Persistent Heavy Downpour in Desert Areas of Pakistan in South Asian Monsoon 2011

Cheema, S. B.[1, 2], Q. Zaman[2], G. Rasul[2]

ABSTRACT

This diagnostic study carried out to understand the phenomenon of heavy rainfall which gripped up the Sindh in August and September 2011. National Center for Environmental Prediction (NCEP) Reanalysis data alongwith satellite and high resolution model (HRM) outputs are used for the post analyses of this downpour. The model output and satellite imagery captured well spatial and temporal distribution of the rainfall event. The analysis showed that heavy rainfall occurred over this province due to orientation of monsoon currents. A low pressure system developed over Bay of Bengal (BoB) passed over India and entered in Pakistan from 07 August, afterwards this tropical depression merged into seasonal low on 10th Aug and accentuated the weather system. Moisture was supplied from (BoB) and Arabian Sea (AS) during the monsoon season. Orientation of Tibetan high also played a crucial role for spatial distribution of precipitation over Sindh. This high blocked the monsoon current from penetration in north. At same time, another high pressure system was lying over Iran and its ridge was extended up to Baluchistan and Karachi Region. It blocked westward movement of monsoon depressions. A mid tropospheric cyclone (MTC) generated along the coastal boundary of Mumbai (India) and caused another heavy rainfall event from 29thAug to 16th September. The structure and intensification of this MTC has been discussed in this study. This paper also brings out the relationship between precipitation and large scale circulation such as monsoon orientation, tilting of Tibetan High, generation of MTC which are main causes for this rainfall event in 2011.

Key words: Tropical Depression, Low pressure system, Tibetan high, Mid Tropospheric Cyclone, Monsoon Orientation.

Introduction

South Asia is a region with variant land surface conditions, complex topography and vast coastlines. The region is generally dominated by the South Asian monsoon along with East Asian Monsoon. South Asian monsoon yields a heavy rainfall in this area (Rasul et al., 2005). Monsoon circulation, its variability and heavy weather systems have been studied extensively by different scientist. Dr.Q.Z.Chaudhry (1991) fond inter annul variability of Monsoon rainfall and its relationship with global /regional circulation features by using a large data sets (1901-1990). He suggested that normal rainfall for country is 132.6 mm and Sindh contribute seasonal monsoon 67% to the annual rainfall. Cheema (2011) concluded by using different statistical tests that if the monsoon rainfall increased in future then it will shift towards south eastern parts of Punjab. Rana (2011) mentioned that severe flood of 2010 was the direct result of interaction between westerly and easterly flows. In Pakistan, the main contribution in the annual rainfall is summer monsoon. Summer monsoon rainfall contributes almost 60% of the total annual rainfall (Muslehuddin et al., 2005).

In Summer (JAS) low depressions originate over Bay of Bengal and on the Arabian Sea that is the fundamental reason for precipitation in Pakistan. These Low Pressure Systems (LPS) that originate over Bay of Bengal move northwest cause heavy rainfall in upper Punjab and Kashmir. That caused flood and disaster in the country. But in 2011, monsoon track deviate towards Southwest and generated worst floods in Sindh. The province has not a long history of flooding, however foulest floods recorded in 2003, 2006 and 2010. All these deadliest floods happened during the monsoon season (JAS) which is augmented by heavy precipitation and snowmelt flows of glaciers. Rainfall in 2011 breaks all previous records since 1961-2010. In general, monsoon depressions reached the eastern border of Pakistan around first week of July. But in July 2011 rainfall was recorded below normal. It was recorded that rainfall was 18 % below than normal in country and 72% below in Sindh. In Aug and September accumulate rainfall above normal with 72% departure in whole country and 248% above than normal in Sindh. Heavy monsoon rainfall

[1] Sohailbabar.cheema@gmail.com
[2] Pakistan Meteorological Department

spells during 9-14 Aug and 29 Aug -16 Sep in 2011 caused a severe flood in Sindh and adjoining areas of Baluchistan. Heavy flooding in country has affected millions of people hectares of crop and caused a significant humanitarian disasters with wide spread economic penalties for the country. This flood event was induced by the severe precipitation event associated with the summer monsoon depression travelling from Bay of Bengal through India toward southeastern parts of Sindh. According to a report of National Disaster management Authority (NDMA) almost 23 districts and 6006545 people were affected. Out of which 269 were died and 14,187 injured. Heavy rains and floods swept away 1,388,331houses, out of which 539,899 houses were completely destroyed and the rest partially damaged as reported by the government's disaster management agency (NDMA, 2011). These people are stranded with no access to food, clean drinking water and other necessities of life. Flood destroyed food stock piles, crops, livestock, structure and developments. The red crescent society estimated that about 881.04ha or 5,938,296 acres of Pakistan cultivated land has been affected by the flood, resulting in the loss of about 65 % of cotton,82.3ha area of rice and tomato damage estimate was 70thousands tons (PRCS, 2011).

Climatology of Study Area

Geographically Sindh is located on the western corner of South Asia, bordering the Iran in the west, Arabian Sea in the south. It is bounded by the Thar Desert to the east and Kirthar Mountains to the west, in the centre is a fertile plain lie around the Indus River. Sindh is the third largest province of Pakistan, which stretch about 579km from North to South and 442km or 281 km from East to West. Annual precipitation is scarcely 10% of annual evaporation and water deficiency is almost 90%, in this way Sindh is a desert. Sindh lies in a tropical to subtropical region; it is hot in the summer and mild to warm in winter. Temperatures frequently rise above 46 °C (115 °F) between May and August, and the minimum average temperature of 2 °C (36 °F) occurs during December and January in the northern and higher elevated regions (Panhwar,1993). The annual rainfall averages about seven inches, falling mainly during July and August. The southwest monsoon wind begins to blow in mid-February and continues until the end of September, whereas the cool northerly wind blows during the winter months from October to January.

Normal Monsoon rainfall for Sindh province is 127.5mm whereas, in 2011 it was recorded as 443.9mm, similarly normal rainfall for Pakistan is 137.5mm but in 2011 monsoon period the rainfall was 236.5mm that show a positive departure from normal.

Table 1: % Departure of Monsoon Rainfall (mm) from Normal 1971-2000

	Normal	2011 Monsoon Rainfall	% Departure
Pakistan	137.5	236.5	72
KPK	225.2	249.2	11
Punjab	235.7	348.7	48
Baluchistan	58.8	81.9	39
Sindh	127.5	443.9	248

Source: A report by PMD-2011

Table 1 shows that maximum departure observed in Sindh. Therefore present study focuses the physical phenomenon that brought heavy rainfall in Sindh. Figure 1 shows spatial variation in precipitation and geographical location of Sindh.

Climate change and global warming during the last half century contributed to the severity and exacerbation of floods in 2010 and 2011.Intergovermental Panel on Climate Change (2007) reported that climate projection reveal more frequent and more intense weather events due to global warming. This report also pointed out an increase in precipitation on Asian Monsoon associated with anthropogenic activities, which caused global warming. In the report it was also in the nature of monsoon precipitation,

especially over Asian Monsoon (IPCC, 2007). Real time data also proved that last two years were also recorded warmest years. Dr Qamar identified that projection of climate change of Pakistan projects heavy rainfall and extreme weather events. Increasing temperature in arid and semi-arid would cause enhanced heat wave frequency water hassle conditions (Qamar, 2011).

