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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'

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सार – विज्ञान और प्रौद्योगिकी विभाग ने अप्रैल और मई 2006 से भीषण तूफान प्रेक्षण और क्षेत्रीय निदर्शन (एस. टी. ओ. आर. एम.) परियोजना आरम्भ की है। इस परियोजना में प्रादेशिक मौसम केन्द्र गुवाहटी ने भी भाग लिया और हर भीषण तूफान की प्रत्येक घटना का मानीटरन किया। 1 अप्रैल से 25 मई की अवधि के दौरान 30 दिनों में कुल 62 घटनाओं का पता लगाया गया है। मानसून के आरम्भ की 27 मई की तिथि को देखते हुए यह प्रयोग 25 मई तक किया गया है। इस शोध पत्र में इन सभी घटनाओं की प्रमुख विशेषताओं के बारे में विस्तार से चर्चा की गई है। इन घटनाओं के विकसित होने की कुछ चुनिंदा घटनाओं के उपग्रह चित्र और रेडार की प्रतिध्वनियों को इस शोध पत्र में सम्मिलित किया गया है। वायुमंडल के तापगतिकीय स्थितियों के साथ साथ प्रबल सिनॉप्टिक स्थितियों से जुडी घटनाओं की विस्तार से चर्चा की गई है। इस अध्ययन से प्राप्त हुए परिणामों से इस बात की पुष्टि हुई है कि ये घटनाएं ब्रह्मपुत्र नदी के समीप असम घाटी में अधिकतम संख्या में हुई है। ऊपरी और दक्षिण असम की अपेक्षा निचले असम में इस तरह की घटनाएं अधिक पाई गई है। इस क्षेत्र में भीषण तूफान की घटनाओं के अपसरण से उप हिमालय पश्चिम बंगाल और समीपवर्ती असम और ब्रह्मपुत्र घाटी के साथ–साथ पूर्व की ओर चलने वाले चक्रवातीय परिसंचरण से प्रकट होने वाले अनुकूल निम्न स्तर अभिसरण की उपस्थिति में चार केन्द्रों नामतः गुवाहटी, अगरतला, सिलिगुडी और डिब्रूगढ़ के धरातल के स्तर के समीप वायु तापमान और आर्द्रता के क्षेतिजीय वितरण में उच्च तापगतिकीय अस्थिरता एकरूप और उपलब्ध संवहनी संभावित उर्जा (सी. ए. पी. ई.) मान प्रमुख घटक है। कुछ स्थितियों में भी इस क्षेत्र में जटिल भूभाग की विशेषताओं की समीपता के कारण पर्यावरण में सी. ए. पी. ई. मानों की अत्याधिक कमी के कारण भीषण तूफानों के स्फोट हुए।

ABSTRACT. A Pilot project on 'Severe Thunderstorm Observation and Regional Modeling (STORM)' was undertaken by the Department of Science and Technology during April and May 2006. Regional Meteorological Centre, Guwahati too participated in this project and attempted to monitor each and every severe thunderstorm event. A total of 62 events have been identified on 30 days during 1st April to 25th May. The experiment was restricted upto 25th May in view of onset of monsoon on 27th May. Significant features of all these events are discussed in detail. Satellite imagery and radar echoes of selected events are included to describe the developments of these events. Thermodynamic state of atmosphere along with prevailing synoptic situation associated with the events has been discussed broadly. Results of the study confirm that the 'Assam valley' along Brahmaputra river experiences maximum number of events. Lower Assam is more prone to these events as compared to upper and south Assam. High thermodynamic instability, inhomogeneity in horizontal distribution of air temperatures and moisture near ground level and Convective Available Potential Energy (CAPE) value at four stations namely Guwahati, Agartala, Siliguri and Dibrugarh are the key factors in presence of the favourable lower level convergence exhibited by cyclonic circulation over sub-Himalayan West Bengal and adjoining west Assam moving eastwards along Brahmaputra valley with divergence aloft for occurrence of severe thunderstorm over this region. Also In some cases severe thunderstorm outbursts happen in the environment of very low CAPE value also due to proximity of complex terrain feature of this region.

Key words − Severe thunderstorm, Analysis, CAPE, Assam, STORM, Instability.

1. Introduction

Events of severe thunderstorm are mesoscale weather systems with space scale of a few kilometers to a couple of 100 kilometers and time scale of less than an hour to several hours associated with heavy showers of rain, lightening, roaring thunder, hailstorms, duststorms, surface wind squalls and on rare occasion even tornadoes.

Northeastern region of India is highly prone to these activities due to its typical geographic location particularly during pre-monsoon season. Many authors have studied this phenomenon all over the world and also over Indian region including the northeastern States of India. Koteswaram and Srinivasan (1958) discussed the synoptic conditions favourable for the development of thunderstorm and infer that the simultaneous presence of low level convergence and upper air divergence is the key factor. Rao and Raman (1961) showed that this region experiences thunderstorm at a higher frequency particularly in pre-monsoon season where as Hoddinot (1986) noticed that it appears with severe intensity causing loss of life and property. Synoptic features associated with pre-monsoon thunderstorms over Assam have been studied by Sen and Basu (1961). An attempt made by Choudhury (1961) on development of this event over northeast region had drawn attention towards low level convergence and lifting mechanism. Mukherjee (1964) has significantly contributed on the different aspects of this event in northeast region. He showed that the frequency of thunderstorm was highest at night in the pre-monsoon at Guwahati. Recently Choudhury (2006) has studied Ampliative reasoning to view the prevalence of thunderstorms over northeast region of India and concludes that for genesis of severe thunderstorm during pre-monsoon minimization of convective inhibition energy is fundamental whereas neither maximization nor minimization of convective available potential energy is of any significance. A climatological study of this event has been done by many scientists. Recently Manohar and Kesarkar (2004) studied climatological aspects of this phenomenon over Indian region during both pre and summer monsoon season. Kumar (1992) studied the climatology of thunderstorm at Lucknow airport whereas Moid (1996) did so for Mohanbari (Dibrugarh) airport. Observed variability in the current field during summer monsoon experiment for the north Bay of Bengal has been well documented by Rao *et al.* (1991). However few attempts have been made by the scientific community to study extensively the occurrences of this phenomenon using radar and satellite images alongwith surface and upper air observations in this region. An attempt has been made to bring out some new observational aspects along with broad scale features of this event as a result of participation by Regional Meteorological Centre (RMC), Guwahati in a pilot project sponsored by the Department of Science and Technology, Govt. of India on 'Severe thunderstorm Observation and Regional Modeling' (STORM) for east/northeast India in pre-monsoon 2006 in which an extensive network of observations had been engaged to capture the occurrence of every event in the region.

2. Observed experimental and recorded data and method of analysis

RMC Guwahati restricted for the pilot study the period of observations for the year 2006 to April and May which are prime months of occurrence of severe thunderstorm events. A special radiosonde observation at 0600 UTC has been taken considering crucial period of development of convective activity. The criteria applied to identify severe thunderstorm is mentioned below.

(*i*) Thunderstorm with squall and rainfall or

(*ii*) Thunderstorm with hailstorm or

(*iii*) Thunderstorm with heavy rainfall, *i.e.*, ≥ 65 mm

Satisfying criteria (*i*) & (*ii*) a total of 30 events of severe thunderstorm at different locations/stations over six States of Northeast India, *viz*., Assam, Meghalaya, Arunachal Pradesh, Nagaland, Manipur and Mizoram had been identified by taking local inputs on the damage caused to human life and property out of which 6 were very severe in nature. Apart from these, following the criteria (*iii*) on the basis of rainfall data reported from all the observatories and raingauge stations under RMC Guwahati 32 additional events have also been considered as some of them triggered landslides in vulnerable hilly areas of this region causing huge loss of property and sometimes life also. A detailed analysis of occurrence of all the events at different places of Assam and adjoining states has been done to see the distribution and extent of the events over the region. Climatology of thunderstorm events based on past 20 years of data of Guwahati has been mentioned in brief to gather climatological support for identification of critical period for significant occurrence of this event on a particular day for the month of April. The study is mainly focused on Assam state which is highly prone to this event mainly due to its physiographic characteristics. Considering the climatological aspects Assam is divided into three different zones such as Upper (central and east Assam), Lower (west Assam), South (Barak valley) Assam to bring out the spatial and temporal variability of the events. A rare occasion like occurrence of series of such events was observed on 19th April, which has been studied in detail and discussed. Satellite imagery and echoes from radar installed at Guwahati have been depicted for selected events. Upper air observations for four stations, *viz*., Agartala, Guwahati, Siliguri and Dibrugarh are discussed for the dates of occurrences of events alongwith prevailing synoptic situation on the basis of weather chart analysis at RMC Guwahati.

