

## An analysis of monthly rainfall and the meteorological conditions associated with cloudburst over the dry region of Leh (Ladakh), India

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**सार** – पश्चिमी हिमालय (30.09 डिग्री उ./77.34 डिग्री पू.) में जम्मू कश्मीर के लद्दाख क्षेत्र में लेह के निकट 6 अगस्त, 2010 को भा.मा.स. के अनुसार करीब 0130-0200 बजे भारी वर्षा होने से भयंकर भूस्खलन हुआ। यह क्षेत्र जांस्कर रेंज के अनुवात की तरफ कम वर्षा वाला क्षेत्र है और इस क्षेत्र में इस परिमाण में घटित हुई मौसमी परिघटनाओं के बारे में अभी तक कोई जानकारी नहीं है। लेह में होने वाली दैनिक और मासिक वर्षा के विश्लेषण से पता चलता है कि जुलाई और अगस्त के माह अधिक वर्षा वाले होते हैं। अत्यधिक वर्षा की वार्षिक घटनाओं के विश्लेषण से भी पता चला है कि अत्यधिक वर्षा की वार्षिक परिघटनाओं के 40 प्रतिशत वर्षा मॉनसून के दौरान जुलाई, अगस्त और सितम्बर के महीनों में ही हुई है। आम धारणा यह है कि भारत में दक्षिण-पश्चिमी मॉनसून लद्दाख तक नहीं पहुँचता है, इसके विपरीत यह विश्लेषण स्थापित हुआ है। अभी हाल ही में भारी वर्षा की दो परिघटनाएँ 5 अगस्त, 2010 और 25 जुलाई, 2011 को घटित हुई हैं जो सक्रिय मॉनसून के दौरान तिब्बत-लद्दाख क्षेत्र के मध्य क्षोभमंडल (~500 हे.पा.) में पश्चिम की तरफ भ्रमण करने वाले चक्रवाती परिसंचरण से प्रभावित था। इस शोध पत्र में इस क्षेत्र के पर्वतीय विशेषताओं के प्रभाव को ध्यान में रखकर विचार विमर्श किया गया है जिसे आमतौर पर वर्षा में बाधक के रूप जाना जाता रहा है, और यह पता चला है कि ये विशेषताएँ वस्तुतः मध्य क्षोभमंडल के बहुत बड़े भाग में सन्निहित अनुकूल पर्यावरण के लिए पश्चिम की तरफ जाने वाले चक्रवातीय परिसंचरणों से होने वाली वर्षा को बढ़ाती है।

**ABSTRACT.** A catastrophic landslide induced by intense rainfall occurred near Leh in Ladakh region of Jammu and Kashmir in western Himalayas (34.09° N/77.34° E) around 0130 - 0200 hours IST of 6 August, 2010. The region is a low rainfall zone on the leeward side of the Zaskar Range and is not known to experience weather event of this magnitude. Analysis of daily and monthly precipitation of Leh showed that July and August are the rainiest months. Also the analysis of annual extreme rainfall events shows that 40% of all the annual extreme events have occurred during the monsoon months of July, August and September. This analysis has established, contrary to the general belief, that southwest monsoon of India does not reach Ladakh. The two recent heavy rainfall events of 5 August, 2010 and 25 July, 2011 have been found to be associated with westward moving cyclonic circulations in middle troposphere (~ 500 hPa) over the Tibet-Ladakh region during active monsoon conditions suggesting that such systems are crucial to produce heavy to very heavy rains over this region. Also the effect of orographic features of the region, which generally are considered to act as obstruction to rainfall, has been discussed and shown that these features may, in fact, be enhancing the rainfall associated with westward moving cyclonic circulations in the middle troposphere embedded in large scale favorable environment.

**Key words** – Leh, Heavy rainfall, Monsoon, Landslide, Cloudburst, Middle troposphere, Himalayas, Orography.

### 1. Introduction

Rainfall-induced landslides cause tremendous damage to life and property across most of the mountainous regions of the world. Rainfall events of either prolonged duration and/or of high intensity combined with favourable topography, unstable geological structures and soft and fragile rocks collectively cause severe landslides and related phenomena in these regions. The Himalayan ranges are

among the major elevated land features of the world; and are prone to heavy and prolonged rainfall events and associated flooding/landslides, particularly during the summer rainy months of June to September (monsoon season). Studies indicate that the loss due to landslides and related problems in the Himalayan region alone constitutes about 30 per cent of the world's total landslide-related damage value (Li, 1990). According to Wulf *et al.* (2010), summer precipitation in Himalayas from May to October accounts for ~80% of the mean annual

precipitation with about 40% of this summer precipitation falling in 4 - 6 rainstorm events. The rainstorm intensity in the orogenic interior of the region varies considerably more than that at the orogenic front. These rainstorm events have a large impact on sediment flux. Thus, despite the great importance of winter westerly-derived precipitation for glaciers and river discharge, sporadic heavy monsoonal rainstorms dominate the sediment flux. Variability in precipitation over the Himalayas during monsoon season is controlled by the atmospheric circulation systems that draw moisture from the Bay of Bengal (Gadgil, 2003).

Ladakh region of Jammu and Kashmir situated in western Himalayas is a low rainfall zone situated on the lee ward side of the Zaskar Range in the western Himalayas with Leh as the main town in the region. A cloudburst occurred near Leh ( $34^{\circ} 09' N$ ,  $77^{\circ} 34' E$ , 3514 metres asl) around 0130-0200 hours IST of 6 August, 2010 (2000-2030 UTC of 5 August) leading to flash flood and mudslides over the region. It caused huge loss to life and property. Unofficial reports put the death toll at more than 200. Though parts of Leh town also bore brunt, centre of the event and the maximum damage was around a locality named Choglamsar, about 5 km south of the city as shown in Fig. 1 taken from website of University of Texas (<http://www.lib.utexas.edu/maps/ams/india/ni-43-08.jpg>). The figure shows that Choglamsar is located just on the bank of river Indus whereas Leh town is located about 5 km north and is uphill compared to Choglamsar. A glacier-fed rivulet Sobu River joins river Indus just close to it.

As the area falls under a very low rainfall zone (with the total annual rainfall of about 10 cm) and does not have a known history of such an event of this magnitude (both in terms of the amount of rainfall and mudslide), it is important to investigate the conditions which led to this kind of a heavy rainfall. The meteorological features associated with this catastrophic events and another event of similar nature which occurred on 25 July, 2011 are investigated in this article using various observational (both in-situ and satellite) and Numerical Weather Prediction (NWP) model diagnostic tools. Detailed climatological analyses of mean monthly and annual extremes of precipitation of Leh have also been made to delineate the seasonal peculiarities favourable for such events. It is generally believed that the monsoon current does not reach Ladakh region. We have tried to show through climatological analyses of monthly rainfall pattern and annual extremes of rainfall over Leh that monsoon is the rainiest season for this region; and that the two episodes of heavy rainfall mentioned above were caused by east to west moving middle tropospheric circulations embedded in large scale monsoon flow.

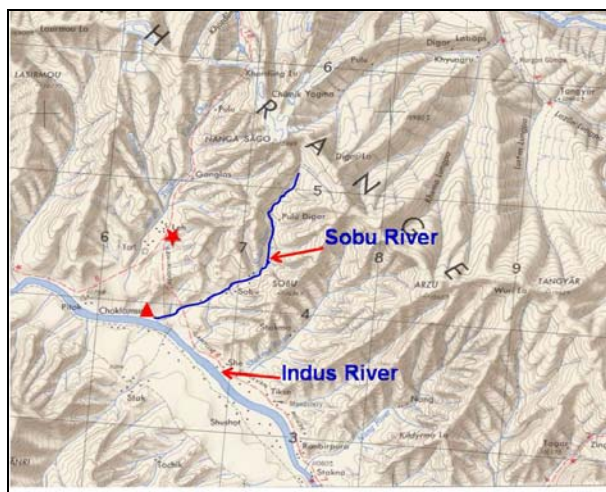


Fig. 1. Physiographic features of the Area of flash floods and mudslides. Leh is marked with  $\star$  and Choglamsar with  $\blacktriangle$

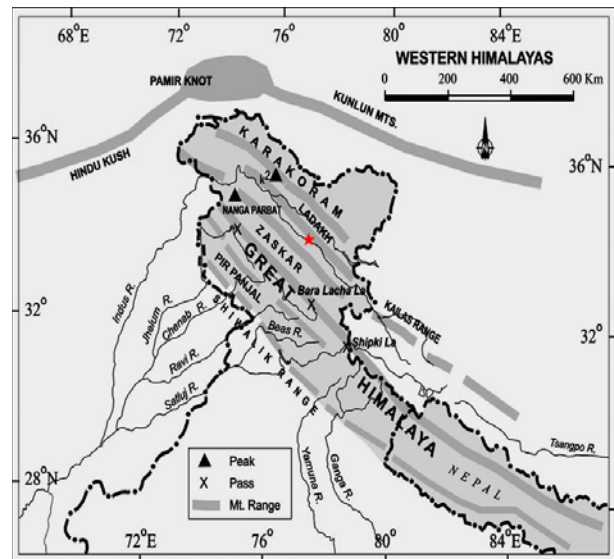
Knowledge of climatology of normal and extreme rainfall in an area is valuable to a variety of groups, especially weather forecasters, disaster management authorities and the public. It is more so important to understand the threat posed by heavy rainfall having potential of inducing mudslides in this low rainfall zone where the level of preparedness may not be high because of very low frequency of such events; but the undulating and barren surface make it more vulnerable to mudslides. Meteorological conditions associated with these events are also discussed in details to understand the conditions which could lead to heavy rainfall over the region.

