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Estimation and validation of offshore wave characteristics of Bay of Bengal cyclones (2008-2009)

Sisir Kumar Patra[a*], P K Mohanty[b], P Mishra[c] and U K Pradhan[c]

[a]National Institute of Ocean Technology, Velachery-Tambram main Road, Pallikaranai, Chennai, 600100, India
[b]Department of Marine Sciences, Berhampur University, Berhampur, Orissa, 760007, India
[c]Integrated Coastal and Marine area Management,ICMAM-PD, NIOT Campus, Pallikaranai, Chennai, 600100, India

Abstract

Offshore wave characteristics viz; significant wave height (Hs) and peak wave period (Tp) during cyclonic storms are important in planning and design of offshore structures, ship operations and other offshore activities. During June, 2008 to May, 2009 four cyclonic storm (CS) and one depression (D) originated over Bay of Bengal (BoB). In this paper, with the help of empirical formulae (Young's model, 1984; SMB method, 1984 and Sanil et al. (2003) we have estimated the offshore wave characteristics along the tracks of the four CS and one depression using the cyclone wind climate of Indian Meteorological Department (IMD). The spectral wave model of MIKE 21 is used to simulate wave characteristics of BOB while the observed wave characteristics off Gopalpur measured at 23 m water depth is used for validation. Various statistical parameters viz. root mean square error (RMSE), scatter index (SI), and correlation coefficient (R) are derived to inter-compare the observed, simulated and estimated results. The observed and simulated values of Hs show very good agreement (correlation coefficient of 0.86) while the agreement in case of wave period is relatively lower (R=0.55). Comparison between simulated and estimated Hs shows good agreement for Young's model and SMB method, while Sanil et al. equation shows over estimation as compared to simulation. Similar comparison for Tp shows good agreement with Young's model and Sanil et al. equation and over prediction for SMB method.

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Keywords: BOB cyclone; MIKE 21 spectral wave model; significant wave height; peak wave period

1. Introduction

Wave forecasting technique is of two types viz., empirical and numerical. The empirical methods/models explicitly give the wave height and period from the input parameters of wind speed, fetch and duration. The numerical methods are mainly based on the solutions of the equations of the wave growth and hence are more accurate than, the empirical models. The numerical models are most justified, when the wind speed varies considerably along with its direction in a given time and area. When the wind speed is assumed to be fairly stationary, and accurate and elaborate wind data are not available, the simplified parametric wind wave relationship involving empirical treatment could be a workable alternative. The common methods that are used for the estimation of extreme wave height and period during cyclonic storm are Young (1988), Hsu(2000), Sverdrup-Munk-Bretschneider(SMB) and Hasselmann et al (1973) etc. The SMB method for deep water (depth more than 90 m)that provided in Shore Protection Manual (SPM, 1984) and Young's model based on JONSWAP fetch limited growth relationship are commonly used for extreme wave prediction.

* Corresponding author.
E-mail address: sisir.skp@gmail.com

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The Evolution of tropical cyclone is a regular feature in pre-monsoon (May) and post-monsoon (October and November) over Bay of Bengal. The east coast of India experiences maximum number of low pressure systems. About 5-6 tropical cyclones hit East Coast of India every year originating from bay of Bengal and the frequencies and intensities has increased recently (Singh, 2001 and Mohapatra and Mohanty, 2004). The wave characteristics during cyclone along India coast and their assessment of storm disaster addressed by many authors in the recent past (Sanil et al., 2003,Sanil et al., 2004 , Rao et al., 2007, Mishra et al., 2011). Evaluation of wave characteristics during cyclone is essential to assess the risk of damages to off-shore structures or for Oceanographers and modellers to calculate trends in the past and future wave fields (Lionello et al., 2007). Tropical cyclones cause damage to properties near coasts due to high wind speed and loss of life on account of severe flooding due to resulting storm surge (Satish Kumar et al., 2003). Storm generated wave, coupled with locally generated waves create complex characteristics in the near shore region. Keeping in view the importance of wave estimation during tropical cyclone, in the present study we made an attempt to compare the wave characteristics between numerical model and empirical equations by considering Bay of Bengal (BOB) cyclone during 2008-2009. During the study period, there were five Cyclonic storms (CS) and one depression system crossed over BOB and recorded by IMD. Out of which, for our study, we interpreted the results of one depression originated on 15-19 September 2008, and four CS's *viz*. Rasmi cyclone (25-27 October, 2008),KhaiMuk cyclone (14 - 16 November, 2008), Bijli cyclone (14-17 April, 2009) and Aila cyclone (23-26 May, 2009).

