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Precursors of hazard due to super cyclone AMPHAN for Kolkata, India from surface observations

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सार – चक्रवात के मार्ग, तीव्रता और संबंधित खतरों का पूर्वानुमान ज्यादातर NWP मॉडल, उपग्रहों और रेडार का उपयोग करके किया जाता है। यद्यपि चक्रवात समुद्र में उत्पन्न और तीव्र होते हैं, लेकिन वे आबादी वाले भूमि क्षेत्र में तबाही का कारण बनते हैंजहां से वे अंततः गुजरते हैं। पिछले कुछ वर्षों में, चक्रवातके पूर्वानुमान की सटीकता में बहुत सुधार हुआ है। फिर भी मार्ग, तीव्रता और संबंधित खतरों के सटीक पूर्वानुमान में कुछ अनिश्चितता है। इस लेख में, हमने कोलकाता, भारत में महाचक्रवात अम्फान और इसके खतरों का अध्ययन किया है। यहां, हमने वक्र आसंजन तकनीकों और सतह प्रेक्षण डेटा का उपयोग करके बहिर्वेशन के आधार पर चक्रवात की दूरी, संबंधित पवन और 12-24 घंटे के अग्रकाल तक के खतरे के लिए पूर्वानुमान सटीकता में सुधार के लिए एक नई योजना प्रस्तावित की है। संबंधित स्टेशन से सिस्टम की दूरी और उसके अनुरूप निर्घाती पवन की गति के पूर्वानुमान के लिए, प्रस्तावित योजना की सटीकता मौजूदा परिचालन पूर्वानुमान और विभिन्न प्रतिष्ठित NWP मॉडल से बेहतर पाई गई है।

ABSTRACT. The track, intensity, and associated hazards of a cyclone are mostly pre- dicted using NWP models, satellites, and radar. Though the cyclones originate and strengthen in the ocean, they cause devastation in the populated land area over which they ultimately pass. Over the years, the accuracy of cyclone prediction has improved a lot. Yet, there is some uncertainty in the accurate prediction of track, intensity and associated hazards. In this article, we have studied super cyclone AMPHAN and its hazards for Kolkata, India. Here, we have proposed a new scheme for improving the forecast accuracy for cyclone distance, associated wind, and hazard for lead time up to 12-24 hours ahead based on curve fitting techniques and extrapolation using surface observational data. For the prediction of distance of the system from the concerned station and corresponding gusty wind speed, the accuracy of the proposed scheme is found to be better than the existing operational forecast and various reputed NWP models.

Key words – Cyclone, Hazard prediction, Precursors.

1. Introduction

A cyclone is one of the most destructive and powerful natural phenomena, affecting coastal and adjacent areas all over the world. Such storms have different names in different parts of the world, *e.g.*, hurricanes in the Atlantic, typhoons in the Pacific, and cyclones in the Indian Ocean. In recent times, cyclone prediction has improved a lot due to sophisticated numerical weather prediction models, satellites, radars, *etc*. (Heming *et al.* 2019; Mohapatra *et al.* 2019; Cangialosi *et al.* 2011). Cyclones, however, continue to cause a significant number of deaths and significant property damage (Cerveny *et al.* 2017). The highest number of deaths due to a cyclone was the Bangladesh cyclone of November 12-13, 1970, with an estimated death toll of 300,000 people (Cerveny *et al.* 2017).

There are various meteorological parameters, *e.g.*, sea surface temperature, mid-level moisture, instability, pre-existing vorticity, Coriolis force, vertical wind shear, etc., indicating the favourable conditions for cyclone development (Gray 1968). Balachandran *et al.* (1998) pointed out that the storm is affected by easterly waves that affect the storm's genesis, movement, and intensification.

In recent times, machine learning has become popular in various fields, and Chen *et al.* (2020) have studied a review of machine learning in cyclone forecasting. One factor affecting the model prediction is the lack of adequate data within the storm region as cyclones originate and spend most of their lives over the data sparse oceans, which has been addressed by some researchers incorporating Doppler radar observation

(Zhang *et al.* 2011). Zhang *et al.* (2016) have attempted to improve data assimilation in a model incorporating satellite radiance and aircraft observations. Nolan *et al.* (2009) have pointed out the planetary boundary layer parameterization in the prediction of cyclones. Gopalakrishnan *et al.* (2011) have studied the role of higher resolution in models in improving prediction. Track prediction using a neural network approach has also been attempted by researchers (Ruttgers *et al.* 2019). There are several studies to overcome the shortcomings of the numerical models in predicting the cyclone track and associated hazards.

