Authors' Response to the Reviewer Comments

Manuscript Ref.: hess-2017-533

Title: Assessment of the Weather Research and Forecasting (WRF) Model for Extreme Rainfall Event Simulations in the Upper Ganga Basin

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We sincerely thank the reviewers for their comments on the manuscript and offering their suggestions and critical input that has helped improve the manuscript. We provide here our replies to the reviewers' comments and highlight the changes made in the revised manuscript based on the comments. Sections which are modified in the revised manuscript are mentioned in this document.

<u>Responses to the comments of Referee #2:</u>

General Comments:

The paper provides results of a case study for an extreme event in northern India using WRF with multiple physics combinations. It evaluates rainfall primarily against observational data at stations and derived from TRMM. This focuses on the heavy rain period of 15-18 June 2013, and therefore conclusions about performance of the different simulations cannot be taken to be very robust in their usefulness for other cases. This limits the usefulness of this study. While it is interesting that certain physics combinations performed well and some parameterizations did well in several different combinations, it was not clearly presented.

Some physics schemes showed greater sensitivity to other schemes combined with C1 them, as seen in Fig. 10 for example. But showing the absolute difference hides some information that could have been seen from the difference itself that may have negative values.

It is also hard to determine signal from noise in Figures 7,8, and 11 when a station mean might have been of value in showing overall trends.

A major problem I have is with the use of CORDEX data. CORDEX is downscaled from climate model simulations and would therefore not be expected to bear any resemblance to real weather on any specific date. These are not comparable with weather models driven by real analysis boundary conditions. Sampling CORDEX on a particular date of a heavy rainfall event therefore will not be a fair comparison because it is more likely to miss such events entirely while it may have them on other days depending on which global data is used. It is no surprise that CORDEX runs underestimate heavy events on a particular date, which does not mean they underestimate them in general. Such data can only be used qualitatively to see if they can capture heavy events over many years that they are run using frequency analyses. I therefore suggest that the CORDEX part serves no value for this case study, and if the authors are using CORDEX it can only be in the context of the climatology of heavy events and whether the observed peak can be captured at other times of those runs. Maybe these runs never have such events, which may be useful to know, or maybe they have them too frequently, also useful.

Response:

"The paper provides results of a case study for an extreme event in northern India using WRF with multiple physics combinations. It evaluates rainfall primarily against observational data at stations and derived from TRMM. This focuses on the heavy rain period of 15-18 June 2013, and therefore conclusions about performance of the different simulations cannot be taken to be very robust in their usefulness for other cases. This limits the usefulness of this study. While it is interesting that certain physics combinations performed well and some parameterizations did well in several different combinations, it was not clearly presented."

We thank the reviewer for the comment. There are two notable changes made in the revised manuscript that directly address the concerns raised. First, we have taken off the CORDEX aspects since the focus was getting diluted regarding the overall goal of the paper; and second, we have built on the study by not restricting on a single case and in fact adding five additional heavy to extremely heavy rainfall events. These cases correspond to the individual month of the monsoon season (June to September), that occurred in the upstream region of the UGB and are now included in the revised manuscript to further strengthen the conclusions and the choice of physics scheme.

Action: The document is thoroughly edited and requisite changes are made in the revised manuscript. We hope the discussion on the results is clear now.

"Some physics schemes showed greater sensitivity to other schemes combined with them, as seen in Fig. 10 for example. But showing the absolute difference hides some information that could have been seen from the difference itself that may have negative values."

Response: We agree with the reviewer that presenting the absolute difference may not bring out some information which may otherwise be important for understanding the effect of interactions between different parametrization schemes.

Action: Figure 10 is changed in the revised manuscript showing the difference in the simulated rainfall. Discussion pertaining to the figure is changed accordingly in the revised manuscript. The revised figure is presented here as Figure R.1 for reference.

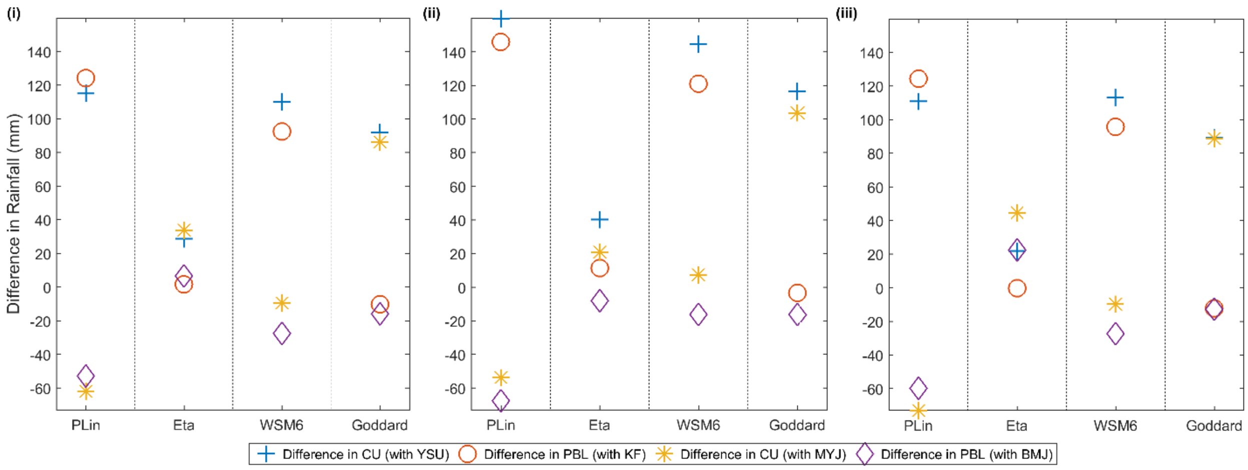


Figure R.1. Difference in simulated rainfall due to PBL, CU and MP parametrization schemes corresponding to (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b over the UGB region.

