Monitoring Convective Activity over India During Pre-Monsoon Season-2013 under the SAARC STORM Project

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ABSTRACT

SAARC STORM Project has been carried out as a multi-year observational-cum modelling campaign with an objective to build appropriate operational early warning systems for highly damaging severe thunder storms over various parts of India. The programme started with a pre-pilot phase in the year 2006 and was originally conceived for understanding the severe thunderstorms known as Nor'westers that affect West Bengal and the North eastern parts of India during the pre-monsoon season. Since rest of India and the neighbouring south Asian countries are also affected by thunderstorms, the STORM programme has now included all South Asian countries under the South Asian Association for Regional Cooperation (SAARC). The programme was monitored at IMD, New Delhi. Data from around 500 IMD manned surface observatories have been used for monitoring and recording the weather all over India. In addition to the above; rainfall activity was monitored through a network of about 2000 raingauge stations spread across the country. The frequency of thunderstorms in Northeast India was the highest in the night while in East India the frequency was highest in the evening. The Sub Himalayan West Bengal and Sikkim subdivision got most of the thunderstorms in the night while remaining states Odisha, Bihar and Gangetic West Bengal got thunderstorms during evening. Thunderstorms are recorded generally on all days in April and May in Northeast India and the dew Point temperature at 850 hPa was more than 5°C on most of the days. Southern Peninsular Region and Northwest India got most of the thunderstorms in the afternoon and evening. CAPE values for New Delhi (0000UTC RS/RW ascent) were found to be very low (<500) on all days during April and May and insignificantly correlated with TS activity over the region.

***Key Words**: Convective Available Potential Energy (CAPE), Low Pressure Area (LOPAR), Thunderstorms, Thunder Squall, Hailstorm.*

1. Introduction

Thunderstorms are the most dominant feature of weather over India during the pre-monsoon season (March-May), which develops mainly due to intense convection and is accompanied by heavy rainfall, thunder, lightning and hail .The towering cumulus or the cumulonimbus clouds of convective origin with high vertical extent have the spatial extent of a few kilometres and life span less than an hour. However, multi-cell thunderstorms which develop due to organized intense convection may have a life span of several hours and spread over a few hundreds of kilometres. These are often known as squall line. Thunderstorms mainly originate over the heated land masses that heat up the air above it and initiate convection. In India, these thunderstorms reach severity when continental air meets warm moist air from ocean in the lower troposphere. The region of maximum solar radiation covers most of north-western India, extending southwards to central India in pre-monsoon season. The region experiences the hottest temperatures during this season with an average of 35–45°C, with occasional highs of about 50°C (Pant and Rupa Kumar, 1997). As a result of high temperatures over the north Indian plains, an intense thermal low pressure area develops over north western India during this season. In addition to the high temperature, the general wind flow is westerly to north-westerly. The westerly continental airflow brings very little moisture throughout the continental region of north India during pre-monsoon season. Therefore, rainfall episodes over most parts of northern India occur in association with synoptic scale westerly troughs that bring moisture to this region (Srinivasan, et. al. 1973). However, unlike the monsoon systems, these westerly systems do not give rise to large-scale cloud systems leading to widespread homogenous rainfall episodes. The most common clouds observed in the low-levels during this season are cumulonimbus and stratocumulus with cloud base normally below 2 km (Chaudhuri 2008). During this season, even in the presence of moisture, the accumulation of convective energy over this region frequently takes place under pronounced capping inversions (Roy Bhowmik et al. 2008). Sawyer (1947) indicates a thick, dry capping layer above 700 hPa over a relatively moist lower atmosphere, over northwest India, which becomes thinner and less prominent further eastwards. In the absence of a strong large-scale synoptic system to trigger the convection and cause widespread rainfall, other, local factors such as topography, orientation with respect to the prevailing wind flow, distance and orientation from the sea, westerly trough, low level wind discontinuities, and downdrafts from already existing convective cells, triggers the release of accumulated convective energy locally, which gives rise to strong convective cells (Soma et al., 2011). The rainfall systems, over eastern India and adjoining Bangladesh, are of greater spatial extent, often organized into bow-shaped squall line systems, and result in heavy localized rainfall accompanied by high winds (Rafiuddin et al. 2009). These are often accompanied by hail and sometimes by tornadoes causing widespread devastation over eastern India (Bhattacharya and Bhattacharya, 1983).

As tremendous amount of observational and research infrastructure were developed in India between 1950 and 2000, a pilot project on "Severe thunderstorm observation and Regional Modeling (STORM) was undertaken by Department of Science and technology during April and May 2006, to carry out intensive observational research and apply mesoscale dynamical models to understand and predict Norwesters. Later on it was taken over by MoES and has been carried out as a multi-year observational-cum modelling campaign with an objective to build appropriate operational early warning systems for highly damaging severe thunder storms over various parts of India. In the Phase-III of SAARC STORM Programme which started in 2013, STORM Field Experiments were carried out in southern peninsular India, Maldives and Sri Lanka to study maritime and continental convective storms during pre-monsoon season of 2013 (Fig.1). Results in detail for the year, 2013 for India are discussed in this communication. Das *et al. (2013)* have reported objectives of the experiment, experimental design, pilot field experiments and the results for the years 2009 to 2012. A number studies were initiated by researchers during the Pre-Monsoon season based on the experiments conducted under this Project. Chakrabarti et al. (2008) analysed 62 severe events in northeast India during the Pilot STORM project and confirmed that "Assam Valley" along Brahmputra river experiences maximum number of events. Kuldeep et al. (2008) simulated two thunderstorm events over Delhi using ARPs model. Jenamani,et.al. (2009) studied characteristics of thundersquall over Delhi airport (Palam), Laskar (2009) over Patna Airport, Das, et al. (2010) over Guwahati airport, Suresh (2005) over Chennai and Mohapatra (2004) over Bangalore airport.

2. Data Used

Commencement of significant pre-monsoon thunderstorm activity takes place from 15 March over different parts of India. Climatological information about occurrence of thunderstorm activity has been used for deciding the duration of the experiment over different parts of the country (Tyagi, 2007). During the Pre-monsoon season of 2013, Storm experiments were conducted in three regions of the country as per the following schedule:

- Northwest India. (15 April-15 June 2013)
- East and Northeast India. (01 April- 31 May 2013)
- Southern Peninsula. (15 March - 15 May 2013)

The overall campaign was monitored and guided by a Weather Advisory Committee (WAC) at National Weather Forecasting Centre (NWFC), IMD. Radiosonde ascents at 0000 UTC were taken at the following Meteorological centres (MC) and Regional Meteorological Centers (RMC).

- 01 April- 31 May 2013. Kolkata, Ranchi, Patna, Bhubaneshwar, Guwahati, Mohanbari, Agartala.
- 15 April-15 June 2013. Jaipur, New Delhi, Srinagar, Chandigarh, Lucknow.
- 15 March- 15 May 2013, Kochi, Thiruvanthapuram, Chennai, Bengaluru, Machilipatnam, Vishakapatnam, Hyderabad.

PPI(V) and MaxZ products were taken from Doppler Weather Radar network of IMD at Agartala, New Delhi, Patiala, Lucknow, Patna, Nagpur, Kolkata, Chennai, Vishkahapatnam, Machilipatnam, Mohanbari and Mumbai. thunderstorms, Thundersqualls, Hailstorms and rainfall were moniteredfor the period 15 March to 15 June, 2013 in around 500 IMD manned surface observatories and a network of about 2000 raingauge stations spread across the country.

3. Results

The results and discussion for various regions is are follows:

3.1 Thunderstorms over East India

East India comprised of Odisha, Gangetic West Bengal, Jharkhand and Bihar plains. From the thunderstorms recorded at various IMD observatories, it was seen that the frequency of thunderstorms increased from March to May over the region. April and May accounted for the maximum thunderstorms. As compared to other states, the thunderstorm activity over Bihar plains was much less. In the month of April, thunderstorms were recorded in the observatories on 20 days over East India. Lowest number of thunderstorms were recorded in Bihar (on 2 days, 14 and 17 April) followed by Jharkhand (3 days, 2, 13 and 14 April). Odisha had 14 thunderstorm days and West Bengal had 10 Days. Out of the 20 thunderstorm days, squall was reported on 9 days.

