A review of Nowcasting of convective weather over the Indian region

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सार – हाल के वर्षों में, प्रेक्षण और संगणना संजालों, पूर्वानुमान तकनीक तथा संचार चैनलों में सुधार के साथ, स्थान विशेष के मौसम के सटीक पूर्वानुमान की सार्वजनिक मांग बढ़ रही है। यह आवश्यकता विशेष रूप से छोटी अवधि के मेसोस्केल मौसम प्रणालियों के लिए महसूस की जाती है, जिसके समाधान की कार्रवाई करने के लिए कम समय होता है। वर्तमान लेख बहुत कम समय अंतराल में भारत में गर्ज के साथ तूफान का पूर्वानुमान देने की हाल के घटनाक्रमों की समीक्षा है । इस लेख में पहले भारतीय क्षेत्र में गर्ज के साथ तूफान के जलवायु विज्ञान, इसकी मौसमी, स्थानिक एवं दैनिक परिवर्तिता पर संक्षिप्त चर्चा की गई है। इसके बाद नए प्रेक्षण संसाधनों की चर्चा की गई है जो वर्तमान पीढ़ी के उपग्रह डेटा तथा उत्पादों, डॉपलर रेडार, तड़ित संसूचन संजाल और सतह एवं उपरितन वायु संजाल के वेधशालाओं से परिचालनात्मक गर्ज के साथ तूफान का पूर्वानुमान देने के लिए उपलब्ध हो रहे हैं। इसके बाद संख्यात्मक मौसम का पूर्वानुमान देने के लिए संवहनीय मौसम का अल्पअवधि का तात्कालिक अनुमान देने की दुनिया भर में उपलब्ध संख्यात्मक तकनीकों की चर्चा की गई है जिन मॉडलों को भारत में प्रचालनात्मक रूप में लागू किया गया है, उनके सॉफ्टवेयर के सत्यापन से प्राप्त परिणामों को संक्षेप में दर्शाते हुए अधिक विस्तार से चर्चा की गई है। अगले खंड में भारत मौसम विज्ञान विभाग (आई एम डी) में प्रचालनात्मक तात्कालिक अनुमान की वर्तमान प्रक्रिया का विवरण दिया गया है जिसमें तात्कालिक पूर्वानुमान के तंत्र को सुधारने के लिए किए गए नवीन प्रयास शामिल हैं। सत्यापन के परिणाम इस तथ्य को दर्शाते हैं कि इन उपायों को सफलतापूर्वक लागू किया गया है और भारतीय क्षेत्र में गर्ज के साथ तूफान का पूर्वानुमान देने में उल्लेखनीय सुधार हुआ है। अंतिम खंड में विभिन्न सरकारी और निजी एजेंसियों द्वारा गर्ज के साथ तूफान और इससे संबंधित मौसम तथा गर्ज के साथ तूफान के प्रभाव का आकलन करने के लिए की गई पहलों का विवरण है। इस खंड में गर्ज के साथ तूफान का पूर्वानुमान देने वाले पूर्वानुमानकर्ता समुदायों के समक्ष प्रस्तुत चुनौतियों का भी जिक्र किया गया है।

ABSTRACT. In recent years, with the improvement of observation and computation networks, prediction techniques as well as communication channels, there is an increasing public demand for location specific accurate forecast of weather. This need is especially felt for short duration mesoscale weather systems, for which there is less time for taking safety measures. The present article is a brief review of the recent developments in the field of operational thunderstorm prediction over India in the short to very short time scale. The article first briefly discusses the climatology of thunderstorms over the Indian region, its seasonal, spatial and diurnal variability. It then discusses the new observation resources that are now becoming available for operational thunderstorm forecasting including the current generation of satellites, Doppler radars, lightning detection network, as well as the surface and upper air network of observatories. This is followed by a discussion of numerical techniques available worldwide for very short range to nowcast scale forecasting of convective weather. The models that have been operationally implemented in India are discussed in greater detail along with brief mention of the results from the verification of these softwares. The next section details the current procedure of operational nowcasting in India Meteorological Department (IMD) including the recent efforts undertaken to improve the nowcast mechanism. The verification results bear out the fact that these measures have been successfully implemented and there has been significant improvement in operational forecasting of thunderstorms over the Indian region. The final section details the initiatives taken by various government and private agencies to improve the forecasting of thunderstorms and associated weather and impact assessment of thunderstorms. The present challenges before the community of thunderstorm forecasters is also detailed in this section.

Key words – Thunderstorm, Nowcasting, Lightening.

1. Introduction

Most of the Indian landmass is prone to several natural disasters, with severe cyclones affecting the east and west coasts, large-scale flooding in the major river systems such as Ganges, Brahmaputra during the monsoon season, etc. There have also been instances of localized heavy rainfall events that have resulted in widespread devastation in the region of interest. This includes instances like the Mumbai rainfall episode of 26th July, 2005 when more than 100 cm of rainfall was received in 24 hours over a very small area (20-30 km) and the cloudburst over Leh on 6th August, 2010 during which 225 people died. The current technology level for
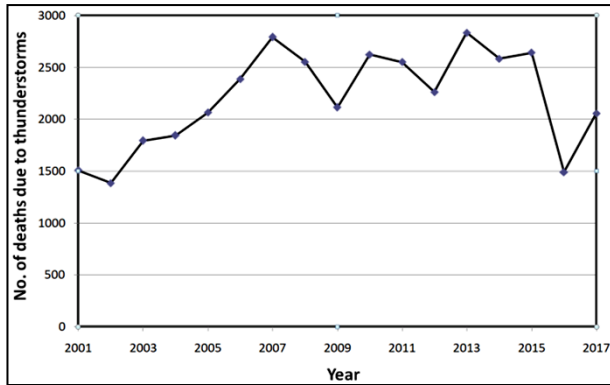
Fig. 1. Annual no. of deaths due to thunderstorms (Source:https://ndma.gov.in/images/pdf/Draft-Guidelines-thundersto rm.pdf)

prediction of damages associated with large scale natural phenomena such as tropical cyclones is improving every year for the Indian region and accurate forecast of track and intensity of such phenomena are available with reasonable accuracy for up to five days in advance (Mohapatra *et al.*, 2013 a,b; Kotal *et al.*, 2014), which has resulted in substantial decrease of human mortality (Haque *et al.*, 2012; Peduzzi *et al.*, 2012; Mohapatra *et al.*, 2012; Mohanty *et al.*, 2015). However, on account of the population density over the Indian subcontinent region and the increasing economic activity, the human and economic cost due to smaller scale convective weather phenomena such as thunderstorms is increasing every year (Fig. 1 displays the deaths due to thunderstorms and lightning during 2001 to 2017 (source: https://ndma. gov.in/images/pdf/Draft-Guidelines-thunderstorm.pdf).

Recently, high winds associated with thunderstorms, resulted in the death of 134 people in Rajasthan and Uttar Pradesh on 2nd May, 2018. Heavy rainfall and high winds from small weather systems in urban areas, causes cascading breakdown of infrastructure systems/networks in civil society. Public awareness of the scope of these weather phenomena is increasing in recent years and there is a growing demand for location specific accurate forecasts of such severe weather events for day to day activities as well as major events such as the Commonwealth Games 2010 in Delhi. However, these mesoscale severe weather events have short life period of about three hours and are highly localized. As a result, it is difficult to detect such phenomena with limited observation network as well as predict by global NWP models in short to medium range. Hence, worldwide there have been attempts to improve the observation network including satellite, Radar, AWS, for better detection; improved mesoscale models outputs with high resolution and local data assimilation; and thence to develop an expert system to provide accurate very short range forecast of weather.

As mentioned by Tyagi (2000), local severe weather systems can be divided into three groups:

(*i*)   Those that are primarily forced by surface in homogeneities (terrain-induced mesoscale systems), e.g., sea and land breeze, valley winds, urban circulations.

(*ii*)   Those that are primarily forced by instabilities traveling in large-scale disturbances (synoptically induced mesoscale system), e.g., squall lines and mesoscale cloud clusters.

(*iii*)   Combinations of the above where instabilities of large-scale features get accentuated and/or persist for longer periods due to orographic features, e.g., heavy precipitation and severe thunderstorm activity at certain locations.

When separated in scale, Thunis and Borstein (1996) noted that weather systems can be in the range of :

(*a*)   meso-gamma scale – Spatial scale of a few km with lifetime of less than an hour

(*b*)   Meso-beta scale – Spatial scale of 20 to 200 km with lifetime of less than six hours

(*c*)   Meso-alpha scale – Spatial scale of 200-2000 km with lifetime of greater than six hours.

