Authors' Response to the Reviewer Comments

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

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

Responses to the comments of Referee #1:

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 a challenging task 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 are still an active area of research.”*

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 (Ratna et al., 2011; Wang et al., 2005; Kang et al., 2002; Gadgil et al., 2005; 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:

"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).

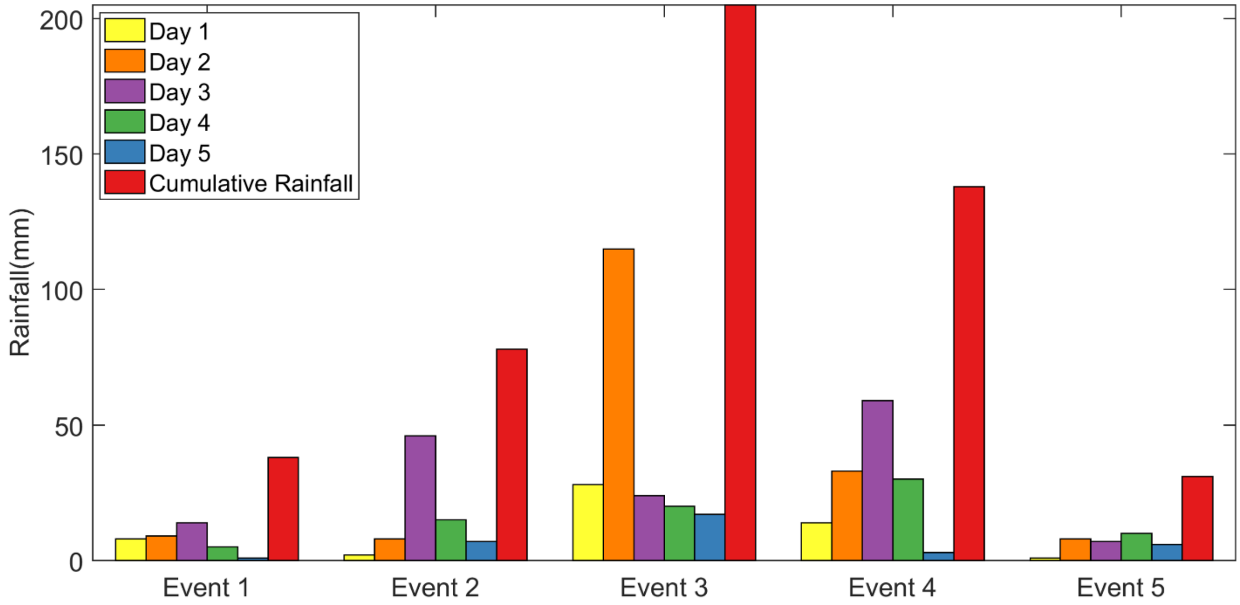


Figure R.1. *Spatially averaged daily and cumulative rainfall for Event 1 (18 – 22 June 2008); Event 2 (29 July – 2 August 2010); Event 3 (15 – 19 August 2011); Event 4 (17 – 21 September 2010); and Event 5 (11 – 15 September 2012) in the upstream region of the UGB.*

Section 3.1.1:

