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Verification of model wave heights with long-term moored buoy data: Application to wave field over the Indian Ocean

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ABSTRACT

This paper describes the results obtained using a modified version (ModWAM) of the global wave model WAM, in which new parameterizations have been applied based on the seasonal changes and extreme weather events that have occurred in the Indian Ocean. Model significant wave heights (H_s) have been verified using H_s data extracted for the period 2000–2006 from 10 moored data buoys, deployed in the north Indian Ocean. Satellite altimeter H_s has also been used for the model comparison. Based on the error estimates of significant wave heights and spectral wave energy, improvement achieved in wave prediction using ModWAM is demonstrated. We find that the ModWAM improved the accuracy of significant wave height prediction in deep water considerably (rmse of ModWAM is less than that of rmse of WAM), and provided better presentation for high waves that prevailed during southwest monsoon (e.g. H_s, of the order of. 6.0 m in June 2005) and extreme weather events (e.g. cyclone that occurred in May 2005), compared to WAM; but, it still underestimates H_s for high waves. Comparison between modeled and measured spectra shows that ModWAM overpredicts spectral energy at low frequencies, and underpredicts at high frequencies.

1. Introduction

Wind waves play crucial roles in marine processes such as exchange of gases, heat and momentum between the atmosphere and the sea, interchange of energy with currents and interaction with bottom. Hence, the requirement for high quality wave data is constantly increasing not only in the areas of offshore oil exploration, marine transportation and structural design, but also in fundamental research. In order to study these processes, high resolution spatial and temporal wave data are required, and this is possible only through wave modeling. Hence, the wave modeling community is ever on the task of understanding and applying the physical processes in wave models in order to increase its accuracy and performance. The main approach to accurate prediction of sea state is to use of numerical modeling techniques in conjunction with atmospheric models, data assimilation systems and statistical techniques (WAMDI Group, 1988; Lionello et al., 1992; Komen et al., 1994; Abdalla et al., 2005; Chu and Cheng, 2008; Tolman et al., 2012). The various techniques mentioned in these scientific works have been successful in predicting the sea state reasonably accurately on global as well as regional scales. It may be noted that besides the time required for the calculations, the issue of model accuracy is the most important, since the discrepancies between the results obtained with different models can sometime appear to be too great (Tolman et al., 2002; Cavaleri et al., 2007).

In deep water, the wind input, nonlinear wave-wave interaction and breaking dissipation are the three most important source terms governing the dynamics of the surface gravity wave evolution (for e.g., Miles (1957), Hasselmann et al., 1973; Phillips, 1977, 1985; Komen et al., 1994; Janssen, 2004, Violante-Carvalho et al., 2004). The physics of these source functions are still active research subjects, and one of the methods to gauge the performance of numerical or theoretical wave models is to compare the model results with fetch- or duration limited wave growth functions (e.g., Komen et al., 1984, 1994; Janssen et al., 1994; Ardhuin et al., 2007; Romero and Melville, 2010). As 'duration limited condition' occurs rarely in the natural environment, by far, research on fetch-limited growth contributes the most to the benchmark database. Over the last few decades, many fetch growth functions have been proposed (e.g., reviews by Hasselmann et al., 1973; Donelan et al., 1985; Kahma and Calkoen, 1994). Kukulka and Hara (2005) proposed a wind input wave growth formulation under the sheltering assumption. According to this approach, the wave-induced stress of longer waves reduces the turbulent stress felt by shorter waves. More recently, Banner and Morison (2010) and Ardhuin et al. (2010) proposed a wave prediction model based on

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quasi-linear theory, resulting in an effective high wave number cut-off, including slight tuning modifications.

The basic equations for nonlinear interactions were proposed by Hasselmann (1962, 1963a,b) and later modified by Zakharov (1968). Further, a lot of parameterizations for the finite depth version of the interaction coefficient were proposed by Webb (1978), Dungey and Hui (1979), Herterich and Hasselmann (1980) and Zakharov and Pushkarev (1999). Gorman (2003) provided a detailed analysis of finite depth interaction coefficient and derived expressions for the treatment of discontinuities. Lavrenov (2001, 2003) gave an efficient numerical algorithm for simulating non-linear energy transfer using the Hasselmann kinetic equation for gravity waves in water surface. In this approach, the kinetic equation for surface gravity waves was investigated numerically taking into account an external generating force and dissipation. Tolman (2013) proposed a new DIA (Discrete Interaction Approximation) approximation as Generalized Multiple DIA (GMD) for nonlinear four-wave interactions in wind wave spectra. GMD was tested for different scenarios and found that GMD is capable of removing most of the errors introduced by the DIA in deep water. In shallow water the GMD is capable of reproducing shallow water behavior of the exact interactions, albeit with some spurious shifting of energy to lower frequencies in extremely shallow water.