While the first type of systems, due to their short temporal and spatial existence, can be difficult to forecast with long lead period, the forecasting accuracy and lead period improves for both the other two types of weather systems. Thunderstorm systems, over the Indian region, exist in all three scales. However, they are pre-dominantly in the meso-beta and meso-gamma scale, especially during the pre-monsoon season (March to May) when they are most hazardous.

The definition and meaning of "nowcasting" have gone through some subtle changes down the years. Originally defined as a combination of description of current situation and extrapolation of recent trends up to two hours ahead (Browning, 1982), it can now extend to several hours ahead with increasingly blurred distinction between "nowcasting" and "very short range forecasting" (VSRF). In view of its increasing importance, in 2010, the WMO Working Group on Nowcasting Research has re-defined the scope of forecasting for such mesoscale phenomena as Nowcasting, which is defined as: forecasting with local detail, by any method, over a period from the present to 6 hours ahead, including a detailed description of the present weather (WMO, 2017). In addition to using Nowcasting for warning the public and
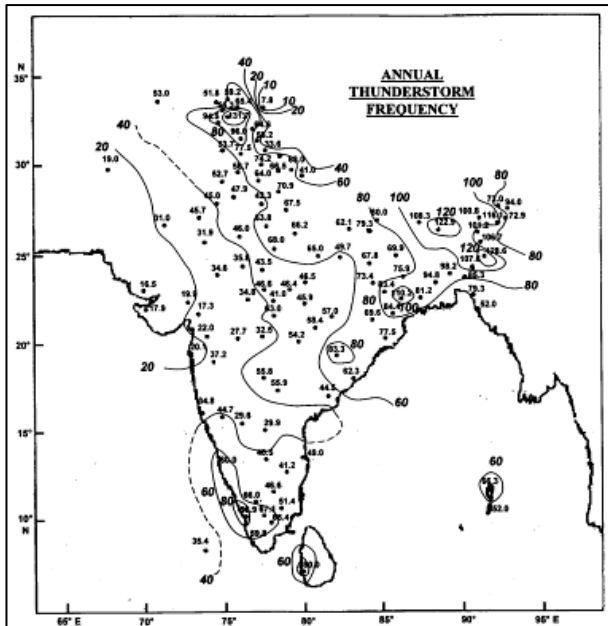
Fig. 2. Annual Spatial distribution of thunderstorms over the Indian region during 1951 to 1980 [Source: Fig. 5 from Tyagi, 2007. Thunderstorm climatology over Indian region, *Mausam*, **58**, 2, p189].

Fig. 3. Intra-Annual frequency of thunderstorms over the Indian region during 2016 and 2017 (Source: IMD)

disaster managers of hazardous weather, it is also used for aviation weather forecasts in the terminal and en-route environment, marine safety, water and power management, off-shore oil drilling, construction industry and leisure industry. Though mesoscale events include various types of severe weather like heavy rainfall events, thunderstorms etc., this article looks at different aspects of nowcasting of thunderstorms and reviews the challenges for nowcasting the different aspects of these weather systems in the Indian context. It is mainly because of the fact that the deaths due to thunderstorms in India are manifold as compared to that due to other events like cyclones and heavy rainfall causing floods. The climatological aspect of thunderstorms over Indian region is presented in Section 2. The observational sources, nowcast tools and their verification, current status of nowcasting in India and its verification, and future scope and challenges of nowcasting are presented in the following sections.

2. Thunderstorms over the Indian region

India Meteorological Department defines a thunderstorm as a meteorological phenomenon in which one or more sudden electrical discharges manifested by a flash of light (Lightning) and a sharp rumbling sound (thunder) occurs from a cloud of vertical development. Most localized severe weather over the Indian region occurs in association with thunderstorms. Associated with
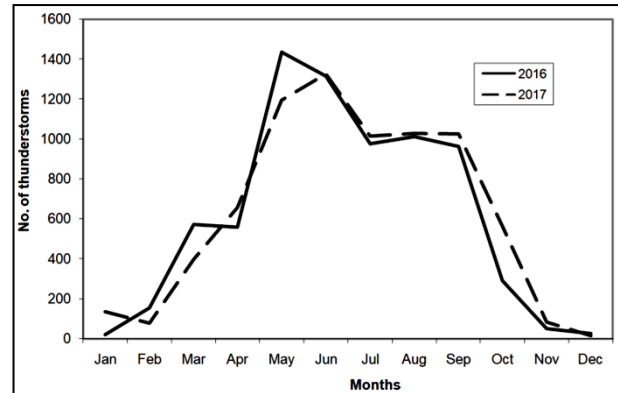
thunderstorms, over the Indian region, primarily five phenomena result in widespread damages: (*i*) High winds (*ii*) Dust storms (*iii*) Hailstorm (*iv*) Lightning (*v*) Heavy rainfall. However, studies have noted that all five phenomena rarely occur concurrently in association with a thunderstorm event over the Indian region, although more than one can occur simultaeously. Fig. 2 displays the annual spatial climatological frequency of thunderstorms over India during 1951-1980 (Tyagi, 2007) over the Indian region, while Fig. 3 displays the monthly frequency of thunderstorms over the Indian region during 2016 and 2017. As may be noted, there are maxima in thunderstorm occurrence along the coast of Kerala and Gangetic West Bengal, as well as along the foothills of the Himalayas. As Fig. 3 indicates, their annual frequency over the Indian region is also primarily uniimodal, peaking in the months of May and June.

However, the character of thunderstorms, as well as their spatial scale and lifetimes shows wide variation during the course of the year and varies regionally (Romatschke *et al*., 2010). The severity of thunderstorms over the Indian region is predominant during the pre-monsoon season (March to May). Most thunderstorms during these seasons are of meso-beta or more commonly, meso-gamma spatial and temporal scale and triggered by meso-scale forcings. Over Northwest India plain regions, in the absence of adequate moisture in the atmosphere, frequent dry convective dust storms called "*Aandhi*" occur during this season. Hailstorms preferentially occur over Northwest India (especially over the Himalayan mountain region) and during the afternoon period 1430 to 1730 IST (FDP Report, 2016). Over eastern India and adjoining Bangladesh, the thunderstorm systems are of large spatial extant, often organized into bow-shaped squall line systems and result in heavy localized rainfall accompanied by high winds and tornadoes and more frequent in the orographically dominant regions as well as the coastal areas (Singh *et al*., 2011). These are called '*Nor'westers*'

or '*KalBaisakhis*' and the accompanying high wind squalls preferentially occur over the east and Northeast Indian region during late evening hours - 1730 to 2030 IST (FDP Report 2016). Peninsular India gets a substantial amount of non-monsoon rainfall due to the passage of easterly waves, which bring extended periods of thunderstorms over the region. The pre-monsoon season is also dominated by high thunderstorm activity over the south-west peninsula, especially Kerala. Orography, coupled with the plentiful supply of moisture from the sea and the effects of sea breeze are some of the causes for the high thunderstorm activity in southwest Peninsula (Rao and Srinivasan, 1969).

As previous studies have noted, during the main monsoon season, the cell lifetimes, as well as the spatial scale of convective regions is more than in other seasons throughout the country and thunderstorms are often accompanied by heavy rainfall and lightning (Sen Roy *et al.*, 2014). This is the period when there is widespread rainfall over most of the Indian region in association with the movement of synoptic scale lows and depressions. Occasionally there are devastating cloudbursts over the Himalayan region and also very heavy rainfall episodes in the plains which are mesoscale in extant (e.g., Mumbai rainfall of 2005) (Rao and Ramamurti, 1968; Srinivasan, 2013; Houze *et al.*, 2007). Monsoon cloud systems are relatively widespread and have a three to four times lower cloud base (Chaudhuri, 2008), with less tall clouds as compared to the pre-monsoon season (Gettelman *et al.*, 2002).

Lightning can be defined as a transient, high-current (typically tens of kiloamperes) electric discharge in air whose length is measured in kilometers. While cloud-to-ground lightning is acknowledged for its potential for causing deaths on the ground, spikes in the amount of cloud-to-cloud lightning is better correlated to storm severity (Liu and Heckman, 2012). Many case studies have been published where lightning activity has been observed to change dramatically before the start of severe damaging weather. Recent studies have shown that extremely high lightning flash rate occur 5-20 minutes before severe weather at ground. For example, Carey *et al.* (2003) found extremely high IC-to-CG ratios and predominantly positive CG lightning (over 74%) when storms produce large hail and weak tornadoes. There are global examples showing how lightning may be used to monitor storm hazards around the globe, while also providing the possibility of supplying short term forecasts (Price, 2008). Although lightning is characteristic of thunderstorms in general, their frequency of occurrence as well as intensity varies from season to season. Over the Indian region, it preferentially occurs during the period of April to September (Ranalkar and Chaudhari, 2009), with

twin maxima over (a) Gangetic West Bengal and adjoining Bangladesh and (b) Northwest Indian Himalayas and adjoining Pakistan.

