*Journal of Geosciences and Geomatics, 2015, Vol. 3, No. 3, 68-78*
Available online at http://pubs.sciepub.com/jgg/3/3/3

DOI:10.12691/jgg-3-3-3

# Some Aspects of Thunderstorm over India during Pre-Monsoon Season: A Preliminary Report-I

**Yashvant Das**[*]

Research and Modeling Division, AIR Worldwide /Verisk Analytics India Private Limited, Hyderabad, India
*Corresponding author: Yashvant.das@gmail.com

*Received June 19, 2015; Revised July 13, 2015; Accepted July 20, 2015*

**Abstract** Thunderstorm, resulting from vigorous convective activity, is one of the most magnificent weather phenomena in the earth's atmosphere. The severe thunderstorms associated with thunder squall, hail storm, tornado, flash flood and lightning cause extensive damage and losses to lives and property. A common feature of the weather during the pre-monsoon season over the Indian region is the outburst of severe local convective storms. This paper presents on the aspects of the realized significant weather phenomena thunderstorm, which is supported through the analyses of thermodynamic instability indices based on the radiosonde and rawinsonde (RS/RW) ascent products from India Meteorological Department (IMD) for the pre-monsoon season for different identified cities of SAARC STORM project region of India. Doppler Weather Radar (DWR) images and Skew-T diagrams are also analyzed which support the thunderstorm activities in different locations of India. The convective available potential energy (CAPE) and convective inhibition (CIN) energy show the favorable conditions for the thunderstorm to occur in some of the identified stations; however, due to physiographic uniqueness of Indian subcontinent, the values of CAPE, CIN and other thermodynamic parameters show different values in different stations. Moreover, the variation in threshold values of CAPE in different regions makes thunderstorm forecasting difficult which may add uncertainty to loss estimation for risk assessment. A simple outline on thunderstorm risk assessment model development steps are also highlighted as a future work for the quantification of losses, so that the likely probability of occurrences of events with their frequency, location, severity and extent of losses can be modeled and accessed ahead of time for the betterment of the society.

***Keywords:*** *thunderstorms (Thunder squall, hailstorm, tornado), thermodynamic instability parameters/indices, modeling, risk*

**Cite This Article:** Yashvant Das, "Some Aspects of Thunderstorm over India during Pre-Monsoon Season: A Preliminary Report-I." *Journal of Geosciences and Geomatics*, vol. 3, no. 3 (2015): 68-78. doi: 10.12691/jgg-3-3-3.

## 1. Introduction

Thunderstorm in the tropics evoke spectacular images of towering cloud masses with sudden electrical discharges manifested by a lightning and thunder enjoined with vigorous circulations and thus have the potential to spawn severe weather [2,20]. Thunderstorm consist of three stages of evolution, namely, cumulus (updraft persisting throughout the cell), mature (presence of both the updraft and the downdraft), and dissipating (marked only by the downdraft throughout the cell) [6,13,38] and are classified as single cell, multicell, squall line and supercell [4,5]. The thunderstorm cloud is almost always cumulonimbus, in which individual cells produce rain, often copious, and sometimes hail, strong winds and even tornadoes [20,38]. A thunderstorm is considered to be severe, if wind gusts reach more than 75 kmph [20]. However, a thunderstorm is considered severe, if winds reach or exceed ~93.34 kmph, and/or produces hail which is one inch (25mm) in diameter or larger, and/or produces a tornado (National Weather Service, USA). Usually, thunderstorms have the spatial extent of a few kilometers (4-8 km, breadth, 10-20 km length, and height exceeding 6 km) and life span less than an hour (30 to < 60 min). However, multi-cell thunderstorms develop due to organized intense convection, may have a life span of several hours and travel over a few hundreds of kilometers [13,38]. A squall line is defined as a line or narrow band of active thunderstorms, if they extend 100's of km leaving almost no gap between them is known as line squall thunderstorms [39]. Thunderstorms constituent a family of severe local storms, which comprises events such as tornadoes, hail stones, strong surface wind speed (gust) and squally winds and flash floods [39], which may also include wind shear and turbulence. The squall of a thunderstorm can gust to 185 kmph, and its effects are often compounded by intense rainfall, large hail or lightening. Individual storms usually affect only small areas, but there may be many such storms at any one time in a particular region. Some thunderstorms and the peripheral circulation of some tropical cyclones are accompanied by tornadoes, which are among the smallest but most destructive features of atmospheric circulation. Tornado wind speeds can exceed 350 kmph. The highest wind speeds in thunder squalls may reach up to 140–150 kmph.

India is a vast tropical country with unique geographical set up, physiography and geomorphology.

Synoptic scale weather phenomenon viz. thunderstorms associated with sub-perils like squall, hail and tornado are the common features in certain and some parts of the country. The intense convection activity due to strong heating of landmass during mid-day over the Jharkhand (Chhotanagpur Plateau) and movement towards southeast and mixing with the warm moist air mass triggers the Nor'westers to develop [38]. The 'Nor'westers' are severe thunderstorms that form and move from northwest to southeast over the eastern and northeastern states of India during the pre-monsoon season, and are locally named as '**Kal-Baisakhi'** which means calamities in the month of Baishakh [13,38].

The degree to which these conditions are present and the synoptic situations causing the favorable conditions differ from region to region [20]. The main regions of high thunderstorm activity in India during the pre-monsoon season are [38]:

i) The area stretching from Jharkhand, Bihar, Sub-Himalayan West Bengal, Gangetic West Bengal, Odisha, Chhattisgarh, Assam and adjacent states to east Madhya Pradesh, east Vidarbha and adjoining Andhra Pradesh , ii) Southwest Peninsula, and iii) Northwest India outside Rajasthan. The favorable environmental conditions and features in these regions give raise the spectacular severe weather phenomenon.

The development of the thunderstorms is greatly governed by the overall synoptic scale disturbances in which mesoscale processes and land surface processes play an important role. The synoptic scale disturbances create the conditions favorable for the occurrence of thunderstorms. The conditions favorable for the occurrence of thunderstorms are [20]:

- Suitable synoptic conditions to cause low level convergence and upper level divergence which will act as a trigger and release the instability present in the air mass,
- A dynamical mechanism to release the instability present in the atmosphere due to some upper air flow which by advecting warm air in the lower troposphere and cold air in the upper atmosphere can increase the instability,
- Day time heating and orography,
- Adequate supply of moisture in the lower troposphere,
- Conditional and convective instability in the atmosphere, and
- Mesoscale distribution of land surface features.

Thunderstorm days are the days, when thunder is heard and flash of light is seen in the sky and it is recorded by observatories. By International agreement a 'thunderstorm day' is defined as a day on which thunder is heard, regardless of the actual number of thunderstorms [44]. According to the National Oceanic and Atmospheric Administration (NOAA) National Weather Service**,** approximately 1800 thunderstorms occur at any given time in the planet, resulting in about 45000 thunderstorms each day in the world i.e., 16-million thunderstorms each year. However, according to Dudhia [15], at any instant there may be about 2000 active thunderstorm around the world.

The activities of thunderstorm phenomena progresses from March onwards as the season advances in India. The frequency of thunderstorm events is higher during the pre-monsoon period (March-April) when the atmosphere is highly unstable because of high temperatures prevailing at lower levels. There are as many as 30–40 days of thunderstorms in parts of northeast India during pre-monsoon months (March–May) [38,40]. However, in March, the mean number of days of thunderstorms is not more than 6 to 8 in any part of the country; it reaches 14 to 16 days in Assam, adjacent areas and in Kerala in May. Thunderstorm activity in the month of March is highest in northwest India, mostly in association with western disturbances.

