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A study on some dynamical aspects of Uttarakhand heavy rainfall events

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सार — **हाल के वर्षों में, उत्तराखंड क्षेत्र में भारी वर्षा की घटनाएं बढ़ रही हैं। ऐसी घटनाओं के पूर्वानुमान में सुधार** NWP **मॉडल में ऐसी घटनाओं के लिए उत्तरदायी भौतिक और गतिकीय प्रक्रियाओं की समझ और समावेशन पर काफी निर्भर है। इस अध्ययन में, इन भारी वर्षा की घटनाओं के गतिकीय पहलुओं की बेहतर समझ के लिए इन प्रक्रियाओं के कुछ हिस्सों को समझने का प्रयास करता है। विभिन्न महत्वपूर्ण व्युत्पन्न** NWP **उत्पाद, जैसे, डिफरेंशियल वोर्टिसिटी एडवेक्शन** (DVA), **डिफरेंशियल थर्मल एडवेक्शन** (DTA), **डिफरेंशियल मॉइस्चर एडवेक्शन** (DMA), **प्रीसिपिटेबल वॉटर** (PW), **नॉन-डायमेंशनल स्टेबिलिटी इंडेक्स** (NDSI) **की गणना** ECMWF **उच्च-विभेदन ग्रिडेड रीएनालिसिस डेटा सेट का उपयोग करके की गई है। भारी वर्षा की घटनाओं को आईएमडी के उच्च विभेदन ग्रिड वाले दैनिक वर्षा डेटा सेट का उपयोग करके निर्धारित किया गया है। प्रारंभिक विश्लेषण से पता चला कि भारी वर्षा की घटना से पहले** DVA **में लगातार वृद्धि**, DTA **में कमी**, PW **में वृद्धि और** DMA **में कमी हुई थी।** DVA **में वृद्धि के परिणामस्वरूप निम्न स्तर अभिसरण सुदृढ़ हुआ**, DTA **में कमी के साथ-साथ** DMA **में कमी से ह्रास दर में वृद्धि हुई**, **जिससे अध्ययन वाले क्षेत्र में गति बढ़ गई जिसके परिणाम स्वरूप भारी वर्षा हुई।**

ABSTRACT. In recent years, heavy rainfall events are increasing over the Uttarakhand region. Improvement in the prediction of such events is significantly dependent on the understanding and inclusion of the physical & dynamical processes responsible for such events, in the NWP model. The study, attempts to comprehend parts of these processes for the better understanding of dynamical aspects of these heavy rainfall events. Different important derived NWP products, *viz*., Differential Vorticity Advection (DVA), Differential Thermal Advection (DTA), Differential Moisture Advection (DMA), Precipitable Water (PW), Non-Dimensional Stability Index (NDSI) have been computed using ECMWF high-resolution gridded reanalysis data sets. Heavy rainfall events are defined using IMD high resolution gridded daily rainfall data set. Preliminary analysis revealed that there was a steady increase in DVA, decrease in DTA, increase in PW and decrease in DMA before the heavy rainfall event. The enhancement in DVA resulted in the strengthening of low level convergence, a decrease in DTA along with a decrease in DMA lead to an enhancement of lapse rate, leading to a rising motion over the study region which has resulted in heavy rainfall event.

Key words – Heavy rainfall, Dynamical aspects, Moisture transport.

1. Introduction

The heavy rainfall event in the Himalayas, accompanied by floods, is one of the worst natural disasters in the region. Such events lead to deaths, injuries and property damages, because of which it has large social and economic impact. Furthermore, the numbers of extreme rainfall events are increasing in India (Goswami *et al*., 2006). A Study of daily rainfall data over the period 1910 to 2000 from 129 stations shows an increasing trend in the rainfall over some parts of Uttarakhand (Sen Roy and Balling 2004). Extreme rainfall event frequency shows inter annual and inter-decadal variation (Rajeevan *et al*., 2008). Exorbitant use of land and natural geomorphology make Uttarakhand, prone to natural disasters (Sharma *et al*., 2013). Numerous studies have tried to explain different mechanisms of heavy precipitation over Uttarakhand. Complex terrain and multiple scale interactions are the major affecting factors for the heavy precipitation over the Himalayan slopes (Rudari *et al*., 1999). Many factors such as continentality, geometry of topography, hill shade and orographic folds are important contributors to increasing orographic rainfall (Smith 1979; Anders *et al*., 2006; Banerjee *et al*., 2020). Not only orography but synoptic scale convergence and convective activities are also crucial for heavy rainfall on windward sides of mountains (Sarker, 1966, 1967; De, 1973). Because of high-pressure over the Tibetan plateau anomalous moisture transport *via* synoptic scale passage can take place, which aids the formation of mesoscale cloud precipitation, which further results in stratiform precipitation over Himalayan slopes (Houze *et al*., 2011). Some studies show that southward penetration of subtropical westerly jet and monsoon circulation interaction enhanced the probability of extreme rainfall events over the western Himalayas (Vellore *et al*., 2016; Priya *et al*., 2016).

