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Prediction of extreme wave heights using neuro wavelet technique

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ABSTRACT

Precise prediction of extreme wave heights is still an evading problem whether it is done using physics based modeling or by extensively used data driven technique of Artificial Neural Network (ANN). In the present paper, Neuro Wavelet Technique (NWT) is used specifically to explore the possibility of prediction of extreme events for five major hurricanes Katrina 2005, Dean 2007, Gustav 2008, Ike 2008, Irene 2011 at four locations (NDBC wave buoys stations)[1] namely; 42040, 42039, 41004, 41041 in the Gulf of Mexico. Neuro Wavelet Technique is employed by combining Discrete Wavelet Transform and Artificial Neural Networks. Discrete wavelet transform analyzes frequency of signal with respect to time at different scales. It decomposes time series into low (approximate) and high (detail) frequency components. The decomposition of approximate components (extreme events in the ocean wave series) can be carried out up to the desired multiple levels in order to provide relatively smooth varying amplitude series. This feature of wavelet transforms make it plausible for predicting extreme events with a better accuracy. In the present study third, fifth and seventh level of decompositions are used which facilitates 3 to 7 times filtering of low frequency events and seems to pay the dividend in the form of better prediction accuracy at extreme events. To develop these Neuro wavelet models to forecast the waves with lead times of 12 hr to 36 hr in advance, previously measured significant wave heights at same locations were used. The results were judged by wave plots, scatter plots and other error measures. From the results it can be concluded that the Neuro Wavelet Technique can be employed to solve the ever eluding problem of accurate forecasting of the extreme events.

1. Introduction

Forecasting of extreme wave heights particularly during the hurricanes (or for that matter in any season) from few hours to few days in advance had been the priority of majority of researchers since last few decades and still remains a most intriguing challenge. The physical process of generation of waves by wind is extremely complex, non stationary, non linear, uncertain and hence not yet fully understood. Traditionally wave forecasting is done by simplified or parametric method and by an elaborate or numerical method. The former method explicitly gives wave heights and period from the knowledge of wind-speed, fetch and duration while the later one requires numerical solution of the wave growth equation. Though the numerical methods are far more accurate than the parametric and give information over a number of locations simultaneously, they require a number of oceanographic and meteorological parameters and are more justified when the wind speed varies considerably along with its direction in a given time duration and area (Deo, 2001).

The wave spectral models are also used by many scientist from well known institutes like European Centre for Medium-Range Weather Forecasts (ECMWF), National Oceanic and Atmospheric Administration (NOAA) and Helmholtz-Zentrum Geesthacht (GKSS) in order to develop the sophisticated wave forecasting systems to predict the extreme events and in particular dangerous sea states by improving the third generation models WAVEWATCH III [30] and WAM [15]. Recently Cardone et al. [4], Ponce de León and Guedes Soares [28], Ponce de León and Guedes Soares [26,27] put forth valuable contributions for hind casting the extreme sea states using third generation wave models in the North Atlantic ocean. Appendini et al. [1], also done the assessment of the three different wind reanalysis on the wave hind cast performances. All the above mentioned efforts are state worthy and case specific

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[1] http://www.ndbc.noaa.gov.

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Table 1
Location map of wave buoy stations.

Sr. No.	Hurricane	Period of Hurricane	Station	Location	Data
1	Irene 2011	20th–28th August 2011	41004	32.501N 79.099W (32°30′2″N 79°5′58"W) 41 NM Southeast of Charleston, SC	3 years data:2009–2011
2	Ike 2008	1st–14th September 2008	42040	29.212N 88.207W (29°12′45″N 88°12′27"W) 64 NM South of Dauphin Island, AL	3 years data:2009,2010,2008
3	Gustav 2008	25th–3rd September 2008	42039	28.739N 86.006W (28°44′22″N 86°0′23″W) 115NM ESE of Pensacola, FL	3 years data:2006–2008
4	Dean 2007	13th–23rd August 2007	41041	14.329N 46.082W (14°19′43"N 46°4′55" W) 890 NM East of Martinique	3 years data:2005–2007
5	Katrina 2005	27th–30th August 2005	42040	29.212N 88.207W (29°12′45″N 88°12′27" W) 64 NM South of Dauphin Island, AL	3 years data:2008, 2009,2005

but all are of hind casting and not of forecasting the extreme wave events which is the focus of the present paper.

