



Understanding and improving tropical cyclone prediction systems

Vandana Kumari¹, Ashish Chourey², Dr. Ritu Shrivastava³, Dr. Rajiv Srivastava⁴

¹ Department of Computer Science, Engineering, Sagar Institute of Research & Technology, Bhopal, Madhya Pradesh, India

² Assistant Professor, Department of Computer Science, Engineering, Sagar Institute of Research & Technology, Bhopal, Madhya Pradesh, India

³ Head of Department & Professor, Department of Computer Science, Engineering, Sagar Institute of Research & Technology, Bhopal, Madhya Pradesh, India

⁴ Director, Sagar Institute of Research & Technology, Bhopal, Madhya Pradesh, Sagar Institute of Research & Technology, Bhopal, Madhya Pradesh, India

Abstract

At present, there is still a bottleneck in tropical cyclone (TC) forecasting due to its complex dynamical mechanisms and various impact factors. Machine learning (ML) methods have substantial advantages in data processing and image recognition, and the potential of satellite, radar and surface observation data in TC forecasting has been deeply explored in recent ML studies, which provides a new strategy to solve the difficulties in TC forecasting. In this paper, through analyzing the existing problems of TC forecasting, the current application of ML methods in TC forecasting is reviewed. In addition, the various predictors and advanced algorithm models are comprehensively summarized. Moreover, a preliminary discussion on the challenges of applying ML methods in TC forecasting is presented. Overall, the ML methods with higher interpretation, intervention and precision are needed in the future to improve the skill of TC prediction.

Keywords: Tropical cyclone (TC), machine learning (ML), forecasting prediction, satellite, radar

Introduction

The frequency of tropical cyclones is the number of cyclones which occur in a given area and period. Climate researchers usually consider this measure on an annual basis either in the tropics of the world or in specific oceanic basins, where such storms are frequent, e.g. the North Atlantic or the South Indian Ocean. The rate of cyclones is a key element in the general risk of cyclones because the rate of occurrence directly affects the possibility of impact; in the event a storm is not formed, no other physical feature comes into play. One of the main scientific questions is about the interaction of cyclone frequency with the overall climate system. Scientists want to know the weather conditions that control the average number of storms witnessed over the past few decades, the natural variability of this frequency, and how the climate change that has been caused by human activities is possibly changing these patterns. Although there is uncertainty, available literature suggests that there is growing confidence that a warming climate is likely to increase cyclone-driven rainfall and even increase cyclone wind speeds.

In order to enhance the accuracy in forecasting the occurrence of cyclones, several models have been considered. To give an example, a study proposed a nonlinear wavelet-neural network model that was developed based on empirical orthogonal functions and cross-combined weighting schemes in prediction of tropical cyclone frequency within the southern coast of China, with good prospects of success. Due to certain problems of the traditional neural networks, including slow convergence, local minimum as well as overfitting, a number of researchers have employed optimization methods, including genetic algorithms, to improve the robustness of the models. These hybrid models have demonstrated that they can be

applied both in short-range climate predictions and in the long-term predictions. Further modeling with finite mixture models and decision tree algorithms have made it possible to classify the landfalls of tropical cyclone in China, and significant relationships between large-scale climatic indices and cyclone movement and strength are found.

Tropical cyclones by themselves are massive, organized atmospheric systems, and take an average of a week. There is an average of 90 such storms every year in the major tropical basins around the world, which provide a good opportunity to study the subseasonal-to-seasonal (S2S) forecasting research. Attempts to determine the behavior of cyclones can be traced back to the late nineteenth century, when Jesuit meteorologists in Cuba used the local weather to forecast the path of Caribbean hurricanes. In the early twentieth century, national meteorological services were issuing track forecasts and warnings utilizing the available observational data. One of the significant developments came during the World War II when the United States started routine aircraft reconnaissance of typhoons, which significantly enhanced situational awareness. The aircraft measurements combined with the early radar technology improved the capabilities of tracking the cyclone structure and movement. In the 1960s, statistical forecast models, based on predictors of the environment calculated using new numerical weather prediction systems, started to demonstrate quantifiable ability to predict the paths of hurricanes. In the following decades, there have been constant advances in observational systems, satellite retrieval, and computational modeling which resulted in significant boosts in the accuracy of track forecasts, especially at short range. There is, however, also a lot of scientific challenge in predicting cyclone intensity even with such advances.

