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INITIAL CHARACTERIZATION OF THE WAVE RESOURCE AT SEVERAL HIGH ENERGY U.S. SITES

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ABSTRACT

Wave energy resource characterization efforts are critical for developing knowledge of the physical conditions experienced by wave energy converter (WEC) devices and arrays. Developers are lacking a consistent characterization of possible wave energy test sites, and therefore Sandia National Laboratories (SNL) has been tasked with developing a catalogue characterizing three high energy U.S. test sites. The initial results and framework for the catalogue are discussed in this paper.

INTRODUCTION

Sea states experienced by WECs impact power production, device reliability, survivability, and the cost of energy. In addition, the industry is lacking a single information source with a well-documented and consistent approach that defines wave energy characteristics at U.S. test sites. For this reason, the U.S. Department of Energy's (DOE) marine and hydrokinetic energy (MHK) Program is supporting the development of a catalogue of wave characteristics at WEC test sites and potential deployment locations. This catalogue will allow WEC developers to compare and select test sites with characteristics that are most suitable for their device and will best meet their testing needs and objectives. The Program also recognizes the value of this initial data set and framework to support a wave classification system, much like the wind classification system, which has become a standard for wind turbine design.

Three high energy wave sites will be included in the catalogue: (1) Humboldt Bay (Eureka, CA), (2) Kaneohe Bay Naval Wave Energy Test Site (WETS) offshore of Oahu, HI, and (3) the Pacific Marine Energy Center (PMEC) site offshore of Newport, Oregon.

Past efforts on wave energy characterization have been reviewed. Although additional variables of interest are still under consideration, we are adopting recommendations from the (draft) International Electrotechnical Commission (IEC) Technical Specification on Wave Energy Characterization. An overview of the Technical Specification (TS) project can be found in Folley et al. [1]. The TS and recent papers regarding the U.S. Pacific Northwest coast [2,3] recommend presenting a number of variables which should be calculated at the test site using simulated hindcast spectral data. Hindcast simulations have been performed at PMEC and WETS by researchers at the Northwest National Marine Renewable Energy Center (NNMREC) and Hawaii National Marine Renewable Energy Center (HINMREC), respectively [3,4]. A hindcast simulation will be completed for Humboldt Bay by SNL, which will be reported on in a future publication.

CHARACTERIZATION FRAMEWORK

Wave energy resources are analyzed and presented in various ways throughout the literature. For example, efforts have included analyses of measured buoy data and/or hindcast simulation data; some consider full directional spectra while some only consider bulk parameters; extreme event analyses are often neglected or considered in separate studies. This ambiguity and difficulty in comparing assessments are some of the reasons that the IEC began the process of creating a technical specification [1]. The IEC Technical Specification on Wave Energy Characterization is nearly completed, with a draft version currently released. The TS provides guidelines for a "design" resource assessment, which is the most detailed stage and is appropriate for particular test sites compared to broader assessments suitable for large regional areas.

For a detailed resource assessment at a particular site of interest, the energy characterization should be based on the analysis of directional wave spectra produced from a simulated hindcast. Measured data (e.g., from buoys) can be useful for boundary conditions, and independent measured data should be used to validate the hindcast model.

The six parameters suggested by Lenee-Bluhm et al. [2] and specified in the TS for characterizing a sea state are: omnidirectional wave power, significant wave height, energy period, spectral width, direction of maximum directionally resolved wave power, and directionality coefficient. These are defined below and can be found in Lenee-Bluhm et al. [2] and García-Medina et al. [3].

The omnidirectional wave power, J, which indicates the resource available, is the sum of the contributions to energy flux from each of the components of the wave spectrum,

$$J = \sum_{i} \rho g c_{g,i} S_i \Delta f_i \tag{1}$$

where ρ is the density of sea water, g is the acceleration due to gravity, $c_{g,i}$ is the group velocity, S_i is the variance density, and Δf_i is the frequency bin width at each discrete frequency index i. Significant wave height, H_{m0}, estimated from spectra, is commonly used to describe the sea state and is defined as

$$H_{m0} = 4\sqrt{m_0} \tag{2}$$

where m_0 is the zeroth moment of the variance spectrum. The moments of the variance spectrum are

$$m_n = \sum_{i} f_i^n S_i \Delta f_i. \tag{3}$$

The energy period, T_e, is also widely used to describe the sea state and is more robust than the peak period (due to a high sensitivity to spectral shape). The energy period is calculated as