3. Observation sources

Since by definition nowcasting involves accurate description of the current weather conditions along with forecast, its efficiency is highly dependent on the accuracy of observation. The current observation framework of IMD, available for thunderstorm nowcasting is briefly reviewed in this section. IMD currently has about 558 weather observatories all over India, of which 141 observatories are departmental and operate full time. These full time observatories take observations of basic parameters at every synoptic hour (eight observations at three hour intervals). Besides, IMD has about 43 GPS sonde stations and 62 pilot balloon stations for monitoring the upper atmosphere. These stations monitor the atmosphere twice a day (0000 UTC and 1200 UTC). IMD also currently has a network of 573 Automatic Weather Stations all over India and 1351 Automatic Rain gauge stations with further plans of expansion. These stations provide hourly data of basic parameters for the Indian region [Figs. 4(a-d)]. All these observation networks cater to the need of Synoptic scale weather systems.

However, as mentioned earlier, a large fraction of thunderstorms over the Indian region have sub-hourly lifetimes and meso-scale extant. Monitoring of these weather systems on a continuous basis is only possible using the observations from the Doppler radar network of IMD and satellite observations. The Doppler radars provide round the clock monitoring of reflectivity, radial velocity and spectrum width in a radius of 500 km around them, as well as rainfall estimates; with ten minutes scanning interval (Roy Bhowmik *et al.*, 2011). IMD currently has about 25 Doppler weather radars all over India. Of these radars, five radars, at Delhi, Jaipur, Sriharikota, Thiruvananthapuram and Kochi are dual polarized. The dual polarization of the radars permits accurate differentiation of hail and water droplets in clouds, thereby permitting more accurate nowcasting of the weather associated with thunderstorms. All the radars permit 4-d analysis of thunderstorm cells and their evolution in time. IMD also has at its disposal the data from the INSAT series of satellites.

Currently, for the Indian region, this data is available from INSAT 3D and INSAT 3DR satellites (Katti *et al.*, 2006). This data is available every thirty minutes from each satellite. However, their scans are staggered in such a way that their timings complement each other and a fresh image for the Indian region is available every 15 minutes. Both satellites have identical multichannel
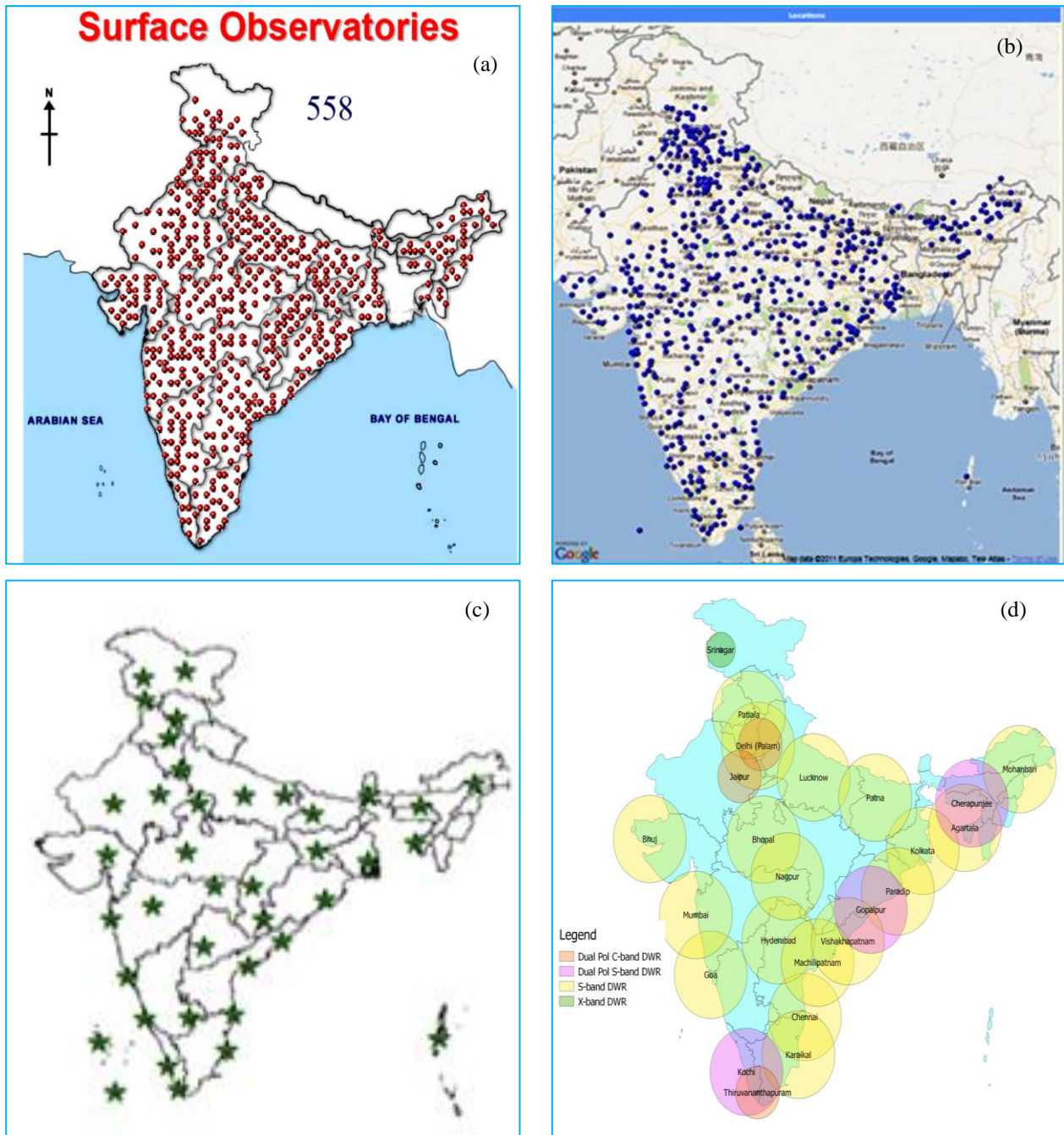
Figs. 4(a-d). Observatory network of IMD in 2018 (a) Surface observatory network (558 nos.), (b) Automatic Weather Station network (573 nos), (c) GPS sonde network (43 nos) (d) Doppler Weather Radar (25 nos) (Source: IMD)

imager as well as a sounder payload to suitably complement each other. In addition to brightness images from different channels, various products derived from data using a combination of channels, is also produced from these satellites. Different satellite derived products such as improved precipitation type and amount estimates from the "Hydroestimator" technique (Varma *et al.*, 2015), Atmospheric Motion vectors (Deb *et al.*, 2016),

vertical temperature and humidity profiles (Krishnamoorthy *et al.*, 2016) greatly aid in analysis of convection over the Indian region. All these data are transmitted and made available for forecasting centres using latest communication tools. Additionally, a web based application RAPID (Real Time Analysis of Products and Information Dissemination) has been developed jointly by Space Applications Centre (SAC),

ISRO, Ahmedabad and IMD (https://www.isro.gov. in/rapid-gateway-to-indian-weather-satellite-data). This application is hosted in IMD website (rapid.imd.gov.in). This tool permits quick interactive visualization and 4-Dimensional analysis of weather based on Indian INSAT satellite data. Data from non-Indian satellites such as Meteosat is also available in a rapid updating mode and provides additional information of the weather (http://foreignsat.imd.gov.in/)

In view of the short lifetime and mesoscale nature of thunderstorms, a ground-based lightning detection network is a useful aid for real-time detection of location and intensity of thunderstorm cells. The Indian Institute of Tropical Meteorology has a ground based Lightning Detection Network with about 48 sensors over various parts of the country and connected to central processing unit at IITM, Pune supplied by Earth Networks. The Earth Networks Total Lightning Network (ENTLN) sensors operate in a frequency range from 1 Hz to 12 MHz (spanning the ELF, VLF, LF, MF and HF ranges). Both cloud and CG lightning discharges are reported by the sensors. When lightning occurs, electromagnetic energy is emitted in all directions. Every ENLS sensor that detected the waveforms records and sends the waveforms to the central lightning detection server via the Internet. The precise arrival times are calculated by correlating the waveforms from all the sensors that detected the strokes of a flash. The waveform arrival time and signal amplitude can be used to determine the peak current of the stroke and its exact location including latitude, longitude and altitude. Although, a comparison with the satellite based Lightning Imaging Sensor (LIS) data for a period of 18 months indicates that the ENTLN data has seasonally and spatially varying coincidence percent (CP) value with the LIS data; however, it was better that other ground based networks (Thompson *et al.*, 2014). The Indian Air Force has a similar network. The data from both networks is currently available to India Meteorological Department for display and aid in detection of severity of thunderstorms. Three sets of products have been developed and kept on the IMD website: lightning data overlaid on INSAT 3D satellite and radar image for the last 30 minutes (http:// www.imd.gov.in/section/satmet/lightning/), lightning data overlaid on Meteosat image (http://foreignsat. imd.gov.in/) while a third product displays current lightning data overlaid on radar and satellite data (http://ddgmui.imd.gov.in/radar/leaflet-map-csv-master/ mosaic.php). The third product also provides district-wise report of occurrence of lightning, every fifteen minutes.

