Ocean Modelling 103 (2016) 2–17

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Virtual Special Issue
Ocean Surface Waves

Comparison and validation of physical wave parameterizations in spectral wave models

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ARTICLE INFO

Article history:
Received 31 January 2015
Revised 8 September 2015
Accepted 14 September 2015
Available online 21 September 2015

Keywords:
WAVEWATCH III
Spectral wave modeling
Wave hindcasting
Source terms
Higher order wave moments
Swell dissipation

ABSTRACT

Recent developments in the physical parameterizations available in spectral wave models have already been validated, but there is little information on their relative performance especially with focus on the higher order spectral moments and wave partitions. This study concentrates on documenting their strengths and limitations using satellite measurements, buoy spectra, and a comparison between the different models. It is confirmed that all models perform well in terms of significant wave heights; however higher-order moments have larger errors. The partition wave quantities perform well in terms of direction and frequency but the magnitude and directional spread typically have larger discrepancies. The high-frequency tail is examined through the mean square slope using satellites and buoys. From this analysis it is clear that some models behave better than the others, suggesting their parameterizations match the physical processes reasonably well. However none of the models are entirely satisfactory, pointing to poorly constrained parameterizations or missing physical processes. The major space-time differences between the models are related to the swell field which stresses the importance of describing its evolution. An example swell field confirms the wave heights can be notably different between model configurations while the directional distributions remain similar. It is clear that all models have difficulty describing the directional spread. Therefore, knowledge of the source term directional distributions is paramount to improve the wave model physics in the future.

1. Introduction

Forecasting and hindcasting marine conditions in sufficient detail have become increasingly important to society. Modeled wave datasets have greatly enhanced our knowledge of the ocean environment by supplementing in-situ and remotely sensed data. Numerical wave models have been in operation for over 50 years (Gelci et al., 1957) providing an essential part of marine weather forecasts and climatology that are used for shipping, offshore operations, the management of coastal hazards, research purposes, and recreational activities. In response to the growing need for accurate sea-state information, the wave modeling community has made significant developments in the physical parameterizations and improved the model performance (WAMDI, 1988; Komen et al., 1994; Tolman and Chalikov, 1996; Ardhuin et al., 2010; Bidlot et al., 2007; Rogers et al., 2012).

WAVEWATCH-III® (hereinafter WW3) is based on the spectral wave model that was initially developed by Tolman et al. (2002). This code has been expanded into an open source community modeling framework, with the addition of many new features and options now available in version 4.18 that was recently made public (Tolman and the WAVEWATCH III ® Development Group, 2014). The integration of advances from several groups outside NOAA has been made possible by the National Oceanographic Partnership Program, as described by Tolman et al. (2013). As the number of users and applications increases, so does the need for shared knowledge of performance by the various options in the WW3 framework. The accuracy of the source term packages listed in Table 1 and referred to as ST2, ST3, ST4, and ST6 will be assessed. Each model describes the wind generation and whitecapping dissipation differently. In deep water these are the dominant processes with the non-linear four-wave interaction. The wave–wave interaction is the same for all models and is

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http://dx.doi.org/10.1016/j.ocemod.2015.09.003
1463-5003/

Table 1
Wave model parameterizations with representative references.

Parameterization abbreviation	References
ST2	Chalikov and Belevich (1993); Tolman and Chalikov (1996); Tolman et al. (2002)
ST3	Janssen (1991); Janssen (2004); Bidlot et al., (2007); Bidlot (2012)
ST4	Ardhuin et al. (2010); Arduin et al. (2009); Leckler et al. (2013); Rascle and Ardhuin (2013)
ST6	Babanin (2006); Babanin (2011); Rogers et al., (2012); Zieger et al. (2015)

parameterized by Hasselmann et al. (1985b) with only a reduction in the strength of this interaction in ST2 (Tolman and Chalikov, 1996). For a specific discussion of shallow water processes and their improvements in WW3, see Roland and Ardhuin (2014).

The models generally produce results that compare well with measurements of the significant wave heights (e.g. Caires et al., 2004; Dee et al., 2011; Chawla et al., 2013; Stopa and Cheung, 2014a). The details and validity of the higher order spectral moments have large differences especially in ST3 and ST4 as demonstrated by Rascle and Ardhuin (2013). Therefore it is expected that the higher order moments from others will have less validity. The accurate description of the high frequency wave components dictates the momentum flux between the ocean and atmosphere, having implications in coupled climate systems (e.g. Cavaleri et al., 2012). Furthermore high frequency waves have important applications in remote sensing because the measured signal responds to sea-state through the mean squared slope.