Heavy rainfall occurred in the Uttarakhand region between 15-18thJune, 2013, which caused catastrophic floods and affected many lives and the economy. It has been the most investigated case till now due to its destructive effects. During this event, 370 mm d^{-1} rainfall was recorded in Deharadun, which was 20% of annual rainfall (Gosain *et al*., 2015). Analysis of this event shows that extreme rainfall occurred due to multiscale interactions such as southward intrusion of the westerly subtropical jet and its interaction with monsoon circulation, constant supply of moisture from the Arabian sea and the Bay of Bengal to the Uttarakhand region (Kotal *et al*., 2014; Rajesh *et al*., 2016; Ranalkar *et al*., 2016) In 2013, Uttarakhand event land surface feedback role was also important (Rajesh *et al*., 2016). This event is also analysed using the WRF model by Shekhar *et al*., 2015.

Appropriate understanding of possible changes in localized weather systems is necessary for damage control and developing measuring infrastructure. Hence, the improved understanding of dynamics, physics involved in heavy rainfall events and the advanced methods for accurate forecasting is necessary.

In 1955, George Lott found Differential thermal advection and moisture have the potential to be used as a forecaster of heavy rainfall. Strong differential vorticity is observed on the day of heavy widespread rainfall during north Indian winter western disturbances. Also, it is found that differential thermal advection plays a role in increasing vertical velocity (Sankar and Babu, 2020). The study presented is an attempt to understand the heavy rainfall event that occurred in the Uttarakhand region on 16th August, 2011 using reanalysis data. The investigation is carried out using Numerical weather prediction products such as Differential Vorticity advection, Differential moisture advection and Differential thermal advection.

2. Data and methodology

This section discussed the different data sets and methodology used in this study. Heavy rainfall events are identified using India Meteorological Department (IMD) gridded rainfall data. For the detailed analysis ECMWF ERA 5 and ERA interim reanalysis data sets are used.

TABLE 1

Heavy rainfall events selected by defined criteria

No.	Date	Rainfall (mm)
1.	17th July, 2016	59.62
2.	19th August, 2010	60.24
3.	4th August, 2012	61.64
4.	6th July, 2010	61.75
5.	31st July, 2010	65.37
6.	19th August, 2010	65.62
7.	1st July, 2011	66.75
8.	26th June, 2015	77.15
9.	21st July, 2010	79.77
10.	17th June, 2013	89.4
11.	19th September, 2010	94.35
12.	18th June, 2013	98.37
13.	19th July, 2014	107.95
14.	16th August, 2011	199.4

2.1. *Data*

2.1.1. *IMD gridded high-resolution rainfall data*

IMD gridded data available at 0.25° × 0.25° resolution is used to calculate rainfall over the Uttarakhand region. Because of the density of the network stations used to prepare the data set and the resolution of this data, it represents better characteristics of rainfall in heavy precipitation regions (Pai *et al*., 2013, 2014).

2.1.2. *ECMWF Reanalysis data*

Two reanalysis data sets from the European Centre for Medium-range Weather Forecasts (ECMWF) are used. ERA 5 is the latest reanalysis data set available from ECMWF. This data is available from 1979 till date (Harbash and Dee 2016). Six hourly ERA 5 data available at 0.25° × 0.25° resolution is used for large scale analysis in this study. Specific humidity, *u* and *v* wind components available at pressure levels are used from this data. This data was obtained from 1000 hPa up to 300 hPa for current study.

For detailed analysis of the heavy rainfall over the region, high resolution ERA- interim global reanalysis data available at 0.125° ×0.125° is used. Era-interim data is available from 1st January, 1979 till 31st August, 2019. Barrisford *et al*. (2011). U wind, V wind, and specific humidity available at vertical pressure levels (Currently from 1000 hPa up to 300 hPa) are the product obtained from this data set.

