MAUSAM, **63**, 1 (January 2012), 29-54

551.501.86 : 551.515.4

A satellite based study of pre-monsoon thunderstorms (Nor'westers) over eastern India and their organization into mesoscale convective complexes

AJIT TYAGI, D.R. SIKKA*, SUMAN GOYAL and MANSI BHOWMICK

India Meteorological Department, New Delhi, India

**40, Mausam Vihar, Delhi-110057*

(*Received 14 February 2011, Modified 6 June 2011*)

e mail : ajit.tyagi@gmail.com

सार – काल बैसाखी के जलवायविक, सिनॉप्टिक और रेडार प्रेक्षणों के अध्ययनों का लंबा इतिहास है। इन अध्ययनों का संक्षेप में जिक्र किया गया है और 1931 से 1941 तक भारत मौसम विज्ञान विभाग में किए गए काल बैसाखी के अध्ययन के क्षेत्रीय कार्यक्रमों पर नजर डाली गई है। इन भीषण स्थानीय तूफानों और मॉडलिंग के जरिए उनकी गतिकीय को समझने के लिए 2007–2010 के दौरान भारतीय वायुमंडलीय विज्ञान समुदाय के बहुवर्षीय एस. टी. ओ. आर. एम. कार्यक्रम आयोजित किया। पूर्वी और उत्तरपूर्वी भारतीय राज्यों और बंगलादेश, भूटान, नेपाल जैसे पड़ोसी देशों पर 2009 में कनवेक्टिव सेल को अभिलेखित करने के लिए इनसेट इनफ्रारेड और दृश्य बिंबचित्रों को उपयोग में लाया गया है। मेसोस्केल कनवेक्टिव कॉम्पलेक्स में सुव्यवस्थित हुए कनवेक्टिव सेल के विषयों में 2007–2010 तक के चार वर्षों की अवधि का अध्ययन किया गया है। कुल मिलाकर यह पाया गया है कि पूर्वी भारत (झारखंड, उड़ीसा उपहिमालय पश्चिम बंगाल और बंगलादेश) इस संवहन के आरंभ के लिए उत्तरदायी है। जब सेलस् पड़ोसी देश बंगलादेश और पूर्वोत्तर भारत में फैलते हैं तो इनका विकास होता है। एम. सी. सी. के आरम्भ होने, परिपक्व होने और विस्तारित आदि होने से जुड़े महत्वपूर्ण प्रेक्षण उपलब्ध कराए गए हैं। इस शोध पत्र में यह बताया गया है कि मल्टीपल ओवरलैपिंग रेडार, जिससे कनवेक्टिव सेल के तात्कालिक पूर्वानुमान में सहायता मिल सकती है, कवरेज के साथ इनसेट बिंबचित्रों का उपयोग करते हुए कनवेक्शन की आधे घंटे से घंटेवार मॉनीटरिंग की जा सकती है। सिनॉप्टिक और थर्मोडायनमिक फोर्सिंग से अच्छा मार्गदर्शन मिल सकता है। उपग्रह और बहु रेडार कवरेज का उपयोग करते हुए प्रभावी चेतावनी के लिए प्रभावी तरीका केवल तात्कालिक पूर्वानुमान हैं।

ABSTRACT. Nor'wester studies have a long history of climatological, synoptic and radar observations. These studies have been briefly mentioned and the field programs for the study of Nor'westers implemented in India Meteorological Department (IMD) from 1931-1941 have been touched upon. Indian atmospheric science community organized a multi-year STORM program during 2007-2010 to understand the formation of these severe local storms and also understand their dynamics through modeling. An attempt is made to use INSAT Infrared and Visible imageries to document the convective cells which developed over Eastern and North-East (NE) Indian states and adjoining countries of Bangladesh, Bhutan and Nepal for the year 2009. Also convective cells which organized themselves into Mesoscale Convective Complexes (MCCs) for the four years period 2007-2010 have been studied. It is found that by and large Eastern India (Jharkhand, Orissa, Sub Himalayan West Bengal and Bangladesh) is responsible for the initiation of convection. Development occurs as the cells propagate over the neighbouring areas of Bangladesh and NE India. Important observations with regard to initiation, maturity and dissipation etc. of the MCCs are provided. It is suggested that half hourly to hourly monitoring of convection can be accomplished by using INSAT imagery, along with multiple overlapping radar coverages, which could help in nowcasting of convective cells. Synoptic and thermodynamic forcing can help as broad guidance. The only effective way for effective warning is nowcasting using satellite and multiple radar coverage.

Key words – Thunderstorm, Nor'westers, INSAT (India National Satellite), CTT (Cloud Top Temperature), MCC (Mesoscale Convective Complex).

1. Introduction

Norwesters are severe thunderstorms that originate over Eastern and north Eastern parts of India, southern Nepal, adjoining Bhutan and Bangladesh during the pre-monsoon season (March to May). They travel preferentially in a general northwest to southeast direction and sometimes in southwest to northeast direction. They are locally known as Kalbaisakhis. The Norwesters produce heavy showers, lightning, thunder, hailstorms, dust storms, squalls, down bursts and sometimes even tornadoes. They cause damage to property and crops and even loss of life; particularly over rural areas, sometime running into hundreds of deaths on a single occasion due to destruction caused by squally winds and occasional tornadoes that accompany them. Strong heating of landmass during midday initiates convection in preferential meteorological sub-divisions of Bihar, Jharkhand, Chattisgarh, Orissa, Sub-Himalayan West Bengal, which move towards the sub-division of Gangetic West Bengal and adjoining Bangladesh areas and get intensified by mixing with the low level warm moist airmass from the Bay of Bengal. The southerly low level strong winds from the Bay of Bengal, are quite frequent during the pre-monsoon season due to the presence of an extended seasonal low pressure region from Bihar to West Bengal and even across NE India. The wind discontinuity, due to thermal low and the low level moist southerly flow from the Bay of Bengal, with trigger mechanism provided by surrounding hills, forested regions and sea breeze initiates convective cloud cells which ultimately develop into severe local thunderstorms with occasional tornadic storms embedded within the convective organizations and aided by strong tropospheric wind shear. Thus the organization of convection passes through a lifecycle of initial development during the day hours and dissipation in the evening or night hours. Several cells, which get initiated do not reach mature or fully developed state and dissipate rather rapidly within 2 to 4 hours. A few among them are able to cover large areal extents in their life history, while migrating over neighboring areas. The full details of the origin, development and migration have not been revealed due to lack of data. Passage of a trough in the sub-tropical westerlies at 500 hPa and the downstream strengthning of the sub-tropical westerly jet stream (STJ) provide the upper level divergence which enhances the low level convergence and together they lead to the development of Norwesters. Individual thunderstorms may also originate *in situ* over Jharkhand, Chattisgarh, Orissa, Gangetic West Bengal, Sub-Himalayan West Bengal (SHWB) and other areas. A range of convective behaviours from isolated moderate to deep convection to mesoscale organization of convection with large stratified region and cirrus canopies are witnessed during the pre-monsoon season over these areas specially in moist Gangetic West Bengal, Bangladesh and NE Indian states. A satellite-based census of origin of cells, their migration to neighbouring areas, development into mesoscale organizations with extensive cirrus canopies and dissipation during the Nor'westers season is much needed. The pre-monsoon rainfall over the region is mostly convective though occasionally stratified anvils also contribute to seasonal rainfall. Also hilly terrains in SHWB, Jharkhand, NE Indian states have strong effects on the occurrence of deep convection.

Usually individual convective cells appear in satellite photographs over different parts of the Eastern and NE parts of India and adjoining Bhutan, Nepal, Bangladesh regions by the afternoon in the pre-monsoon season on many days but cover areal extent of 1000 km^2 to 10000 km^2 with life span of 1-3 hours, as they dissipate before full development into mature thunderstorms. However, once in a while (about once or twice in a week) multicell thuderstorms organise in the form of squall lines, accompanied with deep convection reaching 12-14 km in altitude (some even penetrating tropopause) in which intense convection occurs over an area exceeding 20000 km^2 with the cold cirrus canopy even exceeding 100000 km^2 in horizontal area and lasting for 6-12 hours. Such gigantic convective organizations travel across several hundred kilometers in somewhat organized manner in the form of squall lines. The lifecycle of the outbursts of squall lines passes through three phases *viz*., (*i*) cumulus stage or the first stage of growth with updraft persisting throughout the cell (*ii*) the mature stage characterised by the presence of both the updrafts and the downdrafts which are magnified by the presence of wind shear in the troposphere and (*iii*) the dissipating stage marked by the presence of downdrafts throughout the convective regime. Dissipating stage of an individual thunderstorm even triggers development of new convective cells. It is the development of organized intense convection from the early stage to the dissipating stage in which we are concerned in this paper. We use the INSAT imagery and its visualisation in the form of cloud top temperatures (CTTs) from the INSAT infrared data to document the census of convective cells over the region of study in the Nor'westers season.

In section 2 we briefly describe the development of Nor'westers studies in India from the beginning of the 20th century. Section 3 describes the methodology adopted for generating a census of developing convective organisations using INSAT imagery, Section 4 covers the description of field observational studies on spring-time convective weather developments over India, U.S.A. and other countries. Emphasis is provided on the organization of a field program in India entitled Severe Thunderstorms Observational Research and Modelling (STORM), launched by the Indian Atmospheric Science community in 2007. Section 5 uses the data-base for the pre-monsoon season of 2009 to describe different characteristics of the seasonal mesoscale convection over the area of our study. Section 6 uses the data set of pre-monsoon seasons for four years (2007-2010) to examine the organisation of convection in the form of mesoscale convective complexes (area of convective threshold exceeding

100000 km^2 and CTTs reaching between -30°C to -80°C). Section 7 provides summary and conclusions.

2. Brief description of the past thunderstorm studies in India

Incidence of destructive severe local thunderstorms, locally known as Kalbaisakhis in Eastern India and Bangladesh and Andhis in northwest India and Pakistan, is known from many centuries. Floyd (1888), for the first time vividly described the passage of a tornadic Kalbaisakhi over Kolkata, which had occurred on 8th April 1838. There are other later studies too which describe the furious squalls which occurred over Bengal in the pre-monsoon season and prior to the onset of the summer monsoon. A few of such historical descriptions are given in Section 3.1. Similarly there have been descriptions in the literature about the destructive dust storms (Andhis) which occur over NW India and adjoining Pakistan. Incidence of pre-monsoon thunderstorms over southern peninsular and central India, which are not as severe as Kalbaisakhis or Andhis, have also been known for centuries. Along the east coast of India incursion of moisture by the sea breeze and the presence of a wind discontinuity over central peninsula are responsible for triggering thunderstorms in the pre-monsoon season in the presence of convective instability (potential and latent instability). Towards the end of the 19th century, IMD, for the first time, had organized a campaign in 1897 to collect data on characteristics and frequency of thunderstorms over India based on only 10 stations, well-spread over the sub-continent. Dallas (1900) had used this data set to produce the first organized study of pre-monsoon convective weather over the sub-continent. Sohoni 1928 had produced a documentation on the climatology of thunderstorms of Calcutta (now Kolkata) for the period 1900-1926. Later thermodynamical approach to study convective weather over India was introduced by Sir Charles Normand in 1930s and attempts were made by several researchers in the IMD to use this approach to understand convective developments.

IMD had organized three scientific campaigns between 1930's to 1940's to study Nor'westers by collecting surface and upper air meteorological data. They had even deployed several special radiometer sondes in the campaign of 1941. IMD published charts of monthly frequency of days of thunderstorms in India in the 'Climatological Atlas for Airmen', as a result of their efforts during the Second World War, and also later in 1953 provided frequency of thunderstorm days in the "Climatological Tables of observatories in India". Since then four approaches have been broadly adopted to study Nor'wester thunderstorms in India. They are (*i*) climatological (*ii*) thermodynamical (*iii*) radars and satellites and (*iv*) mesoscale modelling. Krishna Rao (1966) provided a comprehensive review of past thunderstorm studies in India from 1900 to 1960.

(a) *Climatological studies*

Climatological insight about frequency of thunderstorms for individual stations/regions have also been given by different workers and published from time to time in IMD's scientific journal, Indian journal of Meteorology and Geophysics (now Mausam). Recent Studies on climatological aspects are by Manohar *et al.* (1999), Kandalgaonkar *et al*. (2002) and Tyagi (2007).

