MAUSAM, **66**, 4 (October 2015), 741-750

551.579 : 551.577.37 (540.27)

Exceptionally heavy rainfall over Uttarakhand during 15-18 June, 2013 - A case study

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(*Received 8 October 2013, Modified 15 December 2014*)

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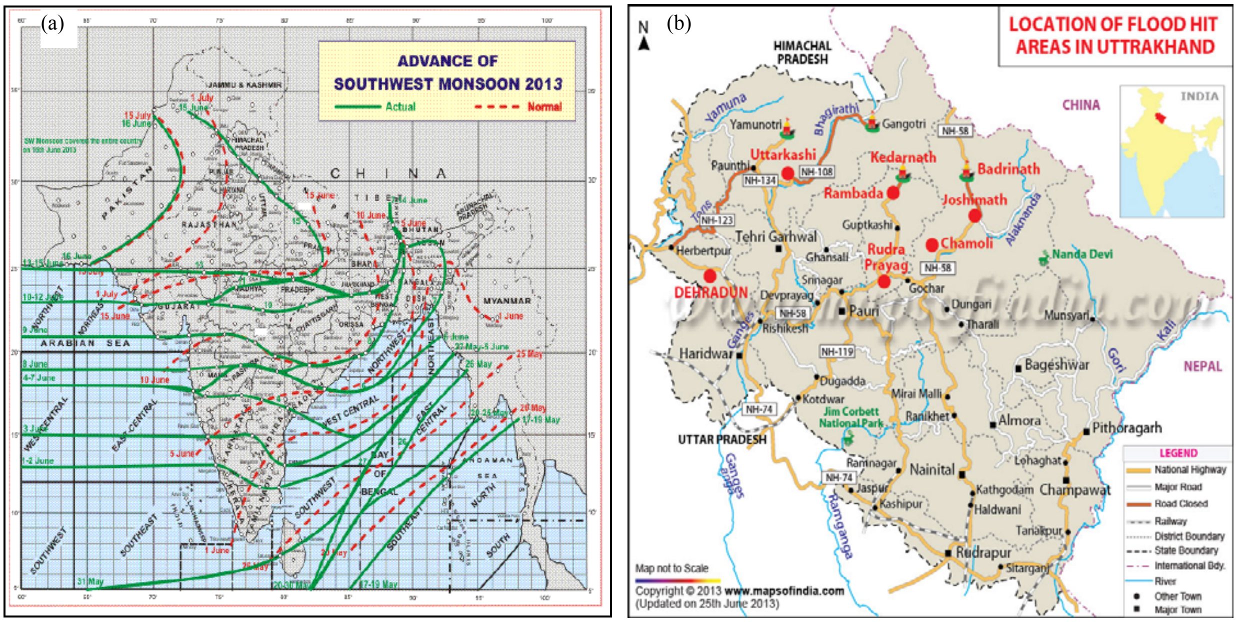
सार – 15 से 18 जून 2013 के दौरान उत्तराखण्ड में असामान्य रूप से बहुत भारी वर्षा हुई जिसकी वजह से बाढ़ आ गई और राज्य में अपार जान-माल की क्षति हुई। इस शोध पत्र में देशांतर 65.0° पूर्व से 70.0° पूर्व के बीच गहन पश्चिमी द्रोणी की गति और पश्चिमी मध्य प्रदेश तथा उससे लगे पूर्वी राजस्थान के ऊपर निम्न दाब का क्षेत्र के साथ-साथ बंगाल की खाड़ी एवं अरब सागर से आई नमी के आने से पश्चिमी हिमालयी क्षेत्र (WHR), इसमें भी विशेष रूप से उत्तराखंड पर पड़ने वाले प्रभाव की जाँच की गई है। नमी का प्रवाह 10 जून को 180 ग्राम/कि.ग्रा. से बढ़ना आरंभ होकर 15 जून को लगभग 250 ग्राम/कि.ग्रा. हो गया था और 16 जून को लगभग 500 ग्राम/कि.ग्रा. पहुँच गया। बहिर्गामी दीर्घतरंगीय विकिरण (OLR) जो 15 से 17 जून के दौरान लगभग 190 वाट/ मी^{2} था वह 18 जून को 220 वाट/मी^{2} तक बढ़ गया। वर्षणीय जल की मात्राएँ 10 जून को 23 ग्राम/सेंमी^{2} से बढ़कर 16 जून तक लगभग 34 ग्राम/से.मी^{2}. तक पहुँच गई। इस क्षेत्र में भारी वर्षा की अवधि के दौरान ऊपरी स्तर अपसरण 15×10^5 S^{-1} से अधिक और निम्न स्तर अभिसरण 20×10^{-5} S^{-1} था। 14 जून के बाद से सापेक्षिक आर्द्रता बढ़ने लगी और 700 है.पा. दाब पर यह लगभग 90 प्रतिशत हो गई और यह 16 जून 2013 को 500 है.पा. पर लगभग 80 प्रतिशत तक हो गई। ऊष्णकटिबंधीय वर्षा मापन मिशन (TRMM) के द्वारा उत्तराखंड के बड़े भाग में मापी गई वर्षा 14 एवं 15 जून को 40-80 मि.मी. प्रतिदिन थी और 16 जून 2013 को 120-160 मि.मी./प्रति दिन थी।

ABSTRACT. Uttarakhand experienced exceptionally heavy rainfall, which caused floods and huge damage to life and property over the state during 15-18 June, 2013. Movement of a deep westerly trough between longitude 65.0° E to 70.0° E and a low pressure area over west Madhya Pradesh and adjoining east Rajasthan along with moisture incursion from Bay of Bengal as well from Arabian sea over western Himalayan region (WHR), more particularly over Uttarakhand have been examined. The moisture flux started rising from 180 gm/kg on 10 June to about 250 gm/kg on 15 June and about 500 gm/kg on 16 June. Outgoing longwave radiation (OLR) was about 190 w/m^2 during 15 to 17 June and it rose to 220 w/m^2 on 18 June. The precipitable water contents increased from about 23 gm/cm^2 on 10 June to about 34 gm/cm2 on 16 June. Upper level divergence was more than $15\times10^{-5}s^{-1}$ and the lower level convergence $20\times10^{-5}s^{-1}$ during heavy rainfall period over the region. Relative humidity started increasing from 14 June onwards and become about 90% at 700 hPa and about 80% at 500 hPa on 16 June, 2013. Tropical rain measuring mission (TRMM) rainfall was of the order of 40-80 mm/day on 14 and 15 June and 120-160 mm/day on 16 June, 2013 over a large part of Uttarakhand.

Key words – Mid-level westerly trough, Easterlies, Monsoon trough, Low pressure system, Cloud top temperature, Moisture flux, Precipitable water contents and outgoing longwave radiation.

