Predictability of Summer Monsoon Rainfall by using High Resolution Regional Model (HRM)

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Abstract

Numerical Weather Prediction (NWP) models are treated as helping tools for the weather forecasters in this era of science and technology. Generally Evaluation of NWP models is made to gauge the level of reliability in particular region as well as phenomena of specific weather pattern. As Pakistan is an agricultural country and precipitation is basic ingredient for agriculture and in Monsoon season it receives more than 60 % rain of the total annual rain. Therefore precise forecasts are believed to be assurance for successful agriculture with sufficient lead time. A hydrostatic NWP model HRM containing 40 vertical model layers and 7 soil layers, is evaluated at horizontal resolution of 22km and 11km for the prediction of precipitation in South Asian Monsoon season. Four rainfall events of different intensities are simulated at 00UTC by HRM at both selected horizontal resolutions with domain 7˚-45˚N latitudes and 55˚-96˚E longitudes. The model simulated rain has been compared with actual rainfall and Analyses of this study show that the performance of HRM with horizontal resolution 22km is better than that of 11km for Monsoon season. The results of extreme rainfall events (28-29 July, 2010) also indicate that the model HRM has good capability to estimate rain over Pakistan region whereas less capability of estimating rain has been observed for21st July and 8th August, 2010. Further, variation in spatial extent of precipitation regime has been observed from simulations at both grid scales.

Key words: HRM, Monsoon, Horizontal Resolution

Introduction

In the age of science and technology, weather forecast has its own significance because of vital role of weather in all phases of human life. Weather forecast is very important for agriculture, transportation, defence matters and all human activities. Early warning systems are also based on weather forecasts at different time scales. Pakistan being situated between 23°-37°N latitudes and 60°-78°E longitudes falls in the Extratropics. Precipitation is received by Pakistan in both summer and winter seasons. Western Disturbances (WD) approaches the upper parts of the country throughout the year; while easterlies (Monsoon) are dominant only in summer (Afzal and Zaman, 2010).

Seasonal variation in winds or reversal of winds is named as Monsoon. Temperature gradient between the ocean and adjacent land is the main cause of this variation (Trenberth et al., 2006). Monsoon or easterly system is mainly associated with the development of depressions in the Arabian Sea and the Bay of Bengal. Overall Pakistan receives nearly 60 % rainfall of annual precipitation from Monsoon system (Adnan and Khan, 2009). Both the weather systems (WD and monsoon) sometimes overlap to extract a heavy downpour for Pakistan. The lofty Himalayas, Karakoram and Hindukush (HKH) mountains play their role to provide orographic lifting to the weather systems. Precipitation not only plays a vital role in agriculture but also in all human activities.

In a case study of heavy rainfall over Karachi and surrounding areas during 27-29 July 2003, a non-hydrostatic numerical model “Mesoscale Model generation 5” (MM5) was used. The analyses of study show that model MM5 has overestimated the observed rain and model has shifted the rain belt somewhat to southward (Rasul et al., 2009). HRM was used to diagnose the reasons for heavy rainfall during March 30 to April 2, 2007 over upper parts of Pakistan. HRM output was compared with NCEP reanalysis datasets and results of the study showed the resemblance between NCEP and HRM output (Qudsia and Rasul, 2009). Another study was made for the evaluation of Lokall Model (LM) for an integration domain covering Romanian territory over the period February-August 2005. For the study some special weather situations (heavy precipitation and strong atmospheric instability) were simulated by LM and results of

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LM were then compared with outputs of HRM and surface observations for 160 meteorological stations. The results of the study showed the capabilities of LM to simulate properly spatial distribution of precipitation but overestimation in precipitation was observed (Pescaru et al., 2005).

In another study Weather Research and Forecast Model (WRF) was used to gauge Lightening Potential Index (LPI). The potential for charge generation in a convective thunderstorm is calculated by LPI. For the study two heavy rainfall events having significant lightening activity were simulated by WRF at different horizontal grid sizes. WRF was found reasonable after comparison of simulated and observed lightening (Lynn and Yair, 2010). To test the performance of HRM, another study was made for the calculation of water vapors over Europe. The results of the study had been found satisfactory when amount of water vapors measured by HRM was compared with water vapors calculated by remote sensors (Johnsen and Kidder, 2002). Another study was made for the predictability of an extreme warm season precipitation Event over central Texas on 29 June to 07 July 2002 using MM5. The event was explored through MM5 with various grid resolutions, initial and boundary conditions. The results showed that MM5 at high resolution convective resolving simulations do not produce the best simulations or forecast (Zhang et al., 2005).

In another study, numerical simulations by MM5 at grid sizes 36km, 12km and 4 km were performed to study scale-interactive dynamics of large-amplitude gravity wave event on 4 January 1994 along East coast of United State. It was observed that model at resolution 12 km compared well with the synoptic and mesoscale observational analysis (Zhang et al., 2003). HRM was used to calculate the atmospheric water vapors over Antarctica. The results were found satisfactory when HRM simulated water vapors were compared with data derived from Global Positioning System (GPS) (Johnsen et al., 2004). A study was made on high resolution mesoscale model MM5 to observe rainfall estimation over Bangladesh. The model was run at two resolutions 45km and 15km for two durations (31 March to 05 April 2002 and 20 to 25 May 2002). In both cases model MM5 showed good capability to estimate rainfall over Bangladesh (Nasreen and Islam, 2007).