$$T_e = \frac{m_{-1}}{m_0}. \tag{4}$$

The spectral width,

$$\epsilon_0 = \sqrt{\frac{m_0 m_{-2}}{{m_{-1}}^2} - 1}, \tag{5}$$

characterizes the spreading of energy along the wave spectrum. The directionally resolved wave power is the sum of the wave power at each direction θ

$$J_\theta = \sum_{i,j} J_{ij} \Delta f_i \, \Delta\theta_j cos(\theta - \theta_j)\delta \qquad \begin{cases} \delta = 1, & cos(\theta - \theta_j) \geq 0 \\ \delta = 0, & cos(\theta - \theta_j) < 0 \end{cases} \tag{6}$$

where J_θ is the directionally resolved wave power in direction θ. The maximum time averaged wave power propagating in a single direction, J_{θ_J}, is the maximum value of J_θ. The corresponding direction, θ_J, is the direction of maximum directionally resolved wave power and describes the characteristic direction of the sea state. The directionality coefficient, d_θ, is the ratio of maximum directionally resolved wave power to the omnidirectional wave power,

$$d_\theta = \frac{J_{\theta_J}}{J}, \tag{7}$$

which is a characteristic measure of directional spreading of wave power (i.e., larger values approaching unity signify narrow directional spread). It is also recommended that annual and seasonal values be reported.

Cumulative probability distributions should be presented, which can be useful for estimating weather windows specific to requirements for installation or operation and maintenance. It will also be necessary to provide additional information about extreme events. Estimates of extreme events reported in the literature are also widely varying in terms of methodology. We will pursue the Inverse FORM technique [5] which is prescribed in the Det Norske Veritas (DNV) standard on position mooring [6]. This includes a "set of combinations of significant wave height and peak period along the 100-year contour." This will provide developers not only with estimates of the largest wave, but also extreme conditions of peak periods that could affect a device or service vessels.

PRELIMINARY RESULTS

Although hindcast simulation data will ultimately be used, an example of results from measured buoy data is presented here. This is a similar analysis to the work by Lenee-Bluhm et al [2], who analyzed data from many buoy records along the coast of Washington, Oregon, and northern California. However, this paper presents an alternate way to present weather windows and will include an estimation of extreme events.

NDBC 46212, west of the Humboldt Bay entrance, measures directional spectral data and is in 40m of water depth which is representative of a WEC deployment area. Gaps invariably occur in measured data sets, however, the data recovery of this particular buoy was generally high. January, with 83%, is the only month with less than 90% data availability. This is largely due to the fact that spectral data at NDBC46212 began on January 22, 2004.

The significant wave height and energy period measured from buoy NDBC 46212 over the period 2004-2012 are shown in the JPDs below. Figure 1A shows the percentage occurrence of each binned sea state and Figure 1B shows the percentage contribution to annual power (omnidirectional wave power), which is 30.2 kW/m. As with other sites reported in the literature (e.g., Cahill and Lewis [7]), the H_{m0}, T_e pairings with the highest frequencies of occurrence do not necessarily correspond to those with the greatest contribution to energy, but are important for understanding the risk of failure (e.g., fatigue, wear). Developers can use these JPD plots to tune their devices for the sea states that will contribute the most energy, rather than just the sea states of highest occurrence [2,7]. Note that occurrences or contributions to annual power of less than 0.01% are not shown in the figure for clarity. For example, sea states with $0.5m \leq H_{m0} < 1m$ and $4s \leq T_e < 5s$ occurred 0.02% of the time, however contribution to annual power was only 0.001% and therefore does not appear in Figure 1B. Similarly, sea states with $7.5m \leq H_{m0} < 8m$ and $11s \leq T_e < 12s$ only occurred 0.00001% of the time, but contributed 0.02% to annual power.