2.2. *Methods*

In this study Heavy Rainfall Events (HRE) are identified using IMD gridded rainfall data. Monsoon months JJAS (June, July, August and September) over 10 years from 2010-2019 are considered for this analysis. We have defined a criterion to identify HRE for which daily average rainfall is calculated over 2° × 2° box (29° - 31°N and 78° - 80°E) in the Uttarakhand region and the top 99th percentile events are selected as a heavy rainfall event. Table 1 lists the identified heavy rainfall events with our defined HRE criteria. The date of occurrence and spatially average rainfall amount recorded is being presented in Table 1. From this table, it can be noticed that the highest rainfall was recorded on the 16th August, 2011, so the same event is considered for further detailed analysis.

The HRE selected from the above method then analyzed in detailed with the help of dynamics. Different important derived NWP products, *viz*., Differential Vorticity Advection (DVA), Differential Thermal Advection (DTA), Differential Moisture Advection (DMA) and Vertically Integrated Moisture Flux (IMFC) have been computed using ECMWF ERA interim high-resolution gridded reanalysis data sets. Precipitable Water (PW) and Non-Dimensional Stability Index (L) are calculated using ERA 5 data (CAPE and CIN are directly available from ERA 5 data).

Precipitable Water (PW) is the vertically integrated value of atmospheric water. PW is an important predictor in weather forecasting (Kelsey *et al*., 2021). PW is calculated for the identified HREs. Calculations are carried out using the following formula:

$$\text{PW} = \int_{p_0}^{p} q\frac{dp}{g}$$

Here p_0 and p are the pressures at the bottom and top of the atmospheric layer of interest. q is the average mixing ratio between two successive layers and g is the acceleration due to gravity.

Differential Moisture Advection (DMA) in a layer bounded by two levels, *viz*., Upper Level (UL) & Lower Level (LL) is defined as, $\text{DMA} = \left(-\vec{V}.\vec{\nabla}q\right)_{UL} - \left(-\vec{V}.\vec{\nabla}q\right)_{LL}$, where $-\vec{V}.\vec{\nabla}q$ is moisture advection computed using horizontal wind $\left(\vec{V}\right)$ and specific humidity (q), available from ERA- interim reanalysis products. A negative value of DMA indicates a net low-level moisture advection.

Differential Vorticity Advection (DVA) in a layer bounded by two levels, *viz*., UL & LL is defined as, DVA

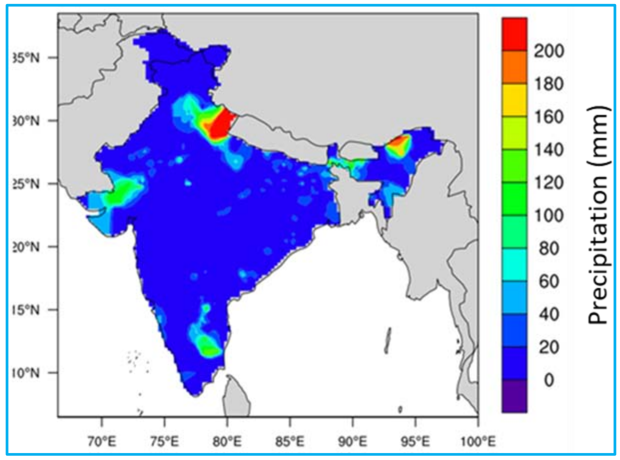

Fig. 1. Rainfall (mm) distribution on 16th August, 2011

$= \left(-\vec{V}.\vec{\nabla}\varsigma\right)_{UL} - \left(-\vec{V}.\vec{\nabla}\varsigma\right)_{LL}$, where $-\vec{V}.\vec{\nabla}\varsigma$ is vorticity advection computed using horizontal wind $\left(\vec{V}\right)$ available from ERA- interim reanalysis products. A positive value of DVA indicates a net upper level cyclonic vorticity advection, resulting in an increase in lower level convergence. Thus, resulting in the rising motion. It is also obvious from the diagnostic omega equation (Holton, 2004).