TABLE 1

Events of severe thunderstorms on the basis of local input

S. No.	Date	Time (UTC)	Location	Event	Damages
1	01 Apr 2006	Night	Dhubri	Squall + Hail	Houses, trees, road, communication, power
2	02 Apr 2006	1755 hrs	Guwahati A/P	Hail	Rabi crops
3	03 Apr 2006	Late night	Nongstoin, Khasi hill, Meghalaya	Squall	3 died, property worth Rs. 7 crore
4	03 Apr 2006	Late night	Mamit, Mizo/Tripura Border	Squall + Hail	850 houses
5	12 Apr 2006	Evening	Bagsa Assam	Squall + Heavy rain	600 families homeless Lifting of a minor girl to 20 meter distance
6	12 Apr 2006	Evening	Brodumsa, Changlang (A.P.)	Squall	6 died, properties
7	19 Apr 2006	Mid-day	Mayang, Morigaon	Squall	1 died
8	19 Apr 2006	0713 hrs	Dibrugarh A/P	Squall	Widespread
9	19 Apr 2006	Mid-day	Dhemaji	Squall	3 died
10	19 Apr 2006	0545 hrs	North Lakhimpur	Squall	Widespread
11	19 Apr 2006	0520 hrs	M.C. Itanagar	Squall	Wide spread
12	19 Apr 2006	0350 hrs	M.O. Tezpur	Squall	Wide spread
13	24 Apr 2006	0538 hrs	C.S.O. Shillong	Hail	Wide spread
14	24 Apr 2006	Mid-day	Sarpur, Hailakandi	Squall	1died, wide spread damage
15	25 Apr 2006	Afternoon	Morigaon, Sadia	Squall	Wide spread
16	26 Apr 2006	2025 hrs	North Guwahati	Squall + Hail	Wide spread
17	26 Apr 2006	Late Evn.	Mayang, Morigaon	Squall + Hail	Wide spread
18	01 May 2006	1615 hrs	Guwahati A/P	Squall	Wide spread
19	02 May 2006	1930 hrs	Guwahati A/P	Squall	Wide spread
20	03 May 2006	1710 hrs	Guwahati A/P	Squall	Wide spread
21	04 May 2006	Early Morn.	Sibsagar	Squall	Wide spread
22	04 May 2006	Early Morn.	Rowta, Darrang	Squall	Wide spread
23	05 May 2006	1215 hrs	Guwahati A/P	Squall + Hail	Wide spread
24	10 May 2006	Evening	Dhubri	Squall	2 died
25	14 May 2006	0810 hrs	M.O. Barapani	Hail	Wide spread
26	15 May 2006	1030 hrs	M.O. Barapani	Hail	Wide spread
27	19 May 2006	Evening	Nagaon	Squall	Wide spread
28	19 May 2006	Evening	Tezpur	Squall	1 died
29	20 May 2006	1700 hrs	M.O. Tezpur	Squall	Wide spread
30	25 May 2006	Evening	Guwahati	Squall	1 died

3. Observational facts, climatology of Guwahati and discussion

3.1. *Significant features of severe thunderstorm with squall and hail*

Table 1 shows 30 events of occurrence of severe thunderstorm and associated phenomenon at different locations of northeastern region of India during the period 1st April to 25th May 2006. As per criteria (*i*) and (*ii*) in view of onset of monsoon on 27th May the observations have been restricted upto 25th May. As seen the Table 1 furnishes information like date, duration, location, type of event and damage reported at different parts of northeastern states. Significant features in terms of damages shows the loss to the property as high as 7 Crore

TABLE 2

Events of severe thunderstorm based on heavy rainfall criteria at different stations

S. No.	Event Date	Location (State)	Rainfall (mm)*
1	02 Apr 2006	Cherrapunji (Meghalaya)	144
2	02 Apr 2006	Mawsynram (Meghalaya)	70
3	03 Apr 2006	Mawsynram (Meghalaya)	65
4	04 Apr 2006	Basar (Arunachal Pradesh)	81
5	05 Apr 2006	Khonsa (Arunachal Pradesh)	98
6	05 Apr 2006	Mon (Nagaland)	78
7	10 Apr 2006	Cherrapunji (Meghalaya)	202
8	10 Apr 2006	Mawsynram (Meghalaya)	71
9	10 Apr 2006	Miao (Arunachal Pradesh)	85
10	10 Apr 2006	Khonsa (Arunachal Pradesh)	93
11	11 Apr 2006	Cherrapunji (Meghalaya)	211
12	11 Apr 2006	Mawsynram (Meghalaya)	110
13	12 Apr 2006	Anini (Arunachal Pradesh)	72
14	13 Apr 2006	Anini (Arunachal Pradesh)	87
15	17 Apr 2006	Khowang (Arunachal Pradesh)	67
16	01 May 2006	Hailakandi (Assam)	104
17	03 May 2006	Dibrugarh (Assam)	65
18	03 May 2006	Khonsa (Arunachal Pradesh)	67
19	04 May 2006	Mawsynram (Meghalaya)	77
20	05 May 2006	Seppa (Arunachal Pradesh)	65
21	05 May 2006	Chouldhowaghat (Assam)	80
22	09 May 2006	Nalbari (Assam)	68
23	10 May 2006	Kokrajhar (Assam)	68
24	10 May 2006	Tezpur (Assam)	65
25	11 May 2006	Kokrajhar (Assam)	78
26	12 May 2006	North Lakhimpur (Assam)	67
27	12 May 2006	Basar (Arunachal Pradesh)	65
28	13 May 2006	Khanapara (Assam)	68
29	13 May 2006	Puthimari (Assam)	66
30	13 May 2006	Dhubri (Assam)	77
31	13 May 2006	Cherrapunji (Meghalaya)	97
32	13 May 2006	Mawsynram (Meghalaya)	116

(* Total rainfall reported at 0830 hrs IST of date following the event)

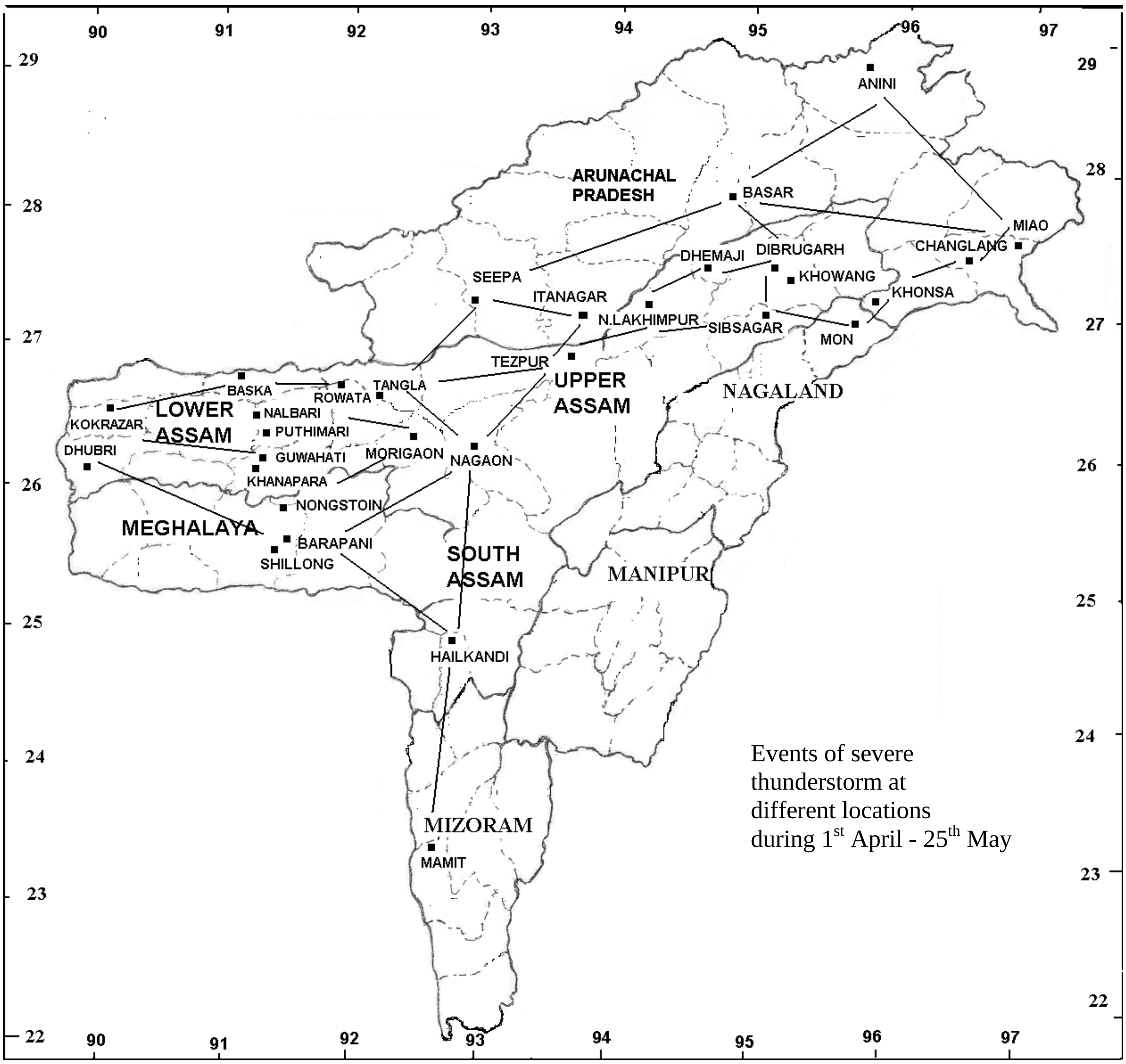


Fig. 1. Distribution of severe thunderstorm over Assam and adjoining states for period under consideration

rupees, destruction to 850 houses, 600 families rendered homeless and human casualties of 6 persons on different days at different locations, thus, demonstrating the severity of hazardness of this event. Hailstorm has been reported on four occasions whereas squall has occurred in almost every event, which is mentioned in Table 1, considering the extent of damage associated. On account of such a huge extent of destruction in few hours there is a need to study this phenomenon in detail and to develop a suitable model to forewarn its occurrence in early hours. Table 1 also shows the occurrence of it on isolated days and at locations as well as series of events on a particular day. It is seen that on 19th April, 2006 a series of thunderstorms have occurred from early morning to midday over upper Assam. Details of such rare incidence are described in detail for this specific region.