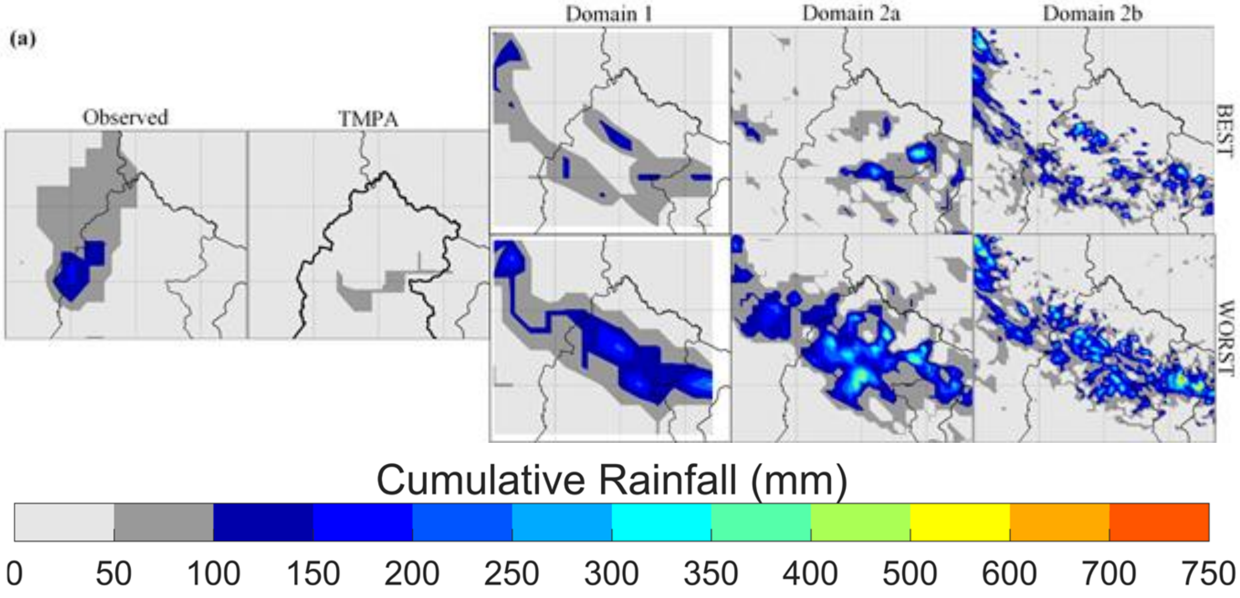
To further assess the sensitivity of configuration (p) and configuration (b) in capturing the extreme rainfall events in the region, additional simulations pertaining to other heavy to extremely heavy rainfall events (as mentioned in Table R.1) are conducted. Spatial plots showing the cumulative rainfall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

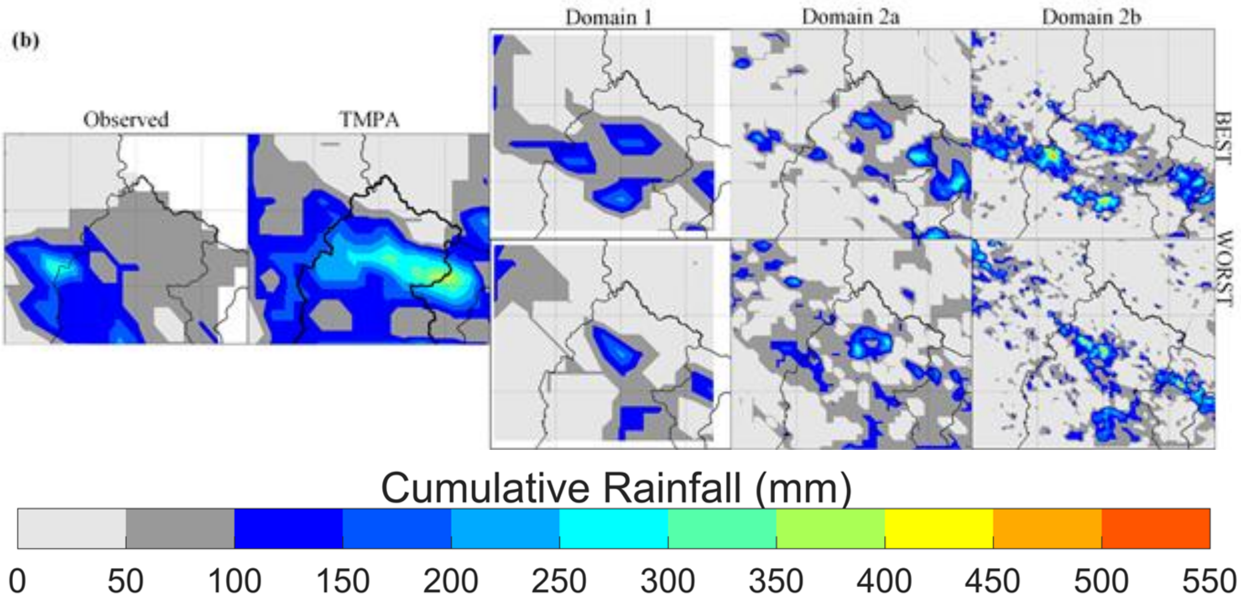
Table R.2. *Mean Absolute Error (MAE) values (in mm) corresponding to WRF configuration (p) and configuration (b) for the three domains*