(b) *Thermodynamical and synoptic studies*

Thermodynamical and synoptic studies on Nor'westers, using different thermodynamical indices for understanding and forecasting convective weather development, have been undertaken in many studies. (Normand 1938, Singh and Agnihotri 1974, Bhattacharya and Bhattacharya 1980, Kanjilal *et al.* 1989, Karmakar and Alam 2006 and several others). However inspite of the importance of different instability indices for development of convective weather, they do not produce desired results on all occasions as unlike the visualisation of convective developments provided by radar or weather satellite surveillance, such indices can only provide indication for the favourable environmental and thermodynamical conditions for the onset of convective weather. Since favourable thermodynamical environment requires a favourable large scale and meso-scale environments for the onset of convective weather locally, many investigators have attempted to understand the Nor'westers-related onset of convection based on synoptic studies. Prominent among the synoptic studies are by Desai (1950), Koteswaram and Srinivasan (1958), Srinivasan *et al.* (1973) and several others. Weston (1972) had shown that the pre-monsoon storms in this region are very tall and Cb tops occasionally reach a height of 20 km in the vertical, penetrating even the tropopause as dry continental air is on top of the low level moist air in an environment of high vertical shears in the presence of STJ. Several individual tornadoes which occured over different cities of India have also been studied by synoptic approach such as Saha (1966), Ghosh (1982), Mukherjee and Bhattacharya (1972) and others. Based on the results of several thermodynamic and synoptic studies, conditions favourable for the occurrence of pre-monsoon Norwester's (thunderstorm) have been explored which are:

(*i*) Presence of latent, potential and convective instability in the lower-mid troposphere which help in generation of thunderstorm by buoyancy force. Roy

Bhowmik *et al*. (2008) have emphasized even the role of high CAPE in summer monsoon season convection over India.

(*ii*) Presence of strong southerly to south westerly flow in the boundary layer over Eastern and north Eastern India from the Bay of Bengal along with the orientation of the seasonal trough in the lower troposphere.

(*iii*) Presence of a dry line on top of low level moist layer.

(*iv*) Strong sea breeze across coastal Orissa and coastal West Bengal.

(*v*) Upper level westerly trough at 500 hPa with cold air advection and the accelerating subtropical jet stream (STJ) at 200 hPa. Dynamical aspect of thickness patterns in the middle and upper troposphere as well as presence of upper tropospheric divergence are involved in this concept. Triggering mechanism is provided by the land surface effects such as orographic features and vegetated fields or forests under strong diurnal land-sea heating contrast in the day-time. Thus large scale flow along with sea breeze, thermodynamic forcing and land surface environment favour outbreak of organized convection in the form of Nor'westers. Operational forecasters during 1950's to 1980's used these concepts for forecasting outbreak of pre-monsoon thunderstorm to provide service for rapidly expanding civil aviation in the region affected by Nor'westers. The skill in 24 to 48 hour forecast remained limited as the phenomenon was mesoscale in nature and there was limited watch on the initiation and development of convection as even the surface meteorological observatories over the region were separated by large distances and the frequency of observations was mostly 2 per day.

(c) *Weather radar and satellite data-based studies on Nor'westers*

Weather radars and satellite-based studies have also contributed to our understanding and forecasting of Nor'westers. Weather radars, fitted into military aircraft, were introduced by the U.S. Air Force during last stage of Second World War in the war zone over NE India as the region was the seat of hazardous convective weather for military aviation. After the war civil aviation began to develop rapidly over India and hence the IMD launched a planned program of installing a network of weather detection radars in India, as they had become available commercially. The first radar (an X-band Decca-41) was installed at Kolkata airport in 1954 which was replaced by a more powerful radar (JRC-NMD-457A) in 1957. Subsequently weather radars were installed in New Delhi, Guwahati, Mumbai, Nagpur, Bangalore, Mohanbari and Agartala, Vishakhapatnam and other stations. Indigenous manufacture of weather radars was also successfully undertaken by Bharat Electronics, Bangalore in 1970's. Weather radars provided a watch on the development of convective weather over different airports in India. The researchers also got experience of interpretation and classification of radar echoes based on synoptic and morphological considerations and a large number of research papers have been published on the detection and development of Nor'westers by radars. Prominent papers on Nor'westers by using radar data are by Subramanian and Sehgal (1967), Kundu and De (1967), Ray and De(1971), Sharma (1978), Basu and Mondal (2002) and others. Based on these early studies the climatology of radar echoes and statistical information on temporal distribution of convective organisations, role of land surface processes (orographic and vegetation) and synoptic forcings were examined. The introduction of S-Band Doppler radar at Kolkata in 2003 brought a powerful tool for the detection and development of Nor'westers and a few papers have resulted from the analysis of data provided by this radar (Pradhan and Sinha 2005, Sinha and Pradhan 2006). These studies have used vertical profiles of radar reflectivity along with thermodynamical features and synoptic settings to provide useful information after analysis of a few severe local thunderstorm which had affected Kolkata region. Large vertical extent (12 to 16 km) of radar echoes, rapid growth and high reflectivity (>40 dBz) with multiple cells organized in squall line formation are the characteristic features of Nor'westers as provided by radar data. The radial velocity derived from Doppler radar data is also now being used for assimilation purpose in the high resolution mesoscale models. Doppler weather radar data are also being used for validation of mesoscale models. Radar signature of a supercell thunderstorm over Kolkata have also been identified. India's STORM program is highly dependent on the S-Band Doppler radar coverage from Kolkata.

Weather satellites since 1960, have provided a vital tool for observing tropical convection. India established its own geostationary satellite program, known as INSAT, in early 1980's which has enabled operational forecasters to continuously monitor development of hazardous weather. Satellite visible imagery has shown that tropical convection is multi-scalar in nature ranging from isolated cumulus to mesoscale convective systems (MCSs) or mesoscale convective complexes (MCCs). MCC was first defined by Maddox (1980) and later the definition has been expanded by Augustine and Howard (1991). An MCC has the dimension of an extensive cloud cluster with cirrus canopy and CTTs below -50°C reaching even upto below -80°C. Satellite information (visible, infrared and water vapour imageries) and precipitation estimates provided by Tropical Rainfall Measuring Mission (TRMM) satellite have provided a wealth of new data to understand tropical convection (Houze *et al*. 2007). In India although INSAT data have been extensively used in research studies on tropical storms and monsoon, they have not been much utilised for the studies on Nor'westers. There are only a few papers (Bhatia and Kalsi (1992) and Mukhopadhyay *et al*. (2005) in which INSAT data were used to examine the development of MCCs. Besides Laing *et al*. (1993) have used nine months of INSAT data at 3 hourly interval to investigate tropical cloud clusters during the pre-monsoon and monsoon seasons of 1988. Hence there is a good scope to use hourly INSAT data for the purpose and the present study uses 4-years of data for the period 2007-2010 to specially investigate the development of MCCs over Eastern and north Eastern India during the Nor'westers season.

(d) *Mesoscale modelling studies on Nor'westers*

High resolution meso-scale models have been adopted in India since 1995 to investigate their utility for forecasting high impact weather. Several workers have employed different meso-scale models for simulation of Nor'westers (Mukhopadhyay *et al*. 2005, Litta and Mohanty 2008 and others). The results of the application of such high resolution meso-scale models suggest that the models have the potential to provide valuable information for severe local storm forecasting. Hence a combination of synoptic analysis and meso-scale model forecasts 48 hours in advance and nowcasting procedures using radar and satellite data along with models could be valuable for warning against Nor'westers outbreak 48 hours in advance and for more precise nowcasting 12 hours in advance.

3. Observational Field Programmes on Severe Local Thunderstorms and Tropical Convection

3.1. *Vivid description of some early nor'westers*

In the 19^{th} century several observers have vividly described the severe local storms (Nor'westers) which they had witnessed in Calcutta. One of the first such descriptions, which appeared in Journal of the Asiatic Society Calcutta was by Mr. J.Floyd (1839) about a Nor'wester (a tornadic storm) which had struck Calcutta on 8th April 1838. The paper was communicated to the Journal by Mr. J. H. Patton, who was then the magistrate of the 24 Pargnas. The account described the violence of the wind, uprooting and burning of stumps and leaves of trees and their twisting out of ground and being thrown away to a distance of 60-100 meters and destruction of lives of men and animals. The area devasted covered the villages of Majaree Gaon, Anarpur, Dum Dum, Bairala, Charbagan, Sambandal, Anandpur, Ballaghata, Saltwater lake, Bayunthapore and adjacent villages. The destruction was worst at Charbagan and Sambandal (where weekly markets (hats) were being held).The storm appeared at the village of Soorala at 0130 p.m. and moved to Anandpore, Ballaghata, Charbagan and Sambandal by 2 to 3 p.m. and died at Codalla by 4 p.m. The storm had followed a southerly direction, destroying all that stood in its path and exhausting itself by the time it had reached Codalla. Two dark columns of clouds were visible, whirling round and round and descending to the earth (tornadic motion). The columns had appearance of two huge 'daitya' (or demons) engaged in destruction. There was sudden darkness, howling of the wind and clouds of dust attending it. The storm had lasted for a period of 90 minutes and almost immediately followed by sunshine, little or no rain but severe fall of hail (no anvil precipitation). Hail accompanied the storm and at Dum Dum hailstones were uncommonly large and one weighed 3.5 pounds (about 1600 gms) (indicating that hail stone must have passed through a process of condensing and freezing of moisture within the cloud). Another horrible account of a similar Nor'wester is by Blanford (1886). H.F. Blanford was the head of the Provincial Bengal Meteorological Department for several years before he took over as the first Imperial Meteorological Reporter at the formation of the IMD in 1875. He described the Nor'wester as "From Calcutta a low bank of cloud is almost always visible to the west and northwest in the afternoon and on approach of a Nor'wester, it rises higher and higher, a sheat of palio cirrus, frequently with a hard straight edge advancing before the lower mass of palio cumulus. At other time a sheet of cirrostratus forms over greater part of the sky early in the afternoon, becomes thicker as the day advances and at last a heavy mass of palio cumulus forms beneath it and completes the storm cloud. Approach of a Nor'wester is heralded by a rise in barometer and by a strong stormy wind blowing outward from beneath the storm (gust front) and always either seaward or from some point east and round by north to southwest. Never a storm had advanced from sea. The wind preceding the storm is very cool and surface temperature sinks by 20°F (11°C) in 10 minutes. The storm raises dust and blows in gusts sometime with great force". Blanford also noted that the most intense storm, witnessed by him, was on 14 May 1856 which had force of severe gale and air was thick with dust and on this occasion large quantity of hail fell. Thus Blanford description contains some details about the weather prior to and on the approach of a Nor'wester such as the gustfront and tall cloud accompanying it, direction of movement from land to sea, the abrupt fall in temperature, furiously gusting winds at the surface and the rise of pressure accompanying the storm. These feature include the role of gust front, meso high and wake low, accompanying such severe local storm, as we know about them today after detailed investigation in USA, India and other countries.

Yet another account of a Nor'westers striking Bangladesh is given by Haughton (1925) in Quarterly Journal of Royal Meteorological Society which contains aspects such as:

- Storm usually commencing to form in afternoon (2 or 3 p.m.),
- Woolpach clouds moving towards SE , very often they commence from some place at about the same time at Dacca, Faridpur and Pamban,
- They (Nor'westers) form once every few days to once every week,
- Hail stones of 3 inches(about 6-7 cm) in diameter are not unusual and hail falls as if small white birds are sweeping down,
- One or two clouds grow taller outward and upward and coalese (cloud merger) forming large and heavy clouds round a central building mass and ascending rapidly to a great elevation at the centre of cloud and extending to a greater diameter,
- There is white precipitation, probably hail,
- As soon as the storm commences, the whole mass of cloud beneath begins to move against SE ground wind(clouds moving from NW),
- The storm may be small or it may cover several square miles which depends on the amount of moisture present at ground current,
- As soon as the storm begins to move in SE direction the wind rises and lightning and thunder occurs commonly,
- Along the southerly rim (ahead of the storm) low rolling clouds form, turning upward and outward on itself and from behind it comes the turmoil,
- The storm progresses until it blows itself out, generally about midnight but occasionally not until the daylight or after.

The above descriptions provides information about build-up of huge clouds, lightning and thunder and even merger of clouds, strong winds, precipitation accompanied with hail, time duration lasting occasionally about 12-16 hours (2 p.m. to 6 a.m). Thus from Floyd's description about the devastation caused by Nor'wester in 1838 we had progressed to that of Haughton on the description of the scientific phenomenology of Nor'westers in 1925. After the IMD had been organised for nearly 50 years, researchers in the IMD devoted more attention to build the climatology of Nor'westers in Calcutta (Sohoni 1928) and the study of thermodynamic and synoptic features which are responsible for generating these severe local storms of Eastern India. In late 1920's, IMD had planned to study the outbreak of such severe convective events by organising field experiments. Three such experiments were organised between 1929 to 1941, under the leadership of Sir Charles Normand, the then Director General of observatories in India, and with the participation of senior scientists of the IMD like Sohoni, Desai, Sen, Pramanik Chatterjee, Sur, Mull and others. The first two experiments used the surface synoptic network and the available pilot balloon observatories data with an additional ascent at 1100 hours every day (time just prior to beginning of convective episodes). For the final experiment in 1941, IMD even deployed a special network of radiometer soundings for obtaining upper air thermal structure of the storm environment. As a result of data obtained under these experiments several research papers were written by the IMD's meteorologists. Thermodynamical approach based on 'buoyant parcel' and 'environment' was adopted to determine the pre-conditioning of the environment for moist parcel ascent parameters like convective instability in the form of CAPE and CINE etc. and other indices were used to quantitatively estimate the pre-conditioning of undiluted moist ascent. The most vital information which resulted from the early field experiments could be summed up as follows:

- Presence of warm moist southerly or south westerly air upto about 2 km in the vertical, topped by dry and cooler air upward from NW to West direction.
- Along this northwesterly to westerly wind drift, an individual Nor'wester or individual squall line travels SE wards until the system is dissipated, sometime after entering north Bay of Bengal.
- Nor'westers are generated on the boundary (wind discontinuity) between the continental airmass (NW to West) and maritime airmass of the Bay of Bengal origin. They also form and drift along the gradients of surface specific humidity.
- A storm is accompanied with lightning, thunder, strong winds, rise of sea level pressure (by 2-6 hPa), rise in relative humidity (by 20-30%), and fall in temperature (by 1-10 °C). Some time warming was

also observed as provided in the very first description by Floyd as trunks of trees and leaves were burnt (heat bursts).