## 2. Review of literature on rainfall and associated landslides

A landslide is defined as the mass movement of rock, debris or earth down a slope and have come to include a broad range of motions whereby falling, sliding and flowing under the influence of gravity dislodges earth material. They often take place in conjunction with earthquakes, floods and volcanoes. It is estimated that approximately 15% of total area of India is susceptible to landslides and that landslides of different types occur frequently in geodynamically active domains in Himalaya, northeast India as also in stable domains in Western Ghats and Nilgiri Hills of southern India (Sharda, 2008). In a detailed study of 125 cases of landslides over India during 16 years period from 1983 to 1998, Ray *et al.* (2001) reported that the highest number of rainfall induced landslides in the western Himalayan state of Jammu and Kashmir and Himachal Pradesh occurred in the month of August. Bhan *et al.* (2004) studied the cloudbursts in the state of Himachal Pradesh for the period 1990-2001. A total of 36 cloudbursts were reported during the twelve

year period resulting in a reported loss of 651 lives. Relationships between landslides and rainfall threshold have been established using empirical intensity-duration thresholds (Caine, 1980; Cannon and Ellen, 1985) as well as process-based approaches (Keefer *et al.*, 1987; Crozier, 1999; Minder *et al.*, 2009). Empirical methods have the benefits that these are simple to establish and to use for predictions. Process-based models can determine the amount of precipitation needed to trigger slope failures, and the location and time of the expected landslides. However, their use is limited by the fact these models require detailed spatial information on the hydrological, lithological, morphological and soil characteristics that control the initiation of landslides. Studies of landslides in the Himalayas also suggest that daily as well as seasonal accumulation thresholds of rainfall must be exceeded before landslides are triggered (Gabet *et al.*, 2004; Sengupta *et al.*, 2010).

Survey of literature mentioned above and others suggest that rainfall is the most dominating cause for inducing landslides except for a few induced by tectonic activities and lake/stream bursts. Studies over the Himalayan region also suggest dominant role played by rainfall in triggering landslides. Precipitating systems containing intense convective rainfall occur frequently in the western Himalayas during the monsoon season. The seasonal precipitation across the Himalayas decreases from east to west as distance from the source of moisture (Bay of Bengal) increases. Anders *et al.* (2006), using the TRMM estimates of daily rainfall of four years (1998-2001), clearly illustrated the decrease in precipitation from east to west along the ranges and also across windward to leeward directions. According to Sikka (2011) the seasonal monsoon precipitation of Bangladesh, Bhutan, Nepal and India is 1750, 1570, 1370 and 880 mm, respectively. Heavy precipitation, however, is limited to the windward side of southern Himalayas (Singh and Kumar, 1997) up to middle ranges of Himalayas [up to 2500 metres above sea level (asl)]. Studies on the distribution of rainfall with elevation in the Himalayas show strong correspondence between rainfall and altitude. Dhar and Rakhecha (1981) using mean monsoon (June to October) rainfall data of 50 rainfall stations in central Himalayas have shown that though no linear relationships exists between elevation and monsoon rainfall, the zones of maximum rainfall occur near the foothills and at an elevation of 2.0 to 2.4 km asl. Beyond this elevation, rainfall decreases continuously as elevation increases. Bookhagen and Burbank (2006) using the Tropical Rainfall Measurement Mission (TRMM) rainfall estimates at a spatial resolution of 5×5 km for the Himalayas have shown two distinct rainfall maxima in the Himalayas. The first rainfall peak occurs along the southern margin of the Lesser Himalaya within a mean elevation of



**Fig. 2.** Physiographic feature of western Himalayan region showing northwest-southeast orientation of major mountain ranges (location of Leh is marked with a star)

0.9 ( $\pm$  0.4) km asl. A second discontinuous, inner band was found to typically occur along the southern flank of the Greater Himalaya at elevations of 2.1 ( $\pm$  0.3) km asl. Shrestha *et al.* (2012) found two significant rainfall peaks over southern slope of the Himalayas during summer monsoon season. The first primary peak appears along the Sub-Himalayas (0.5-0.7 km asl), while the second appears along the Lesser Himalayas (2.0-2.2 km asl). These studies indicate a general reduction in precipitation beyond about 2.5 km asl. Occurrence of such an intense precipitation event close to Leh at an elevation of 3.5 km asl and situated on leeward side is rather unusual and needs further studies, particularly on the climatological analysis of heavy precipitation in the region; and on the meteorological conditions which led to the unprecedented event. The same has been attempted in the following sections.

### 3. Description of the study region

Ladakh region of Jammu and Kashmir state situated in western Himalayas is a low rainfall zone situated on the leeward side of the Zaskar Range (also called Zaskar range) in the western Himalayas with Leh ( $34.09^\circ$  N /  $77.34^\circ$  E, 3514 m asl) as the main town in the region. Physiographically, Leh is bounded by The Ladakh Range (a segment of the Karakoram Range) to its north and east and by Zaskar range to its south and west. Greater Himalayan range lie further southwest of the Zaskar range as given in Fig. 2. The town is situated on right bank of river Indus which traverse the Ladakh region from southeast to northwest.

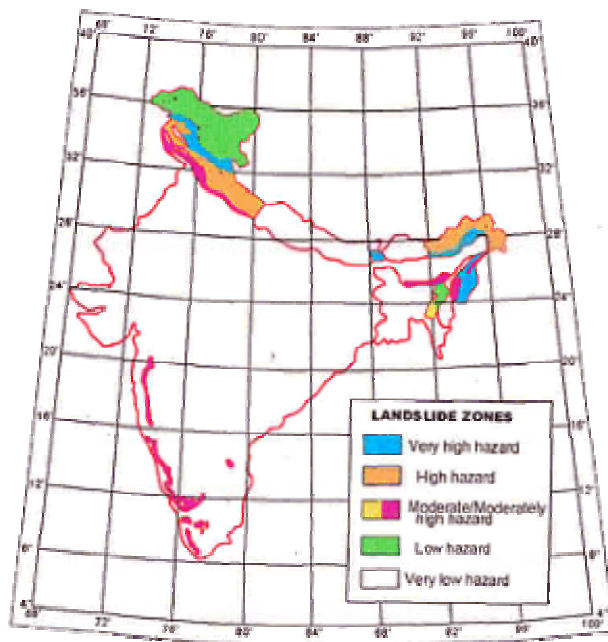


Fig. 3. Landslide zones of India showing Ladakh in a low hazard zone (<http://www.portal.gsi.gov.in/portal>)

The Greater Himalayan ranges are the highest among the three and act as a barrier for the eastward moving systems. Precipitation decreases considerably towards east of this range. Leh being east of Zaskar range receives very little annual precipitation as most of the weather systems move from west to east across the region. Also the area does not have a known history of major landslides. The landslide hazard zonation map of India by the Geological Survey of India (Fig. 3) shows that Ladakh falls in low hazard zone.

