NUMERICAL SIMULATION OF A SEVERE THUNDERSTORM OVER DELHI USING WRF MODEL

A DISSERTATION

Submitted in partial fulfilment of the requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
DISASTER MITIGATION AND MANAGEMENT

By

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CENTRE OF EXCELLENCE IN DISASTER MITIGATION AND MANAGEMENT
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MAY, 2015

CANDIDATE DECLARATION

I hereby declare that the work, that is being presented in this dissertation is an authentic and genuine display of my work done and results obtained in due period of May 2014 – April 2015 under the joint supervision of Dr. Ajay Gairola, Professor, Centre of Excellence in Disaster Mitigation & Management, Indian Institute of Technology- Roorkee, Roorkee and Dr. Someshwar Das, Scientist-G/Project Director, India Meteorological Department, New Delhi.

Place: New Delhi
Date: 1th May 2015

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CERTIFICATE

This is to certify that the above mentioned statement made by the candidate is correct to the best of my knowledge.

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Abstract

A severe thunderstorm affected Delhi and adjoining region between 1630 hrs IST and 1730 hrs IST of 30th May 2014. The system moved eastward and was steered by westerly trough. It propagated through U.P, Bihar and dissipated over West Bengal on 31st May 2014. This event was accompanied by strong winds, lightening, thunder, rainfall & hail and resulted in loss of property, life and also aviation hazards.

In this study Weather Research Forecasting (WRF) system version 3.6.1 has been used to simulate and investigate the severe thunderstorm. Sensitivity experiments are conducted to study the impact of using different grid resolution (9km and 3km) with terrain resolution 5 min (~10 km) and 1 min (~2 km) respectively and the same microphysics and cumulus parameterization schemes on simulation of the system. The results demonstrate that the model simulates better structure and intensity of the thunderstorm at higher resolution domain. The model forecasts are compared with observational data from different sources such as Doppler Weather Radar (DWR), Automatic Weather Station (AWS) and Satellite data. Although the present study is based on only one severe thunderstorm, it could be useful for planning real-time prediction using WRF modeling system. More comprehensive case studies including different physical parameterization sensitivity experiments can be explored for future research work.

Acknowledgment

This final report marks the end of a phase of an extravagant learning experience that appeared in the form of this dissertation, as I complete my Masters in Disaster Mitigation and Management.

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I would also like to thank my family without whose believe in me and constant moral support, survival would have been almost impossible. Their constant queries about my development stir the fire and zeal to perform and bring out the best in me. They are every reason for my being and hence every reason for the success of this dissertation.

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LIST OF ACRONYMS

ARW	Advance Research WRF
AWS	Automatic Weather Station
AFWA	Air Force Weather Agency
BOB	Bay of Bengal
CAPS	Center for Analysis and Prediction of Storms
CP	Cumulus Physics
FAA	Federal Aviation and Administration
FSL	Forecast System Laboratory
GFS	Global Forecast System
IITM	Indian Institute of Tropical Meteorology
IMD	India Meteorological Department
MMM	Mesoscale and Microscale Meteorology Division
MP	Micro Physics
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
NWP	Numerical Weather Prediction
NWS	National Weather Service
USGS	United States Geological Survey
UTC	Universal Time Co-ordinates
WMO	World Meteorological Organization
WPS	WRF Preprocessing System
WRF	Weather Research and Forecasting

1. INTRODUCTION

Thunderstorms/dust storms develop due to intense convection and are generally associated with thunder, heavy rainfall, lightening, hail and squall line. The lightning and thunder are produced by cumulonimbus clouds of convective origin having high vertical extent. Having a spatial stretch or range of few kilometers, these thunderstorms generally have a life span less than an hour. However, the lifespan of multi-cell thunderstorms that evolve due to organized extreme convection may be of several hours and they may cover an extent of few kilometers. Thunderstorms generally form in any particular geographic location, perhaps more frequently in mid latitudes when warm moist air collides with cooler air.

In India, when continental air and warm moist oceanic air meets, the severity of thunderstorm increases, particularly in April - May (pre-monsoon season). In this period, the northern and eastern part of India i.e. West-Bengal, Odisha, Jharkhand, Assam and eastern part of Bihar is influenced by thunderstorms. This period coincide with the Hindi month of Baishakh, so locally they are named as Kal-baishakhi (calamity in Baishakh). In two months period, approximately 28 thunderstorms accompanied with hail and squall line occur in this region (Science Plan, 2005). As these thunderstorms mostly move from north-west to south-east, they are also called Nor-westers.

On the basis of the development of thunderclouds, the life cycle of thunderstorms is divided in three phases (formative stage, mature stage and dissipative stage) as shown in Fig. 1.1 (Markowski and Richardson, 2010).

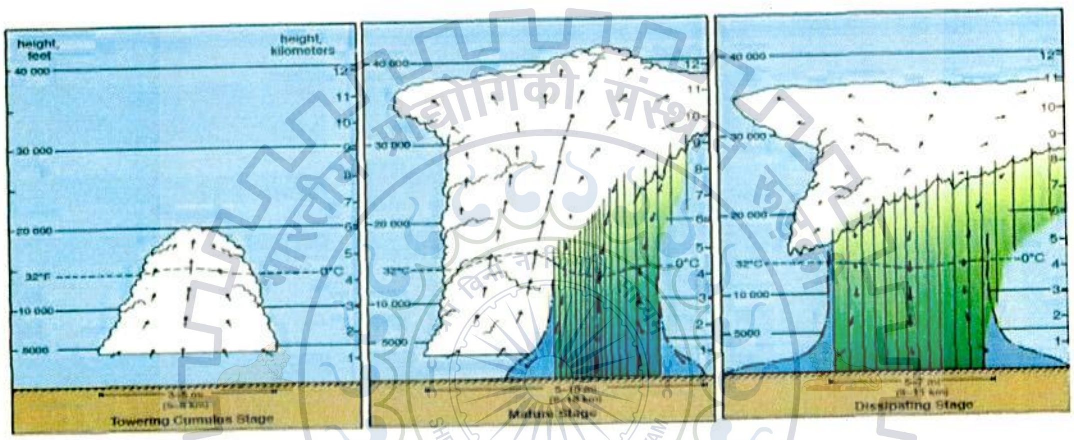
The characteristics of the three phases are summarized below.

1. The updraft lasts throughout the cell.

2. Both updraft and downdraft are present in this stage. Since the upper level shear discriminate the updraft zone and downdraft zone, its presence adds severity to the storm. The duration of the life of cell is also extended by it.

3. The final stage is vanishing stage dominated by downdraft throughout the cell.

The focus of the dissertation is to use the Numerical Weather Prediction (NWP) model (Weather Research & Forecasting model) for simulation of the above severe weather phenomena i.e. Severe Thunderstorm. The aim of this study is to numerically simulate the structure of the event, at finer grid (domain) resolution to understand the atmospheric processes in the storm.



(a) (b) (c)

Figure 1.1: Life cycle of the single cell thunderstorm: (a) Towering Cumulus Stage (b) Mature Stage (c) Dissipating Stage, (Source: Markowski and Richardson, 2010).

1.1 Thunderstorms in India

Kal-baishakhi, which literally mean calamity in the month of Baishakh (a month in Hindi calendar coincide with April). In the period of April-May i.e. pre-monsoon period, the outburst of strong convective storm (Nor-westers) occurs over northeast and Indo-Gangetic plains of India (Desai, 1950).

In the region of Jharkhand, Odisha, Bihar a low pressure area build up in the pre-monsoon period due to high level of insolation. When this low pressure system is superimposed by a passing upper air westerly trough, it acts as a triggering mechanism for the formation of mesoscale convective system that moves from Northwest to southeast direction. The insolation during mid day is very strong, that heats up the landmass and initiates convection over the Chhotanagpur plateau. It shifted towards south and become vehement as it mixes with warm moist air mass originating from BOB.

There is extensive loss of life, and damage to infrastructure, agriculture and overall economy due to the severe thunderstorm accompanied by thunder, squall line, hail and lightening. The number of causality in this region is highest in the world only due to the lightening caused by thunderstorms. Its downdraft produces strong winds and comes in contact with earth surface. It spreads out laterally and is referred to as downbursts. It causes imminent danger to aviation. Reports say that the number of aviation hazards is highest during the thunderstorms. Approximately 72% of tornadoes are accompanied by Nor-westers (Science Plan, 2005).

Convective dust storms which are also locally named as 'Andhi' take place in northwest India from mid March to mid June. During this season, comparatively low moisture and very high temperature of lowest atmosphere stratum creates favorable situation for thunderstorm to have high bases over the surface of earth of the order of 3 to 4 km (Science Plan, 2005).

Due to absence of water for a long time, the land becomes dry and plenty of fine dust is available on the surface of earth. When it rains it evaporates off and do not reach to the ground due to low humidity of the air near the surface of the earth and high bases of thunderstorms, and due to this factor the storms of northwest India produces dust storms or Andhi (Joseph et al. 1980).

1.2 MOTIVATION

Ever since the world began and human have inhabited the earth, man is facing severe calamities, one of them is Thunderstorm. These thunderstorms always fascinate the man and thus create an interest for scientific research in them. The fear and danger of uncertainty and disaster left behind by the severe thunderstorms brought man to study the nature, period and intensity of this strong weather phenomenon.

One can't believe that thunderstorms, so dangerous to human life and property can be a subject of interest of research, and that to, so intense that a person or we may say the scientists employ all their life in studying the thunderstorm. The mighty thunders and the huge astonishing structures of rotating updraft, illuminated with lightening ashes gleaming out of the clouds, allure the author of this thesis in further research in the subject.

In this era of modern science and technology where we are having high computer capacity allowing scientists to improve numerical models with a great degree of fineness, complex model physics, a commendable progress is carried out in the field of severe thunderstorms. Beside all these achievements, we can't be fully sure that one may predict or discover or forecasts all the thunderstorms.

Summer thunderstorms which are small scale phenomenon, still are unpredictable (Hoheneggar and schor 2007) due to coarse net grid of models, global models like weather research and forecasting model (Michalakes et al 2001) still parameterizes the convection. These models fail in predicting the initiation or we may say correct track forecasts due to their weaknesses. Therefore, still there is a need for organization to study and acquire knowledge about severe thunderstorms to discover their location, intensity and time.

Severe thunderstorm poses great danger to the economy. It is a threat to man and material since time immemorial. Therefore, man started taking interest in studying the nature, time, time period and frequency of severe thunderstorms since he became able to collect information and started communicating using pictures, signs and letters. Today, a lot more is to be done in the field of thunderstorms. It is the demand of time that a deep study in this subject is necessary so that we may be able to discover and predict the thunderstorm in time.

1.3 OBJECTIVES AND OUTLINES

Experiences show that, a number of severe thunderstorm events occur over northwestern, northeastern and eastern part of India. Over north India the terrain and the environment conditions are different at different places so the behavior and strength of the severe thunderstorms are different at different places. The first intention of this project is to have an overview about the present knowledge of severe thunderstorms including the genesis, development and propagation over northwest, northeast and eastern part of India which occurred on 30-31 May 2014 using different sources of observational data such as Doppler weather radar, Automatic weather stations (AWS) and satellite. The second intention is to improve the prediction of this important weather phenomenon. For this, numerical simulation of the severe weather event is important to predict the precise time, location and intensity of the upcoming disaster (fig 1.2) so that advance warning can be issued to the people and preventive measures can be taken.