- Storm reaching Calcutta move from NW (present Jharkhand, Bihar areas in NW to SE direction) or from Orissa (movement from SW to NE direction).

- Down currents of cold air (downdraft) from each thunderstorm seem to provide trigger for the next storm. Downdrafts are caused by the air descending through the storm clouds which becomes the source of pressure rise when the cold air strikes the ground. Thus the characteristic thunderstorm high was first noticed by the Indian researchers with Nor'westers campaigns data during 1930-1941 which was later fully documented by the data in U.S. thunderstorm project (Schaffer 1947) several years later.

- In the case of line of thunderstorms (squall lines) a tight pressure gradient is observed at the leading edge of line by the pressure jump associated with individual convective cells.

- Whole series of storms and the pressure jump lines move against the direction of flow of low level moist air i.e. from NW to SE, but with the speed of upper NW/W winds at 3-5 km which is 40-60 kilometer per hour. The surface pressure gradient travels with the storm movement.

- Thunderstorms occur at the same place at different hours in the afternoon and evening on different days.

Later work established that Nor'wester thunderstorms are organised into characteristic mesoscale convective systems and hence meso-scale analysis is needed to predict their life cycle.

3.2. *Present STORM Field Program in India on Nor'westers*

India's field programs on Nor'westers during 1930-1941 were executed much before the thunderstorm project was implemented in U.S.A. in 1949. However for nearly 55 years after the last Nor'westers experiment in 1941, no field program for the study of Nor'westers could be organised in India though meanwhile IMD had built up a considerable network of upper air temperature, moisture and wind sounding stations between 1950 to 1980. Radar network was also in place between 1950-1990. India had installed a geostationary weather satellite (INSAT) at about 80°E to continuously monitor disastrous weather development. India had also introduced operational regional short-range numerical weather prediction system and even installed an operational dynamical general circulation model for medium-range weather prediction by 1992. Also from 1995 onward experimental studies on the use of high resolution meso-scale models had started. A Doppler weather radar was installed in Kolkata in 2003. The scientific research community in India, outside the IMD, had also substantially gained strength and had successfully implemented several field program (MONTBLEX 1989-90, LASPEX 1995-97, BOBMEX 1998-99, and ARMEX 2002-2005. The community also prepared a multi-year science plan for the study of severe pre-monsoon convection over Eastern India (Science Plan, DST 2005) which was approved by the DST under the name 'STORM'. The first experiment (STORM Pilot) under STORM program was implemented in 2007 and subsequently followed by STORM 2009 and 2010. In the campaigns of 2009 and 2010 neighbouring countries of Bhutan, Nepal and Bangladesh were also involved. STORM program has installed a meso-networks of observatories in Eastern India, surface AWS and ARG networks during 2009 and 2010, surface layer instrumented tower at Ranchi and Kharagpur and mobile radiosonde facility etc. Also extensive use of high resolution mesoscale models was made for guiding the field operations during the experiment as well as for research based on the field data collected. Over 20 Indian research organisations participated in this field program. The present paper has resulted from the satellite data collected every hour in the STORM Program. Appendix I provides description of important Field Programs which have been undertaken in USA and also international programs on tropical convection.

4. Data and methodology

The aim of the present study is to use geostationary satellite data to produce a census of Nor'westers related convection during April and May 2009 over Eastern India. For this purpose satellite images from INSAT (Kalpana-1) were used. IR images were examined for the purpose on hourly basis from 0000 UTC to 2300 UTC and visible images used from 0100 UTC to 1100 UTC everyday during the study period. We have used CTTs in the range from -30°C to less than -70°C to identify moderate to deep convection within the domain of the study, bounded by Indian states of Orissa, West Bengal, Chattisgarh, Jharkhand, Bihar, the seven North-Eastern states and neighbourhood countries of Bangladesh, Bhutan and Nepal. Convection characteristics such as areal extent of cold cloud shield and its duration were the basic data set used in the study. By using these hourly satellite images, hourly data for each convective cell, which formed in the domain, were collected and tabulated starting from initiation to dissipation stages. For the years 2007 to 2010, the convective cells which have exceeded horizontal area

TABLE 1

Characteristics of an MCC adopted in our study

Characteristic	Threshold
Size of MCC	A: Cold cloud shield with continuously low IR temperature ≤ -30°C must have an area ≥ 100000 km^2 B: Interior cold cloud region with temperature ≤ -50°C must have an area ≥ 50000 km^2
Initiation of MCC	Size and intensity definitions (A and B) are satisfied. Initiation for MCCs occurred when the IR convective cloud shields reached minimum initiation size of 10000 km^2.
Development of MCC	Size definitions A and B must be met for a period ≥ 6h
Dissipation or Termination Stage	Size definitions of MCC and cold cloud shield (A and B) no longer satisfied.
Life Duration of MCC	Time in hours from the initiation stage of an MCC to its dissipation or termination stage.

100000 km^2 were also identified. Thereafter the history of those very cells (MCCs) was prepared from the stage when the areal extent exceeded 100000 km^2.

4.1. *Size, intensity and life duration of convective cells*

The areal extent of all convective cells, forming within the specific domain was worked out under the following five broad categories. *viz*., (*i*) very small (<10000km^2), (*ii*) small (10000 to 25000 km^2), (*iii*) moderate (25000 to 50000 km^2), (*iv*) large (50000 to 100000 km^2) and (*v*) very large (>100000 km^2). To characterize intensity of convection in the cell, each convective cell was assigned an intensity scale depending upon the minimum CTT threshold values within the ranges as (*i*) -30 °C to -49 °C as moderate convection (*ii*) -50 °C to -69 °C as intense convection and (*iii*) ≤ -70 °C as very intense convection.

Life duration (T) of each cell from its initiation to dissipation stages within the five specified areal extents, mentioned above, were categorized as (*i*) T ≤ 2 hrs as very short-lived (*ii*) 2 hrs < T ≤ 4 hrs as short-lived (*iii*) 4 hrs < T ≤ 6 hrs as moderate-lived (*iv*) 6 hrs < T ≤ 8 hrs as long-lived (*v*) T > 8 hrs as very long-lived.

To determine the weather (rainfall, thunderstorms and squalls) occurring over different days under the areal extent of each cell, we have collected relevant information from the IMD observatories under two Regional Meteorological Centers Kolkata and Guwahati in India.

4.2. *Definition of MCC*

Mesoscale convective fluxes have horizontal scale between scale height H of the atmosphere and the Rossby radius of deformation defined through $\lambda R \approx NH/f$. Where N is Burnt-Vaisala frequency and *f* is the Coriolis parameter. By this definition mesoscale phenomenon occurs on horizontal scale between 10 and several hundred kilometers. Mesoscale processes are local, advective and dynamical and involve preconditioning processes or triggering mechanisms (precursors) to give rise to a meso-scale convective complex (MCC). Maddox (1980) provided the first definition of an MCC, based on satellite IR imagery. This definition is based on the areal extent and cold cloud shield exhibited by the convective system. Principally the cold shield should surpass size threshold, intensity threshold of CTT, remain quasi circular in shape and persist for at least 6 hours. The methodology of Maddox 1980 was adopted by us for the census of all cloud clusters that exceeded 100000 km^2 size for the years 2007 to 2010 over the area of our interest. As generally during the pre-monsoon season MCCs over our area of interest are of smaller size than over USA, we have slightly modified the definition of an MCC as given in Table 1. Finally, it is important to note that the internal structure of MCCs differs from case to case. Also note that the cloud clusters associated with tropical cyclones forming in the Bay of Bengal, satisfying an MCC criteria, are not considered in this study.

5. Census of convective cell that formed over or migrated to Eastern and North-Eastern India during April-May 2009

5.1. *Areal extent of convective cells*

The cells begin from smaller areal dimensions and gradually attain larger dimensions to attain MCC category. This upscale increase in the areal extent occurs by a development process in which each cell gradually achieves larger dimension. However in some cases, the increase in dimension occurs by cell merger. We have analysed the areal extent of each cell in terms of maximum areal extent reached by a cell originating in different areas. Table 2 shows that the contiguous sub-divisions of region A. *i.e*, Orissa, West Bengal, Jharkhand and neighbouring country Bangladesh contribute to the

TABLE 2

Maximum areal extent reached by cell origination in different Sub-area

Sub-area	Area ≤ 10000 km^2 Very small	10000 < Area ≤ 25000 km^2 Small	25000 < Area ≤ 50000 km^2 Moderate	50000 < Area ≤ 100000 km^2 Large	Area > 100000 km^2 Very large
Nepal	0	3	1	3	4
Sikkim	0	0	0	0	0
Bhutan	0	1	0	0	0
Arunachal Pradesh	0	0	0	0	0
Nagaland	0	0	0	0	0
Manipur	0	0	0	0	0
Mizoram	1	0	0	1	0
Tripura	0	1	0	0	0
Meghalaya	3	4	2	0	2
Assam	1	2	3	0	0
Bangladesh	5	1	5	5	8
G. West Bengal	5	2	1	2	3
Shwb	2	2	0	1	4
Bihar	0	1	3	0	1
Jharkhand	3	5	4	1	6
Orissa	8	12	6	4	7
Chattisgarh	5	2	2	2	0
North Coastal A .P.	3	0	4	4	1
East U.P.	0	0	0	1	0
East M.P.	1	0	0	0	0
Total	37	36	31	24	36

TABLE 3

No. of cells and Sub-area where maximum Intensity reached

Sub-area	Moderate	Intense	Very intense
Nepal	4	3	0
Sikkim	0	0	0
Bhutan	1	0	0
Arunachal Pradesh	0	0	0
Nagaland	0	0	0
Manipur	0	0	0
Mizoram	1	1	0
Tripura	1	1	0
Meghalaya	5	3	0
Assam	5	4	0
Bangladesh	8	15	4
Gangetic West Bengal	7	7	1
Shwb	6	3	0
Bihar	0	5	0
Jharkhand	4	6	2
Orissa	17	19	4
Chattisgarh	7	4	2
North Coastal A .P.	6	6	0
East U.P.	0	1	0
East M.P.	1	0	0
Total	73	78	13

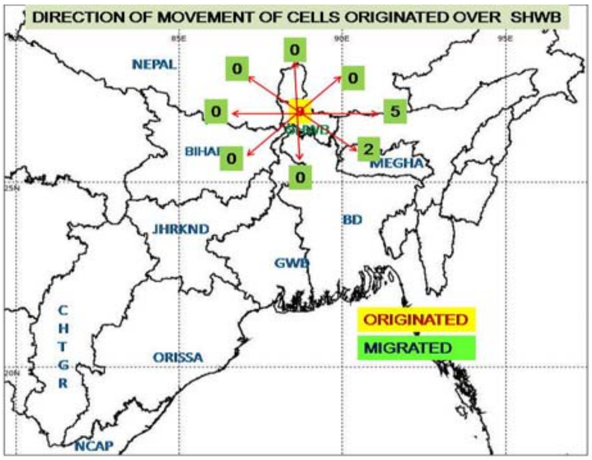

Fig. 1. Direction of movement of cells originated over SHWB

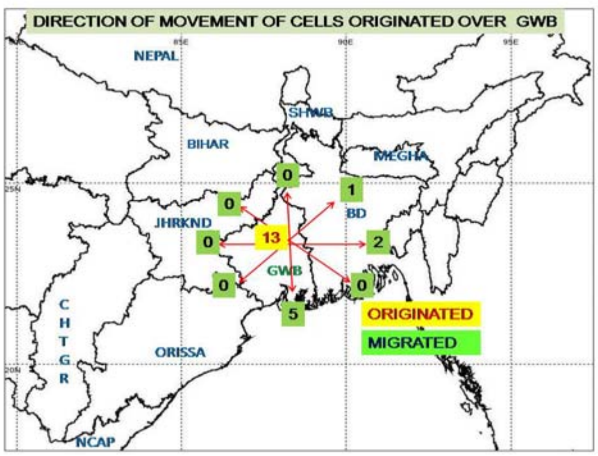

Fig. 2. Direction of movement of cells originated over GWB

maximum number of cells which occupy the area >50000 km^2. These are the areas which lie close to the Bay of Bengal and get low level moisture to sustain maximum areal development of cells which originate over this region. The Table also shows that the number of cells with areal coverage of cells ≤ 50000 km^2 is also significant. This would suggest that those cells that develop to about 50000 km^2 have the potential to attain the size of MCC.

