Diagnostic Study of Heavy Downpour in 2015 Flash Floods over Chitral Area, Northern Pakistan

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Abstract

The weather patterns of the whole world have changed over last five decades as depicted by analysis of the past. This research work presents diagnosis of atmospheric conditions that resulted in the extreme flood events in the northern areas of Pakistan especially over Chitral valley from 28th to 31st July, 2015 by utilizing observed data as well as National Centre for Environmental Protection and National Centre for Atmospheric Research (NCEP/NCAR) and European Centre for Mediun Range Forecasting (ECMWF, ERA-Interim) reanalyses data. Analysis of geopotential height and temperature contours at 200 hpa indicated strong differential development which resulted in protraction of jet stream trough over Chitral valley. Easterly moisture interacted with the westerly moisture contributing to 80 % relative humidity causing heavy down pour. Persistence of heat wave over a week prior to the rain spell attributed to the development of low pressure cells over Chitral valley. Heavy precipitation was also recorded prior to and during the flash flood episode, having a total of 24.8 mm in the second fortnight of July. Another reason of rainfall was the presence of warm temperature conditions at the surface, leading to positive omega values on 28th July. The discrete analysis of the NCEP/NCAR datasets along available data of Pakistan Meteorological Department revealed that the entire interaction led to the development of low pressure system, penetration of moisture at much higher levels, protraction of monsoon over Northern areas, bringing about rain spell and flash floods over the region.

Key Words: Diagnostic study, NCEP/NCAR reanalysis, Chitral floods.

Introduction

The warming patterns of Pakistan are distinctive for different regions attributable to which environmental change stretches over the country (Din et al., 2014). Anticipated atmospheric changes in the region incorporate fortifying of storm frequency, increase in surface temperature and recurrence of heavy precipitation episodes. The impacts general to environmental change hits the region with sea level rise, glacial retreat and formation of conceivably dangerous glacial lakes. These progressions could bring about significant effects on the regional environment and biodiversity; hydrology and water assets; horticulture, fisheries; mountains and seaside lands; human settlements and human wellbeing (Farooqi et al., 2005).

Pakistan currently has a weak defense against environmental changes as its economy is heavily dependent on climate-sensitive sectors like agriculture and forestry, and its low-lying thickly populated deltas are undermined by a potential danger of flooding (Farooqi et al., 2005). In Pakistan, the annual mean surface temperature has a steady rising pattern subsequent to the start of twentieth century pertaining to ascent in mean temperature of 0.6-1.0°C in parched waterfront regions, bone-dry mountains and hyper bone-dry fields, 10-15 % diminishing both winter and summer precipitation over coastal belt and hyper bone-dry fields, 18-32 % expansion of precipitation patterns in monsoon zone particularly the sub-moist and humid ranges is observed. Other extreme events incorporate low temperature winds, for instance, those that blow from the North West into the southern plains of the region amid January. In the urban and suburban communities, high temperatures and heat waves likewise recur. These phenomena are exacerbated by the urban heat island impact and air pollution (Farooqi et al., 2005).

The Hindukush-Karakoram locale of Northern Pakistan is prone to Glacier Lake Outburst Floods (GLOF) and out of around 2000 glacial mass lakes 50 are distinguished as conceivably hazardous. The changing response of glacial masses has brought on the emergence of new lakes and augmentation of previous lakes

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(Rasul et al., 2011). Under this response the likelihood of sudden water discharge from these lakes has increased. Another variable which has brought on to increase the recurrence of GLOF episodes in the region is the change in the pattern of rainfall (Awan, 2000). Gilgit-Baltistan has borne about 35 disastrous GLOF events in the previous 200 year's history (UNDP, 2007). As per the available records, the recurrence and force of GLOF events have expanded during the late years. Examination of GLOF events demonstrates that these events were connected to the climate conditions regarding temperature rise, precipitation, and heat waves. Ascent in temperature, heavy precipitation, especially in the summer season and heat waves, are the meteorological parameters which can provide auxiliary conditions for outburst on the off chance that they will couple with other parameters (Din et al., 2014).

A noteworthy part of the snow and ice mass of the HKH area in Pakistan is concentrated in the watersheds of the Indus basin. As a consequence of rapidly changing climatic conditions, the ice sheets in Pakistan are retreating at a rate of 40 – 60 meters over each decade. The melted ice from these ice masses is expanding the volume of water in the glacial lakes. As per the IPCC'S fourth assessment report, eleven of the most recent twelve years (1995 – 2006) rank among the 12 hottest years in the history of worldwide surface record subsequent to 1850. This quick change in the planet's temperatures is connected with a rapid rate of ice sheet melt. Different studies recommend that the warming pattern in the HKH region has been more prominent than the global normal (ICIMOD, 2007). A major threat of this impact is identified with the rapid melting of ice sheets. As these ice sheets retreat, glacial lakes begin to form and rapidly fill up behind moraines or ice dams at the bottom or on top of these glaciers. The ice or silt bodies that contain the lakes can rupture abruptly, leading to a discharge of huge volumes of water and debris. These GLOF events have the potential to release millions of cubic meters of water and debris, with peak flows as high as 15,000 cubic meters per second. Records show that on average, GLOF events happen in the Himalayas every 3-10 years, with fluctuating degrees of socio-economic impact. From 1950 to 1999, recorded surge have added up to property damage of Rs.380 million, a loss of life of 5,832 lives, and 84,475 affected towns. An aggregate of 35 damaging surges have been recorded in the Karakoram locale in the previous 200 years and no less than 11 surges of remarkable scale have been recorded so far in the Upper Indus Basin (UNDP, 2015). Exact date and location of GLOF events have been collected from several reports published by government and private organizations as well as printed media. The summary of significant events is given in Table I.

Table 1: Historical GLOF events in Gilgit-Baltistan.

Year	Date	Glacier	River
1994	29th July	Sosot/Gupis	Gilgit
1999	6th August	Khalti/Gupis	Gilgit
2000	10th June	Shimshal	Hunza
2000	27th July	Kand/Hushe	Indus
2005	25th July	Sosot/Gupis	Gilgit
2007	5th April	Ghulkin	Hunza
2008	6th January	Passu	Hunza
2008	22nd April	Ghulkin	Hunza
2008	22nd May	Ghulkin	Hunza
2008	24th May	Ghulkin	Hunza
2008	14th/15th June	Ghulkin	Hunza
2009	26th March	Ghulkin	Hunza
2012	8th July	Sosot/Gupis	Hunza

(Source, Archer 2001, UNDP 2007, NARC 2008, Pamir Times June 2008. FOCUS, 2012)

On the night time of around 15th and 16th July, and again on 19th, 24th and 28th July 2015, parts of Chitral district were hit by GLOF which carried massive torrents and flash floods washing away villages, access streets, drinking water supply frameworks, small scale hydel power channels, open/private property and horticultural yields. This phenomenon is unusual; however, areas in the north of Khyber Pakhtunkhwa i.e. Mansehra, Chitral, Battagram, Kohistan (U/L), Torghar and Shangla locale that are prone to such episodes of GLOF have as of now been sensitized by NDMA and PDMA amid different periods of monsoon contingency planning. In Chitral valley, 32 lives were lost ead in different occurrences of GLOF (PDMA and PaRRSA, 2015). Table II gives real insights about Chitral valley.

Table 2: Profile of Chitral valley.