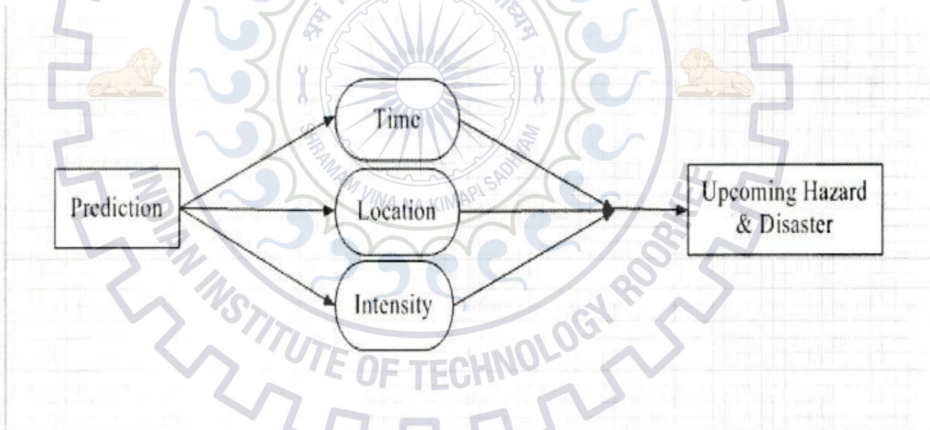


Figure (1.2): Objective of the study

The dissertation is described in following chapters

Chapter 1: Introduction, there is a study of Thunderstorm in India from which the author of the dissertation gets Motivation and Objectives and General outlines are drawn.

Chapter 2: Review of Literatures on Thunderstorms is presented which are important for this project.

Chapter3: Data Description. Model data input and the observational data equipments like Automatic Weather Station, Radiosonde, Doppler Weather Radar and Satellite Observations are given.

Chapter 4: Methodology. Synoptic features of severe thunderstorms are given in detail. The description, configuration, initial and boundary conditions and experimental procedure of the model are discussed. Then forecast skill by India Meteorological Department (IMD) operational Weather Research Forecasting (WRF) model are taken in account.

Chapter 5: Results and Discussion.

Chapter 6: Conclusion.

2. Literature Review

At the time of Second World War, research and progress assignments were carried out which were focused resolving problems of poor weather. At the end of the Second World War, severe weather i.e. Thunderstorm were the only unexplored threats (Committee of four U.S.A agencies, 1949). Even today it is the foremost source of misfortune to private enterprise and defense aircrafts.

In this chapter, a brief review of the works done on thunderstorm is carried out, in particular about the life cycle of thunderstorm, their structure, climatology and predictability.

2.1 Life Cycle

- The towering cumulus clouds of convective origin have the high capability of producing lightning and thunder. It has the geographical range of a few kilometers and duration less than an hour. But in case of multicell, thunderstorm grow due to well ordered intense convection, may have duration more than an hour and may have a journey over a few hundreds of kilometers. It originates because of the heated land masses that heats up the air mass above it and begins convective and happens mostly in the tropical belt (Indian Committee of experts, 2005).
- By Ludlam, 1980 expressed that when the surrounding winds have influential vertical wind shear (VWS), the motion of updrafts and downdrafts of thunderstorm become so systematized that they do not obstruct with each other, with the result that a severe thunderstorm forms noticing the maximum potential of CAPE. Such events are considerably large in size and last for 6 to 10 hours. Condition of CAPE should be larger than 2000 and vertical wind shear from the surface to 500 hPa level should be larger than 6 km. So there is a severe thunderstorm of the super-cell with large value of CAPE and vertical wind shear (a large, long-lasting thunderstorm with a single violently rotating updraft (Ahrens, 2009)) which produce tornadoes and downbursts. The length of the cumulonimbus cloud is 150 to 250 km in which adjoining clouds are very close to each other. It is a mesoscale system which is conducted by a line of squalls called squall line (multicell thunderstorms that form as a line of

thunderstorms. As old cell decay and die out, new ones constantly form, hence the squall line can maintain itself for hours on end (Ahrens, 2009)).

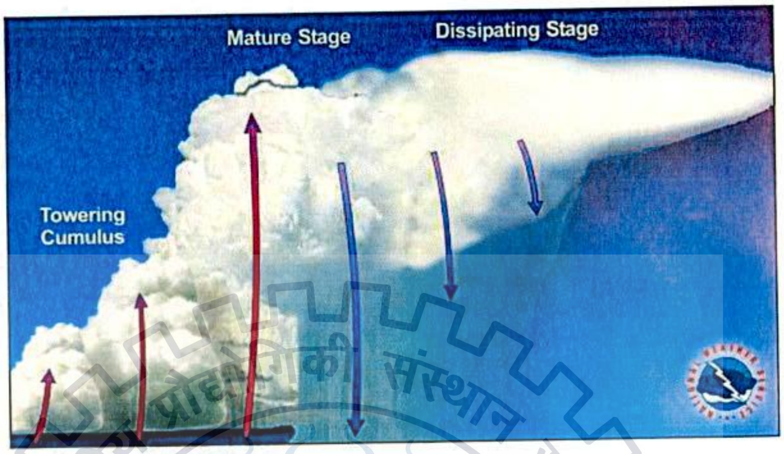


Figure (1.3): Life cycle of thunderstorm (Web 1).

2.2 Structure

- Classification of thunderstorms are generally in four types single cell storms, multicell or cluster storms, multicell lines and super cell storms (Ahrens, 2009). These ranking relate to the structure, duration and its severity. Single cell thunderstorm can produce 20 to 30 minutes storm. Cluster of more than one storm is contained in multicell storm. The development of each storm is different. Squall line storms are associated with multicell clusters and producing large hail, heavy rain and some time tornadoes. A meso-cyclone can be produced by the energy of these super cell storms. Possibility of hail is produced by the high downburst winds greater than 128 km per hour.
- Thunderstorms generally associated with six types of motions. (1) Updrafts (2) Downdrafts (3) Thunderstorm cloud motion (4) anvil motion with respect to thunderstorm (5) speed of squall (6) gust face motion. Each has its different dynamics and all are important particularly for aviation applications. Updrafts depend upon the magnitude of Convective Available Potential Energy (CAPE). It produces an energy resource for the air parcels that are supposed to be in moist adiabatic ascent (Miller,

1958). Downdrafts have very high speed when the mid tropospheric air becomes cool across the large volume by the dissipation of the rain falling into it.

- By Joseph et al 1980 studied 40 cases of Andhi took place at Delhi airport during 1973 to 1977 by using transmissometers, a weather radar and different instrument measuring wind, humidity, pressure and temperature. Four types of Andhi were found by studying the different cases. According to radar study, a distance as large as 30 km may be there between Andhi wall dust on the surface and the associated cumulonimbus cloud. During these severe dust storms the horizontal visibility lowers down to less than 100 meters at Delhi airport. A significance number of papers, journals and articles are available to study the thunderstorm, Andhis that occurred in India during last 30 years in which month wise, season wise frequency of these thunderstorms are successfully investigated.

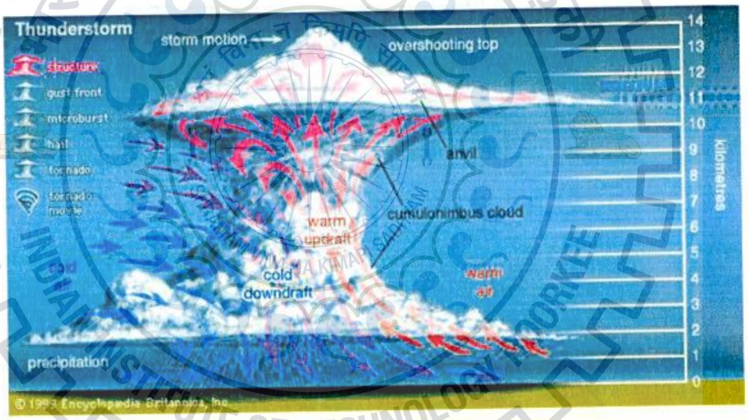


Figure (1.4): Structure of the thunderstorm (Web 2).

2.3 Climatology

- Dallas (1900) in the year 1897, made the earliest study of the frequency of the thunderstorms in India by taking only 10 station data. India Meteorological Department in 1943 published the first series of charts in climatological atlas for airmen. The monthly frequency of days of thunder in India and neighboring countries based on data for short period was published in the charts. Later in 1953 IMD published climatological tables of observations in India in which the frequency of thunderstorms days monthly and annually were given. IMD (1969) prepared climatological tables on the bases of data available from 1931 to 1960 and 1951 to 1980. At the same time the average frequency of thunderstorms days are published in World Meteorological Organization (WMO), publication by WMO (1953). The data, on which these averages are based, are of consistent 15 years.

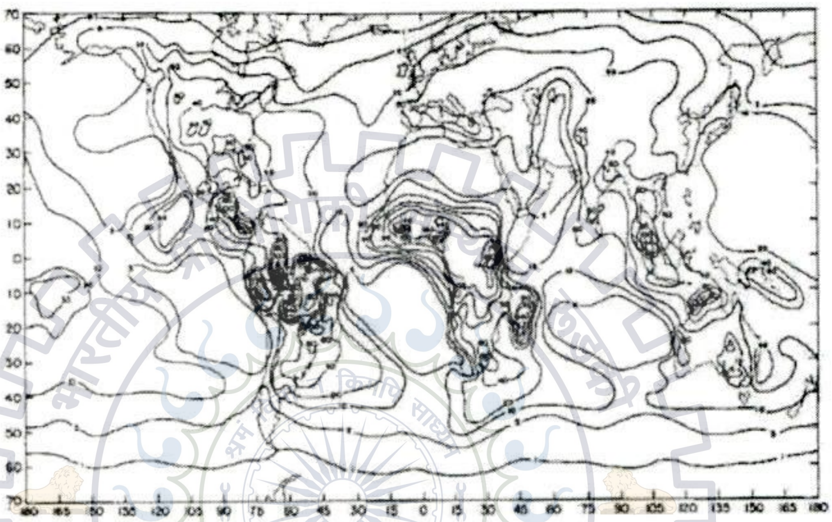


Figure (1.5): Annual number of thunderstorm days (Source: WMO 1953).

- Data of 20 years was used by Rao and Raman (1961) to have a monthly annual frequency of thunderstorms in India. The highest thunderstorms that occurred over Assam, West Bengal, Jharkhand was shown in this study. The annual average of the frequency of thunderstorm of this region surpasses 75 days per year. The systematic study of the diurnal variation of the thunderstorm was first time made by Raman and Raghavan (1961). The diurnal variation in squalls which generally accompany thunderstorm was examined by Alvi and Punjabi (1966). They also found the annual frequency of thunderstorm to be 75 days per year over West Bengal, Bangladesh, bordering Orissa and northeast India. However the most thunder affected area in India is northeast Assam with an average exceeds 100 days per year. Over western Himalayas, Southern Kerala and adjacent Tamil Nadu the average is 50 days per year.

- During the pre-monsoon period, the North-eastern part of India along with Bangladesh and Gangetic West Bengal faces severe thunderstorm. This research study was carried out by Indian Government in 2005. These severe thunderstorms are followed by high surface wind squalls, heavy rainfall, and hail and converted into tornadoes. Every year it affects normal life of human, animals and property heavily. Better performance of the prediction in terms of occurrence, movement and intensity of this extreme weather is therefore of the great socio-economic importance.

2.4 Predictability

- Extreme weather thunderstorm prediction was carried out by Donaldson et al 1964. Although the research study on this event has been done by many people individually but more and more research work is needed. The need of time is to use the present scenario data and find the current results and check whether they are stable with earlier research, in the process of change in climate. For finding the detailed outcomes one will need to restrict the study area.
- Using satellite imagery in severe thunderstorm, forecasting and warning was represented by Purdom (1971). According to him the appearance of the squall lines as a wedge shape cloud was noted. He also represented several ideas to improve prediction by geostationary imagery. It was observed that the detection of the growing squall lines could be done earlier from radar, and that specific regions of convective clusters could be recognized to be under the threat of severe thunderstorm. The plan of except thunderstorm beginning, from the best knowledge of location of boundaries and other mesoscale characteristics in high resolution geostationary imagery, was proposed by Purdom (1976). In the formation of convective clouds, it was also shown that the terrain affects the formation of convective clouds. The accurate location of storm outflow boundaries could be captured from higher resolution Geostationary Operational Environment Satellites. The mechanism of augmentation of the favorable environmental conditions and integrating of boundaries was studied by Maddox et al (1980).