4.   Available nowcasting techniques

A variety of heuristic approaches with varying degrees of complexity and automation are used by different nowcasting systems. Most nowcasting systems concentrate on forecasting of rainfall, or parameters, such as reflectivity, that are directly related to rainfall and its evolution and movement of the rain giving systems. The currently employed approaches to this can be classified in three distinct categories: extrapolation, explicit storm models and expert systems. A list of some operational nowcast systems around the world, are listed in Table 1.

Simpler nowcasting systems are based on radar echo tracking and extrapolation to produce 0-2 hour usable nowcasts over the Indian region. This is because; radar data is very detailed and picks out the size, shape, intensity, speed and direction of movement of individual storm cells on a practically continuous basis. These cells have limited lifetimes (often sub hourly) and non-uniform rate of growth and speed of movement during their lifetimes. The techniques for extrapolating precipitation echoes may either be "area trackers" (Kessler, 1966) or "cell trackers" (Barclay and Wilk, 1970). Cell trackers identify individual storms and then obtain the motion of each storm centroid. Cell trackers have been particularly useful for tracking and warning for individual severe storms. Three of the nowcasting systems mentioned in Table 1, TITAN (Dixon and Wiener, 1993), CARDS (Joe *et al.*, 2003) and Storm Cell Identification and Tracking (SCIT) system (part of the National Severe Storms Laboratory Warning Decision Support System) (Lakshmanan *et al.*, 2007; Johnson *et al.*, 1998) are examples of cell trackers. One advantage of cell trackers is that, since the identified cells have different forecast directions and speeds, they can be allowed to converge and intensify or diverge and dissipate independently. A disadvantage in SCIT and all other cell trackers is, finding cells that are consistently identified for one hour. This disadvantage is a major problem over India, where cell lifetimes in thunderstorms are most often sub-hourly (Sen Roy *et al.*, 2014). In this case, the cell may change identification and the nearest identified cell may not result in an accurate propagation estimation of what appears to be a continuous storm.

When different nowcasting techniques using the same data and the same space-time resolution were compared, it was concluded that cross-correlation methods on area trackers, gave better skill scores of forecast, than the centroid tracking schemes (Elvander *et al.*, 1976) In the simplest area tracker techniques, the computer is used to cross correlate 2-d radar reflectivity images separated in time to find the motion (Lakshmanan *et al.*, 2007). WDSS-II (Warning Decision Support System - Integrated Information) suite of algorithms was used operationally for the Indian region (Sen Roy *et al.*, 2014). In this suite, the quality controlled reflectivity data from multiple radars is time shifted to a common

TABLE 1

Some operational nowcast / short range forecast systems around the world and their main features

Model name	Country applying it operationally	Author	Data inputs	Forecast products	Update frequency of nowcasts	Method used for nowcasting/ short range forecasting
(1)	(2)	(3)	(4)	(5)	(6)	(7)
SCIT [1] (Storm Cell Identification and Tracking)	United States	Johnson *et al.*, 1998	Radar volume data	Characteristics of detected cells, Hail probability and probable direction of movement		Cell Tracker
TITAN[1] (Thunderstorm Identification, Tracking, Analysis and Nowcasting)	Australia, USA	Dixon and Wiener, 1993	Radar volume data field	Detection and tracking of thunderstorm cells in radar data through time to generate size, location and velocity estimates of the thunderstorm	Every 10 min for periods between 10 and 60 min	Cell Tracker
CARDS [1] (Canadian Radar Decision System)	Environment Canada	Joe *et al.*, 2003	Point forecasts, hail, mesocyclone, Microburst, Max reflectivity, echo top, VIL, lightning, rainfall accumulation CAPPIs, gust potential, SCIT tracks	- QPF - Identification of hail, tornado, mesocyclone, downburst, gust strength	0-1 hr	Cell tracker for extrapolation of radar echoes + pattern recognition (for velocity de-aliasing)
OPIC [1] (Convective Objects for Nowcasting) and SIGOONS (SIGnificant weather Object Oriented Nowcasting System)	Meteo-France & MeteoSwiss	Brovelli *et al.*, 2005	Composite reflectivity data field	Cell detection, characteristics and tracking	0-1 hr	Cell tracker for extrapolation of radar echoes
WDSS-II [1,2,3] (Warning Decision Support System-II Generation)	Australia	Lakshm-anan *et al.*, 2007	- Doppler multi radar, single or composite - mesoscale NWP Products	- QPF -Quality control - Identification of hail, tornado, mesocyclone, downburst, gust, BWER -Cell tracking	0-3 hr	Extrapolation of radar echoes by centroid tracking + pattern recognition for velocity field + area tracking + neural network + NWP products
Multi-Radar Multi-Sensor (MRMS)	NSSL (USA)	Smith *et al.*, 2016	- Doppler multi radar, single or composite - Mesoscale NWP Products + lightning data	- QPF -Quality control - Identification of hail, tornado, mesocyclone, downburst, gust, BWER -Cell tracking, Area Tracking	0-3 hr	WDSS-II + National Mosaic and Multi-sensor QPE
SWIRLS[2] (Severe Weather In Rainstorm of Localized Systems)	Hong Kong Observatory, India	Li and Lai, 2004	Radar reflectivity CAPPI product, raingauge data, radiosonde data, lightning data	Radar reflectivity, radar-echo motion, QPE, QPF, track of thunderstorm and its associated severe weather, cloud -to ground lightning, severe squalls and hail, probability of precipitation	6 hours at intervals of 6 minutes updated every 10 minutes	Area Tracker, TREC (Tracking of Radar Echoes by Correlation), GTrack (Group tracking of radar echoes, an object-oriented technique for tracking the movement of a storm as a whole entity) and MOVA (Multi-scale Optical flow by Variational Analysis)

TABLE 1 (*Contd.*)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
RainCast / COTREC[2] (Continuity of Tracking Radar Echoes by Correlation vectors)	Czech Republic since 2003, Switzerland	Novak, 2007, Schmid *et al.*, 2000	PseudoCAPPI 2 km-elevation reflectivity with 1-km horizontal resolution, Raingauge data	PseudoCAPPI 2 km -elevation reflectivity with 1- km horizontal resolution	90 min in 10-min time steps	Area Tracker, the echo motion field is determined by comparing two consecutive radar images using mean absolute difference as the similarity criterion. Motion wind field is constant in time and no growth/decay of radar echo
S-PROG[3] (Spectral Prognosis nowcaster)	BAMS (Australia), Also used in STEPS	Seed, 2003	Rain field, in terms of reflectivity Z [dBZ] or rain intensity R [mm/h]	Rain field, in terms of reflectivity Z [dBZ] or rain intensity R [mm/h]	5 min, 30 min & 60 min forecast of track	Spectral decomposition model which uses scale dependent temporal evolution to formulate forecasts
MAPLE[3] (McGill Algorithm for Precipitation Nowcasting by Lagrangian Extrapolation)	Korea Meteorological Administration Canada, U.S.A.	Germanna nd Zawadzki, 2002, 2004	Radar derived Reflectivity, precipitation rate, precipitation accumulation Quantitative precipitation estimation	Hourly Precipitation forecasts, probabilistic QPF	9-12 hours	Variational echo-tracking with semi-Lagrangian advection of radar reflectivity and correlation of the forecast with the observation. Area tracking method
MUSIC[3] (Multiple-Sensor Precipitation Measurements, Integration, Calibration and Flood forecasting)	European Commission	Burton *et al.*, 2003	Radar, Meteosat and raingauge observations	Rainfall estimation and forecasting	6 hours ahead with a spatial resolution of about 2 km	Decompose a radar image into features. These are tracked from one image to the next using an object-orientated methodology. The tracking uses lag-correlation to estimate velocity
STEPS[3,4] (Short-Term Ensemble Prediction System)	UK Met Office,	Bowler *et al.*, 2006	Radar-based rain analyses and NWP model forecasts	Probability of precipitation at threshold rain rates of 0.125, 0.25, 0.5 and 1 mm h^{-1}	10-90 min at 1 km resolution, updated every 10 minutes	Decompose NWP and rainfall field into a cascade Blend each level in the radar & NWP cascades using weights that are a function of scale and lead time dependant forecast error Add noise component to the deterministic blend Combine the cascade levels to form a forecast
Severe Weather Automatic Nowcast System (SWAN)	China	Feng, 2012	Weather radars base data + MYNOS+SWIFT data	Reflectivity and Quantitative precipitation forecast (QPF)	Greater than 1 hour	A regional 3D reflectivity mosaic is produced. COTREC (continuous tracking radar echo by correlation) vectors are derived from moving radar reflectivity patterns through grid-to-grid cross-correlation blended with mesoscale numerical prediction model output for 2-3 hour nowcasts
NoCAWS	China	Tao Wei, 2011	Mobile Radar data + NWP model data	Reflectivity and Quantitative precipitation forecast (QPF) + Lightning	Greater than 1 hour	COTREC winds are used to nowcast cell motion
Shanghai Typhoon Institute-WRF ADAS-3DVar Rapid Refresh system (STI-WARR)	China	Wang Haibin *et al.*, 2016	NWP model data	NWP model variables	12 hours	3 Km Resolution, 51 level Data assimilation every hour, 12-hour prediction
GRAPES-SWIFT[4] (Global/ Regional Assimilation and Prediction System-Severe Weather Integrated Forecast Tool)	China	Liang *et al.*, 2010	Radar derived reflectivity field and NWP model output	Reflectivity, precipitation rate, precipitation accumulation, Quantitative precipitation estimation, Wind, Initiation, growth decay, Hail, strong winds	0-3 hours	Extrapolation algorithm for short term, which is merged with GRAPES NWP model output for longer term forecast

