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Sensitivity of WRF Model for Simulation of 2014 Massive Flood Over Kashmir Region: A Case of Very Heavy Precipitation

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ABSTRACT

The present study simulates the devastating floods in Kashmir that caused widespread damage in the valley from September 2-6 2014. The study used NCEP-NCAR FNL data for the initialization and simulation of the WRF ARW model. Statistical analysis of temperature over four places namely Anantnag, Srinagar, Pulwama, and Baramulla taking RMSE and MBIAS at 24, 48, 72, and 96 hours was also done against observed ECMWF-ERA5 temperature data. Further analysis of RMSE and MBIAS showed a minimum value at 48, 72, and 96 h indicating the improvement of prediction after 6 hours. Rainfall amount was under-predicted by the model with a time lag of 4 h while temperature time series over four districts were significantly closer to observation. Furthermore, the Model was able to capture the strong vertical velocities along with sufficient moisture content up to 600 hPa at the time of observed rainfall.

INTRODUCTION

Floods can well be described as natural disasters that occur across all countries and cause tremendous damage to life and property (Berz et al. 2001) and leave serious impacts on human societies. The impact of floods is seen more in developing countries due to poor infrastructure and the absence of any flood warning system. People living in mountainous regions are more prone to floods and landslides (Watson & Haeberli 2004). An increase in the frequency of disasters brought about by floods in the mountainous regions has seen an increase during the last few decades (Sepúlveda & Padilla 2008, Korup & Clague 2009). The Indian Himalayan region which witnesses erratic weather often has also witnessed some hydrological disasters in the recent past, which include the Kosi Floods (2008), the flash floods that occurred in Leh in 2010, and the unprecedented Ganga River floods (2010), Brahmaputra floods (2012), flash floods in Kedarnath in 2013 and Srinagar floods (2014). Floods have been described as the main threat to sustainable development in the Himalayas (2004). The Kashmir Valley receives rainfall from two distinctive meteorological systems, i.e. southwest monsoon and extratropical disturbances (western disturbances). Many researchers have simulated events related to flooding by heavy rainfall using the WRF model. Hong & Lee (2009) conducted a study using the Korean Peninsula for a case of very heavy rainfall (around 400 mm). The model was able to capture accumulated rainfall amount distribution, even though the rainfall amount at one station (Goyang) was less than the observed. Nooni et al. (2022), used Weather Research and Forecasting (WRF) model to simulate seven heavy precipitation events that occurred across East Africa in the summer of 2020. The results showed that the WRF model was able to produce heavy precipitation, with recorded rainfall ranging from 6 to >30 mm/day. Kumar et al. (2008), used the WRF model at 3. km resolution to simulate the heavy rainfall event of 26 July 2005 over Mumbai. The model reproduced the intensity, amount, and distribution of the rainfall and the results were at par with observations. Another study using the same event over Mumbai was carried out by Rama Rao et al. (2007) with a WRF model run with a grid resolution of 20 km. The model was able to simulate approximately 250 mm of rain with a location error of 50 km north of Mumbai. Srinivas et al. (2018) used the WRF model for the study of a case of heavy rainfall over Chennai. The researchers concluded that the Model produced the best prediction in terms of timing, intensity, and distribution of rainfall for the domain with 1 km. grid resolution. Chen et al. (2010) used the WRF model to study a high precipitation event over southwestern Taiwan associated with a sub-synoptic cyclone in 2003. They showed that a sub-synoptic cyclone formed at 850 hPa formed over the eastern Tibetan Plateau which in association with a 500 hPa trough intensified and resulted in heavy precipitation in

Taiwan. Several researchers have used the WRF model over the Himalayan region. Kumar et al. (2012) used the WRF model for the study of the cloudburst event of 2010 over Leh. Kumar et al. (2014) and Thayyen et al. (2013) used the WRF model to understand the atmospheric processes that led to the 2010 Leh event. Likewise, Chevuturi et al. (2015) simulated the heavy precipitation event of September 2012 in the central Himalayas using the WRF model. Hassan & Islam (2018) used the WRF model, with different parametrization schemes to forecast rainfall events during the year's monsoon season. The researchers found the Stony Brook University microphysics scheme (SU) along with the Tiedtke cumulus scheme (TD) to be the best-performing scheme over the southeastern hilly regions of Bangladesh. The second-best combination according to the researchers is using WRF single-moment 6-class microphysics scheme (WM) and Grell (GR) cumulus scheme. Ntwali et al. (2016) researched the impacts using the WRF model. The researchers concluded that the impacts of topography during the long rainy season and that of the short rainy season are not the same due to the position and the shift of ITCZ. The researchers further found out that all orographic influences are fundamentally caused by topographically driven ascending and descending atmospheric motions that result in condensation and evaporation. Baki et al. (2021), investigated the combination of various parametrization schemes available in the WRF model to find the best combination of microphysics (MP) and cumulus parameterization (CP) schemes for the simulation of Tropical Cyclones (TCs) over the Indian subcontinent region. Their results showed that the Kain–Fritsch scheme, in combination with all MP schemes, predicts the tracks best among all the available CP schemes, but the performance of microphysics schemes remains indistinguishable.

The present work has been undertaken to investigate the ability of the WRF model to predict the moisture and heat flux between the land surface and the lower atmosphere during a heavy rainfall event. Further, the study tries to analyze the reproducibility of the atmosphere above the observed station in terms of moisture and vertical wind along with near and surface meteorological parameters such as rainfall, and temperature. The current study will also evaluate model performance through statistical analysis such as root mean square error (RMSE) and mean bias (MBias). The paper is organized as a synoptic description of the event as seen in observed data followed by methodology and domain design. Finally, the results have been described.