Intensity prediction is found to be more difficult compared to the track. Researchers have investigated the role of environmental or thermodynamic factors, *e.g.*, sea surface temperature, upper tropospheric environmental flow (Merrill 1988), storm's initial intensity, the thermodynamic state of the atmosphere, heat exchange with the upper oceanic layer under the storm core, *etc*. (Emanuel 1999) responsible for intensification of the storm. Some storms undergo rapid intensification when the water is warm enough, with a temperature >28 °C up to a depth of 30 m. DeMaria *et al.* (2005) attempted to have a statistical intensity prediction model with the inclusion of land effects to improve the prediction of intensity errors for the shorter-range forecasts. Oceanic heat content and thermal structure also influence the intensity prediction (Pun 2007; Mainelli *et al.* 2008). Zhang (2013) studied the role of vertical wind shear in the predictability of cyclones and found that the larger the vertical wind shear, the greater the uncertainty in the intensity forecast. Kolstad (2021) has identified some precursors, *e.g.*, sea level pressure anomalies, specific humidity at 500 hPa, divergence at 200 hPa, *etc*., for the prediction of tropical cyclones. Haghroosta *et al.* (2019) attempted speed prediction using a neural network approach.

Most of the researchers are focused on the prediction of cyclone track and intensity over the ocean and the post-analysis of factors that might have played a role. An important aspect of storm prediction is the probable hazard. Disaster managers and common people take mitigation measures depending on the estimated risk posed by the storm (Eberenz *et al*. 2021). In the context of India, most of the Indian coast line is vulnerable due to cyclone proneness. The cyclone hazard proneness of districts in India has been studied by Mohapatra (2015).

Cyclones in the Bay of Bengal mostly move towards the east coast of India, and the India Meteorological Department (IMD) is the nodal authority to predict cyclones. In the year 2020, Super Cyclone AMPHAN caused havoc and devastation as it crossed the West Bengal coast. FANI in 2019, HUDHUD in 2014, LEHAR in 2013, PHAILIN in 2013, AILA in 2009, NILAM in 2012, VARDAH in 2016, and OCKHI in 2017 caused a lot of damage to the east coast of India.

Cyclone warning services in India in recent times are summarized by Mohapatra *et al*. (2019). The satellites play an important role in providing cyclone information over the sparse data region of the ocean. Ahmed *et al*. (2021) have studied the performance of the advanced Dvorak technique in estimating cyclone intensity. Kotal *et al*. (2008) formulated a statistical model for cyclone intensity prediction by applying multiple linear regression techniques to selected predictors, *e.g*., initial storm intensity, intensity changes in the past 12 hours, storm motion speed, initial storm latitude position, vertical wind shear averaged along the storm track, vorticity at 850 hPa, divergence at 200 hPa, and sea surface temperature. Mohapatra *et al*. (2015) have determined the characteristics, *e.g.*, cross equatorial flow, lower-middle level relative humidity, vertical wind shear and proximity of cyclones to the land surface, affecting the size and asymmetry of cyclones over the north Indian Ocean. Srinivas *et al.* (2012) have investigated high resolution model performance for different convective schemes, and model errors in intensity and landfall prediction for cyclones over the Bay of Bengal. Roy Bhowmik *et al*. (2005) formulated an empirical model for predicting the wind speed after landfall, assuming exponential decay after landfall over the Indian region.

Despite various efforts all over the world, there is still uncertainty about track and intensity forecast accuracy. The inherent uncertainty in the prediction of a nonlinear atmosphere was pointed out long ago by Lorenz (1969). The inherent uncertainty and the practical limits of cyclone prediction are addressed by a few researchers (Palmer *et al*., 2014 and Sun 2016). Marks *et al.* (1998) highlighted the forecast problems of a lack of a comprehensive mobile observing network and the associated scope of research for landfall. Emanuel (2016) pointed out that intensity error growth in real-time forecasts and errors in initial intensity impose limitations on cyclone intensity predictability. Nguyen, *et al*. (2008) opined that there is intrinsic uncertainty in intensity predictability. According to Zhang *et al.* (2014) stronger the intensities and their variations, the larger the forecast errors. A spatial error of 50-100 km may seem insignificant for a coast stretching thousands of kilometers, but it may be difficult to manage in terms of evacuation. Most of the research on cyclone prediction is concentrated on the prediction and analysis of what happens in the ocean or on the coast.