Frequency of thunderstorms was much higher in the month of May. Thunderstorms were recorded on all days except 15 May and 31 May over East India. No thunderstorms were recorded in Bihar and Jharkhand; thunderstorms were recorded on 20 days in Odisha and 21 days in West Bengal. Out of the 29 thunderstorm days during May, squall was reported on 7 days (24% of the thunderstorm days). A large majority of thunderstorms (about 80 %) that occurred in Gangetic West Bengal developed over Bihar Plateau and the adjoining areas, mainly in the afternoon and subsequently move in a south-easterly direction.

An earlier analysis of daily Tephigram (00Z) of Kolkata during April and May by Srinivasan (1973) has indicated that the frequency of thunderstorm days are associated with low level moisture capped with inversion. Days with no moist layer at any level are predominantly dry days. Although the low level capping inversion inhibits the growth of convective clouds, it permits a progressive increase of potential instability beneath the inversion and ultimately punctures inversion (Newton, 1962).

An analysis of the 850 hPa dew point temperatures of Kolkata (00Z) for the period April and May 2013 is given in Table.1. Table brings out the fact that the dew point temperatures in lower troposphere remain above 5°C on most of the days in April and May and also as the moisture increases, the chances of thunderstorm activity becomes more over Eastern India. More than 80% of the thunderstorm activity was supported by dew point temperature more than 5°C at 850 hPa. In the month of April, thunderstorms occurred on 10 days in West Bengal and the CAPE values in RS/RW ascent over Kolkata on all these days were varying in the range 500 J/kg to to 3000 J/Kg with no significant bifurcation. In the month of May, thunderstorms occurred on 21 days in West Bengal and on 8 days, Kolkata had CAPE > 3000J/Kg, 10 days CAPE was between 1000-3000J/Kg and 3 days had CAPE <1000 J/Kg (table.2).CAPE values were greater than 4000 J/Kg on 2 days in pre-monsoon season over Kolkata, and the thunderstorm activity occurred on both days. In 80% instances the thunderstorm activity was nil for CAPE estimates less than 500 J/Kg over Kolkata.

3.1.1 Role of synoptic conditions

Although thunderstorm is a meso-scale phenomenon, the realisation of the instability is largely dependent upon the large scale synoptic systems. The most common synoptic situation in the surface and the lower troposphere, favourable for a good norwester activity in East India is the movement of western disturbances and the induced low pressure area over Northwest India, Uttar Pradesh and North Madhya Pradesh. In a typical case on 17 April,2013 the induced low pressure area was over West Uttar Pradesh and the trough extended east southeast-wards from the low pressure area to Bihar Plateau (Fig.2). The easterlies penetrated westwards over Bihar plateau and adjoining UP up to 1.5 Km., but it moved rapidly to Bihar plateau or Odisha by the afternoon /evening and thus gave good thunderstorm activity in East and NE India. This process continued till the induced low pressure area moved away eastwards and became unimportant on 21 April. Thus, the forecaster has to be on the alert for development of thunderstorms in East and NE India even when the induced low pressure area is over NW Madhya Pradesh or Uttar Pradesh. The location of the east-west trough line east of 80° E, associated with the low pressure area further west, determines the area of thunderstorm activity over East India. This trough may be anywhere from north Uttar Pradesh and North Bihar in the north to southeast Madhya Pradesh and south Odisha in the south. Fig.3 shows the vorticity at 850 hPa on 17 April. The significant thunderstorm activity over coastal Odisha and adjoining West Bengal was associated with deep convection due to high positive vorticity (Cyclonic) over this area.

3.2 Thunderstorms in Assam and adjacent states

Assam and adjacent states is a region of very high frequency of thunderstorm activity during the pre-monsoon season. The thunderstorms over this region are (except Tripura and Manipur) different from the norwesters of Gangetic West Bengal (except Sub-Himalayan west Bengal). Over more than 70 % of thunderstorms in Assam and Meghalaya occur during night time. In Guwahati 50 % of the thunderstorms occur between 1800 and 2400 hrs IST. In contrast, Tripura and Manipur and adjacent areas have thunderstorm frequency maximum in the afternoon/evening as in Gangetic West Bengal.

3.2.1 Tephigram of Guwahati

The Tephigrams of Guwahati differ in many aspects from those of Kolkata. The lower troposphere over Guwahati is colder than Kolkata and the air is humid. The inversion and the rapid decrease of moisture with height in the lower levels characteristic of Kolkata are not usually present at Guwahati. Since the thunderstorms in this area are mostly during night time, the 00z radiosonde ascent is not very representative of the atmospheric conditions over this area. It was seen that the moisture content rather than the lapse rate is more significant for classification of thunderstorm and non-thunderstorm days. Table 3 indicates the dew point temperatures at 850 hPa and the corresponding thunderstorm activity. Thunderstorms were recorded generally on all days in April and May in Northeast India and the dew point temperature at 850 hPa was more than 5°C on most of the days. From the analysis it can be seen that only on days when the dew point temperature is less than 5°C, the thunderstorm activity is nil.

3.2.2 Role of synoptic conditions:

A majority of spells of thunderstorm activity in this region is associated with passage of troughs in westerlies. During the passage of mid-upper tropospheric trough, the lower level winds (850 hPa onwards) over Assam and adjacent states become southerly/southwesterly and are also stronger than normal with a wind speed reaching 35 to 40 kts over Gangetic West Bengal & Bangladesh, particularly during night time. The downstream weakening of the strong southerlies, as they reach further north may cause low level convergence (Fig.4). This may be one of the causes for the night time thunderstorms in Sub-Himalayan West Bengal, Assam and adjoining states. Orography is another important factor in this region as it provides the forced lifting of the low level moist air. The katabatic flows from the mountains into the valley during night time provide the undercutting of the lower level warm moist air. Thus when a strong warm moist advection in the lower levels is superposed by the cold dry advection in the upper levels, instability may set in due to large vertical variations in advection (Fig.3a)

A well marked east-west oriented discontinuity between easterlies over Sub-Himalayan West Bengal and Assam and southerlies or southwesterlies to the south are also a favourable situation for thunderstorm activity over Northeast India. The discontinuity may be noticeable vertically up to 1.0 and 1.5 km. With the east-west discontinuity, the thunderstorms are initiated mainly in the area of the easterly current.

Fig.5 shows an upper level (200hPa) trough with embedded jet stream on 18 April, 2013.The thunderstorm activity was fairly widespread over Northeast/East India on this day, with thundersqualls recorded in Guwahati. These troughs with embedded jet stream were seen to enhance the thunderstorm activity.

3.3 Thunderstorms over Northwest India

Due to the higher frequency of Western disturbances in the month of March, the thunderstorm activity over NW India is very high in March and first fortnight of April. It decreases considerably in the month of May. Since the western disturbances and upper air troughs are better developed and more frequent in the northern latitudes, convective weather is also more in the northern part of northwest India (roughly north of 30 °N) than further south.

During the pre-monsoon season, atmosphere over Northwest India and adjoining areas is very dry with nearly dry adiabatic lapse rates. In spite of high instability, no convective clouds form due to lack of moisture. If we compare the Tephigram of Delhi for thunderstorm and no thunderstorm days (Fig.6 a &b), it is seen that moisture content up to mid-troposphere is more on a thunderstorm day. An analysis of the Total-Total Index (TTI = (T850- T500) + (Td850 - T500)) ,where T850 and T500 are temperatures in °C at pressure level 850 and 500 hPa and Td850 is dew point temperature in°C at pressure level 850) of New Delhi for the period 15 April to 15 June, 2013 was made and results are given in Table.4. Based on earlier studies by Duraisamy et.al. (2011) over New Delhi, it was seen that TT Index above 48 was seen to be crucial for thunderstorm forecast. The authors reported maximum thunderstorms in the TTI range of 48.5 -56.5. It was seen that for the STORM Period of 2013, on 23 days TTI was greater than 48 and out of these 16 days were thunderstorm days. The remaining 38 days had TTI less than 48 and out of these only six were thunderstorm days. The LI index (T500-Tparcel, where T500 is temperature in Celsius of the environment at 500 hPa and Tparcel is temperature in Celsius of the lifted parcel at 500hPa) was also calculated for April and May and it was greater than zero for most of the days. It is possible that in the morning at the time of ascent, the atmosphere is stable and later on the instability sets in due to insolation. CAPE values for New Delhi (0000UTC RS/RW ascent) were found to be very low (<500) on all days during April and May and insignificantly correlated with TS activity over the region.