Hail is observed in the winter and pre-monsoon seasons in India with virtually no events after the onset of the southwest monsoon [13]. There are about 29 hail days per year (basing on analysis of IMD reports from 1982 to 1989) of moderate to severe intensity [29]. Eliot [16] found that, out of 597 hailstorms in India, 153 yielded hailstones of 3-cm diameter or greater. The percentage of hailstorm days out of thunderstorm days decreases from 5% to less than 2% from March to May for northeast India and Bangladesh [13].

Pre-monsoon season (March-May) in India is the most favored season in which ~ 76% of the tornadoes occur and that to ~72% of the reported tornadoes in South Asia occur in northeast India and Bangladesh and are associated with Nor'westers [38]. More number of tornadoes have occurred in the afternoon and evening . A study of tornadoes on the Indian subcontinent identified only 51 events between 1835 and 1977, but the path lengths and widths were larger than those characteristics of USA's, so many smaller tornadoes may have passed unreported [30]. Considering the entire area of the country, this gives a frequency rate of occurrence of about $1 \times 10^{-5}$ per year /$(km)^2$ [18]. Tornadoes exhibit a considerable range of intensity, size, and duration. A few of the Nor'westers even reach the intensity of a tornado.

Thunderstorm (hailstones, strong winds) brings about huge infrastructural damage, crop, livestock's and human lives losses. The highest numbers of aviation hazards due to strong winds of thunderstorm are reported in any parts of the world. In 21 April, 2015, huge loss of lives and infrastructural damage in Bihar (Purina) has occurred due to thunderstorm activities. The World Meteorological Organization [45] estimates hail causes damage worth over $200 million annually to agriculture worldwide. Table 1, below shows the infrastructural and crop damage with their monetary loss due to thunderstorm in India.

**Table 1. Thunderstorm damage/loss in India with their monetary values**

| Date/Weather events/Regions | Damage/ Loss (INR) |
|---|---|
| 17/3/1978: Tornado, New Delhi | 1.0 Crore |
| 02/04/2002: Hailstorm, Karimnagar, Warangal of Andhra Pradesh | 1550 Crore |
| 12/03/2003: Hailstorm: West Bengal | 99.2 Crore |
| 15-30/04/2004: Hailstorm, Andhra Pradesh | 5.16 Crore |
| 13/4/2010: Thunderstorm, East India, Bangladesh & Nepal | 600 Crore (Estimated) |
| 2/6/2014: Thunderstorm, New Delhi | N/A |
| 16/3/2015: Hailstorm, Aurangabad | 1.5 Crore (Estimated) |
| 16-18/3/2015: Hailstorm, Nagpur | 10000 Crore |
| 7/4/2015: Hail storm, Bareilly, Uttar Pradesh | 1100 Crore |
| 2-23/4/ 2015: Thunderstorm, Tripura, Agartala | 8.0 Crore |
| 27-29/4/2015: Thunderstorm, Haryana | 1092 Crore |

With the advancement of the new weather technology and advanced scientific understanding of the weather phenomena a good amount of observational and research infrastructure were also developed in India between 1950 to 2000. Importantly, towards the thunderstorm research, the atmospheric research community in India conceived a program called Severe Thunderstorm Observation and Regional Modelling [38] in 2005, to carry out intensive observational research and to apply dynamical numerical models (meso scale) to understand and predict thunderstorm/Nor‘westers. The financial support and encouragement from Department of Science and Technology from 2006 to 2008, and later by Ministry of Earth Sciences under the aegis of IMD is worth mentioning in this program. Again in collaboration with SAARC Meteorological Centre, Dhaka and with their effort a new program ‘SAARC STORM’ was initiated for further research in this field. The Program since 2013 covers all SAARC countries [13,38]. Koteswaram and Srinivasan [21] have discussed the thunderstorm events over Gangetic West Bengal and attributed the simultaneous presence of low level convergence and upper air divergence for development of thunderstorm. Choudhury studied the development of thunderstorm over northeast region and indicated the low level convergence and lifting mechanism for their development. Mukherjee [27] has studied on the frequency of the thunderstorm events and found the maximum frequency in pre-monsoon season (March – May) particularly during night in Assam valley. Choudhury [11] has advocated that for genesis of this event minimization of convective inhibition (CIN) energy is fundamental whereas, neither maximization nor minimization of convective available potential energy (CAPE) is of significance. Extensive work on climatology of thunderstorms of all the seasons for India using data of 450 stations (IMD observatory, Indian Air Force, Airport observatory) has been done by Tyagi [40]. Chakrabarti et al [9] have utilized the data for the duration of April and May under a pilot project entitled ‘STORM’, 2006 over the Assam and adjoining region and concluded that maximum frequency of thunderstorms was found along the Brahmaputra river. Chan et al [8] have studied on the aspects of nowcasting of heavy rain and thunderstorms and indicated that increase in relative humidity at all altitudes and the accumulation of water vapor in lower troposphere play an important role in nowcasting. Yamane and Hayashi [46] demonstrated that CAPE represents the atmospheric instability required for the evaluation of environmental conditions for the formation of severe local storms over the Indian subcontinent. The isolated rainfall from mesoscale convective activities have been carried out by Moncrieff and Miller [26]; Williams and Renno [43], highlighting the role of CAPE and CIN. During pre-monsoon period (April, 2007) Srivastava and Sinha Ray [36] have also studied the role of CAPE and CIN for occurrence of more convective activities. Studies by De and Dutta [14], Sen [34] and Schneider and Sharp [32] and others highlight on the role of CAPE for the analysis of thunderstorm. Several other studies by Braham and Wilson [3], Shepherd and Burian [35], Niyogi et al. [28] showed that urban land surface can influence local storm structure causing enhanced convection and increased precipitation.

Studies related to modelling of clouds are very scarce and in particular, intense thunderstorm events [12]over India. Moreover, thunderstorm studies have not been carried out proportionate to its socio-economic importance in India. Hence, keeping in view on this aspects a preliminary report on thunderstorm activities over India during pre-monsoon seasons have been attempted to present, which highlight the favorable conditions for the thunderstorm development during the season including the characteristics, frequency and historical losses due to thunderstorm. This paper may serve as a base line information for the development of the thunderstorm risk assessment model for tropical region like India. The outline of the paper is as follows. Section I presents the introduction, section II highlights the data and methodology, in section III the results and discussion are given, section IV highlights the proposed methodological framework for thunderstorm risk assessment model development as future direction/work and conclusions are presented in section V.

## 2. Data and Methodology

Thunderstorm bulletin from IMD for the month of April 2015 (Pre-monsoon season) are made utilized for culling the upper air (RS/RW) ascent products in the present study. DWR images from DWR centers of IMD are also used. The Skew-T diagrams (using which it can be can be infer the presence/absence of conditional instability) from Department of Atmospheric Sciences of University of Wyoming are made utilized for the analysis of thermodynamic instability parameters which favor the thunderstorm events. Stability indices presented here are defined based on the ‘American Meteorological Society (AMS)’ [1]. Details on the different thermodynamic indices are described by Suresh [39] and Litta [23]. Though, several indices signify the Instability parameters used in thunderstorm forecasting and analysis (e.g. Total totals Index, K Index, Showalter index, Lifted index etc.) few of them are mentioned in this study, which my prove vital in quantification of severe weather ingredients as composite indices viz. significant hail parameter (SHiP), significant tornado parameter (STP) and energy helicity index (EHI) for wind.

### 2.1. Convective Available Potential Energy (CAPE)

The maximum energy available to an ascending parcel, according to parcel theory.

On a thermodynamic diagram this is called positive area, and can be seen as the region between the lifted parcel process curve and the environmental sounding, from the parcel's level of free convection to its level of neutral buoyancy. It may be defined as [1]

$$CAPE = \int_{p_n}^{pf} \left( \alpha_p - \alpha_e \right) dp,$$

Where, $\alpha_e$ is the environmental specific volume profile, $\alpha_p$ is the specific volume of a parcel moving upward moist-adiabatically from the level of free convection, $pf$ is the pressure at the level of free convection, and $p_n$ is the pressure at the level of neutral buoyancy [1].

