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A wave model test bed study for wave energy resource characterization

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A B S T R A C T

This paper presents a test bed study conducted to evaluate best practices in wave modeling to characterize energy resources. The model test bed off the central Oregon Coast was selected because of the high wave energy and available measured data at the site. Two third-generation spectral wave models, SWAN and WWIII, were evaluated. A four-level nested-grid approach—from global to test bed scale—was employed. Model skills were assessed using a set of model performance metrics based on comparison of six simulated wave resource parameters and observations from a wave buoy inside the test bed. Both WWIII and SWAN performed well at the test bed site and exhibited similar modeling skills. The ST4 physics package with WWIII, which represents better physics for wave growth and dissipation, outperformed ST2 physics and improved wave power density and significant wave height predictions. However, ST4 physics tended to over-predict the wave energy period. The newly developed ST6 physics did not improve the overall model skill for predicting the six wave resource parameters. Sensitivity analysis using different wave frequencies and direction resolutions indicated the model results were not sensitive to spectral resolutions at the test bed site, likely due to the absence of complex bathymetric and geometric features.

1. Introduction

The recently published International Electrotechnical Commission Technical Specification (IEC TS) provides a standardized methodology for consistent and accurate wave resource assessment and characterization [1]. The methodology relies primarily on spectral wave model hindcasts for deriving recommended wave energy resource parameters. It also includes best modeling practices that depend on the desired class of wave resource characterization and assessment, including model selection, period of simulation, open boundary conditions, grid resolution, forcing (spatial and temporal) resolution, and model validation.

Although buoy observations can provide realistic directional wave spectra data for accurate resource assessment at a particular site, they are often constrained by spatial and temporal distributions. Existing buoy stations may not be close enough to the study site to be representative of the wave climate; or they may have an insufficient period of record to accurately characterize the wave climate statistics. Long-term measurement records are especially important for characterizing extreme sea states, as well as normal sea states when inter-period climate oscillations occur on the order of a few years or decades [2–6]. A minimum 10 years of record is often recommended for characterizing normal sea states, and 20 years for extreme sea states [1]. However, it is rare to find buoy observations that are representative of the wave climate at the study site and have periods of records greater than 10 years. Model hindcasts of the wave climate, therefore, offer an attractive alternative for characterizing wave energy resources [7–14].

Even if a wave model captures all of the key physics (e.g., wave generation, growth and dissipation, nonlinear interactions), accurate wave modeling still highly depends on model configurations such as source term selection and spectral resolutions, specification of forcing inputs, model grid resolutions, proper model calibration, and validation. When selecting models for wave resource characterization it is important to understand the key processes affecting wave dynamics near the shore where wave energy conversion

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devices are expected to be deployed. The most popular third-generation phase-averaged spectral models include the Wave Action Model (WAM) [15], Simulating WAve Nearshore (SWAN) [16], WAVEWATCH III® (WWIII) [17], TOMAWAC [18], and MIKE-21 Spectral Wave models (MIKE-21 SW) [19].

The overall goal of this study was to establish a wave model test bed to benchmark, test, and evaluate modeling methodologies and model skills for predicting the wave energy resource parameters recommended by IEC TS. The following sections review current wave modeling best practices, third-generation wave models, and evaluate model capability in predicting normal and extreme sea states, and recommend future research to improve wave modeling for resource characterization.

2. Methods

This section describes the model test bed site, the selection of wave models, and model setup, which includes data inquiries and processing, grid generation, specification of open-boundary conditions, and input configurations.

2.1. Model domain – test bed

The model test bed for wave resource characterization was selected primarily based on its meeting three criteria: 1) high wave energy resource site with potential for future wave energy converter development, 2) availability of long-term and high-quality wave measurement data, and 3) existing information from previous studies. The Oregon Coast is among the highest wave energy regions along the U.S. coasts, based on the U.S. nationwide wave resource assessment conducted by the Electric Power Research Institute [20]. Therefore, a wave modeling test bed was selected near the central Oregon Coast, approximately centered offshore from Newport, Oregon (Fig. 1). The test bed site covers an area of 44.45° – 45° N and 124.75° – 124° W (61,105 m × 59,401 m) and has annual average wave power densities that range between 35 and 50 kW/m [20]. The test bed site also includes Tier 1 wave energy converter test sites, such as the active North Energy Test Site (NETS) managed by the Pacific Marine Energy Center [10]. An operational real-time wave buoy (46050) owned and maintained by the National Oceanic and Atmospheric Administration's (NOAA's) National Data Buoy Center (NDBC) is located inside the test bed (Fig. 1). The NDBC Buoy 46050 is a 3-m discus meteorological ocean platform moored at a deep water depth of 137.2 m. The buoy station has been collecting standard meteorological data, including wind speed and direction, gust speed, air temperature, sea surface temperature since 1991, and high-quality wave spectral data since 2008.

