Diagnosis and Numerical Simulation of a Heavy Rainfall Event in Winter over Upper Parts of Pakistan

Qudsia Zafar* and Ghulam Rasul†

Abstract

Using observed, NCEP reanalysis and HRM forecasted data, a diagnostic study has been carried out to find out the reasons for a heavy rainfall that occurred and continued for three consecutive days over north western parts while for two consecutive days over northern and upper Punjab region of Pakistan (Mar 30 to Apr 02, 2007). The development and intensification of the baroclinic wave to the west of Pakistan over the adjoining areas of Afghanistan and Iran; east of Caspian Sea resulted in heavy rain and snow. The study was mostly confined to the domain (50° E – 100° E and 21° N – 50° N) keeping in view the baroclinic wave characteristics and limitations of computational facilitates available. The results of the study showed that the cause of this heavy rainfall was the orographic capture of western upper- level disturbance and moisture (>90% with vertical alignment e.g. from surface to 400hPa levels) in northwestern and northern regions (Hindukush – Himalayan Terrain). A jet stream present at 200hPa caused the development and eastward movement of this baroclinic westerly wave due to strong convergence at lower level and positive divergence at upper level over these regions. Early spring heating of the ground surface provided the ignition to generate the local instability conditions to the existing and advected airmasses. The presence of divergent wind field aloft along with orographic lifting aided in vertical rising of this unstable warm moist air resulting in severe weather conditions.

Key Words: Western disturbances, baroclinic waves, orographic capture, upper level divergence.

Introduction

Pakistan is bound by three world famous mountainous ranges which play an important role not only for summer and winter precipitation in Pakistan but also in India and Nepal. In the northwest lies Hindukash Range, in north lies central Karakaram Range and in northeast lie Himalayan regions of Pakistan (e.g. Kashmir). The primary weather systems responsible for wintertime precipitation are the high level westerly synoptic scale waves known as 'Western Disturbances' in the region. In late spring, western disturbances are generally shifted toward north but occasionally extend down to Pakistan's northern latitudes and in the presence of strong convection produce heavy precipitation. Convective instability combined with moisture incursion and cold air advection aloft results in heavy precipitation events in the northern parts of Pakistan [14].

WDs have been discussed by quite a number of authors. Dr. K.M Shamshad [15] has presented a detailed account on the structure, symptoms of approach, frequency, and direction of movement of WDs. According to him the structure of a western disturbance is similar to an extra tropical depression, a cold air in advance and also in the rear with a warm sector in between, however as a result of long journey from the Mediterranean Sea to Pakistan many of them become occluded or in other words their warm sectors are eliminated from the surface on reaching Pakistan. T.J. Lang and A.P. Barrows [16] have conducted an extensive study over winter storms in central Himalayas.

*Qudsia_aries@hotmail.com
†Pakistan Meteorological Department

Their study concludes that WDs are trapped and intensified by the unique large scale topographic features, most notably the notch formed by the Hindukush and Himalayan mountains, hence orographic forcing is the dominant factor in precipitation in the central Himalayas and significant precipitation in this region only occurs when this large scale flow evolves to a favorable geometry with respect to the mountains. A. P Dimri [5] has described the structure of WDs as synoptic systems that are generated as a result of large scale interaction between mid-latitude and tropical airmasses that move from west to east. In his research he has carried out the assessment of winter circulations over western Himalayas during extreme years of seasonal precipitation (which he has named as ‘surplus years’). According to this study the surplus years had significantly lower mean slp, zonal wind showed the development of strong westerlies over the Middle East region, high southerly winds prevailed and high frequency of low pressure systems affected the region bringing more moisture. Keeping in mind the above literature, different case studies on extra tropical cyclones were also reviewed and this study was performed for the event.

The present study seeks to accomplish two goals: 1) Diagnosis of the heavy precipitation event recorded at the upper NWFP, Northern Pakistan and Upper Punjab areas. 2) Numerical Simulation of the event for microanalysis of its genesis and occurrence. The first goal was achieved through analysis of real time data, while the second was acquired with model forecasted data.

Data & Methodology

NCEP/NCAR Reanalysis Datasets

The NCEP/NCAR reanalysis datasets have been used to analyze the synoptic patterns due to unavailability of upper air data for high terrain in these regions. The reanalysis data was available at four times daily basis with horizontal resolution of 2.5o. The data in the pressure variable field was available at 17 vertical levels from (1000 – 100) hPa. The latitude and longitude range of the domain selected to study the synoptic pattern of the developing baroclinic wave was (20° – 50° N, 20° – 100° E) and (21° – 50° N, 50° – 100° E). To analyze the position of jet stream the latitude / longitude domain selected was (10° – 50° N , 50° – 100° E)

Numerical Forecast Model Simulation

The model used to simulate the event is a High resolution Regional Model (HRM) developed by the German Weather Service (Deutscher Wetherdienst - DWD) in 1999. The model configuration was in a single domain with horizontal grid 0.2° x 0.2° (22 km resolution) and 40 vertical levels. The approximate latitude and longitude range of the domain was 15° – 48° N and 56° – 80° E respectively. The domain was pre defined (the model domain had not been enlarged in the dates of this 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. The simulation was initialized to get the forecast from 00UTC, 29th Mar 2007 up to 00UTC, 3rd Apr 2007. The goal of generating this forecast was to analyze the same synoptic weather event on a higher resolution to fill the gaps left by NCEP reanalysis alongside HRM output verification.

Observed Rainfall Data

In this paper a heavy precipitation event has been studied which started on 30th March 2007 and was recorded on the meteorological observatories of NWFP, Azad Kashmir, and upper Punjab. The highest amounts were recorded in Chitral, Drosh, Dir, Mirkhanni and Parachinar observatories of NWFP. At NWFP stations the precipitation gained intensity through 30th March to 1st April. Most of the observatories of northern areas and upper Punjab were recording precipitation through 1st and 2nd April.

