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On the dynamics of an extreme rainfall event in northern India in 2013

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India experienced a heavy rainfall event in the year 2013 over Uttarakhand and its adjoining areas, which was exceptional as it witnessed the fastest monsoon progression. This study aims to explore the causative factors of this heavy rainfall event leading to flood and landslides which claimed huge loss of lives and property. The catastrophic event occurred from 14th to 17th June, 2013 during which the state received 375% more rainfall than the highest rainfall recorded during a normal monsoon season. Using the high resolution precipitation data and complementary parameters, we found that the mid-latitude westerlies shifted southward from its normal position during the intense flooding event. The southward extension of subtropical jet (STJ) over the northern part of India was observed only during the event days and its intensity was found to be increasing from 14th to 16th June. The classical theory of westward tilt of mid-latitude trough with height, which acts to intensify the system through the transfer of potential energy of the mean flow, is evident from analysis of relative vorticity at multiple pressure levels. On analysing the North Atlantic Oscillation (NAO), negative values were observed during the event days. Thus, the decrease in pressure gradient resulted in decrease of the intensity of westerlies which caused the cold air to move southward. During the event, as the cold air moved south, it pushed the mid-latitude westerlies south of its normal position during summer monsoon and created a conducive atmosphere for the intensification of the system.

Keywords. Extreme rainfall events; mid-latitude–tropical-interaction; subtropical jet; North Atlantic Oscillation; westward tilt; instability.

1. Introduction

Extreme rainfall events cause severe hazards to thickly populated areas and urban cities in many parts of the world (Joseph *et al.* 2015). India, which is the second largest populated country in the world, is extremely vulnerable to the impact of flash floods, heavy rainfall events, tropical storms, etc., which take lives, destroy properties and agricultural fields that have major impacts on the society, economy and the environment (Kripalani *et al.* 2003; De *et al.* 2005). Even though the seasonal mean monsoon rainfall over the past century in India shows no significant decreasing trend, Goswami *et al.* (2006) have shown that the number of extreme rainfall events over India is increasing in recent decades. Naidu *et al.* (2015a, b) noted a decrease in monsoon rainfall over India, but increase in extreme rainfall events. In addition to the long-term trend in the increase in extreme rainfall events, Rajeevan *et al.* (2008) have reported that the frequency of extreme rainfall events shows significant inter-annual and inter-decadal variations.

The prediction of extreme weather events is still not promising due to uncertainties in the observational and modelling constraints. Basic knowledge of the physical and dynamical causes and the associated changes in the atmospheric circulation pattern is not yet comprehensive. A proper assessment of likely development of localized extreme weather systems would help in setting up infrastructure for disaster preparedness.

Numerous studies (Rao *et al.* 2004; Watanabe and Yamazaki 2013; Sreekala *et al.* 2014) have shown that the upper level winds (e.g., Jet Streams) have a considerable influence on the surface weather patterns including the monsoon. The relationship between jet streams and monsoon winds is well demonstrated over the Indian subcontinent (Goswami 2005). In the early phase of boreal summer, a strong thermal gradient between southern Asia and the Indian Ocean develops due to increased solar heating over the Indian land area instigating the monsoon circulation. Normally, the subtropical jet stream is located at about 30°N, south of the Himalayan region. When the subtropical westerly jet stream exists over India, it inhibits the arrival of summer monsoon. As the summer season progresses, the subtropical jet shifts towards north and crosses the Himalayas (Yin 1949). At this stage, the summer monsoon circulation becomes active with overlying tropical easterly jet stream. The changeover from westerly to easterly flow in the upper troposphere during the summer monsoon season is quite fast (O'Hare 1997). On the other hand, the slow northward propagation of the subtropical jet can cause the delay of the onset and the northward propagation of Indian summer monsoon from several days to about a month time (http://science.jrank.org/pages/4438/Monsoon-monsoon-India.html). Kripalani *et al.* (1997) suggested that the upper tropospheric circulation plays an important role in Indian summer monsoon by significantly interacting with extratropical westerlies to create abnormal weather conditions through teleconnections.

In 2013, the onset of the Indian summer monsoon was declared on 1st June by the India Meteorological Department (IMD). During this period, widespread rainfall was reported throughout the southern peninsular region, especially over Kerala, with strong southwesterly winds, high cloudiness and intense rainfall (Pai and Bhan 2014). The monsoon rainfall covered the entire country within 15 days, and they reported that the pace of progression of southwest monsoon in 2013 is the fastest since 1941, covering the entire country, one month in advance before schedule.

In the present study, an attempt has been made to explain the instability and dynamics of the abnormal circulation pattern and the intensification of the trough in the upper troposphere observed during the extreme rainfall event which occurred in the early phase of 2013 summer monsoon at the northern Indian state of Uttarakhand. The paper is organized as follows: Section 2 describes the study area and the data used; section 3 deals with the results and discussions. The summary and conclusions are drawn in section 4.

2. Study area and data

2.1 *Study area*

Uttarakhand, a hilly state in the northern part of India situated at the foothills of Himalayas (28°44′–31°28′N, 77°35′–81°01′E), covers an area of about 53,483 km^2 with a population of about 10.08 million (see figure 1). It has many pilgrimage centres, hence commonly referred to as 'Land of Gods' (Phondani *et al.* 2013). The state of Uttarakhand receives 90% of its annual rainfall during the southwest monsoon (http://www.fresheyes.org/uttarakhand/). Its geographical boundaries are Tibet to the north, Nepal to the east, Himachal Pradesh to the west and Haryana to the south. Two important rivers of India, i.e., Ganga and Yamuna, take birth in the glaciers of Uttarakhand. The highest elevation of this land area is above 7000 m.

