# A Report On

***THE IMPLEMENTATION OF DIAGNOSTIC STUDY FOR 2010 FLOOD AND EXTREME MOON SOON RAINS 2011 IN PAKISTAN UNDER SUSTAINABLE DEVELOPMENT THROUHG PEACE BUILDING,GOVERNANCE AND ECNOMIC RECOVERY IN KP AND SUPPORT LANDSLIDE IDPS IN HUNZA NAGAR AND GILGIT DISTRICT WHEN UNDP SURVES AS IMPLEMENTING PARTNER***

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# Diagnostic Study of Heavy Rainfall over Pakistan Producing Catastrophic Floods in 2010 and 2011

## 1. Executive Summary

Pakistan experienced back-to-back heavy flooding during the summer monsoon season in 2010 and 2011. Both the cases were unique in their nature of weather pattern, intensity, persistence over time and geographical extent. Diagnosis has been carried out in order to find out the reasons for the very heavy rainfall over large area of Khyber Pakhtunkhwa (Pakistan) originating cataclysmic flood in Indus River on 28th and 29th July, 2010. Surface and NCEP reanalysis data along with satellite & radar imagery was used for this purpose. It was revealed that heavy rain occurred due to the development of meso-scale convective system (MCS) and evolution of this meso-scale severe weather system was the direct result of interaction between westerly and easterly flows. Tilt and Intensity of Sub-Tropical High (STH) played a crucial role in steering the monsoon low to merge it with the seasonal low. Seasonal low became accentuated due to heavy moisture incursion, both from Arabian Sea and Bay of Bengal, to the northern parts of the country. The subsequent rapid development was the combined result of the presence of the mid latitude westerly's trough aloft in the north and low level moisture feeding through monsoon flow along the Himalayas and also the direct south-westerly current from the Arabian Sea. The cold air advection at the top of the MCS resulted into subsidence whereas warm and moist air tended to rise. This rise and fall generated strong vertical motion in the presence of favorable orogrophic features of the terrain. Torrential rain occurred over upper KP and combined with enhanced snow/ice melt water developed historic flows in the Indus downstream sparing none of the four provinces from inundation.

During 2011, the situation was totally different as the summer monsoon rainfall concentrated over Sindh province instead of Punjab and KP in Pakistan. The axis of the monsoon trough remained oriented from the North Bay of Bengal to Gujrat (India) and Sindh (Pakistan) over a period of one month from the end of July to the end of August. This caused the continuous supply of moisture from the BoB and the Arabian Sea to the low pressure area around Thar Desert. The province of Sindh was the worst hit where deserts were flooded more than cultivated areas and the areas was looking like the Arabian Sea has extended its spread over the province. Diagnostic analyses of monsoon flood 2011 and related meteorological conditions connected this

persistent heavy downpour event with anomalies of the climate change and similar connections can be found in case of 2010 floods. Such rare occurrences have posed the challenge to the meteorologists of the region that the monsoon under climate change may not be following its normal track rather it can reach and focus anywhere beyond expectations. It is clear that wherever monsoon will concentrate, the province of Sindh being lower riparian will suffer the most due to the apparent upstream and downstream connections.

## 2. Introduction

Pakistan having peculiar location over the globe receives rainfall in winter as well as in monsoon. Floods are one of the most devastating meteorological hazards. Many countries around the globe face this turmoil mainly due to excessive rainfall in the catchments of any particular river (Garg, 2002). Pakistan, also, has been facing catastrophic floods in the past such as during the years 1958, 1974, 1988, 1992 etc., all of them occurred during the summer monsoon. The Asian monsoon has two components; the South Asian monsoon and the East Asian monsoon in which the South Asian monsoon is the main source of precipitation over Pakistan. Sometimes, it yields very heavy rainfall in the area when cold air advection aloft takes place due to westerly waves during summer (Rasul *et al*., 2005). The frequency of occurrence of heavy rainfall events is higher in the northern half of Pakistan (Chaudhary, 1991) while it sharply decreases towards the southern half of the country (Rasul *et al*., 2005). It is mainly due to the elevated topography in the northern parts of the country. The moisture which comes from the Arabian Sea or Bay of Bengal becomes cooler as it advances to the northern parts of the country and yields into precipitation.

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 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). 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 PMD2011

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.

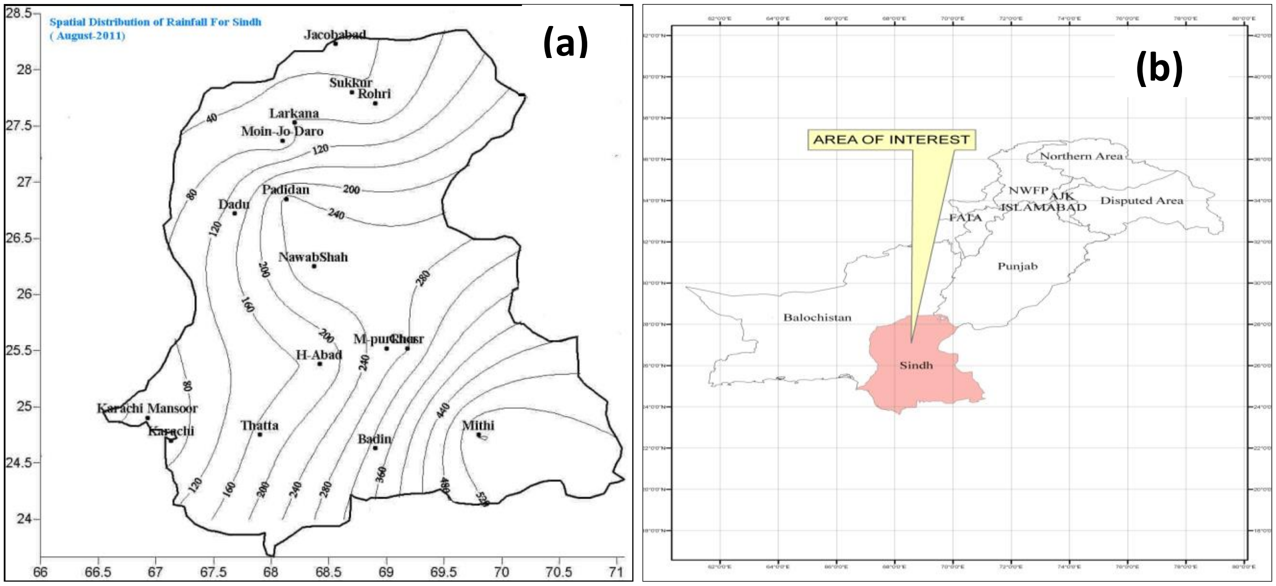



**Figure 1: (a)** spatial distribution of rainfall (mm) from 09-15 Aug, 2011. **(b)** Area of interest for the study. Domain **(05º – 50º N, 50º – 100º E)** has been selected for most of the diagnostic analyses using NCEP Reanalysis datasets.

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.

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 stated that the role of aerosols in general, and carbon aerosols in particular caused complication 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).

## 3. Diagnostic Analysis 2010

Present study is focused on the diagnosis of a very heavy downpour amounting to more than 300 mm over a wide area of Khyber Pakhtunkhwa (KPK); Pakistan, during last week of July, 2010, which caused catastrophic flooding downstream in the Indus River. Due to steep topography and mountain terrain the heavy rainfall turned into flash flooding. This flash flooding resulted into massive destruction of human lives, agriculture, livestock and infrastructure. Torrential rains swept the whole of KPK and claimed 1068 human lives (NDMA). The agricultural land of Nowshehra and Peshawar were inundated by flood water from Kabul River and other tributaries. The torrential rains became the cause of flash flooding as well as river flooding, hence, forged a huge damage to human lives, soil, crops and infrastructure. There is a dire need to forecast these unusual events accurately and timely, so that the colossal loss may be avoided. Such forecast will be highly valuable for the planning in realm of flood control, power generation and hydro-resources management. The spatial distribution of the heavy rainfall over KPK from 26$^{th}$ to 29$^{th}$ July, 2010 is shown in figure 2.

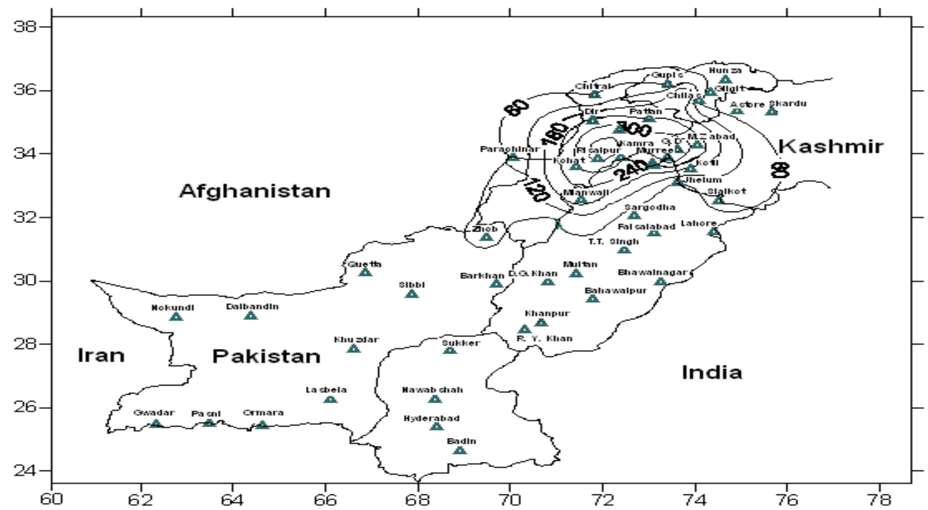



**Figure 2**: Spatial distribution of rainfall (mm) from 26 to 29 July, 2010. Contours are drawn according to amount of rainfall.

Contours are drawn at an interval of 60 mm of accumulative rainfall from 26 to 29 July, 2010. The analysis revealed that during the time a large area of KPK received very heavy rainfall amounting more than 300 mm. Maximum rainfall of all the stations 415 mm was recorded over

Risalpur during the time. From the flood frequency analysis for the past 30 years it was revealed that the heavy rainfall event caused exceptionally high inflows both at Terbela and Kalabagh stations (Flood Report, 2010). The water inflow broke all the previous records and that’s why it was named as “Super Flood 2010”. From figure 3 (a) & (b) the fact is clear that it was the highest flood occurred in the history of Pakistan since 1980.

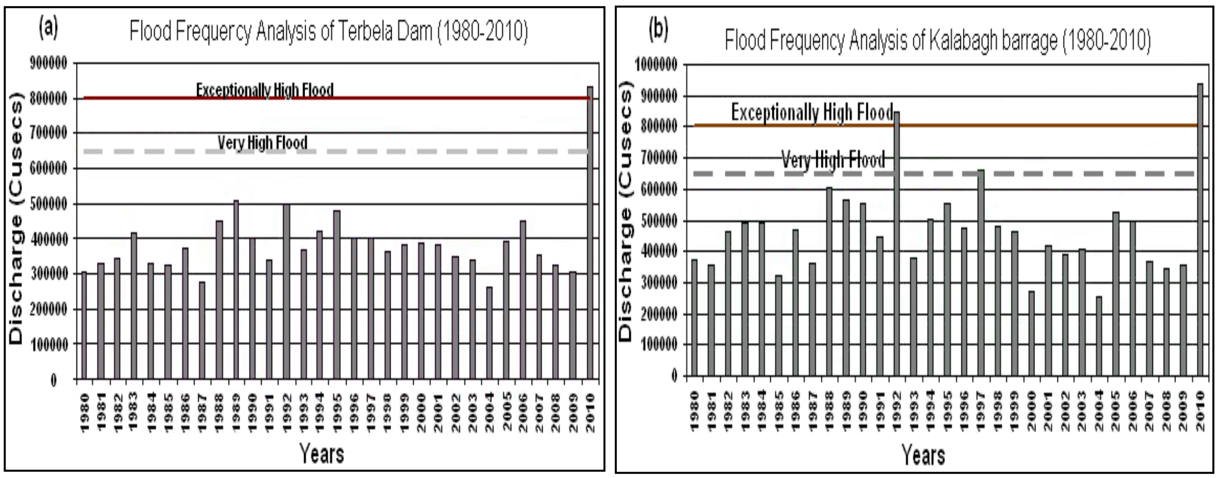



**Figure 3**: Flood Frequency Analysis at Terbela (a) and Kalabagh (b) respectively on Indus River since 1980 (Flood Report, 2010).

### *3.1. Flood Potential in Pakistan*

Floods have a long history associated with the great Indus and its eastern and western tributaries including Upper Indus Basin (UIB) and low elevation flood plains. Some areas experience seasonal inundation and come under water almost every year in the periods of high flows but others either generate flash floods due to their characteristic features of terrain, slope and geomorphology of land. Following map presents the intensity level of floods for different areas of Pakistan (WHO 2007).