The value depends on whether the moist-adiabatic process is considered reversible or irreversible (conventionally irreversible) and whether the latent heat of freezing is considered (conventionally not).

## 2.2. Convective Inhibition (CIN) Energy

The energy needed to lift an air parcel vertically and pseudo adiabatically from its originating level to its level of free convection (LFC). For an air parcel possessing positive CAPE, the CIN represents the negative area on a thermodynamic diagram having coordinates linear in temperature and logarithmic in pressure. The negative area typically arises from the presence of a lid. Even though other factors may be favorable for development of convection, if convective inhibition is sufficiently large, deep convection will not form. The convective inhibition is expressed (analogously to CAPE) as follows [1].

$$CIN = -\int_{p_i}^{pf} R_d \left(T_{vp} - T_{ve}\right) d \ln p,$$

Where, $p_i$ is the pressure at the level at which the parcel originates, $pf$ is the pressure at the LFC, $R_d$ is the specific gas constant for dry air, $T_{vp}$ is the virtual temperature of the lifted parcel, and $T_{ve}$ is the virtual temperature of the environment. It is assumed that the environment is in hydrostatic balance and that the pressure of the parcel is the same as that of the environment [1].

## 2.3. Severe Weather Threat (SW) Index

SW index is used mainly for analyzing the potential for severe thunderstorms [25] and is defined as

$$SW = 20\left(TT - 49\right) + 12D_{850} + 2V_{850} + V_{500} + 150\left[\sin\left(\Delta_{500-850}\right) + 0.2\right]$$

Where, TT is the Total Totals index (set to zero if less than 49), $V_{850}$ and $V_{500}$ are the 850- and 500-mb wind speeds, and $\Delta V_{500-850}$ is the 500-mb wind direction minus the 850-mb wind direction, in degrees. The last term is set to zero if any of the following conditions are not met: i) 850-mb wind direction is in the range from 130 to 250 degrees; ii) 500- mb wind direction is in the range 210 to 310 degrees; iii) the difference in wind directions is positive, or iv) both 850- and 500-mb wind speeds are at least 15 knots. No term in the formula is allowed to be negative. The severe thunderstorm threat is considered to increase from values of about 300 and higher; tornadoes are considered to increase in likelihood from values of about 400 and up [1].

## 2.4. Total Precipitable Water Content (TPWC)

The total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between any two specified levels, commonly expressed in terms of the height to which that water substance would stand if completely condensed and collected in a vessel of the same unit cross section.

The total precipitable water is that contained in a column of unit cross section extending all of the way from the earth's surface to the ‘top’ of the atmosphere. Mathematically, if $x(p)$ is the mixing ratio at the pressure level, $p$, then the precipitable water vapor, $W$, contained in a layer bounded by pressures $p_1$ and $p_2$ is given by

$$W = \frac{1}{pg}\int_{p_1}^{p_2} x dp$$

Where, $\rho$ represents the density of water and g is the acceleration of gravity. In actual rainstorms, particularly thunderstorms, amounts of rain very often exceed the total precipitable water vapor of the overlying atmosphere. This results from the action of convergence that brings into the rainstorm the water vapor from a surrounding area that is often quite large. Nevertheless, there is general correlation between precipitation amounts in given storms and the precipitable water vapor of the air masses involved in those storms [1].

# 3. Results and Discussion

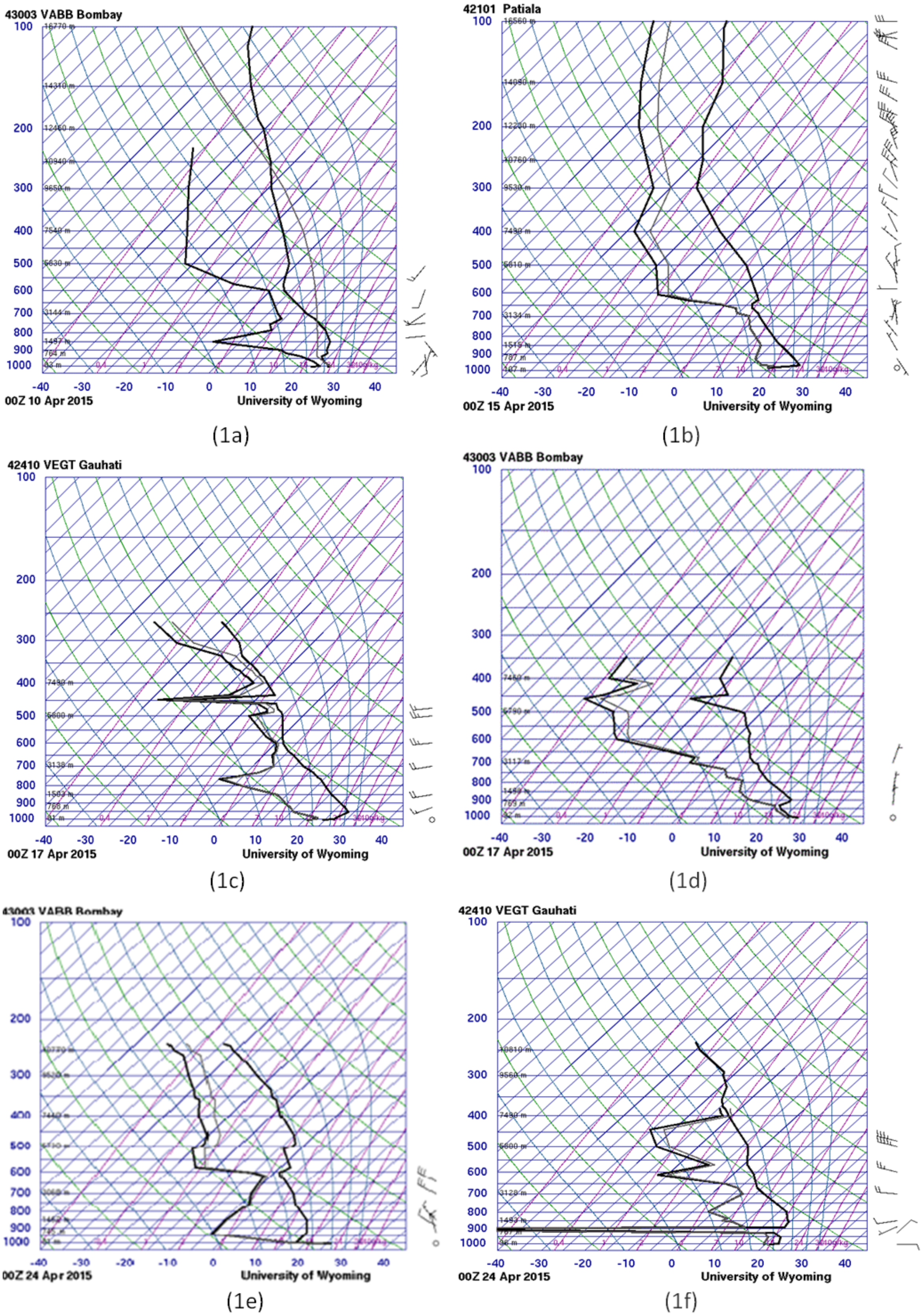
It is evidenced that thunderstorm activity records significant increase in April with the onset of summer conditions over most parts of the country. The main regions of most frequent thunderstorm activities are Assam, Meghalaya and Sub Himalayan West Bengal in the northeast and Kerala and adjoining Tamil Nadu in the south. Physiographic features, insolation and confluence of air masses and advection of moisture under favorable wind regime contribute to thunderstorm maxima over these areas. Synoptically, western disturbances and induced lows in the north and easterly waves in south provide conducive environment for the occurrence of thunderstorm over these regions [40]. In the present study, the realized significant weather phenomena, the thunderstorms including four of the important thermodynamic parameters/indices as discussed in SAARC STORM project bulletin [20] are analyzed by illustrating the cases of pre-monsoon (April) thunderstorms, which may represent the thunderstorm characteristics over the country. Listed below are the thunderstorm events described in this study.