Torrential rainfall occurred over Uttarakhand during 14–17 June, 2013. Initially the event was termed as cloudburst (Sati 2013), a phenomenon which causes torrential rainfall of above100 mm/hr. As the rainfall during the event days did not exceed 23 mm/hr, the possibility of cloudburst was ruled out (Mishra and Srinivasan 2013). This heavy rainfall caused large scale damage to lives and properties. According to IMD report, occasional heavy rainfall over Uttarakhand occurs during the monsoon period (Pai and Bhan 2014). Rivers do not overflow throughout the monsoon season; it is

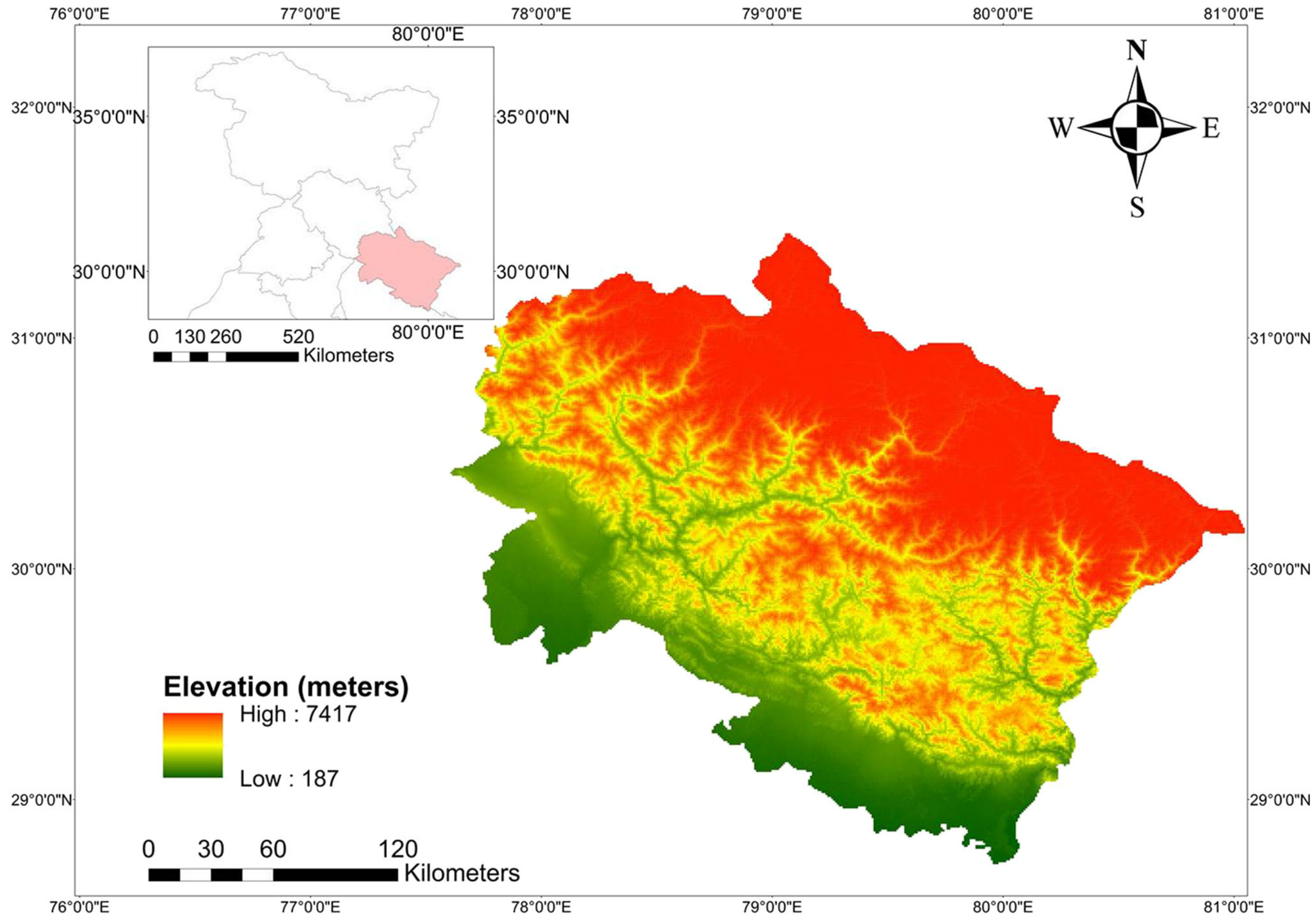

Figure 1. Location and elevation map of Uttarakhand, where the torrential rainfall occurred in 2013.

only after a spell of heavy rains lasting for a period of several hours to several days, large runoff is generated in the catchment areas experiencing unusual floods (Kale 2003).

2.2 *Data*

To study the upper tropospheric circulation during the extreme event which occurred over Uttarakhand from 14th to 17th June, 2013, we selected the daily zonal, meridional and vertical wind data at 12 GMT from European Centre for Medium Range Weather Forecasts (ECMWF) interim re-analysis (ERA-interim) with resolution 0.75° × 0.75° (Dee *et al.* 2011). The ECMWF data has been used for the present study since it has better spatial resolution. In order to understand the southernmost latitudinal position of STJ, we selected the region with coordinates 0−50°N, 60°−100°E. To study the cloud formation due to deep convection, interpolated outgoing longwave radiation (OLR) data (2.5° × 2.5°) of 2013 from national oceanic and atmospheric administration (NOAA) has been used (Liebmann and Smith 1996). The vorticity is calculated for the area bounded by the latitudes 26°−44°N, and longitudes 60°−84°E. To understand the influence of high latitude winds on mid-latitude jets, North Atlantic Oscillation data of 2013 is taken from Climate Prediction Center (CPC) where the indices are constructed using the method given by Barnston and Livezey (1987).

3. Results and discussion

The southwest monsoon generally takes about 45 days to cover the whole India from its date of onset over Kerala, the ‘Gateway’ of Indian summer monsoon (Krishnakumar *et al.* 2009). In the year 2013, it covered the whole country just within 15 days from its date of onset over Kerala (Pai and Bhan 2014). Figure 2 shows the northward progression of monsoon for the year 2013 (solid green line) along with the normal progression (dashed red line). Rapid progression of monsoon occurred in 2013 and an extreme heavy rainfall event over

