A location-specific nowcast and SMS-based dissemination system for thunderstorm and lightning warning over Jharkhand, India

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Effective nowcasting for thunderstorms has been a challenge to operational forecasters in Jharkhand, India as lightning strikes-related deaths are significantly high. Extrapolation of radar echoes is the very foundation of nowcasting. Multiple radar mosaic data are able to pick out the size, shape, intensity, speed and direction of movement of individual storms on a continuous basis. This makes it possible to determine the likely location of a moving storm by extrapolation. This article demonstrates a new approach of location-specific nowcast and SMS (short message service)-based dissemination system for thunderstorm and lightning warning up to 3 h ahead over Jharkhand. There are three components of the system. First, identification of the initial development and tracking of thunder cells by mosaic composite reflectivity data from multiple radars. The future location of thunder cells, and their growth or dissipation in terms of radius is estimated by extrapolation using their past trends. Secondly, based on this forecast information, an SMS is generated by the web-based GIS portal of Jharkhand Space Applications Centre for the forecast location and sent to the concerned state officials and mobile service providers over that region. Finally, the warning SMS is sent to all the active mobile users over that region at that time. The system combining nowcasting and dissemination of warning directly to the likely affected people is expected to be more robust considering its effectiveness in the reduction of human casualty.

Keywords: Dissemination system, lightning, nowcast, short message service, thunderstorm.

JHARKHAND is a state in the eastern part of India where the main seasons are pre-monsoon, summer season, monsoon season and winter. According to the India Meteorological Department classification, March, April and May constitute the 'hot weather period' also known as the 'pre-monsoon season'. This season is mainly dominated by the convective type of weather (thunderstorms, dust storms, hailstorms and their associated features). This is followed by the monsoon season when thundershowers are the most common features of the weather. Major deaths and injuries over Jharkhand are attributable to lightning activity. Additional hazards that can occur include large hail, flash flooding associated with heavy rainfall, and damage from wind due to thunderstorms; but associated damages over Jharkhand from these events are comparatively less.

The terms 'nowcasting' and 'dissemination' are used to highlight the forecasts that are time- and location-specific for periods less than a few hours (1–3 h) and their transmission to the users for effective utilization. Nowcasting is particularly important to aviation, sporting events, power sector, surface transportation and, most importantly, to minimise human casualty. The primary tools for detecting convective cells are (a) Doppler weather radar, (b) satellite imagery with cloud-top temperature and (c) lightning detector array network. Since radar data are available in fine temporal and spatial resolution (minutes and less than a kilometre), they can provide a three-dimensional view of the development of a thunderstorm cell. Very short-range forecasting of the future location of convective cells has generally been based on the extrapolation of radar reflectivity echoes. In view of the high casualty due to lightning over Jharkhand, the main objective of this article is to describe an effective nowcasting and dissemination system for thunderstorms and lightning which has been implemented in Jharkhand recently.

Data used

Data on frequency and time of occurrence of thunderstorms, and rainfall data over the nowcast area were obtained from the records of IMD (India Meteorological Department), Meteorological Centre, Ranchi. The record of death tolls in Jharkhand due to the thunderstorms and lightning was taken from the Department of Disaster Management, Government of Jharkhand. Twenty-five Doppler weather radars (DWRs) located all over India provide reflectivity round the clock at 10 min scanning interval[1]. Figure 1 shows the DWR network of IMD over

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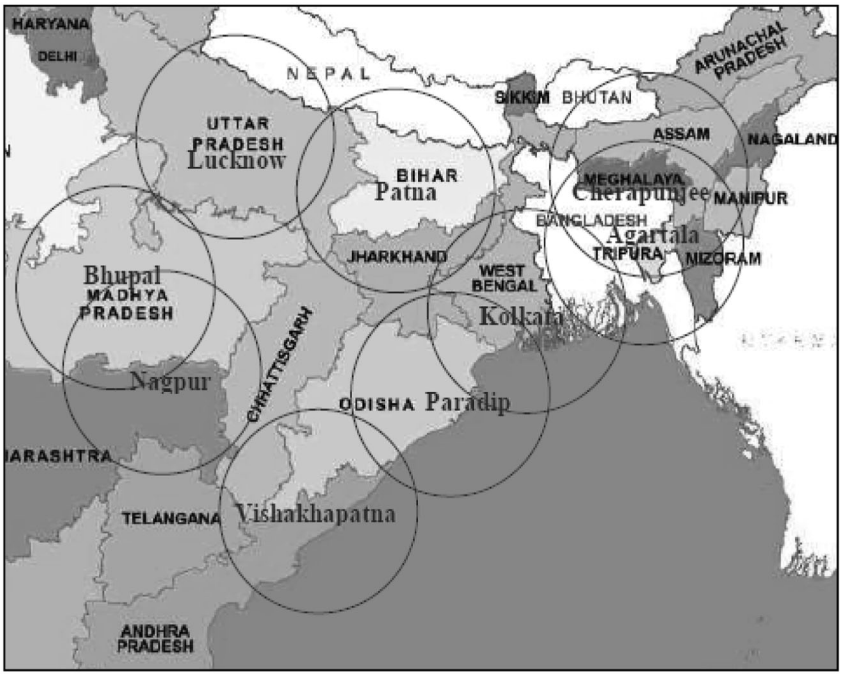

Figure 1. Doppler weather radar network of India Meteorological Department over Jharkhand and the surrounding states.

