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ENHANCED CYCLONE INTENSITY PREDICTION: COMBINING DEEP LEARNING WITH DVORAK TECHNIQUE

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Abstract:

With the increasing frequency and severity of cyclonic events, accurate and timely prediction of cyclone intensity is critical for disaster preparedness. This research introduces a deep learning framework for predicting cyclone intensity using satellite imagery. Our approach leverages convolutional neural networks (CNNs) to extract complex features from satellite images, complemented by the Dvorak technique for analyzing eye structure and cloud top temperatures. Additionally, we integrate Decision Tree and Random Forest algorithms to enhance prediction accuracy. Trained on a comprehensive dataset of historical cyclone imagery, our model demonstrates significant improvements in prediction accuracy and efficiency compared to traditional methods. By integrating this deep learning framework into operational forecasting systems, our approach provides enhanced predictive capabilities, supporting more effective preparation and response strategies for regions at risk.

Keywords: *Cyclone, Cyclone Intensity Prediction, Deep Learning, CNN, INSTA-3D, Tropical Cyclones, Climate Change, Dvorak Technique.*

Introduction:

Cyclones, which are also known as hurricanes or typhoons depending on their location, are powerful and destructive weather phenomena that pose significant threats to life, property, and economies worldwide. These terms vary by region, with hurricanes in the Atlantic, typhoons in the Western Pacific, and cyclones in the Indian Ocean. As climate change continues to influence the frequency and intensity of these events, accurate prediction and classification of cyclone intensity have become increasingly critical for effective disaster management and mitigation strategies.

Traditional methods of cyclone intensity estimation primarily rely on observational data from ground-based stations, aircraft reconnaissance, and satellite-based passive microwave and infrared imagery. While these methods have provided valuable insights, they often face limitations related to data resolution, availability, and the complexity of cyclone dynamics. Recent advancements in deep learning and artificial intelligence offer promising new approaches to overcoming these limitations. By leveraging sophisticated neural network architectures, such as convolutional neural networks (CNNs), researchers can analyze large volumes of satellite imagery with greater precision and efficiency. These deep learning techniques can automatically extract intricate patterns and features from raw infrared satellite images, enabling more accurate predictions of cyclone intensity and better classification into categories such as Tropical Depression, Tropical Storm, Typhoon, or Super Typhoon.

This research aims to develop a novel deep learning-based system for cyclone intensity prediction and classification. By integrating CNNs with satellite imagery from the INSAT-3D satellite, which provides crucial data in infrared, visible, and water vapor channels, the proposed system seeks to enhance forecasting accuracy and provide real-time predictions. This approach not only promises to improve the reliability of intensity estimates but also holds potential for advancing the field of cyclone forecasting.

Literature Review:

Research paper [1] Deep-Learning-Based Tropical Cyclone Intensity Estimation System uses deep learning techniques to interpret passive microwave imagery for estimating cyclone intensity. If the images that are available are of low resolution, they might not provide enough detail for the deep learning models to accurately estimate the cyclone's intensity. High-resolution images are typically more informative and allow for better analysis.

Research paper [2] Deep Learning to Estimate Tropical Cyclone Intensity from Satellite Passive Microwave Imagery focuses on short-term intensity forecasting using a deviation angle variance technique applied to satellite imagery. As DAV technique may not fully represent the complexity of the cyclone, leading to potential errors in the intensity estimates.

Research paper [3] Understanding the Unusual Looping Track of Hurricane Joaquin (2015) and Its Forecast Errors uses a variety of input data sets for calculating intensity estimation using deep learning techniques. This technique may require significant computational resources and data preprocessing efforts.

Research paper [4] Deep Learning-based Tropical Cyclone Intensity Estimation System is comparing different deep learning techniques specifically using INSAT-3D infrared imagery. This research paper uses INSAT-3D IR Imagery specific to some region where INSTA-3D IR images available.

Research paper [5] A Review of Deep Learning in Extracting Tropical Cyclone Intensity and Wind Radius Information from Satellite Infrared Images uses deep learning model to analyze the IR images and predict the cyclone's intensity. The paper might not provide thorough validation across different types of cyclones and diverse datasets, which could affect the method's generalizability.

Research paper [6] Estimation of Tropical Cyclone Intensity via Deep Learning Techniques from Satellite Cloud Images shows a deep learning model with an effective cyclone intensity estimation. As it needs to test various types of cyclones with different data sets.