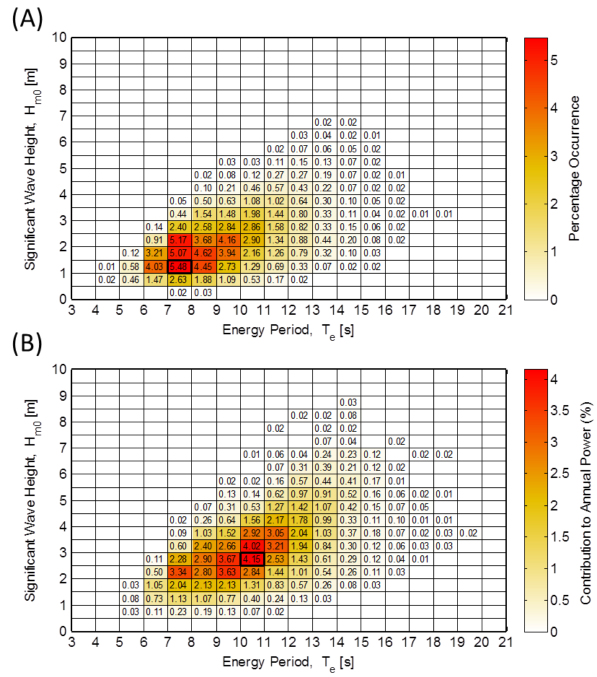

FIGURE 1. (A) PERCENTAGE OCCURRENCE OF SEA STATES AT NDBC 46212 FROM 2004-2012. (B) PERCENTAGE CONTRIBUTION TO ANNUAL ENERGY. THE OMNIDIRECTIONAL WAVE POWER CALCULATED FROM THE BUOY DATA IS 30.2 KW/M.

Figure 2 shows average and seasonal values of the six prescribed variables, with error bars signifying one standard deviation. Summer is the period June through August and winter the period December through February. The mean values of omnidirectional wave power, significant wave height, and energy period are larger during the winter. In addition, the winter has a mean spectral width that is slightly narrower with a slightly larger mean directionality coefficient (less directional spreading) than summer. The direction of maximum directionally resolved wave power (defined as the direction from which waves arrive in degrees clockwise from north) is very consistent throughout the year, coming from the north/northwest. Figure 3 shows the average monthly values for a more detailed display of the annual variation.

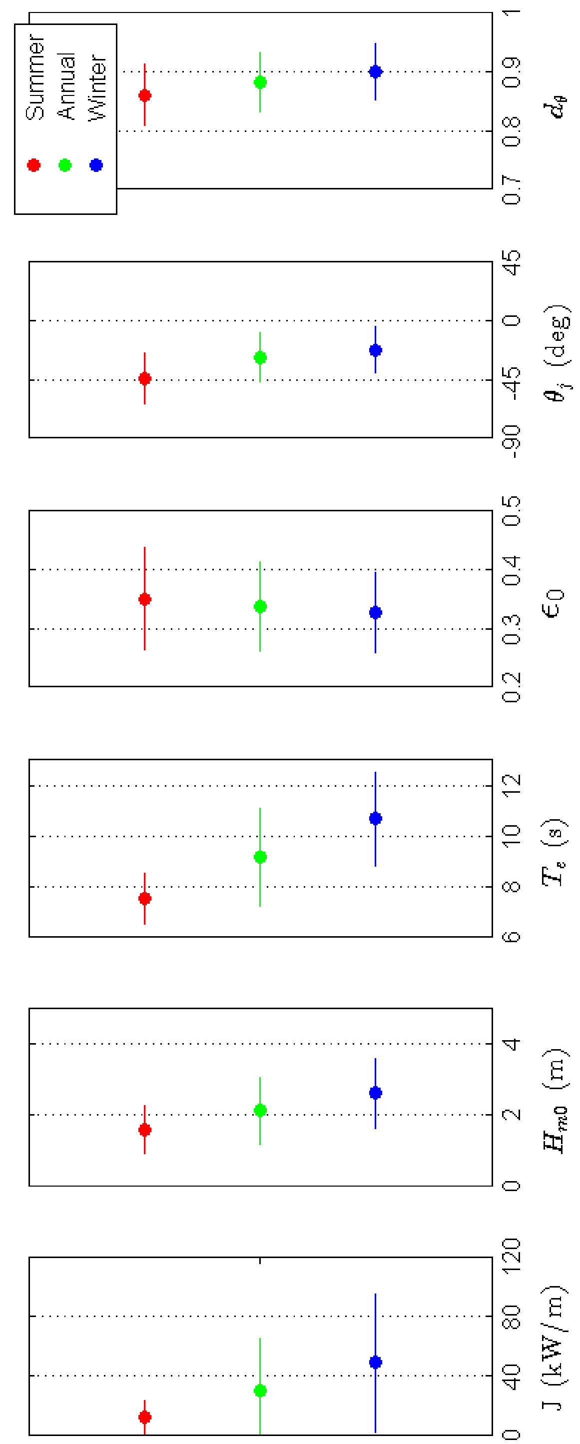

FIGURE 2. ANNUAL, SUMMER, AND WINTER AVERAGES OF THE VARIABLES SPECIFIED BY THE IEC TS AT NDBC 46212 FROM 2004-2012. ERRORBARS INDICATE ONE STANDARD DEVIATION.