Over the past decade, many physical features of the dissipation performance were carried out experimentally and through field measurements. For example, the threshold behavior of wave breaking (Babanin et al., 2001; Babanin, 2011; Banner et al., 2002), the cumulative effect of wave dissipation at smaller scales and therefore two-phase behavior of the dissipation (Manasseh et al., 2006; Young and Babanin, 2006), quasi-singular behavior of the dissipation in the middle wavelength range (Hwang and Wang, 2004). Polnikov (1993) assumed a simplified representation of wave dynamic equations with the efficient stress attenuation that is appropriate for monochromatic waves. Recently, Chalikov and Babanin (2012) studied wave breaking and dissipation by modeling the breaking in spectral environments. Galchenko et al. (2012) carried out laboratory investigation of wave influence on modulational instability, breaking and dissipation.

In most of the present numerical models, the evolution of wind waves is usually written in the form of a wave transport equation for the two-dimensional wave spectrum. From mathematical point of view, a wind wave field has a stochastic feature, and its properties should be governed by a proper statistical ensemble. Therefore, the best way to describe the phenomenon lies in the domain of statistical characteristics. The most significant of them is the two-dimensional spatial wave energy spectrum, $F(k,x,t)=F$, spread in the space, x, and time, t. The space-time evolution is described in the spectral representation (Komen et al., 1984):

$$\frac{\partial F}{\partial t}+C_{gx}\frac{\partial F}{\partial x}+C_{gy}\frac{\partial F}{\partial y}=S\equiv NL+IN-DIS \tag{1}$$

The LHS is the full time-derivative of the spectrum, and the RHS is the source function ("forcing") term, S. Vector (C_{gx}, C_{gy}) is the group velocity corresponding to a wave component with wave vector $\mathbf{k}$, which is defined by

$$\mathbf{C}_g=\frac{\partial\sigma(k)}{\partial k}\frac{\mathbf{k}}{k}=(C_{gx}, C_{gy})$$

Dependence of frequency on the wave vector $\sigma(\mathbf{k})$ is given by the expression, $\sigma=\sqrt{gk}$ known as the dispersion relation for the case of deep water. The LHS of Eq. (1) is responsible for "mathematical" part of the model, which is not discussed here, whilst the physical essence of the model is held by the source function, S. The total source function S, is modeled as the sum of three terms, which are involved in the combined evolution mechanism for wind waves: (i) the rate of energy transfer from wind to waves, IN (input term), (ii) the rate of conservative non-linear energy transfer through a wave spectrum, NL (non-linear term) and (iii) the rate of wave energy loss due to various dissipative processes, DIS (dissipation term). The different parameterizations used for the source functions define physical processes of each model. In our earlier work, we used wave models to study the wave characteristics (swell–sea interaction, waves generated by shamal winds, storm generated waves and propagation of southern swells in the north Indian Ocean) of the Indian Ocean (Aboobacker et al., 2009, 2011a, 2011b, 2013; Vethamony et al., 2009, 2011; Samiksha et al., 2012; Rashmi et al., 2013). In the present study, we have used the modified model of WAM (Pogarskii et al., 2012; Polnikov et al., 2012b, 2013) to study the wind wave variability in the Indian Ocean; the model results were verified with long-term buoy data at several locations in the Indian Ocean.

2. Methodology

The WAM model (Cycle 4) is a third generation wave model, which solves the wave transport equation explicitly without any presumptions on the shape of the wave spectrum (WAMDI group, 1988). It represents physics of the wave evolution in accordance with full set of degrees of freedom of a two dimensional wave spectrum. The model runs for any given regional or global grid system with a prescribed topographic dataset — the grid resolution can be arbitrary in space and time. The propagation can be done on a latitudinal–longitudinal or Cartesian grid.

2.1. ModWAM model

ModWAM is a modified version of WAM model. In ModWAM (Polnikov, 2003, 2005, 2008, 2010, 2012a), the three source functions are modified as follows:

i) The wind-wave energy exchange term, In, is written in the commonly used representation as follows:

$$In=\beta(\sigma,\theta,u_*)\sigma S(\sigma,\theta) \tag{2}$$

In ModWAM, the wave growth increment $\beta(\sigma,\ \theta,\ u_*)$ has been modified as

$$\beta=C_{IN}\max\{-b_L,\beta_Y\} \tag{3}$$

where, C_{IN} is the general fitting coefficient, whilst b_L is the auxiliary fitting parameter responsible for negative values of β for waves overtaking the local wind W_{10} taken at the standard height, $z=10$ m. In the model, wind W_{10} is converted to frictional velocity, u_* using the dynamic water boundary layer approach (Janssen, 2004).
The value β_Y is the combined analytical presentation for β, obtained by Yan (1987) in the form

$$\beta_Y=\left[0.04\left(\frac{u_*\sigma}{g}\right)^2+0.00544\frac{u_*\sigma}{g}+0.000055\right]\cos(\theta-\theta_w)-0.00031 \tag{3.1}$$

σ and θ are the frequency and propagation angle of a wave component, respectively; u_* is the friction velocity, $g$is the acceleration due to gravity and θ_w is the local wind direction. It may be noted that parameter β in the parameterization can take negative values, when β_Y becomes less then b_L (for waves overtaking the wind). The optimum value of the latter, as the fitting parameter, is found to be

$$b_L=0.000002$$