Area (Km^2)	**14,850**
Population	361224
Elevation from sea level	3500-25289 Ft
Number of villages	523
Valleys	34
Passes	22
Farm land	446
Glaciers & Snow	3622

(Source, PDMA and PaRRSA, 2015)

Numerous studies have been conducted which use synoptic maps to recognize the atmospheric conditions at various pressure levels instigating specific anomalies. Sajjad (2015) conducted a study by utilizing observed and NCEP/NCAR reanalysis data alongside satellite imagery keeping in mind to investigate and analyze the reasons for a winter downpour spell that persisted from 16th to 20th December, 2008 attributed to heavy precipitation over different districts of Pakistan. It had been analysed that positive vorticity span stayed dominant over the region from 18th to 20th December 2008 up to 500hPa level. Its subsistence over Persian Gulf and upper east Arabian Sea, particularly at lower levels, upheld the mechanism to get more moisture from these water bodies. There were cut off lows present over central parts of Pakistan at 925 and 850 hPa levels that lead to augmented moisture over Pakistan, thereby bringing heavy and continuous rainfall. Analysis of temporal and spatial distribution of multiple weather parameters at the surface and in the upper air in the episode of heavy rainfall event that brought urban flooding in Multan City in July 2005 was done by using the conventional weather charts of Pakistan Meteorological Department (PMD) and NCEP reanalysis data plots. It was determined that the heavy rainfall resulted due to advancing monsoon depression and westerly wave predominant over Kashmir, encircling Himalayan region inconjuction with the upper air easterly wave (Muhammad et al., 2010). Qudsia and Ghulam, (2009) conducted a diagnostic study to identify the basis for a heavy rainfall event that came off over northern and upper Punjab region of Pakistan for two consecutive days (over Mar 30 to Apr 02, 2007) by employing observed, NCEP reanalysis and High Resolution regional Model (HRM) forecast data. It was established that a jet stream prevalent at 200 hPa provoked the eastward propagation of the baroclinic westerly wave due to strong convergence at lower level and positive divergence at upper level over those regions. Sooner than expected spring heating of the ground surface supported the generation of local instability to the existing and advected air masses. The predominance of upper level divergent wind field, along with orographic lifting assisted vertical ascent of the unstable warm moist air that brought about severe weather conditions. Ali, (2013) aimed at studying the event of heavy rainfall which stranded over to the upper Sindh in September, 2012. HRM output and NCEP Reanalysis data supported with satellite imagery were utilized for the post analysis of that downpour. The analysis revealed that the heavy rainfall occurrence over the upper parts of Sindh was a result of favourable orientation of monsoon currents. Another research discussed outcomes of a diagnostic study of a conventional heavy rainfall event during the South Asian summer monsoon when a mesoscale low in a desert climate blended with a diffused tropical depression. The prior low remained stationed over Pakistan's desert region and the following depression appeared over the Bay of Bengal. Surface analysis of NCEP reanalysis data backed up by satellite and radar imagery were used as diagnostic tools for the event. The linkage between the heavy precipitation mechanism and large-scale circulations such as monsoon trough, subtropical high, westerly jet, low level jet and water vapor transport were inspected to additionally comprehend the process of that unconventional interplay (Rasul et al., 2005). Utilizing surface and NCEP reanalysis data supported with radar and satellite imagery, an analysis was conducted to probe in to the reasons of a very heavy rainfall event that occurred in Islamabad and Rawalpindi on 23rd of July, 2001. Post analysis results showed that the abrupt development of the meso scale stern weather system was the direct result of convective heat transfer to in moist and unstable lower layers of the atmosphere due to intense surface warms (Rasul et al., 2004). In another research, an effort was done to diagnose the desolating dust/wind storm followed by torrential pre-monsoon rain which lashed Karachi and crumbled up the city's foundation. Abrupt and accelerated evolution of supercell cumulonimbus clouds over Karachi in the periphery of strong deep depression over Arabian Sea followed by severe wind storm (whole gale) was inspected (Baig and Rasul, 2008).

The present research work follows the above reviewed framework of the extreme weather diagnosis of atmospheric conditions that resulted in the extreme flood events in upper KPK and G-B especially over Chitral valley from 28th to 31st July, 2015 utilizing observed as well as reanalysis data.

Study Area

The upper KPK and G-B are isolated mountainous terrains in the northern extreme of Pakistan attributed to as the roof of the world and extended over an area of 72,500 square kilometres. They lie between latitude 35° to 37°N, and longitude 72° to 75°E, (ranging from 1500 – 8000m above the sea level) and are surrounded by high mountains. The upper KPK and G-B are sandwiched between three famous mountain ranges, the Himalayas, Karakoram and the Hindukush. Lofty mountain ranges comprise of a large number of gigantic and glorious snow-capped peaks, lush green valleys, lakes and some of the biggest glaciers (Mashabrum, Rakaposhi, Siachen, Passu and Haramoish) in the world (Winter and Mannheim, 2000).

The climate of the upper KPK and G-B is dry continental Mediterranean. The barren mountains absorb solar radiations, which emits out as long-wave radiation that substantially rises temperatures in summer. Average temperature in summer rises from 17.4 to 35 °C (June-August), in autumn it varies from 6.6 to 25.3 °C (September-November), in winter it varies from -2.7 to 10.8 °C (December-February) and in spring (March-May) from 8.8 to 22.8 °C. The upper KPK and G-B occupy outer Himalayas and thus are generally cut-off from the monsoons. As a results the precipitation is low yet moist air occasionally penetrates through the high mountains in late spring (May), summer and sometimes brings heavy and torrential rains bringing hazards like floods, and mud flows. In fact it is majorly an arid region (NASED, 2003).

The upper KPK and G-B are characterized by one of the most treacherous mountainous landscape on the earth, with an arm of the Hindu Kush to the west, the Himalayas to the south, the Karakorum to the east, and the Pamir to the north. In total, 101 peaks above 7,000 meter, including Nanga Parbat and K.2 (the world's second highest mountain), are found in the region, and also contain some of the largest glaciers outside the polar region. The Baltoro glacier, for instance, extends up to 62 km and covers an area of 529 square kilometers. The region also form a pivotal watershed for the Indus River. The early tributaries of the Indus run through the mountain in narrow, steep-sided valleys, and play a paramount role in the ecology and land-use of the region (NASED, 2003).

Chitral lies between the parallels of latitude 35° and 37° North and meridians of longitude 71° and 74° East (Figure 1). The valley about which the Chitral River-of glacial origin flows is narrow, being not more than one mile broad at any location. It is bounded on either side by high hills, ranging between 10,000 and 15,000 feet. It runs due north and south. The ranges bounding the valley are intersected at intervals by narrow nullahs, or valleys, each with its mountain stream, derived from the melting of the snow at high elevations. At the mouths of these nullahs alluvial fans extend with a gentle slope towards the river. These alluvial formations are the only habitable portion of this mountainous terrain; villages and a noticeable amount of cultivation is found in these areas. Snow covers the ground during the winter months, usually up to the end of February. The rainfall is small. The hills in the northern part of the valley are scarcely wooded (McCarrison et al., 1906).