"It is also hard to determine signal from noise in Figures 7, 8, and 11 when a station mean might have been of value in showing overall trends."

Response: We agree.

Action: Figure 7, 8 and 11 are changed in the revised manuscript. An additional column on the x-axis is added representing the spatial mean value for all the models. Discussion on the figures is accordingly changed in the revised manuscript. The revised figures are presented here as Figure R.2, R.3 and R.4 for reference.

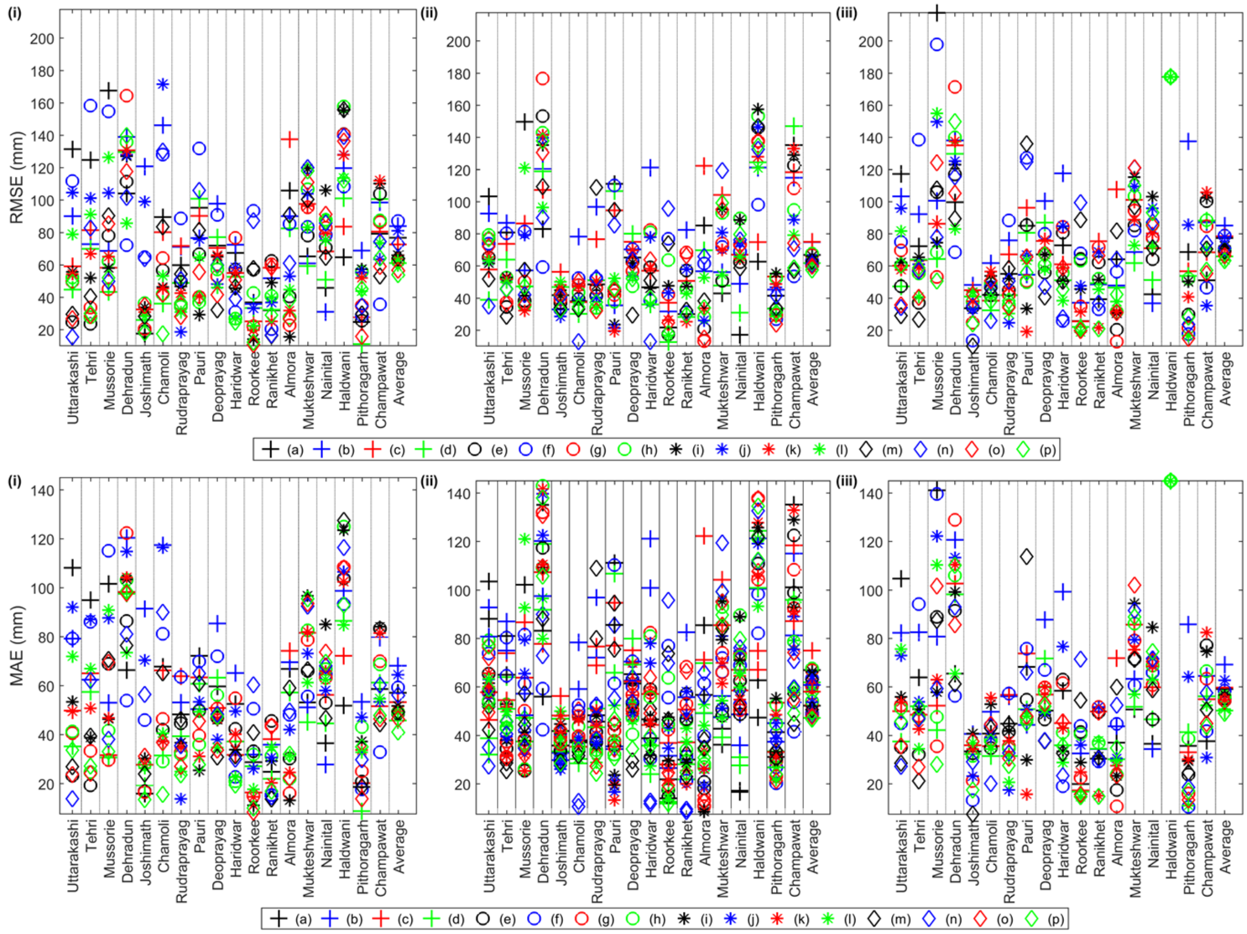


Figure R.2. Root mean square error (top panel) and mean absolute error (bottom panel) computed temporally for (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b for (a) to (p)* WRF configurations.
*Refer to Appendix A (Table A.1) for the list of the WRF configurations.

