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Prediction of tropical cyclone induced rainfall variability over East coast of India using satellite measurements

SP. VIJAYALAKSHMI

Civil Engineering, IISc, Bangalore, Pincode – 560 012, India

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e mail : vijai9111995@gmail.com

सार – चक्रवाती परिघटनाओं के कारण वर्षा की तीव्रता मॉनसून की वर्षा की तुलना में बहुत अधिक होती है, जिससे मनुष्यों और मवेशियों के जीवन को भारी नुकसान होता है और अन्य कई परेशानियाँ होती है। इस तरह के नुकसान को कम करने के लिए वर्षा का सटीक पूर्वानुमान आवश्यक है। किसी भी विश्लेषण के लिए वर्षा के स्थानिक वितरण और इसकी कालिक भिन्नता के बारे में पर्याप्त ज्ञान आवश्यक है। इस अध्ययन का उद्देश्य उष्णकटिबंधीय चक्रवात (TC) **से होने वाली वर्षा का पूर्वानुमान देकर किसी भी राहत कार्य या आपदा न्यूनीकरण योजनाओं की तैयारी में मदद करना है।**

चक्रवात के बनने के लिए आवश्यक स्थितियों, परिभाषा, वर्गीकरण, पर चर्चा की गई है। इस अध्ययन में तूफान कैसे उत्पन्न होता है, आगे बढ़ता है और समाप्त होता है को बताया गया है । यह जानकारी उष्णकटिबंधीय चक्रवात के व्यवहार को बताती है। उष्णकटिबंधीय चक्रवातके ट्रैक के साथ Gis- **आधारित औसत वर्षा** Trmm-3b42 **डेटा से चक्रवाती प्राचलों और वर्षा के बीच संबंध विकसित करने के लिए प्राप्त की जाती है।**

यह सहसंबंध प्रभाव और व्यवहार का आकलन करने में मदद करता है। सामान्यीकृत समाश्रयण मॉडल उष्णकटिबंधीय चक्रवात प्रेरित वर्षा और पवन की गति, स्थान, दबाव, और वर्षा जैसे चक्रवाती प्राचलों के बीच संबंध विकसित करता है, भविष्य की परिघटनाओं का पूर्वानुमान देने के लिए पूर्वानुमानकर्ताओं को चक्रवाती प्राचलों और प्रतिक्रिया के स्वरूप होने वाली वर्षा से मदद मिलती है।

यहाँ 2008 **से** 2017 **तक की वर्षा परिवर्तनशीलता का विश्लेषण किया गया है। गाजा चक्रवात के पूर्वानुमान का परिणाम** 16 **और** 17 **नवंबर** 2018 **को** 0.8 **और** 0.72 **के सहसंबंध मान के रुप में हुआ। परिणाम बताते हैं कि वर्षा का अनुमानित मान वास्तविक वर्षा के मान के लगभाग समान ही है।**

ABSTRACT. Rainfall intensity due to cyclonic events is very high compared to the monsoon rain, causing heavy damage to the lives of humans and cattle and another severe bruise. To minimize such damages, accurate prediction of rainfall is necessary. Adequate knowledge about the spatial distribution of precipitation and its temporal variation is essential for any analysis. The study aims at predicting the rainfall resulting from the tropical cyclone (TC) to help any relief activity or preparation of disaster mitigation plans.

The detailed definition, classification, and conditions necessary for the cyclone to occur are discussed in the study to know how a hurricane originates, grows, and dissipates. GIS-based mean rainfall along the track of TC is derived from TRMM-3B42 data to develop a relationship between the cyclonic parameters and rainfall.

This correlation helps to assess its impact and behaviour. A generalized regression model is developed with the sensitive parameters of TC-induced rainfall and cyclonic variables like wind speed, location, pressure, and precipitation to predict future events with predictors as the cyclonic parameters and rainfall as the response.

Rainfall variability from 2008-2017 is analyzed. 2/3rd of the data (from 2008 -17) is used in analyzing part and the remaining for validation. The prediction for the GAJA cyclone resulted in a correlation value of 0.8 and 0.72 for the 16th and 17th of November 2018. The results show that the predicted value is almost the same as the actual value of rainfall that has occurred.

Key words – Parametric test, Non-parametric test, GAJA cyclone, INSAT-3D.

1. Introduction

Historical reports according to National Cyclone Risk Mitigation Project (NCRMP) signify that the deadliest cyclones with the highest catastrophe and death tolls occurred in the Bay of Bengal (BoB). The four maritime states Tamil Nadu (TN), Andhra Pradesh (AP), Orissa, and West Bengal, located on the east coast of India are hit by 308 cyclones (103 being severe) from 1891-2000.

Torrential rainfall (more than 30cm/hr) associated with TCs is the primary cause of damage. Heavy rainfall from a cyclone is usually spread over a wide area (300-2000 km) and causes large-scale soil erosion and the weakening of embankments. Heavy and prolonged rain because of storms causes flash floods, river floods, and submergence of low-lying areas, causing loss of life and property.