1. Introduction

Occurrence of widespread rainfall with isolated to scattered heavy falls in the month of June is rare over WHR. However, the WHR experiences fairly widespread to widespread rainfall during onset phase of southwest monsoon in general. The southwest monsoon had set in over Uttarakhand including Kedarnath on 16 June, 2013 [Fig. 1(a)]. The arrival of southwest monsoon over WHR was the earliest in 2013 as per IMD record and it was 2 weeks in advance over Uttarakhand. Normally onset of southwest monsoon over Uttarakhand takes place in the last week of June. The southwest monsoon set in over Kerala on 1 June, *i.e.*, around its normal date. Its further advance over other regions of India took place in association of a low pressure area which formed over the Head Bay of Bengal, moved in west-northwesterly direction and lay over northwest Madhya Pradesh and adjoining Rajasthan on 15 June. It created favourable conditions for early onset over Uttarakhand and also over the country by 16 June, 2013. During the onset phase of southwest monsoon Uttarakhand experienced widespread

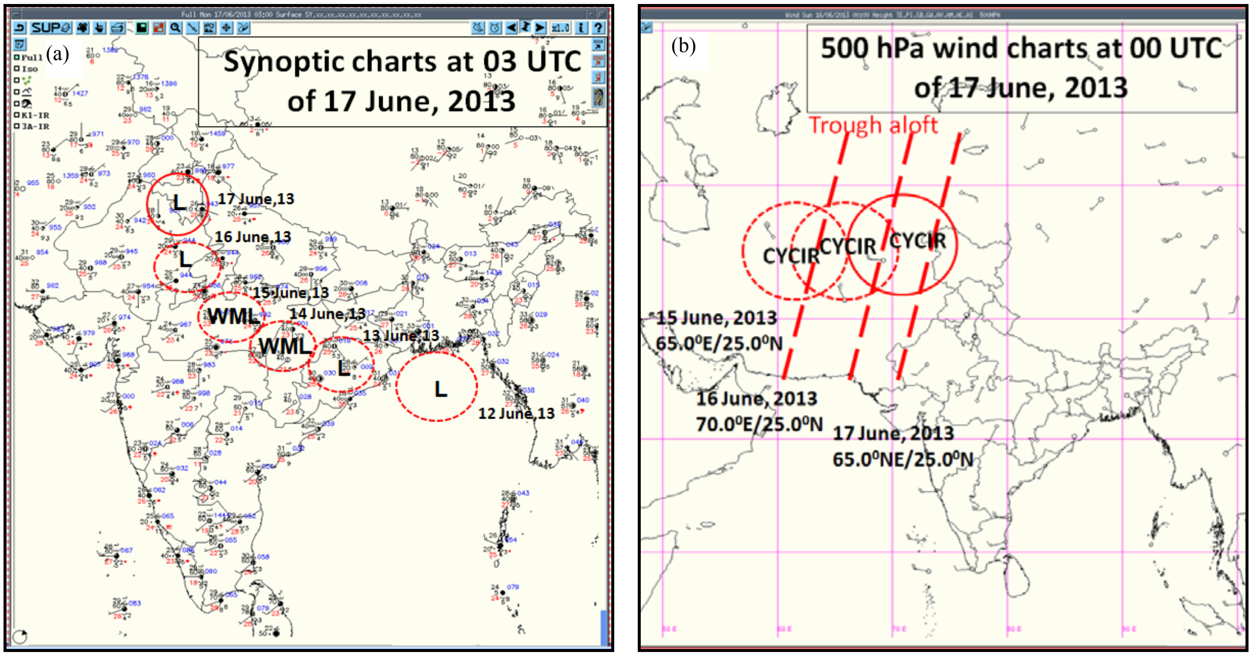


Figs. 1(a&b). (a) Map showing onset and advance of southwest monsoon during-2013 and (b) Map of Uttarakhand, red colour solid circles show flood affected cities (curtsey: http://www.mapsofindia.com)

rainfall with scatted heavy to very heavy and isolated extremely heavy falls during 15-17 June, 2013. It caused severe flood conditions over many parts of Uttarakhand [Fig. 1(b)]. On certain occasions and over certain locations, the mid-latitude westerlies invade sub-tropical areas. Short wave perturbations moving in the broad mid-latitude westerlies amplify the longwave troughs creating new baroclinic zones in relatively southern latitudes. These baroclinic zones interact with the low latitude circulations thus leading to development of new circulation pattern in which low level easterlies extend northward over central and northwest India. Rao (1976) described the effect of mid latitude systems on monsoon as of four kinds; (*i*) Intensifying or developing lower tropospheric lows or troughs, (*ii*) Enhancing rainfall in pre-existing systems, (*iii*) causing re-curvature of depressions and lows and (*iv*) Leading to onset of break conditions. It leads to intensification of western disturbances, outbreak of convection, oscillation of monsoon trough and deformation of circulations including cyclonic storms. Kalsi and Haldar (1992) suggested that the interaction between tropics and mid-latitudes plays an important role in many of the weather producing processes in and around India.

Dimri (2011) described in his study that whenever convergence peaks, a precipitation maximum occurs too. Moreover, temporal distribution shows a periodic 2-3 days association with convergence peak and precipitation maxima. Dimri (2009) and De *et al.* (2005) had listed major rainstorms and compiled rain producing system in their study, which were associated with extreme damage and huge depth of flood water submerging vast areas. A study done by Ugnar (1999) indicates that the losses due to extreme weather events are increasing steeply especially in the last decade of the twentieth century. Yadav and Bhan (2010) studied meteorological factors associated with July 2005 floods in river Jhelum and had concluded that the floods coincided with a spell of heavy rains over Jammu & Kashmir during second week of July 2005 caused by the interaction of a westward moving disturbance over the plains of northwest India and an eastward moving trough in middle troposphere over north Pakistan. Nandargi and Dhar (2012) made a detailed analysis of rainstorms that affected the northwest region of the Himalayas to assess the orographic effects of the Himalayas on precipitation in this region during the 135 years from 1875 to 2010.

The exceptionally heavy rainfall over Uttarakhand was like a cloudburst, which is a highly localized phenomena and a freak disaster. It takes place at the foot of the typically steep hills and recurs at a particular place. In general the cloudburst is an extreme amount of precipitation, which normally lasts not longer than a few minutes but is capable of creating flood conditions. The rainfall rate equal to or greater than 100 mm/hour is generally considered as cloudburst. The associated convective cloud, could extend up to a height of 15 km above the ground. Cloudburst situations are also responsible for flash flood creation. Leh (Ladakh) (India) received 250 mm of rainfall on 5 August, 2010 and National Defence Academy, Pune (India) 144 mm on 29 September, 2010 in an hour.