Jharkhand and surrounding states. The evolution of convective cells in terms of space and timescale was monitored using DWR of resolution 1 km available at 10 min intervals and INSAT-3D satellite. The cloud-top temperature-based colour-coded imagery on IR 10.8 μm channel (MSG-1:SEVIRI) of spatial resolution 3×3 km and locations of lightning flashes overlaid on satellite imagery from the Indian Air Force lightning detector network were also used.

Climatology of thunderstorms and associated casualties over Jharkhand

Jharkhand is prone to severe convective activity during pre-monsoon season (March–May) and monsoon season (June–September). During the pre-monsoon months, the Bihar Plateau and adjoining areas usually come under the influence of an extended trough (or wind discontinuities) caused due to solar heating, which becomes more intense in the afternoon. Trough lines (or wind discontinuities) generally extend from the Bihar Plateau southwards to Chhattisgarh. When the seasonal high over Bay of Bengal (BoB) is situated over the north and the adjoining west central BoB, the southerlies to the east of the trough become strong leading to a well-marked inflow of moisture from BoB into Jharkhand and adjoining areas leading to good nor'wester activity over the state. In some cases, the seasonal westerly and southwesterly winds from anticyclonic circulation over BoB also trigger thunderstorm activity by forming a confluence zone over Jharkhand and adjoining areas. Some of these thunderstorms develop over Bihar Plateau, Chhattisgarh or west Odisha and travel east or southeastwards towards Jharkhand. In some cases, there was *in situ* development of thunderstorms due to conditional and convective instabilities.

The mean annual frequency of thunderstorms in Ranchi was 81 days for the period (2015–19). Highest frequency of thunderstorms was observed 15 days in June followed by 13 in July and 12 in August. Figure 2 *a* illustrates the monthly total number of thunderstorms recorded by the IMD observatory at Ranchi during 2015–19. The frequency of thunderstorms is observed highest in month of June every year (onset of monsoon). During 24 h of a day, if at least one thunderstorm occurrence case is recorded in any time of the day, then that day is considered as a thunderstorm day. Probability of initiation of thunderstorms was found to be 63% and 64% during 1200–1800 h IST, and about 21% and 17% during 1800–0000 h IST in the pre-monsoon and monsoon seasons respectively (Figure 2 *b*). The total number of reported deaths in Jharkhand due to the thunderstorms and lightning during the past five years (2015–19) was 1076 or on average about 215 per year (Figure 3) (Department of Disaster Management, Government of Jharkhand). Therefore, there is an urgent need to address this natural catastrophe comprehensively by accurate prediction of thunderstorms/lightning and dissemination by effective means.

Nowcasting techniques

Nowcasting techniques for thunderstorms can be divided into three types. First is the historically and widely used extrapolation technique assuming change in motion, size and intensity based on past trends. The second allows convection initiation/dissipation based on past training dataset. Finally, the third is the explicit numerical prediction of thunderstorms.

Extrapolation

Nowcasting of severe thunderstorms/lightning is generally extrapolated from satellite imagery or radar echoes[2]. Nowcasting of thunderstorms/lightning refers to the prediction of possible areas and timings of lightning activity that may occur within a short period of time (0–3 h). The parameters observed by radar (radar reflectivity) and satellite (lightning, cloud-top temperature) close to where the lightning occurs are used for nowcasting. Extrapolation algorithms are used to predict lightning activity areas and the probability of development, evolution, movement and dissipation in the next 0–3 h. Forecast techniques based on extrapolation are limited for individual thunderstorm cells of short lifetimes. Many previous observational studies have shown that individual, small convective cells have shorter mean lifetime[3,4], but a study also showed that cells which merged with one another have longer lifetime[3]. The speed of convective cells varies with their size[5], and lifetime and motion are dependent on the scale of the convective phenomena[6]. Large thunderstorm cells can often be extrapolated for much longer time-periods than smaller cells[7]. Various approaches of nowcasting for severe weather have been documented in a recent study[8].

