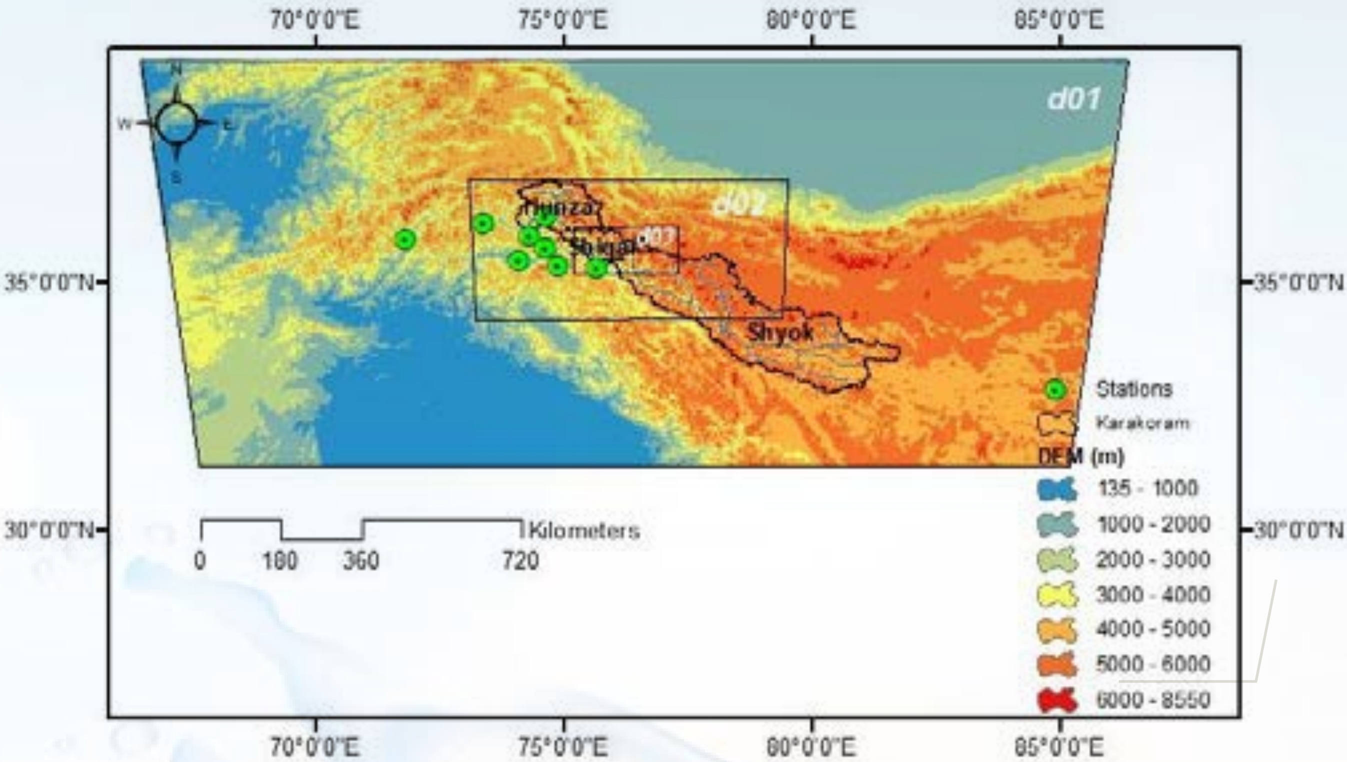
U.S.-Pakistan
Centers for Advanced Studies in Water

Improved Hydro-Meteorological Forecasts for Upper Indus Basin (UIB) under Changing Climate using Robust Modeling Techniques

Final Report 2019



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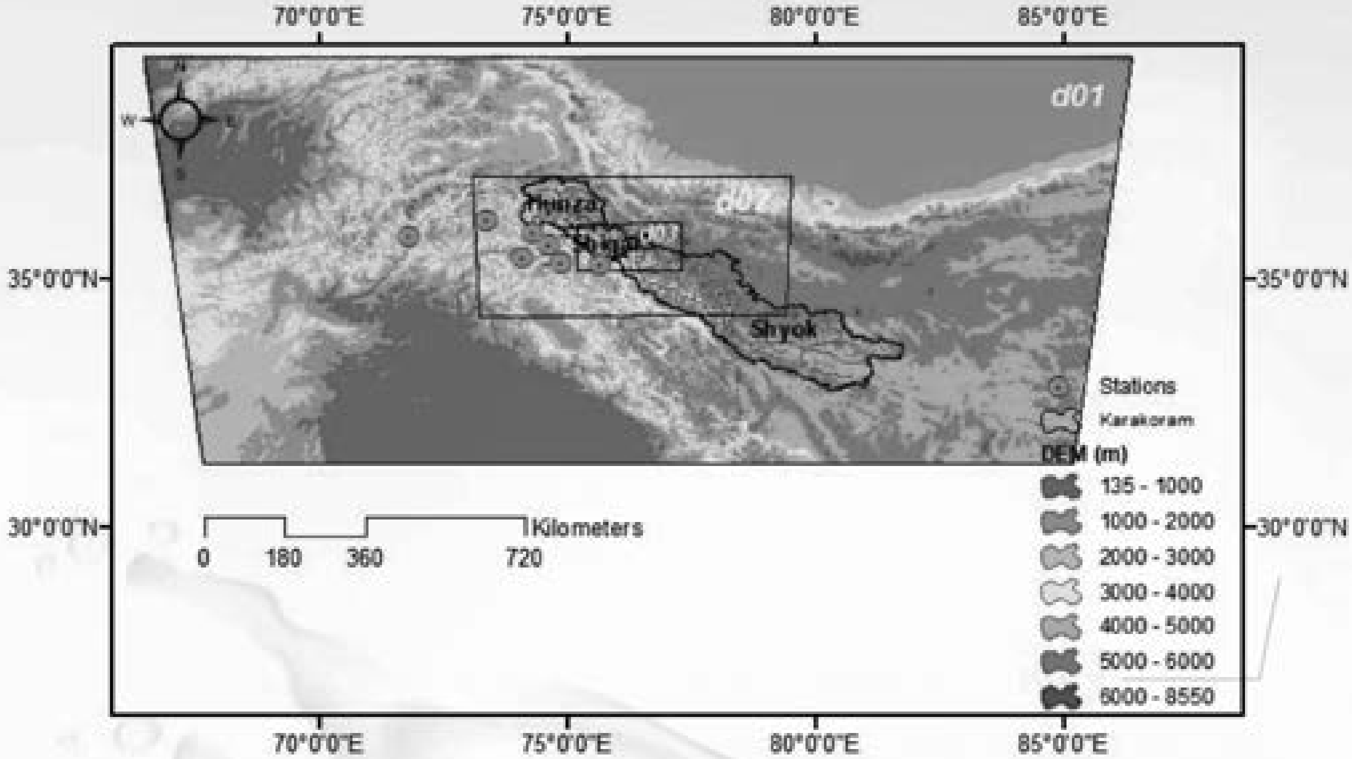