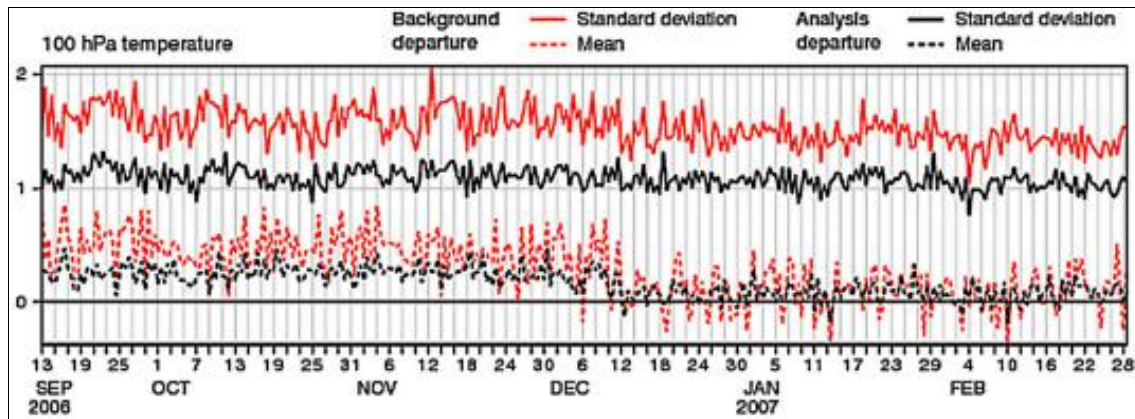


Fig 1: Time series of the mean and standard deviation of short-range forecast and analysis fitted to the radiosonde temperature measurements in the southern hemisphere, for the operational numerical weather prediction (NWP) system at the European Centre for Medium-Range Weather Forecasts (ECMWF)

Literature

1. Overview of traditional detection methods (e.g., pressure drop analysis, cloud pattern recognition)

The performance of a cyclone is often determined by a composite index that multiplies the Euler number by the square-root particle cut-off Stokes number. This composite measure is used to measure the trade off between pressure drop and separation efficiency- the two factors that normally oppose each other. Cyclone geometries with helical roof inlet, cross-cone design, higher geometrical height with the ratio of $h/D = 4.3$ and $H/D = 6.35$, and globally optimized design designs are generally superior to others in terms of practical evaluations. Among them, globally optimized setup can be seen as the most representative and that which can be applied to industry.

Cyclone separators are very important in any industry that produces flue gases by the burning of solid fossil fuel. They have common applications in thermal power plants and Circulating Fluidized Bed Combustor (CFBC) to trap fly ash in exhaust streams. Pressure drop is another important parameter used in measuring the efficiency of the cyclone separator since it is an indication of the resistance that the gas will meet in the system. This pressure loss occurs due to four primary sources, which include losses at the expansion at the inlet, contraction losses in the area of the vortex finder, energy loss in the vortex (eddy losses), and the last one is the kinetic energy loss at the outlet. Of these, the eddy and dissipation losses are of great importance in the total pressure loss. These elements are the subject of often design improvements, such as changing the vortex finder surface, to minimize losses due to turbulence. A decrease in the pressure drop does not only improve the performance of the separation but also decreases the amount of energy needed to move the airflow along the cyclone.

Cloud-pattern recognition is crucial in the situation of tropical cyclone detection with the help of satellite observation. Both manual components and automated computer algorithms are based on unique cloud structure related to cyclone development and progression. Some of the major visual signs are spiral rainbands, eye formation, upper-level outflow, and the central dense overcast (CDO). Spiral bands are formed in the shape of curvy arcs of the convective clouds around the center of the system and these are often observed in the infrared and the visible imagery. The CDO appears as an extensive mass of cold, high altitude clouds around the storm center and this is an

indication of intense convection. The transition to a mature cyclone phase is indicated by a distinct eye surrounded by a strong convection. Also, the outflow of cirrus rays in the outskirts of the core is an upper-tropospheric divergence that promotes cyclone ventilation and intensification. When combined, such cloud signatures enable forecasters to track cyclone structure, intensity and progression with reasonable accuracy.

2. Use of satellite imagery and radar

The modern strategies to predict the strength of tropical cyclones (TC) are heavily dependent on the use of microwave measurements taken at the polar orbit by polar satellites and at the geostationary orbit by geostationary satellites. Nevertheless, under the worst weather conditions in the atmosphere, especially when heavy rain is emitted in an area, the quality of microwave signals can be greatly compromised. Although polar-orbiting satellites are useful in giving information on the near-surface structure of cyclones, they have lower temporal resolution restrictions since they cannot sustain continuous monitoring. Geostationary satellites on the other hand, although incapable of capturing high-resolution low-level storm structure, provide updates on images quite often and have more predictable and consistent image quality, which makes them the best source of operational TC intensity measurements. Initial successes in intensity estimation by satellite were due to the Dvorak technique, which uses patterns of the cloud observed through infrared to measure the strength of the cyclone. This approach is rather academic in nature and highly relies on the skills and judgment of the analyst. Later modifications of the Dvorak method have been trying to minimise these subjective elements, but most versions continue to fail in reliably predicting the strength of the weaker tropical cyclones. The technique was also improved to overcome these drawbacks and enter what is currently referred to as the Advanced Dvorak Technique (ADT) version 9, which is more specifically optimized in order to enhance the accuracy of the intensity estimates, especially when weaker systems are involved. The second notable advancement is the Deviation-Angle Variance Technique (DAT) which is used to measure the extent of axisymmetry in the infrared satellite imagery. Measurement Structural symmetry provides an extra understanding of cyclone intensity and structural organization evolution.

