data set (rain gauge network) during (a) SWM and (b) NEM. The rain gauge data are integrated to match with the timings of MPE. Note that the time is given in universal time (UT).

Table captions:

Table 1: Table 1: Description of MPEs used in the present study, their data availability, spatial and temporal resolutions and input data used to generate the MPE with relevant references.

Table 2: Statistics of rain storms in each quadrant during SWM and NEM. The statistics include the number of storms and mean, ~~interquartile range~~IQR, 90^{th} percentile and maximum values for storm duration and accumulated rain within the storm.

Table 3: Table 3: Comparison of high-resolution MPEs with reference data in terms of detection (POD, MIS and FAR) and accuracy (RMSE and Correlation coefficient) metrics. The comparison has been made at two temporal integrations, 3 hr (first value) and 24 hr (second value).

Table 1: Description of MPEs used in the present study, their data availability, spatial and temporal resolutions and input data used to generate the MPE with relevant references.

Name of MPE (reference)	Data availability	Spatial and Temporal resolution	Basic input sensors data	Data accessibility and Technical documentation
CMORPH (Joyce *et al* 2004)	1998 - Till date	0.25°×0.25°, 3 hourly	PMW from DMSP 13,14&15(SSM/I), NOAA-25,16,17&18 (AMSU-B),AMSR-E and TMI,IR motion vectors form geostationary satellite	http://ftp.cpc.ncep.noaa.gov/precip/CMORPH_V1.0/RAW/0.25deg-3HLY/
~~GsMAP~~ GSMaP (Okamoto *et al* 2005)	2010 - Till date	0.1°×0.1°, Hourly	GPM-core GMI,TRMM TMI, GCOM-W1 AMSR2, DMSP SSMIs, NOAA AMSU, MetOp series AMSU, and geostationary IR developed by GsMAP project.	ftp://hokusai.eorc.jaxa.jp/
PERSIANN (Hsu *et al* 1997)	1997 - Till date	0.25°×0.25°, 3 hourly	IR from GOES-8,10, GMS-5, METEOSAT - 6, 7 and PMW from TRMM,NOAA AND DMSP	http://chrs.web.uci.edu/persiann/data.html
TRMM 3B42 (Huffman *et al* 2007)	1997 - Till date	0.25°×0.25°, 3 hourly	TMI,AMSR-E,SSM/I,AMSU,MHS and microwave adjusted merged geo infrared (IR)	http://mirador.gsfc.nasa.gov/

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Table 2: Statistics of rain storms in each quadrant during SWM and NEM. The statistics include the number of storms and mean, ~~interquartile range~~IQR, 90th percentile and maximum values for storm duration and accumulated rain within the storm.

		Rain duration (min)				Accumulated rainfall (mm)			
Region/ Season	No. of Events	Mean	IQR	90th	Max	Mean	IQR	90%	Max
SWM									
1	674	64.5	55	169	456	6.58	6.2	17.4	70.8
2	792	55.3	47	123	423	6.04	5.6	16	81
3	774	70.1	52	193	592	6.65	6.5	17.8	76
4	670	58	47	133	462	5.83	4.6	14.2	86.4
NEM									
1	549	65.6	55	167	656	6.55	6.2	19.6	79.8
2	746	67.1	55	167	478	7.26	6.2	18.8	126
3	565	60.2	56	140	521	5.76	5.2	14.6	65.4
4	514	68	58	138	1425	6.02	5.1	14.4	99.6

Table 3: Comparison of high-resolution MPEs with reference data in terms of detection (POD, MIS ~~-~~and FAR) and accuracy (RMSE and Correlation coefficient) metrics. The comparison has been made at two temporal integrations, 3 hr (first value) and 24 hr (second value).

