

Unprecedented rainfall in Punjab in August, 2011 : A case study

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सार - इस शोधपत्र में वर्ष 2011 की ग्रीष्मकालीन मॉनसून ऋतु में अगस्त 2011 के दूसरे सप्ताह में पंजाब के कुछ जिलों में हुई अप्रत्याशित वर्षा के बारे में विशेष रूप से विवेचन किया गया है। जिसकी वजह से जनता की और निजी संपत्तियों को भारी नुकसान पहुँचा। इस शोध पत्र में 13 अगस्त 2011 को पंजाब में रिकार्ड की गई इस असामान्य वर्षा के होने के कारणों जैसे कि प्रेक्षणात्मक पहलु मुख्य सिनाप्टिक प्रणाली, भौतिक प्रक्रिया और तापगतिकीय लक्षणों का पता लगाने का प्रयास किया गया है। 2011 की मॉनसून वर्षा ऋतु के दौरान प्रेक्षणात्मक पहलू और भूमंडलीय लक्षणों के विश्लेषण से समूचे मॉनसून वर्षा ऋतु की अवधि के दौरान मध्य अक्षांशिय पश्चिमाभिमुखी प्रणाली के उत्तर में प्रवेश करने का पता चला है। 13 अगस्त, 2011 को मिली सूचना के अनुसार पंजाब के कुछ जिलों में अगस्त के महीने में प्रेक्षणात्मक विश्लेषण के मुताबिक अत्यधिक भारी वर्षा से लेकर अप्रत्याशित भारी वर्षा के होने की सूचना मिली। प्रारंभिक विश्लेषण देश के दक्षिण और उत्तर के लगभग आधे हिस्से में अगस्त के पहले और अंतिम सप्ताह में पछुआ पवनों और पूर्वी पवनों की विसंगतियों के पवन के पैटर्न के सशक्त होने को दर्शाते हैं। इस अध्ययन में किए गए विश्लेषण में जलन्धर जिले में लुधियाना शहर और फिल्लौर समेत पंजाब के कुछ जिलों में 13 अगस्त, 2011 को अत्यधिक भारी वर्षा से अप्रत्याशित रूप से अत्यधिक भारी वर्षा के होने के संकेत पाए गए 13 अगस्त, 2011 को रिकार्ड की गई वर्षा अपने आप में वर्षा का एक रिकार्ड है। पश्चिमी क्षेत्र मानसून लो और चक्रवातीय परिसंचरण के संभावित अन्योन्य क्रिया के कारण यह घटना घटी पश्चिमी उत्तर पश्चिम दिशा में मॉनसून द्रोणी के साथ कम दबाव के क्षेत्र और चक्रवातीय परिसंचरण के रूप में भ्रमिलताओं के साथ मानसून द्रोणी और अधिक सक्रिय हो उठी इस विश्लेषण के अलावा तापगतिकीय सूचकांक से इस अवधि के दौरान पर्यावरणीय वायुमंडल के अस्थिर होने का पता चला है।

ABSTRACT. Summer monsoon season 2011 was highlighted with unprecedented rainfall in some districts of Punjab in the second week of August 2011 causing significant damage to public and private properties. An attempt has been made in this paper to identify the observational aspects, main synoptic system, Physical process and thermodynamic features leading to such unusual rainfall in Punjab recorded on 13th August, 2011. Observational aspects and analysis of global features during monsoon season 2011 indicated that there was intrusion of middle latitude westerly system in to north during the entire monsoon period. Observational analysis during the month of August witnessed very heavy to exceptionally heavy rainfall in some districts of Punjab reported on 13th August, 2011. Preliminary analysis indicates strengthening of wind patterns in the first and last week of August in westerly and easterly anomaly field over south and northern halves of the country. Analysis of the study indicates that extremely heavy to exceptionally heavy rainfall reported on 13th August, 2011 in some districts of Punjab including Ludhiana city and Phillaur in district Jalandhar, which is all time record rainfall reported on 13th August, 2011 was due to possible interaction of monsoon low and cyclonic circulation in the westerly field which was further triggered due to active monsoon trough embedded with vortices in the form of low pressure area and cyclonic circulation moving along with the monsoon trough in west north-westerly direction. In addition to this analysis of thermodynamic indices further indicated that environmental atmosphere was unstable during that period.

Key words – Rainfall, Synoptic features, Instability indices, TRMM.

1. Introduction

Monsoon rainfall in India is characterized by heavy to very heavy rainfall events leading to floods over different regions. These heavy to very heavy rainfall events are caused by the interaction of basic monsoon flow with the orography and the synoptic disturbances developing over Indian region. The seasonal weather

cycles with a unique monsoon period of rains over India is mainly due to permanent and semi-permanent synoptic features, which produce variability in the rainfall distribution both spatially and temporally. Punjab is located in northwest part of India. Bulk of rainfall activities in this region takes place in the month of July and August during monsoon period under the influence of synoptic scale system like monsoon depression etc. There

have been several studies and literatures on heavy rainfall in northwest India and in particular in Haryana and Punjab.

Desai *et al.* (1998) found that very heavy to exceptionally heavy rainfall in northwest India particularly in the month of August and September occur, when low level easterly trough and upper level westerly trough overlaid one over the other. They have also found that when the rear sector of low level easterly trough overlain by forward sector of the diffluent, slow moving or nearly stationary upper level westerly trough, the area in the rear sector of the easterly trough get exceptionally heavy rainfall. Study further reveals that westerly trough aloft move slowly across northwest India and remained stationary for 2-3 days and if there is low level easterly system then because of interaction of these two systems, heavy to very heavy rainfall occur over northwest India. Further they mentioned that presence of blocking high in mid and upper troposphere over Tibet will help the slow movement of upper tropospheric westerly trough and cause increased rainfall.

Changraney (1966) and Ramaswamy (1987) have discussed in details several cases of past severe floods in northwest India caused by similar type of meteorological situations e.g., severe floods of September 1947 and October 1955 over Punjab and Haryana and floods of August, 1928 and August, 1957 in Jammu and Kashmir. Jagannathan and Raghavendra (1966) estimated the contribution of different operating factors for heavy rainfall in this region and found that depression accounted for about 50 percent of rainfall in the month of August, 2011 and concluded that same conclusion can be applied in general to a very heavy rainfall in year as well. Rao (1970) from the study for the period 1966-69 for monsoon season found that cause of heavy rainfall over northwest India was predominantly low pressure areas. Abbi *et al.* (1978) have also found that westnorthwestward movement of depression from Bay of Bengal leads to unusually heavy rainfall in northeast India. Singh (1998) in his study for the floods in north India forecasting aspect have also found that extremely heavy rainfall that ravaged the States of Jammu & Kashmir, Haryana and Himachal Pradesh and Punjab during 2nd half of July and last half of August and in 4th week of September, 1998 was due the interaction of mid-latitudes westerly troughs with monsoon pulse in the form of equatorial zones of maximum cloudiness. Ananthkrishnan and Bhatia (1960) have also found in their studies that flood in Jammu and Kashmir and neighbouring states occurred due to depression recurving over Rajasthan toward north or northeast and reaching these states to give heavy rainfall. Ghosh and Veeraraghavan (1975) have also found heavy rainfall in Jammu and Kashmir and neighbourhood also

occur in absence of depression due to deep penetration of moisture over this area due to the presence of lows in the lower tropospheric levels associated with trough in upper level westerlies with an embedded jet stream.