The region falls in a low rainfall zone on the leeward side of the Zaskar Range in the western Himalayas. The station receives precipitation in form of both rainfall and snowfall. The precipitation figures wherever mentioned in the following sections are equivalent to mm of liquid water (one cm of snowfall is considered equal to one mm of liquid precipitation). The total annual precipitation of Leh is about 105 mm with July and August being the rainiest months with mean rainfall of 15.2 and 15.4 mm, respectively. The average number of rainy days for both the months is two each. The highest 24 hours rainfall ever recorded in the city has been 51.3 mm reported on 22 August 1933 (India Meteorological Department, 1999). The India Meteorological Department has recently published the rainfall climatology of India (Fig. 4) based on daily rainfall data for the period 1951-2000 of 2399 well distributed stations across the country (India Meteorological Department, 2012). It shows that the seasonal rainfall [monsoon season (June-September)

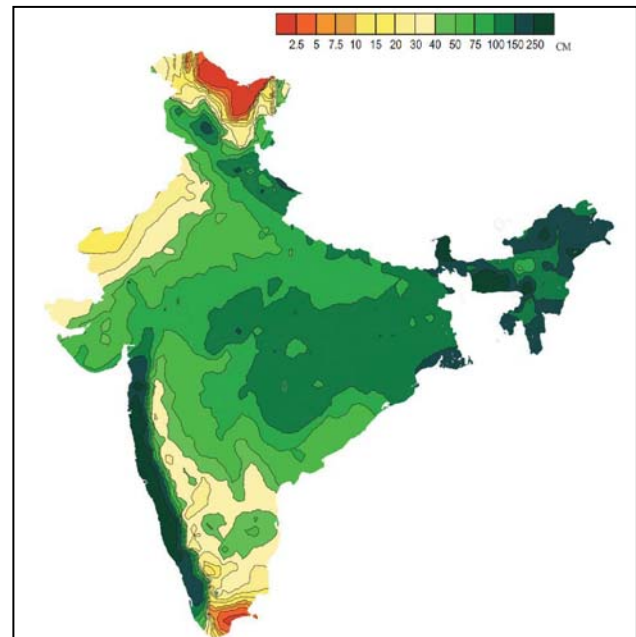


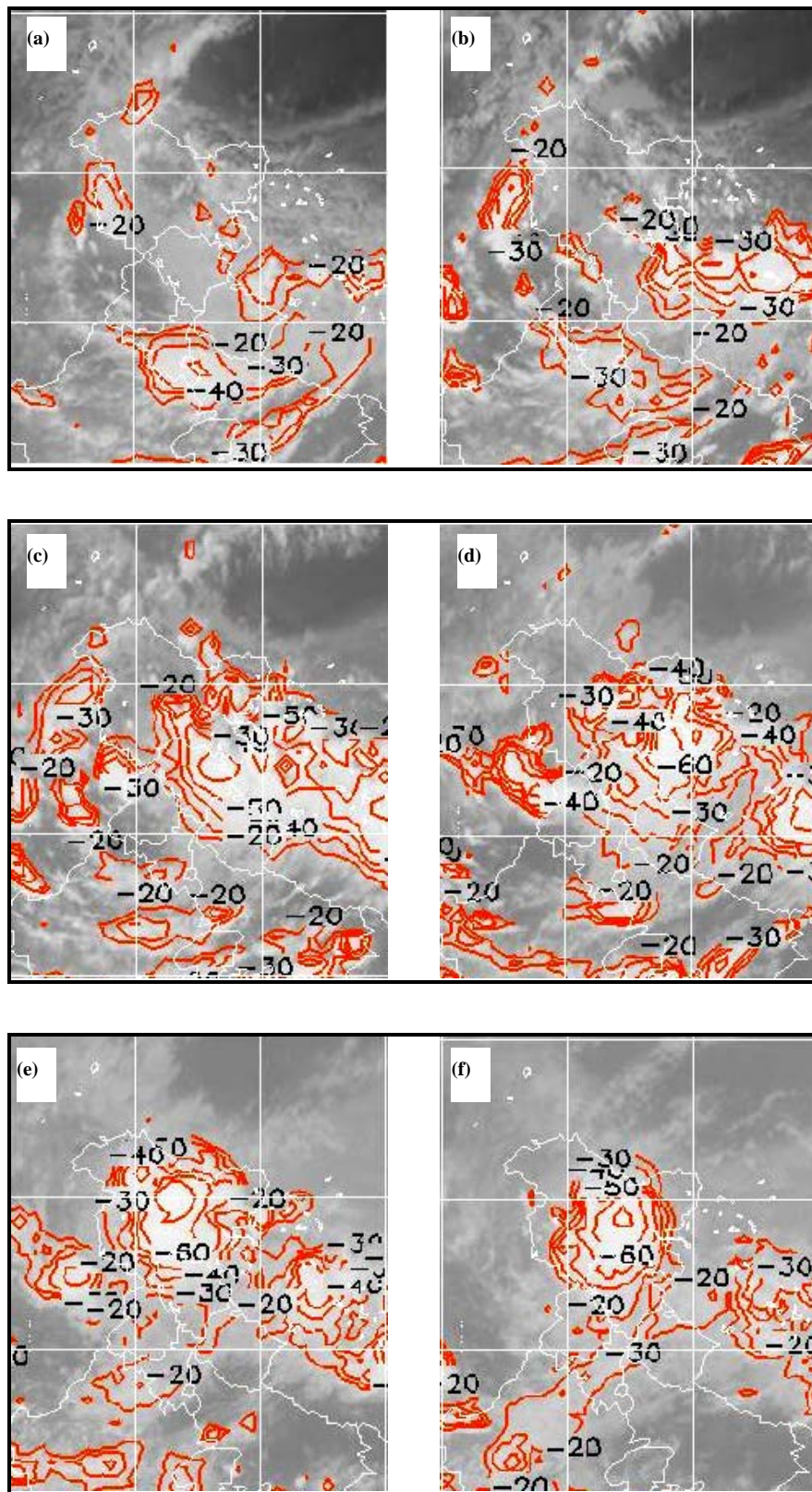
Fig. 4. Total seasonal (June-September) rainfall of India showing steep gradient in rainfall over western Himalayan region caused by orographic features

as a whole] decreases sharply towards northeast of Greater Himalayan Range with most areas of Ladakh having total seasonal precipitation of less than 15 cm.

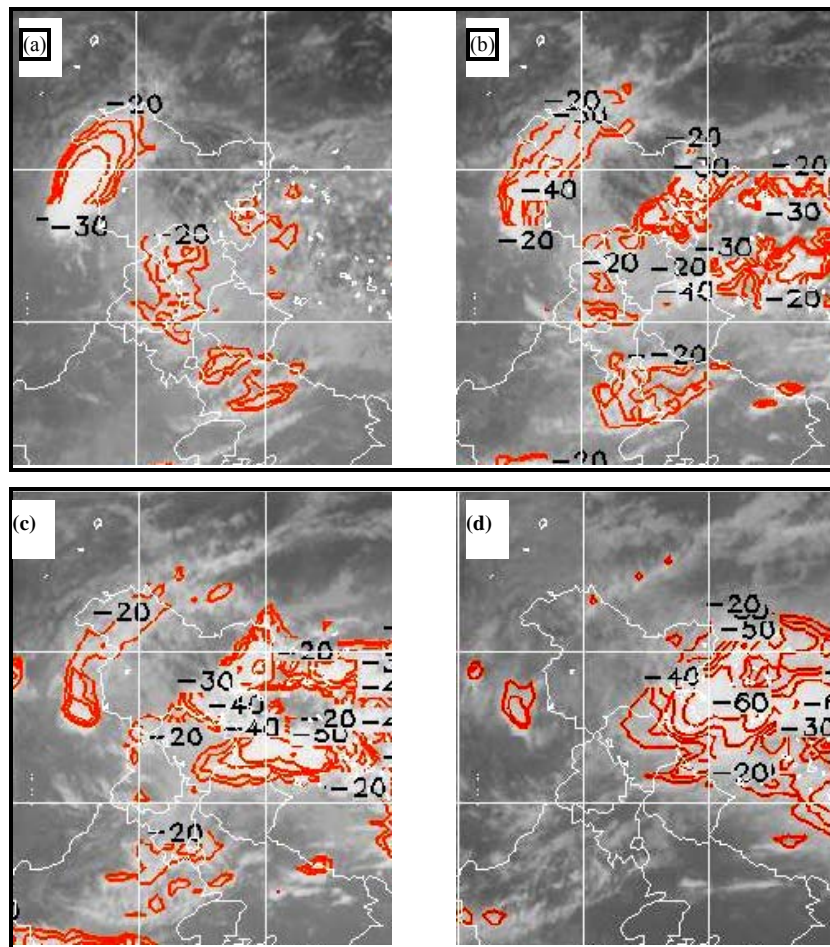
#### 4. Description of the events

An event of very heavy rainfall (which was later described as cloudburst in some quarters) occurred near Leh in Ladakh region of Jammu and Kashmir around 2000-2030 UTC on 5 August, 2010 (0130-0200 hours IST of 6 August, 2010). It was associated with mudslide and flash flood leading to a huge loss of life and property. It claimed the lives of about 200 persons including six foreigners and left another 400 injured. Monitoring of the event through satellite (KALPANA-I) infra red imageries with cloud top temperatures (CTT) in degrees Celsius from 0600 to 2100 UTC of 5 August [Figs. 5(a-f)] shows that the convection started over Tibetan Plateau southeast of Leh around 0600 UTC on 5 August. Moving northwestwards (and possibly regenerating), the convection progressively intensified and reached Ladakh region by 1500 UTC. Very intense convective clouds persisted over the area till 2100 UTC. This was the time during which the most intense rains were estimated through TRMM as described below. Subsequently, the convection shifted further west of Ladakh with hardly any rainfall estimated after 2100 UTC.