3.3.1 Role of synoptic conditions

The synoptic conditions that affect this area during the pre-monsoon season are the western disturbances and their associated induced low pressure areas. Most of the spells of convective activity in northwest India are associated with a western disturbance. In the lower levels, a trough may extend eastwards or south-eastwards from the induced low pressure areas and the trough region is a probable region for thunderstorm activity. In association with the western disturbances and induced low pressure areas, easterlies /south easterlies often prevail over Uttar Pradesh and northern parts of Northwest India in the low levels. The thunderstorm activity was widespread over NW India on 6 June, 2013.M.O. Safdarjung recorded thunder with squall with speed reaching 64 km/hr.Fig.7 shows an induced low pressure area over Punjab and adjoining, and in Fig.8, we can see strong easterlies at 850 Hpa level over U.P, Delhi, Haryana and Punjab.

3.4 Thunderstorms over Southern India

The monitoring over southern Peninsula was from 15 March to 15 May, 2013. During the experimental period, thunderstorms occurred on 30 days in Kerala, 23 days in Karnataka, 22 days in Tamil Nadu and 24 days in A.P. The south-western part of Indian Peninsula consisting of Kerala and the western parts of Tamil Nadu and Mysore is a region of high thunderstorm activity in the pre-monsoon season. The activity was maximum over Kerala. Thunderstorm activity over Southern Peninsula is mainly in April and May. In April and May, thunderstorms occur in Kerala, South Interior Karnataka and adjoining districts of Rayalseema and Tamil Nadu for nearly 10-12 days in each month. The Orography coupled with plentiful supply of moisture from sea and the effect of the sea breeze over Kerala and adjoining areas was one of the causes for the high thunderstorm activity in Southwest Peninsula. Generally early mornings and day time till 1500 hrs IST are free from thunderstorm, unless there is a cyclonic disturbance such as a low pressure area, depression or a storm. In April and May, 2013, RMC Chennai reported thunderstorms on 15 days. The CAPE values ranged from 2000-4000 on thunderstorm days and all days with CAPE value greater than 3000 were thunderstorm days. The analysis of other indices like Total-Total Index and LI Index were found to be insignificant in deciding the convective activity over Southern India.

3.4.1 Role of synoptic conditions

During this season, a wind discontinuity in the lower troposphere extending from south Kerala to east Vidharba and southeast Madhya Pradesh is a seasonal feature. This seasonal wind discontinuity shows some east-west oscillations. The seasonal wind discontinuity is also a line of moisture discontinuity. The air to the south and east is generally moist while the air to the west is much drier, particularly in the north peninsula. Aided by orography and the afternoon isolation, isolated thunderstorm activity may occur along this discontinuity on most of the days.

Troughs in mid and upper tropospheric westerlies sometime amplify and extend southwards into the central parts of the country and north Peninsula. Very occasionally the trough may extend further south even into south Peninsula and the upper westerly regime may cover the whole country (Fig.5). The upper air trough along with the low level wind discontinuity gives rise to large scale thunderstorms over the Peninsula. Over the south Peninsula, the upper northerlies in the rear of the trough can cause an advection of positive vorticity on account of the decrease of Coriolis parameter downstream, leading to thunderstorm development.

Another type of disturbance that produces large scale thunderstorm activity over the peninsula is the system in easterlies. Widespread thunderstorm activity was reported over south India on 25 April (Fig.9). It was seen that the easterly flow was well marked over the peninsula, south Bay, and south Arabian Sea at 925 hPa asl. These disturbances moved across the extreme southern parts of the country and Sri Lanka (Fig.10) and got linked up with the seasonal trough/wind discontinuity over the Peninsula leading to widespread thunderstorm activity. An east west oriented shear line in the upper troposphere (300-200 hPa) across the Peninsula also appears to be another feature causing large scale thunderstorms over the south Peninsula (Fig.11). In addition to the above, onset and advance of Southwest monsoon also gives good thunderstorm activity in the peninsular region.

4. Frequency of Thunderstorm Events over Various Regions During 2013

The frequency of thunderstorms in Northeast India was highest in the night while in East India the frequency was highest in the evening followed by night. The Sub Himalayan West Bengal and Sikkim subdivision get most of the thunderstorms in the night while remaining states Odisha, Bihar and Gangetic West Bengal get thunderstorms during evening. The frequency is very low in the morning and afternoon for both regions. The South Peninsular region gets most of the thunderstorms in the afternoon and evening. The activity was low in morning and forenoon. In NW India the thunderstorm activity was highest in afternoon for all months. There was no thunderstorm activity in morning, evening and night in April and May (Fig.9).

The total events (TS recorded by a station is considered as an event) recorded were highest over Northeast India (393 events) during May 2013 and over Southern Peninsula (234 events). During the month of April, East India also recorded 163 events in the month of May and 126 events in April. The thunderstorm activity was lowest in Northwest India with 4 thunderstorm events in May and only 8 in the second fortnight of April .However a total of 126 thunderstorm events were recorded during the period 1 June to 15 June, 2013over NW India due to early onset of monsoon over NW India.

5. Thundersqualls and Hail Storms

5.1 Thundersquall

It can be defined as a sudden increase of wind speed by at least 3 stages on the Beaufort Scale, the speed rising to force 6 or more, and lasting for at least one minute. Many thunderstorms in East India were associated with squall. The thunderstorm activity was high over Northeast India whereas, the thunder squall frequency was high in East India. A total of 32 thunder squalls were reported from East India during April and May 2013. The frequency of thundersqualls was maximum over Gangetic West Bengal, followed by Odisha and Bihar. Thundersqualls were recorded on 9 days in April in various regions of Eastern India. They were recorded on 6 days over West Bengal, 3 days over Jharkhand and 2 days over Odisha and Bihar (Table.5). In May, thundersqualls were reported on 3 days over Odisha and 4 days over West Bengal. The thundersqualls were mostly from North-westerly direction. The highest wind speed reached in these squalls was of the order of 116 km/hr in Gangetic West Bengal on 17 April, 2013 at Diamond Harbour and Alipore. Thundersquall activity was less over NE region as compared to eastern India (Table.6). Northeast India reported only 5 thundersquall events during the pre-monsoon period (April and May, 2013). The thunderssqualls were reported by Guwahati on 14 and 18 April with maximum wind speed of the order of 77 and 47 km/hr respectively and over Tezpur on 3 April with maximum wind speed of 90 km/hr. In Tripura state, squalls were reported by Agartala on 18 and 19 April with maximum wind speed of 90 and 72 km /hr respectively.

5.2 Hail storms during April –May 2013

Hail can be defined as solid precipitation in the form of balls or pieces of ice (hailstones) with diameters ranging from 5 to 50 mm or even more.The general atmospheric conditions under which hailstorms occur are:

1) High instability, with Cumulonimbus clouds growing to very high levels.
2) Presence of large vertical currents inside the clouds.
3) High moisture content in the atmosphere. The greater the moisture content, the larger is the size of the hailstones.
4) Lower freezing level is conducive to hailstorms. One of the factors favourable for hailstorms in north and central India in winter and early spring is the lower freezing level. Large hails are generally reported with Wet Bulb Zero heights in the range of 2 to 3 Km.

In Southern Peninsula thunderstorm with Squall and hail were reported on 18 April at a number of places, thunderstorms with Hail were recorded on 3 Days in April and May. Gadag in Karnataka reported Hail on 28 April and Kurnool in Andhra Pradesh reported on 29 April. Vellore in Tamilnadu and Vizayanagram in Tamil Nadu reported Hail on 18 April, 2013(Table.7). Northwest India reported Thunderstorm with Squall on 5 days. All thunder squalls were reported by Met office Safdarjung in New Delhi from westerly direction and with maximum wind speed of 148 km/hr recorded on 6 June, 2013 (Table.8).

Hailstorms were reported on 3 days in West Bengal and one day in Odisha (Table.9). Coochbehar, Jalpaiguri and Tadong in Sub-Himalyan West Bengal and Sikkim reported thunderstorms with hail (diameter 0.5 cm) on 10 April, 2013. Thunderstorm with Hail was recorded on 4 Days in Northeast India (Table.10) with Tezpur station in Assam reporting diameter of 2.6 cm on 3 May.

Analysis of the upper tropospheric conditions on the days of hailstorms showed that the occurrence of hail in central and Peninsular India was generally associated with strong upper troposphere south-westerly flow and the Subtropical westerly Jet stream core coming down to lower latitudes (Ray et.al., 2013).

6. Conclusions

From this study the following inference can be made.