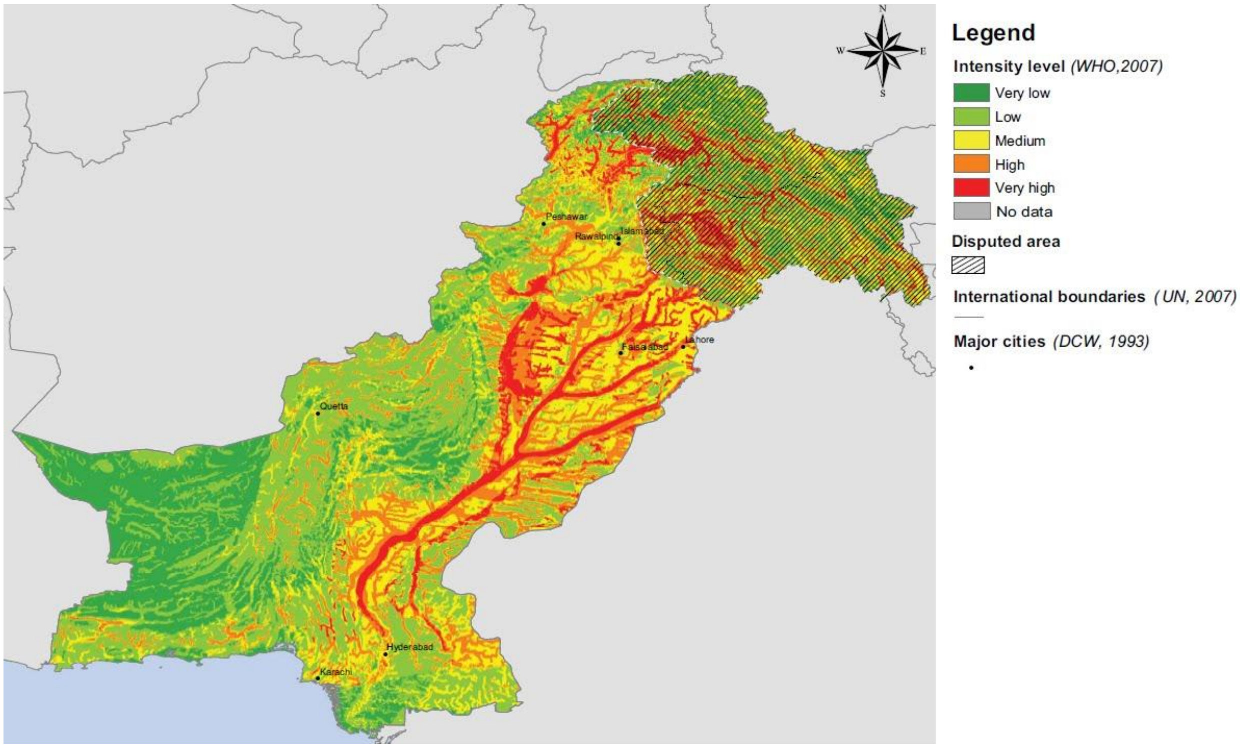



**Fig 4**: Flood intensity level for different climatic zones of Pakistan (WHO 2007). Red colour indicates areas at high risk.

### *3.2. Synoptic Situation and Track of Monsoon Low*

While diagnosing the flood producing rains, it was revealed that a well marked "monsoon low" developed over Northwest Bay of Bengal on 24$^{th}$ July 2010, which initially took northwesterly (NW) course. On 25$^{th}$ July, it moved into West Northwest (WNW) direction and on 27$^{th}$ July, followed by westerly movement finally; it merged into "seasonal low" over Baluchistan. Merger of the tropical low with the seasonal low results in the accentuation of the seasonal low causing the generation of strong Southwest monsoon currents in the upper and lower parts of Pakistan (Majid *et al*, 2006). At the same time, a trough of westerly wave associated with Polar jet extended up to the lower latitudes nearly equal to 30° N in the upper parts of Pakistan. Western disturbance has pronounced effect on the rainfall pattern of India and Pakistan during summer season (Rao *et al*., 1970). It contains cold air mass whereas monsoon currents are warm and moist; therefore, the interaction between westerly and easterly currents resulted in condensation and heavy rainfalls over the catchments of Indus River. The originating monsoon low from the Bay of Bengal and its spatial and temporal variations are obvious from the figure 5(a). During summers monsoon lows are developed over the Bay of Bengal. These monsoon lows carry abundant moisture with them while travelling from the ocean to the land surface. The track of monsoon lows is determined by different parameters e.g. tilts and position of STH, position of seasonal low and westerly wave etc. It is obvious from fig.5 (a) that the monsoon low travelled through the whole India and finally merged into the seasonal low which is generally present over the Baluchistan and adjoining areas. Seasonal low forms over this region due to the strong surface heating during summers. The monsoon currents associated with the monsoon low started penetrating into the upper parts of the country which interacted with the already present westerly currents associated with the trough of westerly wave. A large area of interaction is segregated in the figure 5 (b) which bore the heavy rainfall during the event.

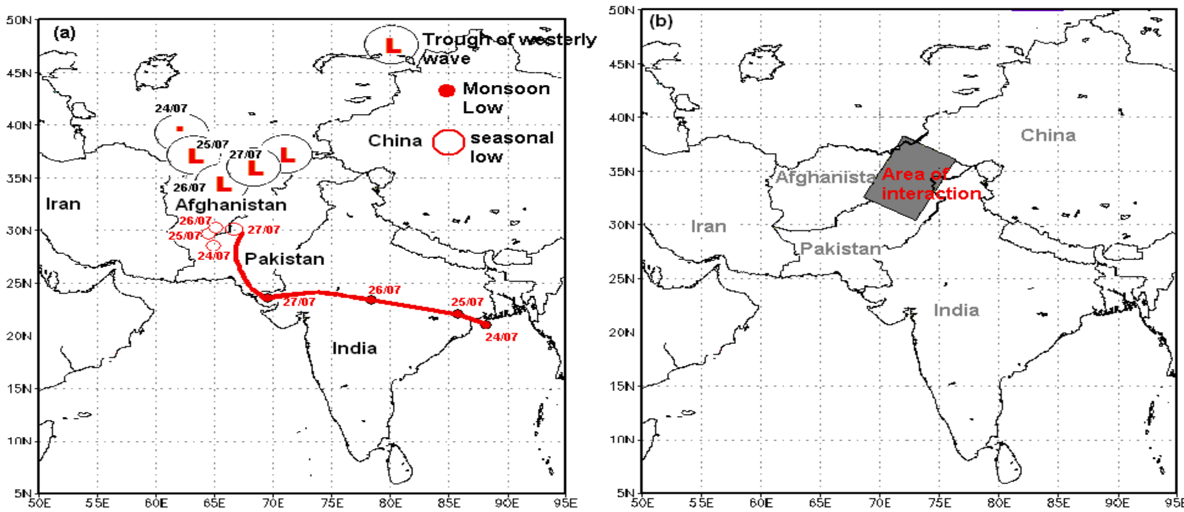



**Figure 5**: **(a)** Synoptic Situation from 24th to 27th July, 2010 at 1200 Z, **(b)** Area of Interaction between Westerly and Easterly currents resulting in heavy rainfall over the northern areas of Pakistan

The situation is also precisely portrayed by using the surface observations during the last week of July, 2010 in figure 6. The line with dots clearly represents temporal variation of the track of monsoon low. It is generally believed that the upper level atmospheric systems steer the ground level systems (Ahrens, 2007). For the intensification of mid latitude cyclones, upper level divergence plays a crucial role. Krishnamurti (1971) explained the existence of divergence at 200 hpa over the northwestern parts of the Indian peninsula in the monsoon season. Mao, *et al*, 2002a, b, 2004, have pointed out the strong relationship between the onset of the summer monsoon and the structure of the Asian Subtropical Anticyclone. Moreover, Qiong and Wu, (2001) has pointed out that the subtropical high at both upper and lower troposphere shifts southward and becomes strengthened during the flood year. From the average streamline pattern at 200mb from 24th July to 31st July, 2010 (Fig. 7), it is obvious that there exists a southwesterly tilt of subtropical high (STH) and its extension up to the western parts of the Pakistan. It is important to observe that the underlying monsoon low followed the same track along the tilt of

STH as it re-curved from the coastal areas of Karachi to the merge into seasonal low, which usually lies over the Baluchistan and the adjoining areas. Presence of jet stream in the north of country and compaction of streamlines shown in fig. 7, played an important role in steering low level weather systems. The position of seasonal low present over Baluchistan also has the temporal variations. The seasonal low shifted northward direction during the last week of July, 2010. This shifting and accentuation may also be attributed to the passing trough of westerly wave from the northern parts of the country. Shamshad (1988), in his book “The Meteorology of Pakistan” describes some salient features of seasonal low. Seasonal low is accentuated while a western disturbance passes through Afghanistan and Northern parts of Pakistan and causes precipitation over Punjab and NWFP now Khyber Pakhtunkhwa when it shifts northeastwards. Figure 6 clearly proves the fact of northeastward shifting of seasonal low.

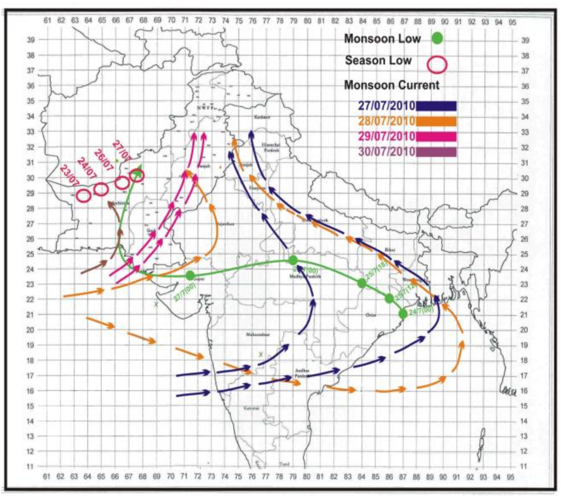



**Figure 6**: Track of monsoon Low from surface observations, moisture incursion and position of seasonal low during the last week of July, 2010 (Flood Report, 2010).

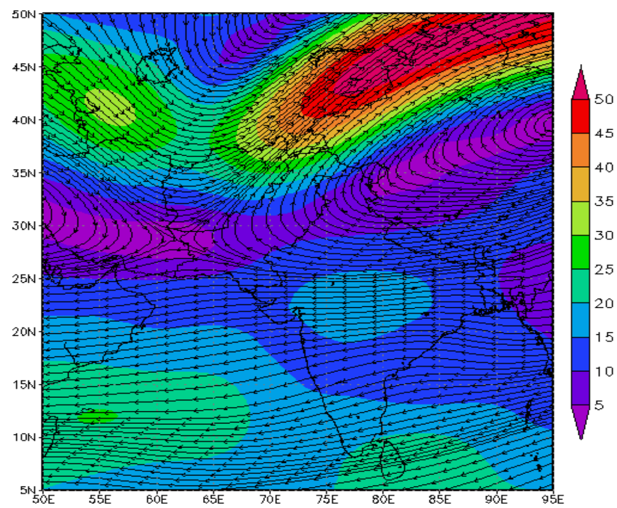



**Figure 7**: Average streamline pattern and position of Jet at **200 mb** from 24-30$^{th}$ July, 2010.

Due to the merging of monsoon low with seasonal low the later became accentuated. This accentuation resulted into the strong moisture flux from both Arabian Sea and Bay of Bengal to the upper parts of the country. From Figure 6 it is also concluded that the moisture from both the sources is penetrating in to the upper parts of the country. Vertical profiles of relative humidity and temperature over Saidu Sharif, Peshawar, Risalpur and Kakul, which lie along the same grid point **72.5° E** for the NCEP reanalysis data, from 26$^{th}$ to 29$^{th}$ July, 2010 are shown by figures 8 (a), (b), (c) & (d). Vertical profile of relative humidity for the region provides the clear indication of moisture penetration up to much higher levels in the atmosphere. The maximum ranging relative humidity 80% prevailed between 1000-850 hpa from 31.5° N to 34° N shown in Fig. 5a. On the following day as shown in Fig. 5b the maximum values of relative humidity ranging 80% to 90% prevailed between 1000-650 hpa from 32° N to 36° N. Analysis of temperatures along the same dimensions reveals that below this high amalgamation of relative humidity warm conditions are prevalent. Temperatures ranging from 30-35°C can be identified between 1000-850 hpa from 32° N to 36° N, the region where maximum values of relative humidity was prevailing. Hence, the prevailing conditions of relative humidity and temperature resulted in highly unstable atmosphere between the above mentioned regions.

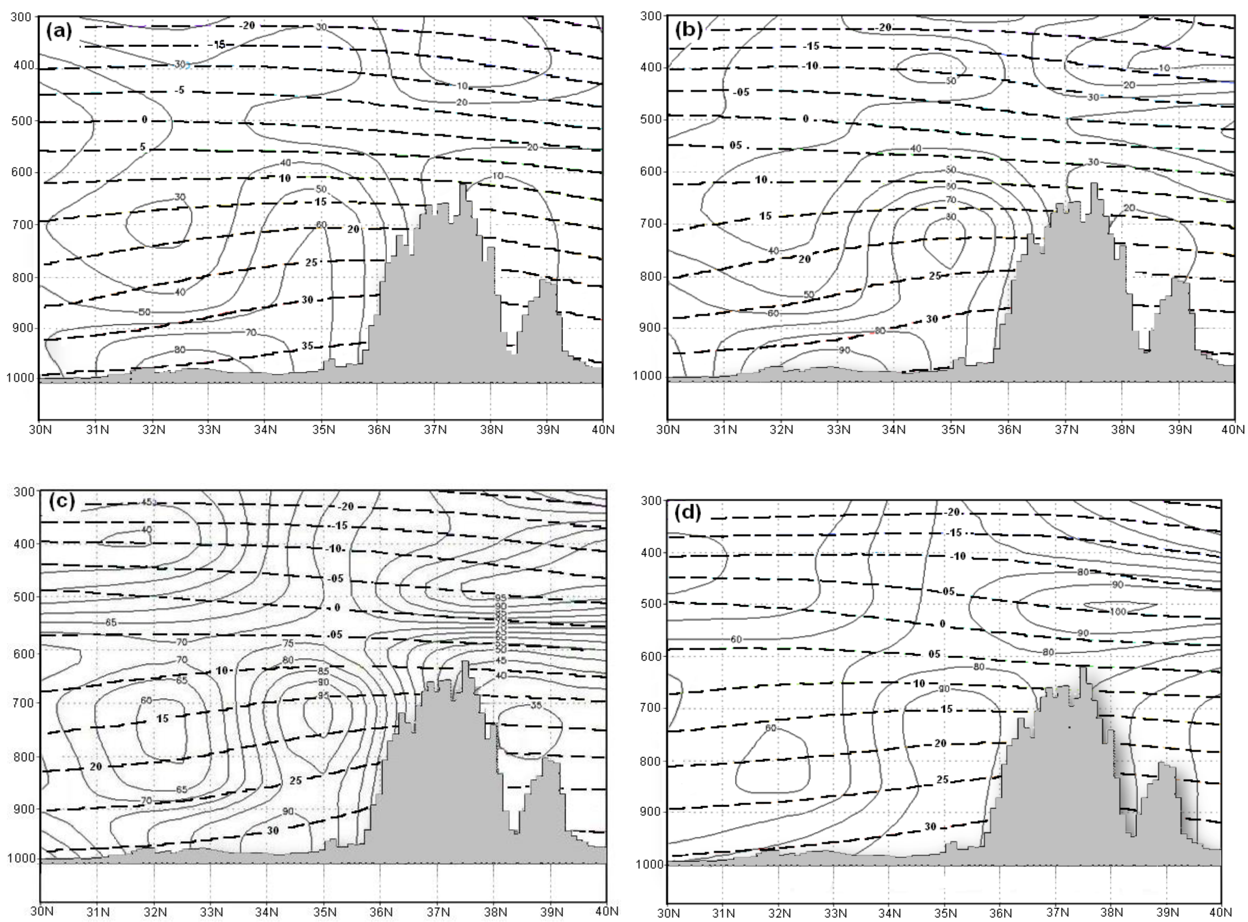



**Figure 8**: Vertical profile of RH (%) and air temperature (°C) for Saidu Sharif, Peshawar, Risalpur, and Kakul from $26^{th}$-$29^{th}$ July, 2010 at 1200 UTC is shown in (a), (b), (c) & (d) respectively. The dotted lines represent the temperature profile while the other contours represent that of relative humidity. The gray bars depict the height correction in each graph. For NCEP reanalysis data longitude **72.5°** E is chosen whose grid encompasses all the above mentioned stations.