5.2. *Favourable pathways*

Favourable pathways for migration of convective cells formed over Sub Himalayan West Bengal (SHWB) and Gangetic West Bengal are shown in Figs. 1 and 2 respectively. Convective cells originating over SHWB generally move eastward/SEward and migrate near Assam, Meghalaya and Bangladesh. Those which originate

TABLE 4

No. of cells originated over the Sub-area

Originated over Sub-area	No. of cells
Nepal	11
Sikkim	0
Bhutan	1
Arunachal Pradesh	0
Nagaland	0
Manipur	0
Mizoram	2
Tripura	1
Meghalaya	11
Assam	6
Bangladesh	24
West Bengal	22 (GWB :-13, SHWB:-9)
Bihar	5
Jharkhand	19
Orissa	37
Chattisgarh	11
North Coastal A .P.	12
East U.P.	1
East M.P.	1

TABLE 5

No. of cells migrated over the Sub-area

Migrated to Sub-area	No. of cells
Nepal	6
Sikkim	8
Bhutan	15
Arunachal Pradesh	9
Nagaland	5
Manipur	12
Mizoram	12
Tripura	16
Meghalaya	14
Assam	25
Bangladesh	22
West Bengal	22 (GWB:-13, SHWB:-9)
Bihar	6
Jharkhand	5
Orissa	16
Chattisgarh	11
North Coastal A .P.	15
East U.P.	1
East M.P.	2

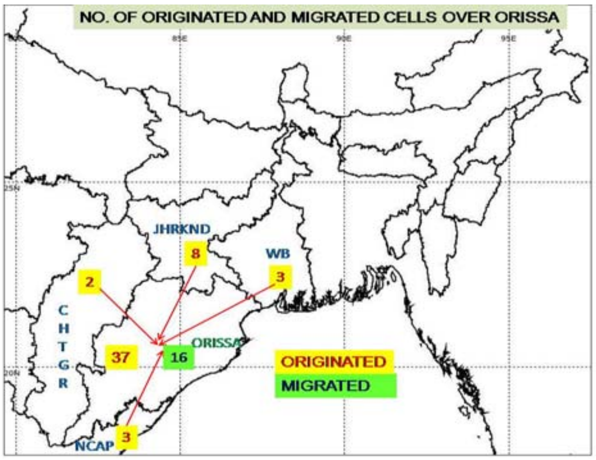

Fig. 3. Number of originated and migrated cells over Orissa

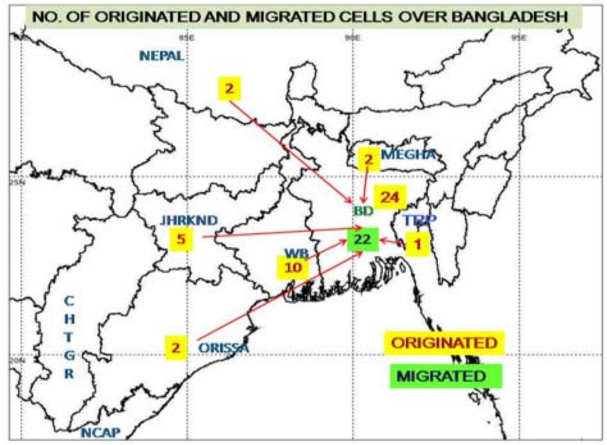

Fig. 6. Number of originated and migrated cells over Bangladesh

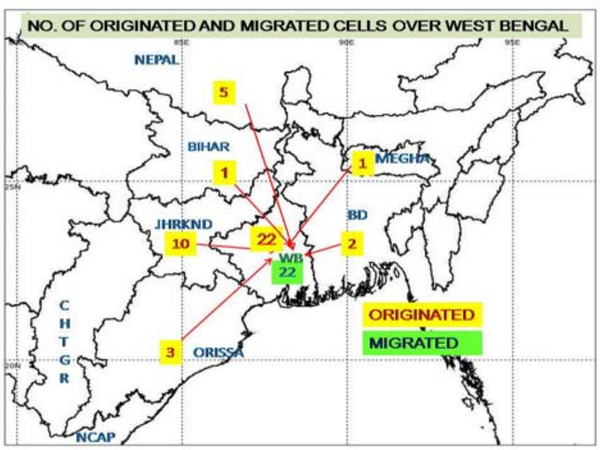

Fig. 4. Number of originated and migrated cells over West Bengal

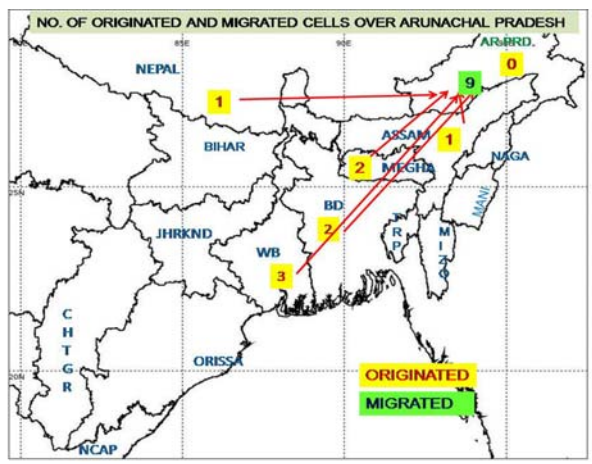

Fig. 7. Number of originated and migrated cells over Arunachal Pradesh

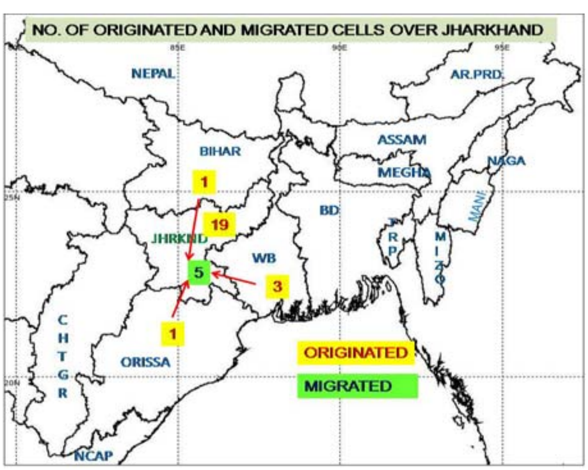

Fig. 5. Number of originated and migrated cells over Jharkhand

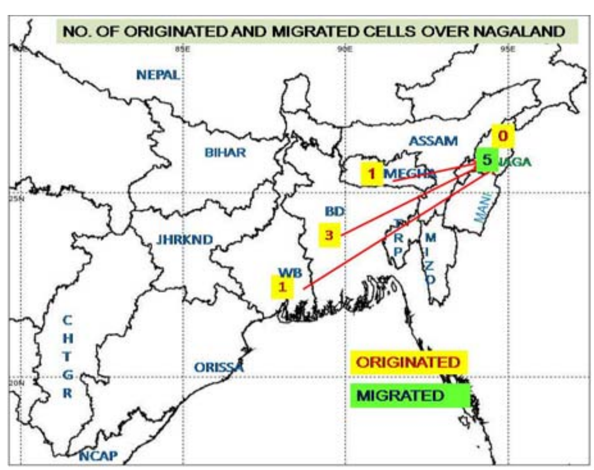

Fig. 8. Number of originated and migrated cells over Nagaland

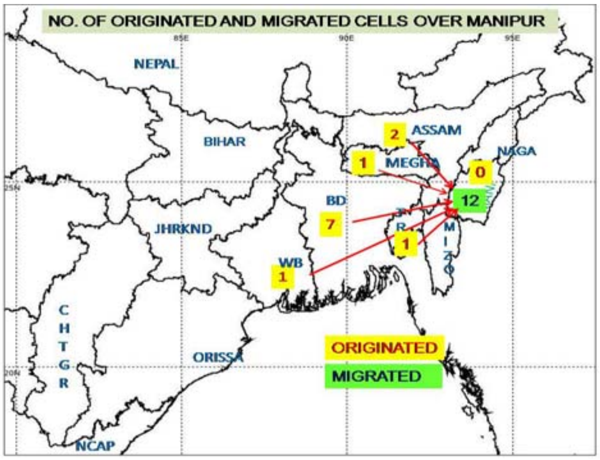

Fig. 9. Number of originated and migrated cells over Manipur

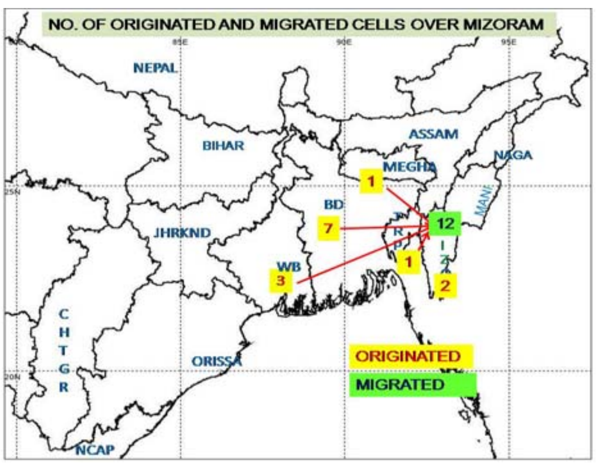

Fig. 10. Number of originated and migrated cells over Mizoram

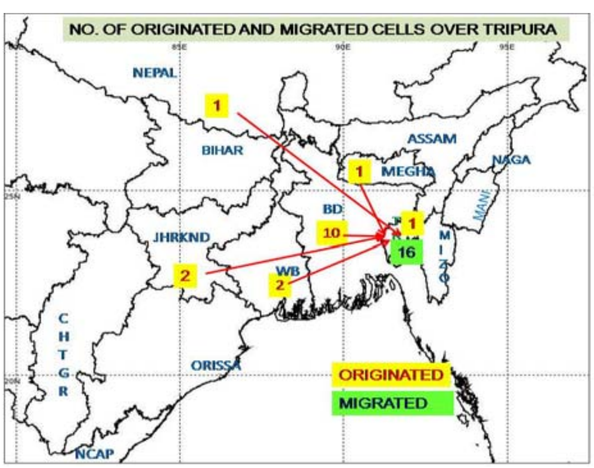

Fig. 11. Number of originated and migrated cells over Tripura

over West Bengal move E/NE towards Bangladesh or Southward over north Bay of Bengal. Cells which originate over Jharkhand move to adjoining West Bengal and north Orissa and those originating over Orissa either migrate to West Bengal or move over adjoining waters of the north Bay of Bengal. Thus the preferable tracks are SEward from Jharkhand, NEward from Orissa, eastward from West Bengal and Eastward/SEastward from SHWB. Movement of these cells depends upon the mid-tropospheric wind field.

5.3. *Intensity of Convection within Cells*

Table 3 shows the number of cells over each specified region according to their intensity classifications into moderate, intense, very intense categories. Note that out of the 164 cells which developed in the season of 2009, only 13 cells reached very intense category. Moderate to intense categories contribute almost equally to the total number of cells. Thus whereas moderate to intense convection is more frequent in the pre-monsoon season over our study region, the very intense convection is rather less frequent. This is another important result which came out of this census of convective cells. Very intense cells occur over Bangladesh and Orissa and intense cells occur over Bangladesh, Orissa, Gangetic West Bengal, North Coastal Andhra Pradesh and Jharkhand. Nearness to coast, position of the cell along the path of low-level moist current, hilly and forested regions and the exit region of the STJ over Eastern India delineate the regions of incidence of intense and very intense convective development. The intense and very intense systems result in high impact weather and heavier rain and because of that they are important. Precipitation and convective fury of storm in terms of squall, hail are not well correlated.