Many mathematical and stochastic models are developed to track TC and predict the associated rainfall (Vincenzo Levizzani *et al*., 2018). For this type of study satellite data are more reliable (Roy Bhowmil *et al*., 2007). The distribution of rainfall patterns during TCs depends on various factors, *i.e*., the internal dynamics of the cyclones and environmental characteristics. A cyclone's translational speed has a significant impact on the azimuthal asymmetries (vertical shear) of rainfall and the total rainfall duration at a location, as slow-moving systems are more likely to stay in a place than fast-moving systems (Stephan *et al*., 2012). The vertical wind shear creates asymmetries in the inner-core field rainfall distribution pattern. The intensity of the storm, the environmental humidity, and the underlying surface properties can influence the amount and distribution of rainfall received from a land-falling TC (Barbara *et al*., 2014).

In the first chapter, a general discussion about the cyclones, their effect and behaviour, the objective, and the need for this study are elaborated. In the second chapter, a detailed methodology has been drafted, and the study area is finalized. In the last chapter, the results that are obtained using the methodology are discussed.

1.1. *Cyclone*

According to the National Disaster Management Authority (NDMA) Govt. of India, a system of winds rotating inwards to an area of low barometric pressure, with an anticlockwise (northern hemisphere) or clockwise (southern hemisphere) circulation is called cyclone. On the other hand, it is the warmcore, originating in tropical or subtropical waters, with organized deep convection and closed surface wind circulation about a well-defined centre.

Cyclones are termed (*i*) Tropical and (*ii*) Extra-tropical or Temperate cyclones. They originate and die between the Inter-Tropical Convergence Zone (ITCZ) and are termed the TCs. Cyclones are named differently in various regions, namely, Typhoons (China, Japan), Hurricanes (Atlantic, Northeastern Pacific), TCs (India, South Pacific), Tornadoes (U.S.A), and Willy-Willy (Australia).

1.2. *Conditions needed for cyclone formation*

(*i*) A warm, moist air derived from tropical oceans with SST (Sea Surface Temperature) normally > = 27 °C for 20m depth.

(*ii*) The ocean surface winds blow from different directions, converging and causing air to rise and storm clouds to form.

(*iii*) Winds that do not vary significantly with height are known as low wind shear. It allows the storm clouds to rise vertically to high levels.

(*iv*) Rapid cooling with the height helps in accumulation of clouds.

(*v*) The formation mechanisms vary across the world, but once a cluster of storm clouds started to rotate, it will become a tropical depression. If continues, it develops into a tropical storm, and later a cyclone / super cyclone.

1.3. *TC category system*

The cyclone is categorized into five types based on (NDMA) the wind- speed as listed below and their impact on the environment is also discussed in Table 1.

1.4. *TCs in Bay of Bengal (BOB)*

Cyclones that occur all over the world are not newly developed ones. They usually grow from the remnants of a previously formed cyclone. Examining the historical cyclone helps in creating a database of its behavioural patterns (Sahoo *et al*., 2018). BoB is famous for the cyclonic events, some of which are presented in Table 2 from 2008-2017.

The following objectives are formulated for the study.

(*i*) To study and analyse the TRMM 3B42 3 hourly data for determining the amount and the distribution of rainfall during the cyclonic event in 2008-17.

(*ii*) To predict the amount of rainfall associated with the cyclone GAJA.

TABLE 1

Categories of cyclone system

Category of TCs	Type of TCs	Damage	Description	Wind speed	Beaufort number
C1	Cyclonic Storm (CS)	Negligible house damage, some crops, trees and caravans	Gales	90-125 Kmph	8 and 9
C 2	Cyclonic Storm (CS)	Minor damage to the house, and significant damage to signs, trees and caravans. Heavy damage to some crops, risk of power failure	Destructive	125-164 Kmph	10 and 11
C 3	Severe Cyclonic Storm	Some roof and structural damage. Some caravans were destroyed. Power failures are likely	Very Destructive	165-224 Kmph	12 (Hurricane)
C4	Severe Cyclonic Storm (SCS)	Significant roofing loss and structural damage. Caravans were destroyed and blown away. Dangerous airborne debris. Widespread power failures	Very Destructive	225 – 279 Kmph	12
C 5	Very Severe Cyclonic Storm (VSCS)	Extremely dangerous with widespread destruction	Very Destructive	>280 Kmph	12

2. Data and methodology

Rainfall is an important prognostic parameter to determine the climatology and weather data at a specific location. Thus, continuous and comprehensive monitoring and measuring of rainfall will assist to understand the climatic conditions. The data and methodology used in this study are described in this chapter.

2.1. *Data used*

The data required for the study include rainfall from satellite observations and rain gauges. In this study, the TRMM, and INSAT satellite data are used along with surface observations from IMD.