Omega which gives the vertical velocity (m/sec) is also a crucial indicator to find out the stability of the atmosphere. Positive values of Omega suggest the upward motion of the atmosphere while negative values conclude the downward motion. An upward vertical velocity of the atmosphere can lead to a large volume of precipitation if the moisture is present to be condensed. Fig.9a gives the clear indication of the negative omega values that is the subsidence of cold air from the 500 hpa on 26th July, 2010 at 1200 UTC in the northern parts of Pakistan. The same situation is further observable for the 27th, 28th and 29th July, 2010 1200 UTC shown in Fig. 9b, c & d.

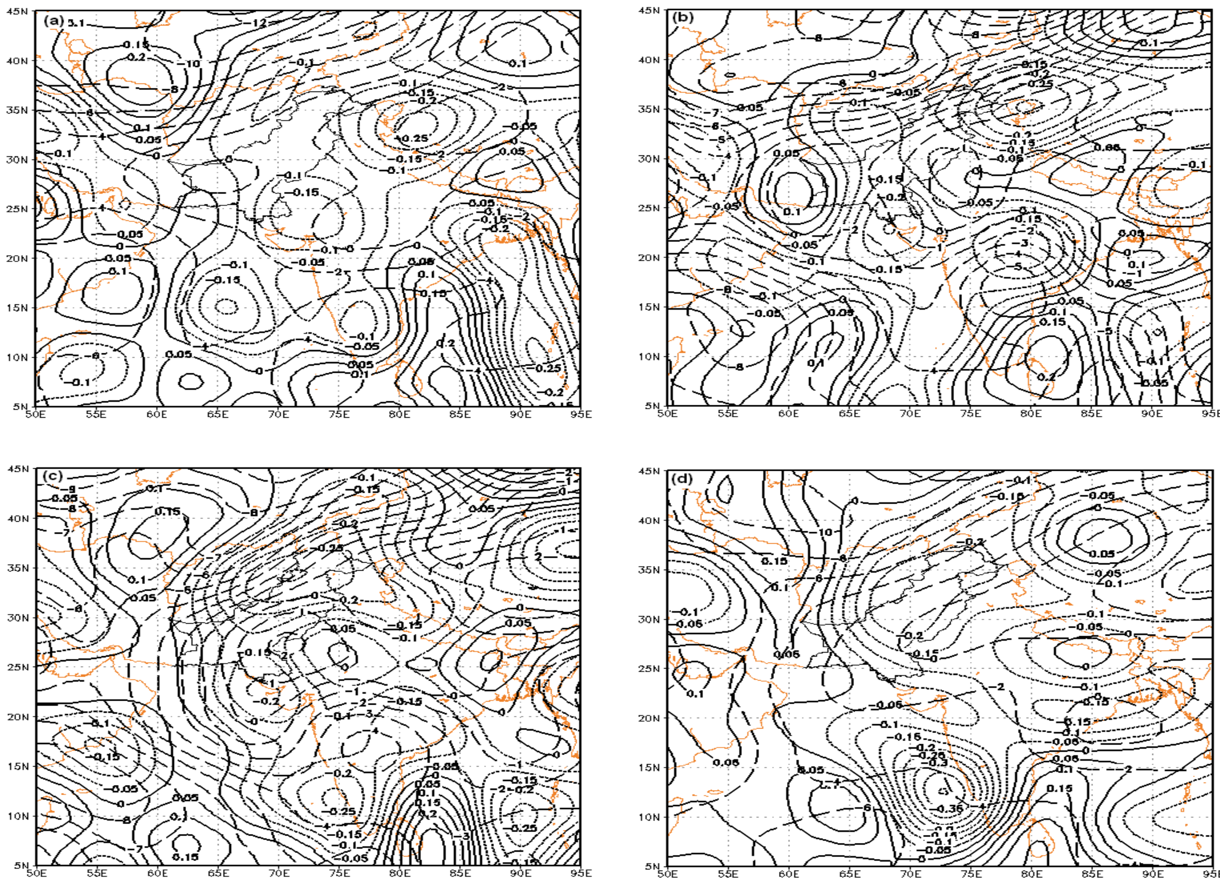



**Figure 9**: Vertical velocity "Omega" (m/sec) in contours and temperature trends (°C) in dotted lines at 500 hpa from 26th to 29th July, 2010 (a), (b), (c) & (d) respectively, at 1200 UTC.

It is interesting to note that at level 850 hpa, during the same period, there are positive values of omega in the north of country, which show the upward motion of the warm moist monsoon air mass during the last week of July, 2010 at 0000 UTC. Figs. 10a, b, c, & d show the positive omega trends over the northern parts of the country at 850 hpa during the period. The below mentioned observations provide a clear cut clue for convective cell development in the upper parts of the country. Temperature contrast between the two levels is also significant which provides a sound basis for the presence of cold air aloft.

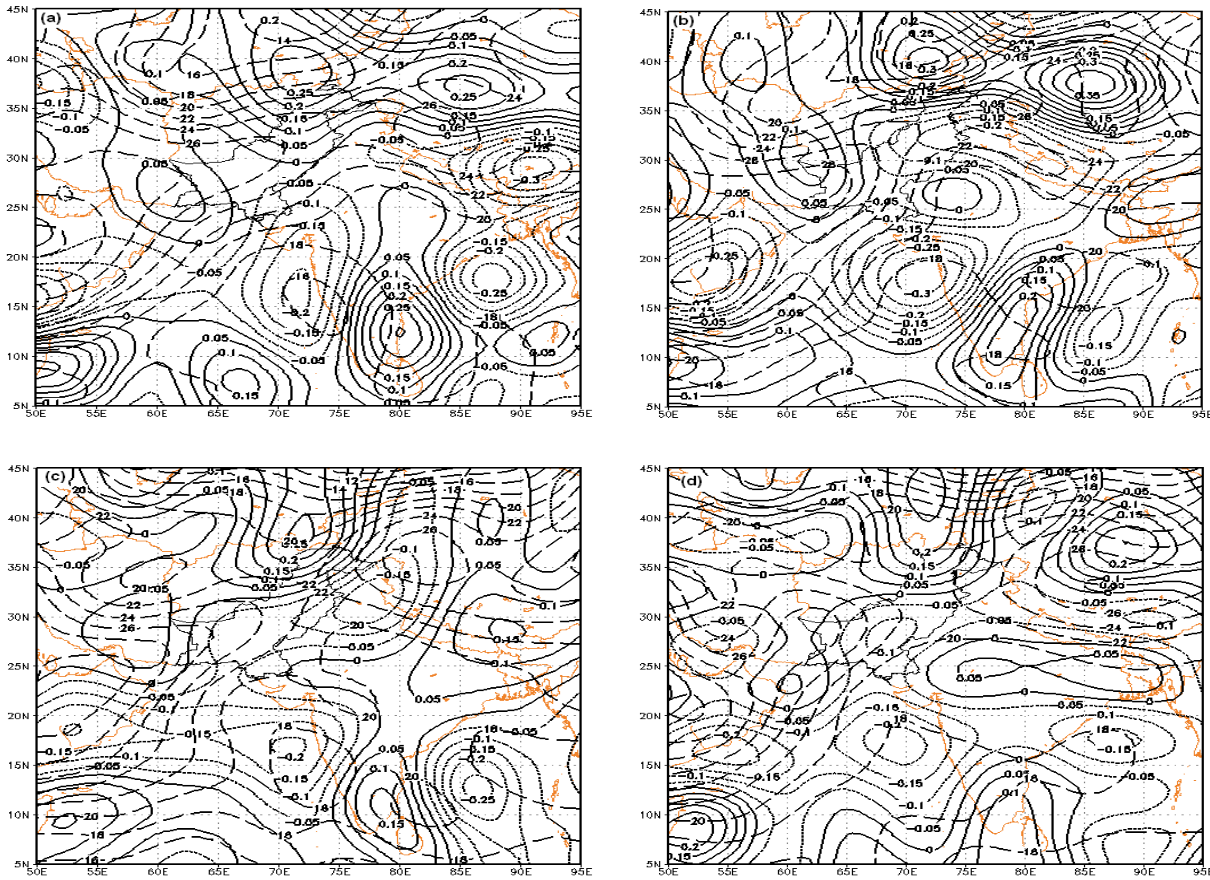



**Figure 10**: Vertical velocity "Omega" (m/sec) in contours and temperature trends (°C) in dotted lines at 850 hpa from 26th to 29th July, 2010 (a), (b), (c) & (d) respectively, at 0000 UTC.

Moreover, this uplifting is observable up to high atmospheric level that is at 700 hpa during the period. The positive trends of the omega value at this level shown in Figs. 11 (a), (b), (c) & (d) suggest that there exists upward motion of the warm and moist air which condensed in to heavy rainfall on cooling.

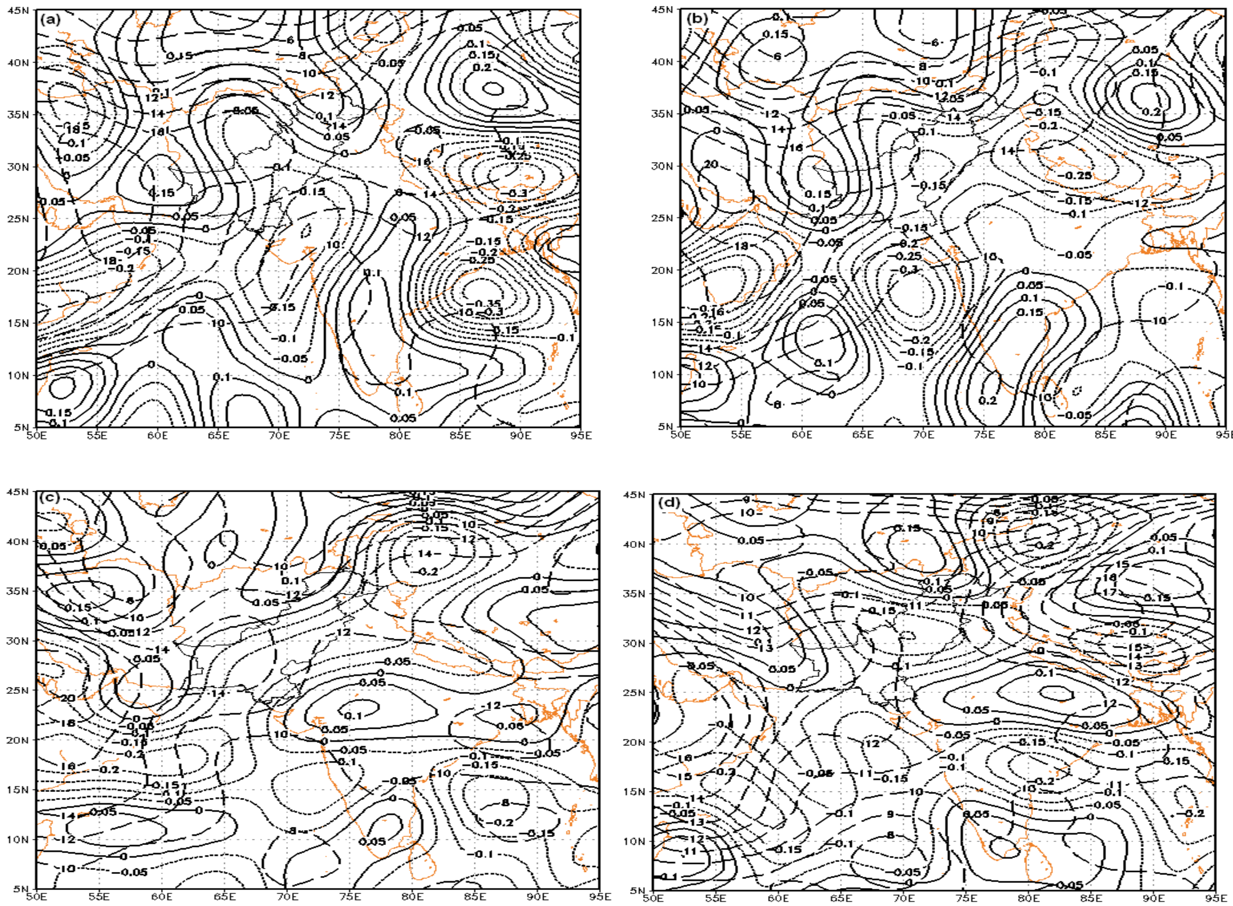



**Figure 11**: Vertical velocity “Omega” (m/sec) in contours and temperature trends (°C) in dotted lines at 700 hpa of 26th to 29th July, 2010 (a), (b), (c) & (d) respectively, at 0000 UTC.