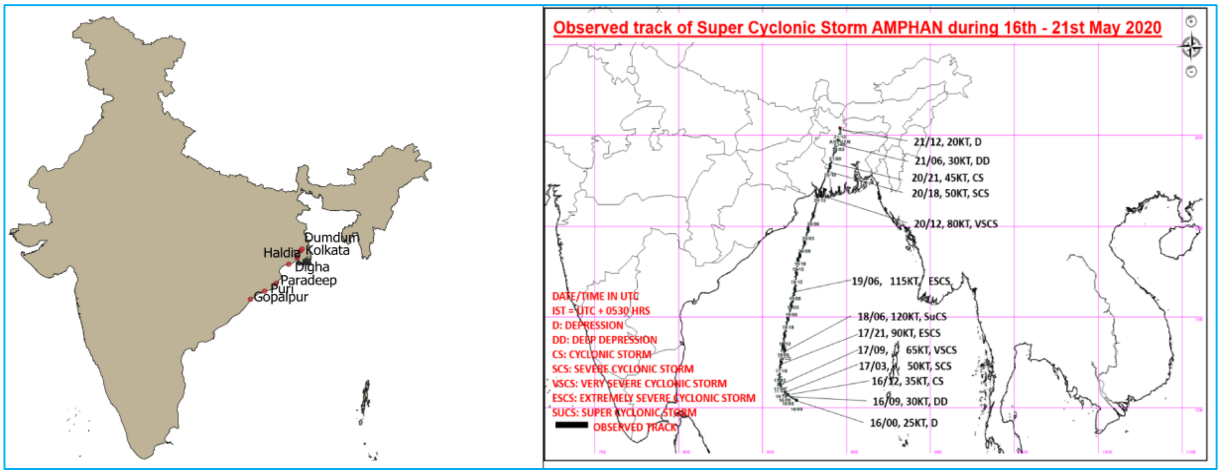


Fig. 1. Left : Location of the coastal stations; Right : Observed track of the cyclone as per report of India Meteorological Department

In this article, an attempt has been made to further improve the accuracy of cyclone prediction and its associated hazard with a period of 12-24 hours lead time, by extracting information from surface observations as precursors to enable the minimum loss of life and property.

2. Brief history of the system

A low-pressure area formed over the southeast Bay of Bengal (BoB) and the adjoining south Andaman Sea on 13th May, 2020. It intensified into a depression over southeast BoB on the 16th, further intensifying into cyclone "AMPHAN" on the same day. It moved slowly northward and further intensified into a very severe cyclone, "AMPHAN," on the 17th. It intensified further into a super cyclone on 18th May and moved northeastward. Weakening slightly into a very severe cyclone, it crossed the West Bengal coast across the Sundarbans, near latitude of 21.6° N and longitude 88.3° E during 10-12 hour UTC (Universal Time Coordinated) on 20th May, with a maximum sustained wind speed of 155-165 km/h gusting to 185 km/h across the Sundarbans in India. Gradually, it weakened into a severe cyclone over Bangladesh and adjoining West Bengal around mid-night of 20th and weakened further into a well-marked low-pressure area over Bangladesh by mid-night of 21st May. The observed track of the system is shown in Fig. 1 right panel. It was the first super cyclone over the Bay of Bengal since the Odisha Super Cyclone of 1999.

West Bengal was the state most affected in India. As per the damage report of the government of West Bengal, about 28.56 lakh houses were damaged, 17 lakh hectares of agricultural land were affected, 2.5 lakh hectares of horticultural land were affected, 15000 trees in Kolkata were uprooted, 2.5 lakh in the Sundarban area were uprooted, 8000 boats were destroyed, fish and other aquatic life suffered losses, 245 km of embankments were flooded and 99 people died in West Bengal state in India. Apart from this, there were complete breakdowns of power, telecommunication, road transport, and drinking water systems in many parts. The estimated total damage to houses, crops and public properties is about Rs.102442 Cr.

