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Evolution of thunderstorm monitoring & forecasting in India

SOMA SEN ROY and M. MOHAPATRA

India Meteorological Department, MoES, New Delhi, India

e mail : senroys@gmail.com

सार – भारत में गरज के साथ बिजली, बारिश, धूल भरी आँधी, तेज़ हवाएँ और ओलावृष्टि जुड़ी हुई हैं। पूर्वानुमान के लिए कम लीड अवधि, छोटा जीवनकाल, तीव्र अस्थायी विकास, घटना का मेसोस्केल क्षेत्र और संबंधित गंभीर मौसम के कारण तूफान भारत में सबसे विनाशकारी मौसम की घटनाओं में से एक है। वर्तमान अध्ययन भारत में तूफान की निगरानी और पूर्वानुमान के क्रमिक विकास की समीक्षा करता है। अध्ययन इस तथ्य पर प्रकाश डालता है कि इन मौसमी घटनाओं की निगरानी और पूर्वानुमान का भारत में एक लंबा इतिहास रहा है, लेकिन हाल के वर्षों में तूफान की निगरानी और पूर्वानुमान में तकनीकी प्रगति, विनाश की क्षमता के बारे में जागरूकता के साथ-साथ संचार में सुधार के साथ इस क्षेत्र को प्रोत्साहन मिला है। तरीके. पिछली सदी के दौरान विकसित हुई इन मौसम प्रणालियों की संक्षिप्त समझ को हाल के वर्षों में सतह वेधशालाओं, डॉपलर मौसम रडार, जमीन आधारित बिजली का पता लगाने वाले नेटवर्क और ऊपरी के नेटवर्क में सुधार और सघनीकरण के कारण उनकी मेसोस्केल प्रकृति की गहन समझ के साथ पूरक किया गया है। वायु ध्वनि और अंतरिक्ष आधारित भूस्थैतिक उपग्रह। इन डेटासेटों ने मेसोस्केल डेटा एसिमिलेशन के साथ एनडब्ल्यूपी मॉडल में भी उल्लेखनीय सुधार लाया है। इन सभी सुधारों को कम दूरी से लेकर वर्तमान पैमाने पर तूफान के पूर्वानुमान के लिए मानक संचालन प्रक्रियाओं में एकीकृत किया गया है, जिसने हाल के वर्षों में आम जनता के लिए तूफान और संबंधित घटनाओं के विश्वसनीय पूर्वानुमान तैयार किए हैं। इसके अतिरिक्त, मानव हताहतों की उच्च लागत के बारे में जागरूकता ने हाल के वर्षों में जोर वाले क्षेत्रों के रूप में प्रभाव की जानकारी और रंग कोडित स्थान विशिष्ट चेतावनियों के साथ स्थान विशिष्ट, कार्रवाई योग्य तूफान के पूर्वानुमान की आवश्यकता को भी जन्म दिया है।

ABSTRACT. Thunderstorms over India are associated lightning, rainfall, dust storms, gusty winds and hail. The short lead period for forecast, short lifetime, rapid temporal evolution, mesoscale region of occurrence and associated severe weather cause thunderstorms to be amongst the most devastating weather phenomena over India. The present study reviews the gradual evolution of thunderstorm monitoring and forecasting over India. The study highlights the fact that while monitoring and forecasting these weather phenomena has a long history in India, this field has gained impetus in recent years with the technological advancement in monitoring and forecasting of thunderstorms, awareness of the devastation potential as well as improvement of communication methods. Synoptic understanding of these weather systems which evolved during the last century has been complemented in recent years with in-depth understanding of their mesoscale nature due to improvement and densification of the network of surface observatories, Doppler Weather Radars, ground based lightning detection network and upper air soundings and space based Geostationary satellites. These datasets have also brought about a remarkable improvement in NWP models with mesoscale data assimilation. All these improvements are integrated into Standard Operating Procedures for thunderstorm forecasting in short range to nowcast scale, which has produced reliable forecasts of thunderstorms and associated phenomena for the general public in recent years. Additionally, the awareness of the high cost of human casualties has also brought about a requirement of location specific, actionable thunderstorm forecasts with impact information and colour coded location specific warnings as thrust areas in recent years.

1. Thunderstorm monitoring through history

Periodic episodes of thunderstorm activity bring relief to the hot and dusty climate of India. The formations of clouds, especially during the onset of the monsoon season, is often a signal for the start of the main rainfall period of the year, after a hot and dry summer season and hence a harbinger of new life in nature. It is welcomed throughout India through poetry, music and folk customs. On the other hand, the uncertainty of the occurrence of thunderstorms and potential of devastation due to associated weather such as heavy rain, strong winds and lightning, has also long fascinated and frightened the people of the Indian subcontinent. To this day, lightning is a source of awe, curiosity, inspiration, and fear. The brilliance, power and destructive capacity of thunderstorms have made it the subject for religion, superstition, politics, and scientific investigation. Various divine explanations were ascribed to their happening. In the Rgveda, Indra is described as the god who wields thunderbolt as his weapon (vajrayudham) and slays the demon Vrtra, thereby releasing the water which is held in captivity in the form of rain. In the early statues of the Buddha, he is often noted as carrying a thunderbolt with arrows at each end. In the rural areas of South India, the goddess Mariamman is venerated as the Hindu goddess of weather (Cullen, 2021). Still later down the ages, entire genres in the field of music, dance and poetry of India developed to venerate clouds and the associated rain and lightning. Not only do thunderstorms form an important aspect of literature and music over the Indian subcontinent, various folk superstitions also exist in association with lightning strikes. A report by an European traveller at the end of the nineteenth century reported that there prevailed a belief in Northwest India that if two persons who are first born children stand close together during a thunderstorm, they will definitely be struck by lightning (Crooke, 1902).

