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Validation of Cloud Burst over Chennai in 2015 using Radar data

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सार – भारत मौसम विज्ञान विभाग द्वारा बादल फटने को किसी क्षेत्र में 10 सेमी / घंटा की दर से दर्ज की गई वर्षा की दर के रूप में परिभाषित किया गया है। अनेक स्थानों पर कई स्वचालित मौसम स्टेशनों (एडब्ल्यूएस) के स्थापित होने के कारण वर्षा की दर को मापना आसान हो गया है, हालांकि कुछ विलग क्षेत्रों में वर्षा की अत्यधिक तीव्रता एडब्ल्यूएस या स्वत:लेखी वर्षा मापी वेधशाला की अनुपलब्धता के कारण अधिकांशत:दर्ज नहीं की जाती है। आईएमडी द्वारा बड़ी संख्या में डॉपलर मौसम रेडार की स्थापना और कई औरस्थापित किए जाने वाले (कुल 55) को देखते हुए, बादल फटने के अधिकांश मामलों को रिकॉर्ड करना संभव हो सकेगा। इस शोध पत्र में हमने डॉप्लर मौसम रेडार के डेटा का उपयोग करके चेन्नै में बादल फटने को मापने की एक तकनीक पर चर्चा की है। 2015 में, तीन सिनॉप्टिक-पैमाने की मौसम प्रणालियों ने पूर्वोत्तर मॉनसून ऋतु के दौरान तमिलनाडु और पाँडिचेरी को प्रभावित किया, जिससे व्यापक वर्षा हुई। चेन्नै और आसपास के जिलों में अत्यधिक भारी वर्षा हुई, जिससे चेन्नै पूरी तरह से जलमग्न हो गया। चेन्नै में बादल फटने के कारण 100-200 मिमी / घंटा की दर से वर्षा हुई। इस शोध पत्र में, हमने वर्षा का आकलन करने के लिए पहली बार रेडार डेटा का उपयोग किया है जिससे 8 से 9 नवंबर और 30 नवंबर से 2 दिसंबर 2015 के दौरान चेन्नै में बादल फटने के कारण हुई मूसलाधार वर्षा की जांच और पुष्टि की जा सके ।

ABSTRACT. Cloudbursts are defined by India Meteorological department as rain rate recorded as 10 cm/hour over an area. Measuring rain rate has become easier due to many Automatic weather stations (AWS) installed at a number of places, however such a high intensity of rainfall over an isolated area is not recorded most of the time due to non-availability of AWS or an observatory having Self-recording rain gauge. In view of a large number of Doppler Weather Radars installed by IMD and many more to come (total 55), it will be possible to record most of the cases of cloudbursts. In this paper we have discussed a technique to measure Cloudburst in Chennai using DWR data. In 2015, three synoptic scale weather systems affected Tamil Nadu and Pondicherry during NE Monsoon season causing extensive rainfall activity over the region. Extremely heavy rains occurred over Chennai and surrounding districts, due to which Chennai was fully inundated. Rain rate of the order of 100-200 mm/hour led to cloudburst over Chennai. In this paper we have for the first time used radar data to derive rainfall estimates in order to examine and substantiate the cloud burst that led to these torrential rains over Chennai during 8-9 November and 30 November-2 December, 2015.

Key words – DWR (Doppler Weather Radar), NE monsoon (Northeast monsoon), Chennai, Cloud burst, Floods.

1. Introduction

Cloud bursts are commonly used to designate a torrential downpour of rain which by its relative high intensity suggests bursting and discharge of a whole cloud in one go (Woolley, 1946). A lot of studies in India particularly are limited to Himalayan region due to some of the past few devastating occurrences of cloudburst over this area for, *e.g.*, The Uttarakhand flash floods in 2013, Leh Cloudburst in 2012 etc (Thayyen *et al*., 2010; Das 2013; Ziegler *et al*., 2016; Kumar *et al*., 2018; Gupta *et al*., 2013; Dimri *et al*., 2016). Torrential & incessant rains during NE Monsoon, 2015, ravaged Chennai city particularly, bringing life to standstill. Three years in a row the agricultural season, Rabi & Kharif, has been getting affected by these floods causing intense heavy rains (Ray *et al*., 2018). A few recent studies have pointed out the increasing frequency of extreme rainfall events over India, due to the warming climate (Ray *et al*., 2019). Also, Indian Ocean have shown a warming trend over the last several decades (Rao *et al*., 2012; Roxy *et al*., 2015), potentially enhancing the supply of moisture to the monsoon region and increasing the rainfall amounts. Year 2005 was recorded as the hottest year of the century and incidentally in the same year, worst urban flooding was reported in Mumbai on 26-27 July, 2005 with historical rainfall of 944 mm.During 3-4 December, 2005 Chennai was affected by floods, when 500000 people were affected after rain fed rivers and lakes inundated almost 75% of the city (De *et al*., 2013). Similarly, in 2015, the flooding over Chennai was another historical event when records were broken. According to WMO, the global average surface temperature in 2015 broke all previous records. It was 1 °C above the pre-industrial era.