TABLE 1 (*Contd.*)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
ARMOR[4] (Adjustment of Rain from Models with Radar)	Operationally run fo Cont. US by WDT Technologies	DuFran *et al.*, 2009	Precipitation forecast from a NWP model, series of radar mosaics over the same domain	Average precipitation rate	10 hour forecast at 15 minute intervals at 5 km grid spacing	Radar reflectivity mosaic is converted to precipitation rates and accumulated to 15 minute intervals. Intensity correction is applied to the model forecast, using corresponding pixels in the model and radar
Nimrod[4] (Nowcasting and Initialisation for Modelling Using Regional observation Data System)	UK Met Office	Golding, 1998	Radar-based rain analyses, satellite IR and visible radiances and NWP model forecasts	Precipitation field, probability of occurrence of fog, visibility.	0-6 hours at 10 minute intervals, updated every 20 minutes	Extrapolation algorithm for short term, which is merged with NWP model output for longer term forecast
VSRF[4] (Very-Short-Range-Forecast of precipitation)	Japan, Korea	Sugiura, 2013	Radar-raingauge Analyzed precipitation field	1 hour accumulated precipitation	1 to 6 hours	1. Forecast of precipitation by simple extrapolation method up to 3-hour 2. Merging with numerical prediction model (Meso-scale Model (MSM)) for 6-hour forecast
HRPN (High-resolution Precipitation High-resolution Precipitation Nowcasts) [4]	Japan	Kigawa, 2014	Radar-based rain analyses and NWP model forecasts	250 m resolution Precipitation	0-30 minutes	Extrapolation algorithm for short term, which is merged with NWP model output for longer term forecast
CINESat[5]	Central Austrian met. Institute (ZAMG) and the German met. office (DWD)	Scheiber, 1998	Image pixel data of a satellite image, vertical temperature profiles	Atmospheric Motion Fields, Predicted Satellite Images, Predicted Trajectories, Cloud Contour Prediction, Cloud Development Maps, Convective Cells	1, 2 and 3 hr forecasts	Forecasts are based on motion fields that describe the movement of clouds from one image to the next one
ADSTAT [6] (Advective-Statistical system)	National Weather Service, (USA)	Kitzmiller *et al.*, 1999	Precipitation field, Radar reflectivity, lightning, gauge measurements and Meteosat Second Generation (MSG) satellite data and Eta model forecasts	Probabilities of rainfall exceeding 2.5,12.5, 25 and 50 mm) at any one location within a grid box and forecast of maximum rainfall amount within the grid box for given precipitation intervals	Precipitation forecasts for the subsequent 3 hr period, updated at 30 minute intervals, at 40 km grid boxes	Predictive algorithm is based on a advective statistical approach
NOW[6]	Czech Republic	Sokol and Pesice, 2009	Precipitation field, Radar Products, lightning, gauge measurements, Meteosat Second Generation (MSG) satellite and NWP model	Probabilities of reaching or exceeding thresholds for mean 3-hourly precipitation	Precipitation forecasts for the subsequent 3 hr period in 9 km by 9 km boxes	Employs logistic regression to describe relationships between predictands and predictors. Similar technique to that of the ADSTAT model
Trident [7]	NCAR (USA), Taiwan	Mueller *et al.*, 2003	- Doppler radar - NWP winds - Human-machine Interface	Forecast thunderstorm initiation/dissipation and location, Reflectivity, precipitation rate, precipitation accumulation, Wind	0-1 hr	Semi-automated expert system: identify collision of convergence zones withradar echoes for the possibility of growth and decay using fuzzy logic and model outputs. Low level winds derived by VDRAS (Variational Doppler Radar Analysis System)

TABLE 1 (*Contd.*)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
TIFS [8] (Thunderstorm Identification and Forecasting System)	BAMS (Australia), China	Bally, 2004	Automated thunderstorm cell detections and tracks from TITAN and WDSS	Graphical and text products from the data after being edited by forecasters	Every volume scan of radar	Post-processing software. Interactively producing severe weather warnings and other forecasts from thunderstorm tracks, automatically diagnosed from radar data
THESPA[8] (Thunderstorm Environment Strike Probability Algorithm)	BAMS (Australia)	Dance *et al.*, 2010	Automated thunderstorm cell detections and tracks from TITAN	Probabilistic thunderstorm location nowcasts	Every volume scan of radar	Post-processing software. Calculates the probability of a TITAN cell passing over a point in the next 60 minutes based on the current velocity and cell size and a climatological TITAN tracking error
COSMO [9]	COSMO member countries	Doms & Schattler, 2002	NWP Model output for boundary conditions. Radar reflectivity and satellite data	Numerical model outputs	- Hourly between 0.0 to 12.0. - Half hourly between 12.0 to 24.0 - Two Hourly between 24.0 to 48.0	Non-hydrostatic limited area atmospheric prediction model for short range weather forecasts
ALADIN [9] (Aire Limitée Adaptation Dynamique développement International)	Czech Republic, Algeria	ALADIN, 2004	Numerical model for short range weather forecasts	Numerical model outputs	Forecasts are generated with 1 h time step up to 54 h	Mesoscale hydrostatic limited area model for short range weather forecasts
ARPS[9] (Advanced Regional Prediction System)	USA, India	Xue *et al.*, 2000	Radar data, NWP model for boundary conditions	Numerical model outputs	20 minute intervals for upto 21 hours	Non-hydrostatic forecast model for short range weather forecasts
University of Wisconsin Convective Initiation (UWCI) nowcasting algorithm[5]	USA	Sieglaff, *et al.*, 2011	Geostationary Satellite Imager data	Convective initiation	1 hour	Extrapolation

1: Extrapolation forecast based on Cell Tracking; 2: Extrapolation forecast based on Area Tracking; 3: Spectral decomposition or image segmentation followed by extrapolation at different scales; 4: Extrapolation algorithm for short term, Blended with NWP model output for longer term forecast; 5: Forecasts based on satellite data; 6: Prediction based on an advective-statistical approach; 7. Explicit Storm Model; 8. Post Processing Software; 9. Short range NWP model

moment in time using the WDSS-II tool "w2merger" and mapped into a 3D Cartesian field (Lakshmanan *et al.*, 2007). A neural network based fuzzy algorithm then forecasts the future locations and intensity of the area of convection, with usable forecast lead times upto three hours for the Indian region. Fig. 5 displays sample 60 minute nowcast reflectivity output from WDSS-II software for the Indian region using the data from the Indian Doppler radars.