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ACRONYMS AND ABBREVIATIONS

asl	Above Sea Level
CFSR	Climate Forecast System Reanalysis
CMIP5	Climate Model Inter-comparison Project Phase 5
DJF	December January February
GCM	Global Climate Model / Global Circulation Model
GCRI	Global Climate Risk Index
HBV	Hydrologiska Byrans Vattenbalansavdeling
HKH	Hindukush-Karakoram-Himalaya
HRB	Hunza River Basin
IPCC-AR	Intergovernmental Panel on Climate Change- Assessment Report
IRB	Indus River Basin
JJA	June July August
LSM	Land Surface Model
MAE	Mean Absolute Error
MAM	March April May
MP	Micro-physics Scheme
MUET	Mehran University of Engineering and Technology
NCAR	National Center for Atmospheric Research
PMD	Pakistan Meteorological Department
RCP	Representative Concentration Pathway
RMSE	Root Mean Squared Error
SON	September October November
SWAT	Soil Water Assessment Tool
TRMM	Tropical Rainfall Measuring Mission
UBCWM	University of British Columbia Watershed Model
UIB	Upper Indus Basin
USAID	United States Agency for International Development
USPCAS-W	U.S.-Pakistan Center for Advanced Studies in Water
W/m^2	Watts per Square Meter
WAPDA	Water and Power Development Authority
WRF	Weather Research and Forecasting Model
WRF-Hydro	Weather Research and Forecasting Hydrological Modeling System

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EXECUTIVE SUMMARY

Water resources management, especially in data-scarce regions such as Upper Indus Basin (UIB), requires more realistic and reliable information about the hydrologic cycle components, including precipitation, temperature, and streamflow. High resolution regional atmospheric models are the best available tools to downscale (i.e., increase the resolution of) the climatic variables which are used as inputs to hydrologic models to predict streamflow. Nowadays, coupled atmospheric-hydrological modeling systems (such as WRF-Hydro) have improved the land-atmosphere interactions, and provide more reliable forecasts.

The overall objective of this project was to assess the applicability of the Weather Research and Forecasting Hydrological Modeling System (WRF-Hydro) model over the Hunza River Basin (HRB) to simulate streamflow for the year 2004. The WRF atmospheric model was applied to simulate the significant hydroclimatic variables (precipitation, temperature, and others) over the UIB with boundary conditions derived from the Climate Forecast System Reanalysis (CFSR) data. The WRF model was configured with three nested domains (d01, d02, and d03) with horizontal resolutions increasing inward from 18 km (d01) through 6 km (d02) to 2 km (d03) grid cell resolution. The simulations were then compared with Tropical Rainfall Measuring Mission (TRMM) and station data for the same period using root mean square error (RMSE), percentage bias (PBIAS), and Pearson correlation coefficient (r).

The results show that WRF tends to overpredict the total annual precipitation in d01 and underpredict it in d02 relative to TRMM and the gauge data. The WRF annual precipitation is significantly correlated ($r > 0.64; p < 0.05$) with both observed datasets in both domains. The results also show that the precipitation simulations are largely improved from d01 to d02. The d01 has a positive bias in all seasons, whereas d02 has a negative bias.

The WRF-Hydro model showed an excellent performance in February and December months with less bias value. However, the model showed a bad performance in the remaining months, especially in June, which has the highest bias value. However, without calibration, the WRF-Hydro model exhibited the same trend with the observed streamflow ($r=0.86, p<0.01$). Despite its limitations, the WRF-Hydro model was able to capture the streamflow trends over the Hunza River Basin. Our analysis of the simulations indicates that larger spatial domains may be required to more reliably resolve the spatial scales of atmospheric processes relevant to the study region’s hydroclimate. Overall, the results suggest that a properly configured and calibrated WRF-Hydro model can be effectively applied over this region for the study of hydroclimate.

Keywords: WRF-ARW model; Upper Indus Basin; Karakoram Region; Pakistan; climate change

1. INTRODUCTION

1.1 Background

Pakistan is one of the top ten countries most affected by the adverse impacts of climate change according to the Global Climate Risk Index (GCRI) 2018 (Eckstein *et al.*, 2017). The country is facing various climate-related challenges, including extreme precipitation events, rising temperatures, and floods and droughts of severe nature. Climate change has negatively impacted almost every sector, including agriculture, water resources, biodiversity, etc. However, the significant melting of snow-capped mountains and glaciers will cause extreme flooding in the region (Adnan *et al.*, 2017). Archer (2003) projected that a 1°C rise in mean summer temperature would increase the runoff of the Shyok River by 17% and the Hunza River by 16%. Although it is not possible to prevent the occurrence of floods, the likelihood of human exposure can be mitigated through planning and management strategies (Khalid *et al.*, 2018).

Pakistan is an agriculture-based country, and its economy depends upon the Indus River Irrigation System (IRIS). It is one of the world's biggest irrigation networks formed by eastern tributaries (Indus, Jhelum, and Chenab) and western tributaries (Sutlej, Baes, and Ravi). The Indus River originates from the Tibetan Plateau, flows toward the northern areas of Pakistan, and ultimately discharges into the Arabian Sea. Its flow mostly depends on the melting of snow and glaciers located in the northern regions of Pakistan, forming the upper catchment known as Upper Indus Basin (UIB). The UIB includes Gilgit, Astore, Shigar, Hunza, and Shyok sub-basins. About 11.5 % (22,000 km^2) of the total area of the UIB is covered by perennial glacial ice (Immerzeel *et al.*, 2009; Tahir *et al.*, 2011). These snow-capped mountains and glacierized regions above 4,000 m elevation contribute 70% of the flow of UIB (Adnan *et al.*, 2017). Most of the annual precipitation in UIB falls in the winter from westerly circulations. The summer monsoon is negligible in UIB because the high mountains of Hindukush-Karakoram-Himalaya (HKH) decrease the effect of monsoon in these catchments.

However, the UIB is a **data-scarce region** where very few hydro-meteorological stations are installed. These stations are unevenly distributed and reside primarily at low-elevation valley locations, raising concerns about their representativeness of higher elevation orographic effects (Maussion *et al.*, 2014). The lack of sufficient hydro-meteorological observations is usually the most challenging for flood forecasting and other hydro-climatic studies over this region. Complex topography, coupled with challenges of field study in this region, has led to considerable uncertainty in assessing glacial mass balance and even meteorological trends. Moreover, the available global reanalysis datasets are useful to evaluate the large scale flow patterns over this region, but their coarse resolution cannot adequately characterize the complex orography and other local dynamics (Maussion *et al.*, 2014; Norris *et al.*, 2017).

Also, the UIB region is expected to be more vulnerable to climate change as rising temperatures will increase the summer runoff as a result of snowmelt (Shrestha *et al.*, 2015b). The rise in runoff will increase the exposure and vulnerability of the region to flooding. Floods cause substantial loss of human life, crop damage, loss of livelihood, and damage to property. In the recent past, flood events have caused many damages across the world and have thus motivated scientists and researchers to focus on its forecasting to mitigate the losses (Silver *et al.*, 2017). This fact emphasizes the need for more accurate hydrological models to predict streamflow.