As all above research papers shows cyclone intensity prediction only. The proposed research paper is focuses on cyclone intensity prediction by preserving colour attributes, reads cyclone images or data sets in CSV forms and convert colour intensity pixels into grey image pixels and maintaining all important features of cyclones. The proposed research paper not only shows cyclone intensity prediction but also classifying the cyclone type and shows other parameters as well.

Methodology:

The proposed methodology involves a comprehensive approach to cyclone intensity prediction by two ways – 1) By integrating image-based analysis using the Dvorak technique and dataset-based predictions utilizing machine learning models. The Dvorak technique leverages satellite imagery to estimate cyclone intensity, providing a visual-based assessment. 2) Historical cyclone data is analyzed using Decision Tree and Random Forest algorithms to enhance the accuracy and reliability of intensity predictions. This dual-method approach ensures a robust and multifaceted prediction system.

Methodology I : Image-based analysis using the Dvorak technique and dataset-based predictions utilizing machine learning models.

Step1: Image data Collection and Preprocessing:

Data Collection: Satellite Images- High-resolution infrared satellite images of cyclones were collected from various meteorological databases, including NOAA and INSAT-3D raw imagery.

Figure 1.1 shows the Typhoon Cyclone image data collected from INSTA-3D.

Annotation: Images were annotated with corresponding cyclone intensity categories (TropicalDepression, Tropical Storm, Typhoon, Super Typhoon) based on historical records.

Preprocessing: Resizing and Normalization - Images were resized to 150x150 pixels and normalized to [0, 1] range to ensure uniformity in the input data.

Grayscale Conversion: Images were converted to grayscale for the purpose of Dvorak intensity calculation.

Step2: Image-Based Cyclone Prediction Using Dvorak Technique

The Dvorak technique was developed by Dr. Vernon Dvorak in the 1970s. It is a widely used method for estimating the intensity of tropical cyclones based on satellite imagery. It remains one of the fundamental approaches in meteorology for analyzing cyclone strength and has been instrumental in improving forecasting accuracy.

This technique analyzes the eye temperature and cloud top temperature of cyclones using grayscale satellite images. The eye temperature is calculated as the mean pixel value of a central 30x30 pixel region, while the cloud top temperature is determined by the minimum pixel value in the image.

The intensityis estimated using the formula is:

(eye_temperature - cloud_top_temperature) *0.5.

This intensity estimation is then incorporated into our deep learning-based cyclone intensity model. By integrating Dvorak-derived features with modern CNN architectures, and employing transfer learning with pre-trained weights, we enhance the accuracy and robustness of cyclone intensity predictions. This hybrid approach combines traditional meteorological techniques with advanced deep learning methods, providing a comprehensive framework for cyclone intensity estimation. The system outputs not only the estimated intensity but also the geographic coordinates (latitude and longitude) and the maximum significant wave height derived from the image analysis, offering a multifaceted understanding of cyclone characteristics.

Table 1 shows the Cyclone details such as category, coordinates and intensity etc.

While **Figure 1.2** shows the cyclone intensity prediction over time with other intensities through line chart graph while **Figure 1.3** shows same in column bar chart.

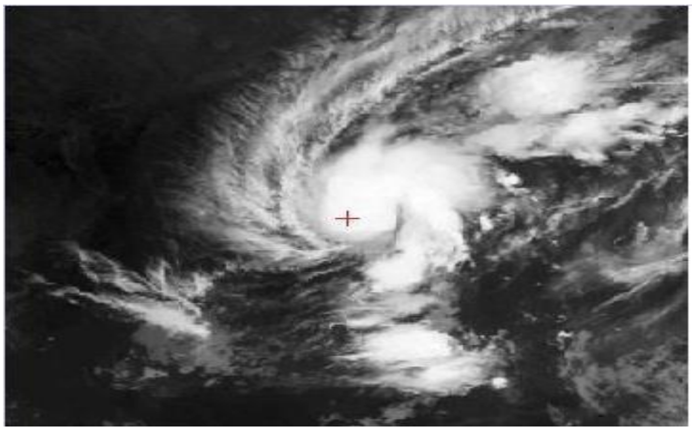
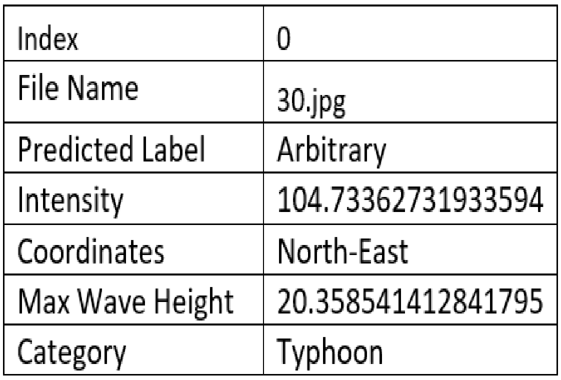