Winter time precipitation over Southern Peninsula is generally attributed to westward propagating tropical waves near 10°N over the Bay of Bengal (Krishnamurti *et al*., 1997 a&b). During this period, the wind flow over Tamil Nadu and parts of southern peninsula is generally from northeast and as the winds veer with height, the flow becomes easterly & further southeasterly. In the upper troposphere, the flow becomes southerly to southwesterly, around the anticyclone over Bay of Bengal. The monsoon easterly jet disappears & the weak southerly/easterly prevails between September to November at 150-100hPa level. This period is also referred to as the Northeast Monsoon period by India Meteorological Department. Heavy to very heavy rains occur in Tamil Nadu & coastal Andhra Pradesh during this period, in association with the passage of Cyclonic Storm and Depressions across the area. This winter rainfall contributes 11% of the annual rainfall received by India. Coastal Tamil Nadu receives 60% of its annual rainfall during this period.

During the month of November, 2015 three important episodes of heavy rainfall over Tamil Nadu, particularly Chennai led to flooding and lot of damage to property & life. The main synoptic systems present during these three episodes of heavy rainfall were:

(*i*) Deep depression over Bay of Bengal (8-10 Nov).

(*ii*) Well marked low pressure area over SW Bay of Bengal (14-16 Nov).

(*iii*) Trough/Low pressure area (30 Nov-2 Dec).

The total accumulated rainfall recorded in Chennai district from 1 November to 5 December was 1416.8 mm against the normal of 408.4 mm.

Raghavan (2003) has pointed out that rainfall recorded by a rain gauge is a point measurement and thus not truly representative of its surroundings. For all practical purposes, whatever be the increase in the number of rain gauges, the rainfall obtained from them would not be fully representing the areal coverage and spatial distribution of rainfall as that obtained from digital Radar. Estimating surface precipitation rates from DWR observations is a complex and challenging task. Not many researchers have attempted that. However, DWR derived surface precipitation rates are assimilated in the high-resolution models by various authors (Routray *et al*., 2021; Prasad *et al*., 2014; Osuri *et al*., 2015; Wang *et al*., 2010).

This paper for the first time measures the heavy rainfall episode and associated cloud bursts over Chennai using Radar data from S-band Doppler Weather Radar (DWR) installed in the Cyclone Detection Centre (CDR) of India Meteorological Department in Chennai. The paper emphasizes the use of Doppler Weather radar data for validating cloudburst over a region. The digital data obtained from the radar has been used from 8 to 10 November and 30 November to 2 December, 2015 to derive rain rate for the heavy rainfall event. Due to technical problems data was not available for 15 November; therefore, analysis was done for other two events. The rain rate is derived from reflectivity using relation z (Reflectivity factor) =267*R (rain rate)$^{1.345}$ based on Marshall-Parmer relationship(Suresh *et al*., 2005). This relationship estimates well the rain rate as measured by the self-recording rain gauges located within 100 km radius from the DWR. The relationship was tested for its operational applicability during March, 2002-December, 2003 and found that the accumulated precipitation from the radar estimation was within an error of 15% from the rain gauge measured values. Rainfall data obtained from precipitation accumulation product of DWR at Chennai has recently been compared and validated with rainfall recorded at 16 stations located within 100 km range of the radar (Amudha *et al*., 2014). Statistical parameters like correlation, mean error and mean absolute error have been calculated. When rainfall is indicated by both radar and observatory, a high degree of correlation, at 0.98, between the conditional means of radar and observatory rainfall in various ranges is observed along with consistency in underestimation of rain by radar. The authors concluded that the information on the twenty-four hours accumulated areal distribution of precipitation can be used by the water managers and operational hydrologists for the effective water management over the catchments since the error in rain rate estimation over a wider area is relatively small in comparison to point rainfall estimation.

2. The underlying science of radar rain estimates

Weather radar is an essential tool for mesoscale observation, prediction and warning. This became feasible because of its better resolution in spatial and temporal scales. Precipitation is one of the parameters which is of much use and depicts the severity of prevailing weather. Precipitation in normally observed by rain gauges and its accumulation is reported in the 0300 UTC surface observation reports. The rain-gauge though a point observation normally represents a wide area spanning several hundred square kilo-meters. Thus, this lags in spatial representation for proper planning. Satellites overcome this lacuna, but however have resolution and observational difficulties, *i.e*., equating the observed radiances/temperature to rain equivalents is still a field of on-going research.

Radar observes the signals of the backscattered clouds and directly attributes it to rainfall through the Marshall Palmer equation.

In general terms the Marshall Palmer equation equating the rain rate with radar observed reflectivity factor is given by:

$$Z = AR^b$$

where, the constants A and b depicts the drop size distribution in the scattering volume. Z is the radar reflectivity and R rain-rate. Thus, by assuming asingle $A$and$b$ we concur that the same Drop size distribution (DSD) in targets exists and accordingly rain fall intensity is derived. This assumption is normally valid for a stable rain with not much variability in space and time.

3. Methodology used

Methodology for retrieval of data from DWR Chennai is discussed in detail below. The NCEP-NCAR reanalysis daily datasets for 9 November, 16 November and 1 December, 2015 were used to study the daily moisture flux. This data has been widely used by many researchers over the last few years in tropical climate researches. The Moisture flux plots were generated at 850 hPa and 500 hPa level using the formula: Specific humidity times the vector wind (u, v) at that level. Roshani *et al*., 2013) has discussed in detail the generation of moisture flux plots. Districtwise rainfall calculated by IMD using area weightage was used for comparisons. AWS data from IMD stations located in Chennai was also considered for analysis.