2. Data and Methodology

Numerical Models

The MIKE 21 Spectral Wave Model (Mike-SW) developed by the Danish Hydraulic Institute, Denmark, is a third generation spectral wind-wave model based on unstructured meshes. The model simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas. The model includes: the Wave growth by action of wind, Non-linear wave-wave interaction, Dissipation due to white-capping, Dissipation due to bottom friction, Dissipation due to depth-induced wave breaking, Refraction and shoaling due to depth variations, Wave-current interaction, Effect of time-varying water depth and flooding and drying.

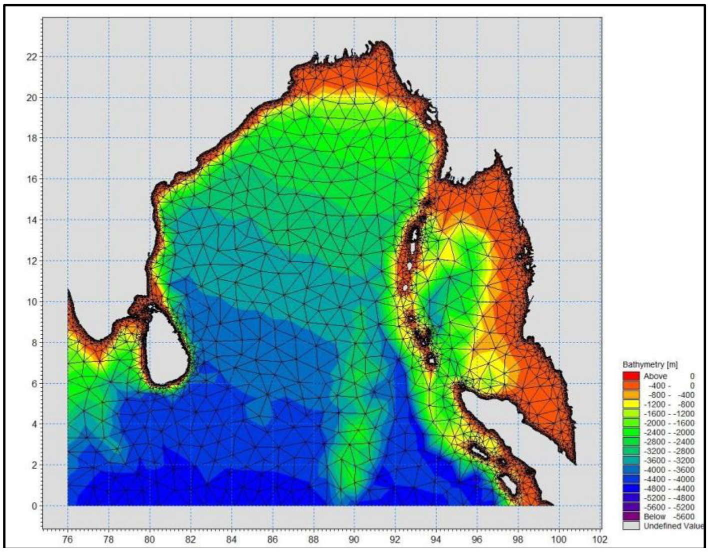

Fig. 1 Model domain & bathymetry used for study

The model is based on the wave action balance equation where the wave field is represented by the wave action density spectrum. The model is based on numerical integration of wave action balance equation formulated in Cartesian co-ordinates (Komen et al. 1994 and Young, 1999). The discretization of the governing equation in geographical and spectral space is performed using cell-cantered finite volume method. In the geographical domain, an unstructured mesh technique is used. The details of the model equations and methods of solution are explained in MIKE-21 user manual (2009).

For this model study, the reanalysed NCEP winds available in the form of U and V velocity components for 2.5°× 2.5° grid spacing for every 6 hours interval is used. The Etopo-1 bathymetry data (National Geophysical Data Centre, USA) is used for offshore with coarser resolution of 0.75°× 0.75° and MIKE CMAP of DHI is used for near shore region (up to 200 m water depth). The model domain (Fig. 1) is about 2775 × 2775 km with a maximum water depth of approximately 5002 m, extended from 0° S to 25° N and 86° E to 101° E. The boundary along 0° S latitude is considered as open boundary, and all other boundaries are closed.

Empirical methods

There are three empirical equations used for the estimation of significant wave height (H_s) and peak wave period (T_p) in this study. The cyclone wind data from India Meteorological Department (IMD) is used. The input parameters for the empirical methods are the radius of maximum wind speed for the storm (R), maximum wind spped (V_{max}), the speed forward motion (V_{fm}), Central pressure of the cyclone (P_0) and pressure drop ($\Delta P = P_n - P_0$).

Sverdrup-Munk-Bretschneider (SMB) equations are based on dimensional analysis considerations and are used here for the calculation of wave height and peak period along the cyclone track. The basic equations are:

$$\frac{gHs}{u^2} = 0.283 \tanh\left[0.0125\left(\frac{gF}{u^2}\right)^{0.42}\right] \quad 1$$

$$\frac{gTp}{u} = 0.24\pi \tanh\left[0.077\left(\frac{gF}{u^2}\right)^{0.25}\right] \quad 2$$

Where g is the acceleration due to gravity, F is fetch length and u is the maximum wind speed.

