Analysis of Cyclonic Storm/Depression Formed Over Bay of Bengal from 19th to 25th September 2018

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Abstract

Analysis of a cyclonic weather system, originating from Bay of Bengal on Sept. 19, 2018 and dissipating at Himachel Pardesh on Sept. 25, 2018, presented in this study shows that comparatively less rainfall was observed in the upper reaches of Jhelum and Chenab rivers in contrast to the issued forecast, that seems to be due to the presence of eastward moving westerly wave that blocked the further penetration of the storm in North-West direction towards the upper reaches of eastern rivers of Pakistan. From Indian Rajasthan, cyclonic system recurved in north-east direction and had a potential to produce catastrophic category II flood however no part of Pakistan and Kashmir came under its direct influence. Storm produced significant rainfall of 80 to 130mm, primarily due to interaction of westerly wave, in the final stages of dissipation in the catchments of Ravi and Chenab Rivers. Discharge at rim stations of Jhelum and Chenab rivers did not approach significant flood level, however the adjoining streams/nullah of Ravi and Chenab rivers attained up to medium flood level and posed damages in the surroundings. Storm has also been analyzed using high resolution quantitative precipitation forecast obtained from regional model WRF. Initial and boundary conditions for regional model are provided from NCEP-GFS. QPF at grid scales of 21 km and 7 km were visually compared with global GFS and CPC global daily total rainfall. Finer scale results at 7 km represent more realistic rainfall as compared to NCEP-GFS and CPC precipitation. However further studies with different domain size and physical schemes are required to get optimal settings of WRF to get improved QPF forecast with adequate lead time.

Introduction

On 19th September 2018 a cyclonic depression was formed in Bay of Bengal (BoB). It crossed the Indian states of Orissa, Madhya Pradesh, and Rajasthan, latter re-curving to enter Haryana and finally dissipating over Himachal Pradesh. This was a very unusual monsoon weather system as most of the monsoon systems formed in mid-September don't travel long distance across India. Path followed by this weather system is commonly associated with depressions formed in peak monsoon season. It triggered flooding in parts of India and caused the water flows to increase in River Ravi and Sutlej and their associated nullahs in Pakistan.

During the summer in northern hemisphere, Inter Tropical Convergence Zone (ITCZ) shifts 20º-25ºN and is present over Indo-Gangetic plain and the southwest monsoons blow from Arabian Sea and BoB. The ITCZ in this position is often called as the monsoon trough. Most of the BoB tropical cyclonic disturbances are formed within the monsoon trough. These are classified as lows, depressions, deep depressions, cyclones and severe cyclonic storms depending on sustained surface winds (Raghavan and Rajesh 2003). These are also jointly known as Low Pressure Systems (LPSs) (Praveen, Sandeep, and Ajayamohan 2015; Mooley and Shukla 1987). Their seasonal variation depends on the location of monsoon trough thus greatly influencing the monthly rainfall over the region (Dhar, Rakhecha, and Mandal 1981; Krishnamurthy and Ajayamohan 2010). LPSs, originating from Bay of Bengal, usually have a life span of 3 to 6 days moving northwestwards and covering a distance of 1000 to 2000 km. (Sikka 1977; Godbole 1977; Krishnamurti et al. 1975). According to a study most number of monsoon weather systems formed over BoB originate in the months of May and November (Alam, Hossain, and Shafee 2003). During the period of 1961-2010 cyclonic depressions have showed a significantly decreasing trend over BoB during the monsoon and post monsoon seasons (Mohapatra et al. 2017).

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Floods in Pakistan are ranked, from less severe to most severe, as category I, II and III. Category I floods occur when heat or seasonal low over Balochistan is intensified, and that mainly due to presence of a strong westerly weather system, transporting the moisture from Arabian Sea to the catchments of Rivers Chenab and Jhelum. It may result in heavy downpour caused due to the orographic lifting of moisture laden winds. Rainfall produced is in short intervals, mainly in late evening/night or early morning causing a sharp flood peak of 3 to 5 lakh cusecs under extreme conditions in River Jhelum. Category II and III floods which are more catastrophic in nature, are associated with monsoon lows/depressions originating from BoB. Major floods in Pakistan have occurred due to depressions/lows moving from BoB crossing India and then producing heavy rainfall in the catchment areas of rivers flowing in Pakistan. In case of category II floods a monsoon low on reaching the Indian state of Rajasthan or its adjoining areas re-curves in the northeast direction towards the upper catchments of Sutlej, Ravi and Chenab Rivers causing extreme heavy rainfalls and consequently floods, first across the border in India, and then within a few hours at the rim stations in Pakistan. Category III floods are most catastrophic in nature as under this situation monsoon low/depression under the influence of the westerly wave continues to move in the northerly direction finally ending up in Rawalpindi/Hazara divisions and adjoining areas. The upper catchments of Rivers Jhelum, Chenab and Ravi come under its influence. These are most threatening floods for Mangla reservoir. Flood of 1992 in River Jhelum is one such example. Meteorological conditions relating to category II and III floods are shown in figure 1 and 2 respectively.

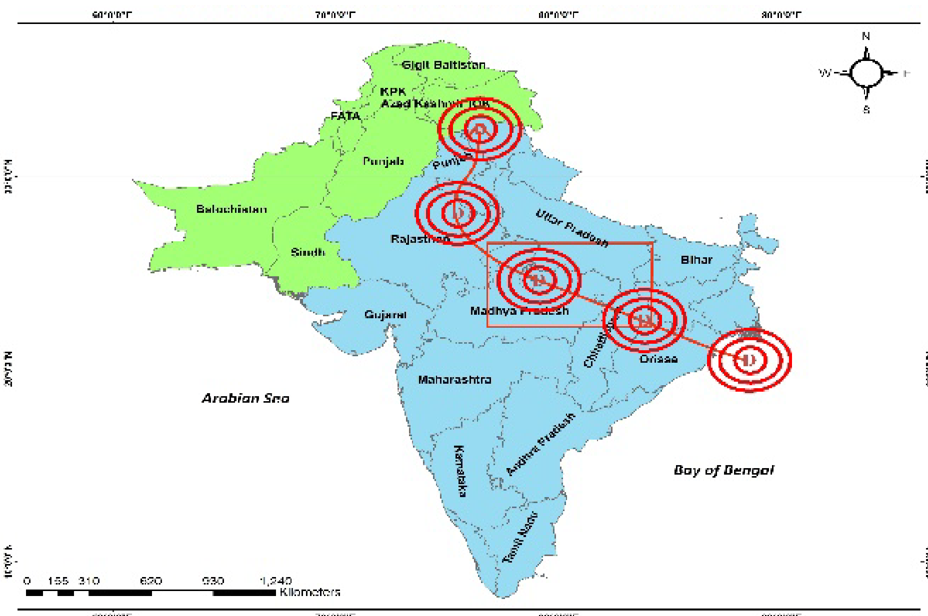


Figure 1: Meteorological situation relating to category II floods.