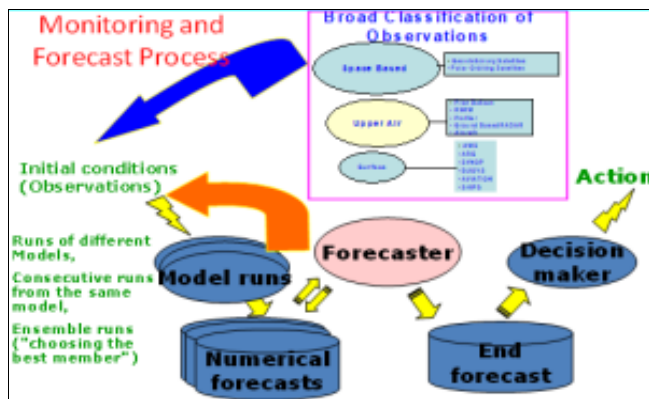


Fig 1: Monitoring and Forecasting process of tropical cyclone

The Southwestern Indian Ocean is known as a highly active tropical cyclone basin in the world and the most susceptible area to cyclones in the South Hemisphere. Along this basin, Mozambique experiences incessant and egregious climate-related problems that ensure frequent droughts, floods, and severe cyclonic incidences. The cyclone season in the country is usually between November and April and the Mozambique Channel produces between 3 and 12 cyclones every year. The central region of Mozambique, specifically Sofala, is the province that is most exposed to cyclones and other related risks, with six big cyclones recorded in a 16-year period. The natural environment of the region in the form of large areas of low-lying land and tidal elevations to 7 meters is what enhances this vulnerability.

Traditionally, there were a series of destructive storms in Sofala, among them in the years 1994, 1996, 1997, 2000, 2003, and the disastrous Cyclone Idai in March 2019. Idai which is a Category 4 storm is said to be one of the deadliest and most destructive cyclones in the Southern hemisphere. The cyclone seriously hit the province of Sofala and other provinces like Manica, Inhambane, Tete and Zambezia and spread its devastation to Zimbabwe. It caused very high rainfall of over 200mm on a single day, high wind speeds of up to 220km/h, and massive floods where the water levels went beyond 10 meters. It affected more than 1.5 million people, claimed lives of more than 600 and injured more than 1,600 people. The full scope of the land use and land cover (LULC) damage has not been adequately reported even though the scale of this occurrence was enormous. Though there are satellite-based cyclone impact evaluation of areas like the United States, the Gulf of Mexico, the Caribbean-Mesoamerican, Australia, India and Bangladesh, the research on the same has been relatively small in Mozambique and the African continent.

Simultaneously, the field of deep learning (DL) has become a revolutionary computational criterion of scientific prediction, which hinges on the theory of neural networks. DL models represent interrelated neurons in layers in a number of nonlinear layers, which allows more complex features extraction and pattern recognition. Emerging developments in the field of GPU computing have greatly increased the capabilities of DL frameworks in carrying out complex image tasks, and can regularly match or surpass human experience in terms of accuracy.

In tropical cyclone studies, convolutional neural networks (CNNs) a state-of-the-art DL architecture have been a growing approach to predicting cyclone intensity by interpreting the patterns of human clouds by designing

satellite-based analyses. Two-dimensional (2D-CNN) and three-dimensional (3D-CNN) models have been used to utilize the features contained in multi-spectral geostationary satellite data and matched it to cyclone strength measures. Best implementation of these models has recorded significant performance improvements. A single such model yielded a root mean squared error (RMSE) of 8.32 kts, which is approximately 35 percent less than previously used CNN methods that made use of single-channel images. More so, visualizations of CNN results as heat-maps indicate that with cyclone intensity, the impact of the inner-core cloud structure, specifically the lower-atmospheric center, is more evident in the learnt representations of the network.