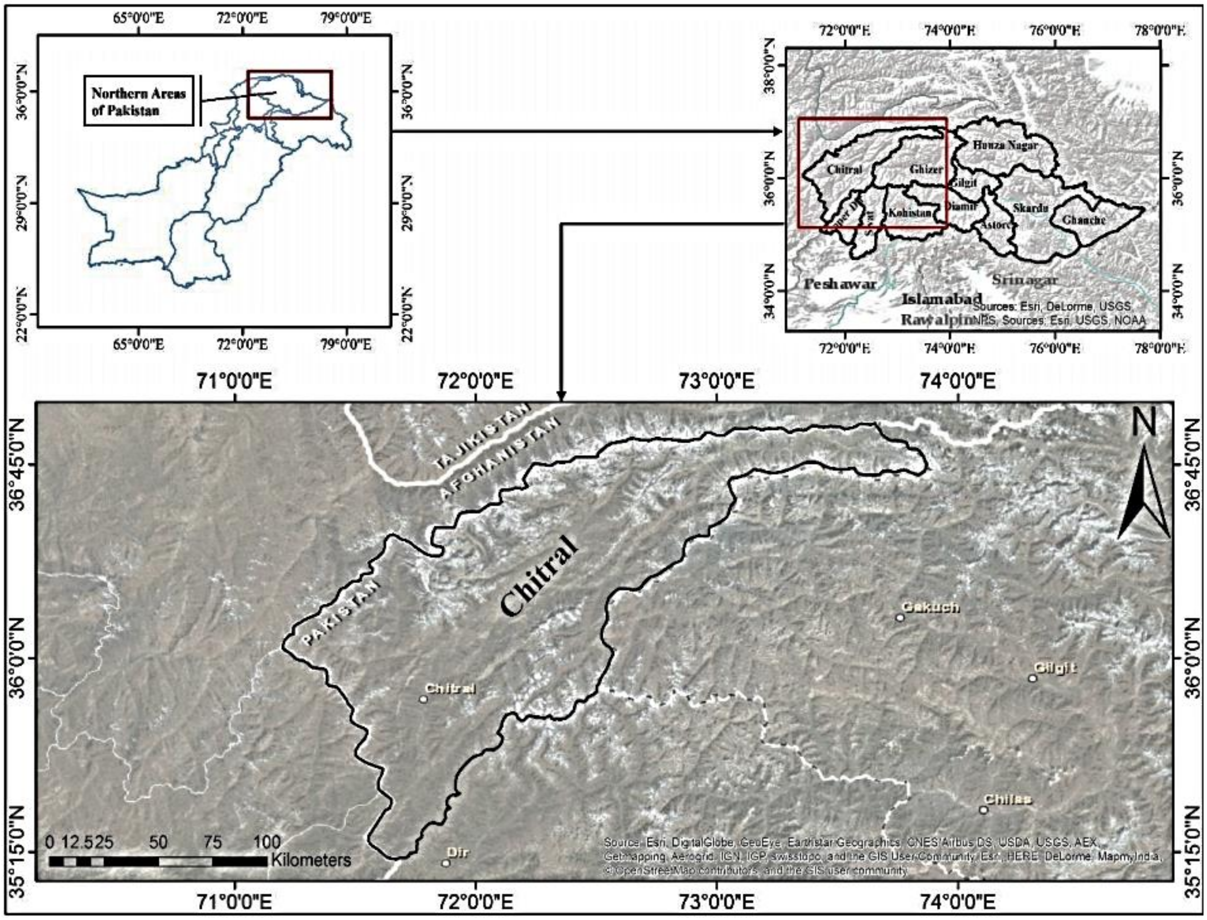

Figure 1: Geographical location of the study area.

Data and Methodology

Present research is a case study which intends to explore the state of synoptic variables at the time of recent GLOF event in Chitral valley. The analysis is presented in the form of weather charts more specifically called synoptic charts which visually represent the information on weather. For surface analysis, PMD daily station data of temperature and precipitation for Chitral has been used to identify weather patterns of June and July of 2015.

For the study of the upper air profile, NCEP reanalysis data was obtained (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html). The NCEP/NCAR Reanalysis 1 project uses state of the art analysis and forecast system to do assimilation and thus provides data for the period starting from January 1948 to present for six hour interval, daily and monthly basis with resolution of $2.5° \times 2.5°$ (250 km^2). A large subset of this data is available from Physical Sciences Division (PSD) in its original 4 times daily format and as daily averages, (NCEP/NCAR Reanalysis 1: Summary). While obtaining the data from the NCEP website, daily datasets were selected. Surface and upper air re-analysis datasets have been used to investigate the reason of heavy downpour that caused flash flooding in the target area.

To investigate spatial magnitude and extent of total rainfall over the target area, a relatively high resolution gridded reanalysis observational dataset, ERA-Interim of the European Centre for Medium Range Forecasting (ECMWF) is used. ERA-Interim is a global atmospheric reanalysis from 1979, continuously updated in real time. The system includes a 4-dimensional variational analysis (4D-Var) with a 12-hour analysis window. The spatial resolution of the data set is approximately 80 km (T255 spectral resolutions) which is conformable to various low and high resolution spatial grids. The presently used grid resolution of the data set is approximately $0.125° \times 0.125°$, which is deemed suitable to capture observed precipitation of the highly heterogeneous rugged terrain of the Chitral region.

Results and Discussion

Streamlines and Humidity

In the 2015 summer monsoon, the seasonal (JJAS) normal patterns of streamlines and humidity at 300 hPa show that the westerly sub-tropical jet is present in the north of Tibetan high (Figure 2). Under normal monsoonal conditions, the upper tropospheric westerly jet over northern Pakistan and adjoining India weakens and the sub-tropical westerly jet shifts to the north of Himalayas. The northward shifting of sub-tropical westerly jet paves way to penetration and advancement of monsoon towards higher latitudes. At 850 hPa level, it is seen that low-pressure area is formed as a belt-shaped zone (Figure 3). Monsoon troughs are seen to be linked with low-level convergence, cyclonic vorticity, and cloudiness. The low pressure system is seen to be oriented along east-west, with 50 to 60 % relative humidity over the Chitral region. A deep trough in its normal position yields finely distributed rainfall over Pakistan. Shifting of the trough northwards shifts the rainfall belt towards the upper KPK and GB-AJK regions.