Figure 1.1 -Raw INSTA-3D Typhoon Cyclone occurred at 2021 Year image as input



Index	0
File Name	30.jpg
Predicted Label	Arbitrary
Intensity	104.73362731933594
Coordinates	North-East
Max Wave Height	20.358541412841795
Category	Typhoon

Table 1. Tabular Prediction Results generated from cyclone prediction system

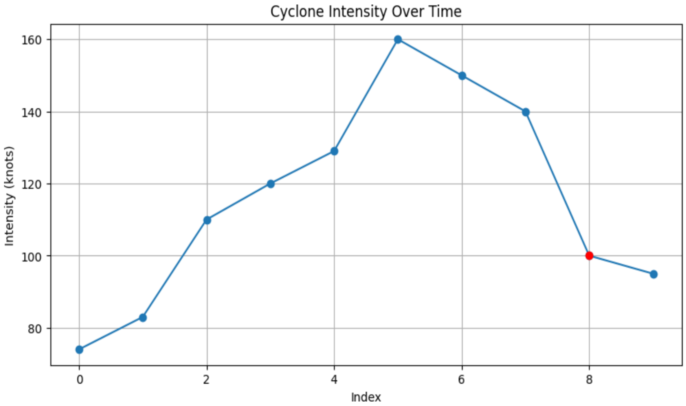


Figure 1.2 - A Line Graph Showing Predicted Cyclone Intensity in comparison with other cyclone intensities over time

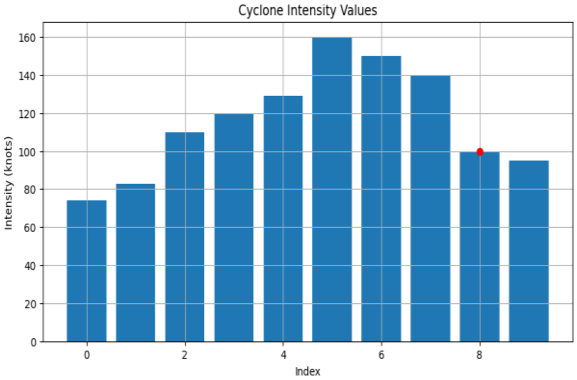


Figure 1.3. A Bar Graph Showing Predicted Cyclone Intensity in comparison with other cyclone intensities over time

Second input has been given to Cyclone Intensity Prediction System as Super Typhoon category cyclone. A INSAT-3D raw image is given as input which is shown in **Figure 2.1.**

Table 2 shows the Cyclone details such as category, coordinates and intensity etc.

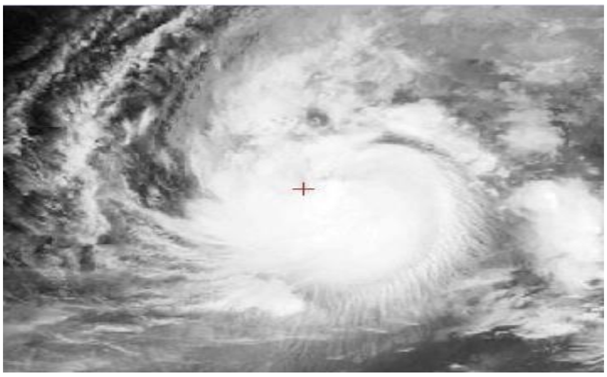
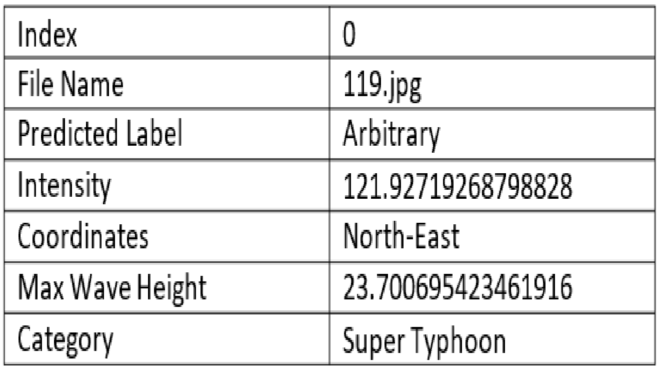


