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Operational nowcasting of thunderstorms in India and its verification

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सार – गर्ज के साथ तूफान एक प्रचंड मौसम परिघटना है जो मुख्यत: तीव्र संवहन के कारण बनती है और इसके साथ भारी वर्षा, गर्जन, तड़ित, ओले व प्राय: चंडवात भी आते हैं। इन गर्ज के साथ आने वाले तूफानों का स्थानिक विस्तार प्राय: कुछ किलोमीटर तक होता है और उनका जीवन काल एक घंटे से कम होता है। भारत मौसम विज्ञान विभाग ने दिसम्बर 2012 में डॉप्लर मौसम रेडार संजाल के क्षेत्र में आने वाले देश के प्रमुख शहरों के लिए गर्ज के साथ तूफान और संबद्ध मौसम हेतु तात्कालिक अनुमान देना आरंभ किया है। गर्ज के साथ तूफान के तीन घंटेवार तात्कालिक अनुमान जारी करने के लिए 120 शहरों का संजाल बनाया गया। इस शोध-पत्र में 2013 में मॉनसून पूर्व और मॉनसून की अवधि में भारत मौसम विज्ञान विभाग के विभिन्न मौसम केंद्रों और प्रादेशिक मौसम केंद्रों द्वारा जारी किए गए गर्ज के साथ तूफान के तात्कालिक अनुमान के मासिक और ऋतु संबंधी सत्यापन तथा तात्कालिक अनुमान की तकनीक पर चर्चा की गई है। गर्ज के साथ तूफान/ चंडवात/ ओले पड़ने/ नहीं पड़ने के तात्कालिक अनुमान के निष्पादन परिणामों को पूर्वानुमान सटीकता (ए सी सी), फॉल्स अलार्म रेशियो (एफ ए आर), संसूचन की संभाव्यता (पी ओ डी), क्रिटिकल सक्सेस इंडेक्स अथवा थ्रेट स्कोर (सी एस आई) तथा इक्वीटेबल थ्रेट स्कोर (ई टी एस) के माध्यम से दर्शाया गया है। परिणामों से पता चला है कि सभी महीनों के लिए औसत पी ओ डी 0.6 से अधिक और एफ ए आर 0.5 से कम रही। इसी प्रकार ई टी एस और सी एस आई दोनों 0.5 और 0.9 के बीच रहे। मॉनसून ऋतु की तुलना में मॉनसून पूर्व ऋतु में संवहनीय पैमाने की घटनाओं के पता लगने की संभावना अधिक होती है और फॉल्स अलार्म रेशियो कम रहता है। एक क्षेत्र से दूसरे क्षेत्र में स्किल स्कोर की भिन्नता पूर्वानुमान करने वाले के अनुभव और घटना की आवृत्ति के ऊपर निर्भर करता है।

ABSTRACT. Thunderstorm is a severe weather phenomenon, which develops mainly due to intense convection and is accompanied by heavy rainfall, thunder, lightning, hail and often with the passage of a squall line. Usually, these thunderstorms have the spatial extent of a few kilometres and life span less than an hour. IMD implemented nowcasting of thunderstorm and associated weather for major cities of the country that come under their coverage of Doppler weather Radar network in December 2012. A total of 120 cities were covered for issue of three hourly thunderstorm nowcast. This paper discusses the nowcasting techniques and monthly and seasonal verification of the thunderstorm nowcast issued by various Meteorological centres and Regional Meteorological Centres of IMD for the Pre-Monsoon and Monsoon Period, 2013. The performance results for occurrence/non-occurrence of thunderstorm/squall/hail Nowcast are expressed in terms of Forecast accuracy (ACC),False alarm ratio (FAR), Probability of detection (POD), Critical Success Index or the threat score (CSI) and Equitable Threat Score (ETS). The results indicated that the average POD for all months remained above 0.6 and average FAR was below 0.5. Similarly ETS and CSI both were between 0.5 and 0.9 for all months. The convective scale events in pre-monsoon season had a higher probability of detection and lower False alarm ratio as compared to monsoon season. The Skill scores varied from one region to another depending upon the experience of the forecaster and the frequency of the event.

Key words – Doppler weather radar (DWR), Nowcasting, CSI, ETS, FAR, POD, ARPS (Advanced Regional Prediction System).

1. Introduction

With the modern use of Doppler weather Radars, which can continuously scan the whole sky and provide pictures every few minutes, severe thunderstorms can be very effectively tracked and predicted. This kind of prediction is valid for only few hours and is called nowcasting. Being an extrapolation of the observation itself, it is highly accurate. Nowcasting is based on the ability of the forecaster to assimilate great quantities of weather data, conceptualize a model that encompasses the structure and evolution of the phenomenon and extrapolate this in time. Nowcasts require a high resolution of spatial and temporal meteorological data to detect and predict the occurrence of an event. Lack of data in mesoscale imposes limit on the ability to diagnose and predict an event. Since the early 1960s, techniques for nowcasting, convective precipitation have been developed by extrapolating radar echoes. Nowcasting is now expanded to include the blending of extrapolation techniques, statistical techniques, heuristic techniques and numerical weather prediction.