Vorticity gives us the turning effect of the parcel of the air present in the atmosphere. Egger and Chaudhry 2009, confirmed that potential vorticity and its inversion theory play an important role in diagnosing the evolution and development of weather systems. High pressure systems are usually associated with the negative vorticity field. Rasul *et al*., 2004 elaborated the upper air divergence to be the crucial factor for the development of the lower unstable monsoon system and its uplifting. Infact upper air divergence provides sufficient space for the moisture to uplift over a particular area. Divergence creates space to accommodate the air hence enhances the chances of convection cell development. Upper air divergence at 200 mb charts from 26th to 29th July, 2010 at 1200 UTC, is explained by the vorticity analysis as shown in Fig. 12 (a), (b), (c) & (d). It is clear that the minimum vorticity centre lies in China with its extension over the northern parts of the country implying that there is a strong divergence zone over the northern parts of the country on 26th July, 2010 at 1200 UTC shown in Fig. 12(a). The situation is further intensified on 27th July, 2010 at 1200 UTC as shown in Fig. 12 (b) and remained the same for 28th and 29th July, 2010 as shown in Fig. 12 (c) & (d).

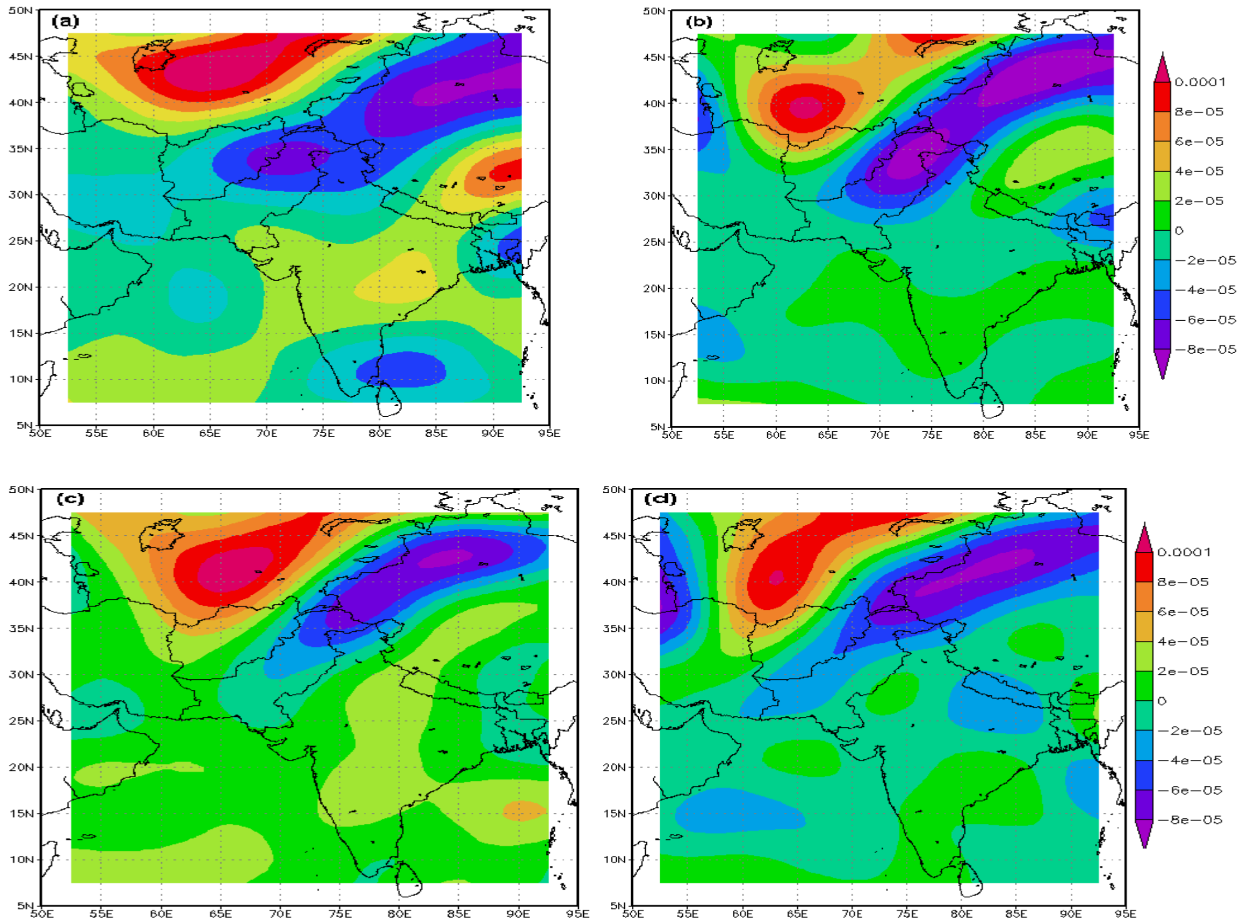



**Figure 12:** Vorticity analysis at 200 hpa from 26th to 29th July, 2010 (a), (b), (c), & (d) respectively at 1200 UTC.

Similarly, the maximum positive vorticity centers were located in the north of Afghanistan and the same trend is observable from 26th July to 29th July, 2010 at 1200 UTC.

## 4. Interaction of Two Weather Systems

Rao (1976) elaborated that the movement of southern wing of westerly waves across Pakistan and northwest India is altered by the sub-tropical ridge in the mid troposphere and one aloft. T. J. Lang and A. P. Barrows have concluded in their studies that the western disturbances are trapped and intensified by the unique large scale topographic features i.e notch formed by the Hindukush and Himalaya mountains. Moreover, Tibetan Plateau exerts profound thermal and dynamical influences on the circulation, energy, and water cycle of the climate system (Wu, *et. al* 2006). Tibetan Plateau plays an important role in the seasonal evolution of the meridional gradient of heating and in triggering the onset of the Asian summer monsoon (Murakami and Matsumoto 1994; Ueda and Yasunari 1996).

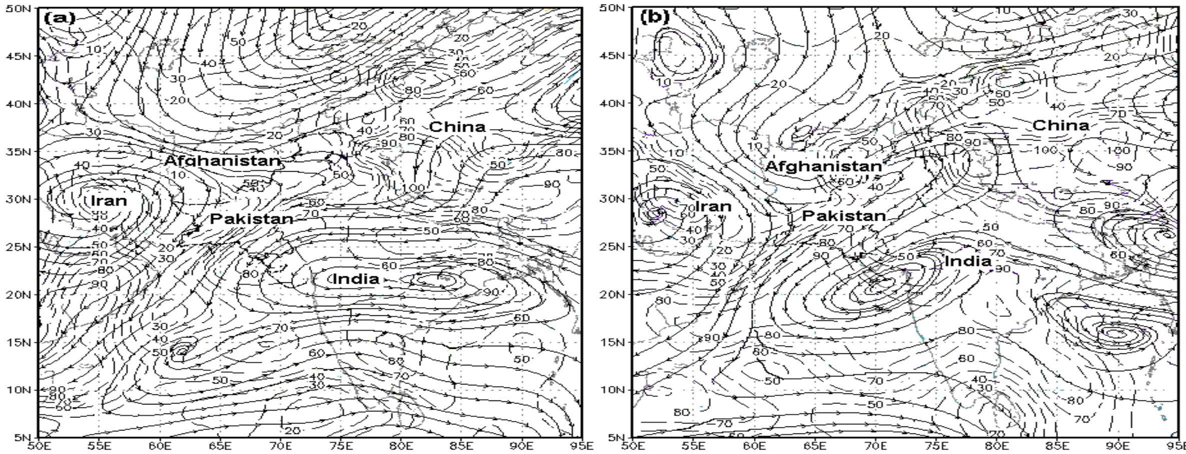



**Figure 13 (a) & (b)**: Streamline analysis with Relative Humidity (**dotted contours**) at 500 hpa from 26th & 27th July, 2010 at 1200 UTC respectively.

Fig. 13 (a) depicts the presence of westerly wave in the north of Afghanistan while the dotted contours of relative humidity show that the moisture supply is limited yet. The situation becomes more favorable on 27th July, 2010 as the trough of westerly at 500 hpa has managed to locate itself about 30 ° N over Afghanistan and adjoining areas of Pakistan as shown in Fig. 13 (b).

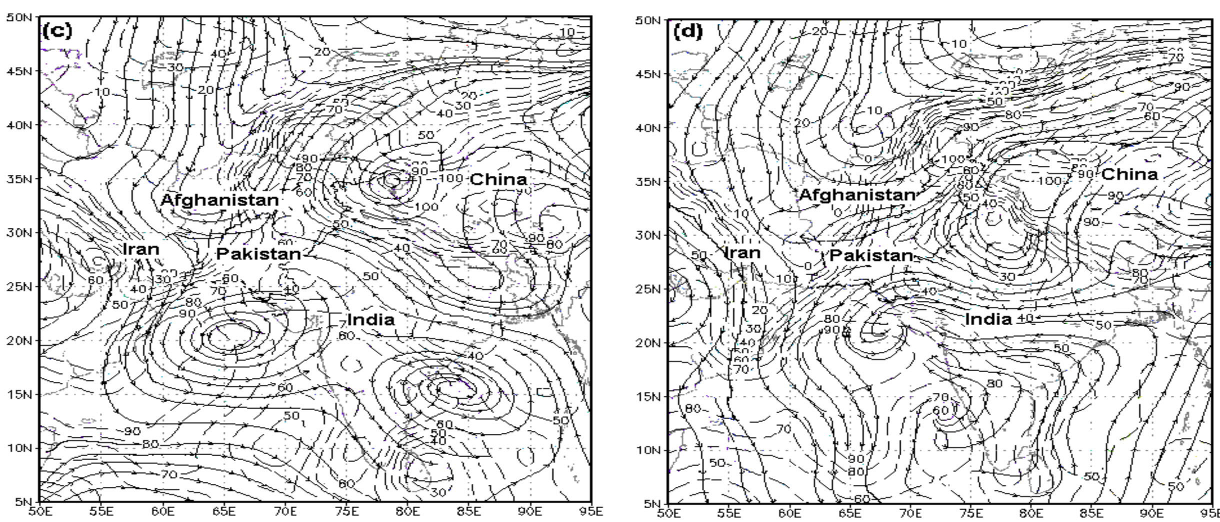
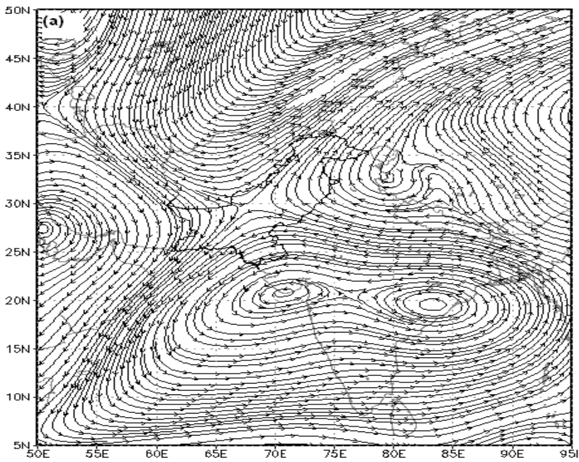



**Figure 13 (c) & (d)**: Streamline analysis with Relative Humidity (dotted contours) at 500 hpa on 28th & 29th July, 2010 at 1200 UTC respectively.

On 28th July, 2010 streamline analysis reveals that there is a moisture penetration along the foothills of Himalaya to the upper parts of the country as shown in Fig. 13 (c). This moisture penetration is very important for the development of severe weather system when there was an existing trough of westerly wave. The interaction of both resulted in very heavy downpour as discussed by Rasul *et al.* 2004.



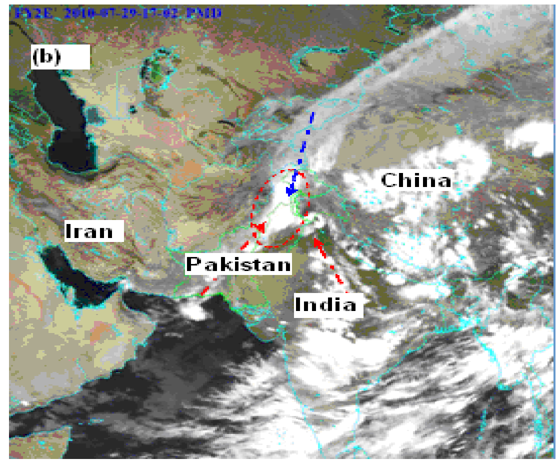




**Fig. 14**: **(a)** Average Streamline pattern at 500mb from 24-30th July, 2010, **(b)** Interaction between two weather systems indicated over the satellite imagery on 29$^{th}$ July, 2010 at 1200 UTC.

Fig. 14 (a) represents the average streamline pattern at 500mb, which also proves the fact that the trough of westerly wave extended to the lower latitudes and the penetration of moisture up to 500 hpa from the Bay of Bengal during the last week of July, 2010. Hence, the warm moist air from both the Bay of Bengal and the Arabian Sea interacted with the westerly wave containing the cold air shown in Fig. 14 (b). It is worth mentioning that the interaction of two weather systems played an important role in setting up a conducive environment for the occurrence of heavy rainfall event. From the Analysis of geopotential heights as well as temperature on 28$^{th}$ and 29$^{th}$ July, 2010 in Fig. 15 (c ) & (d), clearly revealed that there is a cold air penetration due to the extension of Sub-tropical high over the western parts of Pakistan. Cold air from the higher latitude resulted into the development of severe weather where it interacted with the moist, warm and convectively unstable monsoon air mass. The invasion of this cool air from the middle-upper troposphere in the presence of moist and warm monsoon air mass at the lower level leads to the unstable stratification of the atmosphere as discussed by Rasul *et al*., 2004.