Dhar and Shobha Nandargi (1988) in their paper a study of exceptionally heavy rainfall spell of September 1888 over northwest India have found that whenever northwest India experienced heavy rainfall toward the end of monsoon season, it was mostly due to interaction of active monsoon lows/ depression moving in and near this region with the eastward travelling mid latitude westerly waves in the zonal westerlies. This interaction between the two weather systems resulted in bringing in the region copious amount of moistures from Arabian Seas responsible in causing heavy to very heavy rainfall and consequent severe floods. Sengupta (1982) in his study localized floods in Rajasthan owing to exceedingly heavy rainfall had also concluded similar type of synoptic systems and reveals that fractional superimposition and therefore fractional accentuation of pre-existing tropospheric cyclonic vortices by upper anticyclone shear zones formed out of propagation and amplification of an upper air westerly and easterly waves, in close proximity is actually responsible for such exceedingly heavy rainfall. Gupta (1979) also found that unprecedented floods in South Rajasthan in July 1979 is due to well-marked low pressure area over south west Rajasthan and was associated with trough in the westerly's. Veerraghavan and Ghosh (1974) also found that widespread rainfall over west Rajasthan is also due to the movement of monsoon depression over west Rajasthan and intrusion of westerly fields. Ganesan and Prasad (1981) in their study of heavy rainfall in and around Jaipur concluded that apart from depression/ low pressure over Rajasthan and neighbourhood intensification of well-defined depression over west Punjab or increased pressure gradient over the west Rajasthan region or formation of ridge axis along 76° E and inflow of Arabian sea current at lower levels at a time, is followed by formation of cyclonic circulation at 700 hPa level for heavy rain.

2. Materials and method

The State of Punjab lies roughly between 29°30' N and 32°30' N latitudes, 73°30' E and 77°00' E longitudes. General orographic features and absence of oceanic influence affect to large extent the climate of the state. State experiences Steppe, semi-arid, hot subtropical monsoon, mild winter and hot summer. Southwest monsoon season is the principal rainy season when state receives 70 to 75% of annual rainfall (Climate of Punjab, 1996). Rainfall in the winter season (November-March) contribute to about 11 to 16% of total annual rainfall,

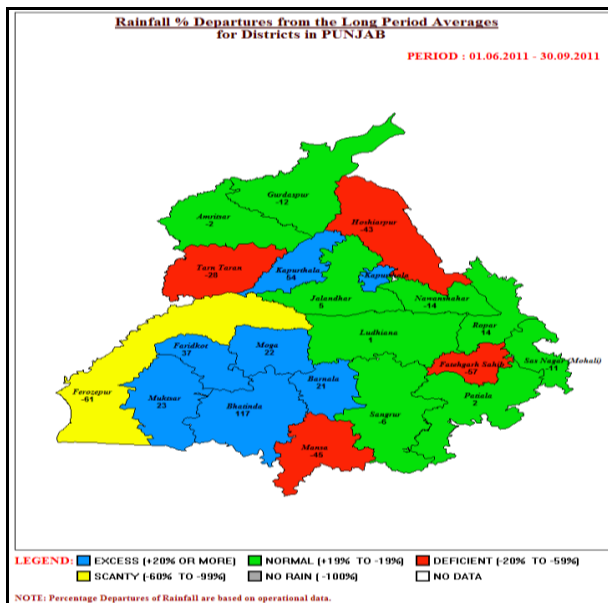


Fig. 1. June-September rainfall Punjab

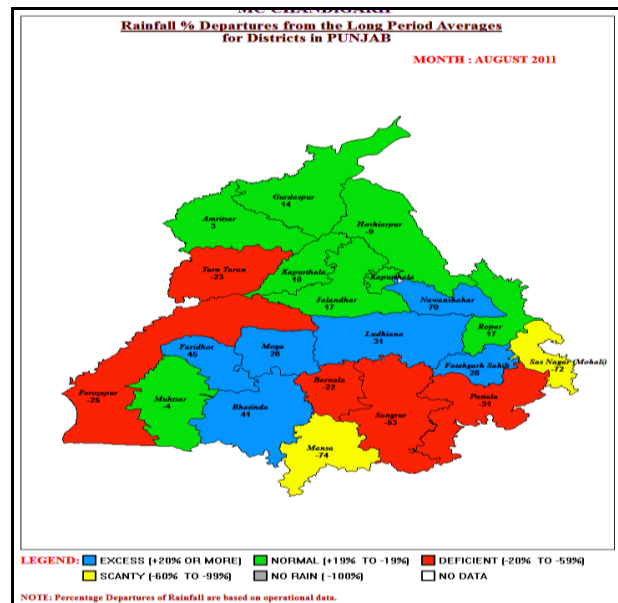


Fig. 2. Rainfall for the month of August, Punjab

while in the hot weather season (April-June) and in post monsoon season about 5 to 11% and 3 to 6% respectively. In Monsoon 2011 Met Subdivision Punjab received 459.3 mm of rainfall against its normal rainfall of 496.3 mm with a deviation of -7% leading to seventy fourth year of normal rainfall in Punjab. In Punjab out of twenty districts for which data was available seven districts received excess rainfall, nine districts received normal rainfall, three districts received deficient rainfall and one district received scanty rainfall during monsoon 2011 (June-September). Rainfall distribution during monsoon 2011 (June-September) in Punjab was normal to excess in the month of June, August and September and were deficient in the month of July. District wise percentage departure of rainfall during monsoon 2011 and in the month of August, 2011 for Met. subdivision Punjab is shown in Figs. 1&2.

