

An Evaluation of the Extreme Rainfall Event of 2010 over the Kabul River Basin using the WRF Model

Fehmida Rafi

U.S.-Pakistan Center for Advanced Studies in Water Mehran
University of Engineering and Technology
Jamshoro, Sindh, Pakistan
fehmidarafi850@gmail.com

Ghulam H. Dars

U.S.-Pakistan Center for Advanced Studies in Water
Mehran University of Engineering and Technology
Jamshoro, Sindh, Pakistan
ghdars.uspcasw@faculty.muet.edu.pk

Courtenay Strong

Department of Atmospheric Sciences
University of Utah
Salt Lake City, Utah, USA
court.strong@utah.edu

Kamran Ansari

U.S.-Pakistan Center for Advanced Studies in Water Mehran
University of Engineering and Technology
Jamshoro, Sindh, Pakistan
kansari.uspcasw@faculty.muet.edu.pk

Syed Hammad Ali

Glacier Monitoring and Research Center (GMRC)
Water and Power Development Authority (WAPDA)
Lahore, Pakistan
syedhammadali2001@yahoo.com

Abstract-Extreme precipitation events are among the most severe weather hazards. Knowledge about the spatial patterns underlying such events in the Upper Indus Basin is limited because estimating precipitation is very challenging due to the data scarcity and the complex orography. Numerical weather prediction models can be applied at a fine resolution to overcome this issue. The Advanced Research Weather Research and Forecasting (WRF) model version 3.8.1 was applied over the Kabul River Basin to simulate the temperature and precipitation of monsoon season 2010, i.e., 1st May to 16th September 2010. We considered the May month as a spin-up period. The initial and boundary conditions were derived from the National Oceanic and Atmospheric Administration, Climate Forecast System Reanalysis data. The model was set up by using two-nested domains with increasing horizontal resolution moving inward from 15km on domain d01 to 5km on domain d02. The simulations were compared with TRMM 3B42, and station data collected from the Pakistan Meteorological Department and Water and the Power Development Authority using bias, percentage bias, root mean square error, and Pearson correlation. The results revealed that the simulated precipitation was improved from d01 to d02. However, the model showed mixed results with overestimation of precipitation at some stations and underestimations at others. Simulated precipitation generally agreed better with TRMM than with station data. Overall, the results indicate that the WRF model can be used to simulate heavy precipitation in complex terrain.

Keywords-WRF-ARW model; Upper Indus Basin; Kabul River Basin; Pakistan; climate change

Corresponding author: Fehmida Rafi

I. INTRODUCTION

The Indus basin is prone to floods and has been hit by massive and destructive flood events in the past. The main causes of floods in various regions of Himalayan Karakoram and Hindukush (HKH) is the intense monsoon rainfall and the rapid snowmelt due to the rising temperatures [1-4]. Pakistan faced an unprecedented and most devastating flood in 2010, which inundated 100,000km², affecting more than 20 million people, with a death toll of 1,980 [5]. Many factors are responsible for the 2010 flood occurrence, however the primary cause was extreme monsoon precipitation [7, 8]. In the early July of 2010, a strong ridge of high pressure was developed over Russia, which moved southward and was combined with the monsoon track and the Phet cyclone [9, 10]. The combination of these three factors caused unprecedented rainfall in Pakistan. The northwestern parts of the country, especially Kabul River Basin (KRB), were struck first by the flooding event of 2010, which then traveled to the south, causing severe damage to houses, crops, and livestock [8]. Authors in [9] reported that on 29 July 2010, Khyber Pakhtunkhwa (KPK) province received more than 200mm of rainfall, which caused severe flash floods. Many stations in KPK received more than 150% of their climatological monthly July rainfall on 29 July. The KRB is a data-scare region, and the lack of sufficient meteorological stations makes performing climate and hydrological studies very challenging [10].

Global Climate Models (GCMs) are basic tools that assess climate change, but their coarse resolution limits their utility

for studying hydrology processes that are sensitive to sub-grid scale variations in precipitation. The complex terrain in the mountainous areas exhibit variations at much finer scales than the grid spacing of GCMs. Therefore, Regional Climate Models (RCMs) are used to perform hydro-climate studies in complex terrain [11, 12]. Numerical Weather Prediction (NWP) models can be applied at higher resolutions to overcome the data scarcity issue and enhance the knowledge of atmospheric variability. The WRF model has been used worldwide for different applications [13, 14], but its application to the Indus River Basin (IRB) or even Pakistan is minimal [9, 15].