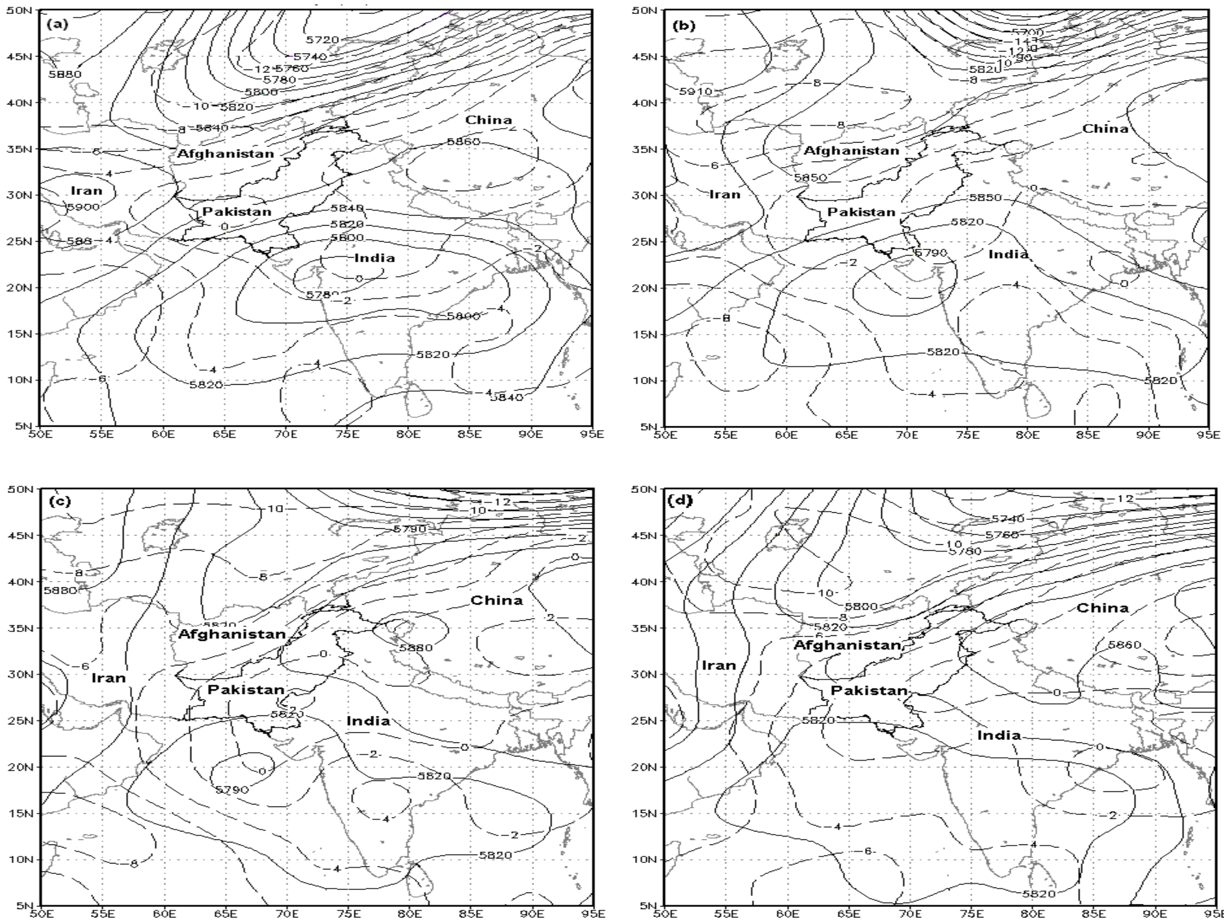



**Figure 15**: Geopotential heights with temperatures **(dotted contours)** at 500 hpa from 26th to 29th July, 2010 (a), (b), (c) & (d) respectively, at 1200 UTC.

## 5. Impact of Jet Stream

The jet stream, a massive ring of high speed winds, was very intense than usual over north western Pakistan, persisted for several days causing moist monsoon currents to be sucked faster and higher into the atmosphere. Shouting and Shiyan (1991-02) have reported that the lower layer frontogenesis was induced by the acceleration of upper jet stream. The prevalent jet stream associated with the westerly wave from figure 16 (a) (b) (c) & (d) a jet stream associated with westerly wave is also passing through the north of Pakistan. The behavior of jet stream is recognized as one of the significant contributing factors which caused nearly stagnation of occluded front as shown in figure 16 (a) & (b). Hence the jet stream provided a conducive stage at the upper atmospheric level for heavy moisture influx to upper parts of the country.

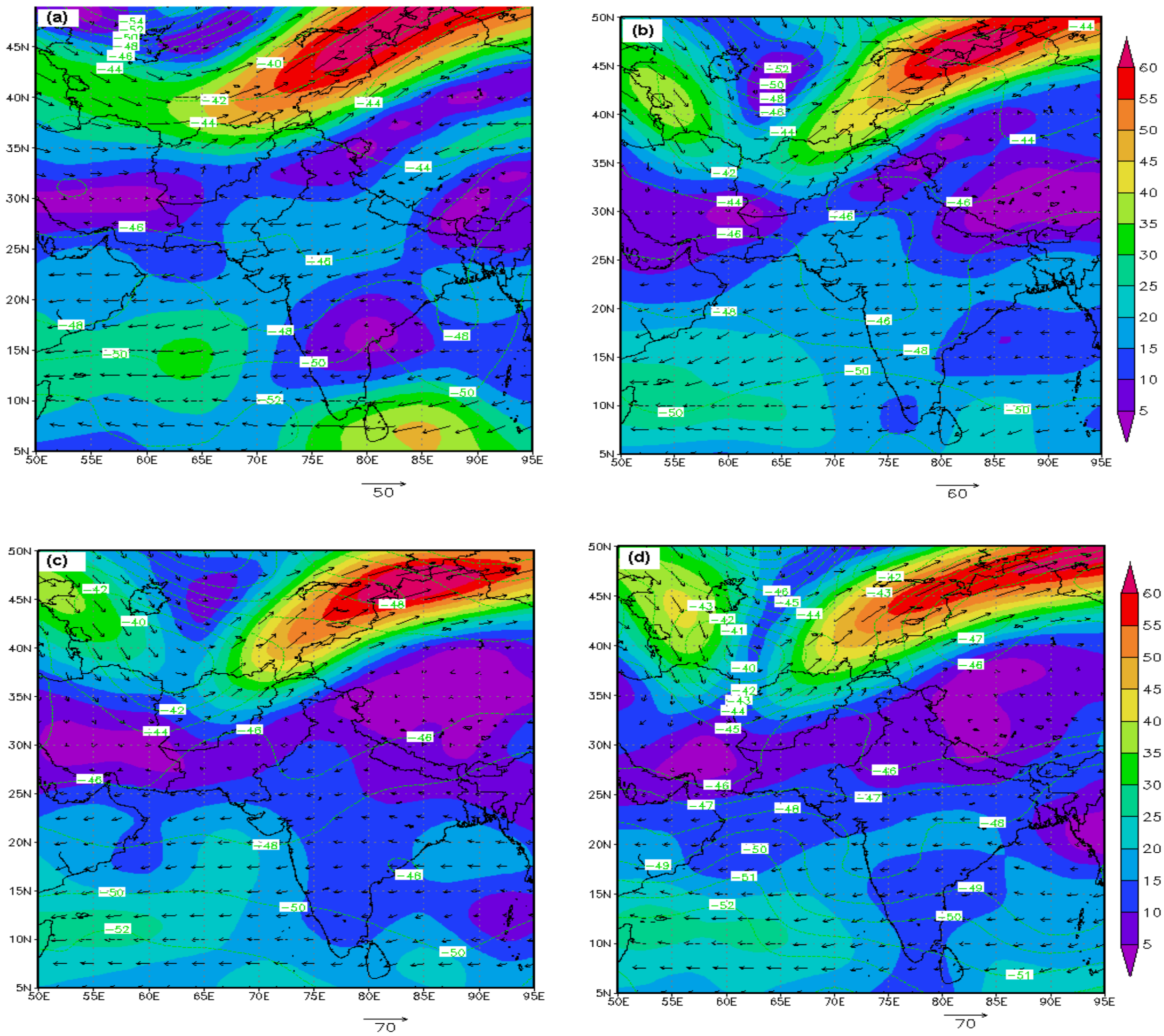


**Figure 16**: Position of Jet Stream at 200 hpa and temperature analysis from 26th July to 29th of July, 2010 **(a)**, **(b)**, **(c)**, & **(d)** respectively at 1200 UTC.

The characteristic of jet stream is that along this high stream of air flow the adjacent atmosphere has two types of circulations. On the left side of jet stream, the adjacent atmosphere has anti-cyclonic circulation while on the right side it is cyclonic. These types of circulations lead to the positive and negative vorticity respectively. Continuous presence of the jet stream over the north of Pakistan leads to the stagnation of the westerly wave there. This stagnant behavior of western disturbance due to the jet stream provides the continuous vacancy for the moisture coming from both Arabian Sea and the Bay of Bengal.

### 6. Satellite & Radar Imagery

Advancement of Remote Sensing and Satellite technology has provided a lot of ease to the meteorologists in order to observe and study different weather patterns in detail (Kelkar R.R, 2007). IR-Satellite cloud imagery (Fig. 17 (a), (b), (c), (d)), courtesy of (NASA) from 26th to 29th July, 2010, showing a large area of intense thunderstorms covered much of Pakistan.

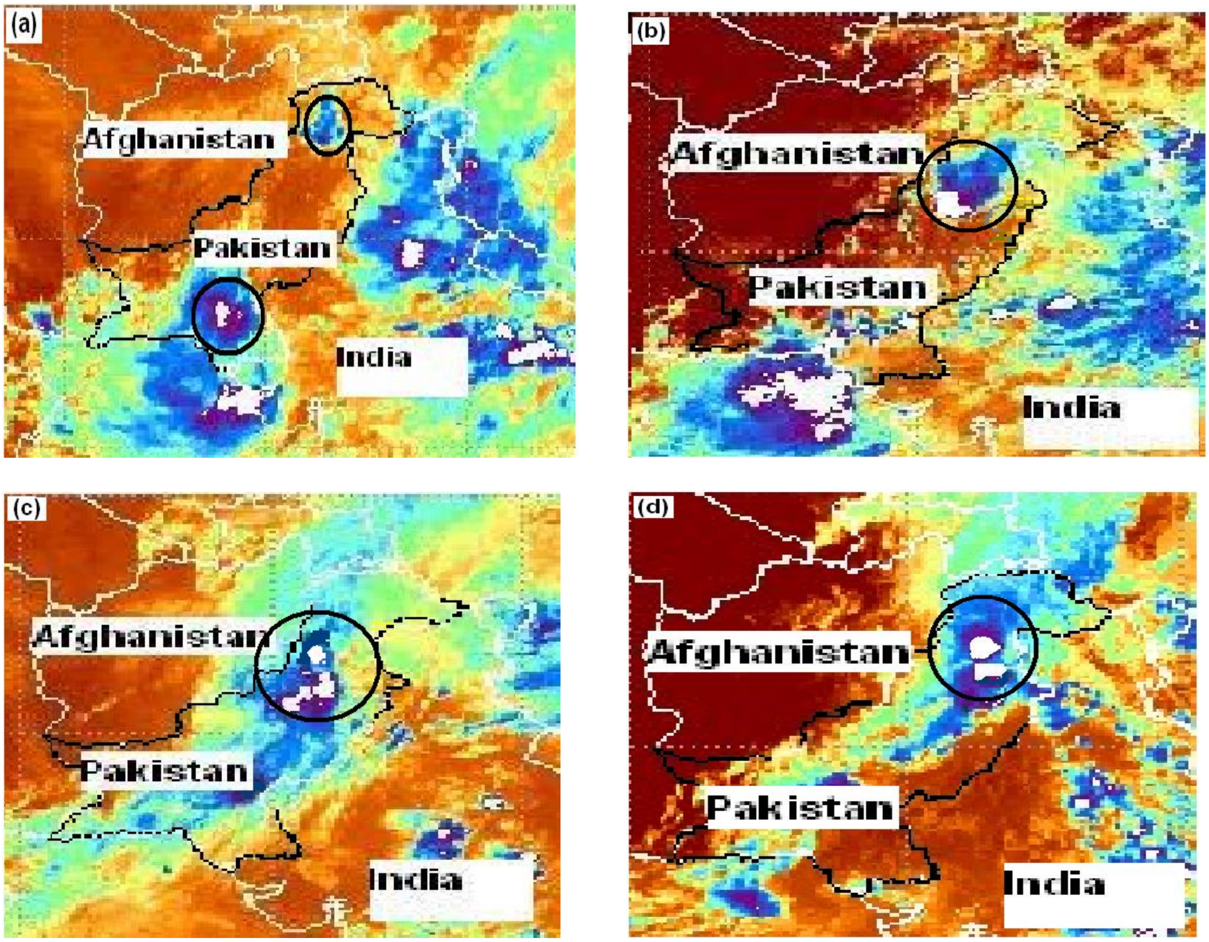



**Figure 17**: IR-Satellite Images from 26th to 29th July, 2010. at 2115 UTC **(a)**, 1015 UTC **(b)**, 1815 UTC **(c), &** 1115 UTC **(d)** respectively. IR stands for Infrared.

From fig. 17 (a) we can observe that there is huge cloud mass present over province Sindh of Pakistan on 26th July, 2010. Encircled portions in the images describe the focused cloud activity over the northern and southern parts of the country. There seems to be a small development in the northern areas of Pakistan by this date. On the next day, the development is in its mature stage as shown in fig. 17 (b). The situation remained the same rather it intensified on 28th and 29th July, 2010 as shown in Fig. 17 (c) & (d). 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 radar images for the study. Radar images, shown in Fig. 18 (a), (b), (c) & (d), give the brief account of the meso-scale weather system in the west of Islamabad.

