Indian Journal of Radio & Space Physics
Vol 49, December 2020, pp. 153-161

Scaling of heavy rainy days with upper air profiles over Chennai during Northeast monsoon

Alvin Singh[a], Manoj Kumar Thakur[b], Purnadurga Geesupalli[a], Naga Rajesh Anandan[a*], T V Lakshmi Kumar[a], Som Sharma[c] & Prashant Kumar[d]

[a]Atmospheric Science Research Laboratory, Department of Physics, SRM Institute of Science and Technology, Chengalpattu, Chennai, Tamil Nadu 603 203, India

[b]Department of Physics, Tri-Chandra Multiple Campus, Tribhuvan University, Kathmandu, Nepal

[c]Space and Atmospheric Sciences Division, Physical Research Laboratory, Ahmedabad, Gujarat 380 009, India

[d]Space Applications Centre (ISRO), Ahmedabad, Gujarat 380 015, India

Received: 23 February 2020; Accepted:10 October 2020

This study aims to scale the heavy rainy days (rainfall > 64 mm per day) with the surface and upper-air parameters over Chennai (12.80° N and 80.03° E), located on the east coast of India, during the Northeast (NE) monsoon (October to December) from 2001 to 2015. The daily rainfall and radiosonde observations that are available from India Meteorological Department (IMD), Outgoing Long-wave Radiation (OLR) from Very High Resolution Radiometer (VHRR) Kalpana-1 Indian satellite, and Total Column Liquid Water (TCLW) and vertical velocity from ERA-Interimre analysis are used. The study commences with the comparison of mean daily Integrated Water Vapor (IWV) and rainfall over Chennai. Further, the study proceeds ahead by analyzing the IWV, TCLW, Instantaneous Condensation Rate (ICR) and precipitation extreme efficiency during the heavy rainy days. The results are such as (i) the heavy rainy days are better scaled using IWV and TCLW than with surface air temperature and OLR (ii) ICR during the all heavy rainfall days found high at 700 mb level, and (iii) the precipitation extreme efficiency which is estimated using the ratio of precipitation extreme (obtained from vertical velocity, specific humidity gradient) and the ICR has shown a linear relationship with the surface reaching rainfall through the temporal and spatial smearing of raindrops expected.

Keywords: Heavy rainy days, Integrated water vapor, Instantaneous condensation and Precipitation efficiency

1 Introduction

It is well known that India receives most of its rainfall from the South West (SW) monsoon which starts from the month of June and ends by September. The retreat of SW monsoon at the end of September from the northern and central Indian regions that flows along the South Bay of Bengal offers rainfall during October to December over the regions of peninsular parts of India. This retreat of SW monsoon is known as North East (NE) monsoon and is the major source of rainfall for Tamil Nadu state and parts of Kerala and Andhra Pradesh. Numerous studies were carried out, and the results are well documented on the causes and variability of SW monsoon[1-4]. But the studies related to NE monsoon and its variability are very limited. Kripalani[5] studied the variability of NE monsoon rainfall and reported that the NE monsoon rainfall increases with the positive phase of the Indian Ocean Dipole (IOD). Also, they have reported that NE monsoon rainfall has shown greater variability from1880 to 1920 and 1980 to 2000 due to the active phases of IOD. Balachandran[6] studied the impact of eastern and western equatorial Pacific sea surface temperatures on NE monsoon rainfall and found an inverse relationship. Rajeevan[7], also reported that NE monsoon has direct link with El Nino Southern Oscillation (ENSO), and found the relation is weakened during 2001 to 2010. They also found that NE monsoon rainfall has shown the inta seasonal variability with 20 to 40 day periodicity.

Chennai being the present study location positioned on the coastline, the landfall of tropical cyclones in addition to heavy rainy days in this region cause severe floods. The excessive rainy days that occur over Chennai during the NE monsoon season are either due to the Mesoscale Convective Systems (MCS) or the depressions over the Bay of Bengal. In the present analysis, our attention has only been on the heavy rainy days with the convective origin, but not on the cyclonic events. The present study has been

*Corresponding author (E-mail: nagaraja@srmist.edu.in)

initiated to understand the meteorological behavior of the weather parameters during heavy rainy days in the NE monsoon season over Chennai during the years 2001 to 2015. The heavy rainfall event is selected based on India Meteorological Department (IMD) definition (> 64 mm per day). The study deals with analysis of the variations of surface and upper air variables such as surface air temperature, Total Column Liquid Water (TCLW), specific humidity, relative humidity, gradient of potential temperature, vertical velocity, Instantaneous Condensation Rate (ICR), etc. during the heavy rainy days. Our attempt in this study is to report the changes in various surface and upper air parameters before, on and after the heavy rainy days. Various parameters from ground, satellite and reanalysis have been used to meet the objectives of this study. The details of the data and methodology, results and discussions, and conclusions are presented in the later sections.