Pakistan is among the top 10 countries affected by climate change. Extreme events due to climate change cannot be completely avoided [16, 17], but their impacts can be reduced by developing effective and efficient forecasting techniques through sophisticated tools. This study has been conducted to simulate the flood-producing rainfall event of 2010, which occurred in KRB by using the WRF model with a two-nested domain with a horizontal resolution of 15km and 5km. The event of 2010 is used as a case study to examine the applicability of the WRF model to simulate extreme precipitation events. The study will help in overcoming the lack of gauge data for forecasting heavy precipitation in complex terrains, such as KRB. We believe that this study will improve the understanding of the flood-producing rainfall event of 2010 and may serve as a baseline for the authorities to devise better strategies to reduce the adverse effects of heavy precipitation events.

II. MATERIALS AND METHODS

A. Study Area

The Kabul River is a 700-kilometer long river which is located between 33°36' N - 36°55' N and 67°36' E - 73°54' E. The river starts from the Sanglakh Range of Hindukush Mountains in Afghanistan and enters Pakistan through Mohmand Agency, where it is first gauged at Warsak Dam, then passes through Nowshera and finally drains into the Indus River near Attock. It contributes about 10% to 20% of its annual flows to the Indus river system [17]. The total catchment area of the Kabul River Basin (KRB) is about 76,908km², out of which 14,000km² are located in Pakistan (Figure 1). The basin has elevation of 305-7690m [18]. Higher discharge in the river is observed in July and August due to the heavy rainfall and, due to the higher temperature of these months, glacier melting. The main cause of flooding in the region is the combination of rainfall and glacier melting [19]. The climate of the basin is semi-arid. The maximum temperature of 28°C is observed in June-August, whereas the mean minimum temperature is -6°C. Due to the complex terrain and the variation in elevation, precipitation varies throughout the basin. The maximum precipitation occurs during winters in the form of snowfall, with an average of 110mm [20, 21]. Chitral, Swat, and lower parts of the Kabul River experience the Indian summer monsoon, On the contrary, the Upper Kabul is influenced by western disturbances [17].

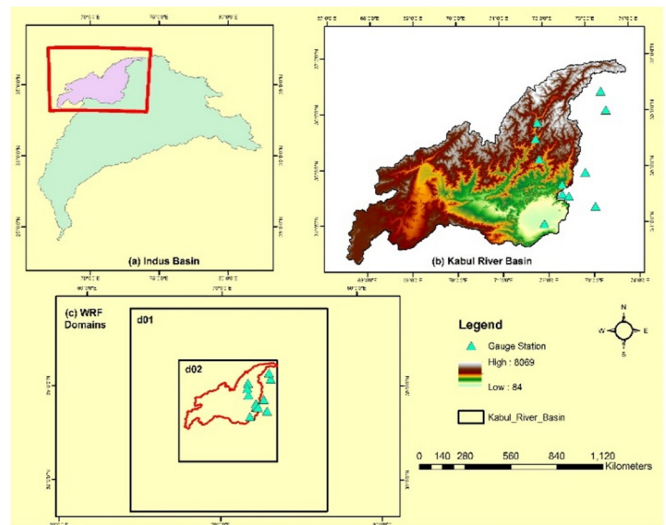


Fig. 1. Map of the two nested domains of WRF simulations at the Kabul River Basin (d01 = 6km, d02 = 2km).

B. WRF Model and Setup

In this study, the Advanced Research Weather Research & Forecasting (WRF) model [21] is used. The WRF model is a next-generation mesoscale numerical weather system, which is used for short-term weather forecasts and long-term climate simulations. The WRF has been developed by the National Center for Atmospheric Research (NCAR) in partnership with National Oceanic and Atmospheric Administration (NOAA) and the US Department of Defense. The WRF model was set up by using two nested domains, domain 1 (d01) and domain 2 (d02) with increasing resolution moving inward from 15km to 5km grid spacing (Figure 1). The Lambert map projection type is chosen for both domains. The inner domain (d02) is centered over northwest Pakistan to represent KRB with two-way nesting. The simulation started at May, 1 at 00:00 hours and ended at September, 16 at 20:00 hours. The hourly simulated data were converted into daily data for the validation process. Initial and boundary conditions for the simulations were derived from the NOAA Climate Forecast System Reanalysis (CFSR) data [22], which has a 38km horizontal resolution. The research shows that the CFSR dataset performs well in simulating atmospheric changes over the HKH region [11, 22].