Due to the data scarcity and rugged terrain, very few studies have been conducted to simulate streamflow or forecast floods. These studies adopted lumped and simplified temperature index-based models, which do not represent the physical characteristics of the watershed. For example, Garee *et al.* (2017) applied the Soil and Water Assessment Tool (SWAT) model combined with a temperature index algorithm to simulate the streamflow over the Hunza watershed using data from Pakistan Meteorological Department's (PMD) three weather stations. The major limitations of the SWAT model include limited snowmelt physics and lack of streamflow simulation capability, especially in the heterogeneous mountainous regions. Ali *et al.* (2018) assessed the Hydrologiska Byrans Vattenbalansavdeling (HBV) Light model's performance to project the streamflow variability of the Hunza River under climate change scenarios using data from three stations. Tahir *et al.* (2011) used the Snowmelt Runoff Model (SRM) to simulate daily streamflow in the Hunza River basin using Aphrodite precipitation product and the Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover product.

Similarly, Adnan *et al.* (2017) used SRM to simulate streamflows in the Gilgit River basin using data from a few stations. A study by Azmat *et al.* (2016) compared SRM with the Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) and snowmelt runoff model (SRM) over the Jhelum River basin and found the SRM model comparatively better in predicting flows. Similarly, Khan *et al.* (2014) applied the University of British Columbia Watershed Model (UBCWM) to simulate the flows of the Shigar River.

Different hydrological models with glacial- and snow-melt components have been used to simulate streamflow in the UIB region. The selection of an appropriate hydrological model is critically important in predicting streamflows in data-scarce regions such as the UIB. Nowadays, coupled atmospheric-hydrologic models (such as WRF-Hydro) have received a lot of attention throughout the world. The land surface has a strong influence on the atmosphere, but this influence or mechanism is still poorly understood (Koster *et al.*, 2014; Arnault *et al.*, 2016). The simple hydrological models cannot fully capture the land-atmosphere mechanisms resulting in non-realistic estimations of streamflows.

Therefore, **coupled atmospheric-hydrologic models (such as WRF-Hydro) are needed to fill this gap**. The WRF-Hydro (Gochis *et al.*, 2018) is an open-source, community-based, and advanced modeling system coupling atmosphere and terrestrial hydrology based on physical principles. WRF-Hydro is a fully distributed model developed by the National Center for Atmospheric Research (NCAR) to represent hydrological processes (Patel, 2015). It can interconnect multi-scale hydro-meteorological processes, including a land surface model (LSM), atmospheric model, and routing models to simulate and predict terrestrial water processes by choosing different parameterizations schemes (Xue *et al.*, 2018).

Combining atmospheric models with hydrologic models (i.e., WRF-Hydro) either in a coupled or standalone mode in the complex river basins and data-scarce regions can reduce the uncertainties and predict streamflow more realistically (Senatore *et al.*, 2015; Yucel *et al.*, 2015; Arnault *et al.*, 2016; Naabil *et al.*, 2017). It can also perform simulations in both coupled and uncoupled modes, and predict hydro-meteorological processes. At this moment, WRF-Hydro only supports two LSMs, i.e. Noah and Noah-MP. WRF-Hydro has been used worldwide for research, and operational prediction uses both in coupled mode (Senatore *et al.*, 2015; Arnault *et al.*, 2016; Naabil *et al.*, 2017), and un-coupled or offline mode (Yucel *et al.*, 2015; Silver *et al.*, 2017; Lin *et al.*, 2018; Xue *et al.*, 2018). To the best of our knowledge, this modeling system has not been used either in a flood forecasting or water resources management applications over the Indus Basin. This study focuses on assessing the capability of the WRF-Hydro version 5 modeling system (Gochis *et al.*, 2018) over the Hunza River Basin (HRB) to predict streamflows for the year 2004.

1.2 Research Hypothesis

The coupled atmospheric-hydrological WRF-Hydro models produce skillful historical runoff predictions in complex terrain and are thus suitable for future runoff modeling.

1.3 Research Objectives

Following are the main research objectives:

i. To estimate the streamflow by using WRF-Hydro model

ii. To determine how accurate the WRF-Hydro coupled atmospheric-hydrologic model is in simulating historical stream flows.

2. DATASETS AND METHODS

2.1 Study Area

The Hunza River Basin (HRB) lies in the mountainous region of central Karakorum stretching from 74°02'-75°48'E and 35°54'-37°05'N having an area of 13,733 km^2. Hunza river is 231.7 km long, and fourteen small tributaries (Danyore, Khunjerab, Verjerab, Chupurson, Khudaabad, Shimshal, Misgar, Khyber, Hoper, Hisper, Rakaposhi, Chalt, Naltar, and Hassanabad) contribute to its flow (Shrestha *et al.*, 2015b; Garee *et al.*, 2017). This basin is snow and glacier-dominated, and its glacier area is 2,754 km^2, of which an area of 2,344 km^2 is clean glaciers (Shrestha *et al.*, 2015a). These glaciated and snow-fed mountains contribute 80% of the total flow of the Hunza River, which is measured at Danyore Bridge. The HRB is one of the sub-basins of the Indus River Basin, having a total drainage area of 13,733 km^2, which contributes approximately 13% of the overall flow in the UIB, upstream of Tarbella dam. The river discharge is minimum during the winter season from November to April and starts to increase from April. The HRB consists of complex topography with an elevation of around 1,400 m above sea level (a.s.l) in southern parts to 7,800 m a.s.l in its northern parts (Ali *et al.*, 2017).

The HRB is situated in the Karakoram region (Fig. 2.1) and contributes about 12% in the IBR irrigation system (Shrestha *et al.*, 2015b). The Hunza basin has arid to semi-arid climate, and effectively only two seasons - summer (April – September) and winter (October – March). Its climate is highly influenced by monsoon and westerly winds. At low altitudes, the weather is hot in summer with cold winters and significant variations in temperature extremes. Precipitation occurs in the form of snowfall in winter, which