According to Young's model, the JONSWAP fetch limited growth relationship (Hasselman et al., 1973) is used for estimation of wave characteristics in deep water. The equations are:

$$\frac{gHs}{V^2{}_{max}} = 0.0016\left(\frac{gF}{V^2{}_{max}}\right)^{0.5} \quad 3$$

$$\frac{gTp}{2\pi V_{max}} = 0.045\left(\frac{gF}{V^2{}_{max}}\right)^{0.33} \quad 4$$

Where, V_{max} is the maximum wind speed, g is the acceleration due to gravity, F is fetch length

Based on multiple regression analysis, Sanil et al. (2003) derived the following empirical equations for Indian Ocean, which holds good for 32 cyclones between the years 1961 to 1982. The empirical equations are:

$$H_s = 0.25V_{max} \quad 5$$

$$T_p = 4.5\, H_s{}^{0.48} \quad 6$$

3. Results and Conclusion

Simulated wave parameters from MIKE 21 spectral wave model are validated with the measured values done during the cyclone September, 2008 to May, 2009. The statistical wave parameters between measured and simulated are depicted in Table 1. The correlation coefficient between measured and simulated H_s, and T_z are 0.86, and 0.55 respectively. Simulated wave parameters are reasonably close agreement with the observed value (Fig. 2). The statistical wave parameters between measured and simulated have bias of -0.06 m and 0.68 s and RMS errors of 0.26 m and -1.47 s respectively. The numerical model and observed wave comparison statistics reveals good agreement with the Bay of Bengal statistics done by Remya et al (2012), where they showed RMSE, R and Bias of H_s are 0.29 mand 0.91 s respectively.

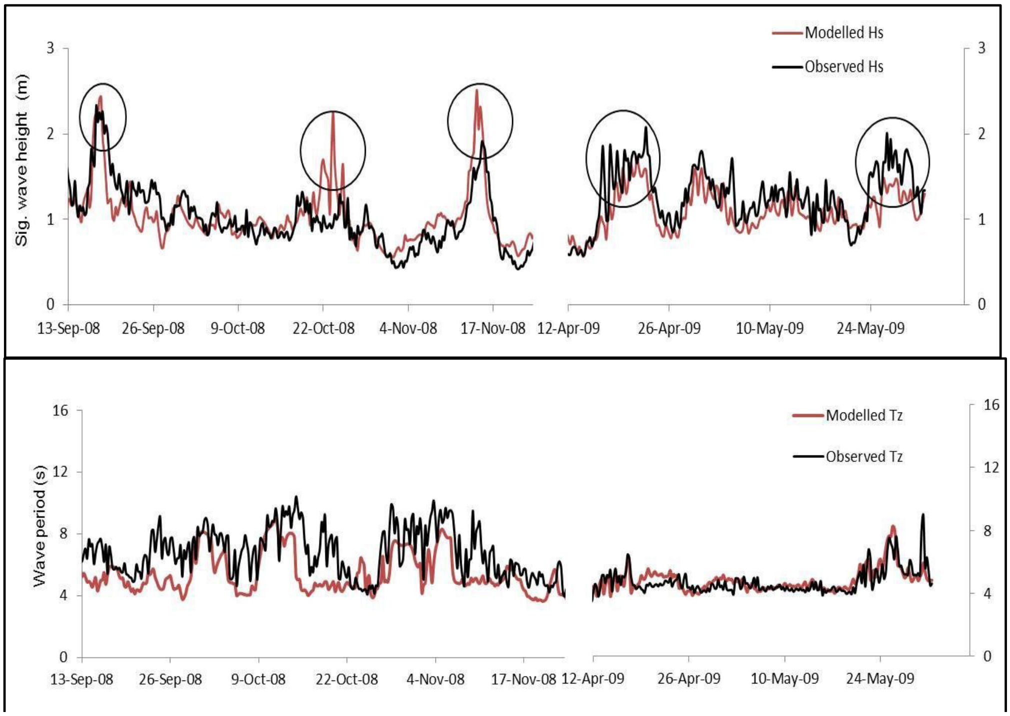

Fig. 2 Comparision between measured and modelled Hs and T_z (the peaks indicated by circle are the periods of CS)