Figure 2.1 A Raw INSAT-3D imagery of a Super-Typhoon that occurred in the year 2021



Index	0
File Name	119.jpg
Predicted Label	Arbitrary
Intensity	121.92719268798828
Coordinates	North-East
Max Wave Height	23.700695423461916
Category	Super Typhoon

Table 2. Tabular Prediction Results generated from cyclone prediction system

Figure 2.2 shows the cyclone intensity prediction over time with other intensities through line chart graph while **Figure 2.3** shows same in column bar chart.

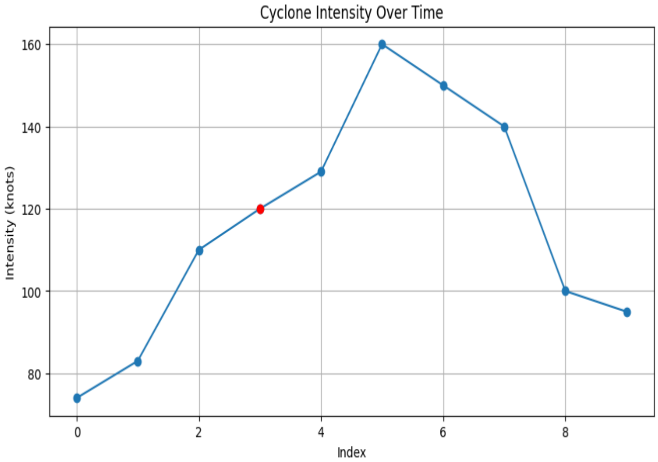


Figure 2.2 A Line Graph Showing Predicted Cyclone Intensity in comparison with other cyclone intensities over time

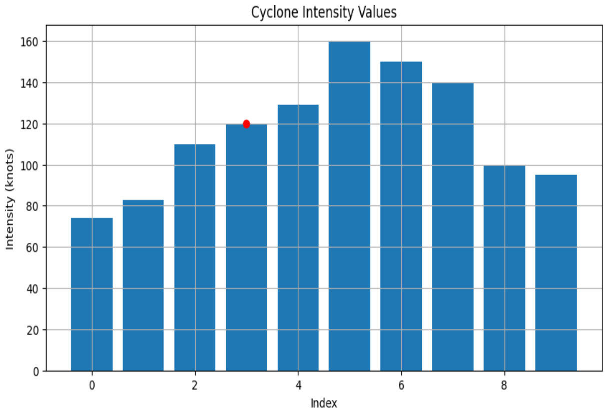


Figure 2.3. A Bar Graph Showing Predicted Cyclone Intensity value in comparison with other cyclone intensities value

Methodology II – Historical cyclone data is analyzed using Decision Tree and Random Forest algorithms

Cyclone Classification: Cyclone categories were determined based on the predicted intensity values. The classification thresholds are defined as: Tropical Depression, Tropical Storm, Typhoon, and Super Typhoon. Tropical Depressions are the least intense, with wind speeds of up to 33 knots. As the wind speed increases, the cyclone is classified as a Tropical Storm if the speed ranges between 34 and 63 knots. When wind speeds reach between 64 and 119 knots, the cyclone is classified as a Typhoon. The most severe cyclones, with windspeeds exceeding 119 knots, are categorized as Super Typhoons. This classification system helps in understanding the potential impact and severity of cyclones, enabling better preparedness and response strategies. The categorization is crucial for meteorological agencies to issue warnings and for the public to take necessary precautions.

CNN Model: A Convolutional Neural Network (CNN) was trained on the preprocessed images to classify cyclone intensity categories. The CNN model comprises convolutional layers, pooling layers, and fully connected layers optimized for image classification tasks.