3.2. *Significant features of severe thunderstorm with heavy rainfall*

Table 2 shows the remaining of 32 events of severe thunderstorm as per the criteria (*iii*), which is based on the amount of rainfall on the day of their occurrence. As such for this study severe thunderstorm is identified as the

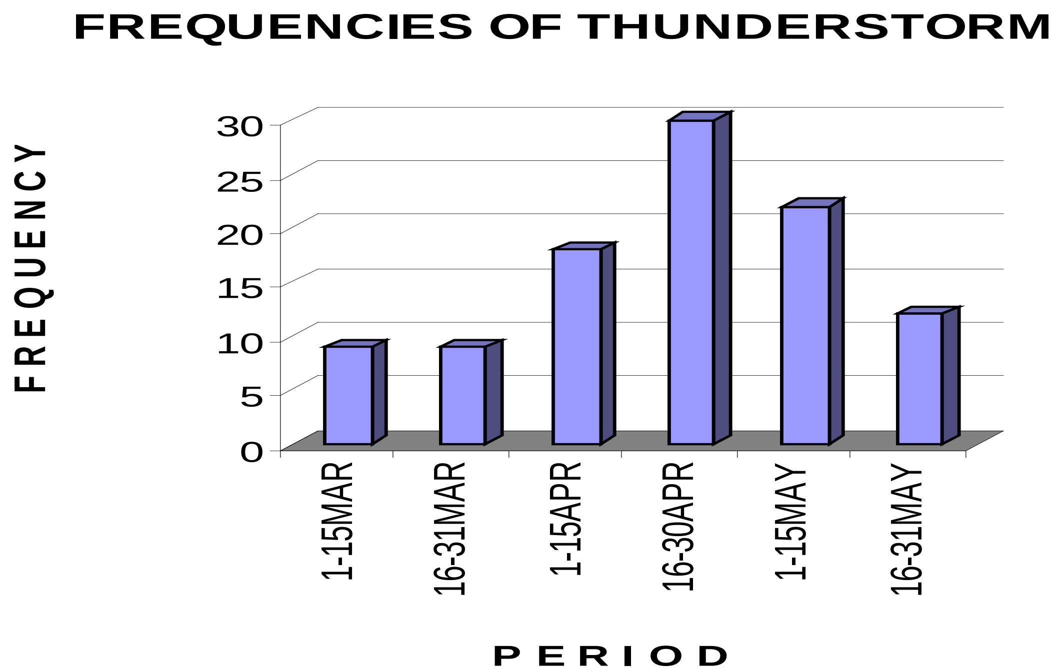
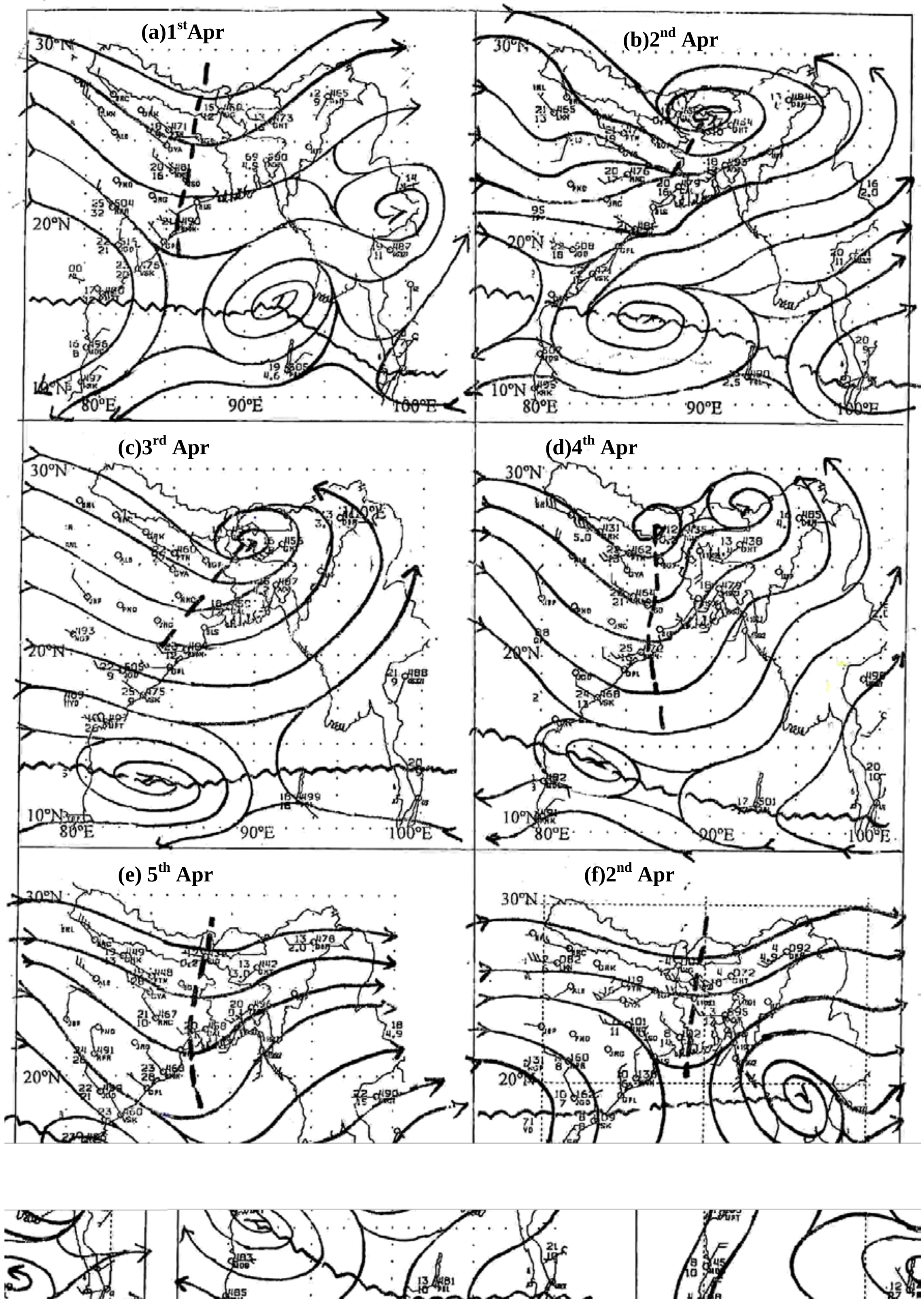


Fig. 2. Histogram showing total frequencies of severe thunderstorm events in different fortnights of April and May at Guwahati for the period 1985 to 2005

event of 'Heavy rainfall≥ 65 mm' during its period. It is seen that stations of Arunachal Pradesh and Meghalaya which is mostly covered by hilly region have experienced this event in large scale. However, damage to human life and to property is not seen to be significant perhaps due to meager population and poor infrastructure. Total 20 incidences have been noticed in these two states. Orographic enhancement of rainfall may be one of the important factors for high frequency of this phenomenon over this area.

3.3. *Distribution of all severe thunderstorm events for period under consideration*

Fig. 1 shows the spatial distribution of all the 62 events of severe thunderstorm observed and recorded at 33 locations during period from 1st April to 25th May, 2006 over Assam and adjoining states. Naturally Assam state experienced maximum number, *i.e.*, 35, Meghalaya-14, Arunachal Pradesh-11, Nagaland-1 and Mizoram & Tripura border-1. Maximum events were observed along the Bank of Brahmaputra river and nearby areas of Assam valley. Analysis of observations reveals that west Assam and Meghalaya between Lat. 25° N & Lat. 27° N and Long. 90° E & 92.5° E is highly prone to this event due to proximity to Gangetic West Bengal (GWB), Sub-Himalayan West Bengal (SHWB) and east Bihar which are the source regions of formation of convective cloud masses in the presence of suitable prevailing synoptic and thermodynamic condition. These cloud masses embedded with cumulonimbus (Cb) cells move towards east under the influence of westerlies which further get intensified due to prevailing unstable atmosphere and abundant moisture incursion from the Bay of Bengal (by southerly or southwesterly flow) and get trapped inside Assam valley due to surrounding hills and ultimately dissipate in the form of heavy thunderstorm accompanied by hail, squall or heavy shower. Assam valley (mainly lower Assam) naturally shows higher frequency as compared to other parts of the region due to proximity of source. The extent of events is seen upto Hailkandi located at south Assam, *i.e.*, Barak valley. Isolated event is seen at Mamit near Mizoram-Tripura border. Towards north Arunachal Pradesh, *i.e.*, between Lat. 27.5° N & 29° N and Long. 95° N & 97° N stations like Anini, Basar and Miao shows two events each. It is seen that the events experienced by Meghalaya (east Khasi hills area) and Arunachal Pradesh in terms of heavy to very heavy rainfall are very high due to physiographic features of these areas which lie on the wind ward side of east west oriented Garo-Khasi-Jaintia hills and eastern Himalayan range. States like Nagaland, Manipur and Mizoram shows only one or two incidences



Figs. 3.(a-f). (a-e) 850 hPa Upper Air charts of 0000 UTC and (f) 700 hPa Upper Air charts of 1200 UTC

as their geographical position is such that these lie to lee side of north south oriented north eastern hill range. Temporal distribution shows that the events have occurred in 9 distinct spells of days, *viz*., (*i*) 1st to 5th April, (*ii*) 10th to 13th April, (*iii*) 17th April, (*iv*) 19th April, (*v*) 24th to 26th April, (*vi*) 1st to 5th May, (*vii*) 9th to 15th May, (*viii*) 19th to 20th May and (*ix*) 25th May. Table 1 shows that out of 30 severe thunderstorm events associated with hail or squall maximum number (11) have been reported in second fortnight of April 6 events have been reported in 1st fortnight of April and remaining in the month of May. Overall observations indicate that severe thunderstorm event over this particular region occurs from first week of April itself. Important feature of occurrence of these events over entire Assam is that the activity is most frequent over lower Assam during night or late night and over upper Assam at late night or early morning. Reason for occurrence of events particularly during night or late night/early morning is due to migratory cloud masses from west to east region. Also a study by Mukherjee (1964) showed that frequency of pre-monsoon thunderstorm over Guwahati is maximum at night.

