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SIMULATION OF A FLOOD PRODUCING RAINFALL EVENT OF 9 SEPTEMBER 2012 OVER JACOBABAD, PAKISTAN USING WRF-ARW MODEL

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ABSTRACT

Simulation of a flood producing rainfall event of 9 September 2012 over Jacobabad (28.28°N, 68.45°E), Pakistan has been carried out using the Advanced Research WRF (ARW) dynamic core of Weather Research and Forecasting (WRF) model (WRF-ARW). On 9 September, 2012, Jacobabad received the heaviest rainfall in last 100 years, and recorded 380 mm in 24 hours, where monthly normal rainfall of September is only 11.2 mm. This was an extraordinary rainfall event and localized over Jacobabad, Pakistan. The WRF model was run with the double nested domains of 27 km and 9 km horizontal resolution using Kain-Fritsch (KF) cumulus parameterization scheme (CPS) having YSU planetary boundary layer (PBL). The model performance was evaluated by examining the different model simulated parameters and some derived parameters. The model derived rainfall was compared with TRMM observed rainfall. The model suggested that this flood producing heavy rainfall event over Jacobabad, Pakistan might be the result of an interaction of active monsoon flow with severe convective activities over the area. The Jacobabad was the meeting point of the southeasterly flow from the Bay of Bengal following monsoon trough and southwesterly flow from the Arabian Sea which helped to transport high magnitude of moisture. The vertical profile of the humidity showed that moisture content was reached up to upper troposphere during their mature stage (monsoon system usually did not extent up to that level) like a narrow vertical column where high amounts of rainfall were recorded. The other favourable conditions were strong vertical wind shear, low level convergence and upper level divergence, strong vorticity field which demarked the area of heavy rainfall. The WRF-ARW model might be able to simulate the flood producing rainfall event over Jacobabad, Pakistan, and associated dynamical and thermodynamical features reasonably well, though there were some spatial and temporal biases in the simulated rainfall pattern.

***Keywords*:** WRF Model, Cumulus Scheme, Convective Systems, High Resolution, Active Monsoon

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1. INTRODUCTION

The monsoon precipitation plays a very important role in the social and economic development of Pakistan. Nearly 60 % of annual rainfall over most parts of Pakistan is received during summer (M. Muslehuddin and N. Faisal 2006). Over Pakistan, monsoon (July-September), normally reaches the eastern border of the country around first of July and persists up to the end of September (A. Mahmood et al., 2010), and started to withdraw from the region by 18th September. On 20th September monsoon completely withdrew from whole of the country.

For September 2012, rainfall for the country as a whole was 337 % of its long period of normal value (Table-1). The September rainfall was ranked highest ever recorded rainfall during the period 1961-2012. Heavy rains during the month over Jacobabad, Sukkur, Khanpur and adjoining areas, caused flash floods and inundated large area resulting in loss of lives besides damages to property and land. Monthly rainfall totals for this month generally ranged between 0-25 mm in these areas, with some occasional little higher amount. Accumulated monthly rainfall records for September were broken at several locations of Jacoabad, Larkana, Rohri, Sukkur, Nawabshah, Chhor and Mithi, when it received monthly total rainfall ranging 150-450 mm.

A low pressure system entered the country on 3 September and lashed across the Southern Punjab, Southern Khyber Pukhtunkhwa, eastern Balochistan and Sindh areas with heavy rainfall. The system continued to stay till 12 September 2012. Heavy rainfall were recorded during the five day wet spell from 5 September to 9 September 2012 in the provinces of Sindh and Punjab. Five days accumulated rainfall based on data from the Pakistan Meteorological Department are as under.

Table-1

City	Rainfall (mm)	Rainfall (in)	Province
Jacobabad	481*	18.94*	Sindh
Khanpur	291*	11.45*	Punjab
Larkana	239	9.4	Sindh
Rahim Yar Khan	236	9.29	Punjab
Sukkur	206	8.11	Sindh
Shorkot	152*	5.9*	Punjab
Chhor	137	5.3	Sindh

** Indicates new record in the month*

On 9 September 2012, Jacobabad (28.28°N,68.45°E) – the capital city of extreme south-east province Sindh of Pakistan (24–37° N latitudes and 62–75°E longitudes) received the heaviest rainfall in last 100 years, and recorded 380 mm in 24 hours, where monthly climatological normal rainfall of September is only 11.2 mm (Wikipedia, 2015a; 2015b). This was an unprecedented heavy rainfall event which disrupted the normal rhythm of life in the province by causing severe flash flood, as a result over 150 houses collapsed. The event was highly localized in nature over Jacobabad, Pakistan. The location of Jacobabad, Pakistan is shown in Fig. 1.

Heavy rainfall events become significant in human affairs when they are combined with other hydrological elements. The problem of forecasting heavy precipitation is especially difficult since it involves creating a quantitative precipitation forecast, recognized as a challenging task (Charles, 1993). Simulation of active mesoscale systems such as western disturbances, severe thunderstorms, tropical cyclones and heavy rainfall episodes during active monsoon season over the subcontinent, with high-resolution mesoscale models such as the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5) and the Weather Research and Forecasting (WRF) model have been attempted by many researchers (e.g., Ahasan and Khan, 2013; Ahasan *et al*., 2011, 2013, 2014, 2015; Kumer *et al*., 2008; Deb *et al*., 2010; Patra *et al*., 2000, Prasad, 2005 and Das, 2005). Application of Numerical Weather Prediction (NWP) models such as WRF model in research and forecasting of heavy to very heavy rainfall events of summer monsoon season (JJAS) is little in Pakistan. Some works have been done on heavy to very heavy rainfall events during summer monsoon season of Pakistan using NWP models (e.g., Thomas *et al*, 2010; Webster *et al*., 2011, Ahasan and Khan, 2013, Ali, 2013).