Similarly, Differential Thermal Advection (DTA) in a layer is defined as $\text{DTA} = \left(-\vec{V}.\vec{\nabla}T\right)_{UL} - \left(-\vec{V}.\vec{\nabla}T\right)_{LL}$. A negative DTA favors in enhancing lapse rate.

Above results indicates that the combined effect of decreasing DTA, decreasing DMA and increasing DVA results in enhancement of the updraft.

Vertically integrated Moisture Flux Convergence (VMFC) is calculated between 925 hPa up to 200 hPa using formula:

$$\text{VMFC} = \int_0^\infty -\vec{\nabla}.\left(q\vec{V}\right)dz$$

A high positive value of VMFC indicates an enhanced availability of moisture, which is demonstrated by an increase in PW. Thus, an enhanced updraft, resulting from the combined effect of decreasing DTA, decreasing DMA and increasing DVA along with an enhanced availability of moisture, resulting from a high positive value of VMFC are most likely to result in an enhancement of precipitation at a point.

Also, a non-dimensional parameter (L) defined in previous studies by [Basu and Mandal (2002); Dutta and Kesarkar (2004)], given by :

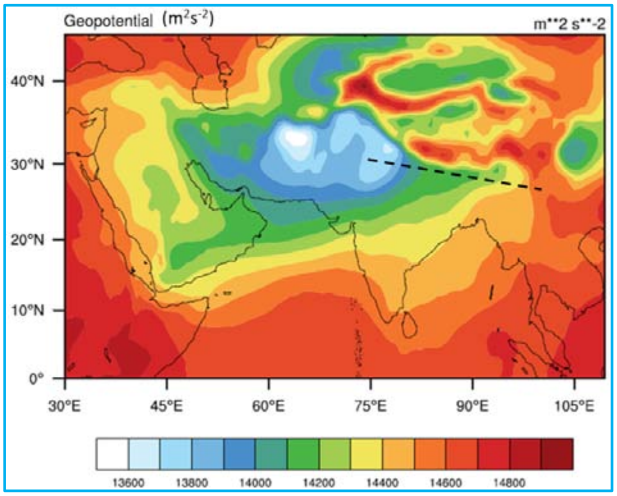

Fig. 2. Geopotential (m^2s^{-2}) at 850 hPa on 15th August, 2011. Dash line represents approximate trough location

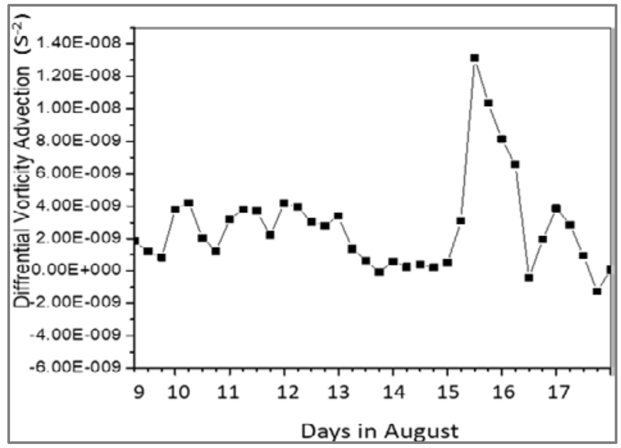

Fig. 4. Differential vorticity advection (s^{-2}) calculated between 1000 hPa and 500 hPa over a region bounded by 29° - 31° N and 78° - 80° E, from 9th to 17th August, 2011

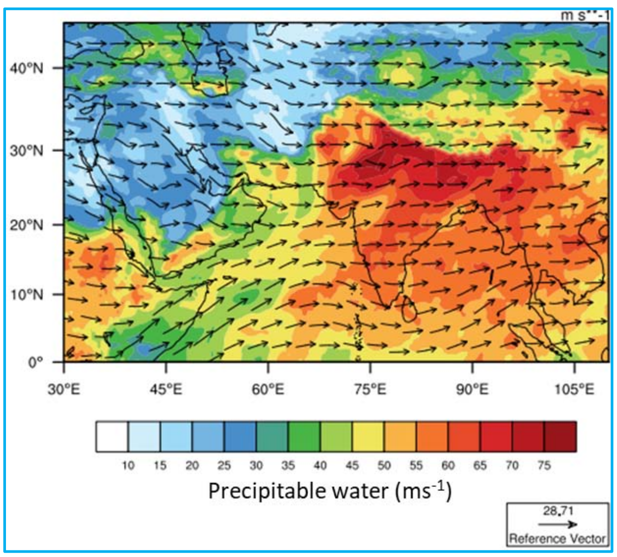

Fig. 3. Precipitable water (ms^{-1}) on 16thAugust, 2011, overlaid with 850 hPa wind

$$L = \frac{CAPE - CIN}{CIN}$$

has also been computed to estimate strength of convective instability.