The first automated operational nowcasting system was implemented in 1976 in Canada utilizing the McGill Weather Radar. The products were sent to the Atmospheric Environment Service Forecast Centre, Quebec Region. McGill University scientists (Austin and Bellon, 1974; Bellon and Asutin, 1978; Bellon *et al.*, 1980) adopted a version of the cross-correlation technique to forecast precipitation amounts called Short-term Automatic Radar Prediction. A later version of this system called RAINSAT (Austin and Bellon, 1982, Austin *et al.*, 1990) was developed at McGill and implemented in both Canada and Spain (Nevado, 1990). It used satellite and radar data and a cross-correlation scheme to make 1-6 hr forecasts of rainfall. The U.K. Meteorological Office implemented FRONTIER (Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite data) in the early 1980s. Thunderstorm Identification, Tracking, Analysis and Nowcasting (TITAN) (Dixon and Wiener, 1993) attempted to nowcast storm initiation and dissipation in addition to echo extrapolation. Corridor Integrated Weather System (CIWS) used spatial correlations between successive images to find storm motions (Evans and Ducot, 2006). The skill of extrapolation-based techniques was found to decrease rapidly with increasing forecast length. Nowcasting and Initialisation for modelling using Regional Observation Data System (NIMROD) (Golding, 1998) was the first system that blended radar echo extrapolation with a numerical model. The increased need for NWP products in nowcasting applications poses great challenges to the NWP community as nowcasting requires accurate specification of the current weather condition with a resolution of a few kilometres, frequent accurate updates of the current weather and the nowcasts is critical and there is a much smaller tolerance for the timing and location errors of forecasted precipitation systems (Juanzhen, *et al*., 2014).

2. Thunderstorm nowcasting activity in IMD

Nowcasting in India has been benefited from major developments in observational meteorology and computer-based interactive data processing and display systems in India Meteorological Department (IMD). In view of the recent improvement in monitoring and forecasting due to introduction of (*i*) digital and image information at 10 minutes interval from a network of 14 Doppler Weather Radars(DWR), (*ii*) dense automatic weather station (AWS) network, (*iii*) half hourly satellite observations from Kalpana and INSAT satellites, (*iv*) better analysis tools in synergy system at forecaster's workstation, (*v*) availability of mesoscale models and (*vi*) computational and communication capabilities, IMD could implement nowcasting of thunderstorms.

In order to deal with the mesoscale weather events, recently various non-hydrostatic mesoscale models such as MM5, RAMS, and ARPS etc are using real time Doppler and Sounder data. ARPS (Advanced Regional Prediction System) model with 0000 UTC Radiosonde data ingested for Delhi station was used for issue of thunderstorm Nowcast for Delhi and was found capable of simulating updrafts and downdrafts and their horizontal propagation associated with a thunderstorm. It could simulate temporal and spatial distribution of rainfall associated with thunderstorm (Kuldeep *et al*., 2008) and thus the model is now run for various regions (Northwest India ingesting DWR data of Delhi, Jaipur, Lucknow and Patna; Northeast India ingesting DWR data for Kolkata and Agartala; Southern Peninsula ingesting DWR data for Nagpur, Hyderabad and Vishakhapatnam) and is utilised as a tool for issue of thunderstorm Nowcast for various stations. Arora and Srivastava (2010) in their study have shown the utilisation of DWR images for Nowcasting of thunderstorms at various IAF stations in NW India. Kuldeep *et al*., (2012) in their study have shown adaptation of SWIRL-2 (Short-range Warning of Intense Rainstorms in Localized Systems) by IMD for use and test at Commonwealth Games in 2010 at New Delhi. They have shown application of algorithm TRE and MOVA to derive the storm motion vector, reflectivity and QPF using DWR data for thunderstorm events over Kolkata and New Delhi.

In India during the year 2013, a 3 hourly nowcast system of thunderstorm, squall and hail storm was developed for 120 cities in India. These nowcasts are primarily made by forecasters at various Meteorological Centres and Regional Meteorological Centres of India Meteorological Department. Since, this was first of its kind exercise of nowcasting in India, it was essential to verify the nowcasts provided by IMD. This paper describes the nowcasting system of India Meteorological Department and its verification results.

The first step in nowcasting of thunderstorm is to analyse the prevailing and forecasted synoptic situation and assess if the conditions are favourable for thunderstorm occurrence. The climatology of thunderstorm of the station selected for nowcasting is known to the forecaster and analysis of surface synoptic charts and streamlines indicates the presence/absence of synoptic features which will lead to instability or moisture incursion in a certain area. For example the position of induced low pressure at surface, during the passage of western disturbance and westerly Jet stream at 200 hPa are important for thunderstorm formation over Northwest, east and Northeast India during pre-monsoon season (Ray *et al*., 2013; Srinivasan *et al*., 1973).