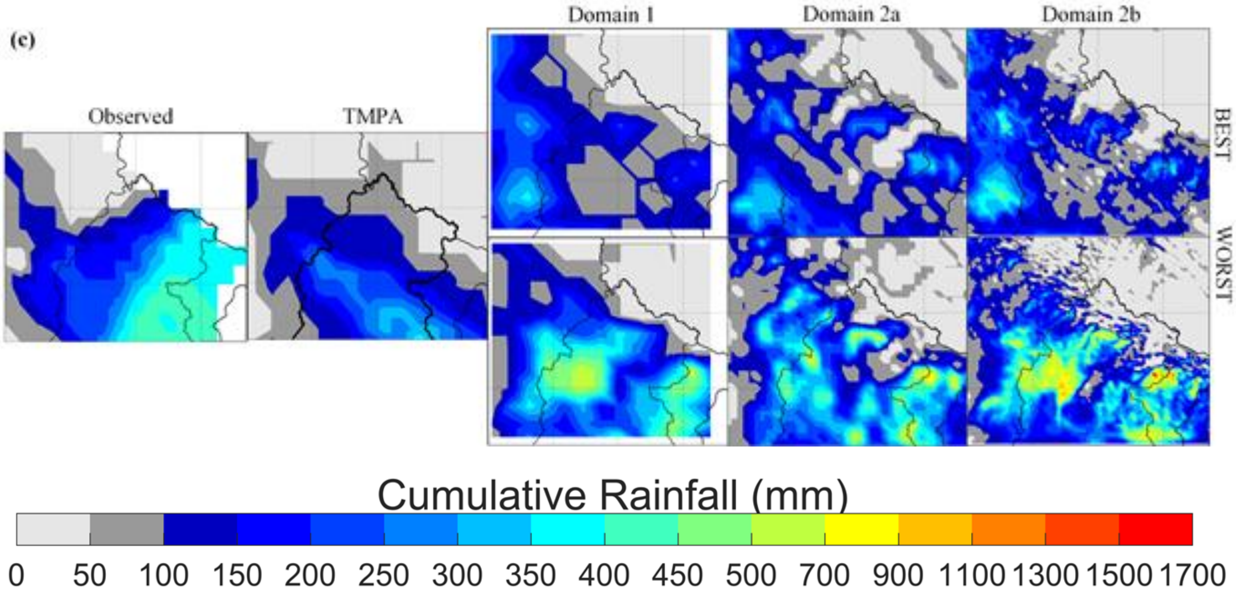
Event No.	***Domain 1***		***Domain 2a***		***Domain 2b***	
	(p)	***(b)***	***(p)***	***(b)***	***(p)***	***(b)***
1	*10*	*13*	*10*	*14*	*11*	*14*
2	*18*	*23*	*18*	*23*	*21*	*22*
3	*39*	*45*	*38*	*44*	*40*	*46*
4	*23*	*28*	*23*	*28*	*24*	*29*
5	*12*	*12*	*9*	*13*	*12*	*11*