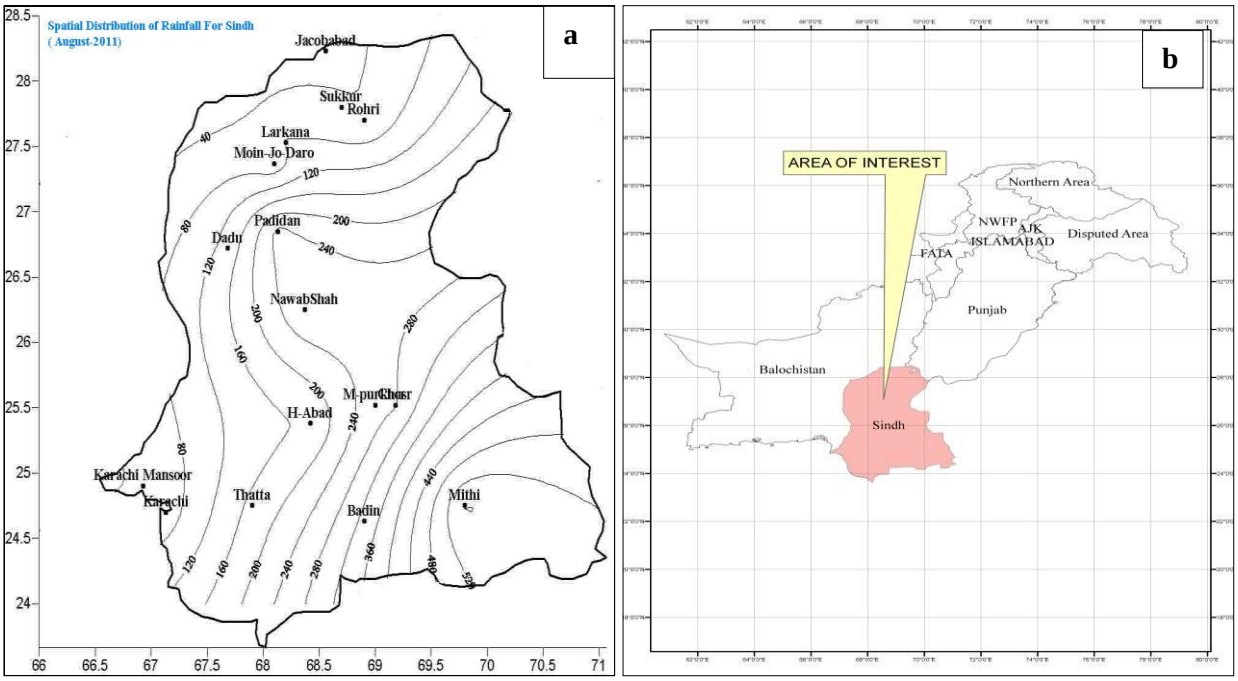

Figure 1: (a) Spatial distribution of rainfall (mm) from 09-15 Aug, 2011**. (b)** Area of interest for the study. Domain (05^{o} – 50^{o} N, 50^{o} – 100^{o} E) has been selected for most of the diagnostic analyses using NCEP Reanalysis datasets.

Climate change has become a global issue and many countries are facing worst climate hazards like floods, Droughts etc. Extreme weather and climate events such as floods, drought, heat waves and cyclonic storms are common in Pakistan since last few decades. In this study we investigate physical processes that were responsible for the extreme downpour amounting above than normal during August and Sep, 2011. The purpose of this research is to diagnose the variation in monsoon track and role of Mid Tropical Cyclone (M.T.C).

Data and Methodology

In order to achieve overall objective of this study, there are several tasks that have been accomplished. First of all 3 hourly real time data of precipitation for the target region was obtained from Climate Data Processing Center (CDPC) Karachi, then scrutinized and compiled on daily as well monthly basis. PMD installed many rain gauges in these areas for this purpose. NCEP (National Center for environmental prediction) Reanalysis II data is utilized with a temporal resolution of six hourly and spatial resolutions (2.5° × 2.5°), along with 17 vertical pressure levels from (100-1000). For this study (05° – 50° N, 50° – 100° E) domain has been selected so that monsoon track and the movement of MTC can easily be understand. GRADS (Grid Analysis Display System) software is helpful to plot gridded reanalysis data in the form of images. Normal precipitation and actual rain fall diagram are plotted by using Surfer software. A high resolution model (HRM) which developed by the German weather service (Deutscher Wetherdienst - DWD) in 1999 used for simulation of event. The model was provided with the initial and boundary conditions with 3 hourly data derived from the German Global Model (GME – Global Model Europe) to initialize the simulation. High Resolution Model (HRM) deployed at horizontal

resolution of 11km along with 60 vertical levels. The approximate latitude and longitude range of the domain was 05° – 50° N and 45° – 95° E respectively as shown in Figure 12. The daily rainfall data for the following stations, Badin, Chhor, Hyderabad, Jacobabad, Larkana, Karachi Masroor, Mithi, Nawabshah, Padidan, Rohri, Sukkur, Moin-Jo-Daro, Thatta, Dadu and Mirpurkhas was used to analyze the rainfall pattern over the large area of Sindh. The bar graphs were also plotted to display the amounts or frequency of occurrence of precipitation for different stations as well as for different dates during first and second spell of rainfall. The spatial and temporal variation of MTC was analyzed through GRADS software. Similarly conventional synoptic weather charts were used to locate the movement of heat low. Position of Tibetan high was observed by plotting average streamlines at 300mb.

Results and Discussions

The division of Results and Discussions is in two events, as

- First spell- (09-15August)
- Second Spell - 29Aug-16Sep

Rainfall Event (09-15 August)

Summer monsoon sets over the eastern border of Pakistan on 28th June 2011. In July 2011 country received below normal monsoon rains. However in August and September of same year, Pakistan received above normal monsoon rains. A strong weather system starts to develop over Uttar Pradesh (India) on 06-August, 2011 and its movement seen westwards. Met office (Pakistan) diagnosed the movement of the system in time and issued a press release. Due to development of this system

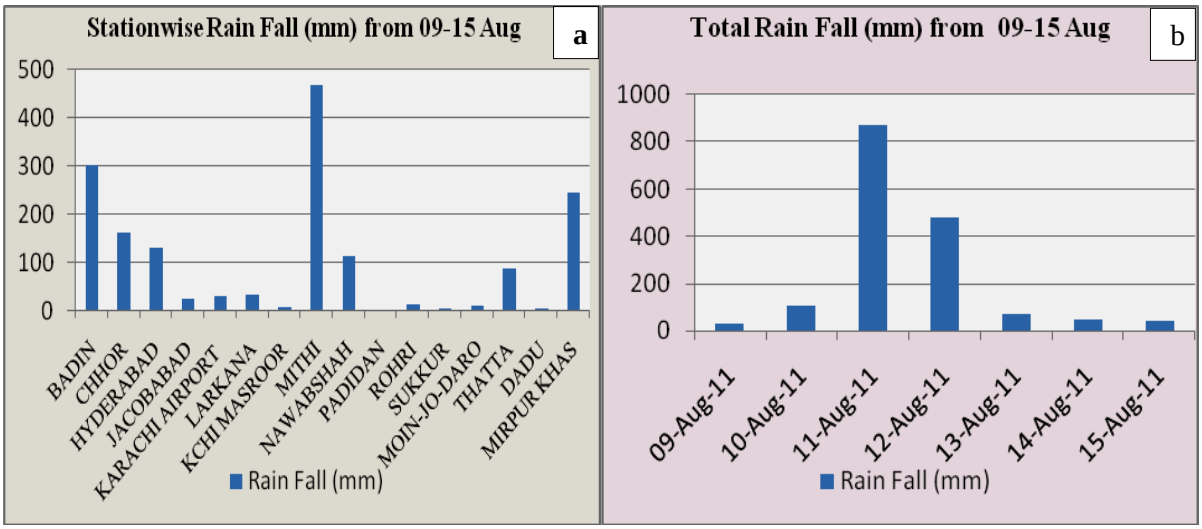

Figure 2: Spatial and temporal variation in rainfall during 1st spell (9-Aug to 15Aug).