3. Machine learning and AI in meteorology

Over the past years, scholars have been gravitating towards machine learning (ML) techniques to examine satellite data, radar imagery, and on-site readings with the aim of improving the forecast capability of tropical cyclones (TCs). Being one of the fundamental elements of the artificial intelligence (AI), the ML algorithms could be broadly categorized into three operational types: feature selection, clustering, or regression or classification. The feature selection techniques would eliminate irrelevant or redundant variables, and this enhances better model efficiency and predictive accuracy. An example is that more complex spatiotemporal relationships can be tackled by using advanced tensors like Tucker decomposition that traditional methods of measuring tensors are not good at capturing. Other tools patterns used in the domain of pattern recognition and data mining include clustering algorithms, which are also popular in the workflow of ML. Such methods automatically divide the datasets into separate clusters, which are useful in exploring big data in general, particularly remote sensing. Some of the common clustering algorithms are finite mixture models (FMM), hierarchical clustering, and K-means. Application of machine learning in remote sensing is both diverse and broad. Key examples include:

- Using other deep neural network models, e.g. sparse autoencoders (SAE), convolutional neural networks (CNN), and recurrent neural networks (RNN) to classify hyperspectral images and identify abnormalities.
- Comparison of synthetic aperture radar (SAR) and high-resolution optical imagery in the classification of the scene, object recognition, image retrieval, and geophysical parameter inversion.
- Creation of effective and precise retrieval and forward model of satellite data items.
- Data fusion and three-dimensional (3D) reconstruction including multi-source data fusion, feature-level and decision-level fusion, heterogeneous dataset fusion, and reconstruction including automated tether-point matching.

ML has been of great promise in the field of meteorology. Two architectures that are heavily used in the field of precipitation forecasting are convolutional long short-term memory networks (ConvLSTM) and trajectory-gated recurrent units (TrajGRU). These models use spatiotemporal data based on radar to predict the development of rainfall in the short term to an extent that they work better as compared

to most traditional numerical or statistical prediction methods.

3.1 Short-Term Forecasting

Short-term forecasting aims at establishing whether a tropical disturbance will be developed to become a tropical cyclone in the next one to two days. Many researches have focused on determining the best predictors and machine learning algorithms to use in this task. An example is the creation of a decision tree (DT) model using the C4.5 algorithm to characterize disturbances on the Northwest Pacific. The experiment revealed that maximum relative vorticity, sea surface temperature, rate of precipitation at 800 hPa, mean divergence between 1,000-500 hPa and temperature anomalies at 300 hPa are some of the variables which are critical in distinguishing between the developing systems and non-developing systems. Relative to the conventional numerical prediction approaches, which often have a success rate of less than 50 percent with 24-48-hour genesis prediction, the DT model yielded an impressive success rate of approximately 64 percent with 24-48-hour genesis prediction that has high potential in operational short-term TC prediction.

3.2 Long-Term Forecasting

The purpose of long-term forecasting is to determine the seasonal occurrence rate of tropical cyclone formation, normally on a quarterly basis. Traditional statistical methods are based on the choice of a group of correlated environmental predictors and employing linear measures to predict the number of seasonal TC. Nonetheless, the correlation between the climate predictors and TC genesis is usually nonlinear and non-conformative to the assumptions underlying the classical linear regression methods. Consequently, scholars have reconstructed seasonal TC forecasting as a regression problem that can be tackled using machine learning tools.

One technique that has become popular in this respect is Support Vector Regression (SVR). As an example, Richman and Leslie (2012) boosted the multiple linear regression prediction by added the quasi-biennial oscillation (QBO) as a new predictor to their SVR. Their modified model had a much better skill as it tested about 40 percent better than standard multiple regression and it provided more than a 120 percent better result than an SVR model that omitted QBO. These results highlight the possibility of machine learning, specifically SVR, in enhancing seasonal-scale prediction of tropical cyclones.

4. Gaps in existing research

Although a lot has been achieved in cyclone prediction, there are still a number of research gaps that frustrate the accuracy of prediction. The cyclone intensity is one of the most recurrent and difficult to predict especially when it is in a rapid intensification stage. Even the current models do not have an ability to describe the intricate processes of strengthening that occur suddenly within the inner-core processes and ocean-atmosphere interactions. This has made the further development of intensity forecasting to remain behind the progress of cyclone track prediction. The application of machine learning solutions may be promising; however, they are still not widespread in practical forecasting systems and are still in an early stage of research. To make matters worse, observational data is only

available in high-resolution in a few areas, notably at the open oceans and in cyclones highly likely areas of the Global South, which amplifies the level of uncertainty about the numerical and ML-based prediction.

The other significant weakness is that local environmental factors that have the potential to alter cyclone pathways like mesoscale wind patterns, oceanic eddies and topography were not adequately represented. These shortcomings require high-resolution modeling and cutting-edge data assimilation. Also, the synergization of socio-economic impact modeling with meteorological forecasts is incompletely developed, which limits the possibility to transfer scientific forecasts into practical early-alarm systems to serve vulnerable groups.

Joint research is very important in solving these challenges. Interdisciplinary collaboration allows the sharing of knowledge in the domains of meteorology, oceanography, computer science, data analytics, and disaster management. This kind of collaboration is more innovative, produces better science, facilitates discoveries and becomes more visible in high-impact publications. It also facilitates sharing of knowledge, development of technology and capacity building among early-career researchers. The collaboration on the international level, specifically, is more likely to make the impact of citation stronger and the availability of funds opportunities broadening.