2.5 Sensitivity Experiments

- There are numbers of papers on sensitivity experiments on these severe weather phenomena. By A J LTTA et al (2012) sensitivity experiments have been conducted to test the influence of different microphysical schemes in prediction the severe thunderstorm event over Kolkata on 15 May 2009. The results demonstrate that the microphysical Ferrier scheme define the cloud and precipitation process more accurately than other schemes. In this paper, a study is also carried out diagnose four severe thunderstorms that happened at the time of pre-monsoon of 2006, 2007 and 2008 through simulated radar reflectivity from WRF-NMM model with same physical parameterization scheme and validated the model results with Kolkata Doppler Weather Radar observations (DWR) observation results. The model simulation shows the reflectivity movement clearly as captured by the DWR imageries, but the intensity was not as clear as the observational results. According to this paper, the potential of the higher resolution i.e. 3 km model has to improve the ability to simulate the severe thunderstorm over east and northeastern region of India.
- Mesoscale models have been developed with a wide range of pliability in the form of varying horizontal and vertical grid resolutions, nesting domains and the changing option of different physical parameterization schemes i.e. MM5, WRF, RAMS, ETA, ARPS, HILRAM etc (Cotton et al, 1994). By Mohanty et al, 2003; different environment of the different parameters in the models can be used for wide varieties of the applications. The initial and boundary conditions in these models have taken by the Global Model and it may be used for prediction up to 72 hours. For the better prediction the model simulation can be run at higher resolutions.
- Numerical Simulation study based on horizontal grid selection and its influence has been carried out by Rosa Salvador et al (1999). To demonstrate the influence of grid size resolution, environmental flow in a complex terrain of the Spanish east coast is simulated by the RAMS (Regional Atmospheric Modeling System) numerical weather prediction system model by using different horizontal grid resolutions. By comparing the different simulated results, the conclusion has been drawn that the

main wind nature does not change dramatically but some more small scale features present when using a grid resolution of 2 km or higher. The result also defined that the vertical convection is influenced highly by the horizontal grid size.

- A research was taken by JEANEE L. HOADLEY et al (2004), study was focused on an event to evaluate the performance of the increased model resolution for prediction of fire danger. Speculated weather parameters were derived from MM5 (Mesoscale Model) and assessed at three different resolutions i.e. 36 km, 12 km and 4 km. Model results were compared with the observational outcomes to determine the model skill in forecasting fire danger. By this experiment little significant improvement were found in skill with increased model grid resolution.

Inference

In this scientific research the classification, motion and the climatology of the thunderstorm in India has been described clearly. It is the most important hazard because of its high impact. During development it is associated with strong wind, heavy gust, heavy rainfall and hail. The most severe form of the thunderstorm is tornado. The impacts of cumulonimbus cloud have been described by many authors. Many numerical weather prediction models as well as sensitivity experiments have been conducted for this mesoscale event.

3. DATA DISCRIPTION

3.1 Model Data Input

In this study, the case of severe thunderstorm which occurred on 30- 31 May 2014 and covered the northwestern, northeastern and eastern part of India particularly (Patiala, Delhi, Lucknow, Patna and Kolkata) is selected. It is selected because of its long time period, long distance and many casualties. In order to carry this study the IMD-GFS data from 00 UTC on 29 May 2014 to 00 UTC of 31 May 2014 has been utilized. WRF model has been used to make 48 hours simulation of the event using different horizontal resolutions.

3.2 Observations

3.2.1Automatic Weather Station

Automatic Weather Station (AWS) is a computerized version of the long-established weather station to save human labor and lack of measurement from remote areas. It is typically consist of weather proof enclosure containing the data logger, rechargeable battery telemetry and meteorological sensors with associated solar panel or wind turbine and climb upon a mast fig (1.6). System specific configuration may vary due to different purpose. Global Telecommunication System and Argos system will receive the near real time report by the system or save the data for later recovery. In the earlier days, automatic weather stations were often placed where electricity and communication lines were available. Today mobile phones, wind turbines and solar panel technology have made it possible to have wireless stations. Most of the automatic weather stations have thermometer, barometer, hygrometer, anemometer Wind vane. Some stations can also have ceilometers, pyranometer, rain gauge, Present weather and Ultrasonic snow depth sensor (Web 3).

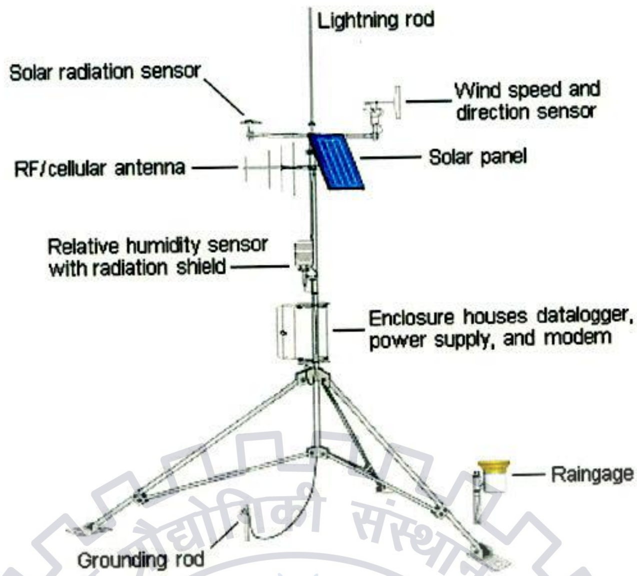


Figure (1.6): Automatic Weather Station with different equipments (Web 4).

3.2.2 Radiosonde

A battery powered telemetry instrument package called radiosonde carried into the atmosphere usually by a weather balloon fig (1.7). It measures various atmospheric parameters and transmits them by radio to a ground receiver. Its frequency as a radio frequency of 403 MHz or 1680 MHz. It is an essential source of meteorological data, and hundreds are launched all over the world.Radiosonde calculates the following variables (Web 5).

- Altitude
- Pressure
- Temperature
- Relative Humidity
- Wind speed and Wind direction
- Geographical position (latitude / longitude)

Figure (1.7): Radiosonde with a Weather Balloon (Web 6).

3.2.3 Doppler Weather Radar

Doppler weather radar obtains weather information (wind and precipitation) based upon returned energy from the present environment of the atmosphere fig (1.8). It emits a burst of signals. The signals are scattered in all the direction of the atmosphere. The signals strikes an object like rain, snow, hail, bug, bird etc in the atmospheric environment. A fraction of that signal is directed back to the radar. Its output is even included into Numerical Weather Prediction (NWP) models to improve the analyses and forecasts. This system offers thunderstorm tracking surveillance. It provides users to get details of each storm cloud being tracked. Usually it shows the sign of organization in the horizontal and continuity in the vertical. By DWR thunderstorm cell is identified, speed, distance covered, direction and Estimated Time of Arrival (ETA) are all identified and recorded (Web 7).

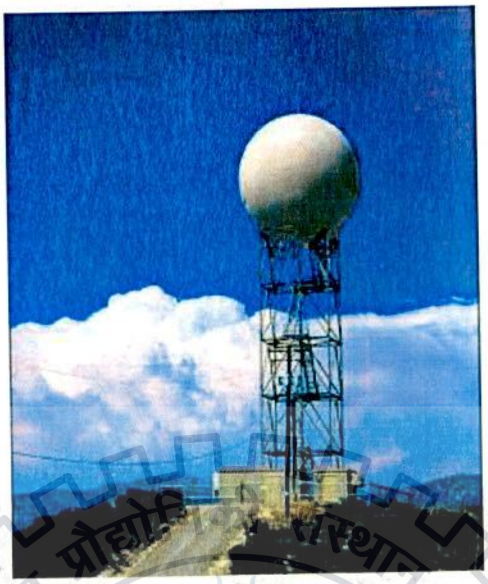


Figure (1.8): Doppler Weather Radar (Web 8).

3.2.4 Satellite Observations

Satellite INSAT-3D is a meteorological, data communication and aided search and rescue developed by the Indian Space Research Organization and was launched successfully on 26 July 2013 fig (1.9) using Ariane 5 ECA launch vehicle from French Guiana. INSAT-3D has many new technology elements; micro stepping solar Array Drive Assembly (SADA) to reduce the space craft disturbances, star sensors and Bus Management Unit (BMU) for telecom, control and telemetry function. It also includes new features of biannual rotation, image and mirror motion compensations for improved performance of the meteorological information. It has goal to provide an operational, environmental and storm warning system to protect life and property and also monitor earth's surface and carryout oceanic observations and also give data distribution capabilities (Web 9).

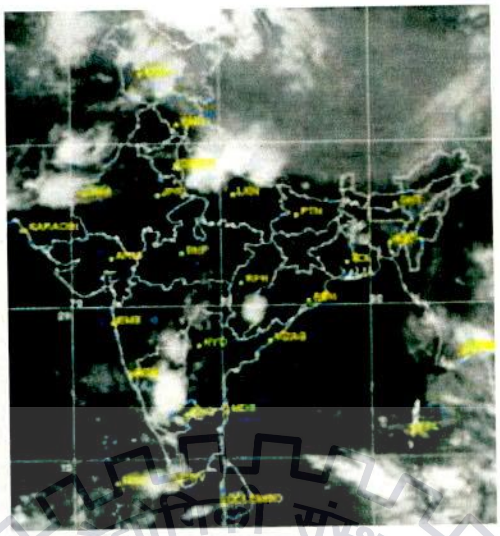


Figure (1.9): Satellite observation image.

(Source: Satellite Meteorological Division, IMD).

4. Methodology

4.1 Severe Thunderstorm Synoptic Features

4.1.1 Favorable Synoptic Condition over Northwest India

In pre-monsoon season, the northwest India is affected by western disturbances accompanied by induced lows. These are the synoptic conditions which influence this region. The western disturbances are seen either as induced lows or as trough. In lower levels, the extension of trough may be towards east or southeast from induced lows and for thunderstorm activity this becomes very strong region. Over northern part of northwest India and Uttar Pradesh, the easterlies and south easterlies frequently exist, accompanied by western disturbances and induced lows. Over western Himalayas the convective activity is also enhanced due to Orography. Analysis concerning the thunderstorm activity in the period from March to June in the vicinity of New Delhi resulted to be 48 i.e. for the formation of thunderstorm the moisture content is necessary. The frequency of western disturbances become higher in the month of March, due to which the thunderstorm activity increases till the first half of the April and start decreasing greatly in may (IMD report 2014).

In the mid and upper troposphere, the western disturbances and induced lows can be seen simultaneously with streaks STJ and trough in sub tropical westerlies that moves across northwest India and Uttar Pradesh from March to May.

The upper air troughs and western disturbance better grow and quite often in northern latitude, due to which there is an occurrence of convective weather over the northern part of India.

The troughs in westerlies over northwest India can move towards southerly latitude and have an extension up to Madhya Pradesh when there is a pressure of blocking high in the north of northern India.

4.1.2 Favorable Synoptic Condition for East India

The western disturbances and induced lows movement in U.P, northern M.P, and northwest India create favorable synoptic situation in lower troposphere and surface for a nor-wester activity in east India. In the month of April, when induced low was over northern India (west U.P) there was an extension in trough towards east and southeast (Jharkhand). In the beginning, the easterlies managed to infiltrate over Jharkhand region and some part of east U.P but till evening it had to moved away towards east resulted into a good thunderstorm in east India as well as northeast India. And as the induced low travel to east in the continuation of above process, it lost its importance.

In east India, the thunderstorm activity is determined by the low pressure area towards west which is associated with the position of east west trough line further east of 80^0E. The location of trough may be from northern part of U.P and Bihar to south east M.P and south Odisha.

In the month of April and May, 32^0C to 34^0C are the mean daily temperature in east India due to the high insolation. This high temperature heats up the low level and creates instability which produces favorable situations for thunderstorm activity (IMD report 2014).