SYNOPTIC WEATHER SYSTEM DURING 2014 FLOODS

Before the disaster of a massive flood hit Kashmir Valley, a noticeable low-pressure area was formed over the Bay of Bengal, which moved northwestwards through central parts of India and interacted with another low-pressure area that had developed over Saurashtra and Kutch and northeast Arabian Sea (September 2–4, 2014). These low-pressure areas resulted in the revival of monsoonal activity in central and northwest India. From September 4 these low-pressure areas moved northwards and interacted with a trough in the midlatitude westerlies lying in the lower troposphere. Due to this, torrential rainfall started in Jammu and Kashmir in the first week of September, which resulted in devastating floods (Nandargi & Dhar 2011). Fig. 1 shows synoptic conditions in terms of wind at 300, 500, and 950 hPa and surface pressure over the Indian subcontinent at the start of the model run (02:09:2014 00:00 hrs)

MATERIALS AND METHODS

For the present study, the WRF model has been used. A nested domain as shown in Fig. 2 was made over Jammu and Kashmir, with the inner domain centered at Srinagar. The parent domain covers an area at 9 km horizontal resolution and extends from 72^{o} E to 77^{o} E and from 32^{o} N to 37^{o} N, while the inner has a resolution of 3 km and covers the entire Kashmir valley where the major rainfall occurred. For the simulation and model initialization, six hourly 25^{o} FNL data from NCAR archives were used. The experiment was conducted for a duration of 110 h. starting from 02:09:2014 to 06:09:2014. The configuration table used for the WRF model is shown in Table 1. The model simulation was chosen with the physical scheme combination already optimized using multiple case studies and their comparative statistical score against IMD-AWS observations has been presented in Table 3. Experiment naming was done by taking the first

Table 1: Configuration table used in the study.

Number of Domains	2	
East-west Dimension	48	91
South-north Dimension	51	76
Vertical Levels	51	
Grid Distance in X-direction in m	9000	3000
Grid Distance in Y-direction in m	9000	3000
Grid ratio	1	3
Microphysics Option	WSM-6 class Graupel Scheme	
Long wave radiation Option	RRTM Long wave Scheme	
Short wave radiation Option	Dudhia shortwave Scheme	
Land surface Option	Unified Noah Scheme (NOAH)	
Planetary Boundary option	Yonsei University Scheme	
Cumulus Parameterization option	Kain-Fritsch scheme (KF)	

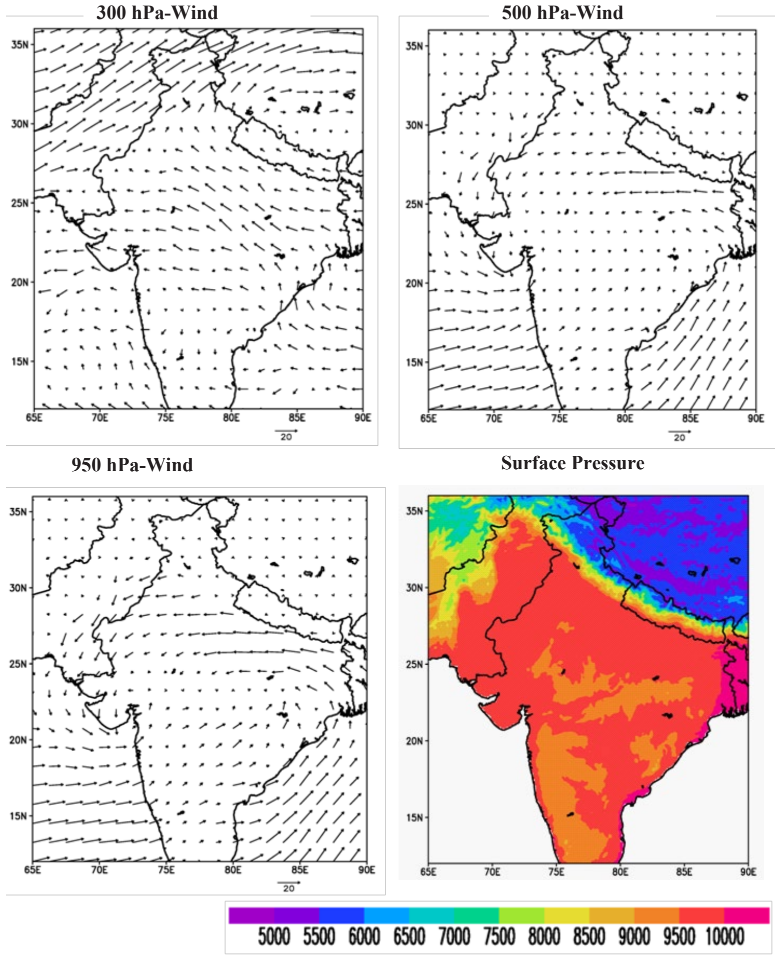

Fig. 1: Synoptic plots of (a) 300-hPa- wind, (b) 500-hPa-wind, (c) 950-hPa-wind and (d) surface pressure derived from ECMWF reanalysis data on 00UTC, 02 Sept., 2014.