A review of the research output on cyclone-related topics has provided evidence on the evident trends of national and international cooperation. In one study that reviewed 487 publications on cyclone separators, the best 20 paying nations had 451 publications. Publications that were single country prevailed (74.33%), with multi-country collaborations being 18.27% of the total. China provided 168 papers of single countries and 28 international works whereas Iran published 32 single-country papers and 10 international works. India was at the second place with 23 single country and 7 multi country papers. Other contributors including those of Turkey, the United Kingdom and Spain were ranked among the top 20 yet no publication between countries was made. It is worth noting that cooperation between the most advanced research countries and African states was minimal, and the international cooperation was the one between the developed states.

Altogether, to address the current gaps in cyclone forecasting, there will be the need to strengthen interdisciplinary and international cooperation, enhance observation systems, develop models of higher accuracy, and further improve the systems of numerical and ML-based predictions. The developments will be critical in increasing the early-warning systems and lessening the effects of cyclones on the susceptible populations.

Global impact and trends in tropical cyclones

One of the most devastating and inevitability large-scale atmospheric disturbances on the planet is tropical cyclones (TCs) also known as hurricanes in the Atlantic and Northeast Pacific and typhoons in the Northwest Pacific. Disturbances are considered as discrete events that interfere with the form, composition and the functioning of the ecosystems by modifying the resources, substrates or the physiographical setting. Due to their large spatial influence, the foot-print of one TC can reach several hundreds of kilometers and their tracks can extend to thousands of kilometers, with extremely high wind velocities which can reach up to 300 km/hr.

The ecological effect of TCs is very much determined by the nature of the disturbance regime which in the case of tropical cyclones is very much dependent on the frequency, size and intensity of the disturbance. This regime of disturbances is very spatially heterogeneous. As an example, forests in Northwest Pacific and Northwest Atlantic are exposed to high frequency and intensity cyclones as compared to other areas in South America and Africa where few such cases occur. Consequently, the tropical forests of the world are faced with a range of disturbance regimes that include the less frequent, low intensity cyclone disturbances and the more frequent, severe disturbances as shown in

Figure 2. The western North Pacific is the most active source of tropical cyclone activity on most measures globally, with the exception being rapid-weakening (RW) occurrences. A disproportionate percentage of the strongest storms produced in the world is produced in this basin with many of these storms being of category 4-5. On the contrary, the North Atlantic is only 11% of the world total category 4-5 cyclones and 16% of the total cumulative cyclone energy (ACE), but storms in this basin cause an astounding 62% of the total economic damages in the whole world to highlight the disproportionate exposure of the region.

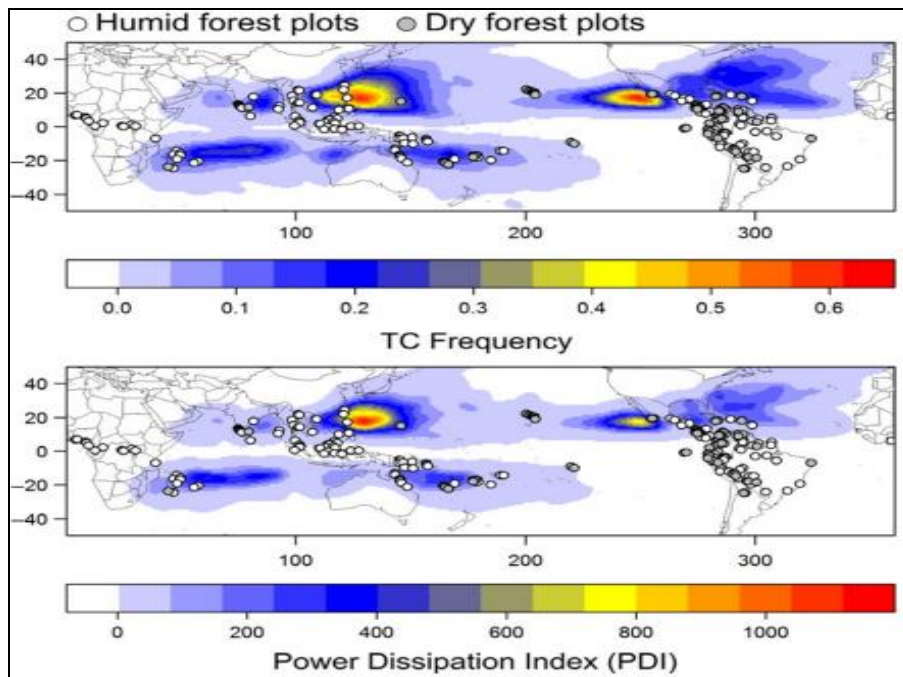


Fig 2: Global distribution of the frequency and energy released (power dissipation index) by tropical cyclones, and locations of forest structure datasets.