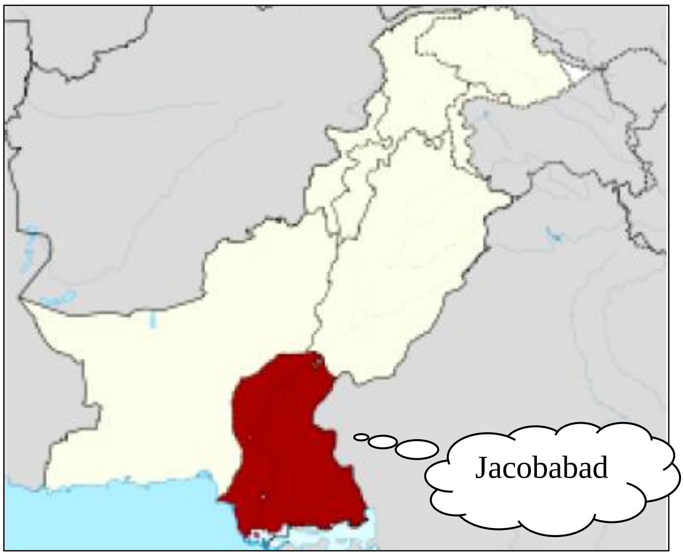

Fig. 1: Map showing the location of Jacobabad (28.28°N, 68.45°E) in Pakistan.

The present study has been undertaken to simulate a flood producing rainfall event which occurred over Jacobabad, Pakistan on 9 September 2012 using the Advance

Research WRF (ARW) dynamic core of Weather Research and Forecasting (WRF) model (WRF-ARW) in double nested domain with grid spacing of 27 and 9 km in the horizontal. The study was also aimed to identify the atmospheric conditions, which triggered and maintained such an event. It is firmly believed that this study will improve the general understanding of the flood producing rainfall processes during summer monsoon season over Pakistan.

2. MODEL EXPERIMENTAL SETUP, DATA USED AND METHODOLOGY

The WRF Model is a new-generation mesocale Numerical Weather Prediction (NWP) system designed to serve both operational forecasting and atmospheric research needs. It features multiple dynamical cores, a 3-dimensional variational (3DVar) data assimilation system, and a software architecture allowing for computational parallelism and system extensibility (Skamarock *et* al., 2008). WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. Applications of WRF include research and operational NWP, data assimilation and parameterized-physics research, downscaling climate simulations, driving air quality models, atmosphere-ocean coupling, and idealized simulations (i.e., boundary-layer eddies, convection, baroclinic waves). There are two dynamics solvers in the WRF system: the Advanced Research WRF (ARW) solver (originally referred to as the Eulerian mass or “em”) developed primarily at NCAR, and the NMM (Nonhydrostatic Mesoscale Model) solver developed at NCEP. The ARW system consists of the ARW dynamics solver with other components of the WRF system needed to produce a simulation. The WRF-ARW (Version 3.6, Release September 2013) has been implemented during the present study.

2.1 Model Experimental Setup

The WRF model was run on the double nested domains D1 and D2 with 27 km and 9 km horizontal resolution respectively. The configuration of the domain in WRF model is shown in Fig. 2. Domain 1 (D1) is the coarsest mesh and has 211x151 grid points in the north-south and east-west directions respectively, with a horizontal grid spacing of 38 km. Within D1, Domain 2 (D2) is nested with 211x235 grid points at 9 km grid spacing which is reasonable in capturing the mesoscale cloud clusters. All these domains were configured to have the same vertical structural of 38 unequally spaced (non dimensional pressure) levels. The model uses two-way nesting, where coarse grid data are interpolated to finer grid boundaries and the finer grid provide updated data to the coarse grid. The map projection type Mercator is chosen for both the domains. All the domains D1 and D2 are centered over Pakistan (30°N, 70°E) to represent the regional-scale circulations and to solve the complex flows in this region. The physics and dynamics employed in the model for the present study are summarized in Table-2.

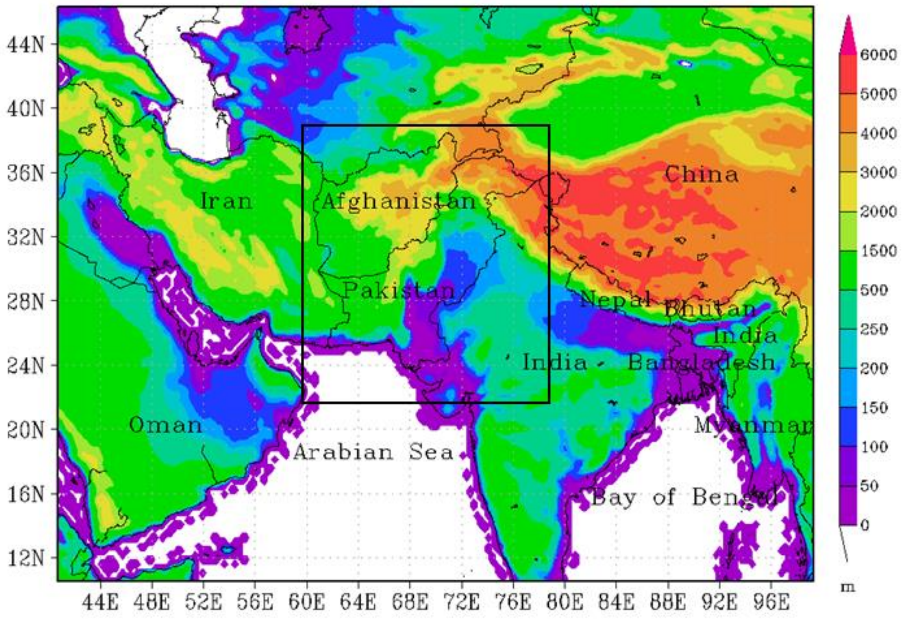

Fig. 2: Double nested domain configuration in WRF model for the NWP study with the topography in the background.