A meteorological observatory at Leh airport (located towards northwest of the city) reported cumulative rainfall



**Figs. 5(a-f).** IR satellite imageries (a) 0600, (b) 0900, (c) 1200, (d) 1500, (e) 1800 and (f) 2100 UTC of 5 August, 2010 showing north-westward movement of intense convection. The outer most contour of CTT is of - 20 °C and further contours are at every 10 °C



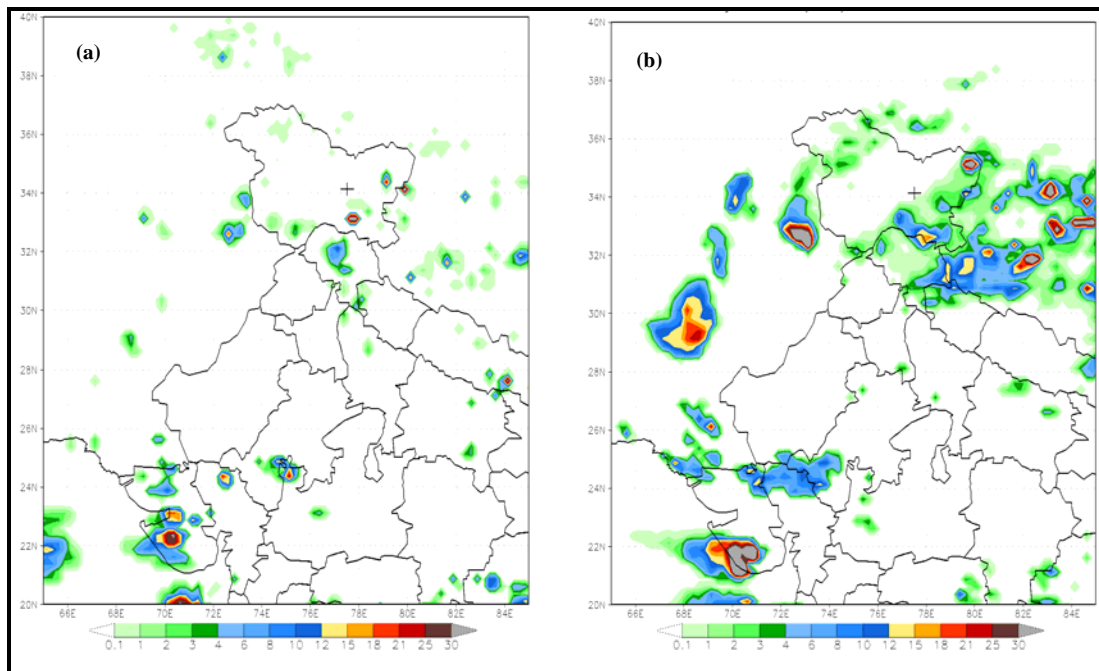
**Figs. 6(a-d).** Satellite images at (a) 0600, (b) 0900, (c) 1100 and (d) 1500 UTC of 25 July, 2011 showing north-westward movement of intense convection. The outer most contour of CTT is of  $-20^{\circ}\text{C}$  and further contours are at every  $10^{\circ}\text{C}$

of only 12.8 mm in 24 hours period between 0300 UTC of 5 August to 0300 UTC of 6 August, 2010. As most of the damage was reported in areas towards south of the city, the intense rains there could not be measured. The satellite estimates (TRMM intermediate IR product - 3B41RT) confirm very intense rainfall activity in the region after 0900 UTC (not shown here but already reported by Ashrit, 2010 and Sravana Kumar *et al.*, 2012). The rainfall activity progressively moved into the affected region from southeast with highest estimates of 4-8 cm between 1500 and 1800 UTC south of Leh. These estimates show significant reduction in rainfall between 1800 and 2100 UTC. As the reported time of landslide in the area is around 2000 UTC, the landslide seems to have occurred after the intense rain spell.

Another event of similar nature (with lower intensity) occurred over the area on 25 July, 2011. The satellite images from Kalpana-I satellite [Figs. 6(a-d)]

show that convection started to the east of Leh at 0600 UTC with a small area of  $\text{CTT} < -30^{\circ}\text{C}$  [Fig. 5(a)]. The convection progressively increased and moved northwards till 1100 UTC with areas of  $\text{CTT} < -50^{\circ}\text{C}$  lying to the south and east of Leh [Fig. 5(b&c)]. The convection then moved eastwards by 1500 UTC. Though no rainfall was reported by the observatory at Leh; and also no landslides/casualties were reported, a description of the event seems necessary as the meteorological conditions were similar to those on 5 August, 2010 and a documentation of the same (given in a following section) could be useful for predicting intense rainfall over the region in future.

As the observational network in the Ladakh region is rather sparse, recourse has been taken to find the estimates of rainfall through the Tropical Rainfall Monitoring Mission (TRMM) data. Prior studies of comparison of TRMM and actual rainfall over India have shown



**Figs. 7(a&b).** TRMM 3 hourly accumulated rainfall estimates (a) 0900 UTC and (b) 1200 UTC of 25 July, 2011 showing intense rainfall activity south of Leh from 0900 to 1200 UTC

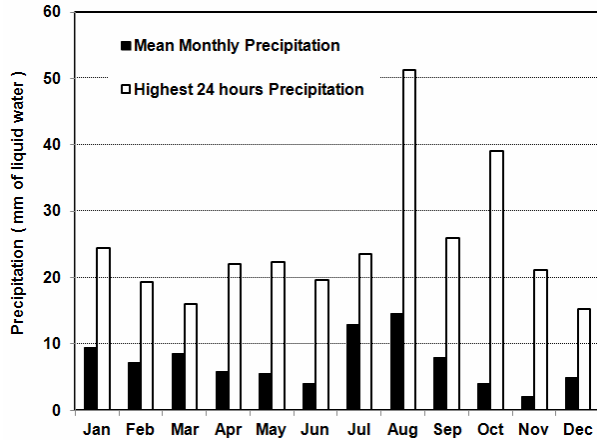
reasonable agreement (Rahman and Sengupta, 2007 and Nair *et al.*, 2009). The TRMM rainfall estimates show accumulated rainfall of 25-30 mm during 0600-0900 UTC and 15-18 mm during 0900-1200 UTC of 25 July 2011 [Figs. 7(a&b)]. No rainfall was estimated after 1200 UTC. These estimates indicate a cumulative rainfall of more than 40 mm in a six hours period of 0600-1200 UTC which can be considered a heavy rainfall event for a region where the total mean monthly rainfall of the rainiest month is only 15 mm.

## 5. Data and methodology

Records of daily precipitation (mm) of a meteorological observatory located at Leh airport available from 1901 to 2003 have been obtained from the National Data Centre of the India Meteorological Department (IMD), Pune and Meteorological Centre, IMD, Srinagar. The same have been used to compute the mean monthly precipitation for Leh. Data for 21 years (1945-47, 1970-78, 1988 and 1990-1997) were missing either completely or partly and, hence, have not been considered. Therefore, the total number of years for which data have been used were 82. The records of the highest 24 hours accumulated precipitation (in equivalent of liquid precipitation in mm) from 1882 to 1980 published earlier by the IMD (India Meteorological Department, 1999) have also been used.

Therefore, the extremes of 24 hours accumulated precipitation are from the year 1882 to 2003 (except for 21 years mentioned above). Above data have been used for computing statistics of monthly rainfall; and for finding the annual values of highest 24 hours accumulated rainfall for Leh. Some other indicators of atmospheric moisture such as mean monthly values of wet bulb temperature (in °C), vapour pressure (in hPa) and number of rainy days have also been taken from the above mentioned publication for their comparison during monsoon and non-monsoon seasons. We have also tried to show the effects of orography on rainfall distribution over Leh through inter-comparison of monthly precipitation statistics of Leh and that of two nearby stations; and tried to establish that monsoon does affect the region.

For study of meteorological conditions associated with the two heavy rainfall events mentioned above, the data from meteorological observatory at Leh were utilised. Infra-red imageries of Indian meteorological satellite (Kalpana I) have been used to depict the movement of convection into the region. Analysis of wind field at different tropospheric levels from the IMD-GFS and ECMWF model (T 799) available in the India Meteorological Department have been used to depict the initial and forecast conditions during the two cases of heavy rainfall under study.