2.1.1. *Tropical Rainfall Measuring Mission (TRMM)*

TRMM 3B42 3hourly data is a joint mission between NASA and Japan Aerospace Exploration (JAXA) Agency to study rainfall for weather and climate research. The TRMM satellite ended collecting data on 15/04/2015. It is launched in late November 1997, with a design lifetime of 3 years, the TRMM satellite produced over 17 years of valuable scientific data. TRMM carried 5 instruments: a 3-sensor rainfall suite (PR, TMI, VIRS) and 2 related instruments (LIS and CERES). (Liu *et al*., 2012) TRMM delivered a unique 17-year dataset of global tropical rainfall and lightning. The data is available in netCDF (network Common Data Format) format. Its Spatio-temporal resolution of 0.25° × 0.25° and 3 hours respectively. This data is used to plot a graph for the variation in rainfall from 2008-2017. The red colour (Fig. 1) indicates the region of higher rainfall and the sea blue colour indicates the region where there is no rainfall.

TABLE 2

Cyclones formed over BoB

S. No.	Name	Pressure (mbar)	Year	Wind-speed (km/hr)
1.	Nisha	996	2008	85
2.	Nagris	962	2008	165
3.	Khaimuk	996	2008	65
4.	Rashmi	984	2008	85
5.	Bijli	996	2009	95
6.	Aila	968	2009	120
7.	Phyan	988	2009	95
8.	Ward	968	2009	110
9.	Laila	986	2010	120
10.	Giri	950	2010	250
11.	Jal	998	2010	100
12.	Thane	972	2011	140
13.	Nilam	992	2012	85
14.	Viyaru	990	2013	85
15.	Phailin	940	2013	260
16.	Helen	990	2013	130
17.	Lehar	980	2013	140
18.	Madi	986	2013	120
19.	Hudhud	950	2014	215
20.	Komen	986	2015	85
21.	Roanu	983	2016	85
22.	Kyant	997	2016	85
23.	Nada	1000	2016	75
24.	Vardah	982	2016	130
25.	Maarutha	996	2017	85
26.	Mora	978	2017	150
27.	Ockhi	975	2017	155

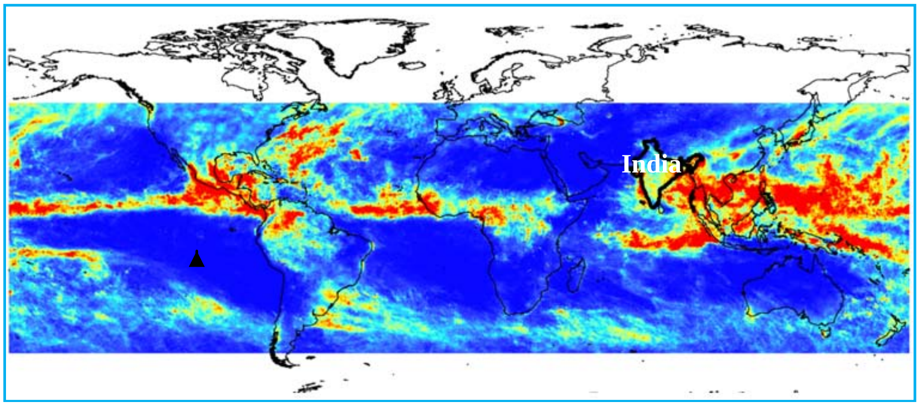

Fig. 1. Rainfall distribution over the world

2.1.2. *Surface rain gauges*

Specific instruments at fixed stations consistently observe the meteorological parameters. Some of these instruments consist of a tipping bucket gauge, weighing type gauge, and float recording. The rain considered, as actual data on the ground at a specific location, is this in-situ instrument's main advantage. It is the globally accepted data to represent the phenomenon, which occurred at the site.

2.1.3. *Satellite INSAT-3D*

Satellite INSAT-3D was developed by the Indian Space Research Organization (ISRO) and successfully launched on 26 July 2013 using an Ariane 5 launch vehicle in French Guiana. It is an advanced weather satellite configured with an improved Imaging System and Atmospheric Sounder. It monitors land and ocean surfaces. The satellite is also designed to generate a vertical atmospheric temperature and humidity profile for weather forecasting and disaster management purposes. The satellite carries four payloads of six-channel multispectral imagers, nineteen channel sounders, a Data Relay Transponder (DRT), and a Search and Rescue Transponder. Thermal Infrared (TIR) spectral channel at a spatial and temporal resolution of 4 km and 30 mins observation will be used as input parameters to the algorithm. Data**:** http://mosdac.gov.in.For this study's purposes, thermal IR or atmospheric window bands at wavelength 10.5 to 12.5 was applied in the algorithm (Gairola *et al*., 2010).