2 Data and Methodology

Upper air data from Global Positioning System (GPS) Radiosonde of IMD, Chennai during the years 2001 to 2015 is used. The daily rainfall observations over Chennai for NE monsoon seasons during the years 2001 to 2015 has been obtained from the 0.25 x 0.25 gridded data sets of IMD[8]. For a better representation of heavy rainy days over the research location, we have considered the study period for 15 years. TCLW in kg/ m^2 has been obtained from the European Centre for Medium Range Weather Forecast (ECMWF) Reanalysis. The frequency of TCLW datasets is 6 hours. Hence, we have averaged forthe entire day, and used daily TCLW for the present analysis by extracting the data for the grid of 0.25° × 0.25° where our study location falls. In addition to TCLW, daily mean vertical velocity profile at different pressure levels from the ERA-Interim reanalysis datasets have also been used in this study. The pressure-dependent vertical velocity is available in pa/s from ERA-Interim and is converted into m/sec unit in the present study.

We have used the Outgoing Long-wave Radiation (OLR) data with 0.25° × 0.25° grid resolution obtained from the Very High Resolution Radiometer (VHRR) onboard Kalpana–1 satellite during the years 2004 to 2015. The data is available on a daily scale from www.tropmet.res.in. The retrieval algorithm for this product has been discussed[9-10]. Using the daily mixing ratio profile from radiosonde, the water vapor has been calculated and further, the IWV from surface to 200mb has been estimated using the trapezoidal rule. The ICR has been estimated by using the formula given by O'Gorman[11], which mainly makes use of vertical velocity, temperature and potential temperature. As the data from radiosonde is not distributed vertically at equal intervals, the B-spline interpolation technique is used to obtain ICR at equal intervals.

$$C \sim \omega \frac{c_p T}{L\theta} \frac{d\theta}{dp}\bigg|_{\theta^*} (\mathrm{ms^{-1} * K * mb^{-1}}) \quad \ldots (1)$$

where, C is the Condensation rate, ω is the Vertical Velocity (m/s), c_p is the Specific heat capacity at constant pressure (kJ/kg K), T is the Temperature (K), L is the Latent heat (kJ/kg), θ is Potential temperature (K), dθ is the Temperature difference, dp is the Pressure difference

The potential temperature (K) at all atmospheric pressure levels has been calculated using the standard formula. The expression for ICR is derived from the saturation specific humidity[11].

The precipitation rate from the thermodynamic processes can be estimated from the condensation rate for an air parcel which is adiabatically raised[12]. The relation between precipitation extreme changes and the changes in the thermodynamical variables can be related using the vertically integrated dry static energy budget[13] and can be written as:

$$\frac{ds}{dt} \approx Lv\left(\frac{d(q_r+q_c)}{dt}\right) + Ls\left(\frac{d(q_s+q_g+q_i)}{dt}\right) + LvP \quad \ldots (2)$$

where, d/dt is the Lagrangian derivative, and "s" is the dry static energy which is the sum of geopotential and specific enthalpy q_r, q_c, q_s ,q_g, q_i are rain mixing ratio, cloud liquid water mixing ratio, snow mixing ratio, graupel mixing ratio and cloud ice mixing ratio respectively. L_v and L_s are latent heats of evaporation and sublimation respectively, and P is the surface precipitation.

The above equation of dry static energy budget can be simplified and can be written as[14]:

$$Pe \approx -\in \left(\omega \frac{dq*}{dz}\right) \quad \ldots (3)$$

where, Pe is the Precipitation Extreme, ω is the pressure dependant vertical velocity and $q*$ is the saturation mixing ratio and $\in$ is the precipitation extreme efficiency.

The value of $\in$ varies from 0 to 1, where 1 is for the entire condensation falls as precipitation, whereas

$\in = 0$ denotes the condensation is transported from the column or build up on different time scales.

The Pe and further $\in$ has been estimated in the present study for the heavy rainy days and related to the surface precipitation to understand the influence of net condensation on heavy rainy days over Chennai.

3 Study location

Situated on the east coast of India, the study location, Chennai has the tropical climate. Chennai receives most of its annual rainfall from the NE monsoon. Based on the IMD rainfall data from the years 2001 to 2015, the contribution of rainfall NE monsoon rainfall over Chennai is ~64%, and the contribution of SW monsoon is ~27%, and the rest is during the summer and winter seasons. The temperatures are maximum in the month of May[15], and surface relative humidity is generally above 70% at the surface throughout the year. Due to the proximity of the sea (Bay of Bengal), Chennai experiences the sea breeze effect and is reported that the sea breeze sets in over Chennai around 9-10 AM and goes till evening[16]. The land breeze is seen during night time in general. Heavy rainy days generally occur in the months of October and November, and rarely in December. The rainfall spells during the NE monsoon season over the regions of Tamil Nadu vary from 1 to 4 days. The main source of rainfall over Chennai is from mesoscale convective systems and tropical cyclones. The depressions formed in the Bay of Bengal during the retreat of SW monsoon help to get rainfall over Chennai and surrounding regions. It is calculated from the Thornthwaite Climate Approach[17] that the seasonal moisture index for the NE monsoon season is around -40 which indicates the semi-arid nature climate. The annual moisture index of Chennai is -24, and it is -14 for SW monsoon (June to September) season. The arid nature climate mainly indicates the dryness of the weather conditions.