SWIRLS (Short-range Warning of Intense Rainstorms in Localized Systems) software (Li and Lai, 2004), is an area-tracking software, developed by the Hong Kong Meteorological Office that is currently operational for the Indian region. It forecasts the future position of radar echoes through linear extrapolation of the radar reflectivity CAPPI field. It uses MOVA (Multi-scale Optical flow by Variational Analysis) which is a gridded echo-motion field that is derived from consecutive radar reflectivity fields by solving an optical-flow equation with a smoothness constraint. To capture multi-scale echo motions, the optical-flow equation is solved iteratively for a cascade of grids from coarse to fine resolutions (about 512 to 3 km). Fig. 6 displays sample 60 minute nowcast reflectivity output from SWIRLS software for the Indian region using the data from the Indian Doppler radars.
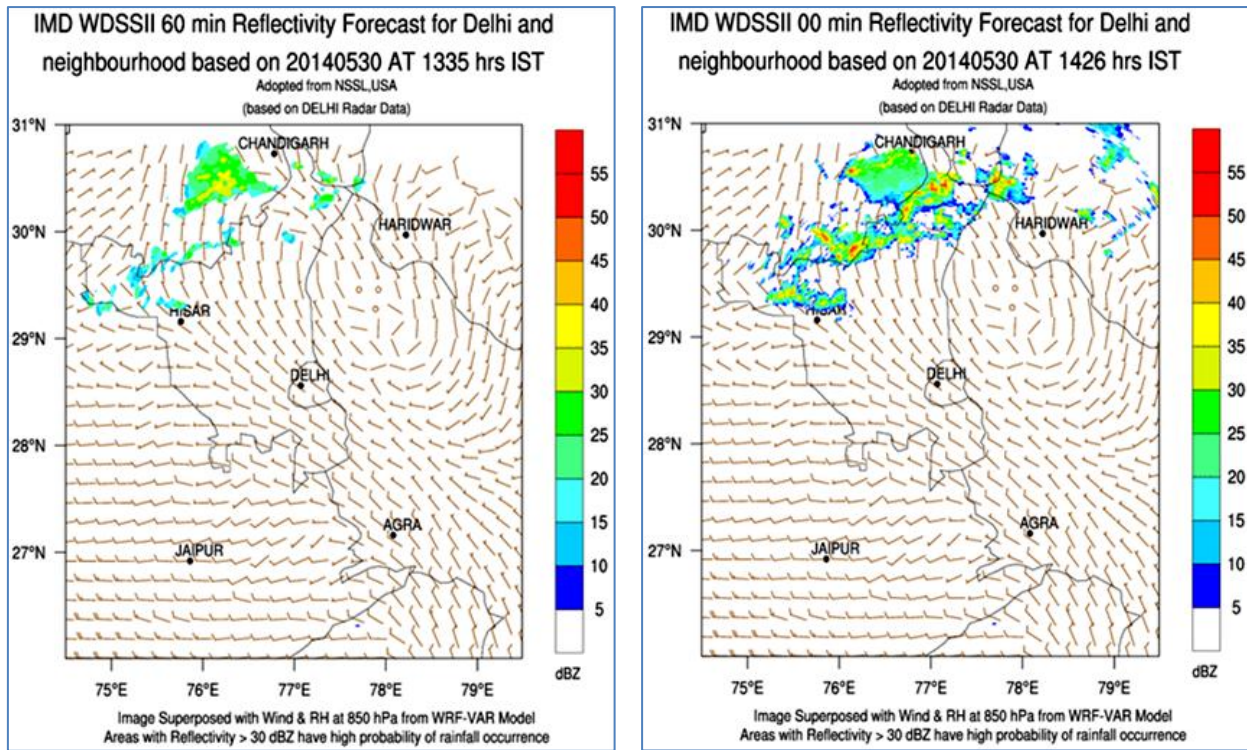
Fig. 5. Sample 60 minute nowcast reflectivity output from WDSS-II software and the corresponding reflectivity observation for the Indian region using the data from the Indian Doppler radars
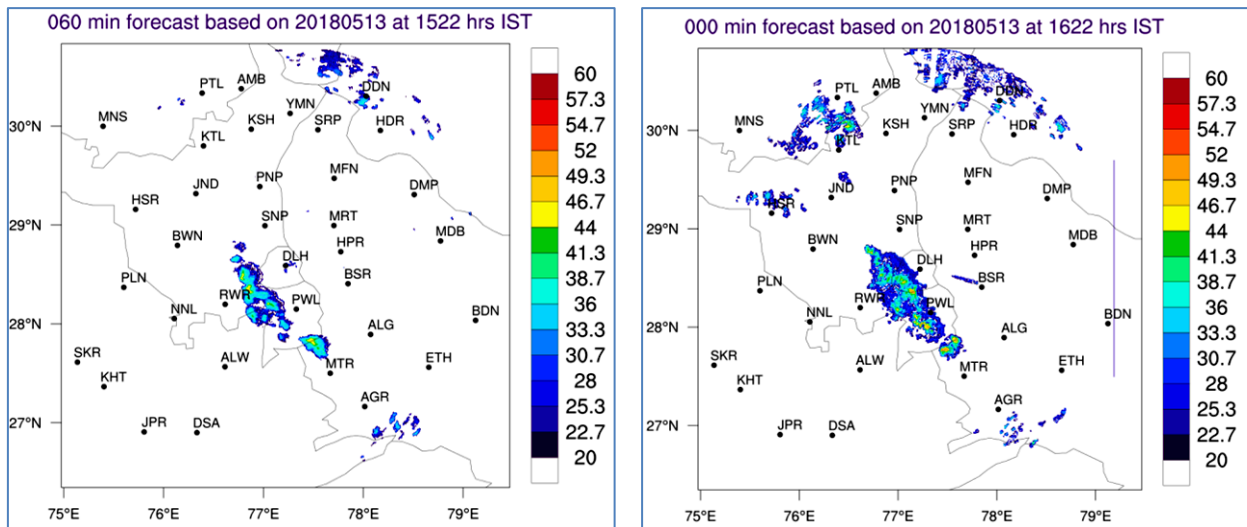

Fig. 6. Sample 60 minute nowcast reflectivity output from SWIRLS software and the corresponding reflectivity observation for the Indian region using the data from the Indian Doppler radars

To increase the accuracy, many nowcasting softwares use spectral and spatial filters to decompose precipitation patterns according to scales. WDSS-II utilizes a K-Means approach described by Lakshmanan *et al.* (2003). This allows identification of storms at different scales, estimate the motion vectors at these various scales and produce a forecast using this information. S-PROG is another spectral decomposition model which uses scale dependent temporal evolution to formulate forecasts (Seed, 2003). The usefulness of such a decomposition model is that it allows for a degree of implicit uncertainty in the final rainfall nowcast. To extend the forecast period and longer term accuracy, many softwares blend in NWP model output to nowcast model

output. For example, SWIRLS blends in the precipitation output from the nowcast algorithm, with the precipitation forecast from the NWP model (Joe *et al.*, 2012).

In addition to Doppler radar based nowcast techniques, satellite based techniques are increasingly being developed as the resolution and quality of the data in geostationary satellite radiometers is improving. A satellite based nowcasting technique implemented in IMD is a customized version of Forecast and Tracking the Evolution of Cloud Clusters (ForTraCC), which uses extrapolation technique that allows for the tracking of Mesoscale convective systems (MCS) radiative and morphological properties and forecasts the evolution of these properties (based on cloud-top brightness temperature and area of the cloud cluster) up to 360 minutes, using infrared satellite channel (10.8 μm) data (Goyal *et al.*, 2016). In addition to continuous, long period data from satellites, uniform coverage over a large area permits generation and availability of nowcast products simply and quickly to users in the National Meteorological Services of smaller or developing nations, where expertise and facilities for processing and utilizing satellite data may be limited or non-existent. With this objective, WMO has implemented a Sustained, Coordinated Processing of Environmental Satellite Data for Nowcasting (SCOPE-Nowcasting) pilot project to use the data from different satellites with a variety of capabilities from different global centres, that can be combined to give high quality basic products as well as nowcast aids to operational forecasters (Bates and Schuller, 2009).

A problem with all the above nowcast systems, based on reflectivity or brightness fields of the past, is their inability to predict any storm initiation. Expert systems is a generic name for nowcasting systems that combine one of the above mentioned techniques with other data, conceptual models and/or explicit solutions of numerical equations. The main goal of these additions on top of the techniques presented above, is the ability to predict storm initiation or decay. The AutoNowCaster software (ANC) (Mueller *et al.*, 2003) for example, produces nowcasts of convective likelihood (CL), with higher values delineating areas where storms are likely to form and be sustained and *vice versa*.

Explicit numerical forecast models that are initialized with radar and/or satellite data form a new category of nowcast systems. Due to the "spin-up" problems of NWP models (Daley, 1991), till late, these have been used only has supporting data for more heuristic techniques. This is because of a lack of suitable data assimilation scheme to input remote sensing observations and the lack of full understanding of the complex nature of convective processes. Of late, with the improvement and increased availability of computing resources that permit finer resolution model runs, as well as methodologies for faster data assimilation such as Rapid Update Cycle (RUC), newer models are being developed, for the explicit purpose of short-range weather forecasting. These models, such as WRF (Schwitalla and Wulfmeyer, 2018) and ARPS (Xue *et al.*, 2000; Pan and Wang, 2019), each with a rapid update cycle algorithm for frequent assimilation of data built into it, have demonstrated significant improvement in the short range to nowcast scale of forecasting. Studies with ARPS over the Indian region demonstrate that the model with DWR data assimilation captures the convective precipitation in the right location very well (Srivastava *et al.*, 2010).