In the month of August, 2011 some districts of Punjab namely Amritsar, Gurdaspur, Ludhiana, Hoshiarpur, Kapurthala, Nawanshahr, Tarntaran, Ropar, Fatehgarh Sahib, Moga, Faridkot, Feorzipur, Muktsar and Bhatinda received very heavy to extremely heavy rainfall with exceptionally heavy rainfall in Phillaur district of Jalandhar and Ludhiana on 13th August, 2011. Punjab Agricultural University, Ludhiana, Jagraon, Balachaur, Nawanshahr, Nangal Dam, Nakodar, received very heavy to extremely heavy rainfall of 48, 40, 23, 22, 20, 18 and 14 cm rainfall during the 24 hrs ending at 0830 hrs on 13th August, 2011 and stations Halwara (IAF), Ludhiana (Sanehwal), Garhshankar, Batala, Hoshiarpur, Amritsar, Malakpur and Phagwara received heavy rainfall of 12, 11,

10 cm respectively ending at 0830 hrs IST of 13th August. Amritsar, Malakpur and Phagwara recorded 7 cm each during the 24 hrs ending at 0830 hrs IST on 13th August. In Ludhiana city there are two observatories one is inside PAU Ludhiana (30°53'53" N and 75°48'27" E) with elevation of 248 m amsl and other is IMD observatory (30°48'01" and 75°54'10" E) located at airport (Sahnewal) with elevation of 259 m asl which is about 20 km east of PAU Ludhiana observatory.

Punjab Agricultural University, Ludhiana observatory received exceptionally heavy rainfall of 40 cm during past 24 hrs ending at 0830 hrs IST on 13th August against it normal rainfall of 3.9 mm which is all time record breaking its previous record of 338 mm received on 24th September, 1988. Total rainfall in the month of August, 2011 in the observatory of PAU Ludhiana was 513 mm against it normal rainfall of 180 mm which is more than three time of normal rainfall for the month. Percentage deviation of actual rainfall from normal for districts which received very heavy to extremely heavy and exceptionally heavy rainfall reported on 13th August, 2011 is given in Fig. 3 below which indicates that departure of actual rainfall from normal was quite high in Ludhiana and adjoining districts on 13th August, 2011. IMD observatory Ludhiana which is located in Sahnewal airport received 170 mm of rainfall recorded on 0830 hrs IST on 13th August against it normal rainfall of 6.6 mm and 236 mm of rainfall in the month of August against it normal rainfall of 180 mm respectively.

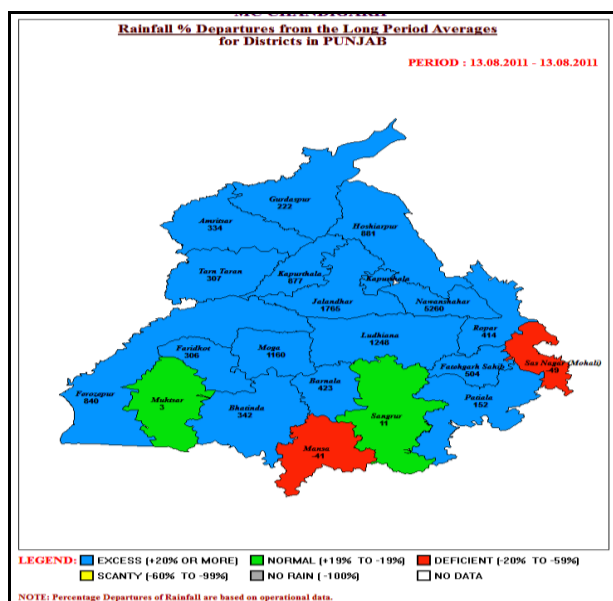


Fig. 3. Rainfall recorded on 13th August Punjab

2.1. Area of study

District Ludhiana and adjoining district of Punjab namely Fatehgarh Sahib, Jalandhar, Nawanshahr, Patiala, Roopnagar, Mohali, Moga, Kapurthala received heavy to very heavy rainfall during on 13th August, 2011. Ludhiana and some adjoining districts received extremely heavy to exceptionally heavy rainfall reported on 13th August, 2011. The worst affected district was Ludhiana city wherein 400 mm of rainfall was recorded on 13th August, 2011. Extremely heavy to exceptionally heavy rainfall recorded at Ludhiana city since 1980 onwards is presented in Table 1. Life was totally paralysed in the city and total death toll was reported to be 14 in various parts of Ludhiana city related to rainwater incidents during 12 and 13 August. Heavy down power inundated crops in several villages and life in Ludhiana city was totally paralysed with disruption of all essential services and significant damage to public and private properties were reported due unprecedented rainfall during 12 and 13 August, 2011. Focus of the present study is to identify the synoptic and thermodynamic features along with broad global features responsible for very heavy to exceptionally heavy rainfall reported on 13th August, 2011 in Ludhiana and adjoining districts. In addition to this, thermodynamic features responsible for heavy to exceptionally heavy rainfall reported on 13th August have been presented in this paper.

Daily rainfall data of DRMS stations during 13th August, 2011 have been collected from Meteorological Centre (M.C.), Chandigarh. In order to analyse the

TABLE 1

Rainfall recorded (in mm) at Ludhiana (1980-2011)

Year	Rainfall	Date
1980	238	12 July
1988	338	24 September
1992	177	25 September
1993	124	10 July
1993	116	12 July
1995	170	22 July
1995	127	2 August
2001	109	8 July
2009	157	27 July
2009	115	20 July
2011	400	13 August

mesoscale features, the radiosonde and DWR data have been collected from Patiala. Data on synoptic scale system like low pressure system, upper air cyclonic circulation developing over the area of study have been collected from Daily and weekly weather report of IMD and Meteorological Centre, Chandigarh. Broad circulation feature for the month of August have also been taken from National Centre for Environmental Prediction (NCEP) reanalysis data set. Some observation aspect pertaining to sequence of weather events during 12 and 13 August, 2011 have been taken from nearby IMD observatories *i.e.*, Patiala, Ambala, Hisar, Ludhiana, Amritsar and Chandigarh. In addition to this observations from in situ and satellite source such as Tropical Rainfall Measuring Mission (TRMM) having 3-hourly accumulated TRMM grid point rainfall data available at very high resolution of 0.25×0.25 (<http://disc2.nascom.nasa.gov/Giovanni/tovas/realtime.3B42RT.shtml>) have also been taken to identify various features responsible for the same.