	SWM				NEM			
	CMORPH	**~~GsMAP~~GSMaP**	**TMPA**	**PERSIANN**	**CMORPH**	**~~GsMAP~~GSMaP**	**TMPA**	**PERSIANN**
RMSE	3.9, 7.8	4.4, 9.4	5.1, 7.7	4.1, 9.5	5.5, 13.8	6, 16.6	6.2, 10.2	5.4, 12.2
CORR.	0.4, 0.6	0.1, 0.3	0.2, 0.6	0.1, 0.3	0.3, 0.4	0.2, 0.5	0.3, 0.6	0.1, 0.5
FAR	8.3, 18.8	10.8, 24.4	8.2, 24.4	16.5, 46.1	3.6, 1.6	5.2, 7.2	2.9, 2.4	7, 12
MIS	32, 18.8	46.6, 18.8	50, 17.8	47.7, 13.8	42.5, 38.3	49.2, 38.3	53.3, 31.6	45, 40
POD	67.9, 81.8	53.3, 81.8	50.8, 82.1	52.2, 86.1	56.6, 61.6	50.8, 61.6	46.6, 68.3	55, 60

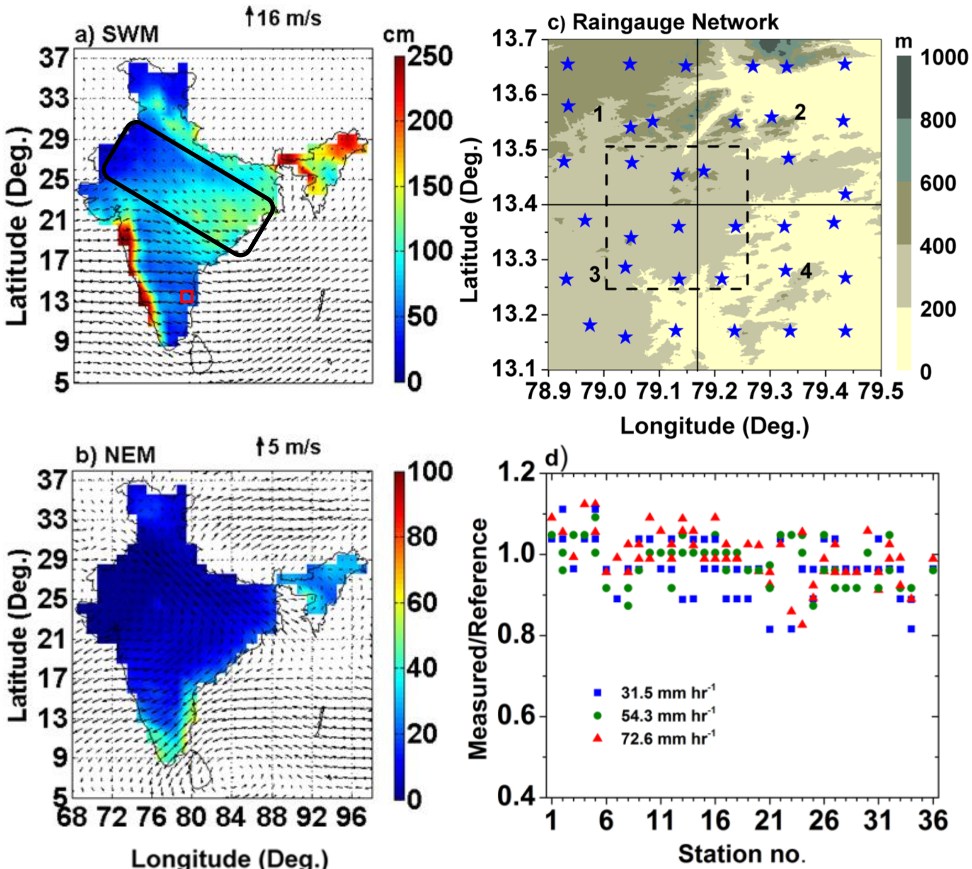


Figure 1: Spatial distribution of mean seasonal rainfall (shading) and wind pattern (arrows) on 850 hPa level during (a) SWM and (b) NEM. Note that the scales are different for SWM and NEM. The black solid contour line covering the north and central India indicates the monsoon trough. The red colored square box in Figure (a) indicates the region of rain gauges. (c) Location of rain gauges in the network (indicated with stars). The shading represents the topography (m). The region is divided into 4 quadrants and each quadrant is numbered as 1, 2, 3 and 4. The data in dashed box are used for the evaluation of MPEs. (d) The ratio of measured and reference (calibrator – Young 52 260) values at 3 rain rates are shown for each rain gauge location, illustrating the data quality by each gauge.