Table 2: Physics and dynamics used in the WRF model

	Physics
Convection	Kain-Fritsch (new Eta) (Kain 2004)
PBL	YSU Scheme (Hong and Dudhia 2003)
Surface Layer Option	Monin-Obukhov
Cloud Microphysics	WSM 6-Class Simple Ice (Hong and Lim 2006)
Radiation	RRTM long wave (Mlawer et al. 1997) and Dudhia short wave (Dudhia 1989)
Land Surface Processes	Unified Noah Land Surface Model
	Dynamics
Time Integration	3rd order Runge–Kutta
Time Steps	60 m
Vertical Differencing	Arakawa’s Energy Conserving Scheme
Time Filtering	Robert’s Method
Horizontal Diffusion	2nd order over Quasi-pressure, surface, scale selective
Spatial difference scheme	6th order centered difference
Horizontal grid	Arakawa C-grid

2.2 Data Used

The United States Geological Survey (USGS) global datasets with 30sec horizontal resolution were used to create terrain/topography and vegetation/land-use field. For initial and lateral boundary condition, the 1°×1° resolution Final (FNL) Global Model Tropospheric data were downloaded from FTP site of National Centre for Environmental Prediction (NCEP). The daily 3B42 V6 rainfall data have been collected from the archive of Tropical Rainfall Measuring Mission (TRMM) to compare or validate the model output. Meteosat-5 cloud imageries were obtained from the website of Dundee Satellite Receiving Station which are also used to justify the model simulated rainfall structure, development time and location.

2.3 Methodology

The WRF model has been used to investigate the possible causes and mechanisms associated with the unprecedented flood producing rainfall event of 9 September 2012 over Jacobabad, of Pakistan. The model was run for 24 hours based on the initial condition on 0000 UTC of 9 September 2012. All parameters were made for 1200 UTC of 9 September 2012 for the analysis of the synoptic conditions responsible for producing such heavy rainfall event. The model performance was evaluated by examining the different predicted parameters like mean sea level pressure, upper and lower level circulations, horizontal and vertical profile of moisture, vertical wind shear of the u component of wind, upper level divergence, lower level relative vorticity, outgoing longwave radiation, convective available potential energy, convective inhibition energy and rainfall. The outputs of the WRF model help to investigate the synoptic and environmental characteristics responsible for flood producing rainfall event. The model derived rainfall was compared with TRMM 3B42 V7 observed rainfall. The model simulated precipitation at surface level was considered as rainfall throughout the study. The Meteosat-5 cloud imageries are also used to justify the model simulated rainfall structure, development time and location.

3. RESULTS AND DISCUSSION

The results are described in the following section in details.

3.1 Mean sea level pressure and low level wind flow

The spatial distribution of model simulated mean sea level pressure (hPa) field with low level (10m height) wind flow (ms^{-1}) valid for 1200 UTC of 9 September 2012 are shown in Fig. 3. The analysis shows that there are three low pressure areas are seen over the northwest head Bay of Bengal, extreme southeast Pakistan and eastern Oman. The low pressure area over the extreme southeast Pakistan and nearby territory of India is stronger among the three low pressure areas. The central pressure of the low pressure area over the extreme southeast Pakistan and nearby territory of India is about 996 hPa. The seasonal monsoon trough area lies over the foot hills of the Himalayan and the eastern end of the trough deeps over the head Bay of Bengal. The intensity of the heat low over the northwest Indian and nearby territory of Pakistan is about 999 hPa. The anticyclone over Tibet is found comparatively weaker than normal and its position is slightly west of Tibet.

The analysis of the wind field shows that the strong southwesterly prevailed over the north Arabian Sea which helped to transport high amounts of moisture to the southeast Pakistan and nearby territory of India. The southwesterly flow divided into two branches due to presence of a low pressure area over extreme southeast Pakistan and nearby territory of India. The confluence of these two branches of southwesterly flows over the northern side of the low pressure area helped to convergence the wind and hence to form severe convection.

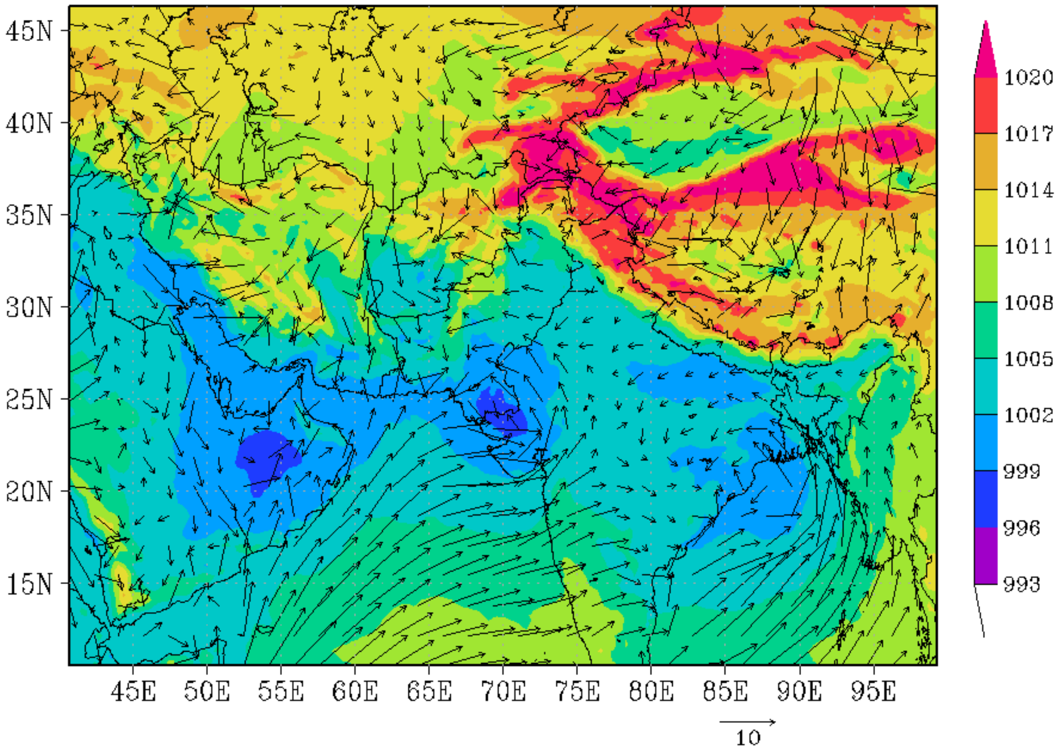

Fig. 3: Spatial distribution of model simulated mean sea level pressure (hPa) filed with 10m height wind field (ms^{-1}) at 1200 UTC of 9 September, 2012.