District Badin in Sindh province received record breaking rainfall of 615.3mm (24.22 in) during the monsoon spell, breaking earlier recorded 121 mm (4.8 in) in Badin in 1936. The area of Mithi also has record rainfall of 1,290 mm (51in) during the Monsoon season, whereas maximum rainfall was recorded 114 mm (4.5 in) in Mithi in 2004. The intensity of rain confined over lower parts (Southern East) of Sindh and system became low intensify as it moved northward. Maximum rainfall from (09-15) August, 2011 was recorded for Mithi station that was about 450mm whereas on 11August system given highest rain for this spell as represented by bar graph in Figure 2.

Here some features (Monsoon Track, Tibetan High, Heat Low and MTC) are mentioned for this heavy rainfall event over aforesaid area.

Monsoon Track

First spell which started from 9th August, 2011 was occurred in consequence of monsoon tilting effect from normal path as shown in Figure 3. Rainfall is never evenly distributed across the country during the monsoon season. It doesn't appear all at once in the entire country. Rather, it builds up over a couple of days of "pre-monsoon showers". Its actual arrival was announced in July but this amount of rainfall that received in July 2011, was less than normal for this month, 2011. Data for the previous years showed that the Southwest Monsoon first hits territory of the Central Punjab. Till the mid of August almost all regions in Pakistan came under sway of Monsoon. Normal dates for on-setting of monsoon are first week of July and its path is shown in Figure 3. Monsoon depression's trough diverges towards southwest at an angle of 40^0, although its normal path is northwest. Normally monsoon enters in Pakistan along the boundary of Lahore and Sialkot. But in 2011 monsoon entered in country from Rajastan (India) to Tharparkar (Pakistan).

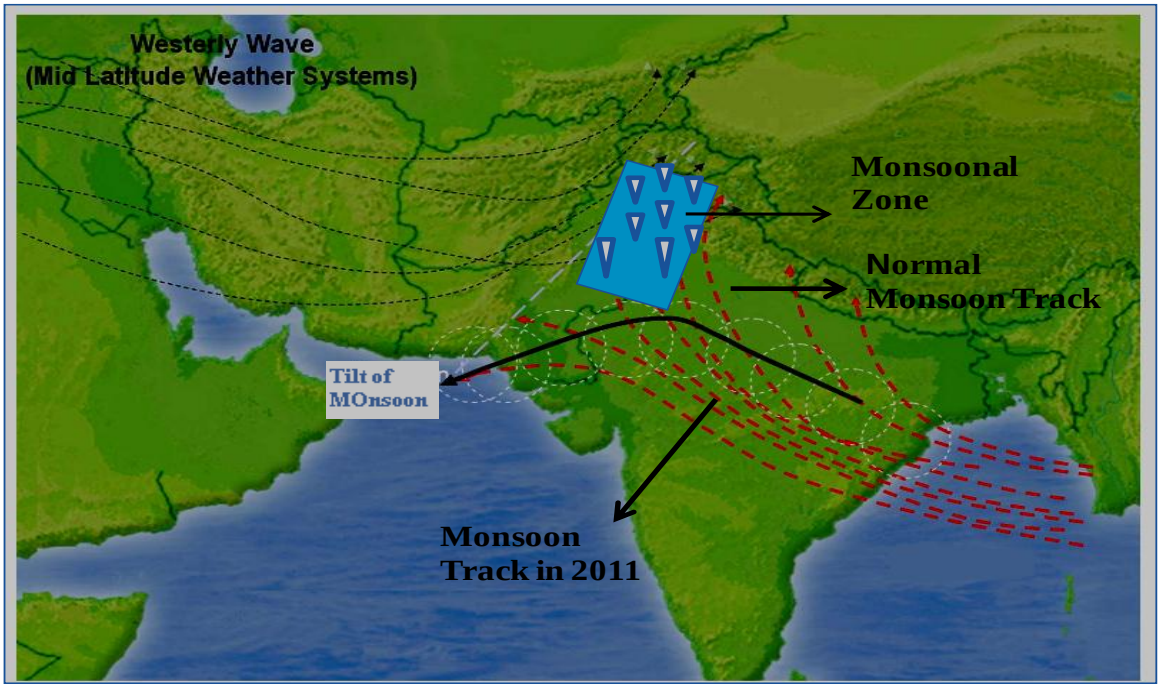

Figure 3: Track of Monsoon Low Depression during Aug & Sep 2011.

Tibetan High (TH) (200 hpa)

High-pressure systems are mostly connected with light winds at the surface and subsidence through the lower portion of the troposphere. Intensity and orientation of Tibetan high plays a vital role in steering the ground level monsoon depressions, normally. Monsoon activity happened below the ridge of TH. Qiong and Wu, has explained in their research that the Tibetan high both in upper and lower troposphere has been shift southward and strengthened during flood season (Wu et al.,2006). This statement is in accordance with present condition of TH. Normal position of TH is represented by black dotted line, normally it is positioned along 32° Latitude and red dotted lines represent actual orientation of this high from 09-16 August 2011, as shown in Figure 4. The Figure depicts clear position of the Tibetan high. In July Tibetan high at (200 hpa) lie at (28-32)°N and 80°E with its center at 98°E (Sarfraz, 2007).. In Figure 4dotted line indicate normal position of TH, whereas solid line represents actual position of the Tibetan High in August, 2011. In this season of monsoon Tibetan high got extension up to 26° N along SW direction and blocked the upward movement of weather system as shown in Figure 4 Therefore

monsoon currents could not penetrate in upper parts and caused heavy rainfall in lower parts (South East) of country.

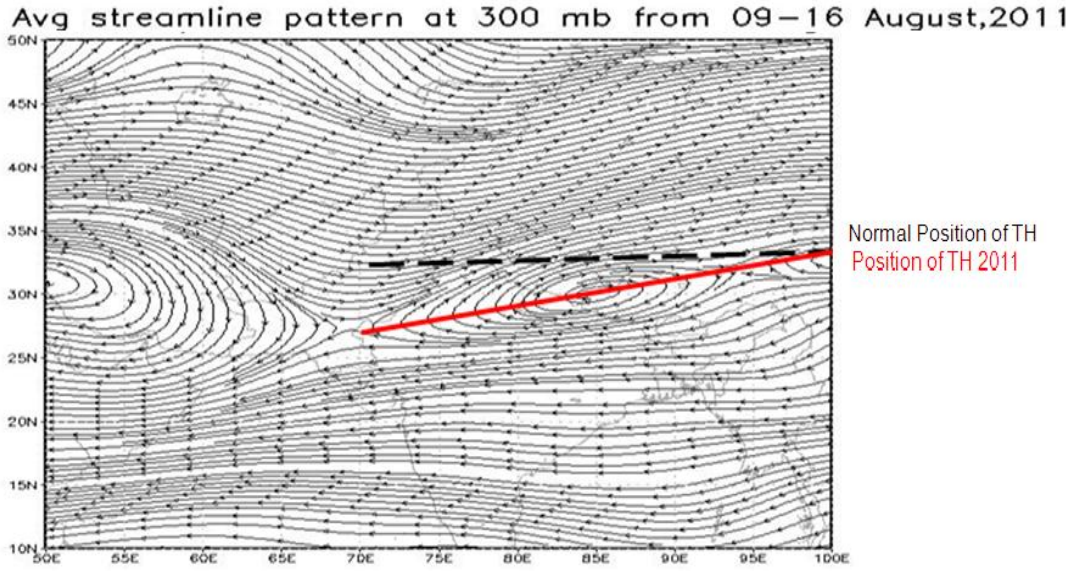

Figure 4: Average stream line patterns at 300 mb from 09-16 Aug showing the southwest tilting of TH.