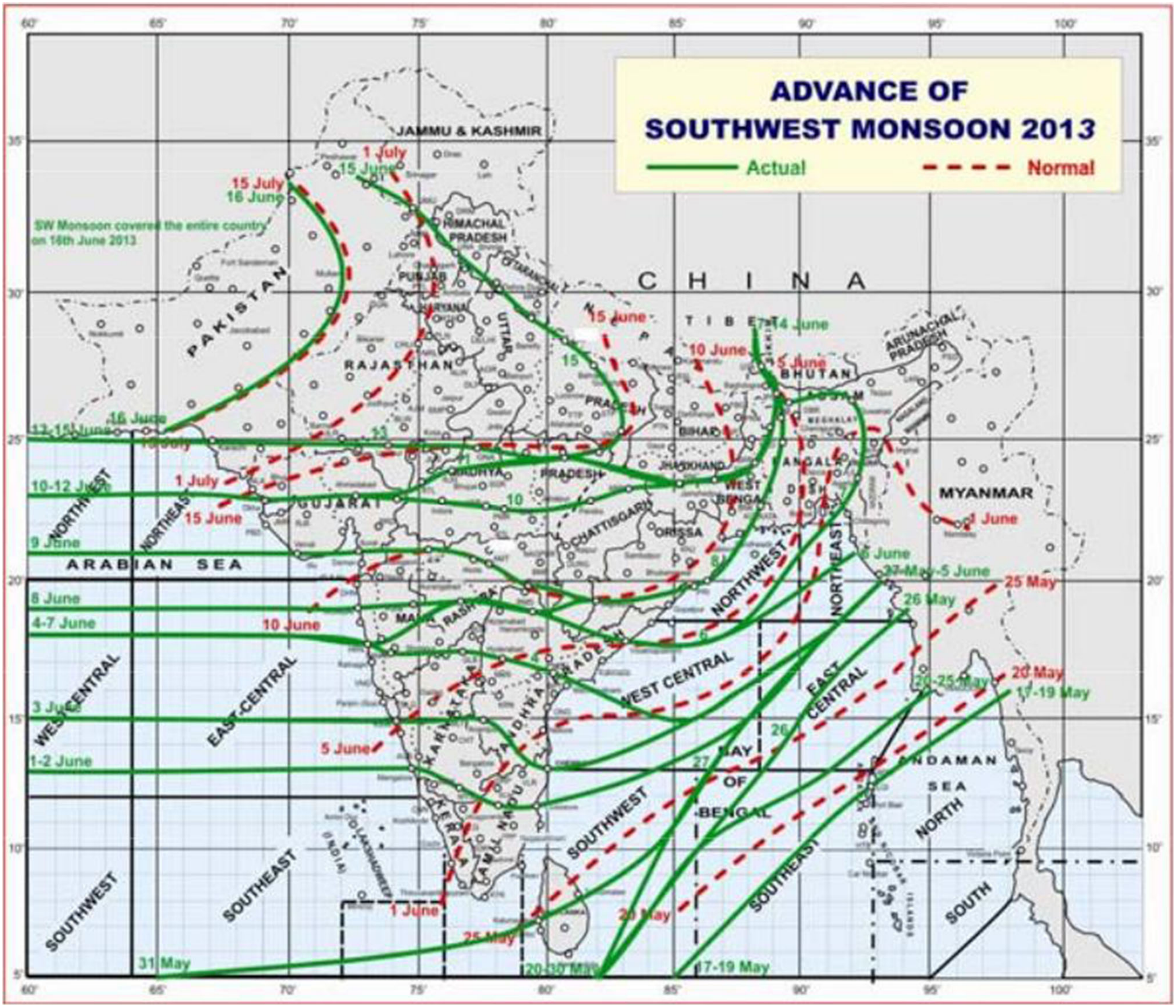

Figure 2. Advancement of monsoon 2013 (source: IMD monsoon report 2013).

Uttarakhand and adjoining areas occurred from 14th to 17th June, 2013 which caused havoc to lives and properties. During this period, the upper troposphere over the northern part of India showed an abnormal circulation pattern. The mid-latitude westerlies which flows north of Himalayas during southwest monsoon season was observed to make a southward intrusion from 14th to 17th June, 2013 coinciding with the days of heavy rainfall event.

Uttarakhand's natural geomorphology and excessive land-use have made it vulnerable to natural disasters (Sharma *et al.* 2013; Chevuturi and Dimri 2016). Srinivasan (2013) suggested that Uttarakhand event could be the result of interaction between mid-latitude system and monsoon current. Other factors like moisture supply from Bay of Bengal and Arabian Sea (Kotal *et al.* 2014; Ranalkar *et al.* 2016) and land surface feedback also played an important role in Uttarakhand 2013 event (Rajesh *et al.* 2016). Rajesh *et al.* (2016) also demonstrated the importance of using model with high resolution land-surface characteristics for better prediction of such heavy rainfall events. Presence of Main Central Thrust (MCT), which bounds higher Himalaya, is seen to act as an orographic barrier and causing confinement of extreme rainfall events (Singh *et al.* 2016) resulting in floods and landslides (Srinivasan 2013; Kotal *et al.* 2014). Hence factors like orography, meteorology, geology and environment played significant role in making 2013 Uttarakhand heavy rainfall event a disaster (Dubey *et al.* 2013).