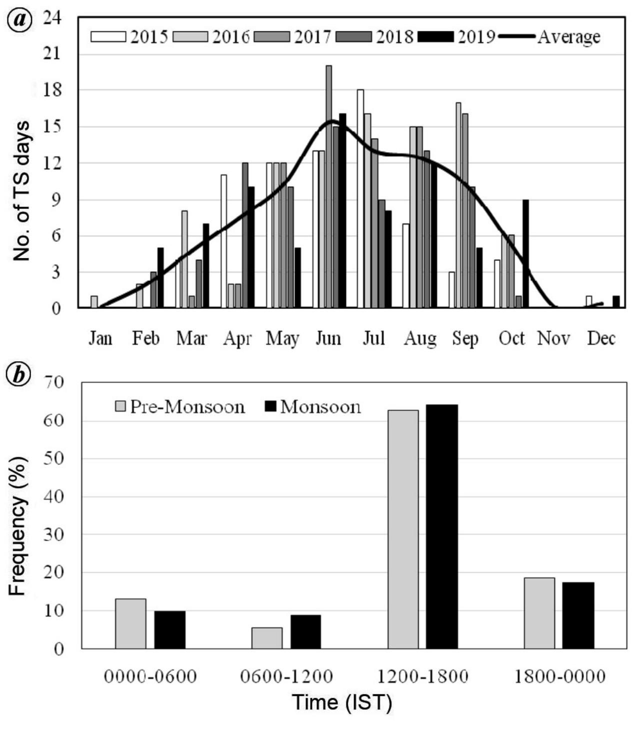

Figure 2. (***a***) Mean annual frequency and (***b***) diurnal variation of frequency of thunderstorm at Ranchi during 2015–19.

Numerical prediction

In recent years, the blending of traditional extrapolation-based techniques with high-resolution numerical weather prediction (NWP) models is a significant development in nowcasting. Blending of radar echo was used in the extrapolation with a numerical model in nowcasting and initialization for modelling using regional observation data system (NIMROD)[9]. Many previous studies have shown that forecasts from a high-resolution model of a few kilometres (convection-permitting scale) can produce more skillful guidance than those from a coarser-resolution model with convective parameterization[10,11]. Although improved weather forecast of high-resolution NWP models is notable, the improvement is inadequate for nowcasting application[12].

Thunderstorm forecasting

Three necessary conditions for the development of thunderstorms are simultaneous occurrence of sufficient atmospheric moisture, convective available potential energy (CAPE) and a lifting/triggering mechanism. All these aspects along with guidance from various numerical models and thermodynamic indices are taken into consideration to forecast for five days. There are three spatial scales[13]: (i) meso-gamma scale of a few kilometres with a lifetime of less than 1 h, (ii) meso-beta scale of 20–200 km with a lifetime of less than 6 h and (iii) meso-alpha scale of 200–2000 km with a lifetime of more than 6 h. Predominantly the meso-beta and meso-gamma scales occur in the pre-monsoon season over the Indian region[8]. The evolution of these systems in terms of space- and timescale is monitored on a continuous basis using observations from DWRs and satellites. Presently, nowcasts are issued mentioning thunderstorms and lightning over parts of some districts typically as ‘Moderate thunderstorm accompanied with lightning likely to affect some parts of Ranchi and Dhanbad districts within two to three hours’. The warnings are disseminated through

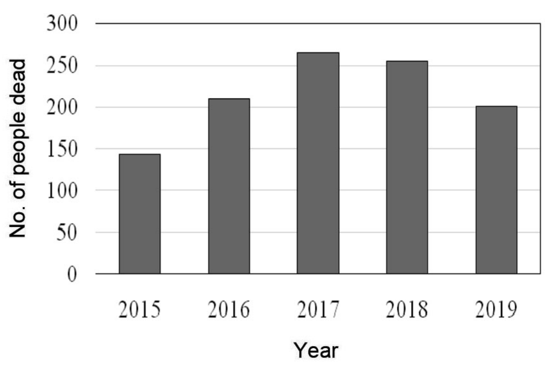

Figure 3. Yearwise death toll over Jharkhand due to thunderstorm during 2015–19.

website, e-mail and WhatsApp to a group of people only, including State Disaster Management Authority (SDMA), district collectors, media, railways, Public Works Department officials, defence personnel. The major shortcoming in the warning bulletin is absence of customized warning at sub-district level and timely dissemination to specific targeted users.

Location-specific nowcast and SMS-based dissemination systems over Jharkhand

In view of high human casualties due to thunderstorms and lightning strikes and less efficacy of the present warning system, a three-step approach for location-specific nowcast and SMS-based dissemination systems (LN-SMS-DS) has been formulated to issue warning of expected thunderstorms and lightning. Such warning is issued over a particular area for a specific period of time using satellite and radar, and disseminated effectively to mobile users active over the region by joint collaboration between IMD Meteorological Centre, Ranchi, Jharkhand Space Application Centre (JSAC) (Government of Jharkhand) and SDMA.