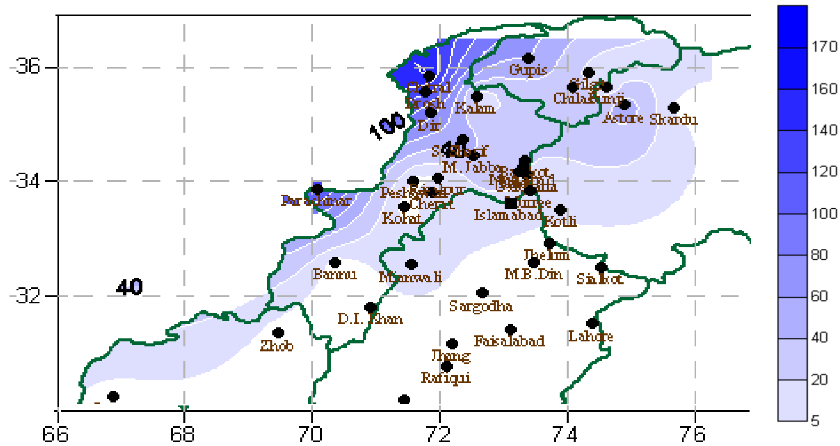

Figure 1: Totals rainfall (shaded) in 'mm' from 29th March 2007 up to 3rd April 2007

The precipitation ended on 2nd April causing avalanches, flash floods and heavy loss of life and infrastructure in these regions. The totals of daily amounts of precipitation along with the names of the observatories have been plotted in Fig 1.

Discussion

Synoptic Patterns Using NCEP Reanalysis Datasets

The waves formed by the disturbances in air stream due to the changes in air density are known as baroclinic waves. At 00UTC – 29th March (fig not shown) a cutoff low was already in its intensification phase at 500hPa level with its center over Black Sea and northeast Turkey. On 30th March 12UTC (fig 2a) the central low of the 500hPa trough can be seen in a defined shape. The vorticity maxima present over Turkey and Persian Gulf correspond to the short wave troughs with particularly high vorticity values for trough over Persian Gulf. The winds have become more southerly advecting warm moist air from Arabian sea up to the northern most areas of Pakistan. After twelve hours the central low of the 500hPa trough has taken the shape of the very well defined low to the east of the Caspian Sea. The whole country is still under the influence of winds coming from the Arabian sea at 500 hPa. On 1st April 00UTC the trough intensification was its peak with a central low dropping height values from 555dkm to 549dkm with high cyclonic southerly winds. In Fig. 2h in the slp field the intensification of the trough is marked by the vertical alignment of slp and the thickness contours. Most of the country is under the influence of cold south westerly winds. This figure also shows similarity with a typical baroclinic wave pattern in which cold front is totally dominant over warm front in its occluded stage. On 1st April after 12 hours the ridge that was present over west china started to shift eastwards and the gradient in the trough east of Caspian sea decreased resulting in the northward shift of positive vorticity region. The direction of wind has changed from south west to west. Due to this shift there was a subsequent increase in the slp (over upper NWFP, northern and upper Punjab areas). The occluded frontal structure that formed 12 hours ago is in the dissipating state now that one baroclinic wave has intensified and now its dissipating. Lower thickness values (i.e.<567dkm) indicate the presence of cold air, whereas the high thickness values(i.e.>570 dkm) indicate the presence of warm air. The trough over Persian Gulf in the thickness field indicates that the advection of cold air was occurring in the southwest of the low at slp and warm air was being advected southwards to the east of the low.

Vertical Velocity

The vertical velocity plays a very important role in the development and intensification of baroclinic waves. The charts for the vertical velocity for the days of maximum precipitation are given in Figs 3a,b,c &d . In the panel when the system is developing most intensely the northward moving air in the region of warm advection in advance of the developing surface low is rising where as the air that is coming from the west to the rear of the trough is sinking. The areas of greatest ascent over Pakistan were present over the extreme western border from north west to south west on 12UTC, Mar 30, 2007 which shifted to the north west as a result of eastward movement of 500hPa trough on 00UTC, Mar 31, 2007.

At this time a heavy precipitation spell was already in progress at Chitral and Parachinar. At 12 UTC – Mar 31, 2007 the areas of greatest ascent over Pakistan included the upper parts of Balouchistan, NWFP and northern most areas of Pakistan including east most areas of Kashmir. In Fig 3 d the region of ascent can be seen as wrapped around the developing surface low in the northern and eastern areas of Pakistan and over central India.

In the same manner the region of subsidence wrap around the surface low in the southern most areas of Pakistan. The areas of ascent have shifted to the regions of upper NWFP and northern areas including upper Punjab as a result of intensification of trough at 500hPa. The ridge can be identified and characterized by the presence of warm air in 500hPa field indicating ascent whereas the max. vorticity trough indicates the presence of cold air (intended to subside) in the vertical velocity field. This subsidence and ascent of the air currents is influential in the shaping of clouds and precipitation patterns [10].