3.2 Upper level wind flow and divergence field

The spatial distribution of upper level wind flow (ms^{-1}) and divergence ($\times 10^{-5}$s^{-1}) field at 200 hPa level valid for 1200 UTC of 9 September 2012 are shown in Fig. 4(a-b). A westerly strong jet stream (20 ms^{-1}) may be seen over Afghanistan and nearby territory of northwest Pakistan at 1200 UTC of 9 September 2012, marking a strong vertical wind shear in the environment. There is a strong mid latitude trough in upper air westerly may be seen over western Afghanistan region at 1200 UTC of 9 September 2012, which may be moved towards further east with the progress of time and give heavy rainfall over the region it travels [Fig. 4(a)]. The interaction between the upper air trough in westerly and the seasonal monsoon flow may be one of the causes of heavy rainfall over southeast region of Pakistan. A significant high pressure area may be seen over the east-central region of Pakistan and nearby territory of India. A trough in upper air easterlies may also be seen near the border between extreme southeast Pakistan and India.

The analysis of the divergence field at 200 hPa level shows that the divergence is the maxima in the order of $20\times10^{-5}s^{-1}$ over the south-east Pakistan and adjoining territory of India at 1200 UTC of 9 September 2012 [Fig. 4(b)] which may be shifted towards further north-westwards with the progress of time due to strong north-westerlies present in the upper atmosphere [Fig. 4(a)].

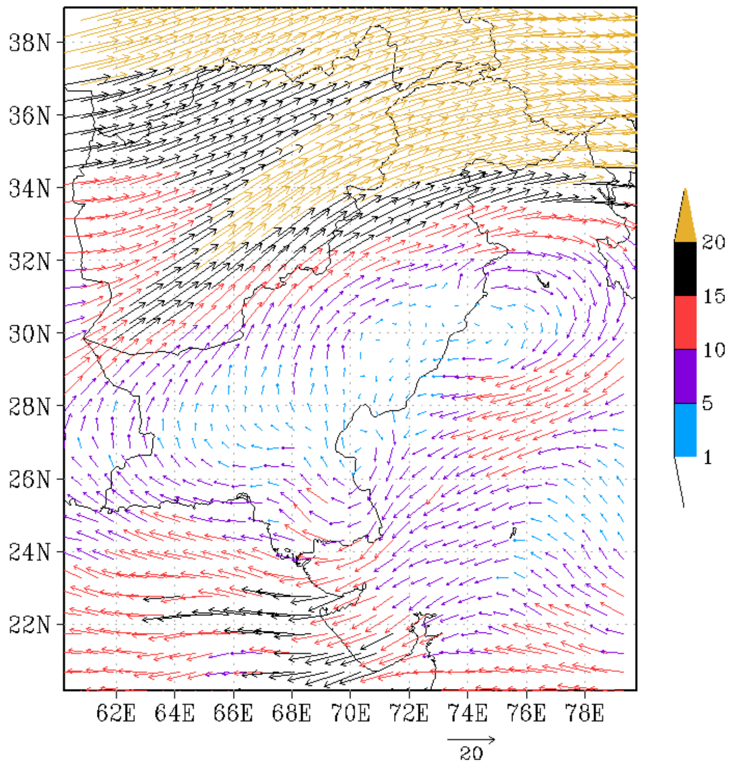

Fig. 4(a): Spatial distributed of upper level (200 hPa) wind flow (ms^{-1}) at 200 hPa valid for 1200 UTC of 9 September 2012.

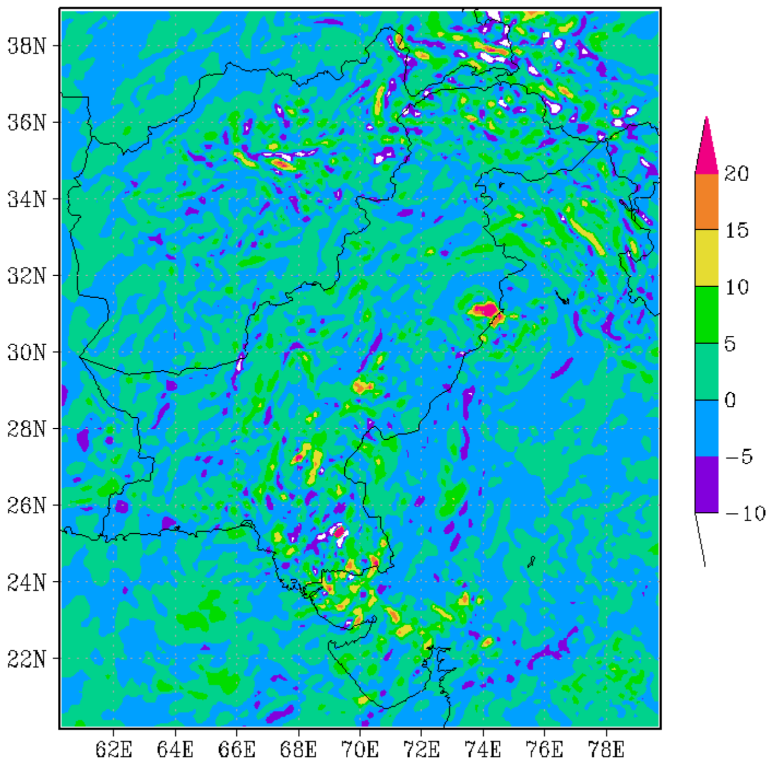

Fig. 4(b): Upper level divergence field ($\times 10^{-5}s^{-1}$) at 200 hPa valid for 1200 UTC of 9 September 2012.