3. Results and discussion

Sequence of weather events and synoptic system which is responsible for very heavy to exceptionally heavy rainfall in some districts of Punjab during 12 and 13 August, 2011, which led to disruption of essential services in Ludhiana and adjoining districts has been mentioned below. Main synoptic system and sequence of weather events during 12 and 13 August and broad circulation features for the month of August, 2011 are presented in sec. 3.1. and 3.2. Thermodynamic features and upper sounding based upon 0000 UTC of Patiala has been analysed and presented in Sec. 3.3. Satellite inferences obtained from Kalpana-1 Satellite during 12 and 13 August, 2011 is given in sec. 3.4. NWP model

TABLES 2 (a-f)

Continuous observations recorded at IMD stations in Punjab and Haryana

Date	Synoptic hrs in UTC	Clouds particulars	MSLP	P24	Wind dir/speed(Knots)
(a) Chandigarh					
12 Aug, 2011	0300	Total Seven Octa with Sc & Ac with base of low clouds Between 1000-1499M	999.3	-1.6	SE/03
12 Aug, 2011	0600	Total Six Octa with Sc & Ac with base of low clouds Between 1000-1499M	999.3	-1.3	SE/03
12 Aug, 2011	0900	Total Five Octa with Sc & Ac with base of low clouds Between 1000-1499M	996.8	-1.6	SE/02
12 Aug, 2011	1200	Total Six Octa with Sc & Ac with base of low clouds Between 600-999M	995.7	-0.1	S/04
12 Aug, 2011	1500	Sky obscured with Sc & As with base of low clouds Between 600-999M	998.5	-0.7	0/0
12 Aug, 2011	1800	Sky obscured with Sc & As with base of low clouds Between 600-999M	999.9	0.5	0/0
12 Aug, 2011	2100	Total Seven Octa with Sc & As with base of low clouds Between 600-999M	1000.2	0.7	0/0
13 Aug, 2011	0000	Sky obscured with Sc & As with base of low clouds Between 600-999M	1000.6	0.7	NW/03
13 Aug, 2011	0300	Sky obscured with Sc & As with base of low clouds Between 300-599M	1002.2	2.1	0/0
(b) Patiala					
12 Aug, 2011	0300	Total Six Octa with Sc & Ac with base of low clouds Between 600-999M	999.1	-0.7	E/04
12 Aug, 2011	0600	Sky obscured with Sc & As with base of low clouds Between 1000-1499M	999.1	-1.2	E/04
12 Aug, 2011	0900	Total Six Octa with Sc with base of low clouds Between 1000-1499M	997.2	-0.4	SE/03
12 Aug, 2011	1200	Total Six Octa with Sc with base of low clouds Between 1000-1499M	995.9	-0.1	SE/02
12 Aug, 2011	1500	Sky obscured with Sc, CB & As with base of low clouds Between 600-999M	998.1	11	0/0
12 Aug, 2011	1800	Total Seven Octa with Sc & Ac with base of low clouds Between 1000-1499M	999	0.1	0/0
12 Aug, 2011	2100	Total Six Octa with Sc & Ac with base of low clouds Between 1000-1499M	997.6	-0.7	0/0
13 Aug, 2011	0000	Total Seven Octa with Sc & Ac with base of low clouds Between 1000-1499M	998.7	0.9	0/0
13 Aug, 2011	0300	Sky obscured with Sc & As with base of low clouds Between 600-999M	1001.4	1.9	0/0
(c) Amritsar					
12 Aug, 2011	0300	Total Seven Octa with Sc, As & Ac with base of low clouds Between 1000-1499M	998.4	-1.8	SE/06
12 Aug, 2011	0600	Total Seven Octa with Sc,Cb, As & Ac with base of low clouds Between 300-599M	998.3	-1.6	SE/09
12 Aug, 2011	0900	Sky obscured with Sc, CB & As with base of low clouds Between 300-599M	996.6	-1.6	SE/07
12 Aug, 2011	1200	Total Seven Octa with Sc, As & Ac with base of low clouds Between 1000-1499M	998.4	-1.8	SE/06
12 Aug, 2011	1500	Total Six Octa with Sc, As & Ac with base of low clouds Between 1000-1499M	997.8	0.5	E/08
12 Aug, 2011	1800	Sky obscured with Sc & As with base of low clouds Between 600-999M	999.8	1.2	EES/06

Table 2(a-f) (Contd.)

Date	Synoptic hrs in UTC	Clouds particulars	MSLP	P24	Wind dir/speed(Knots)
12 Aug, 2011	2100	Sky obscured with Sc & As with base of low clouds Between 600-999M	998.9	0.6	E/07
13 Aug, 2011	0000	Sky obscured with Sc & As with base of low clouds Between 600-999M	999.3	2	E/07
13 Aug, 2011	0300	Sky obscured with Sc & As with base of low clouds Between 600-999M	1002.2	2.1	EES/07
(d) Hisar					
12 Aug, 2011	0300	Sky obscured with Sc & As with base of low clouds Between 300-599M	998.1	-0.9	E/03
12 Aug, 2011	0600	Total Seven Octa with Sc & Ac with base of low clouds Between 300-599M	998.2	-0.7	E/04
12 Aug, 2011	0900	Total Seven Octa with Sc & Ac with base of low clouds Between 1000-1499M	995.9	-0.8	E/04
12 Aug, 2011	1200	Total Five Octa with Sc & Ac with base of low clouds Between 600-999M	995.6	0.1	SE/02
12 Aug, 2011	1500	Total Five Octa with Sc & Ac with base of low clouds Between 600-999M	997	0.6	SE/02
12 Aug, 2011	1800	Total Five Octa with Sc & Ac with base of low clouds Between 600-999M	998.4	0.4	SE/03
12 Aug, 2011	2100	Total Six Octa with Sc & Ac with base of low clouds Between 600-999M	997.5	-	SE/03
13 Aug, 2011	0000	Total Five Octa with Sc & Ac with base of low clouds Between 600-999M	998.2	1.2	SE/03
13 Aug, 2011	0300	Sky obscured with Sc & As with base of low clouds Between 600-999M	999.8	1.7	EEN/01
(e) Ludhiana					
12 Aug, 2011	0300	Total Five Octa with Sc & Ac with base of low clouds Between 600-999M	998.6	-1.6	SE/03
12 Aug, 2011	0600	Total Seven Octa with Sc & Ac with base of low clouds Between 600-999M	999	-0.8	SE/03
12 Aug, 2011	1200	Sky obscured with Sc & As with base of low clouds Between 600-999M	996.6	3	0/0
13 Aug, 2011	0300	Sky obscured with Sc & As with base of low clouds Between 600-999M	1002.4	3.1	E/03
(f) Ambala					
12 Aug, 2011	0300	Total Six Octa with Sc,Cu & Ac with base of low clouds Between 600-999M	999.2	-1.3	SE/09
12 Aug, 2011	0600	Total Seven Octa with Sc, Cu & Ac with base of low clouds Between 600-999M	999.7	-1	SE/06
12 Aug, 2011	0900	Total Seven Octa with Sc & Ac with base of low clouds Between 1000-1499M	997.5	-	SE/06
12 Aug, 2011	1200	Total Six Octa with Sc, Cu & Ac with base of low clouds Between 600-999M	999.2	-1.3	SE/09
12 Aug, 2011	1500	Sky obscured with Sc & As with base of low clouds Between 600-999M	998.4	4	SE/02
12 Aug, 2011	1800	Sky obscured with Sc & As with base of low clouds Between 600-999M	999.5	-0.3	SE/04
12 Aug, 2011	2100	Total Seven Octa with Sc & Ac with base of low clouds Between 600-999M	998.9		SE/06
13 Aug, 2011	0000	Sky obscured with Sc & As with base of low clouds Between 600-999M	999.1		0/0
13 Aug, 2011	0300	Sky obscured with Sc & As with base of low clouds Between 600-999M	1001.2		N/02

inference *i.e.*, IMD GFS and WRF model during 12 and 13 August, 2011 have been presented in sec. 3.5. Rainfall observation as measured by TRMM at 3 hour interval over the area and also the 24 hour accumulated rainfall during 0300 hrs UTC of 12th August to 0300 hrs of 13th August, 2011 is presented in sec. 3.6.