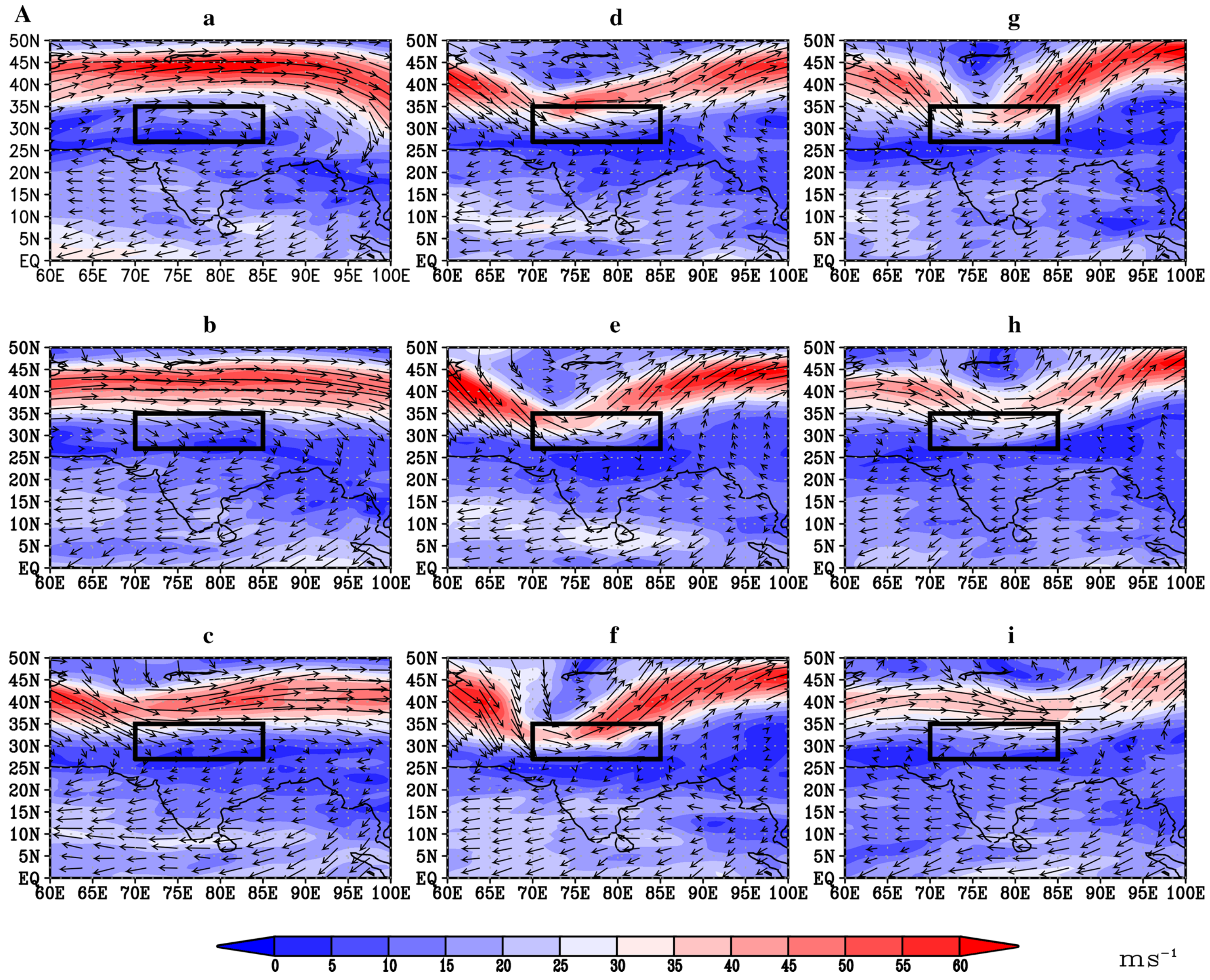

Figure 3(A). Upper tropospheric wind at 200 hPa for (**a**–**i**) 12–20 June, 2013.

3.1 *200 hPa wind anomaly*

In order to study the upper tropospheric changes in wind circulation during the flood event (14 –17 June, 2013), we examined the temporal evolution of circulation two days ahead, during and three days after the event. Figure 3(a) illustrates upper tropospheric wind at 200 hPa (hereafter referred to as subtropical jet stream – STJ) from 12th to 20th June, 2013 over the Indian region. We selected a box from 27°−34°N, 70°−85°E, representing the study area, for detailed understanding of southward intrusion of STJ. Prior to the occurrence of heavy rainfall event, the mid-latitude westerlies was observed to be located at and north of 35°N. Weak westerlies were observed in the box selected for the study. On 13th of June, the westerlies in the region were observed to be strengthening and became northwesterlies, whereas easterlies prevailed in south of the study area. On 14th June, 2013, the day of occurrence of the event, mid-latitude westerlies began to develop a trough with wind direction being northwesterlies upstream and southwesterlies downstream of the trough. The trough deepened and moved further south and is clearly evident within the selected box. As the westerly wind flow within the box appeared to be strengthened, the easterlies south of the box is seen to be weakened. The wave like development of mid-latitude westerlies is seen to intensify and strengthened with wind speed reaching about 60 ms^{-1} on 16th June, 2013. The trough was observed to move south of 30°N. From 18th June onwards, gradual retreating motion of STJ was seen with the westerly winds weakening within the box and easterlies strengthening south of the area. The STJ

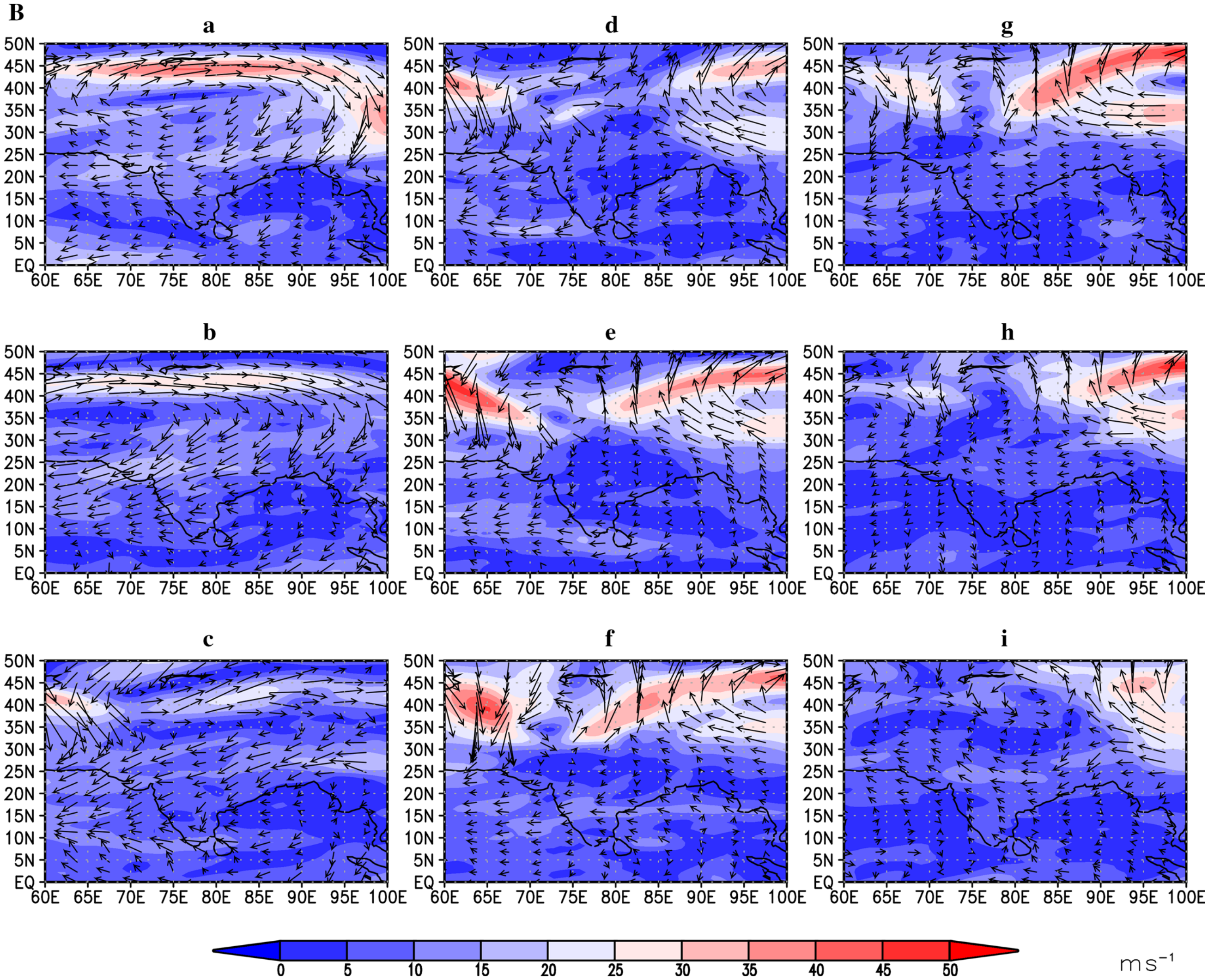

Figure 3(B). Upper tropospheric wind anomaly at 200 hPa (**a-i**) for 12-20 June, 2013, respectively.