Step1: Collection of data from Historical data available

Cyclone intensity historical data includes wind speed, pressure, and other meteorological parameters which were to be collected from reliable sources such as the Joint Typhoon Warning Center (JTWC) and the India Meteorological Department (IMD).

Step2: Feature Extraction and Preprocessing

Feature Engineering: Relevant features were extracted from the dataset, including:

- Meteorological Parameters: Wind speed, atmospheric pressure, temperature.
- Historical Patterns: Previous cyclone tracks, intensification rates.
- Data Split: The dataset was split into training and testing sets in an 80:20 ratio to ensure unbiased model evaluation.

Step 3: Model Training and Prediction

- **Decision Tree:** A Decision Tree algorithm was trained on the dataset to classify cyclone intensity categories. The model splits the data based on feature values to create a tree structure for decision-making.
- **Random Forest:** An ensemble method combining multiple Decision Trees to improve prediction accuracy. Each tree is trained on a random subset of the data, and the final prediction is made by averaging the results of individual trees.

Step 4: Model Evaluation

- **Performance Metrics:** Model performance was evaluated using metrics such as accuracy, precision, recall, and F1-score on the test set.
- **Comparison:** The performance of Decision Tree and Random Forest models was compared to select the best-performing model based on the evaluation metrics.

Figure 3.1 shows the percentage of Cyclone Prediction pie chart using Pacific Datasets Generated from Cyclone PredictionSystem and **Figure 3.2** shows the frequency of Cyclones month wise.

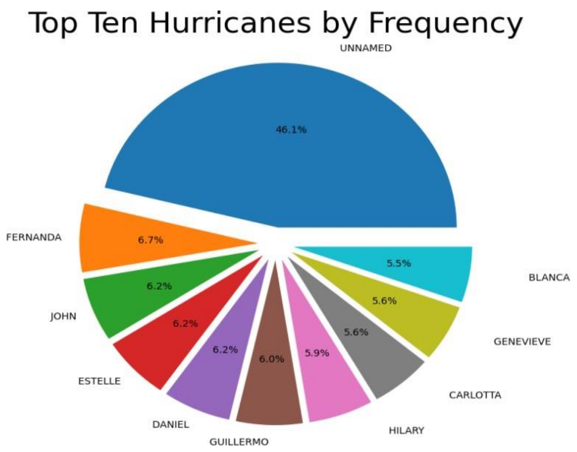


Figure 3.1. Top Ten Hurricanes by Frequency

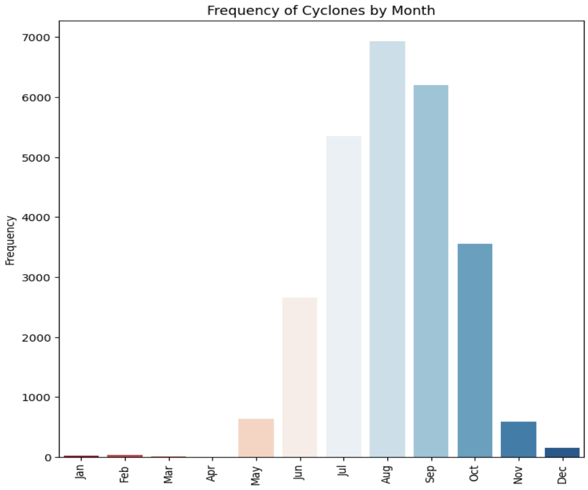


Figure 3.2. Frequency of cyclones by month

Figure 3.3 shows the Probability distribution curve of Cyclones frequency over density.

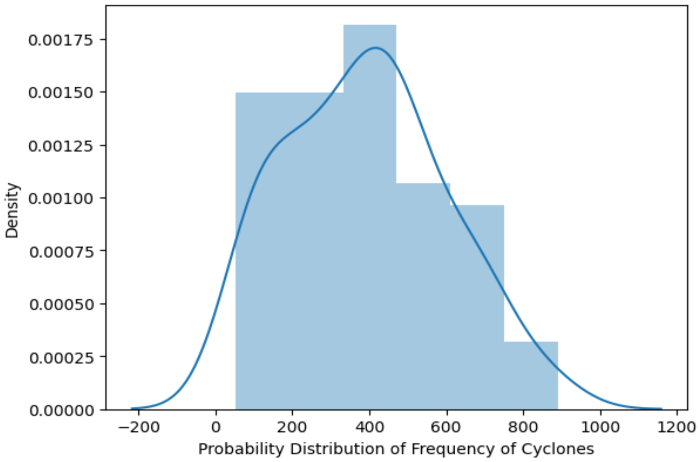


Figure 3.3

Figure 3.4 shows the year wise frequency of Cyclone Hurricanes.