Besides the emotive aspect, various texts in the Indian philosophy corpus - in the Upanishads, Varahamihira's "*Brhat-samhita*" and Kalidasa's "*Meghadootam*" in sixth century CE and Kautilya's "*Arthashastra*" in fourth century CE, provide clear evidence that scientific observation and understanding of atmospheric processes and clouds existed in the Indian subcontinent from two thousand years back. One of the earliest mentions of the scientific reason of formation of clouds appears in the "*Maitrayaniya Upanishad*" of the "*Krishna Yajurveda"* (Stanza 6.37) which was probably composed in first millennium BCE (https://www.kamakoti.org/kamakoti/books/ESSENCE%20OF%20MAITRI%20UPANISHAD.pdf). In this hymn, the importance of the sun to cause rain is highlighted - "ādityāt jāyate vṛṣtih", which translates roughly to "Sun is the cause of rain". This was later adopted as the inscription in the official crest of the India Meteorological Department. Much later, in the middle ages, the seasonal reversal of airflow at the surface between India and East Africa was recognised by Arab ship navigators and named "*Mausin*" from which the word Monsoon is derived (Lockwood, 1965). More recently, studies by European travellers (for example a travelogue by an English traveller - J. Ovington in 1689) described the thunderous onset and departure of monsoon rains at the beginning and end of the monsoon season over the west peninsular coast (Ovington, 1994 as quoted in Sikka, 2011).

2. Evolution of quantitative monitoring and forecasting tools for thunderstorms

Systematic and quantitative study of various weather phenomena including thunderstorms over the Indian region started with the formation of India Meteorological Department (IMD) in 1875 with Dr. H. F. Blanford at the helm. The organization was charged with the responsibility of scientific investigation, weather warning and weather reporting for Atmospheric Physics and Weather and Climate related studies in India. A network of observatories with trained weather observers was set up in different parts of India to report on basic atmospheric parameters such as temperature, wind speed and direction and humidity as well as occurrence of thunderstorms and other weather in their vicinity in order to meet the requirement of operational weather forecasting. WMO defines thunderstorms as one or more sudden electrical discharges, manifested by a flash of light (lightning) and a sharp or rumbling sound (thunder) (WMO 1971). This regular, uniform set of observations engendered some of the first observation based studies of electrification and lightning in thunderstorms over different parts of India (Simpson, 1926, 1927). This observatory network currently comprises of 558 IMD observatories of which 141 observatories are of Class I type, which are manned 24 hours a day. They send three hourly observations globally through the Global Telecommunication System (GTS) as per WMO Resolution No. 40 (Zillman, 2019). With the formation of the Meteorology branch in the Indian Air Force, this data is supplemented in recent years by the data of Indian Air Force (IAF) observatories in this region. Since the 1990s, this data is augmented by a dense network of Automatic Weather Stations which are currently 1008 in number.

With the establishment of meteorological offices in the Quetta and Peshawar aerodromes and flight landing facilities in Karachi between 1920 and 1930, the requirements of the new field of aviation meteorology triggered a deeper interest in local severe storms as an important component of the weather to be forecast. The Pilot Balloon observatory network of IMD which started with the first observatory in 1912 at Agra expanded to more parts of India and improved with the development and implementation of the indigenously developed radiosonde network at five stations throughout India (Pune, Delhi, Allahabad, Veraval and Cuttack) in 1944. The upper air network evolved thereafter and under the modernization project of IMD, there is currently a network of 62 pilot balloon observatories of which 20 are GPS enabled pilot balloon observatories and 56 GPS based rs/rw upper air systems with 1680 MHz ground equipment - first installed in 2009.

With the regular availability of the vertical profile of the temperature, moisture and wind of the atmosphere, meteorologists were able to monitor the atmosphere in all four dimensions (x, y, z, t) over India for the first time and were better able to understand the instability of the atmosphere. The concept of Lifting Condensation Level - which is the height above the ground (AGL) at which is entropically ascending moist (humid) air parcel reaches water-vapor saturation pressure or RH=100% was proposed by Normand in 1924. Normand (1938) further subdivided the concept of conditional instability into additional classifications based on what we now term convective inhibition (CIN) and convective available potential energy (CAPE). He established three theorems known as "Normand Theorems" to diagnose moist processes through the use of "wet bulb temperature". This work contributed to the thermodynamically caused conditional instability of the local convective process known as Conditional Instability of the First Kind (CIFK) (Sikka, 2011). The weather forecasters extensively use these concepts till date to predict local convection in the form of thunderstorms. To analyse upper air soundings, a new thermodynamic diagram was designed along the lines of the thermodynamic tephigram of Sir Napier Shaw for the Indian region by Ananthakrishnan and Yegnanarayana (1947). This replaced the use of all other thermodynamic diagrams in IMD like the meteorograph (Roy and Chatterjee, 1929) for analysing the vertical profile of the atmosphere over India. Pisharoty subsequently presented the use of the Tephigram in diagnosing convective processes (Pisharoty, 1945).

The development in NWP model based weather forecasting field in India is concurrent with the global advancement in the computer industry and the internet. The first NWP model was installed in 1973 in a mainframe computer IBM 360/44. Thereafter, the first non-hydrostatic model Mesoscale Model Version 5 (MM5) which was suitable for mesoscale convective weather forecasting was installed on SGI Origin 200 and Altix 350 servers in IMD (Roy Bhowmik *et al*., 2008) and NCMRWF (Ashrit *et al*., 2006) during 2001-2008 which was later followed by the WRF model. Thereafter under a USAID project in 2006, and with the aid of Hong King Met Office, short-range rapid update model ARPS and Nowcast models such as SWIRLS and WDSS-II were installed (Roy Bhowmik *et al*., 2011). These models- with radar data assimilation were specifically targeted to thunderstorm prediction in the nowcast to short range time scale. With the installation of newer supercomputers, there has been increasing demand for location specific accurate forecasts of thunderstorms in the short-range time scale. Post a devastating series of events with thunderstorm related deaths throughout India in May 2018, the Ministry of Earth Sciences (MoES) has developed various mesoscale model based short range forecast products (upto 48 or 72 hours) for thunderstorms and related hazards such as forecast for lightning occurrence, aerosol cover, wind gusts, equivalent radar reflectivity, rainfall *etc*. They have been developed jointly by Indian Institute of Tropical Meteorology (IITM), National Centre for Medium Range Weather Forecasting (NCMRWF) and IMD with radar and INSAT satellite data assimilation (Choudhury *et al*., 2020, Francis *et al*., 2020). Analysis on a daily basis indicates that some of these products have significantly positive impact on the forecast process. These forecast products are available for every three hours up to 48 -72 hours lead (depending upon the model run). While some of the model products are updated twice a day (WRF model) based on 0000 UTC and 1200 UTC initial conditions, others are updated once a day (NCUM and GEFS) based on 0000 UTC initial conditions. More recently, IMD has operationally established the High-Resolution Rapid Refresh (IMD-HRRR) modelling system in collaboration with Space Applications Centre, Indian Space Research Organisation (SAC-ISRO) and the Weather Research and Forecasting Electrification (EWRF) model on Pratyush High Power Computing System (HPCS) in 2021. The IMD-HRRR system (based on WRF-ARW) is a real-time 2-km spatial resolution, hourly updated, cloud-resolving, convection-allowing atmospheric model updated every hour using the radar wind (radial), radar reflectivity and surface observations (prepbufr) data. The forecast for 12 hours lead time is made available to the forecasters at every 2 hour interval (Srivastava *et al*, 2022). The IMD-EWRF model is a real-time 3-km spatial resolution, model run thrice daily and is a cloud-resolving, convection-allowing atmospheric model. The EWRF model (based on WRF-ARW) additionally assimilates lightning data.