5.4. *Origin and migration of cells*

Convective cloud cells either formed within a sub-region or migrated to a specific sub-region from the neighbouring sub-region. Hourly records of all convective cells were obtained with their CTTs. Tables 4 and 5 show the region-wise origin over and migration into the respective subdivisions of all convective cells during April-May, 2009. It is found that a total of 164 cells originated over different parts of our region and a total of 180 cells migrated from neighbouring regions. The region A, comprising of Orissa, West Bengal, Bangladesh, Meghalaya, Jharkhand, Chhatisgarh and neighbouring countries Bangladesh, Nepal, which is a contiguous region, is responsible for nearly 82% of the total cells which originated. A large part of our domain (Assam, Sikkim, Bhutan, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura) which is region B, contributes only

TABLE 6

No. of cells based on time of development

Sub-area	0000 ≤ *T* < 0400 UTC	0400 ≤ *T* < 0800 UTC	0800 ≤ *T* < 1200 UTC	1200 ≤ *T* < 1600 UTC	1600 ≤ *T* < 2000 UTC	2000 ≤ *T* < 2400 UTC
Nepal	1	2	4	4	0	0
Sikkim	0	0	0	0	0	0
Bhutan	0	0	0	1	0	0
Arunachal Pradesh	0	0	0	0	0	0
Nagaland	0	0	0	0	0	0
Manipur	0	0	0	0	0	0
Mizoram	0	0	2	0	0	0
Tripura	0	0	1	0	0	0
Meghalaya	0	2	2	1	4	2
Assam	1	0	1	1	1	2
Bangladesh	2	3	8	9	1	1
G. West Bengal	3	1	6	2	1	0
Shwb	2	1	1	3	0	2
Bihar	0	1	3	0	0	1
Jharkhand	1	1	15	2	0	0
Orissa	2	1	29	5	0	0
Chattisgarh	0	0	6	4	0	1
North Coastal A .P.	0	0	11	1	0	0
East U.P.	0	0	0	0	1	0
East M.P.	0	0	1	0	0	0
Total	12	12	90	33	8	9

18% to total origin of cells. Thus region B is primarily affected by convective cells which migrate over the region from neighbouring areas. For this purpose, the cells which originate over the region A are much more than those which migrate into this region. Cells forming over Region A migrate to Region B by advective process, while continuing to develop their stratified cloud shield as observed by satellite. Region B is characterised by large number of migrated cells than the cells which originated over the region. In other word, a good number of convective cells migrate from region A to region B and continue to develop over region B and subsequently dissipate. This is an important aspect of convective development over region B which has resulted from this study as earlier studies, which did not have access to satellite based census, showed that the frequency of thunderstorm is higher over NE India compared to Eastern Indian states. However our study has demonstrated that region A is the dominant region over which convective cells originate and continue to develop further, while migrating into more moist region B. For illustration Figs. 3 to 6 depict the no. of originated and migrated cells over Orissa,West Bengal, Jharkhand, Bangladesh respectively (Region A). Similarly Figs. 7 to 11 depict the distribution for sub-areas within the region B: in which migrated cells dominate over those which originates over the region. At the initial stage of origin, the cells is mostly very small to medium areal extent but they grow in size while developing and by merger of cells such that at the maturity stage they attain large to very large dimensions. Relatively the numbers of cells of large and very large dimensions are more frequent over region B compared to region A. This could be due to the environmental conditions as region B is mostly vegetated/forested and the soil is also more moist by the passage of small streams. As such the extra moisture provided by local

TABLE 7

No. of cells based on duration (*T*) of persistence

Sub-area	$T \leq 2$	$2 < T \leq 4$ hrs	$4 < T \leq 6$ hrs	$6 < T \leq 8$ hrs	$8 < T \leq 10$ hrs	$T > 10$ hrs
Nepal	1	4	2	10	0	3
Sikkim	0	0	0	0	0	0
Bhutan	1	0	0	0	0	0
Arunachal Pradesh	0	0	0	0	0	0
Nagaland	0	0	0	0	0	0
Manipur	0	0	0	0	0	0
Mizoram	1	0	1	0	0	0
Tripura	0	1	0	0	0	0
Meghalaya	3	6	1	0	0	1
Assam	1	2	3	0	0	0
Bangladesh	5	9	3	3	2	2
G.West Bengal	6	3	0	1	0	3
Shwb	2	1	0	3	1	2
Bihar	0	2	1	2	0	0
Jharkhand	4	4	5	2	2	2
Orissa	13	12	3	3	2	4
Chattisgarh	5	4	0	1	1	0
North Coastal A .P.	3	4	4	1	0	0
East U.P.	1	0	0	0	0	0
East M.P.	1	0	0	0	0	0
Total	47	52	23	17	8	17

sources and the orography enhance sustained convection which results into build-up of stratiform cloud shield. Rainfall climatology also shows that the pre-monsoon rainfall over region B is higher than over the region A as stratiform rain continues over region B even though convective rain has decreased.

5.5. *Time of maximum development of convective cells, diurnal cycle and duration of convection*

The time of maximum development over different areas are shown in Table 6. It is observed that by and large local afternoon period between 0800-1200 UTC is favourable for maximum development. Diurnal variability with the maximum development in afternoon hours is a well known aspect of Nor'wester development over Eastern India. However for Bangladesh and neighbouring states of NE India, development is continuous even after 1200 UTC and even going into midnight hours. Thus a bimodal diurnal variability of intense convection is noted on the area in which region 'A' is dominated by convection peaking in late evening and B along with parts of Bangladesh, is dominated by convection peaking at night hours. This could be possibly due to the convection over region B being aided by the valley winds as well as the convection development continuing after having migrated from the neighbouring region A (Eastern India). This difference in the time of peaking of convection in two neighbouring region is quit marked.

Information on life duration of convective cells is given in Table 7 shows this statistics. Note that majority of convective cells are within the very short or short-lived categories. Only a few reach the long-lived categories. In summary we have found the following:

(*i*) Eastern India and Bangladesh (Region A) is dominated by the cells which originate over the region and

TABLE 8

Areal extent of the cell and associated weather

Area in km^2 for CTT≤ -30°C	Associated Weather
Below 10000	Light rainfall
10000 to 50000	Light to moderate rainfall
50000 to 100000	Moderate to heavy rainfall
Above 100000	Heavy rainfall with severe weather like thunder squall ,hail etc.

North-East India and adjoining Bangladesh (Region B) is dominated by the cells which migrate from the neighbouring areas.

(*ii*) Very small percentage of cells go to a size of 100000 km^2 or more and hence MCCs are rather infrequent. Also moderate and intense convection is the dominant intensity category and very intense category is rather less frequent. Cells continue to develop for some time over Region B, after crossing from region A and later dissipate over region B.

(*iii*) Diurnal cycle plays a key role in the origin and development of convection as weak and medium intensity cells often peak in afternoon, large and intense cells peak in the evening and early night hours and very intense and very large cells peak in mid-night to early morning hours.

(*iv*) Nearness to the Bay of Bengal and incursion of moisture seems to be linked with the areal extent and intensity of convection.

(*v*) Over Bangladesh and North-Eastern states of India, the convection peaks in the late night hours and occasionally even in early morning hours.

(*vi*) The two peak structure (bimodal) afternoon/evening in Region A and late night /early morning in region B has been noted in earlier studies too.

(*vii*) Medium and large systems peak in the evenin / early night hours and very large systems peak in late night/early morning hours. Region B where systems peak in night/early morning hours is adjacent to the Tibetan plateau which is diurnally heated and as such is seat of low-level convergence in the day time and divergence at night time. The valley wind systems and orographic ascent in NE Indian states add to the enhancement of convection at night hours resulting in later peak in the diurnal cycle.

(*viii*) Majority of the cells are either very short-lived or short-lived with life duration ≤ 4 hours (99 cases out of 164). The number of cells with life duration ≥ 8 hours are not very large (25 out of 164)

Moderate to heavy rainfall with severe weather like squall or hail is associated with cells having areal extent ≥ 50000 km^2.

5.6. *Weather under convective cells*

We have also collected information from Indian network of surface observatories in respect of associated weather for each category of areal extent of cells. The information is tabulated in Table 8. Thus the cells which have the potential to become MCC category are associated with deep convection and also severe weather. As the automatic recorded rainfall data are not available in adequate quantity, we have attempted the study of distribution of weather over IMD met. observatories with the life history of convective development. The study showed that by and large higher amount of rainfall occurred in association with MCCs yet the relationship between the amount of rainfall and CTT was not perfect. Table 9 sums up this information for 22 MCCs which developed in the pre-monsoon season of the year 2007 to 2010 (discussed in section 6). It was also the experience of operational satellite meteorologists in IMD that there was no linear relationship between CTT and the observed rainfall. Low CTT can result from cirrus canopy development resulting from convective elements beneath a canopy. Also very deep isolated towers may produce intense rain but for a short duration whereas continuous anvil rainfall may continue for hours though less in intensity. The mere expansion of cirrus shield without association with the deepening of convective cores would not lead to severity of weather in all cases. Very tall clouds over a wide area in rather moist environment, such as over E and NE India, would be associated with extensive cirrus shields and may thus contribute to the

TABLE 9

MCCs with their characteristics during the year 2007-2010

S. No.	Date	Life duration characteristics in time(UTC) (No. of hours for transition from previous stage to next stage)				Place and central position history (°N/°E) Sequence of development				Maximum areal extent covering CTT≤-30°C in km^2	Maximum intensity reached in life history and time (UTC)	Weather under MCCs
		Initia-tion	Beco-ming MCC	Maturity of MCC	Dissipa-tion of MCC	Initiation	MCC formation	MCC maturity	MCC dissip-ation			
1.	07 May 2007	1100	1300 (2)	1600 (3)	1800 (2)	S.Orissa 19.1/83.3	S.Orissa 19.1/83.9	S.Orissa 19.1/85.2	S.Orissa 18.9/85.0	206070	Very intense (-74 °C) (1400)	Thunder squall with rain at Chikiti (S.Orissa), Baliguda = 5cm(S.Ors), Paralakhemundi=1cm (SE Ors.)
2.	12 May 2007	1000	1130 (2.5)	1500 (3.5)	1700 (2)	S. Orissa 19.9/84.1	Data missing	Orissa, GWB Jharkhand 20.9/84.2	Orissa, Jharkhand 20.8/84.0	224780	Very intense (-73 °C) (1300)	Squall reported at many places of West Bengal Malda=5cm (GWB), Jalpaiguri=3cm(GWB), Ranchi=2cm (Jharkhand)
3.	21 May 2007	0900	1000 (1)	1500 (5)	1800 (3)	S. BD (22.3/88.9) SHWB(24.9/ 87.4) (Merged cells)	GWB,BD 24.0/88.0	GWB, BD, Orissa 21.6/89.0	Myanmar, Bay 20.7/88.9	295220	Very intense (-76 °C) (1200)	Squall at many places of GWB (Kolkata,Alipore, Barrackpore) Puri=3cm(Orissa), Paradip=3cm(Orissa), Cuttack=2cm (Orissa)
4.	22 May 2007	1400	1830 (4.5)	2100 (2.5)	23/0030 (3.5)	E.BD, Meghalaya, Tripura 24.7/91.5	BD adj GWB 24.7/91.5	BD, Meghalaya 25.1/90.1	W. Assam, Meghalaya 26.4/90.1	155830	Very intense (-71 °C) (1900)	Squall over Kolkata Kokrajhar=5cm (Assam) Silchar=5cm(Assam) Kailasahar=3cm (Tripura)
5.	27 May 2007	1000	1200 (2)	1600 (4)	1900 (3)	Bihar 24.9/86.9	Jharkhand 24.3/87.3	W.B., Assam 25.3/88.2	SHWB, Bhutan, China 27.2/89.7	266240	Very intense (-71 °C) (1500)	Squall at Panagarh, Barrackpore(GWB), Purnia(Bihar) Nalbari,Jorhat,Cherapunji=5cm each(Assam) Barpeta,Dibrugarh=3cm each (Assam)
6.	18 May 2008	1200	1500 (3)	2000 (5)	19/0000 (4)	GWB,BD, Tripura 23.3/86.9	Tripura 24.4/90.1	Tripura, Assam 24.3/91.9	Myanmar, Bay 20.7/91.9	428690	Very intense (-77 °C) (1800)	Squall at Dumdum and Alipore(GWB); Thunderstorm with rain at Guwahati and Tezpur(Assam), Shillong (Meghalaya)
7.	27 May 2008	1100	1300 (2)	1800 (5)	2100 (3)	S.Orissa (19.2/83.4) NCAP(17.7/8 2.3) (Merged cells)	Orissa, Chattisgarh 18.3/82.1	Orissa, NCAP 18.6/82.6	NCAP 17.2/82.0	167050	Very intense (-74 °C) (1400)	Weather not available
8.	30 May 2008	1100	1530 (4.5)	1900 (3.5)	2100 (2)	GWB,Jharkh and 24.4/87.7	Bhutan 26.5/89.5	NE India 26.3/92.2	Assam, BD, Meghalaya 25.2/91.1	200900	Very intense (-77 °C) (1700)	Thunderstorm with rain over Guwahati,Silchar, Tezpur(Assam)
9.	02 May 2009	2300	3/0800 (9)	1400 (6)	1800 (4)	Nepal,NE U.P. 28.1/83.0	Bihar 25.9/89.3	GWB, BD, NE India 24.2/90.2	GWB, Orissa, BD,Megha 23.4/88.2	401536	Very intense (-72 °C) (1100)	Squall over Alipore,Dumdum, Hashimara, Panagarh (W.B) Rainfall over many places of Tripura, Assam, Meghalaya, W.B.
10.	11 May 2009	0900	1100 (2)	1500 (4)	1800 (3)	Jharkhand, GWB,BD 23.6/86.5	GWB, Orissa 23.2/88.3	GWB, Orissa, Megha, Assam, BD 23.4/89.3	GWB, Orissa, BD 22.4/89.2	275008	Very intense (-78 °C) (1300)	Squall at many places of W.B. and Jamshedpure (Jharkhand). Rainfall at many places over Bihar, Jharkhand, Orissa, W.B.,Assam, Meghalaya
11.	12 May 2009	0700	1000 (3)	1300 (3)	1800 (5)	BD 25.1/89.5	Orissa,GW B 23.8/88.4	Jharkhand, Orissa, GWB 23.6/87.9	Jharkhand, Orissa, GWB 22.3/87.1	193860	Very intense (-76 °C) (1300)	Weather not available
12.	18 May 2009	1000	1400 (4)	2200 (8)	2300 (1)	Orissa 21.7/87	Orissa 22.6/87.8	GWB 21.3/89.0	N Bay of Bengal 20.9/88.8	147260	Very intense (-82 °C) (1900)	Squall over many places of W.B. Rainfall at many places of W.B.

TABLE 9 (*Contd*.)