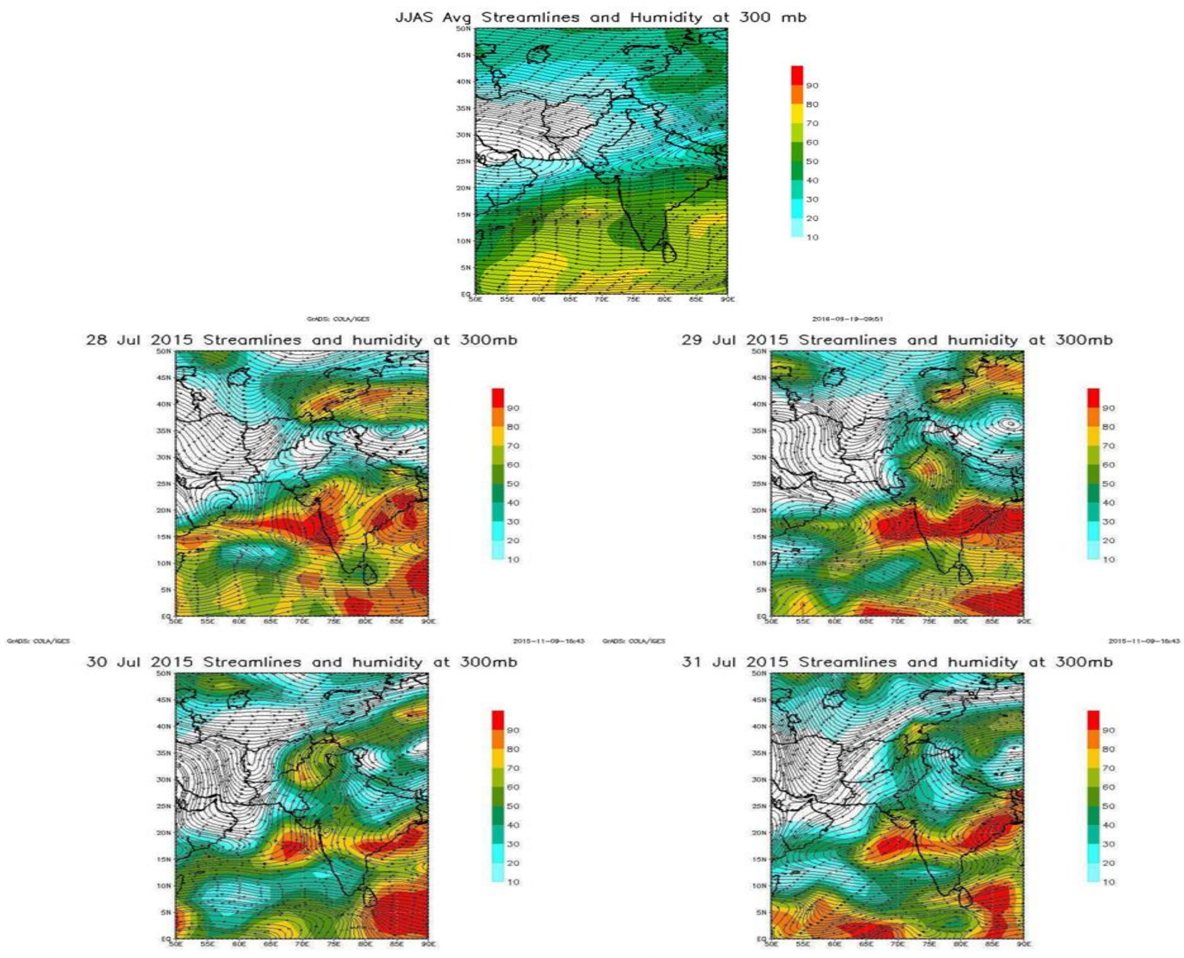

Figure 2: 300 hPa Streamlines with humidity in colours
(JJAS and 28^{th} July to 31^{st} July 2015)

Streamlines indicate the direction of flow of the wind, which is generally from west to east throughout most of the subtropics, mid- and high-latitudes. The streamline charts are drawn for upper air (300 hPa) to display the spatial distribution of flow directions at particular instants (28th-31st July, 2015). As indicated by the arrow heads, the flow direction along the streamlines parallel to the wind direction indicates protraction of upper level jet stream trough over the Chitral region (Figure 2). The 300 hPa level is near the core of the jet stream, so the tracks of the jet streams can be seen very clearly. Low-level convergence (850 hPa), on 28th of July, right over the upper KPK implied horizontally confluent flow and vertically air resulting in inclement weather over the region (Figure 3). Cyclones and anti-cyclones in the upper air are associated with low and high pressure areas on the surface. The strong low-level convergence with divergence aloft at the Chitral region was associated with strong vertical velocities in the middle troposphere, and as a result, severe weather/heavy rainfall occurred on 28th of July which continued till 31st of July 2015.

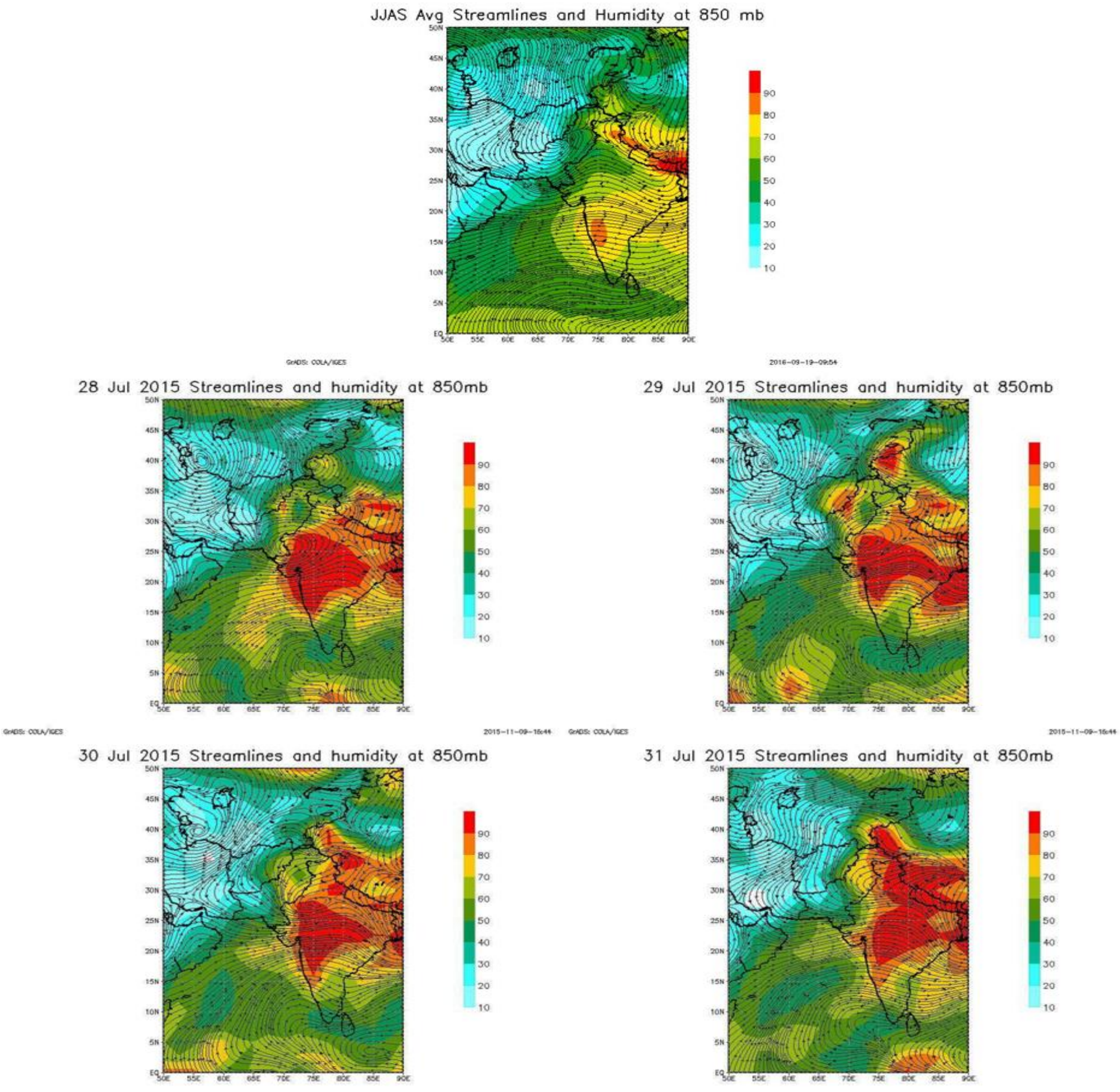

Figure 3: 850 hPa Streamlines with humidity in colours
(JJAS and 28th July to 31st July 2015)

Overlaid maps of upper-air relative humidity reflect the spatial distribution of moisture content in the atmosphere on 28th to 31st July, 2015. Pre-requisite moisture for cloud formation is seen over the Northern Pakistan (including Chitral) at 300 hPa, where relative humidity is high. From an overlaid relative humidity map at 850 hPa, the depth and distribution of clouds in the lower atmosphere is seen. It may be seen that due to rising air through a deep layer of the atmosphere (low levels), the relative humidity increased. Nearly 70 to 80 % relative humidity on 31st of July indicates nearly saturated air. In conjunction, low vapor deficit, trigger mechanism of front and upper level divergence (at 300 hPa) were able to condense clouds and produced precipitation. Heavy downpour occurred under the favourable meteorological conditions.

Geopotential Height and Temperature

Geopotential height is a valuable tool for locating troughs and ridges which are the upper level counterparts of surface cyclones and anticyclones. Black contours indicate the geopotential height at 500 and 850 hPa atmospheric levels (Figure 4 & 5). The visible low geopotential heights of 28th - 31st July 2015 both at 500 and 850 hPa (compared to other locations at the same latitude) indicates the presence of a trough at mid-troposphere and surface levels. The geopotential height of the 500 hPa level had dropped down to 5820 meters, whereas that of the 850 hPa had dropped down to 1400 meters on the 28th - 31st July, 2015 episode. The geopotential height of the 500 hPa pressure surface shows the tropospheric waves that controlled the low height troughs in the middle troposphere over the central and northern regions of Pakistan. Sharp temperature gradients at 500 hPa level steered the weather system towards north and thus heavy precipitation followed on 28th – 31st July, 2015 episode.