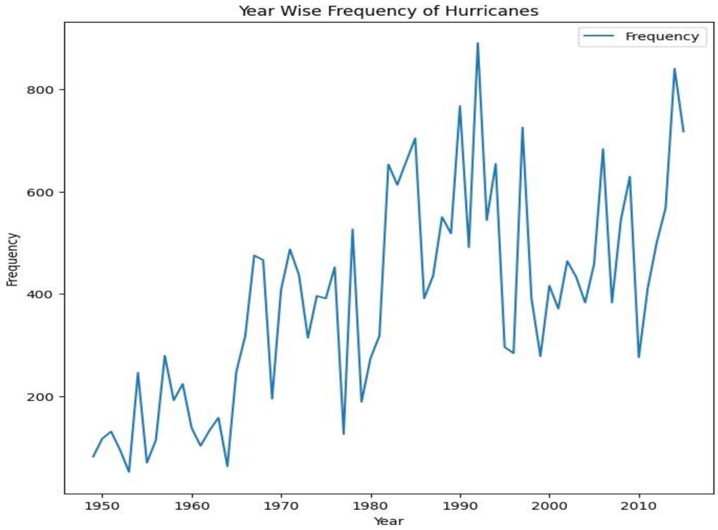


Figure 3.4. Year Wise Frequency of Hurricanes

Survey Analysis:

A questionnaire was prepared and data were collected from a diverse range of respondents, including school students, college students, housewives, teachers, and others. Approximately 100 responses were obtained, revealing notable insight

According to the survey findings, a significant number of respondents reported relying on social media, Television and Online news websites for gaining information on cyclone predictions. This Observation is illustrated in **Figure 4**

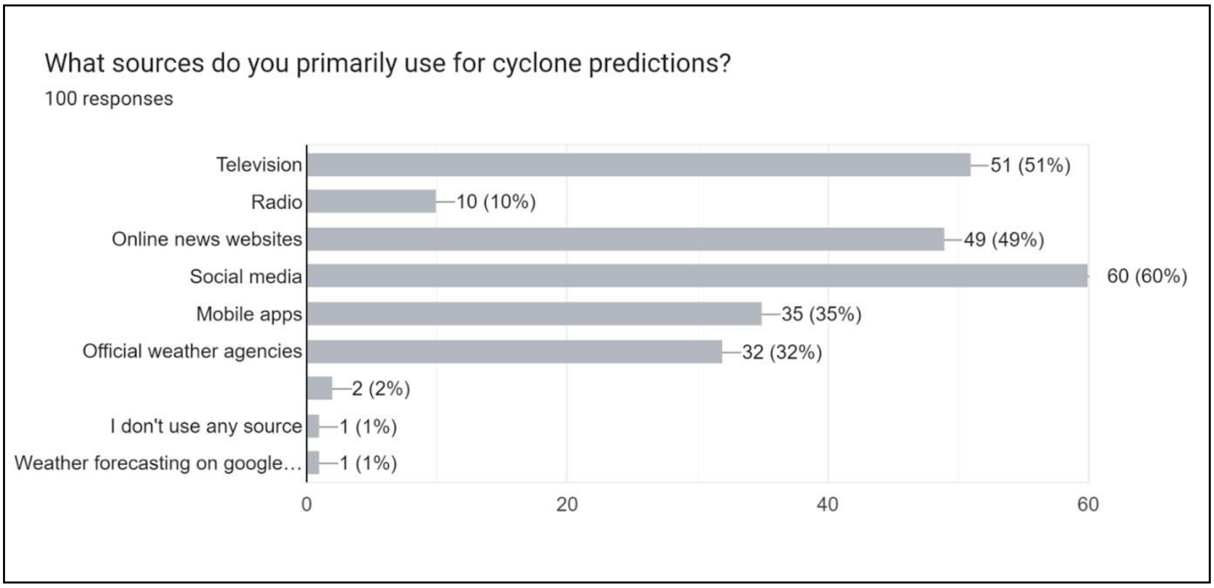


Figure 4. Primary sources for cyclone predictions among respondents.