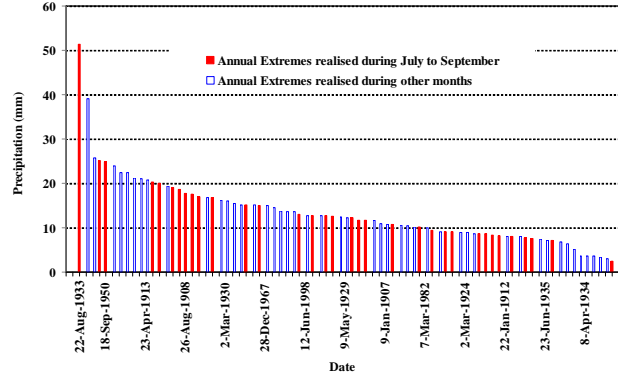


**Fig. 8.** Mean monthly precipitation and highest 24 hours accumulated precipitation over Leh. Mean precipitation is for the period from 1901-2003; and highest 24 hours accumulated precipitation is for the period from 1882-2003 excluding data of 21 years (1945-47, 1970-78, 1988 and 1990-1997)

## 6. Results and discussions

### 6.1. Climatological analysis of mean monthly precipitation over Leh

Climatological studies on precipitation for Leh are rather rare. Therefore, the daily precipitation records of Leh for the years mentioned in the preceding section have been used to compute mean monthly precipitation and highest 24 hours precipitation to know the march of annual precipitation and past records of heavy precipitation over the region. The results (Fig. 8) show that July and August are the wettest months with mean monthly precipitation of 12.3 and 15.1 mm, respectively followed by January (9.1 mm) and September (8.8 mm). The 24 hour accumulated precipitation has also been the highest for the month of August (51.3 mm on 22 August, 1933). Fig. 8 also shows that precipitation amounts 2-4 times the mean monthly total values have been received at Leh during all the months. It has been nearly 10 times for the months of October and November. This indicates high variability in precipitation over the station. Coefficients of variation of monthly precipitation are more than 100% for majority of the months (Table 1). These are lowest for the months of January and February (~93%) followed by July (96%). Above analysis indicates that though the rainfall during the summer monsoon season (July- September) is not very high, the region does get the heaviest precipitation during this season. This raises a question on the general perception that monsoon flow does not reach at all to the Ladakh region. Two recent cases of intense precipitation in the region during monsoon season described above are also in contradiction to this perception.



**Fig. 9.** Annual maximum 24 hr accumulated precipitation over Leh in descending order of precipitation

We have used other indicators of atmospheric moisture such as mean monthly values of wet bulb temperature, vapour pressure and number of rainy days to show that southwest monsoon does affect Leh. Monthly averages of these parameters taken from IMD publication (India Meteorological Department, 1999) given in Table 2 shows that the mean monthly values of all these parameters are the highest during the monsoon months of July and August. Though the average number of days with thunder are the highest during December (1.9), the next higher values are for month of July (1.2) and August (0.9).

### 6.2. Climatology of annual extreme precipitation events: An evidence of relatively heavier precipitation during monsoon season

Study of annual extremes of 24 hours accumulated precipitation is one of the ways to assess as to which part of the year is more prone to heavier precipitation and to what extent. Daily precipitation data of Leh for 82 years mentioned above were used to find the highest 24 hours accumulated precipitation for each year. The highest value for each year was considered for further analysis. These annual extremes plotted in descending order (Fig. 9) show that only two of 82 years reported an annual 24 hours accumulated precipitation extremes of more than 30mm; 69 (84%) of the annual extremes were below 20 mm and 29 (35%) were below 10 mm. This shows that heavier precipitations are a rare occurrence over the station. An analysis of distribution of the annual extremes over the year shows that 40% of the annual extremes were realised during the three months of July to September which indicate the impact of monsoon conditions over the region.



**TABLE 1**

**Mean monthly precipitation, its standard deviation and coefficient of variation at Leh for the period from 1901-2003 excluding data of 21 years (1945-47, 1970-78, 1988 and 1990-1997)**

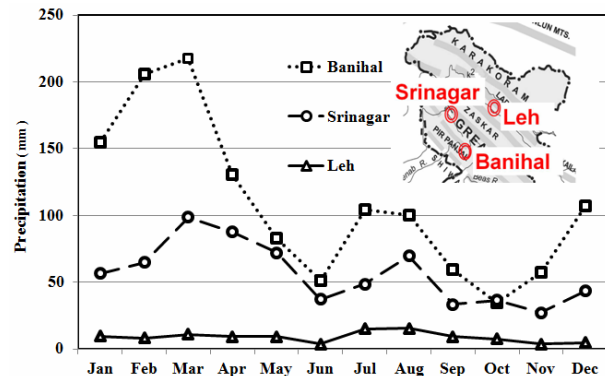
Month	Mean Monthly precipitation (mm)	Standard Deviation (mm)	Coefficient of Variation (%)
Jan	9.4	8.7	92.6
Feb	7.5	7.0	93.3
Mar	8.5	10.2	120.0
Apr	6.1	7.6	124.6
May	5.9	6.6	112.1
Jun	4.3	4.7	108.4
Jul	<b>12.6</b>	12.1	96.0
Aug	<b>15.0</b>	16.7	111.3
Sep	8.5	12.7	149.4
Oct	4.1	11.6	282.9
Nov	2.3	4.2	182.6
Dec	4.8	6.5	135.4

**TABLE 2**

**Mean monthly wet bulb temperature, vapour pressure, number of rainy days and number of days with thunder over Leh during the period 1951-1980**

Month	Wet Bulb Temperature (Deg C)	Vapour Pressure (hPa)	Number of Rainy days	Number of days with Thunder
Jan	-8.2	1.6	1.3	0.1
Feb	-7.25	2.05	1.1	0
Mar	-2.4	3.1	1.3	0
Apr	1.65	3.65	1	0.1
May	4.2	4.3	1.1	0.5
Jun	7.5	5.35	0.4	0.2
Jul	<b>10.5</b>	<b>7.45</b>	<b>2.1</b>	<b>1.2</b>
Aug	<b>10.5</b>	<b>7.85</b>	<b>1.9</b>	<b>0.9</b>
Sep	7.4	5.75	1.2	0.1
Oct	1.95	3.35	0.4	0
Nov	-2.9	2.65	0.5	0
Dec	-8	1.8	0.7	1.9

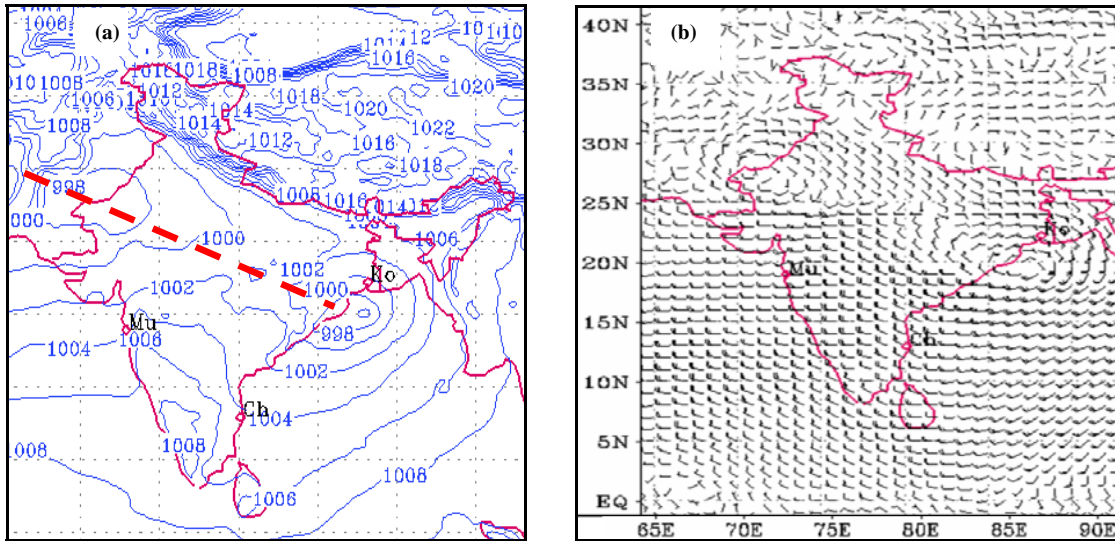
Above analysis of mean monthly rainfall, mean monthly values of wet bulb temperature, vapour pressure and number of rainy days clearly shows that the southwest