3. Data and methodology

Surface observational data for coastal and nearby areas affected by super cyclone AMPHAN, have been studied. This includes the mean sea level pressure and 24 hour pressure change data of coastal stations, *e.g.*, Gopalpur, Puri, Paradeep, Digha and Haldia, located near the Odisha and West Bengal coasts of India in the north Bay of Bengal, as shown in Fig. 1, left panel. Data for two inland stations, namely Kolkata (Alipore) and nearby station Dumdum, have been analyzed, with the focus of the study being the metropolitan city of Kolkata, which was devastated by the super cyclone as the eye passed very close to it. This involves the data for mean sea level pressure, 24 hour pressure change, gusty wind speed at any instant, and rainfall data. The observed track for the cyclone center has been used to obtain the distance from Kolkata at any particular time. Surface observational data and cyclone data are obtained from the India Meteorological Department.

Surface observational data has been analyzed to find whether the distance from the cyclone and the hazards, *e.g.*, wind speed and rainfall, can be estimated prior to occurrence, *i.e.*, to find the elements of predictability for better understanding and prediction of such events. Here, we have used the curve fitting and extrapolation technique

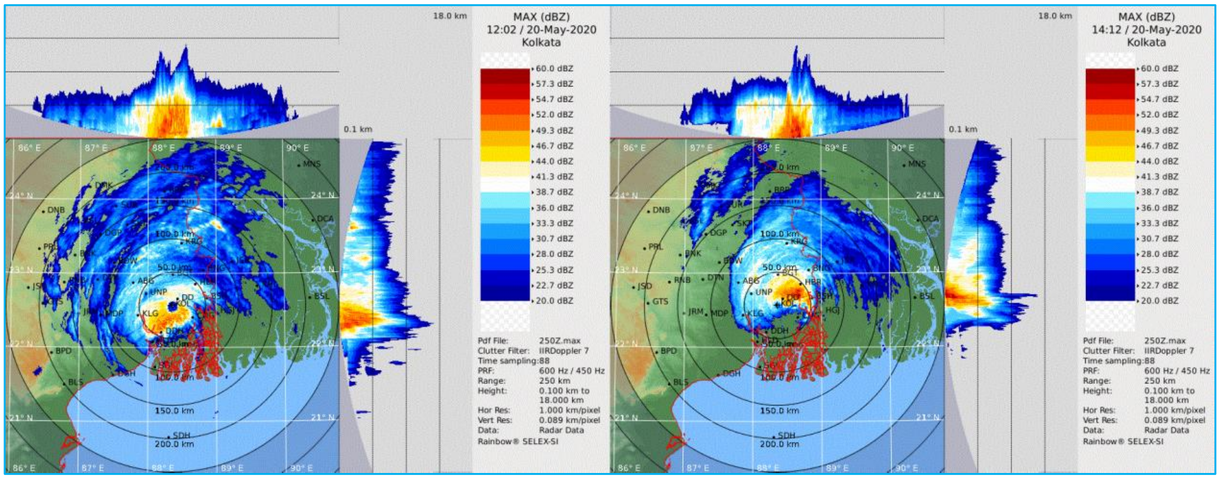


Fig. 2. Left : Kolkata Radar image showing eye of cyclone near Kolkata around 1200 UTC; Right : Radar image around 1400 UTC