Global warming and climate change have been posing a great challenge to the weather forecasters to predict the weather in changing climate pattern. High Resolution Regional Models are required to predict the weather events in a particular region. As such High Resolution Regional Model (HRM) has been adapted by Pakistan Meteorological Department (PMD) for operational weather forecast up to 72 hours. In the era of global warming and climate change, extreme events (precipitation) have been observed. Accurate and advance prediction of such events may be very useful for human beings (Rasul et al., 2005). In current study HRM has been evaluated for the predictability of rainfall in summer monsoon season at different horizontal grid resolutions (11km and 22km).

HRM Model Configuration

High Resolution Regional Model (HRM) is developed by Deutscher Wetterdienst (DWD) Germany which is a flexible tool for Numerical Weather Prediction. The hydrostatic model HRM is designed to simulate or predict mesoscale & regional scale atmospheric circulation. HRM simulates 43 meteorological parameters such as precipitation, maximum and minimum temperature, wind, cloud cover, geopotential height, vorticity etc at different pressure levels. Hydrostatic model HRM treats some variables like surface pressure P_s, temperature T, water vapors q_v, cloud water q_c, cloud ice q_i, several surface / soil parameters as prognostic variables and vertical velocity ω, geopotential height φ as diagnostic variables.

To derive the initial state of HRM, interpolation of the analysis of DWD' global model for Europe (GME) to HRM grid is used whereas for the lateral boundary conditions of HRM forecast of GME is used. DWD prepared topographical datasets for any region of the world containing mesh size between 30 km and 5 km but HRM can be run within the range of 28 km to 5 km horizontal grid resolution depending upon the need of users. The GME data contains 7 soil layers and 60 vertical model layers but for the current study 40 vertical model layers has been used.

Adiabatic part of the model HRM cannot generate some atmospheric processes (cloudiness, precipitation) therefore a set of physical parameterization modules in HRM are used to simulate such important parameters. The physical parameters used by HRM are radiation and cloud, Grid-scale precipitation, convection, Subgrid-scale orographic effects parameterization, soil model, sea ice model.

Data and Methodology

Data

GME data

GME data is actually the analyses and forecast of Global Model for Europe (GME).

DWD provides GME data to HRM users four times (d00, d06, d12, d18) daily at horizontal resolution of 30 km with seven soil layers and 60 model layers.

Meteorological data

Observed daily rainfall data from PMD observatories have been used in the present study.

GrADS

GrADS (Grid analysis and display system) software is used to extract point data from the output of HRM. It is also used to view HRM output in image form.

Methodology

The current study focuses on the verification of HRM at horizontal grid resolutions (22km and 11km) for the prediction of rainfall in Monsoon season. For this purpose selected rainfall events (21, 28, 29 July, 08 August 2010) are simulated by model at both resolutions. From the HRM output, daily point data of precipitation is extracted using GrADS. The extracted data was then compared with the actual rainfall.

For quantitative analysis with observed rainfall, three classes of prediction efficiency have been made on the basis of rain difference between actual and model simulated. The classes are namely well, moderate and poor prediction. The purpose of these classes was only to test the performance of HRM. Difference between actual rainfall and model output was set according to the intensity of events e.g. for intense events 28-29 July, 2010, a threshold of 20mm, 50mm and more than 50mm is set for well, moderate and poor prediction respectively but for moderate events, threshold of 15mm, 30mm and more than 30mm was taken for three classes of prediction.

Results & Discussion

The selected rainfall events are discussed one by one here.

Rainfall on 28th July 2010

On 28th July 2010, the upper parts of Pakistan received heavy rainfall causing severe flooding downstream in the Indus. Chief amounts of precipitation 280mm, 274mm, 257mm, and 233mm were recorded at Risalpur, Peshawar, Cherat and Kohat stations respectively. The event was simulated at 00UTC for next 24 hours forecast and amount of total daily precipitation has been shown in Table 1 at both horizontal grid scales.

From Table 1, it is clear that HRM at resolution of 11 km showed more rain for maximum number of stations than HRM with resolution of 22km. Figure 1 shows the total daily precipitation for selected domain at different grid scale. On spatial extent HRM at finer grid scale Figure1 (a) shows more precipitation in upper part of Pakistan than that of coarser resolution Figure 1 (b). HRM model at finer grid scales covered more area having less intensity of precipitation in Sindh region and eastern part of India whereas at coarser resolution model covered small area but showing more rain. For selected stations HRM with horizontal resolution 11 km showed more intensity of precipitation than that of 22km grid scales as shown in Figure 1.

Table 1: Total daily precipitation on 28th July 2010

Stations	Latitude	Longitude	Actual Rain	HRM_11	HRM_22
Isl-ZP	33.68	73.08	30	181	73
Isb-Shamsbd	33.65	73.08	54	181	73
Isb-AP	33.62	73.1	31	70	41
Isb-Dhamial	33.57	73.07	33	70	73
Isb-SD-PUR	33.74	73.06	72	181	134
Murree	33.85	73.41	40	197	104
Kakul	34.18	73.25	35	159	152
G-Dupatta	34.12	73.62	26	147	99
Balakot	34.38	73.35	45	92	54
Bannu	33	70.1	84	123	97
Kamra	33.87	72.4	68	138	88
Rawalakot	35.85	73.8	19	17	16
Muzaffarabad	34.25	74.04	59	50	70
Pattan	35.1	73	97	60	58
Saidushrif	34.73	72.35	187	102	127
Kohat	33.57	71.43	233	170	96
Dir	35.2	71.85	149	42	92
Cherat	33.82	71.88	257	37	139
Mianwali	32.55	71.55	190	37	6
Risalpur	34.07	71.98	280	108	113
Peshawar	34.02	71.58	274	90	117