3.1. *Data acquisition and analysis from Doppler Weather Radar*

IMD radars perform two types of scan every ten minutes. One for long range surveillance where the reflectivity field is alone used and another volumetric data with ten sweeps, elevation angles 0.2, 1.5, 2.0, 3.0, 4.5, 6.0, 9.0, 12.0, 16.0, 21.0, scan range 250 km useful for weather study with all basic moments, *viz*., reflectivity, velocity, spectrum width availability(Roy Bhowmik *et al*., 2011). The volume data from DWR Chennai is in Rainbow 5 format and is being converted into SIGMET-IRIS RAW format in near time at Central server at New Delhi. For the current study this volume data generated has been used. This RAW data has been ingested in IRIS® Software to generate Surface Rainfall Intensity (SRI) Product (Vaishala, 2014). Rather than the conventional 1km height CAPPI (Constant altitude Plan Position Indicator] the entire volume between 0 km to 10 km above the radar location has been chosen in deriving a weighted reflectivity for generating SRI, this has the advantage of overcoming the under-estimation over cone of silence as the radar and rain affected areas are very close. A Vertical profile of Reflectivity (VPR) has been used in filling up clutter removed regions and also the effect of Bright Band anomaly. VPR reconstruction from Zero Degree isotherm is a part of the software. A height of 4.7 km [long term average of Radio-Sonde Obs.] has been used for zero-degree isotherm. The constants A & b of Marshall-Palmer chosen to be 267 & 1.345 in line with Suresh *et al*. (2005). The generated SRI data has been used in making hourly rainfall accumulation (RAIN1) and subsequently three hourly and daily (RAINN) using IRIS® Software using forward lookup technique. The so generated SIGMET-IRIS formatted Product Data has been decoded using a C code developed by the author based to IRIS Programmers Manual 2014. During this process each of the dumped 940 × 940 ASCII bin has also been matched with the ground points by Geo-referencing over a WGS-84 spherical earth model using PROJ-4Frank, Warmerdam] and GDAL libraries for a Mercator Projection.

As a final quality control measure the non-rainy-day signatures between 26th October, 2015 to 5th December, 2017 both days inclusive has been used as clutter maps in flagging quality rejected bins. This additional Quality stringent scrutiny became a necessity as Chennai being a metropolitan city the mobile tower interference signature power levels which normally vary with weather was getting amplified in by-products that rely upon data integration.

These 250 m (approx.) resolution pixel points were again grouped into categories belonging to each of the preferred study area districts. For this Government of India approved ESRI-Shape files available with IMD have been utilized and feature points extracted using MATLAB® Geo-processing tools. A cumulative average for all the points lying within each of the district of study has been dumped into a separate file (hour wise and day wise) and used for the current study.

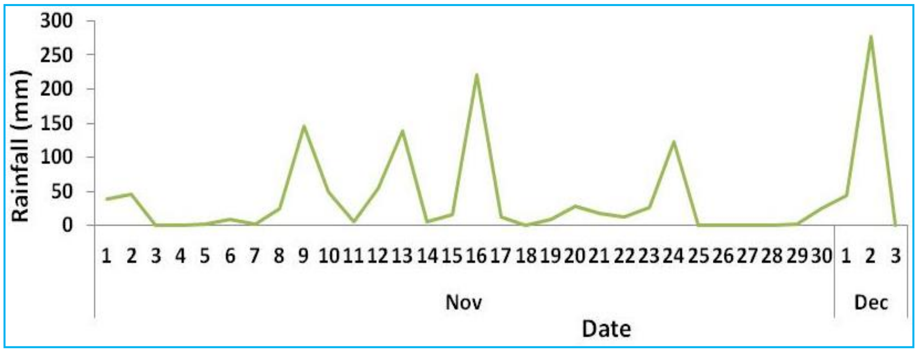

Fig. 1. Daily rainfall from 1 November - 3 December, 2015 over Chennai district

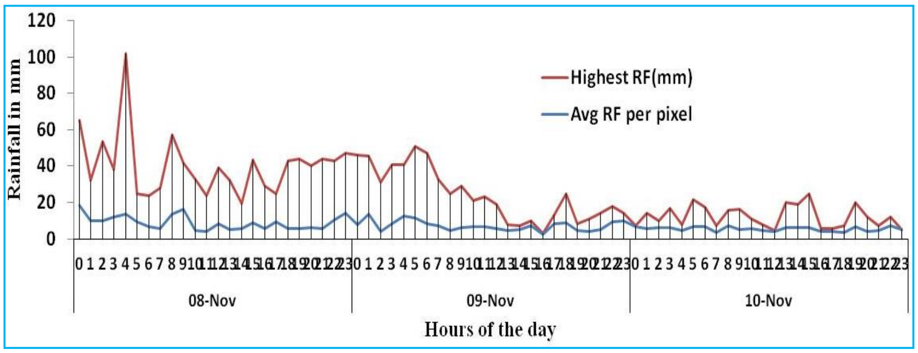

Fig. 2. Hourly variation of maximum and average rainfall recorded over Chennai District, on 8 and 9 November, 2015 as per DWR data

