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Evaluation of two WAM white capping parameterizations using parallel unstructured SWAN with application to the Northern Gulf of Mexico, USA

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ABSTRACT

The performance of two well accepted formulations for white capping and wind input of third generation wave models, viz., WAM-3 and WAM-4, were investigated using parallel unstructured SWAN (PunSWAN). Several alternative formulations were also considered to evaluate the effects of higher order steepness and wave number terms in white capping formulations. Distinct model configurations were calibrated and validated against available *in situ* measurements from the Gulf of Mexico. The results showed that some of the *in situ* calibrated models outperform the saturation level calibrated models in reproducing the idealized wave growth curves. The simulation results also revealed that increasing the power of the steepness term can enhance the accuracy of significant wave height (H_s), at the expense of a higher bias for large waves. It also has negative effects on mean wave period (T_a) and peak wave period (T_p). It is also demonstrated that the use of the quadratic wave number term in the WAM-3 formulation, instead of the existing linear term, ameliorates the T_a underestimation; however, it results in the model being unable to reach any saturation level. In addition, unlike H_s and T_p, it has been shown that T_a is sensitive to the use of the higher order WAM-4 formulation, and the bias is decreased over a wide range of wave periods. However, it also increases the scatter index (SI) of simulated T_a. It is concluded that the use of the WAM-4 wind input formulation in conjunction with the WAM-3 dissipation form, is the most successful case in reproducing idealized wave growth curves while avoiding T_a underestimation of WAM-3 and a potential spurious bimodal spectrum of WAM-4; consequently, this designates another perspective to improve the overall performance of third generation wave models.

1. Introduction

Third generation wave models which solve the spectral form of the action balance equation [1] are efficient tools for simulating wave fields in medium- and large-scale domains [2]. Unlike earlier generations, these phase-averaged models include nonlinear wave–wave interaction, and dissipation terms without any prior assumption of spectral shape [3,4]. Among source/sink terms in deep water (wind input, quadruplet wave–wave interaction and energy dissipation [5]), dissipation is widely considered to be the least understood term [6]. Although several different formulations have been proposed for energy dissipation in deep water [6–10], the pulse-based quasi-linear model for the white capping term proposed by Hasselmann [11] remains in use in third generation wave models [12,13]. This approach successfully reproduces the fully developed wind–sea when used in conjunction with efficient quadruplet nonlinear wave interaction formulation referred to as the Discrete Interaction Approximation (DIA) [14], and rescaled wind input formulation of [15,16]. These sets of equations are used in the WAM cycle 3 model and are referred to as WAM-3 hereafter.

Advancements in understanding of wave growth in open water led to a theoretical description of the wind input term, which results in an acceptable level of agreement with *in situ* measurements [17]. The WAM cycle 4 model (WAM-4) employs wind–wave energy transfer parameterization based on quasi-laminar theory, and also considered quadratic dependence of dissipation on the wave number to provide more flexibility in the formulation for white capping dissipation [18]. This formulation also became part of many recent third generation wave models [12,13,19].

The third generation model, Simulating Wave Nearshore (SWAN) [12], has been well suited for both parameterizations, WAM-3 and WAM-4, and hence provides a tangible platform to compare and contrast their performance. Although originally developed for shallow water, SWAN incorporates all source and sink terms for generation and propagation of waves in deep and shallow water, and has been verified for several geographic settings and for different met-ocean conditions [2,8,20–25].

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The free coefficients of wave models, in this case SWAN, are conventionally set so that the model can reproduce saturation level spectra, among which the one suggested by Pierson–Moskowitz (PM) is probably the most popular [26,27]. However, Rogers et al. [8] stated that the wave models reach the saturation energy level too slowly. Moreover, it is not possible to calibrate the model for all possible wind speeds, because the PM spectrum scales with wind speed while the model formulations are scaled with friction velocity. Finally, tuning the model for unlimited time and fetch conditions may not be a realistic representation of wave growth in real-world situations. Therefore, in this study, the free parameters are determined by comparing the simulated significant wave height (H_s), peak wave period (T_p) and averaged wave period (T_a) with *in situ* observations.

Although a classical approach to adjust the model parameters is implemented in this study, in which the model is calibrated and verified using *in situ* measurements [28], as a reference, the performance of the calibrated model is compared with the same model tuned for the PM spectrum. In addition, Rogers et al. [8] showed that using a higher order wave number term in white capping formulation of WAM-3 enhances the model performance when compared with *in situ* observations. An in-depth analysis of this model performance along with similar modifications to WAM-4 are presented in this study. The same modifications are also applied to the steepness term in the white capping formulation of WAM-3 (see Section 2.2) which has been assumed to be constant without any clear scientific explanation. Therefore, the main objective of this study is to evaluate the effect of possible modifications in WAM-3 and WAM-4 white capping formulations when compared with known fetch-limited and fully developed wave data as well as long term *in situ* measurements.