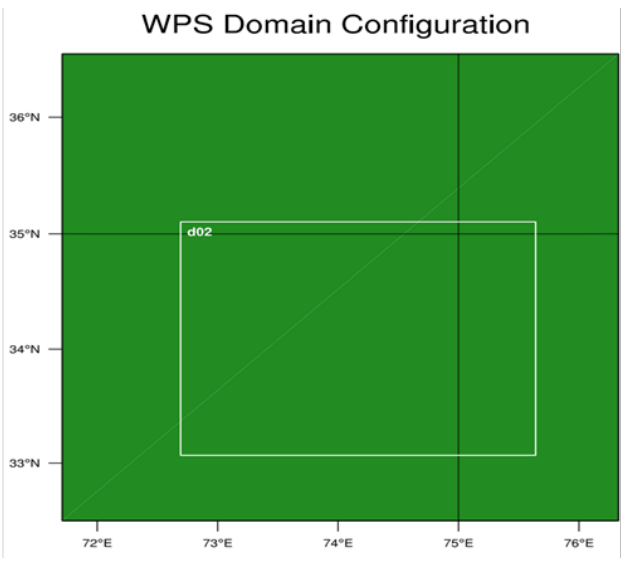

Fig. 2: Domain used in the study.

letter of microphysics, planetary boundary layer, and cumulus schemes mentioned in Table 3. The better-performing physical scheme based on the statistical score table was found to be the WYKF experiment. WYKF experiment had scored least RMSE i.e. 4.74 with least MBIAS of 3.03 among the parametrized schemes. Based on the above statistical score, the physical scheme combination named here as WYKF has been chosen for undertaken flashflood rainfall events that occurred over J&K.

RESULTS AND DISCUSSION

Results have been described in terms of spatial and time series analysis of meteorological parameters. Spatial plots of accumulated rainfall have been validated with CMORPH data. Time series of temperature and rainfall were respectively validated with ECMWF and CMORPH data. To develop an understanding of moisture and heat flux exchange between the lower atmosphere and land surface, time series of land surface parameters like soil moisture, soil temperature, latent heat, and ground flux were also analyzed. Finally, to evaluate the performance of the model, the results were subjected to statistical analysis in terms of Mean Bias and Root Mean Square Error.

Air temperature drop at the time rain is often correlated. Therefore, to analyze rainfall time series progression, the ambient air temperature has been considered to correlate a dip in ambient temperature with rainfall. So, temperature and rainfall are analyzed together hereafter. Fig. 3 shows the hourly progression of temperature and rainfall in the four districts. As shown in the Figure, rainfall in the observation starts from 24 to the 25th hour at all four districts, whereas in the model output rainfall starts at 29 to the 30th hour thus showing a lag of 4-5 h. Observation at Anantnag has recorded a rainfall of 180 mm whereas the model shows rainfall up to 142 mm, which is closer to observed data with little under prediction. Further Srinagar has received 124 mm of rain and the model has simulated 64 mm of rain. Pulwama and Baramulla have recorded 114 mm and 126 mm of rain while

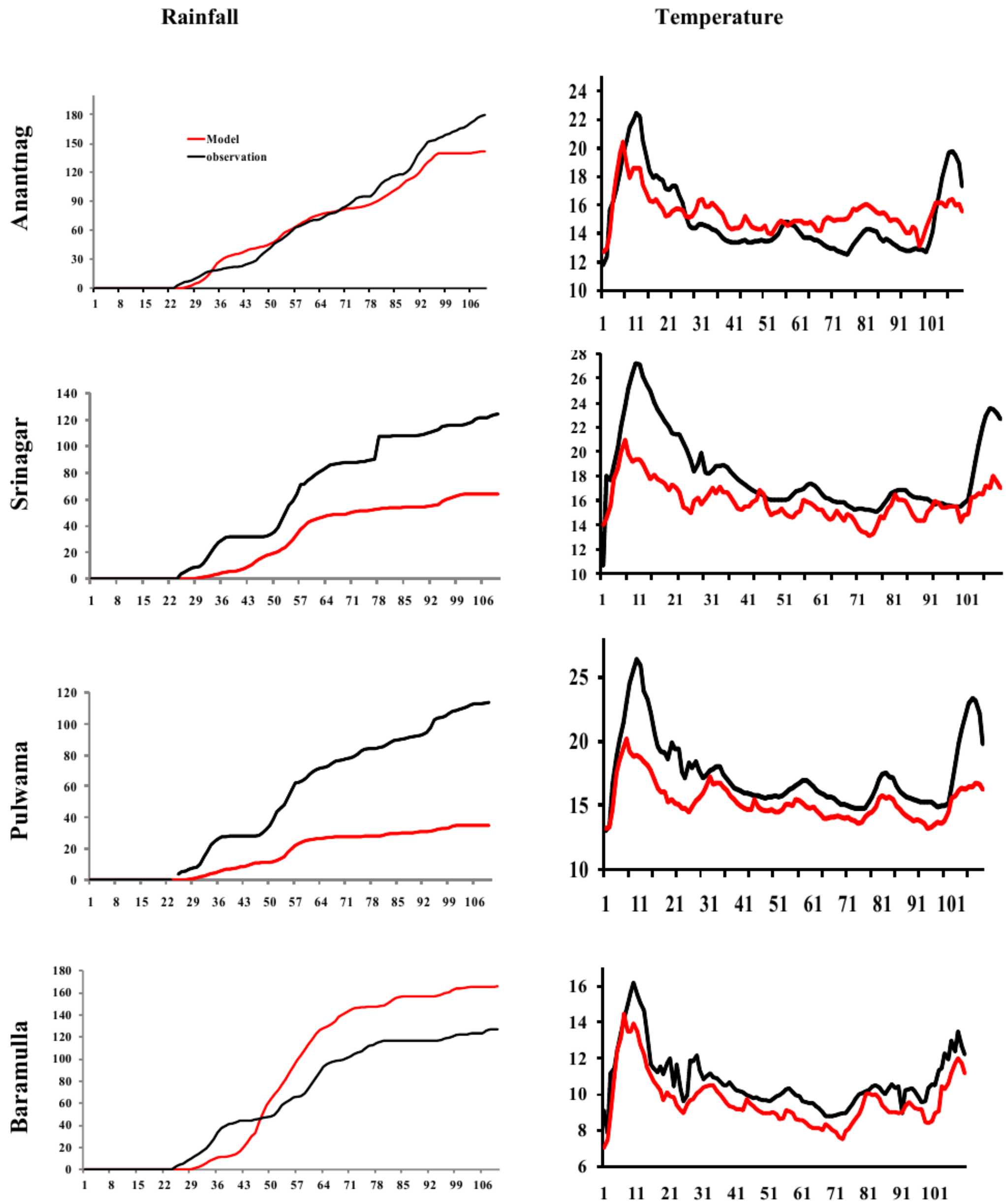

Fig. 3: Time series of rainfall (mm) and temperature (°C) over Anantnag, Srinagar, Pulwama and Baramulla.