Seasonal Low

Normally extensive heating of land causes low pressure over Baluchistan during summer season. In Northern hemisphere, the continents surrounding the Arabian sea start receiving remarkable amount of heat not only in form of solar radiation but also thermal infrared radiation emitted out from earth surface during the months from June to August. Heat flux (160watts/m^2) for the month of June over arid zone of Pakistan , Saudi Arabia, N-W India and middle east countries is very large than December (15 watt/m^2) (P.K.DAS, 2007) . Due to this heat intensity seasonal low generates over Pakistan. Orientation, intensity and tilt of this seasonal low also play a very crucial role in developing the weather over Sindh and Baluchistan during summer monsoon (Shamshad, 1988). This low that exists over Baluchistan has the temporal and spatial variation as shown by Figure 5. The Figure indicate the low pressure cell over the Baluchistan, Normal pressure value for seasonal low is 1000hpa which dropped further 4hpa in this Monsoon Season, this low pressure sucked moisture of tropical low pressure, that present at eastern border of Sindh. The synoptic surface charts of 09 &10 August, 2011, for the diagnosis of the current events were selected. According to Fig 5 (a) on 09 August 2011, seasonal low was present over the Southwest border of Baluchistan and adjoining Iran with its trough was towards Sindh. On 10 August, monsoon low trough became under the influence of this heat low. Monsoon anticyclone supported moisture feeding from Arabian Sea. Heat low has been tilted in Northward direction as depicted in 17 August charts. The tilt of low seemed to be enhancing the chances to provide moisture in Sindh from Arabian Sea during the remaining days of August.

Synoptic Situation

A low pressure system prominently entered the areas of Sindh from the Indian states of Rajasthan and Gujarat in August, 2011 and gained strength over the passage of time that caused heavy downpours. This low depression generated over Southwestern border of India with the wind direction from southwest that provide moisture from Arabian Sea due to which relative humidity in the center reached 80 to 100%. On 7th August streamline analysis reveals that there was no strong weather system over adjoining areas of Pakistan as shown in Fig (a). Fig (b) represents that a low pressure system generates over Rajasthan. On 09th August trough extend to the eastern parts of Sindh, again this trough extended and intensified on 10th August as a result

maximum rains occur. Wind direction was Southwest with speed from 10 to 20 m/s in these rainy days. The system was so intensified that its extension was visible in 500hpa charts. Relative humidity for Mithi was recorded 96% on 10th August. Minimum temperature fell by 2°C. Another low pressure system develops on 11th Aug which did not provided sufficient rain over Pakistan

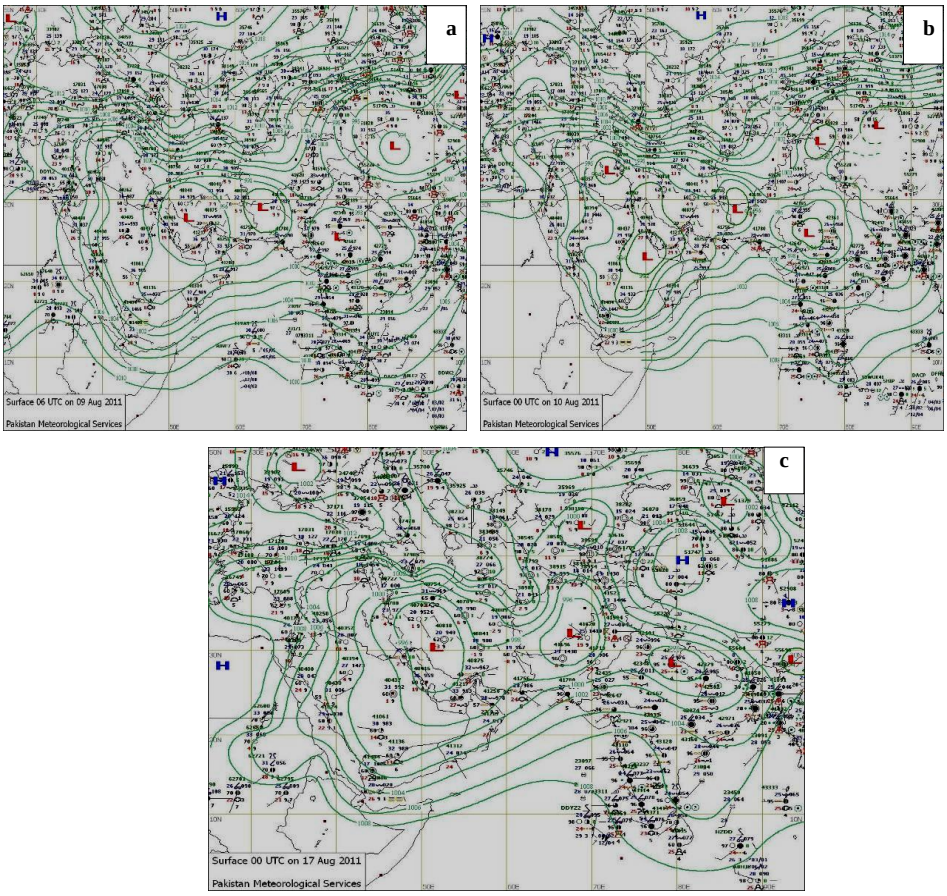

Figure 5: Surface Weather Charts on 9th, 10th& 17th August, 2011

Vorticity Analysis

Vorticity defines as circulations per unit area of the parcel of air exist in the atmosphere. Positive vorticity associated with low pressure system and vice versa. Potential vorticity and its inversion theory play an important part in diagnosing development of weather systems, discussed by Egger and Chaudhary (2009) in their study. Vorticity analysis at 850hpa level is helpful to understand the weather behavior. Blue & green shaded regions in the image depict negative vorticity while red and yellow shaded areas represent positive vorticity. From these analyses it can be concluded that there present convergence over Southern parts of Balochistan, karalla of Indian. Thus strong convergence may provide sufficient chance for weather development over a particular area. On 11th August another depression formed over boundary of Bay of Bengal near Kolkata.

High-pressure system (500hpa)

A high pressure developed over Iran on 09 August to 16 August, which intensified at different times. The ridge of high extended to the Karachi. Figure 8 represent different synoptic charts at 500hpa for different dates. From analysis it was revealed that the high seemed to be present over Balochistan and adjoining areas of Sindh for several days. The behavior of this high pressure was recognized one of the major factors for blocking monsoon currents to enter in Balochistan and KPK.