4.1.3 Favorable Synoptic Condition for Northeast India

During pre-monsoon period, Northeast India receives the thunderstorm activity of very high frequency. The nature of these thunderstorms (except Manipur, Tripura) is different as those of the nor-westers of Gangetic West Bengal. Suitable condition for thunderstorm activity in this region is the discontinuity between southerlies or south westerlies and easterlies over Assam, Sikkim and Sub-Himalayas West Bengal. This continuity can be significant up to 1.0 to 1.5 km above mean sea level. With this east west discontinuity the area of thunderstorm is mainly easterly current.

'Low level Jet' is one of the 'low level' thunderstorms causing synoptic feature. In Bengal region (Gangetic West Bengal and Bangladesh) especially during night, the winds are often strong southerlies with the speed as good as 30 to 40 kts. As these strong southerlies travel further north become weak and cause low level convergence. This may be one of the reasons of the thunderstorm in Assam, Sub-Himalayas West Bengal and other boarding states. So the cold dry advection in upper level superposed the advection of intense warm moist air in the lower level due to the large vertical variation in advection, the situation become instable.

It is also noted in this region that with the most of the troughs in westerlies almost all the spells of thunderstorm are associated. The lower level wind (850 hPa onwards) in Northeast India become stronger than normal and move towards south or southwest during passage of mid upper tropospheric trough.

Referring to a case study, these troughs are accompanied by STJ. Therefore, thunderstorm activity is enhanced due to addition of trough and jet in certain areas.

Another main factor in this region is Orography due to which the low level moist air is lifted up forcibly. The under cutting of warm moist air of low level is also provided katabatic flow during night (IMD report 2014).

4.2 Model Description

In the current study, the Weather Research & Forecasting (WRF) model (Version 3.6.1) with the Advanced Research WRF (ARW) is used to simulate the severe weather phenomena i.e. Severe Norwester's. It is a multi-organization endeavor planned to make available a genX mesoscale predictable system. This is the system to serve both the interpretation and forecast of such mesoscale phenomenon and convey the advance research into operations. The WRF system was evolved as a partnership determined attempt surrounded by National Centre for Atmospheric Research (NCAR), National Oceanic and Atmospheric Administration's (NOAA), Mesoscale and Microscale Meteorology Division (MMM), National Center for Environmental Prediction (NCEP), Department of Defense's Air Force Weather Agency (AFWA), Naval Research Laboratory (NRL), US organizations, Centers for Environmental Prediction (NCEP), Center for Analysis and Prediction of Storms (CAPS) at University of Oklahoma, Forecast System Laboratory (FSL) and Federal Aviation and Administration (FAA) through with the contribution of a number of university scientists. Weather Research Forecasting model is perpetuated and hold up as a group model to easier wide use, specifically for research and development and teaching in the universities. This is worthily applied in a large range of application covering scales ranging from meters to thousands of kilometers. Such applications incorporate with research and operational Numerical Weather Prediction, assimilation of data and different physical parameter fig (2.0) (Skamarock et al. 2008).

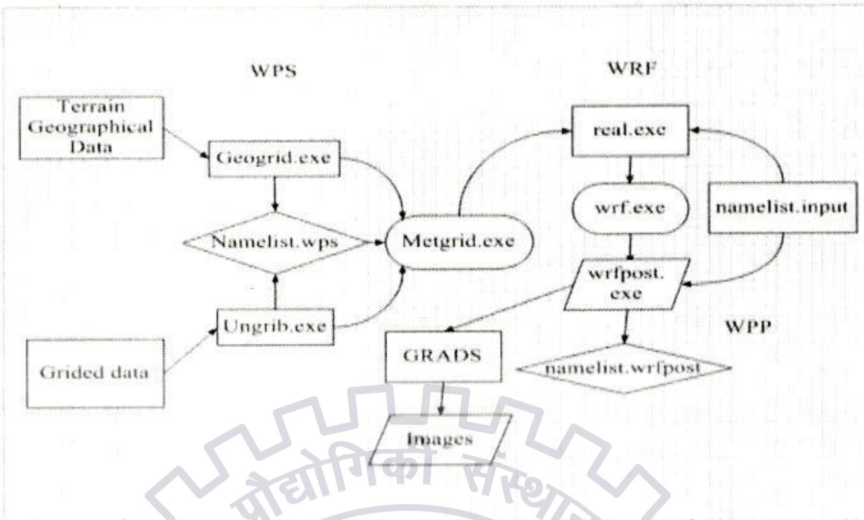


Figure (2.0): Program flow of WRF model.

The WRF model consists of the following four steps (WPS, WRF, WPP and Graphics).

4.2.1 Weather Research Forecasting Preprocessing System (WPS)

Weather Research Forecasting preprocessing system (WPS) has three programs geogrid.exe, ungrib.exe and metgrid.exe to develop material (input) to the real time program for real data simulations. Each program has its own function: geogrid defines model domains and interpolates terrain data to the grids; ungrib interpolates all the time varying meteorological fields' data from GRIB files; and metgrid interpolates the meteorological data horizontally on the model domain. Each program of the WPS understands parameters from a common name list file. This file has distinct name list data for each of the program and a shared name list record, which defines the framework that are used by more than one WPS program. A compact explanation of the three main programs is given below (WRF-NMM, 2014).

Geogrid.exe: Purpose of the geogrid is to interpolate different terrestrial data sets to the model grids. It is using the information given by the users in the geogrid name list record by the WPS name list file i.e. namelist.wps. Additionally to calculate the longitude, latitude, grid points, grid resolutions, geoogrid will interpolate terrain height, land use categories, soil categories, temperature, vegetation fraction, snow and many other categories to the model grid by default. Except interpolating the default terrestrial fields, the geogrid program is enough to interpolate almost all continuous and categorical fields to the model domain (WRF-NMM, 2014).

Ungrib.exe: The purpose of ungrib is to read GRIB files, "degribs" the data and record the data in the simple format, called intermediate format. These GRIB files carry all the time-varying meteorological fields and are typically different from another global or regional model, such as GFS, NAM or NCEP's models. GRIB files contain more fields comparatively to others to computerize Weather Research Forecasting model. GRIB format use different codes to recognize the variables and levels in the GRIB file. Ungrib has the tables of these codes Vtables, "variable tables" – to define which fields have taken from the GRIB file and write to the intermediate format (WRF-NMM, 2014).

Metgrid.exe: The purpose of metgrid program is to interpolate all the meteorological data by the ungrib program on the model domains defined by the geogrid program. The output from the metgrid can be feed by the WRF real program. The data ranges must be specified in the "share" name list record of the WPS name list file. So the work of the metgrid program is like as the ungrib program, is time-dependent, metgrid run every time a new simulation is digitalized (WRF-NMM, 2014).

4.2.2 Weather Research Forecasting (WRF) system

The Weather Research Forecasting system code accommodates an initialization program (real.exe) and a numerical integration program (wrf.exe). The real.exe portion produces the initial and boundary conditions for the wrf.exe program which are obtained from output files produced by the Weather Research Forecasting Pre-processing (WPP) system. The program real.exe achieves the following exercises:

- Read the input data from the name list and assign space.
- Compute the persisting variables.
- Reads the input data from the Weather Research Forecasting Pre-processing (WPP) system.

- Develop different categories of fields for use in the model (vertical interpolation to the requested levels).
- Examine to confirm soil temperature, sea surface temperature, land use, soil categories, land mask are these all consistent with each other.
- Vertically interpolates onto the model domain.
- Generates the initial and lateral condition file.

The numerical integration program that peruses the initial conditions and the lateral boundary conditions are run by the wrf.exe. This set up is for the predict domain throughout the preprocessing steps to produce forecast over the identified duration. The environment in the namelist.input file is used to configure Weather Research Forecasting (WRF) model i.e. real.exe and wrf.exe. The program flow of the WRF model as shown above (Litta A J, 2013).

4.2.3 Weather Research Forecasting Post-processing (WPP) System

The Weather Research Forecasting post-processing (WPP) system i.e. wrfpost.exe was designed to interpolate the Advanced Research WRF output from their native grids to National Weather Service (NWS) degree levels (pressure, height, etc.) and degree output grids (Lambert Conformal, Mercator, etc) in National Weather Service (NWS) and World Meteorological Organization (WMO) in GRIB format. It is also provides an option to output fields on the models native vertical levels (Litta A J, 2013).

4.2.4 Grid Analysis and Display System (GrADS)

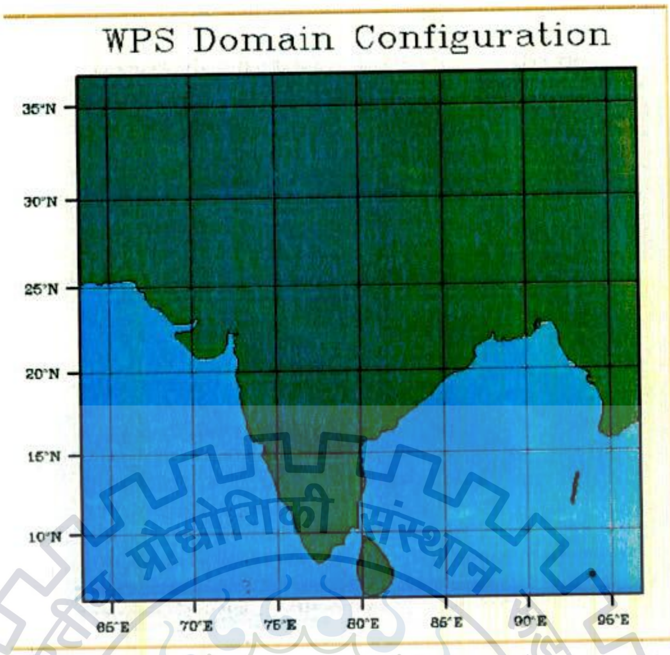
Grid Analysis Display System (GRADS) is an interdependent tool that is used for entrance, manipulation and visualization of the earth science data with distinct file format (GRIB, BUFR, NetCDF, etc). GRADS can visualize the Weather Research Forecasting Post-processing (WPP) system output in image format (Brian Doty, 1995).

4.3 Model Configuration

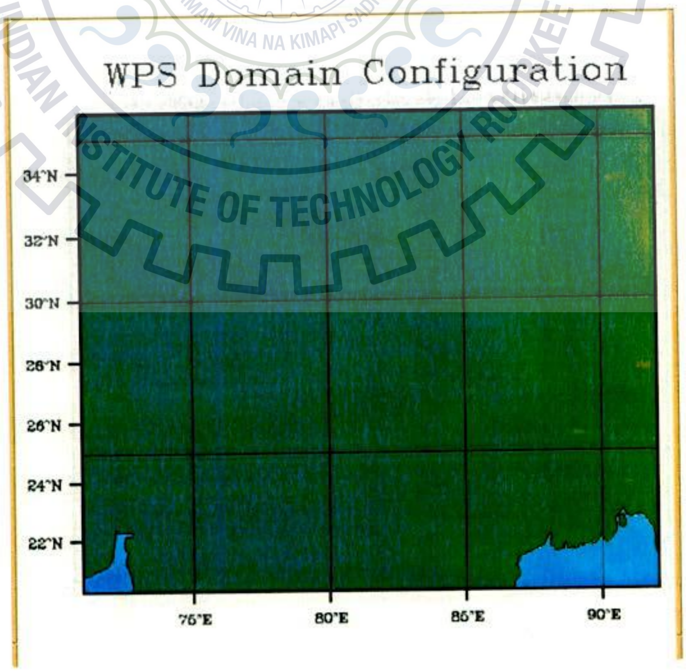
Table - 1 provides the details of the two different experiments.

Table 1: Description of the model

Map projection	Mercator	Mercator
Reference latitude of the domain	22.00^0N	28.30^0N
Reference longitude of the domain	80.00^0E	81.50^0E
Number of domain	1	1
Number of vertical layers	27 sigma levels	27 sigma levels
Horizontal Resolution	9km	3km
Time step	30s	10s
Number of grid points e-we e-sn	 360 360	 680 570
Resolution of geographical data	5min(~10kilometer)	1min(~2kilometer)
Topography	USGS	USGS



Figure(2.1): Experimental Domain 9 km resolution.