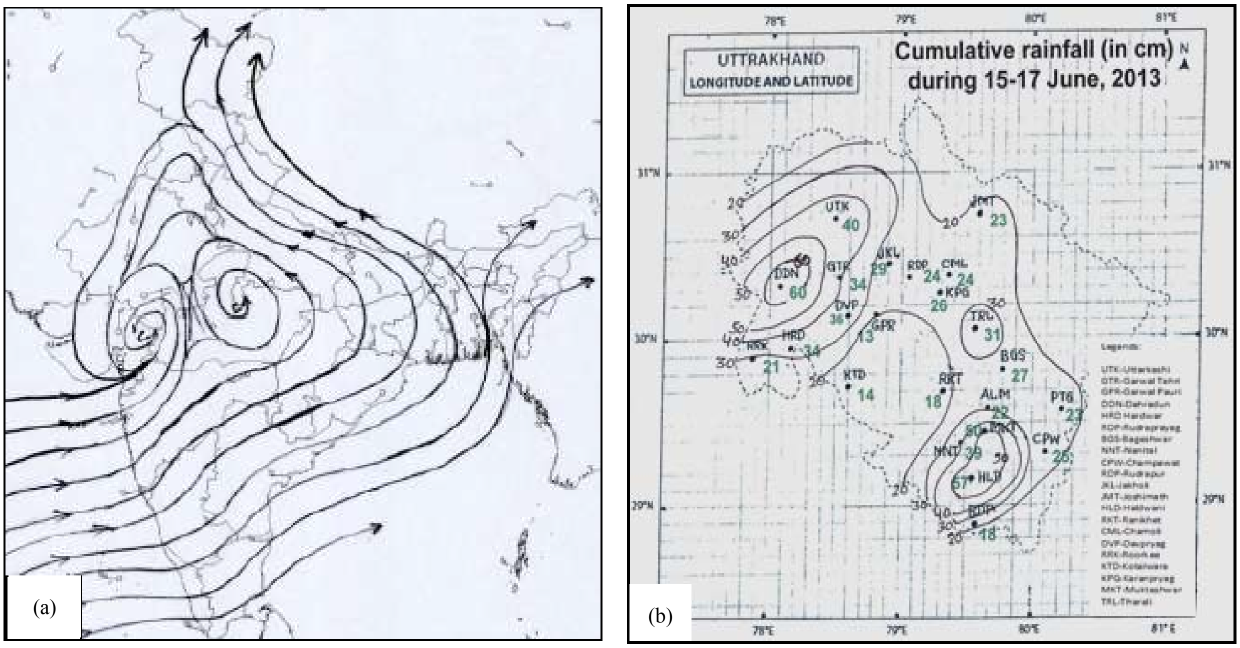
Figs. 2(a&b). (a) Mean sea level charts of 0300 UTC with date wise location of the system and (b) 500 hPa level wind charts of 0000 UTC on 17 June, 2013 with date wise location of cyclonic circulation and trough aloft

2. Data used and method of analysis

In order to describe the day to day activity of monsoon and realised rainfall, daily rainfall data of IMD observatories were used; late received data were also taken into consideration. The daily area weighted rainfall as well as daily station rainfall data for Uttarakhand were taken from Hydrology and NWFC sections of IMD. The pressure field and wind flow pattern were analyzed by using synoptic and upper air data of IMD available in synergy. INSAT satellite images {Infra Red (IR) & Visible (VIS)} and derived products, *i.e.*, water vapour wind, Outgoing Longwave Radiation (OLR) and Quantitative Precipitation Estimation (QPE) etc were also used. Infra Red cloud imageries with Cloud Top Temperature (CTT) were taken from synergie system and visible imageries form satellite division of IMD. Patiala Doppler Weather Radar (DWR) images with reflectivity (dBz) were analysed in detail. The dynamic parameters like upper level divergence, moisture flux, OLR, precipitable water contents were taken from the website of NOAA (www.esrl.noaa.gov/psd/data/grided/data.ncep.reanalysis). The domain of study area, 28.0-34.0° N to 75.0-82.0° E, had been selected keeping in view the exceptionally heavy rainfall events over WHR, particularly over Uttarakhand. In order to show the relations between some dynamical parameters and area weighted rainfall during 10-20 June, 2013, different graphs have been prepared. TRMM rainfall images (http://pmm.nasa.gov./trmm) have also been taken into account to assess the daily rainfall**.** These data are in image form and the values used in the paper are eye estimates from these images.

3. Synoptic conditions

A low pressure area had formed over northwest Bay of Bengal on 12 June and it moved west-northwestwards and lay over west Madhya Pradesh and adjoining east Rajasthan on 15 June [Fig. 2(a)]. A western disturbance as a trough in mid-level westerlies lay over north Pakistan and neighbourhood on 15 June and as a cyclonic circulation over north Pakistan and adjoining Jammu & Kashmir on 16 June [Fig. 2(b)]. The southern end of the trough in mid-levels westerlies extended upto north Arabian Sea. Easterly winds were prevailing over northern plains in lower levels; flow pattern indicates the easterly extended upto 850 hPa and reached upto Jammu & Kashmir [Fig. 3(a)]. The low pressure system reached over Haryana and neighbourhood and interacted with westerly trough over the region. In addition to above synoptic situations, the Tibetan High located west of its normal position provided upper level divergence over the region. The ridge line at 200 hPa had shifted northward to the north of 27.0° N and persisted between 27.0 to 28.0° N during 18 to 20 June, 2013 (Fig. 4). Due to these synoptic conditions moisture incursion was taking place over WHR particularly over Uttarakhand, from Arabian Sea as well as from Bay of Bengal. The orography of WHR also played an important role to enhance the low level



Figs. 3(a&b). (a) 850 hPa wind analysis at 0000 UTC of 16 June, 2013 and (b) cumulative rainfall isohyetal analysis over Uttarakhand during 15-17 June, 2013