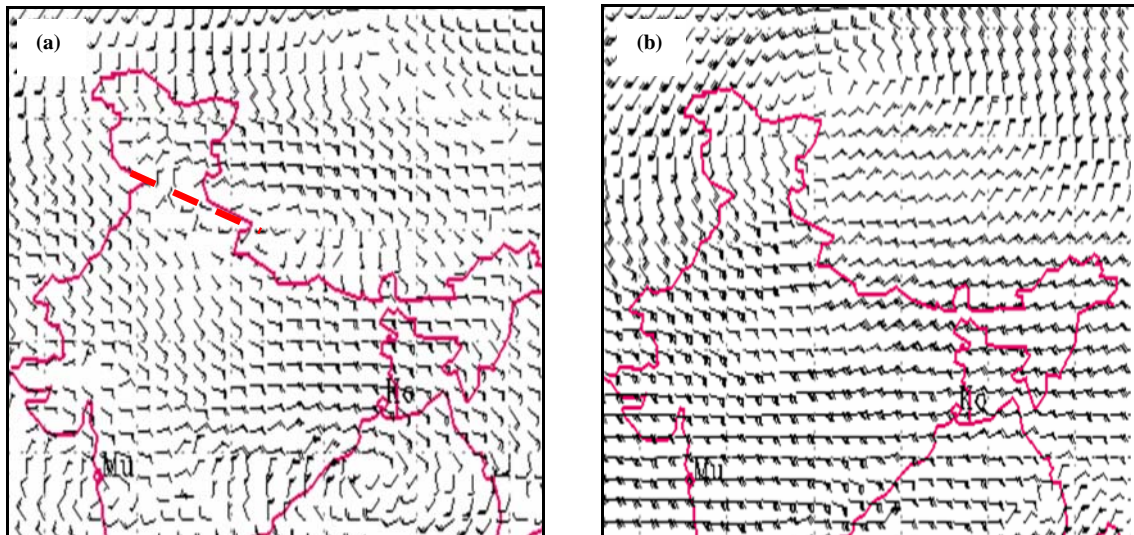
**Fig. 10.** Mean monthly precipitation of Banihal, Srinagar and Leh (relative locations of these stations are given in inset). Both Banihal and Srinagar show highest precipitation during February-March in association with eastward moving weather systems. Leh falling on leeward side does not experience this. Leh shows increase in precipitation only in monsoon season (July-August)

monsoon does affect Leh, though with a much reduced intensity. We further provide a comparison of mean monthly rainfall values of two more stations in the state of Jammu and Kashmir (Banihal and Srinagar) along with those of Leh in Fig. 10 for a clearer picture of rainfall distribution in the state. Banihal (33° 30' N, 75° 10' E, 1630 metres asl) is located on windward side of Pir Panjal Ranges (the western most mountain range and Srinagar (34° 05' N, 74° 50' E, 1587 metres asl) is to the north of Pir Panjal range on windward side of Greater Himalaya Range. The figure shows that rainfalls of both Banihal and Srinagar have pronounced maxima in the month of March. This is because of fact that precipitation during the winter and spring seasons (November-March) is caused primarily by eastward moving weather systems in mid-latitude westerlies which protrude into the Indian Latitudes during this season. Banihal being to the southwest of the outer most range (Pir Panjal) receives the highest precipitation. Leh falling on the leeward side of major mountain ranges does not experience much increase in precipitation in this season.

Rainfall at Banihal and Srinagar also exhibit secondary maxima in the months of July-August suggesting intrusion of Monsoon into the region. Rainfall at Leh, however, has the primary maxima in the months of July-August only indicating intrusion of monsoon rainfall into this region. In case the precipitation causing systems moving from west do not affect Leh during winter-spring season, the rainfall causing currents from southwest should not affect Leh during monsoon season also. This raises a question whether monsoon currents reach Leh from Tibet side (may be as occasional bursts, if not regularly). In a very interesting and one of the earliest accounts of Himalayan rainfall, Mason (1936) had also



**Figs. 11(a&b).** Mean Sea Level Pressure (a) and wind flow pattern at 850 hPa at 0000 UTC of 5 August, 2010 showing monsoon trough (dotted line) south of its normal position with a vortex at both its ends



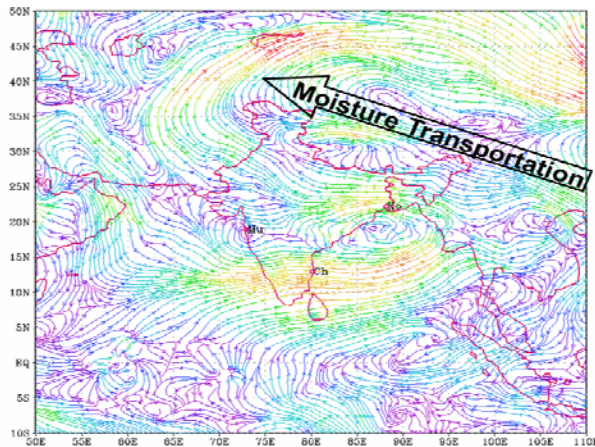
**Figs. 12(a&b).** Wind flow pattern showing a cyclonic circulation at 500 hPa (a) and east-southeasterly steering current at 200 hPa (b) at 0000 UTC of 5 August, 2010

mentioned that Leh, owing to the absence of winter rainfall, shows a maximum during the monsoon months. He had also mentioned that ‘though the stations beyond Greater Himalayas (Gilgit, Skardu, Kargil and Leh) show very little rainfall during the monsoon months, monsoon incursions most certainly reach these areas during July and August, and even occasionally pass northwards beyond the Karakoram’. The climatological analysis presented above does bring out that monsoon affects the Ladakh region, albeit with lesser intensity. This aspect, however, needs further investigation which is a possibility now as long time series of satellite and reanalysis data are available.

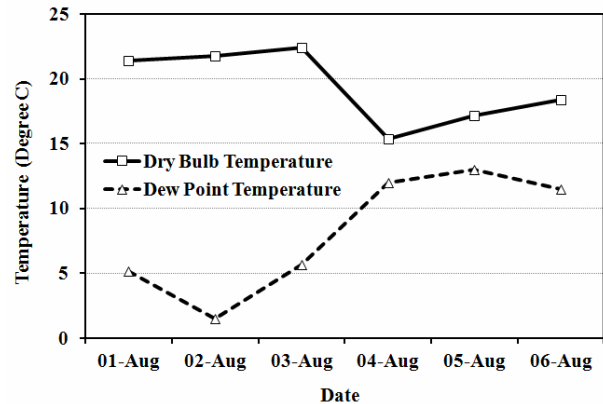
These findings negate the general perception that monsoon does not reach Ladakh; and can, therefore, help disaster managers focus greater attention towards disaster management strategies for the region during the season. Analysis of two recent cases of heavy rainfall presented in the following section shows that these events had been part of large scale monsoon flow over south Asia.

### 6.3. Recent spells of intense rainfall

As mentioned in a preceding section, Ladakh experienced two case of intense rainfall in the recent past (5 - 6 August, 2010 and 25 July, 2011). As there were no



**Fig. 13.** Wind flow pattern at 500 hPa at 0000 UTC of 5 August, 2010 indicating moisture transport from South China Sea to Ladakh



**Fig. 14.** Dry bulb (Solid line) and dew point temperatures (dotted line) recorded at 0300 UTC at Leh observatory from 1 to 5 August, 2010 showing a steady increase in moisture build up over the area during the days leading up to Leh flood

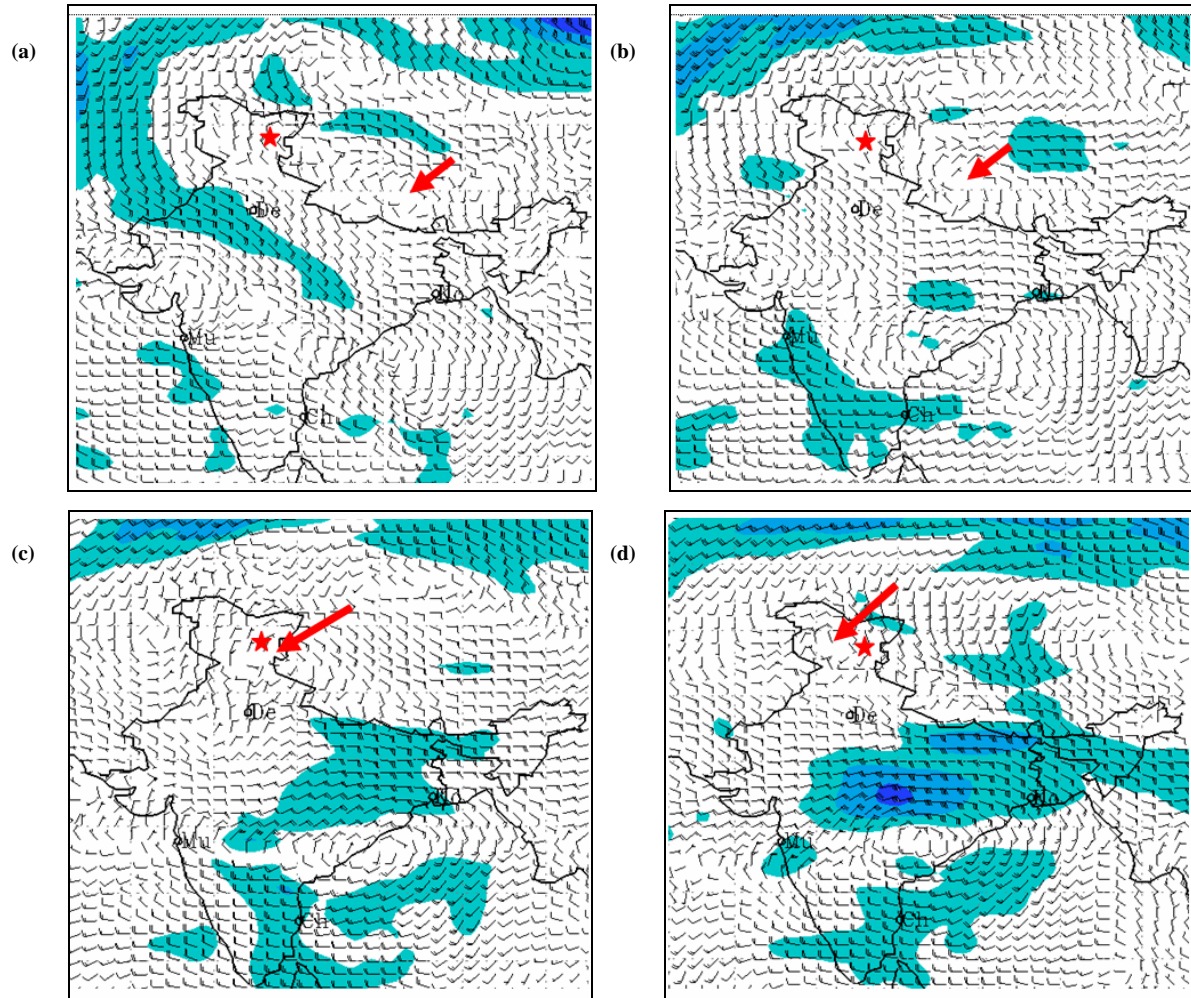
reports of casualties associated with the 25 July, 2011 event, it has gone un-noticed. The event, however, had striking similarities with that of the 5-6 August, 2010; and, therefore, needs analysis. The meteorological conditions associated with these events are discussed in the following sections with an objective that the conditions associated with these rather unusual events are documented for forecasting such events in future.