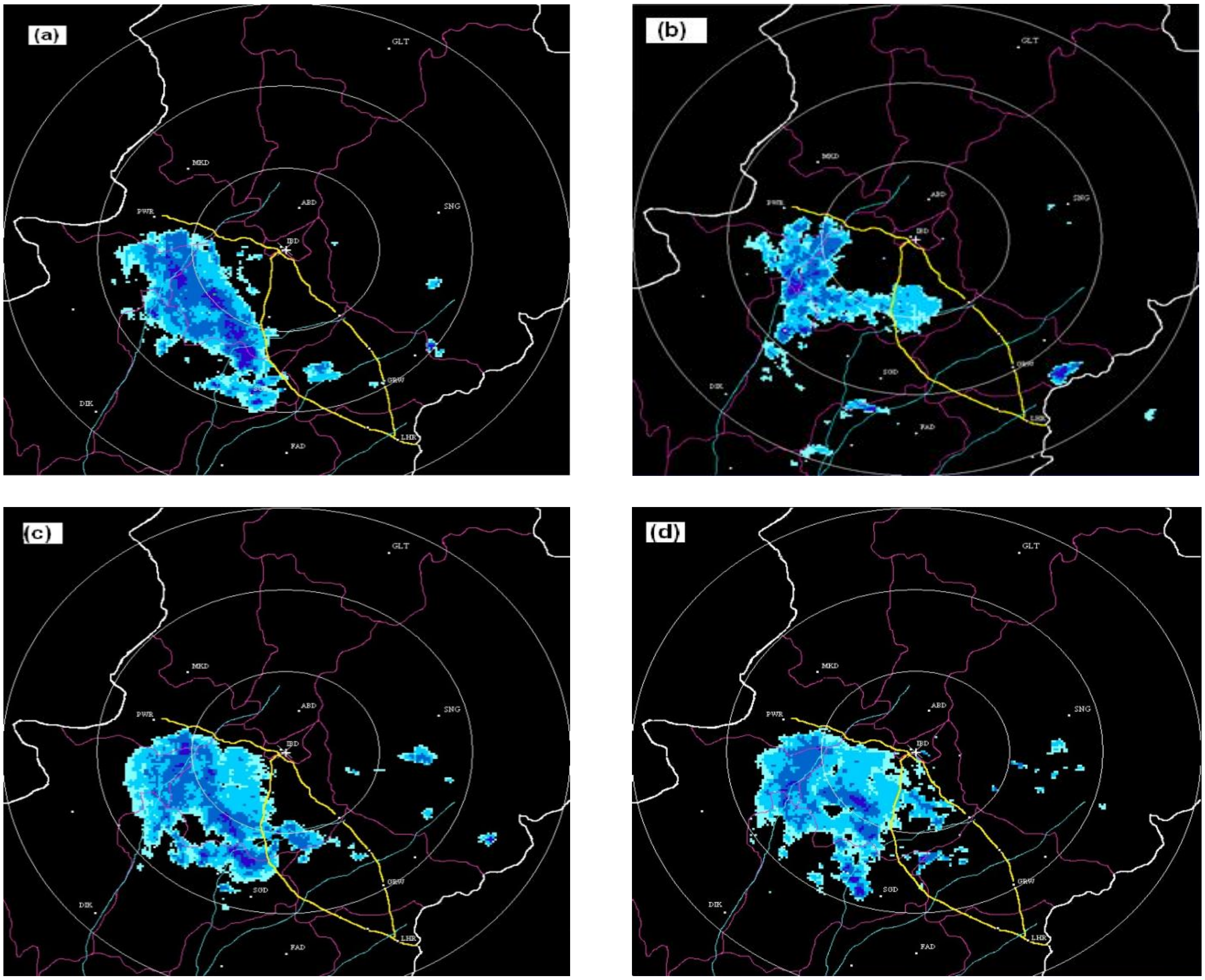



**Figure 18:** Radar echoes of Islamabad Radar station (33°24´N, 73°34´E) on 28/07/2010 at 0140 PST **(a)** & at 1700 PST **(b)**, on 29/07/2010 at 0400 PST **(c)** & at 0525 PST **(d)**. Each circle has radius of 100 kms. PST stands for Pakistan Standard Time.

The radar echoes also reveal the vastness of the weather system. It covered a large area along the Indus River which is in the west of the station. The system remained stagnant for several hours and gave torrential rains in the area. Due to the shadow region the radar is unable to capture the system in the upper catchment of the Indus River therefore; it is recommended that there should also be network of radars in the northern areas of Pakistan.

### 7. High Resolution Model (HRM) Output

The event was successfully simulated by the High Resolution Model at the resolution of 11 kms. The results comparing with the actual data reveal that there is under estimation of intensity of rainfall but it somehow has managed to succeed in predicting the spatial distribution. Fig. 19 (a) (b) & (c) represent the HRM outputs on 27th and 28th July, 2010. Output for 28th July shown in Fig. 19 (a), represents the heavy rainfall up to 200 mm in Kashmir over the Jhelum River Catchment while the output for 29th July, 2010 (b) shows heavy rainfall ranging from 100 mm to 200 mm over a large area of KPK. Same is the case with output for 30th July, 2010 at 0000 UTC as shown in Fig. 19 (c).

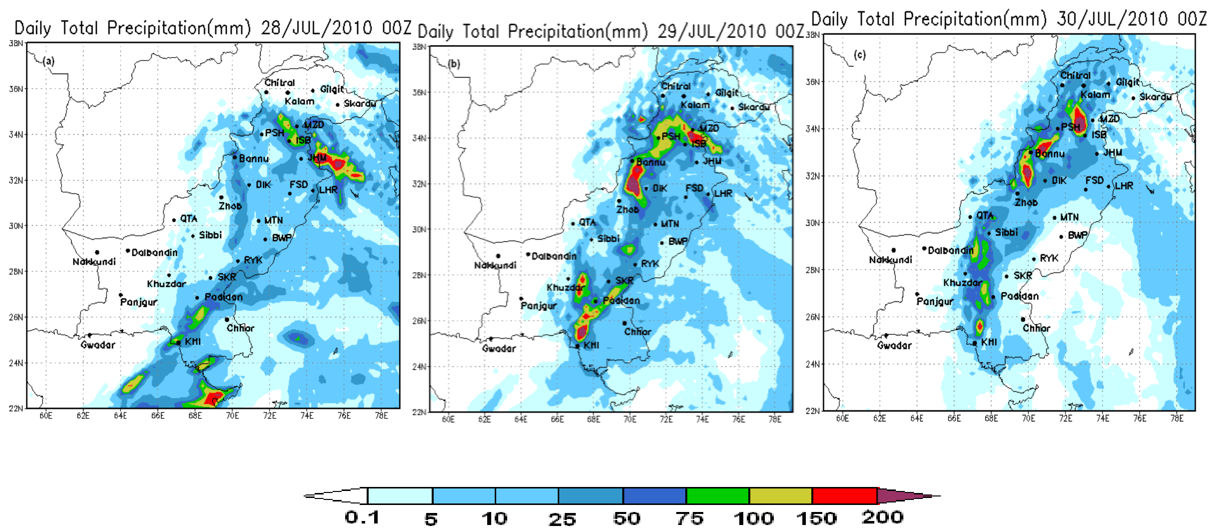



**Figure 19**: High Resolution Model (HRM) output for 28th July **(a)**, 29th July **(b),** and 30th July **(c)**, 2010, on 0000 UTC

## 8. Conclusion on 2010

Possible reasons for the event have been discussed and following are some results.

1. The summer monsoon low originated at Bay of Bengal and following the peripheral path along Sub-Tropical High (STH) at upper level it merged with the seasonal low.

2. Position of seasonal low also changed and it moved to the northeast side over Baluchistan. Under the scenario, large amount of moisture was transported to the northern parts of Pakistan from the Arabian Sea as well as the Bay of Bengal. Both the currents converged over KPK resulting in very heavy rainfall.

3. Topography and the orientation of the rain-hit region played a crucial role in converging and uplifting the moisture. In the middle troposphere, cold air advection from 500 mb took place into Pakistan latitudes. Lower level warm and moist air was compressed by cold air aloft which developed strong cellular vertical circulation. Large cumuli

development took place in the continuous horizontal supply of moisture from both the above mentioned sources.

4. Presence and stagnation of Jet stream at the north of Pakistan was another factor which played a vital role in sucking up the moisture to much higher latitudes and levels.

5. Numerical model captured the process of system development. However, it underestimated the severity of the phenomena in qualitative terms.

## 9. Diagnostic Analysis 2011

In order to achieve overall objective of this study, there are several tasks that have been accomplished. First of all observed data of different weather parameters like, precipitation, relative humidity (R.H) and temperature was collected from Climate Data Processing Center (CDPC) Karachi. 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 ($2.5^{o} \times 2.5^{o}$), along with 17 vertical pressure levels from (100-1000). For this study **(05º – 50º N, 50º – 100º 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.

### *9.1. Rainfall Event (09-15August)*

Summer monsoon sets over the eastern border of Pakistan on 28$^{th}$ 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. The 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 become low intensify as 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 20. Here some features (Monsoon Track, Tibetan High, Heat Low and MTC) are mentioned for this heavy rainfall event over aforesaid area.

### *9.2. 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 21. 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

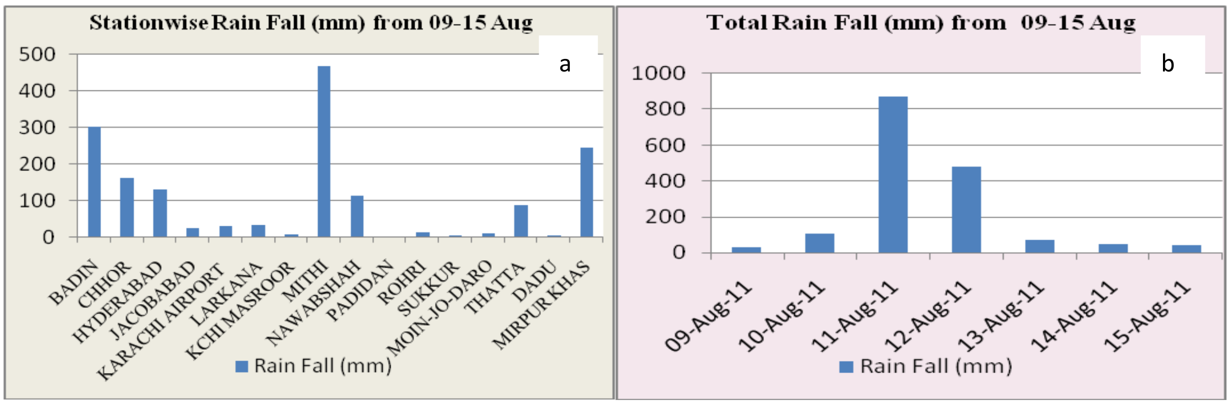



**Figure 20:** Spatial and temporal variation in rainfall during 1st spell (9-Aug to 15Aug).

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 of on-setting of monsoon are first week of July and its path is shown in figure 21. Monsoon depression's trough diverges towards southwest at an angle of 40°, 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).

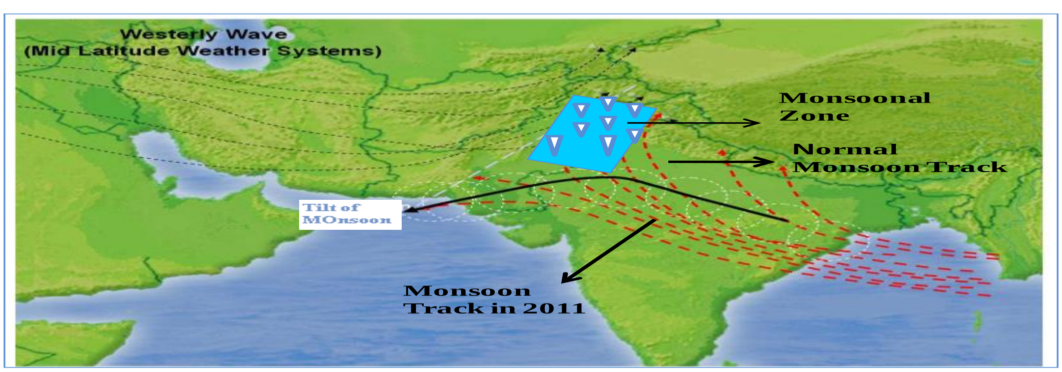



**Figure 21:** Track of Monsoon Low Depression during Aug & Sep 2011.

### *9.3. Tibetan High (TH) (200hpa)*

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 22. 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 figure22 dotted line

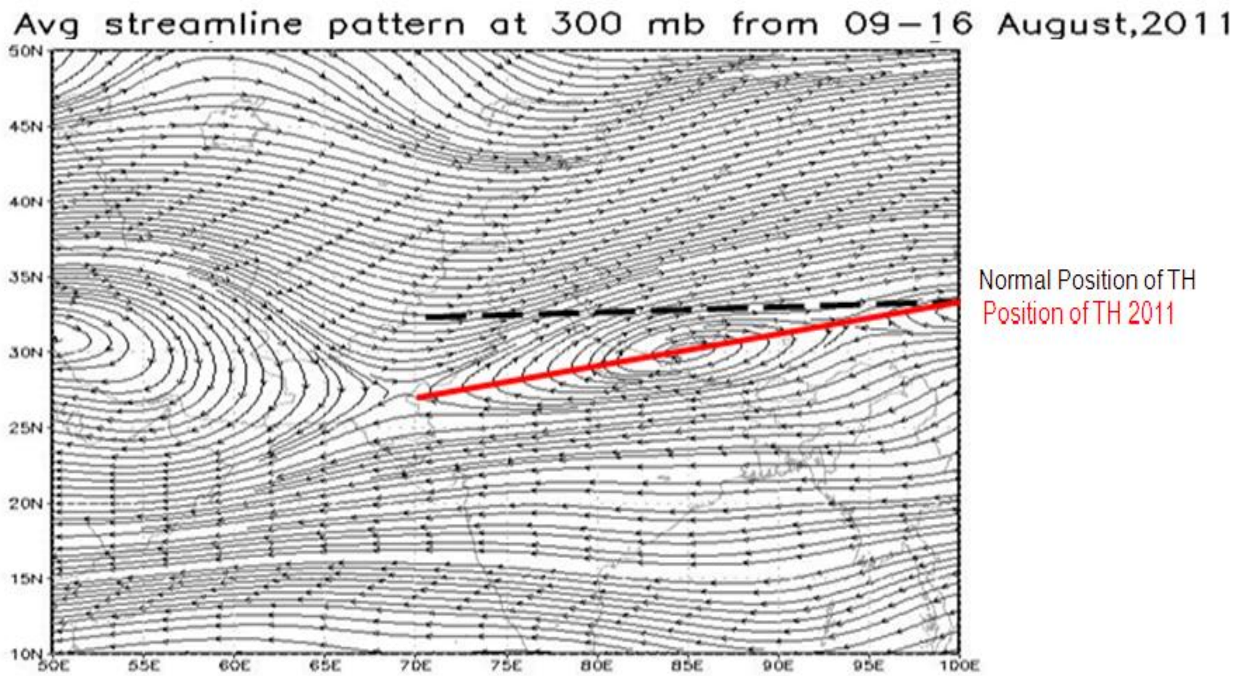



**Figure 22**: Average stream line patterns at 300 mb from 09-16 Aug showing the southwest tilting of TH.

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

**10. Seasona Low:**

Normaly 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 23. 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 23 (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.