returned to its normal position over the north of Himalayas on 20th June. In addition, we examined the wind anomaly at 200 hPa and found a larger positive anomaly (figure 3b). For the period 12th–20th June, 2013, strong winds were seen in general, and anomaly of mid-latitude westerlies attained speed of about 45–50 ms^{-1} from 15th to 18th June. In addition, the southward penetration of westerlies is clearly observed in these days. This clearly indicates that the winds at 200 hPa during June 2013 were stronger than the long term average.

The daily vertical wind (ω) distribution from 850 to 100 hPa over the region ($27° - 34°$N, $70° - 85°$E) for the entire month of June 2013 is illustrated in figure 4. As the pressure decreases with height, the negative values of omega indicate ascending motion, which is associated with intense cloud and rain. Prior to the occurrence of torrential rainfall over Uttarakhand, the vertical wind pattern showed strong descending motion followed by weak ascending motion from lower levels to the upper troposphere (200 hPa). Strong ascending winds from 800 to 150 hPa were seen from 14th June to 18th June, which coincided with the heavy rainfall event. The maximum magnitude of this ascending wind was observed in mid-tropospheric level, around 550–350 hPa. After the heavy rainfall event (from 19th June), strong descending winds were observed again. The interaction between the southward intruding mid-latitude westerly trough and monsoon circulation leads to strong convective motions resulting in flood producing extreme events over western Himalayas (Vellore *et al.* 2016).

3.2 *Dynamical and thermodynamical instability*

Complementary to the vertical velocity, the relative vorticity with height from ERA-interim is analysed

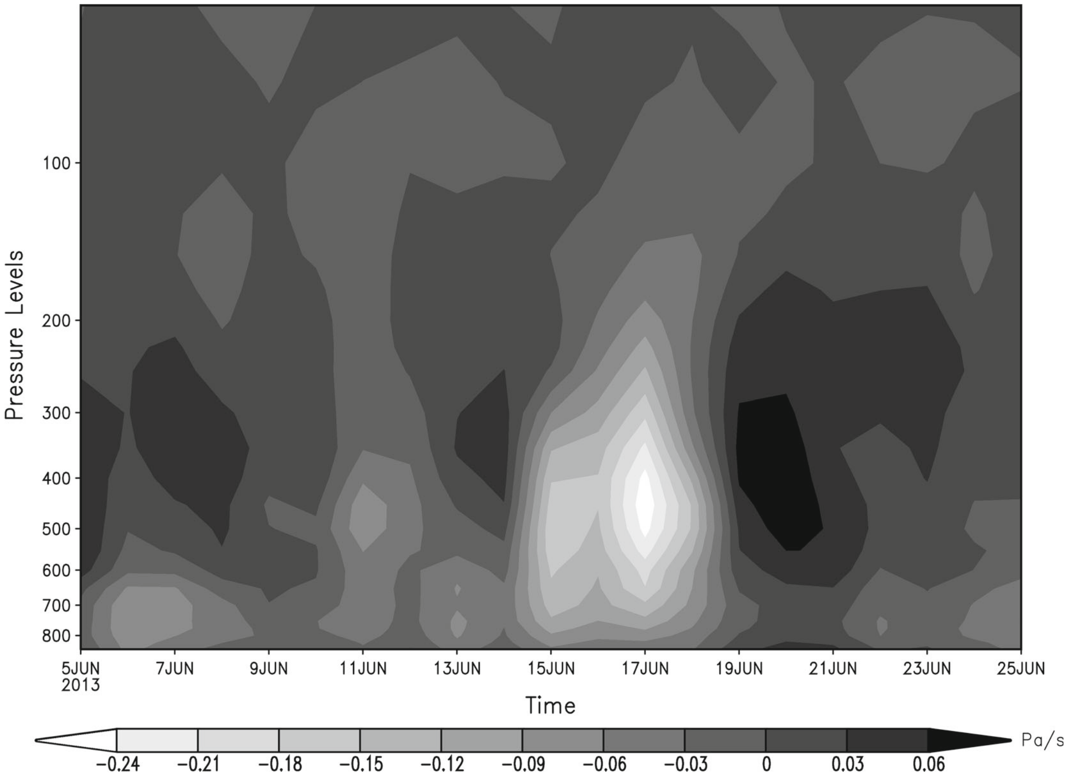

Figure 4. Vertical winds (omega) for the month of June 2013.

in figure 5. Relative vorticity is seen to increase with height and shows a westward tilt. It is known that ridges are associated with warm air aloft, while troughs are associated with cold air aloft. Troughs aloft are usually associated with surface lows. It is well known that mid-latitude systems generally tilt westward with height throughout the troposphere and this is clearly evident in figure 5. The westward tilt with height of troughs and ridges is needed for the potential energy transfer from the mean flow to the developing wave (Holton 2004). Warm air advection occurs in the region ahead of trough. Westward tilt of trough with height is called negative tilt, it indicates strong advection and the thermodynamic instability. Westward tilt of a perturbation suggests that there will be increase in the available potential energy by horizontal temperature advection, whereas the vertical circulation converts available potential energy of the perturbation to its kinetic energy (Wahab *et al.* 2002). Mid-latitude westerly intrusion brings in cold air; hence, cold air aloft and warm air below create convective instability along with thermodynamic instability. Presence of strong jet can cause a trough to become negatively tilted (westward) and give rise to dynamic lifting (www.weatherprediction.com). In order to further substantiate the vertical westward tilt of relative vorticity, we again examined the spatial pattern of convergence/divergence at each height level on 17th June, 2013 (figure not shown). It is seen that the convergence also shows a westward tilt in accordance with the relative vorticity. Since a strong divergence at upper level leads to downstream convergence at lower levels, the observed tilt favours strong upward motion over the Uttarakhand region, which in turn lead to the development of vigorous convection.