3.4. *Climatology of severe thunderstorm over Guwahati*

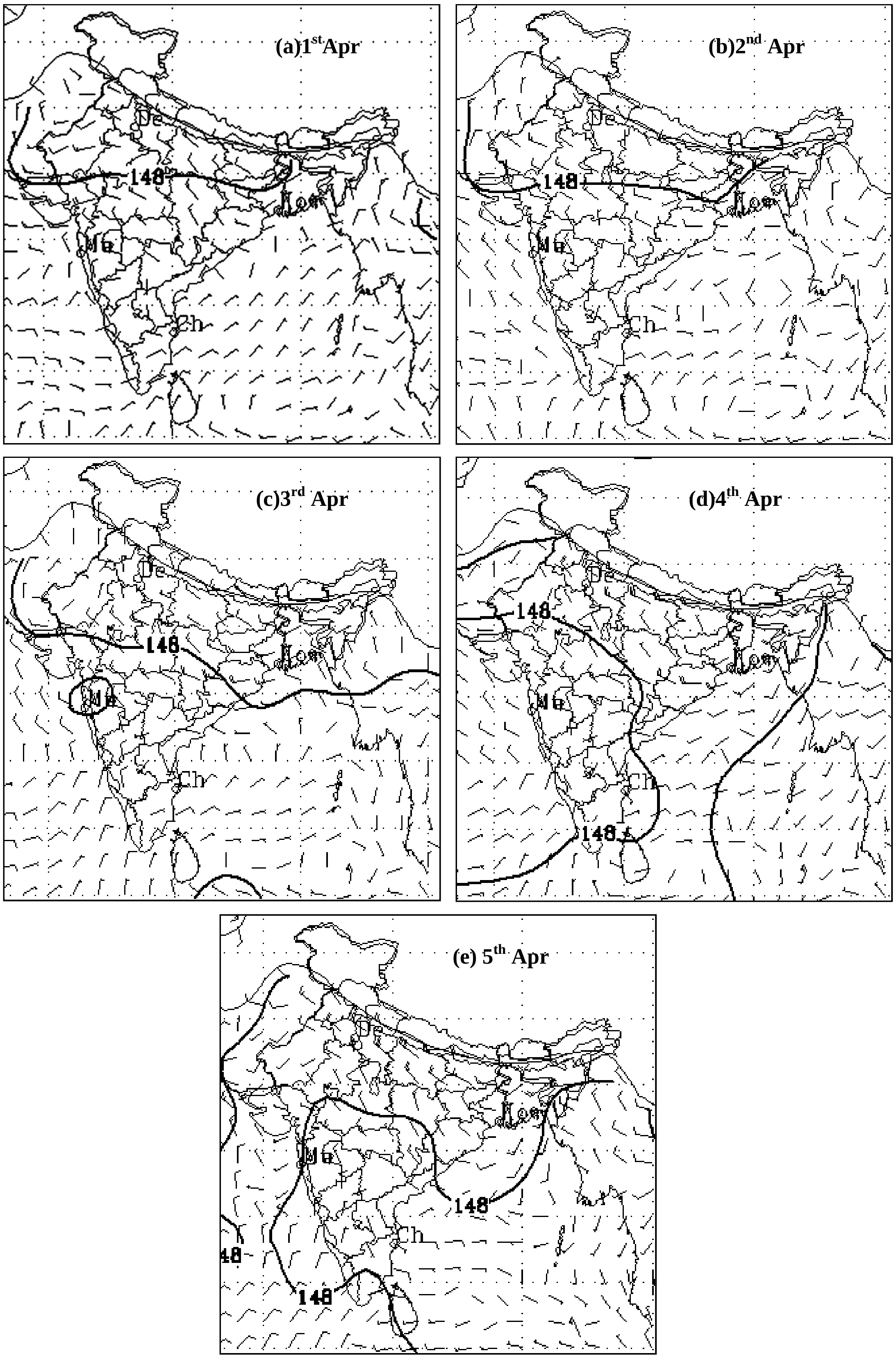
In order to gather climatological inputs regarding the date of initiation of experiment in future for the month of April climatological aspects of this event needs to be checked with the help of past data of selected locations. Guwahati being highly prone to this event has been chosen for climatological study as it has availability of required data, which has been properly monitored and archived. As such data from 1985 to 2005 has been considered for this study, which has been represented graphically in Fig. 2. As seen from Fig. 2 the frequency of this event suddenly increases from 9 in second fortnight of March to 18 in first fortnight of April, thus, indicating that 1st April may be the ideal date to commence the experiment and there may not be loss of significant incidences. Period 16th to 30th April shows maximum frequency, *i.e*., 30. So, utmost attention is needed to monitor this phenomenon during this period. Significant reduction in frequency is observed by the end of May apparently due to onset of monsoon.

4. Analysis of synoptic and thermodynamic features

Intensive Observational Periods (IOP's) were identified and additional surface and upper air observations were organised to capture development of severe weather events. Upper air observations of 850 hPa and 500 hPa alongwith surface level observations of those IOP's of four stations, *viz*., Agartala, Guwahati, Siliguri and Dibrugarh have been taken into consideration to study the behaviour of different thermodynamic parameters. As such temperature, humidity, mixing ratio, wind speed and direction at three levels (surface, 850 and 500 hPa) and convective available potential energy (CAPE) is taken into account and all these information is depicted in Table 3 for some selected date of event. The synoptic and thermodynamic conditions associated with the distinct spells of events are discussed below.

4.1. *1st to 5th April 2006*

During this spell the area affected by severe thunderstorm associated with squall or hail were Dhubri, Guwahati, Nongstein (Khasi hills, Meghalaya) and Mamit (Mizoram and Tripura Border) and thunderstorms with heavy rain occurred over Meghalaya, Arunachal Pradesh and Nagaland. From Tables (1&2) the thunderstorm activity and the rainfall gradually shifted eastward during the period 1-5th April 2006. Spatial distribution of severe thunderstorm events during 1st April to 5th April shows that it started from extreme west Assam (over Dhubri on 1st April) and gradually moved east/northeast wards and finished over east Arunachal Pradesh and Nagaland. Such type of rainfall and thunderstorm pattern could be very well attributed to the synoptic features prevailing prior to and during that period. There was a cycir over SHWB & Sikkim and adjoining Bihar and north Bangladesh extending upto 0.9 km amsl on 1st (not shown). It was seen as a trough extending from Bihar to south coastal Orissa across Jharkhand at 1.5 km amsl [Fig. 3(a)]. A north south trough was seen from SHWB to coastal Orissa at lower levels on 1st and further observed on 2nd along 89° E north of 21° N between 2.1 km and 3.6 km asl. The analysis for the representative level (3.1 km) is shown in Fig. 3(f). With a trough from the system extending upto GWB on 2nd and south coastal Orissa on 3rd, it moved on 4th April to central Assam and adjoining Arunachal Pradesh with vertical extension upto 1.5 km a.s.l. Another trough in westerly extending along 86° E north of 16° N between 1.5 km and 2.1 km a.s.l. was observed on 4th & 5th with a cycir over north Bihar and neighborhood on 4th [Figs. 3(d&e)]. Also the Regional Specialized Meteorological Centre (RSMC), India Meteorological Department (IMD) and Numerical Model (Limited Area Model) analysis of 850 hPa winds for 0000 UTC of 1st to 5th April, 2006 has been shown in Figs. 4(a-e). This distribution was seen to be concurrent with the movement and location of lower level cycir/trough. On 1st April the anti-cyclonic circulation in association with a ridge roughly along 15° north lay over south east and adjoining