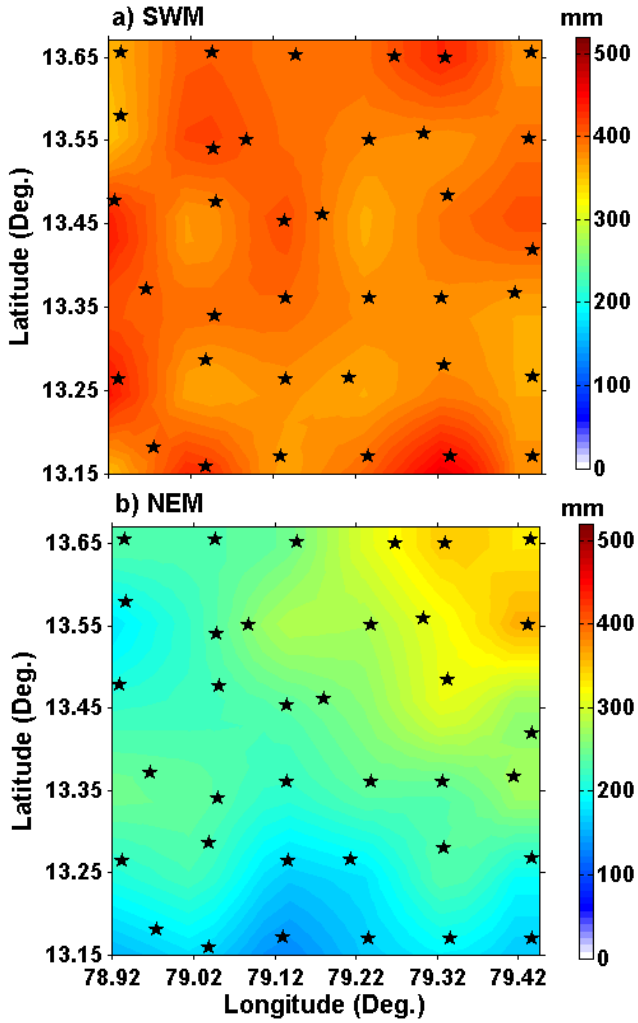


Figure 2: Spatial distribution of average seasonal rainfall for (a) SWM and (b) NEM. Also overlaid is the location of rain gauges.