Table 1 summarizing global trends in tropical cyclones, based on observed data and research findings (as of mid-2020s).

The trends vary by region and metric (frequency, intensity, etc.), and are influenced by climate change, ocean temperatures, and atmospheric conditions.

Table 1: Global trends in tropical cyclones

Trend Category	Global Trend	Notes
Frequency (Overall)	Relatively stable or slight decrease	Total number of tropical cyclones globally has not shown a strong increasing trend. Regional changes may vary.
Intensity	Increasing	More storms are reaching Category 3–5 intensity, linked to warmer ocean temperatures.
Storm Surge Impact	Increasing	Due to sea-level rise and more intense storms, storm surges are becoming more damaging.
Rainfall Rates	Increasing	Warmer atmosphere holds more moisture, leading to higher rainfall rates during storms.
Storm Lifetime	Slightly increasing	Some studies suggest longer-lasting storms, especially those that stall near coastlines.
Storm Size	Inconclusive or regionally variable	Mixed results; some regions show increasing storm size, others do not.
Poleward Shift	Increasing	The latitude of peak cyclone activity is shifting poleward in some ocean basins (e.g., Western North Pacific, Southern Hemisphere).
Rapid Intensification	Increasing	More storms are rapidly intensifying near coastlines, challenging forecasting and preparedness.
Regional Variability	High	Some basins like North Atlantic show increases in activity; others like the South Pacific or Indian Ocean show more variable or even declining trends.
Economic Damages	Increasing	Due to more intense storms, coastal development, and higher exposure of populations and infrastructure.

The post-satellite period (1982-2017) is the time when data on the global tropical cyclone tracks have their highest

reliability and it is the best period which can be used to determine the long-term trends in the tropical cyclone

translation speed (TCTS). Over this period of 36 years, the average TCTS of the world indicates a rise in 5.9 percent, 3.0 percent and 4.8 percent in various metrics. This trend increase is statistically significant as per the nonparametric Mann-Kendall test. Such results are in contrast with the decrease that KS18 reported but even though the period after satellites is the fastest warming phase of the last five decades.

Notably, the increase of global mean TCTS is not always indicative of a global increase in cyclone motions. Rather it is affected by variations in the spatial pattern of tropical cyclone activity- including local differences in storm frequency or northward or southward movements in the formation and the track density of tropical cyclones. Since annual mean TCTS is calculated using position fixes that are usually observed six-hourly, any inaccuracy in identifying or tracing storms at regional scales can bring some bias to the global trend estimates.

An example would be in not identifying a slow-moving cyclone in the low latitudes would increase the world mean TCTS in that year artificially and a fast-moving system at higher latitudes would do the same. The precision of counts and position information of cyclone within a region is therefore important in gauging the accuracy of the global TCTS trend assessments.

Role of Disaster Management and Mitigation in Tropical Cyclones

Climate change has caused more cyclonic events, which have been more frequent and severe leading to severe human and economic losses. The effect of cyclones on people has resulted in the deaths of over 5,000 people and damages to the tune of billions of dollars since 2007. In this context, the current research paper will assess how the precursor preparedness steps against severe tropical cyclones (TCs) have changed since the 1970s with a specific reference to the severe tropical Cyclone Amphan that hit Bangladesh in May 2020. A systematic review of the secondary literature was carried out on the desk to evaluate both the trends in the past as well as the current preparedness strategies.

With the use of technology and better communication channels, the dissemination of early-warnings has been reinforced. However,

significant gaps in disaster preparedness remain that restrict the mitigation actions. Among the primary areas that need to be improved, one will find:

1. Incorporating responsible community members like mosque Imams and school teachers in the dissemination of warnings in order to build greater trust and adherence in the population;
2. Raising the level of awareness and trust in early-warning messages and evacuation directions.
3. The consideration of gender-related obstacles to provide equal participation in the decision-making process and evacuation operations.

Also, the number and physical standards of cyclone shelters are not enough and sometimes do not offer sufficient space and protection. Having a better pre-disaster preparedness is therefore vital especially to populations in the coastal population along the Bay of Bengal (BoB) who are constantly subjected to high-intensity cyclones. The general objective of the present study is to evaluate pre-disaster preparedness in response to the country of occurrence of the severe tropical cyclones in Bangladesh, through the case study of Cyclone Amphan. The detailed objectives include:

- a. **Examining coastal preparedness measures for cyclone disaster risk management, focusing on:**
 - Early-warning dissemination and communication pathways,
 - Evacuation processes and community responsiveness,
 - Conditions and operational capacity of cyclone shelters (CSs).
- b. **Evaluating long-term resilience strategies such as:**
 - Constructing and maintaining adequate cyclone shelters,
 - Reinforcing tidal-surge-protective embankments,
 - Implementing afforestation initiatives to safeguard shelters and embankments while reducing wind intensity, and
 - Improving transportation and communication networks that provide access to shelters.