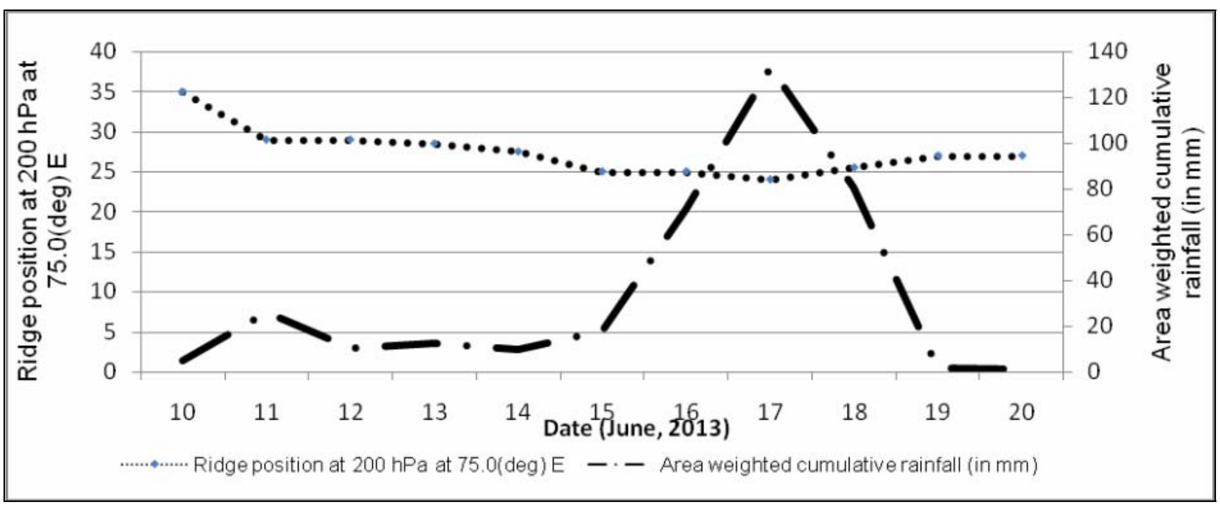
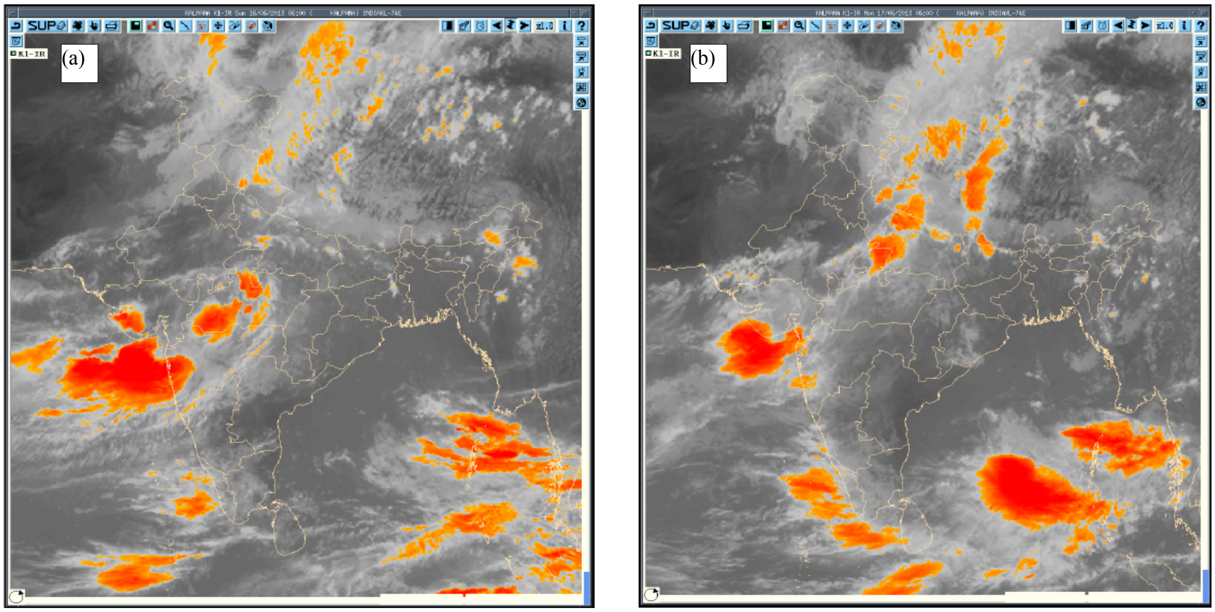
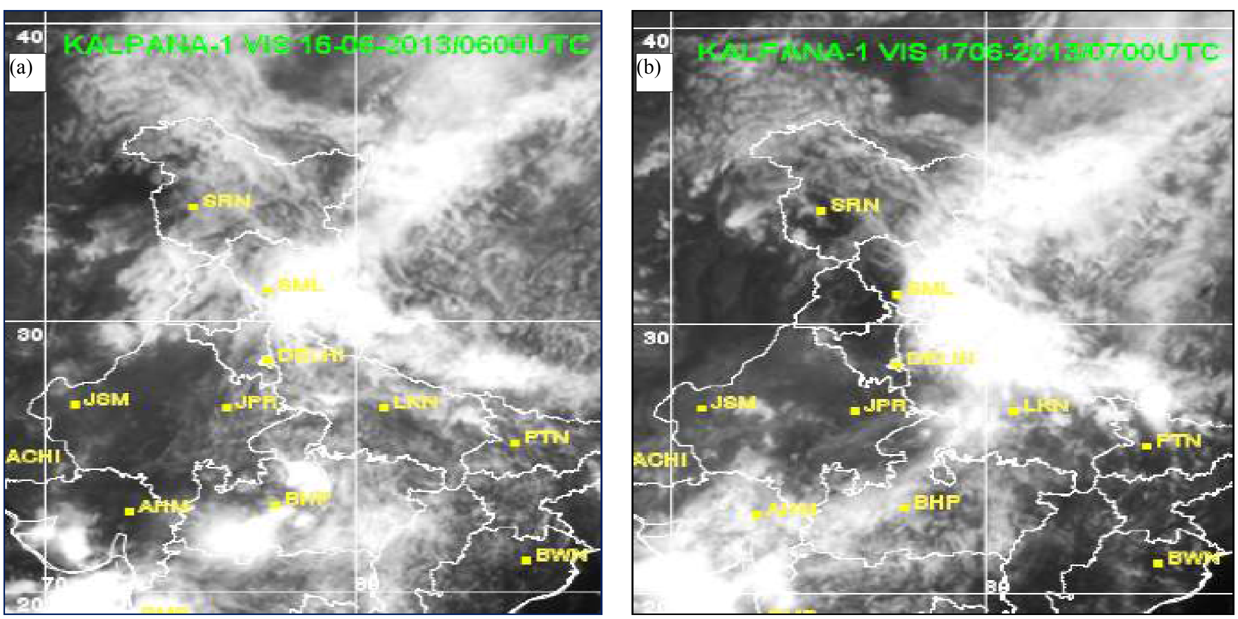


Fig. 4. Area weighted cumulative rainfall (in mm) over Uttarkhand *versus* ridge position at 200 hPa level along 75.0° E longitude during 10 to 20 June, 2013

convergence. The movement of westerly trough was very slow and easterly winds in lower levels continued to prevail over the region till 18 June, 2013. Satellite imageries show intense to very intense convection on 16 & 17 June [Figs. 5 (a&b) and 6 (a&b)] over western Himalayan region and intense convection over northeast Arabian Sea and Madhya Pradesh on 16 June, 2013. The cloud cluster over Madhya Pradesh moved over to west Uttar Pradesh and adjoining Uttarakhand on 17 June. The intense convective clouds over northeast Arabian Sea remained over the same area. The clouds over Uttarakhand in association with the westerly trough had merged with the clouds associated with the low pressure area showing interaction between the two. Visible imagery of 0600 UTC of 16 and 0700 UTC of 17 June showed intense convection over Uttarakhand and neighbourhood. These types of intense convective clouds are rare during onset phase of monsoon over WHR. Dopler weather radar images of Patiala show dBz values 35-40 over southeast Himachal Pradesh and west