Flood forecasting is a three tier process. First one is the precipitation stage in which the amount of rainfall in the river catchments is predicted and latter monitored in real time. Prediction of precipitation amount is done by means of various different resolution Numerical Weather Prediction (NWP) model outputs at different resolutions. Real time monitoring of actual rainfall in the catchments is carried out by using the observations from surface weather observatories, network of Automatic Weather Stations (AWS), RADAR outputs and satellite imageries. Next is the flood formation stage which starts with the generation of runoff and the formation of flood wave. For this purpose, two different models are currently operational in Flood Forecasting Division (FFD). One is Flood Early Warning System (FEWS) and the other one is Integrated Flood Analysis System (IFAS). Apart from these, indigenously developed analytical techniques are also employed to forecast the amount of runoff and the degree of flood peak. Last stage is the routing of flood wave below the rim station. This is done by using a routing model which is operational in FFD, Lahore.

Diffusive wave propagation in Rainfall Runoff Inundation (RRI) model, enables to predict river flow and water depth.

In case of likely category II or III floods a warning system is established to forewarn the concerned authorities, related to local government and disaster management. First alert known as Blue Alert is issued when monsoon low/depression reaches Indian Rajasthan and is expected to re-curve in northerly direction. This alert is an indication that there is a possibility of flood within next 24-72 hours subject to the movement of the weather system towards the catchments areas. Second alert is known as Yellow Alert, which must be treated as a warning, indicating that the weather system has re-curved in the northerly direction and poses an imminent threat of heavy downpour in the catchment areas. Finally a Red Alert is issued when the low/depression starts to directly affect the catchment areas and heavy rainfall has started. These are qualitative forecast which are issued in advance. Actual quantification of flood peak is done when real time storm rain data becomes available.

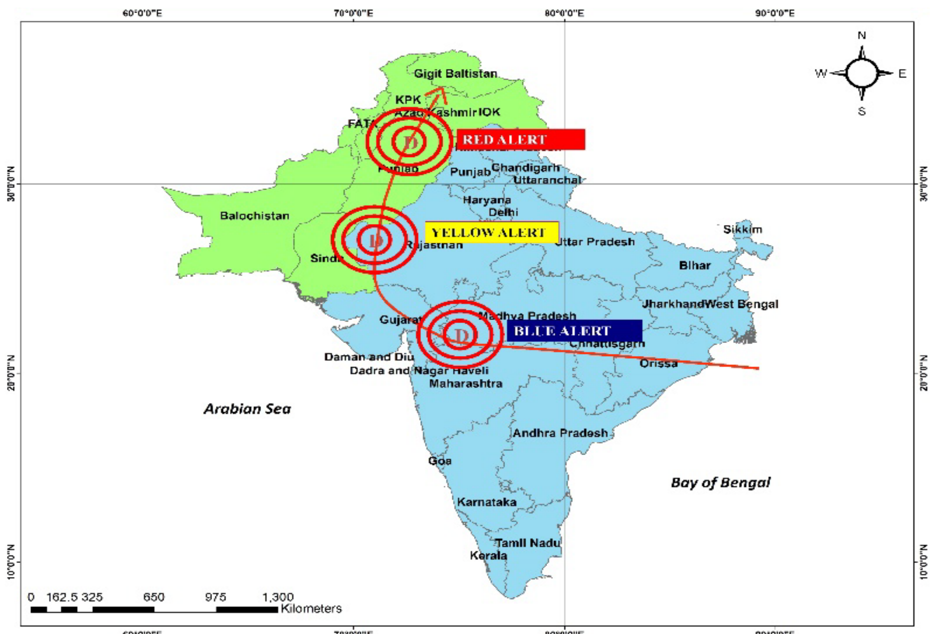


Figure 2: Meteorological situation relating to category III floods.

Track of September 2018 monsoon weather system

On 19th September a depression was formed in east central BoB which was termed as BoB 07. On the same day Joint Typhoon Warning Center (JTWC) also issued a Tropical Cyclone Formation Alert (TCFA). On 20th September this system intensified into a deep depression and later that day further intensified into a Cyclonic Storm Daye. This cyclonic storm made the land fall between 1900-2000 UTC of 20th September over south Odisha, also impacting the adjoining north Andhra Pradesh coast near Gopalpur, producing heavy rains and strong winds of 60 to 70 km/h gusting to 80 km/h in various districts of the region (IMD 2018). This cyclonic storm weakened into a deep depression on 0000 UTC of 21st September after moving in west-northwest ward direction. It took the status of cyclonic storm for only six hours. Following the same track it converted into a depression over west Madhya Pradesh on 1200 UTC of 21st. According to IMD (2018) lowest central pressure attained by the weather system was estimated to be 992 hPa between 1500 UTC to 1800 UTC of 21st September. At 1200 UTC of 22nd September it moved over west Madhya Pradesh and adjoining east Rajasthan as a well-marked low pressure area, it remained as a well-marked low pressure area over south Rajasthan till 0300 UTC of 23rd. The weather system converted into a low pressure area at 0000 UTC of 24th September as it moved over southwest Uttar Pradesh and south Haryana. Before dissipating this low pressure area had come under the influence of a westerly wave which pushed it further eastwards, producing rainfall in Himalayas and the plains in south. It became insignificant in the morning of 25th September. No part of Pakistan or Kashmir came under its direct influence. Track followed by the monsoon depression from 19th to 25th September 2018 is shown in figure 3.