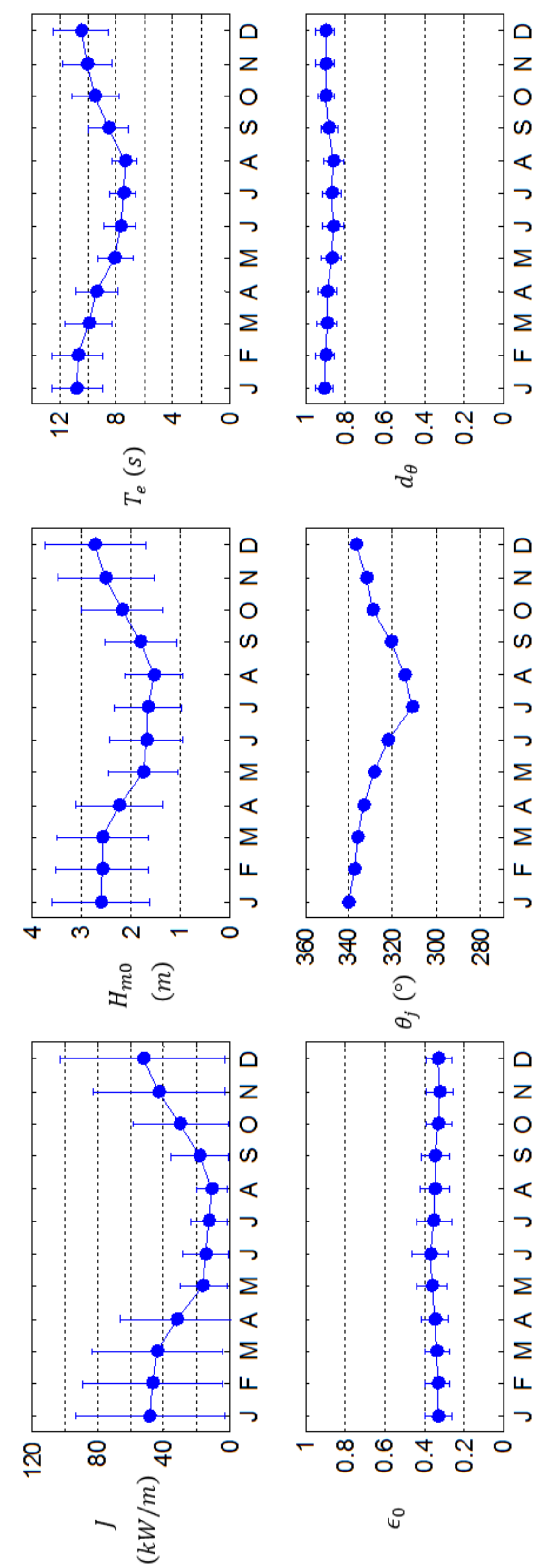

FIGURE 3. MONTHLY AVERAGES OF THE VARIABLES SPECIFIED BY THE IEC TS AT NDBC 46212 FROM 2004-2012. ERRORBARS INDICATE ONE STANDARD DEVIATION.

Figure 4 shows the cumulative probability distributions of significant wave height and energy period. A developer could use cumulative probability distributions to estimate how often they can access the site to install or perform operations and maintenance based on their specific device, service vessels, and diving operation constraints. For example, if significant wave heights need to be less than or equal to 1m for installation and recovery, according to Figure 4, this condition occurs about 13% of the year. If significant wave heights need to be less than or equal to 2m for emergency maintenance, according to Figure 4, this condition occurs about 55% of the year.

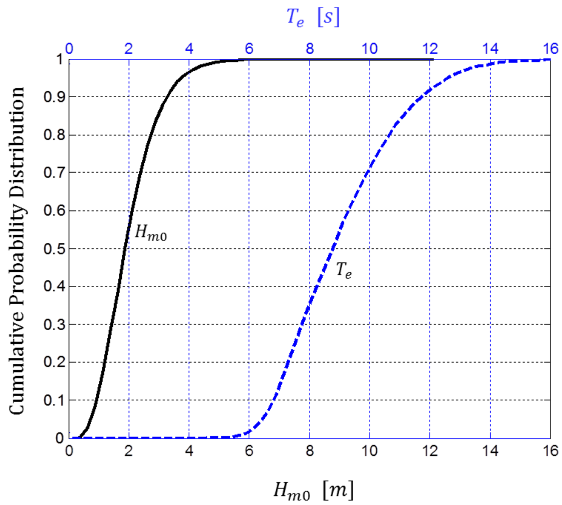

FIGURE 4. CUMULATIVE PROBABILITY DISTRIBUTIONS FOR SIGNIFICANT WAVE HEIGHT AND ENERGY PERIOD AT NDBC 46212 FROM 2004-2012.