Figs. 4(a-e). RSMC (IMD) 850 hPa wind analysis for 0000 UTC of different dates

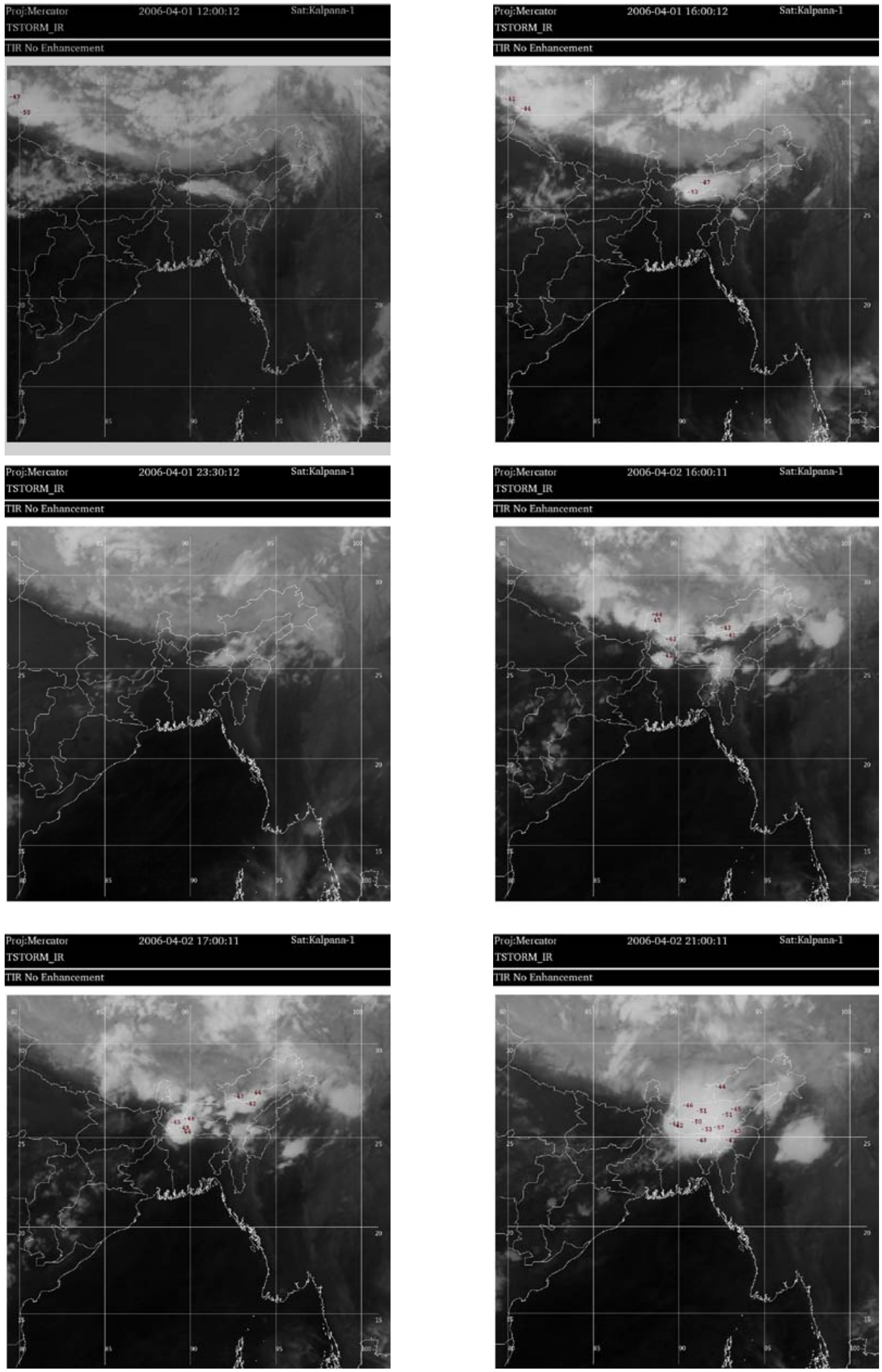


Fig. 5. Satellite imageries of 1st and 2nd April (time in UTC indicated on top of each images) showing development of Cb cells associated with the events (Numbers on clouds indicates CTT)

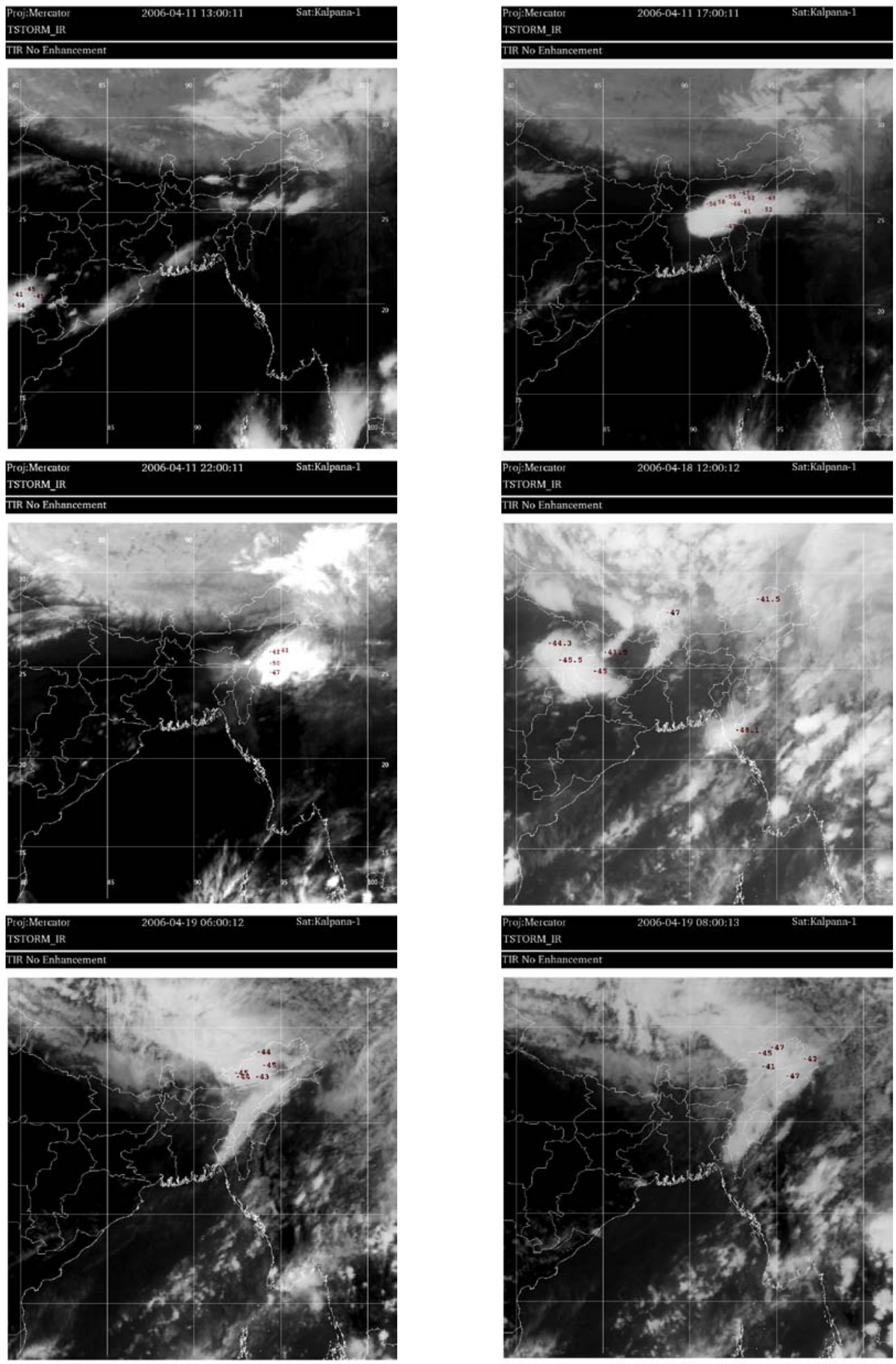
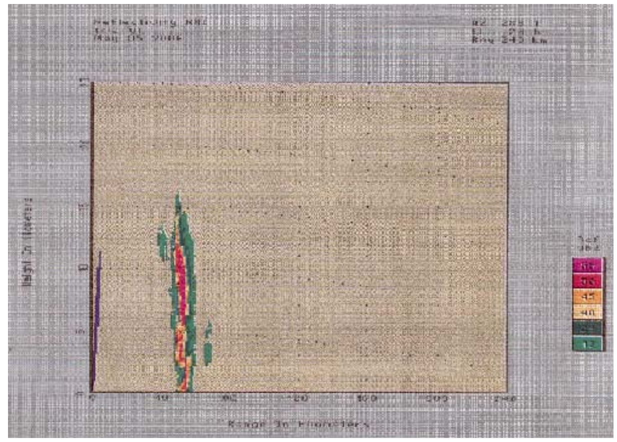


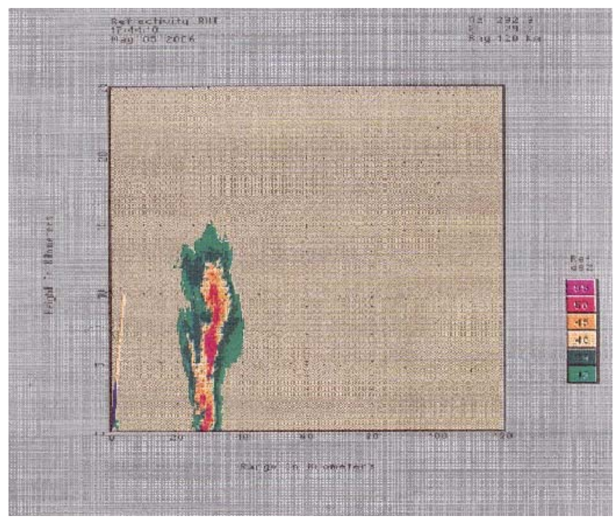
Fig. 6. Satellite imageries of 11th and 19th April (time in UTC indicated on top of each images) showing development of Cb cells associated with the events (Numbers on clouds indicates CTT)

east central Bay of Bengal, thus, helping in building-up of moisture over the north-eastern states. While the ridge continued to lie in the same position, the embedded anticyclonic circulation shifted westwards gradually and lay over coastal AP on 5th. Thus, the moisture incursion was significantly reduced on 5th leading to decrease in activity even though a feeble trough lay to the west of northeast India. From Figs. 3(b&c) it can be seen in presence of the cycir over SHWB, Bihar and west Assam warm and moist southerly/southwesterly winds prevail at lower levels over Tripura, coastal Bangladesh, on the other hand dry and cold northeasterly wind blows from foothills of the Himalayas. As a result a great inhomogeneity of temperature and moisture in lower tropospheric air mass field is generated over west Assam, Meghalaya and adjoining area, which seems to be a prime factor for development of severe convective storms. Apart from this due to presence of the north south trough [Figs. 3(d-f)] strong moisture incursion from the Bay of Bengal takes place over Assam and adjoining states. One hailstorm event over Guwahati airport with hail size of 2.5 cm was recorded on 2 April 2006. This event occurred during 1758 to 1810 UTC. Wind speed from 6 to10 knots gusting to 12 knots from northeast direction was recorded at the station. There is no squall or high wind speed-recording instrument at RMC, Guwahati. The 1800 UTC Synop data showed a pressure drop of -1.7 hPa in 24 hrs, whereas surface temperature and dew point was dropped by 3.4 and 2.2° C respectively in one hour between 1800 and 1900 UTC. Table 3 shows values of surface parameters at 1200 UTC of 2nd April at Agartala, Guwahati and Siliguri respectively. The surface temperatures of Agartala, Guwahati and Siliguri were observed between 27-31º C and moist wind with speed of 4-8 knots having direction as south-westerly/southerly/easterly respectively. Also veering of winds (southerly to westerly) with increasing wind speed from 4 knots at surface to 44 knots at 500 hPa was observed over Guwahati at 1200 UTC of 2nd April. Surface value of CAPE at 1200 UTC of 2nd April was observed as 5274.12 J/kg at Siliguri (which is 400 km north-west of Guwahati), 4911.39 Joule/kg at Agartala (which is 250 km south of Guwahati), 1610 J/kg at Guwahati and least as 448.24 J/kg at Dibrugarh (which is situated about 400 km north-east of Guwahati). Thus, the CAPE values observed at all the four stations about 5 hours before the event provide an indication for the occurrence of these events. Satellite imagery (Fig. 5) of 1st and 2nd April confirm the formation of convective cloud masses during evening hours over SHWB and neighbourhood which moved towards east, got intensified with cloud top temperatures about -60º C to -50º C and finally dissipated in the form of severe thunderstorm associated with hail, squall and heavy rain over lower Assam, Meghalaya and adjoining areas.