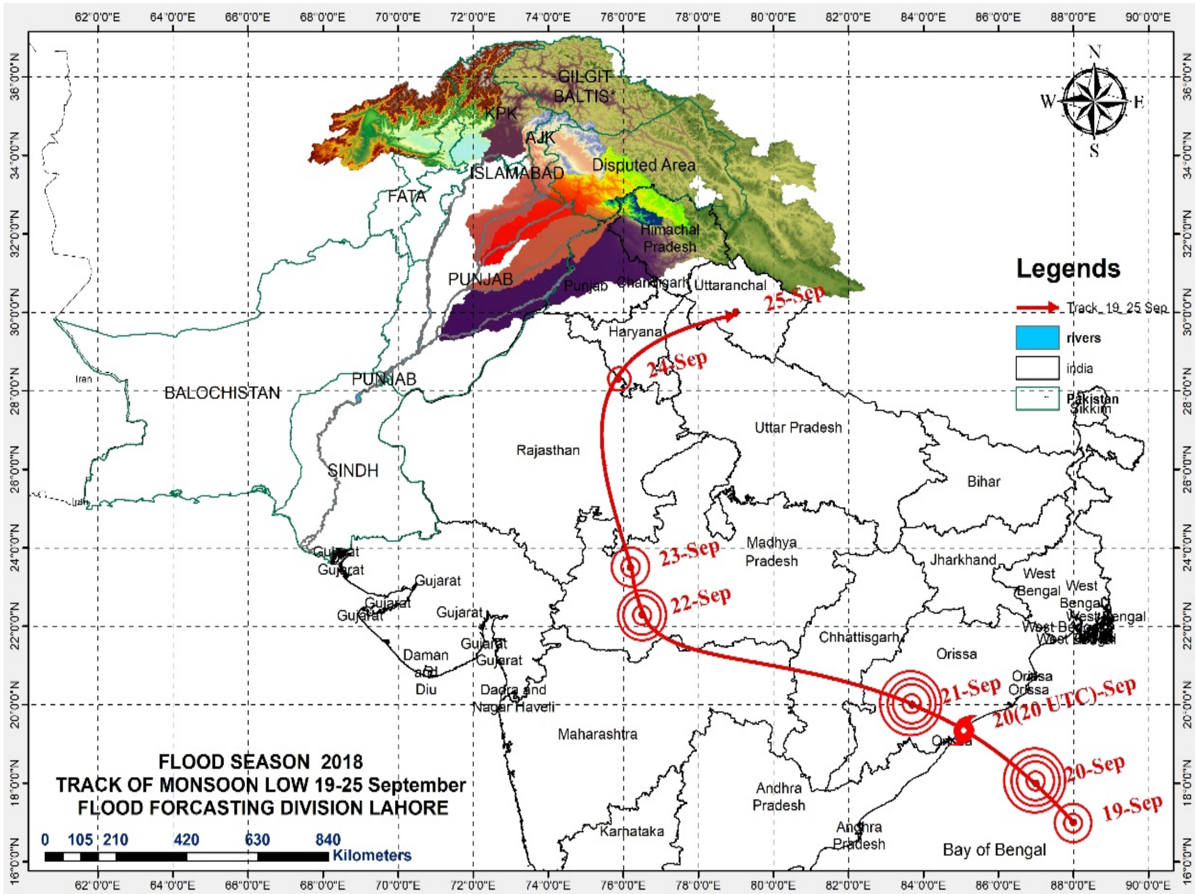


Figure 3: Track of monsoon system 19th-25th September 2018. Red line indicates the track of the system while the number of circles indicate the increasing and decreasing intensity.

Monitoring and forecast

Pakistan Meteorological Department, Flood Forecasting Division, Lahore started the monitoring of this weather system and its likely track before it developed into a depression. Model results from different NWP centers were constantly analyzed, assistance was also taken from satellite imageries. Forecasts issued by regional centers were also considered. FFD started mentioning its development stages and path in its daily flood bulletin from 17th September 2018. Eventually an alert was issued on 21st September and a warning on 22nd September regarding the impact of the weather system on river flows in Pakistan. Synoptic Situation related to this monsoon weather system is shown in figure 4. It can be seen situated over central India on 21st September, swiftly moved to Indian Rajasthan and then is seen re-curving to North where it comes into the grip of a westerly wave present over Pakistan, which moved it further east wards and finally dissipating on 25th September. Precipitation distribution according to CPC .50x.50 Global Daily Unified Gauge-Based Analysis of Precipitation is shown in figure 5. Indicating two peak rainfalls one in the initial stage when the monsoon system makes the land fall and then in the final stage, before dissipating where peak rainfall has more spatial distribution than in the initial stage. The rainfall in the final stage is more owing to the interaction of the westerly wave. CPC datasets show a significant amount of rainfall ranging from 80 to 130 mm in catchment areas of Rivers Ravi and Chenab on 22nd and 23rd September as shown in figure 6.