Figure(2.2): Experimental Domain 3 km resolution.

4.4 Model Initial and Boundary Conditions

The United State Geographical Survey (USGS) 5min (~10 kilometer) and 1min (~2 kilometer) resolution terrain topographical data have been used for two domains in the WRF pre-processing system (WPS). The 0.25^0 resolution Outputs from the IMD-GFS real time prediction has been used as initial and boundary conditions. The simulations of severe thunderstorm were initiated by the following date as given in Table-2.

Table-2: Severe Thunderstorm initial and boundary Condition.

Severe Thunderstorm	Initial Date, Time	End Date, Time
	29-05-2014, 0000UTC	31-05-2014, 0000UTC

4.4 Experimental Procedure

Sensitivity experiments of the severe thunderstorm have been carried out by using different grid resolutions (9km and 3km) as shown in model configuration in order to find out the better structure of the thunderstorm prediction. In this work, WRF-ARW (version 3.6.1) is used to study the structure of this severe weather phenomena. This experimental study has been carried out on the Aaditya HPC system which is 790 + Teraflops High Performance Computing System (HPCS) IBM iData Plex cluster, which features 38,144 Intel Sandy Bridge processors and 149 TB of memory. Aaditya is the India's latest most powerful HPCS installed in Indian Institute of Tropical Meteorology (Web 10) fig (2.3).

Figure(2.3): HPC Aaditya (Web 10).

4.6 Comparison between IMD operational GFS and WRF forecasts

For this purpose simulated results of the severe thunderstorm over Delhi and adjoining region which occurred on 30 May 2014 have been compared between the GFS model and WRF model operational forecast by IMD. By the GFS model, there was no indication of the rainfall in 24 hours forecast fig (2.4). But the rainfall indicated to the adjoining region of Delhi particularly South of Delhi and South East Rajasthan in 24 hours forecast fig (2.5). In case of mesoscale events, the WRF model indicates the better performance as compare to the GFS model. This content shows that the WRF model has the potential to elaborate unique and valuable information for the severe thunderstorms forecasters over the North Indian Region.

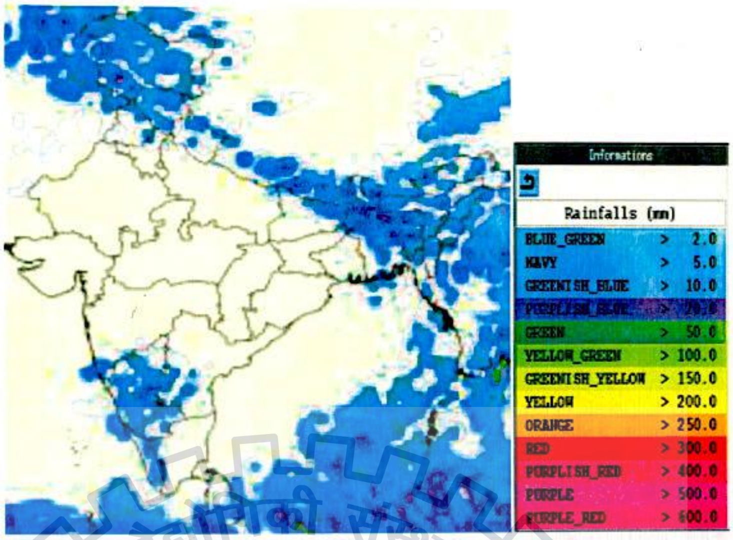


Figure (2.4): GFS 24 hrs rainfall forecast based on 0000 UTC, 30 May 2014.

(Source: NWP Divison, IMD)

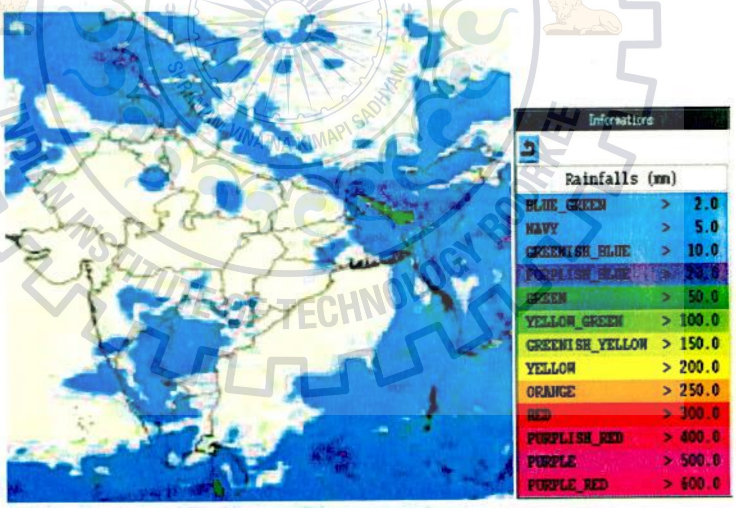


Figure (2.5): WRF 24 hrs rainfall forecast based on 0000 UTC, 30 May 2014.

(Source: NWP Divison, IMD)

5. Results and Discussion

In this chapter the results obtained from observations as well as simulations are discussed as follows.

5.1 Observational Analysis

a. Radiosonde (RS/RW) Observations

Radiosonde RS/RW ascent of 00 UTC of 30 May 2014 in Delhi demonstrate very high instability i.e. Total totals index 48.8, which is a favorable condition for severe thunderstorm formation over north-west India. The temperature 43- 44^{0}C at 1430 hours, encouraged the convective events. The dew point temperature analysis reported by surface observatories fig (2.6) illustrates moisture bands or packets over the north India region.

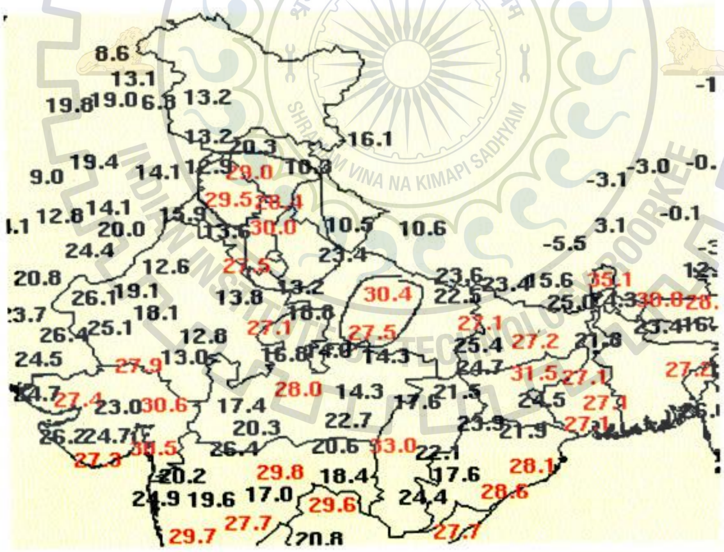
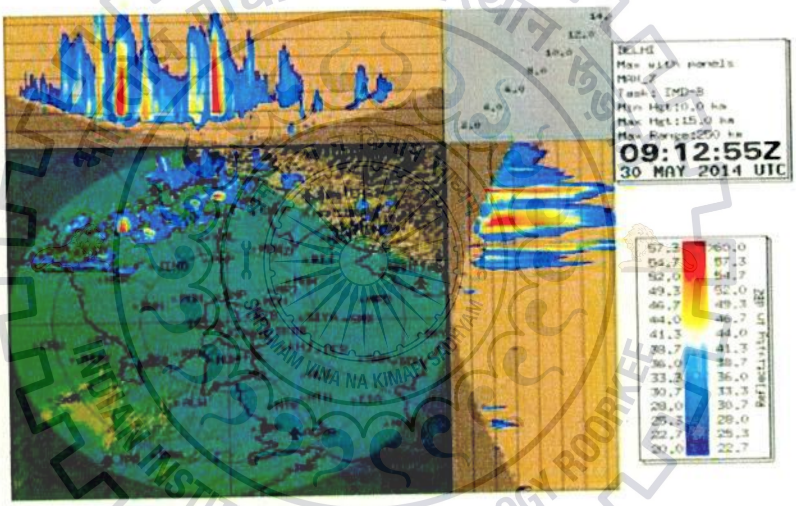


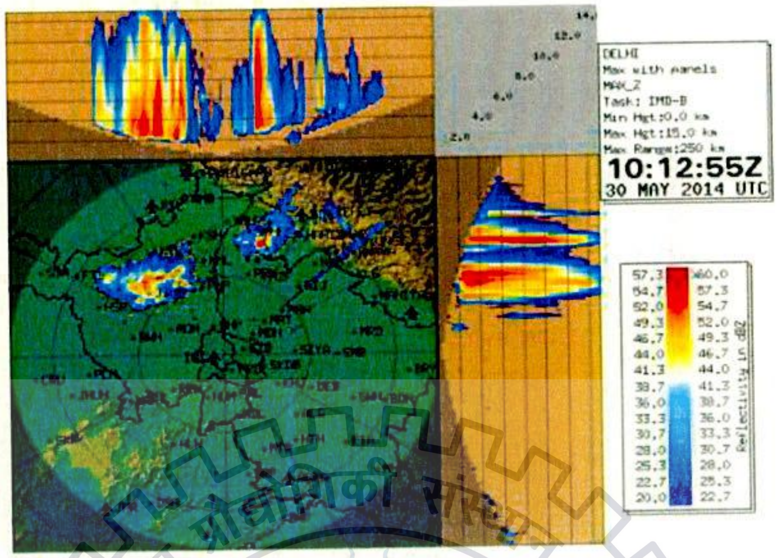
Figure (2.6): Dew Point Temperature recorded at various observatories on 30 May 2014. (Source: Thunderstorm Report-IMD, 2014).

b. Doppler Weather Radar

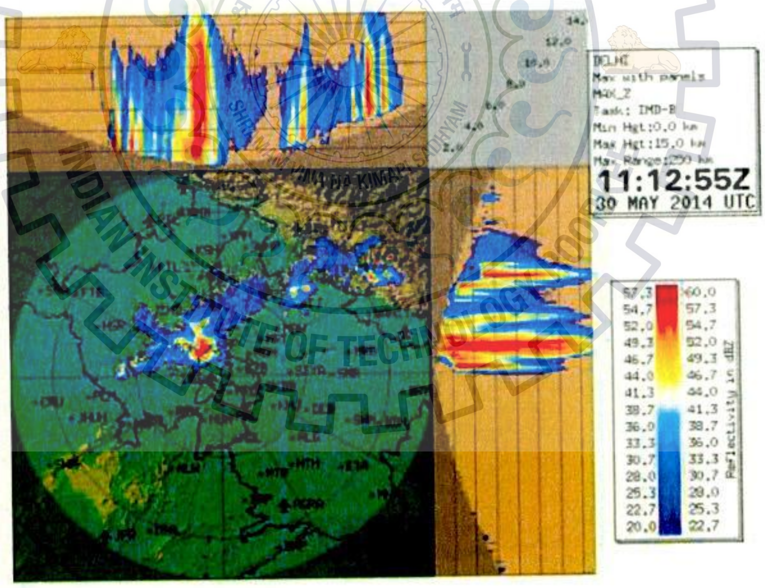
The Doppler Weather Radar shows that individual weak echoes originated from north-western direction near Patiala at 1430 hours. It moved slowly to south-eastern parts of India. Subsequently the echoes intensified as 1530 hours and covered an area of 50 km. Highest echo was observed to be 55 dBZ and the cloud height (top) was more than 14 km. It spread over 100 km in less than 2 hours and reached NCR Delhi by 1730 hours in the evening. The wind speed was recorded very high (greater than 121kmph). It triggered a very high intensity dust storm over Delhi and neighborhood (fig 2.7).