(a) RHI of 5th May, 2006 at 1151UTC



(b) RHI of 5th May, 2006 at 1242UTC

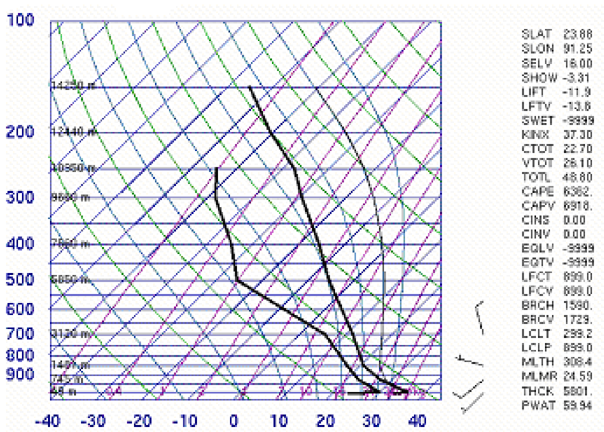


Fígs. 7(a&b). Radar images (RHI) of 5th May for different times

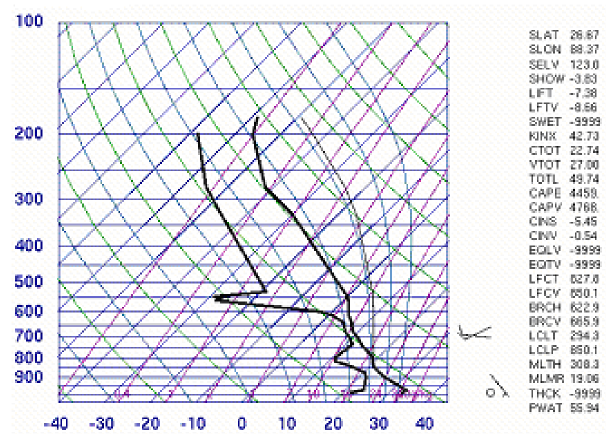
4.2. *10th to 13th April, 2006*

In this spell the areas affected by squall were Bagsa, Bhutan border, north-west Guwahati, north-east Dibrugarh and Changlang (Arunachal Pradesh). During this period heavy to very heavy (≥13 cm) rainfall occurred over Meghalaya and Arunachal Pradesh. Fig. 6 shows dense convective cloud cluster over Meghalaya, which received heavy rain on 11th April over Cherrapunji (21cm) and Mawsynram (11cm). Time of heavy shower apparently coincides with deepening and expansion of cloud top though it could not be checked due to non-availability of Self Recording Rain Gauge (SRRG) records. Synoptic features on 10th shows a cycir extending upto 1.5 km asl over Bihar and adjoining Jharkhand. Another cycir

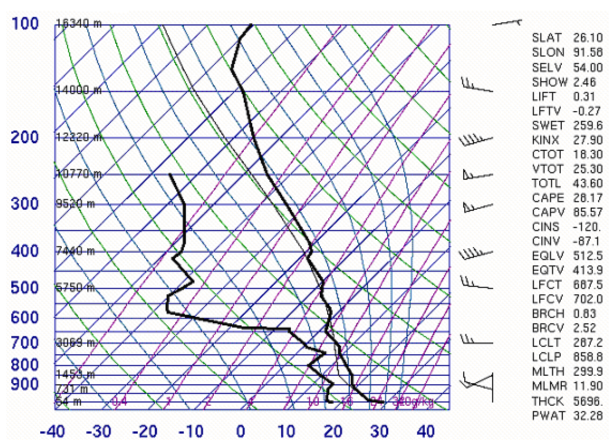
(a) Agartala sounding 1200UTC, 1st May, 2006



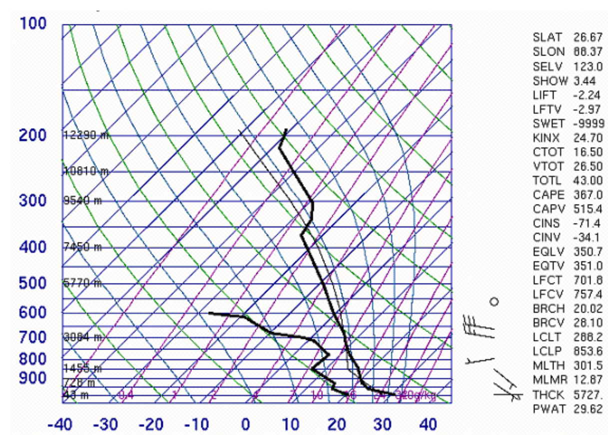
(b) Siliguri sounding 1200UTC, 1st May, 2006



(c) Guwahati sounding 1200UTC, 3rd May, 2006



(d) Siliguri sounding 1200UTC, 3rd May, 2006



Figs. 8(a-d). Sounding diagram (Skew-T) of 1st and 3rd May, 2006 of different stations

between 0.9 km and 2.1 km asl lay over northeast Assam, adjoining Arunachal Pradesh and Nagaland with trough in westerly aloft. The cycirs during 11th to 13th over SHWB, northeast Assam, north Bangladesh and adjoining west Assam extending upto 0.9 km asl must be embedded in the trough from Bihar to Arunachal. A north south trough was also seen from SHWB to Chattisgarh across Gangetic West Bengal and Jharkhand upto 2.1 km asl on 13th. The sub-tropical westerly jet (STWJ) was noticed over Assam during this period with a wind speed over Guwahati about 70 to 80 knots. So the favourable synoptic condition, *i.e.*, lower level convergence exhibited by cycir or east west trough accompanied with upper air divergent flow and suitable vertical wind shear prevailed over affected areas. The surface temperatures of Guwahati and Dibrugarh were high (with relatively higher dew points) and mid level jet (westerlies) blowing at 50 knots at 500 hPa. The point to be noted is that the explosive thunderstorm has occurred even with low values of CAPE of 749.88 J/kg at Guwahati and 791.1 J/kg at Dibrugarh on 12th. Millar (1972) has showed that in some cases slope circulations associated with small hills or urban heat island circulation are contributing factors to flash flood events that are associated with this type of thunderstorms.

4.3. *19th April, 2006*

Extensive severe thunderstorm events were seen as squall line along the north bank of Brahmaputra on 19th April morning to mid day over upper Assam. It seems that