- **i.** The increase in lower troposphere moisture increases the chances of thunderstorm activity over Eastern India. Along with the vertical distribution, the distribution of moisture along the horizontal is also equally important.
- **ii.** Some patterns could be made available with dew point temperature and CAPE that could help forecasting of thunderstorm events in advance over Kolkata (Table.1&2),still the few occurrences of thunderstorms at low CAPE values and low dew point temperatures could not be explained.
- **iii.** Thunderstorms are recorded generally on all days in April and May in Northeast India and the dew Point temperature at 850 hPa was more than 5°C on most of the days.
- **iv.** During the pre-monsoon season, atmosphere over Northwest India and adjoining areas is very dry with nearly dry adiabatic lapse rates. In spite of high instability, no convective clouds form due to lack of moisture. CAPE values for New Delhi (0000UTC RS/RW ascent) were found to be very low (<500) on all days during April and May and insignificantly correlated with TS activity over the region.
- **v.** Easterly disturbances moving across the extreme southern parts of the country and Sri Lanka may get linked up with the seasonal trough/wind discontinuity over the Peninsula leading to widespread thunderstorm activity. An east west oriented shear line in the upper troposphere (300-200 hPa) across the peninsula also appears to be another feature causing large scale thunderstorms over the south Peninsula.

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Table 1 Frequency of occurrence of thunderstorm/non-thunderstorm days in East India with different ranges of Dew point temperature values at 850 hPa level over Kolkata.

Kolkata Range of dew point in °C	Total No. of Occasi	No. of No thunderstorm days	No. of Thunderstorm days
<5°C	5	3	2
5-12°C	24	4(17%)	20(83%)
>12°C	32	5(16%)	27(84%)

Table 2 CAPE values calculated from RS/RW ascent at 0000 UTC over Kolkata for the corresponding Thunderstorm day or No thunderstorm day

CAPE estimates	No thunderstorm	Thunderstorm occured
<500	10	5
500-1000	3	3
1000-2000	8	7
2000-3000	6	8
3000-4000	3	6
>4000	0	2
Total	30	31

Table 3 Frequency of occurrence of thunderstorm/non-thunderstorm days in North-east India with different ranges of Dew point temperature values at 850 hPa level over Guwahati

(Guwahati) Range of Dew point in °C	Total No. of Occasions	No. Of No thunderstorm days	No. Of Thunderstorm days
<5°C	5	3	2
5-12°C	18	0	18(100%)
>12°C	21	1	20(95%)

Table 4 Statistics of Total Index of New Delhi associated with Thunderstorm and non-thunderstorm days

New Delhi	Total No. of occasions	Total-total Index<48	Total-Total Index>48
No. of days of thunderstorm activity	29	8	21(72%)
No. of days of non-thunderstorm activity	33	26(79%)	6

Table 5 Thunderstorm with Squall recorded in East India during April and May, 2013

Date	Subdivision	State	Station	Time and Duration in IST
02/04/2013	JHARKHAND	JHARKHAND	DALTONGANJ	SQUALL: 02/1741 to 02/1743 from SW direction , Max wind speed 56 kmph
04/04/2013	WEST BENGAL	GWB	M.O.KOLKATA	SQUALL: 04/0941 to 04/0942 from W direction , Max wind speed 60 kmph
11/04/2013	WEST BENGAL	GWB	ALIPORE	SQUALL:11/2055 to 11/2056 from NW direction , Max wind speed 63 kmph
13/04/2013	JHARKHAND	JHARKHAND	DALTONGANJ	SQUALL: 13/2151 to 13/2153 from SW direction , Max wind speed 62 kmph
14/04/2013	BIHAR	BIHAR	PATNA	SQUALL: 14/2115 to 14/2117 from SW direction , Max wind speed 58 kmph
14/04/2013	JHARKHAND	JHARKHAND	DALTONGANJ	SQUALL: 14/1810 to 14/1812 from SW direction , Max wind speed 56 kmph
15/04/2013	WEST BENGAL	GWB	ALIPORE	SQUALL:15/0235 to 15/0236 from NNW direction , Max wind speed 56 kmph
15/04/2013	ODISHA	ODISHA	CHANDBALI	SQUALL: 15/0435 to 15/0436 from W direction , Max wind speed 48 kmph
17/04/2013	WEST BENGAL	SHWB & SIKKIM	MALDA	SQUALL: 17/0232 to 17/0233 from SW direction , Max wind speed 44 kmph
17/04/2013	WEST BENGAL	GWB	ALIPORE	SQUALL:17/1915 to17/1920 from NW direction , Max wind speed 116 kmph
17/04/2013	WEST BENGAL	GWB	DUMDUM	SQUALL:17/1939 to 17/1940 from S direction , Max wind speed 68 kmph
17/04/2013	WEST BENGAL	GWB	DIAMOND HARBOUR	SQUALL:17/1945 to 17/1946 from NW direction , Max wind speed 116 kmph
17/04/2013	BIHAR	BIHAR	GAYA	SQUALL:17/2110 to 17/2112 from W direction , Max wind speed 96 kmph
19/04/2013	WEST BENGAL	GWB	DIGHA	SQUALL:19/1650 to 19/1651 from NW direction , Max wind speed 55 kmph
21/04/2013	WEST BENGAL	GWB	ALIPORE	SQUALL:21/2026 to 21/2027 from NW direction, Max wind speed 56 kmph
21/04/2013	ODISHA	ODISHA	PURI	SQUALL:21/1400 to 21/1403 from S direction, Max wind speed 64 kmph
07/05/2013	ODISHA	ODISHA	CHANDBALI	TS: 07/0255 to 07/0650, SQUALL:07/0247 to 07/0249 from NW direction, Max wind speed 56 kmph
12/05/2013	WEST BENGAL	GWB	ALIPORE	TS: 12/1845 to 12/2145, SQUALL:12/1930 to 12/1931 from N direction, Max wind speed 76 kmph
12/05/2013	WEST BENGAL	GWB	SRINIKETAN	SQUALL:12/1615 to 12/1616 from W direction, Max wind speed 44 kmph
12/05/2013	ODISHA	ODISHA	BALASORE	TS: 12/1715 to 12/1805, SQUALL:12/1735 to 12/1739 from NW direction, Max wind speed 74 kmph
12/05/2013	ODISHA	ODISHA	BHUBANESWAR	TS: 12/1840 to 12/2245, SQUALL:12/1910 to 12/1912 from W direction, Max wind speed 52 kmph
17/05/2013	WEST BENGAL	SHWB & SIKKIM	MALDA	TS: 17/0000 to 17/0045, SQUALL:17/0008 to 17/0011 from NW direction, Max wind speed 50 kmph
17/05/2013	WEST BENGAL	GWB	ALIPORE	TS: 17/1850 to 17/1945, SQUALL:17/1818 to 17/1821 from NW direction, Max wind speed 60 kmph
17/05/2013	WEST BENGAL	GWB	DUMDUM	SQUALL:17/1815 to 17/1816 from W direction , Max wind speed 56 kmph
19/05/2013	WEST BENGAL	GWB	ALIPORE	SQUALL:19/1900 to 19/1901 from NW

				direction , Max wind speed 72 kmph
19/05/2013	WEST BENGAL	GWB	DUMDUM	SQUALL:19/1914 to 19/1915 from W direction , Max wind speed 52 kmph
19/05/2013	WEST BENGAL	GWB	BANKURA	SQUALL:19/1638 to 17/1640 from SW direction , Max wind speed 65 kmph
20/05/2013	WEST BENGAL	GWB	DUMDUM	SQUALL: 20/1820 to 20/1821 from NE direction , Max wind speed 60 kmph
22/05/2013	ODISHA	ODISHA	CHANDBALI	TS: 22/1845 to 21/1910, SQUALL: 22/1850 to 22/1852 from NW direction, Max wind speed 46 kmph
26/05/2013	ODISHA	ODISHA	CDR PARADEEP	SQUALL: 26/1943 to 26/1947 from N direction, Max wind speed 56 kmph
26/05/2013	ODISHA	ODISHA	BHUBANESWAR	TS: 26/1615 to 26/2240, SQUALL: 26/1553 to 26/1558 from N direction, Max wind speed 72 kmph

Table 6 Thunderstorm with Squall activity recorded in Northeast India in 2013

Date	Met Sub Division	State	Station	Duration and time in IST
03/04/2013	Assam & Meghalaya	Assam	Tezpur	TS: 03/2055 to 03/2100, TSRA: 03/2100 to 03/2215, TS: 03/2215 to 03/2230, SQUALL: 03/2108 to 03/2110 from NW direction , max wind speed 90 km/hr.
14/04/2013	Assam & Meghalaya	Assam	Guwahati A/P	TSRA: 14/0935 to 14/1105, SQUALL: 14/1013 to 14/1015 from West , max wind speed 77 km/hr,
18/04/2013	Assam & Meghalaya	Assam	Guwahati A/P	TS:18/2140 to 18/2325, SQUALL: 18/2152 to 18/2153 from NW, max wind speed 47 km/hr
18/05/2013	Nagaland, Manipur,Mizoram, Tripura	Tripura	Agartala A/P:	TSRA: 18/1025 TO 18/1250;SQUALL: 18/1148 TO 18/1150 with max wind speed 90 km/hr.
19/04/2013	Nagaland, Manipur,Mizoram, Tripura	Tripura	Agartala	TS: 19/1730 to 19/1950, Squall: 19/1748 to 19/1750 from 280°, max wind 72 km/hr.