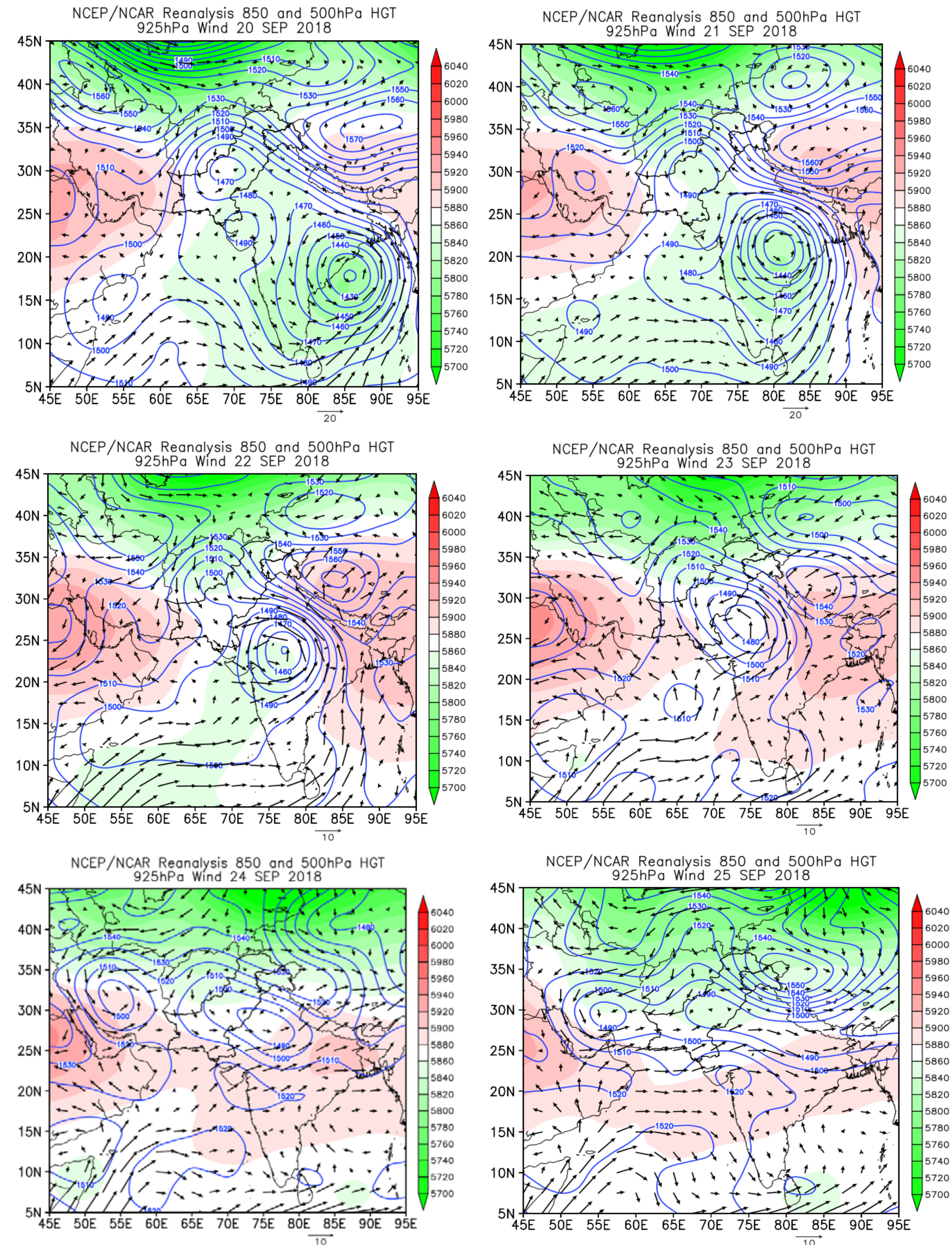


Figure 4: Model outputs from NCEP/NCAR reanalysis datasets with 2.5º resolution. Blue contours indicate 850 hPa, while red and green shades show 500 hPa geo potential heights. Black arrows indicate 925 hPa winds

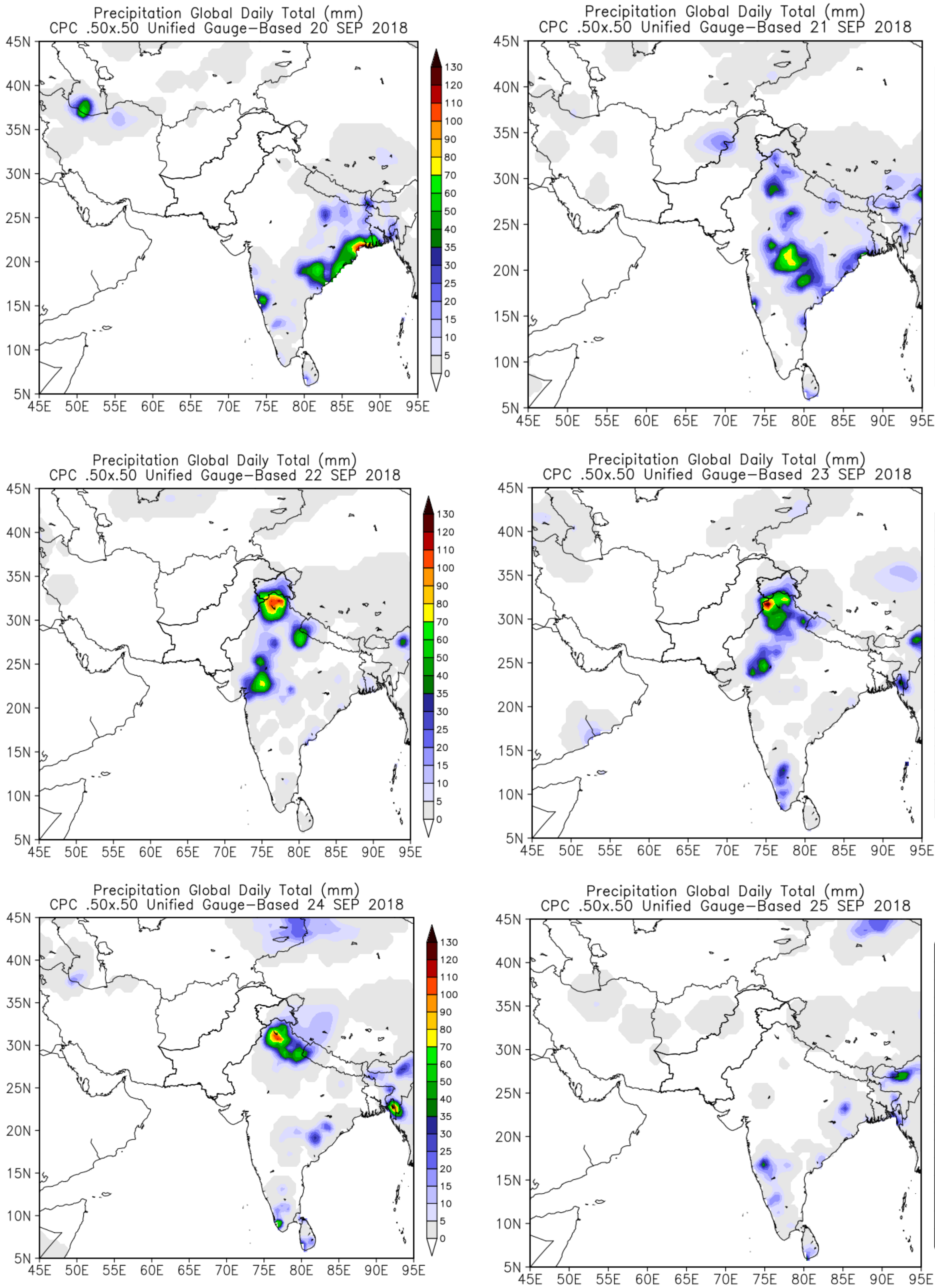


Figure 5: Rainfall (mm) distribution over India and Pakistan.