A summary of commonly adopted mitigation measures for tropical cyclones is presented in Table 2.

Table 2: Tropical cyclones mitigations.

Category	Mitigation Measures
Early Warning Systems	Installation of Doppler radars and weather monitoring systems- Timely forecasts and alerts
Infrastructure Planning	Cyclone-resistant buildings and shelters- Elevated structures in flood-prone areas
Coastal Protection	Construction of sea walls and embankments- Mangrove reforestation to reduce storm surge
Community Preparedness	Public awareness campaigns- Regular cyclone drills and training programs
Policy and Planning	Implementation of coastal zone regulations- Integration of cyclone risk in land-use planning
Emergency Services	Pre-positioning of relief supplies and rescue equipment- Strengthening disaster response teams
Insurance and Financial Tools	Promotion of crop and property insurance- Contingency funds for disaster response

Migration is increasingly viewed as a positive adaptation strategy under climate change ^[16]. It helps ease population pressure in high-risk areas, reduces strain on limited resources, and lowers risks linked to overcrowding, while offering improved economic opportunities for those who remain—thereby strengthening their resilience to climate impacts. Migrant networks and social ties significantly

contribute to the economic and social wellbeing of their home regions. Regular financial remittances, for instance, can substantially boost households’ capacity to withstand environmental shocks ^[17]. Moreover, the skills, knowledge, behaviours, and civic practices that migrants circulate between host and origin areas can further support climate adaptation ^[18].

Training Programmes in Rural and Remote Areas of India

As part of an effort to strengthen the national respond to public health emergencies and communicable disease outbreaks, the Mozambican Ministry of Health (MoH), through the

National Institute of Health (NIH) implemented a Field Epidemiology and Laboratory Training Program (FELTP)^[19]. Table 3 shows Global Cyclone Preparedness Training Programmes in Rural Areas, Detailing Program Locations, Organizing Bodies, Training Methods, and Community Impact.

Table 3: Global Cyclone Preparedness Training Programmes in Rural Areas

Programme Name	Country/Region	Implementing Body	Target Audience	Objectives & Key Components
Cyclone Preparedness Programme (CPP)	Bangladesh	Bangladesh Red Crescent Society + Govt of Bangladesh	Rural coastal communities	Community-based warning systems, evacuation drills, shelter management, and volunteer training
Aapda Mitra Programme	India	NDMA, Govt of India	Community volunteers in rural areas	Train volunteers in search & rescue, first aid, cyclone response, evacuation planning
National Cyclone Risk Mitigation Project (NCRMP)	India	Ministry of Home Affairs, NDMA	Coastal rural populations	Capacity building, infrastructure improvement, cyclone shelters, early warning systems
Pacific Catastrophe Risk Assessment & Finance	Pacific Island Countries	World Bank, SPC, UNDRR	Rural island communities	Risk reduction, evacuation planning, community training, and financial risk assessment
Community-based Disaster Risk Reduction (CBDRR)	Philippines	NDRRMC, NGOs (e.g., CARE, Oxfam)	Rural barangays	Cyclone drills, early warning training, evacuation, and relief planning
CERT – Community Emergency Response Teams	USA (Hurricane-prone states)	FEMA (Federal Emergency Management Agency)	Rural communities, local volunteers	Basic disaster response skills, cyclone/hurricane preparedness, light search and rescue
Vanuatu Climate Resilient Islands Programme	Vanuatu	Vanuatu Govt, Australian Aid	Rural island populations	Education on cyclone impacts, shelter strengthening, livelihood protection strategies
Cyclone Shelter Management Training	Sri Lanka	Disaster Management Centre (DMC), Red Cross	Rural coastal village leaders	Training on shelter operation, logistics during cyclones, community communication systems
Building Resilience to Climate Extremes and Disasters (BRACED)	Myanmar, Nepal, Ethiopia	UKAID, Mercy Corps, Practical Action	Rural and semi-rural populations	Community training for cyclone and flood resilience, climate-smart agriculture, early warning response
Caribbean Climate Resilience Initiative	Caribbean Nations	UNDP, CDEMA, USAID	Coastal rural communities	Training in cyclone preparedness, shelter management, and post-disaster recovery

Conclusion

Accurate prediction of tropical cyclones is crucial for reducing casualties and minimizing property damage in vulnerable regions. Advances in satellite observations, numerical weather prediction models, and machine learning have enhanced forecasts of cyclone tracks, intensity, and landfall timing. Yet significant challenges remain due to the highly dynamic and complex nature of atmospheric systems. Strengthening forecast reliability will require greater investment in observational networks, improved data assimilation techniques, and stronger international collaboration. Ultimately, enhanced tropical cyclone forecasting enables governments and communities to respond more effectively, thereby reducing the human and economic impacts of these destructive events.