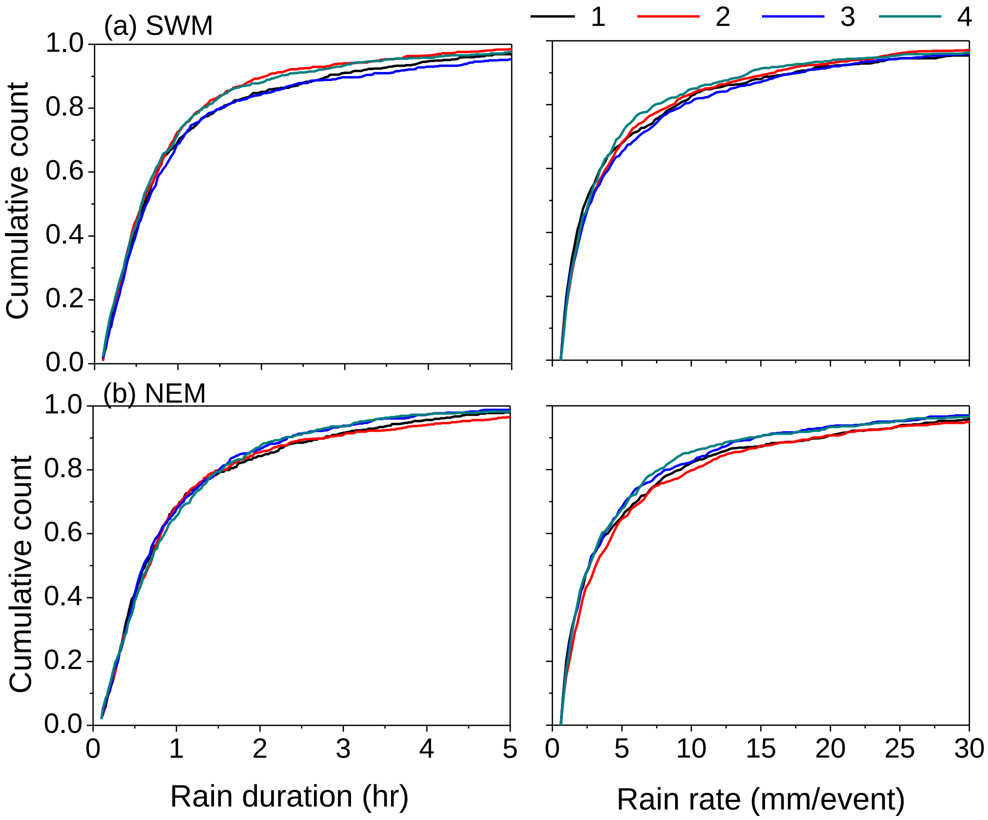
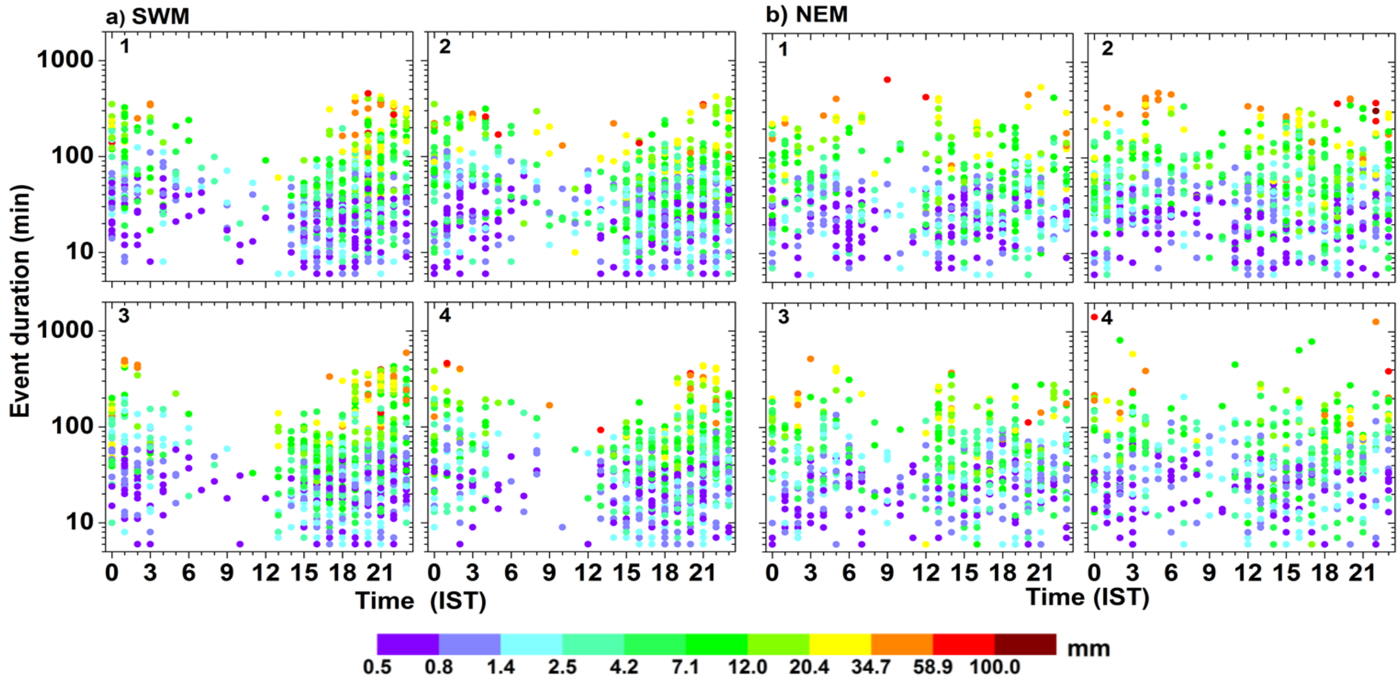


Figure 3: Cumulative distributions for event duration and rain accumulation within the event in 4 quadrants (color-coded) of the study region during (a) SWM and (b) NEM, depicting the regional variability in rain events.