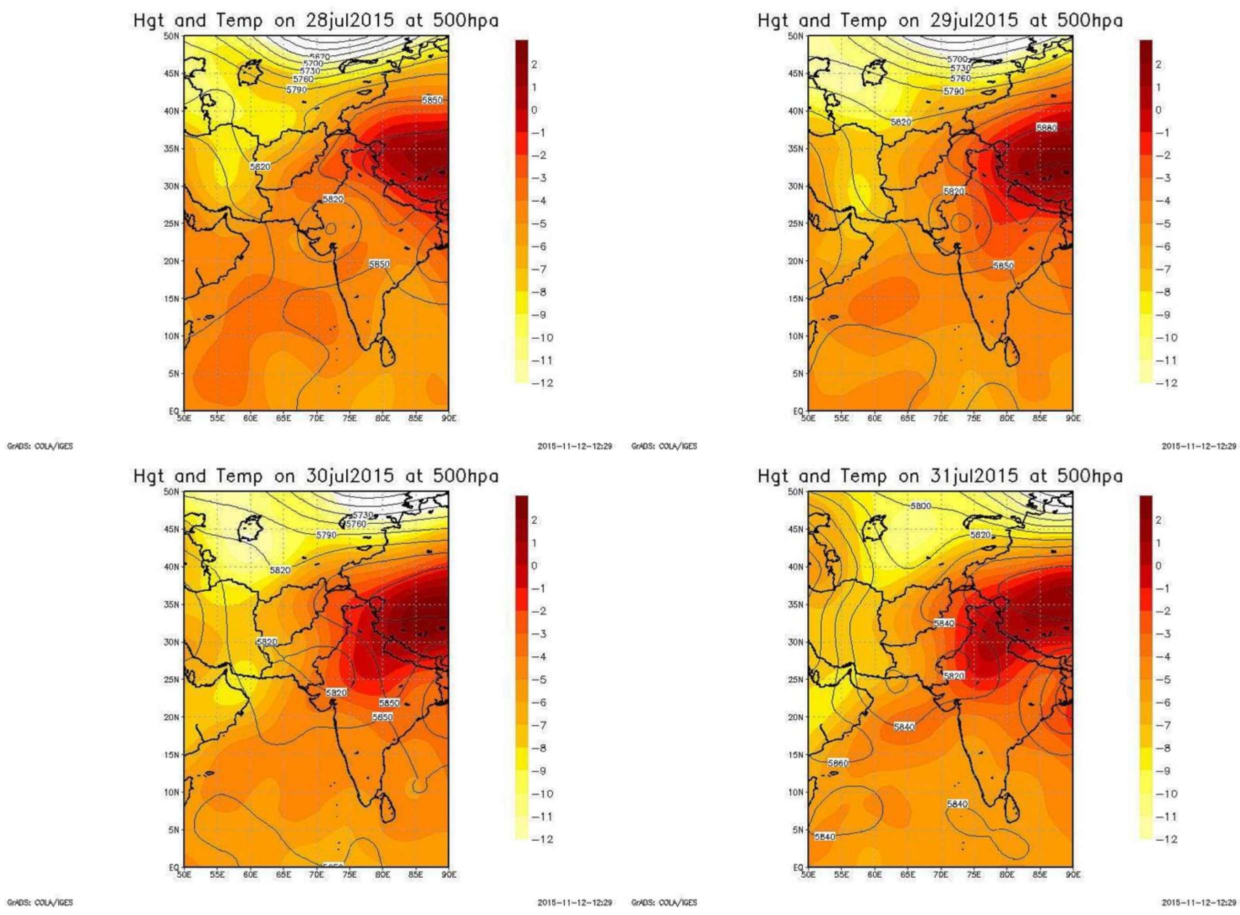

Figure 4: 500 hpa Geopotential heights and temperatures from 28th to 31st July, 2015.

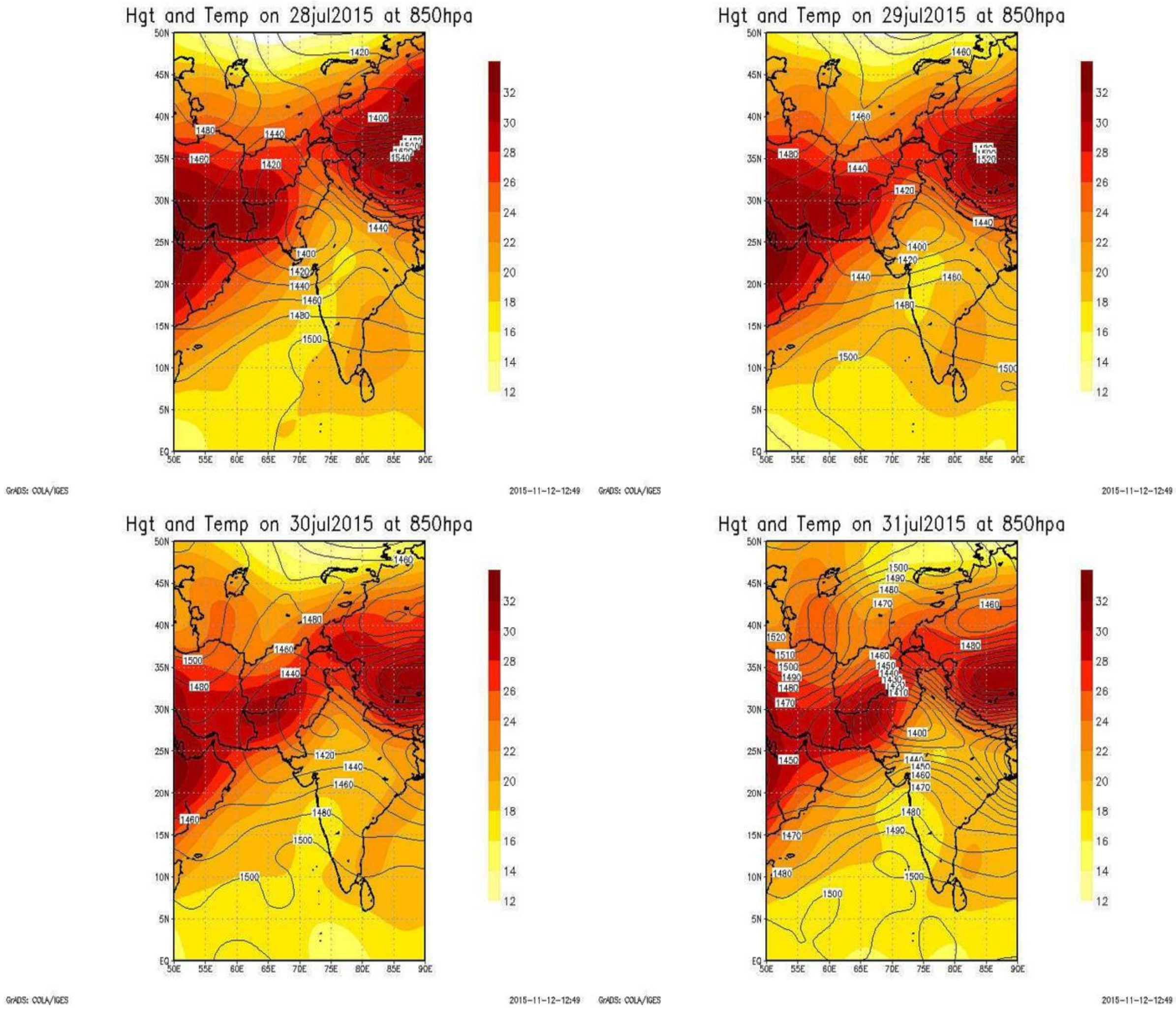

Figure 5: 850 hpa Geopotential heights and temperatures from 28th to 31st July, 2015.