The second step would be to examine the NWP generated products for the area of interest. NWP models do not forecast thunderstorms directly; however, these can predict the atmospheric conditions in advance. Reflectivity forecast from ARP's model run for various regions every three hourly indicates the initiation and track of thunderstorms during next three hours. Various models indicate the movement of certain large scale disturbances, which may affect a certain area on a particular day. Low level convergence, upper level divergence and strong vertical wind shear are ideal conditions for severe thunderstorm development (Kuldeep *et al*., 2008).

Third step would be to examine the thermodynamic features. Many thermodynamic indices are used for thunderstorm forecasting. These are tested and validated for the location of interest for critical values (Ray *et al*., 2013; Srinivasan *et al*., 1973). Based on the Radiosonde ascent the various thermodynamic indices like CAPE (Convective Available Potential Energy), LI (Lifted Index), TTI (Total-Total Index) etc and their threshold values for their region are available to the forecaster to exactly underline the area of occurrence of convective weather.

Once the current & forecasted synoptic condition have been assessed as favourable for thunderstorm occurrence & the NWP products also ensure the same, the thermodynamic parameters/Indices are examined. On concluding that the overall inputs indicate a situation and environment which is favourable for thunderstorm occurrence over the location of interest, the forecaster targets the most probable time of occurrence and that is where the nowcast comes into play. Utilising the latest satellite imagery and Doppler Radar data, the nowcast is issued. DWR tracks the convective echo for its intensity and direction of movement.

3. Methodology

The verification of thunderstorm Nowcasts issued every three hourly (daily) for 120 stations was done based on the past weather reported every three hourly by IMD observatories located in various cities. Due to non-availability of observatory at all locations it was difficult to verify the nowcast for around 55 stations. Therefore the stations used for verification are shown in Fig. 1.The nowcast issued for thunderstorms, every three hourly was verified based on the actual data collected in the nearby IMD observatories.

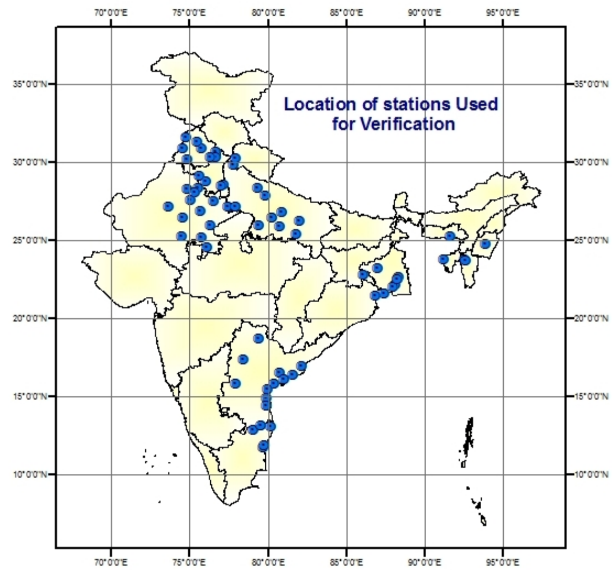

Fig. 1. Location of stations whose nowcast was verified with the IMD observatory data

The occurrence/non-occurrence of the thunderstorm event was verified for each city/station using various statistical parameters like; Forecast Accuracy (ACC) (also called Ratio Score, RS), Probability of detection (POD), false-alarm ratio (FAR), Critical Success Index (CSI) and Equitable Threat Score (ETS) Unlike POD and FAR, CSI does not use the correct non-events value and is sensitive to the climatology of the event, tending to give poorer score for rare events. ETS is designed to help offset this tendency. It removes the hits recorded by chance from the scores. Evaluation and comparison of the accuracy of nowcasts is very difficult. Statistics such as POD and FAR do not adequately represent performance. The events may be observed inaccurately because of short space-time scales and non events may even pass unrecorded. The former penalizes good forecasts and the latter leaves some verification measures indeterminate. For example no credit is given for correctly forecasting a non-event or slightly missing a forecast in either time or space. However, these statistics are useful for comparing techniques that are evaluated precisely in the same manner.

4. Results

The difficulties in prognosticating the development of thunderstorms are well known. A successful forecast of severe thunderstorm depends as much upon the forecaster as on the timely availability of various observations. The skill and experience of the forecaster, his familiarity with the regional weather and meticulous attention to details contribute largely in timely forecasts and warning of thunderstorms.