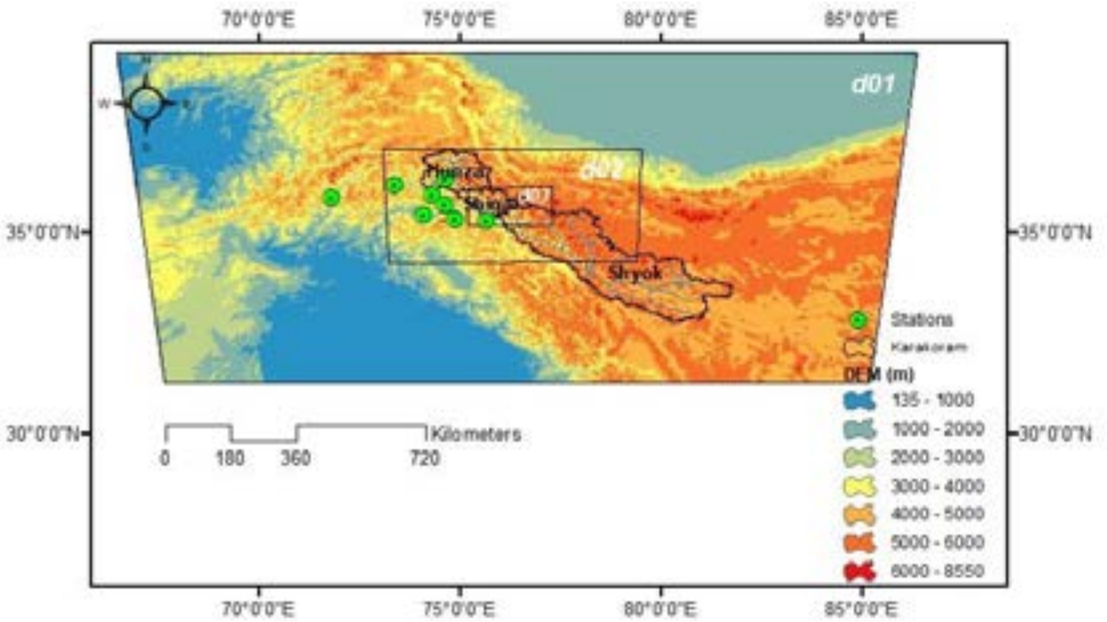

Fig. 2.1: Configuration of the WRF model and its topography

is approximately 70-80%, while 20-30% of precipitation arrives in summer in the form of rain. There are three climatic stations installed by WAPDA at different altitudes, at Khunjerab (4730 m), Ziarat (3669 m), and Naltar (2858 m). During the winter season, the westerly circulations contribute approximately two-thirds of the snowfall in the region. Precipitation from westerly

winds in winter can reach higher altitudes than in summer due to the tropospheric extent of the westerly winds. According to Ragettli *et al.* (2013), the mean annual precipitation in the southern part of the basin (i.e., Naltar) is 625 mm, while in northern parts (Ziarat and Khunjerab) the precipitation is comparatively low at 160 mm. However, the mean annual temperature in Naltat is 6°C while in Ziarat and Khujerab, it is 2.4 and -6°C, respectively. The mean discharge of the Hunza river is 328 m^3/sec, which is 13% of the total discharge of the UIB (Hasson *et al.*, 2017).

2.2 Hypsometric Curve Description of Hunza River Basin

The hypsometric curve shows the distribution of the area of the catchment at the different altitudinal zones in the watershed. It is essential for the planning and management of natural resources. In this study, the hypsometric analysis of the HRB is carried out in ArcGIS 10.3 environment using DEM of SRTM with 90 m x 90 m resolution (Fig. 2.2). The curve is obtained by plotting the cumulative area on the abscissa (x-axis) and elevation on the ordinate (y-axis). The cumulative area is expressed in percentage of the total area of the basin, while the height is expressed in 500-m bands ranging from 1,500 m to 8,000 m. The hypsometric analyses illustrate that the majority of the

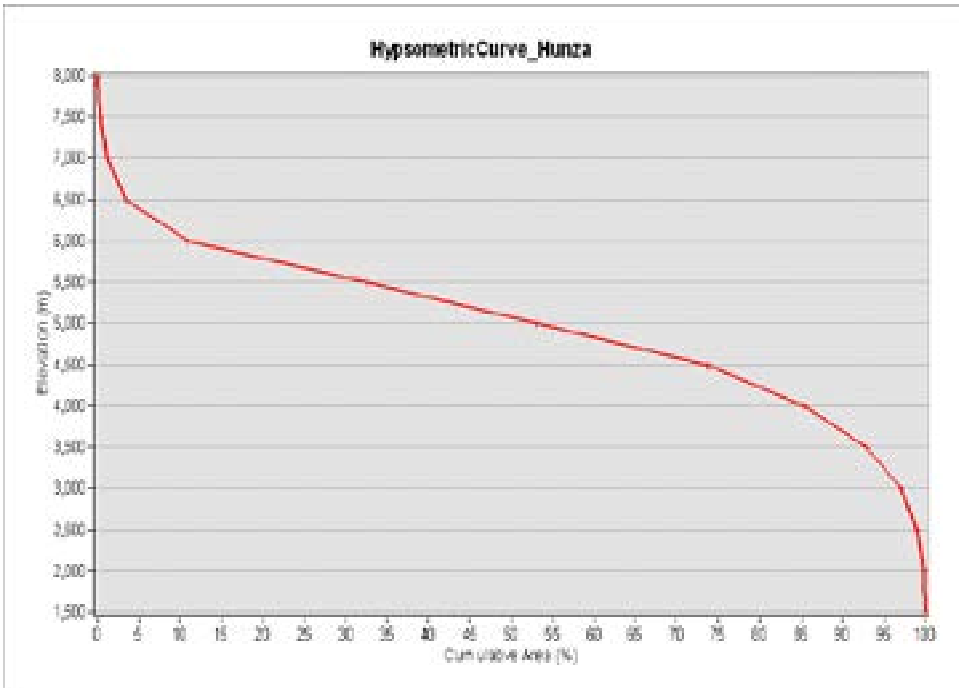

Fig. 2.2: Hypsometric curves of Shigar and Hunza Basins located in d02

catchment area lies between the elevation of 3,500 m to 6,000 m, while it is 4,000 m to 6,000 m for the Hunza basin. Further, it also shows that more than 50% of the area lies above 5,000 m a.s.l. for the HRB.

2.3 Atmospheric Model (ARF-WRF)

The Advanced Research Weather Research & Forecasting model (ARW-WRF, hereafter WRF) version 3.8.1 (Skamarock *et al.*, 2008) was used to dynamically downscale 11 years (1998-2008) of CFSR data (Saha *et al.*, 2010), which has approximately 38-km horizontal grid resolution. Each year was simulated as a single calendar year starting from 1 January at 00 hours and 00 minutes to 31 December at 23 hours and 59 minutes. The motivation for using CFSR data in this study has been taken from Bao and Zhang (2013), who evaluated several datasets over Tibetan Plateau. They found CFSR and the Interim European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis datasets (ERA-Interim) to simulate atmospheric changes effectively. They showed that both datasets presented smaller RMS error and mean bias. The main reason for selecting the CFSR dataset, specifically in this study, was its resolution. The CFSR dataset has a higher spatial resolution (0.5° by 0.5°) than ERA-Interim (0.75° by 0.75°).

The WRF model used in this study is configured with three nested domains (d01, d02, and d03) with gradually increasing horizontal resolution from 18 km (d01) through 6 km (d02) to convection-permitting 2 km (d03) so that the innermost domain (d03) does not rely on a cumulus parameterization. The model configuration presented in Fig. 2.1 was specifically chosen to limit the influence of boundary conditions on the results by assuring large margins between the nested domains. Besides, the relaxation zone of five points used in this study is very small compared to the domain sizes. The choice of the innermost domain size stems from work by Norris *et al.* (2017), who emphasized that a grid cell resolution of 2-km or finer is required to resolve orographic precipitation in this region. The detailed model strategy and parametrization schemes used in this study are given in Table 2.1.