The WRF model is a non-hydrostatic model that has many options for physical parameterization schemes. The model is configured with the Noah Multi-Parameterization (Noah-MP) land surface model [23], Yonsei University (YSU) planetary boundary layer scheme [24], Thompson microphysics scheme [25], Rapid Radiative Transfer Model (RRTM) longwave radiation scheme [26], Dudhia shortwave scheme [27], surface layer scheme [28], and Betts-Miller-Janjic cumulus scheme [29]. All these schemes were applied for both domains, however the resolution of the inner domain (d02) is small enough to allow switching off the convective parameterization.

C. Model Validation

We evaluated the simulations with the station meteorological data obtained from the Pakistan Meteorological Station (PMD) and Water and Power Development Authority

(WAPDA). The daily data come from 11 stations, namely Balakot, Chitral, Drosh, Dir, Saidu-Sharif, Peshawar, Ushkore, Yasin, Phulra, BeshamQila, and Daggar. The WRF precipitation output was also assessed with the Tropical Rainfall Measuring Mission (TRMM) 3B42 version 7 gridded precipitation data at a monthly time scale. TRMM is considered a reliable gridded precipitation dataset in the Himalayan Karakoram region. The TRMM dataset has the best performance among the other remote sensing datasets in the Indus basin [30]. Similarly, authors in [31] revealed that TRMM 3B42V7 is better than the other products when evaluated in the Hunza river. The WRF simulations were assessed by the percentage bias (PBIAS), root mean squared error (RMSE), and Pearson correlation coefficient (r), and bias.

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (O_i - S_i)^2}{N}} \quad (1)$$

$$r = \frac{\sum_{i=1}^N (O_i - \bar{O})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^N (O_i - \bar{O})^2 \sum_{i=1}^N (S_i - \bar{S})^2}} \quad (2)$$

$$Bias = \frac{1}{N} \sum_{i=1}^N (S_i - O_i) \quad (3)$$

$$PBIAS = 100 * \left[\frac{\sum_i (S_i - O_i)}{\sum_i O_i} \right] \quad (4)$$

where S_i denotes the simulated values, O_i denotes the observed values and N is the number of days.

III. RESULTS

In this section, the WRF-simulated precipitation is evaluated by using the PMD meteorological data and the TRMM dataset.

A. Precipitation at Specific Location

This section compares the WRF predicted precipitation to values observed by gauges and TRMM. The main results for both domains are shown in Figure 2. The WRF and TRMM data were bilinearly interpolated to the 11 gauge stations. For the WRF data, interpolations were performed separately for the 15km data from d01 and the 5km data from d02. The WRF reproduced the precipitation from May, 1 to September, 16 at each station at 22 different resolutions. It was seen that more precipitation was simulated by the WRF model on 29 July in each station in both domains.