3.1. *Synoptic situations and broad circulation feature in August, 2011*

PAU, Ludhiana observatory recorded 400 mm of rainfall on 13th August, 2011. Rainfall started at 1200 UTC and dissipated after 0300 UTC of 13th August, 2011. Very high departure from normal was also reported from some other stations in adjoining district of Ludhiana on 13th August. This extremely heavy to exceptionally heavy rainfall was mainly associated with low pressure area, which formed over Northwest Madhya Pradesh on 8th August, 2011 and moved over to South Pakistan & adjoining southwest Rajasthan with associated upper cyclonic circulation extending upto mid tropospheric level on 11th August, 2011. It moved over to southwest Rajasthan and adjoining Pakistan with associated cyclonic circulation extending up to mid tropospheric level on 12th August, 2011. Upper air cyclonic circulation over north east MP and adjoining South-UP merged with the above system. In addition, a western disturbance as an upper air system also lay over Jammu Kashmir and neighbourhood.

Monsoon trough which had been confined to the lower tropospheric levels deepened and became active during this period and passed through Jaismaler, Jaipur, Agra, Allahabad and thence South-eastwards to head Bay of Bengal on 12th August, 2011. This was triggered due to active monsoon trough embedded with vortices in the form of low pressure area and cyclonic circulation moving along monsoon trough in west north-westerly direction. During this period, an interaction between a monsoon flow and cyclonic circulation in the westerly field caused extremely heavy rainfall over the north western parts of the country which seems to be possible cause of extremely heavy rainfall in Punjab including Ludhiana and adjoining district on 13th August, 2011. In addition to this monsoon trough maintained its vertical extent up to mid tropospheric levels except during the period 15 - 24 August, when the monsoon circulation features in general remained weak and led to heavy rainfall activities in Punjab and Haryana. The axis of monsoon trough at sea level exhibited meridional oscillations during the month.

3.2. *Sequence of weather events*

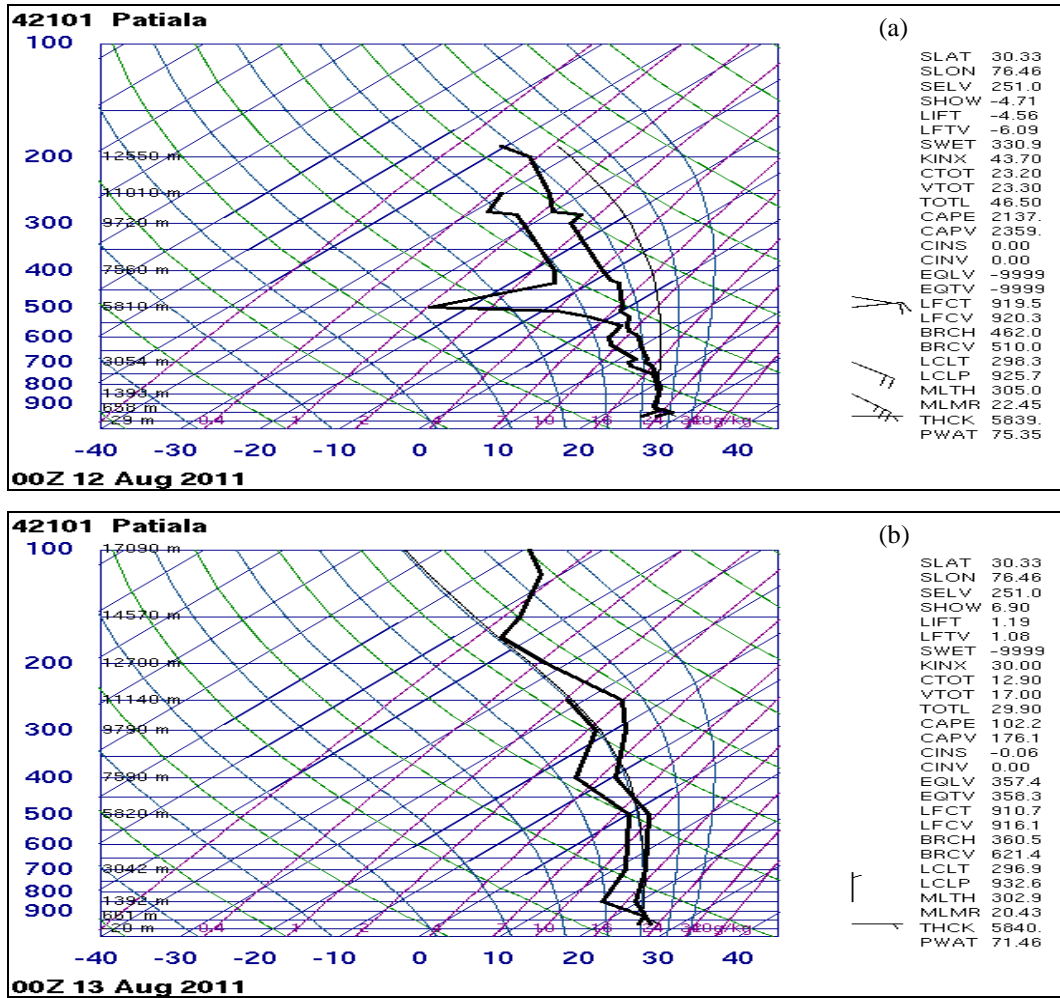
Continuous observations recorded at IMD stations in Punjab and Haryana *viz.*, Ludhiana, Patiala, Amritsar, Hisar, Ambala and Chandigarh for main synoptic hours

during 0300 UTC of 12th to 0300 UTC of 13th August, 2011 is presented in Tables 2 (a-f). Observations indicate that weak south-easterly wind (<5kt) (except Amritsar wherein it was less than 10 kts) was prevailing over these stations with stratocumulus and altocumulus clouds upto 0900 UTC of 12th August, 2011 with wind becoming southerly after 0900 hrs UTC. Mean Sea level pressure tendency during the past 24 hours was also decreasing during this period in all the stations. Notable feature which is seen from the observations that sky became obscured with CB and SC clouds after 1200 UTC and stations reported lightning and thunder at 1200 UTC and thunder with rainfall afterwards. It has observed that rainfall started at 1200 UTC with calm wind in all stations after 1200 UTC and maximum rainfall occurred during 2100 to 0300 UTC. Almost all stations reported cessation of rainfall after 0300 hrs UTC on 13th August, 2011.

