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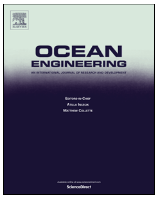

Simulating and forecasting ocean wave energy in western Canada

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ABSTRACT

While the technology now exists to harvest wave energy in coastal regions, the capital expenditures for wave farms can be substantial, so it is important to be able to simulate the power in advance. Further, to integrate wave energy into the grid, utilities need to forecast over short horizons and calculate reserve requirements. Wave farms are simulated at three locations in British Columbia, Canada. Power series are calculated for six types of wave energy converters (WECs), four that operate in deep water, and two in shallow water. Forecasts are run using a physics-based model and statistical models. Five major conclusions emerge from the analysis. First, given the intermittency of buoy data, physics model hindcasts are an effective method of interpolating missing values. Second, the power output from converters does not have the same properties as the wave energy flux. Instead, the power output is a nonlinear function of the wave height and period, with fewer large outliers. Third, time series models predict well over near-term horizons while physics models forecast more accurately over longer horizons. The convergence point, at which the two types of models achieve comparable degrees of accuracy, is in the area of 2–3 h in these data sets, lower than in most prior studies. The recommendation is to use time series methods to forecast at the horizons required for reserves, and physics models for long-term planning. Fourth, the predictability of the power output can differ substantially for individual converters. Finally, wave energy is found to be significantly less costly in terms of reserves than wind and solar.

1. Introduction

While the technology exists to harvest wave energy, there are still several economic and technical barriers to widespread development of wave farms (Esteban and Leary, 2011; Arinaga and Cheung, 2012). The first and most obvious is identifying locations. British Columbia, on the Pacific coast of Canada, is favorably situated. Off the coast of Vancouver Island, the near-shore wave energy flux averages about 30 kW per meter of crest length (kW/m). Further from shore, the mean wave energy increases to 40 kW/m, and at the edge of the continental shelf, it is closer to 50 kW/m (Robertson et al., 2014).

A second issue is that capital expenditures can be substantial, so it is useful to be able to simulate the power output in advance. While some prior studies have used the standardized wave energy transport flux to estimate the power potential, matrices for various types of wave energy converters (WECs) have recently become available. This makes it possible to estimate the power output for particular devices. Simulated power series are calculated for six types of converters, four that operate in deep water, and two in shallow water.

A third issue is the intermittency of wave buoy data. In addition to missing hours or days, buoy records are often incomplete for weeks or months, due to equipment failure or other service issues. The proposed solution is to interpolate using retrospective simulations of a well-known physics-based wave model, SWAN (Simulating WAves Near shore).

A fourth issue is that the data at individual buoy sites is often volatile, with a great deal of random variation due to local sea conditions. Since wave farms are dispersed over wider areas, the noise should average out, making the power smoother and more predictable. Brekken et al. (2012) propose simulating wave parameters over large areas using the wave spectrum. The approach used here is to take weighted averages of nearby buoys. In this respect, the Vancouver data offers one crucial advantage: the buoys are close enough to create realistic simulations.

A final issue is forecasting. Short-term forecasting is used for operational planning, reserve usage, switching sources, and peak

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load matching. The relevant horizons can range from a few minutes to several hours. In forecasting wave energy, the analyst has a choice of two approaches, physics-based models or time series methods. Prior studies have found statistical models to be more accurate at short horizons, while physics models predict more accurately beyond the first few hours (Reikard et al., 2011). It is also possible to combine the two methods, for instance by ensemble averaging or using statistical models to correct the bias (Woodcock and Engel, 2005; Woodcock and Greenslade, 2006; Durrant et al., 2008; Pinson et al., 2012).

This study addresses all five issues. Buoy time series and physics model hindcasts are used to create data for the wave height and period, while WEC matrices are used to calculate power series. Section 2 sets out the databases. Physics model simulations are set out in Section 3. Section 4 deals with alternate measures of power and wave energy converters. The wave farm simulations are presented in Section 5. Section 6 compares the forecasting performance of time series and physics models. In Section 7, the cost of integrating wave energy into the grid is quantified using reserve calculations. Section 8 concludes.

2. The data

The databases were compiled as part of a broader research project by the Institute for Integrated Energy Systems at the University of Victoria. Table 1 reports the depth, time span, latitude and longitude for each of the buoys, along with the number of missing observations. Al the data sets include the significant wave height (H_{St}), in meters, and the mean wave period (T_{Mt}), in seconds, at an hourly resolution or better. Fig. 1 provides a map of the locations, and the bathymetry of the Vancouver coastline.