To realize the intensity of convection developed during the event days, we analysed the outgoing longwave radiation (OLR) data from the NOAA satellites. OLR value <200 Wm^{-2} indicates deep convection in the tropics (Fu *et al.* 1990; Zhang 1993). Low value of OLR corresponds to lower cloud temperature implying higher height of cloud, thus indicating convection. Figure 6 shows the OLR for the Indian region. Strong convection occurred during the heavy rainfall event of June 2013, as indicated by values of OLR <200 Wm^{-2}. It is interesting to note that lower values of OLR (<200 Wm^{-2}) existed only from 14th to 17th June, 2013, the days of occurrence of torrential rainfall over Uttarakhand. The convection is seen to increase in magnitude and extend southwards.

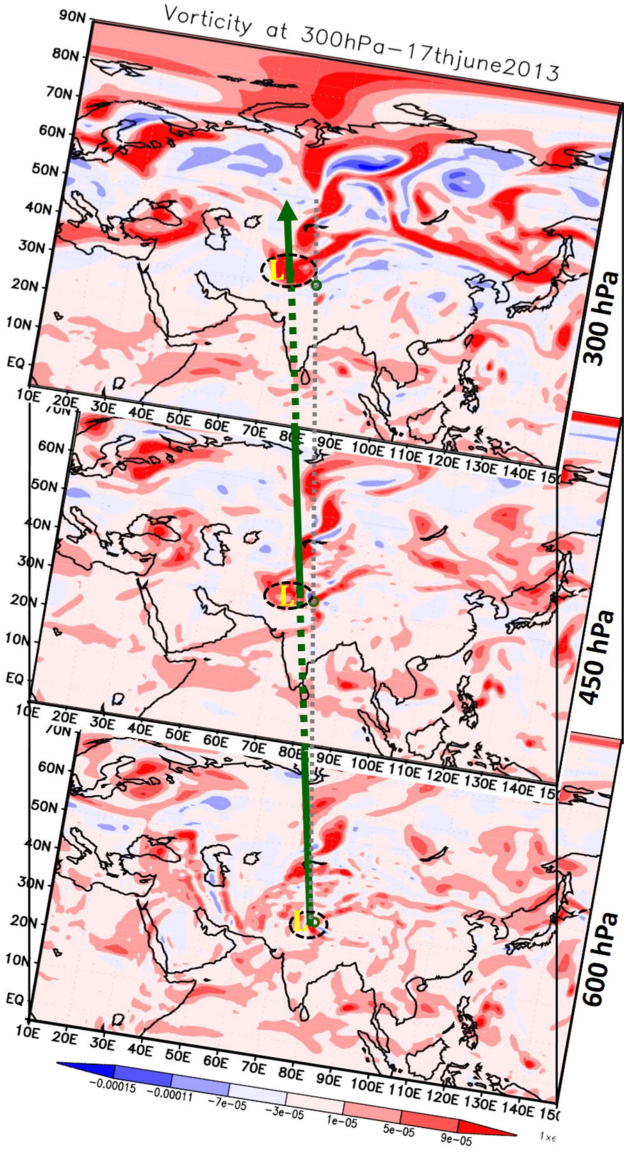

Figure 5. Relative vorticity at different pressure levels showing westward tilt with height.

This scenario existed till 19th June, after which the value of OLR has increased. Before and after the event, higher values of OLR (200$\leq$ OLR $\leq$ 280 W m^{-2}) were observed.

Existence of a thermodynamically unstable atmosphere is the essential criterion behind the development of deep convection. The tropical monsoon environment is characterized by moist convective instability with relatively large amount of convective available potential energy (CAPE). To test the vigour of convection developed during the Uttarakhand heavy rainfall event, we have analysed the moist static instability using the vertical gradient of equivalent potential temperature ($d\theta_e/dz$). It is a quantity related to the stability of air column in the atmosphere (Manoj *et al.* 2011). In stable conditions, θ_e increases with height, and if it decreases with height ($d\theta_e/dz < 0$), then convection can be triggered (Holton 2004). Thus a comparison of θ_e at different heights provides a means of assessing the instability of the air column. In our analysis, it is seen that θ_e decreases strongly with height in the lower levels up to about 500 hPa during the heavy flood event. To portray the transition of this parameter prior to and during the event, we have plotted the vertical gradient of θ_e at 600 hPa. This particular height level is chosen in order to show the maximum strength of variation observed on most of the days. It is noticed from figure 7 that the stability parameter ($d\theta_e/dz$) is highly negative on all the days, and the negative-most value occurred just one day prior to the day of maximum rainfall.

To further test the dynamical lifting associated with this instability, we have analysed the vertical velocity at 500 hPa level. From figure 8, it is observed that there existed a strong negative pressure vertical velocity (ω_{500}) at this level around the time of most of the rainfall events which substantiates that strong moist instability induced higher vertical velocity leading to vigorous convection. For the region selected (27°–34°N, 70°–85°E; shown in box), strong ascending winds were observed from 14th to 18th June, 2013 from 800 to 150 hPa (figure 4). Omega at 500 hPa indicates dynamic uplifting resulting in the heavy precipitation event.

3.3 *Plausible teleconnection with NAO*

Joseph *et al.* (2015) indicated that the cold air which interacted with the mid-latitude westerlies had originated from the Arctic region. In this perspective, we examined how the atmospheric features over the mid-latitude and polar region varied during the heavy rainfall days. The North Atlantic Oscillation (NAO) index which is the characteristic feature of the well-established polar weather phenomenon is selected for understanding the contribution of high latitude pressure pattern. The North Atlantic Oscillation is delineated as the sea level pressure (SLP) difference between Ponta Delagada, Azores and Stykkisholmur, Iceland (Hurrell 1995). NAO was first identified by Sir Gilbert Walker (Walker 1924; Walker and Bliss 1932). The mass fluctuations associated with NAO are present throughout the year (Glowienka-Hense 1990). Summer NAO is shown to have an impact on