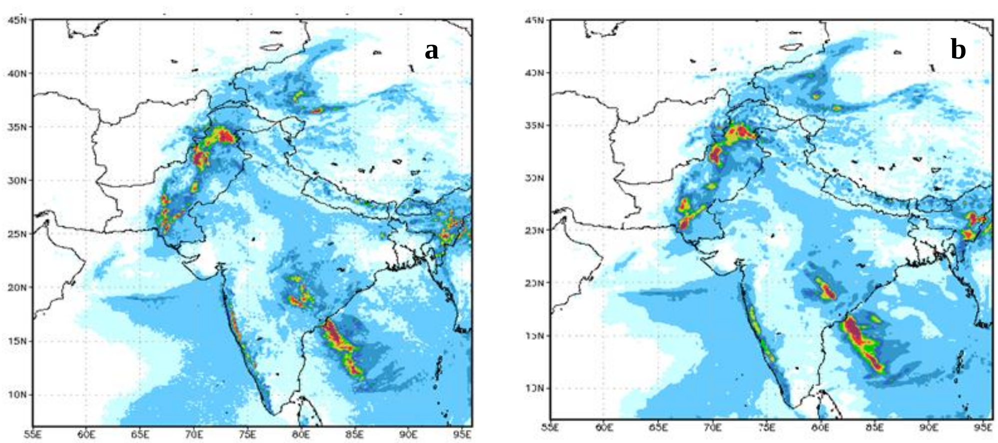

Figure 1: Output of HRM at horizontal resolution of 11 km **(a)** and 22 km **(b)** on 29th July 2010 at 03UTC

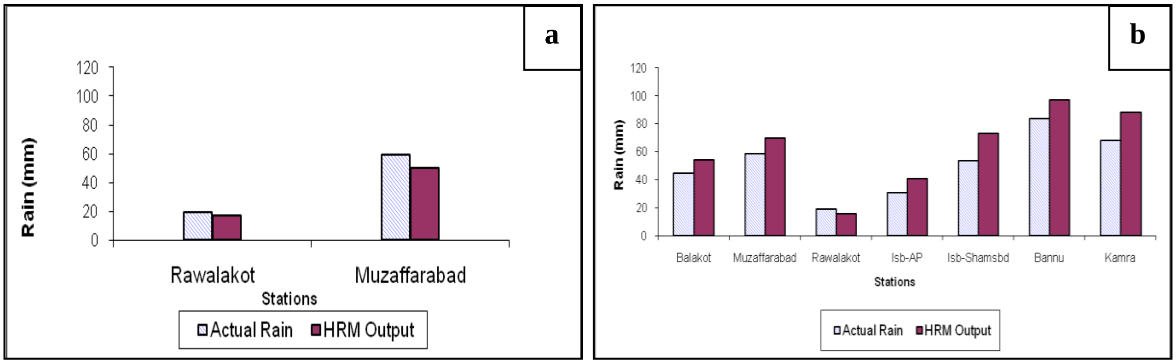

Figure 2: Well predicted stations by HRM at horizontal resolution of 11 km **(a)** and 22 km **(b)** for 28th July 2010 rainfall event

Figure 2 shows the well predicted stations by HRM at horizontal resolutions of 11km and 22km respectively on rain difference between observed and model simulated rain. HRM at finer resolution captures only 2 stations (Rawalakot and Muzaffarabad) out of 21 selected stations whereas HRM at resolution of 22 km predicted 7 stations (Balakot, Muzaffarabad, Rawalakot, Isb.AP, Isb.shamsabad, Bannu and Kamra) well. The stations well predicted by model at finer grid scales were also well captured by simulation of model at coarser resolution but for these stations (Rawalakot and Muzaffarabad) output at resolution of 11km was observed more close to the actual rainfall than that of grid sizes of 22km as shown in Table 1.

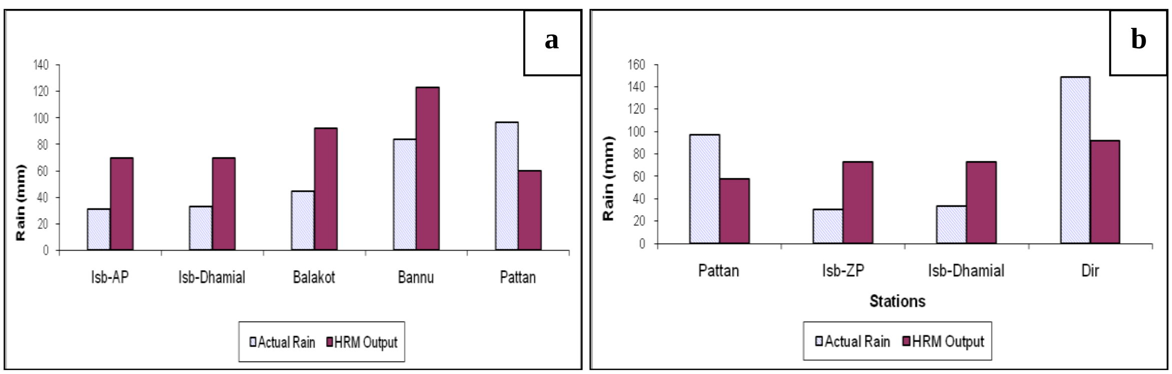

Figure 3: Moderate predicted stations by HRM at horizontal resolution of 11 km **(a)** and 22 km **(b)** for 28th July 2010 rainfall event.