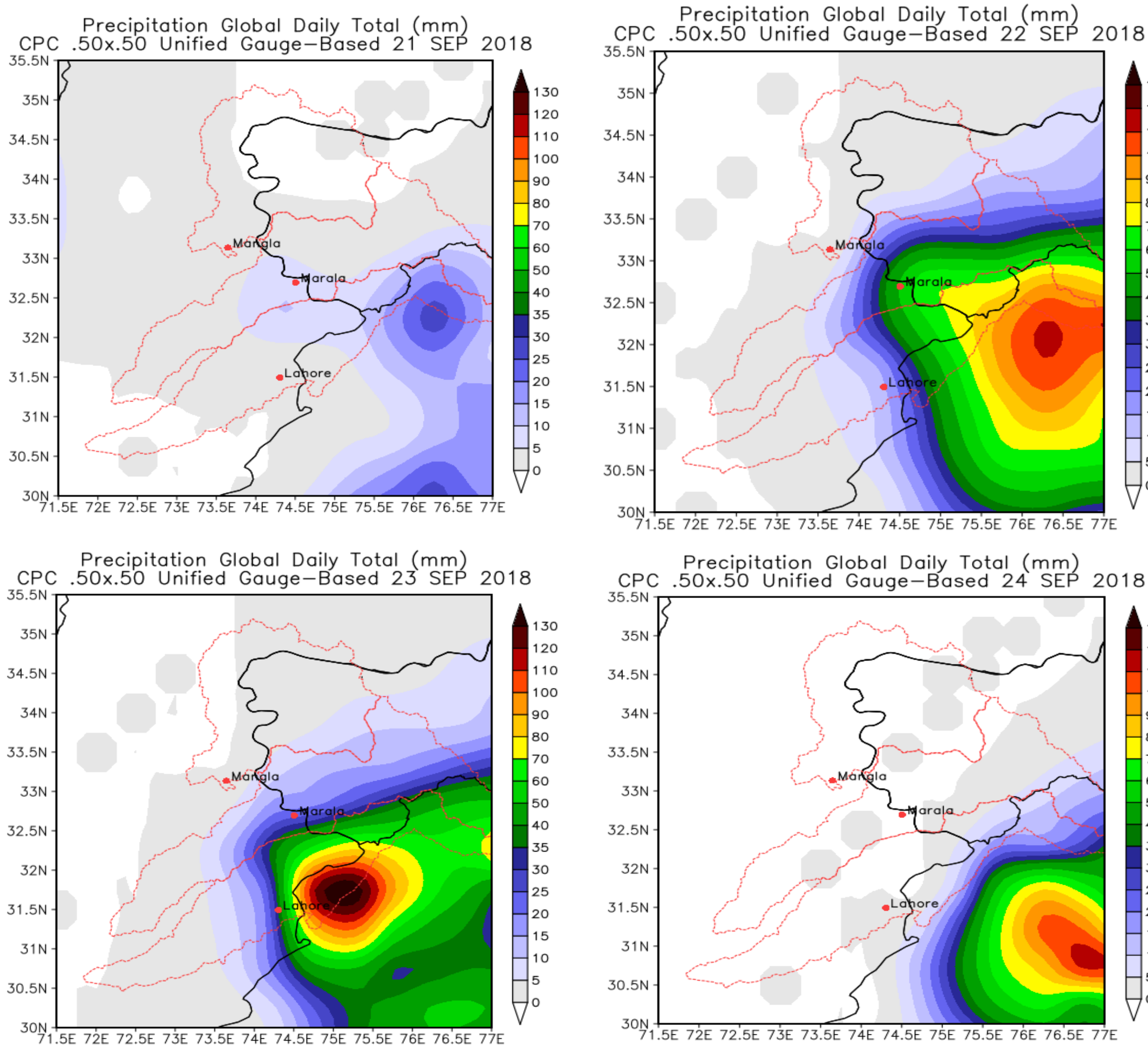


Figure 6: 6 Rainfall (mm) distribution over catchments of Rivers Jhelum, Chenab and Ravi.

High Resolution Quantitative Precipitation Forecast Analysis

An attempt was made to analyze the Quantitative Precipitation Forecast (QPF) of Global Forecasting System GFS by National Centers for Environmental Prediction (NCEP) ("NCEP Global Forecast System (GFS) Analyses and Forecasts" 2007) through dynamic downscaling using regional model, Weather Research and Forecasting system (WRF) (Skamarock et al. 2008). We tried to find out how well distribution and intensity of precipitation could be predicted by global model's forecast at finer scale during the life cycle of a tropical weather system. NCEP-GFS model provides precipitation forecast of eight days at six hour interval with 27 km spatial resolution. GFS is coupled formation of atmosphere, ocean, land/soil, and sea ice models to predict more accurate atmospheric conditions. Forecast is provided in gridded binary format which can be downloaded from NOAA National Operational Model Archive and Distribution System (NOMADS).

Advance Research WRF (ARW), a regional atmospheric non-hydrostatic model supported by National Center for Atmospheric Research (NCAR), has been used for dynamic downscaling of deterministic forecast of NCEP-GFS from Sept 19th to Sept 24th 2018 at 0000 UTC. Two-way nested domain with 1:3 ratio was defined. Outer domain (3200 Km x 2500 Km) covers India, some parts of Pakistan and extends up to Bay of Bengal in the east with grid cell resolution of 21 km.

Inner domain (2500 Km x 2000 Km) is defined at 7 km grid spacing and covers land areas affected by tropical weather system. The extent of nested domain is shown in figure 7. To predict water vapor, cloud water, cloud ice, rain, snow and hail, Lin et al. (Lin, Farley, and Orville 1983) microphysics scheme was used along with Unified Noah land surface scheme with soil temperature and moisture in four layers. Kain-Fritsch (Kain 2004) cumulus scheme and for short wave radiations Dudhia scheme (Dudhia 1989) were used in both domains.