5. Verification of automated nowcasting over the Indian region

Since the nowcast products generated automatically are a public service utility, validation of the software output for the target regions is an essential requirement before putting the products on a public portal for use. In this connection, two major Forecast Demonstration Projects (FDP) were held during the Sydney Olympics (Wilson *et al.*, 2004) and the Beijing Olympics (Wilson *et al.*, 2010) for summer convective weather nowcast systems. A major finding of the FDP during Sydney Olympics was that extrapolation techniques that allowed for differential motion performed slightly better than other softwares, since high-impact storms often have motions different than surrounding storms (Wilson *et al.*, 2004). A more comprehensive FDP for summer convective weather during the Beijing Olympics revealed the following:

(*a*) The skill levels of the numerical techniques were inconsistent without assimilation of real-time radar reflectivity and Doppler velocity fields.

(*b*) Automated blending techniques tended to be no more skillful than extrapolation since they depended heavily on the models to provide storm initiation, growth and dissipation.

(*c*) Human-machine blended forecasts provided the best outputs (Wilson *et al.*, 2010).

Over the Indian region too, WDSS-II software area extrapolation based nowcasts over Delhi have been rigorously validated (Sen Roy *et al.*, 2014). The nowcasts have been analyzed for weather systems representing three typical types of cloud systems over the region. Results indicate that the low intensity convective line zones, which are characteristic of winter and early pre-monsoon weather systems (December to March), show the most

rapid temporal change in the overall area under convection leading to large area errors. On the other hand, pre-monsoon systems (March to June), comprise mostly of isolated cells that reach great heights, move very fast but do not have much a real growth. The error in the nowcasting of these systems is mostly in respect of location error, as well as error in forecast of the intensity of the cells. The overall error in nowcasting is least for the monsoon systems (July to September) over the Delhi region, when the weather systems are longer lived and slow moving.

Over the Indian region, the ForTraCC software implemented using INSAT 3D satellite data 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 (Goyal *et al.*, 2017).

The SWIRLS software, as implemented for the Indian region has also been validated (Srivastava *et al.*, 2012). Results indicate that QPF and Reflectivity forecast based on MOVA technique in SWIRLS is capable of tracking both the large and small scale storm motion reasonably well.

6. Nowcasting efforts in the Indian context

The human-machine mix to provide nowcasts is particularly essential for a country such as India, with diverse characteristics of weather, spatially as well as seasonally. However, Nowcasting is not a new field of forecasting within India. Forecasters in the aviation sector, as represented by the Indian Air Force and the Airport Meteorological Offices issue hourly METAR bulletins for the concerned airport and sub-hourly SPECI bulletins, if there is a requirement for change. These bulletins have a Trend Type Forecast (TTF) appended to it, which is a professionally considered forecast for weather over the following two-hour period and is based on an actual weather report. Since 2013, the major change that has come about is that the nowcasts are no longer confined to only the airports but entire India.

The India Meteorological Department under the then India Department of Science and Technology started the nationally coordinated Severe Thunderstorm Observation and Regional Modeling (STORM) program in 2005, which was focused for thunderstorm prediction during the season with the most severe thunderstorms - March to June of every year (Das *et al.*, 2014). Since 2009, it became a multi-country endeavor, focused on the understanding of the mechanism of the summer Norwesters over eastern India, Bangladesh and Nepal-SAARC-STORM project. From 2017, it has evolved into a project for predicting thunderstorms only over the Indian region and is known as FDP-STORM. Most improvements in thunderstorm forecasting, observations, products and dissemination are sought to be implemented at the beginning of each FDP-STORM period.

The Commonwealth Games of 2010, first brought forth the need for nowcasting of weather for location specific nowcasts over the Indian region. Three hourly location specific nowcasting of thunderstorms, squall and hail storm was initially started for 120 cities across India by Meteorological Centres of IMD in 2013 (Ray *et al.*, 2015). The initial framework of nowcasting, as well as verification of results for the period of March to September of 2013, is discussed in detail in the above study. Since March 2017, a new system of nowcasting has been put in place by IMD to meet the growing requirements of users and various special interest user groups. In this scheme, two main changes have been brought about from the previous methodology.

(*a*) The number of stations for which nowcasts for moderate and severe thunderstorms are issued have increased from 120 to about 433 currently. This includes district headquarters and important cities all over the country, under the coverage of the Doppler weather radar network. This is an ongoing process and increasing in number with the addition of new Doppler radars over the country.

(*b*) Twice daily "Severe Weather Guidance Bulletin" is being issued from the National Weather Forecast Centre (NWFC) about potential area for occurrence of severe weather; and communicated to all Meteorological Centres all over the country for daily watch and warning. The parameters for which Guidance are issued are:

(*i*) Areas with a high probability of thunderstorm occurrence and accompanying weather in the form of gusty or squally wind, lightning or hailstorm.

(*ii*) Rainfall occurrence in the category of 0 to 25 mm, 25 to 50 mm, 50 to 100 mm, 100 to 200 mm and >200 mm.

The methodology for generation of the severe weather Guidance from NWFC is as follows:

Step 1: Analysis of weather during past 24 hours (Rainfall, Relative Humidity, Temperature, Wind, Severe Weather phenomenon like Thunderstorm, Hailstorm, Squall, Snowfall, Heat wave, Cold Wave etc.).

Step 2: Analysis of current weather observation (Synop observation, Satellite observation, Radar etc.) to evaluate:

Location, intensity and direction of movement of Synoptic Systems through analysis of the dynamic and thermodynamic characteristics of the Indian region.

Satellite Characteristics over the Indian region.

Step 3: Identification of weather systems in text and graphics (Area of location, Current intensity, past evolution in terms of intensification and movement).

Prepare summary of synoptic, dynamic and thermodynamic characteristics in the form of checklist.

Step 4: Evaluation of model guidance.

Evaluate each model by comparing their initial condition and performance of their forecast during past 24 hours (by assessing skill and bias) especially with respect to synoptic scale system and severe weather.

Examine forecast of each model for next 24 hrs for different severe weather phenomenon.

Step 5: Development of consensus forecast.

Give more weightage to the best model based on Step 4.

Remove outliers (Models).

Develop consensus on weather system based on various model guidance on Synoptic, Dynamic and Thermodynamic Characteristics.

Develop consensus on the predicted severe weather by different models.

Add Subjective consensus to the Objective consensus developed above by Step 3 and Step 4. Subjective consensus will be based on the video conferencing, experience, knowledge and expertise of the forecaster in interpretation of Synoptic, Dynamic, Thermo-Dynamic and model guidance.

Prepare final consensus Severe Weather Guidance for next 24 hours in both text cum graphic format.

Step 6: Write prognosis and Diagnosis (Text Form) during Storm season.

Step 7: Disseminate Severe Weather Guidance bulletin to all MC/RMC/AMO by E-mail.

Step 8: Follow up action.

Real time round the clock monitoring of occurrence of weather and weather system on hourly basis (both instant and cumulative effect).

As and when situation arises, trigger the concerned MC/RMC to update and issue Nowcast warnings.

Since March 2018, a new nowcast service-district level nowcast warnings for severe weather in the form of the "Nowcast Warning Bulletin" is being issued as required, by all Meteorological Offices through SMS/whatsapp/Phone/E-mail. These warnings are more nuanced and include information for rainfall, thunderstorm and associated hazards, associated wind speed and any other phenomenon that is likely to affect the public. The message is being disseminated to District Collectors, National and State Disaster Management Agency, Power sector, Media including All India Radio and Doordarshan for wide public disseminaton and relief action. The format of the message is included as Appendix 1.

The step-wise procedure for issuing the nowcast warnings by the meteorological centres, on the basis of the Severe Weather Guidance from NWFC is given in Appendix 2. Additionally, in 2017, in addition to the nowcast warnings page, for the first time, a separate Nowcast web page (http://srf.tropmet.res.in/srf/ts_prediction_system/index.php) was created where, in addition to nowcast warnings, various tools for the aid of nowcasting created by the Indian Institute of Tropical Meteorology, National Centre for Medium Range Weather Forecasting, India Meteorological Department and other centres of the Ministry of Earth Sciences are made available to forecasters on a common platform.