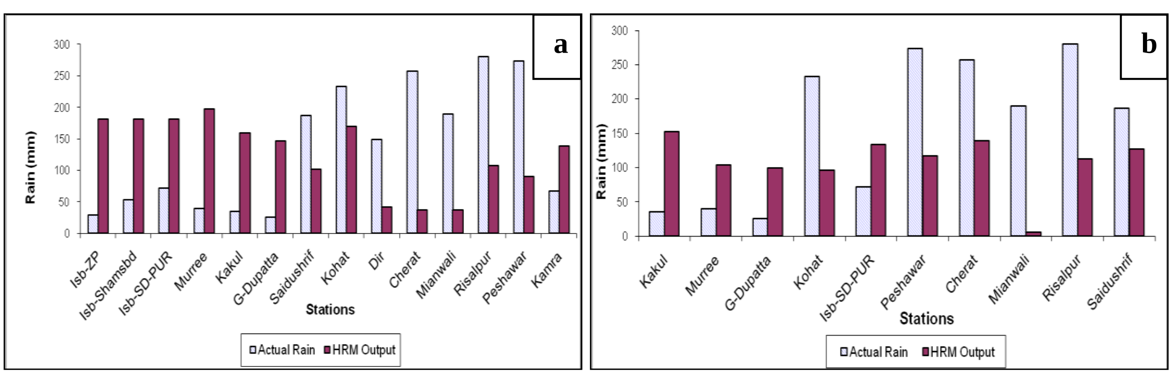

Figure 4: Poor predicted stations by HRM at horizontal resolution of 11 km **(a)** and 22 km **(b)** for 28th July 2010 rainfall event.

Figure 3 shows the stations that have been moderately predicted by HRM at various grid sizes. The simulation by model at finer resolution predicted 5 stations (Isb.AP, Isb.Dhamial, Balakot, Bannu and Pattan) moderately whereas 4 stations (Pattan, Isb.Dhamial, Isb.ZP and Dir) were captured by model at coarser grid scales. Figure 4 shows the extreme deviation (either overestimation or underestimation) of model from actual rainfall. HRM at finer resolution showed deviation for 14 stations out of 21 stations see Figure 4(a) but at coarser resolution only 10 stations exist in this class of prediction Figure 4(b). From the analysis, it has been observed that HRM (22 km) simulated rain has been observed relatively close to actual rain for maximum number of stations. So performance of HRM at coarser resolution has been concluded better than that of finer resolution for this rainfall event.

Rainfall on 29th July 2010

The second rainfall event on 29th July also caused heavy rainfall in the upper parts of the country including Islamabad as well. The maximum amount of rainfall was recorded as 257mm, 240mm, 231mm, and 189mm for Islamabad (saidpur), Kamra, Muree and Ghari-Duppta respectively. The second selected rainfall was simulated by model at 00UTC for next 24 hours forecast at both horizontal resolutions and total daily precipitation was shown in Figure 5. It shows the outputs of model HRM at both horizontal resolutions. Marked variation in intensity of rain has been observed from these outputs of model. At finer grid sizes model showed marked shifting of rain belt somewhat to eastward in upper parts of Pakistan. HRM (22km) has shown more rain for the given domain Fig 5 (b).

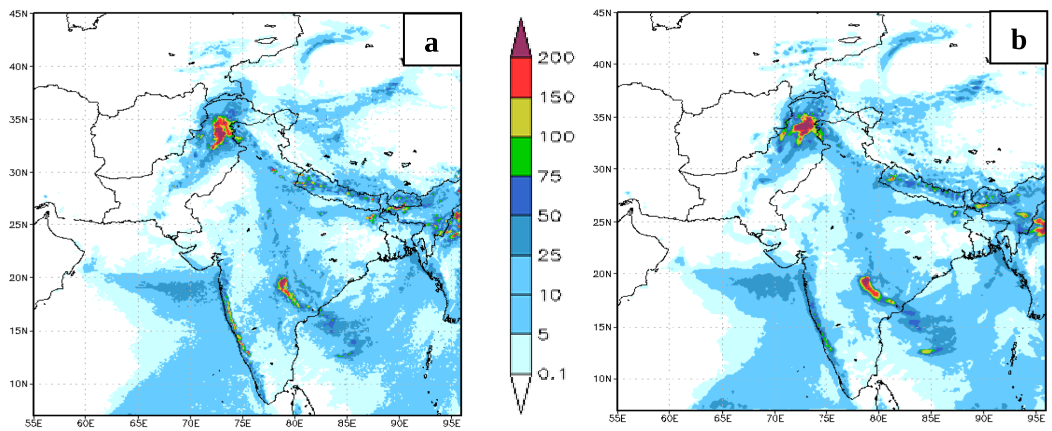

Figure 5: Output of HRM at horizontal resolution of 11 km **(a)** and 22 km **(b)** on 30th July 2010 at 03UTC