2.2. *Study area*

TN is in the southern part of India. Its capital and largest city are Chennai (formerly known as Madras). The union territory of Puducherry and the Southern Indian

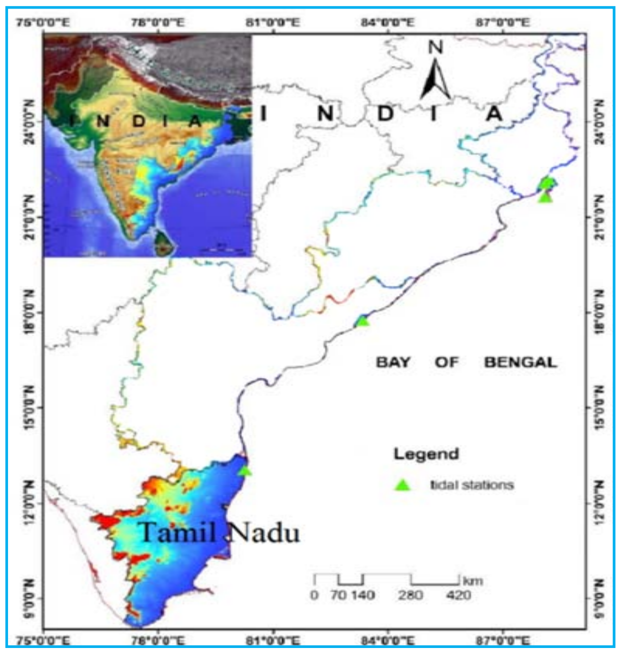

Fig. 2. Study area

states of Kerala, Karnataka, and AP surround TN. The Eastern Ghats bound it by the north. The Nilgiris Mountains, the Meghamalai Hills and Kerala in the west. BoB in the east. The Gulf of Mannar and the Palk Strait in the southeast, and the IO in the south. The state shares a maritime border with the nation of Sri Lanka. Fig. 2 shows the study area. Co-ordinates: 8°-13.09°N 76.10° - 80.27°E.

2.3. *Methodology adopted*

The study predicts the rainfall distribution for the given cyclonic attributes like wind pressure and speed, SST and the track of the cyclone with the idea followed in

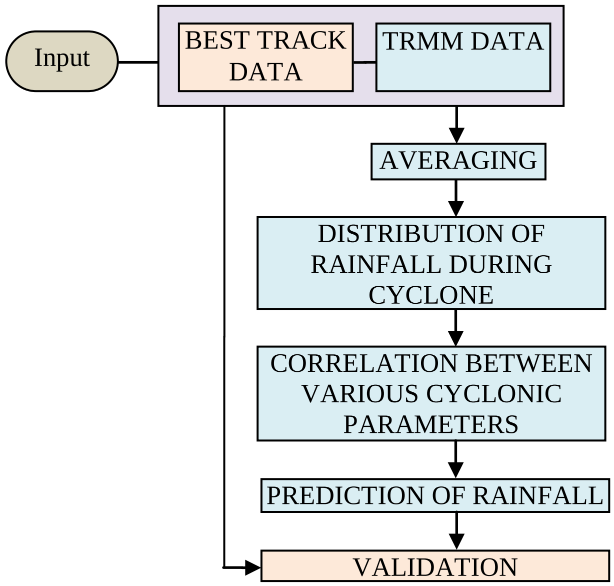

Fig. 3. Methodology

Konrad II *et al*., (2002) and Randall *et al*., (2009). The mean rainfall was obtained for each cyclone in 2008-17. A regression model is developed with the above-mentioned variables. $2/3^{rd}$ (2008-17) of the data is used for calibration of the model and the rest for validation. 250 station data are used to validate the result. The methodology is described in Fig. 3.

The rainfall data from TRMM is averaged for every event to understand the distribution of rainfall during a cyclone. The cyclonic parameters were determined from the Best Track Data of IMD. A correlation is developed between rainfall and various cyclonic parameters to derive the relationship and to know the sensitivity of the variables. Using the correlation developed, rainfall was predicted for a new cyclone (GAJA cyclone).

3. Results and discussions

The study predicts the rainfall using a past cyclonic event database and the correlation data between rainfall and cyclonic parameter. The obtained rainfall value was validated with actual rainfall from the IMD-station data. This chapter describes the results achieved in this study in three sections (*i*) Cyclonic parameters and rainfall observations. (*ii*) Correlation value of different influencing parameters of the NILAM cyclone. (*iii*) Prediction of rainfall from GAJA cyclone.

3.1. *Cyclonic parameters and rainfall observations*

With the insight given by Saha K. *et al*., (2015) for the assessment of TCs, the Nilam cyclone was selected to develop, the relationship between rainfall and cyclonic attributes. The cyclonic attributes: Date/Time of the Cyclone, Pressure, Latitude, Longitude, Wind Speed, and related to Rainfall that occurred during a cyclone. The observations are indicated in Table 3.