Thermodynamic indices clearly reveals that atmosphere was very unstable in Patiala during late 12 to 13 August, 2011, wherein state of Punjab received extremely heavy to exceptionally heavy rainfall recorded on 13th August with high CAPE value ranged from 1400 to 2140 and lower CIN values on these dates. Other thermodynamic indices/ features such as Lifted Index, K-Index, Total-Total Index, etc. which are important features for evaluation of stability and are basic requirement for convective cloud formation were also favourable. Value of Lifted Index was less than -4 on 12th August, 2011 which was favourable for possible severe thunderstorm. Total-Total Index was also more than 40 except during 12th August, 2011 which is again optimum for possible thunderstorm with chance of severe thunderstorm and also content of the atmosphere also the K Index value ranged from 30 to 50 and more than 40 on 12th which indicate 100% probability of thunderstorm.

There was convective instability and relative humidity was higher in lower and middle tropospheric level over Patiala during these days. Perceptible water was higher and ranged between 50 to 75 mm during 12 and 13 August, 2011.

Observed sounding over Patiala based upon 0000 UTC from 12th to 13th has been shown in Fig. 4(a&b). Sounding at 0000 UTC of 12th August, 2011 [Fig. 4(a)] indicates that atmosphere was saturated from surface upto mid and upper troposphere *i.e.* upto 400 hPa with freezing level up to 530 hPa with LCL (lifting condensation level) at 944 hPa. Sounding at 0000 UTC of 13th August, 2011 [Fig. 4(b)] indicates that atmosphere was saturated at the surface upto 700 hPa and was dry afterwards.



Figs. 4(a&b). Observed Sounding over Patiala at (a) 0000 UTC 12th August (b) 0000 UTC 13th August, 2011

3.3. Thermodynamic features

Thermodynamic Indices over Patiala during 12 to 16 August is given in Table 3.

3.4. Satellite inferences

Cloud imageries as obtained from Kalpna -1 Satellite from 0600 UTC of 12th August till 0000 UTC of 13th August are shown in Figs. 5(a-c). Their salient features are enumerated as below:

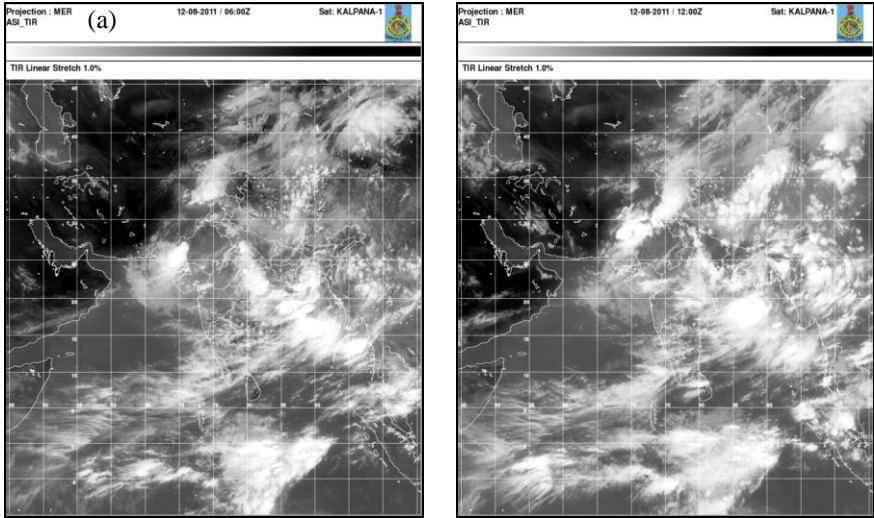
Satellite bulletin based on Kalpna Satellite of 06 UTC of 12th August indicates a convective cell started at 2100 UTC of 11th August over Northeast Pakistan and adjoining to Jammu and Kashmir. The cell expanded & moved eastward and lies over W J&K at 0000 UTC of 12th August, 2011. Tibetan high is observed west of its normal position (29° N 83' E). Satellite low level winds indicate that wind associated with cross equatorial flow about 20 kts. WV imageries indicate that westerly trough

is around 67° E and Tropical easterly jet is seen running from 93° E to African coast passing east coast of India around 10° N. Satellite imageries indicates broken low/medium clouds with embedded moderate to intense convection over West J&K Southeast UP during 0600 to 0900 UTC 12th August. which is seen over south J&K, Punjab, northwest HP, west UP and southwest parts of Eastern UP based upon 1200 UTC of 12th August and over Southeast J&K, Punjab, adjacent Haryana, and HP upto 0000 UTC 13th August which is further seen over west J&K, North Punjab and North HP at 0300 UTC and moved over to Haryana and West UP by 0600 UTC on 13th August, 2011.