Table 2: Total daily precipitation on 29th July 2010

Stations	Latitude	Longitude	Actual Rain	HRM_11	HRM_22
Isb-Shamsbd	33.65	73.08	105	275	226
Isb-Dhamial	33.57	73.07	78	287	226
Isb-AP	33.62	73.1	120	287	103
Isb-ZP	33.68	73.08	156	275	226
Mianwali	32.55	71.55	31	134	48
Balakot	34.38	73.35	90	161	215
Isb-SD-PUR	33.74	73.06	257	275	232
Dir	35.2	71.85	0	30	47
Pattan	35.1	73	84	113	80
Kohat	33.57	71.43	29	38	87
Bannu	33	70.1	1	13	7
G-Dupatta	34.12	73.62	189	138	175
Saidushrif	34.73	72.35	103	123	36
Kakul	34.18	73.25	124	85	172

Muzaffarabad	34.25	74.04	103	56	55
Peshawar	34.02	71.58	59	20	55
Cherat	33.82	71.88	81	28	138
Murree	33.85	73.41	231	139	101
Risalpur	34.07	71.98	121	21	264
Rawalakot	35.85	73.8	171	41	37
Kamra	33.87	72.4	240	166	154

Table 2 shows the total daily actual and model simulated rain at various horizontal grid scales and it has been observed from Table that simulation at finer resolution showed more rain for 14 stations out of selected 21 stations than that of coarser resolution. For Dir station, simulations by model have overestimated the rain although no rain was recorded there in actual.

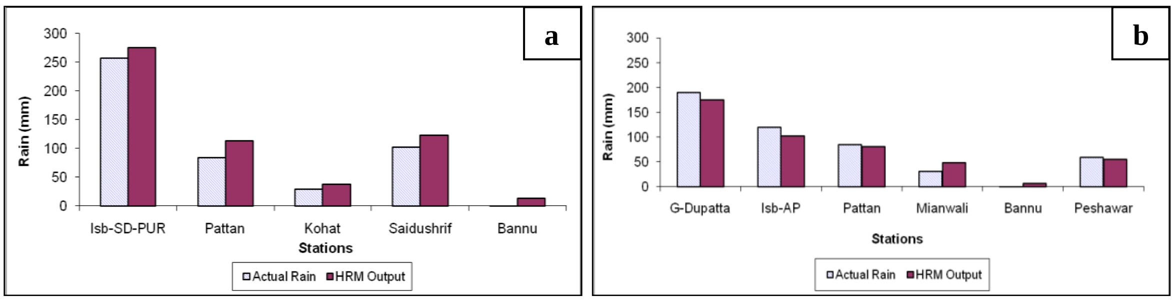

Figure 6: well predicted stations by HRM at horizontal resolution of 11 km **(a)** and 22 km **(b)** for 29th July 2010 rainfall event

Figure 6 (a) shows the well predicted 5 stations (Isb.SD.Pur, Pattan, Kohat, Saidushrif and Bannu) by model at finer resolution whereas 6 stations (G.Dupatta, Isb.AP, Pattan, Mianwali, Bannu and Peshawar) were well captured at coarser resolution. Islamabad (Saidpur) receiving heavy rain, was well captured at finer grid scale simulation. Only a single station (Pattan) remained common in well prediction class by both simulations.

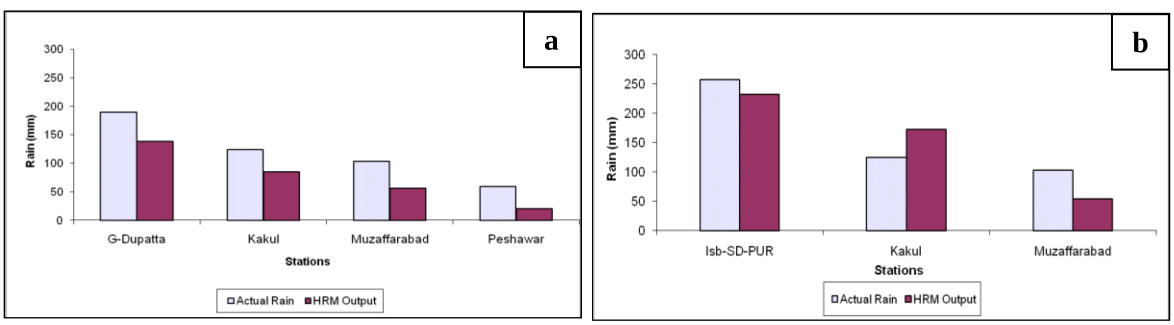

Figure 7: Moderate predicted stations by HRM at horizontal resolution of 11 km **(a)** and 22 km **(b)** for 29th July 2010 rainfall event.

Figure 7 shows the list of stations moderately predicted by HRM at different grid sizes. At finer resolution 4 stations (G. Dupatta, Kakul, Muzaffarabad and Peshawar) were included in this prediction type whereas 3 stations (Isb.SD.Pur, Kakul and Muzaffarabad) were captured at coarser resolution. For moderate prediction class, 2 stations (Kakul and Muzaffarabad) were commonly captured by model at both simulations. In Figure 8 stations are present for which model showed marked deviation. On observing Table 2 and Figure 8, it is obvious that model with finer resolution showed more deviation for Isb.shamsabad, Isb.dhamial, Isb.AP, Isb.ZP, Mianwali, Risalpur than that of coarser resolution.