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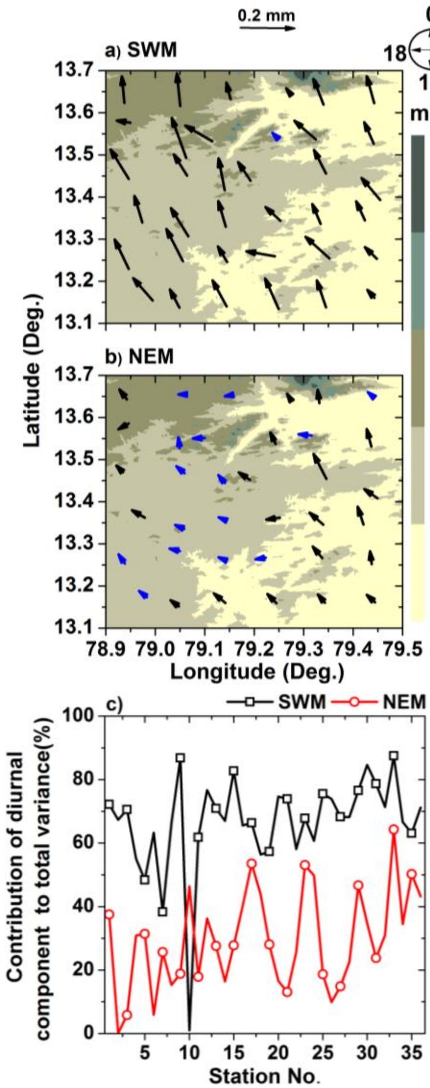

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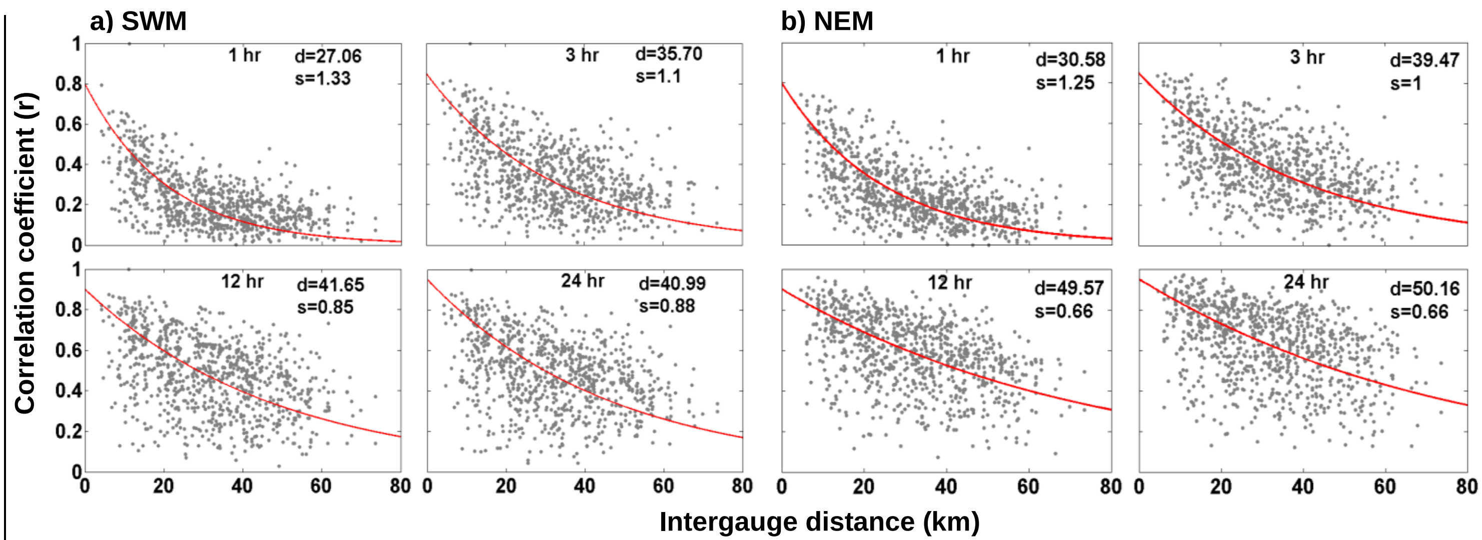