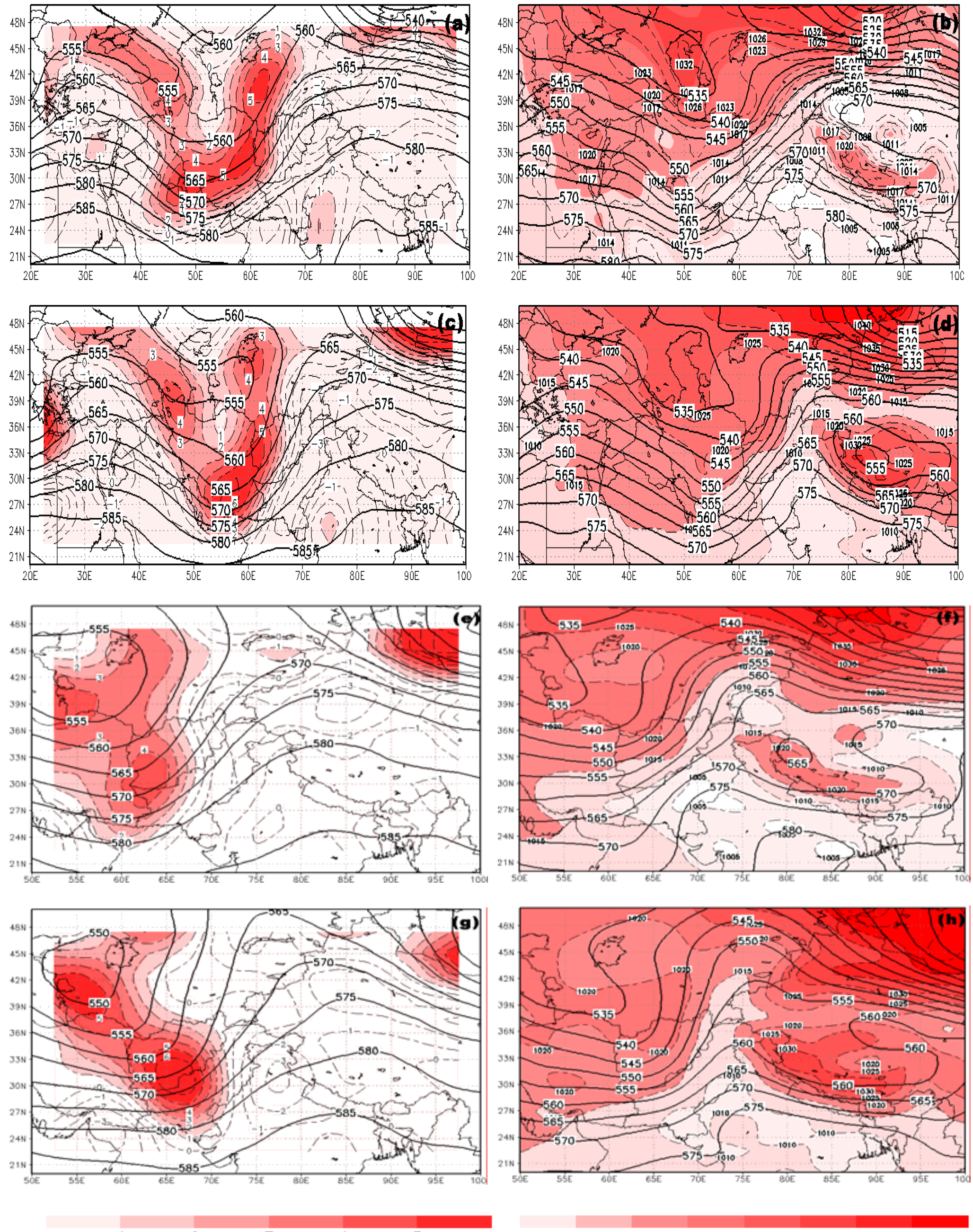

Figure 2: The left hand panel shows 500hPa geopotential height contours(labels in deca m); superimposed on 500hPa relative vorticity (shaded; 10-5 in units of s-1) , where as the right hand panel shows 1000 - to500 - hPa thickness (contours, labels in deca m) superimposed on slp (shaded).(a &b) At 12UTC – Mar 30, 2007, (c &d) At 00UTC – Mar 31, 2007, (e &f) At 12UTC – Mar 31, 2007, (g &h) At 00UTC – Apr 1, 2007

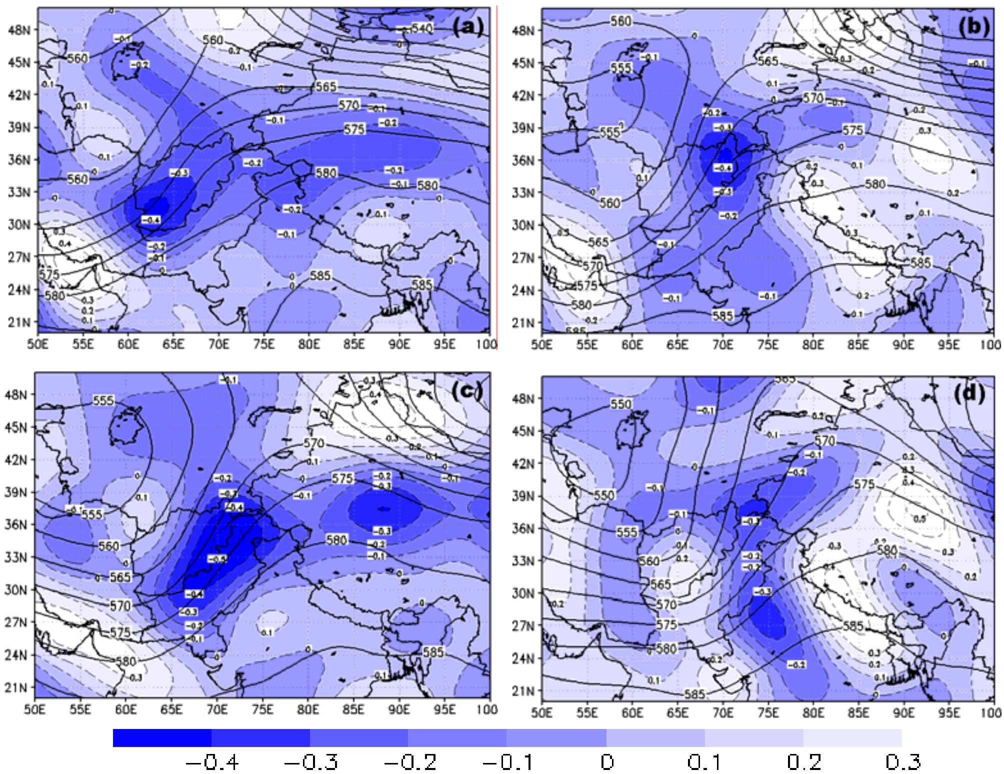

Figure 3: The 500hPa geopotential height contours (labels in deca m) superimposed on Vertical Velocity fields (in Pa s-1 ; shaded) at 700hPa level. (a) At 12UTC – Mar 30, 2007 (b) At 00UTC – Mar 31, 2007 (c) At 12UTC – Mar 31, 2007 (d) At 00UTC – Apr 1, 2007.T

Surface Winds and Sea Level Pressure

On 31st March at the time of developing maximum baroclinic wave activity, two lows were present over the surface. First to the east of Caspian sea and the other over lower Punjab. The first low located to the east of the 500 hPa trough was not a deep low. The wind shift pattern (for the second low present over lower Punjab) is defined by the direction of wind barbs. To the south of the surface low the winds exhibit a southerly component while to the west of the surface low the winds exhibit a strong westerly component. To the east of the low easterly component is dominant due to the present of high pressures prevailing over Tibetan plateau. After 12 hours on 1st April (in fig 4 b) the intensification of the trough at 500 hPa was at its maximum.

The low pressure was located a little south east of its previous location as a result of the trough location to the little south east on 500hPa. Through the two chart sequence the westerly winds advance further eastwards showing some tendency to wrap around the surface low as it moves south eastwards. Hence it appears that the winds are extending and changing the direction as a result of low development.