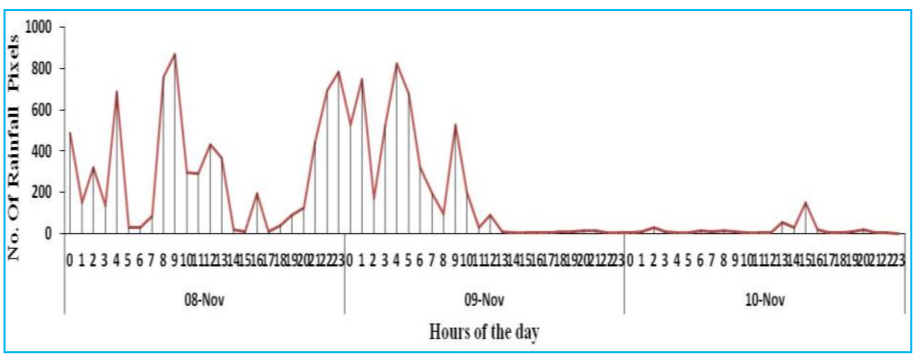

Fig. 3. Hourly variation of Spatial distribution of rainfall over Chennai, during 8-10 November, 2015 using DWR data at IMD, Chennai

4. Results

In Chennai, the weather patterns are dominated by the Northeast monsoon which normally occurs during October-December months. The study area has an average annual rainfall of 1300 mm. The daily total accumulated rainfall for Chennai during the period 1 November to 3 December is shown in Fig. 1. The daily average rainfall was 100 mm and more on a number of days but there were 3-4 major peaks, associated with the above three synoptic systems which led to the extensive rains. They were on 9 November, 16 November and 1 December, 2015. The results in two of these episodes are discussed below.

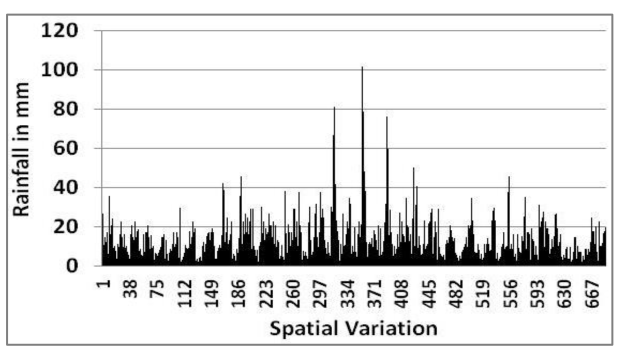

Fig. 4. Spatial variation of rainfall intensity over Chennai district at 0400 UTC of 8th November, 2015

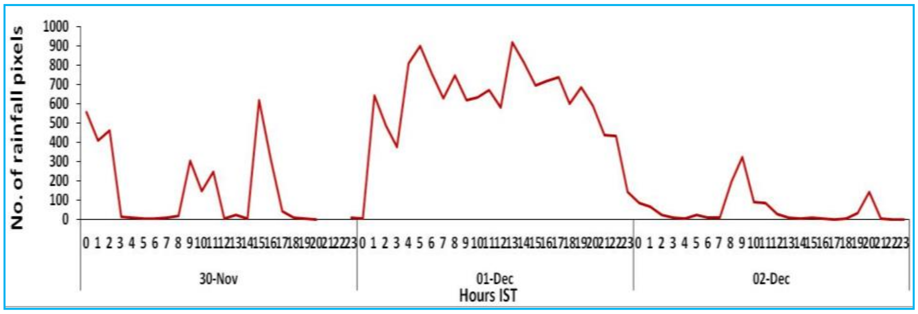

Fig. 5. Hourly variation of spatial distribution of rainfall over Chennai, during 30th November to 2nd December, 2015 using DWR data at IMD, Chennai

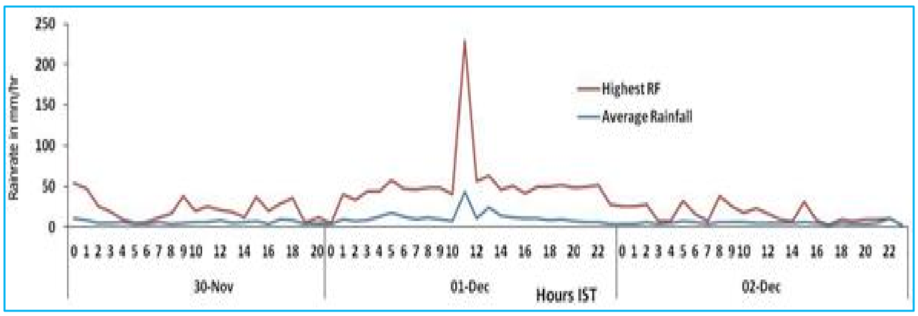

Fig. 6. Hourly variation of maximum and average rainfall recorded over Chennai District, during 30th November to 2nd December, 2015, based on DWR data