1. Thunderstorm on 10 April, 2015,
2. Thunderstorm on 14 April, 2015,
3. Thunderstorm on 15 April, 2015,
4. Thunderstorm on 16 April, 2015,
5. Thunderstorm on 17 April, 2015,
6. Thunderstorm on 18 April, 2015,
7. Thunderstorm on 19 April, 2015,
8. Thunderstorm on 20 April, 2015,
9. Thunderstorm on 21 and 22 April, 2015,
10. Thunderstorm on 23 April, 2015, and
11. Thunderstorm on 24 April, 2015.

## 3.1. Thunderstorm on 10 April, 2015

As per the IMD reports, thunderstorms accompanied with squall/hail have occurred on 10 April, 2015 as realized significant weather at isolated places over Assam and Meghalaya and Nagaland, Manipur, Mizoram and Tripura.

Table 2A shows the different stations of Indian cities with their CAPE, CIN, SW index and TPWC values (from the RS/RW ascent products) for 10 April, 2015 at 0000 UTC. From the Table 2A, it is obvious that the maximum value of CAPE estimated was ~1337.37 J/Kg at Mumbai which is higher than the specified critical value of >900 J/Kg [39] and >1000 J/Kg [41]. The critical values specified were for the northeast (Kolkata) and southern peninsular part (Chennai) of India, respectively. However, present value of CAPE at Mumbai may be the indication of the favorable condition for thunderstorm occurrence at that station, since CIN (-140.97 J/Kg) and TPWC (37.24 mm) were also seem quite favorable in this case. Other thermodynamic parameter/indices on their respective stations are also shown in the Table 2A. Skew-T diagram at Mumbai (0000 UTC, 10 April, Mumbai, 2015) indicates the wind veering up to ~ 5 km above the earth surface (Figure 1a).



(1a) (1b)

(1c) (1d)

(1e) (1f)

**Figure 1.** (a), Skew-T, 10/00 UTC, Mumbai; (b) Skew-T, 15/00 UTC, Patiala (c) Skew-T,17/00 UTC, Guwahati, (d) Skew-T, 17/00 UTC, Mumbai, (e) Skew-T, 24 /00 UTC Mumbai, (f) Skew-T, 24/00 UTC, Guwahati

**Table 2 (A). Thermodynamic instability parameters (0000 UTC of 10 April, 2015)**

| RS/RW ascent products | Patiala | Delhi | Jodhpur | Gwalior | Guwahati | Gorakhpur | Raipur | Mumbai |
|---|---|---|---|---|---|---|---|---|
| CAPE in J/Kg | 298.72 | 0.0 | 90.61 | 0.0 | 211.56 | 0.0 | 118.22 | 1337.37 |
| CIN in J/Kg | -421.29 | 0.0 | -439.24 | 0.0 | -204.86 | 0.0 | -310.91 | -140.97 |
| SW Index | 40.00 | - | 94.40 | - | - | - | 47.01 | - |
| TPWC in mm | 15.90 | 12.57 | 19.20 | 5.15 | 35.75 | 12.50 | 27.85 | 37.24 |

## 3.2. Thunderstorm on 14 April, 2015

On 14 April, 2015, thunderstorms were recorded as realized significant weather at a few places over Uttar Pradesh, Bihar, Andhra Pradesh, and Karnataka and at isolated places over Gujarat, Madhya Pradesh, Chhattisgarh, Odisha, Tamilnadu and Kerala. According to media report, Hanabe village, Doddaballpura taluka of Bengaluru Rural district experienced hailstorm on 13 April, 2015 afternoon. Koppal, Vijayapura, Ballari, Bagalkote districts experienced thunderstorm and hailstorm with gusty winds on 12 April, 2015 night. Hailstorms was reported at Yelahanka (Indian Air Force station) at 1600-1605 hrs, however hail diameter was not available [20].

## 3.3. Thunderstorm on 15 April, 2015

On 15 April, 2015, according to the IMD records/data the activities of thunderstorm as realized significant weather recorded were at a few places over Andhra Pradesh, Karnataka, Tamilnadu and at isolated places over Uttarakhand, Uttar Pradesh, Madhya Pradesh, Vidarbha, Bihar, Jharkhand and Kerala. Hailstorms were recorded at Dehradun (1612-1615 hrs) with hail diameter of ~ 0.4 cm and at Nagpur (1725-1732 hrs) with hail diameter of ~0.4 cm. RS/RW ascent products at 0000 UTC on some of the cities with their respective thermodynamic parameters/ indices are given in Table 2B.

A CAPE value varied from 0.0 (Minimum) at Delhi to 1117.84 (Maximum) at Patiala. CIN varied from -487.29 (Minimum) at Siliguri to 0.0 at Delhi and Lucknow. Higher values of SW index (175.59) were observed at Patiala. Similarly, TPWC varied from 17.45 mm at Delhi to 40.61 mm (Maximum) at Lucknow. Tyagi et al. [41] have studied the thunderstorm activities over Kolkata and found that the critical value of CAPE >1000 was favorable for thunderstorm phenomena. From the Table 2B, it is evident that CAPE value at Patiala was favorable for thunderstorm activity. The threshold values of CAPE >900 for Chennai [39], >1500 [23], have also been used in earlier studies. The values of CIN > -100 as CIN critical limit for supporting environment for thunderstorm [39] over Chennai is used. It is seen that CIN reflects strength of capping inversions and it must be overcome and replaced with sufficient CAPE for commencement of convection. Skew-T diagram for the 15 April 2015 (0000 UTC) at Patiala indicates the wind veering plus shear at ~ 12.6 km (Figure 1b). As per the radar maximum reflectivity (Max, dBz) image which represent the location of the cloud, the horizontal and vertical extents, **i**solated multiple echoes were seen in DWR Vishakhapatnam at 15 April 0940 UTC (dBZ >50 and height around 10 Km) and DWR Bhopal at 15 April 1152 UTC (dBZ >50 and height around 10Km) (Figure 2a, Figure 2b). Isolated weak echoes were also seen in DWR Delhi (15 April, 1212 UTC) and Patiala (15/1222 UTC).

**Table 2. B. Thermodynamic instability parameters (0000 UTC of 15 April, 2015)**

| RS/RW ascent products | Patiala | Delhi | Jodhpur | Gwalior | Lucknow | Gorakhpur | Siliguri | Raipur |
|---|---|---|---|---|---|---|---|---|
| CAPE in J/Kg | 1117.84 | 0.0 | 16.37 | 52.49 | 105.98 | 121.64 | 3.23 | 85.74 |
| CIN in J/Kg | -83.54 | 0.0 | -305.26 | -177.45 | 0.0 | -201.41 | -487.29 | -56.43 |
| SW Index | 175.59 | - | 171.62 | - | - | 144.61 | - | - |
| TPWC in mm | 34.98 | 17.45 | 29.79 | 36.26 | 40.61 | 37.48 | 36.54 | 29.97 |

## 3.4. Thunderstorm on 16 April, 2015

On 16 April, 2015, thunderstorms were recorded as realized significant weather at a few places over Jammu & Kashmir, Tamilnadu and at isolated places over Punjab, Haryana, Himachal Pradesh, Uttar Pradesh, Uttarakhand, Gangetic West Bengal, Bihar, Jharkhand, Odisha, Madhya Pradesh, Chhattisgarh, Vidarbha, Karnataka and Andhra Pradesh. Thunder squall, hailstorms and hail diameter were not reported [20].