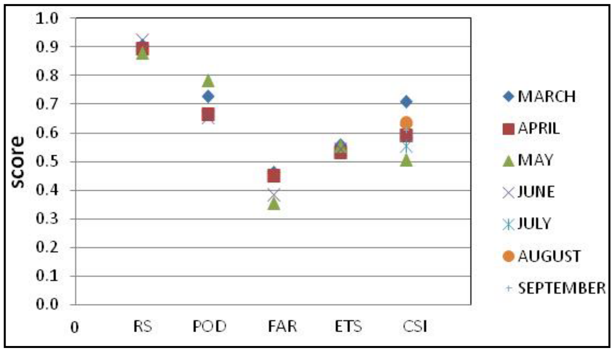

Fig. 2. All India Range of various verification parameters

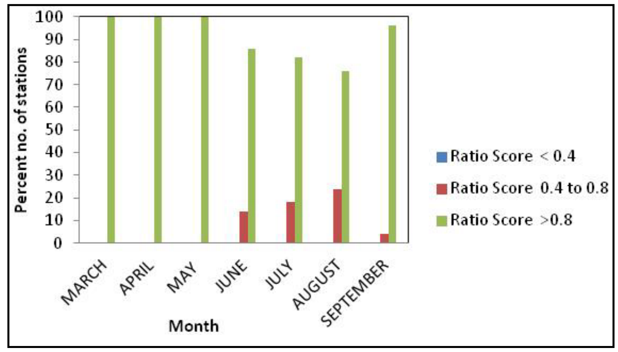

Fig. 5. Range of ratio score for various stations

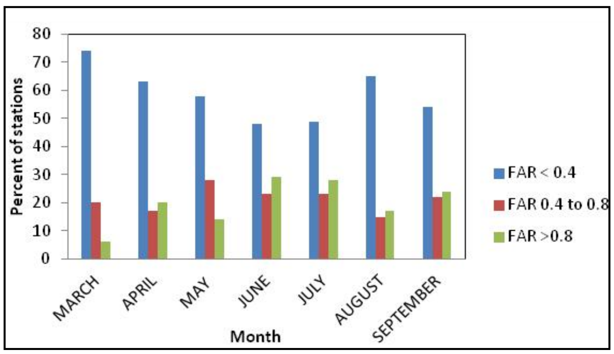

Fig. 3. Range of FAR for various stations

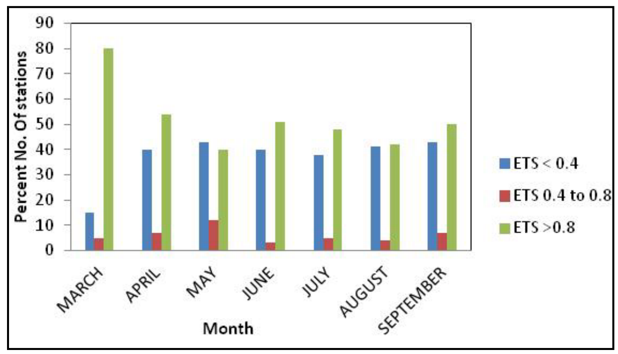

Fig. 6. Range of ETS for various stations

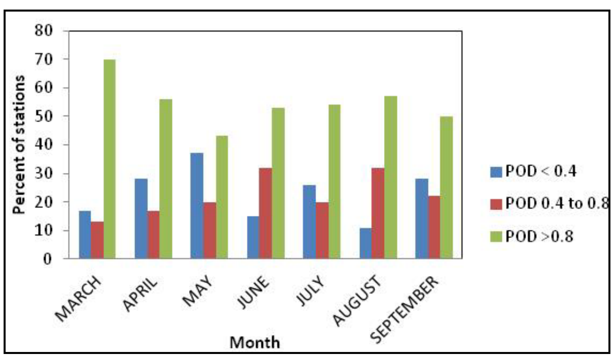

Fig. 4. Range of POD for various stations

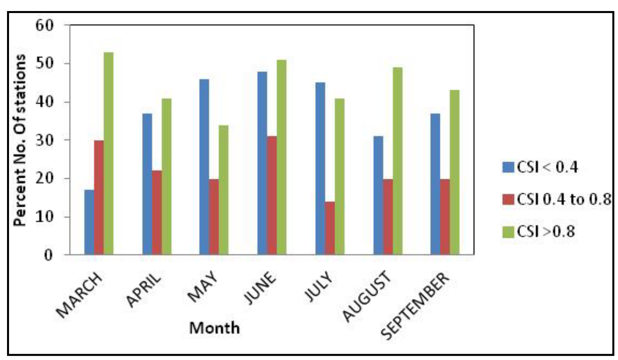

Fig. 7. Range of CSI for various stations

Fig.2 shows the various statistical parameters compiled for India as a whole. It shows the month-wise average scores for all thunderstorm nowcasts made during the period March to September. The results indicate that the Forecast Accuracy (ACC) or ratio-score was very high for all months due to high number of nowcasts for "No thunderstorm" and "None" that was observed. The results indicated that the average Probability of Detection (POD) for all months remained above 0.6 and average FAR was below 0.5. Similarly ETS and CSI both were between 0.5 and 0.9 for all months. Average POD was 0.7 to 0.8 for all months except May when it was 0.6. The average False Alarm Ratio (FAR) was lowest for March and May (0.2 and 0.3 respectively).