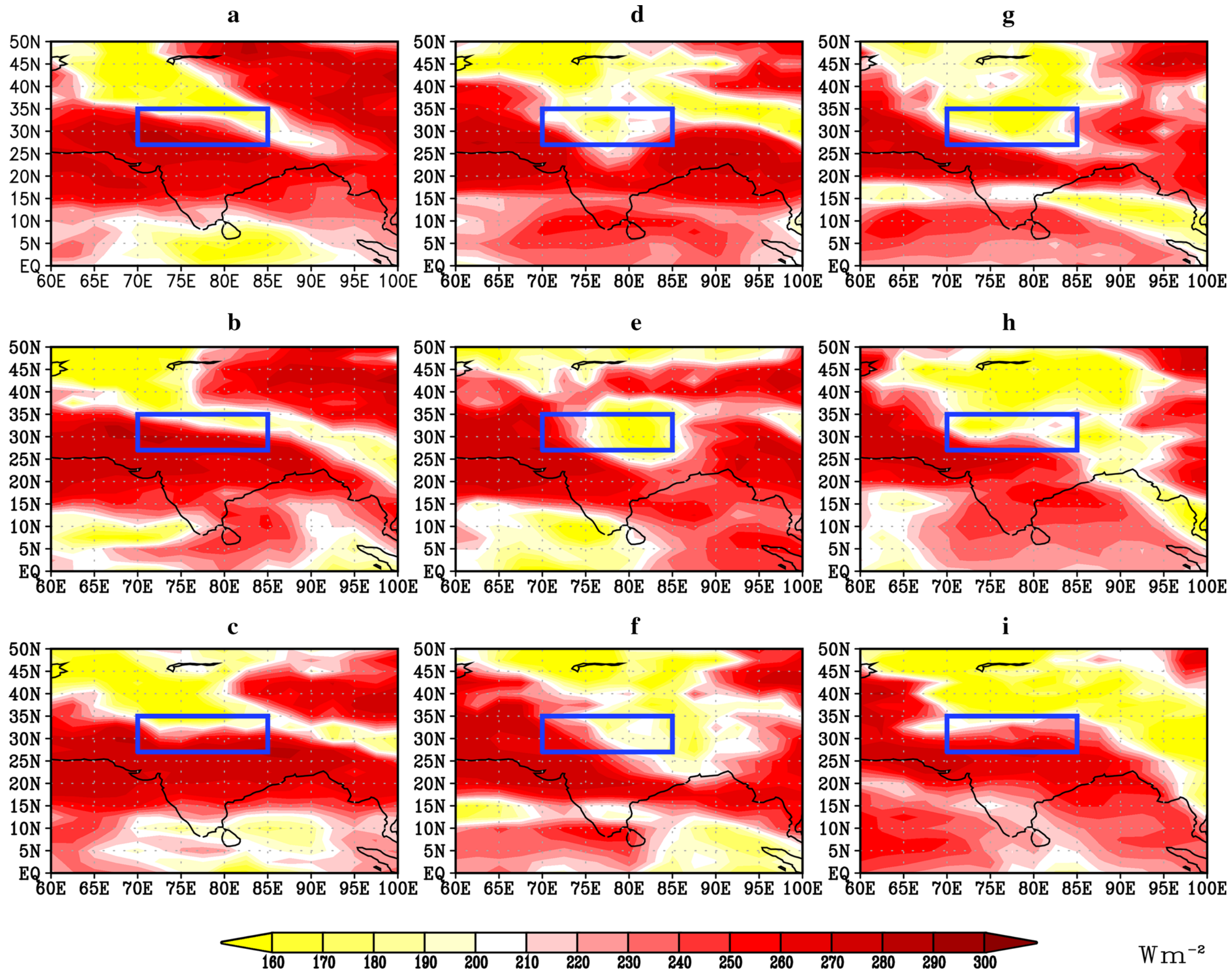

Figure 6. OLR for (**a–i**) 12–20 June, 2013, respectively.

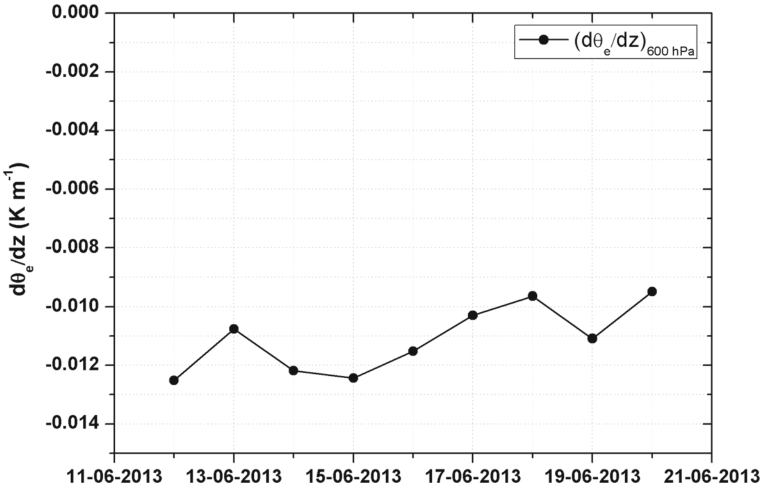

Figure 7. Daily values of equivalent potential temperature instability from 12 to 20 June, 2013.

summer rainfall of Northern Hemisphere (Hurrell and Folland 2002; Folland *et al.* 2009; Linderholm *et al.* 2011).

Negative NOA index indicates decrease of pressure gradient across the North Atlantic and increase of polar front activities movement farther