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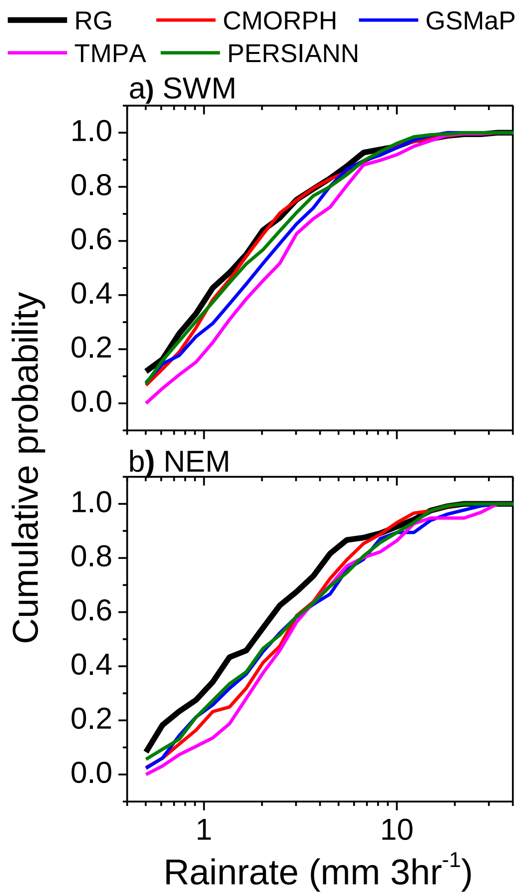

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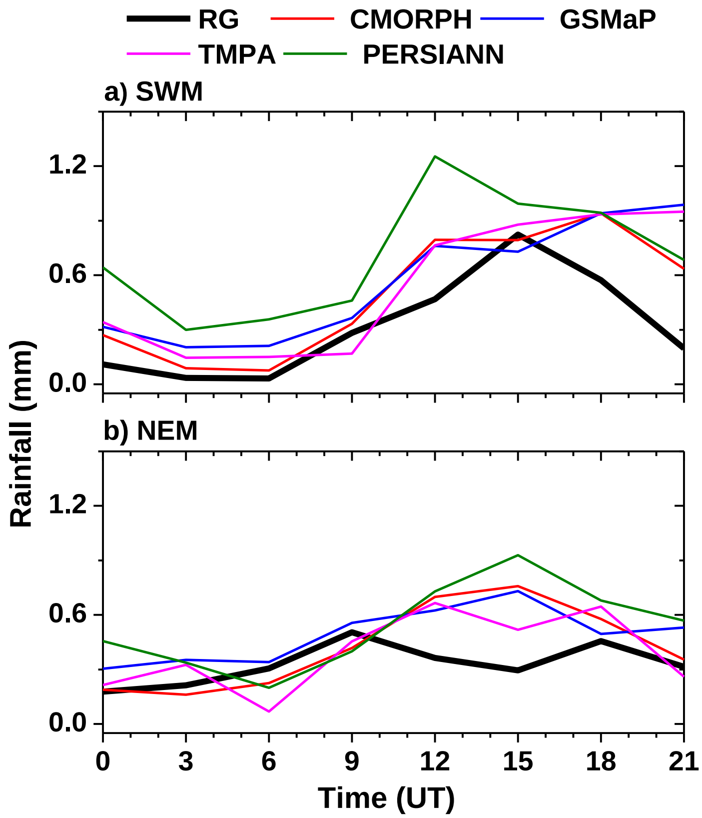

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