A study showed that there are downward trends in information content of the theoretical limits of predictability[9]. This reflects the fact that there is an inevitable loss of information with forecast lead time in a chaotic system like the atmosphere. The initial information capture by DWRs in the form of echo of storms is nearly perfect. For nowcasting method based on extrapolation, information losses with forecast time are due to non-representation of atmospheric physics. Whereas limited resolution and imperfect assimilation algorithms introduce relatively poor representation of the observed state in NWP models. Figure 4 shows a schematic representation of characteristics of error distribution of extrapolation forecast and mesoscale NWP forecast[9]. The figure also indicates least forecast error of extrapolation than NWP forecast for a short period of time. Previous studies showed that extrapolation techniques perform better than, others for a shorter range of time[14,15]. They also showed that the skill of NWP models is inconsistent, automated blending techniques are less skillful than extrapolation, and human–machine-blended forecasts are superior to all other techniques for nowcasting.

In view of the above shortcomings and advantage of the extrapolation technique over NWP for a shorter range of time, a novel approach has been adopted for area-specific warning based on extrapolation and dissemination. The LN-SMS-DS approach has three components and two assumptions. The two assumptions are: (i) a storm cell tends to move along a straight path and (ii) growth or decay of a storm cell follows a linear trend. The three components are: (i) nowcasting, (ii) transmission to JSAC and (iii) dissemination. Figure 5 shows the flow diagram of LN-SMS-DS.

STEP-I: nowcasting

Presently weather systems, particularly thunderstorms, are monitored by radar reflectivity echoes generated from multiple radars as a mosaic product of higher spatial and temporal resolution (Figure 1). A 1 km resolution mosaic of radar echo projected on a GIS platform is generated at

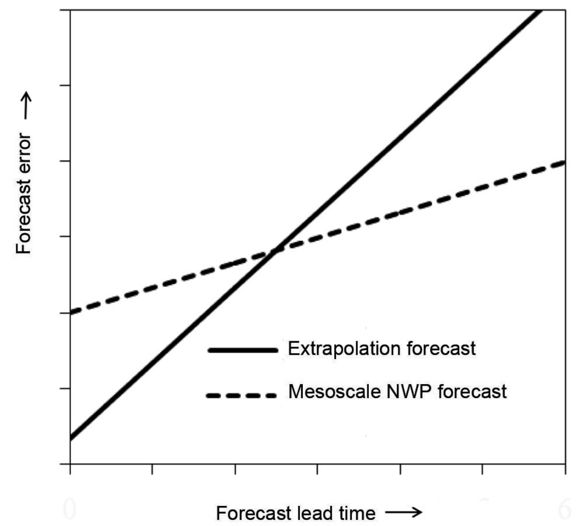

Figure 4. Schematic representation of the characteristics of error distribution of extrapolation forecast and mesoscale NWP forecast.

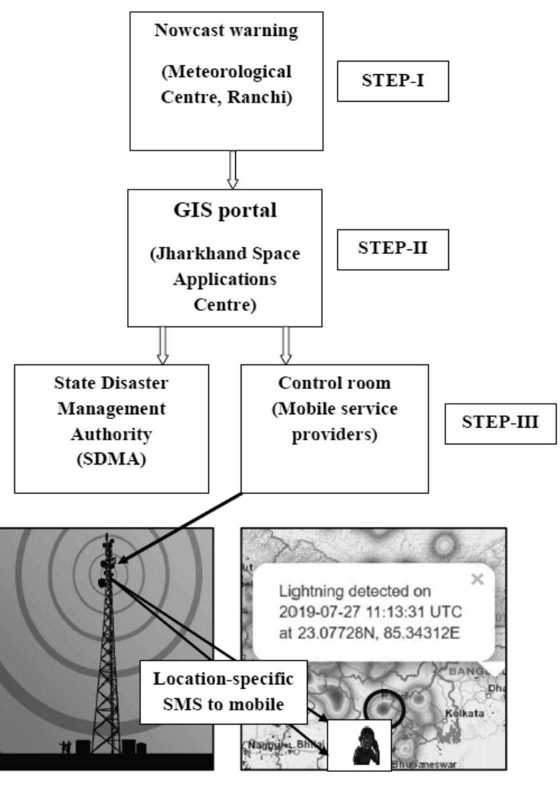

Figure 5. Flow diagram of location-specific nowcast and SMS-based dissemination system (LN-SMS-DS).