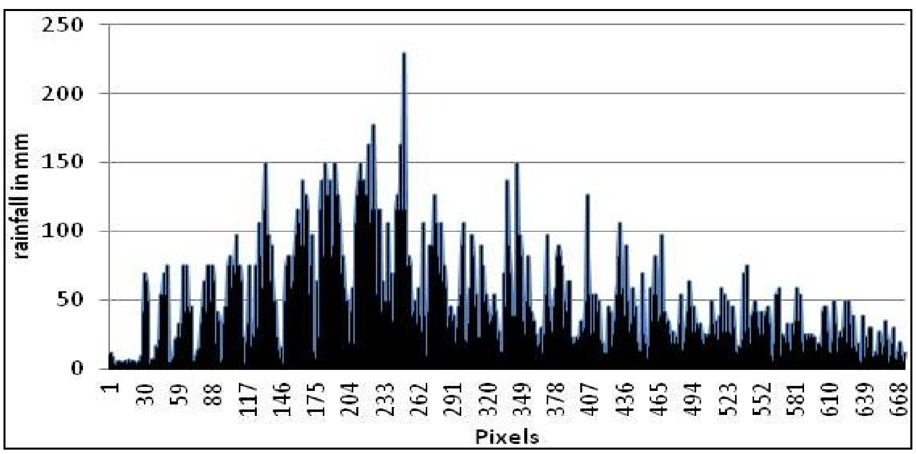

Fig. 7. Spatial variation of rainfall

4.1. *Deep Depression (8-10 November, 2015)*

A Deep Depression crossed north Tamil Nadu coast, close to north of Pondicherry (near Latitude 12.2°N and Longitude 80.0°E) in the evening of 9 November 2015. As per press/media reports, 13 persons lost their lives due to rain related incidents in various districts of Tamil Nadu. 2000 acres of paddy field and 400 acres of bananaplantations were submerged due to heavy rain/strong wind in Villupuram district and 500 acres of banana trees were also damaged due to heavy rain in Cuddalore district on 9 November. Area weighted accumulated rainfall, for Chennai district was 145.6 mm on 9 November. The spatial distribution of hourly rainfall during 8-10 November is shown in Fig. 2. The district was spatially covered with around 900 pixels of DWR; the longest and most intense spell of rainfall was from 0800-1300 UTC of 8 November and 2100 UTC of 8 November to 0500 UTC of 9 November, 2015. The average rain rate varied from 4 mm to 14 mm/hr. The hourly rainfall distribution over Chennai based on DWR data is shown in Fig. 3. In Chennai also there was a nearing cloudburst

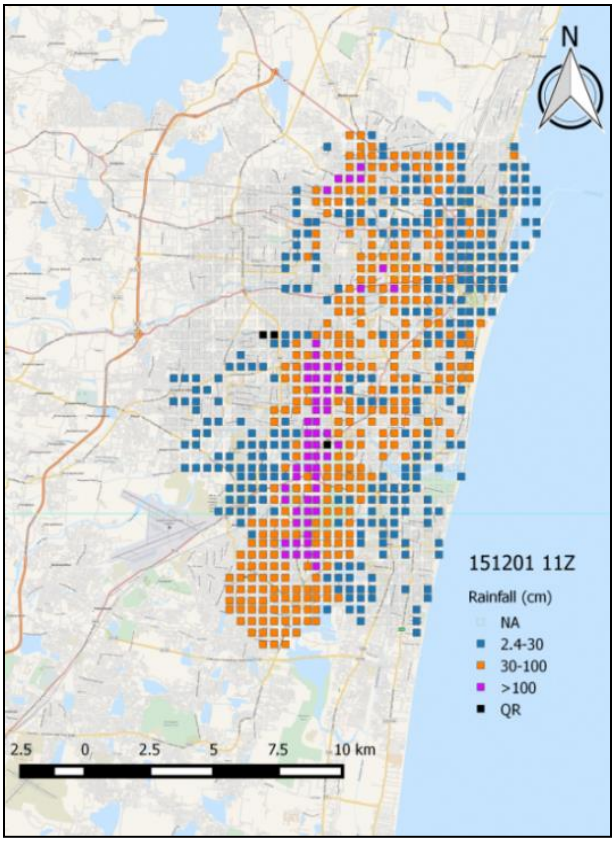

Fig. 8. Radar coverage over Chennai district on 1st December between 1000-1100 UTC

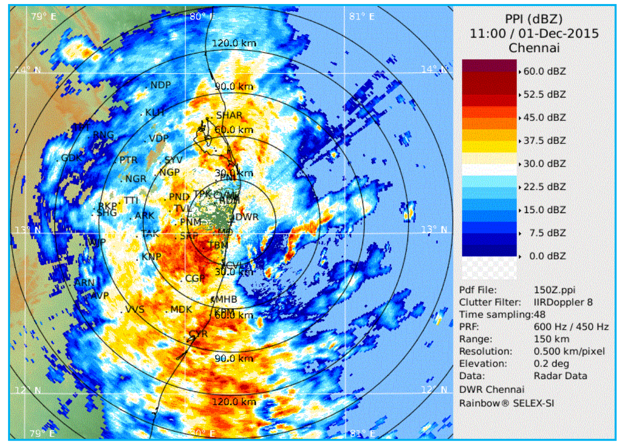

Fig. 9(a). Reflectivity in dBZ for Chennai during the cloud burst hour (1100 UTC of 1st December, 2015)

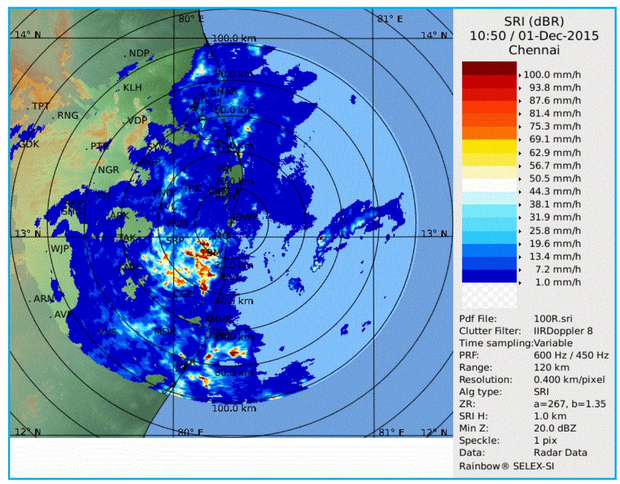

Fig. 9(b). Surface Rainfall Intensity based DWR Chennai radar reflectivity at 1050 UTC of 1st December, 2015