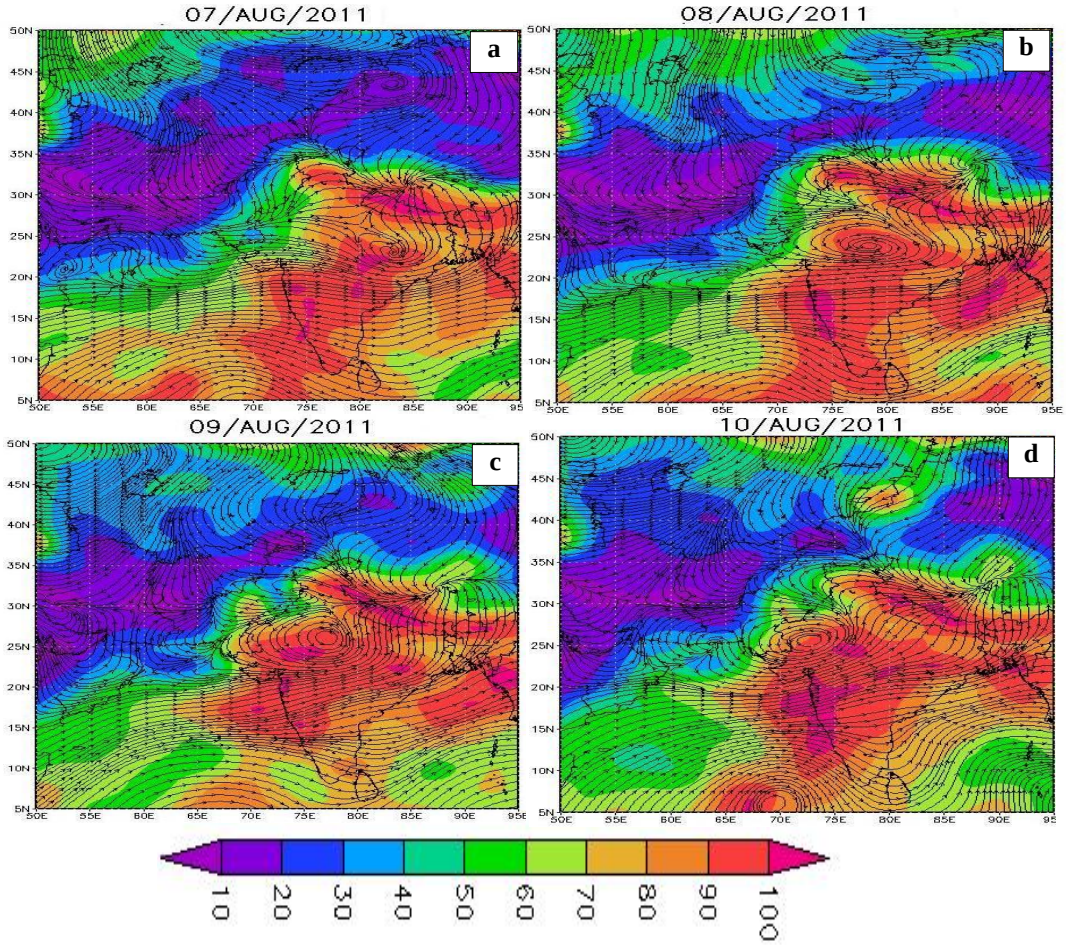

Figure 6: Streamline analysis with (%) Relative Humidity in Shaded at 850hpa on 07th to 10th Aug, 2011 at 1200UTC.

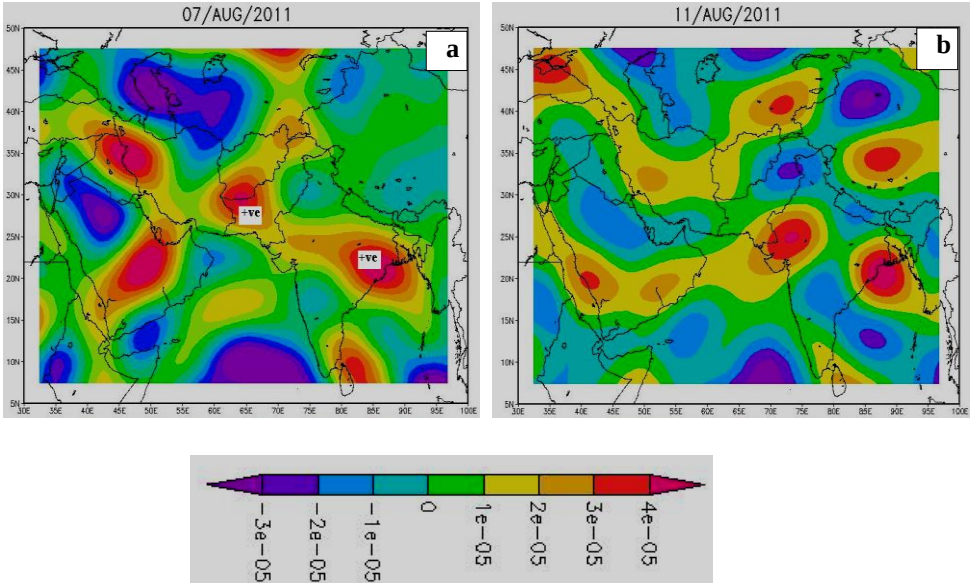

Figure 7: Vorticity analysis at 850 hpa on 07 & 11 August, 2011 at 1200 UTC.