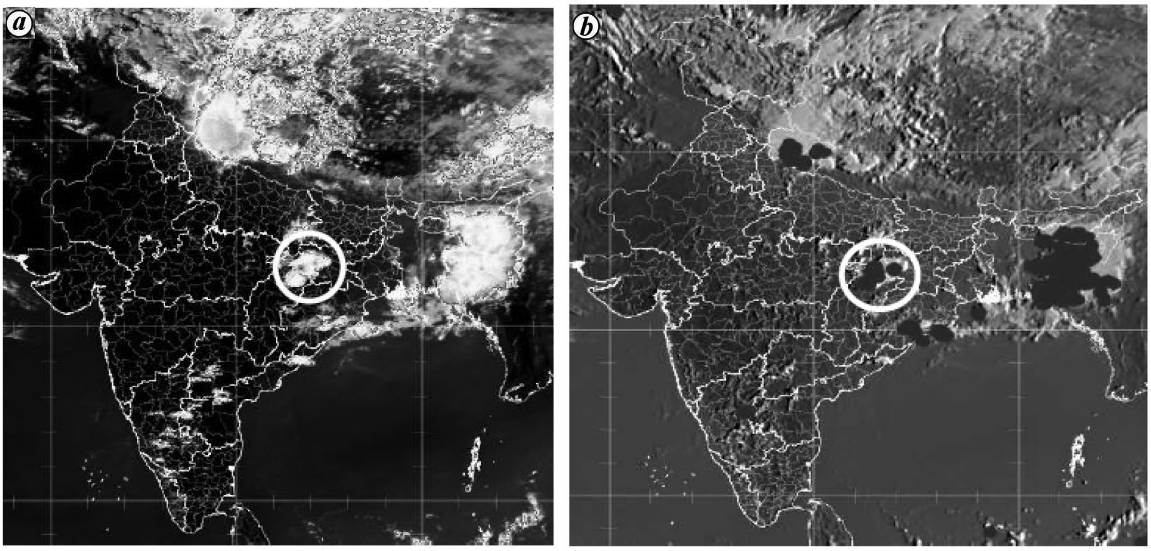

Figure 6. ***a***, Cloud-top temperature-based colour-coded satellite imagery (8 April 2019 at 0900 UTC) on IR 10.8 μm channel (MSG-1:SEVIRI). ***b***, Lightning flashes overlaid and marked with red dots over the satellite imagery (8 April 2019 at 0830 UTC) of MSG-1:SEVIRI.

10 min interval. The cloud-top temperature-based colour-coded satellite imagery of spatial resolution 3 × 3 km on IR 10.8 μm channel (Figure 6 *a*) and lightning flashes overlaid and marked with red dots over the satellite imagery (Figure 6 *b*) are also available to substantiate the radar-based monitoring system. Two important components of monitoring of thunderstorms and lightning are identification of development, and movement of convective cells. Thunderstorms and lightning at a location may occur either due to *in situ* development, or migration of a convective cell from surrounding areas. *In situ* development and migration of a cell and its growth/decay at a location are identified and monitored by successive observations of radar imageries available at 10 min interval. Animation of lightning images overlaid over satellite cloud imageries is also used to monitor the development and migration of a cell. Thunderstorms and lightning over a location are nowcasted by monitoring the past trend of development and movement of convective cells through extrapolation.

In this first component, mosaic radar product and satellite lightning imagery are used to identify the expected area of lightning considering the present location and past movement of a thunder cell. The centre of the cell is located by latitude and longitude, and radius of the cell is estimated from radar mosaic product projected on the GIS platform.

Figure 7 shows a schematic diagram of the extrapolation. In the figure, $B(\varphi_1, \lambda_1)$ is the centre of a present thunderstorm cell and $C(\varphi_3, \lambda_3)$ is the centre of the cell at the extrapolated location.

The radius (r) is calculated by estimating centre $B(\varphi_1, \lambda_1)$ and any point $P(\varphi_2, \lambda_2)$ on the circumference of the cell, where φ is the latitude and λ is the longitude. From the spherical law of cosines[16], the distance (r) between two points (B, P) is given by

$$r = R * \mathrm{acos}(\sin(0.0174533 * \varphi_1) * \sin(0.0174533 * \varphi_2) + \cos(0.0174533 * \varphi_1) * \cos(0.0174533 * \varphi_2) * \cos(0.0174533 * \Delta\lambda)),$$

where R is the radius of earth (mean radius = 6371 km) and $\Delta\lambda = \lambda_2 - \lambda_1$.

A sample mosaic radar product of 1 August 2019 at 0930 UTC is presented in Figure 8 for graphical visualization. As shown in the figure, the red and blue circles indicate the initial and forecast position of the cell respectively. The black arrow indicates the direction of past movement of the cell and the red arrow indicates expected future movement based on past movement.

In Figure 8, a single cell is identified by a single circle (marked as *S*), and for an elongated (curved/line) cell, the whole curved/line cell and its movement is identified by multiple number of circles (marked as *M*).

In Figure 7, vector *AB* indicates past movement of the cell.

The extrapolation vector $BC(d)$ and vector direction angle Ψ are given as follows.

$$D = R * \mathrm{acos}(\sin(0.0174533 * \varphi_1) * \sin(0.0174533 * \varphi_3) + \cos(0.0174533 * \varphi_1) * \cos(0.0174533 * \varphi_3) * \cos(0.0174533 * \Delta\lambda)),$$

where R is the radius of earth (mean radius = 6371 km), $\Delta\lambda = \lambda_3 - \lambda_1$ and the vector direction angle

$$\Psi = \tan^{-1}\frac{|CD|}{|BD|},$$

A simple Excel-based software is used to extrapolate the centre of the forecast location and size of the cell.

Finally, all the information such as number of thunder cells, date, time of issue, validity time, centre (latitude and longitude) and radius of the cell, and thunderstorm and lightning warning are presented in a required format in a 'nowcast.csv' file (Table 1).