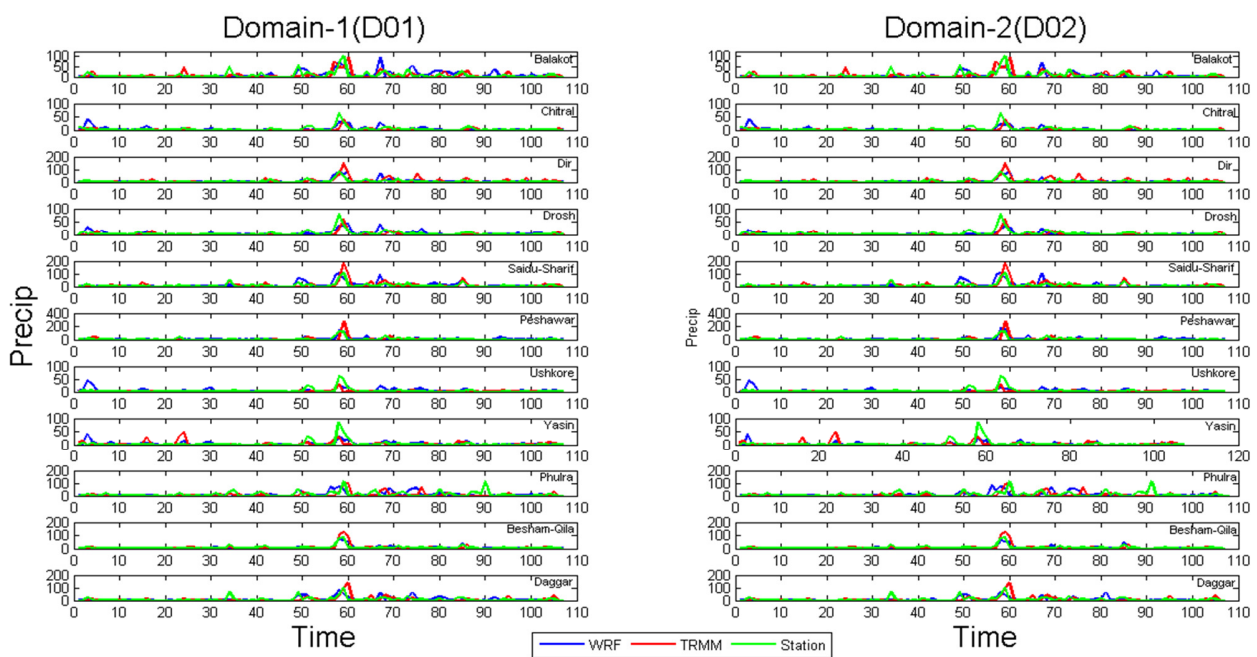


Fig. 2. Time series comparison between the WRF simulated precipitation (blue), observed gauge precipitation (red), and TRMM precipitation (green) for d01 (left column) and d02 (right column).

Before presenting the summarized statistics of the WRF performance, we begin with the specific results for July, 29, 2010, which feature exceptionally high precipitation totals as discussed in the Introduction. When the simulations of each station were compared for d01, the simulated rainfall on July, 29 was 55mm (Balakot), 65mm (Besham Qila), 27mm (Chitral), 47mm (Daggar), 58mm (Dir), 38mm (Drosh), 49mm (Phulra), 63mm (Saidu Sharif), 16mm (Ushkore), and 17mm (Yasin), with the highest rainfall predicted in Peshawar (120mm). Similarly, in domain d02 the rainfall predicted at each station was 46mm, 55mm, 22mm, 40mm, 84mm, 30mm,

53mm, 67mm, 10mm, and 12mm respectively, with the highest rainfall again predicted in Peshawar (153mm). On the other hand, the observed data show that the maximum precipitation recorded on July, 29 was 45mm, 128mm, 41mm, 99mm, 149mm, 61mm, 90mm, 187mm, 0mm, and 2mm for the same stations, with the highest rainfall predicted in Peshawar (274mm). In addition, when simulated precipitation and gauge data were compared for d01, it was found that the WRF model under-predicted the precipitation at all the stations on July, 29, whereas there was over-prediction at Balakot, Ushkore, and Yasin.