Vertical Profile of Relative Humidity and Temperature

Deep convection depends on the vertical profiles of temperature and relative humidity. Relative humidity plotted over a vertical profile chart indicates the rising and sinking of air over Chitral valley (Figure 6). High relative humidity of magnitude above 90 % at 500 hPa on 28th of July 2015, is associated with rising air and moisture advection (convergence) from upstream. The deep convection occurring as mesoscale convective system over Chitral region influences the vertical profiles of temperature and relative humidity. Investigation of the vertical profiles suggests that the precipitation episode of 28th – 31st July, 2015 was associated with relative humidity anomalies throughout the troposphere and that the anomalies were largest in the 300-800 hPa layer. The 300-600 hPa is described by negative temperature, in all likelihood connected with buildup of water vapour in the anvil cloud segment of mesoscale convective system. The 600-800 hPa layer is characterized by a negative temperature anomaly, most likely associated with evaporation of stratiform precipitation falling from the anvil cloud. This is also the layer where westerly moisture interacted with the south-easterly moisture of monsoon on 29th of July, 2015.

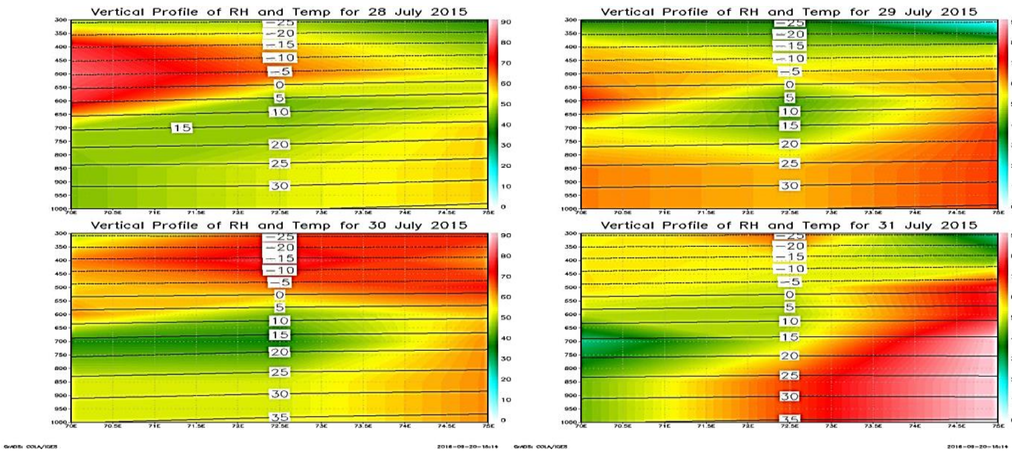

Figure 6: Vertical profile of RH (%) and temperature (°C) from 28th – 31st July, 2015. The lines represent vertical profiles of temperature whilst the shades represent vertical profiles of relative humidity. The grey horizontal bars depict pressure levels in each graph.

Subtropical Jet and Temperature

The jet stream is a complex phenomenon which exists because of the temperature contrast between warm sub tropical air to the south and cold polar air to the north. It is partly controlled by local weather, but is also influenced by distant conditions (like warm/cold ocean temperatures in the tropics).

Peripheral streaks of trough in the jet stream at 200 hPa were positioned directly over Chitral on 28th of July, 2015 that had caused the warm, moist air to draw off the Indian Ocean and to rise strongly leading to a heavy rainfall event over the region (Figure 7). Near the surface, the monsoon easterly winds had extended unusually far along the Himalayan foothills and into the Hindukush over northern regions of Pakistan.

Over northern Iran and Afghanistan the trajectory of jet streaks took on a cyclonic curve (anticlockwise), that led to a dynamic depression aloft on 29th of July, 2015. Simultaneously over the Chitral region, there developed a dynamic depression overlying the thermal depression already established at the surface, and it appeared that the event might well be the trigger that set off the burst of the monsoon, allowing the vigorous inflow of moist air high and deep into the Chitral region.

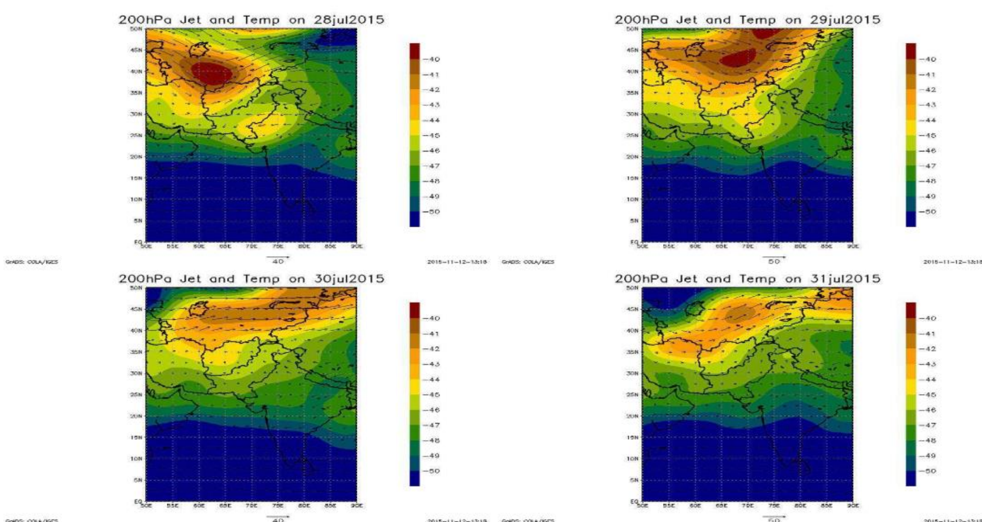

Figure 7: Position of Jet Stream at 200 hpa and temperature analysis from 28th – 31st July, 2015.

700 hPa Geopotential height, temperature and winds

The 700 hPa-level is positioned at approximately 3000 m above sea level. Figure 8 shows the 700 hPa charts for 28th to 31st July 2015 that show similar features of the 850 hPa chart (shown in Figure 6). At 700 hPa, it is seen that baroclinity is prominent than at 850 hPa. Furthermore, it is seen that the propagation speed of air mass depression is approximately same as the speed of 700 hPa winds. The maps show that the predominant tropospheric waves have driven monsoon low up to 5 degrees towards north which had driven the smaller synoptic waves in the Chitral region. The occurrence of warm advection concurrent to upward vertical motion in the lower portions of the troposphere above Chitral region is well evident at 700 hPa, especially on the 30th and the 31st of July 2015. Thus the shallow depression had experienced vertical wind shear steered by winds at the 700 hPa level over Chitral region.