To categorise the Nowcast into excellent, good and bad category respectively for POD, CSI & ETS and *vice-versa* for FAR, the scores were divided into three categories, *i.e.*, greater than 0.8, between 0.4 to 0.8 and less than 0.4. Fig. 3 shows the percentage of stations that

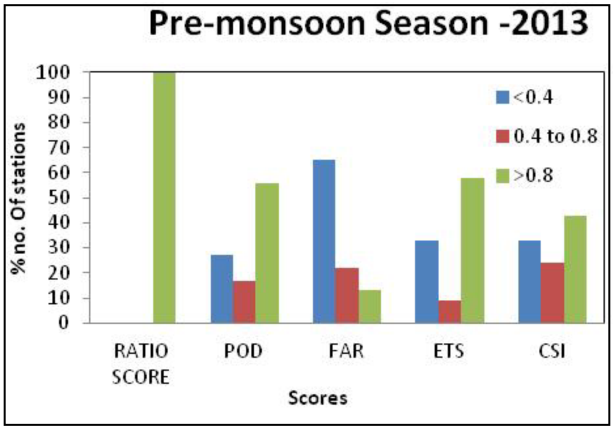

Fig. 8. Scores of various evaluation parameters during the pre-monsoon season of 2013

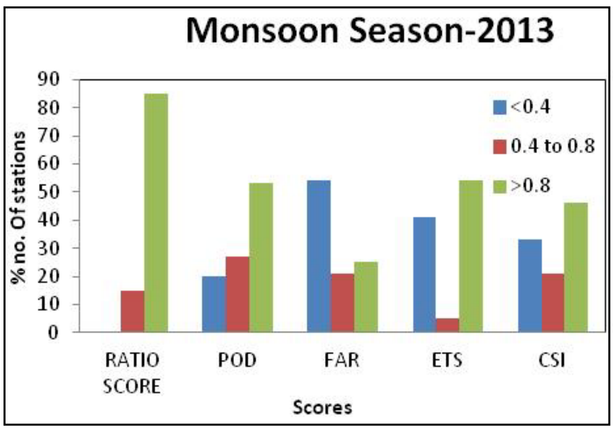

Fig. 9. Scores of various evaluation parameters during the monsoon season of 2013

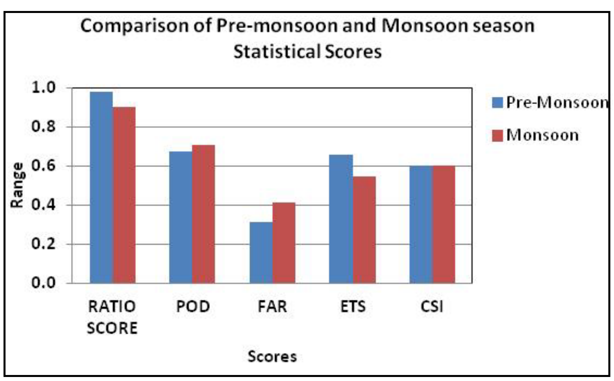

Fig. 10. Comparison of average value of statistical scores for monsoon and pre-monsoon season

fall in the above three scales in FAR. The scores were bad in the month of June when 29% of the stations recorded FAR more than 0.8 and around 23% of stations had FAR between 0.4 and 0.8, while 48% of the stations recorded FAR in excellent category, i.e., lower than 0.4. The FAR was excellent in the month of March, when only 6% of the stations recorded FAR more than 0.8. Twenty per cent (20%) of the stations recorded FAR between 0.4 and 0.8 and 74% of the stations recorded FAR less than 0.4. The percentage of stations in various scales of POD is indicated in Fig. 4. POD was also excellent in the month of March, when 70% of the stations could forecast 80% of the thunderstorm occurrences. The POD was lowest in May when 37% of stations could forecast less than 40% of the thunderstorm occurrences. The ACC was excellent for more than 80 % stations (Fig. 5). The ETS and CSI scores (Figs. 6 and 7) were also good for more than 50% stations.

TABLE 1

Average statistical score for Nowcast of cities in West Bengal and Odisha (Alipore, Dumdum, Diamond harbour, Digha, Haldia, Canning, Bankura, Balasore, Jamshedpur)

Regional Meteorological Centre, Kolkata						
Month	Ratio score	POD	FAR	ETS	CSI	Nowcasts
Mar	1.0	0.7	0.3	0.7	0.7	2232
Apr	0.9	0.7	0.3	0.5	0.5	2160
May	0.9	0.6	0.4	0.6	0.5	2232
Jun	0.9	0.8	0.3	0.5	0.7	2160
Jul	0.8	0.5	0.4	0.3	0.4	2232
Aug	0.8	0.6	0.3	0.2	0.6	2232
Sep	0.8	0.3	0.6	0.1	0.3	2160

Figs. 8 and 9 give the percentage of stations in various score categories during pre-monsoon and monsoon season. 50 to 60% of the stations in both seasons have POD greater than 0.8 and FAR less than 0.4, *i.e.*, in excellent category, but the number of stations with bad FAR (greater than 0.8) are more in monsoon season (22%) as compared to pre-monsoon season (12%). The equitable skill score was bad (lower than 0.4) in higher percentage of stations (42%) in monsoon season. The average monthly results were compiled into pre-monsoon and monsoon season (Fig. 10) and it was seen that for monsoon season, the FAR and POD values were high, indicating over-warning during the season. It is difficult to distinguish a heavy rainfall event with and without thunder during monsoons and thus the false alarm tends to be high. The convective scale events in pre-monsoon season have a higher probability of detection and lesser false alarm ratio. The Threat Score/CSI was same for both seasons and ETS was higher for pre-monsoon season indicating capability of detecting rare events.