3. Results and discussion

3.1. *Precipitation*

Averaged precipitation on 16th August, 2011 is calculated over 2° × 2° area covering the Uttarakhand region (29°-31° N and 78°-80° E) and it is found to be 199.4 mm from IMD gridded data. Precipitation on 16th August, 2011over the entire country is plotted in Fig. 1. We can also notice that the other parts of the country do not record much rainfall on 16th August, 2011. According to the IMD 2011 monsoon report, Uttarakhand received excess rainfall during the month of August 2011 (Tyagi and Pai, 2011).

3.2. *Moisture availability and synoptic conditions*

It is observed that on 14th and 15th August the monsoon trough was situated north of its normal position and then it shifted towards the Himalaya foot hills (Monsoon report 2011, IMD). Fig. 2 represents geopotential at 850 hPa on 15th August available from ECMWF Era 5 reanalysis data. A monsoon trough location near the Himalayan foot hills can be noticed in the figure presented and the approximate location of the trough line is presented with the dotted line.

To understand wind flow pattern and moisture availability, precipitable water (PW) along with 850 hPa wind overlay presented in Fig. 3 for 16th August. If we observe 850 hPa winds in plots, it shows part of the winds reaching towards Uttarakhand are coming from the Arabian Sea. Fig. 3 shows, over the entire northern India, moisture availability is more than in the rest part of the country. Especially over the Uttarakhand region and surrounding area, PW as high as 70 to 75 kg m^{-2} is available, indicating enhanced moisture over the region. We have analyzed PW and wind fields of 200 hPa for all the listed HREs in the given table (Plots are not shown in the paper) and observed that in most of the cases, southward penetration of subtropical westerly jet up to 30° N can be observed.

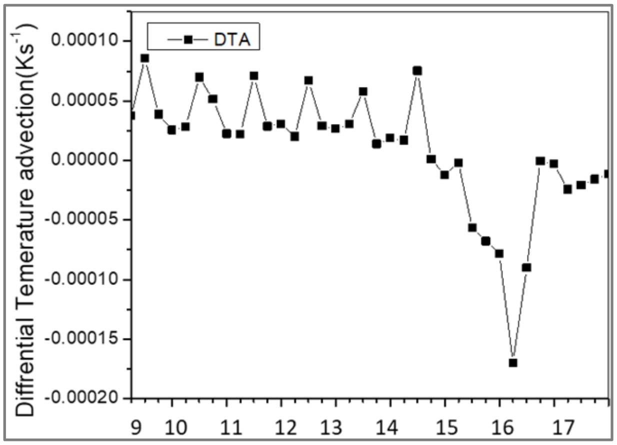

Fig. 5. Averaged Differential Thermal Advection (Ks^{-1}) calculated between 1000 hPa to 500 hPa over the region 29°-31° N and 78°-80° E

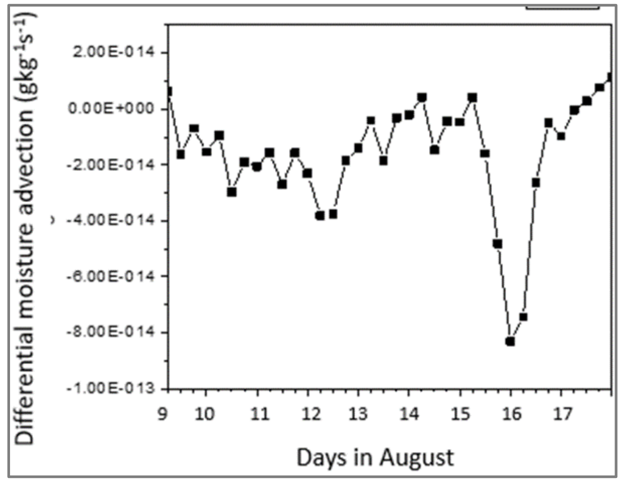

Fig. 7. Averaged Differential Moisture Advection ($gkg^{-1}s^{-1}$) calculated between 925 hPa and 500 hPa over the region 29°-31°N and 78°-80°E