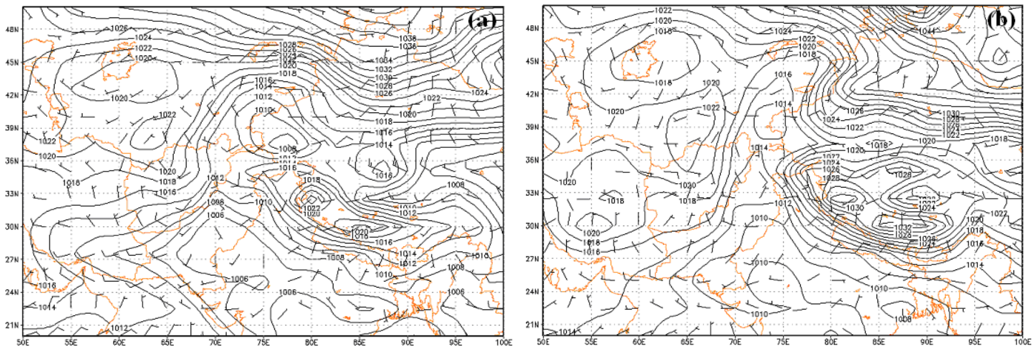

Figure 4: Sea Level Pressure and Surface Winds (a) at 12UTC – Mar 31(b) 00UTC – Apr 1, 2007

Temperature

The surface air temperatures show that the temperatures were cold to the west of the developed low surface pressure. The winds that were blowing from the west having strong westerly component were showing the temperatures below 5° C in the region of cold temperature advection marking an abrupt shift in the isotherms northwards. The cold temperatures to the west of Pakistan are indicating the cold surface air advection in the presence of upper level convergence and divergence (at 200hPa) along with the maximum vorticity trough at 500hPa.

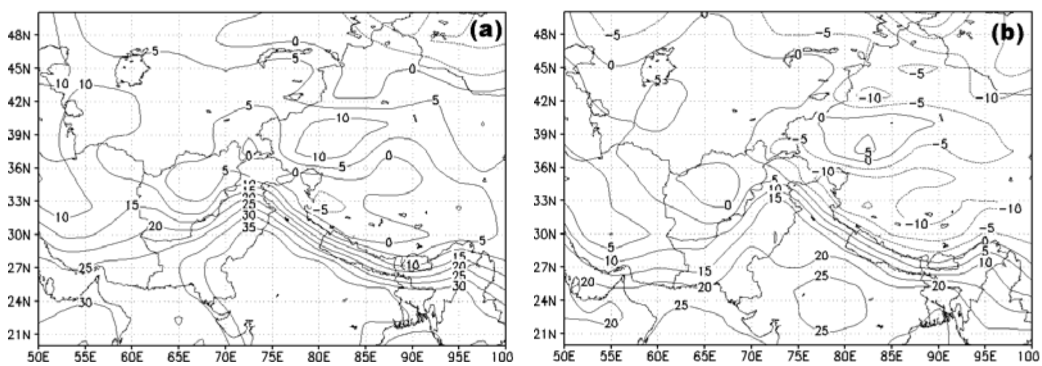

Figure 5: Isotherms showing surface air temperatures (units in 0 C) (a) at 12UTC – Mar 31, 2007 (b) 00UTC – Apr 1, 2007

The winds with strong southerly component were having temperatures above 30° C in the region of warm temperature advection. These high temperatures are indicative of the warm air mass. The tight spacing between the isotherms is indicative of the large horizontal temperature gradients. The 0° C isotherm was passing through the upper NWFP and northern areas of Pakistan on 31st march. On 1st April these low temperature isotherms shifted further southwards over Pakistan.

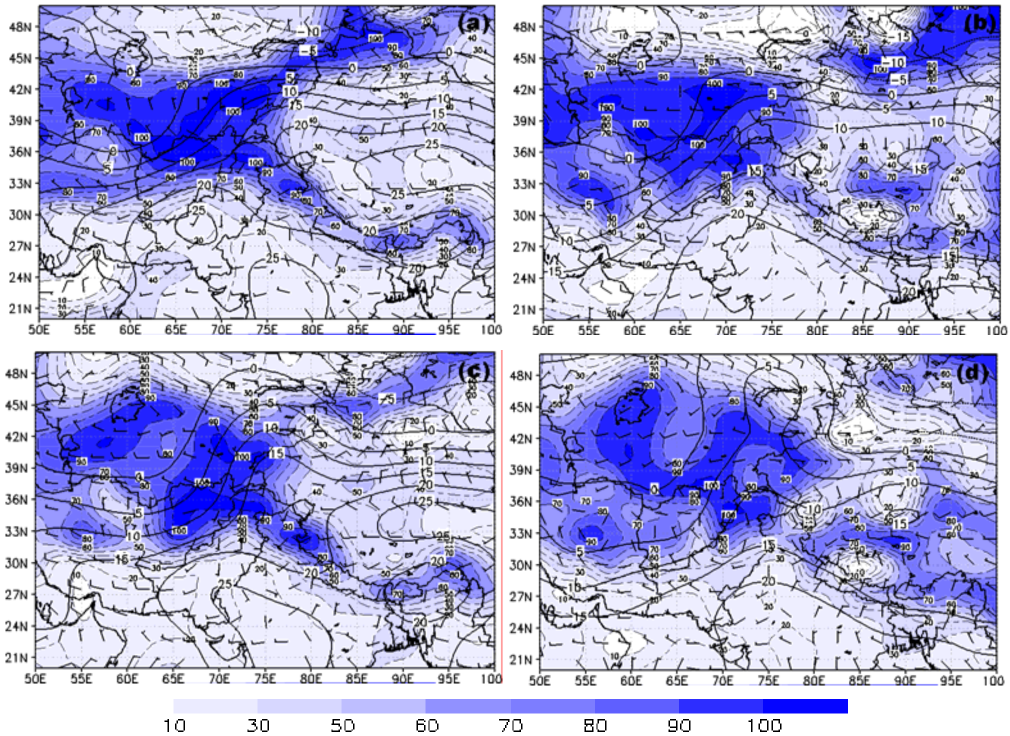

Figure 6: Relative humidity (percentage, shaded), air temperature (o C, contours) and wind (barbs indicate direction and speed of wind in knots) at 850 hPa height level (a) at 12UTC – Mar 30, 2007 (b) 00UTC – Mar 31, 2007(c) at 12UTC – Mar 31, 2007 (d) 00UTC – A pr 1, 2007

Moisture Flux

In figs 6 a, b, c & d, the relative humidity profile shows that a considerable level of humidity was present at 850hPa level in the range from 90% and above being advected by the westerlies. This 90% relative humidity was present over NWFP areas with 80 % to 90 % over lower NWFP, northern areas and upper Punjab. A high percentage of relative humidity infers that the air was nearly saturated. The moisture availability shows that only the upper NWFP areas were receiving the relative humidity of 90% and above, which decreased considerably coming south wards over lower NWFP areas and upper Punjab.