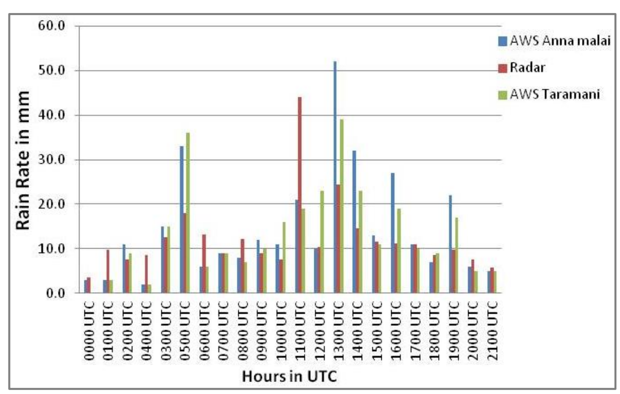

Fig. 10. Comparison of hourly rainfall recorded by Automatic weather stations in Chennai and derived rainfall based on DWR Chennai data

event over a very small area, between 0300-0400 UTC of 8 November with one- or two-pixels recording rainfall between80-100 mm/hr. The spatial distribution of rainfall during that hour of peak rainfall shows that it was limited to a very small area in Chennai (Fig. 4). Average accumulated rainfall over this district was 215 mm on 8 November as per DWR data. The peak rainfall hours of 8 and 9 November were well captured by DWR and AWS data of Chennai.

4.2. *Trough/Low pressure area (30 November - 2 December, 2015)*

Synoptically a trough of low pressure lay over SW Bay and neighbourhood on 28 and 29 November, 2015 and it was seen over SW Bay, off Srilanka & north Tamil Nadu coast on 30 November, 15 and 1 December, 15. This analysis is done for the highest peak of 30 November -2 December. The hourly analysis of spatial and intensity distribution of rainfall was done using Doppler Weather radar data for these three days for Chennai district. The spatial distribution of hourly rainfall during 30 November and 1 December in Chennai district based on DWR data is shown in Fig. 5. The district was spatially covered with around 900 pixels of DWR and the longest and most intense spell of rainfall was from 0000-1800 UTC of