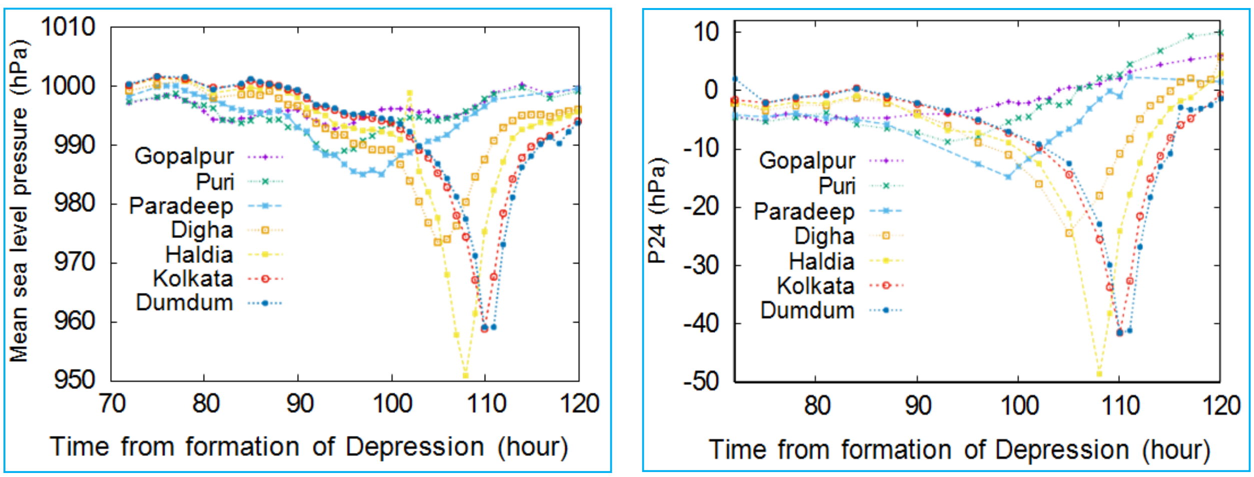


Fig. 3. Left : Variation of pressure with time for different stations near the coast; Right : Variation of pressure change in the past 24 hours with time

to obtain different mathematical expressions for describing the observed distance of the cyclone center as a function of time and mean sea level pressure of the concerned station and the resulting wind speed at various times. Here, we propose a new scheme for improving cyclone prediction as follows: After the formation of a depression, the observed data is considered for a certain period. Curve fitting technique is used to fit the data to obtain the best fit mathematical expression for that data set. Here, we have used gnuplot software for curve fitting which uses the nonlinear least-squares (NLLS) Marquardt-Levenberg algorithm (Levenberg 1944, Marquardt 1963) which minimizes the sum of the squares of the offsets of the points from the curve. Then, extrapolation gives the prediction for some time ahead. More data will become available as the system moves over the next few hours. Again, curve fitting is used for the updated data set by forward shifting the data time window for the training or fitting of data. While shifting the data set for fitting or training, the data time window is kept fixed, thereby skipping some of the initial time and incorporating some forward hour data. The process is repeated and fitting parameters are updated.

4. Results

The system came very close to Kolkata around 12-14 UTC (Universal Time Coordinated) on 20th May, 2020 as captured in the radar images as shown in Fig. 2. The mean sea level pressure and pressure change in the past 24 hours for the coastal stations are given in Fig. 3. It clearly shows that as the system approaches closer to the station, pressure continues to drop, and once the system starts moving away, pressure gradually rises. For Kolkata, the lowest mean sea level pressure (MSLP) of 958.8 hPa was observed around 110 hours from the formation of the depression.

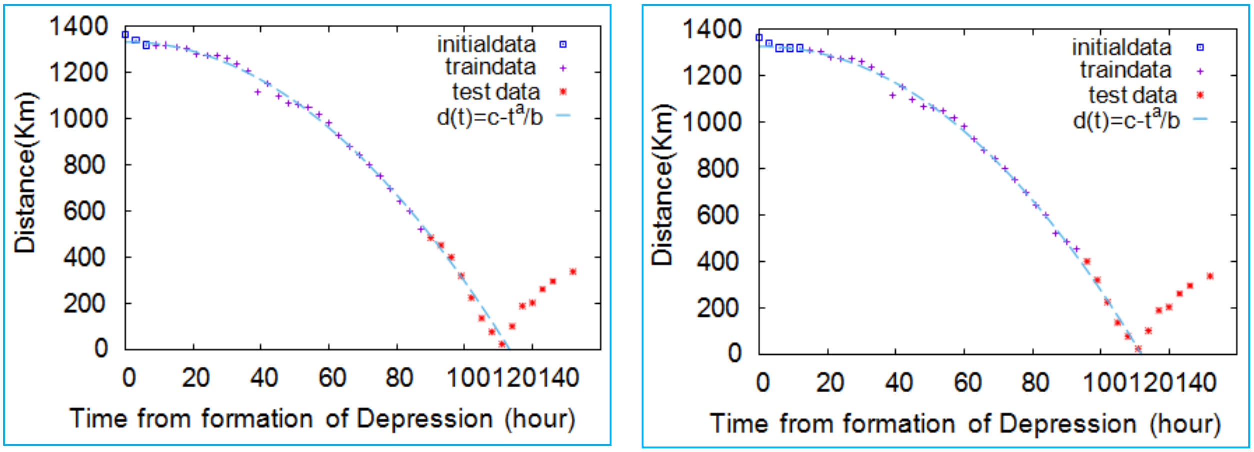


Fig. 4. Left : Curve fitting and prediction of the distance of the cyclone center from Kolkata with a lead time of upto 24 hours using data for the variation of distance with time; Right : Similar fitting and prediction with a lead time of up to18 hours