4 Results and Discussion

Figure 1 represents the mean daily IWV and rainfall for the study period (years 2001 to 2015). It is found from Fig. 1 that the day to day variations in rainfall are very high with the higher monsoon activity is observed in the month of November. The mean daily rainfall over Chennai during the months of October, November and December is 10.1 mm, 11.7 mm and 5.9 mm respectively, and for entire season it is 9.2 mm. Unlike rainfall, water vapor has shown decreasing tendency during the season. The mean daily IWV for October, November, December and for total NE monsoon is 23.6 mm, 20.4 mm, 15.9 mm and 20 mm respectively. It is also seen that the mean daily rainfall and water vapor are in opposite phase during October and as the monsoon advances, they varying tandem with each other. The Pearson correlation for entire season between rainfall and IWV is 0.29, whereas the correlations for the period of October and rest of the period are +0.18 and 0.42 respectively in which the later correlation was significant at 0.05 level. The reason for the high IWV during the beginning of October may be the low-level jet at 850 mb which passes through Southern peninsular parts of India and continues till the mid of October. Lakshmi Kumar[18] have used the National Centre for Environmental Prediction (NCEP) reanalysis data of integrated perceptible water vapor for the Indian region and found a significant correlation of +0.64 with the rainfall. Also, Bretherton[19] studied the water vapor and precipitation relations over tropical oceanic regions using satellite microwave radiometer data, and found that the rainfall increases drastically with the increase in water vapor. It is also reported that the water vapor correlates highly with the temperature[20] and relative humidity than with the rainfall. The main reason behind this is the increase in water holding capacity of the atmosphere due to the rise in surface temperature which also enhances the relative humidity of the particular layer of the atmosphere. Knowing the relation of water vapor and rainfall, we have attempted to see the IWV variations during non-rainy (< 2.4 mm), light (2.4 to 7.4 mm), moderate (7.5 to 35.4 mm), rather heavy (34.5 to 64 mm) and heavy rainy (> 64 mm) days of the study period. We have averaged the value of daily IWV on different days

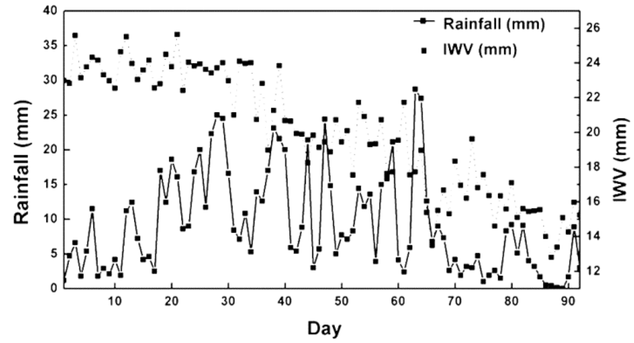

Fig. 1 — Mean daily rainfall and IWV over Chennai during NE monsoon of 2001 to 2015.

falling in an aforementioned category and plotted them. It is important to note that the IWV has gradually increased from 18 mm to 27 mm as the situation reaches from no-rain to heavy rain (Fig. 2). It is also found from Fig. 2 that the difference in water vapor is more between the non-rainy days and light rainy days, whereas this much difference was not found among the other types of rainy days. So, it is clear from the analysis that the changes in average water vapor are very less from moderate to heavy rainy days. But, it has also been found that there is a sudden pick up in IWV when heavy rain occurs which was observed during the time series analysis of IWV and rainfall for individual years.

4.1 Association of IWV, TCLW, OLR and rainfall over Chennai

To understand the association of IWV, TCLW and rainfall over Chennai during this study period, we have carried out a correlation analysis. The data of TCLW has been taken from the ERA-Interim Reanalysis for the Chennai grid of 0.25° × 0.25° on a daily scale for the entire study period. The Pearson correlation technique has been applied to IWV and TCLW for the days when the rainfall exceeds 7.5 mm, and the same has been carried out for TCLW and rainfall as well. We have used the smoothened data of above normalized by its mean for the analysis. It is found that the correlation between IWV and TCLW is +0.13 (Fig. 3a) which is significant at 0.20 level, whereas the correlation between TCLW and rainfall is +0.29 (Fig. 3b) which is significant at 0.01 level. The correlation for all years is given in Table 1. It can be seen from Table 1 that the correlation of IWV and TCLW is less compared to TCLW with rainfall. It is known that the TCLW correlate highly with rainfall, because liquid water is the direct source of precipitation. We tried further to understand the relation of TCLW and rainfall by fixing different time interval's lead of TCLW. We have observed that a substantial correlation is found when we correlate TCLW with the cumulative rainfall of two days. The correlation, in this case, is +0.49 which is with a 99% confidence level obtained from the student t-test with two-tailed significance analysis (Fig. 3c).