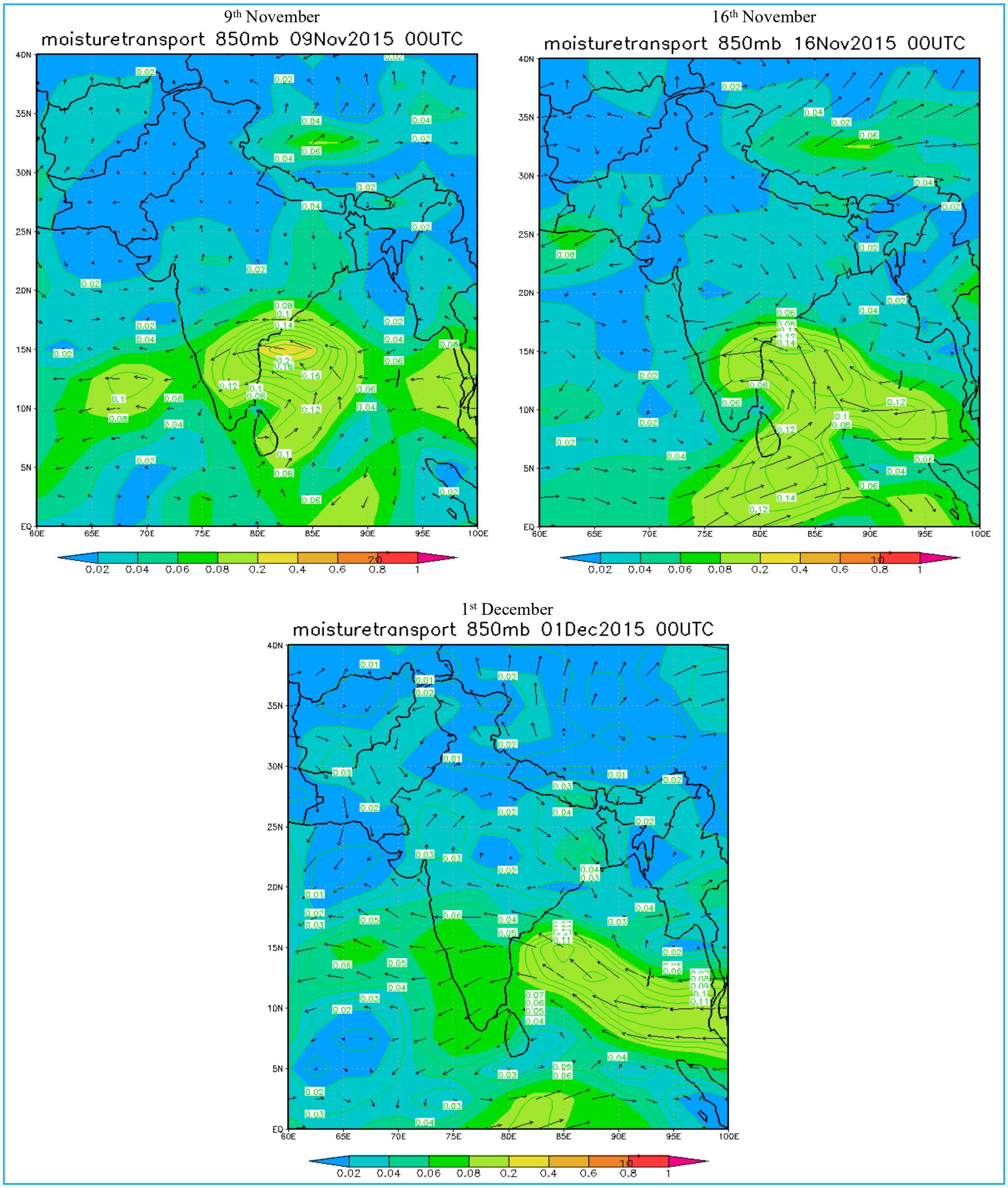

Fig. 11. Wind Surge &Moisture flux (gm*m/sec) at 850 hPa at 0000 UTC of 9th November, 16th November and 1st December, 2015

1st December, 2015. All pixels in the above period reported rainfall; with average rain rate varying from 4 mm to 44 mm/hr. Cloud burst with peak rainfall of 229 mm/hr was reported between 1000-1100 UTC of 1 December in Chennai (Fig. 6). The detailed analysis of the spatial intensity (pixelwise) of rainfall during that hour between 1000 to 1100 UTC is shown in Fig. 7. More than 100 pixels reported >100 mm of rainfall in that hour. All these pixels were located in the form of a squall line (approximately 20-30 kms, north-south, across Adyar river along, Long. 80°E) in the northeast direction of Chennai international airport (Fig. 8). The DWR imagery

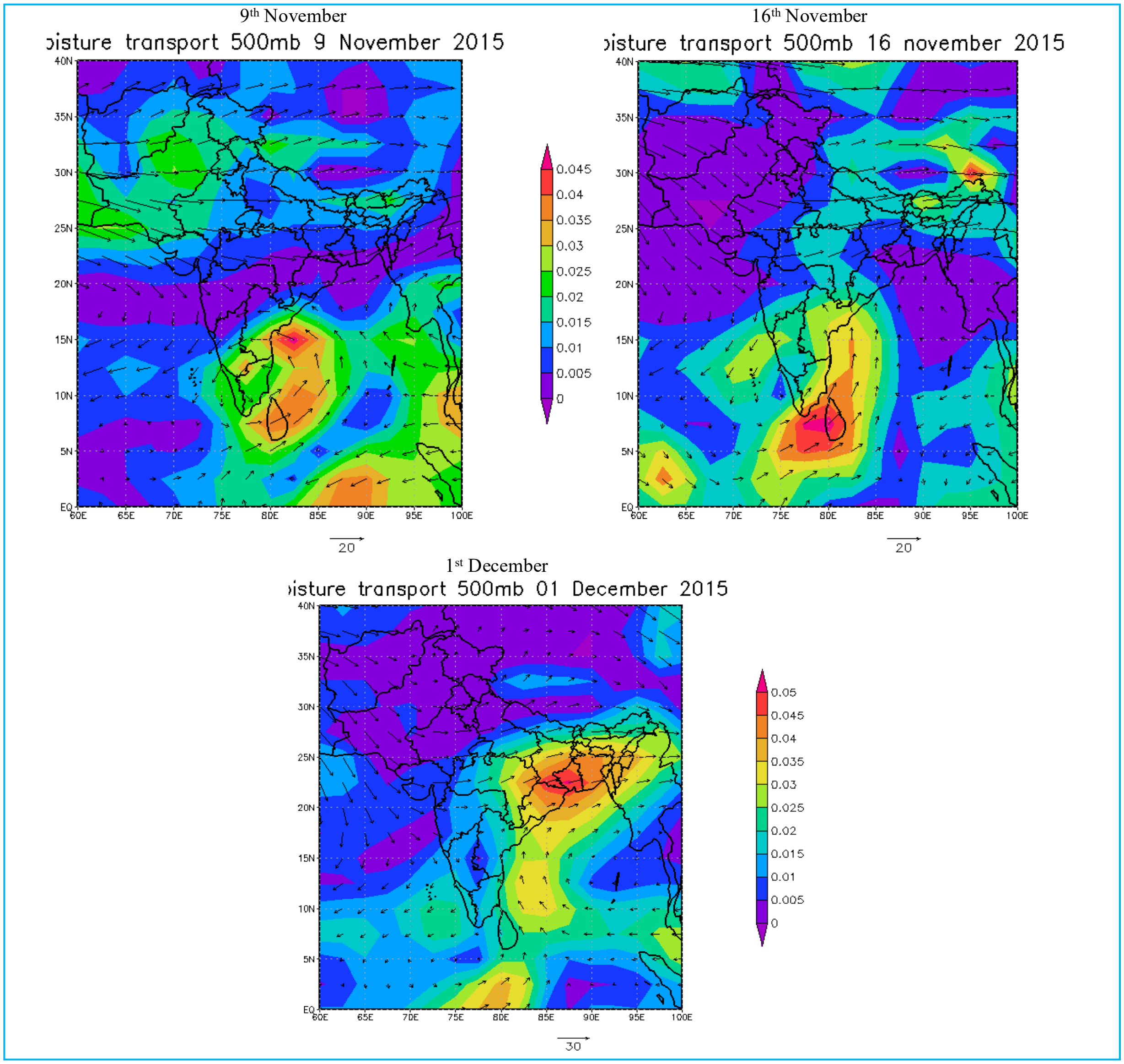

Fig. 12. Wind surge & Moisture flux (gm*m/sec) at 500 hPa at 0000 UTC of 9th November, 16th November and 1st December, 2015