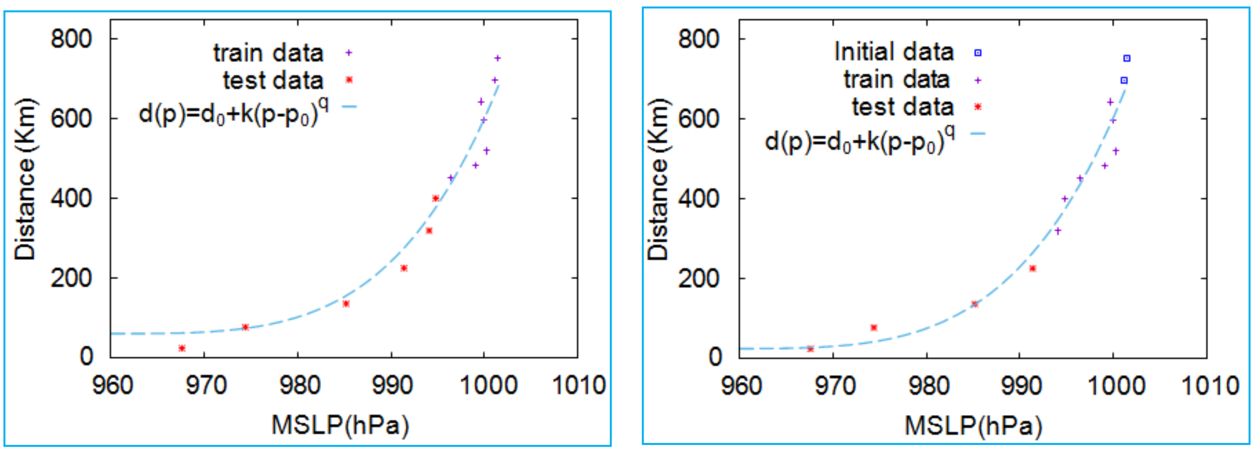
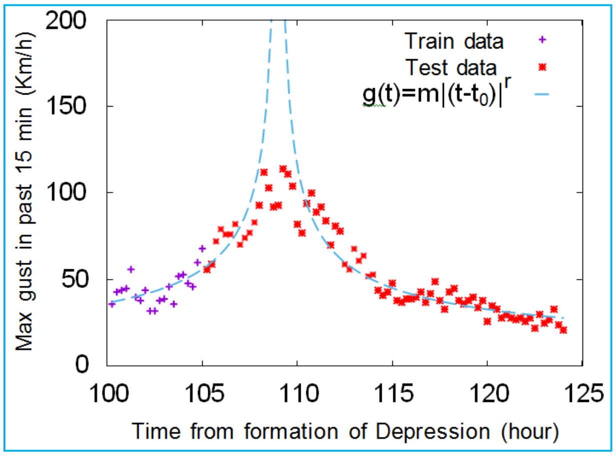


Fig. 5. Left : Curve fitting and prediction of the distance of the cyclone center from Kolkata with a lead time of upto 18 hours using data for the variation of distance with mean sea level pressure (MSLP). Right : Similar prediction with a lead time of upto 12 hours

From the position of the system, the distance from Kolkata is obtained. Starting from the depression stage, the distance of the cyclone from Kolkata is obtained as a function of time, as shown in Fig. 4. The fit function $d\,(t) = c{-}t^a/b$ where, d denotes the distance of the system center from the station as a function of time, which is denoted by t, matches closely with the observed data. The fit function has the parameters $c = 1332.5$, $a = 2.0$, $b = 9.9$ for 78 hour of fitting data and a prediction for a lead time of up to 24 hours before reaching close to Kolkata and updated to $c = 1326.5$, $a = 2.1$, $b = 13.1$ for past 78 hours of data and a prediction for a lead time of up to 18 hours.