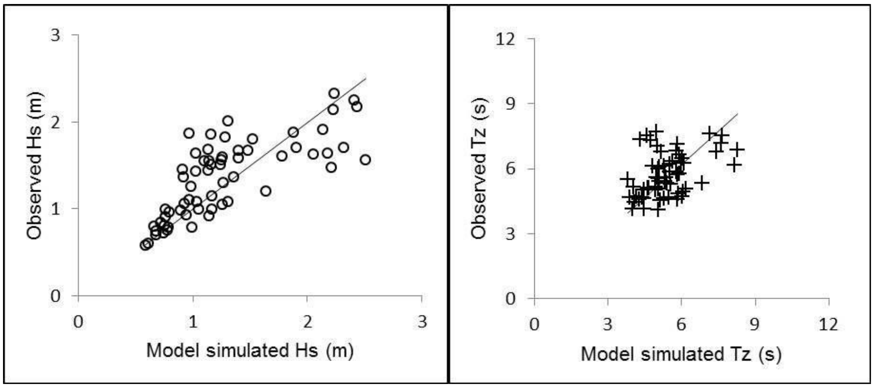

Fig.3 Scattered plot between measured and simulated wave height and period during cyclone events

The scattered plot between measured and modeled H_s and T_z is shown in Fig.3. The discrepancies between measured and simulated wave parameters are mainly due to courser resolution of wind input and deficiency in accurate near shore bathymetry.

Table 1. Statistics of the comparison of model wave parameters with buoy measurement at Gopalpur during cyclone events

Wave Parameters	RMSE	R	Bias	SI
Wave height (H_s) in m	0.26	0.86	- 0.06	0.25
Wave period (T_z) in s	-1.47	0.55	- 0.68	0.26

The significant wave height estimated using Young's model, SMB method and Sanil et al., regression analysis are compared with the MIKE 21 spectral wave model and is presented in Fig. 4. The estimated significant wave height by Young's model and SMB method fitted well with the model simulated value, while Sanil et al. regression analysis found to be deviate from the model value and over predicted. The model simulated H_s during Bijli cyclone is low compared to estimated results obtained by three empirical methods. The comparison between simulated H_s and estimated using empirical equations for all cyclones is presented in Fig. 5. The comparison shows good agreement between model and estimated value for Young's and SMB method.