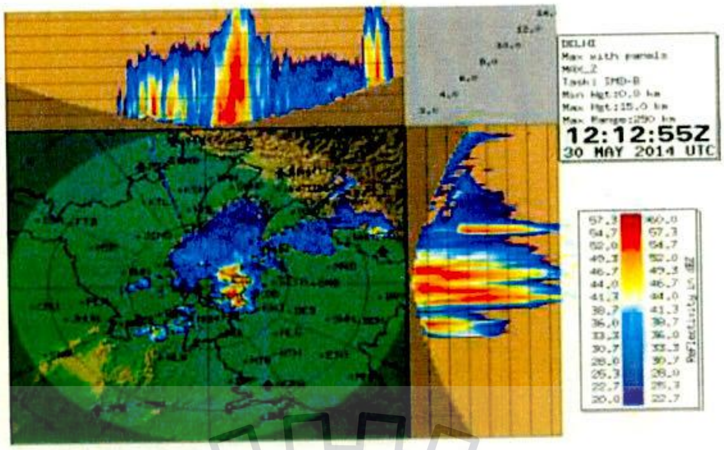
(a)


DELHI
Max with panels
MAX_Z
Task: IMD-B
Min Hgt:0.0 km
Max Hgt:15.0 km
Max Range:250 km
10:12:55Z
30 MAY 2014 UTC
Reflectivity in dBZ

(b)


DELHI
Max with panels
MAX_Z
Task: IMD-B
Min Hgt:0.0 km
Max Hgt:15.0 km
11:12:55Z
30 MAY 2014 UTC
Reflectivity in dBZ

(c)

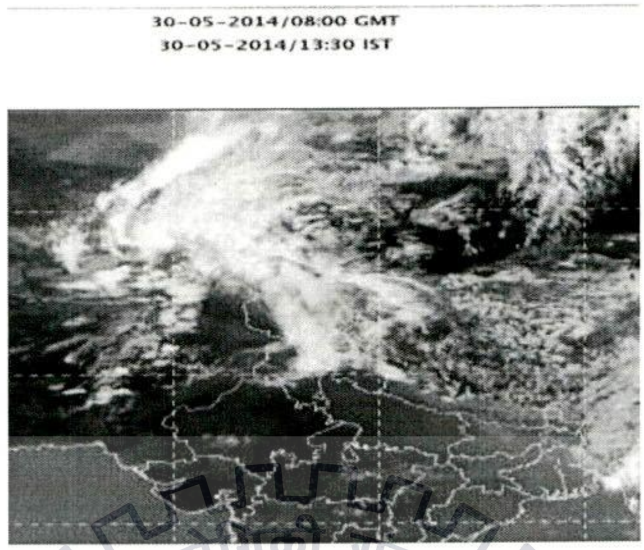


(d)

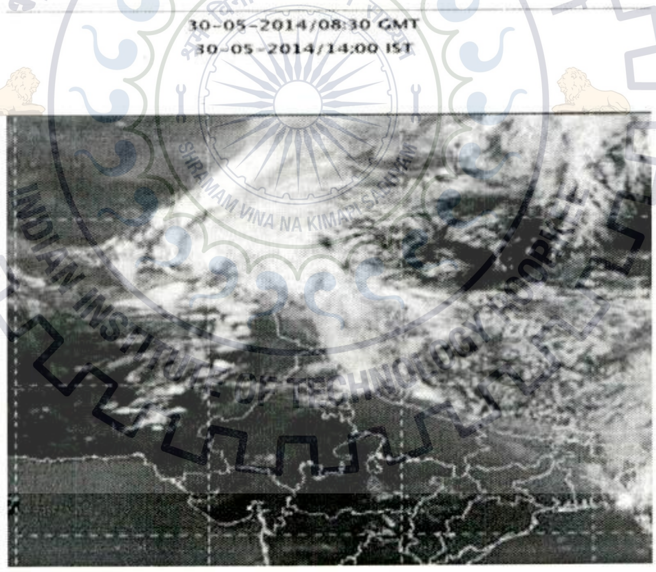
Figure (2.7): Reflectivity in Doppler Weather Radar at DGM office, IMD New Delhi Every hourly starting from 0912 UTC (1440 hours) to 1212 UTC (1740 hours). (Source: Radar Division IMD)

c. Satellite Observations

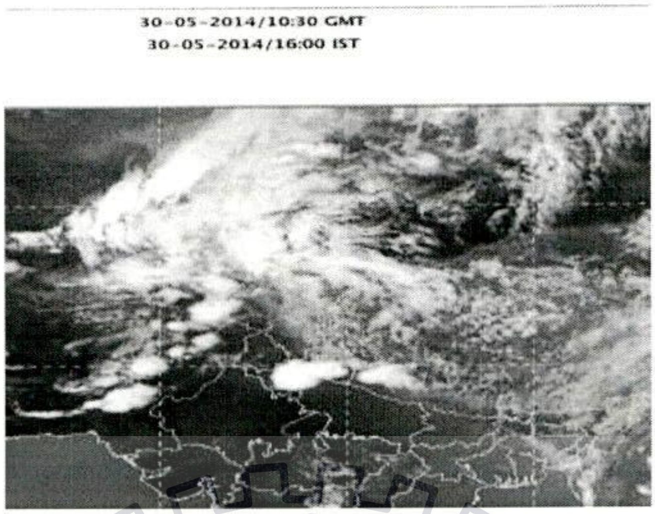
Study of INSAT-3D TIR-2 images depicted in figure (2.8). Shows dispersed convection to the north of the Delhi at 0800 UTC of 30 May 2014. It intensified by 0830 UTC and covered Delhi region. It further intensified at 1030 UTC and began propagating towards north eastern part of India. The cloud cells maintained their high intensity as they moved over eastern parts of India. The storm passed through Uttar Pradesh, Lucknow, Patna, and Bihar and infiltrated West Bengal by 0115 UTC of 31 May 2014.


30-05-2014/08:00 GMT
30-05-2014/13:30 IST

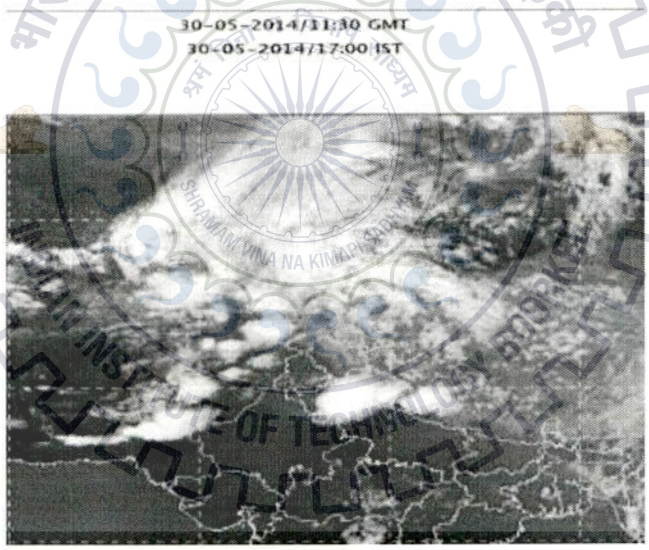
(a)


30-05-2014/08:30 GMT
30-05-2014/14:00 IST

(b)



(c)



(d)

Figure (2.8): Movement of Severe Thunderstorm as seen in INSAT-3D TIR-2

(Source: Satellite Meteorolgical Division, IMD)

d. Synoptic Features

NCR Delhi and neighbourhood were affected by a severe thunderstorm between 1630 hours IST and 1730 hours IST of 30 May 2014. The forecast by the GFS wind investigation at 0000 UTC of 30 May 2014 for surface air observation at 925 hPa pressure level fig (2.9). The upper air observation at 850 hPa pressure level that a imposed the balance over west Uttar Pradesh (east of Delhi) with a powerful horizontal wind shear maintaining lower level concurrence fig (3.0). The 200 hPa wind investigation designated the core jet stream moving over Delhi region fig (3.1).

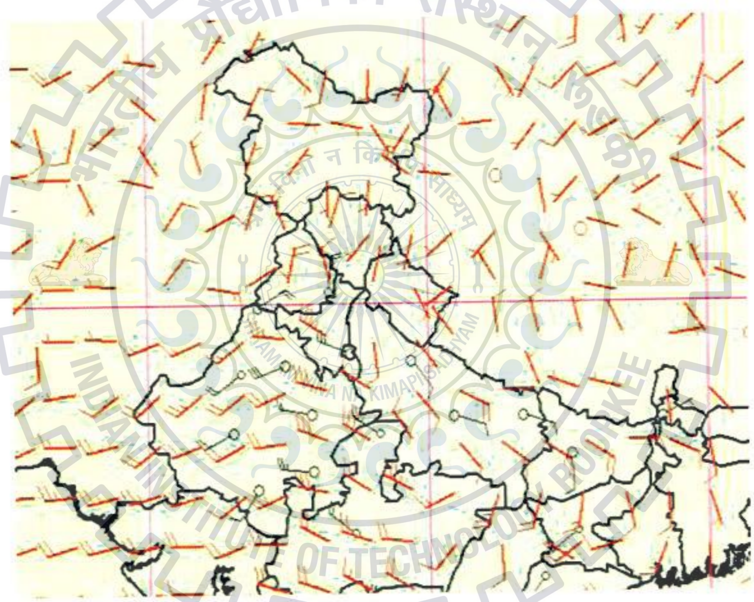


Figure (2.9): Wind analysis at 925 hPa based on 0000 UTC of 30 May 2014

(Source: Thunderstorm Report-IMD, 2014).

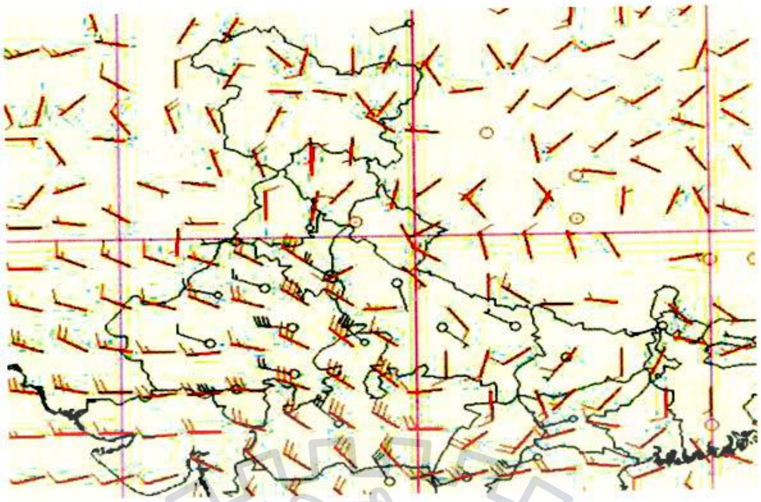


Figure (3.0): Wind analysis at 850 hPa based on 0000 UTC of 30 May 2014

(Source: Thunderstorm Report-IMD, 2014).

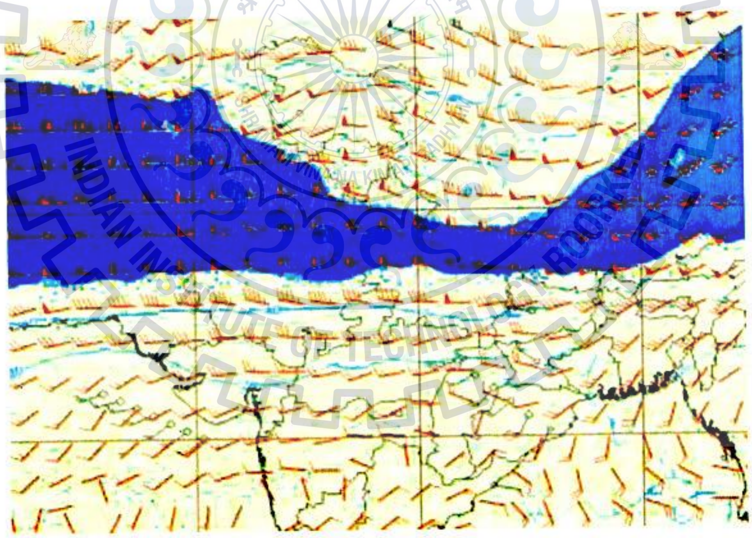


Figure (3.1): Wind analysis at 200 hPa based on 0000 UTC of 30 May 2014

(Source: Thunderstorm Report-IMD, 2014).

e. Realized Weather

1) A chain of thunderstorm covered the entire north Indian region from west (U.P) to east (Assam). Less than 3 mm rainfall was recorded by safdarjung observatory of IMD. The temperature was very high and increased to 43-44^{0}C at 1430 hours triggering the convective event fig (3.2). After the event temperature tumbled down to 26- 28^{0}C fig (3.3). Very low rainfall was recorded at IMD; safdarjung was less than 3 mm as shown in fig (3.4).