Step-II: Transmission to JSAC GIS portal

The file 'nawcast.csv' is provided on-line to the 'GIS portal' of JSAC.

This web-based GIS portal identifies the specific locations based on information (latitude, longitude, radius (km) contained in the nowcast.csv file.

The portal also generates an SMS containing information on locations of thunderstorms/lightning, latitude, longitude, radius (km) and suggested action as given in the nowcast.csv file.

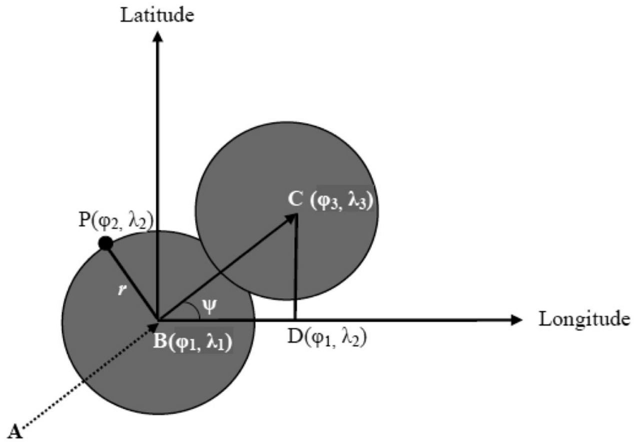

Figure 7. Schematic diagram of extrapolation of thunderstorm cell.

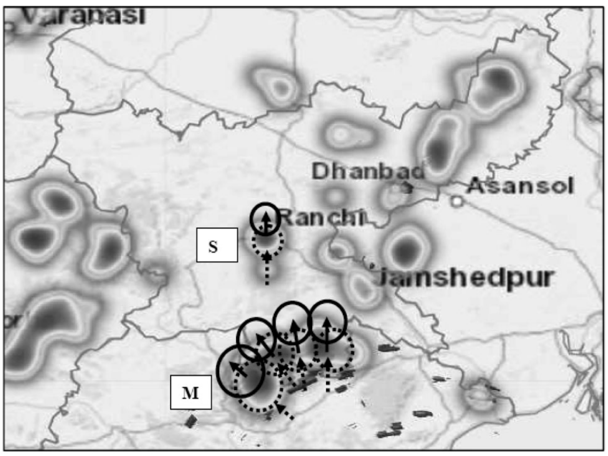

Figure 8. Mosaic composite reflectivity data from multiple Doppler weather radars for single cell (S), and elongated multiple cells (M) of 1 August 2019 at 0930 UTC.

The portal has a component to connect automatically to all concerned registered SDMA officials at the district, block, and panchayat levels, and transmit thunderstorm and lightning warning to their mobile phone.

The GIS portal also has another component to connect with mobile service providers of the affected area only to provide automatically generated SMS.

Step-III: Dissemination of warning

In the final step, the mobile service providers will disseminate thunderstorm and lightning warning SMS as received from the GIS portal, typically as 'thunderstorm/lightning is very likely in your locality, please seek safe shelter. Address: Chatra, Paratappur, Daunapur. Latitude: 24.40, longitude 84.63, radius 20 km' in the local language (Hindi) to mobile users active over the region only. Therefore, the SMS will be disseminated to people in the locations identified by the web-based GIS portal as mentioned in the nowcast.csv file in terms of centre and radius during the validity period of forecast time. The dissemination of location-based early warning of thunderstorms/lightning with suggested action through automatic mobile SMS to people of the location up to 3 h ahead will help them take precautionary measures and also in the reduction of human casualty.

Evaluation of nowcasts

Various thermodynamic indices show inconsistency in predicting thunderstorm activity. For example, thunderstorm occurred under the condition of very low CAPE and vice versa. Evaluation of the accuracy of nowcasts is also difficult. Thunderstorm forecast in pre-monsoon season is closely tied to the observed precipitation. Rainfall over the nowcast area is assumed to be associated with realized thunderstorm during pre-monsoon season, but rainfall during monsoon season cannot be considered as

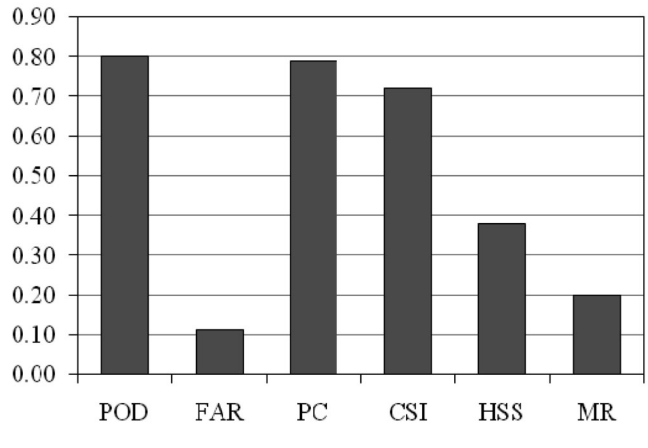

Figure 9. Nowcast skill score for the pre-monsoon season of 2019.