2.3.1 Model validation

The WRF precipitation and temperature output have been validated using station data. The station data were collected from the Pakistan Meteorological Department (PMD). There are only six stations that are being operated by the PMD in the region of interest (d02 – middle domain) for this period. The six stations' details are given in Table 2.2. Because of the limited availability of station data, we also assessed the WRF precipitation output with the Tropical Rainfall Measuring Mission (TRMM) 3B42V7 gridded precipitation data (Huffman *et al.*, 2007) and PMD stations data at monthly

Table 2.1: **Model strategy**

A. Physical parameterization schemes	
Land surface model (LSM)	Noah multi-parameterization (Noah-MP) (Niu *et al.*, 2011a)
Planetary boundary layer (PBL)	Yonsei University (YSU) scheme (Hong *et al.*, 2006)
Microphysics	Thompson microphysics scheme (Thompson *et al.*, 2008)
Longwave radiation	Rapid radiative transfer model (RRTM) (Iacono *et al.*, 2008)
Shortwave radiation	Dudhia scheme (Dudhia, 1989)
Land surface	Revised MM5 scheme (Monin and Obukhov, 1954)
Cumulus parameterization	Betts-Miller-Janjic scheme (Janjić, 2000) in d01 and d02
B. Grids and nesting strategy	
Nesting	Two-way Nesting; Nested in a cascade approach (d01-d02-d03)
Horizontal grid cell resolution	18 km, 6 km, and 2 km
Map projection	Lambert conformal
Number of vertical layers	30
Top-level pressure	5000 Pa
Center point of domains	35.80°N, 76.40°E
Timestep	Parent time step ratio of 1:3 40s in d01, 13.3s in d02, and 4.44s in d03
C. Sensitivity analysis	
Simulation - 1	Thompson and Noah-MP
Simulation - 2	Morrison and Noah-MP
Simulation - 3	Goddard and Noah-MP
Simulation - 4	Thompson and CLM4

Table 2.2: PMD stations, their locations, elevation and the respective domain

Station	Longitude	Latitude	Elevation (m)	Domain (s)
Chilas	74° 06’	35° 25’	1250	d01, d02
Bunji	74° 38’	35° 40’	1372	d01, d02
Gupis	73° 24’	36° 10’	2156	d01, d02
Skardu	75° 41’	35° 18’	2317	d01, d02,d03
Astore	74° 54’	35° 20’	2168	d01, d02
Gilgit	74° 20’	35° 55’	1460	d01, d02
Chitral	71° 50’	35° 51’	1497	d01

temporal scale. The TRMM data are available on a 0.25° by 0.25° latitude-longitude grid at 3-hourly temporal resolution. TRMM data are collected from remote sensing and adjusted based on the monthly gauge data. Several studies have evaluated WRF precipitation with the TRMM dataset (for example, Maussion *et al.*, 2014; Norris *et al.*, 2017). Despite its coarse resolution and other limitations, TRMM 3B42V7 is considered to be one of the reliable gridded precipitation datasets (Norris *et al.*, 2017; Krakauer *et al.*, 2019). Krakauer *et al.* (2019) compared different precipitation datasets with the available station data over the Indus Basin and found the TRMM dataset performed best among the remote sensing datasets. Similarly, Ali *et al.* (2017) evaluated the TMPA satellite precipitation products (3B42V6, 3B42V7, and 3B42RT) with gauge stations over the Hunza Basin in Karakoram mountain range. They also found 3B42V7 to perform reasonably better than the other two products.

The WRF precipitation output is evaluated by the root mean square error (RMSE), percentage bias, and Pearson correlation coefficient (*r*), whereas WRF temperature output is assessed by RMSE, mean bias, and Pearson correlation coefficient. The expressions of RMSE, percentage bias (PBIAS), and mean bias for *n* grid points or *n* stations are

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - O_i)^2}, \quad (1)$$

$$PBIAS = \frac{1}{n}\sum_{i=1}^{n}((M_i - O_i)/O_i) * 100, \quad (2)$$

$$mean\ bias = \frac{1}{n}\sum_{i=1}^{n}(M_i - O_i), \quad (3)$$

where and represent model simulations and observed data, respectively.

Research shows that WRF is highly sensitive to the selection of the land surface model (LSM) and cloud microphysical scheme (Norris *et al.*, 2017). Therefore, a sensitivity analysis was also performed. Based on limited computational resources, four simulation experiments (Table 2.1. Section-C) were performed for the year 2004 with a combination of three cloud microphysical schemes (Thompson, Morrison, and Goddard), and two land surface models (Noah-MP and CLM4). The RMS error and Pearson's coefficient 'r' between WRF, stations, and TRMM data were estimated at Skardu station for the year 2004. The results showed that the RMS error between the WRF and station data is lower in all three domains in Simulation-1. Besides, Pearson's r between the WRF and station data in Simulation-1 is slightly higher than the other three simulations. Therefore, the results suggest that out of the tested configuration, Simulation-1 (Thompson and Noah-MP) offered the best performance. This is also consistent with Norris *et al.*, (2017), who performed sensitivity analysis over the same region for selected summer and winter days. On the other hand, we have performed a sensitivity analysis for a full year.

2.4 Hydrological Model (WRF-Hydro)

2.4.1 GIS preprocessing

The GIS preprocessing was performed using ArcGIS version 10.3. The WRF Hydro GIS preprocessing tool (Sampson and Gochis, 2018) has been prepared by the National Center for Atmospheric Research (NCAR), USA. This GIS preprocessing toolkit contains a python toolbox named "GEOGRID_STANDALONE.pyt", which includes two other toolboxes named as (i) processing toolbox and (ii) utility toolbox. The GIS preprocessing toolkit requires three input datasets, i.e., a digital elevation model (DEM), a geogrid file (geo_em.d02.nc), and forecasting points. The geogrid file (geo_em.d02.nc) includes the terrestrial datasets interpolated to the model domain. Besides, the forecasting points are the outlet points of the rivers where we are interested in estimating the flows. In this case, we have the following two forecasting points (Table 2.3), and these points were obtained by the delineation of Hunza and Shigar Basins.

Table 2.3: Latitude and longitude of Hunza and Shigar Basins

FID	Station	Latitude	Longitude
1	Hunza	35.915	74.37
2	Shigar	35.329	75.628

Regridding (nest) factor allows controlling the output cell size so, it should nest perfectly within the coarse geogrid resolution. The resolution of our land surface model (LSM) is 6,000 m, and we need the resolution of the WRF Hydro model to be 250 m. So, 6,000 divided by 250 will result in 24. Then, we also need several routing grid cells to define a stream. It is used to control the density of the stream network. Here, it is 32. The output will be in the zipped folder, which contains the files, including Fulldom_hires.nc, GEOGRID_LDASOUT_Spatial_Metadata.nc, GWBASINS.nc, GWBUCKPARAM.nc, Route_Link.nc, and Streams.shp (the description of these files is given in the WRF Hydro technical description (Gochis *et al.*, 2018).