3.3 Relative humidity / moisture

The spatial distribution of model simulated relative humidity (%) at 850 hPa level valid for 1200 UTC of 9 September 2012 is shown in Fig. 5(a). It is found that the contents of high moisture of the order of 100% over the south-east and eastern part of Pakistan and nearby territory of India at 1200 UTC of 9 September, 2012 [Fig. 5(a)]. The circulation of strong southwesterly low level flow (Fig. 3) transports plentiful of moisture from the Arabian sea to the plains of the southeast Pakistan and its neighbourhood. The southwesterly flow divided into two branches due to presence a low pressure area over the southeast Pakistan and nearby territory of India at 1200 UTC of 9 September, 2012. The moisture carried by two branches of southwest flow meet together over the Jacobabad, Pakistan and vertically lifted due to convergence and gives heavy rainfall over that region.

The vertical profile of the relative humidity (%) field along 28.228°N latitude (latitudinal position of Jacobabad) valid for 1200 UTC of 9 September 2012 is presented in Fig. 5(b). It is found that the intensity of vertical profile of the relative humidity field reached above 300 hPa. Usually such vertical height of the relative humidity is not observed during monsoon season due to strong vertical wind shear present in the environment.

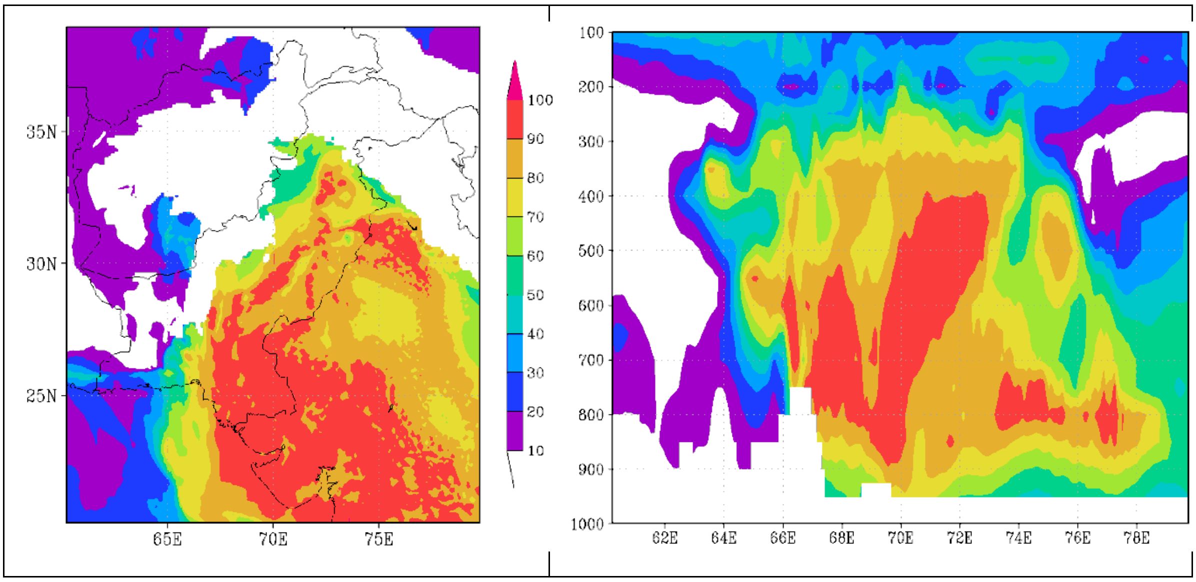

Fig. 5(a-b): Spatial distribution of relative humidity (%) at 850 hPa level valid for 1200 UTC of 9 September 2012 (a) and vertical profile of the relative humidity (%) field along 28.28°N latitude (along Jacobabad) valid for 1200 UTC of 9 September 2012 (b).

3.4 Vertical wind shear

The spatial distribution of model derived vertical wind shear (ms^{-1}) of the u component of wind between 500-950 hPa level of the atmosphere at 1200 UTC of 9 September 2012 is presented in Fig. 6. It is found that the vertical wind shear of the order of 5-10 ms^{-1} may be seen over the eastern Pakistan and nearby territory of India which may help to form low pressure area over that region. Little or no vertical wind shear is a precursor for the formation of a low pressure area.

On the other hand, in the presence of this wind shear (5-10 ms^{-1}) only single cell thunderstorm may be formed. In single cell convective systems, they tend to be short lived (~30 min) and move with the mean wind in the lowest 8 km of the atmosphere (Holton, 2004).

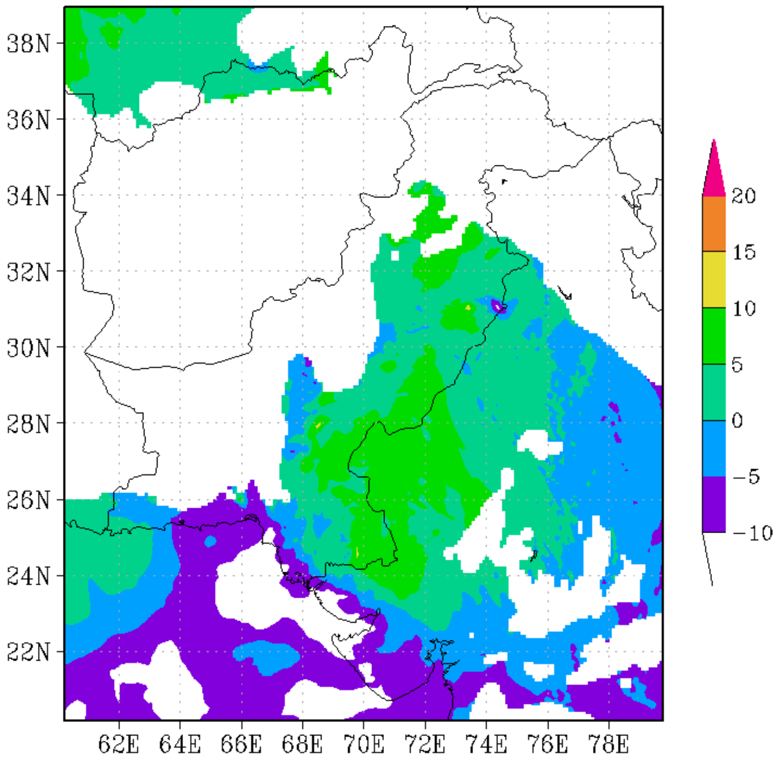

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Fig. 6: Spatial distribution of vertical wind shear (ms^{-1}) of the u component of wind between 500-950 hPa level valid for 1200 UTC of 9 September 2012.