The complexity and uncertainty of the wave generation phenomenon is such that despite of substantial advances in computational techniques, the solutions obtained are neither exact nor uniformly applicable at each and every site and at all the times particularly in case of extreme events. The classical time series models such as Auto Regressive Moving Average (ARMA), Auto Regressive Integrated Moving Average (ARIMA), Kalman Filter [11] have a limited ability to capture non-stationarities and non-linearity in data series. On the other hand, soft computing techniques normally utilize tolerance to uncertainties, imprecision, and partial truth associated with input information in order to come up with robust solution, handling non-linearities and non-stationarities effectively. Forecasting of ocean waves using Artificial Neural Networks (ANN) has been done by many researchers since last two decades or so. Deo and Naidu [7], Makarynskyy [20], Londhe and Panchang [17], and many more developed neural network models with feed-forward or recurrent type of networks for forecasting wave heights in advance without considering the effect of wind (univariate/temporal modeling). A comprehensive review of these applications is done by Jain and Deo [12]. When cause-effect modeling of significant wave heights using ANN is considered significant contributions are by Deo et al. [6], Nitsure et al. [21] and Ponce de León and Guedes Soares [28] and many more. Combining ANN with one or the other soft tools like Fuzzy logic, Genetic Programming etc., was tried by Ozger and Sen [22], Mahjoobi et al. [18], Zamini et al. [31], Ozger [23] and Kamranzad et al. [13]. All the above mentioned works have notified that prediction capability of these soft computing models particularly at extreme events particularly in hurricanes is extremely poor. This becomes the motivation behind the present study where efforts are made to predict the extreme wave heights (SWHs) during five hurricanes in the Gulf of Mexico with better accuracy.

Recently wavelet transform has been used successfully by the authors [10] for removing the prediction lag in wave forecasting in combination with Artificial Neural Networks. Wavelet analysis is multi-resolution analysis in time and frequency domain which decomposes the original signal into several sub signals. The discrete wavelet transform analyzes frequency of signal with respect to time at different scales. It decomposes time series into low (approximate) and high (detail) frequency coefficients preventing any correlation between the sequentially observed wave heights. It's a well known fact that the extreme wave events occur with a low frequency some times of the order of 40,000 year event as in SWH of 15.96 m recorded during Hurricane Ivan at wave buoy 42,040 in Gulf of Mexico as mentioned by Panchang and Li [29]. The decomposition of approximate coefficients (low frequency) can be carried out up to multiple levels in order to provide more detail and approximate components (more information) which provide relatively smooth varying amplitude series. The neural network can then be trained with decorrelated approximate and detail wavelet coefficients. The outputs of networks during testing are reconstructed back using inverse DWT. The multilevel decomposition of signal thus makes it an attractive tool for better prediction particularly in extreme events owing to the multilevel decomposition of approximate coefficients (low frequency). The present work is an extension of the earlier work by the authors [10], in which efforts are directed towards improving the prediction accuracy particularly at extreme events where the Neuro-Wavelet Technique is employed for forecasting Significant Wave Heights at different lead times of 12 hr to 36 hr using the previously measured SWHs and the results are observed particularly during the hurricanes.

The outline of the paper is as follows. Details of the study area and data are presented in the next section followed by information on ANN and Neuro-Wavelet Technique (NWT) in Section 3. Model formulation is explained in Section 4 and result and discussions are showcased in Section 5. Concluding remarks are presented at the end.

2. Study area and data

As mentioned in the introduction, present study is specifically concerned about the accurate prediction of extreme waves (significant wave heights) with a lead time of few hours to few days in advance. For this five hurricanes in the Gulf of Mexico namely; Katrina-2005, Dean-2007, Gustav-2008, Ike-2008, Irene-2011 are considered. The reason behind selecting these hurricanes is that the maximum significant wave heights (SWHs) measured during these hurricanes in the Gulf of Mexico rivals the largest wave heights ever recorded in all US waters, even though on a return period basis. Also the Gulf of Mexico has the smallest wave climate compared with all other regions around the US. The paths of these hurricanes are available on NOAA website which shows that they passed very closely to the wave buoys namely; 42040, 42039, 41004, 41041 in the Gulf of Mexico and therefore these wave buoy stations are selected for the present study. The details of these hurricanes and location of the above buoys are presented in Table 1 and Fig. 1. The hourly data of measured significant wave heights (of consecutive three years considering the year of actual occurrence of particular hurricane) at these stations is used to train and test the models for forecasting the significant wave heights 12 hr, 24 hr and 36 hr in advance at