S. No.	Date	Life duration characteristics in time(UTC) (No. of hours for transition from previous stage to next stage)				Place and central position history (°N/°E) Sequence of development				Maximum areal extent covering CTT≤-30°C in km²	Maximum intensity reached in life history and time (UTC)	Weather under MCCs
		Initia-tion	Beco-ming MCC	Maturity of MCC	Dissipaa tion of MCC	Initiation	MCC formation	MCC maturity	MCC dissipation			
13.	20 May 2009	0600	0900 (3)	1300 (4)	1700 (4)	Jharkhand 23.5/84.4	Jharkhand, Chattisgarh 24.4/84.6	Jharkhand, Chattisgarh 23.6/84.1	Jharkhand 22.1/84.1	284032	Very intense (-79 °C) (0900)	Weather not available.
14.	17 Apr 2010	1300	1600 (3)	2100 (5)	18/0200 (5)	Assam, Ar. Pradesh 27.8/93.8	Assam, Meghalaya 27.2/91.5	SHWB,BD 25.5/93.8	BD, NE India 26.3/93.8	395070	Very intense (-73 °C) (2030)	Thunder squall over Guwahati, Tezpur(Assam). Thunderstorm with rain over Assam, Meghalaya, Manipur
15.	28 Apr 2010	1000	1400 (4)	2200 (8)	2300 (1)	Orissa,GWB 21.7/87.2	Orissa,BD, GWB 22.6/89.3	NE India,BD 25.0/90.2	NE India, Bhutan 26.5/90.5	277820	Very intense (-77 °C) (1800)	Rainfall at many places of GWB,SHWB,Orissa. Squall at few places.
16.	05 Apr 2010	0800	1000 (2)	1600 (6)	1700 (1)	Bihar,GWB 23.7/87.2	Bihar, GWB, BD 23.7/87.7	Bhutan, Meghalaya 25.1/88.6	Bhutan,G WB NE India 25.0/88.9	286720	Very intense (-71 °C) (1100)	Rainfall at many places of Assam. Thunderstorm with rain over Shillong, Cherrapunji, Lakhimpur (Meghalaya)
17.	13 May 2010	1200	1400 (2)	1800 (4)	2000 (2)	Assam 26.8/90.9	Assam,BD, Meghalaya 24.9/90.8	NE India 26.2/93.9	NE India, Myanmar 26.8/95.4	146690	Very intense (-77 °C) (1500)	Squall over Guwahati(Assam) Thunderstorm with rain over Tezpur,Dibrugarh, Bahalpur(Assam). Rainfall at some places of Manipur,Ar. Pradesh, Meghalaya.
18.	14 May 2010	1100	1300 (2)	1500 (2)	2000 (5)	SHWB,BD 24.5/88.2	WB, BD 24.2/89.5	BD,Bhutan Meghalaya 24.8/91.1	BD, NE India 25.1/92.7	202300	Very intense (-78 °C) (1300)	Thundersquall over Guwahati, Thunder with hail over Tezpur(Assam); Rainfall at many places of Assam and Ar. Pradesh
19.	20 May 2010	0900	1100 (2)	1600 (5)	1700 (1)	Bihar, SHWB 25.0/87.2	Bihar, SHWB 24.7/91.8	NE India, Bhutan,BD 26.2/91.1	NE India, China 28.2/92.0	427970	Very intense (-78 °C) (1300)	Thunderstorm with rain at many places of Assam, Mizoram,Meghalaya. Heavy rainfall over cherapunji,Dadri, AP Ghat; Thundersquall over Malda and Patna(Bihar)
20.	23 May 2010	1000	1200 (2)	1700 (5)	1900 (2)	W Nepal 29.4/82.3	Nepal , Bihar 28.4/84.9	Nepal, Sikkim, SHWB 27.7/87.2	Nepal, Sikkim, GWB 27.6/86.8	229950	Very intense (-75 °C) (1400)	Rainfall at some places of Bihar and SHWB
21.	24 May 2010	1100	1400 (3)	1900 (5)	2100 (2)	Jharkhand 22.9/85.6	Jharkhand, Orissa 22.3/85.6	GWB, Orissa 20.7/86.9	GWB, Orissa, Jharkhand 20.1/87.0	234580	Very intense (-86 °C) (2000)	Thunder squall over Alipore(GWB); Rainfall at some place of GWB and Orissa
22.	26 May 2010	1100	1500 (4)	1900 (4)	2100 (2)	Jharkhand 23.0/85.9	Jharkhand, GWB 23.3/87.8	BD,Assam, Meghalaya 23.6/89.3	NE India 25.5/92.5	249860	Very intense (-81 °C) (1500)	Thundersquall at Alipore, Dumdum, Haldia, Bankura (GWB), Jamshedpur (Jharkhand); Rainfall at many places over GWB, Assam, Meghalaya.

process of evolution of MCCs. However similar isolated clouds in dry (arid) environment such as NW India in the pre-monsoon season, may not yield extensive cirrus shields, and yet produce severe squalls with less rain.

6. Study of MCC's during 2007-2010

As defined in section 4.2 MCCs are long-lived convective systems which have very large dimensions and their inner core area has extremely cold CTTs. Based on our definition, we have documented for the four year period 2007-2010, all the MCCs which existed (formed or migrated) over area of our interest as given in Table 9. Based on this statistics, we have prepared the characteristics of MCCs in terms of areal coverage, their intensity and life duration. During the year 2007, 2008, 2009 and 2010, five, three, five and nine MCCs formed respectively in their pre-monsoon season. There could be

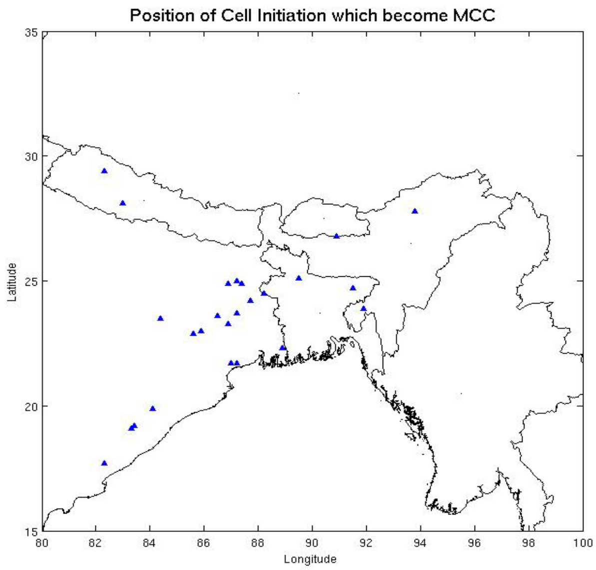

Fig. 12. Position of cell initiation which become MCC

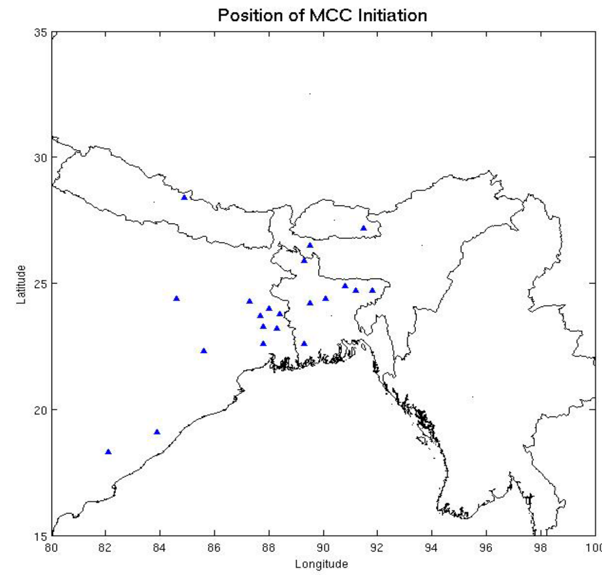

Fig. 13. Position of MCC initiation

years like 2010 when the number of MCCs can exceed the average considerably. Also note that that out of the 164 convective cells which have formed in 2009, only 5 could attain the category of an MCC. Number of cells with areal coverage ≥ 100000 km^2 which existed over our area in 2009, as shown in Table 5, is 36. However difference between 36 cells which existed over different sub-areas and the 5 cells which are classified as MCC has resulted from our method of tabulation. An MCC may acquire dimension 100000 km^2 but may lie over different sub-areas during its life history. To be classified as MCC, we have taken it as a single entity even though it might have existed over different sub-areas. With this in view (counting single MCC on a day even though it may lie over different sub-areas in its life duration) we have shown in Table 9, the number of MCC's and their characteristics for the period under study.

Almost all MCCs except two (serial numbers 14 and 15) have formed in the month of May. May is the dominant month during which convective cloud cells attain the category of MCC and in the month of April this process is less frequent. Thus build-up of the hot season from April to May and corresponding seasonal enhancement of low level moist inflow from the Bay of Bengal appear to play dominant roles in the formation of MCCs. In April convective instability (high CAPE) and high vertical shears are present but convection is almost organised in isolated cells (≤ 50000 km^2) as the environment is not fully conducive for formation of MCCs. During May high CAPE is present but the vertical wind shears are lower than in April, therefore though environment is less favourable for severe storms but the presence of higher moisture over West Bengal, Bangladesh and adjoining NE India allows the convection to develop into MCCs more frequently than in April. The initial stage of an MCC is recognized as when a cell attains minimum horizontal dimension of 100000 km^2. This is the stage when it becomes an MCC. Maturity stage is reached when it loses the maximum intensity category or when it becomes below the MCC category in areal extent. We find a dependence on diurnal scale as an MCC category is reached between 0900 & 1500 UTC. Maturity stage of an MCC is spread over 1300 to 2200 UTC and dissipation stage is achieved between 1700 & 0300 UTC hrs of the next day. Thus we find that it takes nearly 1 to 4 hrs for a convective cell to develop from initiation stage to MCC stage. An MCC reaches a mature stage between 3 to 5 hrs after reaching this category but in an extreme case of 18th May 2009 this process was accomplished in 8 hrs. Thus an MCC category is reached from initiation of a convective cell within as little as 1 hr to as large as 5 hrs and hence it could be accompanied by an explosive development or a slow development. In the same way an MCC becomes mature in 3 to 5 hrs but in extreme case the development could continue upto 8 hrs as it happened in the case of 18th May 2009. Dissipation stage is the areal extent becoming below the MCC category. It could be also a slow process lasting for 5 hrs to a rapid process to be accomplished in just within one hour as it occurred in the case of 18th May 2009. Our analysis suggests that satellite monitoring at half hourly to hourly interval is a

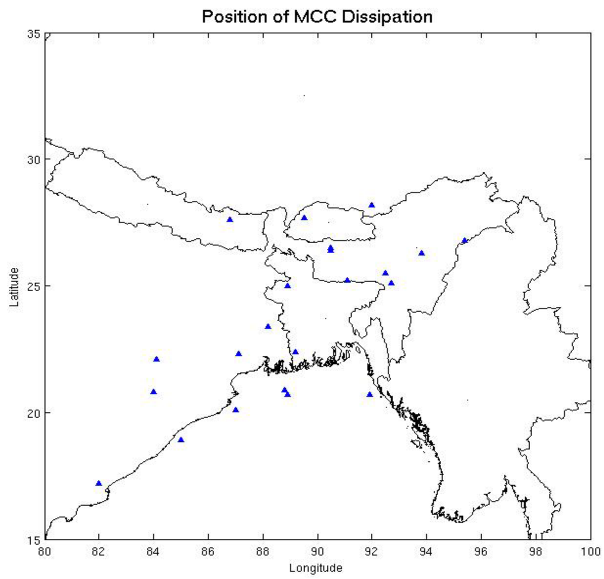

Fig. 14. Position of MCC dissipation

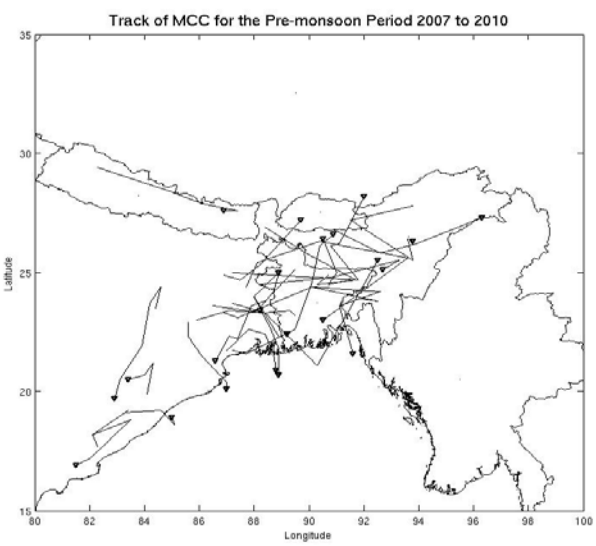

Fig. 15. Tracks of MCC for the pre-monsoon period 2007 to 2010

way to provide nowcasting about the development and life cycle of an MCC. Fig. 12 shows the positions of origination of convective cells which ultimately became MCCs, Fig. 13 shows the position of initiation of those MCCs and Fig. 14 shows position of dissipation of those MCCs. It is clear that majority of the cells originate in region A. By and large they migrate somewhat eastward and become MCCs over West Bengal and Bangladesh within regions A and B in majority of cases and dissipation is favoured over north Bay of Bengal or over states of north east India (over region B).