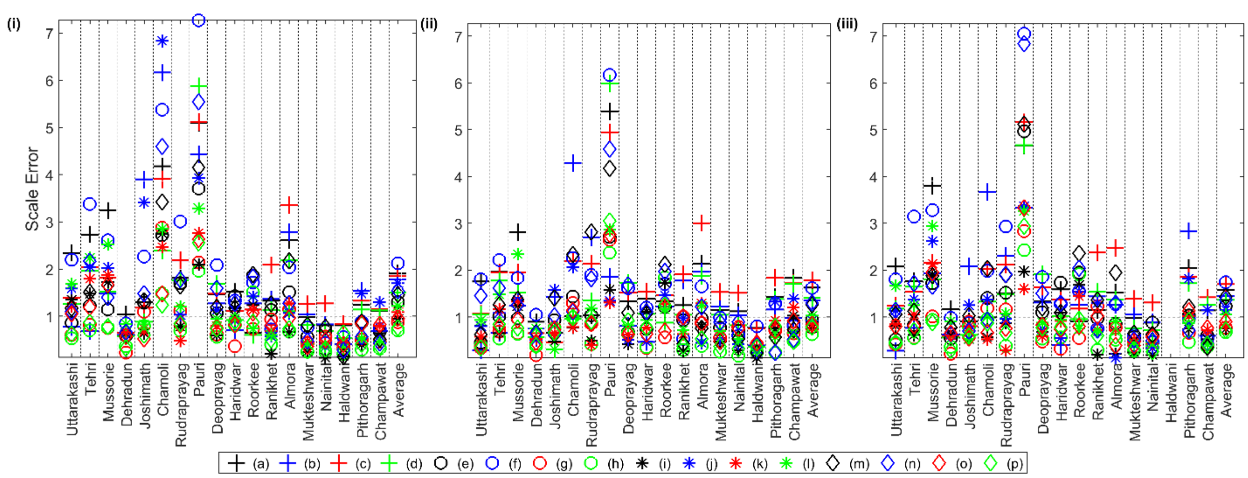


Figure R.3. Scale error (*SE*) in (a) to (p)* WRF configurations for 18 locations in the UGB for (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b.

*Refer to Appendix A (Table A.1) for the list of the WRF configurations.

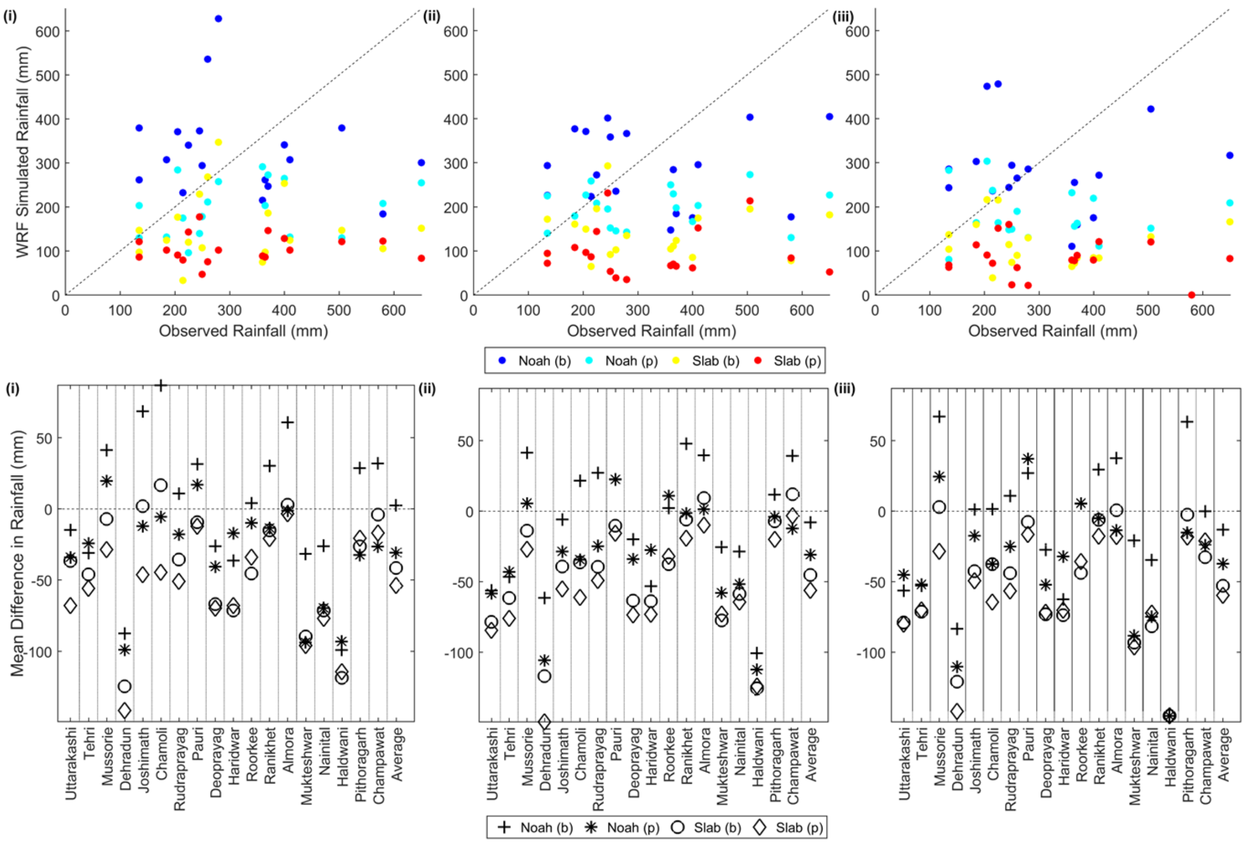


Figure R.4. Scatter plot (top panel) and mean difference in rainfall (bottom panel) for the observed rainfall data and the WRF simulations (for (b) and (p) configurations) pertaining to Noah and Slab LSMs corresponding to (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b.