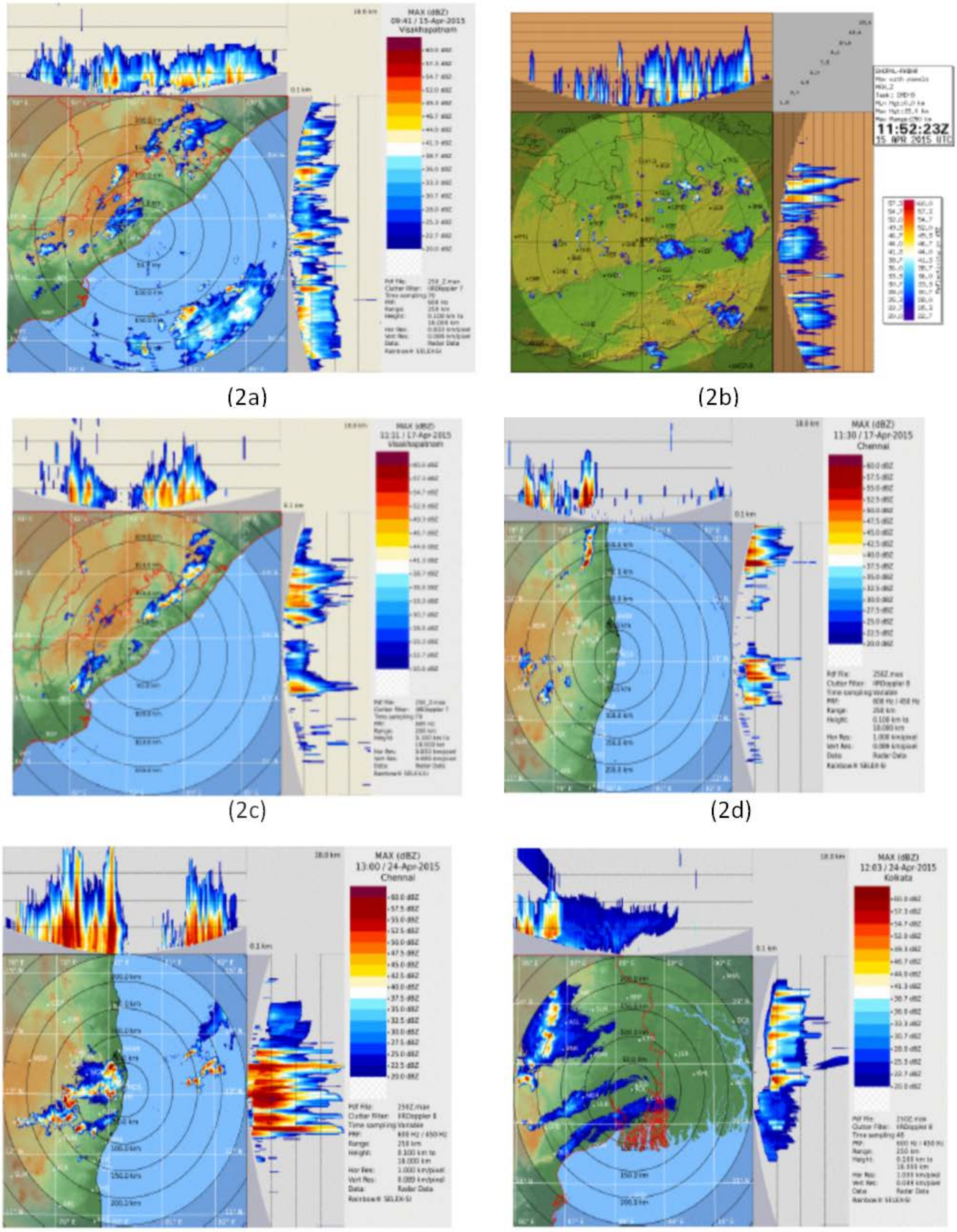
## 3.5. Thunderstorm on 17 April, 2015

As per IMD record thunderstorm were recorded as realized significant weather on 17 April, 2015 at a few places over Karnataka and at isolated places over Jammu & Kashmir, Punjab, Haryana, Uttar Pradesh, Sikkim, Arunachal Pradesh, Assam, Chhattisgarh, Vidarbha, Andhra Pradesh, Tamilnadu and Kerala. Thunder squall, hailstorms and hail diameter were not reported [20].

**Table 2 C. Thermodynamic instability parameters (0000 UTC of 17 April, 2015)**

| RS/RW ascent products | Patiala | Delhi | Jodhpur | Gwalior | Siliguri | Guwahati | Mumbai |
|---|---|---|---|---|---|---|---|
| CAPE in J/Kg | 633.61 | 0.0 | 3.76 | 0.0 | 127.68 | 2138.67 | 2097.69 |
| CIN in J/Kg | -443.82 | 0.0 | -830.39 | 0.0 | -285.98 | -199.97 | 0.0 |
| SW Index | 222.99 | - | 184.79 | 97.00 | - | 154.21 | - |
| TPWC in mm | 27.28 | 28.73 | 30.22 | 18.27 | 34.26 | 35.49 | 35.22 |

On 17 April (0000 UTC), 2015, the values of CAPE was high in Guwahati (2138.67 J/Kg) and Mumbai (2097.69 J/Kg) with favorable CIN values for thunderstorm to occur. Other thermodynamic parameter/Indices are shown in Table 2C, with their respective values on different RS/RW ascent stations. Skew-T diagram for Guwahati and Mumbai are shown in the Figure 1c with lower tropospheric level wind veering, no high values of wind shear was indicated by the diagrams. As per the radar image of IMD, isolated multiple echoes were seen in DWR Vishakhapatnam at 17 April, 1111UTC (dBZ>50 and height around 10 Km) and DWR Chennai at 17 April, 1130UTC (dBZ>55 and height around 10Km (Figure 2c, Figure 2d).



(2a) (2b)

(2c) (2d)

(2e) (2f)

**Figure 2.** (a) Vishakhapatnam, 15/0940 UTC, (b) Bhopal, 15/1152 UTC, (c) Vishakhapatnam, 17/1111 UTC, (d) Chennai, 17/1130 UTC, (e) Chennai, 24/1300 UTC, (f) Kolkata, 24/1203 UTC

## 3.6. Thunderstorm on 18 April, 2015

IMD reports that thunderstorms were recorded on 18 April, 2015 as realized significant weather at a few places over Bihar, Assam, Tamilnadu and at isolated places over Gangetic, Sub Himalayan West Bengal & Sikkim, Jharkhand, Meghalaya, Chhattisgarh, Andhra Pradesh, Karnataka and Kerala. Thunder squalls was reported at Gaya (1809-1811 hrs) from West direction with maximum speed of 82Kmph, however no hailstorms and hail diameter was recorded.

## 3.7. Thunderstorm on 19 April, 2015

Thunderstorms were recorded on 19 April, 2015 at a few places over Assam and at isolated places over Bihar, Sub-Himalayan West Bengal & Sikkim, South Assam, Meghalaya, Manipur, Tripura and Tamilnadu as realized significant weather. Thunder squall, hailstorms and hail diameter were NIL on 19 April 2015 as per IMD bulletin.

## 3.8. Thunderstorm on 20 April, 2015

Thunderstorms were recorded at a few places on 20 April, 2015 over Srinagar, Kerala and at isolated places over Himachal Pradesh, Uttarakhand, Sub-Himalayan west Bengal and Sikkim, Assam, Meghalaya, Andhra Pradesh, Karnataka and Tamilnadu as realized significant weather. Thunder squall, hailstorms and hail diameter were not reported on 20 April 2015 as per IMD bulletin.