It was seen that a bi-modality existed in station-wise distribution of scores, with many stations having either a very high or a very low scores but only a few having

TABLE 2

Average statistical score for Nowcast of cities in Delhi, Haryana and adjoining Uttar Pradesh (Agra, Dehradun, Delhi-Airport, Roorkee, Gurgaon, Karnal, Rohtak, Hissar)

Regional Meteorological Centre, New Delhi						
Month	Ratio score	POD	FAR	ETS	CSI	Nowcasts
Mar	1.0	0.8	0.5	0.8	0.6	1488
Apr	0.9	0.5	0.7	0.2	0.3	1440
May	1.0	0.4	0.7	0.4	0.3	1488
Jun	0.8	0.7	0.8	0.2	0.3	1440
Jul	0.8	0.9	0.7	0.4	0.4	1488
Aug	0.7	0.7	0.8	0.1	0.3	1488
Sep	0.9	0.7	0.8	0.3	0.4	1440

TABLE 3

Average statistical score for Nowcast of cities in Meghalya, Manipur, Mizoram and Tripura (Agartala, Lengpui, Cherrapunji, Imphal)

Meteorological Centre, Agartala						
Month	Ratio score	POD	FAR	ETS	CSI	Nowcasts
Mar	1.0	0.3	0.4	0.5	0.2	1240
Apr	0.9	0.3	0.6	0.1	0.2	1200
May	0.9	0.4	0.6	0.1	0.2	1240
Jun	0.9	0.4	0.8	0.1	0.2	1200
Jul	1.0	0.2	0.5	0.1	0.1	1240
Aug	0.9	0.3	0.8	0.1	0.2	1240
Sep	0.9	0.3	0.8	0.1	0.2	1200

TABLE 4

Average statistical score for Nowcast of cities in Tamil Nadu (Chennai, Vellore, Tiruttani, Cuddalore, Puduchheri)

Regional Meteorological Centre, Chennai						
Month	Ratio score	POD	FAR	ETS	CSI	Nowcasts
Mar	1	1	0	1	1	1240
Apr	1	1	0.1	1	0.9	1200
May	1	1	0	1	1	1240
Jun	1	1	0	1	1	1200
Jul	1	1	0	1	1	1240
Aug	1	1	0	1	1	1240

TABLE 5

Average statistical score for Nowcast of cities in Uttar Pradesh (Lucknow, Allahabad, Kanpur, Orai, Fatehpur, Sultanpur, Sahjahanpur, Bareilly)

Meteorological Centre, Lucknow						
Month	Ratio score	POD	FAR	ETS	CSI	Nowcasts
Mar	1.0	1.0	0.3	1.0	0.8	1984
Apr	1.0	0.0	1.0	0.0	0.0	1920
May	1.0	0.0	0.0	0.0	0.2	1984
Jun	0.7	0.6	0.9	0.4	0.4	1920
July	0.8	0.3	0.9	0.0	0.2	1984
Aug	0.9	0.3	0.9	0.0	0.3	1984
Sep	0.9	0.3	0.9	0.0	0.3	1920

TABLE 6

Average statistical score for Nowcast of cities in Rajasthan (Pilani, Churu, Jhunjhunu, Kota, Ajmer, Nagaur, Jhalwar, Sikar, Jaipur, Sawimadoipur, Bhilwara, Alwar, Bharatpur)

Meteorological Centre, Jaipur						
Month	Ratio score	POD	FAR	ETS	CSI	Nowcasts
Mar	1.0	0.8	0.1	0.8	0.7	3224
Apr	1.0	1.0	0.1	1.0	0.9	3120
May	1.0	0.5	0.2	0.5	0.5	3224
Jun	1.0	1.0	0.2	1.0	0.8	3120
July	1.0	1.0	0.0	1.0	1.0	3224
Aug	1.0	1.0	0.1	1.0	0.9	3224
Sep	1.0	1.0	0.0	1.0	1.0	3120

TABLE 7

Average statistical score for Nowcast of cities in Andhra Pradesh and Telengana) (Hyderabad, Vishakhapatnam, Ramgundam, Annavaram, Machilipatnam, Nellore, Ongole, Narsapur, Bapatia, Kavali, Kurnool