3.5 Low level relative vorticity

The spatial distribution of model derived low level relative vorticity ($\times 10^{-5} s^{-1}$) at 850 hPa level valid for 1200 UTC of 9 September 2012 is presented in Fig. 7. The prominent feature is a core of vorticity maxima of the order of ~$20\times 10^{-5} s^{-1}$ over the southeast region (Jacobabad) of Pakistan. The persistence of this low level relative vorticity helps to generate severe convective activities over that region.

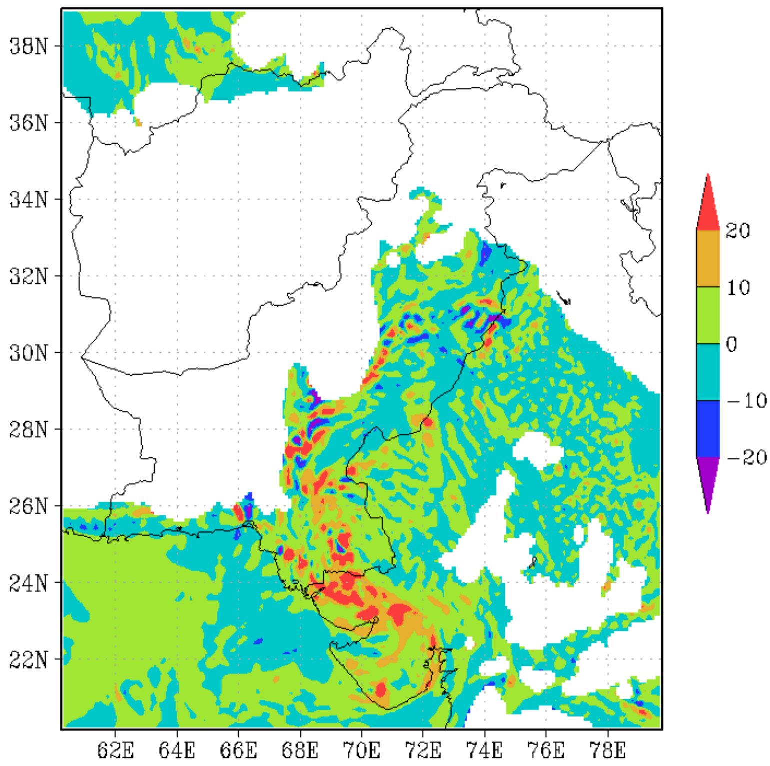

Fig. 7: Spatial distribution of low level relative vorticity ($\times 10^{-5} s^{-1}$) at 1200 UTC of 9 September 2012.

3.6 Outgoing longwave radiation

The spatial distribution of outgoing longwave radiation (Wm^{-2}) is shown in Fig.8. It is found that the areas of southeast region of Pakistan where heavy rainfall occurred on 9 September 2012 is characterized by very low outgoing longwave radiation in the order of 150-200 Wm^{-2} which indicate the areas are covered with high densely convective cloud.

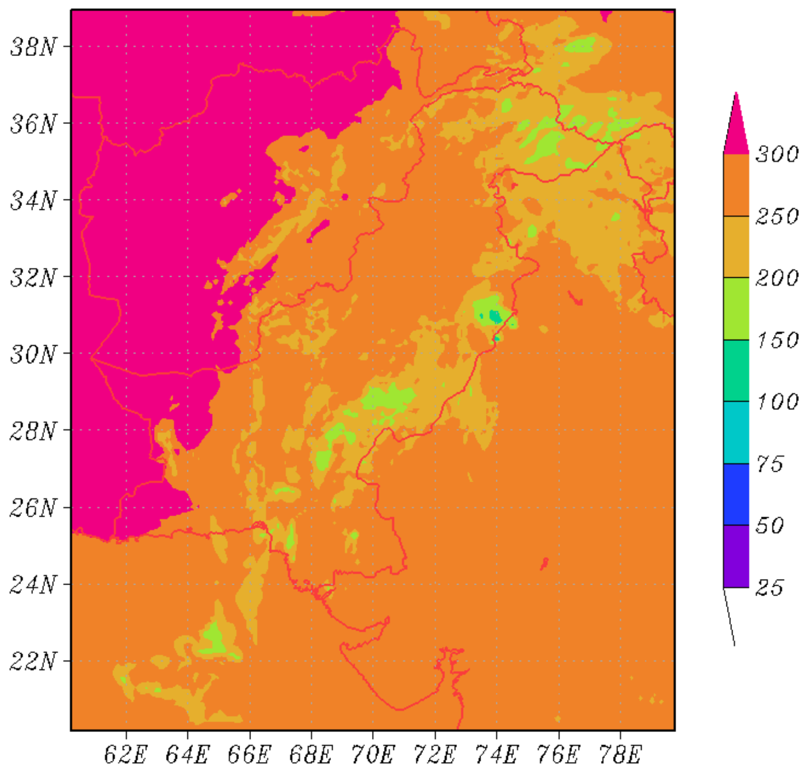

Fig.8: Spatial distribution of outgoing longwave radiation valid for 1200 UTC of 9 September, 2012.