TABLE 3

Surface and upper air observations at selected levels of four stations

	Station	*T*	*T*d	RH	Mx.	WS	WD	CAPE	*T*	*T*d	RH	Mx.	WS	WD	*T*	*T*d	RH	Mx.	WS	WD
		02 Apr 2006 (1200 UTC) Surface level							**02 Apr 2006 (1200 UTC) 850 hPa**						**02 Apr 2006 (12UTC) 500 hPa**					
	1.Agartala	31.6	21.6	55	16.5	4	255	4911.4	18.0	11.0	64	09.8	18	235	-17.3	-25.3	50	1.0	44	310
A	2.Guwahati	27.2	15.2	48	10.9	2	180	1601.1	17.8	07.8	52	07.9	19	235	-16.3	-24.3	50	1.08	44	270
	3.Siliguri	28.0	18.0	55	13.3	8	090	5274.1	11.8	-1.2	40	4.14	05	160	-27.1	-	-	-	23	280
	4.Dibrugarh	23.0	18.0	73	13.2	8	045	0448.2	15.8	05.8	51	6.85	09	125	-15.7	-23.7	50	1.14	-	-
		12 Apr 2006 (1200 UTC) Surface level							**12 Apr 2006 (1200 UTC) 850 hPa**						**12 Apr 2006 (1200 UTC) 500 hPa**					
	1.Agartala	30.4	26.4	79	22.3	4	135	4389.1	20.6	13.6	64	11.7	18	300	-07.3	-	-	-	49	260
B	2.Guwahati	28.4	23.5	75	18.7	4	270	0749.9	19.0	08.0	49	08.0	05	235	-05.3	-	-	-	50	270
	3.Siliguri	31.0	13.0	33	09.6	0	0	0163.6	19.6	02.6	32	05.5	-	-	-12.3	-20.3	51	1.5	-	-
	4.Dibrugarh	23.2	20.3	84	15.4	8	45	0791.1	22.6	14.6	61	12.4	13	210	-05.5	-	-	-	-	-
		19 Apr 2006 (0000 UTC) Surface level							**19 Apr 2006 (0000 UTC) 850 hPa**						**19 Apr 2006 (0000 UTC) 500 hPa**					
	1.Agartala	23.0	22.2	95	17.0	0	0	2567.2	15.8	13.8	88	11.8	23	240	-12.7	-33.7	15	0.5	-	-
C	2.Guwahati	22.0	20.5	91	15.3	4	0	-	13.2	11.6	90	10.2	08	105	-14.1	-23.1	46	1.2	24	225
	3.Siliguri	21.0	19.5	91	14.5	6	50	1306.7	09.8	07.4	85	07.7	08	165	-15.5	-21.5	60	1.4	-	-
	4.Dibrugarh	19.0	18.3	96	13.4	0	0	-	17.0	09.0	59	08.5	05	155						
		24 Apr 2006 (0000 UTC) Surface level							**24 Apr 2006 (0000 UTC) 850 hPa**						**24 Apr 2006 (0000 UTC) 500 hPa**					
	1.Agartala	23.0	21.8	93	16.65	0	0	1853.15	19.8	6.8	43	7.34	7	280	-10.1	-41.1	6	0.21	29	265
D	2.Guwahati	25.0	21.2	79	16.1	0	0	47.71	13.2	12.4	95	10.75	12	245	-5.5	-21.5	27	1.38	25	290
	3.Siliguri	25.2	18.2	65	13.42	0	0	882.98	15.6	6.6	55	7.24	3	100	-12.7	-21.7	47	1.36	31	295
	4.Dibrugarh	29.8	29.1	96	26.3	8	90	286.33	14.8	4.8	51	6.38	-	-	-3.5	-6.3	81	4.8	-	-
		25 Apr 2006 (0000 UTC) Surface level							**25 Apr 2006 (0000 UTC) 850 hPa**						**25 Apr 2006 (0000 UTC) 500 hPa**					
	1.Agartala	20.4	18.9	91	13.9	2	45	-	20.0	02.0	30	05.2	14	270	-09.7	-19.7	44	01.6	32	260
E	2.Guwahati	19.0	16.3	84	11.8	0	0	-	15.2	08.2	63	08.9	12	280	-10.7	-22.7	37	01.2	29	280
	3.Siliguri	23.4	19.4	78	14.5	6	90	-	13.4	09.2	76	08.7	11	110	-12.1	-17.1	66	02.0	21	290
	4.Dibrugarh	21.8	19.5	87	14.5	0	0	-	15.4	10.5	73	09.5	08	070	-08.3	-12.4	72	02.9	15	235
		26 Apr 2006 (1200 UTC) Surface level							**26 Apr 2006 (1200 UTC) 850 hPa**						**26 Apr 2006 (1200 UTC) 500 hPa**					
	1.Agartala	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
F	2.Guwahati	28.0	21.0	66	15.9	4	45	-	16.2	10.2	68	09.3	09	270	-09.7	-45.7	04	0.1	31	260
	3.Siliguri	29.6	21.6	62	16.7	4	90	-	19.6	17.1	85	14.7	01	235	-08.7	-09.3	95	3.8	34	265
	4.Dibrugarh	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		1 May 2006 (1200 UTC) Surface level							**1 May 2006 (1200 UTC) 850 hPa**						**1 May 2006 (1200 UTC) 500 hPa**					
G	1.Agartala	33.4	23.4	56	18.4	6	225	6362.9	20.6	17.2	81	14.8	07	285	-5.5	-25.5	19	0.97	-	-
	2.Guwahati	30.4	19.4	52	14.4	2	45	0956.4	19.0	13.0	68	11.2	18	265	-7.5	-26.6	20	0.8	09	350
	3.Siliguri	33.0	19.4	52	17.1	0	0	4460.0	20.8	15.8	73	13.7	04	208	-1.7	-18.7	26	1.65	-	-
	4.Dibrugarh	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		04 May 2006 (0000 UTC) Surface level							**04 May 2006 (0000 UTC) 850 hPa**						**04 May 2006 (0000 UTC) 500 hPa**					
	1.Agartala	26.0	24.8	93	20.2	2	90		22.6	10.6	47	09.5	12	235	-1.7	-25.7	14	0.95	-	-
H	2.Guwahati	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-
	3.Siliguri	25.2	20.2	74	15.3	0	0		18.4	12.4	68	10.8	-	-	-9.3	-	-	-	-	-
	4.Dibrugarh	22.4	21.7	96	16.7	0	0		16.0	13.9	87	11.9	8	185	-18.9	-20.5	87	1.5	-	-

TABLE 3 (*Contd.*)

	Station	*T*	*T*d	RH	Mx.	WS	WD	CAPE	*T*	*T*d	RH	Mx.	WS	WD	*T*	*T*d	RH	Mx.	WS	WD
		05 May 2006 (1200 UTC) Surface level							**05 May 2006 (1200 UTC) 850 hPa**						**05 May 2006 (1200 UTC) 500 hPa**					
	1.Agartala	34.0	21.0	47	15.9	2	180	5762.2	22.8	15.8	65	13.5	4	240	-4.5	-27.5	15	0.8	-	-
I	2.Guwahati	29.4	21.4	62	16.3	2	0	1383.2	18.8	14.0	74	11.9	18	235	-8.5	-50.5	02	0.1	24	250
	3.Siliguri	30.6	19.6	52	14.7	0	0	00.35	21.6	15.6	69	13.3	03	30	-2.7	-19.7	26	1.6	-	-
	4.Dibrugarh	-	-	-	-	-	-	-	-	-	-	-	-	-	--	-	-	-	-	-
		10 May 2006 (1200 UTC) Surface level							**10 May 2006 (1200 UTC) 850 hPa**						**10 May 2006 (1200 UTC) 500 hPa**					
	1.Agartala	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
J	2.Guwahati	25.2	22.0	82	17	4	180	778.3	15.8	15.1	96	12.9	07	325	-7.1	-7.9	94	4.2	28	220
	3.Siliguri	27.0	22.6	77	17.8	0	0	484.7	16.2	9.2	63	8.7	08	80	-8.3	-18.3	44	1.8	14	275
	4.Dibrugarh	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		14 May 2006 (1200 UTC) Surface level							**14 May 2006 (1200 UTC) 850 hPa**						**14 May 2006 (1200 UTC) 500 hPa**					
	1.Agartala	28.4	23.8	76	18.9	02	45	8838.8	15.8	15.6	99	13.3	04	240	-15.5	-16.2	94	2.2	-	-
K	2.Guwahati	24.4	17.4	65	12.6	02	0	0	15.4	7.4	59	7.65	17	95	-7.9	-24.9	24	1.1	22	355
	3.Siliguri	28.6	20.6	62	15.7	04	90	1461.9	16.4	12.0	75	10.5	16	100	-11.1	-13.4	83	2.7	26	315
	4.Dibrugarh	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		19 May 2006 (1200 UTC) Surface level							**19 May 2006 (1200 UTC) 850 hPa**						**19 May 2006 (1200 UTC) 500 hPa**					
	1.Agartala	35.0	25.0	56	20.5	0	0	2374.2	26.0	18.0	61	15.5	11	305	-2.1	-15.1	36	2.4	15	220
L	2.Guwahati	23.0	19.3	80	14.3	6	180	146.0	21.0	10.0	49	09.2	07	290	-7.9	-13.9	62	2.6	27	215
	3.Siliguri	27.4	22.7	76	17.9	4	90	1166.0	17.0	10.0	63	09.2	05	175	-9.9	-12.9	79	2.9	15	265
	4.Dibrugarh	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		

T: Temperature (°C), *T*d: Dew point temperature (°C), Mx: Mixing ratio (gm/kg), WS: Wind speed (knot), WD: Wind direction, RH: Relative humidity

the weather events originated from Bihar on 18th evening and then moved east/northeastwards upto northeast Assam. The following severe weather phenomena were observed from 18th evening to midday of 19th April : (*i*) A squall passed over Gaya at 1830 hrs IST of 18th April, (*ii*) Hailstorm occurred over Malda at 1828 hrs IST of 18th and a squall passed over Malda at 0045 hrs IST of 19th, (*iii*) A squall passed over Tezpur at 0920 hrs IST of 19th April, (*iv*) A squall passed over Itanagar at 1050 hrs IST of 19th April, (*v*) A squall passed over Dibrugarh at 1243 hrs IST of 19th April and (*vi*) A squall passed over Dhemaji at midday of 19th April. Fig. 6 includes three satellite images taken by Kalpana-1 during the period of these events, which clearly shows the extent of these events as described above. The synoptic situation was "A trough of low at sea level extended from northeast Madhya Pradesh to Northwest Bay and a cycir lay over Bihar and neighbourhood extending upto 1.5 km asl with an upper air trough extending to south southwestwards on 18th. A trough/wind discontinuity line in lower levels ran from Nagaland to north Tamilnadu across Assam, SHWB, Jharkhand, Chattisgarh, Telangana and Rayalaseema with an embedded cycir over SHWB and adjoining Bihar and north Bangladesh upto 3.1 km asl and a trough in westerly in mid and upper tropospheric levels upto south Andhra Pradesh across Bihar, Jharkhand and Orissa on 19th. STWJ with wind speed 95 knots over Guwahati was present over the region. Synoptic condition was, thus, highly favourable for outburst of severe thunderstorm. The remarkable point is the presence of high surface humidity and sharp lapse rate with comparatively low wind speed as recorded in the morning sounding.