Table 7 Thunderstorm with Squall/Hail recorded in Southern Peninsular India in 2013

Date	Subdivision	State	Station	Event	Time and Duration in IST
18/4/2013	TAMILNADU	TAMILNADU	VELLORE	Thunderstorm With Squall/Hail	HEAVY TS 14:00 TO 15:05 ,TS WITH HAIL,SQUALLY WIND from 14:00 to 14:05 Hrs IST
18/4/2013	COASTAL AP	ANDHRA PRADESH	Vizayanagaram	Thunderstorm With squall/Hail	MEDIA REPORT Srungavarpukota (Vizianagaram dt) experienced Thunderstorm with Hail and Squall from 1430 HRS IST
28/4/2013	KARNATAKA	KARNATAKA	GADAG	Thunderstorm with Hail	TS: 17:00 ,TSRA 17:10 TO 17:55 ,HAILSTORM 17:22 TO 17:53 THIKNESS 3 MM
29/4/2013	ANDHRA PRADESH	ANDHRA PRADESH	KURNOOL	Thunderstorm With Hail	TS:15:45 TO 15:58, TSRA 15:58 TO 16:10,TS WITH HAIL 16:10 TO 16:30

Table 8 Thunderstorm with Squall/Hail recorded in Northwest India in 2013

Date	Met Sub Division	State	Station	Realisd Weather	Duration and time in IST
16.04.13	J&K	J&K	Banihal	Thunder with Hail	TS: 16/0345 to 16/1530, Hail16/1155 to16/1530
17.04.13	West U.P	U.P	CHURK	THUNDER WITH HAIL	Hail:17/1710 to 17/1735
26.04.13	Uttarakhand	Uttarakhand	Mukteshwar	THUNDER WITH HAIL	Hail26/1150 TO 26/1315 TS:26/1316 TO 26/1340
26.04.13	Himachal Pradesh	H.P	SHIMLA	Thunder with hail	TS: 26/1245/ TO 26/1320, HAIL : 26/1220 TO 26/1223 DIAMETER=0.3CM
11.05.13	Haryana, Chandigarh & Delhi	Delhi	MO Safdarjung	Thunder with Squall	SQ: 11/1837 TO 11/1839 (SW-LY /051KMPH)
13.05.13	J&K	J&K	Kupwara	THUNDER WITH HAIL	TS:13/1745 to 13/1800, Hail:13/1745 to 13/1800
13.05.13	J&K	J&K	Pahalgam	THUNDER WITH HAIL	TS: 13/2100 to 13/2400, Hail:13/2205 to13/2220
14.05.13	Haryana, Chandigarh & Delhi	Delhi	MO Safdarjung	Thunder with Squall	SQ: 14/1332 TO 14/1334 (W-LY/050KMPH)
26.05.13	J&K	J&K	Jammu	THUNDER WITH HAIL	TS: 26/1505 to 26/2310, Hail: 26/1505 to26/1506
26.05.13	J&K	J&K	Batote	THUNDER WITH HAIL	TS: 26/1400 to 26/2400, Hail 26/1855to26/1900
27.05.13	Haryana, Chandigarh & Delhi	Delhi	MO Safdarjung	Thunder with Squall	SQ: 27/1548 TO 27/1550 (NE-LY/048KMPH)
29.05.13	J&K	J&K	Srinagar	THUNDER WITH HAIL	TS: 29/1615 to 29/1640, Hail: 29/1640 to 29/1641
06.06.13	Haryana, Chandigarh & Delhi	Delhi	MO Safdarjung	Thunder with Squall	SQ: 1652 TO 1653, (W-LY/072KMPH) & SQ: 1705 TO 1707,(W-LY/148KMPH) TS: 1700 TO 1810
14.06.13	Haryana, Chandigarh & Delhi	Delhi	MO Safdarjung	Thunder with Squall	TS: 1326 TO 1445, SQ:1300 TO 1301 (NE-LY/042KMPH),SQ:1325 TO 1326 (E-LY/050KMPH)

Table 9 Thunderstorm with Hail recorded in East India in 2013

Date	Subdivision	State	Station	Time and Duration in IST
10/04/2013	WEST BENGAL	SHWB & SIKKIM	**FMO JALPAIGURI**	HAIL : 10/2235 to 10/2236, Diameter=0.5 cm
10/04/2013	WEST BENGAL	SHWB & SIKKIM	**CWO COOCHBEHAR**	HAIL : 10/2110 to 10/2112, Diameter=0.5 cm
10/04/2013	WEST BENGAL	SHWB & SIKKIM	**M.O.TADONG**	HAIL : 10/1700, Diameter< 0.5cm
16/04/2013	WEST BENGAL	GWB	**RAMPURHAT**	Moderate Hail 16/1630, Diameter not mentioned.
17/04/2013	ODISHA	ODISHA	**BALASORE**	HAIL : 17/1510 to 17/1511, Diameter < 0.5 cm ;
05/05/2013	WEST BENGAL	SHWB & SIKKIM	**GANGTOK**	TS: 05/1250 to 05/1310, Hail: 05/1435 to 05/1440, Diameter not mentioned.

Table 10 Thunderstorm with Hail recorded in Northeast India in 2013

Date	Met Sub Division	State	Station	Duration and time in IST
01/04/2013	NMMT	Mizoram	Lengpui	TS : 01/ 0050 to 01/0250, 01/0900 to 01/1130, Hail : 01/0900 to 01/0910
15/04/2013	NMMT	Tripura	Agartala	TS: 15/0855 to 15/0950, 15/1015 to 15/1320, 15/2300 to 15/2400 HAIL : 15/0905 to 15/0915 , Size=2 cm,
29/04/2013	NMMT	Tripura	Agartala A/P	TS: 29/1400 to 29/1520, TSRA: 29/1520 to 29/1605, TSRA with HAIL : 29/1605 to 29/1620, Hail Size = Small in size. Diameter not mentioned. TSRA: 29/1620 to 29/1650.
03/05/2013	Assam &Meghalaya	Assam	Tezpur	TS : 03/1430 to 1715, TSRAGR: 03/1715 to 03/1735, TS : 03/1735 to 03/1840, TSRA : 03/1840 to 03/1945, HAIL: 03/1715 to 03/1735, Diameter=2.6cm
03/05/2013	NMMT	Manipur	Imphal A/P	TSRA : 03/0300 to 03/073003/1545 to 04/0015; HAIL : 03/2010 to 03/2025, Diameter =5mm and weight=3gm