On 20 April 2015 (0000 UTC), very high values (~4186 J/Kg) of CAPE was estimated at Mumbai. The value is well above the critical values >900 J/Kg [39], >1000 J/Kg [41], >1500 J/Kg [23], and >2500 J/Kg [10] and is quite favorable for thunderstorm to occur. Other thermodynamic parameter/indices for different stations are as indicated in the Table 2D. Skew-T diagrams for stations Mumbai and Patiala are shown in the figures which depict wind veering and wind shear (Figure 1d).

**Table 2. D. Thermodynamic instability parameters (0000 UTC of 20 April, 2015)**

| RS/RW ascent products | Delhi | Patiala | Jodhpur | Mumbai | Guwahati |
|---|---|---|---|---|---|
| CAPE in J/Kg | 0.0 | 37.25 | 0.0 | 4180.61 | 0.0 |
| CIN in J/Kg | 0.0 | -738.70 | 0.0 | -237.23 | 0.0 |
| SW Index | -- | 66.79 | 114.01 | -- | -- |
| TPWC in mm | 8.17 | 21.99 | 12.28 | 41.07 | 37.92 |

## 3.9. Thunderstorm on 21 and 22 April, 2015

Thunderstorms have been observed on 21 and 22 April, 2015 at isolated places over Jammu and Kashmir, Assam and Meghalaya, Manipur Sub Himalayan West Bengal, Tripura, Madhya Maharashtra, South Interior Karnataka, Tamilnadu and Kerala [20].

Severe Thunderstorms were observed on 21 April, 2015 in Bihar, Jharkhand and West Bengal region. Bihar state's Purina was badly hit by thunder squalls with maximum speed of ~150-200 kmph (2140-2250 hrs) from northwest direction. The occurrence of hail storm was reported but no hailstorm diameter was reported. Air Force Station, Chunar reported the squally winds from northwest direction which was moving towards southeast(~1630 UTC) with the speed of ~115 kmph [20].

## 3.10. Thunderstorm on 23 April, 2015

On 23 April, 2015, thunderstorms were recorded at many places over Karnataka, at a few places over Odisha and at isolated places over West Bengal and Sikkim, Assam, Meghalaya, Mizoram, Andhra Pradesh, Telangana, Tamilnadu and Kerala as per the reports of IMD as realized significant weather. Thunder squall was observed at Dumdum (2106-2107 hrs) from northwest direction with maximum speed of 64 kmph and at Silchar (2140-2142 hrs) from Northwest direction with maximum speed of 64 kmph. Hailstorm was observed at Haveri (1815-1820 hrs); however Hail diameter was not provided.

## 3.11 Thunderstorm on 24 April, 2015

As per the IMD record thunderstorm activities as realized significant weather were observed on 24 April, 2015 at many places over Andhra Pradesh, Karnataka, at a few places over Gangetic West Bengal, Assam, Odisha and at isolated places over Sub Himalayan west Bengal and Sikkim, Manipur, Tripura, Tamilnadu and Kerala. Thunder Squalls were reported at Guwahati (0217-0221 hrs) from South-easterly with maximum speed of 45 Kmph. Thunder Squalls were also observed at Bengaluru Hindustan Aeronautical Limited, Airport (1807-1809) from Easterly with maximum speed of 106 Kmph and at Gaya(1556-1558 hrs) from South-westerly with maximum speed of 92 Kmph [20]. Hailstorms were reported at Bengaluru City (1845-1900 hrs), (Bengaluru Hindustan Aeronautical Limited, Airport (1815-1820 hrs) and at Raichur (1800-1830 hrs).

**Table 2. E. Thermodynamic instability parameters (0000 UTC of 24 April, 2015)**

| RS/RW ascent products | Patiala | Delhi | Jodhpur | Guwahati | Mumbai |
|---|---|---|---|---|---|
| CAPE in J/Kg | 475.86 | 0.0 | 0.0 | 1009.05 | 0.0 |
| CIN in J/Kg | -343.45 | 0.0 | 0.0 | -9.15 | 0.0 |
| SW Index | 66.81 | - | 29.99 | 115.80 | - |
| TPWC in mm | 18.15 | 16.03 | 10.98 | 31.93 | 19.62 |

The value of CAPE was ~1009 J/Kg at Guwahati on 24 April 2015 (0000 UTC) as per the RS/RW ascent estimation. Favorable CIN value was also supporting the conducive environment for thunderstorm to occur. Thermodynamic parameters/indices of the other stations are shown in the Table 2E. Skew-T diagram for Guwahati/Mumbai are shown in the Figure 1e and Figure 1f. As per the radar image of IMD, isolated Multiple echoes were seen in

DWR Chennai at 24 April, 1300 UTC (dBZ around 60 and height >15km) and DWR Kolkata at 24 April ,1203 UTC (dBZ>50 and height>10Km) (Figure 2e and Figure 2f).

## 4. Future Work: Development of Thunderstorm Risk Assessment Model

Based on the realized thunderstorm events over the short period of time during the pre-monsoon season and their adverse impact on the socio-economic conditions and GDP of the nations, the importance of such extreme weather could be well perceived; therefore, it is imperative to forecast and model accurately to know in advance or/well before the time on the severity, location and time of the events for the early warning system/advisories and to access the loss cost due to such severe weather events. Two widely used and accepted approaches to forecast weather are i) the empirical approach and ii) the dynamical approach [24]. The first approach is referred to as analogue forecasting method in which by using past weather data future events are predicted. The most widely used empirical approaches are regression, Artificial-Neural-Network, stochastic, fuzzy logic and group method [23]. The second approach is based upon governing equations and forward simulations of the atmospheric state using computer technique, and is often referred to as Numerical Weather Prediction (NWP). A complete set of equations that govern the evolution of the atmosphere are,

- Newton’s second law of conservation of momentum (three equations for the three components of velocity),
- Conservation of mass or the continuity equation,
- Conservation of energy or 1st law of thermodynamics,
- The equation of state for gas, and
- Conservation equation for water mass.

These governing equations are solved using numerical methods adopting suitable gridding techniques, applying the required initial and boundary conditions in a domain of the study and results are obtained by forward integration of the sets of equations ahead in time for prediction of the weather phenomenon. Numerical modeling studies and research on thunderstorm in India by Vaidya [42], Chatterjee et al. [9], Rajeevan et al. [31] and Litta et al. [23] have been documented well.

The synoptic charts and the radiosonde ascents provide a broad scale picture of the areas favorable for development and prediction of thunderstorms. At the same time, the radars have proved a boon in the detection of thunderstorm cells including squall lines/tornado and their development with time and space and to prognosticate their movement. Similarly, using satellite technology and images the clusters of cumulonimbus clouds (identified by their high reflectivity, cirriform anvils and the shadows) associated with severe thunderstorms could be analyzed. Analysis of satellite images may help in interpreting subsidence and other weather phenomenon. Thus, thermodynamic instability and radar/satellite techniques are also essential for accurate forecasting of the weather events (thunderstorm). Srivastava et al. [37] and Sen Roy et al. [33] have studied the severe weather events using radar data.

Hence, the forecasting techniques involve the Analogues (historical) → NWP based methods → Thermodynamics instability indices →Radar/satellite imageries.

Importantly, the thunderstorm risk assessment and loss cost can be evaluated by developing the suitable techniques which follows the catastrophe risk model development procedures and comprises the steps viz: Forecasting (stochastic event set generation)→Intensity calculations →Vulnerability→Loss cost estimation (Figure 3). In this paper brief outline on methodological framework of thunderstorm catastrophe risk assessment modeling steps are highlighted. Since such models are mostly proprietary in nature so details literature on this aspects are skeletal.