the model has shown 34 mm and 165 mm of rain respectively. Similarly, temperature progression has been well captured by the model at all four districts with slight over-prediction. The declining trend in air temperature over Anantnag and Srinagar is 6^{o}C at 24 h and 5^{o}C at 24 h and the model has shown a similar trend. Further, a similar progression of temperature has been shown by the model at Pulwama and Baramulla also (Fig. 3).

Land surface parameters such as soil moisture, soil temperature, latent heat, and ground heat flux provide insight into moisture and flux between the lower atmosphere and land surface. The heat and moisture in the lower atmosphere are carried deeper into the atmosphere providing a convective atmosphere for convection to occur. Fig. 4 and Fig. 5 show time series of soil temperature, soil moisture, and latent heat, ground heat flux respectively at the four districts during

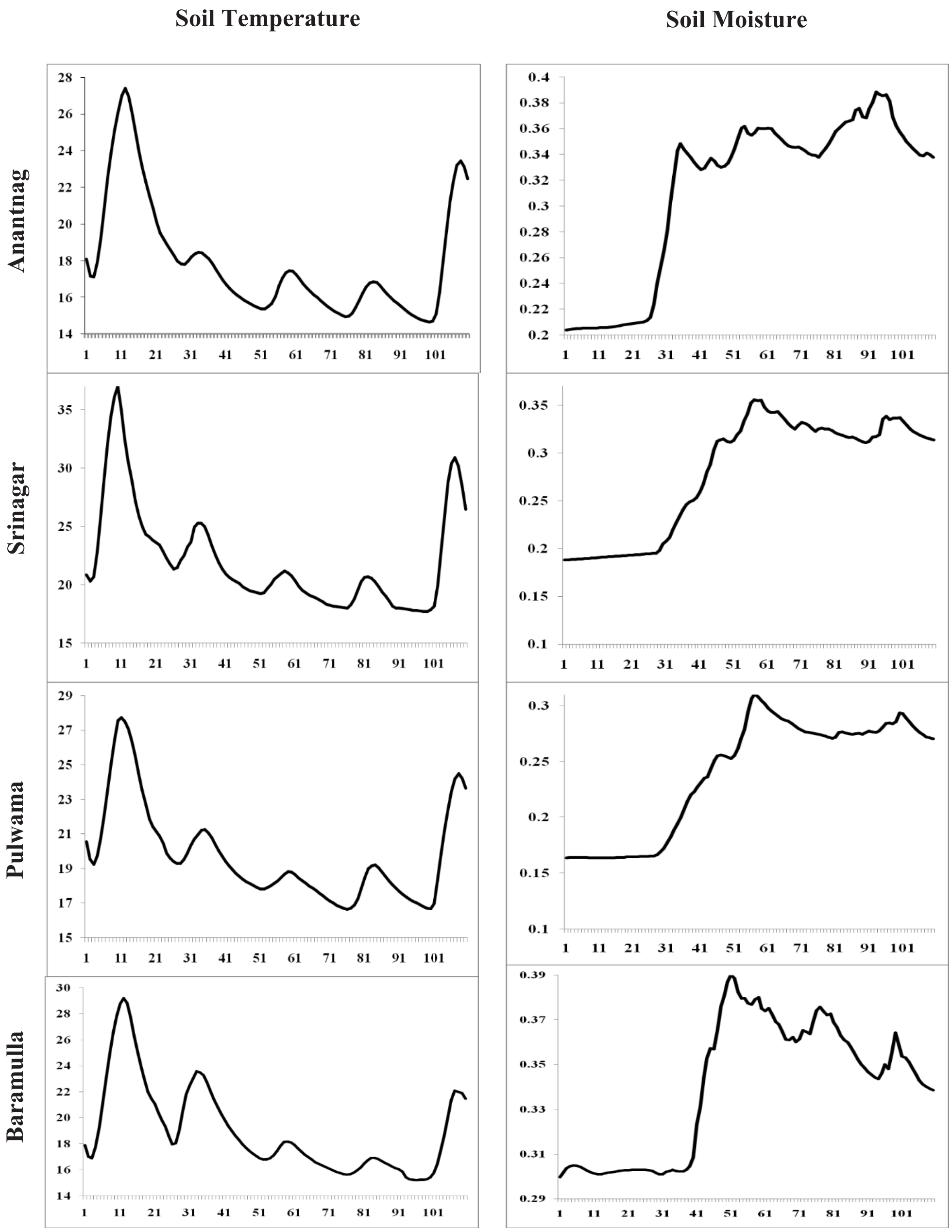

Fig. 4: Soil temperature (°C) and soil moisture (m/m^3) progression over Anantnag, Srinagar, Pulwama and Baramulla for simulation period.