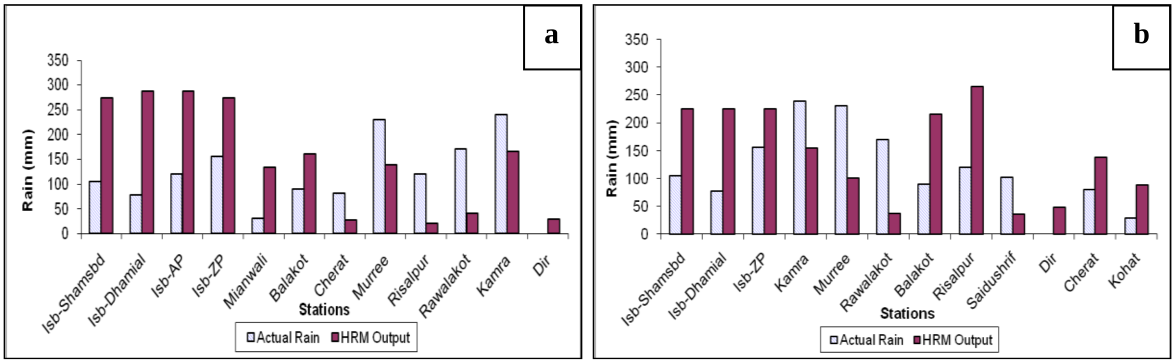

Figure 8: Poor predicted stations by HRM at horizontal resolution of 11 km **(a)** and 22 km **(b)** for 29th July 2010 rainfall event

Taken as a whole model with both resolutions showed deviations but for maximum number of stations output of HRM (22 km) has been found relatively close to actual rainfall. Therefore simulation by model at coarser resolution performed better than that of finer resolution for this rainfall event.

Rainfall on 21st July 2010

On this rainfall event, plain areas of Punjab got rain of less intensity than the early mentioned events. The chief amount of rainfall during this event was recorded as 179mm, 133mm, 120mm, 95mm, and 87mm at Mianwali, Lahore AP, Kamra, and Sargodha respectively. Table 3 describes the actual total daily rainfall and model outputs.

Table 3: Total daily precipitation on 21st July 2010

stations	Latitude	Longitude	Actual Rain	HRM_22	HRM_11
T.T.Sing	30.59	72.58	95	21	24
DG_Khan	29.96	70.82	46	5	23
Faisalbad	31.43	73.1	52	61	188
Jhang	31.47	72.53	45	53	163
Kamra	33.87	72.4	120	22	1
Murree	33.85	73.41	55	5	7
Mianwali	32.55	71.55	179	42	10
Noorpur_Thal	31.88	70.9	72	30	25
Gujrawala	31.08	72.42	62	19	39
Sargodha	32.05	72.67	95	291	463
Shorkot	30.78	72.1	87	17	17
Rawalakot	35.85	73.8	73	1	1
Barkhan	29.88	69.72	56	12	17
Lahore-AP	31.52	74.4	133	22	22

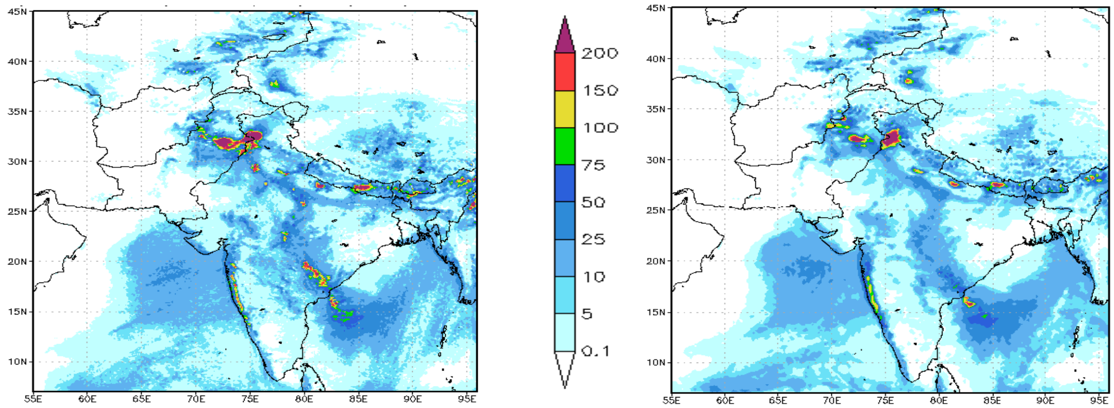

Figure 9: Output of HRM at horizontal resolution 11 km **(a)** and 22 km **(b)** on 22nd July 2010 at 03UTC

Figure 9 shows the total daily precipitation at horizontal grid scale of 11 km and 22 km. A marked spatial variation and intensity of precipitation has been observed at upper Punjab and Kashmir region from the outputs of the HRM. The simulation at finer grid scale produced more rain especially at Faisalabad and Sargodha region than that of coarser resolution as shown in Figure 9 (a). From Table 3, extreme overestimation has been observed for Sargodha (463 mm) at resolution of 11 km whereas actual rainfall was 95mm. Variation in intensity of precipitation has also been observed in Nepal region and eastern part of India as well.

On the rain difference basis, Figure 10 (a) shows the well predicted stations (Faisalabad and Jhang) by model at horizontal resolution of 22km whereas at finer scale simulation HRM could not predict even a single station for well prediction class due to over estimation of precipitation. Figure 10 (b) shows the moderately predicted stations (DG.Khan, Gujranwala and Barkhan) by HRM at finer grid scales.