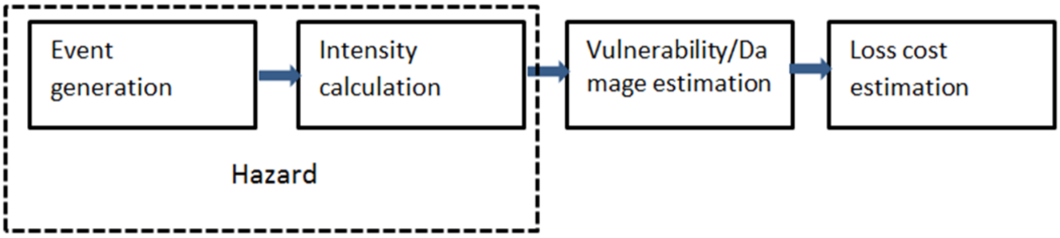


**Figure 3.** Diagram showing the thunderstorm risk assessment model development steps/components

As a first step towards the development of thunderstorm risk assessment model, the frequency of the events may be modeled based on the adjusted historical data. Historical data could be procured from the well certified and accepted data sources or region/country specific recognized nodal agencies, which archive for long period of time and disseminate for research and other applications. Recent science and technological development in the field of observations, tracking and reporting have led to an apparent increased frequency in thunderstorm occurrences. Moreover, the advancement of DWR and high resolution Satellite products have enabled to provide better detection and reporting of the events and to provide quality data. Even then historical data must be adjusted before a valid thunderstorm risk model may be developed. Thus, the de-trended historical data is considered as better approach for stochastic event set generation for tornadoes, hail storms, and straight-line winds/thunder squall using a smoothing (e.g. smooth bootstrap) procedure that randomly samples from this seed set and spatially perturbs each selected event. The process may also include the temporal and spatial clustering of events so that the simulated event sets could be evaluated against the historical data set for completeness and validation. Importantly, simulated storms can occur where no historical storms have been reported. For the simulation of stochastic events, the probability distribution function (Pdf) of annual frequency, event intensity, size of the storm areas, (testing them for goodness-of–fit and robustness) could be created as a further step and Pdf’s can then be combined with historical data to produce a ‘seed set’ of thunderstorm events, which may form the basis for the stochastic simulation for thousands of scenario years. The intensity variables are wind speed for tornadoes and straight-line wind storms, and hail impact energy for hailstorms. The damageability for straight-line windstorms is a function of 3-second gust speed and storm duration, which could be computed. The severity of hail damage depends on hailstone size, accompanying wind speed, the spacing between hailstones, the hailstorm area, and storm duration. The impact energy for hailstorms and violently rotating wind speed and direction of tornados could be computed. Vulnerability curves for the thunderstorm risk model could be developed basing on the reviews of the historical loss data and wind/hail risk studies for over a quite good number of years. Different vulnerability curves for different sub-perils viz. tornado, straight-line winds and hail (damage due to the kinetic energy associated with impact) are essential for overall thunderstorm risk assessment model. The coverage type may include damage to structure (building damage), contents, and damage related to time (loss of operations or loss of use) for which separate vulnerability functions could be used for calculating losses related to each coverage type. Consideration of damage to crops and damage function at different stages of crop development is of added advantage in thunderstorm risk assessment model development.

In a nut shell, in the processes of building the thunderstorm risk assessment model the updated building codes and construction practices plus plant phenology could be integrated with the latest science and engineering. So that, both the hazard and vulnerability components of the model offer important modeling innovations, viz. stochastic event simulation (hail, straight line winds, tornadoes), intensity computation model for hazard footprints, different vulnerability functions for different sub-perils of thunderstorms.

Thunderstorm risk assessment model output may include Exceeding Probability (EP) Curve that also include occurrence EP (OEP)/ aggregate EP (AEP), Average annual loss (AAL), Tail value at risk (TVAR), and event-by-event losses with associated uncertainty. Reporting of results could be in total aggregate portfolio, ZIP code, detailed output by policy and site etc. Such model may be useful for reinsurance/insurance companies, Government agencies, financial institutions and others to perform a variety of crucial analyses and provide risk perspectives at site, policy and portfolio level in pricing and managing risk, communicating to stakeholders, including rating agencies, regulators, shareholders, and counterparties.

## 5. Conclusions

Tropical country India being bestowed with unique geographical set up, topography and proximity to equator experiences severe thunderstorm of different intensities in different seasons, though frequency of thunderstorm in higher in pre-monsoon season; when the atmosphere is highly unstable because of high temperatures prevailing at lower levels. It is evidenced that Severe thunderstorms are concentrated downstream of high terrain and poleward of moisture sources in the form of warm water or rainforest. However, the confluence of continental cold, dry air from northwest at the upper level with warm, moist air masses at lower level from southeast (Bay of Bengal region) creates the conducive environment for the development of the thunderstorm in India. The change of the wind direction with height associated with this configuration implies the presence of significant vertical wind shear, one of the important parameter for severe thunderstorms development. Thus, the atmospheric instability, lower level ample moisture availability, vertical wind shear and vertical lifting constituent the main ingredient in thunderstorm activity.

The thunderstorm damage in terms of its sub-perils viz. thunder squall, hail stones, tornadic winds, flash floods and lightening is well documented, which wreck havoc and have the adverse impact on human society.

Present study highlights the RS/RW ascent products in terms of thermodynamic instability parameters/indices for the pre-monsoon season for some of the identified cities of India of SAARC STORM project region for the analyses of the thunderstorm activities. The Skew-T and radar images supporting thunderstorm activities are also analyzed/presented in this regards. It is evidenced that, thunderstorm activity records significant increase in April with the onset of summer conditions over most parts of the country. Physiographic features, insolation and confluence of air masses and advection of moisture under favorable wind regime contribute to high frequency of thunderstorm over these areas. The western disturbances and induced lows in the north and easterly waves plus wind/moisture discounity in south provide conducive environment for the occurrence of thunderstorm over these regions.

In this paper some important identified stations have been selected for which the data have analyzed for thunderstorm activities. Therefore, it warrants establishing the dense network of mesoscale observational stations with continuous automated monitoring system for archiving and dissemination of the data for research and development and different applications. Importantly, in this direction an additional network of stations including the automatic weather stations, global positioning systems sounding system and DWR are being set up by the Government of India through the Indian Space Research Organization (ISRO). This initiative my help research community to answer some of the important questions relating to thunderstorm viz. exact threshold value of CAPE, exact values of updrafts/downdrafts, relationship/behaviors of synoptic/mesoscale environment with thunderstorms, low-level jets, wind shear and predictability of hailstorm etc. over Indian region and other parts of continents.

Moreover, for better understanding the complex thunderstorm activities for accurate prediction/modeling and for the development of thunderstorm risk assessment model, which is proposed in this study as a next step of research work, may require in-depth knowledge on the various aspects of thunderstorm genesis/development, movement and dissipation mechanisms.

The research outcomes of this paper may form the base line information in thunderstorm risk quantification approaches and may also prove useful for the insurance/re-insurance companies, financial institutions, Government organizations and others for decision making, policy issue formulation and their implementation.

## Acknowledgement

Thanks are gratefully acknowledged to India Meteorological Department, New Delhi for availing the thunderstorm data and Doppler Weather Radar Data/images. Department of Atmospheric Sciences, University of Wyoming, USA is kindly acknowledged for upper air data/Skew-T diagrams. I am indebted to my former mentors at SES, JNU, New Delhi and CAS, IIT Delhi for their invaluable support and blessings on various aspects of the study. Personal communications with Airport Meteorological Officials of India helped immensely in preparation of this manuscript.

Author is thankful to the editor and anonymous reviewer for their critical and constructive comments for the improvement of the manuscript.

## References

[1] AMS: http://www.ametsoc.org.

[2] Barnes, G. (2001): Severe Convective Storms, edited by Charles Doswell, III, AMS, 2001, Pp.527.