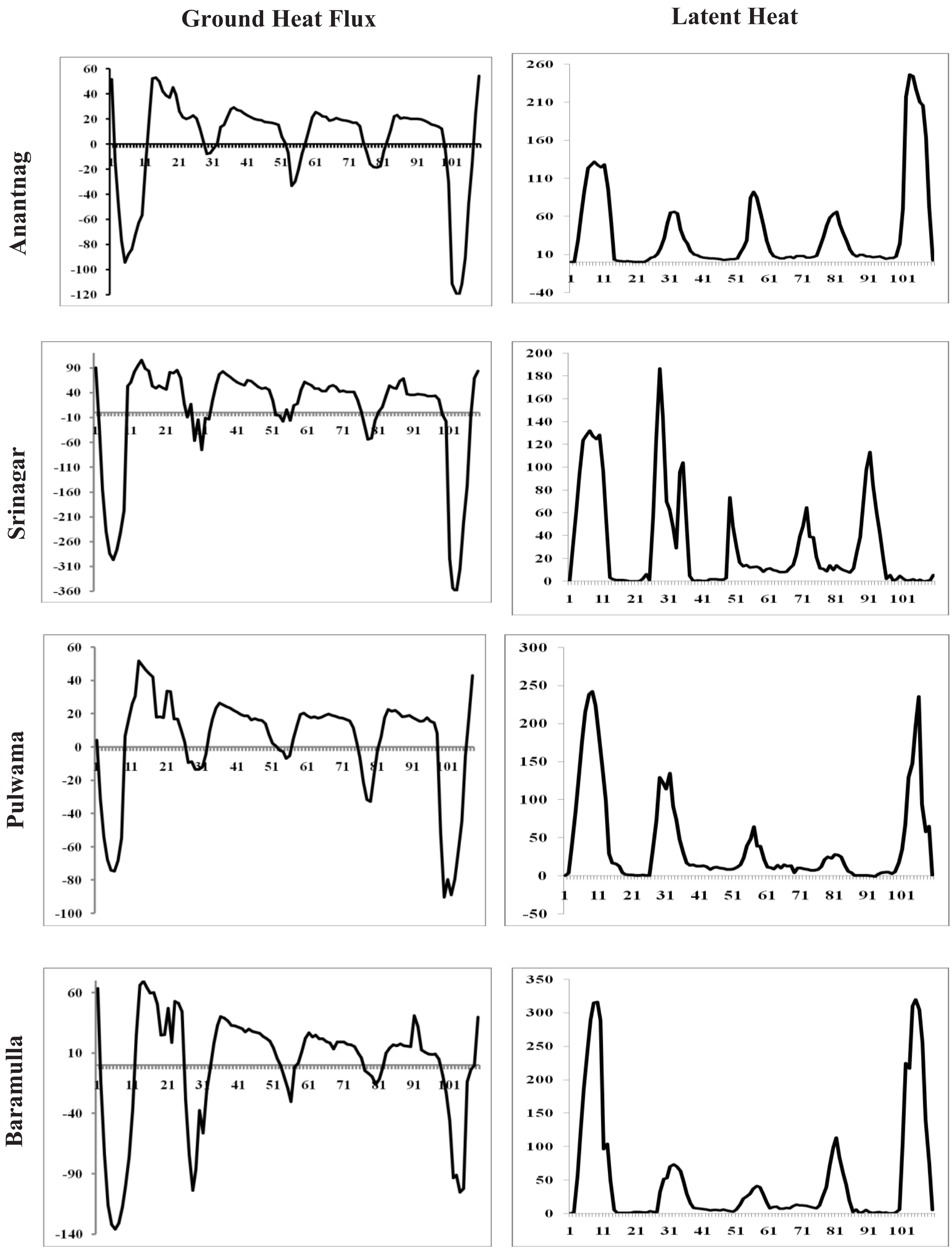

Fig. 5: Latent heat (watt/m^2) and ground heat flux (watt/m^2) progression over Anantnag, Srinagar, Pulwama and Baramulla for simulation period.

the event. As evident from the Figure, the soil temperature drops by over 10°C at around the 24th h of the model run as the rain starts. The reason could be a drop in temperature and rainfall may have brought down the temperature of the soil. Soil temperature further dips by 5°C around 45 h which could be attributed to colder air brought about by consistent rain. Soil temperature, later on, fluctuates till 100 h after which soil temperature shoots up by over 10°C at all four districts. Soil moisture starts increasing around 24th h when the rainfall begins and continues to increase till the 50th hr. after which there is a gradual decrease in the amount of moisture held by the soil. The reason could be the evaporation of moisture brought about by an increase in lower temperature also the soil may have reached saturation level. Ground heat flux helps to evaporate the soil moisture. The latent is used to evaporate the soil moisture which can be correlated with the diagram of the time series diagram of soil moisture. A decrease in ground heat flux contributes to an increase in the latent heat flux. The latent heat might have been consumed to evaporate soil moisture decreasing its value.

The vertical wind is responsible for carrying moisture into the atmosphere. The intensity of vertical wind would determine the vertical distribution of moisture providing a convective atmosphere for the condensation process. Therefore, the analysis of vertical wind velocity and moisture profile will help to understand the convective structure of the atmosphere and its available moisture which might contribute to a possible convective event. Fig. 6 shows the vertical profile of wind and moisture over four districts. Further, a strong updraft in the range of 15cm.s^{-1} at 48 h is seen over Anantnag up to 600 hPa with the presence of a downdraft of 3cm.s^{-1} which is coinciding with the time of observed rainfall. Over Srinagar, the model has simulated multiple strong updrafts at 36hr, 72, 84, and 96 h in the range of 15cm.s^{-1}. Availability of moisture is more over Anantnag than in Srinagar which could be a reason for the occurrence of more rainfall over Anantnag. The model has captured a strong