Figs. 5(a&b). Satellite (IR) imagery with colour of CTT -40.0 °C (a) at 0000 UTC of 16 June, 2013 and (b) 0000 UTC of 17 June, 2013

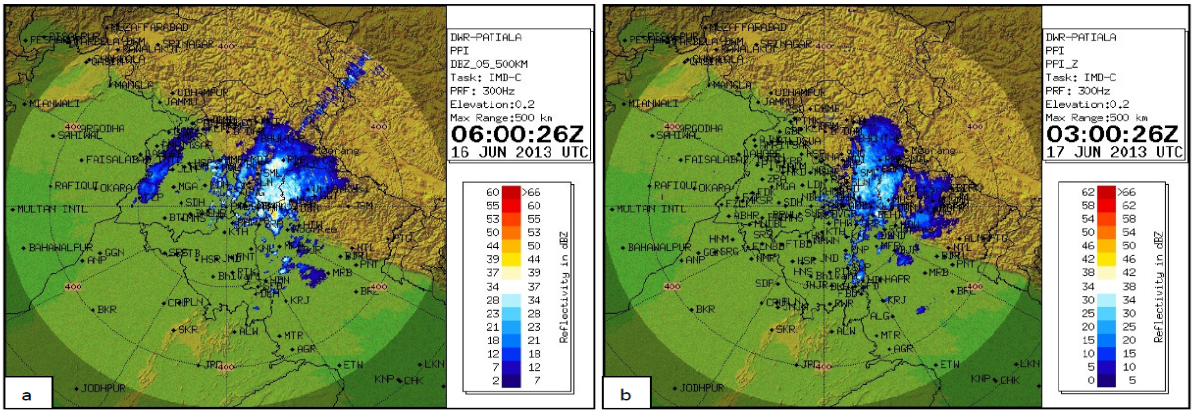


Figs. 6(a&b). (a) Satellite (Kalpana-1) visible imagery at 0600 UTC of 16 June, 2013 and (b) at 0600 UTC on 17 June, 2013

Uttarakhand at 06:00:26 UTC of 16 June and (b) dBz 30-35 over western parts of Uttarakhand and adjoining Himachal Pradesh at 03:00:26 UTC of 17 June, 2013 further confirm *intense* convection north of Kedarnath in Uttarakhand [Figs. 7(a&b)]. Interaction between the low pressure area which formed over Bay of Bengal on 12th June, moved upto Madhya Pradesh and adjoining Rajasthan on 15 June and a deep westerly trough together with the orography created a very favourable situation for heavy rainfall with spells of extremely heavy over Uttarakhand during 15-18 June, 2013.

4. Dynamical aspects

An examination of moisture flux, precipitable water content, lower level convergence, relative humidity, upper air divergence showed that these started increasing gradually from 12 June onwards. Divergence between 150-300 hPa rose from 0 on 10 & 11 June to about 8×10^{-5} s^{-1} on 12 June and again on 14 June. As the trough in mid-level westerlies moved over Jammu & Kashmir, vergence increased significantly and remained more than $7 \times 10^{-5}s^{-1}$ during 15-18 June, 2013 (Fig. 8). Outgoing



Figs. 7(a&b). Patiala Doppler Weather Radar (DWR) images with dBz (a) at 06:00:26 UTC of 16 June and (b) at 03:00:26 UTC of 17 June, 2013

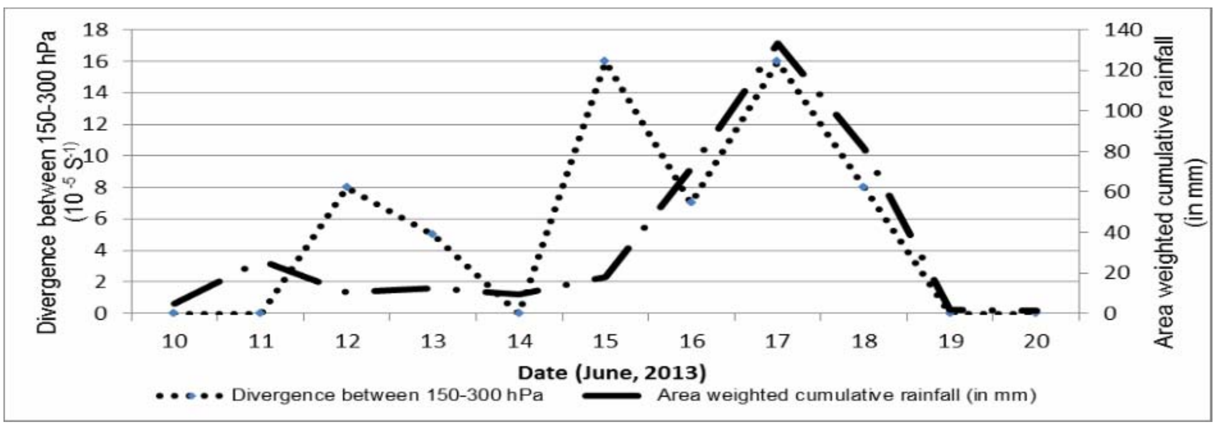


Fig. 8. Area weighted cumulative rainfall (mm) of Uttarakhand *versus* Divergence (10^{-5} S^{-1}) between 150- 300 hPa level during 10 to 20 June, 2013

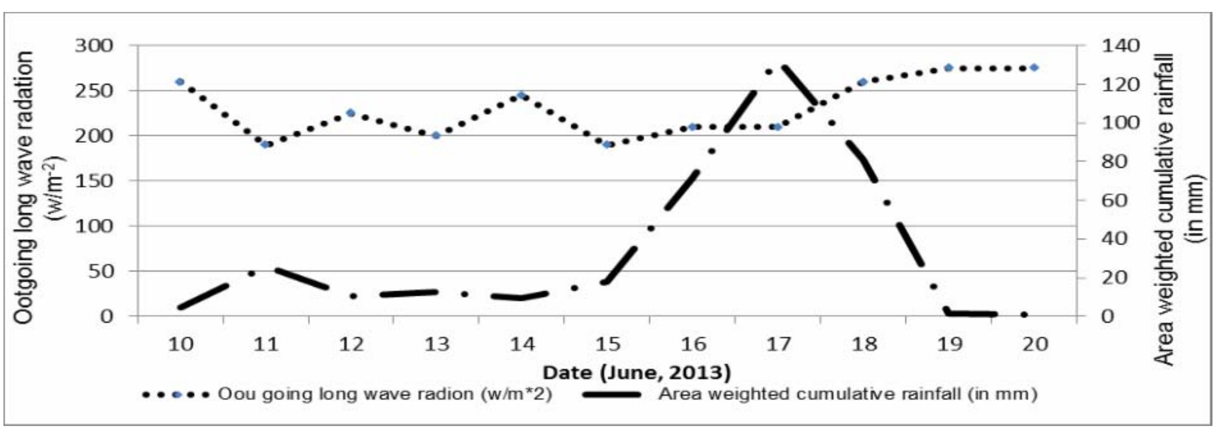


Fig. 9. Area weighted cumulative rainfall (mm) of Uttarakhand *versus* Outgoing long wave radiation (w/m^2) during 10 to 20 June, 2013