[3] Braham, R. R. and Wilson, D. (1978): Effects of St. Louis on Convective Cloud Heights, J. Appl. Meteor., 17, 587-592.

[4] Browning, K. A. (1977): The structure and mechanism of hailstorms; Hail: A Review of Hail Science and Hail Suppression; Meteor. Monogr., American Meteorological Society , 16 1-43.

[5] Browning, K. A. (1986): General circulation of middle latitude thunderstorms; In: Thunderstorm morphology and dynamics; (ed.) Kessler E; Univ. Oklahoma Press, Norman, OK, 133-152.

[6] Byers, H. R. and Braham, R. R. (1949): The thunderstorms, U.S. Govt. Printing Office, Washington D.C., USA, 287 pp.

[7] Chakrabarti, D., Biswas H.R. Das, G.K. and Kore, P.A. (2008): Observational aspects and analysis of events of severe thunderstorms during April and May 2006 for Assam and adjoining states –A case study on ‘Pilot Storm Project’, Mausam, 59, 461-478.

[8] Chan et al. (2009): Performance and application of a muliti-wavelength ground based microwave radiometer in intense convective weather, Meteol. Z, vol-18, 3, 253-265.

[9] Chatterjee, P., Pradhan, D. and De, U. K. (2008): Simulation of hailstorm event using mesoscale model MM5 with modified cloud microphysics scheme, Ann. Geophy., 26, 3545-3555.

[10] Chaudhari, H.S., Sawaisarje, G. K., Ranalkar, M. R., and Sen, P. N. (2010): Thunderstorms over a tropical Indian station, Minicoy: Role of vertical wind shear, *J. Earth Syst. Sci.* 119 (5), 603-615.

[11] Chaudhury, S. (2006): Ampliative reasoning to view the prevalence of severe thunderstorm, Mausam, 57, 523-526.

[12] Das, S. (1999): Suggested observational network for simulation of cloud processes during the Indian Ocean Experiment (INDOEX); Curr. Sci., 76, 7, 912-915.

[13] Das, S., and coauthors (2014): The SAARC STORM: A Coordinated Field Experiment on Severe Thunderstorm Observations and Regional Modeling over the South Asian Region, Bull. Amer. Meteor. Soc., 95, 603-617.

[14] De, U. S. and Dutta, S. (2005): West coast rainfall and convective instability, J. Indian Geophysics Union 9 71-82.

[15] Dudhia, J. (1996): Back to basics: thunderstorms: part I. Weather, 51 (11); 371-376.

[16] Eliot, J. (1899): Hailstorm in India during the period 1883–1897 with a discussion on their distribution. Indian Meteor. Mem., 6, 237-315.

[17] Encyclopedia of world climatology; John E. Oliver.

[18] Goliger, A. M., and Milford, R. V.(1998): A review of worldwide occurrence of tornadoes. Journal of Wind Engineering and Industrial Aerodynamics, 74, 111-121.

[19] http://www.n-d-a.org/tornado.php.

[20] IMD: http://www.imd.gov.in.

[21] Koteswaram, P. and Srinivasan, V. (1958): Thunderstorms over Gangetic West Bengal in the pre-monsoon season and synoptic factors favorable of their formation, Indian J. Met. & Geophys., 9, 301-312.

[22] Kumar, G. and Mohapatra, M. (2006): Some climatological aspects of thunderstorms and squalls over Guwahati airport, Mausam, 57, 2, 231-240.

[23] Litta, A. J., Mohanty, U. C. and Idicula, S. M. (2012): The diagnosis of severe thunderstorms with high-resolution WRF model, *J. Earth Syst. Sci.* 121 (2) 2, 297-316.

[24] Lorenz, E. N. (1969): Three approaches to atmospheric predictability. Bulletin of the American Meteorological Society, 50, 345-349.

[25] Miller, R. C. (1972): Notes on analysis and severe storm forecasting procedures of the Air Force Global Weather Central. Tech. Rept. 200(R). Headquarters, Air Weather Service, USAF, 190 pp.

[26] Moncrieff, M. W. and Miller, M. J. (1976): The dynamics and simulation of tropical cumulus and squall lines; Quart. J. Roy. Meteor. Soc., 102 373-394.

[27] Mukherjee, A.K. (1964): Study of thunderstorm around Guwahati airport, Indian J. Met. & Geophys., 15,425-430.

[28] Niyogi, D., Holt, T., Zhong, S., Pyle, P. C., and Basara, J. (2006): Urban and land surface effects on the 30 July 2003 mesoscale convective system event observed in the Southern Great Plains, J. Geophys. Res., 111, D19107.

[29] Nizamuddin, S. (1993): Hail occurrences in India,Weather, 48 (3):90-92.

[30] Peterson, R.W. and Mehta K.C. (1981): Climatology of tornadoes in India and Bangladesh, Archiv fur Meteorologie, Geophysik, una Bioclimatologie, Ser. B. 29, 345-356.

[31] Rajeevan, M., Kesarkar, A., Thampi, S. .B, Rao, T. N., Radhakrishna, B. and Rajasekhar, M.(2010): Sensitivity of WRF cloud microphysics to simulations of severe thunderstorm event over Southeast India, Ann. Geophys., 28, 603-619.

[32] Schneider, D. and Sharp, S. (2007): Radar signatures of tropical cyclone tornadoes in central north Carolina, Wea. Forecasting, 22 278-286.

[33] Sen Roy, S., Lakshmanan, V., Roy Bhowmik, S. K. and Thampi, S. B. (2010): Doppler weather radar based nowcasting of cyclone Ogni, J. Earth Syst. Sci., 119, 183-199.

[34] Sen, P. N. (2005): Thermodynamics of the atmosphere; Lecture notes of the second SERC school on aviation meteorology, AFAC, Coimbatore, India.

[35] Shepherd, J. M. and Burian, S. J. (2003): Detection of Urban-Induced Rainfall Anomalies in a Major Coastal City, Earth Interactions, 7, 1-17.

[36] Srivastava, A. K. and SinhaRay, K. C. (1999): Role of CAPE and CINE in modulating the convective activities during April over India; Mausam, 50, 257-262.

[37] Srivastava, K., Roy Bhowmik, S. K., Sen Roy, S., Thampi, S. B. and Reddy, Y. K.(2010): Simulation of high impact convective events over Indian region by ARPS model with assimilation of Doppler weather radar radial velocity and reflectivity, Atmosfera, 23, 53-73.

[38] STORM (2005): STORM science plan. India Department of Science and Technology Rep., 118 pp.

[39] Suresh, R. (2012): Forecasting and nowcasting convective weather phenomena over southern peninsular India-Part I-Thunderstorms, Ind. Jour. of Radio & Space Physics, 41, 421-434.

[40] Tyagi, A. (2007): Thunderstorm climatology over Indian region. Mausam, 58(2), 189-212.

[41] Tyagi, B., Naresh Krishna, V. and Satyanarayana, A. N. V. (2011):Study of thermodynamic indices in forecasting pre-monsoon thunderstorm over Kolkata during STORM pilot phase 2006-2008, Nat. Hazards,. 56, 681-698.

[42] Vaidya, S. S. (2007): Simulation of weather systems over Indian region using mesoscale models, Meteorol. Atmos. Phys., 95, 15–26.

[43] Williams, E. and Renno, N. (1993): An analysis of the conditional instability of the Tropical atmosphere, Mon. Wea. Rev., 121, 21-36.

[44] WMO (1953): World distribution of thunderstorm days, Part I: Tables, WMO TP 6. N0. 021.

[45] WMO: http://www.wmo.int.

[46] Yamane, Y. and Hayashi, T. (2006): Evaluation of environmental conditions for the formation of severe local storms across the Indian subcontinent. Geophys. Res. Lett., 33, L17806.