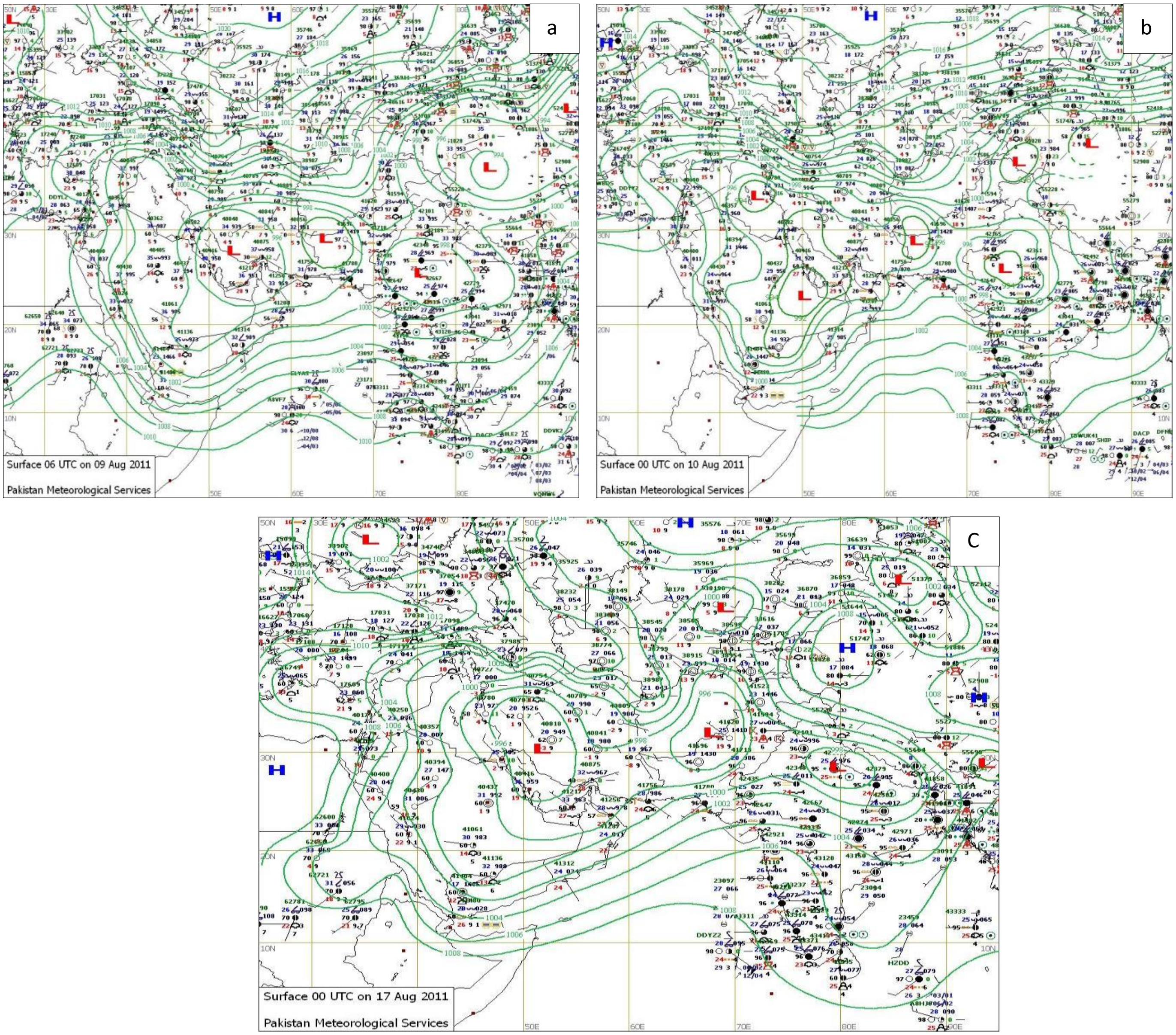



**Figure 23:** Surface Weather Charts on 9th, 10th& 17th August, 2011.

## *10.1. 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.

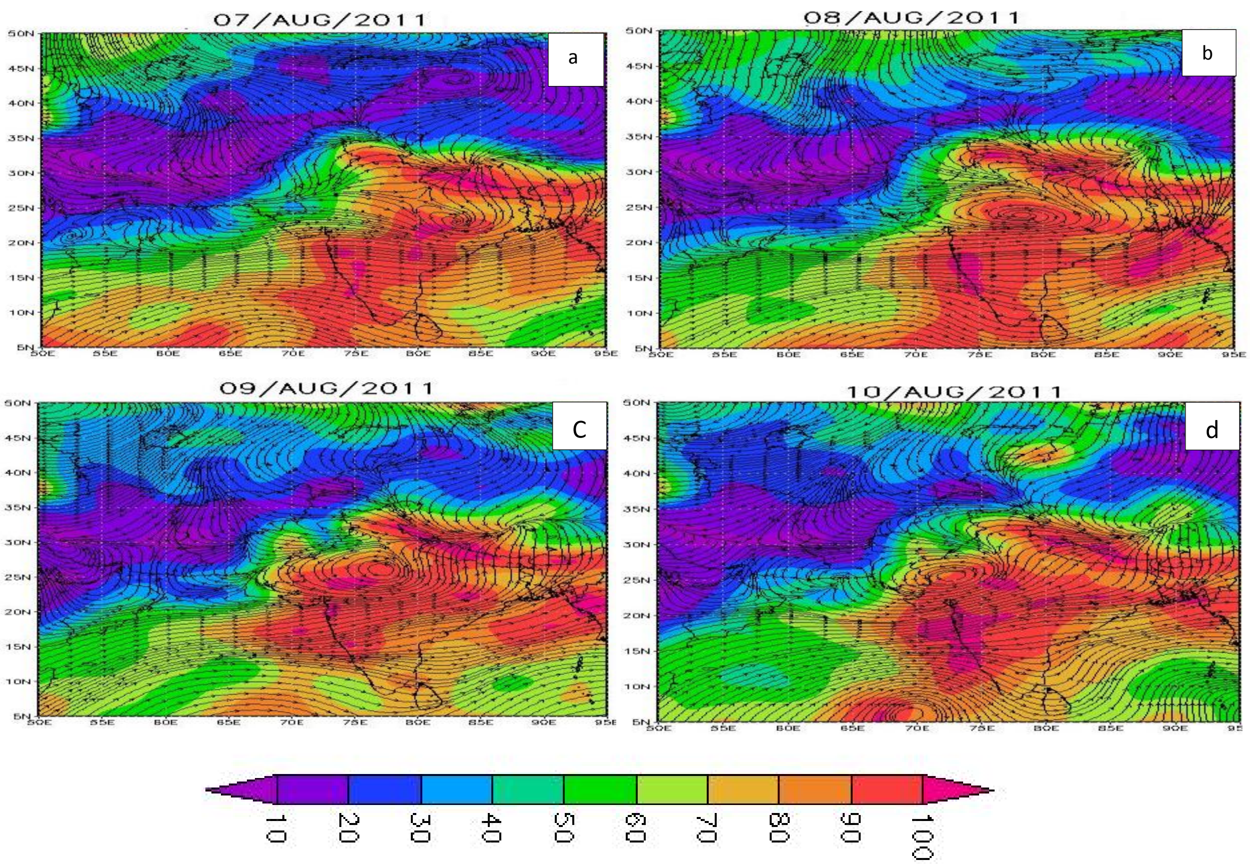



**Figure 24:** Streamline analysis with (%) Relative Humidity in Shaded at 850hpa on 07th to 10th Aug, 2011 at 1200UTC.

### *10.2. 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.

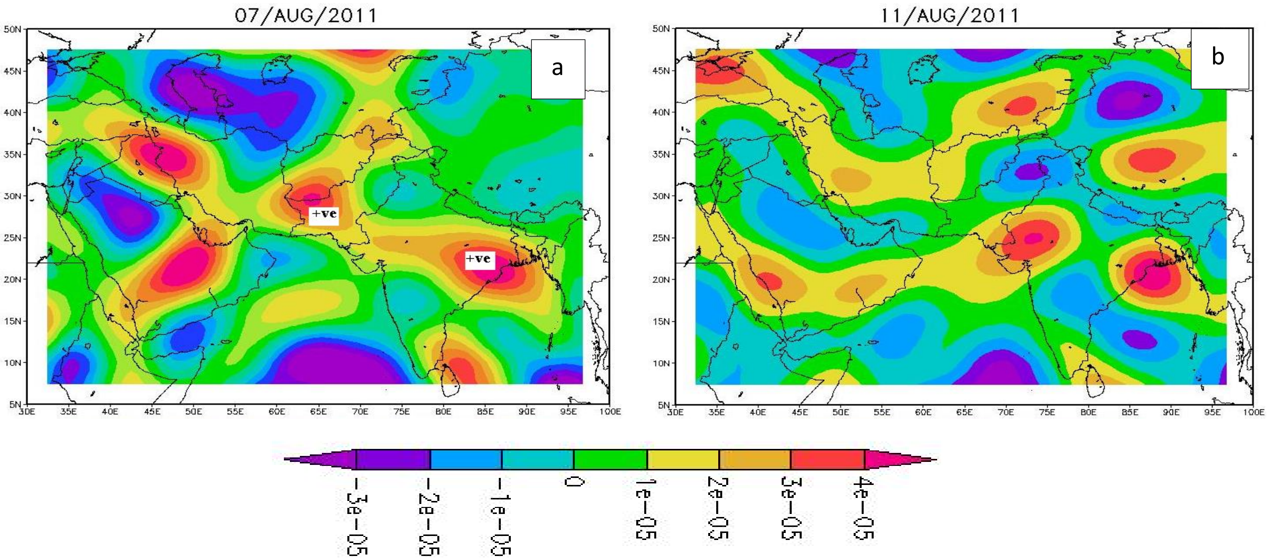



**Figure25:** Vorticity analysis at 850 hpa on 07 & 11 August, 2011 at 1200 UTC**.**

### *10.3. 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 26 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 Balochistan and KP.

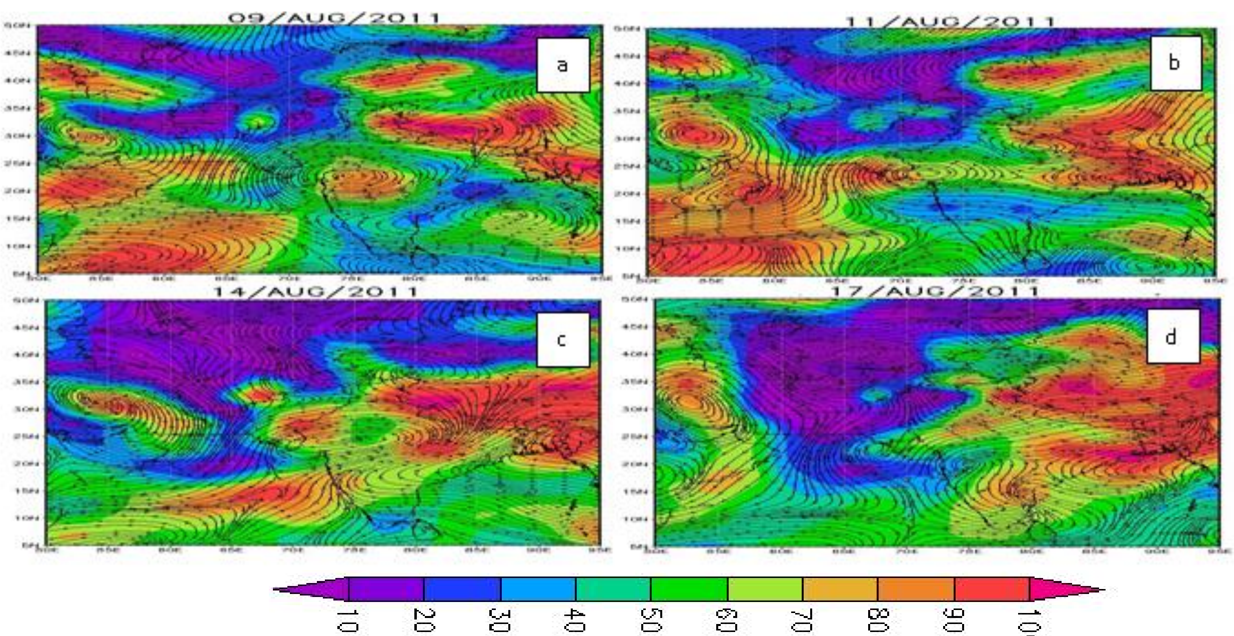



**Figure 26:** Streamline analysis with Relative Humidity (%) Shaded at 500hpa at 1200 UTC

### *10.4. Second 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 from 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.