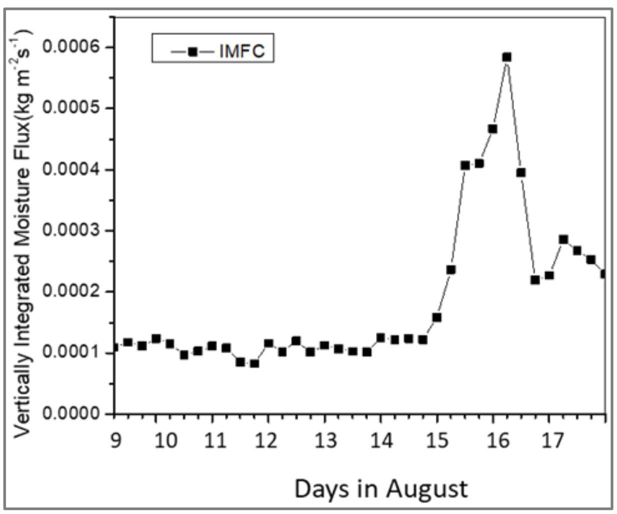

Fig. 6. Averaged vertically integrated moisture flux convergence ($kgm^{-2}s^{-1}$) calculated between 1000 up to 200 hPa over the region 29°-31°N and 78°-80°E

3.3. *Derived parameters for NWP guidance to understand the dynamics associated with heavy precipitation*

(*i*) *Differential Vorticity Advection (DVA)* : Using ERA interim data values, *viz*., horizontal components of wind (*u*, *v*) at each grid point (*i*, *j*); the vertical component of vorticity (ζ), DVA is calculated at 0000 UTC between 1000 hPa and 500 hPa over an 2° ×2° area which covers the Uttarakhand region (29°-31° N and 78°-80° E). Averaged DVA over the selected region is presented in Fig. 4 from 9th to 17th August, 2011. Diurnal variation in the DVA in the form of small peaks can be observed between 9th to 14th August where maximum DVA can be observed up to 4.00E-09s^{-2}. Positive DVA is present in selected region and it increase after 15th August, peaked between 15th and 16th August. Positive DVA indicates net rising air motion. Lifting air motion is an important phenomenon as it gives rise to clouding and precipitation. Increasing positive DVA is an indicator of the low-level convergence over the region. The peak in the DVA, just before heavy rainfall, indicates moisture rising due to convergence over the region.

(*ii*) *Differential Thermal Advection (DTA)* : Using ERA interim data, *viz*., the temperature and horizontal wind components, the derived product DTA has been computed. Lapse rate in the column is crucially dependent on Differential Thermal Advection (DTA). Averaged DTA between 925 hPa and 500 hPa is calculated over region 29° -31° N and 78° -80° E from 9th August till 17th August (Fig. 5). Diurnal variation in DTA with small positive peaks can be observed from 9th to 15th August. After 15th August, an increase in the negative DTA can be observed, which peaked on 16th August. An Increase in the negative DTA indicates an increase in the lapse rate in the column, this again is conducive to convective instability over the region during HRE.

(*iii*) *Vertically Integrated Moisture Flux Convergence (IMFC)* : This derived NWP product has been computed using the grid point values of ERA interim data, *viz*., specific humidity and components of horizontal wind at different levels between 1000 hPa and 200 hPa. Averaged IMFC computed over the region (29°-31° N and 78°-80° E) from 9th to 17th August is presented in Fig. 6. It can be observed that VMFC was negligible till 15th August, but it started increasing after 15th August and picked up on 16th August. The increase in IMFC indicates

