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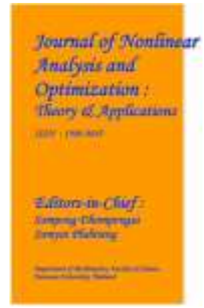

A DATA-DRIVEN FRAMEWORK FOR SAR WAVE PARAMETER ESTIMATION DURING TROPICAL CYCLONES

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ABSTRACT— Tropical cyclones pose significant challenges for ocean wave monitoring due to their complex interactions between high wind speeds, heavy precipitation, and turbulent sea states. Traditional physics-based algorithms often struggle to accurately retrieve wave parameters such as significant wave height, wave period, and wave direction from Synthetic Aperture Radar (SAR) imagery under such extreme conditions. This study proposes a machine learning-based approach for reliable and accurate retrieval of wave parameters from SAR images during tropical cyclones. The algorithm leverages convolutional neural networks (CNNs) for automatic feature extraction from SAR imagery and integrates auxiliary meteorological data such as wind speed and cyclone intensity. By training the model on historical cyclone datasets with collocated buoy measurements and numerical wave model outputs, the proposed method demonstrates improved performance over conventional retrieval techniques.

Index Terms – Machine learning, synthetic aperture radar (SAR), tropical cyclone, wave parameter.

I. INTRODUCTION

Tropical cyclones (TCs) associated with heavy rain are a typical disaster in coastal waters and play a Manuscript received 7 February 2024; accepted 13 August 2024. Date of publication 16 August 2024; date of current version 5 September 2024. This work was supported in part by the National

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Armando Marino is with the Earth Observation, Biological and Environmental Sciences, University of Stirling, FK9 4LA Stirling, U.K. (e-mail: armando.marino@stir.ac.uk). Xingwei Jiang is with National Satellite Ocean Application Service the momentum and heat exchange at the sea–air interface. Due to the extreme state, it is difficult to measure the TC dynamics by the on-scene technique such as National Data Buoy Center (NDBC) buoy. Since 1980s, ocean numerical models based on theory of oceanography and computing technology have been developed. Based on the theory of third-generation wave model two numeric models, i.e.,WAVEWATCH-III (WW3) and simulation wave nearshore have capability for hindcasting wave over global ocean and polar region. The accuracy of hindcasting wave by numeric models relies on the forcing field, however, the underestimation of wind speeds obtained from meteorological numerical models [i.e., European Centre for Medium-Range Weather Forecasts (ECMWF)] in TCs leads to distortion of wave simulations. Remote sensing is a mature technology for earth surface observation with a wide spatial coverage.

At present, the products of upper oceanic dynamics are operationally released over global seas, i.e., sea surface wind from scatterometer and polarimetric microwave radiometer and sea surface wave from altimeter and wave spectrometer (surface waves investigation and monitoring, SWIM). The scatterometer-measured wind has a coarse spatial resolution (~12.5 km) and the spatial resolution of SWIM-measured wave is 18 km. Synthetic aperture radar (SAR) can capture upper ocean dynamics and maritime targets with a finer spatial resolution, i.e., a 10 and 40 m pixels for Sentinel-1 (S-1) in interferometric wide (IW) and extra wide (EW) mode. According to backscattering theory, sea surface roughness affects the radar returns represented by normalized cross section (NRCS). This was confirmed through the very first experiment of the Seasat mission, where co-polarization [vertical–vertical (VV) and horizontal–horizontal] NRCS were correlated with a wind vector. Following this rationale, a geophysical model function (GMF) initially tailed for scatterometer, can be used for C-band SAR wind retrieval, called CMOD family, i.e., CMOD5N and its latest version CMOD7.

II. LITERATURE SURVEY

A. The WAM model A third generation ocean wave prediction model

A third generation wave model is presented that integrates the basic transport equation describing the evolution of a two-dimensional ocean wave spectrum without additional ad hoe assumptions regarding the spectral shape. The three source functions describing the wind input, nonlinear transfer, and white-capping dissipation are prescribed explicitly. An additional bottom dissipation source function and refraction terms are included in the finite-depth version of the model. The model was calibrated against fetch-limited wave growth data. Only two tuning parameters am introduced in the white-capping dissipation source function. The model runs on a spherical latitude-longitude grid for an arbitrary region of the ocean. Hindcast results am shown for six North Atlantic-North Sea storms, three Gulf of Mexico hurricanes, and a global run for the SEASAT period. The agreement with measurements is encouraging.

B. Source terms in a third-generation wind wave model

A new third-generation ocean wind wave model is presented. This model is based on previously developed input and nonlinear interaction source terms and a new dissipation source term. It is argued that the dissipation source term has to be modeled using two explicit constituents. A low-frequency dissipation term analogous to wave energy loss due to oceanic turbulence is therefore augmented with a diagnostic high-frequency dissipation term. The dissipation is tuned for the model to represent idealized fetch-limited growth behavior. The new model results in excellent growth behavior from extremely short fetches up to full development. For intermediate to long fetches results are similar to those of WAM, but for extremely short fetches the present model presents a significant improvement (although the poor behavior of WAM appears to be related to correctable numerical constraints). The new model furthermore gives smoother results and appears less sensitive to numerical errors. Finally, limitations of the present source terms and possible improvements are discussed.