We have also studied the variations of the aforementioned variables during the heavy rainy days over Chennai from2001 to 2015. We found that there are a total of 38 heavy rainy days during this period.

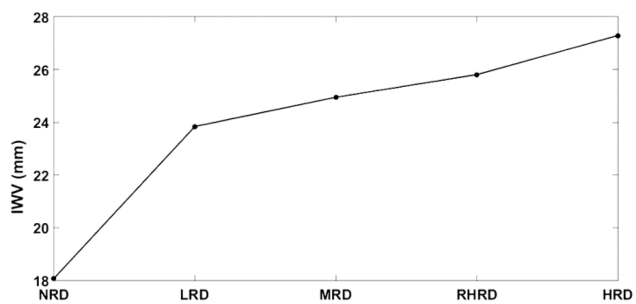

Fig. 2 — Scaling of IWV with the non-rainy, light, moderate, rather heavy and heavy rainy days over Chennai during NE monsoon of 2001 to 2015

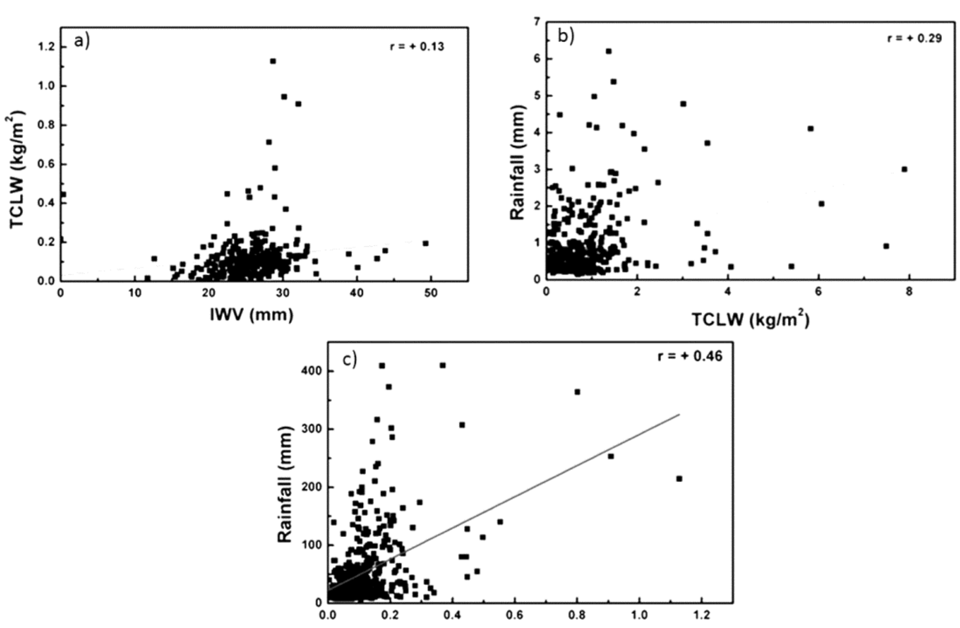

Fig. 3 — Correlation between a) TCLW and IWV, b) TCLW and rainfall and c) TCLW and rainfall of two consecutive days.

Table 1 — Correlation coefficient between IWV and TCLW, TCLW and rainfall, TCLW and rainfall of two consecutive rain during Northeast monsoon of the year 2001 to 2015.

Year	Correlation between TCLW and water vapor	Correlation between TCLW and rainfall	Correlation between TCLW and rainfall of two consecutive days
2001	+0.14	+0.56	+0.76
2002	+0.70	-0.34	-0.31
2003	-0.05	-0.34	-0.34
2004	+0.37	+0.51	+0.63
2005	+0.08	+0.57	+0.58
2006	+0.27	+0.15	+0.094
2007	+0.34	+0.44	+0.14
2008	+0.29	+0.35	+0.57
2009	+0.15	+0.19	+0.28
2010	+0.34	+0.36	+0.63
2011	+0.17	+0.50	+0.48
2012	-0.06	+0.34	+0.47
2013	-0.06	-0.006	+0.58
2014	+0.21	+0.17	+0.16
2015	+0.41	+0.45	+0.40
2001-2015	+0.12	+0.29	+0.49