2. Model description

2.1. Wind input

The wind input source term in SWAN can be described by a superposition of linear and exponential wave growth terms:

$$S_{\text{in}}(\sigma,\theta) = A + BE(\sigma,\theta) \tag{1}$$

in which E is energy density over relative frequency σ and propagation direction θ. The linear growth rate A, is based on the expression proposed by Cavaleri and Rizzoli [29] and is generally important during the early stages of wave growth. There are two different formulations for the coefficient B in the exponential wave growth term in WAM-3 and WAM-4. In WAM-3 the rescaled version of the experimental formulation of Snyder is employed [15,16] whereas in WAM-4, a set of equations presented by Janssen [17] is used. The latter formulation is based on the quasi-linear theory of wave generation, and the energy exchange from wind to wave is taken into account by interaction of atmospheric boundary layer and sea surface roughness length [30].

It is not surprising that all of the aforementioned formulations for wind input are a function of wind speed. The wind velocity components for this study were extracted from the North American Regional Re-analyzed (NARR) database from the National Center for Environmental Prediction (NCEP/NOAA) server. The NARR data grid 221 covers the entire continental US and the Gulf of Mexico with a horizontal resolution of approximately 32 km. More details regarding the wind data used in this study can be found in [31].

2.2. White capping

The White capping formulations implemented in SWAN for WAM-3 and WAM-4 are given as

$$S_{wc\_\text{WAM3}} \equiv -C_{ds}\left(\frac{\tilde{k}^2}{\tilde{s}^2_{\text{PM}}}E_{\text{tot}}\right)^n\left(\frac{k}{\tilde{k}}\right)^m\tilde{\sigma}E(\sigma,\theta) \tag{2a}$$

$$S_{wc\_\text{WAM4}} \equiv -C_{ds}\left[(1-\delta)+\delta\left(\frac{k}{\tilde{k}}\right)^m\right]E^2_{\text{tot}}\tilde{k}^3k\tilde{\sigma}E(\sigma,\theta) \tag{2b}$$

in which $\tilde{k}$, $\tilde{\sigma}$ and E_{tot} denote the mean wave number, mean frequency and total energy respectively. Moreover, $\tilde{s}_{\text{PM}} = \sqrt{3.02\times10^{-3}}$ denotes steepness of the PM spectrum. The parameters $n = 2$ and $m = 1$ are fixed in the original model, and the main tuning coefficients are C_{ds} and δ which are conventionally determined to reproduce H_s; resulted from a fully developed PM spectrum. There are some recent studies that show WAM-3 can perform better in terms of the T_a estimation, when $m > 1$. However, it also leads to overestimation of H_s [8,10]. In this study, a similar investigation is made for WAM-4 to evaluate the effects on the simulated bulk wave parameters, by using higher order wave number terms in the white capping sink term. While having some fair support from measurements [32,33], the original $n = 2$ in Eq. (2a) was originally introduced by Komen [16] for a fully developed spectrum. Since the steepness of the spectrum would not change in such an asymptotic condition, choosing any different value for n was equivalent to redefining the coefficient C_{ds}. This is not the case for "young sea" in which the steepness of the wave field is evolving. Thus the effect of higher order dependence of the dissipation term on the steepness is also worthy of investigation. Our initial numerical efforts showed that using $n < 2$ could initiate numerical instabilities in shallow waters, that persist for long time periods; therefore only larger values of n were further pursued.

2.3. Other physical processes

Nonlinear quadruplet wave interaction plays an important role in controlling the shape and evolution of the wave spectrum [14]. Although the accurate physical description of nonlinear energy transfer is available [34,35], it is computationally intensive and cannot be used in operational models. The DIA formulation is the most common method for calculating nonlinear quadruplet wave interactions and is used in phase-averaged wave models such as SWAN, Mike21 and WAVEWATCH-III [12,13,19]. Although considered three orders of magnitude faster than best implementations of exact representation of nonlinear energy transfer, DIA is criticized to be inaccurate in reproducing the full wave spectrum [8,10]. Considering only a few possible configurations from the complete set of quadruplet interactions, results in unrealistic shape of the wave spectrum in the high frequency end of the wave spectrum, and also a broader spectrum near peak frequency [7,10,36,37]. Since our focus was on operational use of wave models, and it has been shown that DIA is capable of reproducing bulk wave parameters with sufficient accuracy [38], we used DIA for this study.

As the *in situ* measurements used in this study, to evaluate the performance of Parallel Unstructured SWAN (PunSWAN), are from deep to intermediate depths, the coastal wave transformation processes are not expected to significantly influence the bulk wave parameters. Therefore, the models with the least computational requirements are employed for parameterization of coastal processes: The nonlinear triad interaction is considered according to Eldeberky [39], bed friction according to Hasselmann et al. [40], and depth-induced wave breaking according to Battjes and Janssen [41].

2.4. Mesh file

The computational grid requires enough resolution to accommodate the complex bathymetry of shallow water for accurate coastal wave modeling [42]. In the recent versions, especially since 40.72, SWAN employs a Finite Volume scheme, and affords