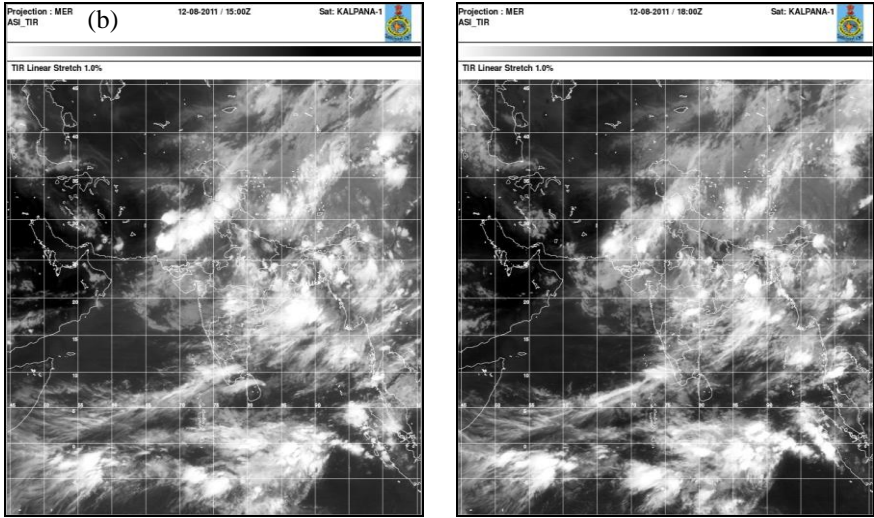
3.5. NWP guidance

3.5.1. NWP model product

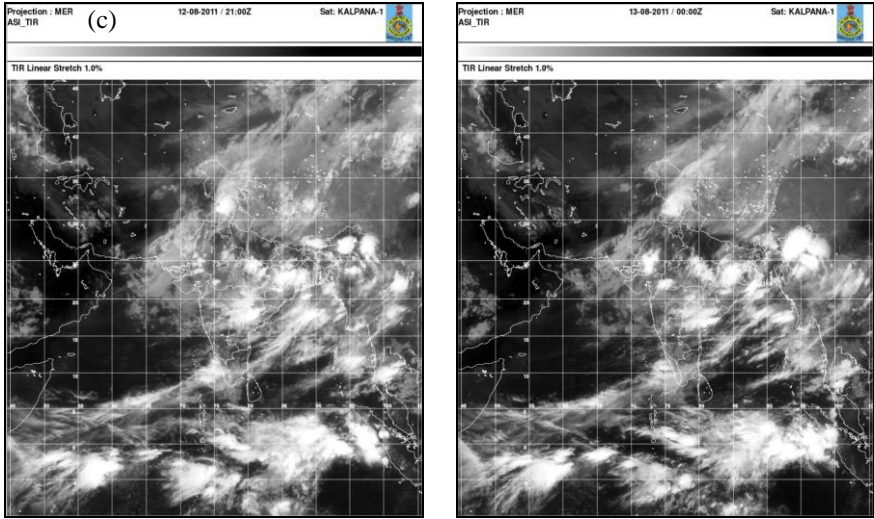
Analysis of WRF (9 km) model run at M. C. Chandigarh for surface 850, 700 and 500 hPa during



Figs. 5(a). Kalpna IR imageries 0600 UTC and Kalpna IR imageries 1200 UTC



Figs. 5(b). Kalpna IR imageries 1500 UTC and Kalpna IR imageries 1800 UTC



Figs. 5(c). Kalpna IR imageries 2100 UTC and Kalpna IR imageries 0000 UTC 13 August

TABLE 3

Thermodynamic Indices over Patiala (12-16 August)

Indices/parameters	Significant rainfall days				
	12 Aug	13 Aug	14 Aug	15 Aug	16 Aug
Showalter index	-4.71	6.9	-8.1	-1.71	-0.75
Lifted index	-4.56	1.19	-4.32	-5.28	-1.58
K index	43.7	30	49.6	39.5	33.4
Cross total index	23.2	12.9	25.3	21.8	21.2
Vertical total index	23.3	17	31.3	23.7	22.5
Total total index	46.5	29.9	56.6	45.5	43.7
CAPE (J)	2137.97	102.24	1422.37	2100.26	95.46
CINE (J/Kg)	0	-0.06	-337.25	-17.2	-19.53
Level of free convection (hpa)	919.53	910.76	730.99	872.48	829.74
Temperature of lifted condensation level (K)	298.37	296.98	294.77	296.14	294.17
Pressure of lifting condensation level (hpa)	925.71	932.6	908.72	924.66	929.58
Precipitable water (mm)	75.35	71.46	63.26	62.2	50.33

11 and 12 August, 2011 is shown Figs. 6(a-h). Analysis shows low pressure on mean sea level lies over South Pak and adjoining SW Rajasthan on 11th August and over to Southwest Rajasthan and adjoining Pak with associated cyclonic circulation extending up-to mid tropospheric level. Analysis also shows trough in westerly field at 300 hPa. Model forecast also shows fairly widespread rainfall with isolated heavy rainfall over northwest India 48 hours in advance.

3.5.2. Synoptic features based upon 0000 UTC NWP GFS model of 11th August, 2011

IMD GFS low levels wind (925 and 850 hPa) analysis shows an upper air cyclonic circulation over southwest Rajasthan and adjoining south Pakistan with associated upper air cyclonic circulation extending up to 500 hPa level; tilting southwards with height. IMD GFS wind analysis shows an upper air cyclonic circulation (WD) over Jammu & Kashmir and adjoining areas. Model analysis shows the axis of monsoon trough run to its normal position at mean sea level. Analysis based upon 0000 UTC of 12 and 13 August shows well-marked low in mean sea level pressure over Jharkhand, Gangetic West Bengal and adjoining Bihar and Orissa. Associated cyclonic circulation is extended up to 500 hPa level with a southward tilt with height.

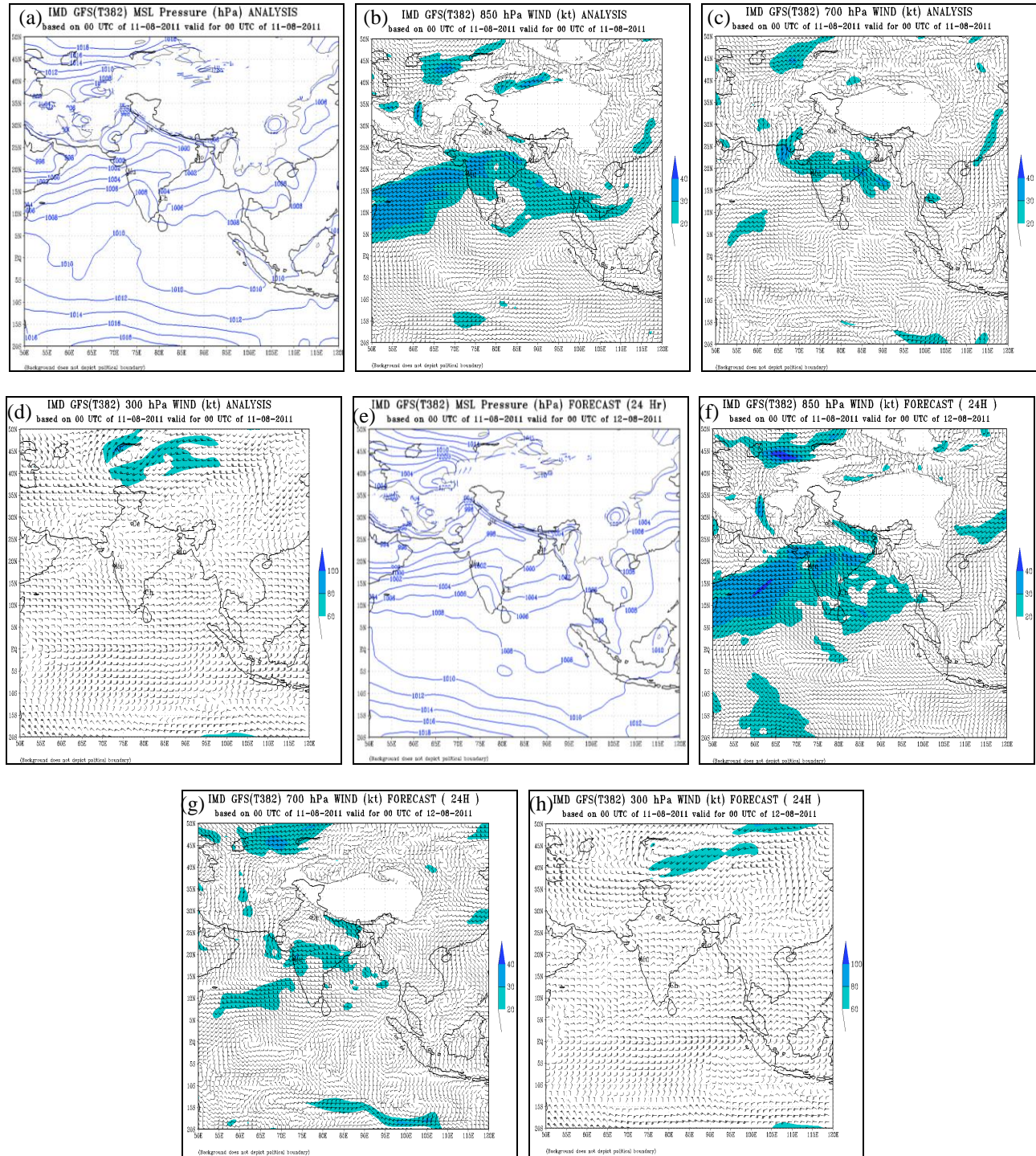
Analysis further shows cycir in low levels wind (925 and 850 hPa) over southwest east Rajasthan and adjoining