We have averaged the surface air temperature (T_{air}), IWV, TCLW, OLR and Rainfall for all these days and denoted it as D(0), corresponding to a heavy rainy day. The data has been averaged similarly for three days before and after the heavy rainy day and are denoted as D(-3), D(-2), D(-1) and D(+1), D(+2) and D(+3) respectively. Figure 4 depicts variation of T_{air}, IWV, OLR, TCLW and rainfall during the above mentioned days for the study period from the year 2001 to 2015. It is reported that the life cycle of tropical convective systems over land vary from 8 hours to a maximum of 50 hours and are shorter than that over oceans[21]. The general features of convective systems such as the initiation phase, building up of deep convection and dissipation phase can be studied from Fig. 4. It is noted that all the variables, except T_{air} show a Gaussian distribution during these days by maintaining the peak on the heavy rainy day. The T_{air} is one of the main characteristics during convective rainfall event which increases the moisture content at the surface. It is also reported that not only T_{air} but also water vapor plays a role in moisture convergence at different levels which strengthens the updraft changes due to warming[14]. The IWV, TCLW and rainfall have the maximum values of 27.5 mm, 0.175 kg/m^2 and 120 mm, respectively during the heavy rainy day, and dropped to minimum at 3 days in advance and before. (Fig. 4) illustrates the building up of IWV and TCLW before the heavy rain indicates the triggering of convective cells and reaches to higher amount portraying the precipitation via the condensate aloft due to deep convection. Further, a decline in the IWV and TCLW after the heavy rain shows the dissipation stage of

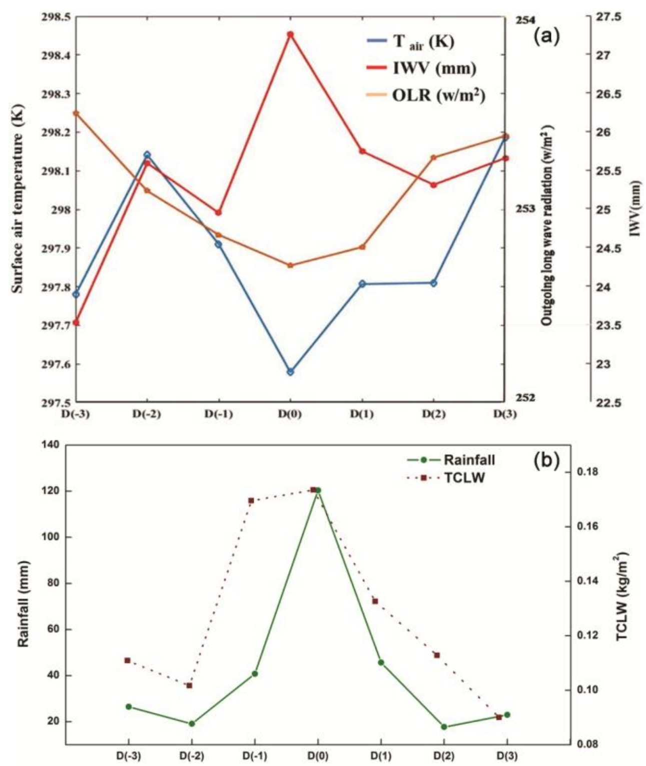

Fig. 4 — Distribution of a) T_{air} , IWV, TCLW and b) rainfall during three days before and after of heavy rainfall events over Chennai during 2001 to 2015.

convective systems. It is also understood that the IWV increase reflects the moistening of the atmosphere due to the convective systems over the study location and after the rainfall occurrence, the atmosphere becoming dry by the removal of IWV in the atmosphere. It is also paramount to note that TCLW cycle looks to mirror the rainfall than IWV. The studies of Zuidema[22] on water vapor, cloud liquid water paths and rain rates retrieved from Special Sensor Microwave Imager (SSMI) over Barrow, Alaska for the period 1987 to 2006 found that the cycles of water vapor, cloud liquid water paths and rain rates are tandem with each other but in different magnitudes during different seasons.

4.2 Scaling of heavy rainy days with the upper air variables

This section mainly deals with the heavy rainy days and associated changes in the upper air variables such as vertical velocity, specific humidity, condensation rate, etc. during heavy rainy days. Figure 5 shows the vertical velocity profile at different pressure levels from surface to 10km altitude during three days before and after the heavy rainfall days. The vertical velocity has been averaged for all heavy rainfall days. The green line of vertical velocity represents the heavy rainy day. It is observed from Fig. 5 that vertical velocity increases from surface to 2 km of altitude during all days (before and after heavy rainfall day). It can be understood from Fig. 5 that before the heavy rainfall, the vertical velocity is very less which is indicated in the blue line, and as heavy rain occurs, the value of vertical velocity increased gradually. After the rainfall occurrence, again the vertical velocity slowly diminished over the study location. It is also to be noted from Fig. 5 that