The comparatively high speed winds (e.g. 10m/s) indicate that the trend of moisture advection was westerly and moisture appears to be blown towards the areas of convergence (wind speeds also decrease in convergence). The direction of wind barbs across the isotherm also indicate that low level cold air is being advected from the west and warm air is being advected from the southwest.

The vertical cross sections of moisture are also provided below in Fig 7 a, b, c & d for 31st march 12UTC and 1st April 00UTC

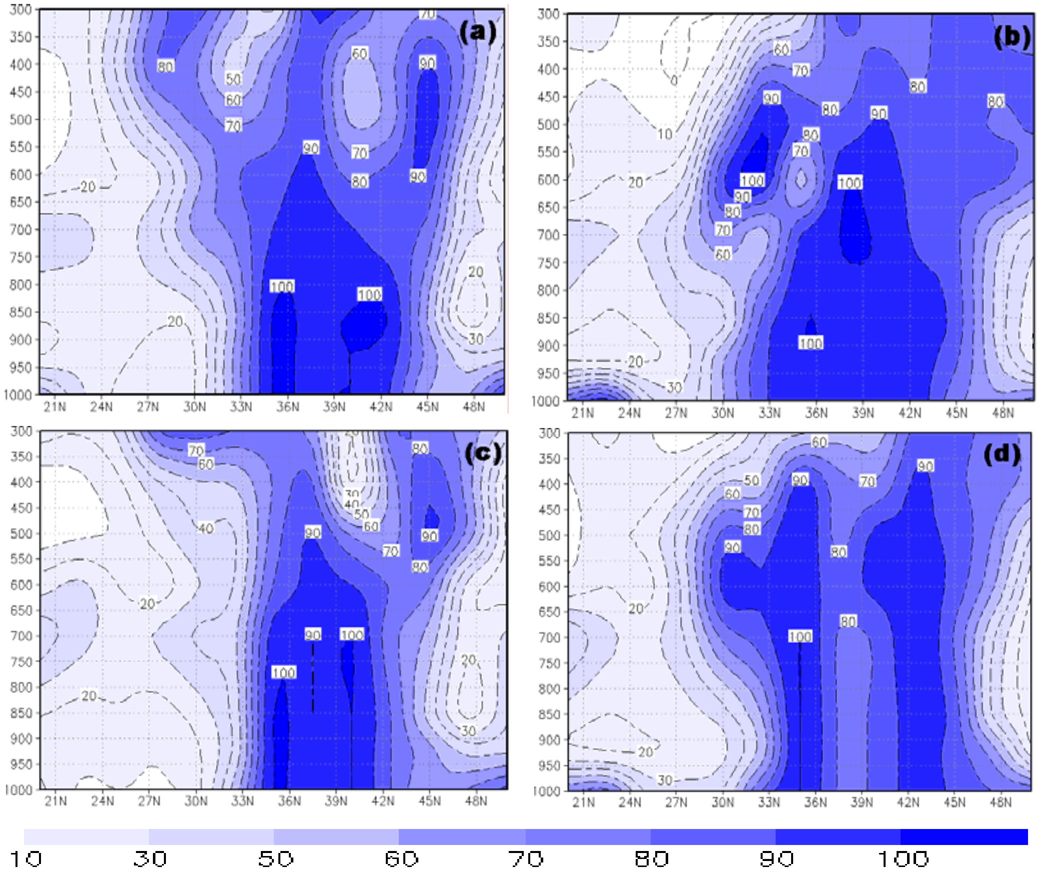

Figure 7: Vertical cross-sections of relative humidity (percentage, shaded) from 1000hPa level to 300hPa level (a) at 12UTC – Mar 31, 2007 at lon 70° E (b) at 00UTC – Apr 1, 2007 at lon 70° E (c) at 12UTC – Mar 31, 2007 at lon 72.5° E (d) at 00UTC – Apr 1, 2007 at lon 70° E (c) at 12UTC – Mar 31, 2007 at lon 72.5° E (d) at 00UTC – Apr 1, 2007 at lon 72.5° E. The areas enclosed by rectangles indicate the highest values of relative humidity in the upper latitudinal belts of Pakistan (33° N - 39° N). The illustrations show a relative humidity of 90% and above between the latitudes 33° N – 43° N.

Location of Jet Stream

In this study we also see the presence of a sub tropical jet on upper tropospheric levels with a magnitude of 70 m/s and 60m/s in the vicinity of jet streak. On 31st of March the southern and the northwestern areas of Pakistan were under the influence of the jet stream winds with magnitude of 40m/s. The jet shifted its position on 1st April with increasing magnitudes over north western regions and south eastern regions with magnitude of average 40m/s winds. In Figs 8 a, b, c & d, it can be seen that the jet is drawing air from above the developed weather system but the central low of the system has not intensified on the surface very much (which can be seen in the slp charts).