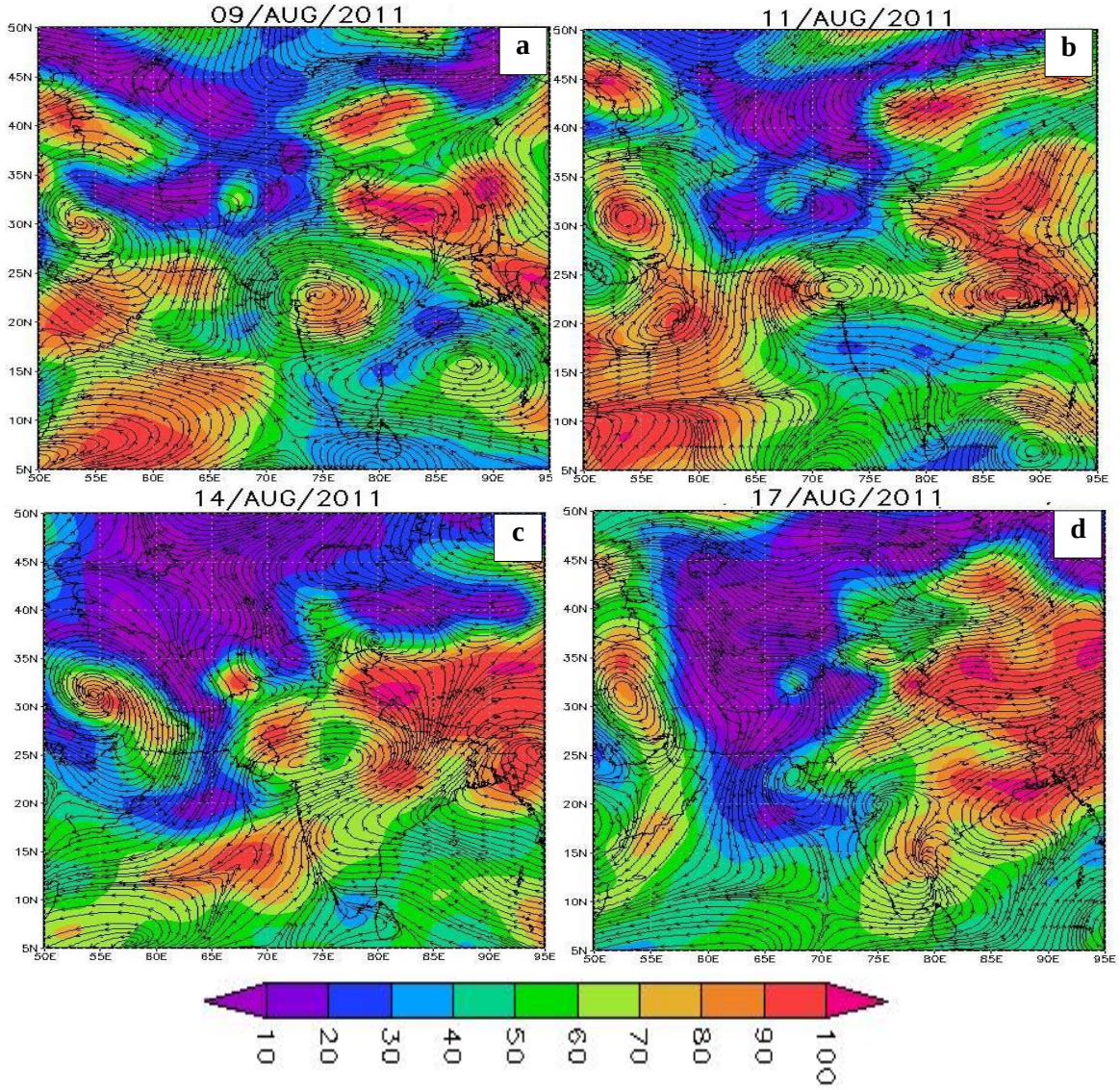

Figure 8: Streamline analysis with Relative Humidity (%) Shaded at 500hpa at 1200 UTC

2nd Spell of Monsoon from 29Aug - 16Sep

Rainfall in Sindh Occurred in two different spells. First spell occurred on account of direct effect of monsoon tilt during 09-15 August. The second rainfall spell occurred from 29 August -16 September, 2011due to indirect effect of monsoon over Sindh and adjoining areas of Baluchistan. In second spell the tropical depression also penetrate up to upper Punjab KPK in Sep 2011. Sindh experienced large spatial variation in monsoon rain than normal. Spatial distribution of heavy downpour caused heavy to moderate rain from southeast to northwest, moderate to light in north and southwest parts of Province as indicated in Figure below.

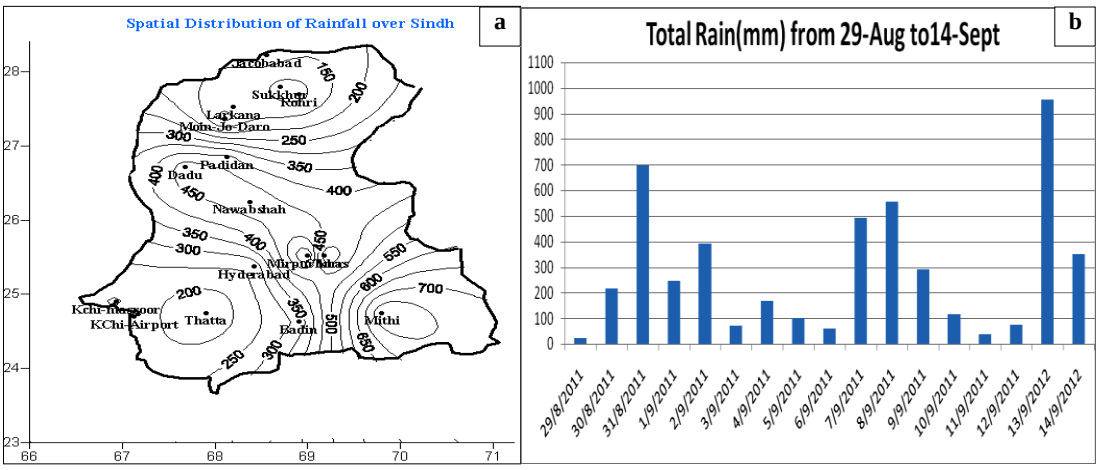

Figure 9: Spatial and temporal variation in rainfall during 2nd spell (29-Aug to 15 Sep).

Mid Tropospheric Cyclone (MTC)

During the 2nd event (29August-15 Sep) a well marked monsoon low lie over Indian Gujrat and adjoining areas of southeast Sindh on 29 August,2011. Its path was same as discussed for (09-15 August) system. All other meteorological conditions were same as discussed earlier. But the main important component for this heavy rainfall was MTC. Therefore for this time MTC discussed in detail. Mid tropospheric cyclone is believed to be one of the major components of the monsoonal air circulation over the western coast of India in summer. The life span of such cyclones are 10 days, they formed once or twice in these months (June-August) normally. The exact reason of its development is yet not known, but it may be developed due to differential heat of Sea and land along the coastal periphery. These cyclones can produce heavy rainfall in coastal areas of India and Pakistan. Mid-tropospheric cyclones can be observed on daily as well as on monthly weather charts over the west coast of India during the southwest monsoon season. These cyclones developed between the 700- to 500-hPa levels in the monsoon trough. The cyclonic signature at the 600-hPa level is much stronger than that at the surface. Maximum convection is found west of the cyclone center. These depressions are also formed periodically over the north and central Bay of Bengal in the southwest monsoon season. Such depressions not only strength the monsoon current over the Arabian Sea but also cause extension of the monsoon rains over India and Pakistan (Ramage, 1966). Miller & Keshvanmurti (1968) investigate the structural feature along with energetic behavior in their diagnostic analysis.

A number of similar mid tropospheric cyclones formed over Northeast Arabian Sea, and adjoining surashtra, kuch region during last week of August and first two week of September. At the initial stage on 25-29 August it gave only some cloudiness and moderate rain. But when developed fully it gave heavy rain over south eastern parts of Sindh including Karachi. This cyclone did not move but oscillate about its mean position, 20°N and 70°E as indicated in Figure 10 (d, e &f) depict that when this low developed, monsoon low did not developed near the Southern parts of Sindh. Another condition that helps the development of such cyclonic depression is a temporary retreat of the southwest monsoon current.

Same conditions support formation of Tropospheric cyclone this year. The strength of the monsoon current increased from June to mid July; it then remains stable, and starts retreating towards the end of August, though occasionally, it continued to be active even in September. Precipitation spell in August have left sufficient moisture on the surface which would support development of meso-scale convective cells in September. Actual data showed that maximum rain phenomenon happened on 31-08, 7, 8 & 13 September. On these days monsoon system dispersed completely and no monsoon system approached near Sindh. It means rainfall in the

month of September, was not a consequence of monsoon depressions. These rains phenomenon happened due to MTC activation. Figure 10(a, e & f) reveals that on 30 August, 07 & 08 September monsoon system was visible over India. Maximum rain produced due to accumulation of remaining moisture of soil and moisture provided from Arabian Sea by MTC. In fig (b), (c) & (d) monsoon depression lie across Southern Sindh and mid tropospheric cyclone was not clearly visible. While data show a moderate rain was recorded for these dates.