TABLE 3

Rainfall corresponding to the cyclone type

S. No.	Cyclone Name	Type of Cyclone	Date	Time (hrs)	Pressure (hPa)	Lat.	Lon.	Wind Speed	Rainfall (mm/hr)	
1.	NILAM	CS	30.10.2012	0300	998	9.0	82.0	35	18	1.8
2.	NILAM	CS	30.10.2012	0600	996	9.0	82.0	35	11.63	1.163
3.	NILAM	CS	30.10.2012	0900	996	9.5	82.0	35	19.04	1.903
4.	NILAM	CS	30.10.2012	1200	994	9.5	82.0	40	24.53	2.452
5.	NILAM	CS	30.10.2012	1500	994	9.5	82.0	40	20.88	2.088
6.	NILAM	CS	30.10.2012	1800	992	10.0	82.0	40	17.64	1.764
7.	NILAM	CS	30.10.2012	2100	990	10.0	82.0	40	15.6	1.559
8.	NILAM	CS	31.10.2012	0000	988	10.5	81.5	45	15.53	1.552
9.	NILAM	CS	31.10.2012	0300	987	11.0	81.0	45	23.9	2.39
10.	NILAM	CS	31.10.2012	0600	987	11.5	81.0	45	19.33	1.933
11.	NILAM	CS	31.10.2012	0900	987	12.3	80.5	45	17.01	1.7
12.	NILAM	CS	31.10.2012	1200	986	12.7	79.8	35	14	1.4
13.	NILAM	CS	31.10.2012	1500	981	13.0	79.5	35	20.04	2.004

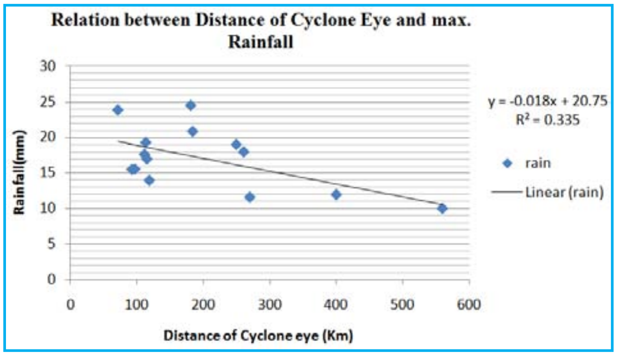

Fig. 4. Correlation between the distances of cyclone eye to rainfall

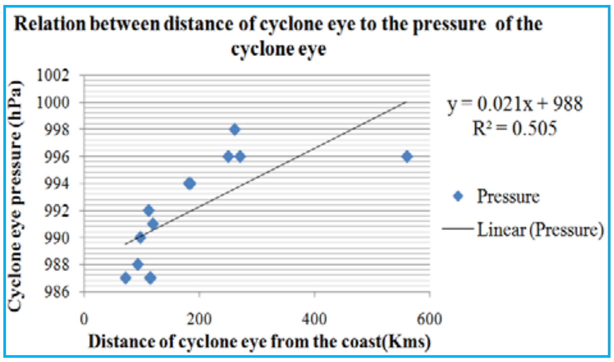

Fig. 5. Correlation between the distances of cyclone eye to the pressure of cyclone eye

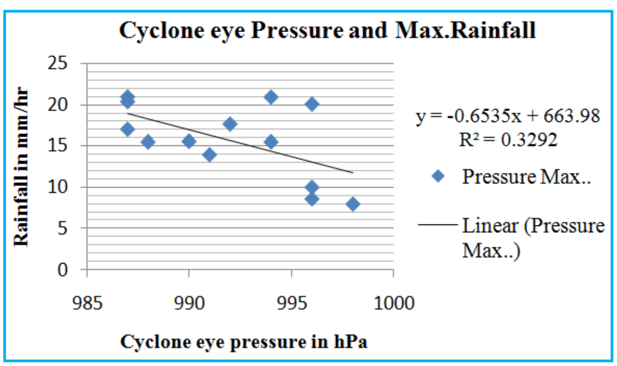

Fig. 6. Correlation between cyclone eye pressure and rainfall

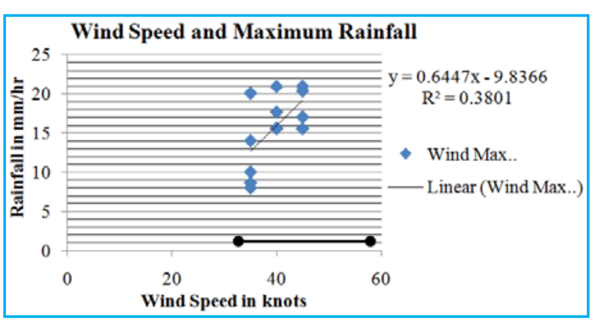

Fig. 7 Correlation between wind speed around the cyclone to rainfall

TABLE 4

Relation between rainfall and cyclonic parameter

S. No.	Relation parameters	Equation	Value of R^2
1.	Eye pressure *vs* rainfall	$y = 0.004x - 4.551$	0.043
2.	Wind sped *vs* rainfall	$y = -1.659x + 1680$	-0.711
3.	Distance of cyclone eye *vs* pressure of the cyclone eye	$y = 0.020x + 0.263$	0.397

3.2. *Correlation value of different influencing parameters of the NILAM cyclone*

The correlation between Cyclone Eye Pressure in hPa and rainfall is developed to understand how it varies as the pressure drops. The variation is shown in Fig. 4.

From the figure, it is understood that the relation between the distance of the cyclone eye (from the land) to the rainfall is inversely related: when the cyclone pressure drops, the rainfall increases. The correlation value that is obtained is 0.335 which indicates the cyclonic parameter distance influences rainfall.