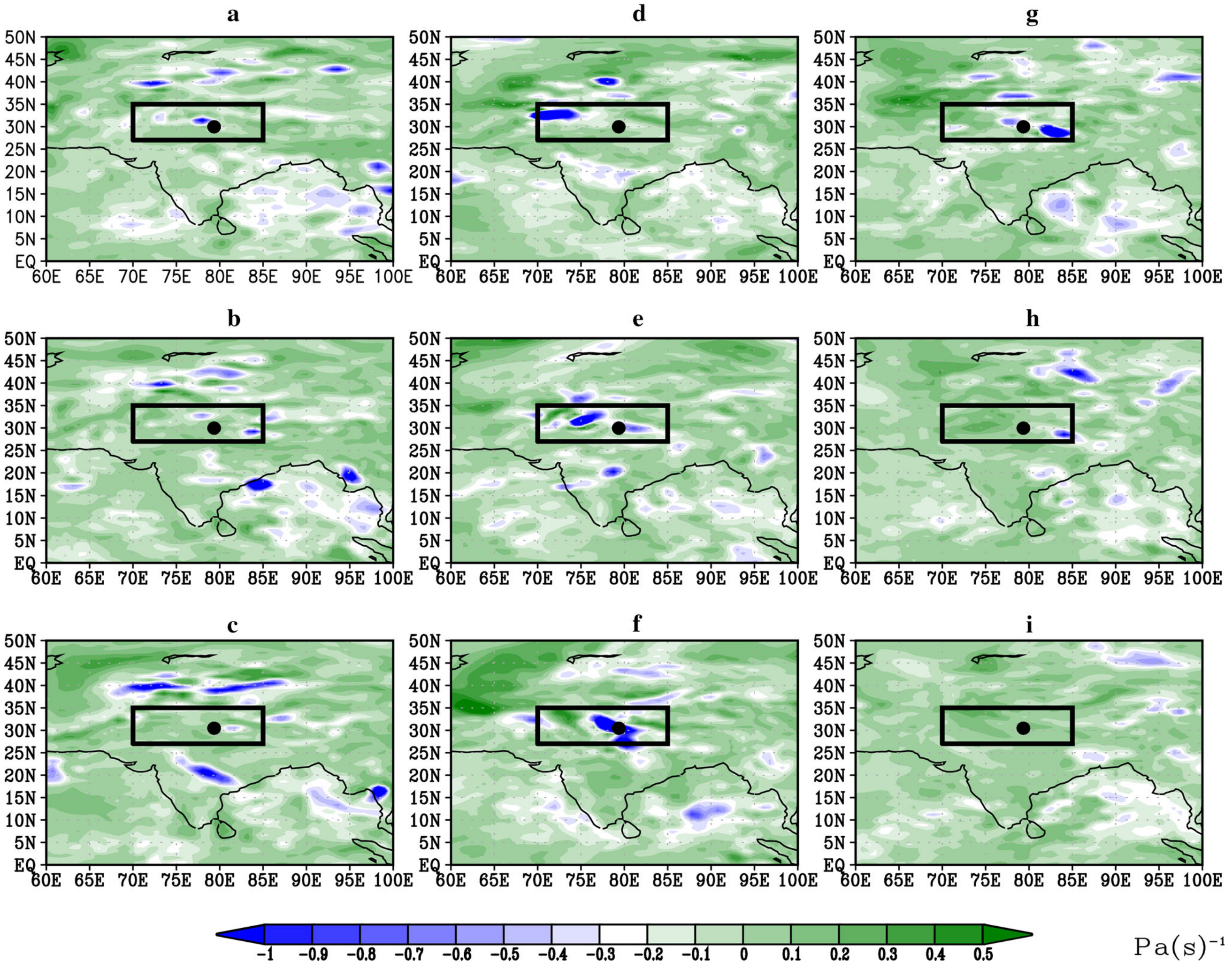

Figure 8. Pressure vertical velocity (ω) at 500 hPa for (a-i) 12–20 June, 2013 respectively (dot mark indicates location of Uttarakhand).

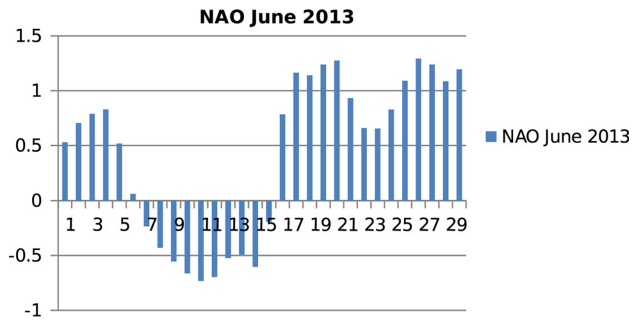

Figure 9. Daily variation of North Atlantic Oscillation index in June 2013.

south than usual. During negative phase of NAO, divergence at 200 hPa over Indian land is observed to be positive which influences the convection over the region (Dugam 2008). It is established that the only teleconnection pattern in Northern Hemisphere which is present throughout the year is NAO (Barnston and Livezey 1987). Negative NAO is associated with slowed polar vortex and polar jet stream, and when jet slows, it moves in waveform pattern (Rossby waves) (http://appinsys.com/globalwarming/ao_nao.htm#nao). Northeastern Africa and Karakoram regions are also influenced by NAO; rainfall occurs during the negative phase of NAO (McHugh and Rogers 2001; Archer and Fowler 2004). Many studies have also shown that NAO can influence the Asian summer monsoon through subtropical jet (Yang *et al.* 2004; Li *et al.* 2008). Studies have also linked the teleconnection of NAO with circulation and SST in North Atlantic to Indian monsoon (Chang *et al.* 2001; Srivastava *et al.* 2002; Krishnamurthy and Krishnamurthy 2016). Ding and Wang (2005) showed the existence of circum-global teleconnection during NH summer which has significant correlation to Indian summer monsoon (a Rossby wave generated from North Atlantic is seen to influence the Indian summer monsoon precipitation). Though most of the studies used monthly values of NAO, it is shown that daily values of NAO also influence the Indian summer monsoon rainfall (Dugam 2008). Figure 9 shows the daily variations of North Atlantic Oscillation (NAO) for the month of June 2013. It is worth noting that the NAO has negative values from 7th to 16th June, 2013. The negative values of NAO indicate weakening of both Icelandic low and Azores High, and cause decrease in pressure gradient. The decrease in pressure gradient results in a decrease in the zonal westerlies that causes the cold air to move southward. Though, the monthly mean NAO for June 2013 was found to be positive, the daily variation specifically during the event days was observed to be negative. As the NAO becomes negative, westerlies weakened and cold air moved south, which led to the southward intrusion of the mid-latitude westerlies south of its normal position during the extreme rainfall days in 2013 Indian summer monsoon.

4. Conclusion

The heavy rainfall event in 2013 over Uttarakhand, which had caused havoc to lives and properties, was due to the sudden intrusion of mid-latitude westerlies towards south for a few days which coincided with the heavy rainfall event in the Uttarakhand region. Strong vertical winds, high cyclonic vorticity, low values of OLR, etc., provided a conducive atmosphere for the occurrence of heavy rainfall. The westward tilt of the mid-latitude trough with height intensified the system through transfer of potential energy of the mean flow. These mid-latitude westerlies which was pushed southward by the southward moving cold air is clearly evident from the negative North Atlantic Oscillation values seen prior and during the event days. A similar extreme rainfall event of tropical–extratropical interaction was observed in 2010 flood in Pakistan where southward penetration of extra-tropical potential vorticity in the trough east of European blocking coincided with the monsoon arrival (Hong *et al.* 2011) and abundant moisture was supplied from Bay of Bengal and Arabian Sea (Martius *et al.* 2013). Studies have shown an increasing probability of extreme rainfall events over Western Himalayas due to the interaction between monsoon circulation and penetrating mid-latitude westerly troughs in the region (Vellore *et al.* 2016; Priya *et al.* 2016). Comprehensive modelling studies should be carried out to understand extra-tropical influence on the development of extreme rainfall events during the Indian summer monsoon and its improved predictability.

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