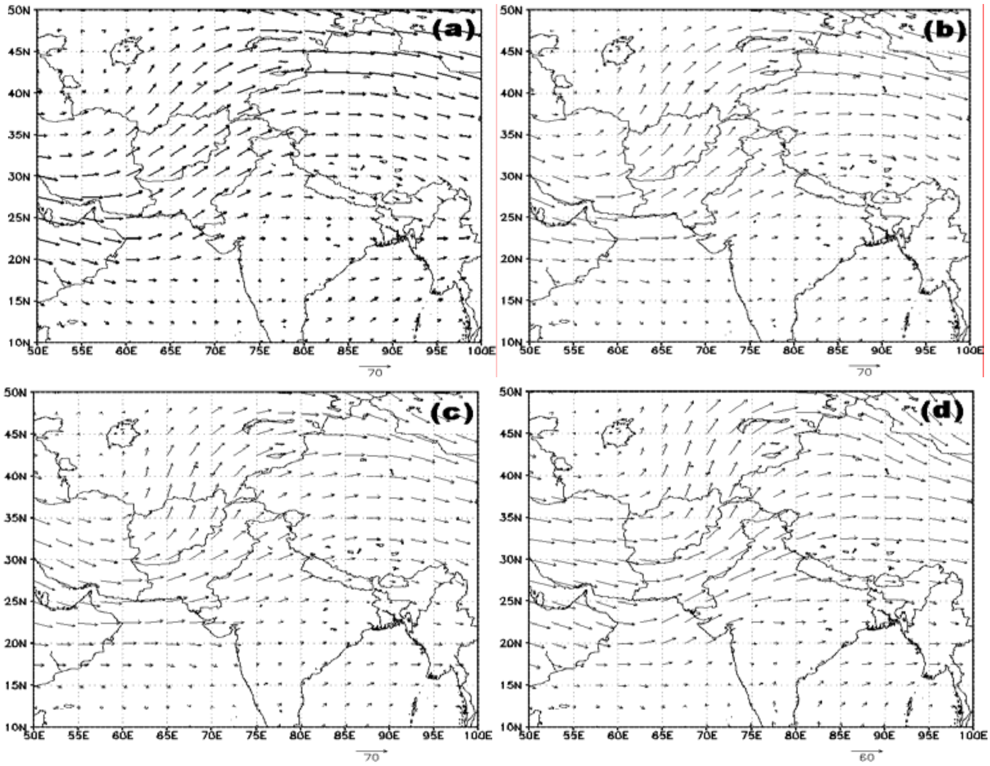

Figure 8: Jet Stream wind vectors (speed in m/s) at 200 hPa (a) 12UTC – Mar 30, 2007 (b) 00UTC – Mar 31, 2007(c) 12UTC – Mar 31, 2007 (d) 00UTC – Apr 1, 2007

In Figs 8 a, b, c & d, it can be seen that the jet is drawing air from above the developed weather system but the central low of the system has not intensified on the surface very much (which can be seen in the slp charts). This is due to the reason that enough moisture is present to feed the surface storm centre hence it stops to decrease the pressure further in spite of a jet present above. The position of the jet has taken a northern loop (northeast direction) on 31st march and is more aligned in this direction on 1st April. Since the diverging jet air is present aloft hence this front has started to fill up as more surface air is drawing in the system. Therefore it is inferred that the presence of the jet at 200hPa level plays some role in the intensification and easterly movement of the system from the Mediterranean to out region and might server a cause of severe weather. Synoptic Patterns (HRM Forecast & NCEP reanalysis) - A Validation / Comparison:

500 hPa Heights & Vorticity

By observing the illustrations below we can see that the position of the central low is over the same areas. Both the HRM forecast and the NCEP reanalysis are showing the extension of the trough of this central low reaching and entering into Balouchistan. The vorticity field is the extension of high positive vorticity cells (cyclonic winds) extending from Chitral to lower NWFP (due to various short wave troughs present over the region). Also the same pattern of geostrophic wind (i.e. south west) has been obtained using both of these data sets.

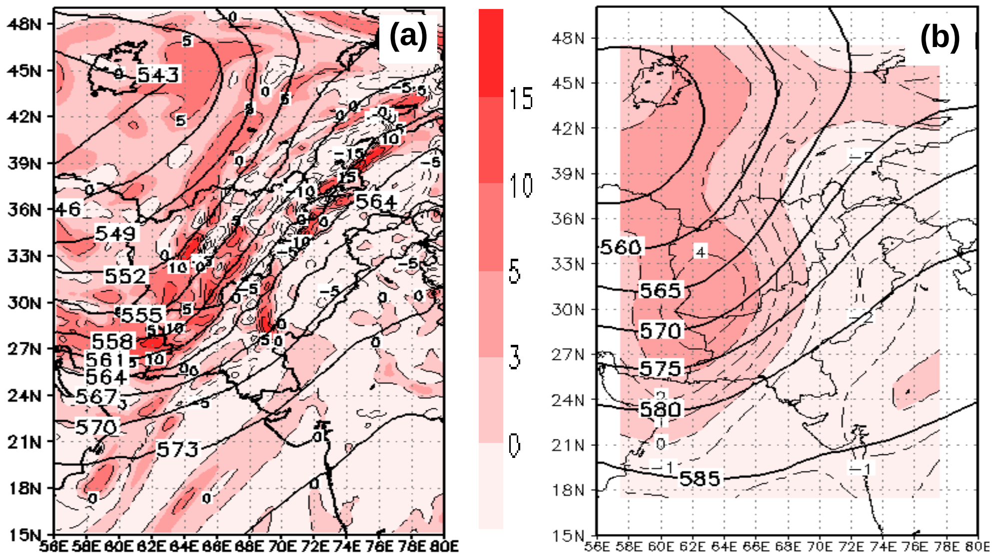

Figure 9: 500hPa geopotential height (contours) and relative vorticity (shaded;10-5 in units of s-1) at 12UTC – Mar 31, 2007 (a) HRM forecast, (b) NCEP reanalysis.

Vertical Velocity

The forecast shows that maximum ascent is occurring in the NWFP region of Pakistan on 12UTC, 31 Mar where the 500hPa trough is curving sharply along the jet stream. This is also the region of the presence of short wave (see fig 10 a), The NCEP reanalysis shows the region of ascent and subsidence on a course resolution over same locations.

Moisture Flux

The relative humidity predicted by the HRM forecast shows 90% and above values in the northern areas of Pakistan on 12UTC-31Mar2007 and 00UTC-01Apr2007 clearly showing colder air being advected from the west and north west where as warmer air being advected from the south and south west. These humidity patterns at 850 hPa match well with the NCEP reanalysis charts (the analysis of these charts has been provided in section 3.5) meaning that the forecast is also showing large quantities of moisture being accumulated in the north and northwest of Pakistan.

Location of Jet Stream

The jet stream pattern in our domain of selected time interval show almost the same patterns and magnitude depicted by the NCEP reanalysis (the detailed account of which is provided in section 8). In figs 12 a & b, The winds entering Pakistan are southerly at 200hPa level with maximum wind speeds between 40m/s – 45m/s approaching northern and upper NWFP regions.