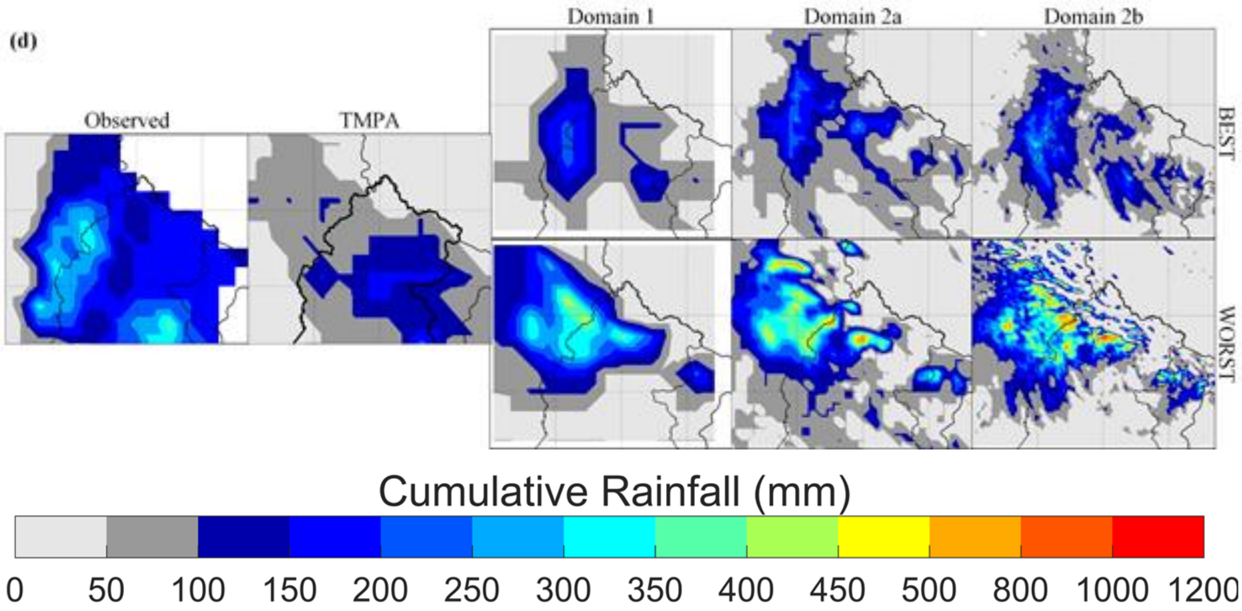
From the analysis conducted over the additional rainfall events, it is noted that configuration (p) gives less error in comparison to the configuration (b) for all the rainfall events. This makes configuration (p) with MYJ PBL, BMJ CU, and Goddard MP the 'best' in simulating the spatial and temporal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

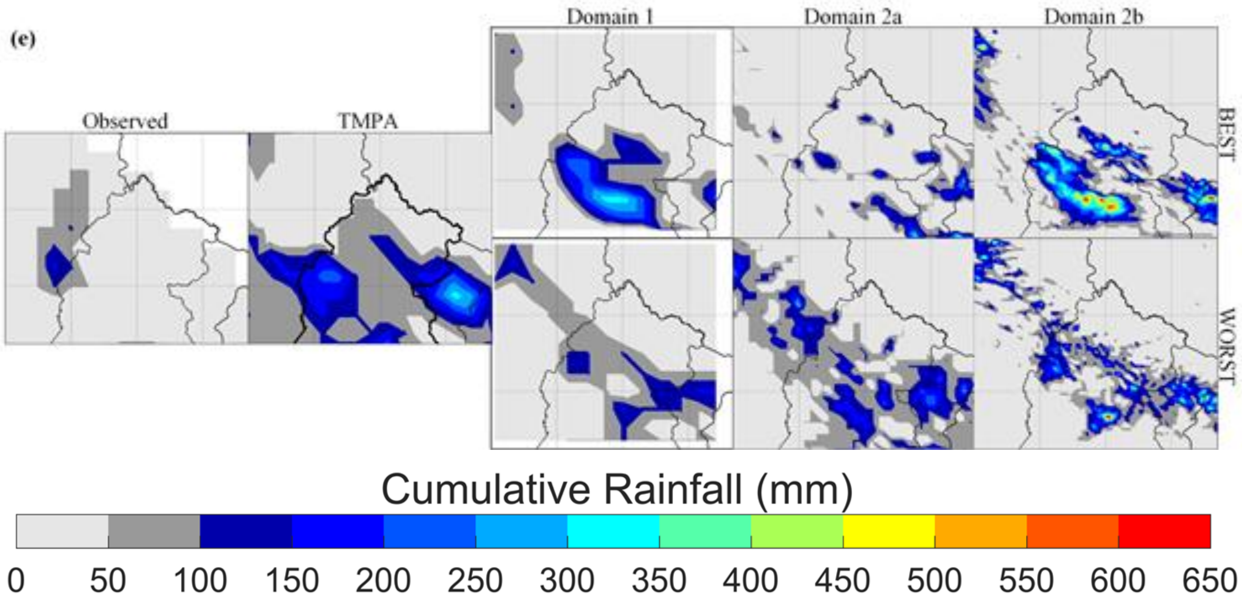


Figure R.2. *Spatial plots presenting the rainfall simulations obtained across the three domains for the best and the worst configuration for heavy to extremely heavy rainfall events during (a) Event 1 (18 – 22 June 2008); (b) Event 2 (29 July – 2 August 2010); (c) Event 3 (15 – 19 August 2011); (d) 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); Lei et al., (2008); and Osuri et al., (2017) 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 five-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):

"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."

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