The WRF Hydro GIS preprocessing tool creates data layers for terrestrial overland flow, subsurface flow, and channel routing processes, which are required by the model. The middle domain (d02) contains three basins, namely Hunza, Shigar, and Shyok. However, Shyok sub-basin is not fully covered in the domain. Therefore, only two basins (i.e., Hunza and Shigar) have been considered in this study. The two catchments were delineated by using an arc hydro toolbox in the ArcGIS software. A 30-m resolution digital elevation model (DEM) was collected from NASA's shuttle radar topography mission (SRTM). The latitude and longitude of the Hunza and Shigar basins are given in Table 2.3.

2.4.2 Model configuration

The full description of the WRF-Hydro modeling system is available in Gochis *et al.* (2018), and the options used in the model experiments are explained here. For this study, WRF-Hydro has been configured in an "offline" mode with the Noah-MP land surface model (Niu *et al.*, 2011b) to perform the simulations. The model was initialized on January 01, 2004, to simulate the streamflow for a whole year (February 2004 to January 2005) considering the January 2004 as a spinup. The model spin-up can be defined as the internal adjustment followed by unusual initial conditions (Rahman *et al.*, 2016). Normally, the model results for the spin-up time are deeply impacted by the initial conditions (such as soil moisture, etc.), and are often erroneous. The time required by the model to be stabilized to simulate the variables effectively and efficiently is known as a model spin-up time. The research shows that the spin-up time varies with the starting time and the dryness of the river basin (Gochis *et al.*, 2018).

However, WAPDA does not have data for the year 2005. Therefore, the analysis is limited to eleven months (February 2004 to December 2004). Generally, for hydrological applications studies, Gochis *et al.* (2018) have recommended a longer spin-up time, but due to the computational resources limit, we have kept one month (i.e., January 2004) spin-up time. Likewise, Lin *et al.* (2018) have also considered a 1.5-month spin-up time sufficient for flood modeling in rivers.

2.4.3 Channel routing

Numerous channel routing options are available in WRF-Hydro. In this study, we have used the Muskingum-Cunge routing method, which involves time-varying parameter estimates.

2.4.4 Subsurface flow routing

In WRF-Hydro, subsurface lateral flow is estimated before the routing of overland flow. The main reason for doing this is exfiltration, which may contribute to the infiltration excess overland flow and increase the water head later on. In the present version of WRF-Hydro, there are four soil layers in a 2-meter soil column. The depth of each layer is described in Table 4.

Table 3.4: Depths of four soil layers in WRF-Hydro (Gochis *et al.*, 2018)

Layer	Soil thickness (m)	Cumulative depth of the top layer (m)
1st	0.1	0.1
2nd	0.3	0.4
3rd	0.6	1
4th	1	2

3. RESULTS AND DISCUSSION

3.1 Model Performance for Precipitation Estimation

This section describes the extent to which WRF is accurate in reproducing the spatio-temporal variability of precipitation in the two domains (d01 and d02) of UIB for the year 2004. The mean monthly precipitation trends for WRF, TRMM, and station data are shown in Fig. 3.1. Also, the Pearson correlation coefficient, RMSE, and PBIAS are computed between WRF and both observed datasets (Table 3.5).

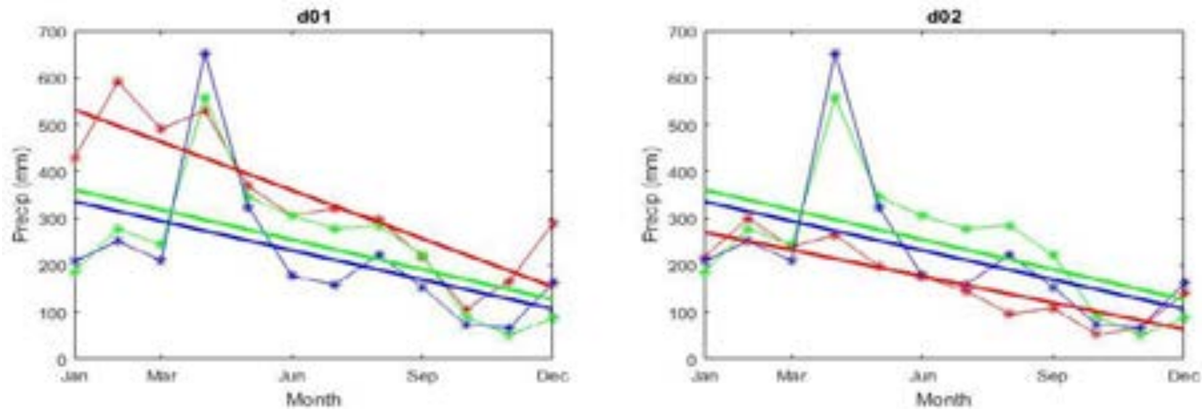

Fig. 3.1: Time series comparisons of precipitation (mm) between annual WRF (red), TRMM (green), and mean of PMD Stations ("Observed"; blue) for domain-01 (d01) (left), and domain-02 (d02) (right). The straight lines are least-square linear regressions.

There are six stations in d02 (Table 2.2), and WRF and TRMM data are extracted at these gauge stations. When WRF, TRMM, and gauge data at these six stations are averaged and compared, WRF tends to overpredict the total annual precipitation in d01 and underpredict in d02 in comparison to TRMM and the gauge data (Fig. 3.1). Similarly, WRF annual precipitation is significantly correlated ($r > 0.64; p < 0.05$) with both observed datasets (Table 3.5) in both domains. The critical aspect is how the simulated precipitation amount and bias changes as resolution increases. We evaluated the PBIAS of WRF with the six stations, which are located in both d01 and d02. The results (Fig. 3.2) show that the precipitation simulations are largely improved from d01 to d02. The d01 has a positive bias in all seasons, whereas d02 has a negative bias. The PBIAS between WRF and TRMM in d01 is estimated to be 70% whereas it is reduced to -17% in d02. The PBIAS between WRF and stations data in d01 is estimated to be 75% whereas it is reduced to -19% in d02. The RMSE between WRF and TRMM data in d01 is 152 mm whereas it is reduced to 127 mm in d02. Similarly, the RMSE between WRF and stations data in d01 is 168 mm, whereas it is reduced to 125 mm in d02. Analysis during postprocessing of the simulations suggests that larger spatial domains may be required to more reliably resolve the spatial scales of atmospheric processes relevant to the study region's hydroclimate changes.