3.7 Convective Available Potential Energy (CAPE) & Convective Inhibition Energy (CINE)

The spatial distribution of model derived CAPE (J/kg) and CINE (J/kg) valid for 1200 UTC of 9 September 2012 are shown in Fig. 9(a-b). The CAPE field shows that the Jacobabad located in the south-east region of Pakistan is demarked as high CAPE in the order of 2000-2500 J/kg. The significant magnitudes of CAPE are confined to the south-east part of Pakistan with strong gradient, the values decreasing sharply as we move away from the region of maxima. While existence of significant CAPE is considered to be favourable for severe convection and its role in the convective activity over Pakistan has been clearly brought out. On the other hand the CINE regime is characterized by almost zero values (>25 J/kg) over the south-east Pakistan, which keeps the environment favourable for convection as a general rule may be seen.

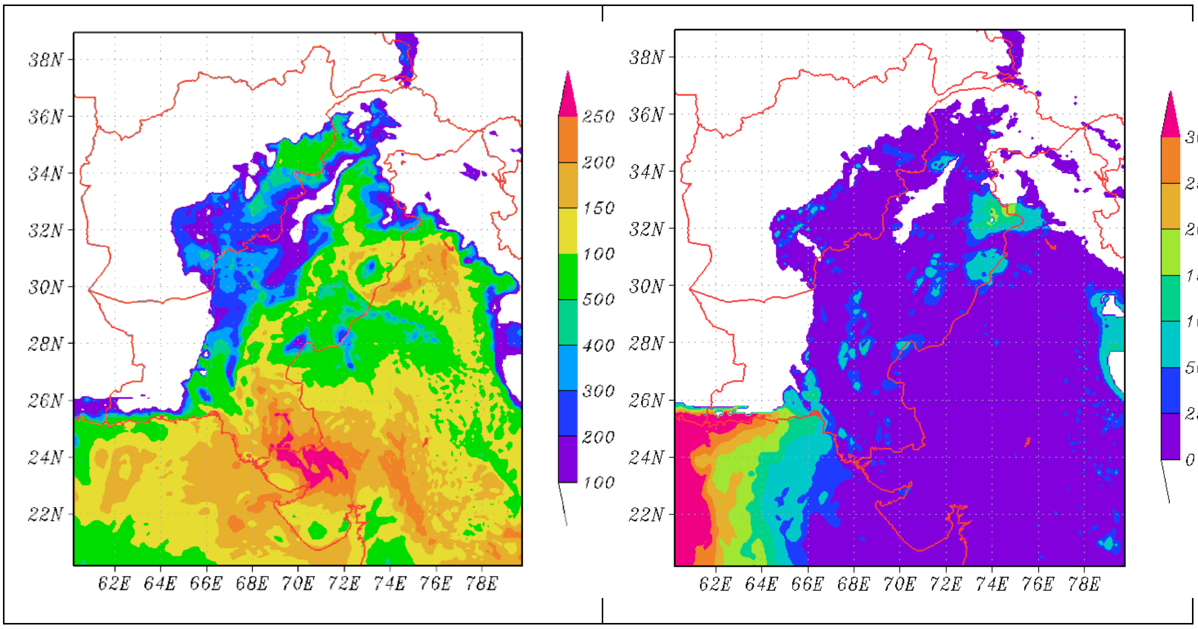

Fig. 9(a-b): The distribution of Convective Available Potential Energy (CAPE) (a) and Convective Inhibition Energy (CINE) (b) valid for 1200 UTC of 9 September, 2012.

3.8 Rainfall analysis

The model simulated 24-h accumulated rainfall valid for 9 September 2012 (0000 UTC, 10 September 2012) for domain 2 (D2) at 9 km resolution is shown in Fig. 10(a). It is found that the advanced research WRF (ARW) dynamic core of WRF model (WRF-ARW) has captured the heavy rainfall over southeast region of Pakistan and nearby territory of India in reasonably well, though the amount of the simulated rainfall is comparatively less than that of observed. The model simulated rainfall was compared with daily TRMM 3B42V7 observed rainfall [Fig.10(b)]. TRMM 3B42 V7 observed rainfall is also seems to be lower than that of observed. However model simulated rainfall over the southeast region of Pakistan is match with that of TRMM 3B42 V7 observed in reasonably well. The WRF model captured well the location and structure of the studied case reasonably well. Model simulated rainfall is found to be 46% lower than TRMM observed rainfall. It is also found that the model simulated rainfall is spatially deviated by 50-100 km in respect of TRMM observation. Thus the WRF model simulated rainfall seems to be realistic though there are spatial and temporal biases in the simulated rainfall pattern.

The Meteosat-5 cloud images valid for 9 September 2012 are presented in Fig. 11(a-d). The signature of the dense convective cloud is seen in the cloud imageries. The source of moisture is also indicated in the images. It also seen that two cloud masses meet together over the area of northeast region of Pakistan which helps to heavy downpour over the region.