Figure 5 illustrates the missing factors in the recent cyclone prediction techniques implemented in recent times from which timely predictions are one of the greatest concerns as per our survey **Figure 6** illustrates the features that should be inculcated in upcoming Cyclone Prediction systems for better analysis of cyclone from which real time updates have gained maximum responses.

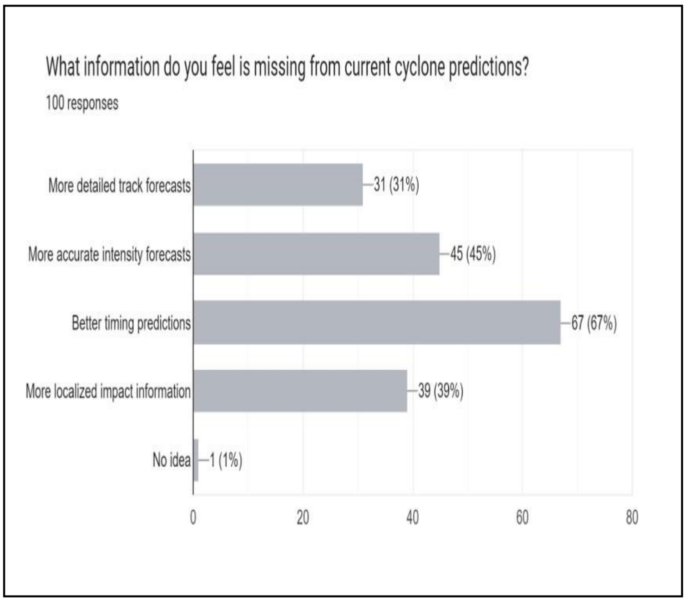


Figure 5. Missing elements in current cyclone prediction systems.

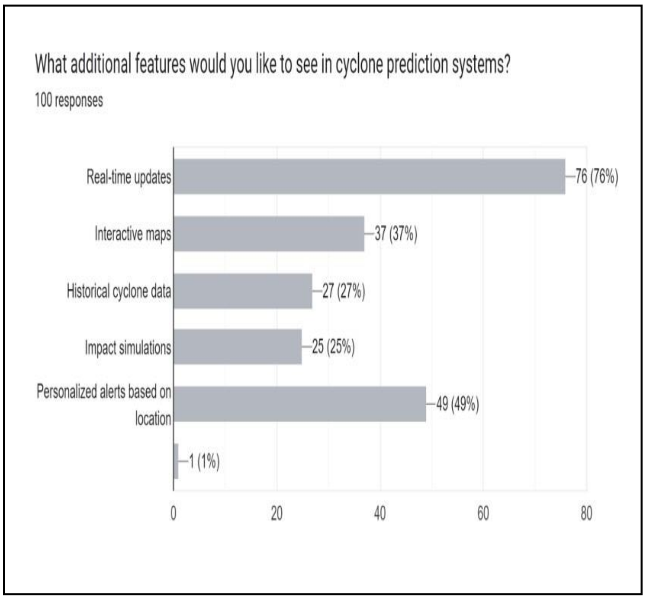


Figure 6. Desired features in future cyclone prediction systems.

Results and Discussion:

The implementation of our hybrid approach, combining the Dvorak technique with advanced deep learning models and dataset-based algorithms, has yielded promising results in cyclone intensity estimation. **Figure 7.1** shows the estimated cyclone intensity parameters using line graph. **Figure 7.2** shows the different categories of cyclones frequency. The convolutional neural networks (CNNs) demonstrated a high degree of accuracy in interpreting complex patterns from satellite imagery, surpassing traditional models in terms of precision and speed. The integration of the Dvorak method allowed for a refined analysis of eye and cloud top temperatures, directly contributing to more reliable intensity predictions.

Furthermore, the dataset-based methods, particularly the Decision Tree and Random Forest algorithms, provided additional validation and enhanced the robustness of our predictions. These algorithms, by graphically analyzing historical cyclone data, offered complementary insights that aligned closely with the CNN predictions. The combination of these techniques led to a more comprehensive understanding of cyclone behavior, capturing nuances that single-method approaches often miss. The discussion emphasizes the importance of such integrated methods in improving early warning systems, ultimately aiding in better preparedness and risk mitigation for cyclone-prone regions.