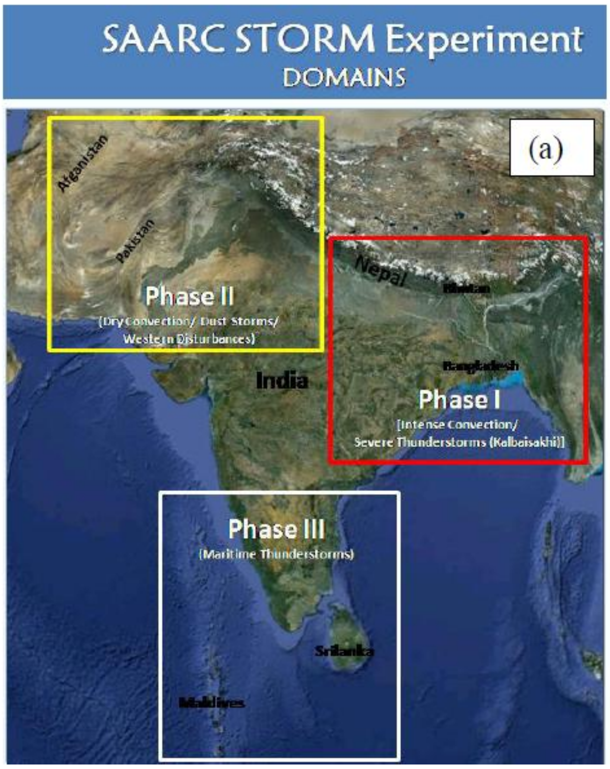

Fig.1: SAARC STORM Phases considered for the year 2013

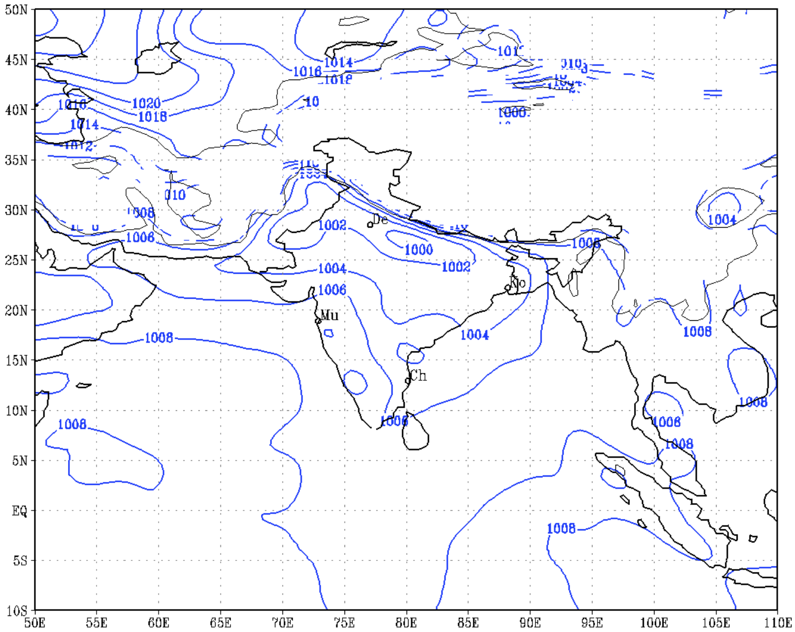

Fig.2: IMD GFS (T574) MSL analysis of 17 April, 2013 based on 00 UTC

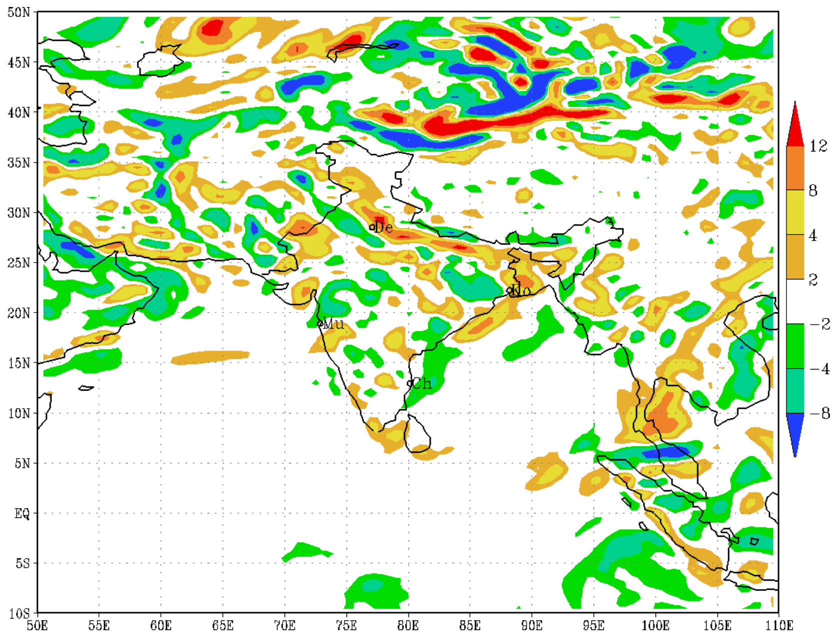

Fig.3: IMD GFS (T574) 850 hPa Vorticity analysis based on 00 UTC of 17 April, 2013

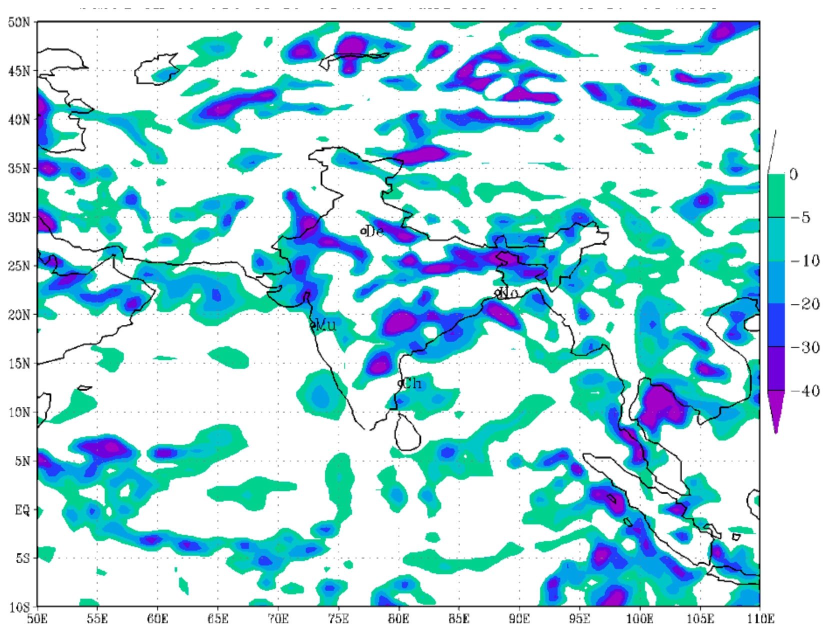

Fig.3a: IMD GFS(T574) 850 hPa Vertical Velocity analysis based on 00 UTC of 17 April, 2013