Table 1. Sample input for the GIS portal (as nowcast.csv file)

TS cell no.	Date	Time of issue (IST)	Validity time (IST)	Centre of cell Latitude (N)	Centre of cell Longitude (E)	Radius of cell (km)	Nowcast warning
1	05.03.2020	1500	1700	24.40	84.63	20	'Thunderstorm/lightning is very likely in your locality, please seek safe shelter. Address: Chatra, Paratappur, Daunapur. Latitude: 24.40, longitude 84.63, radius 20 km' (in local language Hindi)
2							

Table 2. Contingency table for categorical variables

	Observations →	
Forecast ↓	Thunderstorm	No thunderstorm
Thunderstorm	a (YY)	b (YN)
No thunderstorm	c (NY)	d (NN)

a, No. of hits (predicted and observed). b, No. of false alarms (predicted, but not observed). c, No. of misses (observed, but not predicted). d, No. of correct predictions of no thunderstorm (neither predicted nor observed).

associated with realized thunderstorm, because monsoon rainfall is also associated with stratiform clouds[17]. Therefore, three-hourly nowcast warnings issued in the pre-monsoon season 2019 were verified. The standard method according to the guidelines of World Meteorological Organization for verification of dichotomous (yes/no) forecasts was followed using contingency table[18]. The familiar statistical metrics such as probability of detection (POD) and false alarm ratio (FAR) do not adequately represent the performance because correct forecast of a non-event or slightly missing forecast of an event in time or space is not reflected. Therefore, statistical measures should not be taken at face value. Nevertheless, the statistical metrics POD, FAR, per cent correct (PC), critical success index (CSI), Heidke skill score (HSS) and missing rate (MR) are computed for forecast skill using a 2×2 contingency table (Table 2)[19].

(i) Probability of detection: A measure of discrimination, POD is defined as the number of hits divided by the total number of events observed.

POD = $a/(a + c)$. Range: 0 to 1. Perfect score: 1.

(ii) False alarm ratio: A measure of reliability, FAR is defined as the number of false alarms divided by the total number of events forecast.

FAR = $b/(a + b)$. Range: 0 to 1. Perfect score: 0.

(iii) Critical success index: This is a value of warnings which combines hit rate and false alarm ratio into one score. It is calculated as follows:

CSI = $a/(a + b + c)$. Range: 0 to 1. Perfect score: 1.

(iv) Heidke skill score: This is a measure of the fractional improvement of forecast over the standard forecast.

$$\mathrm{HSS} = \frac{2(ad - bc)}{(a+c)(c+d)+(a+b)(b+d)}.$$ Range: $-\alpha$ to 1. Perfect: 1

(v) Per cent correct: This is the percentage of forecasts that are correct.

PC = $(a + d)/(a + b + c + d)$. Range: 0 to 1. Perfect score: 1.

(vi) Missing rate: A measure of missed events, MR is defined as the number of hits divided by the total number of events observed.

MR = $c/(a + c)$. Range: 0 to 1. Perfect score: 0.

Figure 9 depicts the nowcast skill of the extrapolation technique. It can be seen from the figure that POD of the nowcast is 0.80, FAR is 0.11, PC is 0.79, CSI is 0.72, HSS is 0.38, and MR is 0.20 for 90 forecast events during pre-monsoon season (March–May 2019). The skill scores show that POD is much higher than FAR and high CSI and PC indicate that the extrapolation technique is reasonably skillful in nowcasting of thunderstorm warning.

Summary

Nowcasting of thunderstorm includes description of the current intensity of storm cells in terms of radar reflectivity, size and location along with location of the forecasts for 0–3 h ahead. Extrapolation of radar echoes is the mainstay of nowcasting because of the ability of radars to pick out the size, shape, intensity, speed and direction of movement of individual storms on a continuous basis. Considering the accuracy of the extrapolation technique, it has become a powerful tool for warning the public regarding high-impact weather events such as thunderstorms and tornados in a nowcast scale. For the prediction of hazardous weather like thunderstorms and lightning, there is clear requirement for manual quality control. In this study, three-step, location-specific nowcast and