C. Simulating typhoon waves by SWAN wave model in coastal waters of Taiwan

The SWAN wave model is typically designed for wave simulations in the near-shore region and thus is selected for evaluating its applicability on typhoon waves in the coastal waters around Taiwan Island. Numerical calculations on processes of wave heights and periods during the passages of four representative typhoons are compared with measured data from field wave stations on both east and west coasts. The results have shown that waves due to typhoons of paths 2, 3 and 4 can be reasonably simulated on east coastal waters. However, discrepancies increase for the simulated results on west coastal waters because the island's central mountains partly damage the cyclonic structures of the passing-over typhoons. It is also found that the included nested grid scheme in SWAN could improve the accuracy of simulations in coastal waters to facilitate further engineering practices.

III. PROPOSED SYSTEM

The overview of our proposed system is shown in the below figure.

Fig. 1: System Overview

Implementation Modules

Service Provider Module

- ✓ In this module, service provider login to the system using valid username and password. After login successful, he can perform the following operations like train and test dataset, view trained and tested accuracy and view remote users.

Train and Test Model

- ✓ In this module, the service provider split the Used dataset into train and test data of ratio 70 % and 30 % respectively. The 70% of the data is consider as train data which is used to train the model and

30% of the data is consider as test which is used to test the model

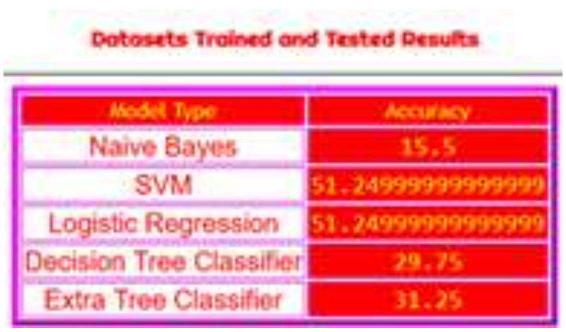
Remote User

- ✓ In this module, the remote user register to the system, and login to the system valid username, and password. After login successful, he can perform view profile, predicting cyclone type.

Graphical Analysis

- ✓ In this module, display the graphs like accuracy and predicted ratio of the system. Various factors take into consideration for the graph analysis. In this phase plot the charts like bar chart and so others.

IV. RESULTS


Datasets Trained and Tested Results

Model Type	Accuracy
Naive Bayes	15.5
SVM	51.24999999999999
Logistic Regression	51.24999999999999
Decision Tree Classifier	29.75
Extra Tree Classifier	31.25

Fig.2: View Model results

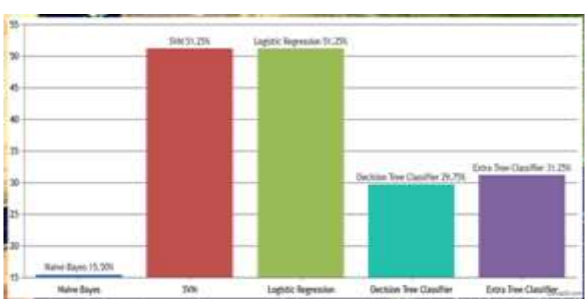


Fig.3: Model Accuracy Results

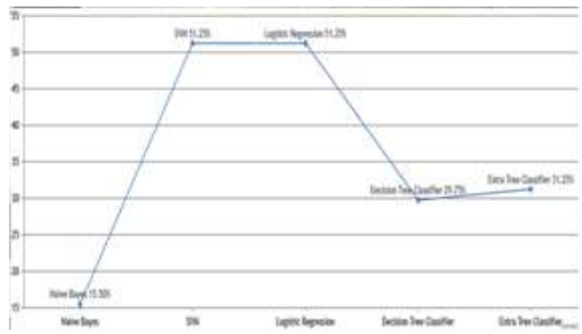


Fig.4: Model Accuracy Results in charts

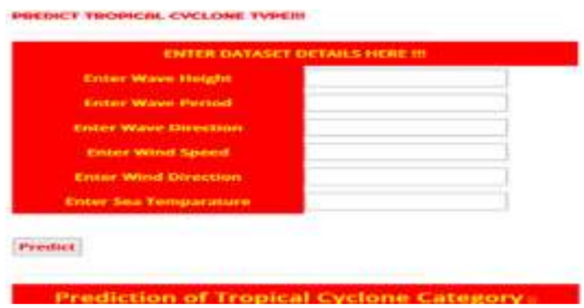


Fig.5: Prediction

V. CONCLUSION

At present, upper ocean dynamics can be monitoring by several sensors, i.e., sea surface wind from scatterometer and spaceborne polarimetric microwave radiometer and sea surface wave from altimeter and SWIM. However, the spatial resolution of these products (i.e., >10 km) does not satisfy the requirement of complicated air–sea interaction in TCs. In this article, more than 2000 dual-polarized S-1 images obtained in IW and EW mode during 200 TCs are collected, which are matched with hindcasted wave parameters using WW3 model, in which H-E wind, CMEMS sea surface current and CMEMS sea level are applied as forcing fields. The SWH, MWL, and MWP simulated by WW3 were validated against the measurements of NDBC buoys, and the RMSE of SWH was 0.35 m, COR was 0.96, and SI was 0.18; the RMSE of MWL was 13.86 m, COR was 0.87, and SI was 0.26; and the RMSE of MWP was 0.73 s, COR was 0.88, and SI was 0.17. The difference sea states result show that the entire dataset under four different sea state condition demonstrates satisfactory results in terms of statistical results.

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