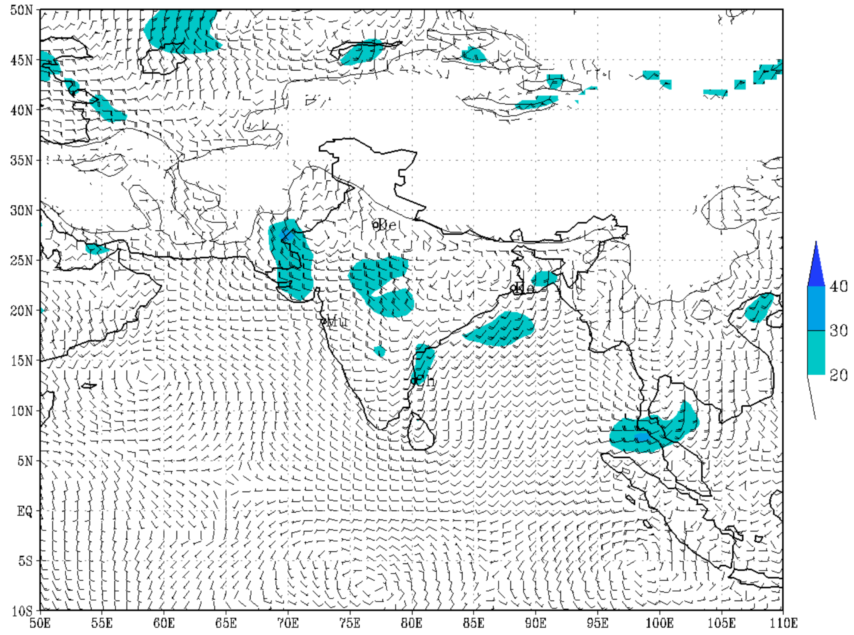

Fig.4: IMD GFS(T574) 925 hPa Wind(kt) analysis based on 00 UTC of 17 April, 2013

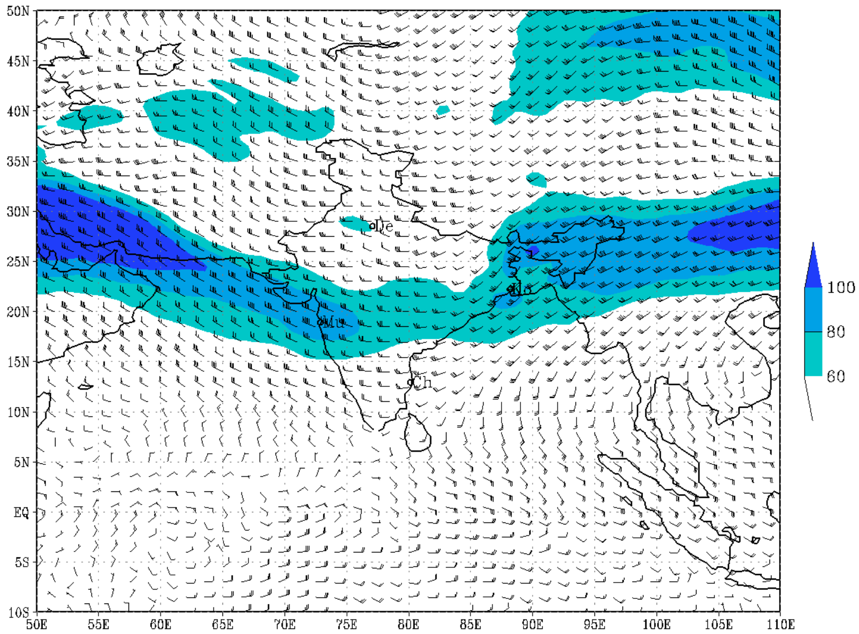

Fig.5: IMD GFS(T574) 200 hPa Wind(kt) analysis based on 00 UTC of 18 April, 2013

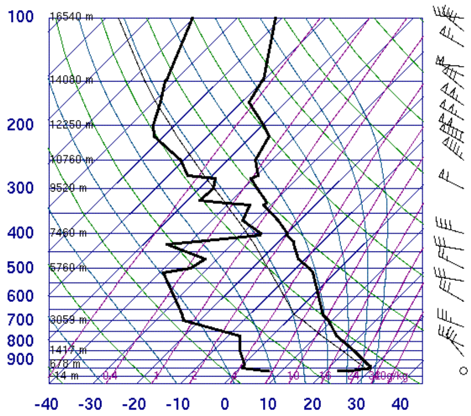

Fig.6a: Tephigram of 3 May, 2013 based on 0000UTC sounding data (No thunderstorm) (source:http://weather.uwyo.edu/upperair/sounding.html)

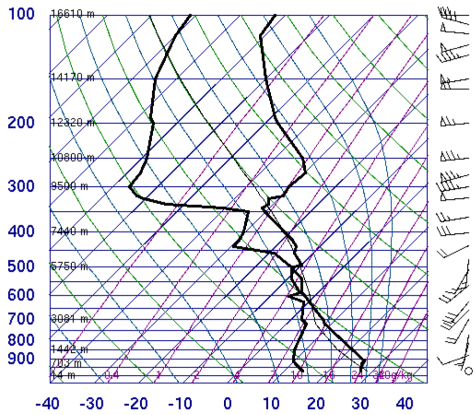

Fig.6b: Tephigram of 12 May, 2013 based on sounding data (Thunderstorm day) (source:http://weather.uwyo.edu/upperair/sounding.html)