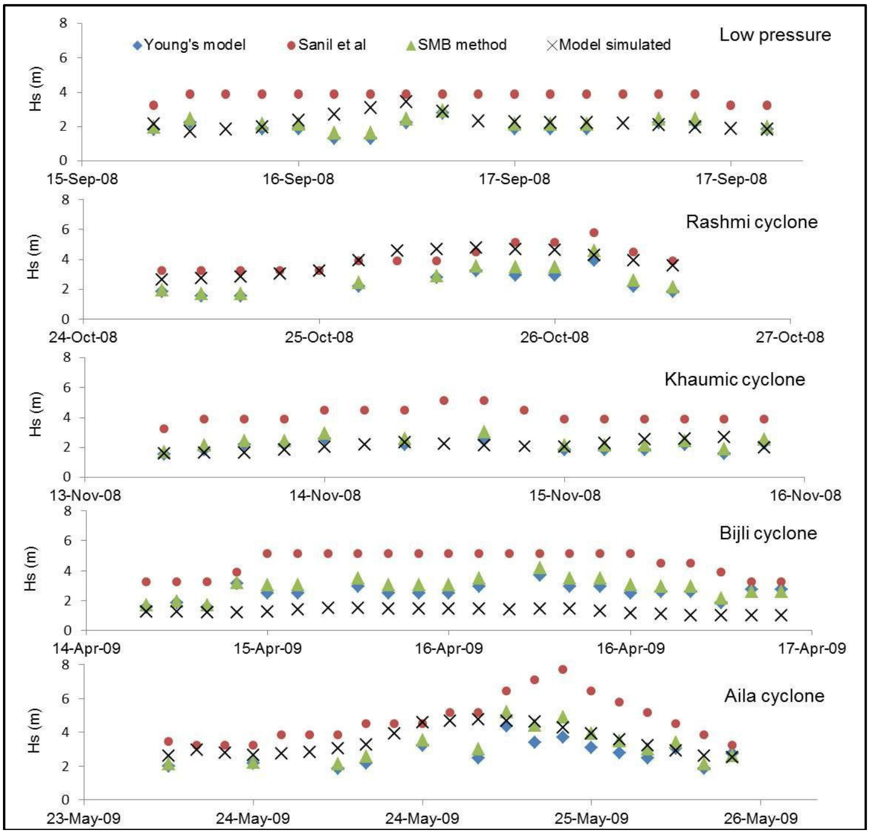

Fig. 4 Time series plot of estimated and model H_s along the cyclone track

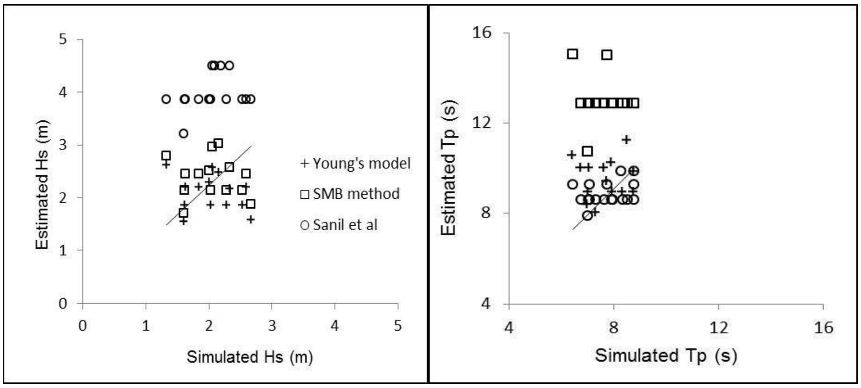

Fig. 5 Comparison between numerical model and empirical result between H_s and T_p

The time series plot of peak wave period (T_p) between simulated and estimated by using empirical equations is depicted in Fig. 5. The simulated value of T_p matches well with estimated values by Young's method and Sanil et al. empirical equations. The SMB method over estimated in the prediction of T_p. The scatter plot between estimated values and model simulation of T_p (Fig. 6), confirms reasonable fair agreement by Young's model and Sanil et al. equation and over prediction by SMB method.

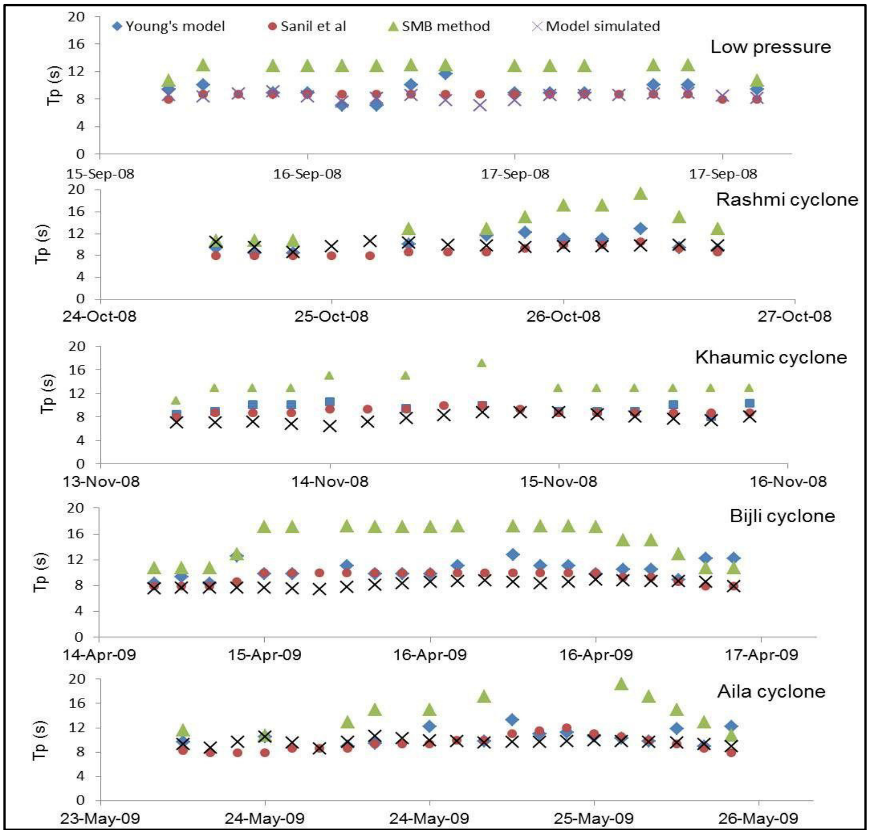

Fig. 6 Time series plot of estimated and simulated T_p along the cyclone track

4. Conclusion

The third generation numerical wind wave model is accurate in the prediction of wave characteristics during cyclone events, due to its solution technique on the wave action balance equation. Most of the empirical equations are dimensionally incorrect, and not valid for all CS's and depressions. The empirical equation by Young's method can be used for estimation of significant wave height and peak wave period from the known storm variable.

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