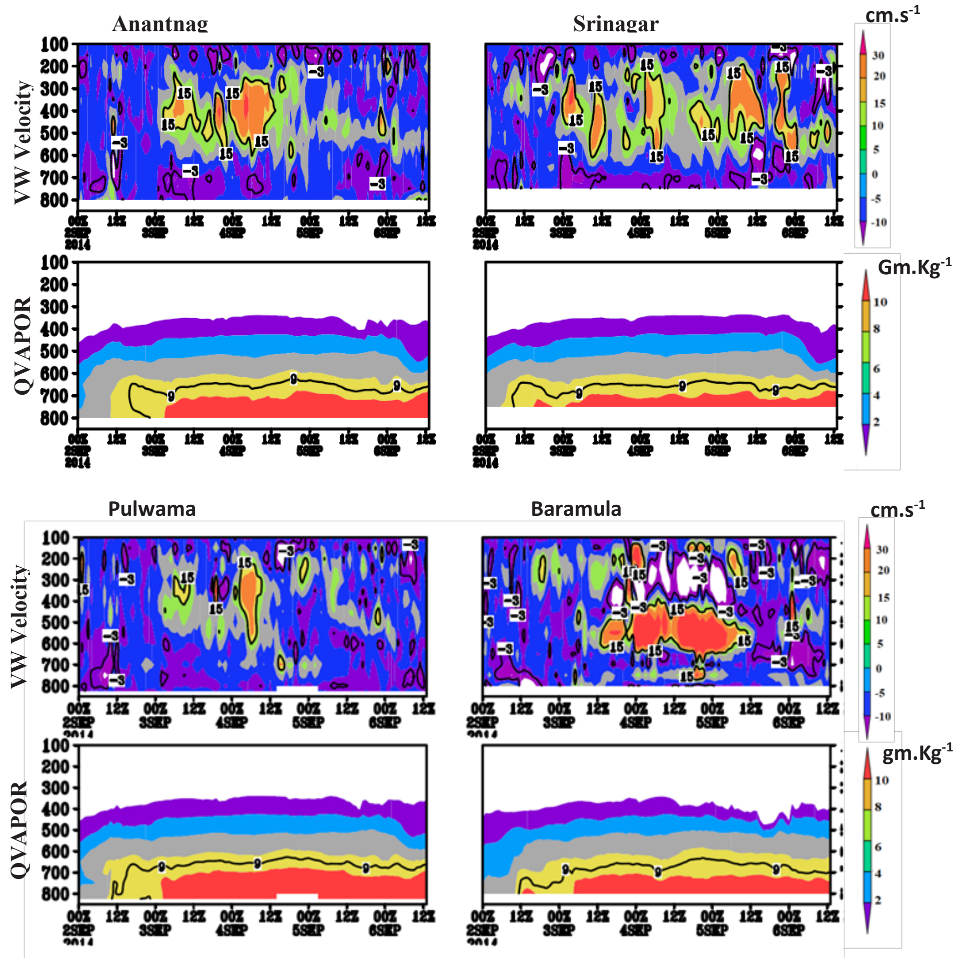

Fig. 6: Vertical Profile of QVAPOR (gm.kg^{-1}) and Verticle wind velocity (cm/s) over Anantnag, Srinagar, Pulwama and Baramulla.

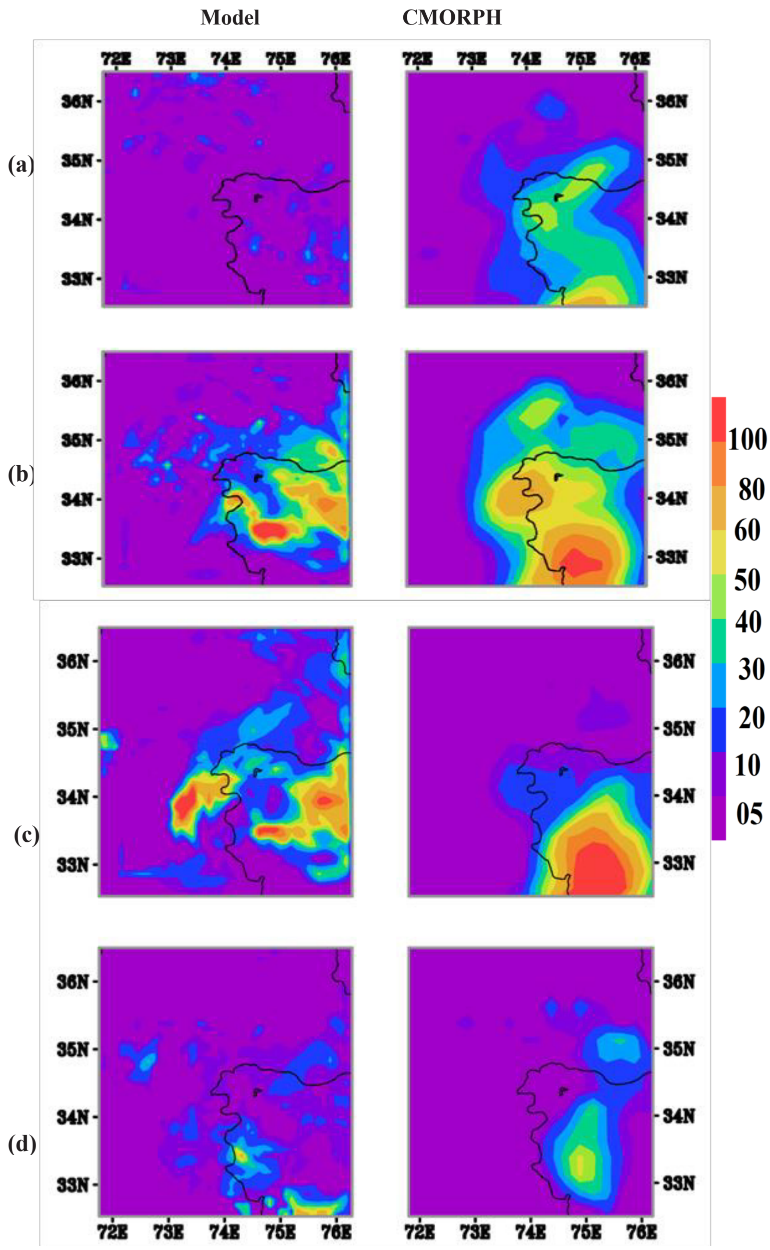

Fig. 7: Accumulated spatial rain plots at (a) 0-48, (b) 48-72, (c) 72-96 and (d) 96-110 hrs along with CMORPH observations.