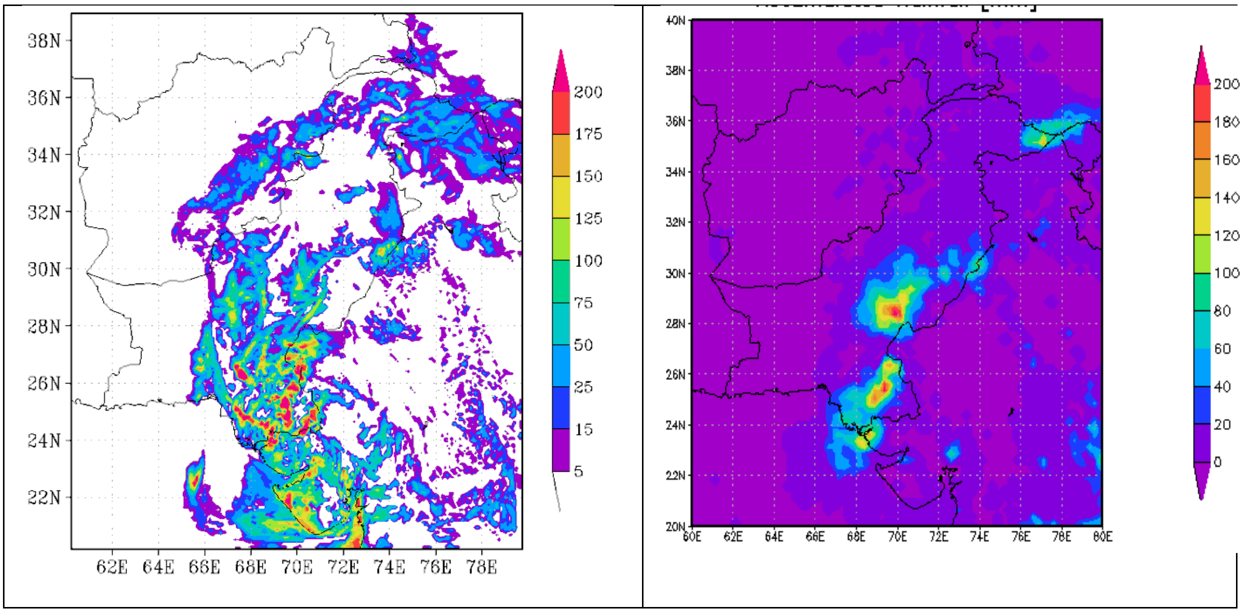

Fig. 10(a-b): Spatial distribution of model simulated 24-h accumulated rainfall (mm) (a) and PMD observed rainfall (mm) (b) valid for 9 September, 2012.

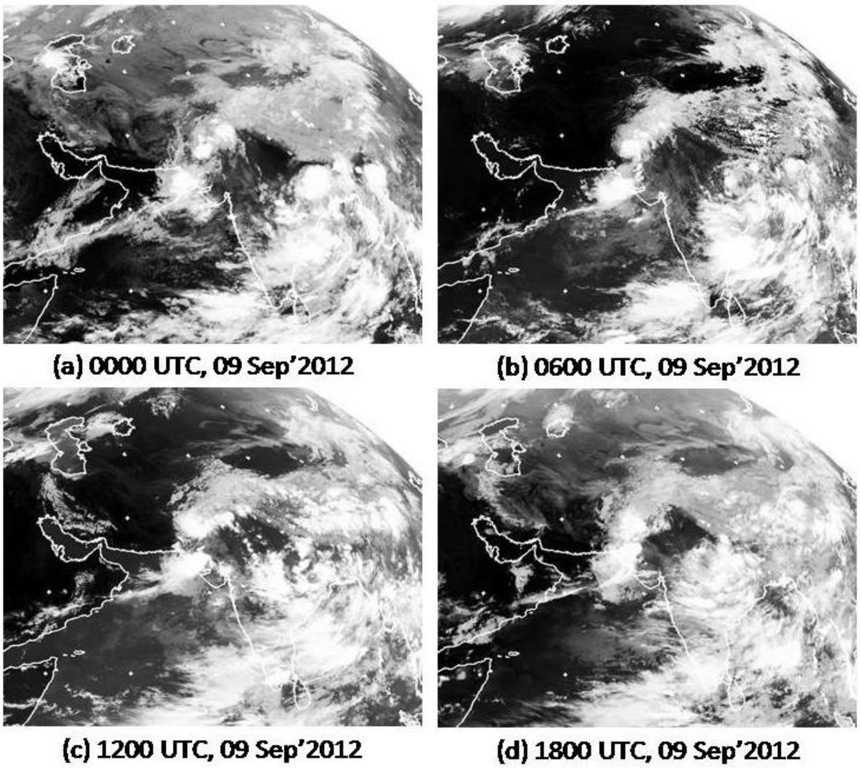

Fig. 11(a-d): Meteosat-5 cloud imageries valid for 9 September 2012 at 0000 UTC (a), 0600 UTC (b), 1200 UTC (c), 1800 UTC (d)

4. CONCLUSIONS

On the basis of the present study, the following conclusions can be drawn:

1) The WRF model suggests that the flood producing rainfall event over southeast region (Jacobabad) of Pakistan might be the result of an interaction of trough in upper westerlies with a cyclonic circulation as well as active monsoon flow.
2) The analysis of the mean sea level pressure field shows that a significant low pressure area is persisted over the southeast region of Pakistan.
3) The analysis of the wind field shows that the strong southwesterly flow divided into two branches due to a low pressure persisted over the southeast Pakistan and nearby territory of India, and the Jacobabad region of Pakistan was the meeting point of the two branches of wind flow from the Arabia Sea and from the plain of India.
4) The circulation of strong southwesterly low level flow transports plentiful of moisture from the Arabian sea to the plains of the southeast Pakistan and its neighbourhood. The moisture carried by two branches of southwest flow meet together over the Jacobabad, Pakistan and vertically lifted due to convergence and gives heavy rainfall over that region.
5) The vertical profile of the relative humidity shows that the intensity of vertical profile of the relative humidity field reached above 300 hPa. Usually such vertical height of the relative humidity is not observed during monsoon season due to strong vertical wind shear present in the environment.
6) Model simulated rainfall was well matched with the TRMM 3B42 V7 observed rainfall having spatial and temporal biases. The model simulated rainfall was spatially deviated by 50-100 km in respect of TRMM 3B42 V7 and 46% lower than that of observed by PMD.
7) The studies show that the areas of heavy rainfall (southeast Pakistan) are characterized by very low outgoing radiation, low vertical wind shear, high low level relative vorticity, strong upper level divergence, high CAPE and low CINE field which make the environment favourable for the unprecedented heavy rainfall.
8) Finally, It may be concluded that the advance research dynamic core of WRF model (version 3.6) might be able to simulate the flood producing rainfall event over the southeast region of Pakistan and associated synoptic features reasonably well, though there are some spatial and temporal biases in the simulated synoptic features.

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