The system reached near Kolkata almost 110 hours after the formation of a depression in the Bay of Bengal. Similarly, variation of distance with the mean sea level pressure (MSLP) is given in the right panel of Fig. 5. The mathematical expression $d(p) = d_0 + k(p - p_0)^q$ for distance as a function of MSLP is determined, with $d_0 = 61.4$, $k = 4.9 \times 10^{-5}$, $p_0 = 955.6$, $q = 4.3$ for the past 18 hour of fitting data and prediction for lead time up to 18 hour, and updated to $d_0 = 24.9$, $k = 9.8 \times 10^{-5}$, $p_0 = 955.2$, $q = 4.1$ for the past 18 hour of fitting data and prediction for lead time up to 12 hours. This provides a prediction of the distance of the system from the station if the MSLP of the concerned station is known. It is seen that d_0 is the probable closest approach distance of the cyclone center and p_0 is the lowest MSLP at the station, where $d_0 = 24.9$ and $p_0 = 955.2$ as predicted for a lead time of 18 hours. It may be noted that the observed lowest MSLP for Kolkata was 958.8 hPa, around 110 hours from the formation of the depression.

One of the major components of the cyclone hazard forecast is prediction of gusty wind speed, which can be achieved as shown in Fig. 6 left panel. To fit the data, the associated mathematical relationship is $g(t) = m|t - t_0|^r$ with $m = 116.2$, $r = -0.52$ for the past 5 hours, fitting data



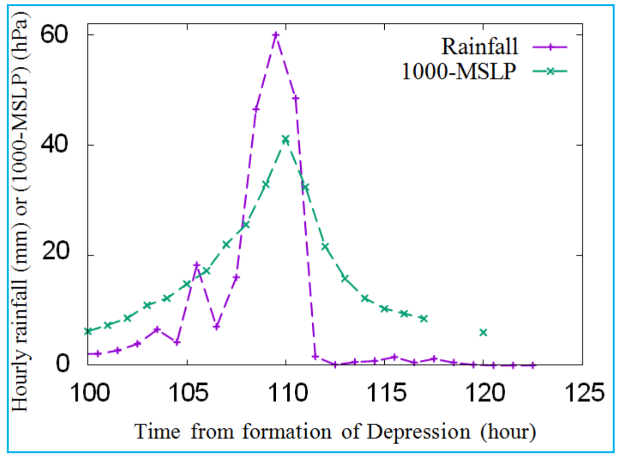


Fig. 6. Left : Curve fitting and prediction of maximum gusty wind speed in a 15-minute interval for Kolkata with a lead time upto 18 hour; Right : Hourly rainfall along with departure of mean sea level pressure (MSLP) from 1000 hPa at different times for Kolkata

and prediction for lead time up to 18 hours. Here, the parameter t_0 corresponds to the time of the highest gusty wind speed, *i.e.*, the closest approach of the cyclone wall cloud. From the relation $d(p) = d_0 + k(p - p_0)^q$, the closest approach of the cyclone center is predicted to be around 110 hours from the formation of the depression. Thus, the highest gusty wind speed is expected at around 110 hours. Therefore, we start with $p_0 = 110$ and update it to $p_0 = 109$ for better fitting of the updated observed data.

The hourly observed rainfall showed a sharp rise, with a peak around 110 hours from the formation of the depression and a sharp fall thereafter. The mathematical expression for rainfall can not be found, but it is evident that as the pressure started to fall sharply, rainfall increased significantly, attaining a peak when pressure was near the minimum value and then suddenly decreasing sharply as pressure started to rise, as shown in Fig. 6, right panel.