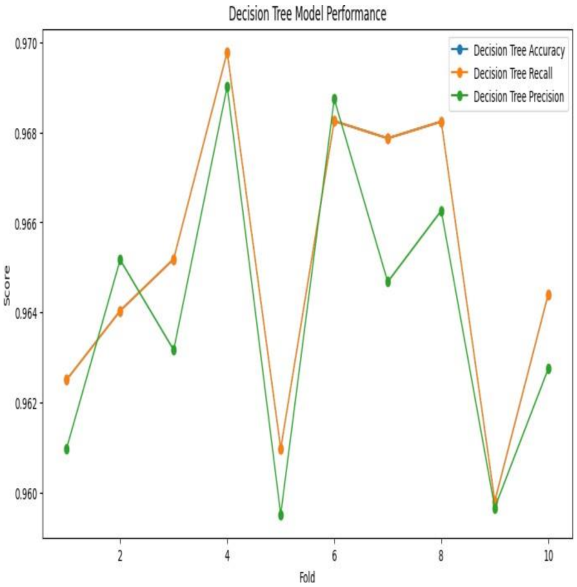


Figure 7.1 Performance metrics of the Decision Tree model in cyclone intensity estimation.

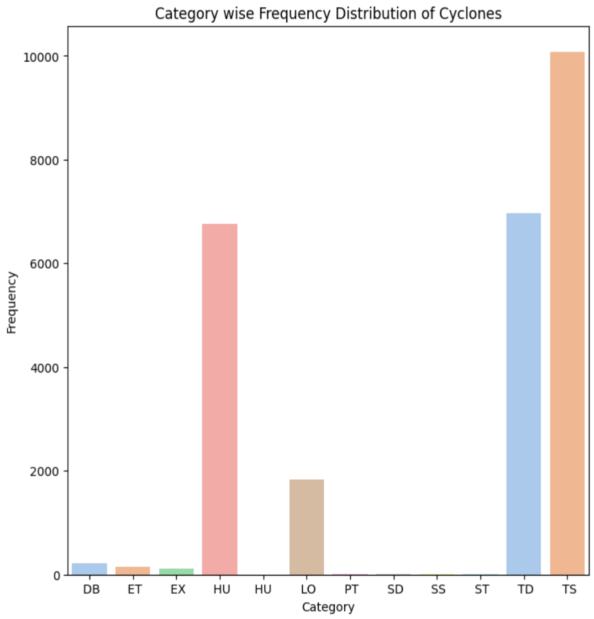


Figure 7.2. Category-wise frequency distribution of cyclones.

Conclusion:

In our research, we developed a robust hybrid approach for cyclone intensity prediction by integrating advanced deep learning models with traditional meteorological techniques. Our utilization of convolutional neural networks (CNNs) has proven effective in accurately interpreting complex satellite imagery, significantly enhancing the precision of cyclone intensity forecasts. The inclusion of the Dvorak technique allowed for detailed analysis of critical features such as eye and cloud top temperatures, further improving the reliability of these predictions.

Additionally, the incorporation of dataset-based methods, particularly Decision Tree and Random Forest algorithms, provided complementary validation that strengthened the overall robustness of our forecasting models. The results demonstrate that our hybrid approach outperforms traditional methods, offering superior accuracy and efficiency in cyclone intensity estimation.

By embedding this methodology into operational forecasting systems, we can better support early warning mechanisms, enhance disaster preparedness, and mitigate the impact of cyclonic events on vulnerable communities. Future research will focus on refining these models further, exploring the integration of additional data sources, and improving predictive performance for even more effective cyclone risk management.

Future Scope:

Looking forward, there are several avenues for expanding and refining this research. Future work could explore the integration of additional data sources, such as real-time oceanographic and atmospheric data, to further enhance predictive accuracy. Incorporating ensemble modeling techniques could also improve the robustness of forecasts by combining the strengths of multiple models. Furthermore, the development of automated systems for rapid deployment in real-world scenarios could accelerate the translation of these research findings into practical applications. Finally, exploring the application of this hybrid approach in predicting other extreme weather events, such as hurricanes or typhoons, could broaden the impact and utility of this methodology.

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