updraft of 15 cm.s^{-1} at 48 hr along with moisture availability over Pulwama. Strong vertical wind in the range of 15 cm.s^{-1} is seen at 24-96 h over Baramullah. The persistence of updraft and downdraft for 48 h combined with moderate moisture availability may have resulted in more rain over Baramula. Strong updrafts/downdrafts accompanied by moderate to high moisture content (6-10 gm.kg^{-1}) have shaped the atmosphere more conducive over four chosen places i.e. Anantnag, Srinagar, Pulwama, and Baramulla. In addition to the above, the presence of strong updrafts and moisture are also coinciding with observed rainfall timing. Furthermore, the presence of strong vertical velocity in the range of -3 to 15 cm.s^{-1} (updraft and downdraft) coinciding with each other, provides a strong indication for convection to happen over all four districts and the model-generated vertical wind is coinciding with the observed rain time duration signifying the model results.

From Fig. 7 the following observations are drawn from CMORPH rain data. The southeastern part of the domain has received 40-60 mm of rain during 48-72 h of rain

(48 h accumulated rain). Further, the spatial pattern of rain has shown north-west expansion during the next 48 h (72 – 96 h) with >100 mm accumulated rain. On the other hand, the model has captured the accumulated rain from 48 h onwards. The results were also able to capture the northwestern expansion of spatial rain patterns with 60-100 mm of accumulated rain for 48-72 h and 72-96 h Spatial patterns of rain at 96-110 h were also represented quite well as seen in the model result. On a whole note, well representation of temperature, rainfall, soil moisture, and soil temperature along with a conducive atmosphere (vertical profile of moisture and vertical wind velocity) have shown a good agreement with an observed atmospheric feature found in ECMWF, CMORPH data.

Model performance can be accessed through (a) Error estimation and bias evaluation.Root Mean Square Error and Mean Bias have been analyzed by taking time series progression over four districts against the ECMWF (ERA5) temperature data. RMSE and Mean Bias were calculated at 24 h. difference. Mean Bias RMSE is two statistical operations for measuring the performance of a model. The mean bias deviation or mean bias tells difference between observed values and model output. Mean bias finds the average bias in the model. A positive bias or error in a variable (for example in soil temperature) represents that model has overestimated its value and vice versa. Root mean square error or root mean square deviation is one of the most commonly used measures for evaluating the quality of predictions. It shows how far

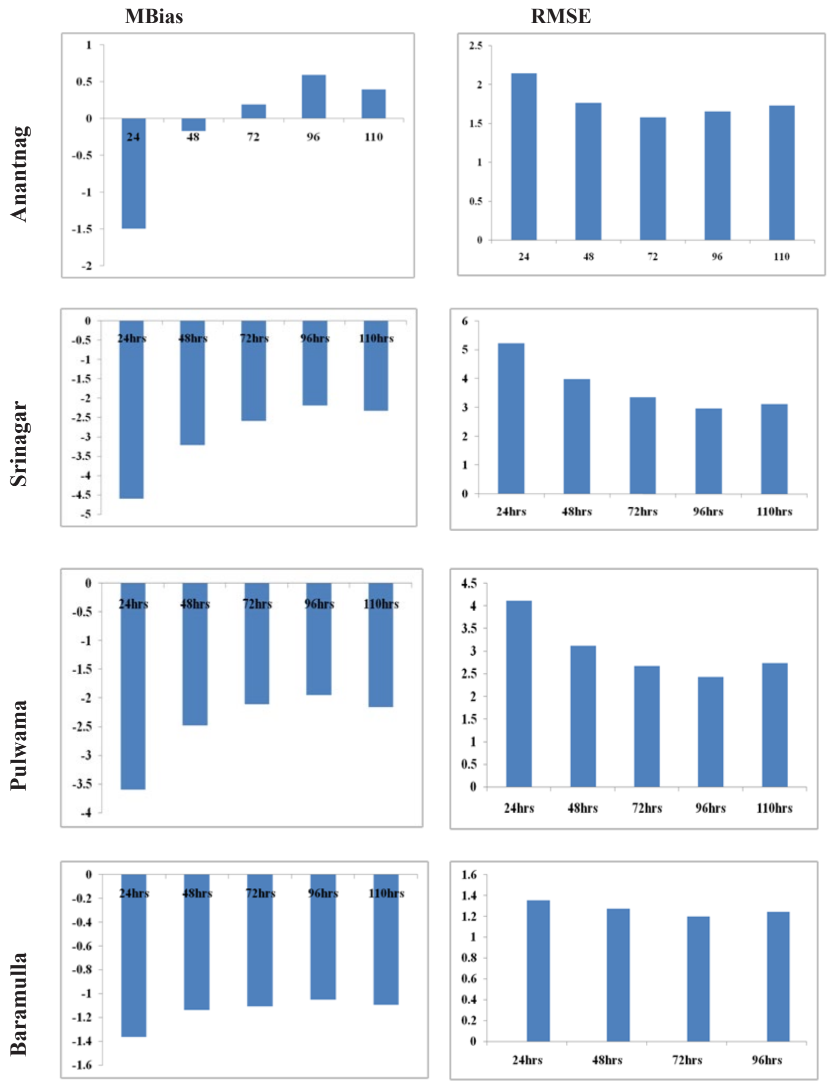

Fig. 8: 24-hourly calculated mean bias and RMSE of temperature time series against ECMWF ERA5 temperature data over Anantnag, Srinagar, Pulwama and Baramulla.