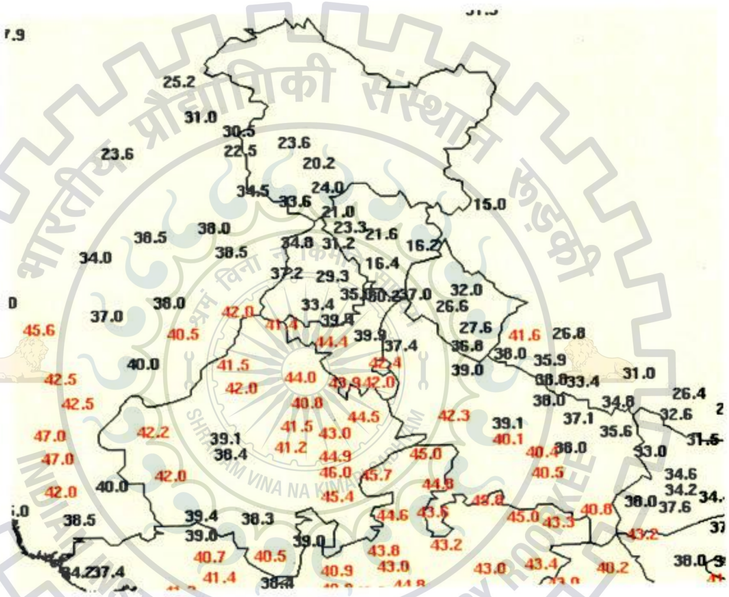


Figure (3.2): Temperature at 1430 hours IST of 30 May 2014 before the event (Source: Thunderstorm Report-IMD, 2014).

Figure (3.3): Temperature at 1730 hours IST of 30 May 2014 after the event (Source: Thunderstorm Report-IMD, 2014).

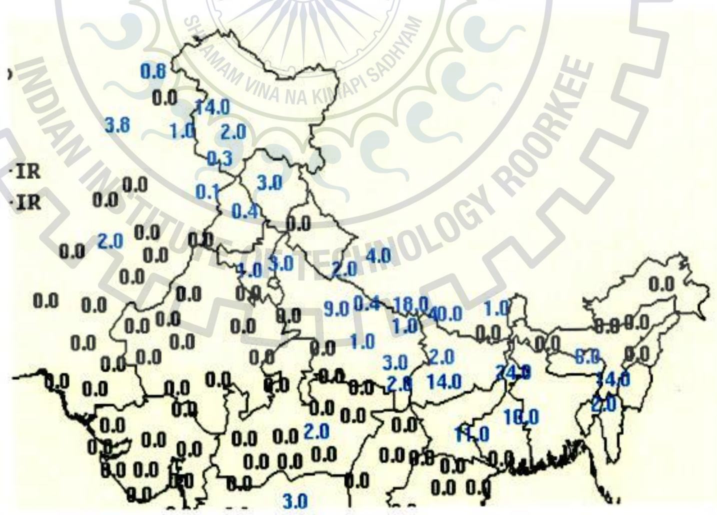


Figure (3.4): Accumulated Rainfall for past 24 hours at 0830 hours of 30 May 2014 (Source: Thunderstorm Report-IMD, 2014).

1) Some of the AWS's station in NCR Delhi region (NCRMWF region) recorded high rainfall of 15-16 mm per hour. A sudden change in wind direction from north – north easterly (before the event) and south easterly (after the event) was observed because of quick variation of temperature by 10-15^{0}C between 1100 and 1300 UTC.

f. Observations at IMD Observatory

1) A severe thunderstorm was reported at safdarjung. A squall wind speed in packet (>92 kmph) from northwest direction occurred between 1658-1703 hours IST. The temperature dropped down by 13^{0}c (40^{0}c to 27^{0}c) between 1700 to 1730 hours IST at the observatory.
2) The thunderstorm was reported at IAF Hindon station between 1650-1930 hours IST.
3) At Palam station a thunderstorm associated with squall was recorded. The period of thunderstorm associated with squall was 1654-1656 hours IST with wind speed, 115 kmph with wind from northwest direction was recorded at IMD palam.

5.2 Sensitivity Experiments

The WRF V-3.6.1 model has been run for 48 hours to simulate the severe thunderstorm. The output is post processed to obtain geopotential (850hPa), wind vector (850 hPa), wind speed (10m), CAPE, reflectivity and rainfall. The results were obtained at different grid resolution (9km and 3km) with the same MPs and CPs schemes. The USGS terrain/vegetation data was used at 5 min (~10 km) and 1 min (~2 km) corresponding to the grid resolution at 9 km and 3 km.

These variables are plotted through Grid Analysis and Display System (GrADS) and discussed are as follows.

(i) Geo-potential and Wind vector

Fig (3.5 & 3.6) illustrate the simulated wind vectors and geo-potential at 500 hPa, valid at 00 UTC of 30 May 2014 based on the initial condition of 00 UTC of 20 May 2014 at grid resolutions of 9 km and 3 km respectively. The diagrams indicate predominately north westerly winds over Delhi and neighborhood. The simulation at 3 km indicate a convergence line extending from north to south over east Rajasthan and West U.P illustrated by a thick line in the fig (3.6).

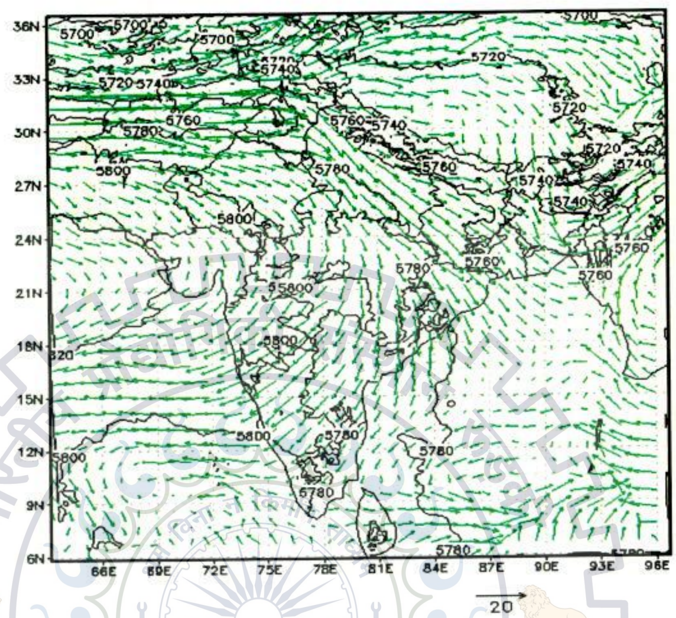


Figure (3.5): Simulated Geo-potential and Wind vector at 500 hpa valid at 12 UTC, 30052014 based on the IC: 00 UTC, 29052014, using WRF model at 9 km resolution.

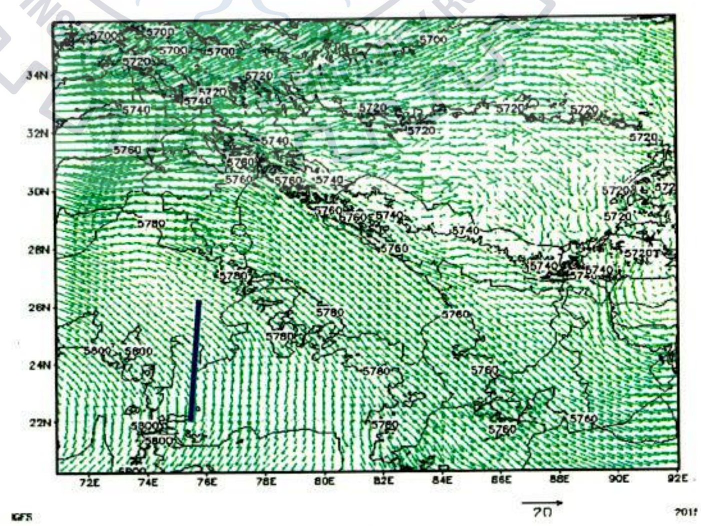


Figure (3.6): As in fig (3.5) but at 3 km resolution.

(ii) Wind vector and Wind speed

Fig (3.7 & 3.8) illustrate wind vector at 850 hPa and wind speed at 10 m valid at 00 UTC of 30 May 2014 based on the initial condition of 00 UTC of 29 May 2014, at grid resolution of 9 and 3 km respectively. The diagrams indicate pockets of high wind speed surrounding Delhi region in the 3 km simulation which is not seen in the 9 km resolution. Thus the simulation at higher resolution is closer to the reality.

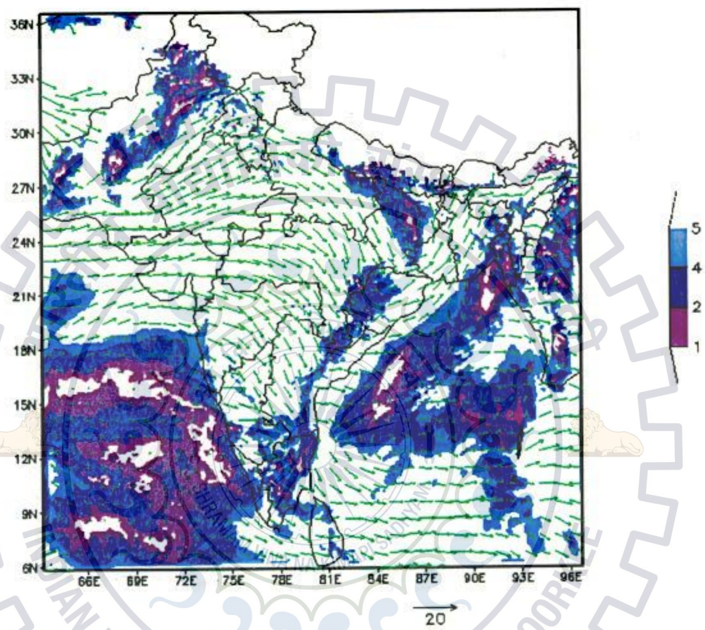


Figure (3.7): Simulated Wind vector at 850 hPa and Wind speed at 10 m valid at 12 UTC, 30052014 based on the IC: 00 UTC, 29052014, using WRF model at 9 km resolution. The shaded values indicate iso-tech.

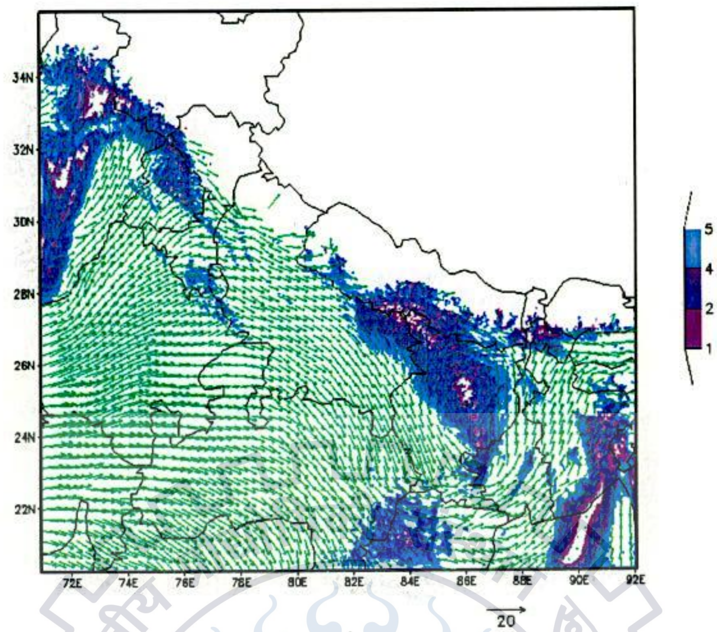


Figure (3.8): As in fig (3.7) but at 3 km resolution.