Longwave Radiation values were between 190 to 250 w/m^2 during 10 to 20 June, 2013 and less than 200 w/m^2 during 15 to 17 June and it started rising further and it became about 250 wm^{-2} on 18 June, 2013 (Fig. 9). It suggested that dense cloud mass was present over Uttarakhand during 15-17 June. OLR values increased from 18 onwards**.** Satellite IR and V is imagery were also indicating intense convective cloud mass over the region. Moisture flux at 700 hPa level and precipitable water contents are shown in [Figs. 10&11].

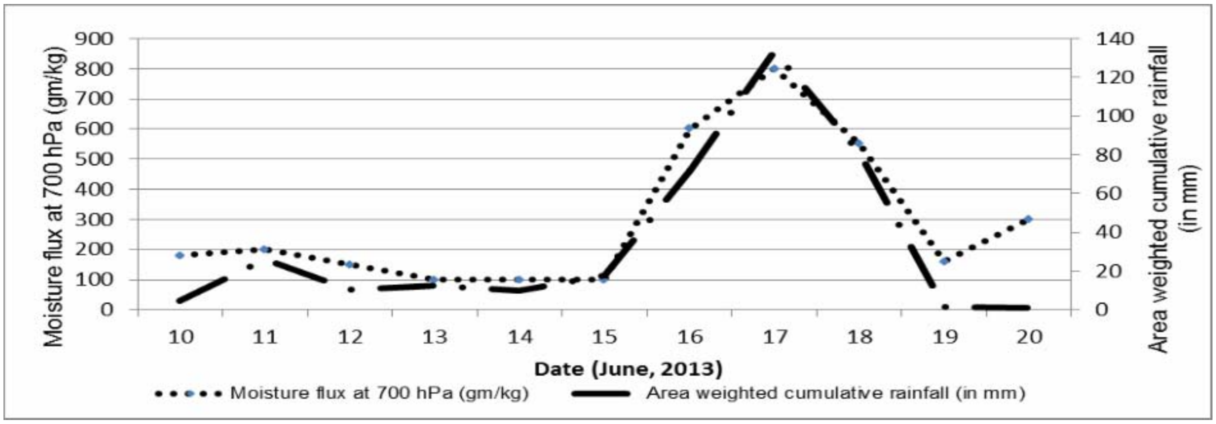


Fig. 10. Area weighted cumulative rainfall (mm) of Uttarakhand *versus* moisture flux (gm/kg)at 700 hPa level showing positive correlation during 10 to 20 June, 2013

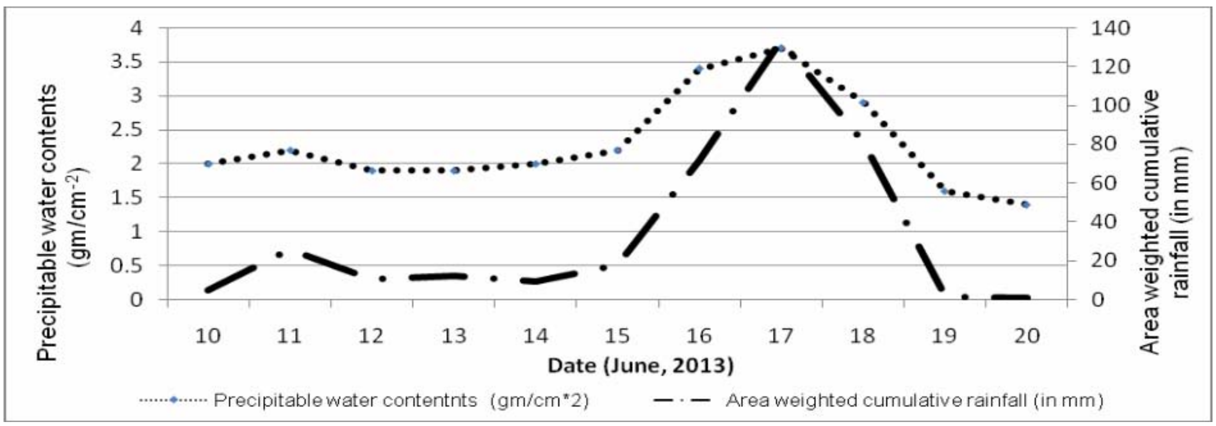


Fig. 11. Area weighted cumulative rainfall (mm) of Uttarakhand *versus* Precipitable water contents (gm/cm^2) during 10 to 20 June, 2013