The region of becoming an MCC from the initiation is covered within latitude 18.0°N to 29.5°N and longitude 83.0°E to 97.5°E. This is fairly a large region covering both the regions A and B of origin of Nor'westers. However majority of the MCC formations (13 out of 22) have occurred over region A, covered by 17.0° N to 29.0°N and 80.0° E to 89.0° E *i.e*., region A. Some of the MCCs migrate to area B where they dissipate. A good number of MCCs (9 out of 22) also reached MCC category and matured over region B. However the dissipation of the MCCs occurred on almost equal number of cases (11 out of 22) over region A as well as region B. This entails that a continuous watch for the MCC formation and dissipation is required over the preferred areas of formation and dissipation. For this purpose, besides the half hourly satellite images multiple weather radar watch (Kolkata, Dacca and Agartala) would be needed.

The maximum areal coverage of an MCC in our record has been about 430000 km^2 but the range is from 150000 km^2 to 430000 km^2 (third last column of Table 9). Majority of these (59%) have areal coverage between 200000 & 300000 km^2. Only 3 cases covered areal extent of 300000 to 400000 km^2 and only 2 had the areal dimensions between 100000 & 150000 km^2. We have also noticed that a few cases of MCCs were initiated by merger of two convective clusters which had formed close to each other. Thus developing convective cell may merge into a single cell which later on may develop into an MCC.

Our study has shown that MCCs over our area of interest can reach extensive areal extent exceeding occasionally 300000 km^2 in area They are also long-lived convective systems with average life duration of 12.5 hours from its becoming an MCC stage to dissipation stage. Though the areal extent of MCCs over Eastern India is slightly less than those in USA, but the maximum life duration of MCCs over India is similar to those occuring over USA.

Some of the MCCs over Eastern India have lasted from the afternoon hrs (local hrs) to the early hrs of the next day. We also find that the MCCs tend to cluster around a favorable area A of our study which is surrounded by special physiographic features *viz*., low level stronger southerly to southwesterly winds from Bay of Bengal, close to coastal areas, moist vegetated region and hilly tracks. Thus boundary layer forcing and forced lifting of moist winds are the triggers which help in the formation of an MCC from the initial stage. High impact weather like heavy rain, squall and hailstorms generally formed only in those convective systems which achieved the stage of MCC.

Fig. 15 shows the tracks followed by MCCs examined in our study. The tracks are rather chaotic but overall it appears that majority of these originate in region A and terminate in region B and preferred direction of movement is from SW to NE. This is contrary to general perception as in the initial stages of development cell movement is from NW to SE (hence the name Nor'wester), but after becoming an MCC, the movement from SW to NE is perhaps preferred. Some MCCs were moved over the Bay of Bengal after crossing Gangetic West Bengal and neighbouring Bangladesh. This aspect of movement of MCCs would require further study. A few tracks originate in region A and dissipate within the same region or over the adjoining Bay of Bengal.

7. Summary and conclusions

INSAT geostationary satellite imagery on hourly basis during the STORM Program campaign for the period 1st April to 31st May and for the year 2009 have been used to identify the places of origin, development, maturity and dissipation of mesoscale convective organizations over the STORM region. This data set provided information about the areal coverage, intensity and life duration of the convective organizations. Additionally similar information have been collected for the period of 15th April to 31st May but for four years 2007 to 2010 in respect of the organization to MCC category. Identification of MCCs was based on the definition similar to what has been used in U.S. by Maddox (1980). The following features have been noted with respect to census of convective cells and MCCs in our data:

(*i*) Eastern India (states of Orissa, Jharkhand, West Bengal) and Bangladesh are dominated by convective cells which originate over different parts of the region A. A large number of cells are found to originate over Orissa, West Bengal and Bangladesh. Some even originate over SHWB and move towards Bangladesh and Assam-Meghalya.

(*ii*) Convection over North-East Indian states (Sikkim, Mizoram, Manipur, Arunachal Pradesh, Nagaland, Assam, Meghalaya) and Bhutan is dominated chiefly by the migration of cells from the neighboring areas from region A or from SHWB.

(*iii*) Convective cells which develop deep structures almost exclusively form over land areas influenced by vegetation, forests, orography and coastal topography. They form over the land area with existence of gradients of near-surface specific humidity and move over neighbouring regions where the land surface is moist and complex orography is present.

(*iv*) Convective cells begin from shorter areal extent and gradually attain larger dimensions. Areal dimension of the cell is classified into five types (a)Very small (less than 10000 km^2) (b) small (10001 to 25000 km^2) (c) moderate (25001 to 50000 km^2) (d) large (50001 to 100000 km^2) (e)very large (>100000 km^2).

Cells which attain the category (d) have the potential to attain the size of MCCs which is equal or greater than 100000 km^2 in area. Although severe weather is often associated with MCCs, but there is no direct linear relationship between cell size as well as CTT with the severity of weather or the intensity of rainfall.

(*v*) Intensity of convection in each cell was based on CTT threshold value in the ranges of (a) -30 °C to -49 °C as moderate convection (b) -50 °C to -69 °C as intense convection (c) ≤ -70 °C as very intense convection.

The events of very intense convection are rather rare suggesting that the convective development over Indian region is mostly of moderate to intense category and very severe convection is rather rare which is evident from only a few cases of observed tornadoes. Intense convective elements (CTT<-50°C) were not necessarily associated with severity of weather. Zipser *et al*. (2006) have also noted that convective elements reaching greatest heights in regions of notably low rain accumulation. Also very severe convective elements are infrequent outliers in the spectrum of convective clouds and sub-regional rainfall climatology is built on the statistics of moderately intense convection. Hence rainfall from isolated very deep convective clouds may or may not contribute to total rainfall as the duration of high intensity rainfall is rather short to the total duration of rainfall. However it must be recognized that climatologically rainfall over Eastern and NE India in pre-monsoon season is primarily convective (deep convection mixed with wide moderate convection accompanied with stratified anvil rainfall).

(*vi*) Life duration of each cell from initiation to dissipation stages have been specified into five categories, *viz*, : (a) $T \leq 2$ hrs as very short-lived (b) 2 hrs < $T \leq$ 4 hrs as short-lived (c) 4 hrs < $T \leq$ 6 hrs as moderate-lived (d) 6 hrs < $T \leq$ 8 hrs as long-lived (e) T > 8 hrs as very long-lived.

Majority of the convective cells fall within very short-lived or short-lived category with life duration of less than 4 hours which together account for 60% of the cases. The number of cells with life duration greater than 8 hours are small in number (about 15% of total cases). Diurnal cycle plays a key role in the origin and development as moderate intensity cells often peak in the afternoon in region A whereas intense and very intense cells peak early night to early morning in region B. Bimodal diurnal life cycle prefers peaking in evening hours over region A and during night and early morning hours of the next day over region B.

(*vii*) Weather under the convective cells has been examined based on the synoptic data from surface observatories of IMD. Even though the information is not based on the full day -long observations, our analysis suggest that the cells with large dimension are mostly associated with severe weather like squall and higher amount of rain. However the dimension of the cells and their intensity do not have linear relationship with rainfall. Further study is needed which is possible only through the analysis of Automatic Weather Station (AWS) and Automatic Rain Gauge (ARG) data network currently under installation over the region. Also wider overlapping radar coverage would help greatly in understanding several processes involved in convective organizations.

A few cells that originated over Orissa migrated to neighbouring Gangetic West Bengal but the majority dissipated over Bay of Bengal. Majority of the cells originating over Gangetic West Bengal dissipate within the region A or Bay of Bengal. Only a few of them migrate to Bangladesh and adjoining North-East India. The cells, which originate over Bangladesh, also dissipate within the region but a few migrate to east of Bangladesh to the north east Indian states. There are three or four important pathways for the migration of cells (a) cells originating over Jharkhand and Bihar move from NW to SE into Gangetic West Bengal; (b) those originating over Chhatisgarh and Orissa move towards east or in the direction SW to NE reaching Bay of Bengal and Gangetic West Bengal respectively; (c) cells originating over foothills of Himalaya move into GWB and adjoining Bangladesh (southward or SE track) and some even move eastwards towards North-East Indian states. Our study shows that dominating pathways are fairly well known from the results of earlier studies.

(*viii*) Convective cells which attain the category of MCC mostly originated over region A during the four year period 2007-2010. Only 22 cells reached the MCC category during the study period. A vast majority of these MCCs (20 out of 22) formed in the month of May. Thus the month of May is conducive for the formation of MCC. This is because the surface heating has intensified from April to May and the incursion of moist south to south westerly flow from the Bay of Bengal is dominant even though the STJ is weakening after mid-May.

(*ix*) Initiation of MCCs occurs between 0900 & 1500 UTC, maturity is reached between 1300 & 2200 UTC and dissipation stage is reached between 1700 & 0300 UTC of the next day.

(*x*) The maximum areal coverage of 22 MCC's has been 4.3 × 105 km^2 but the range is between 1.5 × 105 to 4.3 × 105 km^2. Though the areal extent covered by the MCC over Eastern India and neighbourhood is slightly less than those in U.S.A. but the maximum life duration of MCC over Eastern India is similar to those of U.S.A.

(*xi*) Pathways of MCC are quite erratic but MCCs have a preference to move from SW to NE direction. This is contrary to general perception of Nor'westers which are known to drift southeastwards. However more detailed study using data for some more years is required on this aspect.

(*xii*) There are days when convective developments occur in region A at different locations such as Jharkhand, SHWB, Orissa at different times on the same day and may or may not merge with each other over Gangetic West Bengal to form an MCC. Initial convection on such days is over a wide spread area with no initiation in between separate area. There are also days when initiation is bound over a specific area. It is difficult to analyze the factors which distinguish between these two types of episodes. Hence localized factor play important role along with synoptic forcing for MCC formation. The only way for weather warnings is to monitor development with satellite and multiple radar coverage.

INSAT satellite imagery provides important clue for the study of convective formations and their growth into MCC category as overlapping radar coverage over the region of study is another alternative. Synoptic information would not provide full data for the study of different life stages and intensity categories in the development of mesoscale convection in the pre-monsoon season over Eastern India and adjoining Bangladesh, Nepal and Bhutan. Even though our data is limited only two to four years, it has provided vital information with regard to development of mesoscale convection over the region. It has demonstrated that for predicting and nowcasting of mesoscale convection hourly observations from INSAT, when combined with radar coverage, are necessary to warn the public about the outburst of convection two to three hours in advance over specific area. More data are required to be analyzed at inter-annual variability of MCCs is considerable. Individual cases of MCC formation need to be studied with synoptic data and using mesoscale dynamic model to understand the growth of MCC. Our study have only demonstrated the census of convective cells and their development to MCCs. As IMD has program to continue STORM- related observations and modeling, we intend to probe further into convective developments over E and NE India using available information.

Acknowledgements

The authors wish to acknowledge the support of participants in the discussions on STORM Program held thrice a week during the pre-monsoon. Shri D. R. Sikka acknowledges support of IMD for his participation in the discussion. He is also thankful to Prof. J. Shukla of COLA, U.S.A. for encouraging him to help engaged in research even in his late years of formal retirement from service. Dr. Suman Goyal and Mansi Bhowmick like to extend their thanks to Sh. A.K. Sharma, Scientist F, (Head Satellite Meteorology Division) for his valuable support during writing this paper. Authors also thank the reviewer of the paper for his painstaking reading of the paper and his suggestions helped in improving the final version of the paper.

References

Augustine, J. A. and Howard, K. W., 1991, “Mesoscale convective complexes over United States during 1986 and 1987”, *Mon. Wea. Rev*., **119**, 1575-1589.

Basu, G. C. and Mondal, D. K., 2002, “A forecasting aspect of thundersquall over Calcutta and its parameterization during pre-monsoon season”, *Mausam*, **53**, 271-280.

Blanford, H. F., 1886, “Dirunal period of rainfall at Calcutta”, *Indian Meteor Memoirs*, **IV**, 39-46.

Byers, H. R. and Braham, R. R., 1949, “The thunderstorm: Final Report of the Thunderstorm project”, U.S. Govt. print off.

Bhatia, R. C. and Kalsi, S. R., 1992, “Satellite observations of development of thunderstorm complexes in weakly forced environments”, *Vayumandal*, **22**, 3-4, 65-76.

Bhattacharya, S. G. and Bhattacharya, P. K., 1980, “Diurnal variation of rainfall in the upper catchments of north Bengal rivers”, *Mausam*, **31**, 51-54.

Carlson, T. N. and Ludlam, F. H., 1968, “Conditions for the occurrence of severe local storms”, *Tellus*, **20**, 203-228.

Cotton, W. R., Lin, M. S., McAnelly, R. L. and Tramback, C. J., 1989, “A composite model of mesoscale convective complexes”, *Mon. Wea. Rev*., **117**, 765-785.

Dallas, W. L., 1900, “A discussion of Thunderstorm observations recorded in 1897 at 10 selected stations in India”, *India Met. Memoirs*, **6**, part VII.

Desai, B. N., 1950, “Mechanism of Nor'westers of Bengal”, *Indian J. Met. & Geophys*., **1**, 74-76.