References

- Sobel AH, Wing AA, Camargo SJ, Patricola CM, Vecchi GA, Lee CY, *et al.* Tropical cyclone frequency. *Earth's Future*,2021;9(12):2021002275.
- Tan J, Liu H, Li M, Wang J. A prediction scheme of tropical cyclone frequency based on lasso and random forest. *Theoretical and applied climatology*,2018;133:973-983.
- Robertson AW, Vitart F, Camargo SJ. Subseasonal to seasonal prediction of weather to climate with application to tropical cyclones. *Journal of Geophysical Research: Atmospheres*,2020;125(6):2018029375.

- Zhao B, Qian W, Li H, Su Y. Cyclone pressure drop reduction and its effect on gas-particle separation capability: principle, performance, and assessment. *Reviews in Chemical Engineering*,202 2:38(8):1045-1063.
- Prasanna N, Subramanian K, Ajay S, Rajagopal T, Vigneshwaran V. CFD study on the performance of reducing pressure drop holes in cyclone separator. *Materials Today Proceedings*,2021:43:19 60-1968.
- Teng HF, Lee CS, Hsu HH, Done JM, Holland GJ. Tropical cloud cluster environments and their importance for tropical cyclone formation. *Journal of Climate*,2019;32(13):4069-4088.
- Zhang CJ, Wang XJ, Ma LM, Lu XQ. Tropical cyclone intensity classification and estimation using infrared satellite images with deep learning. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*,2021:14:2070-2086.
- Charrua AB, Padmanaban R, Cabral P, Bandeira S, Romeiras MM. Impacts of the tropical cyclone idai in Mozambique: A multi-temporal landsat satellite imagery analysis. *Remote Sensing*,2021:13(2):201.
- Wimmers A, Velden C, Cossuth JH. Using deep learning to estimate tropical cyclone intensity from satellite passive microwave imagery. *Monthly Weather Review*,2019:147(6):2261-2282.

10. Lee J, Im J, Cha DH, Park H, Sim S. Tropical cyclone intensity estimation using multi-dimensional convolutional neural networks from geostationary satellite data. *Remote Sensing*,2019;12(1):108.
11. Chen, R, Zhang W, Wang X. Machine learning in tropical cyclone forecast modeling: A review. *Atmosphere*,2020;11(7):676.
12. Wang Z, Zhao J, Huang H, Wang X. A review on the application of machine learning methods in tropical cyclone forecasting. *Frontiers in Earth Science*,2022;10:902596.
13. Alex FJ, Tan G, Agyeman PK, Ansah PO, Olayode IO, Fayzullayevich JV, *et al.* Bibliometric network analysis of trends in cyclone separator research: research gaps and future direction. *Sustainability*,2022;14(22):14753.
14. Ibanez T, Keppel G, Menkes C, Gillespie TW, Lengaigne M, Mangeas M, *et al.* Globally consistent impact of tropical cyclones on the structure of tropical and subtropical forests. *Journal of Ecology*,2019;107(1):279-292.
15. Klotzbach PJ, Wood KM, Schreck CJ, Bowen SG, Patricola CM, Bell MM, *et al.* Trends in global tropical cyclone activity: 1990–2021. *Geophysical Research Letters*, 2022, 49(6). 2021095774.
16. Kim SH, Moon IJ, Chu PS. An increase in global trends of tropical cyclone translation speed since 1982 and its physical causes. *Environmental Research Letters*,2020;15(9):094084.
17. Moon IJ, Kim SH, Chan JC. Climate change and tropical cyclone trend. *Nature*,2019;570(7759):3-5.
18. Islam MT, Charlesworth M, Aurangojeb M, Hemstock S, Sikder SK, Hassan MS, *et al.* Revisiting disaster preparedness in coastal communities since 1970s in Bangladesh with an emphasis on the case of tropical cyclone Amphan in May 2020. *International Journal of Disaster Risk Reduction*,2021;58:102175.
19. Ahsan MN, Khatun A. Fostering disaster preparedness through community radio in cyclone-prone coastal Bangladesh. *International journal of disaster risk reduction*,2020;49:101752.
20. Swain D. Tropical cyclones and coastal vulnerability: assessment and mitigation. *Geospatial technologies for land and water resources management*, 2022, 587-621.
21. Chapungu L. Mitigating the impact of cyclone disasters: Lessons from Cyclone Idai. *Clim. Chang. Migr*, 2020.
22. Mohapatra S, Harish VSKV, Dwivedi G. Climate change, cyclone and rural communities: Understanding people's perceptions and adaptations in rural eastern India. *Materials Today: Proceedings*,2022;49:412-417.