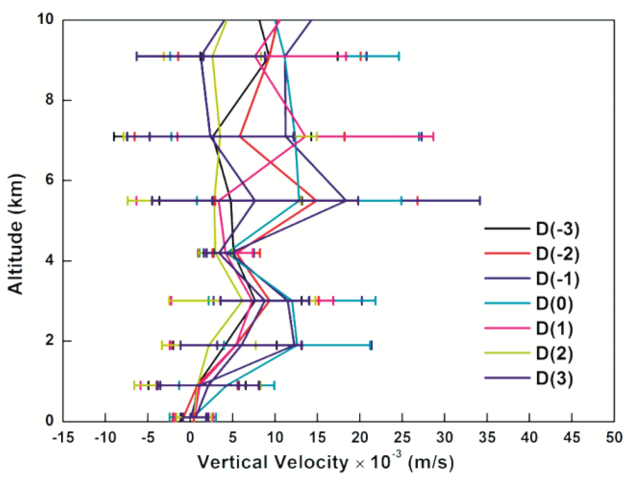

Fig. 5 — Averaged vertical profile of vertical velocity (m/sec) before, on and after the heavy rainfall events over Chennai.

behavior of vertical velocity around 6 km is very high. The average vertical velocity for entire profile during the heavy rainy days is 0.014m/sec, whereas it is minimum during the 3rd day before and after the heavy rainy days with the values of 0.004 m/sec and 0.003 m/sec, respectively. The increase in vertical velocity from surface to 10 km altitude also indicates the negative buoyancy by which the positive restoring force can be preserved which in turn is useful for the deep convective events.

The study also attempted to figure the thickness of the atmospheric layer between 1000 mb and 500 mb pressure levels during heavy rainy days. This is one of the measures by which the information on the type of rainfall occurrence may be provided. We have used the hypsometric equation which mainly makes use of the mean temperature of two levels, specific gas constant, acceleration due to gravity, and the pressure values of two levels. The layer thickness of 1000 mb and 500 mb was verified and found to be higher than 5400 m which are favorable conditions for rainfall activity. As the values that have been obtained in the present work are also higher than 5400 m which represents the rainfall activity over the study location. It is also reported by Uma[23], that the scale height of water vapor over the Bay of Bengal is found to be varied from 1.3 to 2.8 km during the non-convective days, whereas it exceeds 3km during convective days. The increase in scale height infers the mass distribution of water molecules in the atmosphere, which is an indication of higher surface heating over region under consideration. It is also reported that the mean relative humidity of the 1000 mb and 500 mb layer is one of the indicators of heavy rainy days[24]. The mean relative humidity for 1000 – 500 mb layer was obtained in the present study during the heavy rainy days and is found to be more than 70 % on all the days. A maximum of mean relative humidity (100 %) was found on 13 Nov 2014, where the day experienced 78 mm of rainfall, and minimum of mean relative humidity (71 %) has been observed on 18 Oct 2002 with a rainfall of 73 mm. It is also seen that mean relative humidity for the non-rainy days (i.e. with zero rainfall days) at 1000mb-500mb layer is found to be less than 70 %. The mean relative humidity on 02 Dec 2015 is found as 91 % when Chennai experienced 345 mm of rainfall, which is maximum rainfall experienced during the entire study period. In addition to intensity of rainfall, the duration of rainfall is also a very important parameter to consider in the present analysis. The 100 % relative humidity on 13 Nov 2014 is associated with the moderate rainy days one day before and after the heavy rainfall occurrence, where the day with minimum relative humidity on 18 Oct 2002 is found to be an isolated rain event.

4.4 Relation of condensation rate with the heavy rainy days over Chennai

It is reported that the extreme precipitation events are scaled with ICR and specific humidity[11]. This scaling is mainly useful to understand the heavy rainy days, and the associated behavior of lapse rate, temperature etc. The ICR which includes the coordinates of vertical velocity, saturation specific humidity and potential temperature is of great importance in scaling the heavy rainy days. The scaling of heavy precipitation events with the ICR and specific humidity has been reported by O'Gorman[11] using the idealized General Circulation Model (GCM). It is found from their study that the scaling of heavy precipitation events is very important over warmer regions. It is also reported that the heavy precipitation events are scaled globally with the mean surface temperature need not scale regionally. In the present study, we have estimated the ICR during all heavy rainy days, and also three days before and after the heavy rainy days. Figure 6 shows ICR over the study location for all the heavy rainy days. Since, it is known that a minimum of 3-7 days are required to form 10^2 microns of cloud droplet, we have averaged the ICR for three days, i.e. one day before and after, and on the day of heavy rainfall as one set, remaining as the average of three days prior to heavy rainfall days and after the heavy rainfall days. The bars in Fig. 6 depict the standard deviations for the respective levels. It is conspicuous from Fig. 6 that ICR is high during heavy rainfall days, whereas it is less before and after the heavy rainfall days. Though the maximum ICR is found at 300 mb which does not produce rains normally, the second maximum of ICR is at 700 mb and followed by 500 mb with values of 2.70×10^{-7} and $2.66 \text{ x } 10^{-7}$. The ICR at 900 mb level is very less which infers the condensation starts occurring at levels above 1km altitude. The gradient in the condensation rate is very steep between the regions 900 mb – 700 mb. The higher values of condensation rate reveal the higher values of vertical velocity, potential temperature and the gradient of potential temperature at the saturated level.