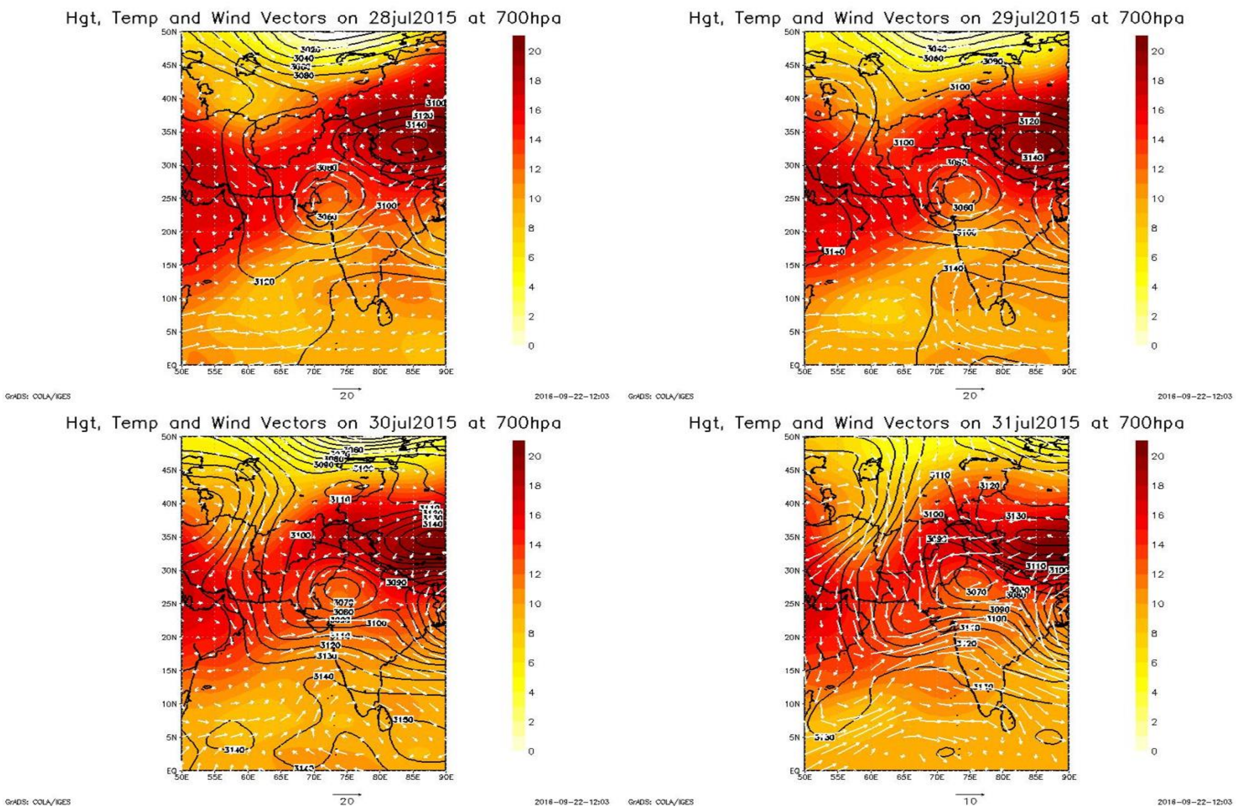

Figure 8: 700 hPa Geopotential heights (m, contours), temperature (°C, shaded), and winds (m/s, vectors) from 28th to 31st July, 2015.

Vertical Velocity Omega and Temperature

Upward vertical velocity is the compilation of all lifting and sinking mechanisms over a fixed point. Negative values of Omega are indicative of where uplift is occurring, which is an important factor when locating areas of convective development and potentially heavy falls of precipitation. As we look at the 500 hPa analysis panel, we notice emergence of upward vertical velocities over the Chitral region. The region is seen to experience mechanisms such as low level convergence, jet streak divergence and orographic uplift that caused the air to rise in the vertical direction. Convective upward vertical velocity is rapid and occurs due to the release of convective available potential energy.

Figure 9 shows temperature (shaded) and vertical velocity (contours, Pa/s) along latitude 35°N-37°N on the flood dates from 28th – 31st of July, 2015. There is instability at 500 hPa over Chitral region (-0.15 Pa/s vertical velocity) with strong temperature gradients. There is upward motion over the Chitral region on 28th of July, 2015 with maximum upward motion seen at around 35°N and 71°E, with values between -0.15 Pa/s to -0.10 Pa/s. This upward motion is associated with upsloping and downsloping winds, as the lower levels have enhanced vertical velocities, while at the same time a westerly cross barrier flow exists. The westerly winds at 500 hPa curve to the northwest for western portions of Chitral region indicating an area of warm advection. On 29th of July, 2015 the area of instability at the 500 hPa level moved east and brought stable weather conditions over the region.

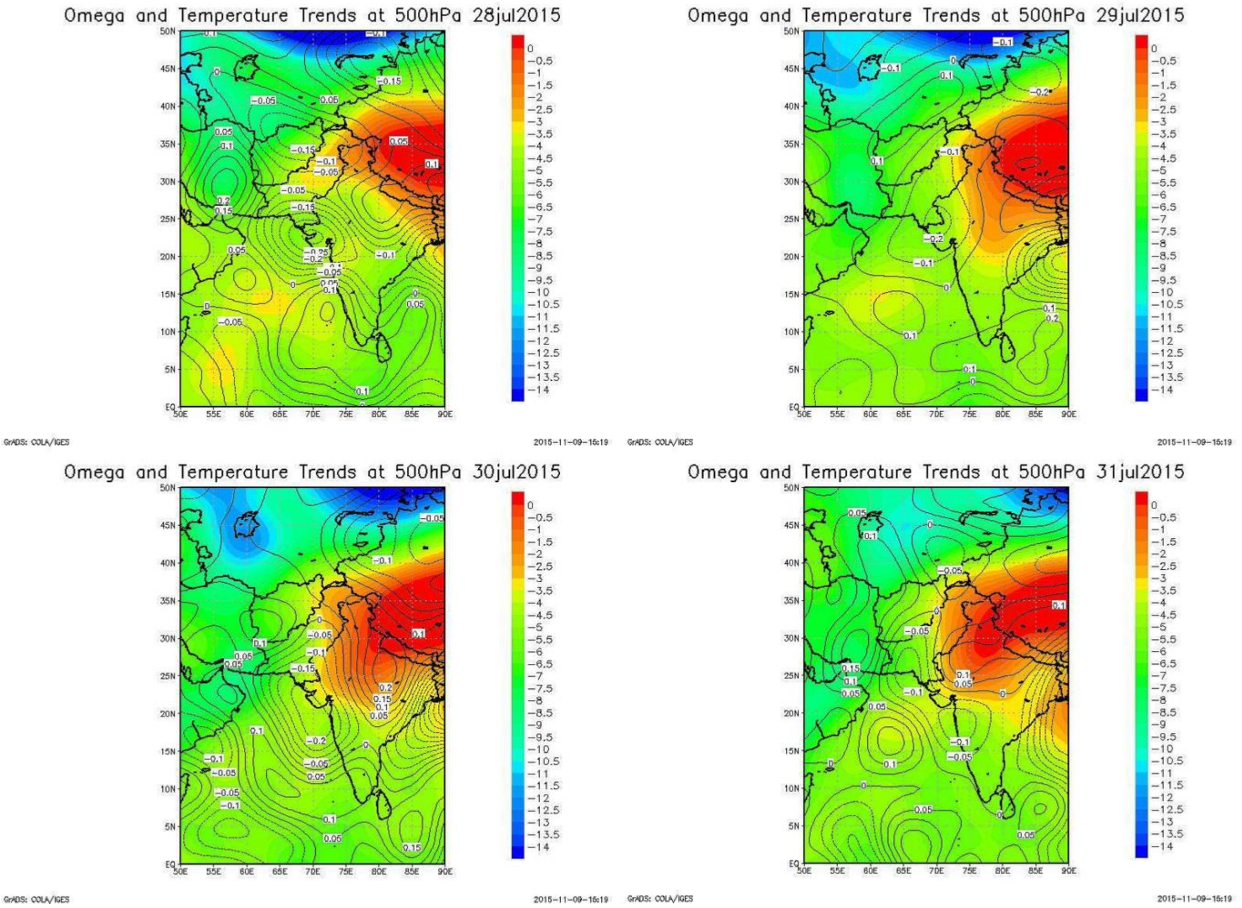

Figure 9: Vertical velocity "Omega" (m/sec) in contours and temperature trends (°C) at 500 hPa from 28th to 31st July, 2015.