### 6.3.1. Meteorological conditions associated with the rainfall event of 5-6 August 2010

According to synoptic analysis of 0000 UTC of 5 August, 2010, a well marked low pressure area lay over northwest Bay of Bengal; and the monsoon trough at the mean sea level lay to the south of its normal position [Fig. 11(a)] indicating active monsoon conditions over India. The analysis of wind field at 850 hPa [Fig. 11(b)] and 500 hPa [Fig. 12(a)] shows that the upper air cyclonic circulation associated with the well marked low pressure area over northwest Bay of Bengal extended upto mid-tropospheric levels. The western end of the monsoon trough had shifted from about 27° N at 850 hPa to about 19° N at 500 hPa. A cyclonic circulation in the middle troposphere was seen at 500 hPa over Tibet at about latitude 30° N and longitude 82° E. A trough from this circulation extended north-westwards towards Ladakh region of Jammu and Kashmir [Fig. 12(a)]. Under the influence of these systems, strong southeasterly winds with speed of 15-20 knots prevailed over western Himalayan region upto middle troposphere. The analysis of 200 hPa winds shows that the seasonal anti-cyclone at 200 hPa had a marked shift towards northwest with its centre at latitude 35° N and longitude 78° E [Fig. 11(b)] and that the steering winds were easterly/south-easterly above the circulation/trough at 500 hPa.

For an active convective system to survive on a dry, arid and elevated region such as Tibet-Ladakh, a continued source of moisture is a must. Streamline analysis of winds at 0000 UTC of 5 August (Fig. 13) clearly show transport of moisture at 500 hPa to Tibet-Ladakh region from South China Sea. This incursion of moisture is also indicated in dew point temperatures (0300 UTC) of Leh which increased from 1.5 °C on 2 August to 13.0 °C on 5 August (Fig. 14). Rasmussen and Houze (2012) have also reported that during the days leading up to the Leh flood, mid level southeasterly winds strongly advected moisture into the region. Numerical simulations of the event carried out by Ashrit (2010) and Sravana Kumar *et al.* (2012) also show that the circulation and moisture incursion at 500 hPa associated with other dynamic and thermodynamic parameters were the main causes of this extreme weather event.

Analysis of satellite imageries in Fig. 5 above and the analysis of streamlines at 500 hPa from 0400 to 0600 UTC of August [Fig. 13 & Figs. 15(a-d)] show that the cyclonic circulation at 500 hPa tracked towards west-northwest from southern parts of Tibet into Ladakh in response to the steering winds at 200 hPa. Rasmussen and Houze (2012) in their study of the event, have reported that during the summer monsoon season (June through September), the climatological 500 hPa winds near Leh are generally weak westerly. However, during the three days leading up to the Leh flood, the 500 hPa flow pattern field showed an easterly jet which was relatively persistent over this period, constituting a quasi-stationary synoptic situation. Winds above 500 hPa also were generally easterly. Doswell *et al.* (1996) have reported that the basic ingredients of potential flash flood – producing storms are the sustained high rainfall rates



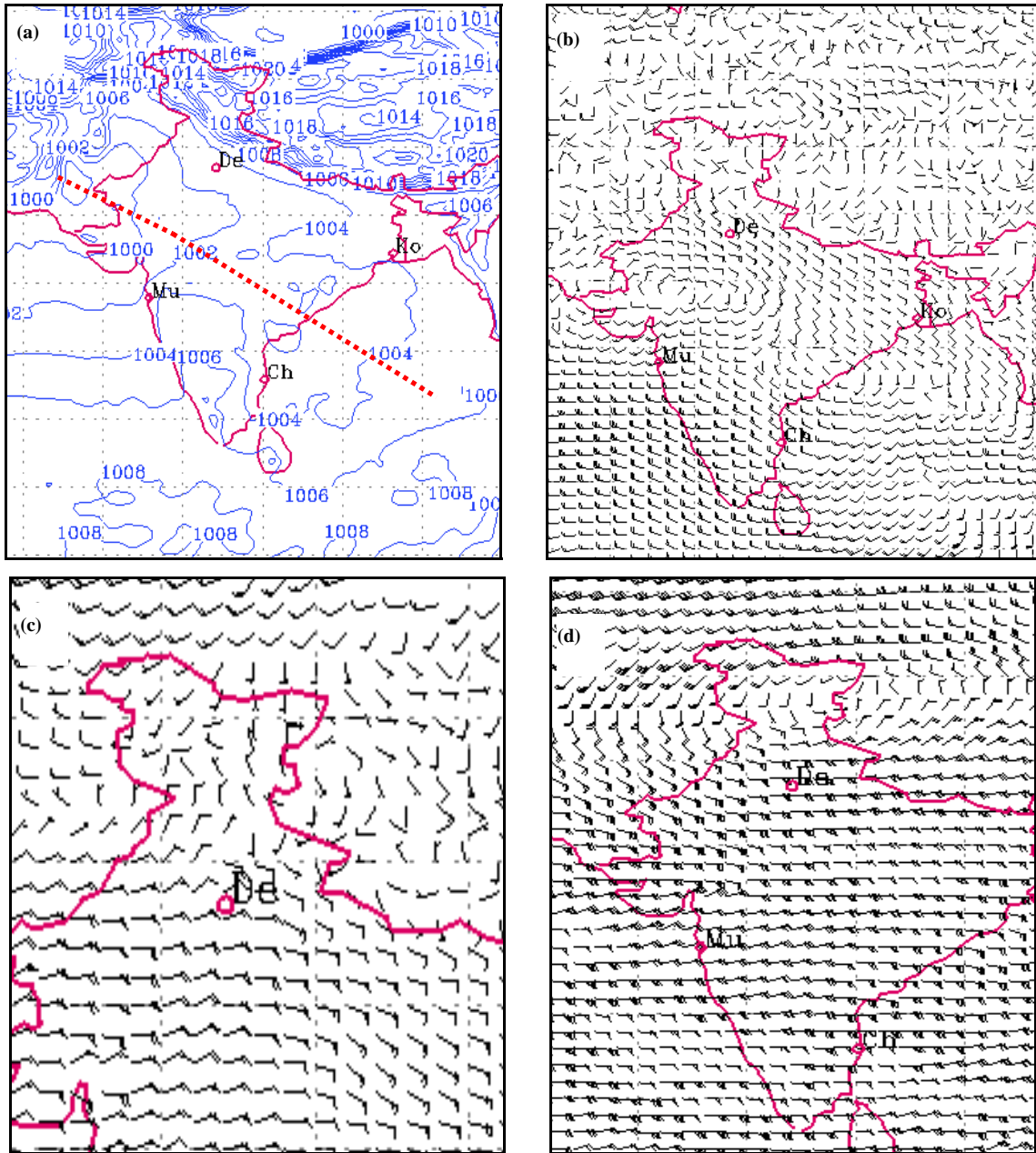
**Figs. 15(a-d).** Streamline analysis (500 hPa) valid for (a) 0000 UTC of 4, (b) 1200 UTC of 4, (c) 1200 UTC of 5 and (d) 0000 UTC of 6 August, 2010 showing movement of the rainfall causing vortex towards Leh (Position of Leh is marked with a star; and head of the arrow shows centre of the cyclonic circulation)

which, in turn, involve the rapid ascent of air containing substantial water vapour. In the present case, steep orographic barriers to the west of Tibetan Plateau (described in a following section) and building up of moisture by middle level southeasterly winds over the Plateau seem to have added up to intense rain associated with the storm.