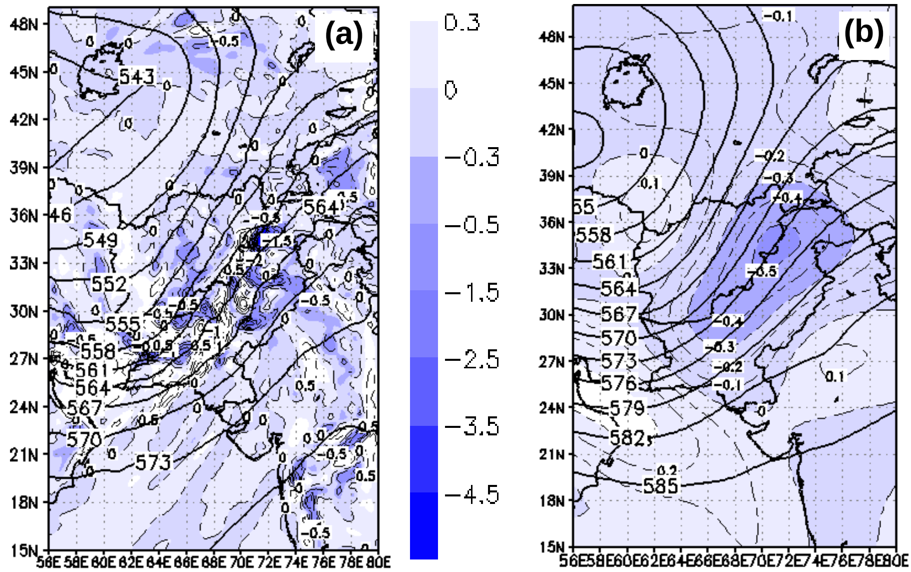

Figure 10: The 500hPa height (contours) and vertical velocity (in Pa s-1 , shaded) fields at 700hPa level at 12 UTC – Mar 31, 2007 .The dark shading (negative omega) indicates ascent and light shading (positive omega) indicates subsidence. (a) HRM Forecast (b) NC EP reanalysis.

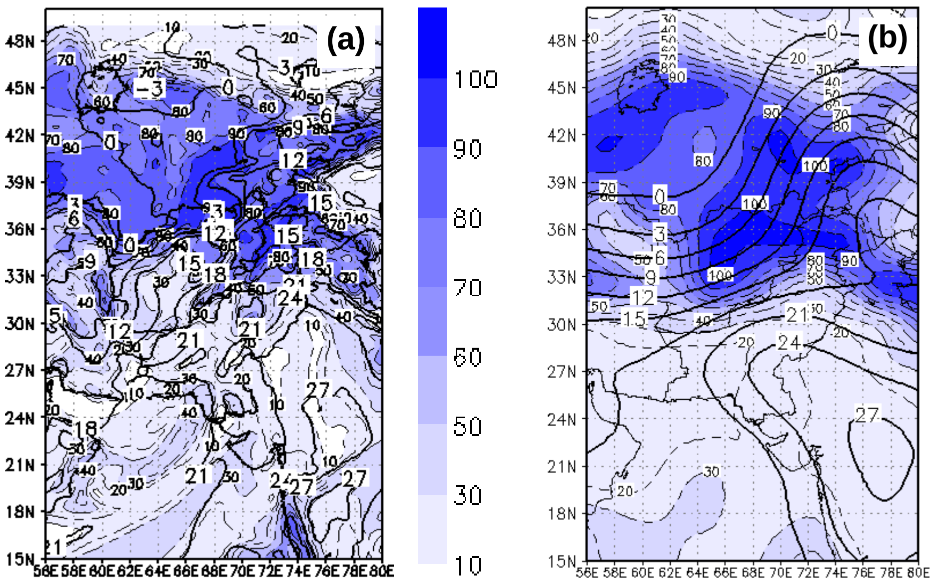

Figure 11: Relative humidity (percentage; shaded), Isotherm (0 C, contours) and wind 850hPa level at 12 UTC, Mar 31, 2007 (a) HRM forecast (b) NCEP reanalysis.

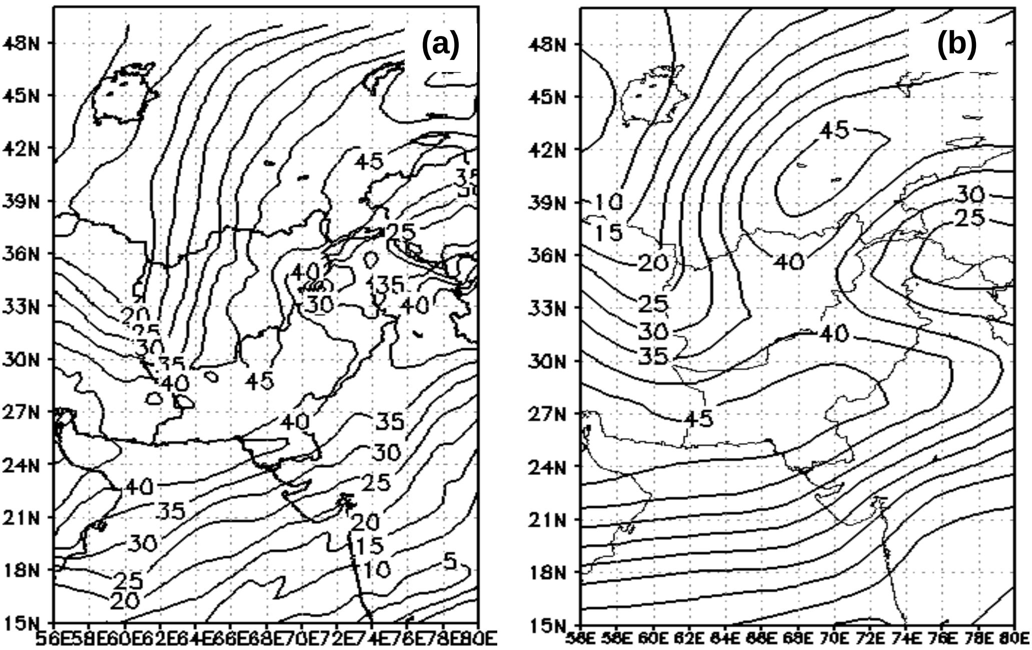

Figure 12: Jet stream winds at 200hPa (contours indicate the magnitude) in units of m/s at 12UTC, Mar 31, 2007(a) HRM forecast (b) NCEP reanalysis.

Conclusions

The analyzed feature/ results are as follows:

The geopotential height trough at 500hPa indicates that at subsequent intervals of twelve hours the depression showed an eastward slow moving trend. At 00UTC – 30Mar2007 a secondary started developing east of Caspian Sea which intensified in to a central low on 00UTC – 01Apr2007 with a pressure drop from 5550gpm (555 dkm) to 5490 (549 dkm)gpm (see figs 2 a upto h). Fig 2g shows the maximum intensification phase of the westerly low and the associated trough, after which the system started to dissipate. In figs 2c, e & g, the lower 500hPa heights (compared to the other locations at the same latitude) along with the positive vorticity (counterclockwise rotation of winds) are indicative of a developed cold core low.

Analysis of 1000-500hPa- thickness contours and sea level pressure showed that a very well defined (intensified) low did not develop over the surface. But the synoptic features did show the properties of a baroclinic wave (when it was intensifying) e.g. in all illustrations of thickness and sea level pressure, the surface low can be seen developed to the east of 500hPa trough.