The landfall increases as the TC approaches the land, so there must be a relation between the pressure drop and the TC location. This relation is explained in Fig. 5.

The correlation between Cyclone Eye Pressure in hPa and the distance of the cyclone is developed and inferred that the distance of the cyclone eye has a greater influence overpressure of the cyclone. The correlation value is 0.505 which is highly correlating, and shows as the cyclone approaches landmass the fuel for its growth is depleted and hence it loses its pressure and dies. It is clearly shown in Fig. 5. This pressure drop is due to the unfavourable condition prevailing in the landmass.

From Fig. 6 it is concluded that the relation between the cyclone eye pressure to rainfall is inversely related, *i.e.*, When the cyclone eye pressure drops, we get high rainfall or if the cyclone moves towards land, it loses its strength, and the rainfall is high over the land at that time. The correlation value that is obtained is 0.3292.

Fig. 7 conveys the relation between wind speed around the cyclone to rainfall is directly related, *i.e.*, When the wind speed around the cyclone is very high, it is expected to have a high rainfall over the region. The correlation value that is obtained from the graph is 0.32. Similar work is done for each cyclone in 2008-17 years and the correlation equation is obtained which is tabulated below. This correlation is not seen for the VSCS, or super-cyclone and a negative correlation is observed for such type of cyclone because as the wind speed is very high the rainfall is <150mm or no rainfall, as the clouds are carried away, so a negative correlation is observed which is clearly stated in Table 4.

3.3. *Prediction of rainfall for GAJA cyclone*

Prediction is carried out after analyzing the rainfall variability over the BoB for all the cyclonic events from 2008-17 using a regression model. The model is first trained with the amount of actual rainfall, cyclone track, the pressure of the cyclone, wind speed, and SST (inputs). When these inputs are given to the model for prediction, it navigates through the database for past event occurrences. It is compared and the result is displayed with the previous experience it has. The prediction is more precise when the number of variables is increased while training the model. The predicted result for cyclone GAJA 2018 is shown in Fig. 8.

The predicted and actual values are more or less similar. The portion which is highlighted in red colour is nearby the true value whereas the one which is highlighted in black colour varying the most. This inconsistency is seen because the input given includes only 10 years of data. For consistency of the resulting minimum of 50 years is to be considered. Fig. 9 explains the rainfall variation for the given value of pressure as input. From Fig. 6 it is evident that at high-pressure low rainfall is experienced and if the pressure is less high rainfall is seen. Fig. 9 also proves that the above-mentioned statement is valid.

At the point of cyclogenesis, the pressure will be high, as it grows the pressure drops after landfall it starts to die. From the above graphs, it is inferred that at the start of the cyclone the rainfall is minimum as it moves it loses its energy, so pressure drops hence the rainfall started increasing. At a certain stage, the rainfall stabilizes, and it declines.

Correlation and bias are calculated it is seen that both the values go in hand, but when we plot the region of rainfall that happened, we can see the difference. The predicted rainfall is cross-checked with actual rainfall from the IMD station data. The correlation and the bias of the predicted and actual rainfall for the GAJA cyclone on the 16th and 17th of Nov, 2018 are shown in Fig. 10.

Fig. 10 shows the bias and the correlation value, (-0.35, -0.67) and (0.8, 0.72) respectively. The following plot shows the predicted and actual rainfall event on 16th Nov. 2018.

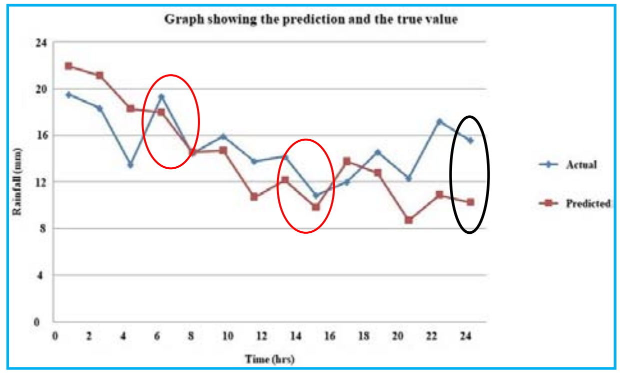

Fig. 8. Predicted rainfall for the cyclone GAJA 2018

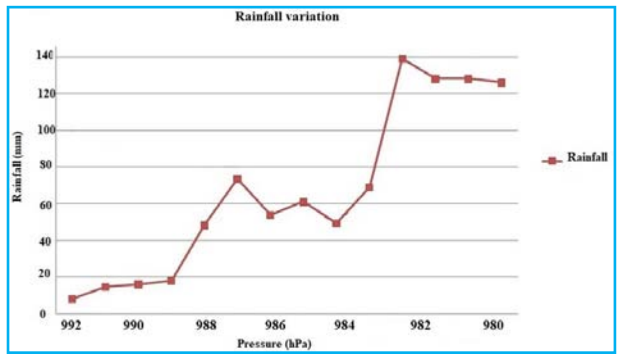

Fig. 9. Rainfall variation for a given pressure (Input)