Thus, we have proposed two schemes: distance-time extrapolation (*d-t*) and distance- pressure extrapolation (*d-p*) for predicting the distance of the cyclone. Also, we proposed a gusty wind speed-time extrapolation for predicting the gusty wind speed. The accuracy of the proposed schemes has been compared with the track and intensity errors of the India Meteorological Department's (IMD) operational forecast (RSMC report 2021) using the IMD Multi Model Ensemble (IMD-MME) for track prediction and the IMD Statistical Cyclone Intensity Prediction Model (IMD-SCIP) for intensity prediction. Also, the accuracy of different numerical weather prediction (NWP) models (RSMC report 2021), *viz.*, European Centre for Medium-Range Weather Forecasts (ECMWF), National Centers for Environmental Prediction Global Forecast System (NCEP-GFS), UK

TABLE 1

Comparison of the error of distance (km) prediction with the track error of the IMD operational Forecast and other NWP models at different lead times

Schemes	12 hour	18 hour	24 hour	12-24 hour Average
Proposed *d-t* Scheme	43	2	29	25
Proposed *d-p* Scheme	3	–	–	3
IMD-MME	26	–	36	31
ECMWF	51	–	73	62
NCEP-GFS	31	–	42	37
UKMO	50	–	61	56
JMA	40	–	59	50
HWRF	53	–	80	67
IMD-GFS	52	–	62	57
NCUM	58	–	62	60
NEPS	58	–	77	68
GEFS (CNTL)	61	–	64	63
GEFS (MEAN)	53	–	71	62

TABLE 2

Comparison of error of gusty wind speed (km/h) prediction with intensity error of the IMD operational forecast and other NWP models

Schemes	Average absolute error (AAE 12 hour)	Root means quare error (RMSE 12 hour)
Proposed Scheme	0.5	7.9
IMD-SCIP	6.1	8.1
HWRF	12.9	15.6
IMD-GFS	12.2	14.5
GEFS(CNTL)	20.0	23.0
GEFS(MEAN)	24.0	27.0

Meteorological Office (UKMO), Japan Meteorological Agency (JMA), Hurricane Weather Research and Forecasting (HWRF), IMD Global Forecast System (IMD-GFS), National Centre for Medium Range Weather Forecasting Unified model (NCUM), NCUM ensemble prediction system (NEPS), Global Ensemble Forecast System (GEFS), have been compared as shown in Tables 1, 2. It has been found that the error is much less compared to other models.

5. Discussion and conclusion

In this article, we have focused on precursors of super cyclone AMPHAN and its associated hazards from a surface observational point of view with respect to Kolkata, India. All nearby coastal stations experienced a sharp fall in pressure as the system approached closer. We have proposed a new scheme by applying the curve fitting technique and extrapolation using the surface observational data to improve the prediction of cyclone hazards with a lead time of up to 12-24 hours ahead. A precursor has been obtained in the form of a mathematical equation for the variation of the distance of the system from the concerned station as a function of time. Also, we have obtained a mathematical expression for the distance of the system as a function of the mean sea level pressure of the concerned station. Using either equation, the distance of the system from the concerned station can be well predicted 24 hours in advance. From the expression of distance as a function of mean sea level pressure, the lowest possible approach distance of the cyclone and the corresponding lowest pressure at the station are also well predicted 12 hours in advance.

Similarly, gusty wind speed can be predicted by curve fitting and extrapolation techniques with a lead time of up to 18 hours in advance. Fitting parameters are updated from time to time based on the latest observations. Also, precursors for rainfall peaks and decay have been identified. Rainfall rises following the sharp fall of mean sea level pressure and falls sharply once the pressure drop stops or pressure starts to increase.

The forecast accuracy of the proposed scheme has been compared with the operational forecast of the India Meteorological Department and forecasts from various reputed NWP models. In respect of the prediction of system distance from the concerned station and associated gusty wind speed, it is found that the accuracy of the proposed scheme is better than all other forecasts and models considered in the present study for cyclone AMPHAN. The proposed scheme may be useful for other cyclonic storms as well. Though there are several atmospheric and oceanic parameters that control the track, intensity, and associated hazards, surface observation-based extrapolation may be useful for the prediction of hazards for 12-24 hours ahead. Also, this may be useful to identify the model that provides the best prediction for a particular cyclone by comparing the model prediction with that of the pro- posed scheme for the upcoming hours. In case of any change in the track or intensity, it may be reflected in the surface observational data well in advance and hence be captured in the prediction of the scheme. Thus, a lot of information can be extracted from surface observational data to enable accurate short-term prediction of such systems and their associated hazards with lead times up to 12-24 hours. However, it may be used as a guidance tool along with other tools, *e.g.*, NWP models, satellites, and radar etc. for final decision making and prediction for operational purposes.

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