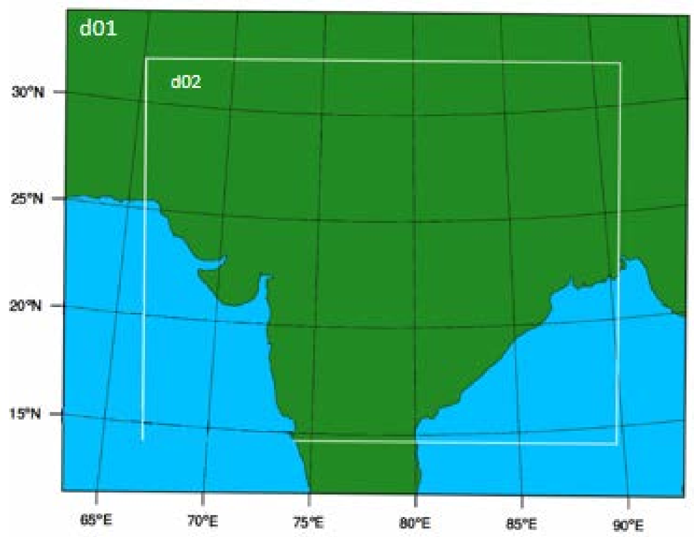
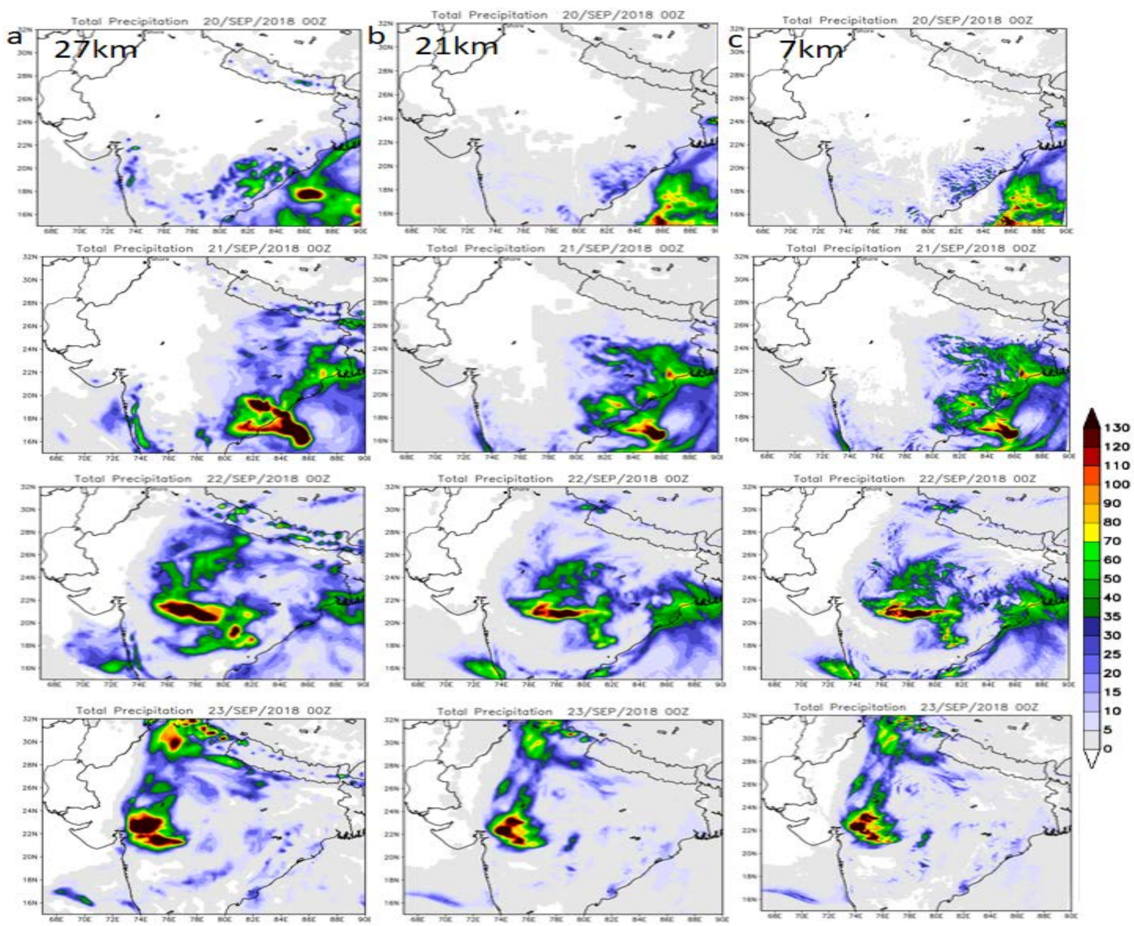


Figure 7: Domain settings for the WRF model, map showing extent of study area with outer domain (d01) of 21 km grid resolution and 7km grid resolution of inner domain (d02)

CEP-GFS forecast ("NCEP Global Forecast System (GFS) Analyses and Forecasts" 2007) with three hour interval was obtained at resolution of 0.25° and with 32 vertical levels. Global model data sets were provided as initial and boundary conditions to WRF for dynamic downscaling at finer regional scale resolutions. 24 hour precipitation forecast at grid scales of 21 km and 7 km are given in figure 8. Figure 8 (a) represents the original GFS forecast of 27 km initialized at 0000 UTC, every day, from 19th to 23rd September 2018. Figure 8 (b & c) shows dynamically



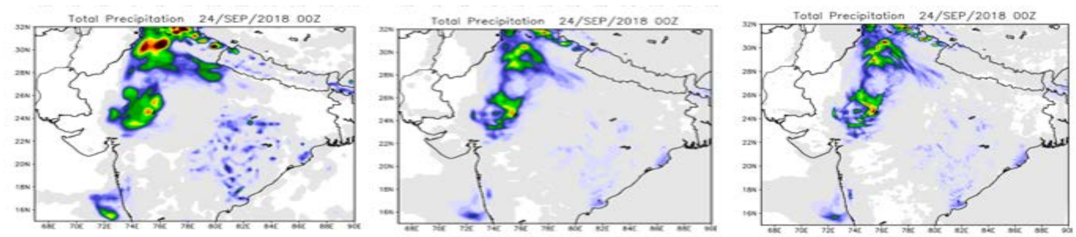


Figure 8: Daily total precipitation by **(a)** GFS forecast at 27 km **(b)** downscaled rainfall through WRF at 21 km and **(c)** downscaled rainfall at 7 km, from 20th Sep 2018 to 24th Sep 2018. Colour bar represents the amount of rainfall in mm during twenty four hours.

downscaled precipitation through WRF at 21 km and 7 km grid spacing respectively. Original GFS forecast shows relatively more spatial distribution and higher intensity of precipitation in the study period. Particularly in the latter stages, from 22nd to 24th September, the amount of precipitation indicated in downscaled outputs seems to be more realistic as the catchment areas of rivers flowing in Pakistan did not receive heavy amount of precipitation forecasted by different GCMs. These results need to be further verified by using actual observed rainfall in the region and by adjusting the domain of the study which could not be considered currently due to limited computation power.