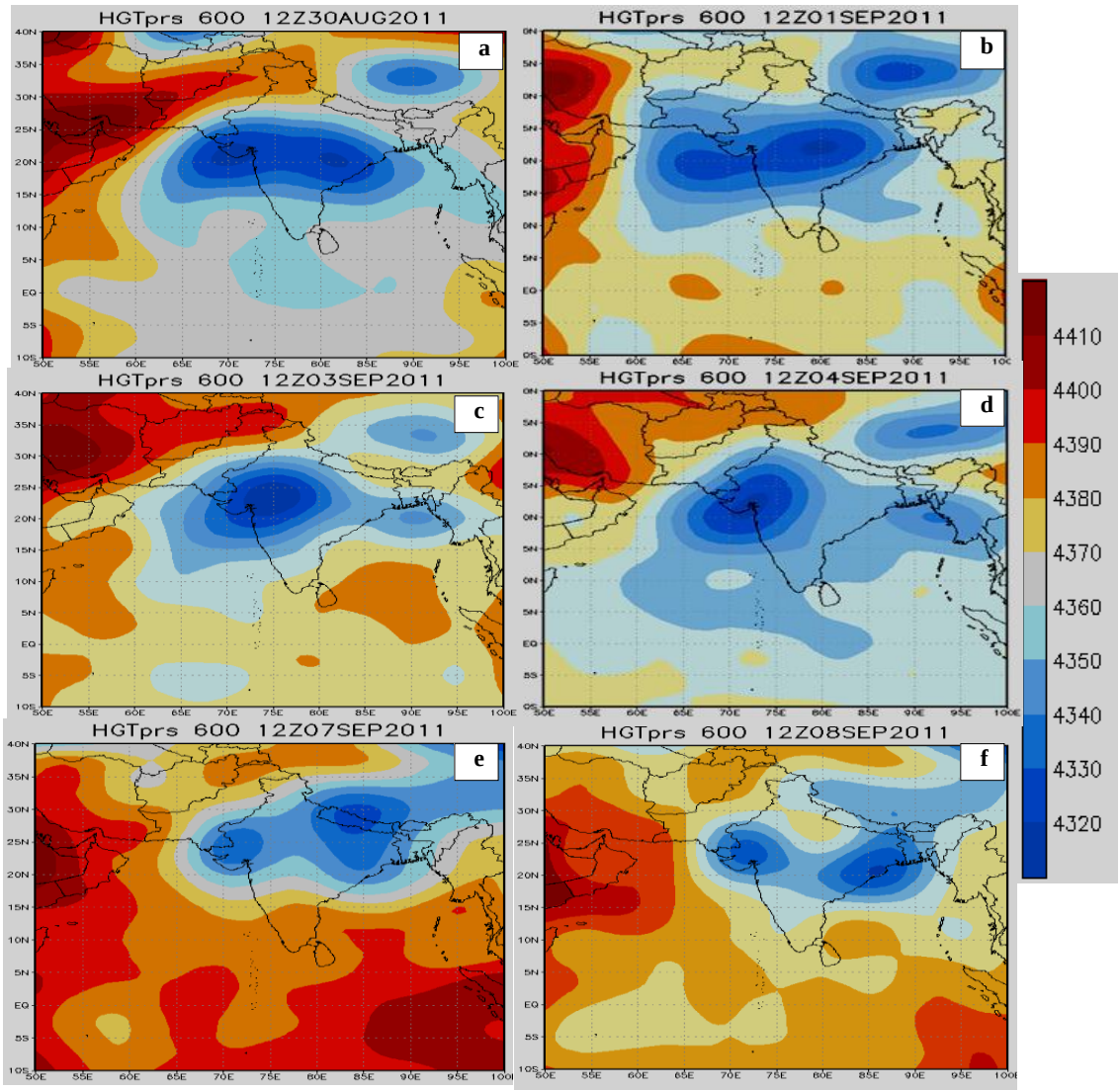

Figure 10: MTC analysis at 600hpa for different dates.

Satellite Images & HRM Model output

From Figure 11 it can be seen that there is a massive cloud over Mahya pardesh on 07 August. Red (dark) region in the satellite picture describes the cloud activity over that particular area. On 10th August, the development is in its mature stage as shown in Figure 11 (b).From the image moisture feeding from Bay of Bengal is also very apparent. These images are obtained FY2E, Chines satellite; images are uploaded after each 30 minutes. According to Kelkar R.R (2007) innovation of remote sensing and satellite technology has facilitate meteorologist in order to observe and study different weather pattern and their mechanism in detail (kelkar, 2007). From Figure11 (c) we can observe that there is huge cloud mass present over province Sindh of

Pakistan on 30th August, 2011. There seems to be a small development in the northern areas of Pakistan after 2nd week of September. Direct moisture feeding from Arabian Sea, on the south of Pakistan, is obvious from the images. In addition to these satellite images, it is a very good idea to incorporate the HRM model output.

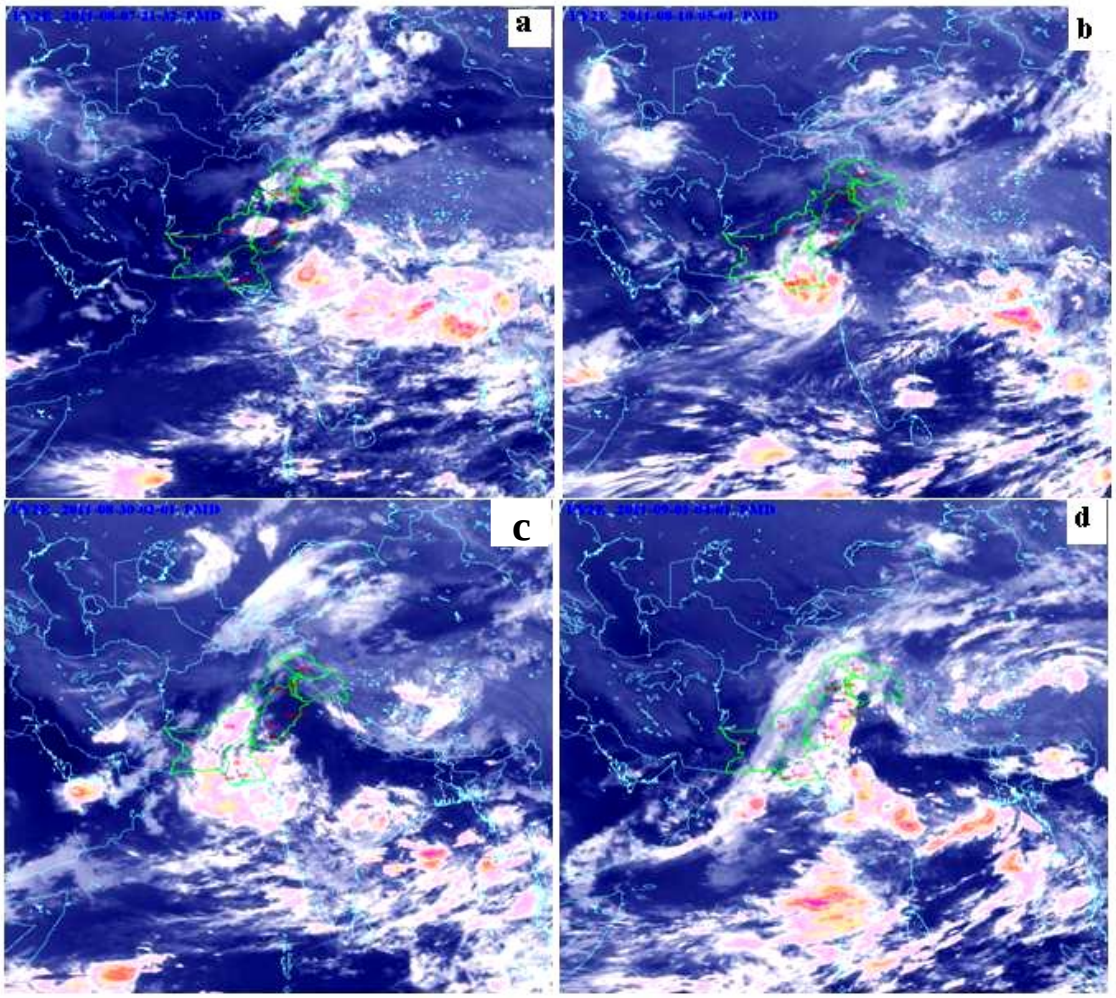

Figure 11: (a) & **(b)** Satellite images 07th and 10th August**, (c)** & **(d**) Satellite images 30th Aug and 4th Sep during first and second spell

Comparison of actual data with model output showed that heavy rainfall event was well predicted by model. Here the intensity, timing and exact location of model for 02 & 16 September has been well captured as shown in Figure 12. Same is the case with output for first spell and other dates.