showing reflectivity and surface rainfall intensity in that period is shown in Figs. 9(a&b). The squall line can also be seen in SRI Imagery, depicting rainfall rate >100 mm/hour. The average accumulated rainfall recorded on 2 December (past 24 hour accumulated) as per the raingauge data for Chennai District was 276 mm and the accumulated average rainfall as per DWR data was 279 mm. The hourly comparison of rainfall rate recorded in two AWS stations in Chennai district and hourly average radar data is shown in Fig. 10. The diurnal variation of rainfall as captured by AWS and DWR was alike and the peak rainfall was reached between 1000 and 1500 UTC of 1 December, 2015.

5. Discussion

Westward movement of trough of low, well-marked seasonal trough, low pressure systems and easterly waves enhance the NE monsoon rainfall over south peninsula. An important feature during NE monsoon is the frequent wind surges which move from east to west along with the easterly flow. These surges often carry a wind as high as 13-14m/s. Moisture Convergence is the measure of the degree to which moist air is converging into a given area, considering the effect of converging winds and moisture advection. Areas of persistent moisture convergence are favoured regions for thunderstorm development, if other factors (*e.g.*, instability) are favourable. Moisture flux convergence has also been used extensively for real time severe-weather forecast operations. It is highly effective in highlighting mesoscale boundaries between different air masses near the earth's surface. The heavy rainfall episode over Chennai in southern India during December 2001 was analysed by Krishnamurthy *et al*. (2002) and they had suggested that the wind surges resulted in mass and moisture convergence ahead of the wind maxima, contributing to rising motions and rainfall over Chennai. The trade wind easterlies, the waves embedded within these easterlies and the trade wind surges and associated mass convergence also convey moisture zonally near 10° N. The same was attempted for this episode and it was seen that during the above synoptic events, the strong easterly wind surge was seen in 850 hPa level along 12°C on the east coast (Fig. 11). These wind surges led to moisture convergence ahead of the wind maxima, contributing to rising motions & rainfall. The streamline analysis at 850 hPa for 1 December and other two events indicated the presence of an east west trough extending between 5-10°N from 60°E to 80°E and feeding moisture into the winds converging over Chennai & adjoining area (Fig. 11). There was a prominent subtropical westerly trough at 500hPa, extended much southwards than its normal latitude, producing favorable environment for sustained rising motions ahead of the upper trough over coastal Tamil Nadu (Fig. 12). The latent heat released in the lifting process provided the buoyancy to the cloud air to lift the moist air above the freezing level. Generated strong upward velocities in the clouds lifted the cloud tops to very high levels forming deep convective clouds. These clouds provided very heavy rainfall of the order of 100-200 mm/hour amounting to cloud burst. The upper level anticyclonic circulation over Bay of Bengal at 15°N also provided favorable environment for the southeast winds to provide continuous supply of moisture to the heavy rainfall episodes. The presence of trough caused further lifting of the moist air to above freezing levels, thus transforming the stratus clouds to deep convective clouds. In order to bring out the area of cloudburst (100 mm rainfall) the analysis done in this paper using Doppler Weather Radar is different from the traditional analysis and is described in data analysis section. Data extracted in each pixel is analysed and plotted to provide a detailed rainrate over a period of time. For validation with available raingauge data it was necessary to do the analysis for the district as a whole since the error in rain rate estimation over a wider area is relatively small in comparison to point rainfall estimation.

Because of El Nino effect, Southwest monsoon of India 2015 was weaker than normal. The seasonal monsoon rainfall was 86% of long-term averages. Studies have shown that south west and northeast monsoon (NE monsoon) have negative correlation (Kothawale & Kulkarni, 2014). This year's high NE monsoon rainfall performance is consistent with earlier findings of negative correlation between the two monsoons and in the El Nino years.

Although El Nino has a positive effect on winter monsoon, but the phenomenon is not the only factor deciding excess rain during NE monsoon. Some of the non-el-nino years like 2005 saw the state receive 79% excess rainfall. Similarly, years 2007, 2008 and 2009 also recorded excess rainfall, but they were not due to the El Nino effect.

In the present study it could be concluded that

(*i*) Radar data could substantiate the cloud burst phenomenon, which occurred due to continuous formation of deep convective clouds and their movement from Bay of Bengal to Chennai city during all three events and particularly very prominent on 1 December, 2015.

(*ii*) The unprecedented rainfall in the three episodes resulted due to frequent wind surges (carrying wind of 13-14 m/s^2) that moved from east to west along with the easterly wave.

(*iii*) High moisture fluxes, upward lifting of moisture to above freezing levels led to the continuous formation of deep convective clouds.

(*iv*) Using Radar data, we could track movement of clouds, their transformation into deep convective clouds and their spatial and temporal scales.

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Disclaimer : The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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