"A major problem I have is with the use of CORDEX data. CORDEX is downscaled from climate model simulations and would therefore not be expected to bear any resemblance to real weather on any specific date. These are not comparable with weather models driven by real analysis boundary conditions. Sampling CORDEX on a particular date of a heavy rainfall event therefore will not be a fair comparison because it is more likely to miss such events entirely while it may have them on other days depending on which global data is used. It is no surprise that CORDEX runs underestimate heavy events on a particular date, which does not mean they underestimate them in general. Such data can only be used qualitatively to see if they can capture heavy events over many years that they are run using frequency analyses. I therefore suggest that the CORDEX part serves no value for this case study, and if the authors are using CORDEX it can only be in the context of the climatology of heavy events and whether the observed peak can be captured at other times of those runs. Maybe these runs never have such events, which may be useful to know, or maybe they have them too frequently, also useful."

Response: We agree.

Action: Analysis related to the CORDEX data is removed from the revised manuscript.

Specific Comments:

Comment 1: line 222. It said KF is shallow convection when it has both deep and shallow convection.

Response: This sentence has been clarified.

Action: Correction is done in the revised manuscript.

Comment 2: line 231. Both PLin and WSM6 are 6-class if vapor is included as a class.

Response: This is restated in the revised manuscript.

Comment 3: Figure 5. It is noted that domain 2b has no cumulus scheme within the domain, yet shows sensitivity to cumulus schemes, presumably through its boundaries and parent domain.

Response: That is correct. The effect of the cumulus scheme in Domain 2b is through the boundary feedback. It is generally accepted that at finer spatial resolution, such as 3 km or less, representing convective precipitation explicitly may yield better simulation results (Sikder and Hossain, 2016; Pieri et al., 2015; Yu and LEE, 2010; Done et al., 2004).

Comment 4: Figure 6. Over what period is this rainfall summed? Is it interpolated to the station point?

Response: Rainfall is summed over the 4 days' period (15 – 18 June 2013). Because of the complex variability in the domain, rainfall is not interpolated to the station location. The grid point closest to the gauge location is considered for comparison.

Action: Following line is added in the revised manuscript:

"Figure 6 summarizes the comparison of WRF rainfall with rain gauge observations, accumulated over the 4 days' period (15 – 18 June 2013) for the three domains. For comparison, grid points from the WRF domains closest to the gauge location are considered."

Comment 5: line 288. Presumably the complex terrain is also a factor in the bias at stations. Even at 3 km, there may be flow and rainfall differences because the model does not fully resolve all the terrain details.

Response: This is correct and is one of the challenge in simulating this complex region.

Action: Following line is added in the revised manuscript:

"(iv) inability of the model to fully resolve the complex topography (Cardoso et al., 2013;Argüeso et al., 2011;Chevuturi et al., 2015)".

Comment 6: Figure 7. Is this the MAE for the total 4-day precipitation at each station?

Response: No, *MAE* is computed for daily rainfall over the 4 days' period. The absolute error between the simulations and the observations is computed for each day and then averaged over the 4 days to get the mean absolute error.

Action: The sentence is modified in the revised manuscript and now reads as:

"To assess the performance of the WRF simulations, quantitative scores (MAE and RMSE) with respect to the observed data are computed for daily rainfall data, which is then averaged over the 4 days. The results are shown in Figure 7."

Comment 7: Care should be taken when suggesting Goddard is best especially as it has less overall precipitation. Lower precipitation itself may lead to lower absolute errors than schemes that more correct total amounts in the wrong places. Smoother precipitation fields may always score favorably in MAE. Total precip is an important factor to evaluate.

Response: We agree. We have added spatially averaged *MAE* and *RMSE* values in Figure 7, 8 and 11 in the revised manuscript. Through the spatially averaged values, it is noted that the errors are lowest when the configuration with MYJ PBL, BMJ CU, and Goddard MP is used.

Furthermore, 5 additional heavy to extremely heavy rainfall events, each corresponding to the individual month of the monsoon season (June to September), that occurred in the upstream region of the UGB are performed and included in the revised manuscript. These results also indicate that the configuration with MYJ PBL, BMJ CU, and Goddard MP is indeed the 'best' in simulating the spatial and temporal variability of the extremely heavy rainfall over the upstream region of the UGB.

Comment 8: line 316. BMJ even does better in 2b where it is not used and only would contribute through the boundaries, and this is surprising.

Response: The 'good' performance of BMJ CU is mentioned based on the overall results obtained for all the three domains. However, as mentioned in the response to Comment 3 (Referee #2), in Domain 2b, although cumulus scheme is not considered, still the simulations are sensitive to cumulus parameterizations used in the outer domain. This is typically due to the boundary conditions provided by the parent domain. This feature is also observed in several other studies (Sikder and Hossain, 2016; Pieri et al., 2015; Yu and LEE, 2010; Done et al., 2004), wherein it was seen that resolving convective precipitation explicitly at higher resolution gives better simulation results.

Comment 9: line 354. SE has not been defined. It looks like a ratio of model to observed variance.

Response: Scale Error (SE) is the ratio of standard deviation of model simulations to the observed standard deviation and is now explicitly defined.

Action: Following line is modified in the revised manuscript and it now reads as:

"Ability of the WRF model configuration to simulate an extreme rainfall event is evaluated by comparing the simulated rainfall with the observations through indices such as Scale Error (SE), which is the ratio of standard deviation of model simulations to the observed standard deviation and Coefficient of Variation (CV) in addition to MAE, RMSE and β."

Comment 10: Figure 9. It is confusing that colors are used both for rainfall and CV. Perhaps rainfall can be contoured.

Response: The figure is modified in the revised manuscript. Revised Figure 9 is presented here as Figure R.5.

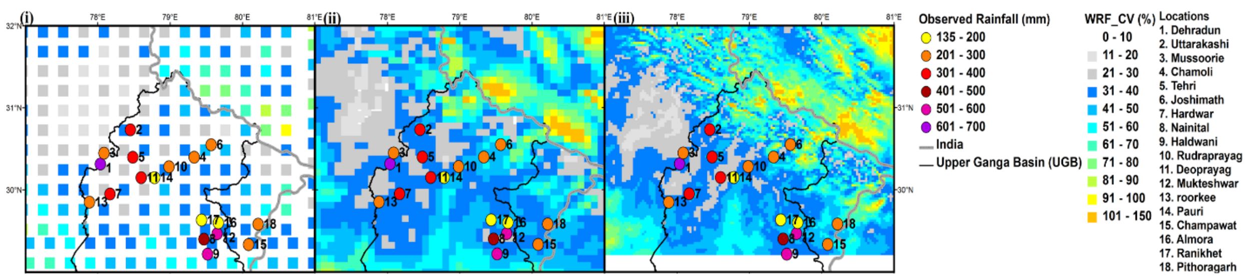


Figure R.5. Coefficient of Variation (*CV*) value across different WRF configurations in the UGB for (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b.

Comment 11: line 416-424. Slab underestimates rainfall. This raises the issue of its moisture availability value in this region. How high is it? Can a higher value give a better rainfall?

Response: The Slab run uses the default soil moisture availability term, unlike the Noah model which has a prognostic soil moisture (and temperature) equation. In response to the reviewer's comment, we analyzed soil moisture values in Slab and Noah runs and highlight that a dry soil (soil moisture less than 0.05 m^3/m^3) persists through the integration in Slab runs. In the case of Noah, with the availability of rainfall induced soil moisture changes, soil moisture is found to vary between 0.25 m^3/m^3 to 0.45 m^3/m^3. Indeed, higher surface moisture leads to improved mass flux, by aiding convective updrafts and diabatic heating in the boundary layer that contributes to low level positive potential vorticity or convective potential which leads to enhanced rainfall (Osuri et al., 2017). In our prior study (Osuri et al., 2017), we studied the soil moisture and soil temperature impact on severe convection over India and demonstrated that drier the soil, lesser the rainfall and vice versa. (Rajesh et al., 2016) also obtained improved rainfall prediction with the realistic soil conditions for Uttarakhand heavy rainfall case.

Action: Following lines are added in the revised manuscript:

"Better performance of using the Noah model could be attributed to the temporal evolution of soil moisture fields. Analyzing the soil moisture in Slab and Noah model, the soil is noted to be relatively dry in Slab (soil moisture less than 0.05 m^3/m^3) and the value is constant throughout the model run (since in the Slab model there is no prognostic soil moisture term). In case of Noah, soil moisture varies in response to the rainfall and is found to vary between 0.25 m^3/m^3 to 0.27 m^3/m^3. Higher surface moisture conditions improve mass flux, convective updrafts and diabatic heating in the boundary layer that contributes to low level positive potential vorticity or convective potential which leads to enhanced rainfall potential (Osuri et al., 2017a). The importance of representing soil moisture variability over India for extreme weather conditions is also highlighted through this work."

Comment 12: Major issue with using CORDEX as it is. See above comments.

Response: CORDEX section (Section 2.2 (old manuscript) and part of Section 3.2) is removed from the revised manuscript.

Comment 13: Major issue with conclusions being drawn from one case. See above.

Response: We have performed analysis for additional events to support our conclusion as stated above. The simulations for five different (additional) heavy to extremely heavy rainfall events, each corresponding to the individual month of the monsoon season (June to September), that occurred in the upstream region of the UGB are now included in the revised manuscript.

Action: Following details are added in the revised manuscript:

Section 2.1:

"In addition to June 2013 case, five additional heavy to extremely heavy rainfall events are also considered in the present study for the analysis, details of which are presented in Table R.1. Rainfall from the IMD gridded data at 0.25° resolution (Pai et al., 2014) is considered as the observed data for these events.

Table R.1. *Heavy to extremely heavy rainfall events recorded in the UGB region*

Event No.	*Time Period*	*Maximum Rainfall Day*	*Maximum Rainfall Amount (mm)*
1	*18 – 22 June 2008*	*20 June*	*126*
2	*29 July – 2 August 2010*	*31 July*	*271*
3	*15 – 19 August 2011*	*16 August*	*234*
4	*17 – 21 September 2010*	*19 September*	*218*
5	*11 – 15 September 2012*	*14 September*	*38*

It is to be noted that on 13 – 14 September 2012, cloudburst event was reported in the region and the total amount of rainfall on 14 September was recorded approximately to be 210 mm (Chevuturi et al., 2015). This event is significantly underestimated in the IMD gridded data, indicating that caution must be exercised while using the data for applications involving heavy rainfall events, such as flood modeling and validating the rainfall simulations from the mesoscale models. Figure R.6 presents the spatially averaged daily and cumulative rainfall received during different events (as specified in Table R.1).

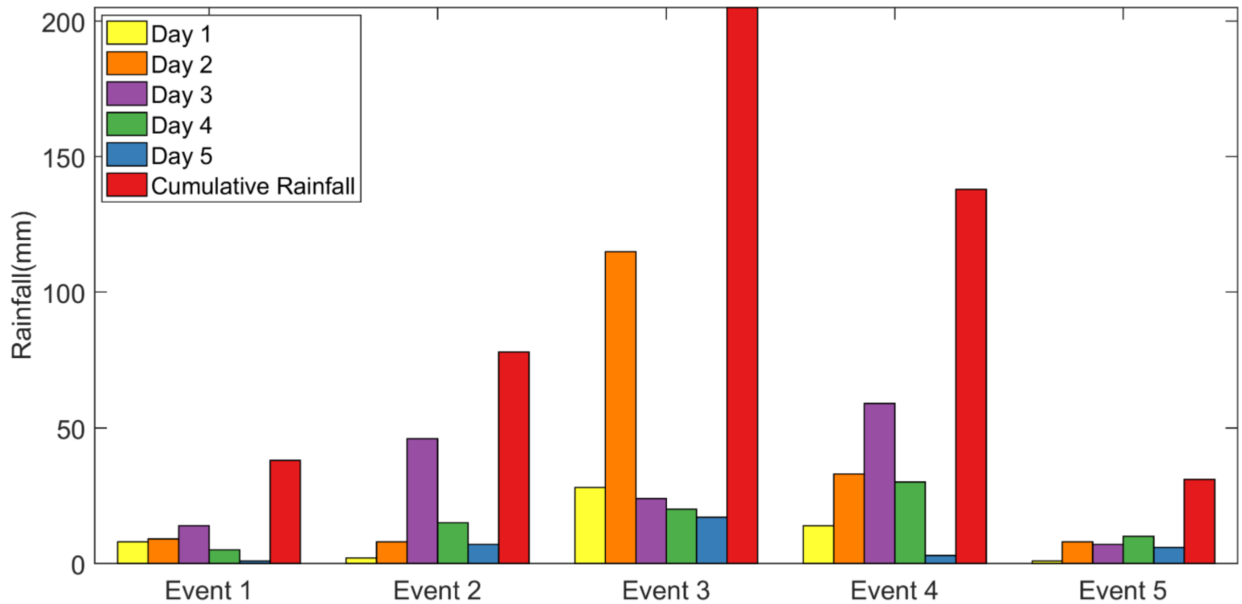


Figure R.6. *Spatially averaged daily and cumulative rainfall for Event 1 (18 – 22 June 2008); Event 2 (29 July – 2 August 2010); Event 3 (15 – 19 August 2011); Event 4 (17 – 21 September 2010); and Event 5 (11 – 15 September 2012) in the upstream region of the UGB.*

Section 3.1.1:

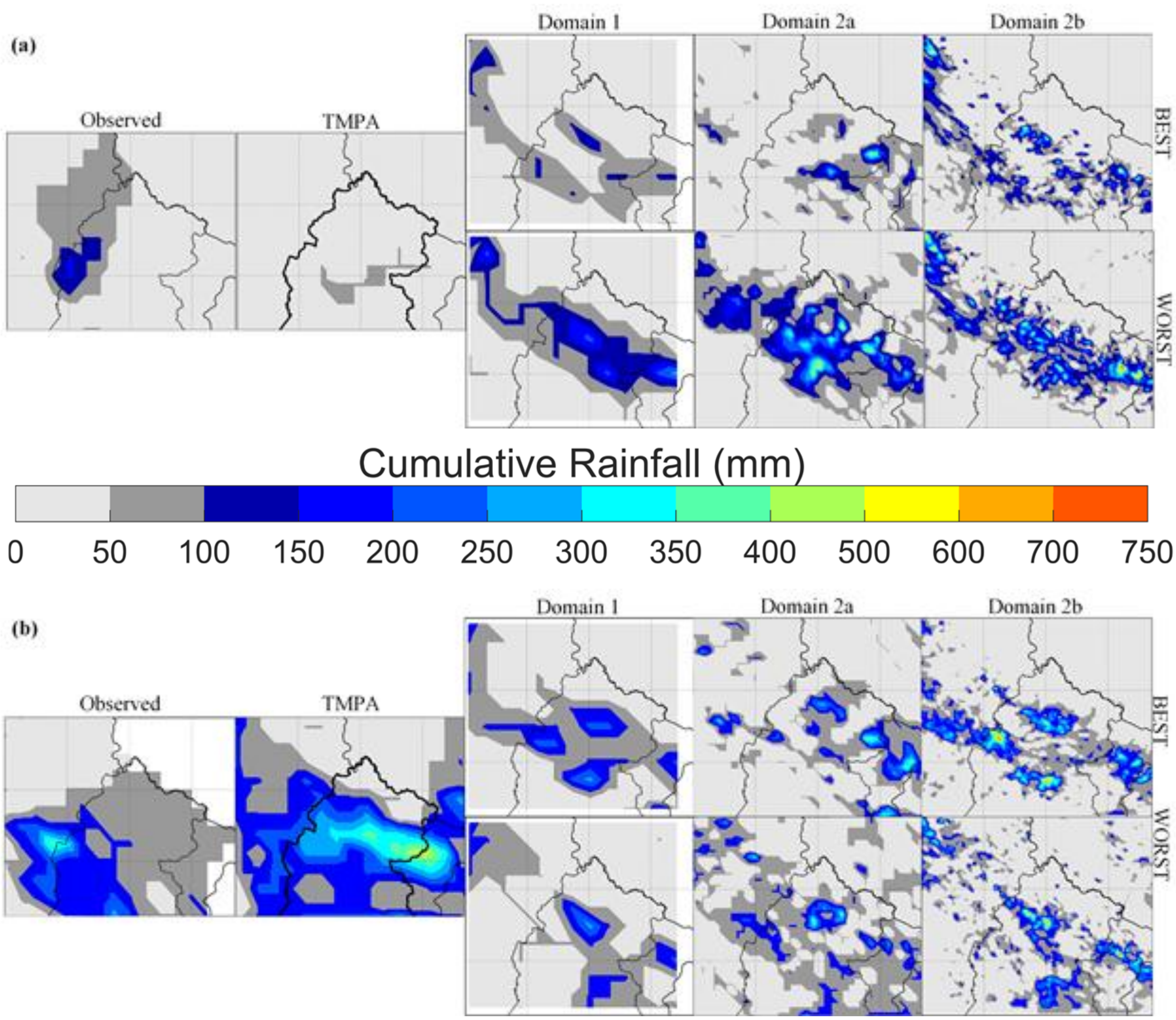
To further assess the sensitivity of configuration (p) and configuration (b) in capturing the extreme rainfall events in the region, additional simulations pertaining to other heavy to extremely heavy rainfall events (as mentioned in Table R.1) are conducted. Spatial plots showing the cumulative rainfall estimates obtained for the three domains in comparison to the observed IMD gridded data and the TMPA data are presented in Appendix C. To summarize the performance of configuration (p) and configuration (b) against the observations (IMD gridded data), spatio-temporal MAE values are computed, which are presented in Table R.2.

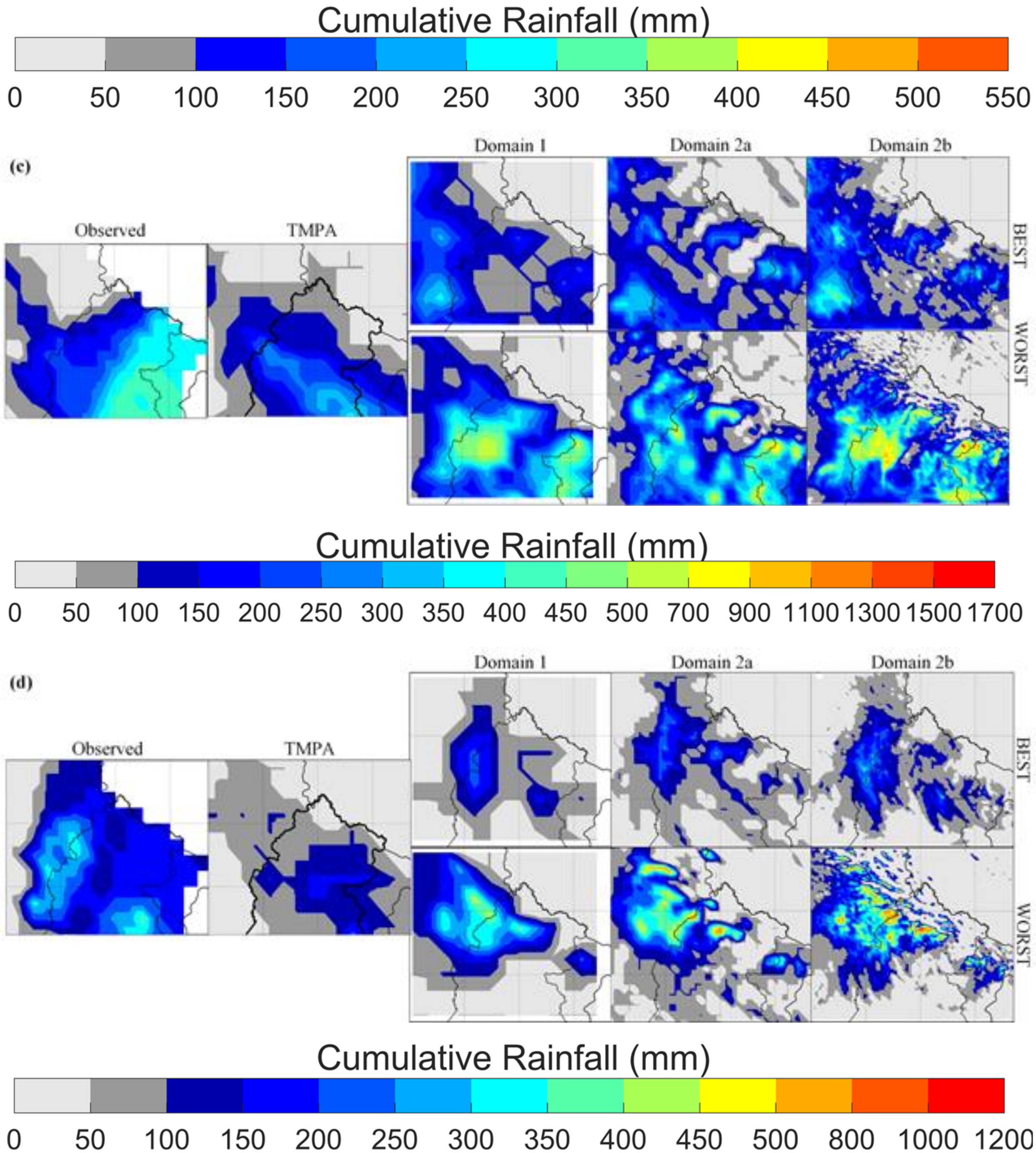
Table R.2. *Mean Absolute Error (MAE) values (in mm) corresponding to WRF configuration (p) and configuration (b) for the three domains*

Event No.	***Domain 1***		***Domain 2a***		***Domain 2b***	
	(p)	***(b)***	***(p)***	***(b)***	***(p)***	***(b)***
1	*10*	*13*	*10*	*14*	*11*	*14*
2	*18*	*23*	*18*	*23*	*21*	*22*
3	*39*	*45*	*38*	*44*	*40*	*46*
4	*23*	*28*	*23*	*28*	*24*	*29*
5	*12*	*12*	*9*	*13*	*12*	*11*

From the analysis conducted over the additional rainfall events, it is noted that configuration (p) gives less error in comparison to the configuration (b) for all the rainfall events. This makes configuration (p) with MYJ PBL, BMJ CU, and Goddard MP the 'best' in simulating the spatial and temporal variability of the extremely heavy rainfall over the upstream region of the UGB."

Appendix C:





Cumulative Rainfall (mm)
0 50 100 150 200 250 300 350 400 450 500 550
(c)
Observed
TMPA
Domain 1
Domain 2a
Domain 2b
BEST
WORST
Cumulative Rainfall (mm)
0 50 100 150 200 250 300 350 400 450 500 700 900 1100 1300 1500 1700
(d)
Observed
TMPA
Domain 1
Domain 2a
Domain 2b
BEST
WORST
Cumulative Rainfall (mm)
0 50 100 150 200 250 300 350 400 450 500 800 1000 1200

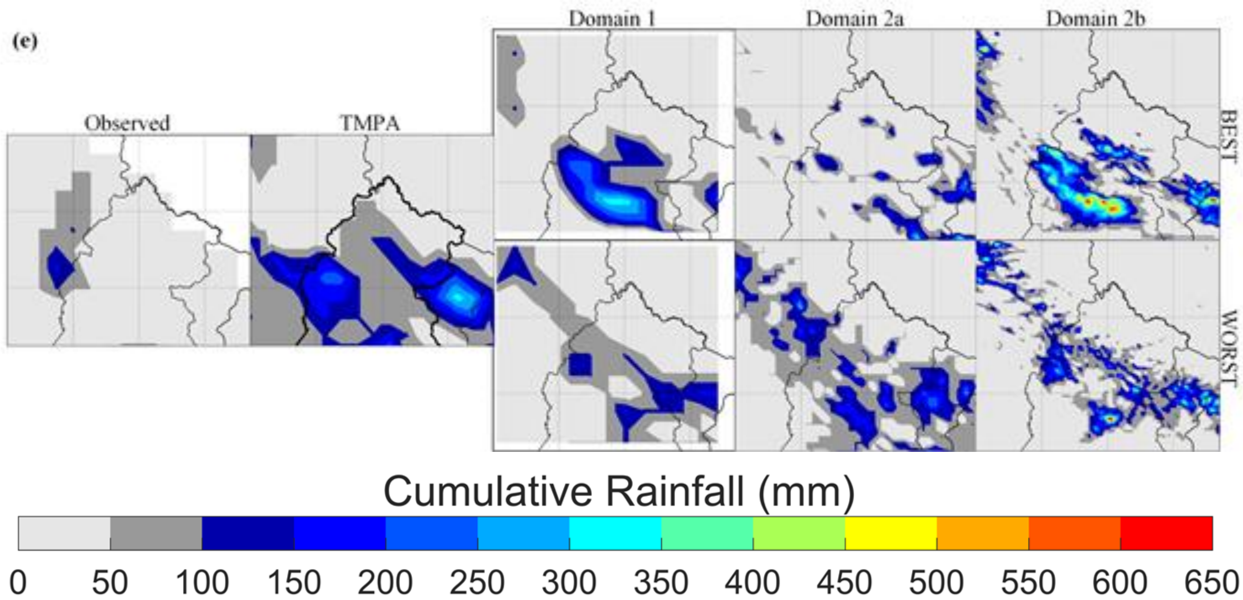


Figure R.7. *Spatial plots presenting the rainfall simulations obtained across the three domains for the best and the worst configuration for heavy to extremely heavy rainfall events during (a) Event 1 (18 – 22 June 2008); (b) Event 2 (29 July – 2 August 2010); (c) Event 3 (15 – 19 August 2011); (d) Event 4 (17 – 21 September 2010); and (e) Event 5 (11 – 15 September 2012).*

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