Table 3.5: RMSE (mm), PBIAS (%) and Pearson's correlation coefficient (r; unitless) of six-stations averaged total annual precipitation between WRF, stations, and TRMM in d01 and d02 for 2004

	d01			d02		
Data compared	RMSE (mm)	PBIAS (%)	Pearson's r (*p*)	RMSE (mm)	PBIAS (%)	Pearson's r (*p*)
WRF & TRMM	152	70%	0.64 *(< 0.05)*	127	-17%	0.63 *(< 0.05)*
WRF & Stations	168	75%	0.67 *(< 0.05)*	125	-19%	0.65 *(< 0.05)*

3.2 Model Performance for Average Temperature Estimation

This section describes the extent to which WRF is accurate in reproducing the spatio-temporal variability of average temperature in the two domains (d01 and d02) of UIB for the year 2004. The mean monthly precipitation trends for WRF, and station data are shown in Fig. 3.2. Also, the Pearson correlation coefficient, and mean bias are computed between WRF and observed dataset.

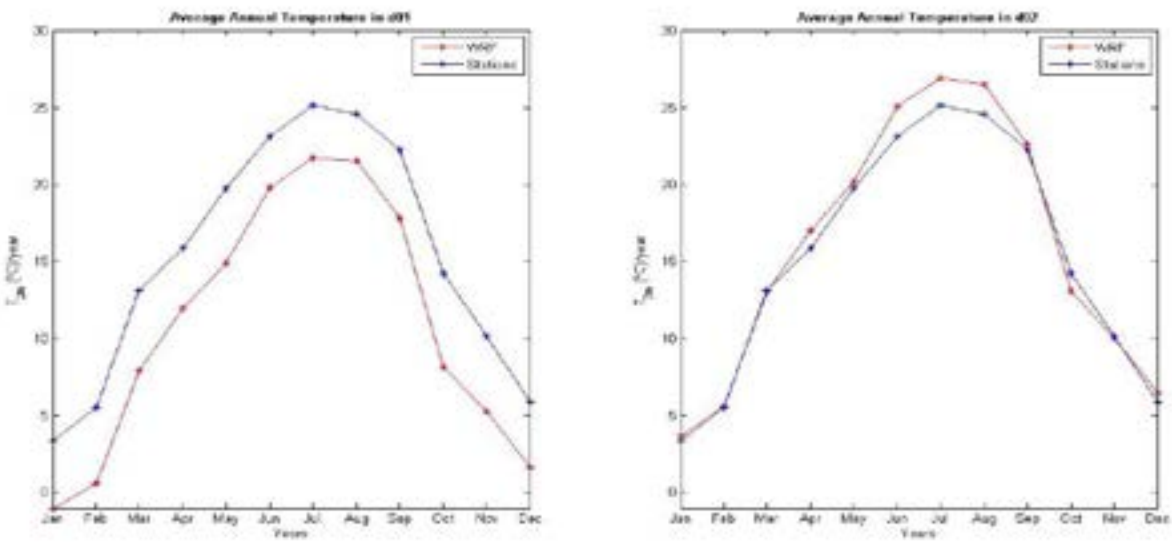

Fig. 3.2: Time series comparisons of average temperature (T2) in Celsius between monthly WRF (red), and mean of PMD Stations ("Observed"; blue) for domain-01 (d01) (left), and domain-02 (d02) (right) after lapse rate corrections

Fig. 3.3 shows the change in the mean lapse rate with altitude in the two domains. The average lapse rate for d01 and d02 is estimated to be -7.2816 and -8.0419 °C/km, respectively. These lapse rates are used to vertically interpolate the simulated

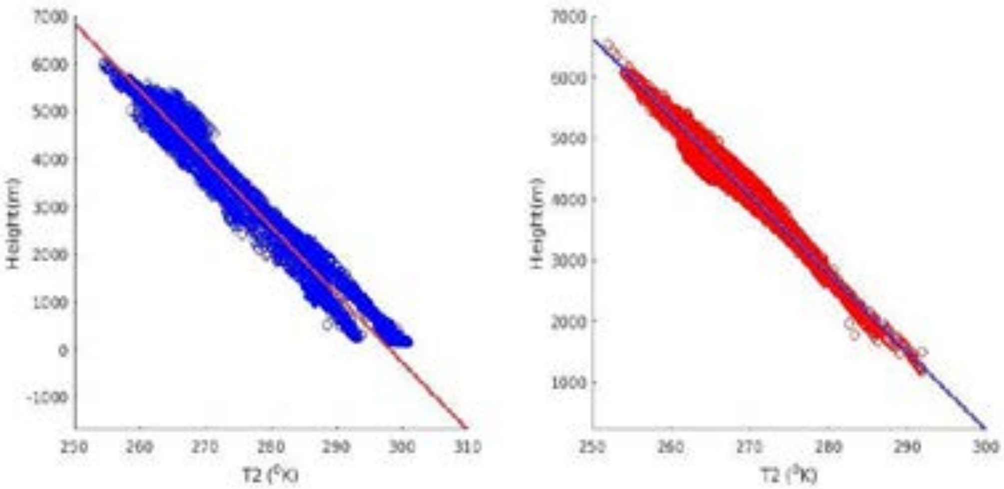

Fig. 3.3: Lapse rate between T (Kelvin) and height (m) in d01 (a), and d02 (b)

temperature time series to the actual heights of the stations. For each station, the difference between the station height and WRF height is computed, multiplied by the average lapse rate, and added to the simulated temperature values.

There are six stations in d02 (Table 2), and WRF data is extracted at these gauge stations. When interpolated WRF and gauge data at these six stations are averaged and compared, WRF tends to underpredict the monthly average temperature in d01 and overpredict in d02 in comparison to the station data (Fig 3.2). Similarly, WRF monthly average temperature is significantly correlated ($r > 0.9; p < 0.01$) with the station data in both domains. The critical aspect is how the simulated temperature and bias changes as resolution increases. We evaluated the mean bias between WRF and the six stations, which are located in both d01 and d02. The results (Fig. 3.2) show that the temperature simulations are largely improved from d01 to d02. The d01 has a negative bias (-4.4°C) in all seasons, whereas d02 has a positive bias (0.59°C).

3.3 Model Performance for Streamflow Estimation

This section describes the extent to which WRF-Hydro is accurate in reproducing the streamflow variability in the Hunza River Basin for 11 months (February through December). The PBIAS is used to assess model performance. Fig. 3.4 shows the daily simulated and observed streamflow at Dainyor Bridge, Hunza River. Without calibration, the model exhibited the same trend with the observed streamflow ($r=0.86, p<0.01$). Overall, the WRF Hydro model has overpredicted the streamflow. Table 3.6 shows the PBIAS between the simulated precipitation and modelled precipitation and simulated and observed streamflow at the monthly time scale. The results show that the model does not show a good performance. The model showed a good performance in February and December months with less bias value. However, the model showed the worst performance in the remaining months, especially in June, which has the highest bias value.