With advancement in the fields of communication, weather modelling, remote sensing observations, as well as the expansion of the observatory network, in recent years there was urgent requirement for integrating and making available all the information in a common terminal for the use of forecasters. Under a multiyear modernization project of IMD, the entire operations of IMD including data transmission from observatories, data processing, quality control, storage and display was overhauled. As a part of this project, all observation data was collected at a central server in Delhi- TRANSMET and a forecaster workstation-SYNERGIE was implemented throughout all offices of IMD in an agreement with METEO-FRANCE for display and analysis purposes (Lefort, 2013). More recently, this set-up has been replaced by a web-based Nowcast Decision Support System portal which incorporates newer sources of data, techniques of data processing and visualization to simplify the process of thunderstorm forecasting.

3. Thunderstorm climatology over India

Initial studies of the climatology of thunderstorm, using the data of observatories spread throughout the Indian subcontinent, were initially regional or for specific observatories which had long periods of reliable data. The first significant regional studies were focused on thunderstorms during the summer season-March to May, which are often accompanied by squall winds and hail (Srinivasan *et al*., 1973 for example). These studies first

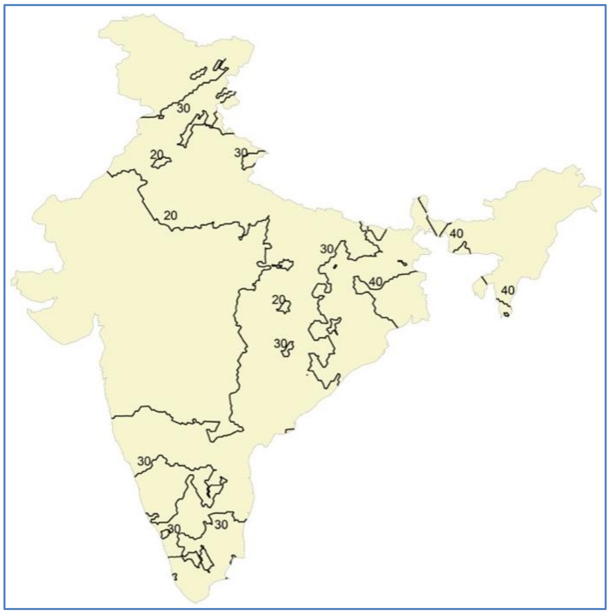

Fig. 1: Annual Climatology of Thunderstorm days over India based on the data recorded at IMD observatories (1967–2016)

noted the gradual evolution from winter synoptic conditions to that during the summer season, and its effect on the occurrence of thunderstorms over various parts of India. Especially significant results were obtained for East India. It was noted that summer nor'westers (Kal Baisakhi storms) over this region can be classified into one of four types based on the region of origin and subsequent movement of the thunderstorm cells. Type A thunderstorms develop in the afternoon over Bihar Plateau and move southeastwards, Type B thunderstorms originate during night and early morning in the submontane districts of north Bengal and move southwards, Type C thunderstorms originate in the hills of Nagaland, Manipur and Mizoram and travel westwards while Type D thunderstorms are very similar to type B but the place of origin is near the Khasi hills, and move southwards. Around this time the discovery of the north Indian dryline over east India provided further understanding of the mutual interaction of the land-sea with the topography and synoptic weather systems to provide suitable conditions for occurrence of severe thunderstorms over East India (Weston, 1972). Subsequent studies using surface observing data from the entire Indian subcontinent indicated that the annual frequency of thunderstorm days is highest over (*i*) east and northeast India and adjoining Bangladesh, (*ii*) southwest peninsular India and (*iii*) western Himalayas bordering Pakistan (Pant and Rupa Kumar, 1997; Tyagi 2007; Sen Roy and Sen Roy, 2021). Fig. 1 displays the annual frequency of thunderstorm days over the Indian region. The above studies and others also highlight the intraseasonal variability of thunderstorm activity. Thunderstorms are short lived and accompanied by hail and squally or gusty winds during the summer season. The frequency of thunderstorm days and the lifetime of thunderstorm cells increases after the onset of the southwest monsoon season, when the combined effect of high sensible heating and moisture produced long-lived organized thunderstorm systems (Romatschke and Houze *et al*., 2011 a and b; Sen Roy *et al.*, 2019 a). The monsoon thunderstorms were also accompanied by frequent lightning strikes especially over east and east central India. Space based analysis of annual lightning flash rates supports the above findings (Nag *et al*., 2017; Mondal *et al*., 2023). From 1968, the annual National Crime Research Bureau report of the Government of India has also brought out the annual death statistics due to lightning (https://ncrb.gov.in/adsi-all-previous-publications.html).