For the gauge data, the results showed that the PBIAS decreased in magnitude in domain d02 at Balakot, Chitral, Daggar, Drosh, Peshawar, Phulra, Saidu Sharif, and Ushkore, whereas it increased at Besham Qila, Dir, and Yasin. This means that the resolution increase from d01 to d02 lessened the bias against the gauge data for 8 stations and worsened the bias for 3 stations. On the other hand, when the simulated precipitation was compared with the TRMM dataset, it was found that there were 4 stations (Balakot, Peshawar, Dir, and Yasin) where the bias was decreased in magnitude on d02 and 7 stations (Chitral, Saidu Sharif, Ushkore, Besham Qila, Phulra, Drosh, and Daggar) where the bias was larger in magnitude on d02. Overall, the gauge data comparison provided a stronger indication of bias reduction on d02 than the TRMM data comparison. Similarly, when the WRF predicted precipitation was compared with the gauge data, the correlation between the simulated and the observed data varied for each station. The WRF showed a high correlation ($r \geq 0.5$) to 5 stations (Balakot, Chitral, Besham Qila, Dir, and Drosh), whereas the rest of the WRF results had a lower correlation with the station data. The highest correlation was observed in Besham Qila ($r = 0.8$) and the lowest in Phulra ($r = 0.2$). On the other hand, when the correlation was considered for the simulation precipitation and TRMM dataset, 8 stations (Balakot, Chitral, Yasin, Besham Qila, Dir, Drosh, Saidu Shaarif, and Daggar) showed high correlation to the TRMM dataset, whereas 3 (Peshawar, Ushkore, and Phulra) did not. The highest correlation was observed in Besham Qila and Peshawar with $r = 0.8$, whereas the lowest was observed in Phulra with $r = 0.3$. Overall, at each location, the correlations with station data were similar in domains d01 and d02.

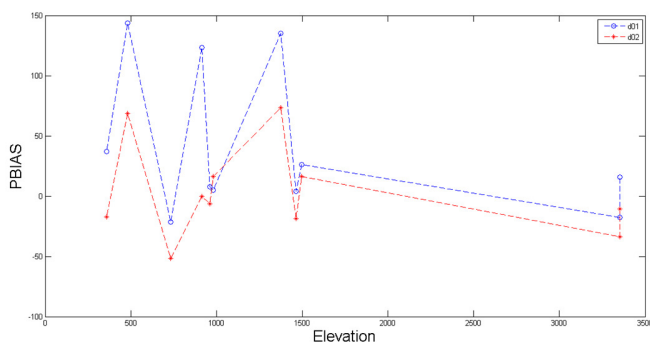


Fig. 3. WRF precipitation percent bias against gauge data in domain d01 and domain d02.

To illustrate how the performance statistics were organized on the topography in each domain, Figure 3 shows the PBIAS of WRF simulated precipitation relative to gauge data as a function of elevation. The shape of the PBIAS graphs as a function of elevation was similar on both domains, and the largest magnitude biases were positive and occurred at higher-elevation stations above approximately 1500m. At all but one station, as shown in Figure 3, the PBIAS was smaller in d02, which shows that at all stations there was a smaller bias between modeled and observed precipitation in d02 as compared to d01. The PBIAS averaged -9% in d02 and 17% in

d01. The t -test was used to identify cases where the mean precipitation simulated by WRF differed significantly from the observed precipitation at the 95% confidence level ($p \leq 0.05$). For most gauge data, the null hypothesis of no difference in mean could not be rejected at the 95% confidence level. However, in domain d01, a significant difference in mean was found at 3 stations: Chitral, Drosh, and Ushkore. When the WRF predicted precipitation was compared with station data in domain d02, significant differences were found at Dir and Ushkore. For TRMM data, no significant differences were found in d01, and only 2 locations (Drosh and Besham Qila) had significantly different results in d02. The patchy significance of these t -test results indicates the encouraging performance of WRF, especially given that we assumed one degree of freedom per day (i.e. use of effective degrees of freedom reduced to account for autocorrelation would be less likely to reject the null). Table I lists the p values associated with the t -test comparing the mean WRF precipitation to gauge (TRMM) precipitation in d01 and d02.

TABLE I. P VALUES FOR D01 AND D02

Station	p-value d01 (TRMM)	p-value d02 (TRMM)
Balakot	0.12 (0.14)	0.3 (0.2)
Chitral	0.004 (0.7)	0.1 (0.3)
Dir	0.2 (0.2)	0.003 (0.2)
Drosh	0.002 (0.3)	0.9 (0.02)
SaiduSharif	0.7 (0.07)	0.8 (0.3)
Peshawar	0.8 (0.05)	0.6 (0.3)
Ushkore	0.0005 (0.06)	0.03 (0.6)
Yasin	0.86 (0.4)	0.4 (0.8)
Phulra	0.4 (0.5)	0.6 (0.3)
BeshamQila	0.3 (0.1)	0.1 (0.02)
Daggar	0.5 (0.6)	0.7 (0.4)

B. Multilocation Mean Precipitation

This section examines the precipitation averaged across the station locations for WRF, TRMM, and gauge data. WRF, TRMM, and gauge data were averaged at the 11 gauge location. WRF over-predicted the precipitation at some days and under-predicted at others (Figure 4). Similarly, it was observed that WRF under-predicted the average precipitation on July, 29 in both d01 and d02. The TRMM value for this extreme event was intermediate between the WRF and the station values (the station average precipitation for both domains on July 29 was 98mm, and the TRMM dataset indicate 76mm in both d01 and d02, whereas the WRF model simulated 50mm in d01 and 49 mm in d02).