Using the moist adiabatic derivative of saturated specific humidity and vertical velocity, precipitation extremes can be calculated between two pressure levels. We have calculated the precipitation extreme by using the above method from surface to 300 mb corresponding altitude[11]. These are plotted with the ICR during the heavy precipitation events. The scatter plot of integrated ICR and heavy rainfall is shown in Fig. 7. From the plot, it can be seen that the integrated ICR is well correlated with the heavy precipitation extreme, and infers the linear proportionate relationship between them. The correlation value is +0.46 at a 0.01 level of significance. It is also found that the correlation between integrated ICR and precipitation extreme is high at 700 mb level (r = +0.62) which shows the close association of specific humidity with condensation rate. As it is evident that the ICR is directly proportional to

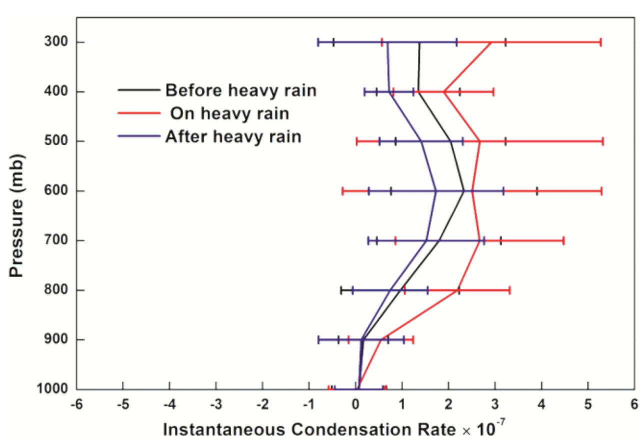

Fig. 6 — Vertical profile of condensation rate over Chennai before, on and after the heavy rainfall events during the northeast monsoon of 2001 to 2015.

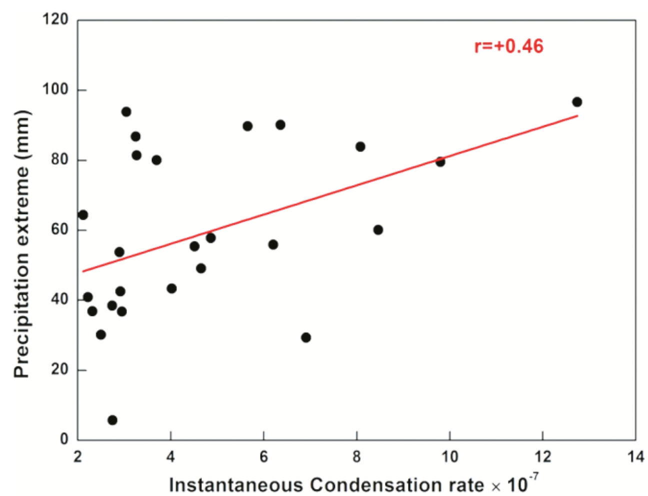

Fig. 7 — Scatter plot of integrated instantaneous condensation rate and integrated precipitation extreme over Chennai during heavy rainfall events.

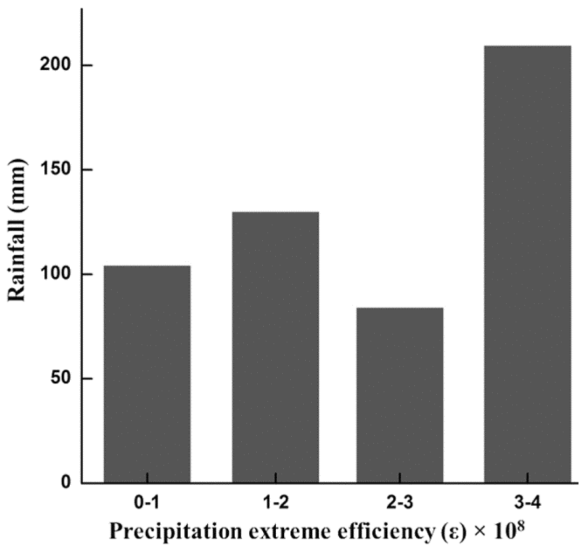

Fig. 8 — Precipitation extreme efficiency (ϵ) during the heavy rainfall events over Chennai.