### 6.3.2. Meteorological conditions associated with the rainfall event 25 July, 2011

The analysis of mean sea level pressure, 850, 500 and 300 hPa winds [Figs. 16(a-d)] at 0000 UTC of 25 July, 2011 show active monsoon conditions with the monsoon trough south of its normal position and two cyclonic circulations at 850 hPa. A cyclonic circulation at 500 hPa lay just southeast of Ladakh region. Incursion of

moisture, however, was not as prominent as was on 5 August, 2010. As wind analysis at 0600 UTC was not available, 6 hrs forecast winds valid at 0600 UTC have been considered for depicting movement of the cyclonic circulation. The 6 hr forecasts of 500 hPa winds valid for 0600 UTC and analysis of 500 hPa winds at 1200 UTC of 25 July [Figs. 17(a&b)] show that the circulation initially moved north-westwards into Ladakh region till 0600 UTC and then towards northeast under influence of the upper level steering current. These conditions, though of lesser intensity were similar to those of 5 August 2010. No rainfall was recorded at Leh observatory during this event. However, the TRMM estimate, as mentioned above, show cumulative rainfall of more than 40 mm (to the south of Leh) in a six hours period of 0600-1200 UTC which can be considered a heavy rainfall event for this low rainfall region.



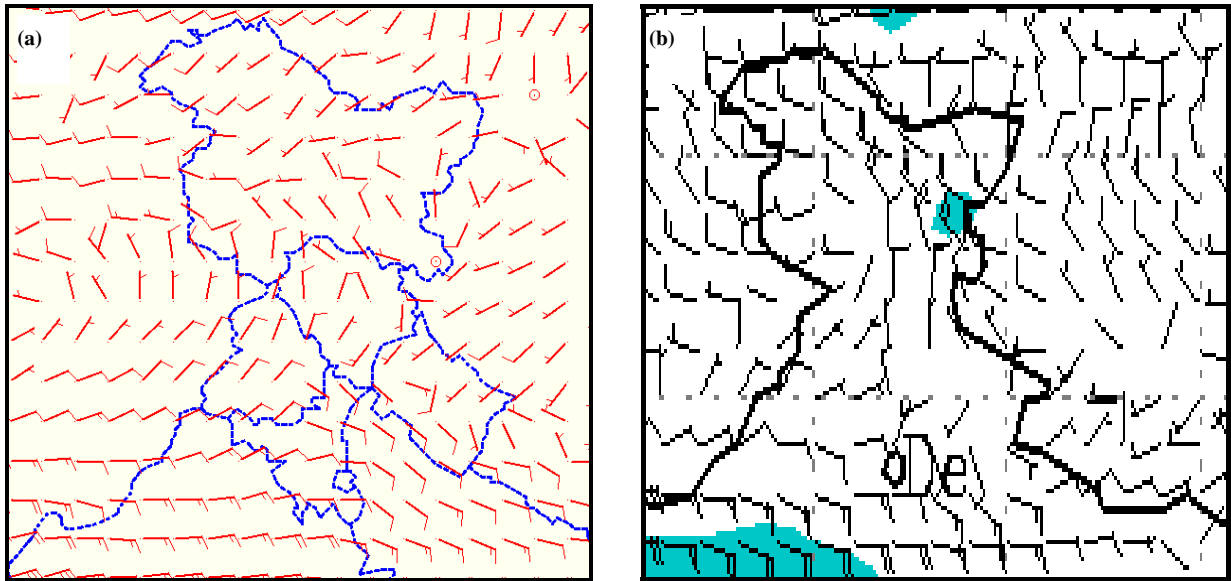
**Figs. 16(a-d).** Mean Sea Level Pressure showing monsoon trough south of its normal position (a) wind flow pattern at 850 hPa showing monsoon flow over India, (b) cyclonic circulation at 500 hPa southeast of Leh, (c) steering current at 200 hPa and (d) at 0000 UTC of 25 July, 2011

**7. Possible role of topography in causing heavy precipitation over Ladakh**

In case of both the events described above, intense precipitation was caused by eastward moving cyclonic circulations at 500 hPa. This brings out the importance of cyclonic circulations at 500 hPa in causing intense rainfall over the region. As the average height of the Tibetan

Plateau and Ladakh is 4-5 km, the cyclonic circulations at 500 hPa acted as a low level circulation for the area. Also in case of their westward movement, the impact seems to be enhanced by the orographic features of the region which is described in this section.

The circulations at 500 hPa, in both the cases under study, moved towards Ladakh in response to the winds at



**Figs. 17(a&b).** Forecast winds (500 hPa) valid for (a) 0600 UTC and (b) analysis of 500 hPa winds at 1200 UTC of 25 July 2011 showing movement of cyclonic circulation

200 hPa. The region is considered to be in the rain shadow zones with very little precipitation. This perception seems to hold true only for the eastward moving systems (which is the case for most of the times during the year), as the major mountain ranges in the region (Figs. 1 & 2) are oriented in a northwest-southeast direction. In the two cases of heavy rainfall described above, the weather system moved from east to west; and the mountain ranges seem to have acted favourably in enhancing the convection over the region. Relationship between precipitation and topography is a well documented fact. Recently, Anders *et al.* (2006) making use of the high resolution TRMM data showed that this relationship is sufficiently robust in the Himalayas to explain very small variations in measured rainfall. Rasmussen and Houze (2012) have also concluded that a strong, moist flow from the lower elevations toward Leh rose up to higher elevations to provide the developing systems with precipitable water and latent energy.

## 8. Conclusions

The intense rainfall and the associated landslides over Leh flood was a tragedy and unprecedented event for the region hitherto not known to be affected by such events. The present paper is an attempt to understand the pattern of normal and extreme rainfall events; and the conditions associated with the recent heavy rainfall events for help in weather prediction and disaster preparedness for the region. Analysis of daily and monthly rainfall of Leh has brought out that July and August are the rainiest

months for the region. The Mean monthly rainfall for August (15.0 mm) is more than one and half times the mean monthly rainfall of any other month (except that of July). Other indicators of rainfall and moisture such as mean monthly wet bulb temperature mean monthly vapour pressure, average number of rainy days and days with thunder are also the highest during the months of July and August. This analysis is in contrast to the general belief that monsoon does not impact the Ladakh region. Also the analysis of annual extreme rainfall events shows that 40% of all the annual extreme events have occurred during the monsoon months of July, August and September indicating that the region is more vulnerable to extreme events during monsoon season.

The analysis of the meteorological conditions associated with the two recent heavy rainfall events has brought out that the westward moving cyclonic circulations in middle troposphere (~500 hPa) over the Tibet- Ladakh region during active monsoon conditions in combination with favourable steering current in the upper troposphere are crucial to produce heavy to very heavy rains over this region. A critical analysis of the flow patterns in middle and upper troposphere combined with their prognosis by the NWP models can provide effective guidance to the operational forecasters in keeping a track of such systems for prediction of heavy rainfall/flash floods over the region which otherwise does not experience much rainfall activity. Also the orographic features of the region, which generally are considered to act as obstruction to rainfall over the region, may be

adding towards enhancing the rainfall associated with westward moving cyclonic circulations in the middle troposphere. Considering that the region is in a low precipitation zone, the structure for warning against heavy rainfall and associated hazards of the land/mudslides need to be strengthened given the recent event and climatological analysis which brought out that about a third of the years receive daily precipitation of more than 15 mm which is greater than monthly rainfall of the rainiest month.

As there has been no known history of the kind of landslide/mudslide that occurred on 5-6 August, 2010, it is difficult to establish rainfall-landslide relationship for the area based on this single event. The year 2010 had been a year of increased landslide activities across the Himalayas as reported by Kirschbaum *et al.* (2012). They reported a pronounced increase in landslides in the Himalayan region during 2010 owing to increased rainfall activity during the year. They found that the daily threshold exceedance rates for 2010 were approximately 1.5 times higher than the average values from previous years. Loose soils of the region with low water holding capacity and sparse vegetation (Butola *et al.*, 2012) combined with increased urbanisation around Leh (Goodall, 2004) seem to have enhanced the impact of the intense rainfall event. However, this study and others related to this event (Ashrit, 2010; Rasmussen and Houze, 2012 and Sravana Kumar *et al.*, 2012) have brought out the capability of NWP models in possible prediction of such events over the area; and role played by westward moving mid-tropospheric circulations peculiar topography of the region in causing the event.

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