Impact on River Flows in Pakistan

Historically monsoon weather systems re-curving from Indian Rajasthan have the tendency to move and dissipate over Kashmir and adjoining areas, producing heavy rainfall and devastating floods in the downstream of rivers having catchment areas there (PMD 2008). Keeping in view these historical tracks and the prevailing meteorological situation FFD, Lahore issued a warning on 22nd September 2018 regarding a very high flood, on 23rd September, in River Chenab at Marala and downstream, River Jhelum at Mangla, Rivers Ravi and Sutlej along with associated Nullahs of Rivers Chenab and Ravi. Flows in Rivers Ravi and Sutlej in Pakistan depend on releases from across the border. As the system latter tracked northeastwards, the catchment areas of Rivers Jhelum and Chenab remained practically unaffected by this weather system thus having no significant influence in the flows of the said two rivers. However the flows in the feeding Nullahs of Rivers Chenab and Ravi increased significantly. Water level at the rim stations of Ravi and Sutlej in Pakistan also increased to a larger extent as the amount of water released from water works across the border was amplified due to the prevailing weather system over there.

Inflow at Mangla attained its highest value of 25000 cusecs at 0000 PST of 24th September not even reaching the low level flood limits. Chenab at Marala peaked 91000 cusecs at 1200 PST of 24th September almost touching the low level flood limits. River Ravi at Jassar reached to more than 66000 cusecs crossing the low level flood limit of 50000 cusecs at 0600 PST of 25th September. GS Wala at River Sutlej recorded a gauge height of 17.7 feet almost reaching the low level flood limits. Flows at Jassar and GS Wala are dependent on the releases from the Indian water reservoirs. Bein Nullah at Shakargarh recorded a maximum peak of almost 4500 cusecs crossing the medium flood limits at 1800 PST of 23rd September. It remained in medium flood for almost 18 hours. Nullah Deigh at Kingra also reached 16500 cusecs crossing the medium flood level at 0000 PST of 24th September. Nullah Aik at Ura crossed the lower flood limits of 20000 cusecs at 1200 PST of 24th September. Nullah Basantar at Jassar peaked almost 5500 cusecs crossing the medium flood limits at 0000 PST of 25th September. It remained in medium flood for nearly 18 hours. Nullah Palku at Wazirabad remained below low flood level during the event. Hydrographs of these selected water channels are shown in figure 9. Each figure showing the maximum peak attained during the period.

Qualitative forecast issued on 22nd September proved to be over estimating the situation related to the monsoon low. From the hydrographs it can be assessed that inflow at Mangla remained unthreatening. Even Chenab at Marala could not reach low flood level limits. Nullahs Bein, Dek and Basantar crossed the medium flood limits and proved catastrophic in the areas where no well-marked channels were present. According to one news report Nullah Dek in particular destroyed many houses and farms in district Sialkot (Ahmad Shahzad 2018). However quantitative forecasts issued every day for the flows during next 24 hours proved to be much accurate. Apart from River Jhelum at Mangla for which 50 to 110 thousand cusecs was forecasted on 23rd September, however, only 25000 cusecs was recorded. For River Chenab at Marala 50 to 150 thousand cusecs was forecasted and almost 100 thousand cusecs was recorded on 24th. River Ravi at Jassar was expected to peak between 40 to 90 thousand cusecs on 25th and almost a peak of 67 thousand cusecs was recorded. At GS Wala a gauge height of 16 to 18 feet was forecasted whereas 17.7 feet was recorded on 27th September.

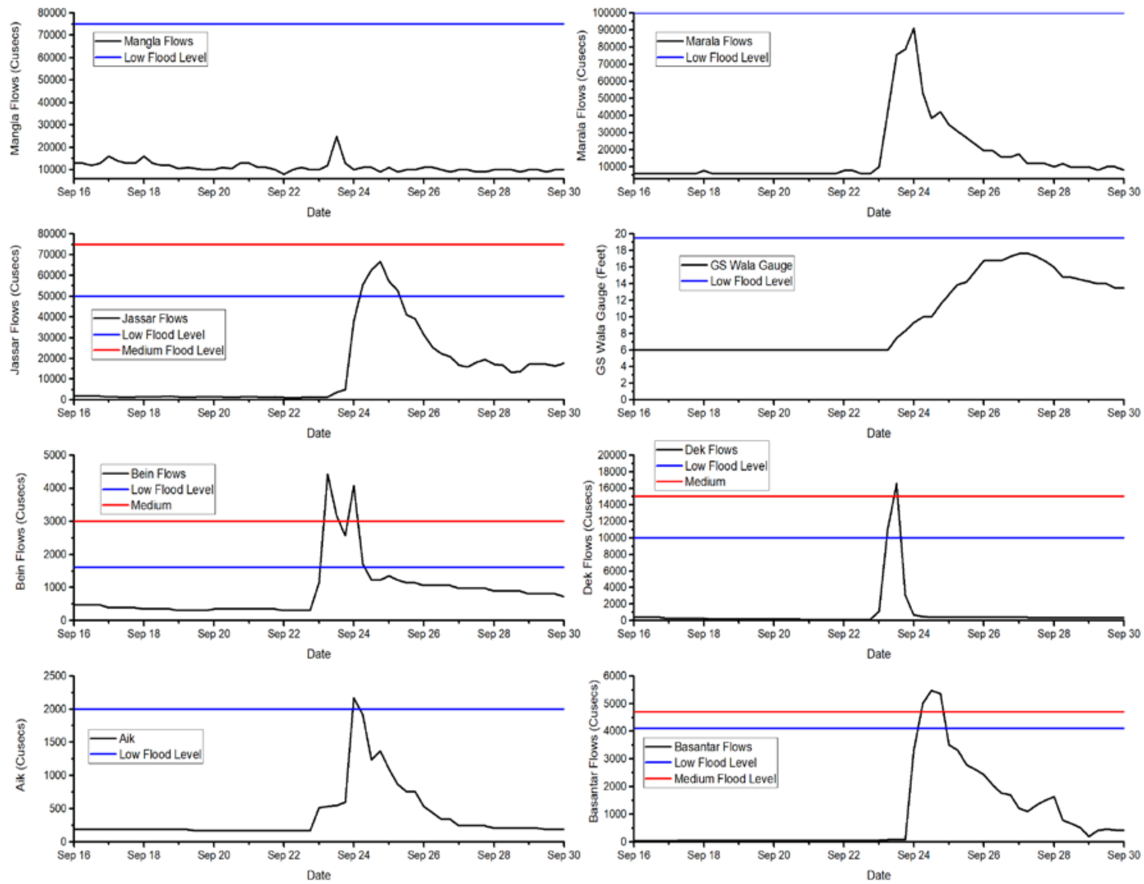


Figure 9: Hydrographs of selected rivers and nullahs during 16th to 30th September. Blue and red lines indicate low and medium flood limits of each water channel respectively while the black line indicates flow at that point during the period.