SMS-based dissemination system for thunderstorm and lightning warning up to 3 h ahead over Jharkhand is demonstrated. In the first step, the initial development of thunder cells is identified by mosaic composite reflectivity data from multiple radars. The forecast location of thunder cells and their growth/dissipation is estimated by the extrapolation technique using their past trends. The method was successfully applied during the pre-monsoon season 2019 in Jharkhand. The statistical measures show that it performs well in real-time nowcasting. The dissemination of warning to the public is an important component of public weather services, particularly for hazardous weather events like thunderstorms and lightning. Presently, no mechanism over Jharkhand is available to warn people directly. In view of the lacuna between nowcasting and effective dissemination, in the second and third steps, an SMS-based, location-specific dissemination approach is formulated. Forecast information, e.g. centre of the cell (latitude and longitude), radius, date and validity period in a specific format is transmitted on-line to the GIS portal of JSAC. Based on this information, a warning SMS is sent to the concerned state officials and SDMA up to Panchayat level. The warning SMS is also sent to all active mobile users over the affected region at that time. The system combining nowcasting and dissemination of warning is expected to be more robust and effective as it will give direct warming to the people likely affected and can reduce human casualty. It should be noted that there are limitations in the extrapolation-based technique for individual thunderstorm cells of smaller lifetimes. Extrapolation-based nowcast can overestimate the development of such cells, and thereby the location error. In view of such limitations, warning for a shorter range of time (less than 1 h) could minimize errors and human casualty. However, there is further scope to make the system more user-friendly by automizing it with higher temporal resolution.

1. Roy Bhowmik, S. K. *et al.*, Processing of Indian Doppler weather radar data for mesoscale applications. *Meteorol. Atmos. Phys.*, 2011, **111**(3–4), 133–147.
2. Wilson, J. W., Crook, N. A., Mueller, C. K., Sun, J. and Dixon, M., Nowcasting thunderstorms: a status report. *Bull. Am. Meteorol. Soc.*, 1998, **79**, 2079–2099.
3. Battan, L. J., Duration of convective radar cloud units. *Bull. Am. Meteorol. Soc.*, 1953, **34**, 227–228.
4. Foote, G. B. and Mohr, C. G., Results of a randomized hail suppression experiment in northeast Colorado. Part VI: Post hoc stratification by storm type and intensity. *J. Appl. Meteorol.*, 1979, **18**, 1589–1600.
5. Newton, C. W. and Fankhauser, J. C., On the movements of convective storms, with emphasis on size discrimination in relation to water-budget requirements. *J. Appl. Meteorol.*, 1964, **3**, 651–668.
6. Wilson, J. W., Movement and predictability of radar echoes. Technical Memo ERTM-NSSL-28, National Severe Storms Laboratory, 1966, p. 30 (available from the National Information Service, Operations Division, Springfield, VA, USA).
7. Hill, F. F., Whyte, K. W. and Browning, K. A., The contribution of a weather radar network for forecasting frontal precipitation: a case study. *Meteorol. Mag.*, 1977, **106**, 68–89.
8. Sen Roy, S., Mohapatra, M., Tyagi, A. and Roy Bhowmik, S. K., A review of nowcasting of convective weather over the Indian region. *Mausam*, 2019, **70**(3), 465–484.
9. Golding, B. W., Nimrod: a system for generating automated very short range forecasts. *Meteorol. Appl.*, 1998, **5**, 1–16.
10. Done, J., Davis, C. A. and Weisman, M. L., The next generation of NWP: explicit forecasts of convection using the Weather Research and Forecasting (WRF) model. *Atmos. Sci. Lett.*, 2004, **5**, 110–117.
11. Kain, J. S., Weiss, S. J., Levit, J. J., Baldwin, M. E. and Bright, D. R., Examination of convection-allowing configurations of the WRF model for the prediction of severe convective weather: the SPC/NSSL Spring Program. *Weather Forecast.*, 2004, **21**, 167–181.
12. Sun, J. *et al.*, Use of NWP for nowcasting convective precipitation: recent progress and challenges. *Bull. Am. Meteorol. Soc.*, 2013, **95**(95), 409–426.
13. Tunis, P. and Borstein, R., Hierarchy of mesoscale flow assumptions and equations. *J. Atmosp. Sci.*, 1996, **53**(3), 380–397.
14. Wilson, J. W. *et al.*, Sydney 2000 Forecast Demonstration Project: convective storm nowcasting. *Weather Forecast.*, 2004, **19**, 131–150.
15. Wilson, J. W., Feng, Y. and Chen, M., Nowcasting challenges during the Beijing Olympics: successes, failures, and implications for future nowcasting systems. *Weather Forecast.*, 2010, **25**, 1691–1714.
16. Kotal, S. D. and Bhattacharya, S. K., Improvement of wind field forecast for tropical cyclones over the North Indian Ocean. *Trop. Cyclone Res. Rev.*, 2020, **9**, 53–66.
17. Kumar, S., Arora, A., Chattopadhyay, R., Hazra, A., Rao, S. and Goswami, B. N., Seminal role of stratiform clouds in large-scale aggregation of tropical rain in boreal summer monsoon intraseasonal oscillations. *Climate Dyn.*, 2017, **48**, 999–1015.
18. WMO, Guidelines for nowcasting techniques. World Meteorological Organization, WMO-No. 1198, Geneva, Switzerland, 2017 edition.
19. Brown, B. G. and Brandes, E., An intercomparison of 2D storm motion extrapolation algorithms. Preprints. In 28th Conference on Radar Meteorology, Austin, TX, USA, Amer. Meteor. Soc., 1997, pp. 495–496.

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