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

K. Sunilkumar, T. Narayana Rao, and S. Satheeshkumar

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.

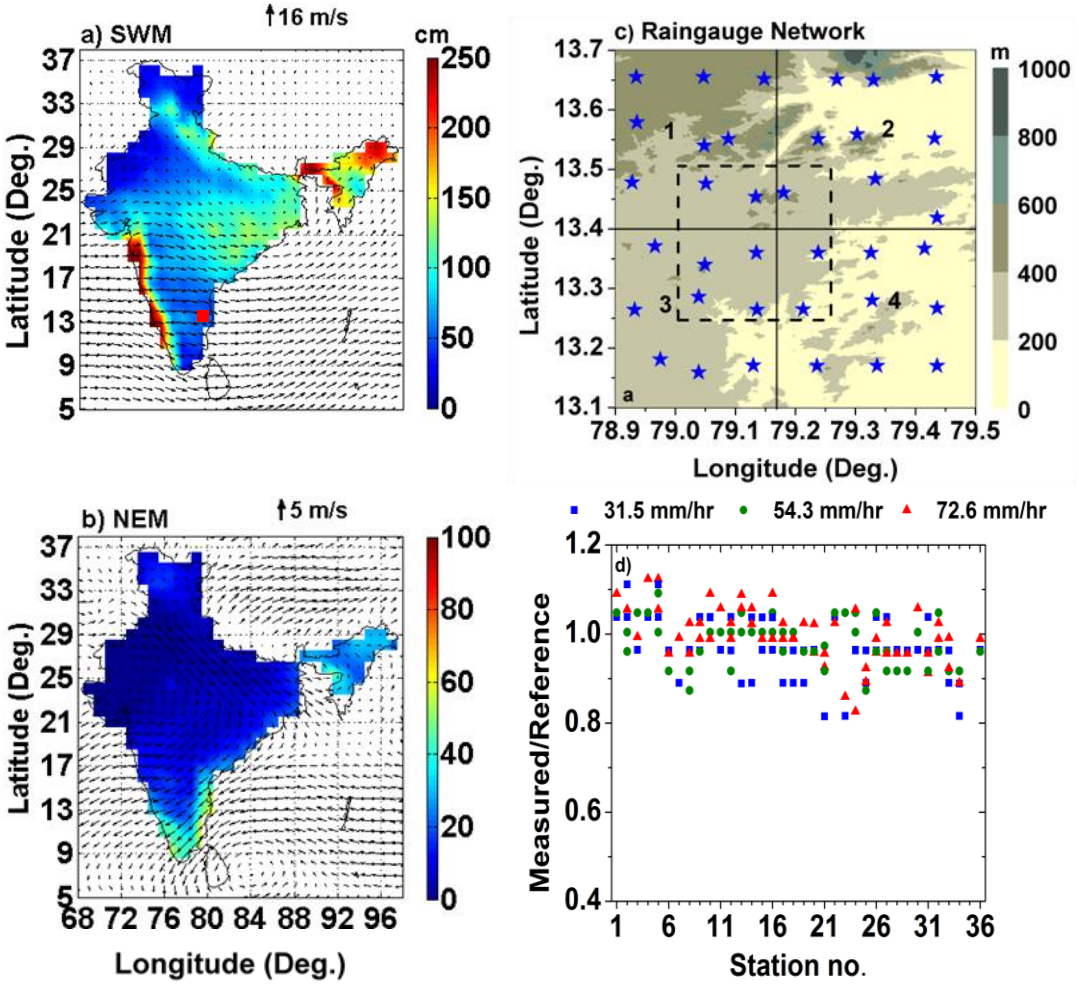

*Figure 1: Spatial distribution of seasonal rainfall (shading) and wind pattern (arrows) on 850 hPa level during **(a)** SWM and **(b)** NEM. Note that the scales are different for SWM and NEM. **(c)** Location of rain gauges in the network. The shading represents the topography (m). The region is divided 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 (It is explicitly indicated in the revised version). 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.

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.

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. Over the study region, cyclones occur during the NEM, but not during the SWM. During the SWM, 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.

No. 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 (probably covering cyclones/depressions/MCS) and small-scale (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 that 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 used 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. 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).

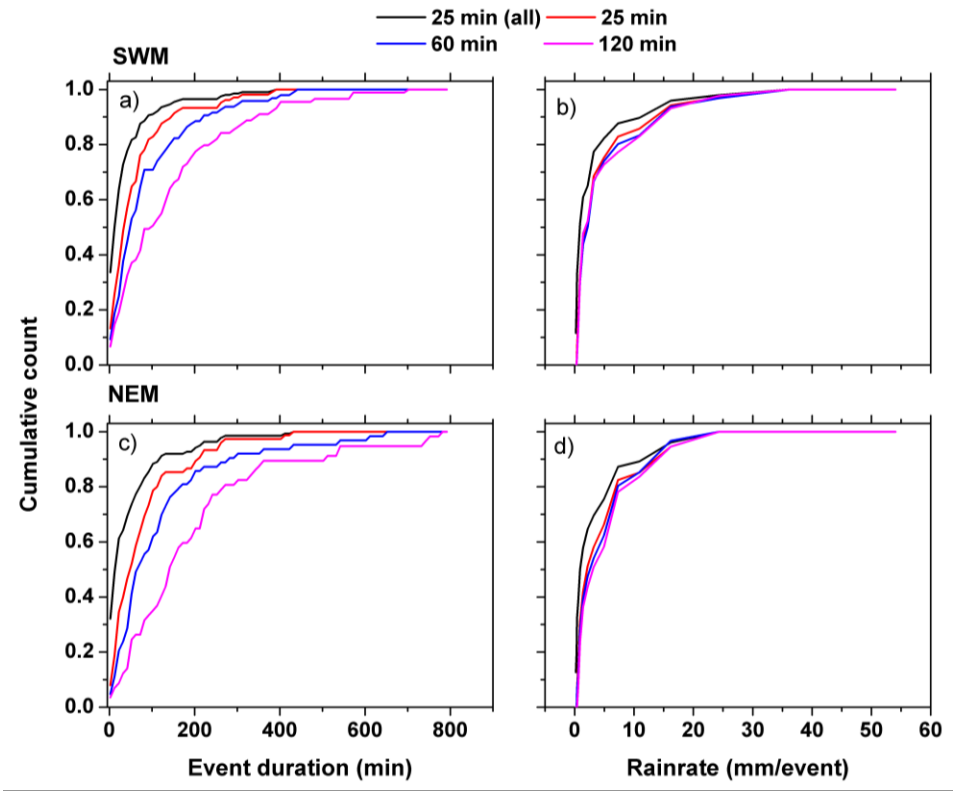

*Figure 2: Cumulative distributions for rain event duration and rain accumulation in the study region for a variety of thresholds for shower separation during **(a)** SWM and **(b)** NEM, depicting the sensitivity of the threshold used in the present study. It also shows cumulative distribution curves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

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

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.

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' 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 8.5-11 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.

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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 northeastward.

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 northeastward 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.