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Wave resource assessment in Oregon and southwest Washington, USA

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ABSTRACT

Detailed wave energy resource assessments are necessary for the planning and design of wave energy converters. The waves in the U.S. Pacific Northwest have been identified as very energetic making this coast potentially suitable for wave energy harvesting. Several efforts to harvest this resource are under way in this region, however no long term, high resolution description of the resource is presently available. Here, the results of a 7 year hindcast are presented at a 30 arc-second resolution using the numerical models WAVEWATCH III and SWAN. The hindcast accuracy was quantified by comparing to measured buoy data yielding linear correlation coefficients ~0.90 for the significant wave height. This study describes the alongshore variability of the resource over the continental shelf. The general decline of the wave power with depth is explained by considerations of wave refraction and shoaling. Further, due to wave refraction, areas off the central and southwest Oregon coast are identified that show increased wave power at 50 m of water in comparison with the 250 m value. These areas also show increased temporal variability. In addition, areas with preferentially narrower wave spectra in both frequency and direction are identified off southwest Oregon. Further, general trends in the directionality of the resource indicate a systematic switch in the wave direction with latitude. The seasonality of the resource is also assessed in terms of variability and trends relevant to the planning and deployment of wave energy converters. The continental shelf is mapped in terms of the coefficient of variability, which is greater (smaller) than unity during the summer (winter) and regardless of the season smaller in southwest Oregon.

1. Introduction

Global wave energy resource assessments have identified the Pacific Northwest (PNW) coast of North America to be potentially suitable for wave energy harvesting [1–4], and efforts are under way to take advantage of this resource. For example, in the state of Oregon, the Oregon Wave Energy Trust (OWET) has set as a goal that two coastal communities will be powered completely by marine energy by 2025. To be able to harvest wave energy, a detailed understanding of the availability of the resource is necessary. Previous studies have suggested that the wave energy resource is not constant along the PNW coast [3–5] and that bathymetric features on the continental shelf influence the inner-shelf wave patterns [6]. In addition, Lenee-Bluhm et al. [5] found significant temporal and spatial variability in the resource, based on analyzing buoy data. For example, their analysis suggests that buoys in shallower water measured smaller omnidirectional wave power, but the reasons for this decrease could not be determined. Further, some buoys located in shallower waters measured more directionally uniform spectra; however it could not be confirmed if this holds true all along the coast or if there are specific areas that favored directionally narrow spectra. In order to remedy these shortcomings, a data set that covers the PNW coast at high resolution is needed so that effects related to latitude and depth can be isolated and a detailed local understanding of the wave resource can be achieved.

The present study seeks to further expand our knowledge of the Oregon and southwest Washington wave energy resource, complementing the analysis by Lenee-Bluhm et al. [5], by performing a high resolution multi-year wave hindcast using numerical wave models that provide information at all relevant latitudes and water depths on the continental shelf. This technique has been recently applied at global [1,7] and at other regional/country scales [8–12] supporting assessments based on measured data. A high resolution multi-year hindcast aids in the determination of cross and along shelf varying patterns in the wave energy resource.

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This paper describes the set-up and results from a 7-year wave hindcast for the PNW continental shelf using the wave propagation model SWAN with offshore conditions provided by several nested WAVEWATCH III model simulations. The numerical models and their implementation are described in Section 2. The hindcast accuracy is quantified using available buoy observations in Section 3. The wave energy resource is described in Section 4. We start by discussing the alongshore varying and depth dependent characteristics of the resource. Zones of energy focusing and divergence are identified along with large scale patterns. Then we describe the seasonal trends of the resource and map the shelf in terms of relative seasonal variability. Finally, we discuss how the nearshore (i.e. water depths less than 50 m) patterns in the resource differ from those at the shelf level. Concluding remarks follow in Section 5.

2. Methodology

The characterization of the wave energy resource is achieved by performing a 7-year wave hindcast using numerical models. We focus on the region with water depths between 250 and 50 m, which we will refer to as the continental shelf. Two numerical wave models were used in tandem to generate data for the assessment, WAVEWATCH III® v3.14 [13] (hereafter WW3) and the Simulating WAves Nearshore (SWAN) v40.81 [14,15]. WW3 is an accurate and efficient model for predicting wave generation, propagation and dissipation at oceanic scales. It has been proven skillful for hindcasting ocean waves in the PNW [6,16]. In the shallower water depths of the continental shelf and in the nearshore ocean, SWAN has been successfully implemented in previous studies on the PNW coast [17,18]. Thus, WW3 and SWAN are implemented at the oceanic and shelf scales, respectively.