In view of these consequences the validity of the higher order wave moments must be established and interrelated for the different parameterizations. Here we extend our efforts to document the validity of additional moments of the wave spectrum like the orbital wave velocity, average wave period, mean square slope, and Stokes drift that might be useful for some communities. Our purpose is to provide an overall assessment of the most up-to-date source terms under real conditions. In order to simplify the discussion, we focus our efforts at the global scale, with a hindcast of 2011. In-situ wave spectra from the National Data Buoy Center (NDBC) network and remotely sensed data from altimeters and synthetic aperture radar (SAR) are used to demonstrate the differences between the models and assess their validity. Each source of observations has its advantages and offers complementary perspectives to assess the models. Buoys offer high fidelity full frequency-direction spectra from which many important wave parameters can be validated; but are limited to their specific locations. Altimeters cover a large expanse of the ocean and have very accurate significant wave heights once corrected (Zieger et al., 2009). The return radar signal from altimeters gives a measure of the mean square slope creating an interesting diagnostic of the high-frequency gravity waves. Complementing the buoys and altimeters, SARs provide a global view of partitioned wave quantities. In practical engineering applications, partitioned wave components are often more intuitive and useful; therefore, we place emphasis on documenting their accuracy using both buoys and SAR observations. Since wave models have the ability to estimate an enormous amount of space-time information, we also inter-compare the models paying close attention to the swell field.

The manuscript will proceed as follows. Section 2 is dedicated to explaining the datasets with separate subsections that describe the model settings, measurements, and forcing fields. Satellite altimeters cover large spatial expanses and we make use of this ability to present a global comparison of the model performance in Section 3. To accompaniment the global view, the buoys measurements are used to validate and inter-relate different geophysical wave parameters from the models in Section 4. Section 5 follows directly from the outcomes in the previous section to highlight the spatial-temporal differences between the models. A discussion and summary of conclusions are presented in Section 6.

2. Datasets

2.1. Model details

The wave datasets are generated using WW3 version 4.18. WW3 integrates the spectral wave action equation in space and time, with discretized wave numbers and directions. Conservative wave processes like propagation, represented by the local rate of change and spatial and spectral transport terms are balanced by the non-conservative sources and sinks (simply called source terms throughout this manuscript). This study uses a global model grid of 0.5° resolution in longitude and latitude with a spectral grid composed of 24 directions and 32 frequencies exponentially spaced from 0.037 to 0.7 Hz at an increment of 10%. All model simulations are forced by the same wind fields and sea ice concentrations from CFSR (v2) of Saha et al. (2014), and iceberg distributions (Ardhuin et al., 2011).

Sub-grid islands smaller than 0.5° are accounted by apportioning the energy in the zonal and meridional directions (Tolman, 2003a,b; Chawla and Tolman, 2008). The nonlinear wave–wave interactions are modeled using the discrete interaction approximation (DIA) of Hasselmann et al. (1985b). Dissipation due to bottom friction uses the SHOWEX formulation to parameterize sandy bottoms, here with a constant sand grain size of 0.2 mm (Ardhuin et al., 2003). Depth-induced wave breaking is accounted for by using the Battjes and Janssen (1978) formulation with a Miche-style shallow water limiter for maximum energy. The Ultimate Quickest third order propagation scheme is implemented along with garden sprinkler reduction (Tolman, 2002a).

The physical formulations in WW3 that describe the wind input, wave breaking due to whitecapping, and swell dissipation are briefly summarized for each of the four models. Also it must be clarified that data assimilation was not included in any of the model simulations. Our first choice will be referred to as “ST2” and is based on the Tolman and Chalikov (1996) parameterization, as updated by Tolman (2002b). It combines a wind input adjusted to the numerical model of airflow above waves by Chalikov and Belevich (1993), and a dissipation consisting of two separate terms, one for low frequency waves and the other for the high-frequency tail of the spectrum. The high-frequency dissipation shape is adjusted to produce a roll-off of the wave spectrum proportional to f^{-5} at high frequencies, as proposed by Phillips (1958). Next we use the ECMWF WAM parameterization, “ST3”, described by Bidlot (2012). This parameterization combines the wind input term originally based on the wave growth theory of Miles (1957) with the feedback on the wind profile parameterized by Janssen (1991). There is a linear swell dissipation component that was introduced by Janssen (2004). A parametric f^{-5} shape is imposed at frequencies above 2.5 times the mean frequency.

Our third choice, “ST4”, is described by Ardhuin et al. (2010), and updated by Leckler et al. (2013). This parameterization is built around a saturation-based dissipation, closely following Banner and Morison (2010), a cumulative effect that dissipates short waves due to the breaking of long waves, and a swell dissipation that transitions from non-linear in turbulent conditions, to linear in the viscous regime (Ardhuin et al., 2009; Perignon et al., 2014). The wind input is loosely adapted from the Janssen (1991) formulation, with an important reduction of input at high frequencies necessary to achieve a balance with the whitecapping term. This modification reduced the unrealistic large drag coefficients under high winds but it removed the wave age dependence in the wind stress, which is not realistic (Rascle and Ardhuin, 2013). It should be noted that this set of parameterizations does not have any prescribed shape of the high frequency tail, which tends to decrease like $f^{-4.5}$, which is typically not steep enough for