precipitation extreme, we have obtained the value of precipitation extreme efficiency by dividing the integrated precipitation extreme with the ICR. Singh[25] studied the fall speed of hydrometeors in scaling the precipitation extremes and reported that the efficiency of precipitation extremes represents the conversion of large scale condensation into rainfall as the condensed rain reaches the surface. Figure 8 depicts the precipitation extreme efficiency (ϵ) binned for different heavy rainy days. The difference in ground reaching heavy rainfall and the precipitation extreme derived from the specific humidity may be due to the change in space and time of rainfall in accordance with the condensation. From Fig. 8, it can be seen that (ϵ) is linearly varying with the surface reaching rainfall over Chennai. The higher bin of ϵ ($3 - 4 \times 10^8$) falls for average rainfall of 220 mm and the minimum average rainfall (100 mm) occurred for the bin of 0 to 1×10^8. This clearly indicates that as the rainfall increases, there is a lesser possibility of temporal and spatial smearing of rainfall which occurs due to the fall speed of hydrometeor after the condensation takes place. The spatial smearing might happen due to turbulence and cloud – scale circulation as reported by Singh[25]. In order to quantify the region effective condensation that explains the changes in surface reaching rainfall, more observation on space and time scale are essential.

5 Conclusions

A comprehensive study has been made to understand the meteorological behavior during the heavy rainy days over Chennai for the NE monsoon during the years 2001 to 2015. The heavy rainy days (a total of 38) are studied by scaling them with IWV, TCLW, OLR, ICR etc. Based on the work carried out, the following conclusions are made.

i) The linear association of IWV and rainfall over Chennai is very poor during the early season of NE monsoon, and the relationship gradually improved as the season advances.
ii) A close association has been observed between TCLW and rainfall of two consecutive days over Chennai.
iii) The correlation between integrated ICR and integrated precipitation extreme is +0.65, and the efficiency of precipitation extremes distinctly varied among the heavy rainy days and is varied linearly with the surface reaching rainfall.

Acknowledgements

The authors are thankful to the Scientific and Engineering Research Board (SERB), Govt. of India, for sponsoring this work under the EMR scheme.

References

1 Mooley D A & Parthasarathy B, *Clim. Change*, 6 (1984) 278.
2 Krishnamurthy V & Goswami B N, *Journal of Climate, 13*(3) (2000) 579.
3 Rajeevan M, Bhate J & Jaswal A K, *Geophys. Res. Lett.*, 35 (2008) L18707.
4 Lakshmi Kumar T V, Koteswara Rao K, Barbosa H & Uma R, *Nat. Haz.*, 73(2) (2014) 1003.
5 Kripalani R H, Kumar & Pankaj, *Int J Climatol*, 24 (2004) 1267.
6 Balachandran S, Asokan A & Sridharan S, *J. Earth. Syst. Sci.*, 115 (2016) 349.
7 Rajeevan M, Unnikrishnan C K, Bhate J, Niranjan Kumar K & Sreekala P, *Meteorol. Appl.*, 19 (2012) 226.
8 Rajeevan M, Jyoti Bhate, Kale J D & Lal B, *Current Science*, 91(3) (2006) 296.
9 Singh R, Pal P K & Joshi P C, *J. Geophys. Res.*, 115 (2010) D18124.
10 Mahakur M, Prabhu A, Sharma A K, Rao V R, Senroy S, Singh R & Goswami B N, *Curr. Sci.*, 105(8) (2013) 1124.
11 O'Gorman P A & Schneider T, *J. Clim.*, 22 (2009) 5676.
12 Iribarne J V & Godson W L, *Atmospheric Thermodynamics*, 2nd Ed. D. Reidel, (1981) 25.
13 Khairoutdinov M F & Randall D A, *J. Atmos. Sci*, 60 (2003) 607.
14 Muller C J & P A O'Gorman L E, *J. Climate*, 24 (2011) 2784.
15 Aruna K, Lakshmi Kumar T V, Narayana Rao D, Krishna Murthy B V, Suresh Babu S & Krishnamoorthy K, *J. Atmos. Solar Terr. Phys.*, 103 (2013) 116.
16 Suresh R, *Pure Appl. Geophys.*, 164 (2007) 1511.
17 Thornthwaite C W, *Geographical Reviews*, 38(1) (1948) 55.

18 Lakshmi Kumar T V, Koteswara Rao K, Uma R & Aruna K, *J. Water Clim. Change*, (2014) 128.
19 Bretherton C S, Peters M E & Back LE, *J Clim*., 17 (2014) 1517.
20 Ross J R, Elliott P W & Seidel D J, *J. Hydrometeorol*, 3 (2002), 26.
21 Roca R, Fiolleau T & Bouniol D, *Journal of Climate*, 30 (2017) 4283.
22 Zuidema P & Joyce R, *J. Geophys. Res*., 113 (2008) D05205.
23 Uma R, Lakshmi Kumar T V & Narayanan M S, *Theor. Appl. Climatol.*, (2015).
24 Junker N W, Schneider R S & Fauver S L, *Weather and Forecasting*, 14 (1999) 701.
25 Singh M S & O'Gorman P A, *Geophys. Res. Lett.*, (2014).