Floyd, J., 1839, “Account on the hurricane on whirl wind of the 8th April, 1838”, *J. Asiatic Soc Bengal*, 422-428.

Fujita, T., 1955, “Results of detailed synoptic studies of squall lines.”, *Tellus*, **7**, 405-436.

Ghosh, A. K., 1982, “A tornado over Orissa in April 1978”, *Mausam*, **33**, 235-240.

Haughton, W. R., 1925, “Thunderstorm in Eastern Bengal”, *QJRMS*, **51**, 406-408.

Houze, R. A. Jr., Wilton D. C. and Smull, B. F., 2007, “Monsoon convection in the Himalayan region as seen by the TRMM Precipitation Radar”, *Quart. J. Roy. Meteor. Soc*., **133**, 1389-1411.

Kandalgaonkar, S. S., Tinmaker, M. I. R., Kulkarni, M. K. and Nath, A., 2002, “Thunderstorm activity and sea surface temperature over Island station and along the east and west coast of India”, *Mausam*, **53**, 245-248.

Kanjilal, T., Basu, B. and Roy, A., 1989, “Growth of thunderstorm and latent instability over Eastern India”, *Mausam*, **40**, 293-298.

Kanjilal, T., Basu, B. and Roy, A., 1989, “Potential convective instability analysis on squall days at Calcutta”, *Mausam*, **40**, 409-412.

Karmakar, S. and Alam, M., 2006, “Instability of the troposphere associated with thunderstorm /nor’westers over Bangladesh during pre-monsoon season”, *Mausam*, **57**, 629-638.

Koteswarm, P. and Srinivasan, V., 1958, “Thunderstorm over Gangetic West Bengal in the pre-monsoon season and the synoptic factors favourable for their formation”, *Indian J. Met. & Geophys*., **9**, 301-312.

Krishna Rao, P., 1966, “A study of the onset of the monsoon over India during 1962 using TIROS IV radiation data”, *Indian J. Met. & Geophys.*, **17**, 347-356.

Kundu, K. K. and De, A. C. ,1967, “Radar study of line type echoes as observed at Agartala aerodrome ,Tripura during February-October 1964”, *Indian J. Met. & Geophys*., **18**, 247-254.

Laing, A. G. and Fritsch, J. M., 1993, “Mesoscale convective complexes over Indian Monsoon Region”, *J. Climate*, **6**, 911-919.

Litta, A. J. and Mohanty, U. C., 2008, “Simulation of a severe thunderstorm event during the field experiment of STORM programme 2006, using WRF-NMM model”, *Current Sci*., **95**, 204-215.

Maddox, R. A., 1980, “Mesoscale convective complexes.”, *Bull. Amer. Meteor. Soc*., **61**, 1374-1387.

Manohar, G. K., Kandalgaokar, S. S. and Tinmarker, 1999, "Thunderstorm activity over India and Indian south-west monsoon", *J. Geosphys. Res*., **104**, 4169-4188.

Mukherjee, A. K. and Bhattacharya, P. B., 1972, "An early morning tornado at Diamond harbour on 21 March 1969", *Indian J. Met. & Geophys*., **23**, 227-230.

Mukhopadhyay, P., Sanjay, J., Cotton, W. R. and Singh, S. S., 2005, "Impact of surface meteorological observations on RAMS forecasting of monsoon weather systems over Indian region", *Meteorol. Atmos. Phys*., **90**, 77-108.

Newton, C. W. and Newton, H. R., 1959, "Dynamical interaction between large scale convective clouds and environment with vertical shear", *J. Meteor*., **16**, 483-496.

Normand, C. W. B., 1938, "On instability index for thunderstorm forecasting", *Bull. Amer. Met. Soc*., **34**, 250-252.

Pradhan, D. and Sinha, V., 2005, "Thunderstorm genesis over Kolkata: A case study", *Vatavaran*, *AFAC, J. Meteorol (India)*, **29**, 20-27.

Ray, T. K. and De, A. C., 1971, "Radar study of pre-monsoon squall lines as observed at Gauhati airport", *Indian J. Met. & Geophys.*, **22**, p223.

Roy, Bhowmik, S. K., Sen Roy, S. and Kundu, P. K., 2008, "Analysis of large scale conditions associated with convection over the Indian monsoon region", *J. Climatology*, **28**, 797-821.

Saha, K. R., 1966, "The Cooch Bihar-Assam tornado of 19 April 1963", *Indian J. Met. & Geophys*., **17**, 41-46.

Schaffer, W., 1947, "The thunderstorm high", *Bull. Amer. Meteor. Soc*., **28**, 351-353.

Science Plan, 2005, "Severe Thunderstorms Observations and Regional Modeling (STORM) Programme", Department of Science and Technology, Govt. of India.

Sharma, G. N., 1978, "Cumulonimbus tops around Gauhati airport", *Indian J. Met. Hydrol. & Geophys*., **29**, 705-716.

Singh, G. and Agnihotri, C. L., 1974, "Comparative study of Showalter's stability index and George's instability value K for predicting local thunderstorm over Calcutta airport", *Indian J. Met. Hydrol. & Geophys*., **25**, 51-54.

Sinha, V. and Pradhan, D., 2006, "Supercell at Kolkata, India and neighbourhood: Analysis of thermodynamic conditions, evolution structure and movement", *Indian J. of Radio and Space Physics*, **35**, 270-279.

Sohoni, V. V., 1928, "Thunderstorms of Calcutta 1900-1926.", IMD Scientific Note No. 3, Vol. **1**.

Srinivasan, V., Ramamurthy, K. and Nene, Y. R., 1973, "Summer Nor'westers and Andhi and large scale convective activity over peninsula and central parts of the country", *Forecasting Manual*, **Part 3**, India Meteorological Department.

Subramanian, D. V. and Sehgal U. N., 1967, "Radar study of thunderstorm activity in northeast India during the pre-monsoon season", *Indian J. Met. & Geophys*., **18**, 111-114.

Tepper, M., 1950, "A proposed mechanism of squall line : the pressure jump line.", *J. Meteor.*, **7**, 21-29.

Tyagi, A., 2007, "Thunderstorm climatology over Indian region", *Mausam*, **58**, 189-212.

Williams, D. T., 1948, "A surface micro study of squall line thunderstorm", *Mon. Wea. Rev*., **76**, 11, 239-246.

Weston, K. J., 1972, "The dry line of northern India and its role in cumulonimbus convection", *Quart. J. Roy. Meteor. Soc*., **98**, 519-532.

Zipser, E. J., Cecil, D. J., Liu, S., Nesbit, S. W. and Yorty, D. P., 2006, "Where are the most intense thunderstorms on earth?", *Bull. Amer. Meteor. Soc*., **87**, 1057-1071.

Appendix I

Brief Description of Field Programs on Mid-Latitude Severe Local Storms in U.S.A. and International Programs on Tropical Convection

1. *Programs on Mid-Latitude Severe Local Thunderstorms in U.S.A.*

US weather Bureau had organised a massive field program to systematically study severe thunderstorms soon after the Second World War. A project was carried out in the spring season of 1946 in Florida and in 1947 in Ohio. This project was conducted after about 5 years of the 1941 Nor'westers project in India. The US thunderstorm Project involved micro analysis of data at 5 minute interval using automatic weather stations. Scientific results of the project were discussed in several papers (Byers and Braham 1949, Williams 1948, Tepper 1950 and others). Important results were the three phase structure of a developing thunderstorm from initiation to dissipation stage and the pressure jump line travelling with the propagating storm which had high pressure gradient with narrow zone of intense ageostrophic winds and the recognition of the mesoscale nature of thunderstorm development. Fujita (1955) and his collaborators in USA during 1950's employed weather radar and mesonet of weather stations to probe further into the dynamics of mid-latitude spring- season convection. They delineated individual thunderstorms moving, developing and weakening in 2-6 hours , all ahead of a cold front. At the formation stage the areal coverage of convection was small; the mature stage witnessed rapid growth of convection with meso-high and pressure surge accompanied with marked wind shift, strong divergence of the squally weather and the collapse of the system in the dissipating stage. Role of vertical wind shear in the development of severe convection was emphasized by (Newton and Newton 1959) and Carlson and Ludlam(1968). With the establishment of Severe Local Storm Centre(Laboratory) at Oklahoma by the USWB, yearly field experiments were conducted during 1960's to 1980's. Weather radars began to be used routinely in these experiments. Later from 1978 onwards a series of special field programs have been carried out in USA to investigate deeper and deeper into the dynamics of spring-time severe local thunderstorm in mid-west USA. These programs deployed synoptic and meso-scale surface and upper air networks, mobile mesonet, weather radars (S-Band and C-Band Doppler) mobile radars, weather satellites, wind profilers and even research aircraft. Maddox (1980), using satellite IR imagery, had defined a class of systems called Meso-scale Convective Complexes (MCCs) with large horizontal extent and cold cloud shield with life duration greater than 6 hours. Later Augustine and Howard (1991) and several others further investigated the characteristics of MCCs. Cotton et al (1989) prepared a composite model of an MCC and with that MCCs have become a well defined mesoscale weather entity in the literature on deep convection. Researches, during the preparatory stages and with data collected from field phases of several field experiments, have led to the role of moist downdrafts and updrafts in the life cycle of severe storms, role of low level jet in initiation of severe storms, moisture and energy budget, large scale environment and storm scale environment interactions etc. Other features investigated refer to the initiation and development of MCCs with geostationary IR satellite data, Doppler radar structure of severe storms and super cell storms, identification of bow echo, tracks of severe thunderstorms, numerical modelling of severe storm development etc. These studies have led to the formulation of high resolution mesoscale models, role of cloud microphysics in storm dynamics etc. The major field program on different aspects of severe local storm carried in USA since 1970's are

Northern Illinoi's Meteorological Research on Down Draft (NIMROD) in 1978,

Atmospheric Variability Experiment and Mesoscale Severe Storm Experiment (AVE-SESAME)-1979,

Joint Airport Wind Shear (JAWS) in 1982 in Denver, Colorado to study microbursts

Central Preliminary Regional Experiment for Storm Scale Operation and Research Meteorology -Central Phase (PRE-STORM) in 1984 and the Oklahoma- Kansas Regional Experiment for Storm Central in 1985,

Program of Regional observations and Forecasting Services (PROFS) in 1985, Microbursts and Severe Thunderstorms (MIST) in Albama in 1986,

Crystal- FACE Cumulus Regional Study of Tropical Anvil and Cirrus Layers- Florida Area cirrus Experiment 2004.

Cooperative Meteorological Experiment (COMEX) in 1986,

Convection and Precipitation/ Electrification Experiment (CAPE),

Storm Scale Operational Research and Meteorology Front and Experimental System (STORM FEST) in 1994,

Program Verification of Origin of Rotation in Tornadoes (VORTEX 1993-1995) - specially focused on Tornado studies.

Program ROTATE 1998 specially focused to understand rotating storms such as tornadoes,

Severe Thunderstorm Electrification Study (STEP) – 2000

International H2O Project (IHOP), 2002 and the Bow echo and MCV Experiment (BAMEX) 2004.

VORTEX-2 or V2 in 2009 with the largest array of observational systems ever deployed to capture unprecedented detail of tornadoes.

Many research papers on the kinematics, dynamics, numerical simulations of thunderstorms have been publised in the American meteorological journals base on the data collected during these experiments.

2. *International Field programs to investigate Tropical Convection over land and seas*

Several field programs have been also carried out over tropical land and oceanic regions in different parts of the world through interanational effort to probe into tropical convection. The experiment facilitated cooperation between research and operational community. The prominent experiments among them are:

(*i*) Line Island Experiment in central Pacific in 1966,

(*ii*) Caribean Sea BARBODAS Experiment in 1968,

(*iii* Venezuela International Meteorology and Hydrology Experiment (VIMHEX) in 1972,

(*iv*) GARP Atlantic Experiment (GATE) in 1974,

(*v*) Convection Profile Tropical experiments in Africa COPT- I in 1979 and COPT- II in 1981 and

(*vi*) TOGA- COARE in 1995 in Central Pacific.

These experiments have established that tropical convection is organized from several isolated cells aligned perpendicular to low level wind in a region favourable for convection. The leading edge of convection propagates and the vertical cell development occurs along the leading edge. An individual cell is 5-50 km in horizontal extent and area of rainfall is across 10000 to 250000 km^2. Tropical squall line has convective and stratified anvil regions. Convective region is characterized by mesoscale boundary layer convergence which feeds into deep convective updraft and mid to upper level divergence results from outflow of cells. It has been recognised that severe local storms are initiated and several are controlled by mesoscale processes. Studies have been undertaken on early growth of MCCs and mesoscale cycle of convective rainfall and the roll of meso-high, wake-low and build-up of gust front etc. The anvil region has been found to be composed of mid-level convergence which feeds both into mesoscale downdraft below the anvil and a mesocale updraft within the anvil. Thus the field program data have resulted into defining the characteristic features of mesoscale convection and for developing models to simulate and predict mesoscale convection realistically. Many research papers have appeared in international journals. As stated earlier we have used INSAT data for preparing census of meso-scale convection in STORM Program during 2007-2010.