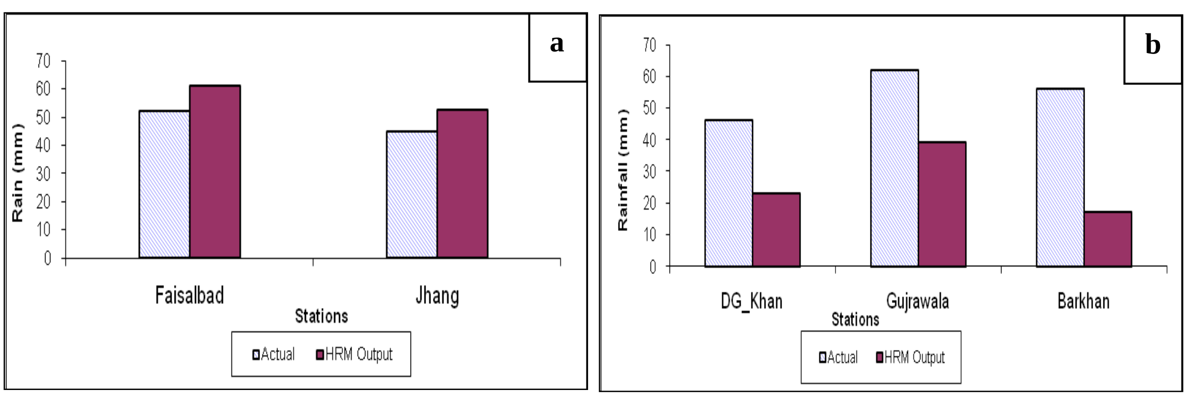

Figure 10: Well predicted stations by HRM at horizontal resolution of 22 km **(a)** and moderate predicted station by model 11 km **(b)** for 21st July 2010 rainfall event.

In Figure 11 poor predicted stations were listed which showed the marked deviation from actual rainfall. For maximum number of stations the model at both resolutions showed the underestimation except only one station Sargodha. Overall output of HRM at horizontal grid scale of 22 km has been found relatively better than that of finer resolution.

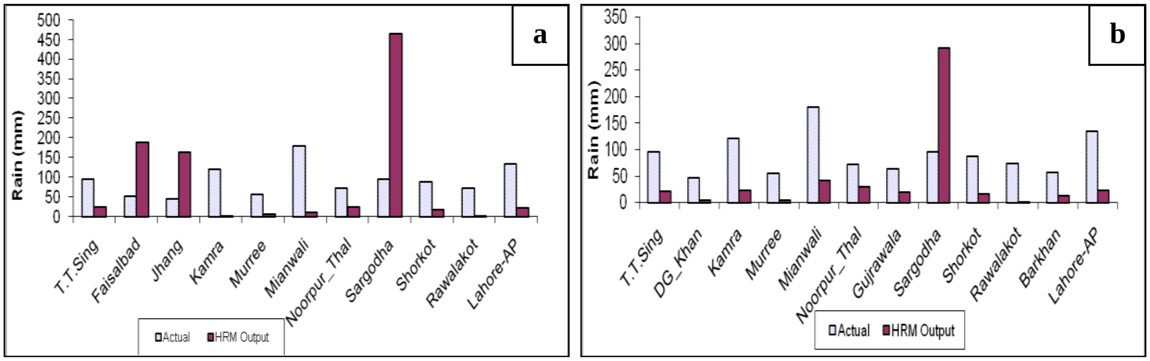

Figure 11: Poor predicted stations by HRM at horizontal resolution of 11 km **(a)** and 22 km **(b)** for 21st July 2010 rainfall event.

Rainfall on 8th August 2010

For the present study another monsoon rainfall event has been simulated at 00UTC for next 24 hours forecast by model at both horizontal resolutions (11km and 22km).The areas of Sindh and some upper stations of Pakistan received rain during this event. The chief amount of rainfall was recorded by PMD as 107mm, 102mm at Badin and Thatta respectively. Table 4 shows the actual and model simulated rain.

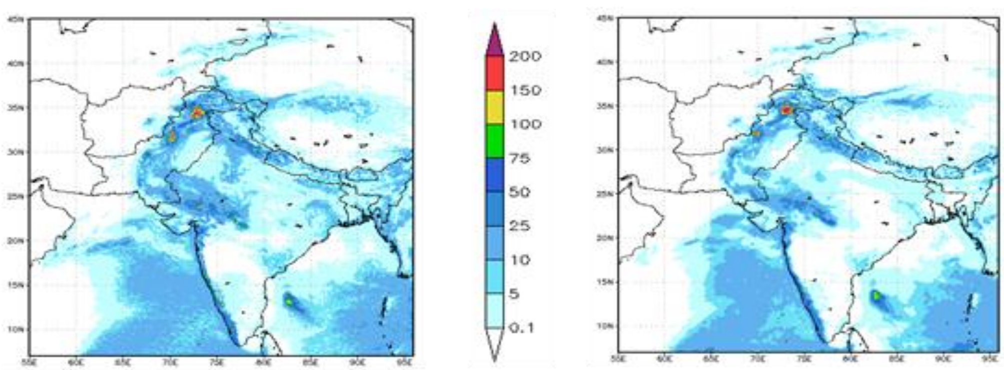

Figure 12: Output of HRM at horizontal resolution of 11km **(a)** and of 22km **(b)** on 9th August 2010 at 03UTC