(iii) Convective Available Potential Energy

Fig (3.9 & 4.0) illustrate the simulated CAPE valid at 12 UTC of 30 May 2014 based on the initial condition of 00 UTC of 29 May 2014 at grid resolutions of 9 km and 3 km respectively. The diagrams indicate that the highest CAPE value is greater than 2000 (j/kg) over the northwest India in 9 km resolution while the highest CAPE value from 3 km resolution is 2400 (j/kg). The simulation from very high resolution WRF model (3 km) shows the higher value of CAPE as compare to the lower resolution (9 km).

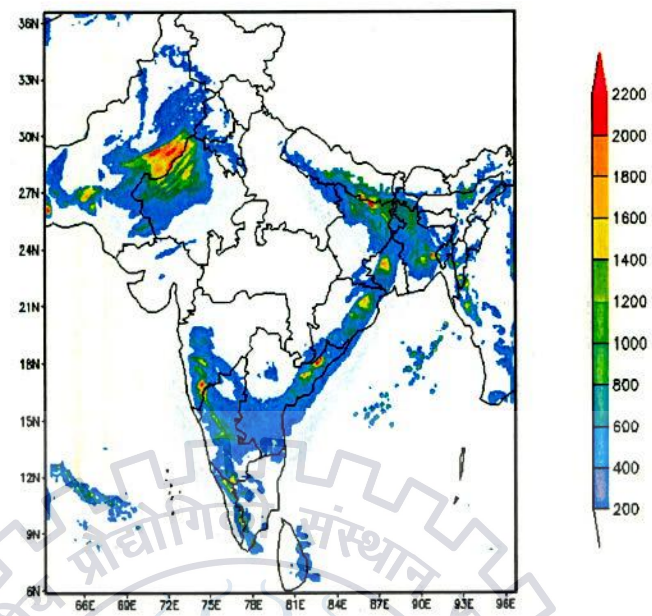


Figure (3.9): Simulated CAPE valid at 12 UTC, 30052014 based on the IC: 00 UTC,29052014, using WRF model at 9 km resolution.

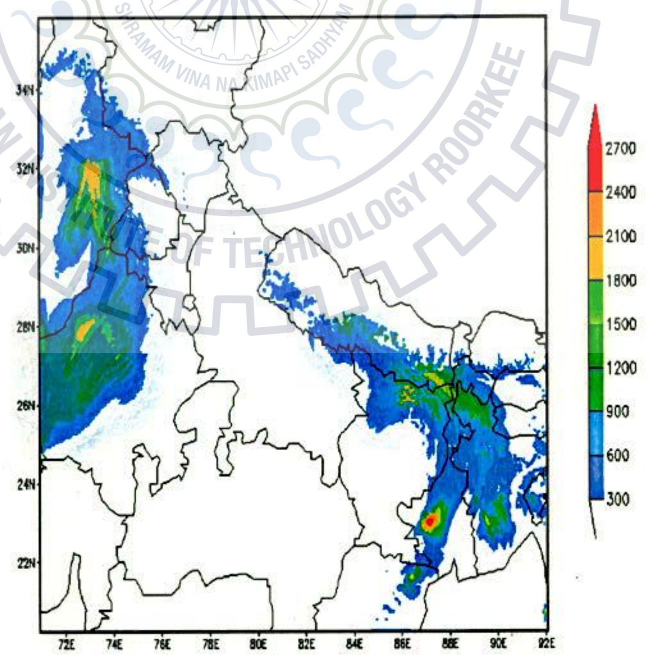


Figure (4.0): As in fig (3.9) but at 3 km resolution.

(iv) Reflectivity and Rainfall

The reflectivity values simulated by the model show some echoes south of the Delhi region by simulation in the 3 km resolution. Whereas the simulation at 9 km resolution does not show any echo surrounding Delhi fig (4.1 & 4.2). None of the simulations (at 9 and 3 km resolution) rainfall values around Delhi region. This may be because the observed rainfall was very less. A few pockets of rainfall are seen over Punjab and Haryana in the 9 km resolution which is not seen in the 3 km resolution. It may be noted that echoes may be obtained from rain bearing clouds, which may not rain in reality fig (4.3 & 4.4).

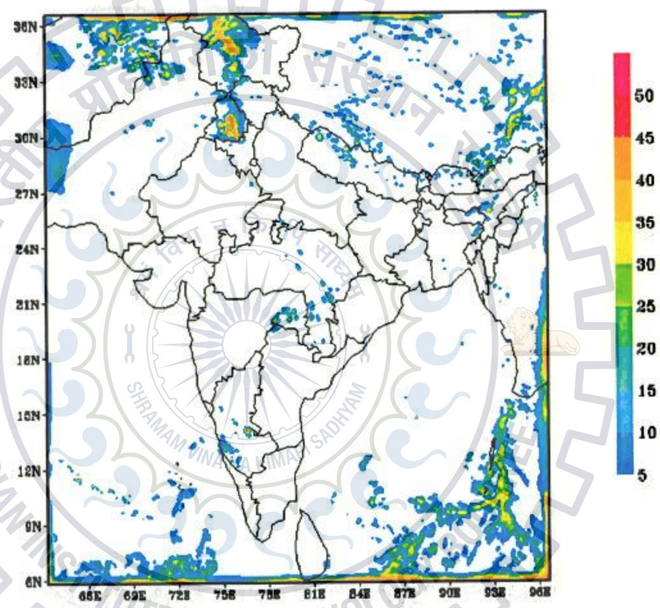


Figure (4.1): Simulated reflectivity valid at 12 UTC, 30052014 based on the IC: 00 UTC, 29052014, using WRF model at 9 km resolution.

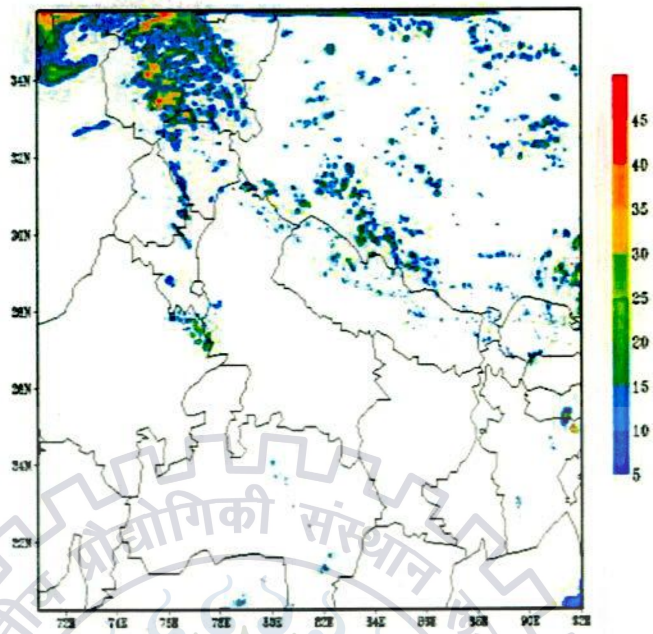


Figure (4.2): As in fig (4.1) but at 3 km resolution.

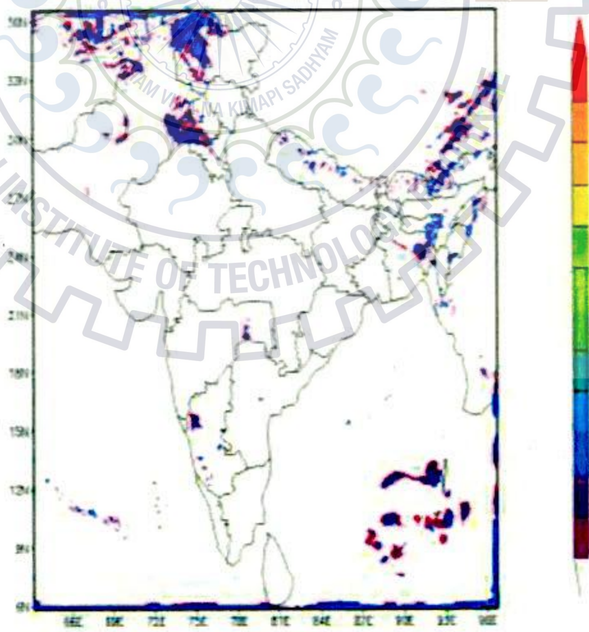


Figure (4.3): Simulated Rainfall valid at 12 UTC, 30052014 based on the IC: 00 UTC, 29052014, using WRF model at 9 km resolution.

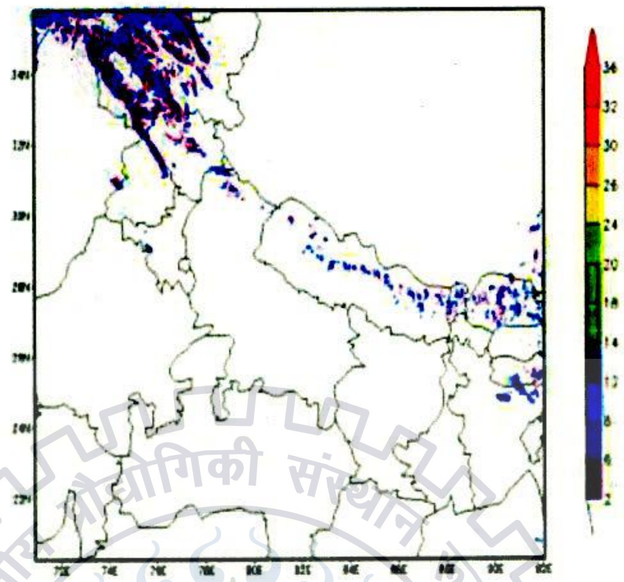


Figure (4.4): As in fig (4.3) but at 3 km resolution.

6. Conclusion

During April and May, the northwestern, northeastern and eastern parts of India get highly affected by severe thunderstorms called "Nor-wester as it generally travels from northwest to southeast. A better prediction in accordance with the time, location and intensity is necessary. But it is one of the most difficult challenges to forecast the thunderstorm accurately due to lack of better understanding and mesoscale observations. An attempt is made to improve the understanding and forecasting of such event in this study.

- WRF V3.6.1 has been used to simulate and investigate the severe thunderstorm which affected Delhi and adjoining region between 1630 hours IST and 1730 hours IST of 30 May 2014.
- The system moved eastward and steered by a westerly trough. It was accompanied by strong wind, lightning, thunder and squall causing destruction to the life and property.
- Sensitivity experiments are conducted to study the impact using different grid resolutions (9 and 3 km) using different terrain resolutions corresponding to the domains with the same MPs and CPs. Model simulated results are compared with the observations.
- Results have shown that the simulation at 3 km resolution provides better distributions of convergence zone in the wind fields at lower level then compare to simulation at 9 km resolution. The simulation at higher resolution also demonstrates better structure.
- However there are many deficiencies in the simulated results in terms of maximum wind speed observed at the surface, precise time, location and intensity of the storm. Many experiments need to be conducted using higher resolution, nested domain, better physical parameterization schemes, data assimilation and ensemble forecasting.

Annexure

Publication

- **International**

Jaya Singh, Ajay Gairola and Someshwar Das, Numerical Simulation of A Severe Thunderstorm over Delhi Using WRF model, International Journal of Scientific and Research Publication (communicated).

Conference

- **National**

Jaya Singh, S. Das, A. Gairola, A. K. Das and K. Ray 2015, Numerical Simulation of a Severe Thunderstorm over North India Using WRF Model during 30-31 May 2014. *National Symposium on 'Weather & Climate Extremes-* TROPMET-2015', Punjab University, Chandigarh, 15-18 February 2015. (Paper Presented)

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