From March 30th to 31st, 2007 (0300UTC – 0300UTC) considerable rain had already down poured in Chitral and Parachinar regions. From figs 6 a, b, c &d it can be clearly seen that 90% and above relative humidity was present in northwest of Pakistan and 80% to 90% over northern and upper Punjab areas up to the vertical column of 400hPa (fig 7) which aided the high instability of lower atmosphere. From fig 3 the areas of larges ascent can be seen over northern, northwest and upper Punjab. So high relative humidity combined with large vertical velocities resulted in heavy rain.

It can be seen from fig 6 that wind barbs show a 10knot wind in the zone of westerlies (which are advecting the moisture to the northwest of Pakistan from Black sea and Caspian Sea) where as the southerly wind barbs (advecting moisture from Arabian sea) indicate a wind of 5knots. Hence westerlies exhibited more moisture advection tendency than the southerly winds from the Arabian Sea. The interaction of both moisture inputs different in their thermal characteristics triggered this heavy rainfall event.

Temperature advection can also be inferred from fig 6. The wind barbs are crossing the isotherms from lower temperatures to higher temperatures indicating cold temperature advection to the west (which made the cold air mass to the west and southwest of Pakistan). Similarly to the south of Pakistan the wind barbs are crossing from the warm temperatures to low temperatures indicating warm air advection making warm air mass to the south and southeast of Pakistan. It can also be noticed that although warm air was present to the east and southeast of Pakistan, no rains occurred over south eastern Pakistan due to the absence of large vertical velocities and unavailability of moisture.

From figs 8 a, b, c & d we can observe that Pakistan was not under the region of 'jet streak'). The magnitude of winds blowing at 200hPa level to the north of Pakistan was between 35 m/s to 45m/s.Therefore we can assume that jet stream played a little role in creating zones of diverging air which created vertical velocities at 700hPa level. Hence the jet stream was not strong enough to create a perfect baroclinic storm. Therefore the major triggering factor in this heavy rainfall and snow event has been the presence of huge quantity of moisture that remained entrapped in the northwest and northern mountain ranges of Pakistan (figs 6 & fig 7) and resulted in heavy snow and rainfall.

In the validation/ comparative analysis of the NCEP reanalysis with HRM forecast for the selected domain with selected time interval, the comparison showed that HRM forecast illustrations had a high degree of similarity with the NCEP reanalysis observed illustrations. According to the HRM forecast a short wave trough was present in the ridge at 500hPa (fig 9 a) with positive vorticity over northwest Pakistan. This short wave trough remained in the northwestern and northern mountain ranges from 00UTC – Mar 31, 2007 up to 12 UTC – Apr 01, 2007. Strong vertical velocities were observed along this short wave trough (fig 10 a). From fig 12 a, the HRM forecast showed strong divergent winds over northwest and northern regions. For the same locations the vertical velocities can be viewed in fig 10 a. Moisture convergence and advection and direction of winds were forecasted similar to the NCEP reanalysis (figs 11 a, b). Therefore by taking the forecast of HRM into account the jet stream seems to play an important role for the east ward movement and intensification of this system over northern and northwestern Pakistan.

References:

Bruintjes, R.T., T. L Clark, and W. D. Hall, 1994: Interactions between topographic airflow and cloud/precipitation development during the passage of a winter storm in Arizona. J. Atmos. Sci.

C. Donald Ahrens, Published 2002, Meteorology Today, Seventh Edition, Brooks Cole Publishers.

Climatic Data Processing Center (CDPC) Karachi, Published 2005, Climatic Normal of Pakistan (1971-2000), Pakistan Meteorological Department.

Dash, S.K., Shekhar, M.S., and Singh, G.P., 2006: Simulation of Indian Summer Monsoon Circulation and Rainfall Using RegCM3, Theor. Appl. Climatol, 86, 161-172.

Dimri, A.P., 2006: Surface and Upper air fields during extreme winter precipitation over the western Himalayas, Pure and Applied Geophysics, 163, pp. 1679-1698.

Dimri, A.P., 2007: A study of mean winter circulation characteristics and energetics over southeastern asia, Pure and Applied Geophysics,164, pp. 1081-1106.

Dimri, A.P., Mohanty, U.C. and Mandal, M., 2004: Simulation of Heavy Precipitation associated with an Intense Western Disturbance over Western Himalayas, Natural Hazards, 31, pp. 499-521.

Dimri, A.P., 2005: The Contrasting Features of Winter Circulation during Surplus and Deficient Precipitation over Western Himalayas, Pure and Applied Geophysics, 162, pp. 2215-2237.

Hatwar, H. R., Yadan, B. P., Rama Rao, Y. V., 2005: Prediction of western disturbances and associated weather over western Himalayas, Current Science, 88, pp. 913-920.

John M. Wallace, Peter V. Hobbs, Published 2005, Atmospheric Science; An Introductory Survey, Second Edition, Elsevier Publishers.

Khan, F. K., Published 2006, The New Oxford Atlas for Pakistan, Eleventh Impression, Oxford University Press.

Majid, A., Mohammad Riaz., Mohammad Iqbal, J., 2006: Upper Tropospheric Westerly Trough as an Instrument for the Development, Intensification and Northward movement of the Tropical LPS – With reference to Case study of 1988 Flood Event, Pakistan J. of Meteorology, 3, pp. 69-78.

Mujumdar, M., 2006 : Diagnostic Analysis of Wintertime rainfall event over the Arabian Region, Indian Institute of Tropical Meteorology, ISSN 0552-1075, Contribution from IITM, Research Report No. RR-111.

Rasul, G., Q. Z. Chaudhary, S.X. Zhao and Q.C Zeng, 2004: A Diagnostic study of record heavy rain in twin cities Islamabad-Rawalpindi, Advances in Atmospheric Sciences, 21, pp. 976-988.

Shamshad, K.M., Published 1988, The Meteorology of Pakistan, First Edition, Royal Book Company Publishers.

Timothy J. LANG, Ana P. BARROS, 2004: Winter Storms in the Central Himalayas, Journal of the Meteorological Society of Japan, 82, pp. 829-844.

XIE Aihong, REN Jiawen, QIN Xiang, KANG Shichang, 2007; Reliability of NCEP/NCAR reanalysis data in the Himalayas/ Tibetan Plateau, J. Geo. Sci., DOI: 10.2007/s11442-007-0421-2.

http://www.cdc.noaa.gov/cdc/data.ncePp.reanalysis.html

http://www.pakmet.com.pk/

http://en.wikipedia.org/wiki/Surface_weather_analysis