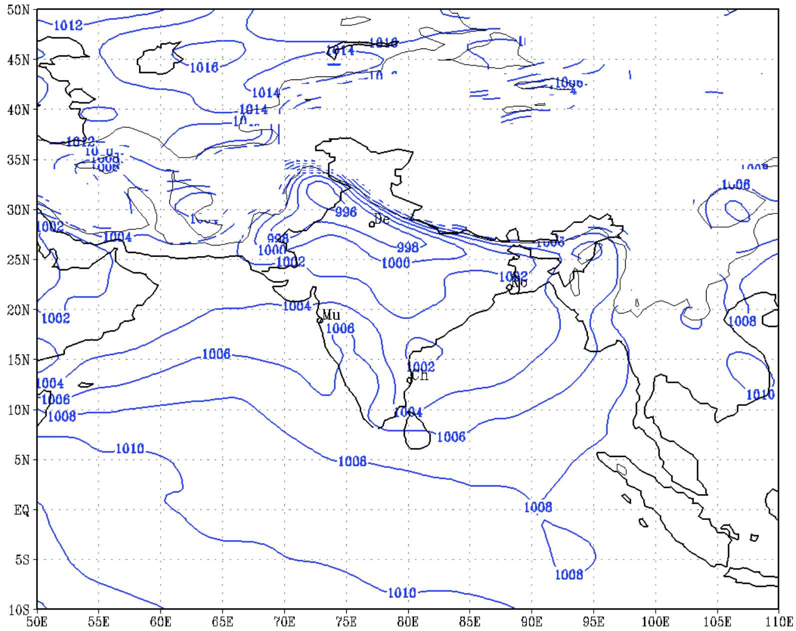

Fig.7: IMD GFS(T574) MSL Pressure (hPa) analysis based on 00 UTC of 6 June, 2013

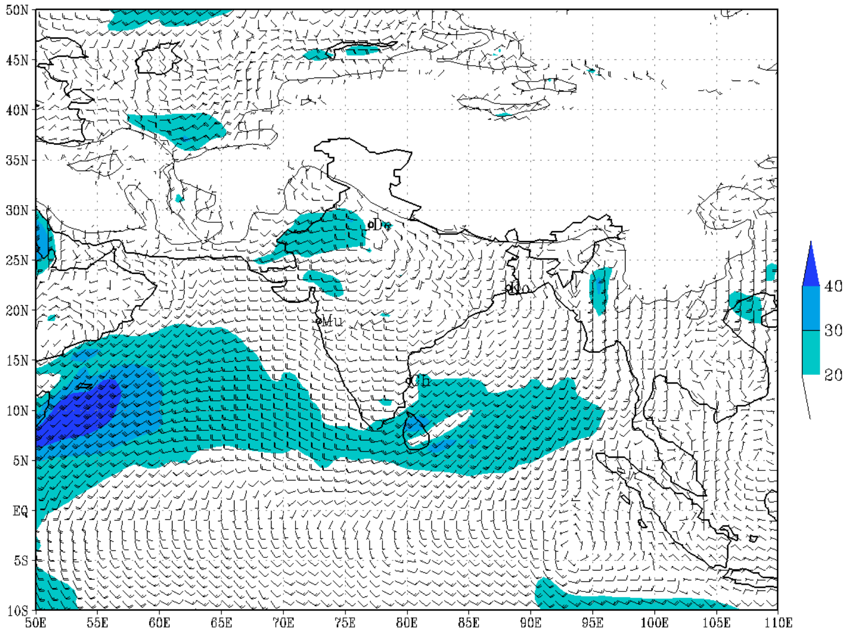

Fig.8: IMD GFS(T574) 925 hPa Wind(kt) analysis based on 00 UTC of 6 June ,2013

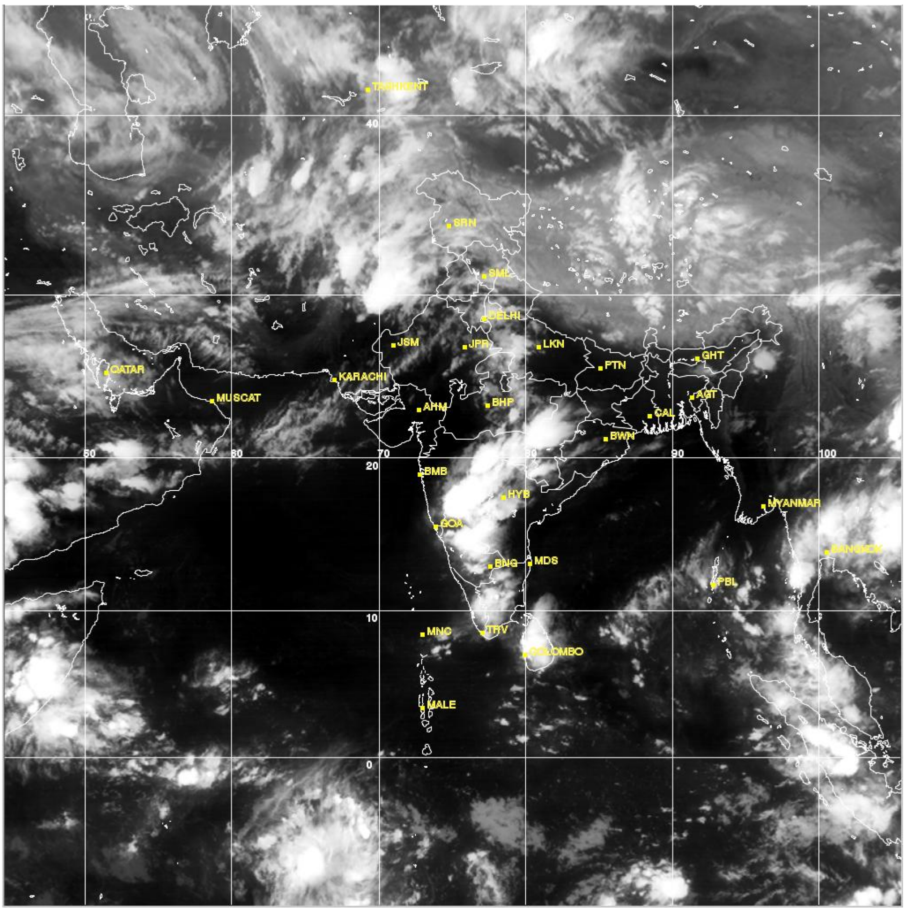

Fig.9: Kalpana TIR satellite Imagery on 25 April, 2013 at 1500 UTC

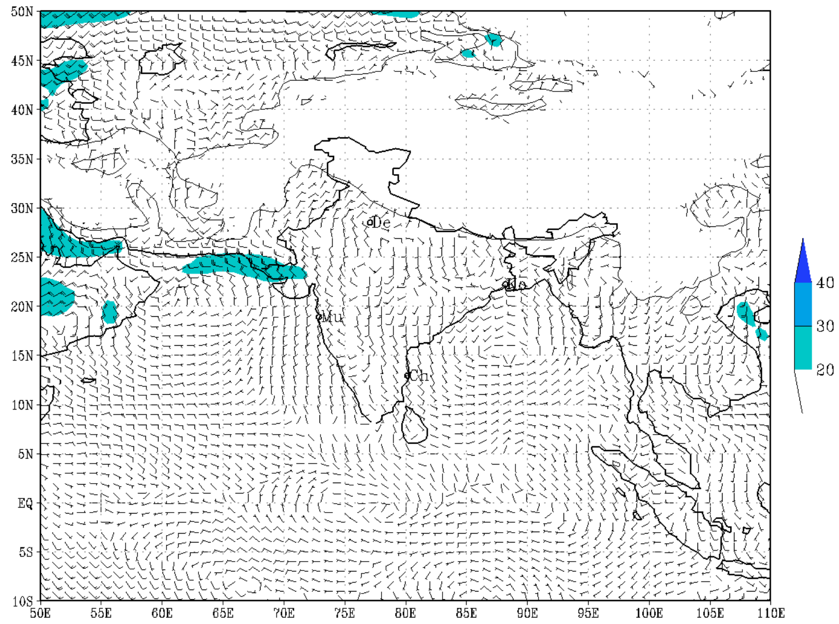

Fig.10: IMD GFS (T574) 925 hPa Wind (kt) analysis based on 00 UTC of 25 April ,2013

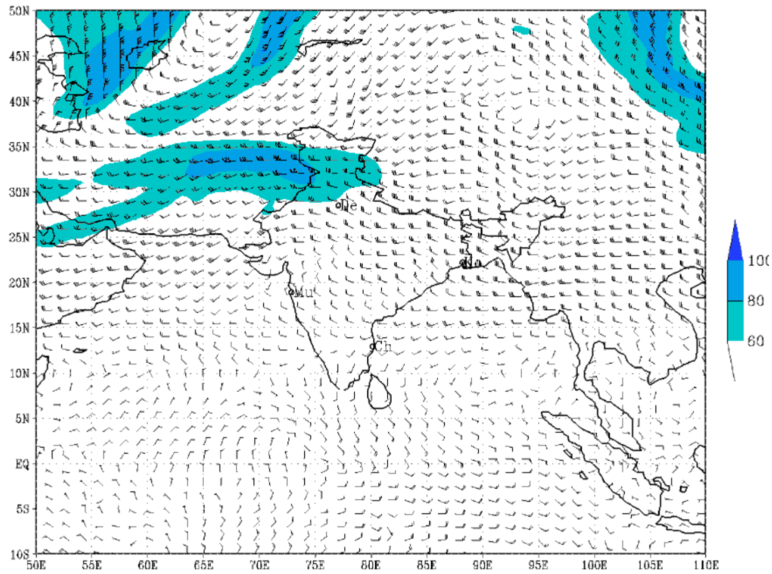

Fig.11: IMD GFS(T574) 300 hPa Wind(kt) analysis based on 00 UTC of 28 April ,2013

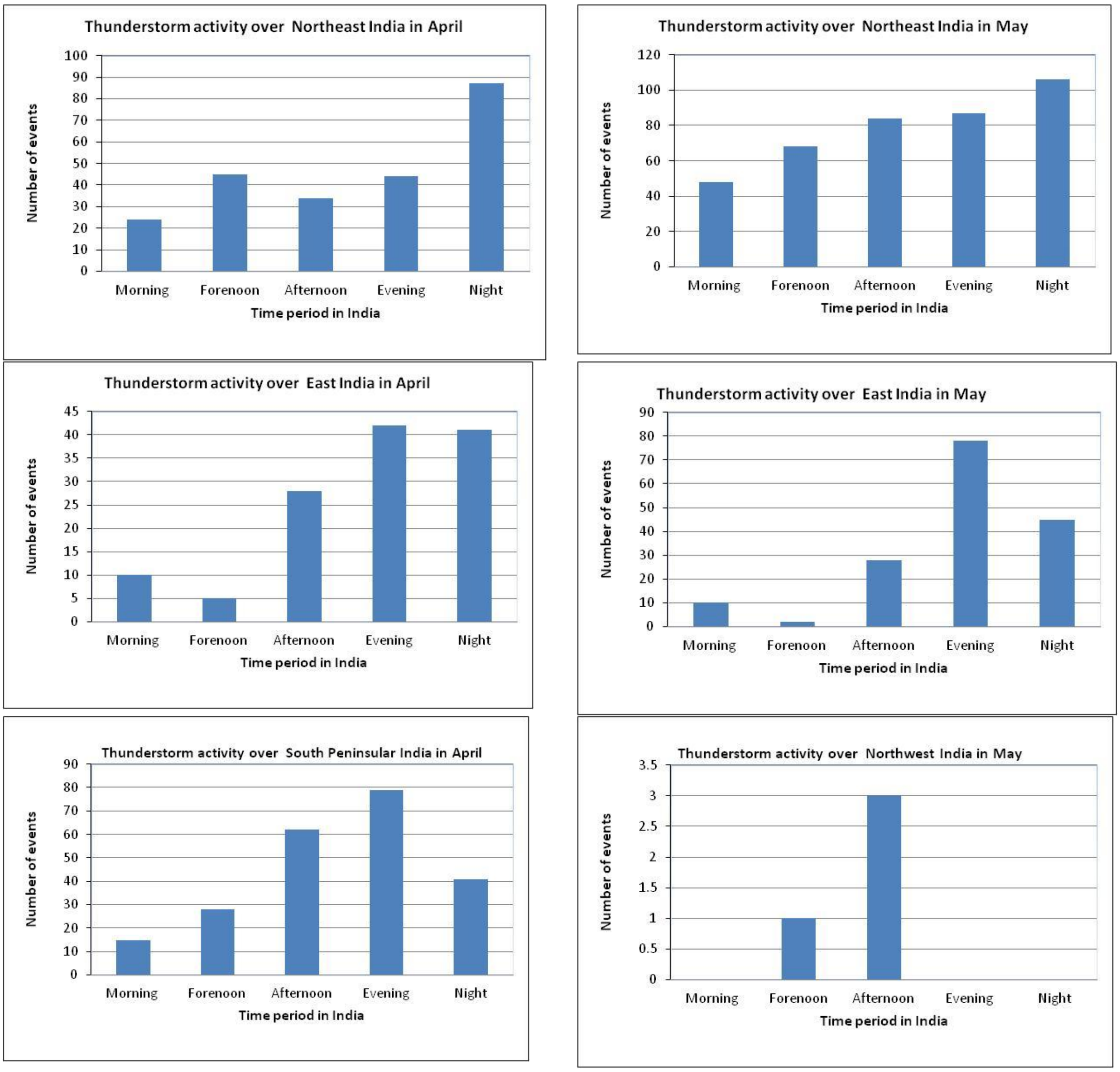

Fig.12: Number of events of thunderstorms over various regions during various time periods of the Pre-monsoon season, 2013 (Morning: 0400 to 0800 hrs IST, Forenoon: 0800 to 1200hrs IST, Afternoon: 1200 to 1600 hrs IST, Evening: 1600 to 2000 hrs IST, Night: 2000 to 0400 hrs IST.)