Meteorological Centre, Hyderabad						
Month	Ratio score	POD	FAR	ETS	CSI	Nowcasts
May	1.0	0.6	0.8	0.4	0.3	2728
Jun	0.9	0.3	0.9	0.1	0.3	2640
Jul	0.9	0.3	0.9	0.3	0.2	2728
Aug	0.9	0.4	0.9	0.1	0.2	2728

TABLE 8

Average statistical score for Nowcast of cities in Punjab (Biwani, Amritsar, Ferozepur, Ludhiana, Chandigarh, Bhatinda, Ambala, Patiala, Jalandhar)

Meteorological Centre, Chandigarh						
Month	Ratio score	POD	FAR	ETS	CSI	Nowcasts
Jun	1.0	1.0	0.0	1.0	0.9	2160
Jul	0.9	1.0	0.2	0.9	0.9	2232
Aug	0.9	1.0	0.1	0.9	0.9	2232
Sep	1.0	0.8	0.1	0.9	0.8	2160

TABLE 9

The Nowcasts issued for various regions during the entire year (2013)

S. No.	State	No thunderstorm Warnings	Thunderstorm warnings
1.	Rajasthan (Meteorological Centre, Jaipur)	28345	4018
2.	Punjab (Meteorological Centre, Chandigarh)	33190	3513
3.	Andhra Pradesh (Meteorological Centre, Hyderabad)	45218	3490
4.	Delhi and Haryana (Regional Meteorological Centre, New Delhi)	32153	5656
5.	West Bengal (Regional Meteorological Centre, Kolkata)	31612	4795
6.	Uttar Pradesh (Meteorological Centre,Lucknow)	31738	4590
7.	Mizoram, Manipur, Meghalya, Tripura (Meteorological Centre, Agartala)	22038	1967
8.	Tamil Nadu (Regional Meteorological Centre, Chennai)	31108	2962

intermediate values. In order to explain this, the results were analysed region wise based on the Doppler weather Radar installations. Tables 2 to 8 show the average statistical score for Thunderstorm Nowcast for cities in various states. The scores were found excellent for some states and bad for others. They were good for very less number of states. The performances of Delhi, Uttar Pradesh, Andhra Pradesh, Meghalaya, Mizoram, Manipur, and Tripura was bad and the performance of Tamil Nadu, Rajasthan, and Punjab was excellent. The stations in West Bengal and Odisha gave a good performance. Table 9 gives the number of 'No thunderstorm' nowcasts as against the 'Thunderstorm Warning' nowcast for various regions. Maximum thunderstorm warnings were issued for Delhi and Haryana region and lowest for Northeast India. This is contrary to the actual occurrence of thunderstorms in these areas, which is much higher in northeast India as compared to Delhi and surrounding areas. Improvements in the statistical skill scores can be achieved by adopting warning strategies that specifically target deficiencies in assessing 'Over-warning' or under-warning'. The high false alarm could also be due to non-recording of the convective event by the nearest IMD station and occurrence of event in its near vicinity. In severe weather, individual forecasters have different thresholds for issuing warnings. Most forecasters believe that the penalty for not forecasting severe weather is greater than the penalty for issuing a watch/warning that proves false. This increases the likelihood of false warnings and although recent research by Barnes *et al*. (2007) suggests a significant segment of the user community does not become desensitized by false alarms, eventually some segments of the user community may not take action when necessary.

5. Conclusions

Location, time and intensity specific prediction of thunderstorms and precipitation, using conventional methods has its own limitations. Although Nowcast Expert system 'Warning Decision Support System - Integrated Information (WDSSII)'are tuned to nowcast thunderstorms for specific stations, many of the forecaster's activities in nowcast units are still manually intensive and prone to error; therefore partial automation of nowcaster's activities is recommended for improvement in skill of forecast. Automation will allow the forecaster more time to use his/her physical reasoning and pattern recognition capabilities to assess data quality, evaluate automated forecast material and apply broad based meteorological reasoning to the forecasts. The forecasters need to have automated cell and boundary detection algorithms. These features will be automatically extrapolated to the forecast time, based on past motion. Thus a continually evolving human/computer nowcast system is needed where the activities which are routine are automated and the nowcaster will have more and more time to apply his/her deductive reasoning abilities to the nowcast (Wilson *et al*., 1993).

However, nowcasting significant weather cannot be left to purely automated systems as the risks and consequences are too high for neglecting human expertise. Wilson *et al*., 1993 had compared human nowcasts with persistence and extrapolation techniques for two years and it was found that forecaster results were better than persistence or extrapolation forecasts because of the ability of forecaster to nowcast storm initiation and dissipation.

The quality of human resource was another factors found to affect the quality of nowcast at various IMD offices. A lot of error was found in precisely timing and placing the location of storm initiation and also forecasting the evolution of existing storm. This could be due to deficiencies in the knowledge of details of storm initiation and evolution which needs to be improved by studying the Doppler data in detail, for a number of years and preparing guidelines regarding storm initiation and movement. Nowcasting requires accurate specification of the current weather condition with a resolution of a few kilometres, frequent accurate updates of the current weather, as there is a much smaller tolerance for the timing and location errors of forecasted precipitation systems. The increased need for NWP products in nowcasting applications poses great challenges to the NWP community. Thus, some of the future challenges in Nowcast of convective events would be; the predictability of precipitation systems, the need for improved mesoscale observation networks and the improvement of rapid update Numerical Weather Prediction and Data Assimilation systems (Juanzhen *et al*., 2014).

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References

Arora, P. K. and Srivastava, T. P., 2010, "Utilisation of Aerostat Doppler Weather Radar in nowcasting of convective phenomena", *Mausam*, **61**, 1, 95-104.

Austin, G. L. and Bellon, A., 1974, "The use of digital weather records for short-term precipitation forecasting", *Quarter. J. Roy. Meteor.* Soc., **100,** 658-664.

Austin, G. L. and Bellon, A., 1982, "Very-short-range forecasting of precipitation by objective extrapolation of radar and satellite data Nowcasting", *K. Browning*, Ed., Academic Press, 177-190.

Austin, G. L., Kilambi, A. and Biron, H. P., 1990, "The operational use of a high-speed interactive radar data processing system (RDPS). Part 1: A technical description. Weather Radar Networking", Seminar on COST Project 73, C. G. Collier and M. Chapuis, Eds., Kluwer Academic Publishers, 237-241.

Barnes, L. R., Gruntfest, E., Hayden, M. H., Schultz, D. M. and Benight, C., 2007, "False alarms and close calls: A conceptual model of warning accuracy", *Wea. Forecasting*, **22**, 1140-1147.

Bellon, A. and Austin, G. L., 1978, "The evaluation of two years of real time operation of a short-term precipitation forecasting procedure (SHARP)", *J. Appl. Meteor*., **17**, 1778-1787.

Bellon, A., Lovejoy, S. and Austin, G. L., 1980, "Combining satellite and radar data for the short-range forecasting of precipitation", *Mon. Wea. Rev*., **108**, 1554-1566.

Dixon, M. and Wiener, G., 1993, "TITAN: Thunderstorm Identification, Tracking, Analysis and Nowcasting - A radar-based methodology", *J. Atmos. Oceanic Technol*., **10**, 785-797.

Evans, J. E. and Ducot, E. R., 2006, "Corridor Integrated Weather System", *Lincoln Lab. J*., **16**, 59-80.

Golding, B. W., 1998, "Nimrod: A system for generating automated very short range forecasts", *Meteor. App*., **5**, 1-16.

Juanzhen, Sun, Xue, M., Wilson, J. W., Zawadzki, I., Ballard, S. P., Hooimeyer, J. O., Joe, P., Barker, D. M., Li, Golding, P. W., Xu, B. M. and Pinto, J., 2014, "Use of NWP for Nowcasting convective precipitation recent progress and challenges", *Amer. Meteor. Soc.*, **95**, 3, 409-426.

Kuldeep, S., Roy Bhowmik, S. K., Hatwar, H. R., Das, A. K. and Kumar, A., 2008, "Simulation of mesoscale structure of thunderstorm using Arps model", *Mausam*, **59**, 1, 1-14.

Kuldeep, S., Lau, S. Y., Yeung, H. Y., Cheng, T. L., Bhardwaj, R., Kannan, A. M., Bhowmik, S. K. R. and Singh, H., 2012, "Use of SWIRLS nowcasting system for quantitative precipitation forecast using Indian DWR data", *Mausam*, **63**, 1, 1-16.

Nevado, T., 1990, "Composite radar and satellite data processing in the meteorological system in Spain. Weather Radar Networking", Seminar on COST Project 73, C. G. Collier and M. Chapuis, Eds., Kluwer Academic Publishers, 136-146.

Ray, Kamaljit, Mohapatra, M., Bandopadhyay, B. K., Sikka, D. R., Chakravarthy, Kalyan, Sen, Bikram, Debnath, G. C., Stella, S., Das, Sunit, Duraisamy, M., Sai Krishnan, K. C., Kannan, B., Goyal, Suman, Jordar, D., Saxena, Rahul, Bhan, S. C., Tyagi, Ajit, Mohanty, U. C., Das, Someshwar and Rathore, L. S., 2013, "Report on Pre-monsoon Season 2013 Thunderstorm over India", Report No. SMRC STORM Project-2013/2/2013, India Meteorological Department.

Srinivasan, V., Ramamurthy, K., Nene, Y. R., 1973, "Discussion of typical synoptic weather situation, summer nor'westers and andhis and large scale convective activity over peninsula and central parts of the country", F.M.U. Rep No. III-2.2, India Meteorological Department.

Wilson, J. W. and Mueller, C. K., 1993, "Nowcasts of thunderstorm initiation and evolution", *Amer. Met. Soc*., **8**, 113-131.