area on 0000 UTC of 13th August. Axis of seasonal trough was situated near to its normal position with it western end towards south latitudes. Both IMD GFS and WRF wind analyses show a western disturbance was passing north of Jammu & Kashmir and adjoining areas. IMD GFS model forecast based upon 0000 UTC of 12th August 2011 also predicted widespread rainfall in northwest India during next 48-72 hours.

3.6. TRMM

Tropical Rainfall Measuring Mission (TRMM) is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA), to monitor tropical and subtropical precipitation and to estimate its associated latent heating. TRMM provides systematic visible, infrared and microwave measurements of rainfall in the tropics as key inputs to weather and climate research. TRMM rainfall measurements are also analysed for the heavy rainfall recorded on 13th August, 2011 in Punjab. The TRMM 24 hrs rainfall estimates (mm/ hr) during 0300 UTC of 12th August to 0300 UTC of 13th August, 2011 and 3 hourly estimate from 0300 UTC of 12th August to 0300 UTC of 13th August, 2011 for Ludhiana and adjoining area shows that widespread rainfall in central and south eastern districts of Punjab comprising districts Ludhiana, Jalandhar, Fatehgarh Sahib, Nawanshahr, Patiala and Kapurthala, and also located the main centre of the rainstorm which was near Ludhiana wherein 24 hour accumulated rainfall estimation was more than 10 mm/ hour and underestimated the observed rainfall at PAU Ludhiana but some districts/ stations received rainfall near to estimation and also the storm centre was also captured by TRMM. Rainfall estimation by TRMM in Ludhiana and adjoining districts namely Jalandhar, Fategarh Sahib, Kapurthala and Patiala was more than 8 mm/ hour and rainfall estimate in neighbouring districts *i.e.* Lat./Long. 31.2/31.3° N 75.8 to 77.3° E was less than 8 mm/ hrs. It is clear from 3 hour rainfall estimation of TRMM that a convective cell started at 2100 UTC of 11th August over Northeast Pakistan and J&K. Cell expanded and moved eastwards and lies over West J&K during 0300 UTC to 0600 UTC of 12th August 2011 and entire cloud mass shifted eastward with large portion lay over West J&K and North Punjab (CTT -41 to -75 °C). During 0900 UTC to 1200 UTC cell moved over to South J&K Punjab, Northwest HP, West UP, southwest parts of Eastern UP (CTT -41 to -70 °C). During 1200 UTC to 1500 UTC cloud mass extended over South J&K Punjab, adjoining Haryana HP and West UP.

During the subsequent observations *i.e.*, between 1500 UTC to 1800 UTC entire cloud mass move further south-eastwards and covered entire Punjab, adjoining Haryana and WUP with very intense convection between



Figs. 6(a-h). (a) Mean Sea level pressure GFS (b) Analysis 850 hPa GFS Analysis (c) 700 hPa GFS (d) Analysis 300 hPa GFS (e) Mean Sea level pressure WRF (f) Analysis 850 hPa WRF (g) Analysis 700 hPa WRF (h) Analysis 300 hPa WRF, for 0000 UTC

Lat./Long. 30-31.8° N/ 76-76.5° E near Ludhiana. It further moved south-eastward and lay centred over Lat./Long. 31-3.8° N/ 75.7-76.5° E between 1800 UTC to 2100 UTC. During 2100 UTC to 0000 UTC entire cloud

mass moved further south-eastward with intense to very intense convection and rainstorm was centred between Lat./Long. 31-31.5° N/ 75.5 -76.8° E near Ludhiana and adjoining districts . During 0300 to 0600 UTC system

started weakening and moved over to Haryana adjoin Northwest UP by 0900 UTC. It has been observed that maximum rainfall occur during 2100 of 12th August to 0300 UTC of 13th August, 2011 with rainfall rate of more than 18 mm/ hr during 2100 to 0300 UTC.

4. Conclusions

Based upon the analysis and discussion broad synoptic and dynamical feature which is responsible for very heavy to exceptionally heavy rainfall in Punjab during 12 and 13 August are follows.

(i) Low pressure area lay over Southwest Rajasthan and adjoining Pakistan with associated cyclonic circulation extending up to mid tropospheric level on 12th August, 2011. Upper air cyclonic circulation over northeast MP and adjoining South-UP merged with the above system. In addition to this western disturbance as an upper air system also lay over Jammu Kashmir and neighbourhood.

(ii) Presence of active monsoon trough with embedded vortices in the form of the above mentioned low pressure areas as well as various cyclonic circulations, which predominantly moved along the monsoon trough in a west north-westerly direction.

(iii) The monsoon trough which had been confined to the lower tropospheric levels deepened and became active from the beginning of the second week of the month. Thereafter it maintained its vertical extent up to mid tropospheric levels except during the period. When the monsoon circulation features in general remained weak. During this period, an interaction between a monsoon low and cyclonic circulation in the westerly field caused extremely heavy rainfall over the north western parts including Punjab. The axis of monsoon trough at sea level exhibited meridional oscillations during the month.

(iv) Analysis of this study based upon synoptic, dynamic and other observational features confirm the earlier findings that the system which leads to heavy rainfall and subsequent floods in northwest India including Punjab and Haryana is related to the interaction of the mid latitude westerly troughs with monsoonal flow. These interaction leads to the activation of Arabian Sea current and enhanced the supply of moisture over the region due to proximity of the axis of monsoon trough which favours confluence of easterlies and westerlies over the region.

(v) Tibetan high was observed to the west of normal position *i.e.*, 29° N/ 83° E let the trough in westerly to penetrate in to the region.

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