The Amphitrite Bank and Estevan Point buoys are located along the coast, at depths of 42–43 m, at a distance of 89 km from each other. The overlapping period for the two data sets is April 19, 2013 through January 27, 2014. The Amphitrite time series are more complete; the Estevan record is sparser. Further out on the continental shelf, there are two buoys at La Perouse bank, about 2 km from each other, at a depth of 74 m. The Environment Canada (EC) buoy provides a longer history, beginning November 23, 1988, and running through the present day. The second buoy, operated by the Coastal Data Information Program (CDIP), contains observations from April 30, 2012 through April 28, 2013. The data is at a 30 min resolution, but to make it compatible with the EC data, it was consolidated to 1 h. While the CDIP data set is much shorter, it is more complete for the overlapping period. The Florencia Bay site is at a depth of 25 m. The data consist of irregular observations, sometimes several records within the hour, while in other hours the values are missing completely. The database contains usable observations only for June 1, 2013 to January 27, 2014.

3. The Physics model simulations

Large-scale physics-based wave models have been in operation since the 1960s, and undergo continuous revision to improve performance (Hasselmann et al., 1976, 1980, 1985; Janssen, 1991, 2007). SWAN is a third generation phase-averaged Eulerian numerical wave model, designed to simulate the propagation of waves in shallow near-shore areas (Booij et al., 1999; Holthuijsen, 2007).

The wave action density (N) evolves as a function of time (t), distance in the Cartesian coordinates (x,y), the shifting of relative frequency due to variation in depths and currents (σ), and depth and current induced refraction (θ). Let C_g denote the wave action propagation speed in (x, y, σ, θ) space. Let S denote the combined source and sink terms. In deep water, the three major components of S are the input by wind (S_{IN}), nonlinear wave–wave interactions (S_{NL}) and wave dissipation through white-capping (S_{WC}). In shallow water, S includes the effects of bottom friction (S_{BF}) and shoaling-induced breaking (S_{BR}). The action balance equation can be expressed in the following form:

$$\partial N/\partial t+\partial C_{g,x}N/\partial x+\partial C_{g,y}N/\partial y+\partial C_{g,\sigma}N/\partial \sigma+\partial C_{g,\theta}N/\partial \theta=S/\sigma;$$

$$S=[(S_{IN})+(S_{NL})+(S_{WC})+(S_{BF})+(S_{BR})] \tag{1}$$

To develop the SWAN model simulations, a choice of ocean scale wind and wave inputs, and numerical wind wave growth/white capping solvers is required. The preferred boundary conditions for the SWAN model are directional wave buoy measurements. Unfortunately, appropriate directional measurements were not available for Vancouver Island. The best alternative is to use results from ocean-scale wind–wave models such as WAVEWATCH III (WW3). This study utilized publically available wave results from the Fleet Numerical Meteorology and Oceanography Center (FNMOC) ocean-scale operational WW3 model (Wittmann, 2001), and transient wind fields from the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) wind model. An unstructured grid was used to provide both greater computational efficiency and improved resolution of nonlinear wave effects in shallower water. Within the area covered by the simulation, the depth ranges from approximately 1000 m at the continental shelf to 12 m just beyond the surf zone. In the deeper water, large grid spacing is sufficient, while in shallow water closer to shore the grid spacing must be much smaller, to capture the small scale wave transformations that occur due to interaction with the ocean floor. Grid spacing was specified proportional to water depth with a lower limit on spacing of 75 m. The proportionality constant was determined though a convergence analysis using the significant wave height (H_{St}) as a metric for convergence. The final SWAN model setup included Westhuysen's wind-growth/white capping formulation and SWAN frictional effects. For further documentation on optional set points, see SWAN (2006).

Table 1
The Vancouver buoy data.

Location	Depth (m)	Starting Date	Data End Date	Resolution	Latitude (N)	Longitude (W)	Missing values
Amphitrite Bank	43	4/19/2013	1/27/2014	Hourly	48.88	125.62	757
Estevan Point	42	4/23/2013	1/27/2014	Hourly	49.35	126.61	1682
Florencia Bay	25	5/31/2013	1/27/2014	Hourly	48.96	125.62	–
La Perouse Bank, Environment Canada buoy	74	11/23/1988	1/22/2014	Hourly	48.83	125.98	1421
La Perouse Bank, Coastal Data Information Program buoy	74	4/30/2012	4/28/2013	30 min	48.84	126.01	74

At all buoy sites, the data consist of the significant wave height and mean wave period.
At Florencia Bay, the observations are spaced irregularly for several months, with multiple values within an hour. The data is reasonably complete for the period from June 1 2013 through January 27, 2014. No data is available prior to May 31.