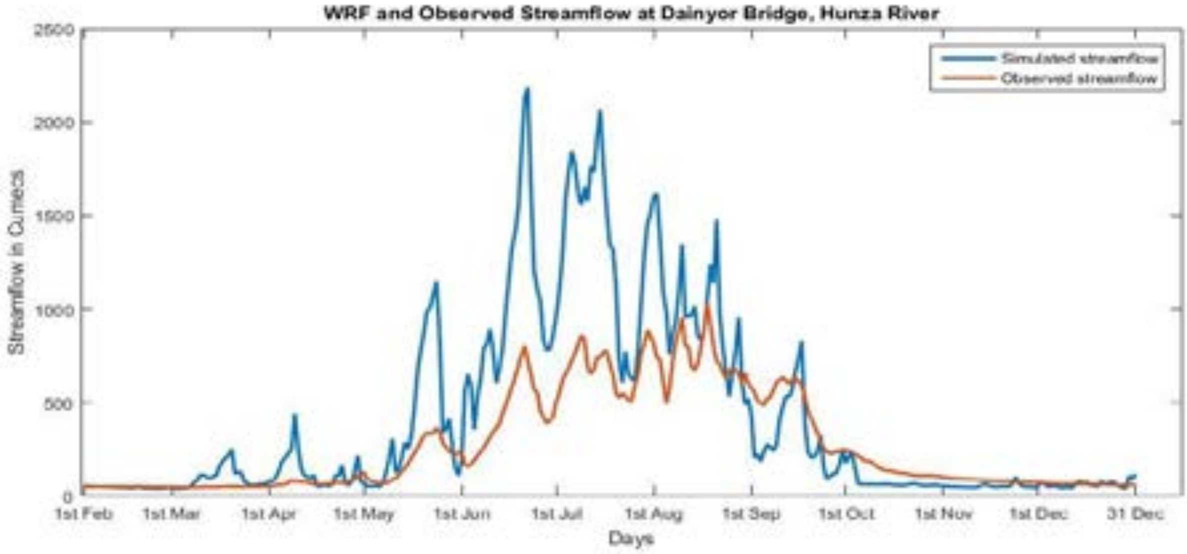

Fig. 3.4: Simulated and observed streamflow at Dainyor Bridge, Hunza River

Table 3.6: PBIAS (%) for precipitation and streamflow by each month

Month	PBIAS (%) in precipitation in d02	PBIAS (%) in streamflow in the Hunza catchment
January	4	Spin up
February	20	-7
March	14	96
April	-59	81
May	-39	73
June	-1	137
July	-1	93
August	-57	33
September	-29	-32
October	-28	-50
November	-0.4	-36
December	-14	0

3.4 Discussion

The WRF model was applied to simulate the spatio-temporal variability of precipitation and temperature over the UIB for the year 2004 using boundary conditions derived from the CFSR reanalysis dataset. The WRF model was configured with three nested domains with increasing horizontal resolution moving inward from 18 km through 6 km to 2 km grid cell resolution. The WRF Hydro modeling system was applied to the middle domain (d02) at 6 km grid spacing to simulate the streamflow for the year 2004.

The WRF precipitation simulations were then compared with TRMM 3B42V7 and PMD stations data for the same time period. Satellite-based products (for example

TRMM 3B42V7) can be used as a potential source of observed datasets for hydro-meteorological studies in the data-scarce regions such as UIB.

This region is a very data scarce region. Pakistan Meteorological Department (PMD) operates only six stations in this region. The simulations showed that the WRF tends to overpredict the total annual precipitation in d01 and underpredict in d02 relative to the observed datasets. However, WRF tends to underpredict the monthly average temperature in d01 and overpredict in d02 in comparison to the station data.

However, the results show that both precipitation and temperature simulations are largely improved from d01 to d02 i.e. with increasing resolution from 18 km to 6 km. In addition, WRF simulations (precipitation and temperature) are significantly correlated (*at 95% confidence level*) with both observed datasets in both domains.

The streamflow results obtained from WRF Hydro does not seem to be the best simulated. It needs calibration of the various paramters with in WRF Hydro model.

3.5 Building Research Partnerships

This research project provided an opportunity to work in collaboration with Dr. Courtenay Strong, Associate Professor, and Dr. Adam Kochanski, Research Assistant Professor, Department of Atmospheric Science, University of Utah. Court, Adam, and Dars have sustained this research partnership to analyze the climate change impacts on water resources using more robust tools and models. Their partnership was able to get more funds for research over the Indus River Basin (IRB) and Pakistan. They have applied to the Higher Education Commission (HEC), Pakistan, for securing more research grants.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This study aimed to investigate the applicability of the WRF Hydro model over the Hunza River Basin. This model was applied to simulate streamflow for the 2004 year. First, the WRF atmospheric model was used to generate the forcing output with boundary conditions derived from the Climate Forecast System Reanalysis (CFSR) data. The WRF model was configured with three nested domains (d01, d02, and d03) with horizontal resolutions increasing inward from 18 km (d01) through 6 km (d02) to 2 km (d-03) grid cell resolution. The simulations were then compared with TRMM and station data for the same time period using root mean square error (RMSE), percentage bias (PBIAS), and Pearson's correlation coefficient (r). The results show that WRF tends to overpredict the total annual precipitation in d01 and underpredict it in d02 compared to TRMM and the gauge data. WRF annual precipitation is significantly correlated ($r > 0.64; p < 0.05$) with both observed datasets in both domains. The results also show that the precipitation simulations are largely improved from d01 to d02. The d01 has a positive bias in all seasons, whereas d02 has a negative bias. Analysis during postprocessing of the simulations suggests that larger spatial domains may be required to more reliably resolve the spatial scales of atmospheric processes relevant to the study region's hydroclimate.

The WRF-Hydro model was applied over d02, wherein two catchments (Hunza and Shigar) exist. In this study, we have evaluated the performance of the Hunza Basin only. The resolution of the Noah-MP LSM and WRF-Hydro model are 6,000-m and 250-m, respectively. The results showed an excellent performance in February and December months with low bias values. However, the model showed relatively poor performance in the remaining months, especially in June, which had the highest bias value. However, without calibration, the WRF-Hydro model exhibited the same trend with the observed streamflow *($r=0.86, p<0.01$).* Despite its limitations, the WRF-Hydro model was able to capture the streamflow trends over the Hunza River Basin. Overall, the results suggest that a properly configured and calibrated WRF-Hydro model can be effectively applied over this region for the study of hydroclimate.

4.2 Recommendations

Following are some suggestions for future studies:

i. A comparison of CFSR and ERA-Interim datasets may be carried out over the UIB. Out of these two, whichever dataset performs better, may be used.

ii. Spin-up time may be selected carefully.

iii. The WRF-Hydro model should be calibrated and validated properly. In the inception report, we committed to run the model for one or two days to check its applicability over UIB. However, we ran the model for the whole year. Depending on the time and resources available, we could not perform the calibration and validation, which is very important and should be added in future studies. We believe that the calibrated WRF Hydro model will outperform over this region.

iv. Larger spatial domains may be required to more reliably resolve the spatial scales of atmospheric processes relevant to the study region's hydroclimate.

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Main thrust of Applied Research component of the Water Center is to stimulate an environment that promotes multi-disciplinary research within the broader context of water-development nexus to support evidence-based policy making in the water sector. This is pursued using the framework provided by the six targets of the Sustainable Development Goal on Water i.e. SDG-6.

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