2.1. Numerical wave models

WW3 and SWAN are third-generation phase-averaged wave models that solve the spectral wave action balance equation:

$$\frac{\partial N}{\partial t}+\frac{\partial (c_{gx}+U_x)N}{\partial x}+\frac{\partial (c_{gy}+U_y)N}{\partial y}+\frac{\partial c_\theta N}{\partial \theta}+\frac{\partial c_\sigma N}{\partial \sigma} = \frac{1}{\sigma}\left(S_{in}+S_{ds}+S_{nl}+S_{bf}+S_{brk}\right) \tag{1}$$

where $N(t,x,y,\sigma,\theta) \equiv E/\sigma$ is the wave action, E is wave energy, t is time, x and y are the position in the 2D plane, θ is the direction of wave propagation, and σ is the radian frequency. $\mathbf{U} = (U_x,U_y)$ represents the depth- and time-averaged current velocity vector and $\mathbf{k} = (k_x,k_y)$ is the wave number vector which points in the direction of wave propagation. $c_{gx},c_{gy},c_\theta,c_\omega$ represent the velocity of energy propagation.

The right hand side of Equation (1) represents energy sinks and sources. In the WW3 implementation, energy input by wind (S_{in}) and whitecapping (S_{ds}) are parameterized with the Tolman and Chalikov [19] source term package. The non-linear quadruplet wave interactions (S_{nl}) are modeled with the discrete interaction approximation by Hasselmann et al. [20]. García-Medina et al. [6] showed that wind input and bottom friction (S_{bf}) have little effect on numerically modeled bulk wave parameters at the shelf scale in the PNW; thus, S_{bf} is not considered. Because the SWAN simulation will cover a small region very close to shore (see next section on information about the domains), we also neglect S_{in}, S_{ds}, and S_{nl} in SWAN. Finally, S_{brk} is the energy dissipation due to wave breaking. It is modeled with the Battjes and Janssen [21] approach, the default breaking ($\Gamma = 0.73$) and intensity ($\alpha = 1$) coefficients were used in both models. For a more detailed discussion of the action balance equation the reader is referred to Booij et al. [14] and references therein.

WW3 solves Equation (1) explicitly with a third-order propagation scheme [22]. While providing an accurate representation of wave generation processes important at oceanic scales, this can be computationally expensive for high spatial resolution. If the continental shelf is narrow, as it is in the PNW, the outer shelf conditions propagate with very little lag to the inner shelf and stationary conditions may be assumed ($\partial N/\partial t = 0$). SWAN has the capability of solving Equation (1) in stationary mode using an implicit numerical scheme [23]. This results in a more efficient computation with minimal errors in the context of this study.

2.2. Model implementation

To perform the numerical simulations four grids were implemented. The first two levels are based on NOAA's National Centers for Environmental Prediction's (NCEP) Global and Eastern North Pacific Ocean grids and are part of our model (see Fig. 1). These have a resolution of 1° by 1.25° and 0.25° by 0.25°, respectively. As a third level of nesting, shown in Fig. 1, a regional grid with a three arc-minute resolution was implemented to provide a transition from the basin scale to the shelf. It covers a region from 41.45°N to 47.50°N and from 127°W to 123.75°W. This resolution is still too coarse for an accurate representation of the bathymetric features at the shelf scale. Thus a fourth level was implemented at a 30 arc-second resolution. It covers a region from 41.50°N to 47.35°N(~650 km) and from 125.25°W to 123.75°W. To generate the grids for the last two levels, data from ETOPO1 [24] and NGDC Gridded Tsunami Bathymetry [25–30] were combined.

The first three levels make up a mosaic that is executed in WW3. It is forced with hindcasted 10 m wind fields from the Global Forecasting System (GFS) [31,32]. During the hindcasts wave spectra are stored hourly at a 6 arc-minute resolution bordering the 30 arc-second grid. A 2D stationary model simulation is then performed using SWAN over the shelf grid. The wave spectrum (D) was discretized with 25 logarithmically spaced bins from 0.04118 to 0.5 Hz in both models. In WW3 24 bins are used in direction space while in SWAN 72 are used to better simulate the process of refraction. To characterize the wave energy resource, wave spectra are stored every hour at the 50, 100, 150, and 250 m contours, approximately every 5 km alongshore.

2.3. Metrics

Lenee-Bluhm et al. [5], proposed the use of a common set of metrics to characterize wave energy resources. These are: omnidirectional wave power (OWP), significant wave height (H_s), mean energy period (T_e), spectral width (ν), direction of maximum directionally resolved wave power (ϕ), and directionality coefficient (DCO).

The OWP of a sea state is defined as:

$$\mathrm{OWP} = \sum_{i,j} \rho g c_{g,i} D_{ij} \Delta f_i \Delta\theta_j, \tag{2}$$

where ρ is the fluid density, g is the gravitational constant, c_g is the group velocity, D is the frequency-direction wave spectrum, f is the wave frequency, and θ is the wave incidence angle. The OWP represents the non-directional wave power; it is a metric that quantifies the total sea state. Another such metric is the H_s, by definition it is the average of the 1/3 highest waves. Under the assumption that waves are Rayleigh distributed, it may be estimated from spectral data as: