Author 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

Authors: Ila Chawla, Krishna K. Osuri, Pradeep P. Mujumdar, and Dev Niyogi

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. Line numbers mentioned here are corresponding to the clean version of the manuscript

<u>Responses to the comments of Referee #1:</u>

General Comments:

The authors have used Weather Research and Forecasting model for extreme events over upper Ganga basin and evaluated the simulations. The work is of importance; however, there are certain comments that need to be addressed.

Comment 1: I have reservation in stating " However, setting up the WRF model, that simulates extremely heavy rainfall over the ISMR region is still considered as a challenging task..". In my opinion setting up WRF is no longer a challenging task, given multiple works have been reported on the same. However, finding the best physics parameterization option or understanding of the combinations of good parameterization options for different purposes is still an area of research and that needs to come out through the first paragraph of introduction.

Response: We agree and have modified the statement. The statement was meant to highlight that it is challenging since it involves consideration of several aspects such as forcing data, model grid spacing/resolution, land surface parameterization and choice of an appropriate physics scheme.

Action: Lines "However, setting up the WRF model, that simulates extremely heavy rainfall over the ISMR region is still considered as a challenging task, which involves consideration of several aspects such as forcing data, model grid spacing/resolution, land surface parameterization and choice of an appropriate physics scheme." are modified in the revised manuscript and now read as:

"*However, finding the optimal set of physics parameterization schemes (along with the selection of an appropriate model grid spacing/resolution) to simulate extreme/heavy rainfall events, and understanding the effect of the combination of different parametrization schemes on rainfall estimates over the Indian monsoon region is still an active area of research."* (Lines 80-83)

Comment 2: I also have reservation in selecting an extreme event without understanding how does the regional model work for seasonal monsoon rainfall over the region. Do they add value to the simulations by global models? What about the existing literature on evaluation of CORDEX in adding values? Which one is more sensitive, microphysics parameterization or cumulative parametrization. How does WRF perform in different years, dry, wet or normal years? There are multiple works that have been published recently. The authors need to perform a good review of recent literature, identify the gap and define the problem. This is missing in the present version of the manuscript.

Response:

'How does the regional model work for seasonal monsoon rainfall over the region? Do they add value to the simulations by global models?'

Global models have been employed in several studies to understand the large-scale circulation pattern and for quantitative analysis of the monsoon rainfall, but due to their coarse resolution, they are unable to represent the local to regional characteristics of monsoon rainfall. Regional models, on the other hand, can explicitly simulate the interactions between the large-scale weather phenomenon and regional topography, making the climate simulations reliable (Gadgil and Sajani, 1998; Ratna et al., 2011; Srinivas et al., 2013). Furthermore, regional models have a better representation of convection thus offsetting one of the major sources of errors and uncertainties in the global models. Therefore, mesoscale models, such as the Weather Research and Forecasting (WRF) model, becomes a preferred choice to study seasonal monsoon rainfall.

The WRF model has been used as a diagnostic tool to understand the Indian Summer Monsoon Rainfall (ISMR) over the Himalayan region. For example, Kumar et al., (2012) used the WRF model to simulate the cloudburst event of 2010 in the Leh area over the north-western Himalayan belt. While, Kumar et al., (2014) and Thayyen et al., (2013) used the WRF model to gain insight into the atmospheric processes and the mesoscale convective system (MCSs) that led to the 2010 Leh event. Similarly, Chevuturi et al., (2015) simulated the heavy precipitation event of September 2012 in the central Himalayas using the WRF model. Medina et al., (2010) used the WRF model to understand how topography and land surface conditions affect the extreme convection in western and eastern Himalayas. Particularly for the 2013 heavy rainfall episode in the Uttarakhand region, the WRF model is used in several studies, including those by Kotal et al., (2014); Vellore et al., (2016); and Hazra et al., (2017) to understand the physical processes leading to the event. Shekhar et al., (2015); Dimri et al., (2016); and Chevuturi and Dimri, (2016) performed in-depth synoptic and mesoscale analysis of the June 2013 heavy rainfall event using the WRF model. Rajesh et al., (2016) presented the role of land surface conditions in simulating the heavy rainfall event. Therefore, from the existing literature, it can be established that the regional model performs considerably well over the region.

Although model analysis of the June heavy rainfall event in the Uttarakhand state has been studied, ensemble analysis emphasizing the impact of the interaction between different model configurations in simulating the heavy rainfall event, and the associated variability (uncertainty) is still lacking. With this perspective, this paper seeks to assess the sensitivity of the WRF model to predict extremely heavy rainfall events.

'What about the existing literature on evaluation of CORDEX in adding values?'

In the earlier submitted version of the manuscript, we attempted to analyze the extreme rainfall event from the CORDEX data and observed that the rainfall is significantly underestimated by the CORDEX products (Section 2.2, old manuscript). Based on the comments received from both the reviewers and the focus we wish to keep in this study – which is the ability and the sensitivity/variability within WRF runs for simulating the heavy rain event(s) – we have now eliminated the analysis related to the CORDEX data in the revised manuscript. Nonetheless, with regards to the existing literature on this topic, Ali et al., (2014) studied the extreme rainfall projected by the CORDEX RCMs over the urban areas in India. They observed CORDEX-RCMs have a significant bias in the monsoon maximum rainfall, which could be attributed to model parametrization (Gutowski Jr et al., 2010) and model resolution (Wehner et al., 2010; Tripathi and Dominguez, 2013).

'Which one is more sensitive, microphysics parameterization or cumulative parametrization?'

The experiment results indicate that the microphysics parameterization and cumulative parametrization work in tandem in simulating the rainfall. The former appears to influence the spatial pattern of the rainfall better, while the convective parameterization influences the quantity of rainfall (Section 3.1.2). However, the results from this study alone, and the interdependency of the two aspects limit the ability to ascertain whether the simulated rainfall is 'more' sensitive to which of the two parameterization processes.

'How does WRF perform in different years, dry, wet or normal years?'

Since the main aim of the paper is to assess the sensitivity of the WRF model to simulate heavy rainfall events and understand the effect of the combination of different parametrization schemes, the performance of the WRF model for dry, wet or normal years deemed not to be a major concern.

Action: The introduction section is significantly modified and additional literature is now added in the revised manuscript.

Comment 3: The authors need to present the evaluation of the regional model at least for one season of monsoon (for all 122 days). We have to make sure that the selected parameterization does not overestimate for all the days and hence performing well for the extreme days. This simulation needs to be performed.

Response: This comment was again more aligned with the CORDEX part of the study – which has been taken off from the revision. In the study, we are using a mesoscale model configuration to obtain the reliable forecasts for which typically 3- 5 days period is considered. Therefore, to run the model for entire monsoon season (i.e. 122 days), the model needs to be reinitialized after every few days, wherein boundary conditions are obtained from NCEP FNL reanalysis dataset while the initial conditions are obtained from the forecasted data of the previous cycle. This process is computationally expensive, and not central to the study goal (as revised now), nor is it feasible under the current model set-up. Nonetheless, we appreciate the point the reviewer is making and as an alternative approach to test the performance for more than one setting, we have identified additional cases of heavy to extremely heavy rainfall events over different months of the monsoon season and conducted model experiments for these additional events to access the model performance. The configuration with MYJ PBL, BMJ CU, and Goddard MP is again found to perform 'best' in simulating the spatial and temporal variability of the extremely heavy rainfall over the upstream region of the UGB – adding more credence and generality to the study findings.

Action: Results pertaining to the additional heavy to extremely heavy rainfall events are added to the revised manuscript (Section 3.1.1). Please refer to the response to comment 7 (Referee #1) for further details.

Comment 4: Figure 4 is wrongly interpreted. The CORDEX models have the boundary conditions from CMIP5 models that do not have any observed initial condition. Hence, it is not correct to pick up specific dates from the simulations and compare. I think it is better to delete this figure.

Response: The analysis related to the CORDEX data is deleted from the revised manuscript.
Action: Figure 4 (old manuscript) presenting the variability in daily and cumulative rainfall obtained from the CORDEX downscaled data is removed from the revised manuscript.

Comment 5: Similarly Figure 12 also has the same problem if the bias is for those specific days.

Action: Figure 12 (b) (in the old manuscript) presenting the comparison of CORDEX data with the WRF simulations is removed in the revised manuscript.

Comment 6: I would specifically suggest to delete the CORDEX part, as it may not be directly related to the work (if authors want they may pick up the evaluation runs that are forced with reanalysis data, but such simulations may not be available for 2013). They should focus on identifying the added value by regional model in comparison with the reanalysis data that is being used as boundary condition.

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

Comment 7: I am not very sure, if the use of single extreme is sufficient for any conclusion.

Response: We agree, and 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, Lines 183-197:

"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.1 presents the spatially averaged daily and cumulative rainfall received during different events (as specified in Table R.1).

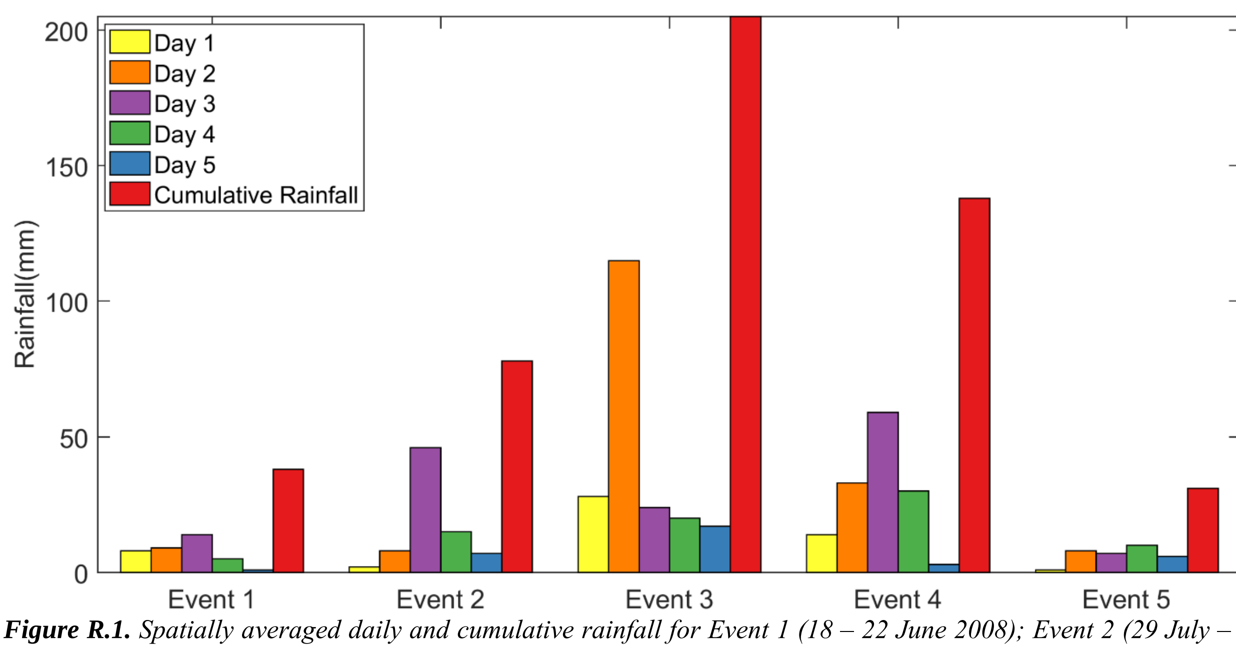


Figure R.1. *Spatially averaged daily and cumulative rainfall for Event 1 (18 – 22 June 2008); Event 2 (29 July – 2 August 2010); Event 3 (15 – 19 August 2011); Event 4 (17 – 21 September 2010); and Event 5 (11 – 15 September 2012) in the upstream region of the UGB.*

Section 3.1.1, Lines 339-351:

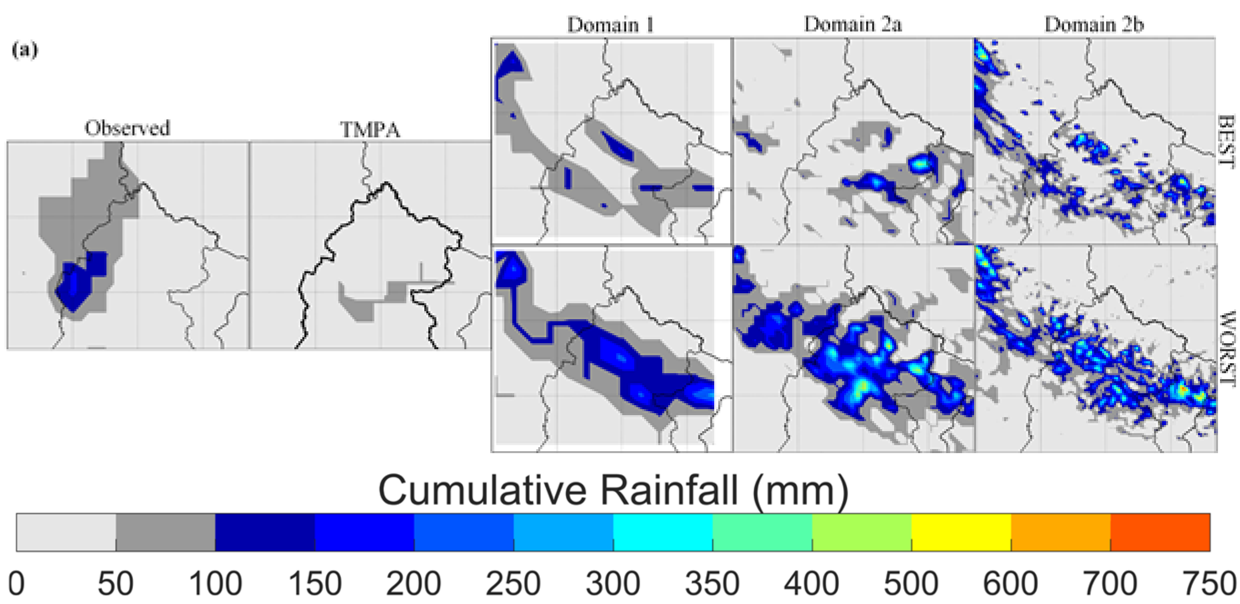
To further assess the sensitivity of configuration (p) and configuration (b) in capturing the extreme rainfall events in the region, additional simulations pertaining to other heavy to extremely heavy rainfall events (as mentioned in Table R.1) are conducted. Spatial plots showing the cumulative rainfall 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.

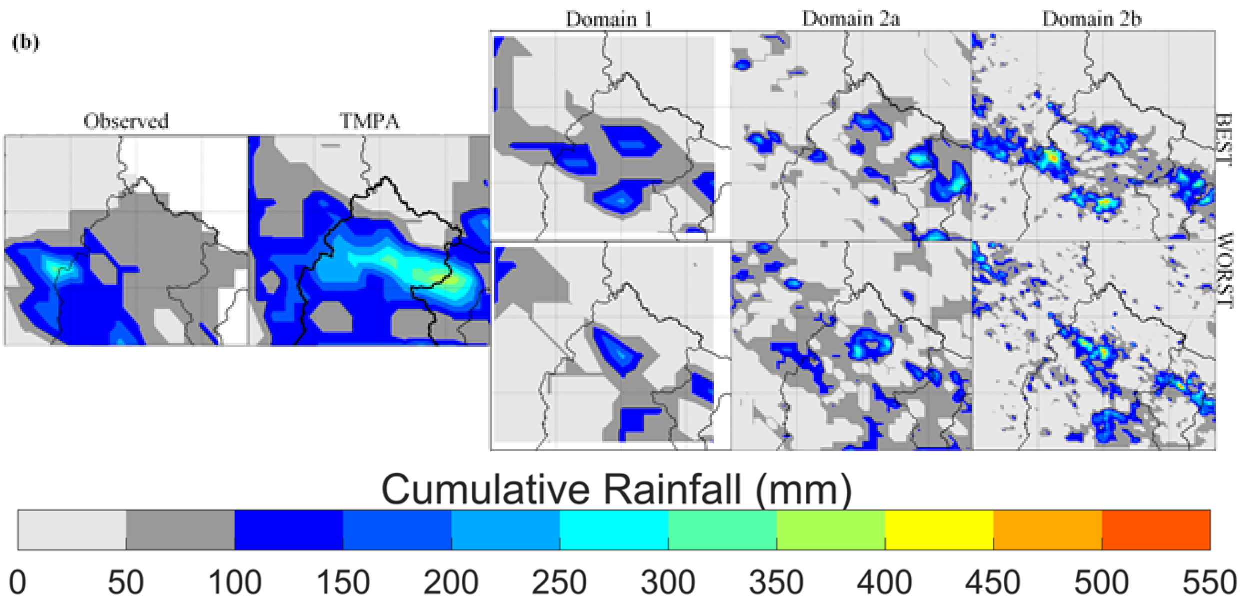
***Table R.2.** Mean Absolute Error (MAE) values (in mm) corresponding to WRF configuration (p) and configuration (b) for the three domains*

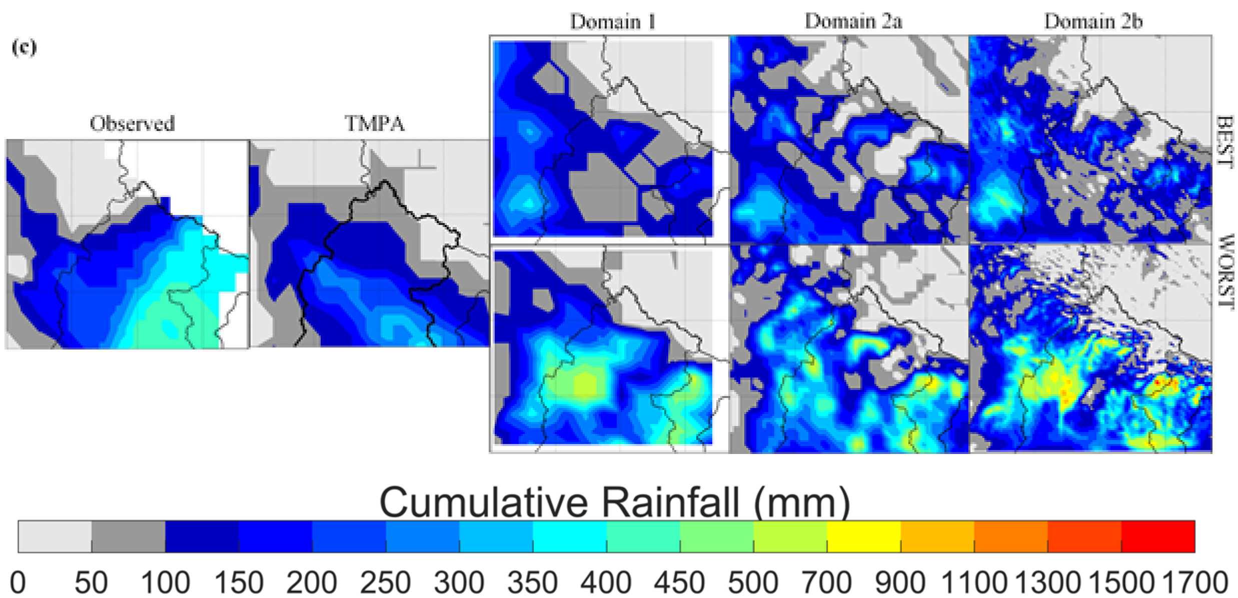
Event No.	Domain 1		Domain 2a		Domain 2b	
	(p)	(b)	(p)	(b)	(p)	(b)
1	10	13	10	14	11	14
2	18	23	18	23	21	22
3	39	45	38	44	40	46
4	23	28	23	28	24	29
5	12	12	9	13	12	11

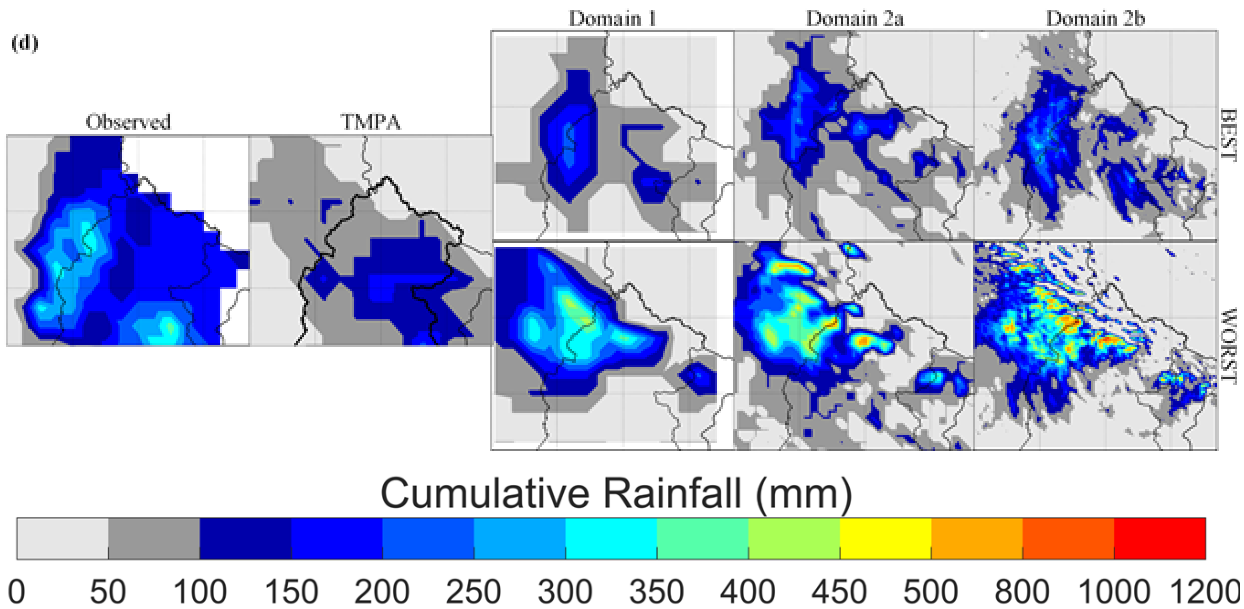
From the analysis conducted over the additional rainfall events, it is noted that configuration (p) gives less error in comparison to the configuration (b) for all the rainfall events. This makes configuration (p) with MYJ PBL, BMJ CU, and Goddard MP the 'best' in simulating the spatial and temporal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

Appendix C:




(b)
Observed
TMPA
Domain 1
Domain 2a
Domain 2b
BEST
WORST
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

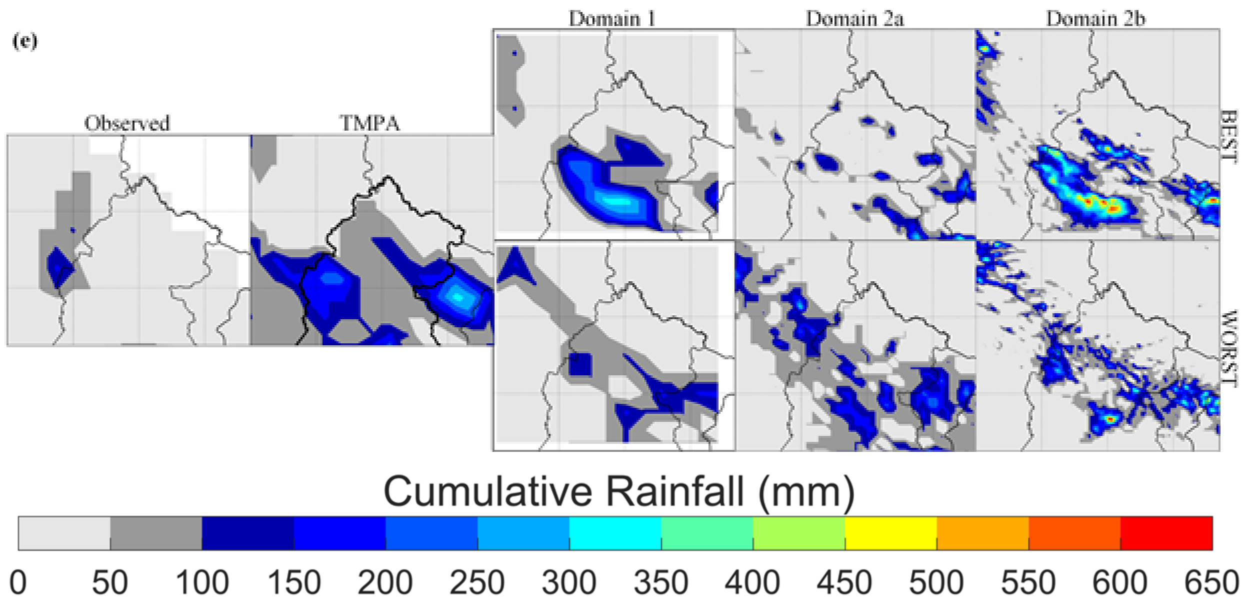


Figure R.2. *Spatial plots presenting the rainfall simulations obtained across the three domains for the best and the worst configuration for heavy to extremely heavy rainfall events during (a) Event 1 (18 – 22 June 2008); (b) Event 2 (29 July – 2 August 2010); (c) Event 3 (15 – 19 August 2011); (d)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

Comment 8: I also would like to know the role of land surface processes in this extreme event. Some details on the land surface module that has been coupled to WRF, may also be useful.

Response: Previous studies such as by Chang et al., (2009); Rajesh et al., (2016); Kishtawal et al., (2010); Osuri et al. (2017); and Lei et al., (2008) have focused exclusively on the impact of land surface characteristics in influencing the rainfall events. In particular, Rajesh et al., (2016) have discussed the role of land surface conditions on this particular event of heavy rainfall (June 2013 in Uttarakhand). They conducted two sets of experiment – one, without land data assimilation (referred as control experiment) and the other, with land data assimilation through utilization of high-resolution soil moisture and soil temperature in the WRF model (LDAS experiment). Their results indicate that the model accurately simulated the heavy rainfall in the LDAS case due to better representation of lower boundary conditions. The land model being used in the WRF configuration is the community Noah model and it has been cited.

Further, we have undertaken experiments to assess the effect of the land surface schemes on the rainfall simulations by considering two Land Surface Models (LSMs) – Noah LSM and the simple 5-layer soil model (Slab). The Slab LSM based run resulted in a significant underestimation of the rainfall simulations in comparison to the Noah LSM. The better performance of using the Noah model could be attributed to the temporal evolution of soil moisture fields. Additional details related to the land surface module used in the current study are added in the revised manuscript.

Action: Following paragraph is added in the revised manuscript (Section 2.2), Lines 255-271:

"The sensitivity of various WRF configurations to simulate heavy rainfall events is assessed using the Noah LSM (Chen and Dudhia, 2001; Tewari et al., 2004; Ek et al., 2003). The Noah LSM is a community model that is included in the WRF suite with the prime aim of providing reliable boundary conditions to the atmospheric model. As a result, Noah LSM is moderately detailed model, which includes single canopy layer with canopy resistance scheme of Noilhan and Planton, (1989) and four soil layers (at 0.1, 0.3, 0.6 and 1.0 m) with a total soil depth of 2 m. The last soil layer of 1 m acts as a reservoir for drainage of water under gravity and the above three layers serve as root zone depths. There is a provision in the model to change default root zone depths with the actual values from the field, subjected to data availability. In the Noah LSM, surface (skin) temperature is obtained using a single linearized surface energy balance equation, which effectively considers the ground and vegetation surface. Frozen soil parametrization based on Koren et al., (1999) and surface runoff scheme of Schaake et al., (1996) are also included in this model. Soil moisture, soil temperature, water intercepted by the canopy and snow stored on the ground are also included as the prognostic variables in the model. More detailed information on the Noah LSM can be obtained from Ek et al. (2003).

To assess the effect of the land surface scheme on simulations, the Noah LSM is replaced with the simple five-layer Soil Model (Slab; (Dudhia, 1996)). In contrast to the relatively sophisticated Noah LSM, Slab is based on simple thermal diffusion in the soil layers that has constant soil moisture availability but a prognostic soil temperature term (Deardorff, 1978). Further differences between the two LSMs are presented in Section 3.1.3."

<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 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.3 for reference.

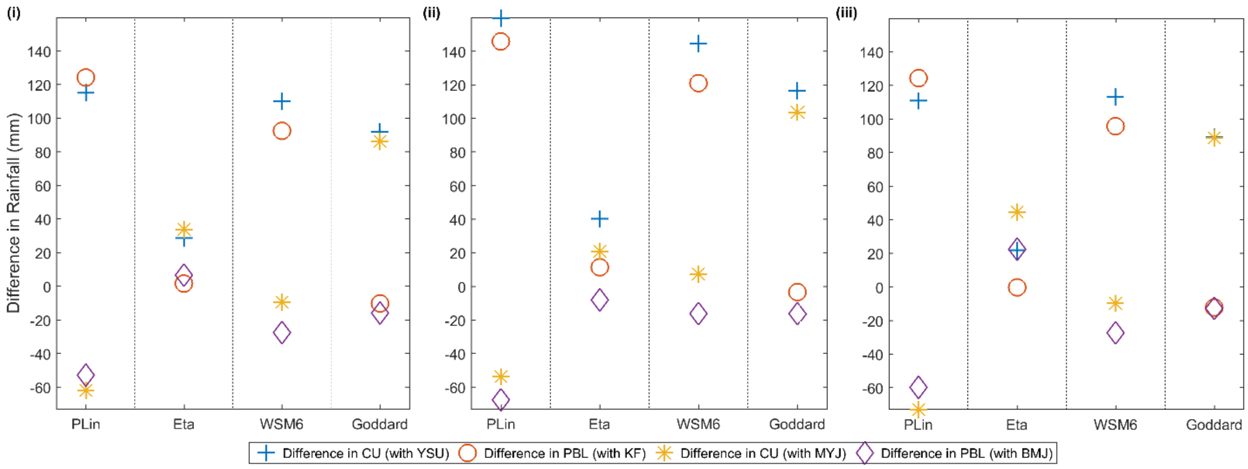


Figure R.3. Difference in simulated rainfall due to PBL, CU and MP parametrization schemes corresponding to (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b over the UGB region.

"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.4, R.5 and R.6 for reference.

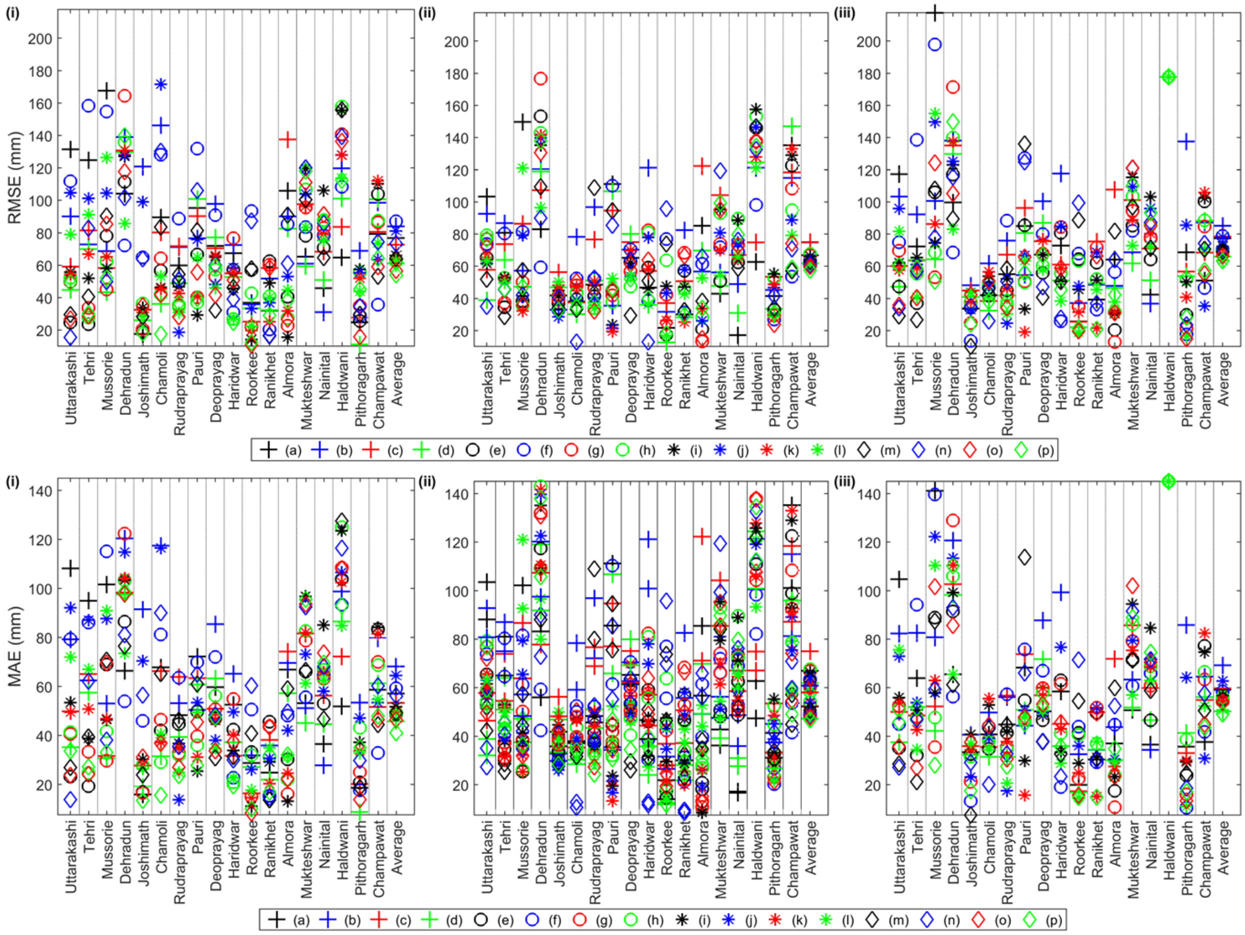


Figure R.4. Root mean square error (top panel) and mean absolute error (bottom panel) computed temporally for (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b for (a) to (p)* WRF configurations.

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

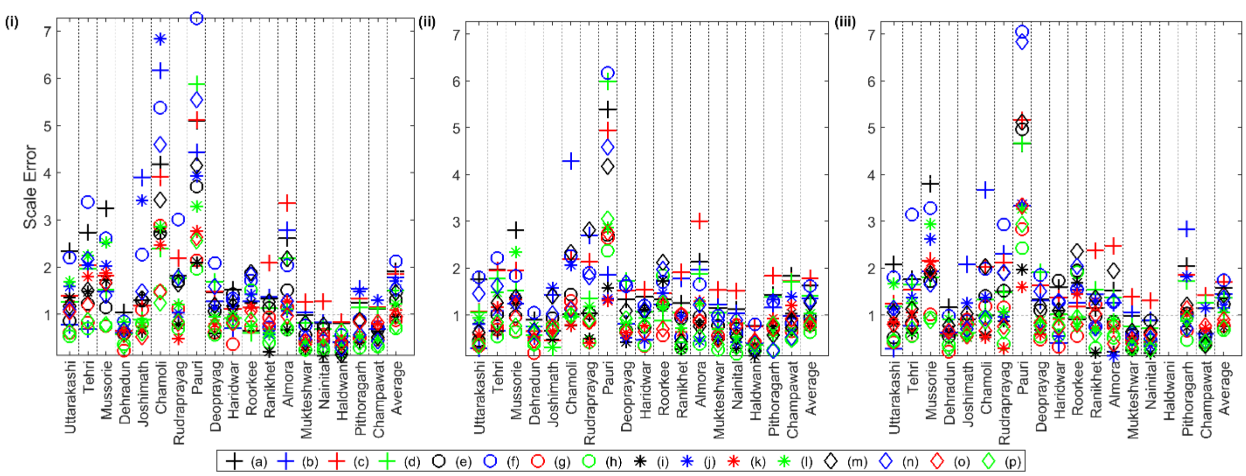


Figure R.5. Scale error (*SE*) in (a) to (p)* WRF configurations for 18 locations in the UGB for (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b.

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

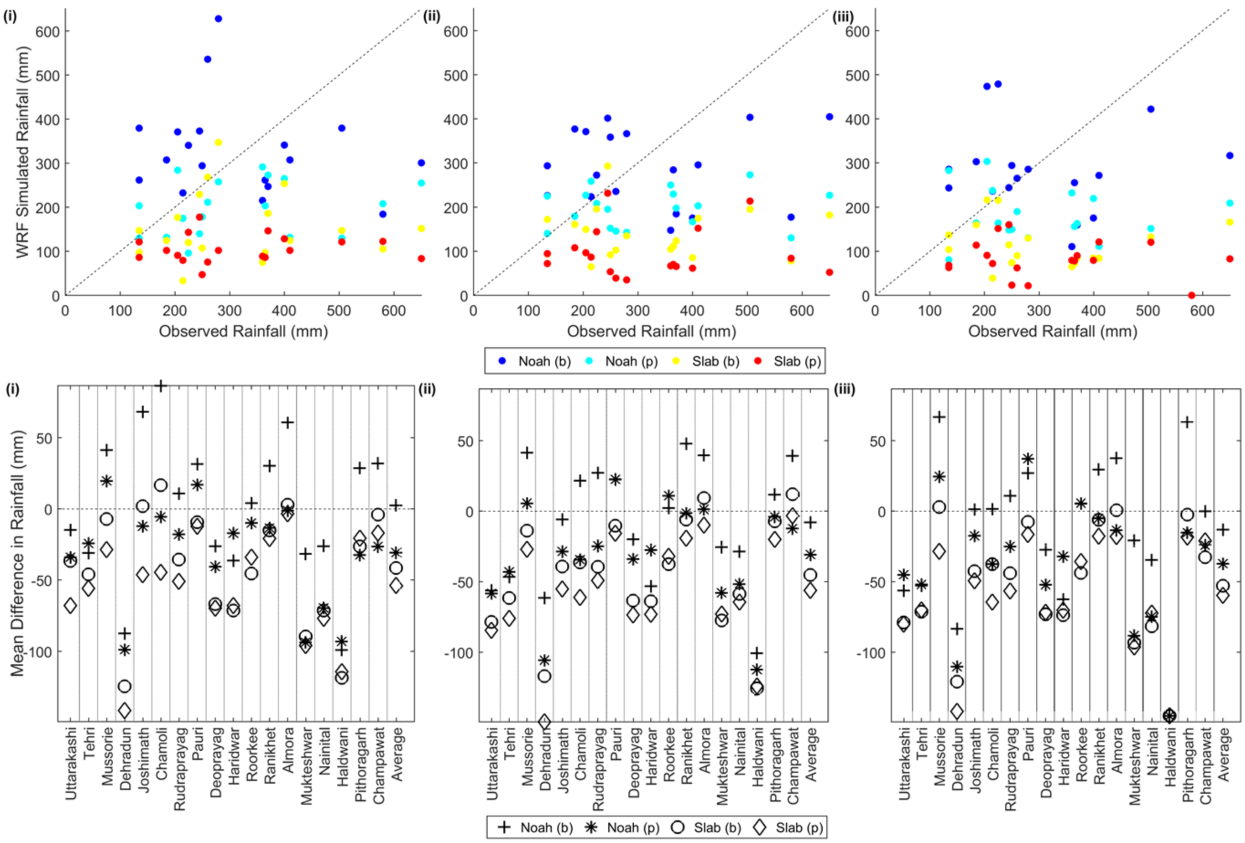


Figure R.6. Scatter plot (top panel) and mean difference in rainfall (bottom panel) for the observed rainfall data and the WRF simulations (for (b) and (p) configurations) pertaining to Noah and Slab LSMs corresponding to (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b.

"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 (Line 237-237).

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 (Lines 245-248).

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 (Lines 303-305):

"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 (Lines 319-320):
"(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 (Lines 320-322):
"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 (Lines 276-279): *"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.7.

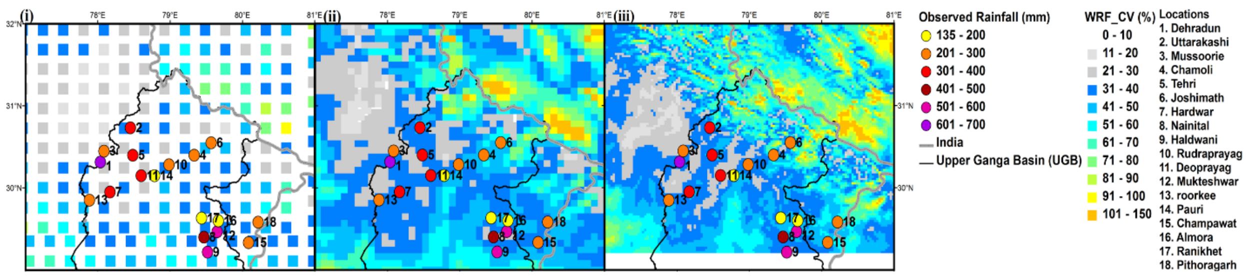


Figure R.7. Coefficient of Variation (*CV*) value across different WRF configurations in the UGB for (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b.

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 (Lines 473-480):

"The 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 0.45 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, Lines 183-197:

"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.3. 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.3. *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.8 presents the spatially averaged daily and cumulative rainfall received during different events (as specified in Table R.3).

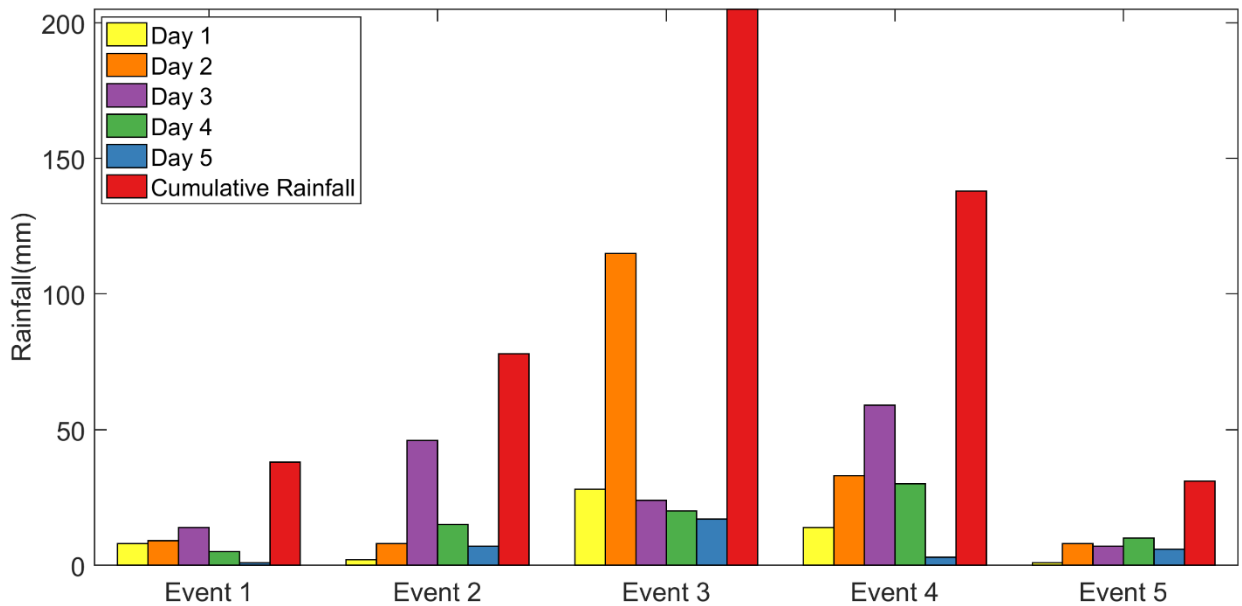


Figure R.8. *Spatially averaged daily and cumulative rainfall for Event 1 (18 – 22 June 2008); Event 2 (29 July – 2 August 2010); Event 3 (15 – 19 August 2011); Event 4 (17 – 21 September 2010); and Event 5 (11 – 15 September 2012) in the upstream region of the UGB.*

Section 3.1.1, Lines 339-351:

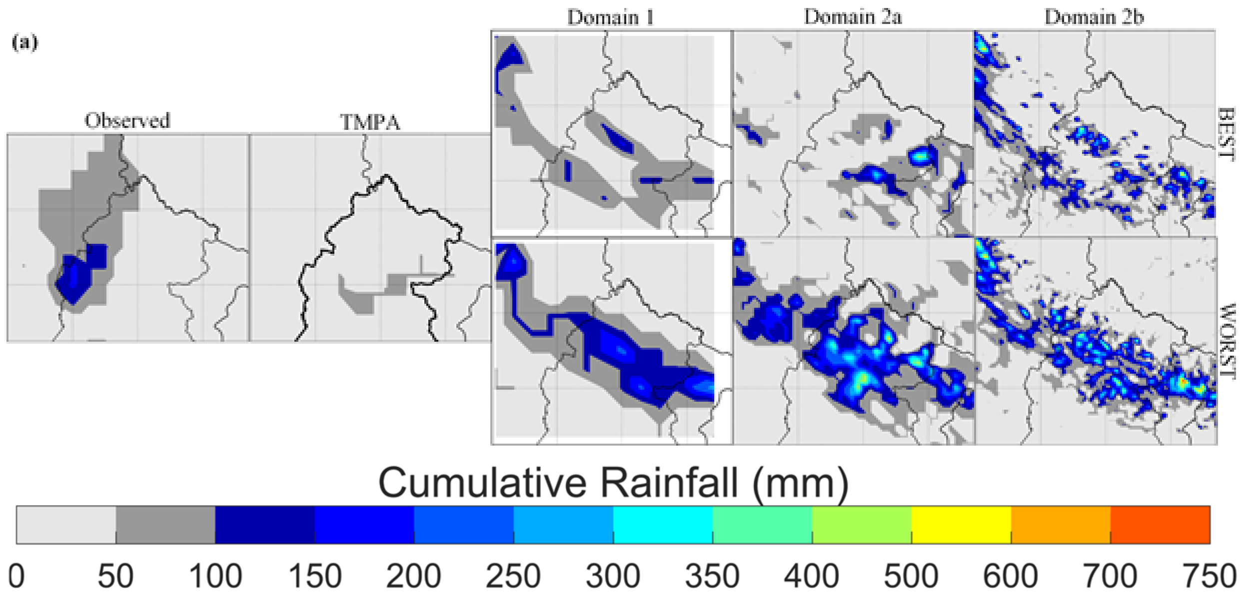
To further assess the sensitivity of configuration (p) and configuration (b) in capturing the extreme rainfall events in the region, additional simulations pertaining to other heavy to extremely heavy rainfall events (as mentioned in Table R.3) are conducted. Spatial plots showing the cumulative rainfall 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.4.

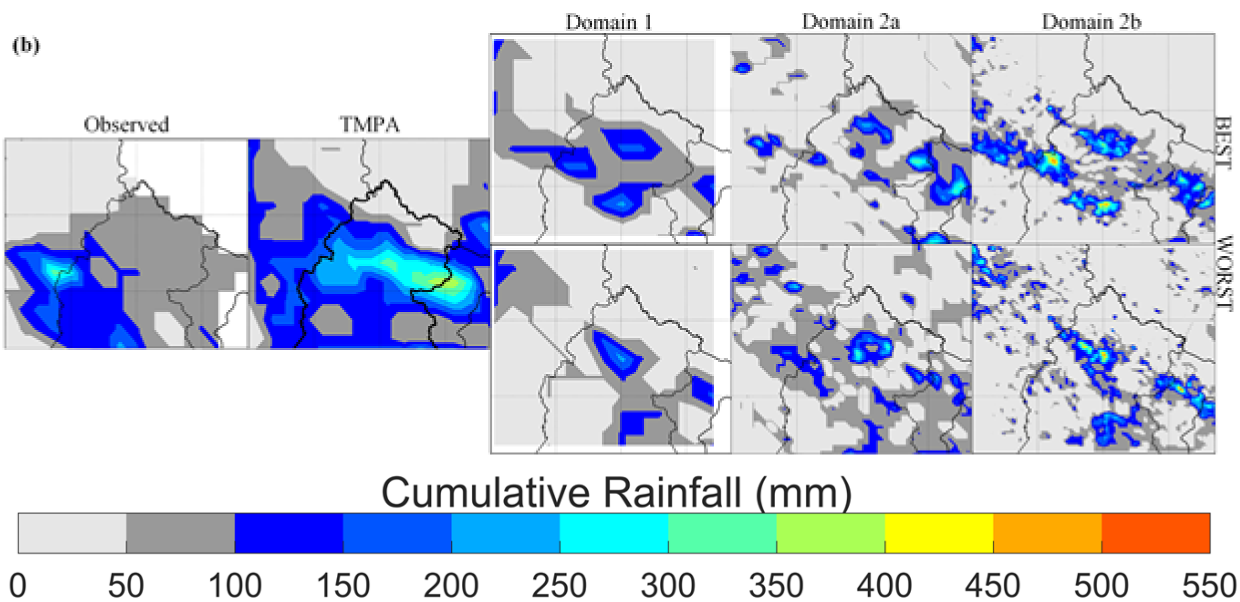
Table R.4. *Mean Absolute Error (MAE) values (in mm) corresponding to WRF configuration (p) and configuration (b) for the three domains*

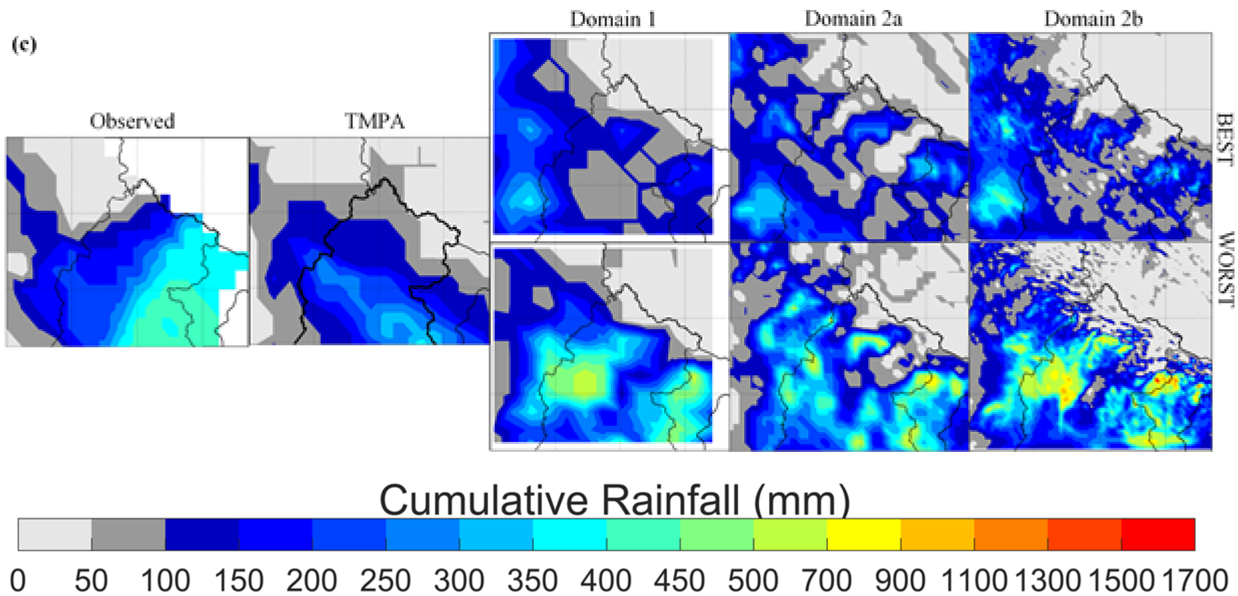
Event No.	*Domain 1*		*Domain 2a*		*Domain 2b*	
	(p)	*(b)*	*(p)*	*(b)*	*(p)*	*(b)*
1	*10*	*13*	*10*	*14*	*11*	*14*
2	*18*	*23*	*18*	*23*	*21*	*22*
3	*39*	*45*	*38*	*44*	*40*	*46*
4	*23*	*28*	*23*	*28*	*24*	*29*
5	*12*	*12*	*9*	*13*	*12*	*11*

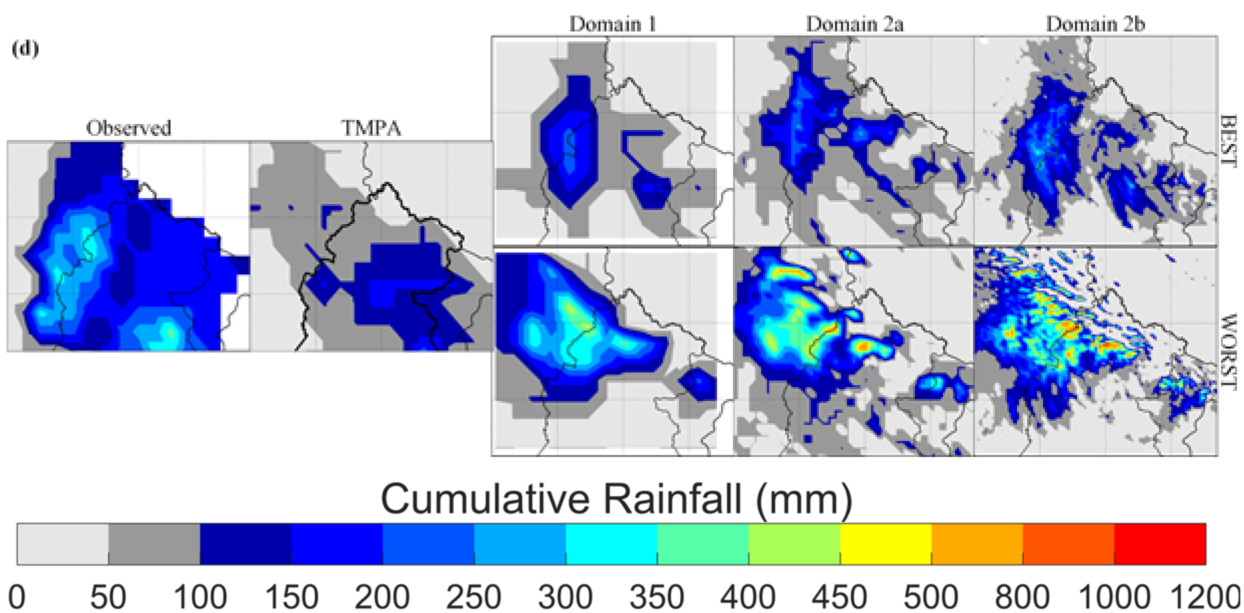
From the analysis conducted over the additional rainfall events, it is noted that configuration (p) gives less error in comparison to the configuration (b) for all the rainfall events. This makes configuration (p) with MYJ PBL, BMJ CU, and Goddard MP the 'best' in simulating the spatial and temporal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

Appendix C:


(a)
Observed
TMPA
Domain 1
Domain 2a
Domain 2b
BEST
WORST
Cumulative Rainfall (mm)
0
50
100
150
200
250
300
350
400
500
600
700
750


(b)
Observed
TMPA
Domain 1
Domain 2a
Domain 2b
BEST
WORST
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

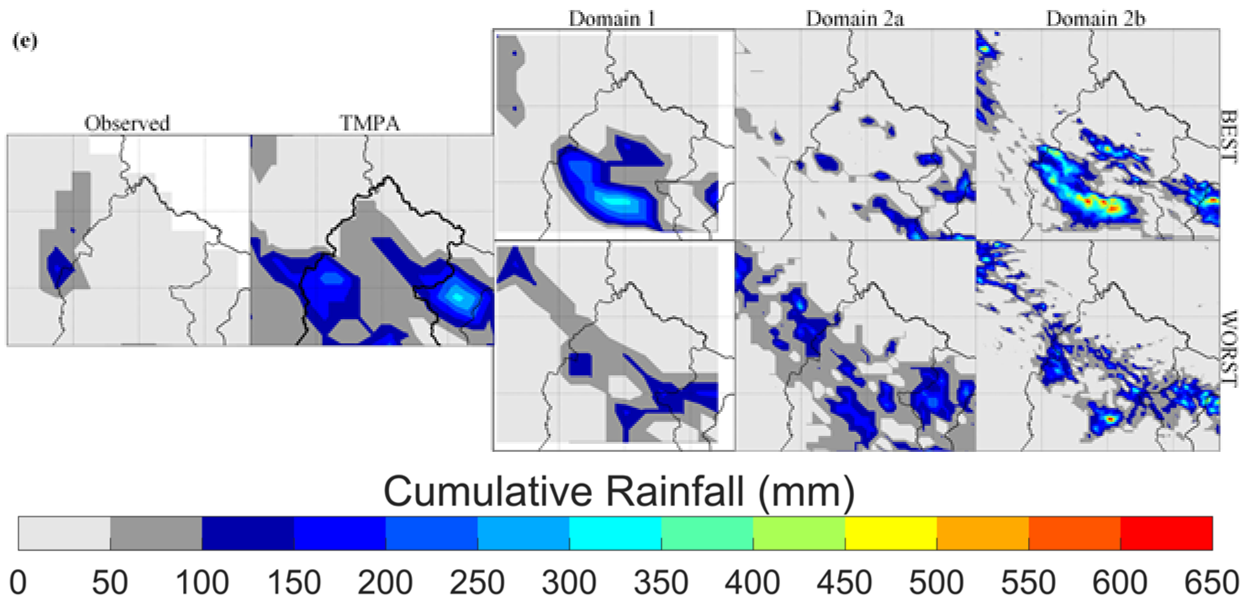


Figure R.9. *Spatial plots presenting the rainfall simulations obtained across the three domains for the best and the worst configuration for heavy to extremely heavy rainfall events during (a) Event 1 (18 – 22 June 2008); (b) Event 2 (29 July – 2 August 2010); (c) Event 3 (15 – 19 August 2011); (d) Event 4 (17 – 21 September 2010); and (e) Event 5 (11 – 15 September 2012).*

References

Ali, H., Mishra, V., and Pai, D.: Observed and projected urban extreme rainfall events in India, Journal of Geophysical Research: Atmospheres, 119, 2014.

Argüeso, D., Hidalgo-Muñoz, J. M., Gámiz-Fortis, S. R., Esteban-Parra, M. J., Dudhia, J., and Castro-Díez, Y.: Evaluation of WRF parameterizations for climate studies over Southern Spain using a multistep regionalization, J. Clim., 24, 5633-5651, 2011.

Cardoso, R., Soares, P., Miranda, P., and Belo-Pereira, M.: WRF high resolution simulation of Iberian mean and extreme precipitation climate, Int. J. Climatol., 33, 2591-2608, 2013.

Chang, H.-I., Kumar, A., Niyogi, D., Mohanty, U., Chen, F., and Dudhia, J.: The role of land surface processes on the mesoscale simulation of the July 26, 2005 heavy rain event over Mumbai, India, Global Planet. Change, 67, 87-103, 2009.

Chen, F., and Dudhia, J.: Coupling an advanced land surface–hydrology model with the Penn State–NCAR MM5 modeling system. Part I: Model implementation and sensitivity, Mon. Weather Rev., 129, 569-585, 2001.

Chevuturi, A., Dimri, A., Das, S., Kumar, A., and Niyogi, D.: Numerical simulation of an intense precipitation event over Rudraprayag in the central Himalayas during 13–14 September 2012, J. Earth Syst. Sci., 124, 1545-1561, 2015.

Chevuturi, A., and Dimri, A.: Investigation of Uttarakhand (India) disaster-2013 using weather research and forecasting model, Nat. Hazards, 82, 1703-1726, 2016.

Deardorff, J.: Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation, Journal of Geophysical Research: Oceans, 83, 1889-1903, 1978.

Dimri, A., Thayyen, R., Kibler, K., Stanton, A., Jain, S., Tullos, D., and Singh, V.: A review of atmospheric and land surface processes with emphasis on flood generation in the Southern Himalayan rivers, Sci. Tot. Environ., 556, 98-115, 2016.

Done, J., Davis, C. A., and Weisman, M.: The next generation of NWP: Explicit forecasts of convection using the Weather Research and Forecasting (WRF) model, Atmos. Sci. Lett., 5, 110-117, 2004.

Dudhia, J.: A multi-layer soil temperature model for MM5, Preprints, The Sixth PSU/NCAR mesoscale model users' workshop, 1996, 22-24,

Ek, M., Mitchell, K., Lin, Y., Rogers, E., Grunmann, P., Koren, V., Gayno, G., and Tarpley, J.: Implementation of Noah land surface model advances in the National Centers for Environmental

Prediction operational mesoscale Eta model, Journal of Geophysical Research: Atmospheres, 108, 2003.
Gadgil, S., and Sajani, S.: Monsoon precipitation in the AMIP runs, Clim. Dyn., 14, 659-689, 1998.
Gutowski Jr, W. J., Arritt, R. W., Kawazoe, S., Flory, D. M., Takle, E. S., Biner, S., Caya, D., Jones, R. G., Laprise, R., and Leung, L. R.: Regional extreme monthly precipitation simulated by NARCCAP RCMs, J. Hydrometeorol., 11, 1373-1379, 2010.
Hazra, A., Chaudhari, H. S., Ranalkar, M., and Chen, J. P.: Role of interactions between cloud microphysics, dynamics and aerosol in the heavy rainfall event of June 2013 over Uttarakhand, India, Q. J. Roy. Meteorol. Soc., 143, 986-998, 2017.
Kishtawal, C. M., Niyogi, D., Tewari, M., Pielke, R. A., and Shepherd, J. M.: Urbanization signature in the observed heavy rainfall climatology over India, Int. J. Climatol., 30, 1908-1916, 2010.
Koren, V., Schaake, J., Mitchell, K., Duan, Q. Y., Chen, F., and Baker, J.: A parameterization of snowpack and frozen ground intended for NCEP weather and climate models, Journal of Geophysical Research: Atmospheres, 104, 19569-19585, 1999.
Kotal, S., Roy, S. S., and Roy Bhowmik, S.: Catastrophic heavy rainfall episode over Uttarakhand during 16–18 June 2013—observational aspects, Curr. Sci, 107, 234-245, 2014.
Kumar, A., Houze Jr, R. A., Rasmussen, K. L., and Peters-Lidard, C.: Simulation of a flash flooding storm at the steep edge of the Himalayas, J. Hydrometeorol., 15, 212-228, 2014.
Kumar, M. S., Shekhar, M., Krishna, S. R., Bhutiyani, M., and Ganju, A.: Numerical simulation of cloud burst event on August 05, 2010, over Leh using WRF mesoscale model, Nat. Hazards, 62, 1261-1271, 2012.
Lei, M., Niyogi, D., Kishtawal, C., Pielke Sr, R., BeltrĂĄn-Przekurat, A., Nobis, T., and Vaidya, S.: Effect of explicit urban land surface representation on the simulation of the 26 July 2005 heavy rain event over Mumbai, India, Atmos. Chem. Phys., 8, 5975-5995, 2008.
Medina, S., Houze, R. A., Kumar, A., and Niyogi, D.: Summer monsoon convection in the Himalayan region: Terrain and land cover effects, Q. J. Roy. Meteorol. Soc., 136, 593-616, 2010.
Noilhan, J., and Planton, S.: A simple parameterization of land surface processes for meteorological models, Mon. Weather Rev., 117, 536-549, 1989.

Osuri, K., Nadimpalli, R., Mohanty, U., Chen, F., Rajeevan, M., and Niyogi, D.: Improved prediction of severe thunderstorms over the Indian Monsoon region using high-resolution soil moisture and temperature initialization, Scientific Reports, 7, 2017.

Pai, D., Sridhar, L., Rajeevan, M., Sreejith, O., Satbhai, N., and Mukhopadhyay, B.: Development of a new high spatial resolution (0.25× 0.25) long period (1901–2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region, Mausam, 65, 1-18, 2014.

Pieri, A. B., von Hardenberg, J., Parodi, A., and Provenzale, A.: Sensitivity of precipitation statistics to resolution, microphysics, and convective parameterization: A case study with the high-resolution WRF climate model over Europe, J. Hydrometeorol., 16, 1857-1872, 2015.

Prein, A. F., Langhans, W., Fosser, G., Ferrone, A., Ban, N., Goergen, K., Keller, M., Tölle, M., Gutjahr, O., and Feser, F.: A review on regional convection-permitting climate modeling: Demonstrations, prospects, and challenges, Rev. Geophys., 53, 323-361, 2015.

Rajesh, P., Pattnaik, S., Rai, D., Osuri, K., Mohanty, U., and Tripathy, S.: Role of land state in a high resolution mesoscale model for simulating the Uttarakhand heavy rainfall event over India, J. Earth Syst. Sci., 125, 475-498, 2016.

Ratna, S. B., Sikka, D., Dalvi, M., and Venkata Ratnam, J.: Dynamical simulation of Indian summer monsoon circulation, rainfall and its interannual variability using a high resolution atmospheric general circulation model, Int. J. Climatol., 31, 1927-1942, 2011.

Schaake, J. C., Koren, V. I., Duan, Q. Y., Mitchell, K., and Chen, F.: Simple water balance model for estimating runoff at different spatial and temporal scales, Journal of Geophysical Research: Atmospheres, 101, 7461-7475, 1996.

Shekhar, M., Pattanayak, S., Mohanty, U., Paul, S., and Kumar, M. S.: A study on the heavy rainfall event around Kedarnath area (Uttarakhand) on 16 June 2013, J. Earth Syst. Sci., 124, 1531-1544, 2015.

Sikder, S., and Hossain, F.: Assessment of the weather research and forecasting model generalized parameterization schemes for advancement of precipitation forecasting in monsoon-driven river basins, J. Adv. Modeling Earth Sys., 8, 1210-1228, 2016.

Sridhar, V., Elliott, R. L., Chen, F., and Brotzge, J. A.: Validation of the NOAH-OSU land surface model using surface flux measurements in Oklahoma, Journal of Geophysical Research: Atmospheres, 107, 2002.

Srinivas, C., Hariprasad, D., Bhaskar Rao, D., Anjaneyulu, Y., Baskaran, R., and Venkatraman, B.: Simulation of the Indian summer monsoon regional climate using advanced research WRF model, Int. J. Climatol., 33, 1195-1210, 2013.

Tewari, M., Chen, F., Wang, W., Dudhia, J., LeMone, M., Mitchell, K., Ek, M., Gayno, G., Wegiel, J., and Cuenca, R.: Implementation and verification of the unified NOAH land surface model in the WRF model, 20th conference on weather analysis and forecasting/16th conference on numerical weather prediction, 2004,

Thayyen, R. J., Dimri, A., Kumar, P., and Agnihotri, G.: Study of cloudburst and flash floods around Leh, India, during August 4–6, 2010, Nat. Hazards, 65, 2175-2204, 2013.

Tripathi, O. P., and Dominguez, F.: Effects of spatial resolution in the simulation of daily and subdaily precipitation in the southwestern US, Journal of Geophysical Research: Atmospheres, 118, 7591-7605, 2013.

Vellore, R. K., Kaplan, M. L., Krishnan, R., Lewis, J. M., Sabade, S., Deshpande, N., Singh, B. B., Madhura, R., and Rao, M. R.: Monsoon-extratropical circulation interactions in Himalayan extreme rainfall, Clim. Dyn., 46, 3517-3546, 2016.

Wehner, M. F., Smith, R. L., Bala, G., and Duffy, P.: The effect of horizontal resolution on simulation of very extreme US precipitation events in a global atmosphere model, Clim. Dyn., 34, 241-247, 2010.

Yu, X., and LEE, T. Y.: Role of convective parameterization in simulations of a convection band at grey-zone resolutions, Tellus A, 62, 617-632, 2010.

Assessment of the Weather Research and Forecasting (WRF) Model for Simulation of Extreme Rainfall Events ~~Simulations~~ in the Upper Ganga Basin

Ila Chawla[1,5], Krishna K Osuri[3,4], P P Mujumdar[1,2], and Dev Niyogi[4,5]

[1]Department of Civil Engineering, Indian Institute of Science, Bangalore, 560012, India
[2]Divecha Centre for Climate Change, Indian Institute of Science, Bangalore, 560012, India
[3]Department of Earth and Atmospheric Sciences, NIT Rourkela, Odisha, 769008, India
[4]Department of Agronomy- Crops, Soils, Water Sciences, Purdue University, West Lafayette, IN 47907, USA
[5]Department of Earth, Atmospheric and Planetary Sciences, Purdue University, West Lafayette, IN 47907, USA

Correspondence to: P P Mujumdar (pradeep@iisc.ac.in)

Abstract. Reliable estimates of extreme rainfall events are necessary for an accurate prediction of floods. Most of the global rainfall products are available at a coarse resolution, rendering them less desirable for extreme rainfall analysis. Therefore, regional mesoscale models such as the advanced research version of the Weather Research and Forecasting (~~WRF-ARW~~WRF) model, are often used to provide rainfall estimates at fine grid spacing. Modeling heavy rainfall events is an enduring challenge, as such events depend on multiscale interactions, and the model configurations such as grid spacing, physical parameterization, and initialization. With this background, the ~~WRF-ARW~~WRF model is implemented in this study to investigate the impact of different processes on extreme rainfall simulation, by considering a representative event that occurred during 15 – 18 June 2013 over the Ganges basin in India, which is located at the foothills of the Himalayas. This event is simulated with ensembles involving four different microphysics (MP), two cumulus (CU) parametrizations, two planetary boundary layer (PBL), and two land surface physics options; and different resolutions (grid spacing) within the WRF model. The simulated rainfall is evaluated against the observations from 18 rain gauges and the Tropical Rainfall Measuring Mission Multi-Satellite Precipitation Analysis (TMPA) 3B42 version 7 data. From the analysis, it is noted that the selection of MP scheme influences the spatial pattern of rainfall, while the choice of PBL and CU parametrizations influence the magnitude of rainfall in the model simulations. Further, WRF run with Goddard MP, Mellor–Yamada–Janjic PBL and Betts–Miller–Janjic~~-~~ CU scheme is found to perform ‘best’ in simulating this heavy rain event. The selected configuration is evaluated for several heavy to extremely heavy rainfall events that occurred across different months of the monsoon season in the region. The model performance improved through incorporation of detailed land surface processes involving prognostic soil moisture evolution in ~~NOAH~~Noah scheme as compared to the simple ~~SLAB~~Slab model. To analyze the effect of model grid spacing, two sets of downscaling ratios – (i) 1:3, Global to Regional (G2R) scale; and (ii) 1:9, Global to Convection-permitting scale (G2C) are employed. Results indicate that higher downscaling ratio (G2C) causes higher variability and consequently, large errors in the simulations. Therefore, G2R is opted as a suitable choice for simulating heavy rainfall event in the present case study. Further, the WRF simulated rainfall is found to exhibit ~~least~~ less bias when compared with the ~~that of the Coordinated Regional Climate Downscaling Experiment (CORDEX) data and the~~ NCEP FiNaL (FNL) reanalysis data.

1. Introduction

Indian Summer Monsson Monsoon Rainfall (ISMR) is often associated with very heavy (124.5 to 244.4 mm/day) to extremely heavy (more than 244.5 mm/day) rainfall– (Indian Meteorological Department, Terminologies and Glossary; http://imd.gov.in/section/nhac/termglossary.pdf)(Ray et al., 2014), particularly during June to September months. The extremely heavy rainfall events often usually occur due to the presence of organized meso-convective systems (MCSs) embedded in large-scalelarge scale monsoonal features such as offshore troughs and vortices, depressions over the Bay of Bengal /Arabian Sea, and mid--tropospheric cyclones (Benson Jr and Rao, 1987; Sikka and Gadgil, 1980; Zipser et al., 2006) (Sikka and Gadgil, 1980; Webster et al., 1998; Fasullo and Webster, 2003).

Extremely heavy rainfall at shorter time scales are particularly difficult to predict in mountainous terrains, and continue to be a challenge to operational and research community (Das et al., 2008; Li et al., 2017). Because of the multiscale features associated with these events, there has been an ongoing effort to implement mesoscale Numerical Weather Prediction (NWP) models for the ISMR simulations. Global models have been employed in several studies to understand the large-scale circulation pattern and for quantitative analysis of the monsoon rainfall, but due to their coarse resolution, they are unable to represent the local to regional characteristics of monsoon rainfall. Regional models, on the other hand, can explicitly simulate the interactions between the large-scale weather phenomenon and regional topography, making the climate simulations reliable (Gadgil and Sajani, 1998; Ratna et al., 2011; Srinivas et al., 2013). Furthermore, regional models have a better representation of convection thus offsetting one of the major sources of errors and uncertainties in the global models. Therefore, regional models become a preferred choice to study seasonal monsoon rainfall.

The advanced research version of the Weather Research and Forecasting model (hereafter referred as the WRF model) is a regional popular community model that is widely used for both studying as well as forecasting a variety of high impact meteorological events, such as rainfall (Vaidya and Kulkarni, 2007; Deb et al., 2008; Kumar et al., 2008; Chang et al., 2009; Routray et al., 2010; Mohanty et al., 2012), tropical cyclones (Raju et al., 2011; Routray et al., 2016; Osuri et al., 2017b) and thunderstorms (Madala et al., 2014; Osuri et al., 2017a). Several works are reported in the literature which have considered the WRF model over the Himalayan region. Kumar et al., (2012) used the WRF model to simulate the cloudburst event of 2010 in the Leh area over the north-western Himalayan belt. While, Kumar et al., (2014) and Thayyen et al., (2013) used the WRF model to gain insight into the atmospheric processes and the MCSs that led to the 2010 Leh event. Similarly, Chevuturi et al., (2015) simulated the heavy precipitation event of September 2012 in the central Himalayas using the WRF model. Medina et al., (2010) used the WRF model to understand how topography and land surface conditions affect the extreme convection in western and eastern Himalayas. Particularly for the 2013 heavy rainfall episode in the Uttarakhand region, the WRF model is used in several studies, including those by Kotal et al., (2014); Vellore et al., (2016); and Hazra et al., (2017) to understand the physical processes leading to the event. Shekhar et al., (2015); Chevuturi and Dimri, (2016); and Dimri et al., (2016) performed in-depth synoptic analysis of the June 2013 heavy rainfall event using the WRF model. Rajesh et al., (2016) presented the role of land surface conditions in simulating the heavy rainfall event. Therefore, from the existing literature, it can be established that the regional model performs considerably well over the region. The operational and research community has widely adopted the Advanced Research version

Field Code Changed

Field Code Changed

~~of the Weather Research and Forecasting (WRF-ARW) model (hereafter referred as the WRF model), to simulate a variety of high impact meteorological events, such as rainfall (Vaidya and Kulkarni, 2007; Deb et al., 2008; Kumar et al., 2008; Chang et al., 2009; Routray et al., 2010; Mohanty et al., 2012), tropical cyclones (Raju et al., 2011; Routray et al., 2016; Osuri et al., 2017b) and thunderstorms (Madala et al., 2014; Osuri et al., 2017a). However, setting up the WRF model, that simulates extremely heavy rainfall over the ISMR region is still considered as a challenging task, which involves consideration of several aspects such as forcing data, model grid spacing/resolution, land surface parameterization and choice of an appropriate physics scheme.~~However, finding the optimal set of physics parameterization schemes (along with the selection of an appropriate model grid spacing/resolution) to simulate extreme/heavy rainfall events, and understanding the effect of the combination of different parametrization schemes on rainfall estimates over the Indian monsoon region is still an active area of research~~finding the optimal set of physics parameterization schemes(along with) events, and understanding the effect of the combination of different parametrization schemes on rainfall estimates are~~.

Earlier studies such as by Krishnamurthy et al., (2009); Misenis and Zhang, (2010); Rauscher et al., (2010); Mohanty et al., (2012); and Chevuturi et al., (2015) indicated that heavy rainfall predictions can be improved through ensemble model techniques and fine grid resolution. However, the influence of the interaction between model parameterization schemes on mesoscale rainfall simulations over India is still an understudied issue. In particular, heavy rain simulations studies have reviewed the impact of individual parameterization options such as the Microphysics (MP) scheme (Rajeevan et al., 2010; Raju et al., 2011; Kumar et al., 2012), Cumulus (CU) parameterization scheme (Deb et al., 2008; Mukhopadhyay et al., 2010; Srinivas et al., 2013; Madala et al., 2014), Planetary Boundary Layer (PBL) scheme (Li and Pu, 2008; Hu et al., 2010; Hariprasad et al., 2014), and Land Surface Model (LSMs) options (Chang et al., 2009). However, the ensemble analysis that reviews the relative impact of different configurations, and the associated variability (uncertainty) is lacking. It is important to study the impact of different parameterizations in an ensemble mode because it is often likely that the performance of one scheme depends on other model configurations considered. For example, the conclusions regarding which CU scheme performs best would be intimately tied to the choice of the MP or land surface options considered in conducting the numerical experiments. With this perspective, ~~an attempt is made in this paper,~~this paper seeks to assess the sensitivity of the WRF model to predict heavy to ~~an~~ extremely heavy rainfall ~~episode,~~episodes ~~that occurred from 15 June through 18 June 2013,~~ over the Ganges basin in ~~in India, which is located at~~ the foothills of the Himalayas. ~~Thus, the~~Specific tasks undertaken in this work are: (i) quantitative verification of the WRF model to simulate an extremely heavy rainfall event; (ii) assessment of the sensitivity of the model simulated rainfall to different parameterization options, downscaling ratios, and land surface models; (iii) validate the selected configuration for other rainfall events over the region; and (iv~~ii~~) comparison of the WRF simulated rainfall with the global reanalysis data ~~and the Coordinated Regional Climate Downscaling Experiment (CORDEX) downscaled data~~ to investigate the impact of local versus global factors on rainfall simulations. A related objective is to provide suitable recommendations on a possible optimal choice for model configuration to simulate such heavy rainfall events in the region. ~~Additional details regarding the event are presented ahead. The performance of the WRF model is evaluated against the global reanalysis and downscaled data.~~

~~Thus, the tasks undertaken in this work are: (i) quantitative verification of the WRF model to simulate an extremely heavy rainfall event; (ii) assessment of sensitivity of the model simulated rainfall to different parameterization options, downscaling ratios and land-surface models; and (iii) comparison of the WRF simulated rainfall with the global reanalysis data and the Coordinated Regional Climate Downscaling Experiment (CORDEX) downscaled data to investigate the impact of local versus global factors on rainfall simulations. A related objective is to use the model results and provide recommendations on a possible optimal choice for model configuration to simulate such events in the region.~~

Description of the heavy rainfall event

The 2013 summer monsoon had a normal onset but the trough advanced rapidly, covering the whole of India by mid-June, instead of mid-July (Ray et al., 2014). This large-scale setting is thought to have created a platform for interaction of two synoptic scale events – northwest moving depression from the Bay of Bengal and preexisting westerly trough in mid-troposphere. Meteorological studies conducted over the region (Kotal et al., 2014; Ray et al., 2014; Chevuturi and Dimri, 2016; Rajesh et al., 2016) established that there was a monsoon ~~low~~ low-pressure system during this period. The longitudinal time section for 850 hPa geopotential height along with anomaly averaged over 20° – 26° N showed high negative anomaly on 14 June, which migrated to the west, over 75° E by 17 June. The meridional wind anomaly within the belt of 35° – 45° N showed a westerly wave, moving from 10° E on 12 June to 70° E on 17 June. These two anomalies are found to be in phase, consequently causing interaction between the eastward moving trough in the mid-upper troposphere and ~~westward~~ westward-moving monsoon low in the lower troposphere. The monsoon low provided the moisture feed and the ~~upper~~ upper-level westerly trough provided the divergence to lift the moisture. This whole system eventually led to an unanticipated heavy rainfall during 15 – 18 June 2013 in the Kedarnath valley and adjoining areas in the state of Uttarakhand, India (Kotal et al., 2014; Ray et al., 2014; Chevuturi and Dimri, 2016; Rajesh et al., 2016). The region received rainfall greater than 370 mm in one day (17 – 18 June 2013), which is 375% above the daily normal rainfall (65.9 mm) during the monsoon season (Ray et al., 2014). Consequently, heavy floods occurred in the region, causing unprecedented damage to life and property.

The synthesis of the synoptic setting of the event has been carried out in a number of studies such as Dube et al., (2014); Kotal et al., (2014); Ray et al., (2014); Shekhar et al., (2015); Chevuturi and Dimri, (2016); and Rajesh et al., (2016), but the mesoscale assessment pertaining to the simulation of this rainfall event is still lacking. Therefore, the present study emphasizes on quantitatively evaluating and conducting the sensitivity analysis of the WRF model in predicting extreme rainfall. The ability of the WRF model to simulate heavy rainfall events is further verified by considering additional episodes (apart from the June 2013 event, details of which are presented in Section 2.1) that occurred within this region across different monsoon months.

~~Since the epicenter of the heavy rainfall was Kedarnath, s~~Study region comprising of the upstream part of the Ganga Basin in India, referred as Upper Ganga Basin (UGB) hereafter, is selected for the analysis in this paper. Figure 1 presents the topography of the UGB as described for the three ~~Domains~~ domains of the WRF model (Domain 1, Domain 2a and Domain 2b with 27, 9 and 3 km grid resolution respectively) along with the 18 rain gauge stations located within the region. The region is of social, cultural and economic importance to India, further making this study necessary.

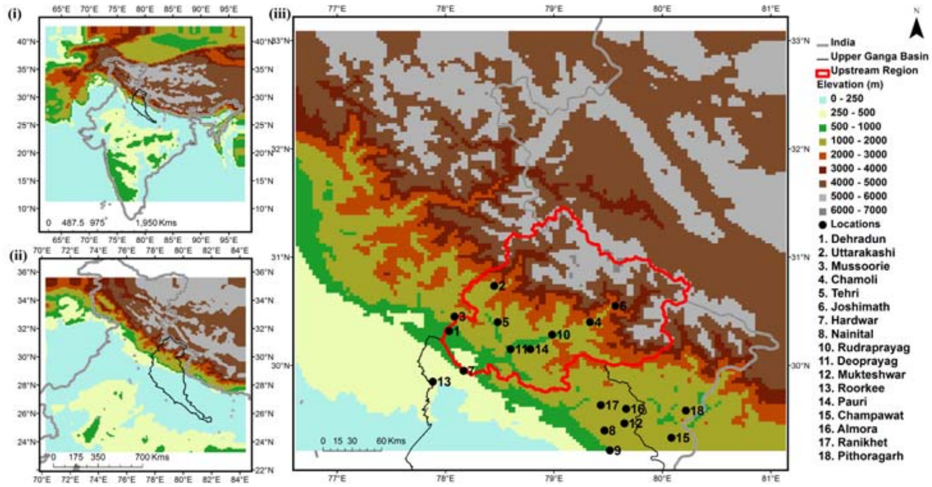


Figure 1. Topography of the study region (shown with black outline) as represented in the WRF model for (i) Domain 1 – 27 km grid spacing; (ii) Domain 2a – 9 km grid spacing (downscaling ratio – 1:3); and (iii) Domain 2b – 3 km grid spacing (downscaling ratio – 1:9). Locations of the rain gauge stations within the UGB are presented as black dots in Figure 1 (iii).

2. Data and Experimental Setup

2.1 Observed Data

Figure 2 presents daily and cumulative rainfall data from 15 to 18 June 2013 (obtained from the Indian Meteorological Ddepartment (IMD) and the literature (Ray et al., 2014) for the 18 official rain gauges located within the UGB.

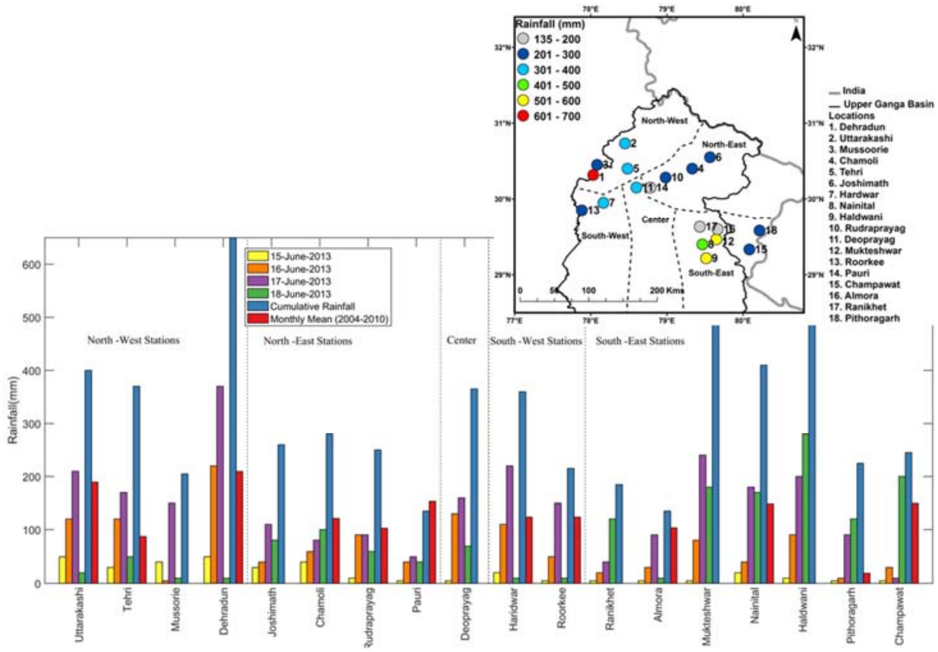


Figure 2. Observed daily and cumulative rainfall along with historic monthly mean (2004 – 2010) values at the 18 rain gauges in the upstream region of the UGB.

It is noticed that the northwest part of the region received higher rainfall compared to the northeast, with stations such as Tehri and Dehradun showing 327% and 210% (respectively) more rainfall than their historic means. A few stations like Chamoli in the northeast region, received 250 mm of cumulative rainfall over the 4 days' period, which is 144% higher than the historic mean. In general, most of the stations in the southern part of the basin, which are located at a lower elevation, recorded relatively less rainfall with a cumulative range of 445 mm, in comparison to the northern part (at higher altitude) having a rainfall range of 515 mm. Additionally, three stations in the southeast region, i.e., Mukteshwar, Haldwani and Nainital received extremely heavy rainfall with a cumulative average of 498 mm. From the above analysis, it is evident that the system moved from east to west direction with two distinct regions in the UGB – southeast, and northwest, receiving extremely heavy rainfall.

The region has complex topography and a limited number of rain gauges because of the difficulty in operating a network in this region. To further capture the spatial variability in rainfall, Tropical Rainfall Measuring Mission Multi-Satellite Precipitation Analysis (TMPA) 3B42 (version 7) product, which is available at 0.25° resolution at daily scale is analyzed (Fig. 3). It is to be noted that, since the focus area for the analyses is the upstream region of the UGB (Fig. 1 (iii) and Fig. 2), results are presented ~~in this paper~~ with respect to the geographical extent of Domain 2b throughout this paper. From Figure 3, it can be noted that the TMPA data is able to capture the spatial variability in the rainfall – with distinct clusters corresponding to heavy rainfall in the northwest and southeast regions of the study area. However, the rainfall amount is significantly underestimated by the TMPA product, with the maximum value of 265 mm against the recorded 650 mm. This under reporting for gridded satellite product versus rain gauge in the ISMR region is a well-known feature (Rahman et al., 2009; Mishra and Srinivasan, 2013; Kneis et al., 2014; Bharti et al., 2016). The TMPA estimates are verified against the IMD station observations for baseline quality check. Mean absolute error (*MAE*), root mean square error (*RMSE*) and bias (β) are computed using the nearest neighborhood mapping approach and are presented in Table 1.

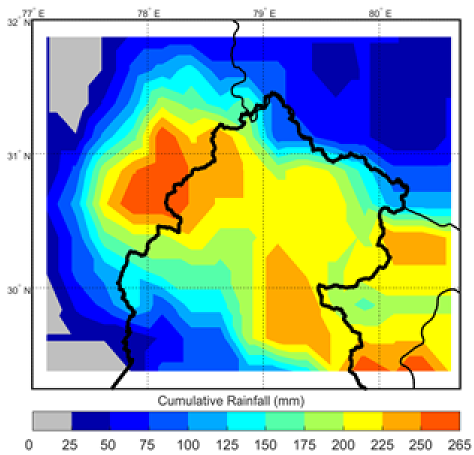


Figure 3. Cumulative rainfall in the upstream region of the UGB obtained from the Tropical Rain Measurement Mission (TMPA) 3B42V7 product at 0.25° resolution. The domain shown is similar to the insert shown in Figure 2.

Table 1. Comparison of TMPA data with station data

Station	**Mean Absolute Error (mm)**	**Root Mean Square Error (mm)**	**Bias* (%)**
Uttarakashi	64	97	-40
Tehri	63	83	-44
Muss~~e~~orie	75	94	-6
Dehradun	126	191	-70
Joshimath	51	55	-21
Chamoli	44	55	-27
Rudraprayag	48	53	-22
Pauri	34	44	37
Deoprayag	95	98	-56
Hardwar	83	114	-76
Roorkee	64	82	-39
Ranikhet	71	77	27
Almora	26	30	63
Mukteshwar	90	118	-60
Nainital	86	111	-67
Haldwani	115	157	-80
Pithoragarh	56	69	-6
Champawat	100	126	1

$*Bias\ (\%) = \frac{(Station\ data - TRMM\ data)}{Station\ data} \times 100$

Formatted: Font: 10 pt, Not Bold
Formatted: Font: 10 pt
Formatted: Font: 10 pt
Formatted: Font: 10 pt
Formatted: No Spacing
Formatted: Font: 10 pt
Formatted: Font: 10 pt
Formatted: Font: 10 pt

TMPA data is observed to behave differently for different ranges of rainfall values over the study domain. TMPA overestimated the rainfall at stations with cumulative rainfall less than 200 mm (e.g., Pauri and Almora). In contrast, rainfall at stations receiving more than 250 mm of cumulative rainfall is underestimated. Stations that received rainfall of 200 – 250 mm are well represented in the TMPA data (e.g., Mussorie, Pithoragarh, ~~Pithogarh~~ and Champawat). From the analysis, it could be inferred that in the TMPA data rainfall values are clustered towards the mean value. Errors noticed in the TMPA data could be attributed to two factors: first, large spatial coverage and coarse resolution of the TMPA data, and second, for comparison with the observed data a simple approach of selecting nearest grid point is implemented.

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 2. Rainfall from the IMD gridded data at 0.25° resolution (Pai et al., 2014) is considered as the observed data for these events.

Table 2. 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 4 presents the spatially averaged daily and cumulative rainfall received during different events (as specified in Table 2).

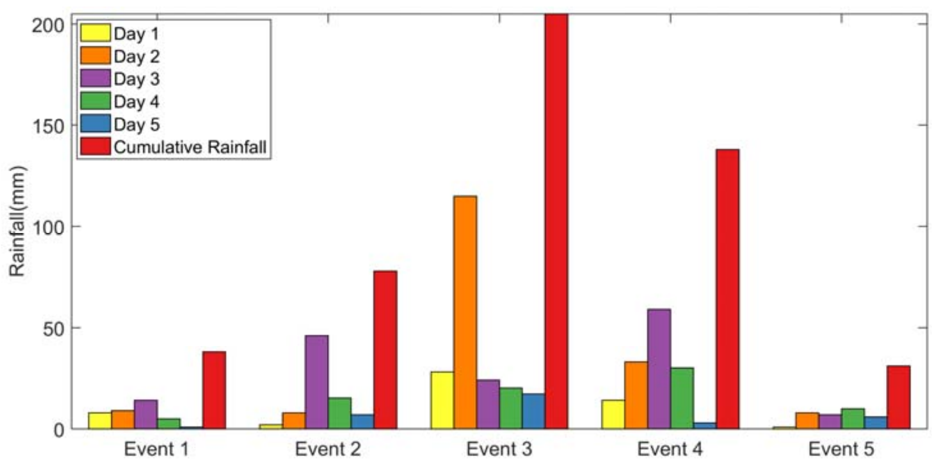


Figure 4. Spatially averaged daily and cumulative rainfall for Event 1 (18 – 22 June 2008); Event 2 (29 July – 2 August 2010);

Formatted: Font: Not Bold
Formatted: Font: Bold
Formatted: Font: Bold
Formatted: Centered, Line spacing: single
Formatted: Centered, Line spacing: single
Formatted: Centered, Line spacing: single
Formatted: Centered, Line spacing: single
Formatted: Centered, Line spacing: single
Formatted: Centered, Line spacing: single
Formatted: Font: Not Bold

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.

2.2 CORDEX Data

The Coordinated Regional Climate Downscaling Experiment (CORDEX; http://www.cordex.org/) aims at providing high-resolution climate projections for historic and future time periods. To achieve this, climate scenarios from the Atmosphere-Ocean coupled General Circulation Models (AOGCMs) under Coupled Model Intercomparison Project Phase 5 (CMIP5) are dynamically downscaled. For downscaling limited domain, relatively finer resolution Regional Climate Models (RCMs) are used with lateral boundary conditions from the coarse resolution AOGCMs. RCMs resolve the topographic details and land surface heterogeneity in order to obtain climate variables at finer spatial scales, in contrast to the driving AOGCMs. CORDEX provides data for historic simulations from 1971 to 2005 and future projections from 2006 to 2099/2100. For the present paper, CORDEX data corresponding to dynamically downscaled projections from six CMIP5 AOGCMs at 0.5° (~ 50 km) resolution (Table 2), for two Representative Concentration Pathways (RCPs), RCP 4.5 and RCP 8.5 are procured from Centre for Climate Change Research (CCCR), India (http://cccr.tropmet.res.in/home/cordexsa.jsp).

Table 2. List of six CMIP5 AOGCMs considered to obtained CORDEX dynamically downscaled RCM simulations

Driving AOGCMs	Institution	Downscaling RCMs
ACCESS1.0	CSIRO	Commonwealth Scientific and Industrial Research Organization, (CSIRO) Australia CCAM
CNRM-CM5	Centre National de Recherches Meteorologiques	
CCSM4	National Center for Atmospheric Research	
GFDL-CM3	Geophysical Fluid Dynamics Laboratory	
MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M)	
NorESM1-M	Norwegian Climate Centre	

Rainfall values from 15 to 18 June 2013 (consistent with the observed data) extracted from 12 climate scenarios (6 models × 2 RCPs), are presented as boxplots in Figure 4. CORDEX grids falling within the geographic extent of Domain 2b, along with the rain gauge data are spatially averaged to obtain single rainfall value for each day.

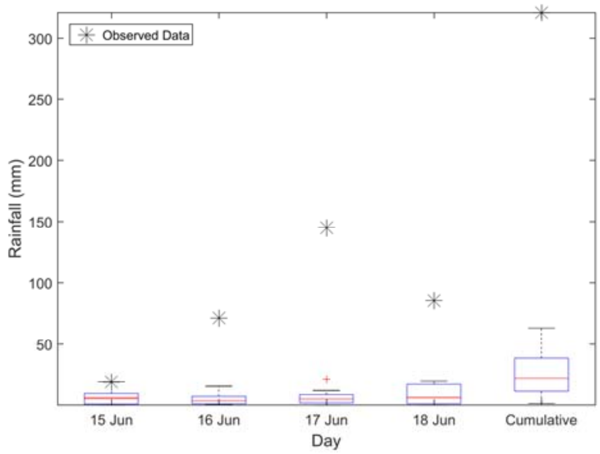


Figure 4. Boxplot presenting the variability in daily and cumulative rainfall obtained from the CORDEX downscaled data for six models and two RCPs for 15 to 18 June 2013.

The CORDEX projections significantly underestimate the heavy rainfall event. Further, negligible variability is observed across the models for all the days except 18 June, indicating that none of the models is able to capture the realistic magnitude of the event. A few models (NorESM1-M with RCP 4.5 and ACCESS1.0 with RCP 8.5) simulated rainfall close to the observed value of 18 mm for 15 June. Cumulative rainfall across all the models has relatively higher variability, primarily due to the variability in heavy rainfall on 18 June. From the analysis, it can be concluded that the CORDEX data is capable of estimating the qualitative features of the rainfall and has significant under-prediction, indicating that care must be exercised while using the data for applications involving heavy rainfall events, such as flood modelling.

2.23 Model Configuration and Experimental Setup

The simulation experiments in this paper are conducted using the Advanced Research Weather Research and Forecasting (ARW-WRF, or simply WRF) model, version 3.8. WRF is a widely used, NWP Numerical Weather Prediction (NWP) non-hydrostatic, mesoscale model, available with several advanced physics and numerical schemes, designed for better prediction of atmospheric processes. The model description and updates can be found from Skamarock et al., (2005) and the WRF user webpage (http://www2.mmm.ucar.edu/wrf/users/).

The WRF model utilizes large-scale atmospheric forcing as input for initialization and lateral boundary condition. These large-scale conditions are regridded by the model domain considering the grid spacing, and local topographical as well as other terrain conditions. As is common for most WRF studies over the Indian region, National Centers for Environmental Prediction (NCEP) global FiNaL (FNL) analysis dataset, based on Global Data Assimilation System (GDAS) with Global Forecast System (GFS) is considered. The FNL data is available at a coarse resolution of 1° × 1°, at every six hours' interval – 00, 06, 12 and 18 UTC (Coordinated Universal Time) and is used to provide initial and boundary conditions to the model. The WRF model is initialized using the FNL dataset

~~from 14 June 2013:00 UTC through 19 June 2013:00 UTC, for 121 hours of forecast that was output at 1-hour interval.~~ The lateral boundary conditions in the WRF model are updated at 6-h intervals. Considering the short duration of the run, the model was forced with fixed Sea Surface Temperature (SST) throughout the integration, and no regional data assimilation is carried out. The land surface boundary conditions are taken from the Moderate Resolution Imaging Spectroradiometer (MODIS) International Geosphere–Biosphere Programme (IGBP) 21-category landuse/cover fields that are available with a horizontal grid spacing of 10 min. Three telescopically-nested domains are used in this study – the parent domain (Domain 1) is fixed between 60°E and 100°E with grid-spacing of 27 km; the first nested domain (Domain 2a) covers 70-85°E, 22-37°N with 9 km grid spacing and is indicative of "global to regional scale" (G2R) downscaling; and the second nested domain (Domain 2b) covers 76-81.5°E and 28.5-34°N at 3 km grid spacing (Fig. 1), for "global to convective scale" (G2C) downscaling (Trapp et al., 2007). The parent domain provides lateral boundary conditions to the inner domains, resulting in the downscaling ratios for simulations as 1:3 and 1:9. The three domains use 30 vertical pressure levels, with the top fixed at 50 hPa. The model time steps were a function of grid spacing: 135 s, 45 s and 15 s respectively for the three domains.

The model configuration used default parameterization options following Osuri et al., (2012). For example, shortwave radiation is based on Dudhia (Dudhia, 1989), and long~~-~~wave based on Rapid Radiative Transfer Model (RRTM; (Mlawer et al., 1997)) scheme. Other physical parameterization options such as Microphysics (MP), Cumulus (CU) parameterization schemes, Planetary Boundary Layer (PBL) and Land Surface Models (LSMs) were selected as outlined ahead. There is currently no known unique configuration that can best simulate an extremely heavy rainfall event. Therefore, based on the literature (e.g. (Kumar et al., 2008; Hong and Lee, 2009; Misenis and Zhang, 2010; Mukhopadhyay et al., 2010; Argüeso et al., 2011; Cardoso et al., 2013; Efstathiou et al., 2013)), four MP schemes, two CU schemes, two PBL schemes and two LSMs are considered ~~representative~~ to obtain an ensemble of rainfall simulations. The two PBL schemes considered are the Yonsei University (YSU) scheme (Hong et al., 2006) and the Mellor–Yamada–Janjic (MYJ) scheme (Janić, 2001). YSU is a non-local scheme, wherein fluxes are calculated at a certain height in the PBL considering the profile of the entire domain. MYJ scheme, on the other hand, is a local scheme in which fluxes are calculated at various heights within the PBL and are related to vertical gradient in the atmospheric variables at the same height. Further details regarding the difference between the YSU and the ~~BMJ~~ MYJ schemes can be obtained from Misenis and Zhang, (2010); and Efstathiou et al., (2013). The two CU schemes considered are the ~~-~~Kain – Fritsch (KF) scheme (Kain, 2004) and the Betts-Miller-Janjic (BMJ) scheme (Janjić, 1994, 2000). The KF scheme is both~~a~~ shallow and deep convection scheme, wherein shallow convection is allowed for updrafts that do not reach minimum precipitating cloud depth. This scheme is based on entrainment and detrainment plume model with updrafts and downdrafts of mass flux. Potential energy is removed in the convective time scale within this scheme. Furthermore, it includes cloud, rain, snow and ice detrainment at cloud top. BMJ, on the other hand, considers convection at both shallow and deep levels. However, there is no updraft and downdraft of mass flux and no cloud detrainment. Domain 2b is configured without any CU scheme, assuming MP to explicitly solve the convection at the finer resolution (Sikder and Hossain, 2016). Four MP schemes considered are, the Purdue Lin (PLin) scheme (Lin et al., 1983; Chen and Sun, 2002), the Eta Ferrier (Eta) scheme (NOAA, 2001), the WRF Single-Moment 6-class (WSM6) scheme (Hong and Lim, 2006) and the Goddard scheme

(Tao et al., 1989). Although bBoth, the PLin scheme and the WSM 6 scheme are based on the parameterization from Rutledge and Hobbs, (1984)) and have , former has 5-class microphysics while the latter has 6-class microphysics, which includes the mixing ratios of water vapor, cloud water, cloud ice, snow, rain, and graupel. The main difference between these two schemes is related to the treatment of ice-phase microphysical processes. Details of the PLin and the WSM6 schemes are available in Hong et al., (2009). The Eta scheme was designed primarily for computational efficiency in NWP models, wherein the total condensate and the water vapors are directly advected into the model. The Goddard scheme is a slight modification from the PLin scheme for ice-water saturation. In general, all the MP schemes are known to influence the rainfall simulations at fine grid resolution by influencing the water phase component (Li et al., 2017). Since each physics scheme is associated with a distinct feature, it is important to examine the effect of their interactions on the rainfall simulations.

The sensitivity of various WRF configurations to simulate heavy rainfall events is assessed using the Noah LSM (Chen and Dudhia, 2001; Ek et al., 2003; Tewari et al., 2004). The Noah LSM is a community model that is included in the WRF suite with the prime aim of providing reliable boundary conditions to the atmospheric model. As a result, Noah LSM is moderately detailed model, which includes single canopy layer with canopy resistance scheme of Noilhan and Planton, (1989) and four soil layers (at 0.1, 0.3, 0.6 and 1.0 m) with a total soil depth of 2 m. The last soil layer of 1 m acts as a reservoir for drainage of water under gravity and the above three layers serve as root zone depths. There is a provision in the model to change default root zone depths with the actual values from the field, subjected to data availability. In the Noah LSM, surface (skin) temperature is obtained using a single linearized surface energy balance equation, which effectively considers the ground and vegetation surface. Frozen soil parametrization based on Koren et al., (1999) and surface runoff scheme of Schaake et al., (1996) are also included in this model. Soil moisture, soil temperature, water intercepted by the canopy and snow stored on the ground are also included as the prognostic variables in the model. More detailed information on the Noah LSM can be obtained from Ek et al., (2003).NOAHNOAHNoilhan and Planton, (1989){Chen, 2001 #9}NOAHKoren et al., (1999)Schaake et al., (1996)NOAHEk et al., (2003); Sridhar et al., (2002); and Chen and Dudhia, (2001){Niu, 2011 #124}

NOAHIn addition to the physics options mentioned above, two LSMs considered in the present work are, Simple 5-layer Soil Model (SLAB; (Dudhia, 1996))NOAH and the Noah LSM {Chen, 2001 #9;Tewari, 2004 #77;Ek, 2003 #121}. SLAB is based on simple thermal diffusion in the soil layers that has constant soil moisture availability but a prognostic soil temperature term(Deardorff, 1978). To assess the effect of the land surface scheme on simulations, the Noah LSM is replaced with the simple five-layer Soil Model (Slab; (Dudhia, 1996)). In contrast to the relatively sophisticated Noah LSM, Slab is based on simple thermal diffusion in the soil layers that has constant soil moisture availability but a prognostic soil temperature term (Deardorff, 1978). Further differences between the two LSMs are presented in Section 3.1.3.

The Noah LSM is a modestly detailed model, which includes explicit land surface parameterization with prognostic soil moisture and soil temperature evolution{Chen, 2001 #9}{Koren, 1999 #123} and snow cover prediction. (Skamarock et al., 2005)

Formatted: Check spelling and grammar
Field Code Changed
Field Code Changed
Formatted: Check spelling and grammar
Formatted: Check spelling and grammar
Formatted: Check spelling and grammar
Field Code Changed
Formatted: Check spelling and grammar
Formatted: Check spelling and grammar
Field Code Changed
Formatted: Check spelling and grammar
Formatted: Check spelling and grammar
Formatted: Check spelling and grammar
Field Code Changed
Field Code Changed
Formatted: Check spelling and grammar

~~Since each scheme is associated with a distinct feature, it is important to examine the effect of their interactions on the rainfall simulations.~~ Table 3 provides the summary of the WRF physics schemes considered to simulate the extremely heavy rainfall events.

Table 3. Configuration of the WRF model considered for simulation of rainfall

Model Options	Dataset/Value
Domains	3
Grid Resolution (spacing)	27 km; 9 km; 3 km
Downscaling ratio	1:3; 1:9
Projection System	Mercator
Land Surface Boundary Condition	21-class MODIS
Initial Conditions	NCEP FNL
Short Wave Radiation Scheme	MM5 Shortwave or Dudhia
Long Wave Radiation Scheme	Rapid Radiative Transfer Model (RRTM)
PBL Schemes	1. Yonsei University (YSU) 2. Mellor–Yamada–Janjic (MYJ)
Cumulus Schemes	1. Kain-Fritsch (KF) 2. Betts-Miller-Janjic (BMJ)
Microphysics Schemes	1. Lin (Purdue) 2. Eta (Ferrier) 3. WSM 6 4. Goddard
Surface Layer Option	Monin-Obukhov Similarity Theory
Land Surface Models	1. Simple 5-layer Soil Model (~~SLAB~~Slab) 2. ~~NOAH~~Noah

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.

3. Results and Discussion

3.1 Sensitivity Analysis

3.1.1 Verification of WRF Simulations

Figure 5 presents cumulative rainfall for 15 – 18 June 2013 from 16 WRF simulations (4 MP, 2 CU and 2 PBL) corresponding to each of the three domains.

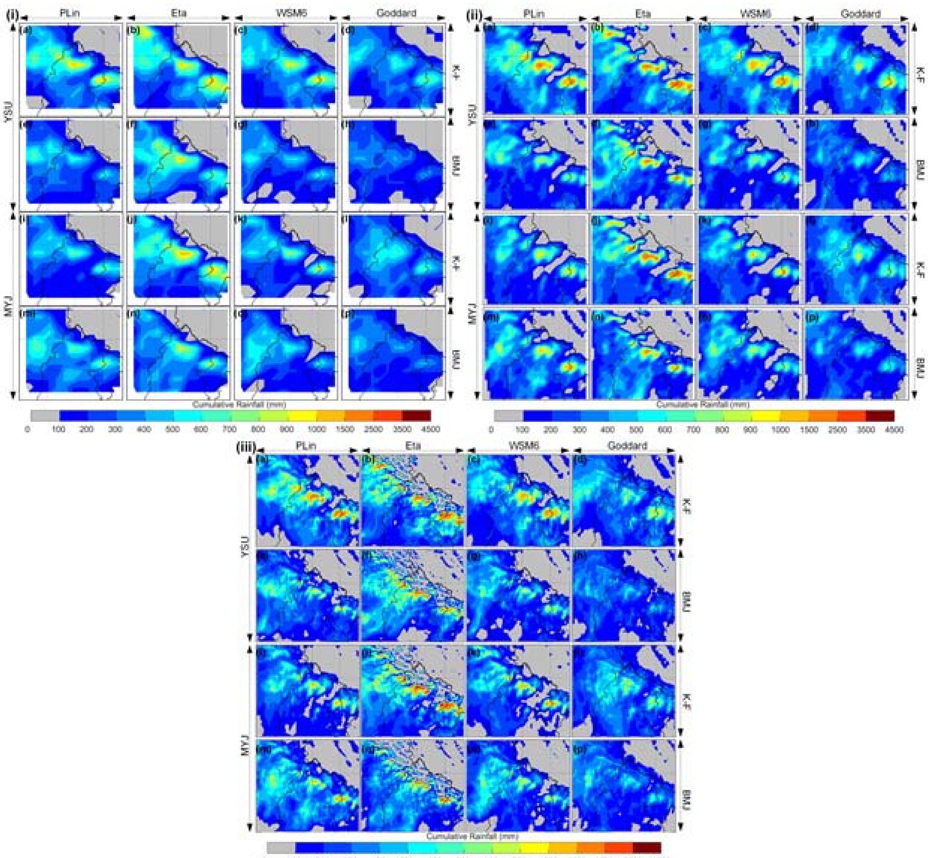


Figure 5. Spatial plots showing rainfall estimates obtained for (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b. Arrows in the left indicate the PBL scheme, arrows in the right represent the CU scheme and the top arrows present the MP scheme considered for the simulation runs. (a) to (p)* are the WRF configurations, for instance, Figure 5 (i) – (a) represents the WRF configuration with YSU PBL scheme, KF CU scheme and PLin MP scheme for Domain 1.

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

From Figure 5 (i) to (iii), it may be seen that the spatial pattern of rainfall appears to be sensitive to the microphysics, i.e., PLin, Eta, and WSM6 MP schemes, while the amount of rainfall is more dependent on the PBL and CU scheme options. There is a considerable difference in the rainfall amount simulated with the Goddard MP scheme option as compared to other MP schemes. Further, most of the model runs are able to reproduce the spatial gradient in the rainfall amount, which is perhaps primarily due to the topographical variation in the region. For locales below 1000 m, observations show distinctly lower rainfall as compared to the high elevation regions (> 1000 m). Further, distinct clusters corresponding to heavy rainfall event are observed in the northeast and northwest areas of the study region. These clusters are found to be consistent with the TMPA data; however, due to lack of surface rain gauge observations, amount of rainfall in these regions could not be verified at this stage. Incidentally, the observed heavy rainfall event in the southeast part of the region is seen in a few WRF configurations, such as configuration (b) and (c). In general, WRF simulated rainfall fields show a similar spatial pattern as that of TMPA rainfall product. However, the magnitude of WRF rainfall is significantly high as compared to TMPA and is attributed to the negative bias in TMPA for heavy rains. 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.

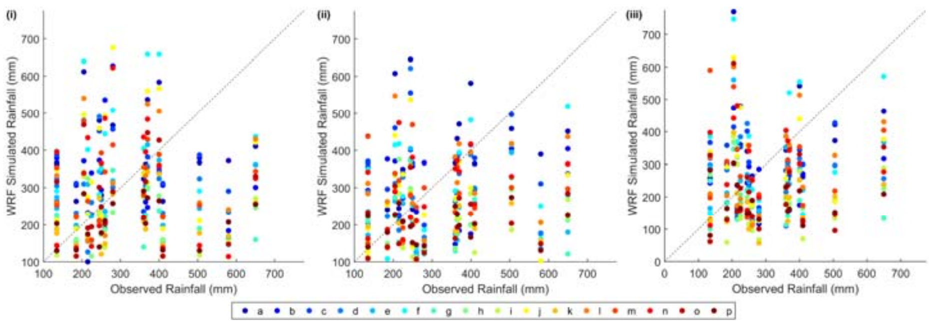


Figure 6. Scatter plots between the rainfall data from the rain gauges and the WRF simulations for (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b for (a) to (p)* WRF configurations.
*Refer to Appendix A (Table A.1) for the list of the WRF configurations.

Figure 6 indicates that Domain 1 captures rainfall within the range of 150 to 400 mm for most of the WRF configurations. For Domain 2a and Domain 2b, increase in the predicted rainfall amount is noted, particularly; for small rainfall thresholds. Further, the WRF runs still under predict extremely heavy rainfall and each of the configuration considered (across all the three domains) underestimated the rainfall amount more than 400 mm. However, the underestimation of rainfall is less in Domain 2b (G2C scale) compared to others, indicating the necessity of finer grid spacing as the first-order requirement for simulating the magnitudes of the extremely heavy rainfall events. The bias in the WRF simulations is typically due to number of interactive factors: (i) scale feedback between mesoscale convection and large-scale processes within the model (Bohra et al., 2006); (ii) lack of local observations that can add mesoscale features (Osuri et al., 2012; Osuri et al., 2015); ~~and~~ (iii) lack of proper land surface processes (Niyogi et al., 2006; Chang et al., 2009; Osuri et al., 2017a); and (iv) inability of the model to fully resolve the complex topography (Argüeso et al., 2011; Cardoso et al., 2013; Chevuturi et al., 2015). To assess the performance of the WRF simulations, quantitative scores (*MAE* and *RMSE*) with respect to the observed data are computed for daily ~~cumulative~~ rainfall data, which is then averaged over the 4 days' period. The results are shown in Figure 7. The last column in the figure presents the spatially averaged values obtained for different model configurations.

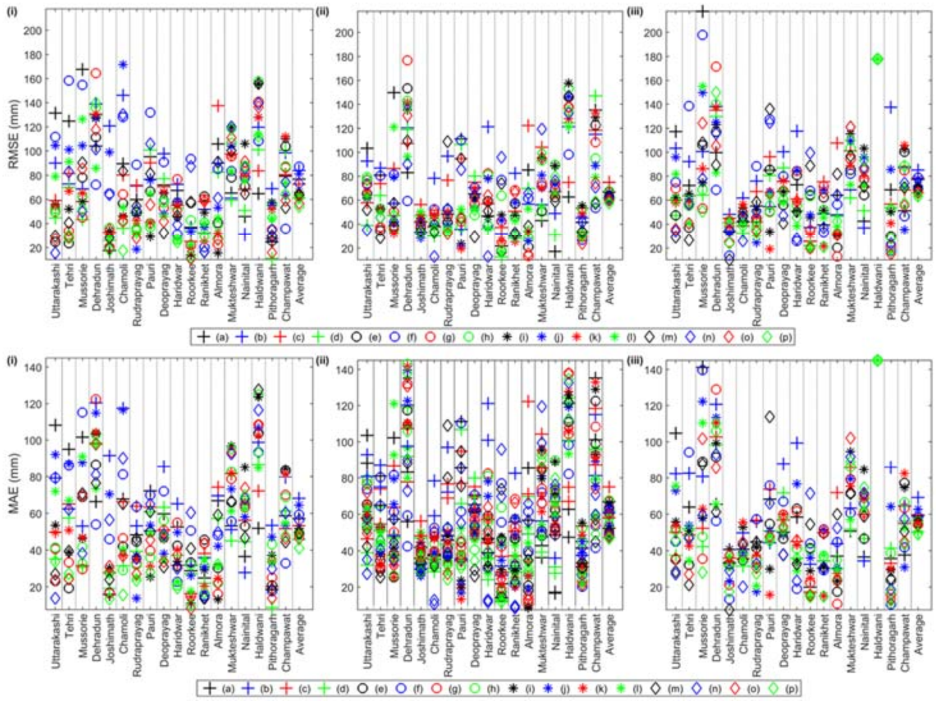


Figure 7. Root mean square error (top panel) and mean absolute error (bottom panel) computed temporally for (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b for (a) to (p)* WRF configurations.
*Refer to Appendix A (Table A.1) for the list of the WRF configurations.

Figure 7 indicates that there is more error at the stations Dehradun and Haldwani, which received higher rainfall. The highest rainfall obtained in different WRF configurations for these stations was less than 500 mm and this underestimation is highlighted in the error statistics. The model results show higher error and variability in the simulations for the northern part of the domain as compared to southern. This is likely due to the complex terrain in the northern part of the domain.

To identify the 'best' and the 'worst' performing configurations, temporal errors across all the stations are summed up and reviewedtemporal errors (wherein *MAE* across the 18 locations are summed up) and spatial errors (wherein *MAE* obtained over the entire region for the 4 days' is summed up) for all the three domains are obtained (Appendix B, Table B.1), which. From this, indicate that the configuration (b) with that is, YSU PBL, KF CU, and Eta MP, produces maximum error, whereas configuration (p) with MYJ PBL, BMJ CU, and Goddard MP, gives minimum error. This was also the 'best' performing configuration across all the locations for the three domains. In addition to this, spatial analysis is also conducted, wherein *MAE* across the 4 days' is computed and averaged across the station locations. Corresponding results are presented in Appendix B (Fig. B.1). These results are consistent to the temporal analysis and again configurations (b) and (p) give maximum and minimum error respectively. Therefore, through this analysis, it can be inferred that the WRF model with MYJ PBL, BMJ CU and Goddard MP schemes is the 'best' in simulating the spatial and temporal variability of the extremely heavy rainfall over the upstream region of the UGB. Why this combination emerged as the best performing is an intriguing but difficult question to address, and needs to be studied through more cases and observational analysis as it becomes available. Note that the rainfall prediction is the combination of many nonlinear, interactive factors including behavior of each configuration and cannot be realistically studied with the sparse rainfall data and absence of vertical sounding observations. Some possible factors that could contribute would be that local boundary formulation in MYJ may be more appropriately capturing the vertical environment in the complex terrain as compared to the nonlocal YSU scheme which seeks to simulate vertical mixing and boundary layer evolution using averaged and grid representative fields (Alapaty et al., 1997). As regards to the BMJ CU emerging in the top configuration, there are a number of studies for the ISMR where it has emerged as performing "overall best" {Kumar, 2010 #79;Mukhopadhyay, 2010 #4;Rao, 2007 #80;Ratnam, 2005 #82;Srinivas, 2013 #63;Vaidya, 2006 #81;Vaidya, 2000 #119;Sikder, 2016 #75}. As for the MP scheme, there are limited studies in comparison to those that have studied the CU configuration for the ISMR. Further, the MP scheme performance has been evaluated for tropical cyclone cases because of the warm versus cold pool processes that are critical in the simulation of the cyclone intensity. Of those available in literature, studies such as (Sing and Mandal, 2014) found that the Goddard scheme has a "slightly better" performance than other schemes. This conclusion is also supported by studies such as (Choudhury and Das, 2017) and has been used in hailstorm studies such as (Chevuturi et al., 2014). Note that in citing these studies there is no claim being made about proving or even explain why the configuration that has emerged as the 'best' is indeed such. What these studies do provide is a reasonable basis to support the notion that the 'best' configuration that has emerged is realistic and plausible to be considered as such.

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 2) 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 4.

Table 4. *Spatio-temporal 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*

a2b a2b

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. Why this combination emerged as the best performing is an intriguing but

Formatted: Font: Not Italic

Formatted: Font: Not Italic

Formatted: Font: Not Italic

Formatted: Font: Not Bold, Italic

Formatted: Font: 9 pt, Not Bold

Formatted Table

Formatted: Font: Not Italic

Formatted: Normal

difficult question to address at this stage. Note that the rainfall prediction is the combination of many nonlinear, interactive factors including the behavior of each configuration and cannot be realistically studied with the sparse rainfall data and absence of vertical sounding observations. Some possible factors that could contribute would be that local boundary formulation in MYJ may be more appropriately capturing the vertical environment in the complex terrain as compared to the nonlocal YSU scheme which seeks to simulate vertical mixing and boundary layer evolution using averaged and grid representative fields. As regards to the BMJ CU emerging in the top configuration, there are a number of studies for the ISMR where it has emerged as performing "overall best" (Vaidya and Singh, 2000; Ratnam and Kumar, 2005; Vaidya, 2006; Rao et al., 2007; Kumar et al., 2010; Mukhopadhyay et al., 2010; Srinivas et al., 2013; Sikder and Hossain, 2016). As for the MP scheme, there are limited studies in comparison to those that have studied the CU configuration for the ISMR. Further, the MP scheme performance has been evaluated for tropical cyclone cases because of the warm versus cold pool processes that are critical in the simulation of the cyclone intensity. Of those available in the literature, studies such as Sing and Mandal, (2014) found that the Goddard scheme has a "slightly better" performance than other schemes. This conclusion is also supported by studies such as Choudhury and Das, (2017) and has been used in hailstorm studies such as Chevuturi et al., (2014).

The impact of downscaling ratio on the rainfall simulations is addressed next. On comparing the simulations of June 2013 event from G2R and G2C domains with the rain gauge data, it is noted that the former gives less error for most of the locations (Appendix CD). G2C scale has large resolution (grid spacing) gap from outer to the inner domain in comparison to G2R, which could result in less accurate initial and lateral boundary conditions, and consequently, more simulation errors in G2C. Another possibility is that the metric being used, which is the rainfall observation from in-situ data, itself is more conservative with regards to the grid in which rainfall occurs in the coarser domain and may slightly favor the G2R. However, on reviewing the overall structure of rainfall fields and the amounts across the domain, results suggest that the G2R scale with moderate downscaling ratio may be better suited for simulation of the extreme rainfall event as in the present case study. The results are found to be consistent with other studies, such as by Liu et al., (2012), wherein moderate ratio of 1:3 is found to perform best. However, it is to be noted that errors corresponding to the grid point nearest to the rain gauge are considered here for comparison. Result The result may vary upon selection of another grid point.

3.1.2 Impact of Different Parametrization Schemes

Although configuration (p), with MYJ PBL, BMJ CU, and Goddard MP, appears to be the 'best' physics configuration for the study region, significant variability exists among the simulations pertaining to different configurations of the WRF model. This variability causes significant uncertainty across different runs, which is quantified through computation of *SE and CV* (Fig. 8 and 9) for the June 2013 event. Deviation in model simulations with respect to observed data provides the *SE*, however, *CV* gives variation within different model simulations.

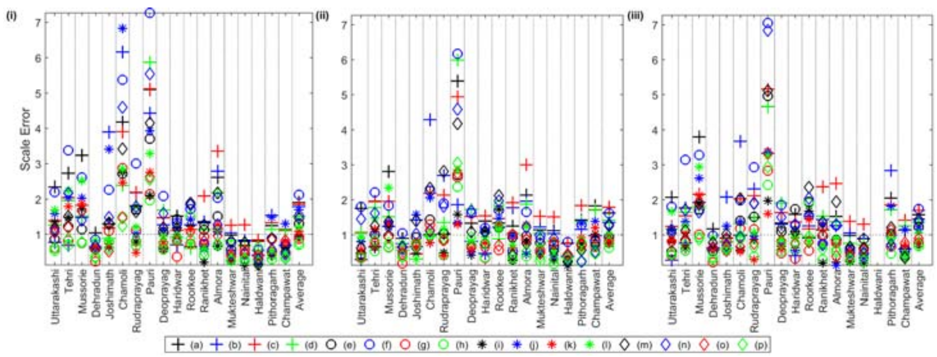


Figure 8. Scale error (*SE*) in (a) to (p)* WRF configurations for 18 locations in the UGB for (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b.

Formatted: Space After: 10 pt

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

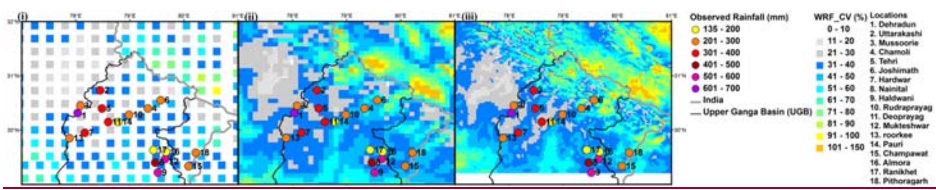


Figure 9. Coefficient of Variation (*CV*) value across different WRF configurations in the UGB for (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b.

Most of the model configurations have *SE* value clustered around 1 (Fig. 8), indicating that the variability in simulated rainfall is similar to the observed rainfall. However, variability in the northeastern part of the domain is observed to be high compared to others. Same is reflected in the *CV* plot (Fig. 9), wherein grid points around the Chamoli station (on the northeastern side) have *CV* between 41-51 %, whereas stations closer to Uttarakashi and Tehri have values ranging between 11 – 30 %. Further, grid points closer to Dehradun have low *CV* value, which could be due to the models consistently underestimating the rainfall in this subdomain. ~~S~~The southern part of the region, which received low rainfall, also exhibited high variability. In general, it can be inferred that uncertainty in rainfall is more in the northeastern part compared to the northwest. The regions that received very high or very low rainfall during this period also displayed higher uncertainty. Uncertainty in rainfall simulations varies between the domains, with Domain 2b having maximum uncertainty. This could be attributed to high variability in the simulated values at higher spatial resolution.

Since consideration of different parametrization schemes is the reason for variability in rainfall simulations, it is of interest to understand how former influences the model output. For this, the average cumulative rainfall over the region, across different configurations is considered. The differences between various configurations ~~is~~ are evaluated to assess the influence of PBL, CU and MP parametrization schemes on the rainfall simulations. Results for the same are presented in Figure 10.

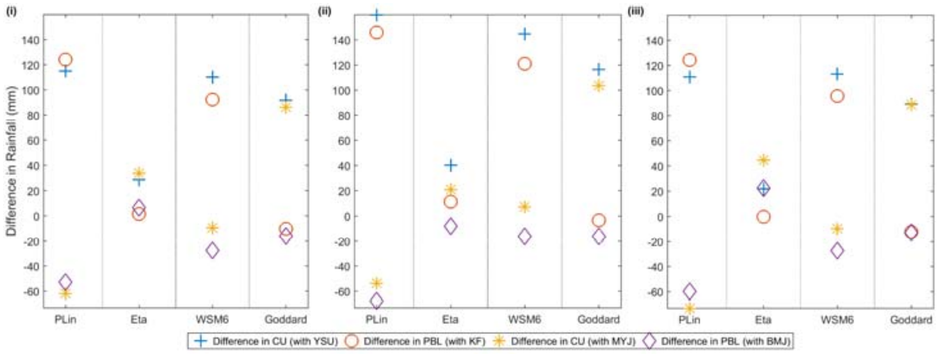


Figure 10. Difference in simulated rainfall due to PBL, CU and MP parametrization schemes corresponding to (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b over the UGB region.

It is noticed that, in general, the WRF configurations with KF convective scheme produce rainfall of higher magnitudes. This result is consistent with previously conducted studies (Gallus Jr, 1999; Fonseca et al., 2015; Pieri et al., 2015). For PLin MP, it is noted that considering YSU PBL along with KF CU scheme has a synergistic effect, leading to the maximum amount of rainfall over the region. This additive effect could be attributed to the YSU being a non-local scheme making it suitable for convective, unstable PBL conditions (Bright and Mullen, 2002). Upon changing the PBL scheme (from YSU to MYJ), and maintaining the convective scheme as KF, notable difference in the fields is simulated (as shown by red circles in Fig. 10). This difference obtained for changing the PBL (with PLin MP and KF CU), is found to be ~~either~~ equivalent to ~~or more compared to~~ the case when only the CU is changed (from KF to BMJ) under ~~either~~ YSU PBL scheme (shown by blue plus sign in Fig. 10)~~ or MYJ PBL (shown by yellow star in Fig. 10) conditions~~. Similarly, the difference in rainfall obtained for two cases – changing the PBL (from YSU to MYJ) with PLin MP and BMJ CU; and changing the CU (from KF to BMJ) with PLin MP and MYJ PBL is also found to be approximately equal. This indicates that the average cumulative rainfall values obtained under two configurations – PLin MP, BMJ CU, and YSU PBL and PLin MP, KF CU, and MYJ PBL are almost equal. Further, BMJ CU, irrespective of the PBL scheme, results in less simulated rainfall across the region. ~~Therefore, it can be inferred that with PLin MP, CU plays a dominant role in determining the amount of rainfall over the region.~~ For WSM6 MP, within YSU PBL scheme, changing the CU (from KF to BMJ) parametrization produces significant variability (displayed by blue plus sign) in rainfall than changing the PBL scheme itself (from YSU to MYJ PBL with KF CU). However, with MYJ PBL, the effect of changing CU scheme is insignificant (yellow star in Fig. 10). Furthermore, with BMJ the difference in rainfall produced due to changing the PBL is minimal. With Eta and Goddard MP, changing the PBL (irrespective of the CU scheme) produces a negligible difference in the rainfall simulations, as represented by red circles and purple diamonds in Figure 10. However, changing the CU ~~CU~~ schemes (irrespective of the PBL condition) ~~have~~ is seen to have a significant influence on rainfall ~~irrespective of the PBL condition~~. It can be concluded from this section that the relationship between PBL and CU is interlinked, wherein YSU and MYJ PBLs complement (contradicts) the effect of KF (BMJ) and BMJ (KF) CUs respectively on the quantity of rainfall. ~~, for Eta and Goddard MPs, the choice of PBL and CU schemes dominates the rainfall~~

~~simulation. The relationship between PBL and CU for PLin and WSM6 MPs is interlinked and th~~Overall, the choice of CU appears to have ~~dominant~~ significant impact on the simulation of rainfall over the region. This conclusion is consistent with the earlier studies such as by Sikder and Hossain, (2016), where they found ISMR to be more sensitive to CU than to MP.

3.1.3 Impact of Land Surface Boundary Condition

It is well established that the soil moisture plays a significant role in weather predictions (Chen and Brutsaert, 1995; Betts et al., 1996; Entekhabi et al., 1996.; Betts et al., 1997). Therefore, ~~SLAB~~Slab and ~~NOAH~~Noah LSMs, which differ significantly in two factors – ~~The main differences in the two LSMs – Slab and Noah, considered here are related to~~ (i) the soil depths along with the inclusion of land surface processes and (ii) the temporal evolution of soil moisture, are selected in the present study to assess the impact of land surface conditions on simulation of heavy rainfall events. The ~~SSLAB~~Slab is a relatively simple LSM with 5 soil layers (at 1, 2, 4, 8 and 16 cm depths) and uses a thermal diffusion equation to compute surface fluxes based on a surface temperature and drag coefficient formulations. ~~NOAH~~ Noah LSM is modestly detailed (compared to ~~SlabSLAB~~Slab) LSM with 4 soil layers (at 10, 30, 60 and 100 cm depths) and explicit representation of land surface parameters, which includes the effect of soil moisture changes, snow cover, evapotranspiration and hydrologic processes such as runoff and drainage (to sub surface layers). Further, in the ~~NOAH~~ Noah LSM soil moisture and temperature is prognostically computed for each of the 4 soil layers, whereas in the ~~Slab SLAB~~Slab LSM only soil temperature is prognostic and moisture is considered as a constant value based on the land-use. ~~SLAB~~Slab lacks the feature of predicting the snow cover and does not capture the evaporation and runoff processes over the region.

To understand the influence of each LSM on the rainfall estimation, simulations using the ~~SLAB~~Slab LSM are conducted for the 'best' and the 'worst' performing configurations from the ~~NOAH~~ Noah LSM case (configuration (p) and (b), respectively). Results comparing the two land model based runs are presented in Figure 11. The top panel in Figure 11 presents the scatter plot of the cumulative rainfall obtained with ~~NOAH~~Noah and ~~SLAB~~Slab LSM runs versus the observed cumulative rainfall. Bottom panel (Fig. 11) presents the mean difference in the simulated and the observed rainfall values over the 4 days' period for 18 locations along with the spatially averaged values (last column in the bottom panel) within the region.

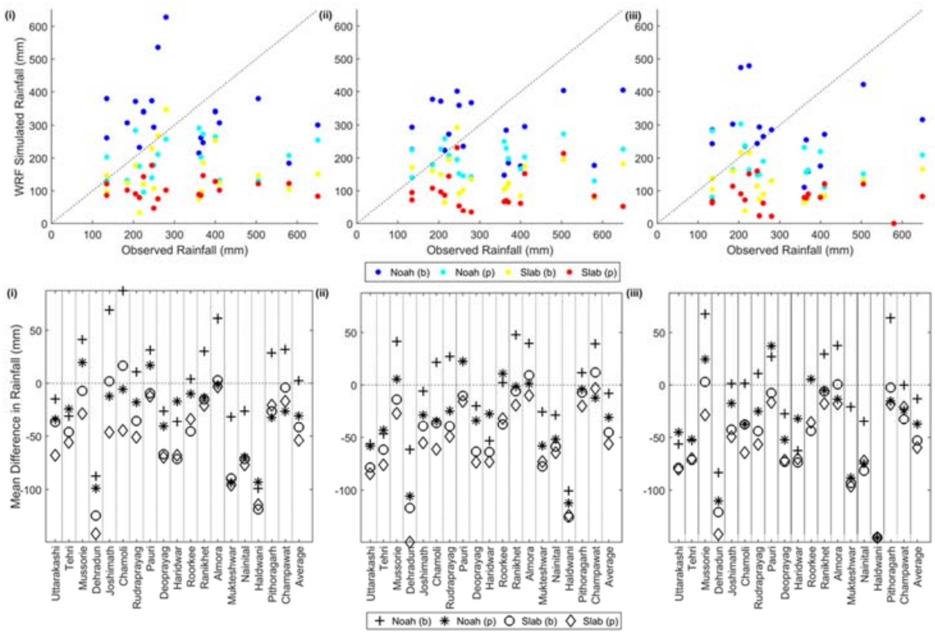


Figure 11. Scatter plot (top panel) and mean ~~absolute error~~difference in rainfall (bottom panel) for the observed rainfall data and the WRF simulations (for (b) and (p) configurations) pertaining to ~~NOAH~~Noah and ~~SLAB~~Slab LSMs corresponding to (i) Domain 1; (ii) Domain 2a; and (iii) Domain 2b.

The ~~SLAB~~Slab LSM based run significantly underestimates the rainfall in comparison to the ~~NOAH~~Noah LSM. For example, the locations which recorded rainfall greater than 400 mm have the ~~SLAB~~Slab LSM based simulated values in the range of 100 – 150 mm. As stated earlier, although ~~NOAH~~Noah LSM also underestimated the rainfall for such stations, the bias with the ~~NOAH~~Noah LSM is significantly less than the ~~SLAB~~Slab LSM (-26 % with the ~~NOAH~~Noah LSM, in contrast to -64 % with the ~~SLAB~~Slab LSM for domain 2a and (p) configuration). ~~Further, *MAE*~~ Further, the mean difference in rainfall obtained with ~~SLAB~~Slab LSM ~~in rainfall~~ is ~~also~~ found to be higher ~~with the Slab LSM~~ in comparison to the ~~NOAH~~Noah LSM. This is essentially due to significant underestimation of rainfall during 16 and 17 June 2013 by the ~~SLAB~~Slab LSM.

~~(Misenis and Zhang, 2010)~~In a number of studies, the differences in the surface energy fluxes simulated by the choice of different LSMs i.e. ~~SLAB~~Slab versus ~~NOAH~~Noah has been discussed (see (Niyogi et al., 2016) for a review). The main reason being that the surface processes affect the boundary layer feedbacks which in turn create zones of mesoscale convergence that can affect the location and intensity of convection. These convective systems then contribute to the simulated rainfall. The results obtained in this study emphasize this feature with differences in the rain amounts and locations ~~through the domain~~ in response to the change in LSM. The 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)

Formatted: Font: Not Italic

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 0.45 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.~~performance of using Noah NOAHmodel could be attributed to temporal evolution of soil moisture fieldsSLABNOAHSLABNOAH(Osuri et al., 2017a) and thus, the importance of soil moisture initialization over India for extreme weather conditions is highlighted through this work (Osuri et al., 2017a).~~

3.2 Comparison between Rainfall from the WRF~~, CORDEX~~ and the FNL datasets~~s~~

Simulated rainfall from the WRF model runs is assessed with respect to the ~~CORDEX downscaled data and the~~ NCEP FNL reanalysis dataset. To achieve this, it is necessary to bring ~~all~~ both the datasets to a common spatial resolution. Therefore, the WRF simulated rainfall is upscaled, through averaging of the grids, to match the resolution of NCEP FNL (1°×1°). ~~and CORDEX (0.5°×0.5°) data.~~ For the analysis, simulations pertaining to the 'best' performing configuration (p), are only considered. Bias (*β*) in rainfall simulations from the ~~three~~ two datasets corresponding to 18 rain gauge locations is obtained, results for which are presented in Figure 12.

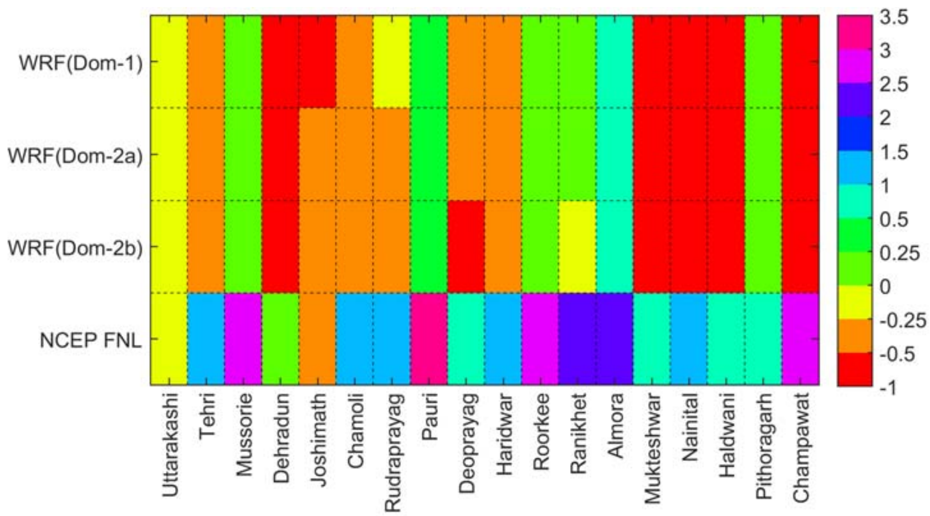


Figure 12. Bias (*β*) in rainfall simulations obtained from the ~~(a)~~ NCEP FNL and WRF (upscaled to 1°×1°) data~~; and the (b) CORDEX and WRF (upscaled to 0.5°×0.5°) data.~~

From Figure 12~~(a),~~ it can be observed that the NCEP FNL data overestimates the rainfall for most of the locations. Upon dynamic downscaling of the FNL data through the WRF model, rainfall simulations improved over the UGB

Formatted: Font: Not Italic

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Formatted: Centered

region. Locations such as Mussorie, Pauri, and Roorkee, which have shown β between 2.5 to 3.5 in the FNL data, reduced to 0 to 0.25 in the WRF simulations. Uttarakashi, and Pithoragarh locations having a small bias in the FNL data, show similar small bias in the WRF simulations. Dehradun along with three stations from the south-eastern region, (Mukteshwar, Haldwani, and Nainital), which recorded heavy rainfall (Section 2.1), are observed to have a small bias in the FNL data, and the rainfall at these location is underestimated by the WRF model. Overall, rainfall simulations from the WRF model (for all the three domains) have less β compared to the FNL data even after upscaling to the resolution of 1°×1°. As expected, upon upscaling, the spatial variability between the domains is reduced due to averaging across several grid points.

~~Figure 12 (b) presents comparison between the CORDEX data and the WRF simulations upscaled to the resolution of 0.5°. Rainfall is underestimated across all the locations by the CORDEX downscaled data, with most of the models having β in the range of -0.9 to -1. The WRF simulations are observed to have less β compared to the CORDEX data. Locations in the northeast along with Roorkee, Ranikhet, Almora and Pithoragarh from the southern part of the region are noticed to have negligible β in the WRF simulations. Northwestern locations (except Mussorie) have shown slight underestimation within the range of -0.2 to -0.5. Only three locations, Mukteshwar, Nainital and Haldwani, which are not simulated well by the WRF model (Section 3.1.1), have shown maximum underestimation in the range of -0.6 to -0.8. It is noticed that despite upscaling, spatial variability is preserved in the WRF simulations which is not seen in the CORDEX data, wherein rainfall is consistently underestimated, within the same range, across all the locations. In addition to this, slight variability in rainfall across the three domains is noticed unlike the earlier case (a), wherein the WRF simulations are compared with the NCEP FNL data. This is attributed to the fact that in this case the simulated data is upscaled to 0.5°, whereas in the previous case it was upscaled to 1°.~~

From the above analysis, it is evident that the WRF model can simulate extreme precipitation better than the ~~CORDEX data and the~~ reanalysis data. This can be attributed to increase in spatial resolution, and better representation of surface and meteorological features, with respect to the lateral boundary conditions as suggested in some of the previous works such as by Argüeso et al., (2011); Mishra et al., (2014); Giorgi and Gutowski Jr, (2015); and Singh et al., (2017).

4. Summary and Conclusions

The main ~~aim~~ focus of this ~~study~~ paper is to provide a general guideline for setting up the WRF model configuration to simulate heavy rainfall events. In this regard, sensitivity of the WRF model to predict heavy to extremely heavy rainfall events is examined through (a) quantitative verification of the rainfall simulated by the WRF model; (b) investigating sensitivity of the simulated rainfall to different parametrization schemes, downscaling ratios, and land surface models; (c) testing the selected scheme for other rainfall events; and (d) assessing the effect of local and global factors by comparing the simulated rainfall with global reanalysis dataset.

For the analysis, an extremely heavy rainfall event, which occurred from 15 to 18 June 2013, over the Ganges basin, in the foothills of the Himalayas ~~Himalayas~~ in the Uttarakhand State of northern India is considered. Most of the studies conducted earlier over this region (Medina et al., 2010; Kumar et al., 2012; Thayyen et al., 2013; Kumar et al., 2014; Chevuturi et al., 2015; Shekhar et al., 2015; Chevuturi and Dimri, 2016; Rajesh et al., 2016; Hazra et al., 2017) are based on the general/default WRF configuration with WSM 6 microphysics, Kain-Fritsch cumulus parametrization scheme and planetary boundary layer of Yonsei University scheme. In this paper, ensemble experiments are conducted ~~with~~ using the WRF model with different grid spacing, four microphysics schemes, two cumulus parametrization schemes, two planetary boundary layer schemes and two land surface model conditions. The rainfall simulations are evaluated against the observed rain gauge data and the TMPA precipitation data. The WRF configuration with Goddard microphysics, Mellor–Yamada–Janjic planetary boundary layer condition and Betts–Miller–Janjic~~´~~ cumulus parameterization scheme is found to perform 'best' in simulating extremely heavy rain event of June 2013. The selected configuration is then verified by simulating several other heavy to extremely heavy rainfall events that occurred across different months in the monsoon season over the upstream region of the UGB. The results for the additional events indicate that the selected configuration (~~with~~ Goddard microphysics, Mellor–Yamada–Janjic planetary boundary layer condition and Betts–Miller–Janjic~~´~~ cumulus parameterization scheme) is indeed the 'best' in simulating the spatial and temporal variability of the extremely heavy rainfall over the region. Therefore, through the exhaustive analysis conducted in this paper, the recommended WRF configuration for extreme rainfall simulations in the Himalayan region is Goddard microphysics, Mellor–Yamada–Janjic planetary boundary layer condition and Betts–Miller–Janjic~~´~~ cumulus parameterization scheme.

Although complex interactions are observed between different physics options, microphysics schemes are noticed to influence the spatial pattern of the rainfall, while the choice of cumulus scheme is found to modulate the magnitude of the simulated rainfall. Upon analyzing the impact of downscaling ratios on rainfall simulations, it is concluded that downscaling from global to regional scale with moderate downscaling ratio may give least model errors and thus, be considered as suitable for reproducing the extreme rainfall event. In addition to this, the effect of land surface models (LSMs) on rainfall simulations is also assessed in this paper. The ~~SLAB~~Slab LSM significantly underestimates the rainfall values, and incorporating ~~NOAH~~Noah helped improve the performance. The underperformance of the ~~SLAB~~Slab model is attributed to dry soil conditions in the region for this LSM.

In addition to the sensitivity experiments, the WRF simulated rainfall is also compared with ~~the CORDEX downscaled data and~~ the NCEP FNL reanalysis data. The NCEP FNL data is found to overestimate the rainfall ~~whereas, the CORDEX downscaled data significantly underestimated this event,~~ whereas, the WRF simulated rainfall exhibited less bias. The comparison results indicated ~~indicating~~ that care must be taken while employing global datasets for regional analysis. ~~The WRF simulated rainfall, on the other hand, has least bias.~~ Through this, it can be established that the rainfall values obtained from the high-resolution mesoscale model can be effectively used in hydrologic models for realistic streamflow estimates.

The analyses presented in this paper are subjected to a few limitations: first, results are limited to the physics parametrization schemes considered in this paper, and may vary upon inclusion of other schemes;~~ second, the best configuration obtained needs to be evaluated for reproducing another extremely heavy rainfall event; third~~second, only two sets of downscaling ratios, i.e., 1:9 and 1:3 are tested in the current work. The sensitivity of simulations pertaining to other downscaling ratios should be tested in future; and ~~fourth~~third, only G2R and G2C sensitivity is assessed in this work.

Acknowledgment

The work is part of the study supported by the US National Science Foundation (CAREER AGS0847472) and the Government of India/MOES National Monsoon Mission (Grant no./Project no.: MM/SERP/CNRS/2013/INT-10/002) at Purdue University. The s~~S~~econd author gratefully acknowledges the financial support of ESSO, Ministry of Earth Sciences, Government~~t~~ of India and ~~SERB~~Science and Engineering Research Board (SERB), Department of Science and Technology, Government ~~Govt.~~ of India. ~~Authors thank the climate modelling groups and the climate data portal hosted at the Centre for Climate Change Research (CCCR), Indian Institute of Tropical Meteorology (IITM) for providing the CORDEX South Asia data.~~

Appendices

Appendix A

Table A.1. List of different WRF configuration

WRF Configuration	Microphysics Scheme (MP)	Cumulus Scheme (CU)	Planetary Boundary Layer Scheme (PBL)
a	PLin	KF	YSU
b	Eta	KF	YSU
c	WSM6	KF	YSU
d	Goddard	KF	YSU
e	PLin	BMJ	YSU
f	Eta	BMJ	YSU
g	WSM6	BMJ	YSU
h	Goddard	BMJ	YSU
i	PLin	KF	MYJ
j	Eta	KF	MYJ
k	WSM6	KF	MYJ
l	Goddard	KF	MYJ
m	PLin	BMJ	MYJ
n	Eta	BMJ	MYJ
o	WSM6	BMJ	MYJ
p	Goddard	BMJ	MYJ

Appendix B

Table B.1. Mean Absolute Error (MAE) values corresponding to different WRF configuration for the three domains

WRF Configuration	Domain 1		Domain 2a		Domain 2b	
	Temporal	**Spatial**	**Temporal**	**Spatial**	**Temporal**	**Spatial**
a	1028	228	943	210	1066	237
b	1227	273	1097	244	1249	278
c	960	213	1048	233	1077	239
d	825	183	852	189	908	202
e	877	195	885	197	995	221
f	1068	237	886	197	1055	234
g	887	197	950	211	979	218
h	885	197	976	217	1010	225
i	932	207	939	209	1024	228
j	1161	258	970	215	1131	251
k	894	199	888	197	987	219
l	883	196	855	190	918	204
m	890	198	913	203	974	217
n	1012	225	870	193	976	217
o	837	186	863	192	976	217
p	740	164	843	187	886	197

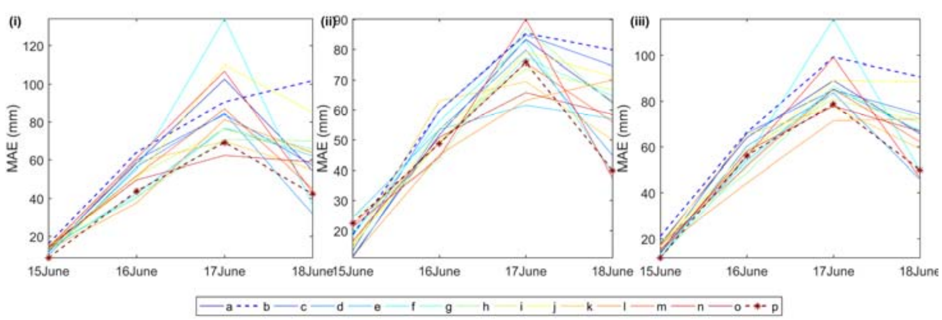
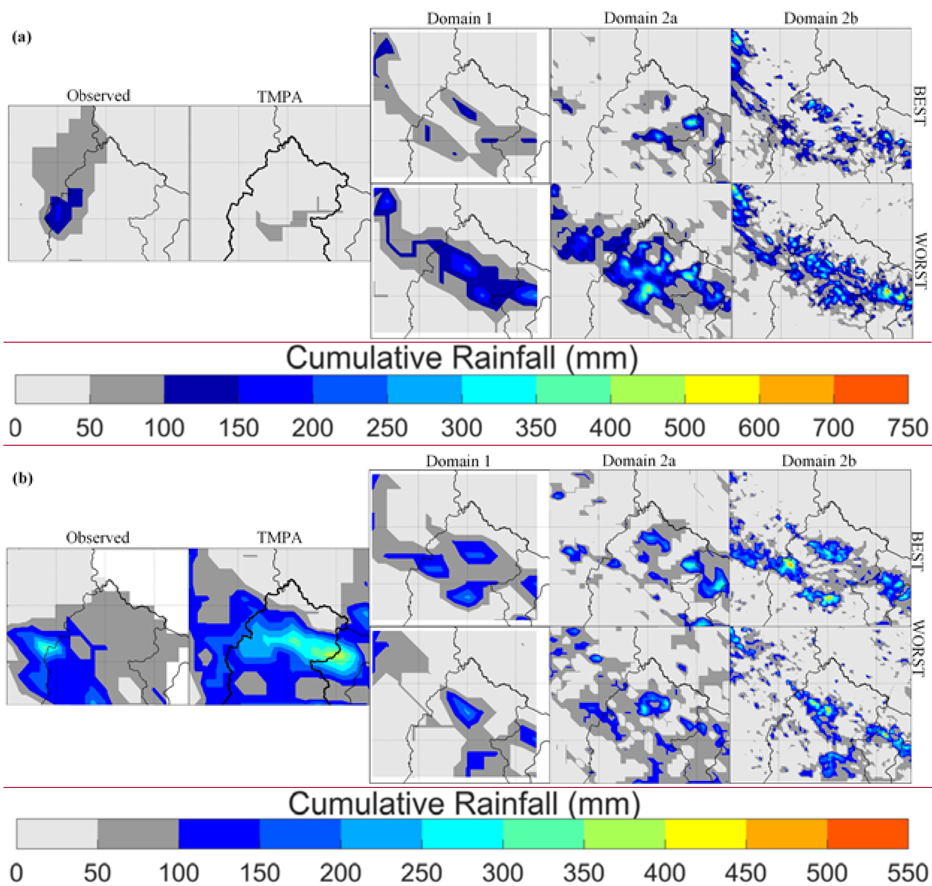


Figure B.1. Mean absolute errors in space corresponding to different WRF configurations for (i) Domain 1; (iii) Domain 2a; and (iii) Domain 2b. Blue dotted lines present the 'worst' performing configuration, i.e., configuration (b) and red dotted lines show the 'best' performing configuration, i.e., configuration (p).

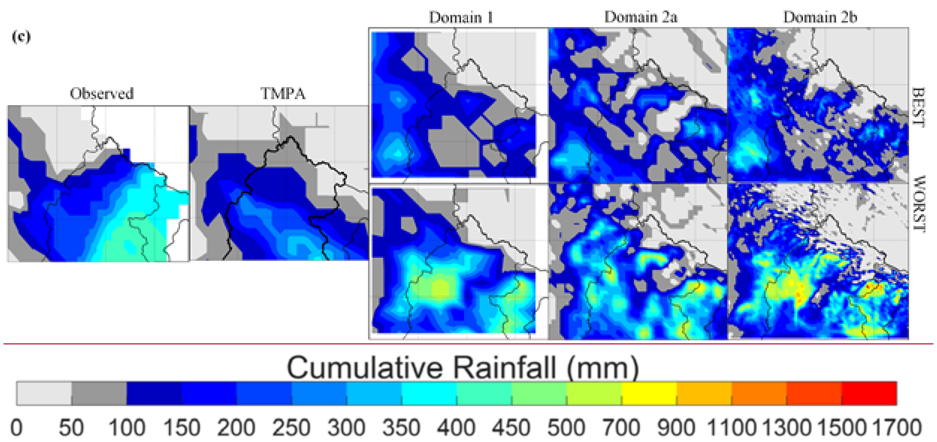
Appendix C

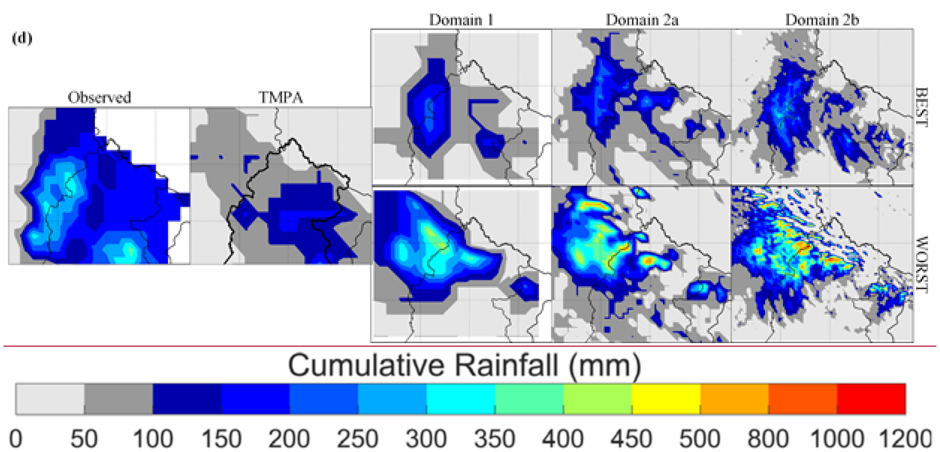
685 **Figure C.1.** Bar plot representing the mean absolute errors in simulating rainfall across the 18 rain-gauge locations at Global to Regional (G2R) scale (1:3) and Global to Convection-permitting (G2C) scale (1:9).

Appendix C



Formatted: Normal


(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

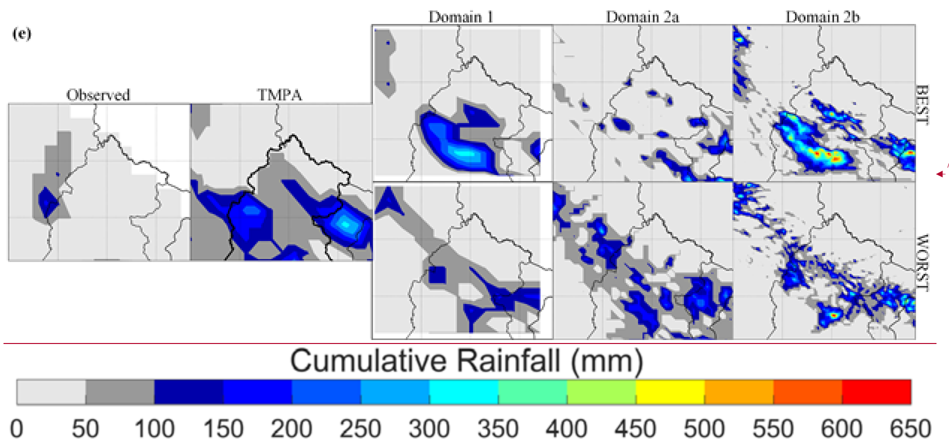


Figure C.1. Spatial plots presenting the rainfall simulations obtained across the three domains for the best and the worst configuration for heavy to extremely heavy rainfall events during (a) Event 1 (18 – 22 June 2008); (b) Event 2 (29 July – 2 August 2010); (c) Event 3 (15 – 19 August 2011); (d) Event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

Formatted: Normal

Formatted: Normal

Appendix D

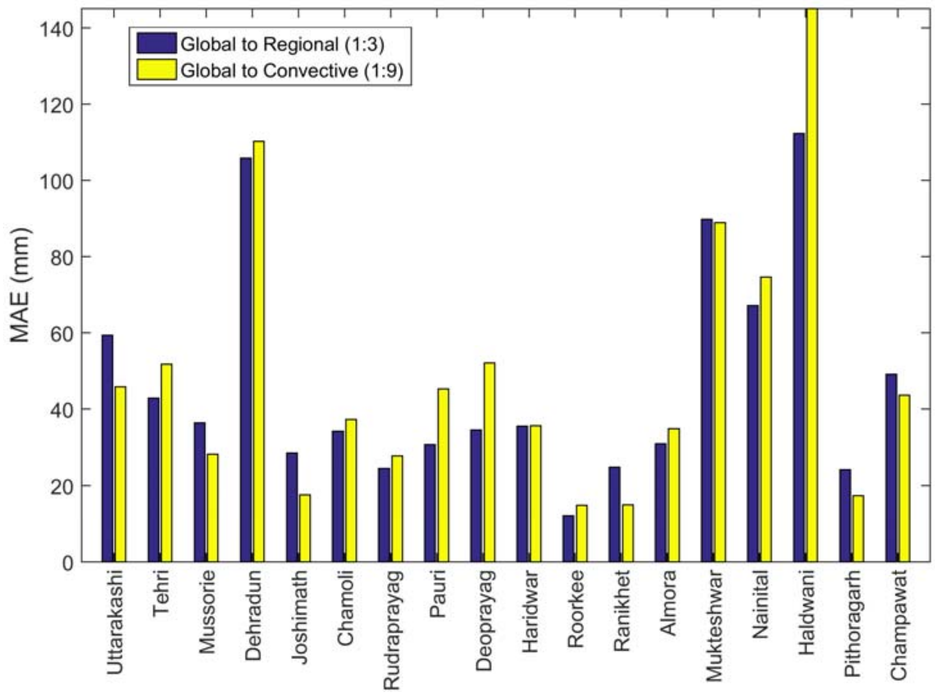


Figure D.1. Bar plot representing the mean absolute errors in simulating rainfall across the 18 rain gauge locations at Global to Regional (G2R) scale (1:3) and Global to Convection-permitting (G2C) scale (1:9).

References

Argüeso, D., Hidalgo-Muñoz, J. M., Gámiz-Fortis, S. R., Esteban-Parra, M. J., Dudhia, J., and Castro-Díez, Y.: Evaluation of WRF parameterizations for climate studies over Southern Spain using a multistep regionalization, J. Clim., 24, 5633-5651, 2011.

Betts, A. K., Ball, J. H., Beljaars, A., Miller, M. J., and Viterbo, P. A.: The land surface-atmosphere interaction: A review based on observational and global modeling perspectives, Journal of Geophysical Research: Atmospheres, 101, 7209-7225, 1996.

Betts, A. K., Chen, F., Mitchell, K. E., and Janjić, Z. I.: Assessment of the land surface and boundary layer models in two operational versions of the NCEP Eta model using FIFE data, Mon. Weather Rev., 125, 2896-2916, 1997.

Bharti, V., Singh, C., Ettema, J., and Turkington, T.: Spatiotemporal characteristics of extreme rainfall events over the Northwest Himalaya using satellite data, Int. J. Climatol., 36, 3949-3962, 2016.

Bohra, A., Basu, S., Rajagopal, E., Iyengar, G., Gupta, M. D., Ashrit, R., and Athiyaman, B.: Heavy rainfall episode over Mumbai on 26 July 2005: Assessment of NWP guidance, Curr. Sci., 1188-1194, 2006.

Bright, D. R., and Mullen, S. L.: The sensitivity of the numerical simulation of the southwest monsoon boundary layer to the choice of PBL turbulence parameterization in MM5, Weather and Forecasting, 17, 99-114, 2002.

Cardoso, R., Soares, P., Miranda, P., and Belo-Pereira, M.: WRF high resolution simulation of Iberian mean and extreme precipitation climate, Int. J. Climatol., 33, 2591-2608, 2013.

Chang, H.-I., Kumar, A., Niyogi, D., Mohanty, U., Chen, F., and Dudhia, J.: The role of land surface processes on the mesoscale simulation of the July 26, 2005 heavy rain event over Mumbai, India, Global Planet. Change, 67, 87-103, 2009.

Chen, D., and Brutsaert, W.: Diagnostics of land surface spatial variability and water vapor flux, Journal of Geophysical Research: Atmospheres, 100, 25595-25606, 1995.

Chen, F., and Dudhia, J.: Coupling an advanced land surface–hydrology model with the Penn State–NCAR MM5 modeling system. Part I: Model implementation and sensitivity, Mon. Weather Rev., 129, 569-585, 2001.

Chen, S.-H., and Sun, W.-Y.: A one-dimensional time dependent cloud model, Journal of the Meteorological Society of Japan. Ser. II, 80, 99-118, 2002.

Chevuturi, A., Dimri, A., and Gunturu, U.: Numerical simulation of a rare winter hailstorm event over Delhi, India on 17 January 2013, Nat. Hazards Earth Syst. Sci., 14, 3331-3344, 2014.

Chevuturi, A., Dimri, A., Das, S., Kumar, A., and Niyogi, D.: Numerical simulation of an intense precipitation event over Rudraprayag in the central Himalayas during 13–14 September 2012, J. Earth Syst. Sci., 124, 1545-1561, 2015.

Chevuturi, A., and Dimri, A.: Investigation of Uttarakhand (India) disaster-2013 using weather research and forecasting model, Nat. Hazards, 82, 1703-1726, 2016.

Choudhury, D., and Das, S.: The sensitivity to the microphysical schemes on the skill of forecasting the track and intensity of tropical cyclones using WRF-ARW model, J. Earth Syst. Sci., 126, 57, 2017.

Das, S., Ashrit, R., Iyengar, G. R., Mohandas, S., Gupta, M. D., George, J. P., Rajagopal, E., and Dutta, S. K.: Skills of different mesoscale models over Indian region during monsoon season: Forecast errors, J. Earth Syst. Sci., 117, 603-620, 2008.

Deardorff, J.: Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation, Journal of Geophysical Research: Oceans, 83, 1889-1903, 1978.
Deb, S., Srivastava, T., and Kishtawal, C.: The WRF model performance for the simulation of heavy precipitating events over Ahmedabad during August 2006, J. Earth Syst. Sci., 117, 589-602, 2008.
Dimri, A., Thayyen, R., Kibler, K., Stanton, A., Jain, S., Tullos, D., and Singh, V.: A review of atmospheric and land surface processes with emphasis on flood generation in the Southern Himalayan rivers, Sci. Tot. Environ., 556, 98-115, 2016.
Dube, A., Ashrit, R., Ashish, A., Sharma, K., Iyengar, G., Rajagopal, E., and Basu, S.: Forecasting the heavy rainfall during Himalayan flooding—June 2013, Weather Clim. Extr., 4, 22-34, 2014.
Dudhia, J.: Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model, J. Atmos. Sci., 46, 3077-3107, 1989.
Dudhia, J.: A multi-layer soil temperature model for MM5, Preprints, The Sixth PSU/NCAR mesoscale model users' workshop, 1996, 22-24,
Efstathiou, G., Zoumakis, N., Melas, D., Lolis, C., and Kassomenos, P.: Sensitivity of WRF to boundary layer parameterizations in simulating a heavy rainfall event using different microphysical schemes. Effect on large-scale processes, Atmos. Res., 132, 125-143, 2013.
Ek, M., Mitchell, K., Lin, Y., Rogers, E., Grunmann, P., Koren, V., Gayno, G., and Tarpley, J.: Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model, Journal of Geophysical Research: Atmospheres, 108, 2003.
Entekhabi, D., Rodriguez-Iturbe, I., and Castelli, F.: Mutual interaction of soil moisture state and atmospheric processes, J. Hydrol., 184, 3-17, 1996.
Fasullo, J., and Webster, P.: A hydrological definition of Indian monsoon onset and withdrawal, J. Clim., 16, 3200-3211, 2003.
Fonseca, R., Zhang, T., and Yong, K.-T.: Improved simulation of precipitation in the tropics using a modified BMJ scheme in the WRF model, Geoscientific Model Development, 8, 2915-2928, 2015.
Gadgil, S., and Sajani, S.: Monsoon precipitation in the AMIP runs, Clim. Dyn., 14, 659-689, 1998.
Gallus Jr, W. A.: Eta simulations of three extreme precipitation events: Sensitivity to resolution and convective parameterization, Weather and Forecasting, 14, 405-426, 1999.
Giorgi, F., and Gutowski Jr, W. J.: Regional dynamical downscaling and the CORDEX initiative, Annual Review of Environment and Resources, 40, 2015.
Hariprasad, K., Srinivas, C., Singh, A. B., Rao, S. V. B., Baskaran, R., and Venkatraman, B.: Numerical simulation and intercomparison of boundary layer structure with different PBL schemes in WRF using experimental observations at a tropical site, Atmos. Res., 145, 27-44, 2014.
Hazra, A., Chaudhari, H. S., Ranalkar, M., and Chen, J. P.: Role of interactions between cloud microphysics, dynamics and aerosol in the heavy rainfall event of June 2013 over Uttarakhand, India, Q. J. Roy. Meteorol. Soc., 143, 986-998, 2017.

Hong, S.-Y., and Lim, J.-O. J.: The WRF single-moment 6-class microphysics scheme (WSM6), J. Korean Meteor. Soc, 42, 129-151, 2006.

Hong, S.-Y., Noh, Y., and Dudhia, J.: A new vertical diffusion package with an explicit treatment of entrainment processes, Mon. Weather Rev., 134, 2318-2341, 2006.

Hong, S.-Y., and Lee, J.-W.: Assessment of the WRF model in reproducing a flash-flood heavy rainfall event over Korea, Atmos. Res., 93, 818-831, 2009.

Hong, S.-Y., Sunny Lim, K.-S., Kim, J.-H., Jade Lim, J.-O., and Dudhia, J.: Sensitivity study of cloud-resolving convective simulations with WRF using two bulk microphysical parameterizations: ice-phase microphysics versus sedimentation effects, Journal of Applied Meteorology and Climatology, 48, 61-76, 2009.

Hu, X.-M., Nielsen-Gammon, J. W., and Zhang, F.: Evaluation of three planetary boundary layer schemes in the WRF model, Journal of Applied Meteorology and Climatology, 49, 1831-1844, 2010.

Janić, Z. I.: Nonsingular implementation of the Mellor-Yamada level 2.5 scheme in the NCEP Meso model, US Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, National Centers for Environmental Prediction, 2001.

Janjić, Z. I.: The step-mountain eta coordinate model: Further developments of the convection, viscous sublayer, and turbulence closure schemes, Mon. Weather Rev., 122, 927-945, 1994.

Janjić, Z. I.: Comments on "Development and evaluation of a convection scheme for use in climate models", J. Atmos. Sci., 57, 3686-3686, 2000.

Kain, J. S.: The Kain–Fritsch convective parameterization: an update, J. Appl. Meteorol., 43, 170-181, 2004.

Kneis, D., Chatterjee, C., and Singh, R.: Evaluation of TRMM rainfall estimates over a large Indian river basin (Mahanadi), Hydrol. Earth Syst. Sci., 18, 2493-2502, 2014.

Koren, V., Schaake, J., Mitchell, K., Duan, Q. Y., Chen, F., and Baker, J.: A parameterization of snowpack and frozen ground intended for NCEP weather and climate models, Journal of Geophysical Research: Atmospheres, 104, 19569-19585, 1999.

Kotal, S., Roy, S. S., and Roy Bhowmik, S.: Catastrophic heavy rainfall episode over Uttarakhand during 16–18 June 2013—observational aspects, Curr. Sci, 107, 234-245, 2014.

Krishnamurthy, C. K. B., Lall, U., and Kwon, H.-H.: Changing frequency and intensity of rainfall extremes over India from 1951 to 2003, J. Clim., 22, 4737-4746, 2009.

Kumar, A., Dudhia, J., Rotunno, R., Niyogi, D., and Mohanty, U.: Analysis of the 26 July 2005 heavy rain event over Mumbai, India using the Weather Research and Forecasting (WRF) model, Q. J. Roy. Meteorol. Soc., 134, 1897-1910, 2008.

Kumar, A., Houze Jr, R. A., Rasmussen, K. L., and Peters-Lidard, C.: Simulation of a flash flooding storm at the steep edge of the Himalayas, J. Hydrometeorol., 15, 212-228, 2014.

Kumar, M. S., Shekhar, M., Krishna, S. R., Bhutiyani, M., and Ganju, A.: Numerical simulation of cloud burst event on August 05, 2010, over Leh using WRF mesoscale model, Nat. Hazards, 62, 1261-1271, 2012.

Kumar, R. A., Dudhia, J., and Roy Bhowmik, S.: Evaluation of Physics options of the Weather Research and Forecasting (WRF) Model to simulate high impact heavy rainfall events over Indian Monsoon region, Geofizika, 27, 101-125, 2010.

Li, L., Gochis, D. J., Sobolowski, S., and Mesquita, M. D.: Evaluating the present annual water budget of a Himalayan headwater river basin using a high-resolution atmosphere-hydrology model, J. Geophys. Res. [Atmos.], 122, 4786-4807, 2017.

Li, X., and Pu, Z.: Sensitivity of numerical simulation of early rapid intensification of Hurricane Emily (2005) to cloud microphysical and planetary boundary layer parameterizations, Mon. Weather Rev., 136, 4819-4838, 2008.

Lin, Y.-L., Farley, R. D., and Orville, H. D.: Bulk parameterization of the snow field in a cloud model, J. Clim. Appl. Meteorol., 22, 1065-1092, 1983.

Liu, J., Bray, M., and Han, D.: Sensitivity of the Weather Research and Forecasting (WRF) model to downscaling ratios and storm types in rainfall simulation, Hydrol. Processes, 26, 3012-3031, 2012.

Madala, S., Satyanarayana, A., and Rao, T. N.: Performance evaluation of PBL and cumulus parameterization schemes of WRF ARW model in simulating severe thunderstorm events over Gadanki MST radar facility—case study, Atmos. Res., 139, 1-17, 2014.

Medina, S., Houze, R. A., Kumar, A., and Niyogi, D.: Summer monsoon convection in the Himalayan region: Terrain and land cover effects, Q. J. Roy. Meteorol. Soc., 136, 593-616, 2010.

Misenis, C., and Zhang, Y.: An examination of sensitivity of WRF/Chem predictions to physical parameterizations, horizontal grid spacing, and nesting options, Atmos. Res., 97, 315-334, 2010.

Mishra, A., and Srinivasan, J.: Did a cloud burst occur in Kedarnath during 16 and 17 June 2013?, Curr. Sci., 105, 1351-1352, 2013.

Mishra, V., Kumar, D., Ganguly, A. R., Sanjay, J., Mujumdar, M., Krishnan, R., and Shah, R. D.: Reliability of regional and global climate models to simulate precipitation extremes over India, J. Geophys. Res. [Atmos.], 119, 9301-9323, 2014.

Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J., and Clough, S. A.: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave, J. Geophys. Res. [Atmos.], 102, 16663-16682, 1997.

Mohanty, U., Routray, A., Osuri, K. K., and Prasad, S. K.: A study on simulation of heavy rainfall events over Indian region with ARW-3DVAR modeling system, Pure Appl. Geophys., 169, 381-399, 2012.

Mukhopadhyay, P., Taraphdar, S., Goswami, B., and Krishnakumar, K.: Indian summer monsoon precipitation climatology in a high-resolution regional climate model: Impacts of convective parameterization on systematic biases, Weather and Forecasting, 25, 369-387, 2010.

Niyogi, D., Holt, T., Zhong, S., Pyle, P. C., and Basara, J.: Urban and land surface effects on the 30 July 2003 mesoscale convective system event observed in the southern Great Plains, J. Geophys. Res. [Atmos.], 111, 2006.

Niyogi, D., Subramanian, S., and Osuri, K. K.: The Role of Land Surface Processes on Tropical Cyclones: Introduction to Land Surface Models, in: Advanced Numerical Modeling and Data Assimilation Techniques for Tropical Cyclone Prediction, Springer, 221-246, 2016.

NOAA: National Oceanic and Atmospheric Administration Changes to the NCEP Meso Eta Analysis and Forecast System: Increase in resolution, new cloud microphysics, modified precipitation assimilation, modified 3DVAR analysis, 2001.

Noilhan, J., and Planton, S.: A simple parameterization of land surface processes for meteorological models, Mon. Weather Rev., 117, 536-549, 1989.

Osuri, K., Nadimpalli, R., Mohanty, U., Chen, F., Rajeevan, M., and Niyogi, D.: Improved prediction of severe thunderstorms over the Indian Monsoon region using high-resolution soil moisture and temperature initialization, Scientific Reports, 7, 2017a.

Osuri, K. K., Mohanty, U., Routray, A., Kulkarni, M. A., and Mohapatra, M.: Customization of WRF-ARW model with physical parameterization schemes for the simulation of tropical cyclones over North Indian Ocean, Nat. Hazards, 63, 1337-1359, 2012.

Osuri, K. K., Mohanty, U., Routray, A., and Niyogi, D.: Improved prediction of Bay of Bengal Tropical cyclones through assimilation of doppler weather radar observations, Mon. Weather Rev., 143, 4533-4560, 2015.

Osuri, K. K., Nadimpalli, R., Mohanty, U. C., and Niyogi, D.: Prediction of rapid intensification of tropical cyclone Phailin over the Bay of Bengal using the HWRF modelling system, Q. J. Roy. Meteorol. Soc., 2017b.

Pieri, A. B., von Hardenberg, J., Parodi, A., and Provenzale, A.: Sensitivity of precipitation statistics to resolution, microphysics, and convective parameterization: A case study with the high-resolution WRF climate model over Europe, J. Hydrometeorol., 16, 1857-1872, 2015.

Rahman, S., Sengupta, D., and Ravichandran, M.: Variability of Indian summer monsoon rainfall in daily data from gauge and satellite, J. Geophys. Res. [Atmos.], 114, 2009.

Rajeevan, M., Kesarkar, A., Thampi, S., Rao, T., Radhakrishna, B., and Rajasekhar, M.: Sensitivity of WRF cloud microphysics to simulations of a severe thunderstorm event over Southeast India, Ann. Geophys., 2010, 603-619,

Rajesh, P., Pattnaik, S., Rai, D., Osuri, K., Mohanty, U., and Tripathy, S.: Role of land state in a high resolution mesoscale model for simulating the Uttarakhand heavy rainfall event over India, J. Earth Syst. Sci., 125, 475-498, 2016.

Raju, P., Potty, J., and Mohanty, U.: Sensitivity of physical parameterizations on prediction of tropical cyclone Nargis over the Bay of Bengal using WRF model, Meteorol. Atmos. Phys., 113, 125, 2011.

Rao, Y. R., Hatwar, H., Salah, A. K., and Sudhakar, Y.: An experiment using the high resolution Eta and WRF models to forecast heavy precipitation over India, Pure Appl. Geophys., 164, 1593-1615, 2007.

Ratna, S. B., Sikka, D., Dalvi, M., and Venkata Ratnam, J.: Dynamical simulation of Indian summer monsoon circulation, rainfall and its interannual variability using a high resolution atmospheric general circulation model, Int. J. Climatol., 31, 1927-1942, 2011.

Ratnam, J. V., and Kumar, K. K.: Sensitivity of the simulated monsoons of 1987 and 1988 to convective parameterization schemes in MM5, J. Clim., 18, 2724-2743, 2005.

Rauscher, S. A., Coppola, E., Piani, C., and Giorgi, F.: Resolution effects on regional climate model simulations of seasonal precipitation over Europe, Clim. Dyn., 35, 685-711, 2010.

Ray, K., Bhan, S., and Sunitha Devi, S.: A METEOROLOGICAL ANALYSIS OF VERY HEAVY RAINFALL EVENT OVER UTTARAKHAND DURING 14-17 JUNE, 2013, Monsoon2013, 37, 2014.

Routray, A., Mohanty, U., Niyogi, D., Rizvi, S., and Osuri, K. K.: Simulation of heavy rainfall events over Indian monsoon region using WRF-3DVAR data assimilation system, Meteorol. Atmos. Phys., 106, 107-125, 2010.

Routray, A., Mohanty, U., Osuri, K. K., Kar, S., and Niyogi, D.: Impact of satellite radiance data on simulations of Bay of Bengal tropical cyclones using the WRF-3DVAR modeling system, IEEE Trans. Geosci. Remote Sens., 54, 2285-2303, 2016.

Rutledge, S. A., and Hobbs, P. V.: The mesoscale and microscale structure and organization of clouds and precipitation in midlatitude cyclones. XII: A diagnostic modeling study of precipitation development in narrow cold-frontal rainbands, J. Atmos. Sci., 41, 2949-2972, 1984.

Schaake, J. C., Koren, V. I., Duan, Q. Y., Mitchell, K., and Chen, F.: Simple water balance model for estimating runoff at different spatial and temporal scales, Journal of Geophysical Research: Atmospheres, 101, 7461-7475, 1996.

Shekhar, M., Pattanayak, S., Mohanty, U., Paul, S., and Kumar, M. S.: A study on the heavy rainfall event around Kedarnath area (Uttarakhand) on 16 June 2013, J. Earth Syst. Sci., 124, 1531-1544, 2015.

Sikder, S., and Hossain, F.: Assessment of the weather research and forecasting model generalized parameterization schemes for advancement of precipitation forecasting in monsoon-driven river basins, J. Adv. Modeling Earth Sys., 8, 1210-1228, 2016.

Sikka, D., and Gadgil, S.: On the maximum cloud zone and the ITCZ over Indian, longitudes during the southwest monsoon, Mon. Weather Rev., 108, 1840-1853, 1980.

Sing, K. S., and Mandal, M.: Sensitivity of Mesoscale Simulation of Aila Cyclone to the Parameterization of Physical Processes Using WRF Model, in: Monitoring and Prediction of Tropical Cyclones in the Indian Ocean and Climate Change, Springer, 300-308, 2014.

Singh, S., Ghosh, S., Sahana, A., Vittal, H., and Karmakar, S.: Do dynamic regional models add value to the global model projections of Indian monsoon?, Clim. Dyn., 48, 1375-1397, 2017.

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Wang, W., and Powers, J. G.: A description of the advanced research WRF version 2, National Center For Atmospheric Research Boulder Co Mesoscale and Microscale Meteorology Div, 2005.

Srinivas, C., Hariprasad, D., Bhaskar Rao, D., Anjaneyulu, Y., Baskaran, R., and Venkatraman, B.: Simulation of the Indian summer monsoon regional climate using advanced research WRF model, Int. J. Climatol., 33, 1195-1210, 2013.

Tao, W.-K., Simpson, J., and McCumber, M.: An ice-water saturation adjustment, Mon. Weather Rev., 117, 231-235, 1989.

Tewari, M., Chen, F., Wang, W., Dudhia, J., LeMone, M., Mitchell, K., Ek, M., Gayno, G., Wegiel, J., and Cuenca, R.: Implementation and verification of the unified NOAH land surface model in the WRF model, 20th conference on weather analysis and forecasting/16th conference on numerical weather prediction, 2004,

Thayyen, R. J., Dimri, A., Kumar, P., and Agnihotri, G.: Study of cloudburst and flash floods around Leh, India, during August 4–6, 2010, Nat. Hazards, 65, 2175-2204, 2013.
Trapp, R. J., Halvorson, B. A., and Diffenbaugh, N. S.: Telescoping, multimodel approaches to evaluate extreme convective weather under future climates, J. Geophys. Res. [Atmos.], 112, 2007.
Vaidya, S., and Singh, S.: Applying the Betts–Miller–Janjic scheme of convection in prediction of the Indian monsoon, Weather and Forecasting, 15, 349-356, 2000.
Vaidya, S.: The performance of two convective parameterization schemes in a mesoscale model over the Indian region, Meteorol. Atmos. Phys., 92, 175-190, 2006.
Vaidya, S., and Kulkarni, J.: Simulation of heavy precipitation over Santacruz, Mumbai on 26 July 2005, using mesoscale model, Meteorol. Atmos. Phys., 98, 55-66, 2007.
Vellore, R. K., Kaplan, M. L., Krishnan, R., Lewis, J. M., Sabade, S., Deshpande, N., Singh, B. B., Madhura, R., and Rao, M. R.: Monsoon-extratropical circulation interactions in Himalayan extreme rainfall, Clim. Dyn., 46, 3517-3546, 2016.
Webster, P. J., Magana, V. O., Palmer, T., Shukla, J., Tomas, R., Yanai, M., and Yasunari, T.: Monsoons: Processes, predictability, and the prospects for prediction, Journal of Geophysical Research: Oceans, 103, 14451-14510, 1998.