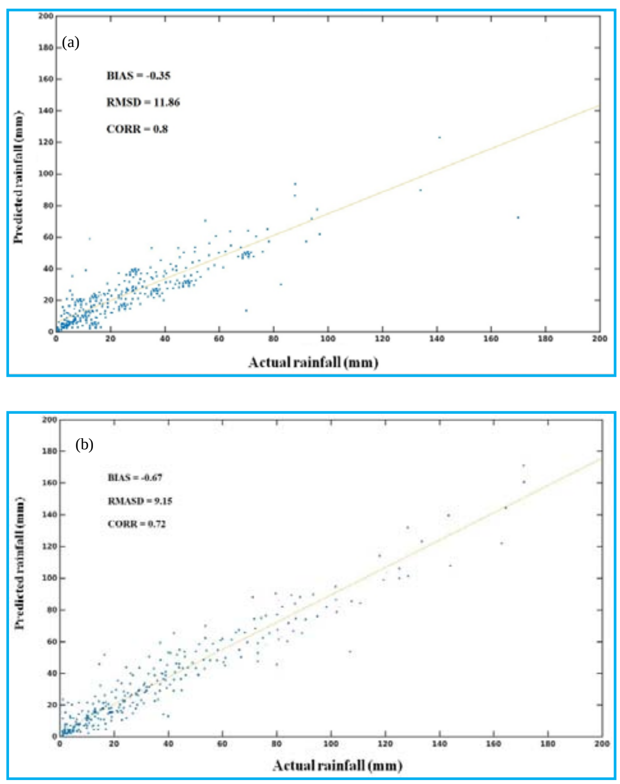

Fig. 10 (a&b). Correlation between predicted and actual rainfall (IMD) on (a) 16th Nov, 2018 (b) 17th Nov, 2018