Table 4: Total daily precipitation on 8th August 2010

Stations	Latitude	Longitude	observed	HRM_22	HRM_11
Bunji	35.67	74.63	30	0	1
Cherat	33.82	71.88	42	7	7
Parachinar	33.87	70.08	33	0	3
Badin	24.63	68.9	102	2	2
Chhor	25.52	69.18	55	26	26
Hyderabad	25.38	68.42	26	6	10
Karachi-AP	24.7	67.13	44	0	0
Karachi-Masroor	24.9	66.93	28	0	0
Mithi	24.75	69.8	59	24	24
Nawabshah	26.25	68.37	46	3	2
Thatta	24.75	67.9	107	2	2
Mirpur-Khas	25.52	69	48	20	21
Barkhan	29.88	69.72	53	15	15

Figure 12 shows total daily precipitation at both horizontal grid scales. Both simulations showed precipitation in upper parts of country whereas actual maximum amount of rain was recorded at southern region of Pakistan (Badin and Thatta). Simulation at coarser grid scale showed more intensity of precipitation in upper part of Pakistan than that of finer grid size. But for selected domain Figure 12 (a) output of finer scale simulations shows more spatial extent for precipitation than the output at coarser resolution. From Table 4, it has been observed that for selected stations the model could not capture this rainfall event at both horizontal resolutions.

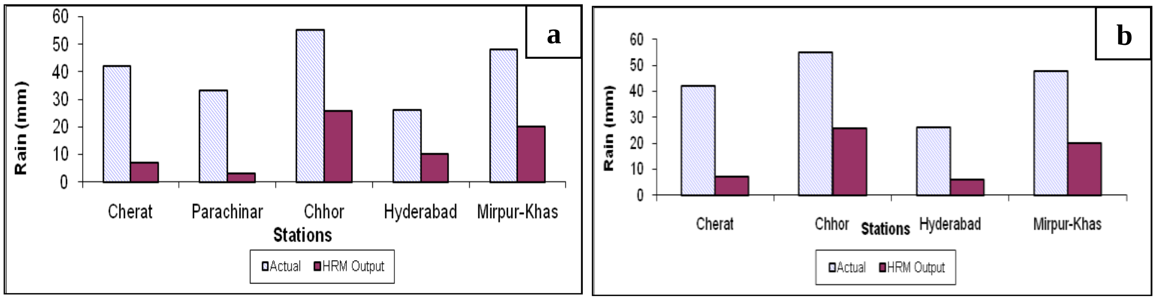

Figure 13: Moderate predicted stations by HRM at horizontal resolution of 11km **(a)** and 22km **(b)** for 8th August rainfall event

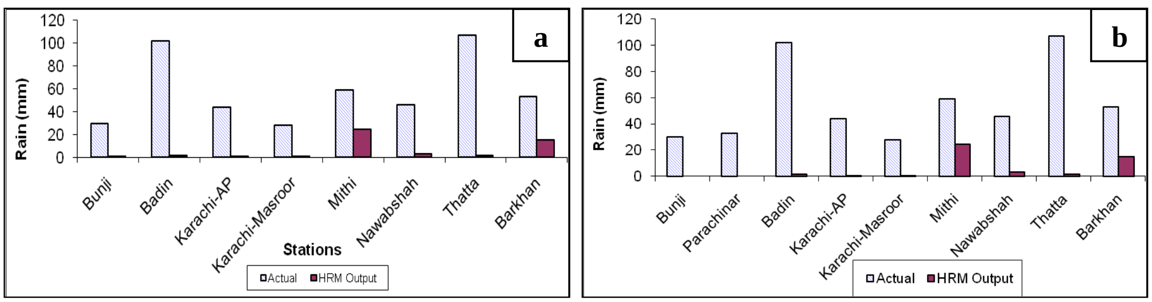

Figure 14: Poor predicted stations by HRM at horizontal resolution of 11 km **(a)** and 22 km **(b)** for 8th August 2010 rainfall event

Figure 13 shows the moderate predicted stations by HRM at various horizontal resolutions. For this rainfall event model could not predicted even a single station for well prediction class. For moderate prediction class, the model at finer grid scales has predicted 5 stations (Cherat, Parachinar, Chhor, Hyderabad and Mirpur-khas) whereas 4 stations (Cherat, Chhor, Hyderabad and Mirpur-khas) were predicted at coarser resolution of 22km. Figure 14 shows the poor predicted stations by model. It has been observed from Figure 14 that for many stations model completely failed to predict rainfall at both grid scales (11km and 22km) simulations. So from the above analysis it was concluded that for this rainfall event HRM at both horizontal grid scales could not capture the event so well.

Conclusion

In current study four rainfall events were simulated by HRM at horizontal resolutions (22km and 11km) and analysis were made to test the Performance of Numerical Weather Prediction (NWP) model HRM for the forecast of rainfall in Monsoon season including that event which caused devastated flood 2010 in Pakistan. The findings of current study are

- Three out of four simulations depict that the Performance of HRM at horizontal resolution 22km is better than that of 11km and only event of August is not so well captured by model at both resolutions.
- HRM with horizontal resolution 11km overestimates the precipitation than that of 22 km.
- Spatial variation of precipitation regime and cloud cover by model HRM has been observed for both horizontal resolutions.
- Weaker predictability of HRM at finer resolution may be due to coarse input of data such as GME output (30km horizontal resolution).

Recommendation

- More rainfall event should be simulated for the evaluation of model
- Unusual and normal rainfall event should be examined for selected season's i.e. Monsoon.
- Other parameters such as temperature should be considered
- HRM should be evaluated at different precipitation schemes

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