Recent studies also indicate that there is a gradual increasing trend in frequency of thunderstorm days, especially over east India, where the devastation is highest (Sen Roy and Sen Roy, 2021). This large number of casualties every year has triggered greater interest in monsoon time thunderstorms and the short range to nowcast scale prediction of episodes of damaging cloud-to-ground lightning. Another aspect of thunderstorm activity which is being monitored in greater detail in recent years is the diurnal cycle of occurrence of thunderstorm events. This is to enhance understanding of the interaction of the various synoptic and mesoscale forcings with the local topography that trigger thunderstorms over the Indian region. Analysis of the diurnal cycle of thunderstorm occurrence during the March to June period indicates that the gradual intensification and migration of the day-time shallow heat low towards northwest India during May and June, reinforces the western disturbances over this region during this period of the year, thereby intensifying the thunderstorm activity during the afternoon to evening hours over the western Himalayas and northwest India region. The role of the low-level anticyclones over the Arabian Sea and the Bay of Bengal is seen in the east-west oriented moisture gradient across the Indian subcontinent which makes the east Indian subcontinent generally more prone to thunderstorm activity during this season. The east west oriented discontinuity line across north India is particularly intense during the morning hours along the foothills of the Himalayas. Its location directs moisture from the Bay of Bengal into the Himalayas causing early morning initiation of thunderstorm activity over the Himalayas. The western end of the discontinuity line become less marked and the eastern end moves southwards to the north Indian plains later in the day. The north-south oriented discontinuity line across the Indian subcontinent between the two anticyclones - intensifies during the afternoon hours due to land heating and combines with the east-west wind discontinuity to become a T-shaped maximum convergence zone for thunderstorm activity during the afternoon hours over the east Indian region, whose frequency increases towards May and June (Sharma *et al*., 2023).

4. Use of eadar in thunderstorm studies

Since the independence of India, there has been a concerted effort towards more detailed and continuous observations of weather through remote sensing sources like weather radars and weather satellites. With the installation of the Decca Type 41 radar (3 cm wavelength) at Dumdum airport in Kolkata in 1954, India (IMD) entered a new era of radar observation of thunderstorms over the Indian region (Das *et al.*, 1957). Subsequently the first S-Band analog radar was installed at Visakhapatnam in 1971. These radars were later replaced by a new generation of digital Doppler Weather Radars (DWR) starting with the radar in Kolkata in 2003. As of date there are 39 DWRs of which 12 X-band and 4 C-band and 1 S-Band radars are dual polarized. These radars have permitted deeper analysis of the structure of thunderstorm cells and hydrometeors within clouds (Sen Roy *et al.*, 2019 a; Singh *et al.*, 2011 for example).

In view of the short lifetime and mesoscale nature of thunderstorms, a ground-based DWR network is a useful aid for real-time detection of location and intensity of thunderstorm cells. A variety of heuristic approaches with varying degrees of complexity and automation are used by various meteorological services of the world for short range to nowcast scale prediction of thunderstorms and their associated weather using DWR data. Radar based nowcasting systems concentrate on forecasting of rainfall, or parameters such as reflectivity, hail potential, downdraft potential that are directly related to thunderstorms and their evolution and movement (Sen Roy *et al*., 2019 b). Two such softwares were adapted for use over the Indian region - WDSS-II (Warning Decision Support System) from NSSL USA (Sen Roy *et al*., 2014) and SWIRLS (Short-range Warning of Intense Rainstorms in Localized Systems) from Hong Kong Observatory (Srivastava *et al.*, 2012). Both softwares are area tracking softwares (Sen Roy *et al.*, 2019 b). Verification results with the WDSS-II software of nowcasts for up to 2 hour over Delhi indicate that area errors are more for wintertime low intensity convective areas which evolve rapidly. Intensity and location errors are more for pre-monsoon thunderstorm systems which comprise mostly isolated cells that reach great heights and move very fast, but do not have much horizontal area growth. The overall error in nowcasting is least for the monsoon systems in which cell evolution and movement is slow (Sen Roy *et al*., 2014).

5. Use of satellite in thunderstorm studies

The use of satellite data for meteorology started with the reception of satellite imagery from the first meteorological satellite TIROS-1, from December, 1963 through an Automatic Picture Transmission at Mumbai. The first meteorological Meteorological Earth Observation (EO) instrument-VHRR (Very High Resolution Radiometer) for imaging the Earth in the visible and thermal infrared bands was put on board the geosynchronous INSAT 1A satellite at the insistence of Prof. P. R. Pisharoty, who convinced the stakeholders of the use of Meteorological data for an agricultural society like India (Asokan, 2023). Currently, the INSAT 3D and INSAT 3DR satellites of India are in orbit and have identical on board meteorological payloads comprising of six channel imager and nineteen channel sounder. The data from these and other satellites and the RAPID viewer in particular have greatly enhanced the medium range to nowcast scale operational forecasting of thunderstorms through incorporation into Standard Operating Procedures (Sen Roy *et al*., 2021) and assimilation into mesoscale cloud resolving NWP models (Prasad *et al*., 2021, Francis *et al*., 2020). Since Mesoscale convective systems (MCS) can be identified based on cloud-top brightness temperature and area of the cloud cluster, the Forecast and Tracking of Active Cloud Clusters (ForTraCC) has been developed by Vila *et al*., (2008) which uses extrapolation technique to track Mesoscale convective systems (MCS) and forecast their movement and evolution for up to 360 minutes ahead. This technique, using infrared satellite channel (10.8 μm) data of INSAT satellites has been tested and operationally implemented in India (Goyal *et al*., 2017). The results indicate that over the Indian region, the ForTraCC software could predict the minimum cloud top brightness temperature of the convective cells reasonably well, with Average Absolute Error (AAE) of <7 K for different lead periods (30-180 min). However, there is underestimation of the intensity for all lead periods of forecasts. There is over estimation in prediction of size for 30 and 60 min forecasts (17% and 2.6% above the actual size of the cluster, respectively) and underestimation in 90 to 180 min forecasts (–2.4% to –28% below the actual size). The direct position error (DPE) based on the location of minimum CTBT ranges from 70 to 144 km for 30-180 min forecast respectively.

6. Lightning remote sensing: satellite and ground-based lightning location systems

Ground based lightning detection system is the latest observation dataset that has proved useful for thunderstorm monitoring and forecasting and complements the observations from the DWR network. The current network of 83 lightning detection sensors of the Indian Institute of Tropical Meteorology and the 23 sensors of the Indian Air Force are spread throughout India. Since lightning is an essential component of thunderstorms, the dataset has provided a much needed impetus to operational thunderstorm forecasting – especially in areas with limited radar data coverage, as well as further development of mesoscale NWP models for effective simulation of thunderstorms and their associated rainfall and lightning over India (Hazra *et al*, 2022 for example).