Table 2: Mean Bias and RMSE averaged for a simulation period of temperature time series data over Anantnag, Srinagar, Pulwama, and Baramulla.

Name of Districts	Mean Bias	Root Mean Square Error
Anantnag	0.3934	2.43
Srinagar	-2.3220	3.128
Pulwama	-2.1602	2.738
Baramulla	-1.09	1.246

predictions fall from measured true values using Euclidean distance. RMSE and MBIAS have been calculated at 24 h intervals against ECMWF-ERA5 temperature data over four districts. As shown in Fig. 8 and Table 2, MBIAS of -1.09 with 1.24 RMSE is calculated over Baramula while Srinagar has scored the highest MBIAS -2.32 with 3.12 RMSE value. Further, Anantnag has shown 0.39 MBIAS with a 2.43 RMSE value and -2.1 MBIAS with 2.7 RMSE is calculated for Pulwama. It is also observed that with the progression of time, MBIAS and RMSE have reduced significantly during 48hr to 96 hr over four districts. The statistical calculation was also done over Srinagar and Jammu coordinates only against IMD-AWS observed data. This is done to compare the statistical score of the model against ECMWF and IMD-AWS observed data. The unavailability of IMD-AWS data over Anantnag, Pulwama, and Baramula has limited the statistical analysis with reference o IMD-AWS data for Srinagar and Jammu only. The model has shown an RMSE of 2.6 and MBIAS of -1.38 (Table 4) over Srinagar against IMD observation which is a little more as compared to ECMWF. The statistical analysis has signified the satisfactory model performance as the model has scored MBIAS -1.29 with 2.38 RMSE for temperature averaged over four districts for 96 h.

CONCLUSIONS

The present research tested the performance of the WRF Model in simulating an extraordinary event of heavy rainfall that caused the flood in Kashmir valley in the first week of September 2014. FNL data from NCAR archives was used for Model initialization and simulation. To validate the model output CMORPH and ECMWF (ERA5) data was used. To test the statistical significance of the Model, MBIAS and RMSE errors were calculated from ERA5 temperature data. The results were described in terms of time series analysis of rainfall, temperature, soil temperature, soil moisture, latent heat, and ground heat flux. Spatial plots of rainfall were made for 0-48, 48-72, 72-96, and 96-110 h. The results showed the model has captured the amount of rainfall with slight underprediction and with a time lag of 4-5 h. In terms of temperature progression, the model is in good agreement with ECMWF ERA5 data. The temperature drop up to 6^{o}C at the start of rainfall was also well captured by the model. The model showed an increase in the amount of soil moisture from 24hrs. as the rainfall began till 50th hr. when soil may have reached saturation level. The model also captured a drop of up to 10^{o}C in soil temperature as the convective event

Table 3: Statistical score (Mean Bias and RMSE) of Parametrized schemes.

Experiment Name	Statistics	6	12	18	24	30	36	42	48	54	Average Score
WYKF	MBIAS	5.34	5.15	-0.59	0.30	2.93	5.11	1.84	3.82	3.39	3.03
	RMSE	6.62	5.71	4.32	3.43	4.15	6.17	3.17	3.86	5.20	4.74
WYGD	MBIAS	-0.67	1.65	-2.84	-3.68	-0.98	2.72	0.35	-3.70	-3.62	-1.20
	RMSE	6.65	5.84	3.66	4.02	4.24	5.89	3.15	8.73	8.42	5.62
WMGD	MBIAS	-2.10	3.36	-1.49	-4.53	-2.16	2.09	0.04	-1.20	-0.85	-0.76
	RMSE	5.16	7.18	3.17	4.77	5.54	6.73	4.20	4.65	4.69	5.12
WMKF	MBIAS	-2.23	3.11	-1.78	-5.01	-3.22	1.61	-0.38	-1.35	-0.30	-1.06
	RMSE	5.23	7.25	3.34	5.37	6.46	6.88	3.55	4.49	4.75	5.26

Each letter in the experiment name refers to the physical scheme mentioned in the WRF user guide and names are as follows:

W→WRF Double-Moment 6-class microphysics scheme; Y→Yonsei University PBL scheme; M→Mellor-Yamada-Janjic PBL scheme; KF→Kain-Fritsch Cumulus Scheme; GD→ Grell-Devenyi Cumulus Scheme

Table 4: Mean Bias and RMSE averaged at a 6-hourly interval over Srinagar and Jammu using IMD AWS temperature data.

	Time	06	12	18	24	30	36	42	48	54	Average Score
Srinagar	MBIAS	-4.52	-3.56	1.45	2.77	-0.13	-0.35	0.53	-0.95	-7.64	-1.38
	RMSE	4.52	3.57	1.78	2.95	0.59	0.37	0.6	1.27	7.78	2.6
Jammu	MBIAS	-2.16	-1.3	0.37	0.16	-1.18	0.26	0.66	0.99	-3.17	-0.6
	RMSE	2.17	1.45	0.57	0.45	1.33	0.63	0.93	1.34	3.34	1.36

starts. The model captured a decrease in surface heat flux and an increase in latent heat as the rainfall starts. Profile of the atmosphere in terms of vertical wind velocity and moisture availability shows the presence of strong updrafts and downdrafts around 600 hPa. The availability of moisture at the time was rainfall as shown by the model could well have resulted in heavy rainfall. The spatial pattern of rainfall showed northwestern expansion of rain from 48-72 and 72-96 h Model was able to capture the spatial distribution of rainfall. Statistical results reveal improvement in model performance with the progression of time. With a Mbias of -1.29 with an RMSE of 2.38, the performance of the model can be described as satisfactory.

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