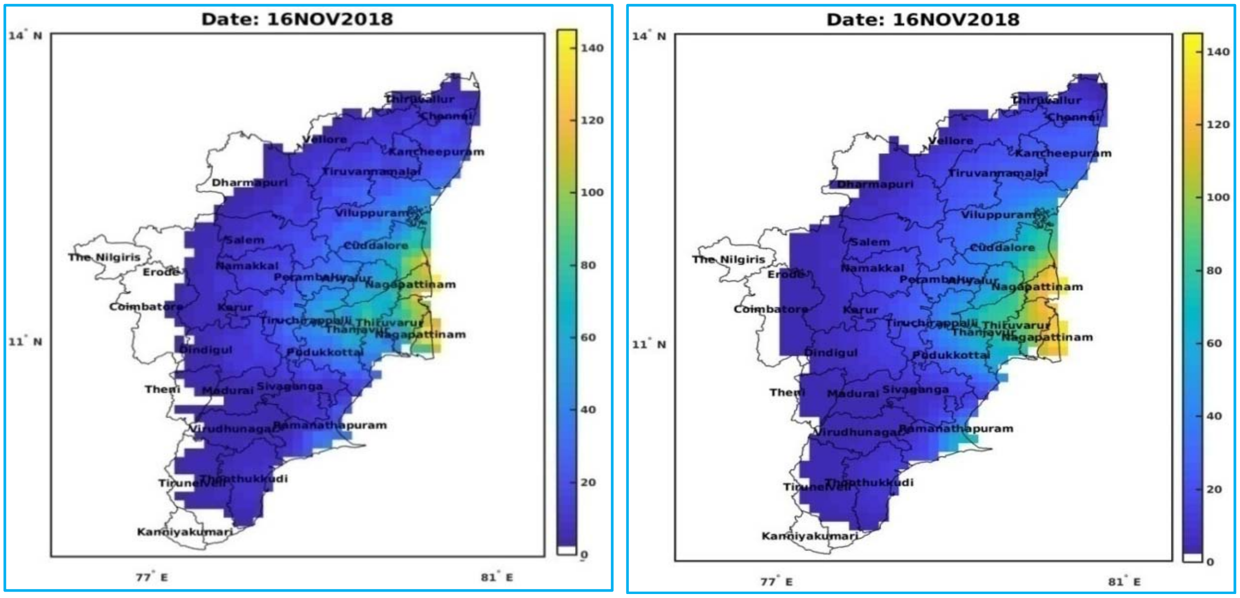

Fig. 11. Predicted (L) and actual (R) rainfall on 16th Nov, 2018

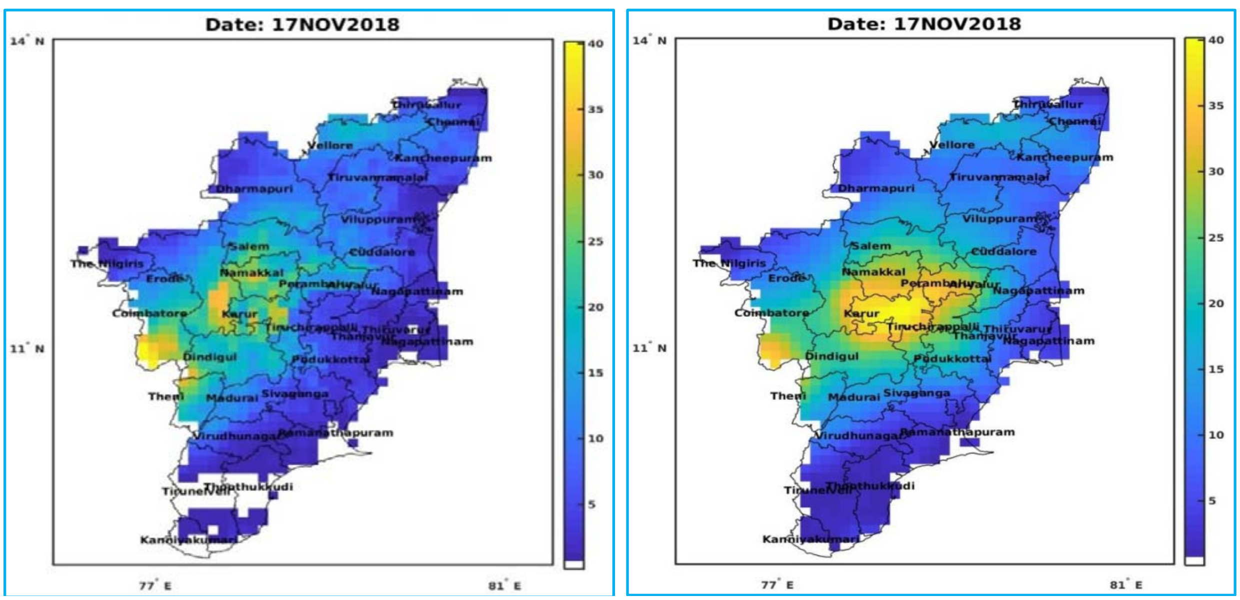

Fig. 12. Predicted and actual (INSAT 3D) rainfall on 17th Nov, 2018

Figs. 11 and 12 show the predicted and actual rainfall on 16th and 17th of Nov 2018 for the GAJA cyclone. The most affected areas during the GAJA cyclone are Tanjore, Nagapattinam, Thiruvarur, Karaikal, Pudukottai, Cuddalore, Trichy and Ramanathapuram.

For both the days of landfall, the area of inundation is the same as predicted as the actual area of inundation. The amount of rainfall is estimated to be the same on the 16th of November but on the 17th of November, the rainfall is less in predicted value than actual. The rainfall ranges from 25-35 mm per hr as per the predicted value but in actuality, the value varies from 30-40mm. This discrepancy is due to the less duration (only 10 years of data) as input.

But overall, it shows the same area of inundation, and it estimates correctly on the day of landfall. Though it is underestimated on the 17th of November, it shows the same area of outpouring as that of actual and the value does not deviate much.

4. Conclusion

The work aims to study the rainfall variability induced by a TC over the east coast of India and to develop a simple and ready-to-use model for the prediction of TC-induced rainfall (Kishtawal (2013 & 17), Baskarana, R. (2013), Aggarwal *et al*. (2013). The TRMM 3B42 data for different cyclonic events like CS, SCS, and VSCS at an interval of 3 hours is collected. Corresponding rainfall values (max. and min.) are monitored. The INSAT-3D half-hourly data is also collected to get the rainfall information during the cyclonic period. The track information of the cyclone is obtained from the best track data released by the IMD station, which says information on wind speed, the pressure of convective clouds, and the cyclone's location.

Rainfall for all 27 events is plotted to determine the relationship between the rainfall and the cyclonic attributes, stated earlier. Using the INSAT 3D data, the plot obtained is compared to know the correctness. After getting the rainfall and the other attributes, the regression model is trained to estimate future events. (Timothy Marchok *et al*., 2017)

The model is trained several times with the cyclonic attributes to predict correctly. If the model is trained for one-time prediction of rainfall value, it is less accurate, and the accuracy increases after training the model several times. So it is evident that the iterative training of the model enhances the model accuracy. Further, it is also noticed that the correlation between the predicted and actual rainfall value is 0.72 (obtained at 30th iteration after that accuracy decreased). As the model depicts the scenario very much near to the real situation, this model can be used for rainfall estimation, distribution analysis, etc.,

The study also has some limitations. The best track data from IMD for 2008-2017 for developing the database of variation of rainfall for different cyclonic parameters are mentioned in section 4.1. INSAT -3D data is used to validate the predicted amount of rainfall for the GAJA cyclone 2018. The mathematical model was developed with only a few variables like cyclone pressure, wind speed, and location to predict rainfall; though the correlation value is good, and the bias value is small, this cannot be used for further analysis of work. For consistency of results, the investigation period should be increased. Also, the study uses only ten years of data, which is the minimum duration for any climatological study.

4.1. *Future work*

(*i*) The investigation period should be increased for at least 50 years and more cyclonic parameters are included other than the one which is used in this study.

(*ii*) The study investigates only cyclonic activity further, the analysis is to be made for monthly, and seasonal variation also.

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