Heat Wave

Heat waves, depending on their intensity, can have serious consequences. The most direct impact is due to the excess heat itself. However, if heat waves occur in regions where glaciers exist, the impact can be even more profound. July's record heat wave dealt a terrible blow to the glacial lakes in the Chitral region. Beginning on 4th of July, 2015, an oppressive heat wave settled over North-western area of Pakistan including the Chitral region. Temperatures peaked to record levels for the next 14 days. Extreme maximum temperatures of greater than 40°C were repeatedly recorded from 4th - 7th of July, 2015, and of greater than 35°C were repeatedly recorded from 8th – 17th of July, 2015, over the target region. Total sunshine hours were recorded between 8 to 10 hours a day during the heat wave episode. The air was recorded relatively dry with relative humidity ranging from 20 % to 40 % at 12 Z (Figure 10). The extreme weather was caused by an anti-cyclone firmly anchored over the Iranian land mass holding back the rain-bearing western depression that usually enter the Northern Pakistan grabbing moisture from the Caspian Sea. This situation was exceptional in the extended length of time (over 16 days) during which it conveyed hot and dry conditions over the Chitral valley. The dissipitation of anticyclone and the emergence of cyclonic depression over the Chitral valley in the second fortnight of

July 2015 recorded a total rainfall of 24.8mm which became cause of several occurrences of GLOF events in the region.

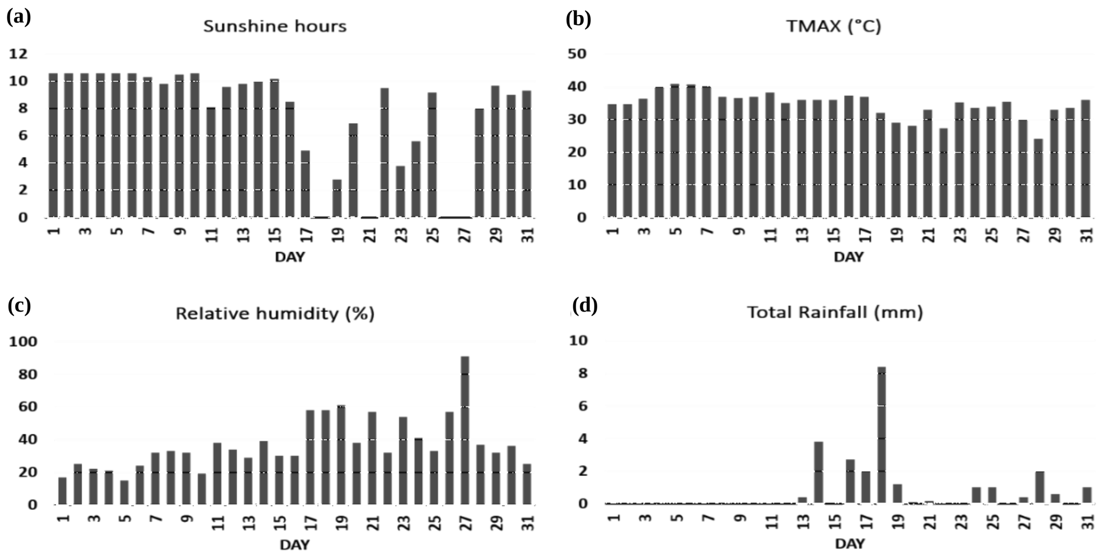

Figure 10: Observed weather data analysis of July 2015 for **(a)** sunshine hours, **(b)** maximum temperature, **(c)** relative humidity, and **(d)** total rainfall recorded by Pakistan Meteorological Department over Chitral station.

Accumulated rainfall of the 28th -31st July episode

Albeit meteorological perceptions over the Chitral city were recorded as not more than 4 mm along the GLOF occasion, yet the massive size of surge water immersion requires clarification. Investigation is made using a high resolution gridded observational reanalysis data of the European Centre for Medium range Weather Forecasting (ECMWF, ERA-Interim) for depiction of both magnitude and extent of the possible heavy rainfall event. It is seen that the 0.125° × 0.125° grid resolution of the ERA-Interim data captures more than 15 mm accumulated rainfall over the western confines of the highly heterogeneous terrain of the Chitral region (Figure 11). Infact the heavy rainfall occurred over the snow covered ranges of the Hindukush in Chitral that feed to Chitral/Kunar river. The temperature gradient between the cold snow covered peaks and the relatively warm monsoonal rain rendered a rapid snowmelt that flowed along the river water and heavily inundated the region.

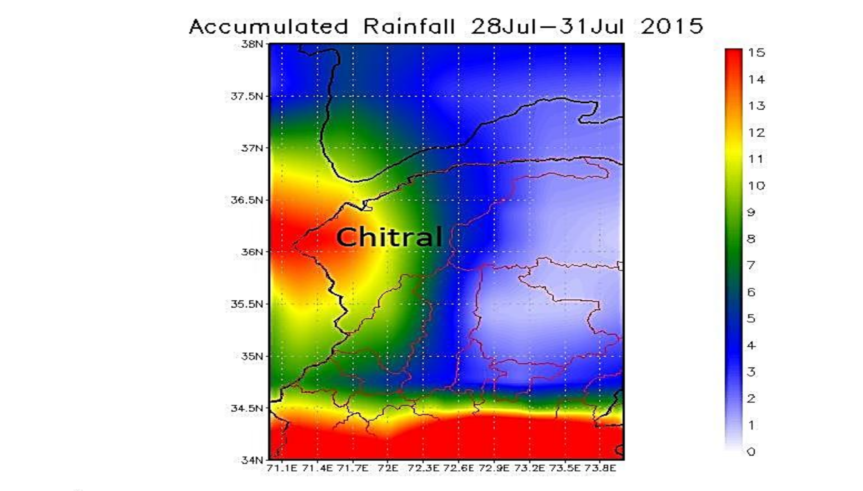

Figure 11: Total Rainfall of the 28th – 31st July 2015 episode as depicted by 0.125° × 0.125° ECMWF Era-Interim daily reanalysis observations.

Conclusions

The earth's climate has been evolving continuously over last millennia. Observations of the climate & weather system are based on direct measurements, and remote sensing from ground stations and satellites. In this research work a diagnostic study has been carried out by using observed data and National Centre for Environmental Protection and National Centre for Atmospheric Research reanalysis data to diagnose synoptic situation of the atmosphere above and around Chitral valley that led to flash floods from 28^{th} - 31^{st} of July, 2015. The temporal and spatial distribution of various weather parameters of this event in Chitral valley have been analysed both at the surface and in the upper atmospheric levels through synoptic charts. It has been observed that there was 80 % cumulative easterly and westerly moisture present in the upper atmosphere during 28^{th} - 31^{st} of July; whereas during the same time span, orographic uplift was provided by Hindukush at the surface, thus lead to heavy rainfall. Moreover, there was presence of jet stream on 28^{th} of July above Chitral valley which assisted the development of a low pressure system. Another reason of heavy rainfall was the presence of warm temperature conditions at the surface which led to strong negative omega values on 28^{th} of July at 500 hPa. The analysis of observed meteorological data further reveals that high temperatures ranging from 35°C to 41°C prevailed in study area (identified as heat wave) prior to the GLOF incident.

Our study has indicated potentially reliable diagnostic atmospheric parameters like temperature, humidity, geopotential height, and omega that provided auxiliary conditions for heavy downpour of the 2015 flash floods over the Chitral region which may further be useful for forecasting GLOF calamities in the future. This characterisation of synoptic-scale forcing mechanisms can be also helpful for better understanding and anticipating weather extremes and their long-term changes.

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