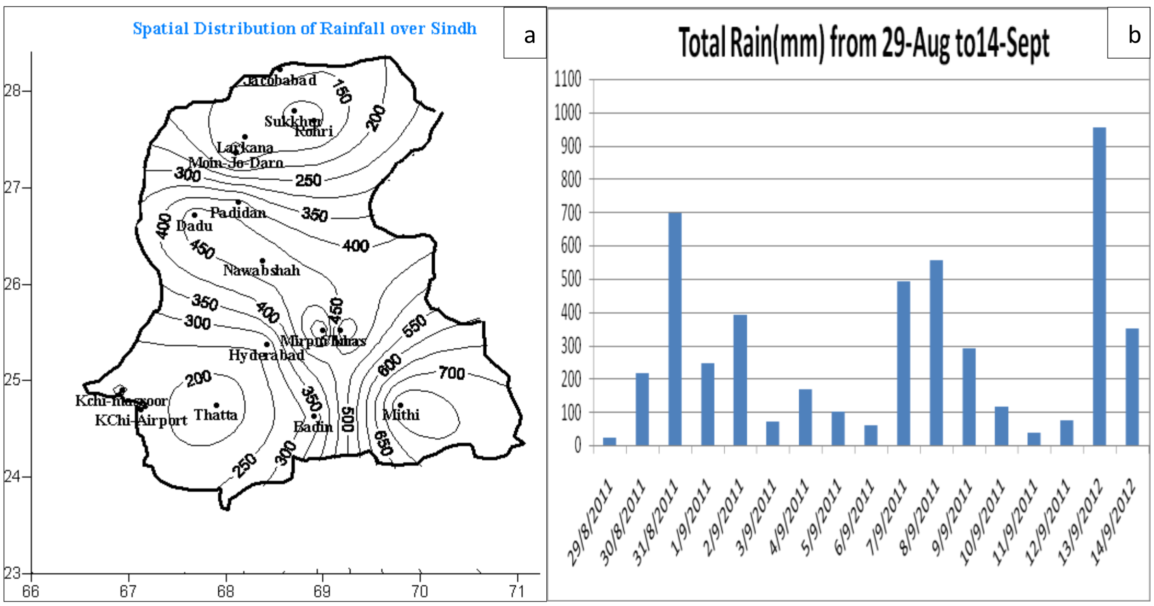



**Figure 27:** Spatial and temporal variation in rainfall during 2nd spell (29-Aug to 15 Sep).

### *10.5. 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 the 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 cyclone formed over Northeast Arabian Sea , and adjoining surashtra, kuch region during last week of August and first two week of September. At its initial level in on 25-29 August it gave only some cloudiness and moderate rain. But when it developed fully it gave heavy rain over south eastern parts of Sindh including Karachi. This anticyclone did not move but oscillate about its mean position, 20°N and 70°E as indicated in Figure 28. Fig 28 (d, e &f) depict that when this low develop monsoon low did not developed near the Southern parts of Sindh. Another condition that helps the development of such 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 28(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.

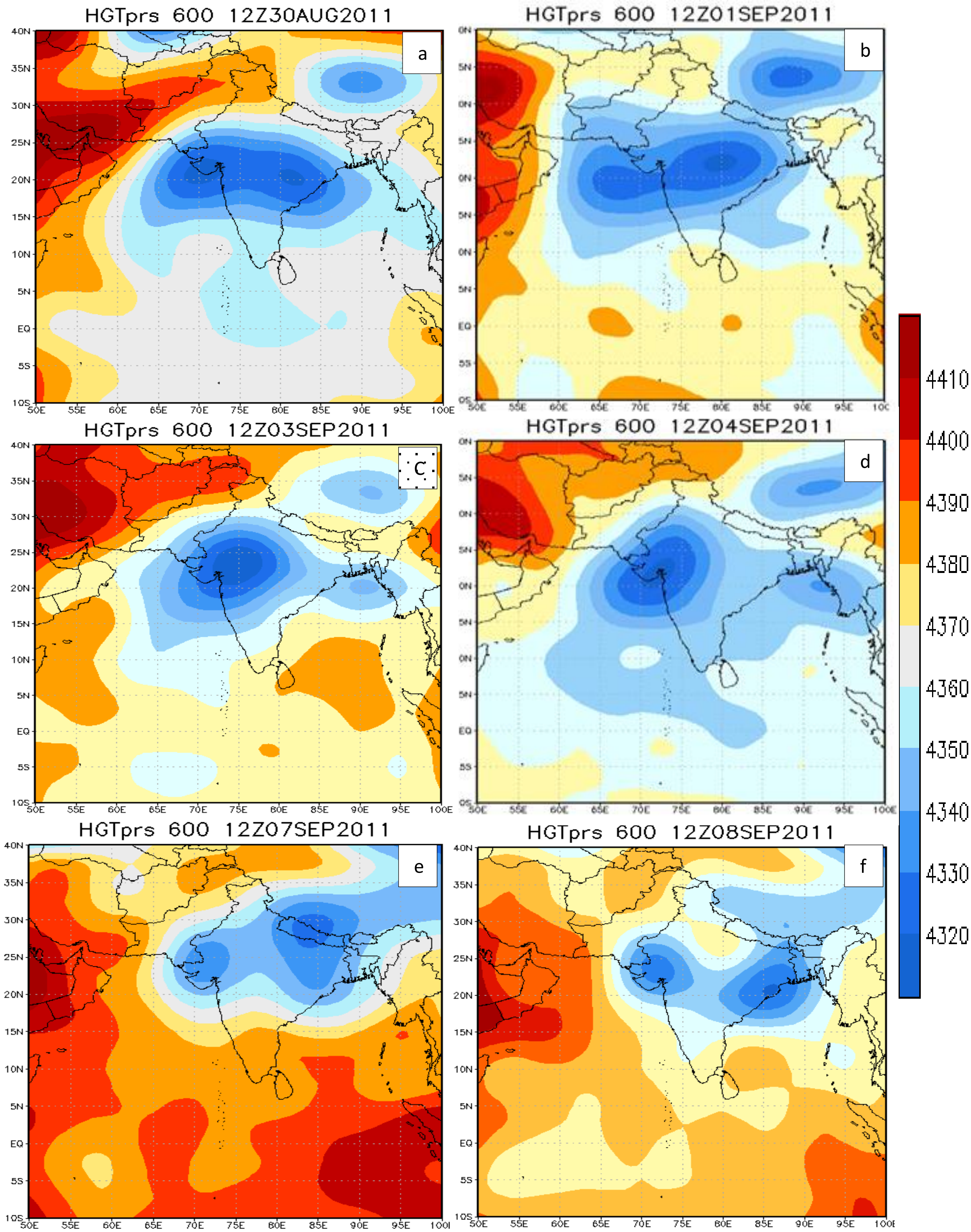



**Figure28**: MTC analysis at 600hpa for different dates during the second spell of the monsoon rains 2011**.**

### *10.6 Satellite Images & HRM Model output*

From figure 29 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 fig. 29 (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 fig.29 (c) we can observe that there is huge cloud mass present over province Sindh of Pakistan on 30th August, 2011.

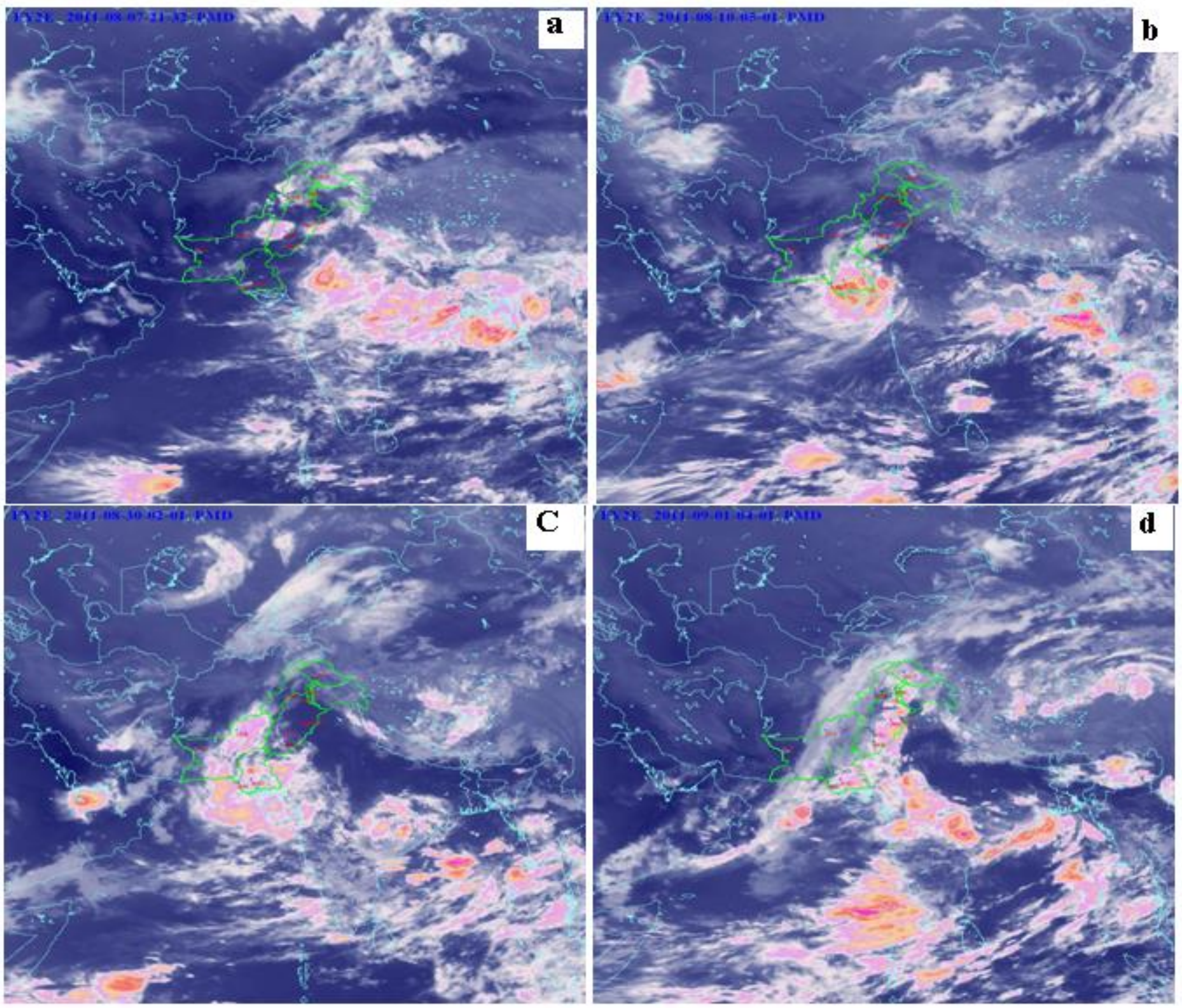



**Figure29: (a) & (b)** Satellite images 07th and 10th August**,(c)& (d)** Satellite images 30th Aug and 4th Sep during first and second spell .

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.

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 30. Same is the case with output for first spell and other dates.

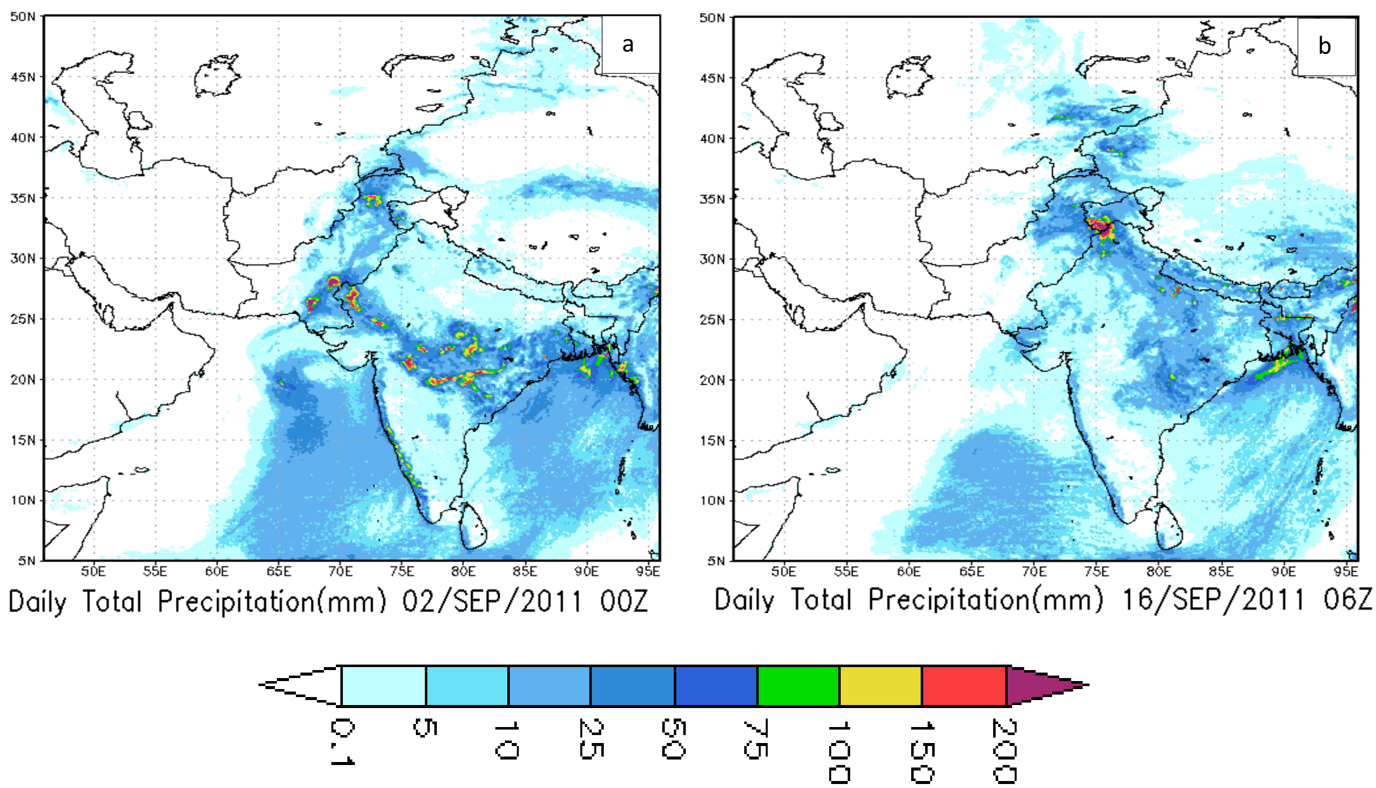



**Figure30:** High Resolution Model (HRM) output for 2nd September (a) and (b)16th September 2011

### 11. Conclusions on 2011

Following conclusions are drawn from diagnostic study.

- The position of the monsoon depression, that usually extends from eastern parts to north western parts of Indian. 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.

- 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.

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