Conclusion

Generally, the storms originating from BoB do not travel long distance in the mid of September but the unusual track of cyclonic weather system towards Rajasthan generated threat of category II flood in the upper reaches of eastern rivers of Pakistan. Early warnings of significant flood were issued, however storm did not hit danger zone due to its eastward shift in the presence of eastward moving westerly wave. Jhelum and Chenab rivers did not attain significant flood level. Upper catchments of Chenab and Ravi rivers received rainfall up to 130mm due to the interaction of low pressure with westerly wave and the water level of adjoining nullah/streams of Chenab and Ravi Rivers posed damages in surrounding. NCEP-GFS also forecasted high intensity widely distributed rainfall however the dynamically downscaled rainfall at finer scale through WRF showed more realistic results. NWP has a significant role in determining the intensity and distribution of rainfall with enough lead time. In this study we downscaled NCEP-GFS forecast at grid scale of 21 km and 7 km with fixed domain size and one set of physical schemes, however precipitation forecast at finer scale need to be further analyzed using different domain sizes and physical schemes to find the optimal settings of regional model to have better results.

References

"NCEP Global Forecast System (GFS) Analyses and Forecasts.", 2007: Boulder, CO: Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. doi:10.5065/D65Q4TSG.

Alam, M. M., M. A. Hossain, and S. Shafee, 2003: "Frequency of Bay of Bengal Cyclonic Storms and Depressions Crossing Different Coastal Zones." International Journal of Climatology 23 (9): 1119–25. doi:10.1002/joc.927.

Dhar, O. N., P. R. Rakhecha, and B. N. Mandal, 1981: "Influence of Tropical Disturbances on Monthly Monsoon Rainfall of India." Monthly Weather Review 109 (1): 188–90. doi:10.1175/1520-0493(1981)109<0188:IOTDOM>2.0.CO;2.

Dudhia, Jimy,1989: "Numerical Study of Convection Observed during the Winter Monsoon Experiment Using a Mesoscale Two-Dimensional Model." Journal of the Atmospheric Sciences 46 (20): 3077–3107. doi:10.1175/1520-0469(1989)046<3077:NSOCOD>2.0.CO;2.

Godbole, R. V., 1977: "The Composite Structure of the Monsoon Depression." Tellus 29 (1). John Wiley & Sons, Ltd: 25–40. doi:10.1111/j.2153-3490.1977.tb00706.x.

IMD, 2018: "Cyclonic Storm, Daye, over Eastcentral Bay of Bengal and Adjoining Myanmar (19-22 September 2018): Summary."

Kain, John S., 2004: "The Kain–Fritsch Convective Parameterization: An Update." Journal of Applied Meteorology 43 (1): 170–81. doi:10.1175/1520-0450(2004)043<0170:TKCPAU>2.0.CO;2.

Krishnamurthy, V., and R. S. Ajayamohan, 2010: "Composite Structure of Monsoon Low Pressure Systems and Its Relation to Indian Rainfall." Journal of Climate 23 (16): 4285–4305. doi:10.1175/2010JCLI2953.1.

Krishnamurti, T. N., M. Kanamitsu, R. Godbole, C. Chang, F. Carr, J. H. Chow, Masao Kanamitsu, et al. 1975: "August 1975 Study of a Monsoon Depression (I) Synoptic Structure."

Lin, Y.L., R. D. Farley, and H. D. Orville, 1983: "Bulk Parameterization of the Snow Field in a Cloud Model." Journal of Climate and Applied Meteorology. American Meteorological Society. doi:10.2307/26180993.

Mohapatra, M., A. K. Srivastava, S. Balachandran, and B. Geetha, 2017: "Inter-Annual Variation and Trends in Tropical Cyclones and Monsoon Depressions Over the North Indian Ocean." In , 89–106. Springer, Singapore. doi:10.1007/978-981-10-2531-0_6.

Mooley, D. A., and J. Shukla, 1987: "Variability and Forecasting of the Summer Monsoon Rainfall over India." Monsoon Meteorology, no. 7. Oxford University Press: 26–59.

Pakistan Meteorological Department (PMD), 2008: "SOP Regarding Hydro meteorological Forecasting."

Praveen, V., S. Sandeep, and R. S. Ajayamohan, 2015: "On the Relationship between Mean Monsoon Precipitation and Low Pressure Systems in Climate Model Simulations." Journal of Climate 28 (13): 5305–24. doi:10.1175/JCLI-D-14-00415.1.

Raghavan, S., and S. Rajesh, 2003: "Trends in Tropical Cyclone Impact: A Study in Andhra Pradesh, India." Bulletin of the American Meteorological Society 84 (5). American Meteorological Society: 635–44. doi:10.1175/BAMS-84-5-635.

Shahzad, A., 2018: "Nullah Dek Flood Ravages at Least 60 Villages in Sialkot." Accessed November 8. https://www.samaa.tv/news/2018/09/nullah-dek-flood-ravages-at-least-60-villages-in-sialkot/.

Sikka, D. R., 1977: "Some Aspects of the Life History, Structure and Movement of Monsoon Depressions." Pure and Applied Geophysics PAGEOPH 115 (5–6). Birkhäuser-Verlag: 1501–29. doi:10.1007/BF00874421.

Skamarock, C., B. Klemp, J. Dudhia, O. Gill, D. Barker, G. Duda, X. Huang, W. Wang, and G. Powers, 2008: "A Description of the Advanced Research WRF Version 3." doi:10.5065/D68S4MVH.