There are some previous studies along the Oregon Coast with areas inside or overlapped with the test bed site. An initial effort was made to characterize the wave energy resource of the US Pacific Northwest by Lenee-Bluhm et al. [21] using archived spectral records from ten wave measurement buoys operated and maintained by NDBC and the Coastal Data Information Program (CDIP). García-Medina et al. [9,22] conducted a wave resource assessment along the Pacific Northwest coast using WWIII and SWAN models with a nested-grid approach. Model results from the 7-year hindcast with a 30 arc-second grid resolution were used to evaluate the temporal and spatial variability and trends of wave resource in the Pacific Northwest coast. Dallman and Neary [10] used historical data from buoy NDBC 46050 inside the test bed to present representative spectra and predict extreme sea states. Different from previous studies, the present study focuses on establishing a wave model test bed to evaluate approaches and wave models for simulating wave resource parameters recommended by IEC TS.

2.2. Wave models

A wide range of numerical models exist for simulating surface wave dynamics based on different physical assumptions and numerical frameworks. Wave models can be divided into two major categories based on different governing equations in time and frequency domains: 1) phase-resolving models and 2) phase-averaged models. Phase-resolving models are based on fundamental wave equations that involve rigorous approximations. Evolution of the sea state over time is simulated using a model grid resolution much smaller than the wavelength and fine model time step, which typically requires huge computational resources. In addition, some of the phase-resolving models, such as Boussinesq type models, are only applicable in the simulation of waves for shallow water. Therefore, phase-resolving models are impractical for hindcasts for long-term simulations (multiple years) and relatively large model domains (dimension >10 km). In contrast, phase-averaged models provide a statistical description of the wave conditions in spatial and temporal domains by solving the phase-averaged wave energy action balance equation, and they compute the distribution of wave energy in the frequency and direction domain and its evolution over time. Therefore, use of phase-averaged wave models is the most practical approach for characterizing wave resources.

Since the 1990s, third-generation wave models explicitly account for all the relevant physics for the development of ocean waves in two dimensions. WAM, WWIII SWAN, TOMWAC and MIKE-21 SM are the five most popular third-generation models that have been widely validated in many applications around the world. The present study focused on evaluation of structured-grid wave models. Among the aforementioned five third-generation wave models, TOMWAC and MIKE-21 SM are unstructured-grid models and will not be considered in the present study. WAM is very similar to WWIII and the main difference is the numerical schemes. Therefore only SWAN [16,23] and WWIII [24–26], the two most widely used third-generation, phase-averaged wave models, were evaluated in this study. Both SWAN and WWIII have been used to simulate wave climate and resource characterization around the world [9,10,13,14,20,27–32]. One of the fundamental differences between WWIII and SWAN is the numerical scheme used to solve the spectral wave action balance equation. WWIII uses explicit numerical schemes, so the model time steps are constrained by the Courant–Friedrichs–Lewy (CFL) stability criteria. SWAN uses implicit schemes, which allows much larger time steps for high computational efficiency.

WWIII was developed and is maintained by NOAA's National Centers for Environmental Prediction (NCEP) [17,25,33], as part of the marine operational forecast system. The current version of WWIII (version 4.18) consists of a collection of physics packages, including curvilinear grids, structured and unstructured-grids, effects of sea ice, and various wind-wave interaction and dissipation packages, such as the source term 2 (ST2), ST4, and ST6 physics package options [34–37]. The ST2 physics package was developed by Tolman and Chalikov [37] based on previously developed input and nonlinear interaction source terms and a new dissipation source term for low and high frequencies. The ST4 physics package consists of new parameterizations for spectral dissipation of wind-generated waves based on known properties of swell dissipation and wave breaking statistics that are consistent with observations [34]. The ST6 physics package, or the so-called BYDRZ (abbreviation for Babanin-Young-Donelan-Rogers-Zieger) source term, implements observation-based physics for wind input source term and sink terms due to negative wind input, whitecapping dissipation and wave-turbulence interactions [17,38].

In contrast to WWIII, SWAN solves the action balance equation