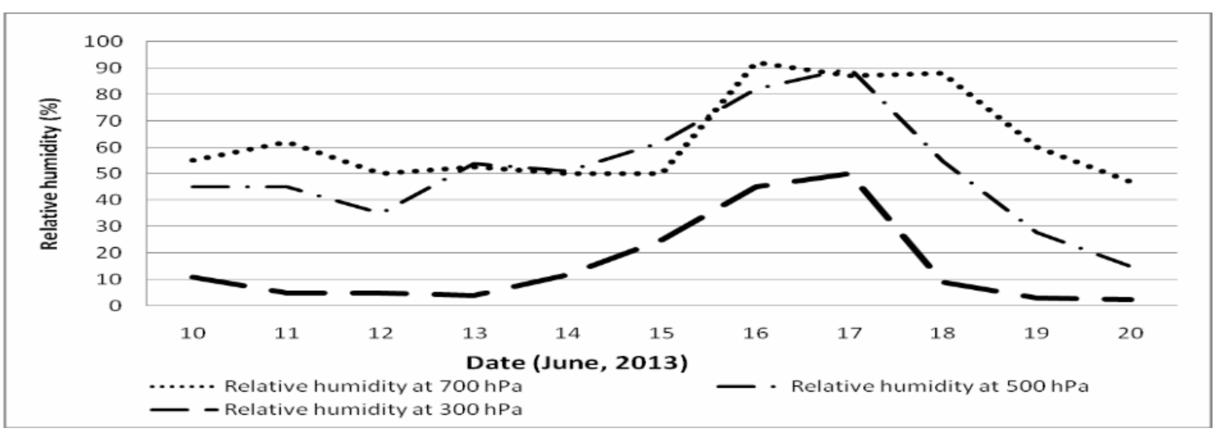
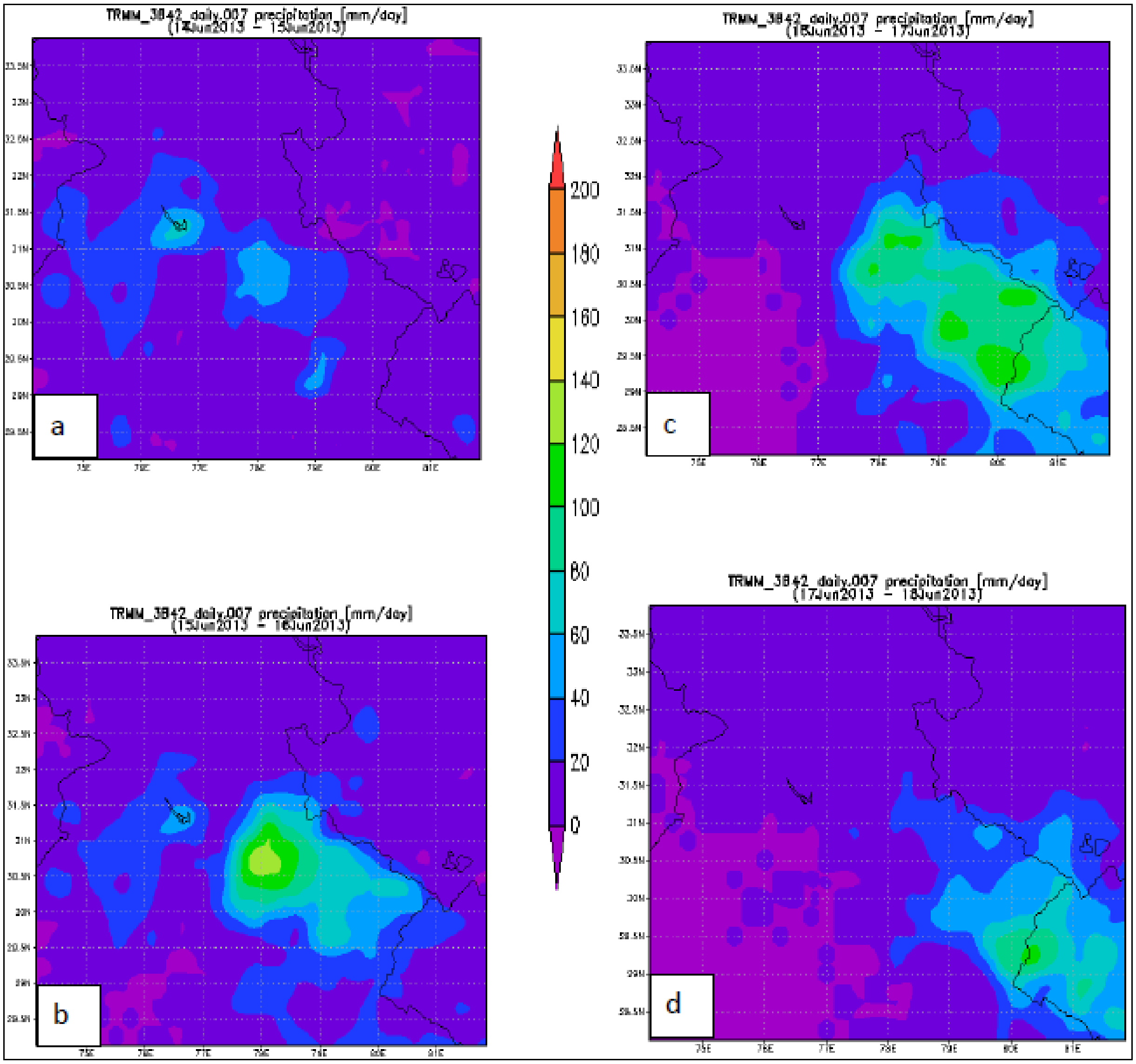


Fig. 12. Relative humidity (%) over Kedarnath, Uttarakhand (lat.30.7° N/long.79.1° E) at 700, 500 and 300 hPa levels during 10-20 June, 2013

Relative humidity (RH) around and over Kedarnath at 700, 500 and 300 hPa increased significantly on 16 June and remained almost the same on 17 June, 2013 (Fig. 12). These figures clearly indicate that the values of these parameters was significantly high and moisture flux at 700 hPa was 700 gm/kg and precipitable water contents 3.5 gm/cm^2 on 17 June, whereas on 16 and 18, it was little less. Singh *et al.* (2007) found that TPW of the order