Conclusions

Following conclusions are drawn from diagnostic study.

- The position of the monsoon depression, that usually extends from eastern parts to north western parts of India. During this monsoon season the orientation of monsoon trough remained south west in lower latitude over India. The anticyclone formed over Bay of Bengal, moved westwards during season instead of their normal northwest movement which ultimately resulted in heavy rains over Sindh.

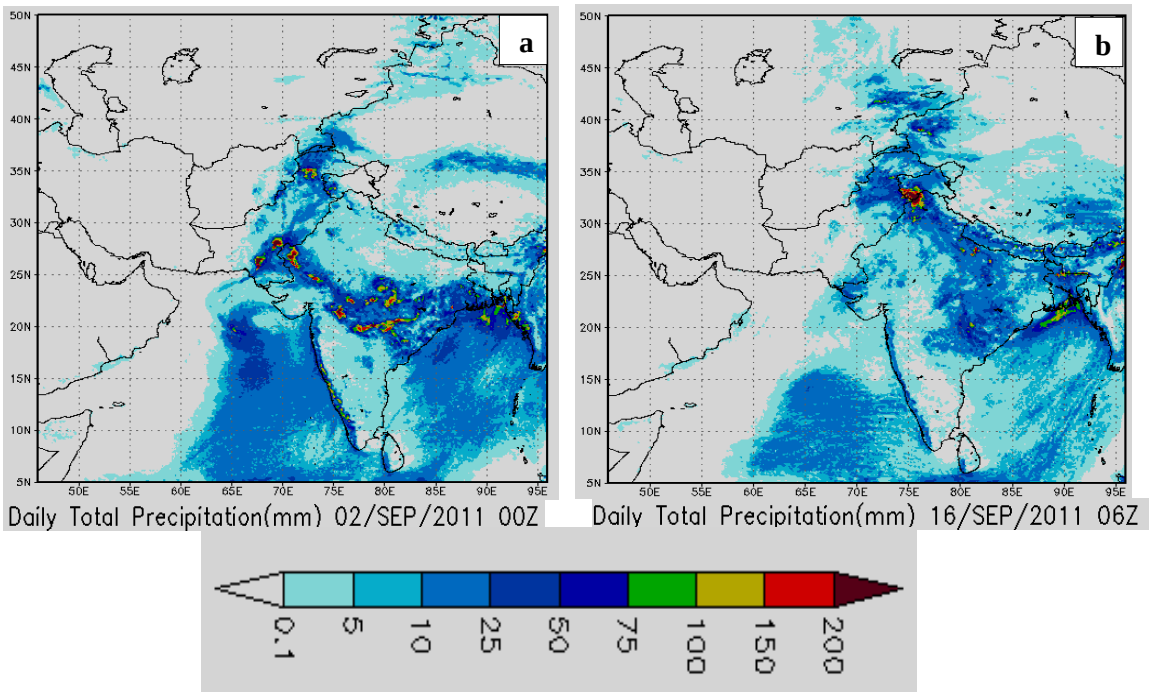

Figure 12: High Resolution Model (HRM) output for 28th July (a), 29th July (b), and 30th July (c), 2010, on 012 UTC

- The main question that need to inquired, why the rain confined only in Sindh. This study focuses these causes. The second cause of rainfall over Sindh was the weak low pressure of season low. Position of low remained above Northwest parts of Baluchistan and pressure was 996hpa in July and August that was lower than the average pressure during these months
- Mid Tropospheric Cyclone persist along coastal areas of Sindh and Mumbai during last week of August and first half of September. These mid tropospheric cyclones also contributed heavy rainfall in Sindh and its adjoining areas, especially in Balochistan.
- Orientation of Tibetan was observed being southeast during most of the period. This blocked the monsson currents to enter in KPK and Punjab. That is why in August Normal rainfall was recorded in KPK and slightly above normal rainfall in Punjab. Another high pressure ridge line was passing through Balochistan and some parts of Sindh. That did not permit the currents to move west wards.

References:

Atif, R.M.., 2011: Diagnostic Study of Heavy Rainfall over Pakistan Producing Catastrophic Flood 2010. M.S dissertation at the University of Comsats,Islamabad. 1-78.

Chaudhry, Q. Z., 1991: Analysis and Seasonal Prediction of Pakistan Summer Monsoon. Ph.D. dissertation at the University of the Philippines, 1-215.

Cheema, S.B., 2011: Variability of Rainfall in Punjab and its impacts on Crops. M.S dissertation at the University of Comsats,Islamabad. 1-121.

Egger, J., Chaudhry, Q. Z., 2009: Progress of Research on Potential Vorticity and its Inversion, Pakistan Journal of Meteorology, 5(10), 3-11.

Flood Report, 2011: Pakistan Meteorological Department, Climate Data Processing Center, Karachi http://en.wikipedia.org/wiki/2011_Sindh_floods

IPCC Third Assessment Report 2011: Climate Change 2007 (AR4). Online publication. http://www.ipcc/publication_and_data.

Kelkar, R. R., 2007: Satellite Meteorology, BS Publications, Hyderabad, 1.

Miller,F.R. and R.N.Keshavamurthy, 1968: Structure of an Arabian Sea Summer Monsoon System.Honolulu, East-West center press,94pp.

Muslehuddin, M., Hazrat. M, and Nadeem, F.2005: Sindh Summer (June- September) Monsoon Rain fall Prediction. Pakistan Journal of Meteorology. 7(13), 55-73.

P.K.DAS, 2007: The Monsoon, Global Moonsoon, p-23-30.

Pakistan National Disaster Management Authority (NDMA), 2011. http://ndma.gov.pk/flood-2011.html

Pakistan Red Crescent Society (PRCS). http://www.prcs.org.pk/disaster_mgt.html.l

Panhwar.M.H, 1993: climatic changes in sindh, 67 million years ago to 1850, J. Sindh Quarterly, Vol. XXII, No. 3, 1993.

Ramage, C.S., 1966: The summer atmospheric circulation over the Arabian Sea, J. Atmos.Sci., 23, 144-150.

Rasul, G., Q. Z. Chaudhary, S. Zhao, Q. Zeng, L. Qi, and G. Zhang, 2005: A Diagnostic Study of Heavy Rainfall in Karachi Due to Merging of a Mesoscale Low and a Diffused Tropical Depression During South Asian Summer Monsoon Advances in Atmospheric Sciences, 22(3), 375-391.

Sarfraz, 2007: Monsoon dynamics: It's Behavioral Impact in Pakistan's Perspective. Pakistan Journal of Meteorology. 4(7), 55-73.

Shamshad, K. M., 1988: The Meteorology of Pakistan, Royal Book Co. Karachi, 128.

Wu, G., Y. Liu, T. Wang, R. Wan, X. Liu, W. Li, Z. Wang, Q. Zhang, A. Duan, and X. Liang, 2006: The influence of Mechanical and Thermal Forcing by the Tibetan Plateau on Asian Climate, Journal of Hydrometeorology-Special Section, 08, 770-789.