7.   Verification of operational nowcasts

The new methodology, coupled with the improved forecast aids have resulted in substantial improvement in operational forecasting of thunderstorms for the Indian region. Figs. 7 (a&b) displays the verification statistics for (a) the daily Severe Weather guidance for thunderstorm occurrence issued by the nowcast unit of
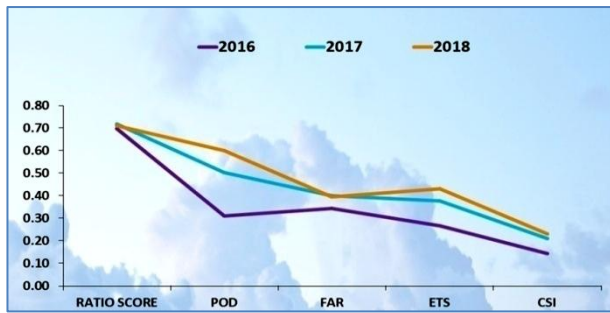
Fig. 7(a). Verification statistics for the daily 24 hour severe weather guidance for thunderstorm occurrence issued by the nowcast unit of NWFC at IMD HQ during the FDP STORM period over three years 2016, 2017 and 2018
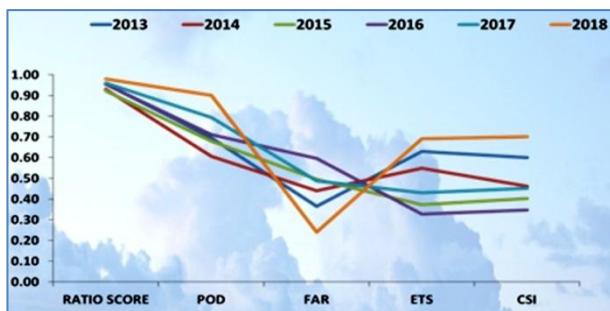

Fig. 7(b). Verification statistics for the three hourly nowcast guidance issued by various Meteorological Centres and its performance during the FDP STORM period over six years 2013 to 2018 respectively

NWFC at IMD HQ during the FDP STORM period over three years 2016, 2017 and 2018 and (b) the three hourly nowcast guidance issued by various Meteorological Centres and its performance during the FDP STORM period over six years 2013 to 2018 respectively. For the daily guidance, the occurrence/non-occurrence is calculated on subdivision scale. The verification of the three hourly nowcast warnings are calculated at a higher resolution for each station for the occurrence/non-occurrence of a thunderstorm event for which nowcast is generated. Since operational thunderstorm forecastsare dichotomous - (0 or 1 indicating nonoccurrence-occurrence), their verification is carried out using a standard 2×2 contingency table for categorical variables (Gotway *et al.*, 2018). Five scores, namely, (*i*) Ratio Score (*ii*) Probability of detection - POD (*iii*) Equitable Threat Score - ETS (*iv*) Critical Success Index - CSI (*v*) False Alarm Ratio - FAR are calculated. For a good forecast, the first four variables should be close to or equal to 1, while the FAR should be close to 0. The statistics that reveal that the accuracy of nowcasting has shown marked improvement in the last two years 2017 & 2018 on account of the recent modifications in the nowcast procedure.

8.   Outlook and challenges for the future

IMD is in the process of augmenting its network of surface and upper air observatories as well as its radar network. In addition to the current network of 25 Doppler Weather Radars, there are plans to install 22 new Doppler Radars by 2024. This will be supplemented by the Air Force Doppler Weather Radar network. From the present network of 62 Pilot Balloon stations and 43 GPS sonde stations, there is a proposal to increase the number to 100 Pilot Balloon stations & 120 GPS sonde stations by 2024.

The format of the warnings must be standardized to global standards. The communication network and the mode of dissemination of the warnings play a major role in increasing the efficiency and effectiveness of the weather forecasts. Currently, the warning messages are being disseminated through whatsapp, sms and e-mail. However, this still has limited coverage. GAGAN (GPS Aided Geo Augmented Navigation) Message Service (GAMES) is currently being put in place by the Airport Authority of India to provide a warning message broadcast facility for timely delivery of warnings to a large number of users over a wide spatial coverage. The Common Alerting Protocal (CAP) is an international standard format for emergency alerting and public warning designed for "all-hazards". The NDMA is coordinating with IMD, DoT and other stakeholders to implement CAP in the country through the "Integrated Disaster Messaging Service". This will permit deeper penetration of the nowcast warnings to other sectors such as Roadways, Railways and Power sector. The farming community is currently a major risk prone sector for severe weather associated with thunderstorms. Each year, many thousand hectares of standing crops are destroyed due to hail storms and squally or gusty winds. A major cause of weather related deaths in the rural farming community of India is in association with lightning due to thunderstorms (Fig. 1). Currently efforts are being made to penetrate this sector through the Gramin Krishi Mausam Seva Kendras (GKMS). The warnings page of the Nowcast portal is linked to the GKMS site and severe thunderstorm warnings are disseminated through SMS to registered farmers. However, awareness of the events and remedial measures for affected people is still very low.

The huge human cost of lightning related deaths in recent years, has brought about action from many affected state governments. For the region of Maharashtra, Indian Institute of Tropical Meteorology, Pune, using the Lightning Location Network mentioned earlier, has developed a Mobile App, DAMINI LIGHTNING. This App gives exact location of current lightning strikes, probable locations of impending lightning around an area of 40 sq. km and direction of movement of thunderstorm.

DAMINI also lists precautionary steps to be taken during lightning and some general information on lightning. A Lightning Early Warning System (LEWS) has also recently been operationalized in Karnataka. The Government of Andhra Pradesh has set up a Lightning Monitoring Mechanism in the State Emergency Operation Centre (SEOC) in coordination with Earth Networks. Other state governments such as those of Bihar and Odisha are also setting up similar networks and also investing in outreach programs to educate the general public about the damages and associated preventive actions to take during the occurrence of thunderstorms. In this connection, the National Disaster Management Authority is taking a lead role in informing and educating the public about preventive action to be taken for severe weather in association with thunderstorms. A draft "Guidelines for Thunderstorm & Lightning/ Squall/ Dust/hailstorm and Strong wind" (https://ndma.gov.in/ images/pdf/Draft-Guidelines-thunderstorm.pdf) has been brought out by the agency in 2018, detailing the respective roles of different government agencies for action to be taken on the basis of the nowcasts issued by IMD.

A major lacuna in thunderstorm forecasting, despite the improvement of the forecast capabilities in the recent years, is the absence of proper understanding of the spatial variation of the intensity and type of thunderstorms in an atmosphere primed for convection and their impact. The correct thumb rules with regards to dynamic and thermodynamic conditions for occurrence of severe thunderstorms, have to be developed for sub-regions of the Indian subcontinent, to improve the quality of the nowcasts.

Measuring such events in entirety is also a major challenge in view of the mesoscale nature of these weather systems. Under the SAARC STORM program, a multi-country mesonet comprising of surface and upper air instruments was set up to study thunderstorm characteristics over one of the most frequently thunderstorm prone areas of the world, namely Eastern India and Bangladesh (Das *et al.*, 2014). A similar meso-network over Maharashtra is in the process of being set up, comprising 100 AWS and 3 X-Band radars.

The numerical weather modeling community of India is also contributing in a big way to develop new algorithms and customized products for improvement in thunderstorm forecasting. A new set of products have been introduced by the Indian Institute of Tropical Meteorology at Pune and National Centre for Medium Range Weather Forecasting at NOIDA, for forecast of lightning, wind gusts, as well as other weather phenomena associated with severe thunderstorms in the short range scale. These products have been introduced on experimental basis during 2019, and have already proven to be very useful for the forecast of thunderstorms. These products are also displayed in the Thunderstorm Nowcast web page.

Nowcasting is a developing field of services and it is hoped that with accurate forecasts and suitable mitigation measures will contribute to the well being of the general public. Hence a lot more research is necessary in the impact assessment of the thunderstorms to better prepare the public about the effect of the thunderstorms.

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ANNEXURE 1

Format for issue of Severe weather Nowcast in TEXT format

Time of issue…..

………………… (e.g. Thunderstorm/Dust storm etc.) …..………likely to affect ……….…. District/ ………..within next ……... hours. It may be accompanied with …..………………..and strong winds reaching ………………..kmph   or more.

………………… (light/ moderate/ heavy) rainfall. likely to affect ……………… District/ ………..……..within   next …….. hours.

Visibility may reduce to below …………….metres during the period.

………………….……..district/region is likely to be affected by fog for the next ….hours, reducing visibility to   below …………….metres.

Signature

To:

User1

User2

ANNEXURE 2

DECISION TREE OF NOWCAST CENTRE