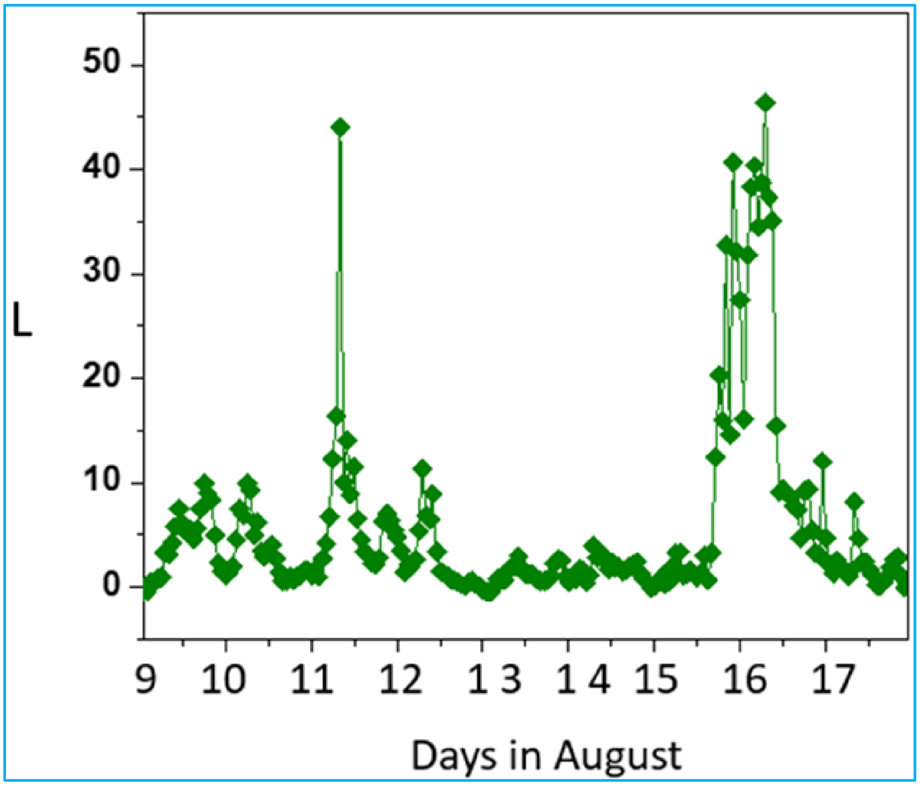

Fig. 8. Parameter L averaged over the region 29°-31° N and 78°-80° E

the moisture availability in a large amount over the selected region, suggesting availability of the moisture in high amount, along with convergence and rising motion during 16th August HRE.

(*iv*) *Differential Moisture Advection (DMA)*: This derived NWP product has been computed using the grid point values of ERA interim, *viz*., specific humidity and components of horizontal wind. Computed averaged DMA between 925 hPa and 500 hPa over region 29°-31° N and 78°-80° E from 9th August till 17th August is shown in Fig. 7. Fall in DMA with attainment of the highest negative value, as being approached to the day of HRE, can be seen from this figure. This feature indicates an enhancement in positive buoyancy of the air and thus, making the environment more conducive for moist convective instability.

(*v*) *Non-dimensional stability index(L)* : The average value of this parameter has been computed over region 29°-31° N and 78°-80° E from 9th August till 17th August and is shown in Fig. 8. L will be large when convective available potential energy (CAPE) is large and convective inhibition (CIN) is small. Higher values of L indicate favourable conditions for higher convective activities.

4. Summary

In the present study, an attempt has been made to understand some of the dynamical processes involved in a heavy rainfall event over the Uttarakhand region on 16th August 2011, by examining the day to day variation of certain derived NWP products, *viz*., differential vorticity advection, differential thermal advection, differential moisture advection, vertically integrated moisture convergence and precipitable water content, along with the synoptic conditions prevailed then and there. These derived products have been computed using ERA 5 direct NWP model output parameters, *viz*., horizontal wind, temperature and specific humidity and averaged over an 2° × 2° area covering the Uttarakhand region (29°-31° N and 78°-80° E).

Synoptic conditions show that the event occurred when there was a typical break like situation present over central India and monsoon trough was observed over the Himalayan foothills. An increase in the DVA over the region before the event suggests low level convergence and rising motion in the atmospheric column. An increase in negative DTA during the heavy rainfall event represents increasing in lapse rate in the column. A large amount of moisture availability can be seen with increase in the IMFC. Favourable conditions for moisture availability up to higher depths in the atmosphere can be seen using thermodynamics parameters. A large amount of moisture was gathered due to low level convergence and it was lifted to higher levels due to the conductive atmosphere, so rising motion in the air and large moisture availability together possibly resulted in the heavy rainfall on 16th August, 2011 over the region.

Numerical weather prediction products play a very crucial role in atmospheric models. The importance of the NWP products and its usefulness as a diagnostic tool is highlighted in this study. Detail study with model simulation can improve the understanding of possible linkages between extra tropical interactions and heavy rainfall events

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