4.4. *1st to 5th May, 2006*

Like other spells as mentioned above, cycirs over Bihar, SHWB or north Bangladesh & neighbourhood moving towards east or east-west oriented trough in the lower troposphere with mid-tropospheric westerly trough were present during this period. On 1st May a squall passed over Guwahati at night and thunderstorm with heavy rain was observed over Hailakandi, south Assam. Deep layer of moisture from the surface upto 500 hPa with veering north easterly to strong westerlies aloft and high lapse rate (as can be seen in the evening sounding) has provided condition for the squall and hailstorm to develop in the evening/night hours. Notwithstanding some technical problem at Guwahati on that day the sounding of

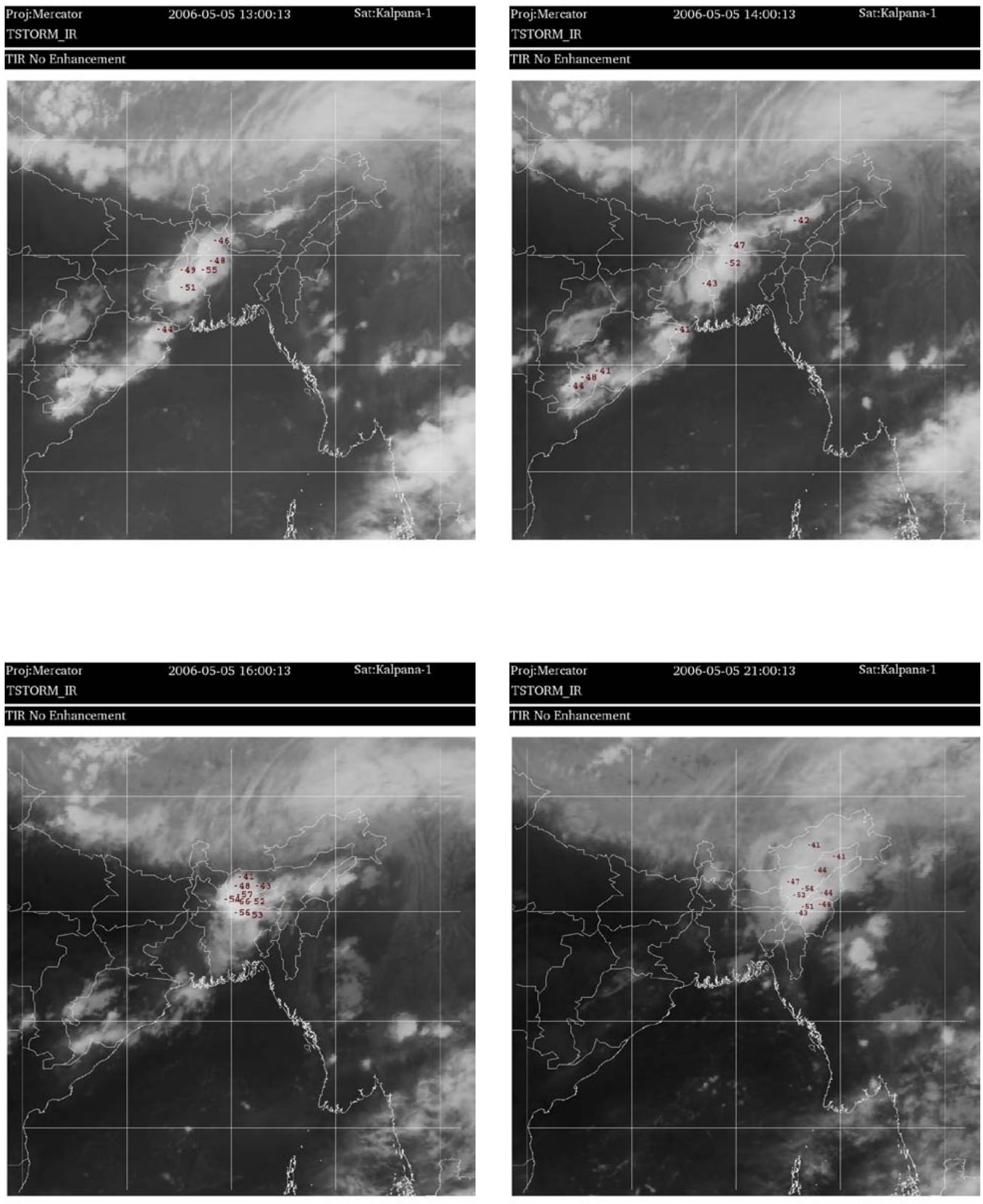


Fig. 9. Satellite imageries of 5th May (time in UTC indicated on top of each images) showing development of Cb cells associated with the events (Numbers on clouds indicates CTT)

Agartala and Siliguri at 1200 UTC, 1st May has been shown in Fig. 8(a) and Fig. 8(b) respectively. High surface CAPE values at Agartala and Siliguri were noticed as shown in Table 3. Again in the midnight of 2nd and 3rd May thunderstorms associated with squall were observed over Guwahati. In these cases low CAPE value existed over all three stations, *viz*., Siliguri, Guwahati and Agartala. The sounding of Guwahati and Siliguri at 1200 UTC of 3rd May has been presented in Fig. 8(c) and Fig. 8(d) respectively. On 3rd heavy rainfall was reported from stations in northeast Assam and adjoining Arunachal Pradesh. The areas affected by squall were Sibsagar and Darrang in the early morning hours however Mawsynram in Meghalaya experienced heavy rainfall on 4th May. It may be due to high level of moisture, high lapse rate and veering of southerly winds to west-north westerly direction, which may be the reason for squall in the affected areas and outbursts of convective cells. Severe thunderstorm associated with squall and hail occurred over north Guwahati on 5th May. The high value of surface CAPE at Agartala, the presence of moisture upto 500 hPa and very sharp lapse rate were indicative of explosive instability and the consequent squall and hailstorm at Guwahati. The propagation and movement of Cb cells towards Guwahati airport on 5th May has been well captured by Guwahati radar. The Range Height Indicator (RHI) images are shown in the Figs. 7(a&b). The RHI indicates very high reflectivity with Cb - top reaching 18 km height. The propagation and movement of Cb cells can also be seen in the satellite imagery presented in Fig. 9. Very low (-66° C) cloud top temperature was seen over Guwahati and neighbourhood area.

4.5. *9th to 15th May, 2006*

The areas affected during this period were mainly Meghalaya, west Assam and adjoining areas. A thunder squall passed over Dhubri at evening of 10th May. High moisture content upto 500 hPa, high dew point temperature and sharp lapse rate were the main reason for explosive squall or thunderstorm. High surface CAPE value at Agartala as well as over Siliguri may be the indicative of severe thunderstorm over Barapani (Meghalaya) on 14th & 15th May. A trough of low at sea level extended from Uttar Pradesh to west Assam in addition to upper air trough with embedded cycirs and mid-tropospheric trough in westerly flow was also observed over the area during this spell. This spell of severe convective activity is mostly associated with heavy rainfall from 9th to 13th May over Meghalaya, west Assam and adjoining areas. It may be due to presence of east west pressure gradient exhibited by trough of low, presence of westerly trough in mid and upper tropospheric levels and abundant moisture incursion from Bay of Bengal.

4.6. *Brief summary of other spells (4 numbers)*

These were on 17th April, 24th – 26th April, 19th – 20th May and 25th May, 2006 respectively. Common elements were squall with wide-spread heavy rainfall. South-west monsoon advanced over Assam on 27th May, 2006.

5. Summary of all 9 spells of severe thunderstorm events

It is obvious from the above discussion that lower level cycirs that originate over Bihar Plateau or Jharkhand, SHWB adjoining north GWB areas move eastward under influence of upper air westerlies and pass along the Brahmaputra valley. The north south trough in westerlies lying along 89° E (±1°) in between 3 & 6 km asl enhances the lower levels convergence below in its forward sector, *i.e.*, the area of northeastern states and also helps in incursion of abundant moisture from the Bay of Bengal. The position of STWJ plays a vital role by increasing the vertical wind shear for occurrence of severe thunderstorm over this region. Thermodynamic instability, inhomogeneity of temperature and moisture of air mass field near ground level with high CAPE value are the key factors for occurrence of severe thunderstorm over this region. On rare occasion it is noticed that outburst of severe thunderstorm with very low CAPE value also occurs. Hence it is necessary to set up a dense observational surface as well as upper air observational network during next phases of 'STORM' Project to improve our understanding of the influence of local environment on the generation of these convective systems.

6. Conclusions

(*i*) Assam valley surrounded by hills alongwith presence of large water body like Brahmaputra river experiences maximum events of severe thunderstorm and consequent incidences of large-scale damage.

(*ii*) Severe thunderstorm season starts from 1st April and lasts till the end of May when the southwest monsoon hits northeast India.

(*iii*) Lower level cycir over SHWB and adjoining west Assam moving towards east or trough in lower levels (sometimes trough of low) across Brahmaputra valley and the trough in westerly along 89° E (±1°) in between 3 & 6 km asl are the key synoptic features associated with pre-monsoon convective weather phenomena over Assam and adjoining states. Also STWJ plays important role for this event.

(*iv*) High thermodynamic instability, inhomogeneity of temperature and moisture of air mass field and high CAPE value are the key factor for occurrence of severe thunderstorm over this region. However, there are some incidents of severe thunderstorm outbursts that happen in the environment of very low CAPE value due to proximity of complex terrain feature of this region.

(*v*) Monitoring of the upper air instability using four Radiosonde/Radiowind stations in the north east, namely, Siliguri, Agartala, Guwahati and Dibrugarh can provide prior warning about impending severe thunderstorms in the region.

(*vi*) For measuring squall intensity the current airport instrumentation is not adequate and need to be supplemented by digital high wind speed measuring recorders as in the east coast.

(*vii*) Radar observation hour in Guwahati need to be extended during the night specially to capture night and early morning severe thunderstorm and hail occurrences at least during the Intensive Observational Period (IOP) in the next phases of the storm project.

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