7. Evolution of operational forecasting of thunderstorms

The evolution of operational service of thunderstorm forecasting has kept pace with the development of all the above. Since, the scale of thunderstorms over the Indian region being in the meso-gamma to meso beta scale (a few km to about 200 km) with lifetime ranging from a few minutes to a few hours (Thunis and Bornstein, 1996), providing an actionable public service of thunderstorm forecasts has long proved to be a challenge. The first systematic forecast of thunderstorms and associated weather on a scale of 1-2 hours was issued as a part of the Aviation Meteorology forecast bulletins in India. Non-aviation 3 hourly nowcasting of thunderstorms and associated weather in India first started during the 2010 Commonwealth games, when efforts were made to issue these nowcasts for the venues of the games for the duration of the event. Thereafter in December 2012, IMD operationally implemented the service of nowcasting of thunderstorm and associated weather for the general public for major cities of the country which were under the coverage of the newly developing Doppler weather Radar network (Ray *et al*, 2015). A total of 120 cities were covered for issuance of three hourly thunderstorm nowcast. The network of cities and services continued to expand thereafter and IMD is currently issued for more than 1200 stations all over India. Since March 2017, IMD has put in place a 3 stage integrated system for thunderstorm forecasting. In this scheme, five day forecasts are issued for thunderstorms at subdivision and district level throughout the country, which is upgraded daily. Closer to the event, a "Severe Weather Guidance Bulletin" is issued daily and updated twice daily from the National Weather Forecasting Centre (NWFC) of IMD (New Delhi), which provides more detailed information about potential areas for occurrence of severe weather 24 hours in advance and further outlook for the period upto 48 hours ahead. The same is communicated to all Meteorological Centres all over the country for daily weather watch and issuance of warning as and when necessary. These areas are fixed after discussions with the respective Meteorological Centres of IMD during the daily Video Conference during 1030-1130 IST. The Severe Weather Guidance includes potential area of thunderstorm and associated (*i*) gusty wind (*ii*) damaging cloud to ground lightning (*iii*) hailstorm (*iv*) duststorm (*v*) rainfall. More detailed, impact based quantitative forecasts of thunderstorms and associated phenomena are issued at district level for 732 districts as well as more than 1200 significant stations at 3 hour intervals, round the clock, throughout the year by all State Meteorological Centres. This list includes the district headquarters all over India, locations of IMD observatories as well as towns and cities that are important for commercial, religious, tourism and other purposes for public gathering. It may be noted that initially the rate of addition of stations was slow, dependent upon installation of new Doppler Weather Radars (DWR). Only district headquarters that were within 250 km of the C and S-Band DWR stations and 100 km of X Band DWR stations were included in the list. However, post 2018, many new products have become available, including real time lightning flash information from the ground based lightning networks of the Indian Institute of Tropical Meteorology (IITM) as well as the Indian Air Force. This has permitted expansion of the nowcast service to stations and districts, not under the purview of the DWR network. These Nowcast warnings are updated on the IMD website at 3 hourly intervals at https ://mausam.imd.gov.in/imd_latest/contents/stationwise-nowcast-warning.php(for stations) and (https ://mausam.imd.gov.in/imd_latest/contents/districtwisewarnings.php) (for districts). When severe weather is expected, for maximum effectiveness of the warning, detailed SMS/Whatsapp messages and e-mails are issued to district collectors, State Disaster Management Authorities and local administration of the district concerned apart from print and electronic media. The impact expected due to the severe weather has also been added to the nowcast warnings in text terms as well as in terms of colour codes following WMO Technical Note, 2015 (WMO. 2015) and National Disaster Management Authority (NDMA) guidelines (https://ndma.gov.in/images/pdf/Draft-Guidelines-thunderstorm.pdf) as mentioned below:

(*i*) Green colour (No severe weather)

(*ii*) Yellow colour (Light rain: < 5 mm/hr/Light snow < 5cm/hr /Light Thunderstorms with maximum surface wind speed up to 40 kmph / Slight dust storm with wind speed up to 40 kmph and visibility is less than 1,000 metres but more than 500 meters due to dust / Low (< 30%) probability of cloud to ground lightning occurrence).

(*iii*) Orange colour (Moderate rain: 5-15 mm/hr /Moderate snow: 5-15 cm/hr /Moderate Thunderstorms with maximum surface wind speed between 41 - 61 kmph (In gusts) /Moderate dust storm with wind speed between 41- 61 kmph and visibility between 200 and 500 metres due to dust /Moderate (30 - 60%) probability of cloud to ground lightning occurrence).

(*iv*) Red colour (Heavy rain: >15 mm/hr/Heavy snow: >15 cm/hr / Severe Thunderstorms with maximum surface wind speed between 62-87 kmph (In gusts)/Very Severe Thunderstorms with maximum surface wind speed > 87 kmph (In gusts) / Thunderstorms with Hail / Severe dust