IV. DISCUSSION

In this paper, the WRF model was used to simulate the precipitation of the flood-producing rainfall event of 2010. It was found that there were 3 heavy precipitation events observed during these 5 months, namely May 17, June 3, and July 29. The findings of the study revealed that the precipitation event of July, 29 was the main cause of the flood of 2010, which was consistent with [8, 9]. The results showed that the precipitation simulations were improved from d01 (15km) to d02 (5km), which is attributable to the increased resolution or the combination of the parameterization schemes,

which is consistent with [32], in which it was found that WRF simulates convective precipitation quite effectively using Noah LSM, which predicts both soil temperature and moisture. The findings are also consistent with [33], the authors of which found that at higher resolution the WRF model shows better results. The results of the study are similar to that of [34], in which it was found that complex terrains need higher resolution to accurately forecast precipitation.

The study showed that the WRF has a weak positive correlation ($r = 0.3$) with the observed data at high-elevation stations (Ushkore and Yasin). However, the WRF results tend to have a stronger positive correlation with the observed datasets at some of the low-elevation stations (e.g. Besham Qila and Peshawar). This is consistent with [34-36]. In addition, the WRF showed a higher overall correlation with the TRMM dataset than with the gauge data. The station-averaged precipitation indicated a mix between over-prediction and under-prediction. For the extreme event on July, 29, WRF's simulated precipitation (~50mm) was smaller than the TRMM (76mm) and gauge results (98mm). Discrepancies from observations may stem from not resolving subgrid-scale terrain effects or limitations of the chosen physical parameterization schemes [36]. The high-elevated stations showed more PBIAS except for Yasin and Dir station, where the WRF showed a low PBIAS of 3.8% in d01 and -18% in d02 in Yasin and -21% in d01 and -51% in d02 in Dir. In addition, the WRF showed less bias at the low-elevated stations except from SaiduSharif and BeshamQila stations where the model showed underestimation of precipitation, as large as -34%.

Overall, it was concluded that the WRF model performed well with higher resolution with slightly overestimation at some locations and underestimation at others, which is consistent with [38]. Hence, it can be said that WRF can be used to predict the extreme precipitation events over complex regions such as the Upper Indus Basin.

V. CONCLUSION AND RECOMMENDATIONS

Kabul River Basin is an integral part of the Indus basin and has been frequently hit by massive floods in the past. The worst flood in KRB was the flood of 2010. It is expected that due to the climate change, the frequency and intensity of floods will increase in the future. This study was conducted to simulate the flood of 2010 by using the WRF model over the KRB. The findings of the study revealed that the WRF model was able to predict the extreme precipitation event of 2010. The overall favorable performance indicates that the one-month spin-up period was sufficient for short-term simulations. Two domains were used to simulate the precipitation over the region, and the result showed that the WRF model performed better in the higher resolution domain. It was concluded that the model proved to be useful for precipitation simulations in the HKH region.

Although the WRF model performed well in the KRB, substantial biases were found at some of the higher elevation stations. Continued work is thus needed on the sensitivity analysis of the WRF model, which is important for determining the optimal combination of physical parameterization schemes over the Upper Indus Basin. In addition, the WRF output

should be compared with other available satellite and remote sensing datasets in addition to TRMM to evaluate the effectiveness of the model performance.

Keeping in view the shortcomings of the GCMs over hilly and complex areas such as KRB, the RCMs are the best tools to perform modeling climate studies. This study showed that WRF was able to simulate extreme events over the KRB. Therefore, it could be suggested that the WRF model with the right combination of physical parameterization schemes, horizontal resolution, and nesting domain can be used to forecast similar future events in the complex and rugged terrain of the HKH region.

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