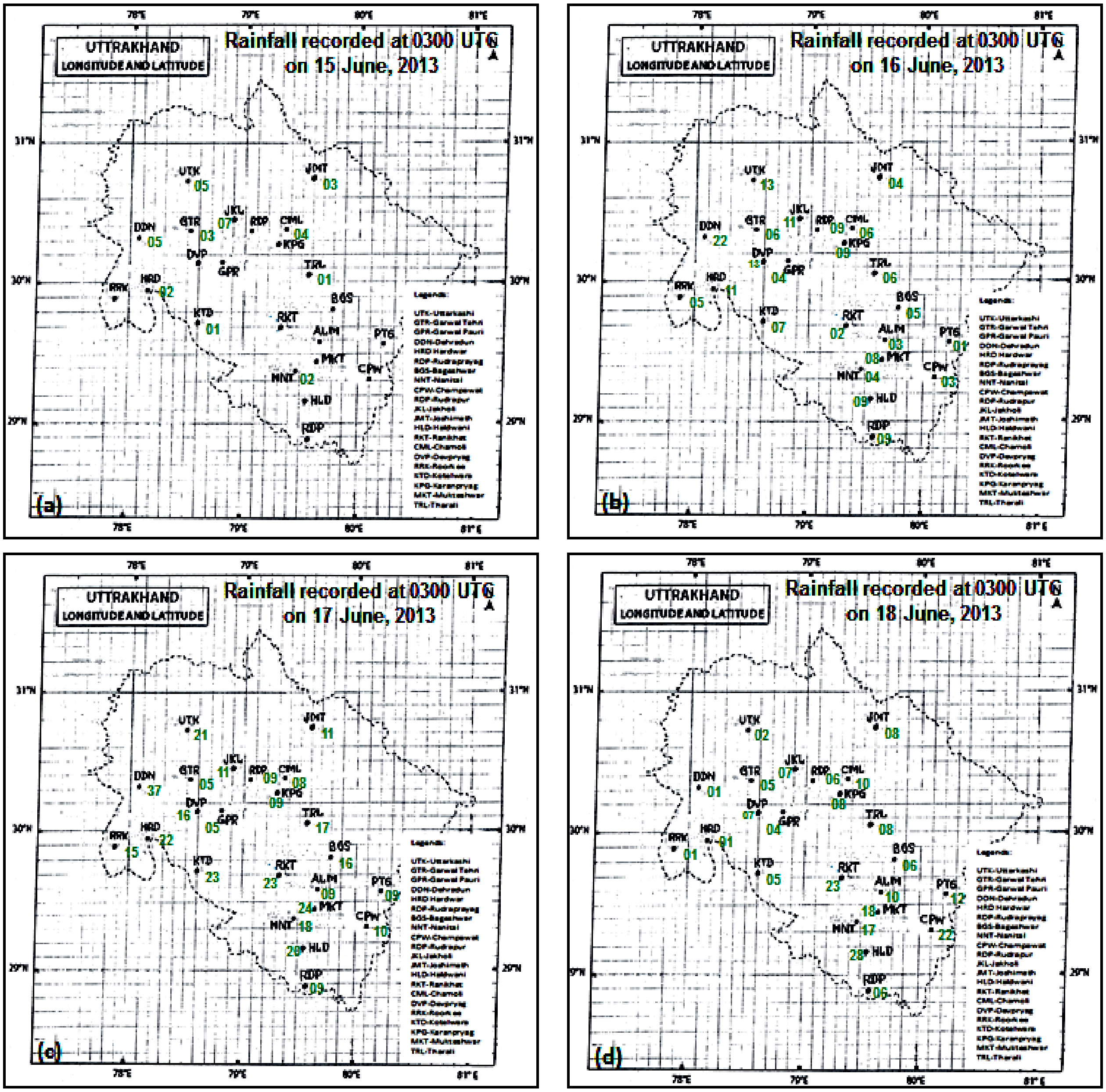


Figs. 13(a-d). Tropical Rain Measuring Mission (TRMM) images (a) on 14-15 June, 2013 (b) on 15-16 June, 2013 (c) on 16-17 June, 2013 and (d) on 17-18 June, 2013

of 70 mm accompanied by favourable wind speed over the eastern Arabian Sea is one of the important factors contributing to heavy rainfall during next 24 hours over the west cost of India and neighbourhood. Both, moisture flux and precipitable water contents over Uttarakhand area started rising from 12 onwards gradually. As per Asnani (2005) the maximum value of total water vapour contents of vertical column with unit area of horizontal cross section is around 4.5 gm/cm^2 and minimum value 2.5 gm/cm^2 in tropical latitude. The values of dynamic parameters (Figs. 8-13) are directly proportion to the area weighted cumulative rainfall over Uttarakhand. These are good indicators of such type of heavy rainfall over WHR.

5. Precipitation

The rainfall activity over WHR increased gradually from 10 June onwards, rainfall pattern showed a sudden rise and heavy rainfall over the WHR particularly over Uttarakhand during 14 to 17 June, 2013. Tropical rain measuring mission (TRMM) images showed that on 14 June rainfall was less, the rainfall areas as well intensity increases on 15 June and continued over a large area with peak around Kedarnath (30.7° N/79.1° E), it decreased around Kedarnath and area of higher rainfall shifted towards southeast on 17 June, 2013 [Figs. 13(a-d)]. The major amounts of rainfall of previous 24 hours recorded at 0300 UTC of date were: (15 June) Dunda-8,



Figs. 14(a-d). Rainfall at some stations over Uttarakhand recorded at 0300 UTC of (a) 15 June, 2013, (b) 16 June, 2013, (c) 17 June, 2013 and (d) 18 June, 2013.

Jakholi & Kashipu-7 each and Dehradun-5; (16 June) Dehradun-22, Purola-17, Devprayag-13, Uttarkashi-13 and Tehri-12; (17 June) Dehradun-37, Mukteshwar-24, Hardwar-22 & Uttarkashi-21 and (18 June) Haldwani-28, Champawat-22, Haldwani-28, Nainital-17 and Ranikhet-12 cm. Daily rainfall recorded at 0300 UTC of each day during 15 to 18 June, 2013 [Figs. 14(a-d)] and isohyetal analysis of cumulative rainfall during 15-17 June, 2013 over Uttarakhand shows two peaks of rainfall one over west-northwest of Kedarnath with cumulative rainfall of the order of 600 mm and another over south Uttarakhand with more than 500 mm [Fig. 3(b)].

6. Loss of lives

Around 4094 persons went missing in the hydro-metrological disaster that struck Mandakini valley of Higher Himalaya in Rudraprayag district of Uttarakhand, India in June, 2013. The disaster took place in two phases; in the evening hours of 16 June, 2013 breach of landslide dammed lake formed close to Kedarnath on Mandakini river ravaged Rambara and Gaurikund while in the morning hours of 17 June, 2013 breach of the glacial lake, Chorabari Tal, devastated temple township of Kedarnath. Disruption of communication and adverse weather and terrain conditions complicated the situation and people could not be rescued in time (Rautela, 2013).

Flash flood induced landslide caused death of 680 people and 4,117 people were reported missing. It also caused huge devastation to infrastructures and other properties mainly in 5 districts of Uttarakhand, *i.e.*, Bageshwar, Chamoli, Pithoragarh, Rudraprayag and Uttarkashi. [Source: National Institute of Disaster Management, Uttarakhand [National Disaster Risk Reduction Portal (2013) http://nidm.gov.in/default.asp].

4. Conclusion

(*i*) Interaction took place between mid-tropospheric westerlies with easterlies over western Himalayan region and it led to intensification of western disturbance, outbreak of convection and enhancement of rainfall over western Himalayan region particularly over Uttarakhand.

(*ii*) The favourable synoptic conditions were, the Tibetan High much west of its normal position, approaching deep westerly trough between 65.0° to 70.0° E, a low pressure area over east Rajasthan and & neighbourhood and moisture incursion from Bay of Bengal as well from Arabian sea over western Himalayan region particularly over Uttarakhand.

(*iii*) The favourable dynamical conditions were continuous rise of moisture flux which started to rise from 10 June from about 180 gm/kg ,it became about 250 gm/kg on 15 June and about 500 gm/kg on 16 June, OLR was about 190 (w/m^2) on 15 to 17 June and it rose to 220 (w/m^2) on 18 June and the perceptible water contents started rising gradually from about 23 g/m^2 on 10 June to about 34 g/m^2 on 16 June, 2013.

(*iv*) Upper level divergence (more than $15 \times 10^{-5} s^{-1}$) and lower level convergence ($20 \times 10^{-5} s^{-1}$) were also favourable for heavy rainfall over the region.

(*v*) Due to above favorable synoptic and dynamical conditions western Himalayan region experienced widespread rainfall, particularly Uttarakhand experienced exceptionally heavy rainfall in some area. This type of combination of synoptic and dynamical situation occurred rare in nature.

Acknowledgements

The authors are thankful to Dr. L. S. Rathore, Director General of Meteorology for encouragement. Authors are also thankful to Shri J. R. Prasad, Director, DWR Patiala for providing real time radar images. Authors are also thankful to anonymous referee for providing valuable suggestions for improvement of the paper.

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