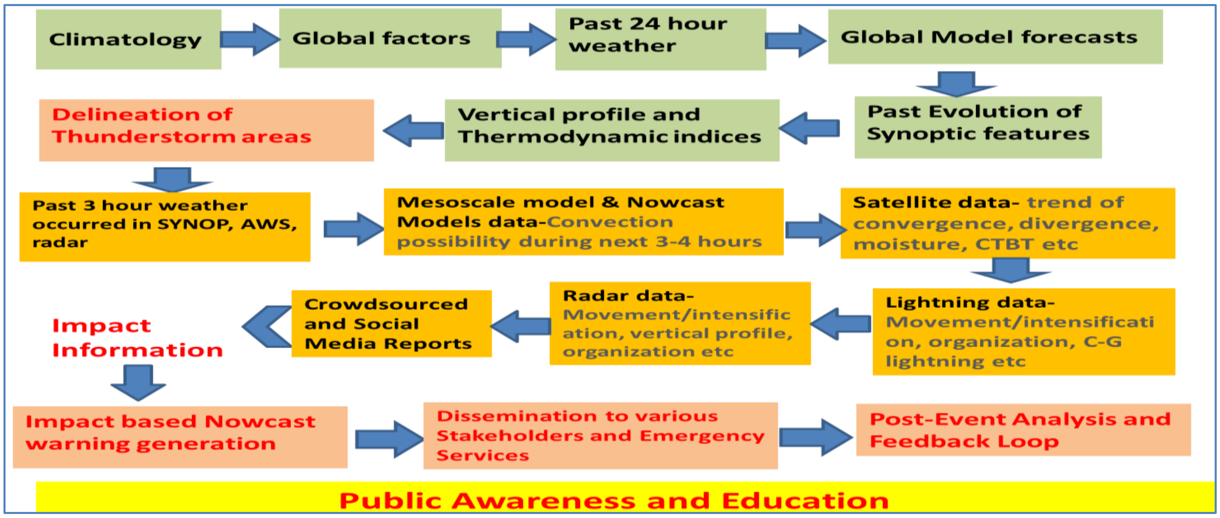

Fig. 2: Standard Operating Procedure for operational thunderstorm forecasting over India

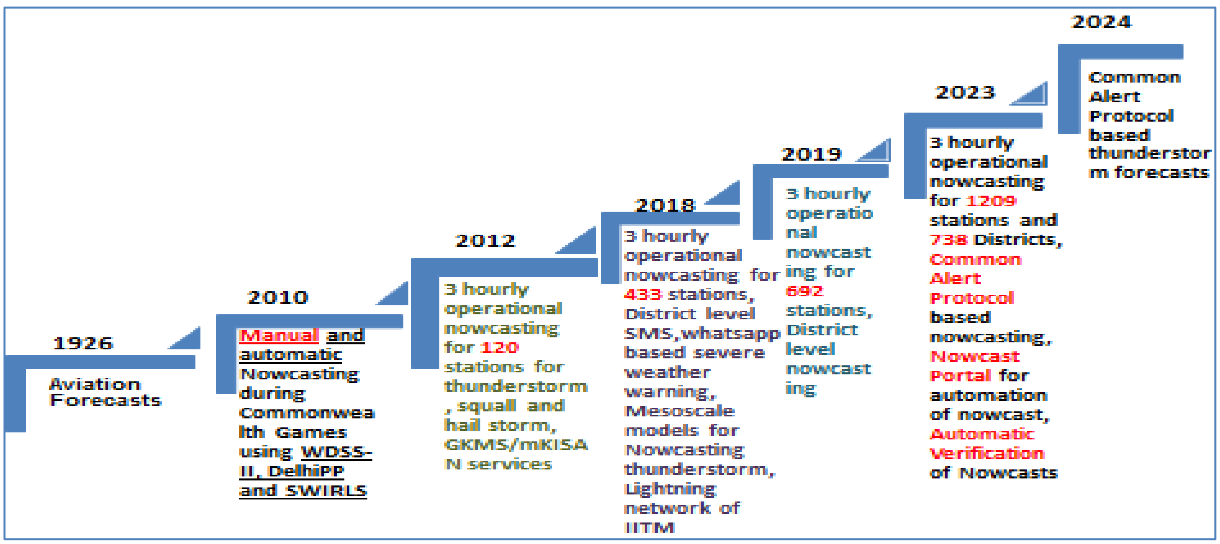

Fig. 3: Evolution of operational Thunderstorm forecasting over India

storm with surface wind speed (in gusts) exceeding 61 kmph and visibility is less than 200 metres due to dust /High (> 60%) probability of cloud to ground lightning occurrence).

The generation of thunderstorm warnings from medium range to nowcast scale utilizing climatology, model products, previous and current observations follows a common Standard Operating Procedure which is displayed in Fig. 2.

The warnings are also available for use by the general public through web based weather apps such as MAUSAM, UMANG and MEGHDOOT. The other major initiative in recent years is the Common Alert Protocol (CAP) as recommended by WMO and as implemented under the leadership of the National Disaster Management Authority (Mohapatra *et al*, 2022). The areas selected for warning under the Common Alert Protocol are automatically warned through their mobile phones. IMD has launched a public outreach initiative through a website for crowdsourcing of weather information where citizens will be able to record realized weather and can upload their local weather conditions (Chug *et al*, 2021).

Since thunderstorm is a highly localized event, the three hourly forecasts at district level are not location specific enough to take immediate action. In this context, the Indian Institute of Tropical Meteorology (IITM) has launched 'Damini', a free mobile-based application that can warn people about lightning in their vicinity at least 30-45 minutes before it strikes.

All these developments have greatly increased the quality, outreach and effectiveness of severe weather warnings issued by IMD (Sen Roy *et al.*, 2021). Fig. 3

summarizes the milestones of operational thunderstorm forecasting over India.

8. Performance of operational thunderstorm nowcast/forecast over the years

As mentioned above, since forecasts for thunderstorm occurrence are issued at 24 hour lead time for meteorological subdivisions and nowcasts are issued at 3 hourly lead time for individual stations and districts, the quantitative evaluation of the performance of the operational forecasts are evaluated on both scales- at 24 hour time scale for meteorological subdivisions and 3 hourly lead time for individual stations. Subdivision is a meteorologically homogenous part of India, which may comprise part of or a complete state or multiple small states. The dataset used for verification of both types of forecasts is the set of thunderstorm reports obtained from 141 Meteorological Observatories of IMD and Indian Air Force as well as media information if available. In view of the poor density of observing stations compared to the scale of most thunderstorms, if any observatory or news media reports the occurrence of thunderstorms in a location within the area of the subdivision delineated by the IOP, the 24 hour forecast for thunderstorm for the subdivision is considered correct. On the other hand, the thunderstorm nowcast for the three hour period for a station is considered correct if there are any observatory or news media reports of the occurrence of thunderstorms at the station. As may be inferred, the three hourly verification method is applied only to a limited number stations throughout India. The verification results for nowcasts for these stations are considered representative of the skill of the larger nowcasting dataset. Details of the methodology may be seen in Sen Roy *et al.*, (2021). For verification purposes, a yes-no criterion (2x2 configuration table) is applied for occurrence-non-occurrence of thunderstorms. This data is used to compute various categorical skill scores in terms of (*i*) Probability of detection (POD), (*ii*) False Alarm Ratio (FAR) (*iii*) Critical Success Index (CSI) which is defined as the ratio of the number of hits (correct thunderstorm forecasts) to the number of events which occurred plus the number of false alarms and (*iv*) Equitable Threat Score (ETS) which is a modification to the CSI, takes into account the number of correct forecasts of events (hits) that would be expected purely due to chance. The all India verification scores combined during the four month period of March, April, May and June as a whole during 2016 to 2023 are displayed for 24 hour thunderstorm forecasts in Fig. 4 and for 3 hour thunderstorm nowcasts in Fig. 5.

As may be noted in Fig. 4 for 24 hour thunderstorm forecasts, there is systematic 200% improvement in the all India Probability of Detection (POD) scores, from 0.3 in 2016 to 0.86 in 2023. The False Alarm Ratio (FAR) score has remained nearly constant between 0.3 and 0.4. The Critical Success Index (CSI) score has also had a systematic improvement through the years with accuracy more than doubling in 2023 (0.61) over its value in 2016 (0.27). The Equitable Threat Score (ETS) score indicates that there was a 150% improvement in the forecast accuracy for rare events, increasing from 0.14 in 2016 to 0.34 in 2023.

The verification of 3 hourly station level nowcasts for thunderstorms indicates that there is systematic improvement in the all India POD scores - from 0.74 in 2016 to 0.92 in 2023 (a 24% improvement) with slight deterioration in 2021 and 2022 (0.83). The FAR score also significantly reduced in 2017 (0.37) as compared to 2016 (0.64) before decreasing up to 2023 (0.43). The CSI score has also had a systematic improvement through the years up to 2020, with accuracy almost doubling (0.58 in 2020) over its value in 2016 (0.32) before deteriorating slightly up to 2023 (0.54). The ETS score showed similar trend with accuracy almost doubling in 2020 (0.56) over its value in 2016 (0.29) before deteriorating up to 2023 (0.51). Despite year-to-year variability, all scores indicated significant improvement up to 2023.

9. Expeditions and special field campaigns and thunderstorm testbed

The discussion of thunderstorm monitoring & forecasting in India is incomplete without discussing the various specialized expeditions and field campaigns undertaken for in-depth analysis of thunderstorms. The first major initiative in this regard was formulated by the then Director General of Meteorology (IMD) - Dr J. H. Field in the form of an expedition led by an Indian meteorologist G. Chatterjee in 1925, to study Nor'wester thunderstorms (Kalbaisakhi storms) of south Bengal. The results of the expedition produced the first scientific study of these thunderstorms (Roy and Chatterjee, 1929). Subsequently, between 1930 and 1940, three major field campaigns were launched by IMD to understand the incidence and dynamics of Nor'westers. The results of these field campaigns and the thrust in thunderstorm studies derived therefrom, produced some of the finest forecasting manuals of Synoptic features and forecasting of thunderstorms which form the basis of all weather forecasting till date (Srinivasan and Ramamurty, 1973 for example).

The next phase of special field campaigns was started by IMD in the form of a Forecast Demonstration Project for thunderstorm prediction in 2005 through a program known as the **S**evere **T**hunderstorm **O**bservation and **R**egional **M**odelling (STORM) program (Das *et al*., 2014). Initially, pilot experimental campaigns were conducted during the premonsoon seasons (April-May) of 2006 and 2007, focused on study and forecast of severe Nor'wester

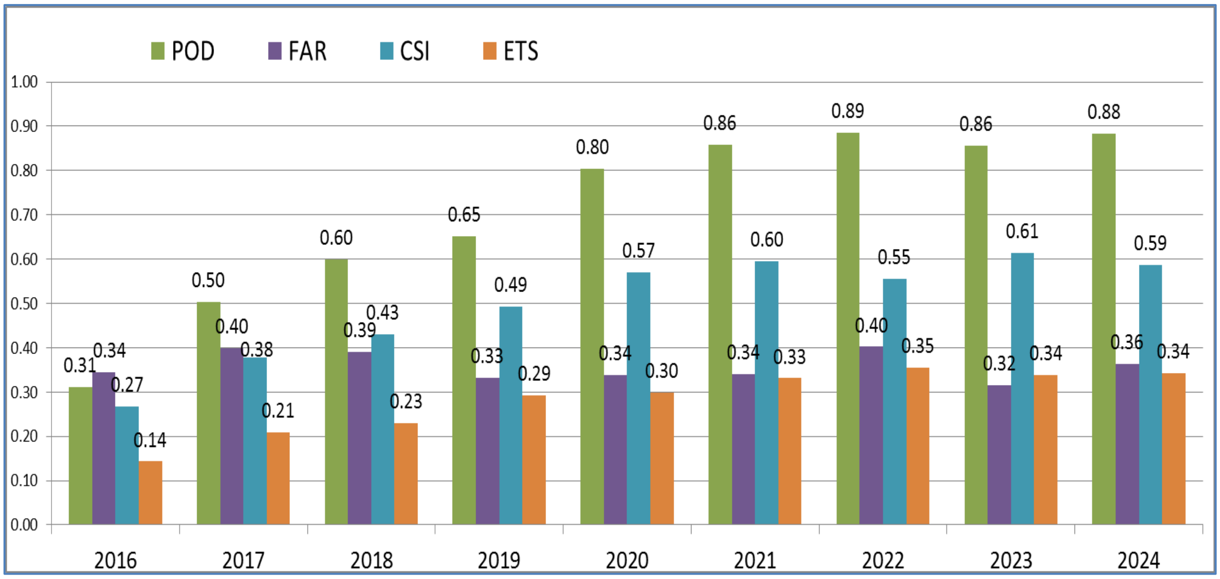

Fig. 4: 24 hour thunderstorm forecast verification result for the entire FDP season of 2016 to 2024

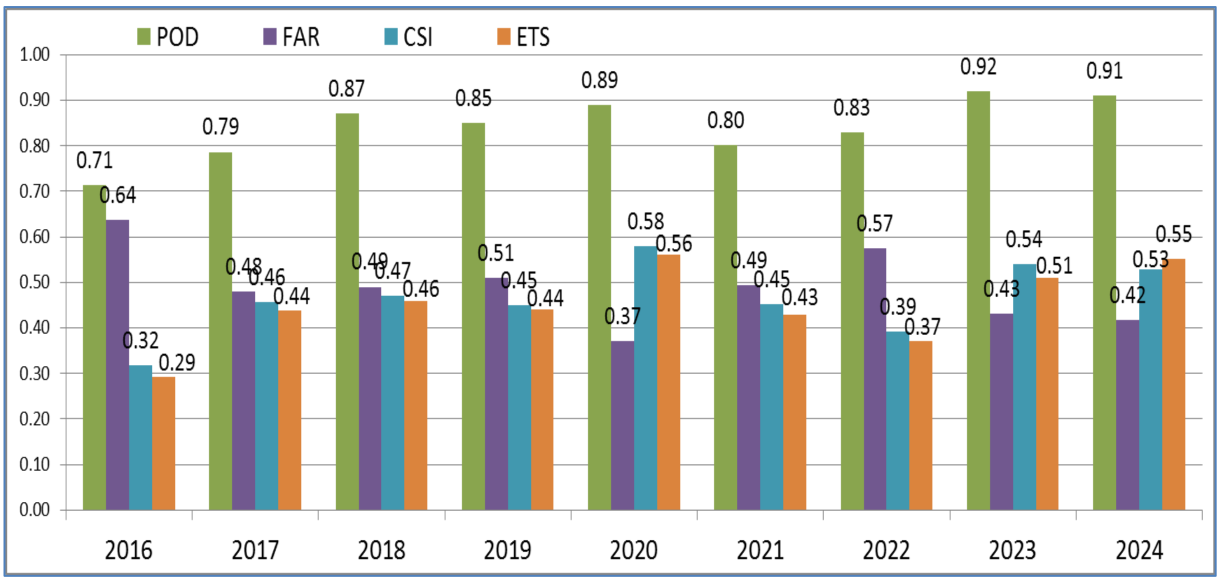

Fig. 5: 3 hour thunderstorm nowcast verification result for the entire FDP season of 2016 to 2024

thunderstorms that affect east and northeast India during this season (Mohanty *et al.*, 2006; Mohanty *et al.*, 2007).The STORM program was expanded in later years to cover larger regions involving countries neighbouring India in 2009, with focus on commonality of occurrence of trans-boundary Kalbaisakhi activity over east and northeast India, Bangladesh, Nepal and Bhutan. The focus of the program was multi country additional observations for potential areas of thunderstorms during Intense Observation Periods (IOP). Additionally, operational thunderstorm forecast improvement was sought through running and evaluating various mesoscale models. In the second phase, from 2012, the program also brought other thunderstorm regimes within its ambit. This included the analysis and forecast of dry thunderstorms and deep, moist thunderstorms over northwest India, Pakistan and Afghanistan. In the third phase, from 2013, the scope of the STORM project was extended to encompass all continental thunderstorms over central and south India as well as maritime thunderstorms that affect the extreme south peninsular India as well as Sri Lanka and Maldives. A tri-weekly FDP STORM Bulletin was generated, delineating thunderstorm prone areas over the Indian subcontinent for the subsequent two to three days. Simultaneously, the Commonwealth Games of 2010 first brought forth the need for a service for operational location specific accurate forecast of convective weather with short lead times and intensity all over the Indian region. Three hourly location specific nowcasting of thunderstorms, squall and hail storm was initiated for 120 cities across India in 2013 (Ray *et al*., 2015). This continued up to 2016. From 2017, the FDP STORM program has shifted focus to severe weather only over the Indian region during the period from March to June (Sen Roy *et al*., 2019). Standard Operating Procedures for Nowcast and short range forecasting of thunderstorms have been put into place. Instead of a thrice weekly, a "Severe Weather Guidance Bulletin" is being issued twice daily from the National Weather Forecasting Centre (NWFC), IMD (New Delhi) about potential areas for occurrence of severe weather 24 hours in advance and further outlook for the period upto 48 hours ahead. Other changes are discussed in the previous section.

The newest initiative towards detailed analysis of thunderstorms is the **Thunderstorm Testbed Project** over east India, planned for the five year period of 2021-2026. The project is being organized by the Ministry of Earth Sciences comprising of scientists of IMD, IITM, NCMRWF for planning in-depth field experiments and numerical experiments with available and augmented instrumentation and computing facilities. This will be a first experiment of its kind in India. The equipment on the ground will be set up in the contiguous area of north Odisha, east Jharkhand and south West Bengal. Simultaneously a multi-agnecy thunderstorm project is proposed through joint collaboration of the Indian Space Research Organization, Defence Research and Development Organization and the Ministry of Earth Sciences in Balasore in East India. The observation equipment will comprise, ground based observations, remote sensing measurements as well as drone measurements of the thunderstorms during their life cycle including formation, growth, movement and dissipation.

10. Conclusions

Thunderstorms are some of the most devastating weather phenomena over India. Recent records of the National Crime Research Bureau indicate that more than 2500 people die all over India due to lightning alone (https://ncrb.gov.in/en/adsi-reports-of-previous-years).

Thunderstorms and associated lightning, rainfall, dust storms and hail together constitute the majority of human and animal casualties due to natural hazards over India and associated loss or crops and property is a huge drain to the state exchequer. Due to their short lifetimes, mesoscale area of occurrence and fast temporal evolution over India, monitoring and forecasting these phenomena in a way that has an impact on the weather forecasting aspect is an evolving field. While monitoring these weather systems has a long history, this has gained impetus in recent years with the technological advancement in monitoring and forecasting of these systems as well as improvement of communication methods. The discussion may be ended with the beautiful description of cumulonimbus clouds during monsoon onset over central India in the famous poem "Meghdootam" by the great Sanskrit poet Kalidasa, which is scientifically accurate to this day in terms of the date of onset around 15 July (first day of Ashwina).

"Ashadhasya Prathama Diwase, Megham Ashlishta Sanum, vaprakrida parinata gajah prekshaniyam dadarsha"

which translates to : "On the first day of Ashadha (15 July), clouds on the mountain base charge the peak in mimic fray, as a mature elephant attacks a bank of earth in play".

Disclaimer: The contents and views presented in this research article/paper are the views of the authors and do not necessarily reflect the views of the organizations they belongs to.

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