Cumulative probability distributions, however, do not account for the duration. Deployment and maintenance activities will require wave thresholds for a certain period of time. The average cumulative number of occurrences per season for each wave height threshold is shown in Figure 5, similarly to the plots presented by Lenee-Bluhm [8] and O'Connor et al. [9]. We have defined winter as December – February, spring as March – May, summer as June – August, and fall as September – November. Note that, because the table is cumulative, an occurrence of $H_{m0} \leq 1m$ for at least 36 consecutive hours in the fall is included in the count for 30 consecutive hours as well. It is clear that there are significantly more occurrences of lower wave heights during the summer than winter, which corresponds to increased opportunities for deployment or operations and maintenance. For example, if significant wave heights need to be less than or equal to 1m for at least 12 consecutive hours, this occurs 28 times in the average summer and not at all in the average winter.

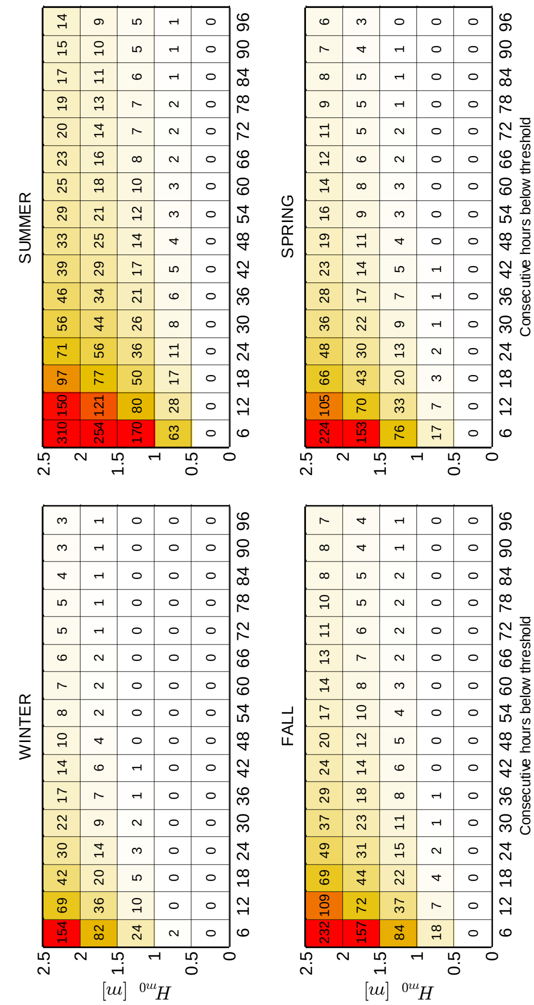

FIGURE 5. AVERAGE CUMULATIVE OCCURRENCES OF WAVE HEIGHT THRESHOLDS FOR EACH SEASON AT NDBC 46212.

Often estimates of extreme events reported in the literature consist only of a wave height and the period is not considered. We will use the Inverse FORM technique which is described in detail in Winterstein et al., Berg, and Baarholm et al. [5,10,11] to find a 100-year contour line consisting of a set of combinations of significant wave height and period. This requires the joint probability distribution of wave height and period, and the general methodology, which is described in Berg [10], consists of four steps. First, the marginal distribution of H_{m0} is calculated and a three parameter Wiebull distribution is fit. Second, the marginal distribution of T_e, conditioned on H_{m0}, is calculated and a parameterized lognormal distribution is fit. Third, the 100-year contour line is determined by transforming the standard normal variables into H_{m0} and T_e. Finally, the contour line is "inflated" to compensate for approximations in the technique.

Figure 6 shows the scatter plot of measured T_e conditioned on H_{m0} at NDBC 46212, along with the 100-year contour. The "inflated" contour (by 20%) is also shown, which is prescribed to account for the approximations in the technique. Selected sea states (signified by open circles) along the contour are listed in Table 1. As previously mentioned, although an estimate of the largest wave height is important, developers should also consider other extreme events that could severely affect their device. For example, the frequencies of specific wave periods could match natural frequencies of the device or subsystems to cause failure.

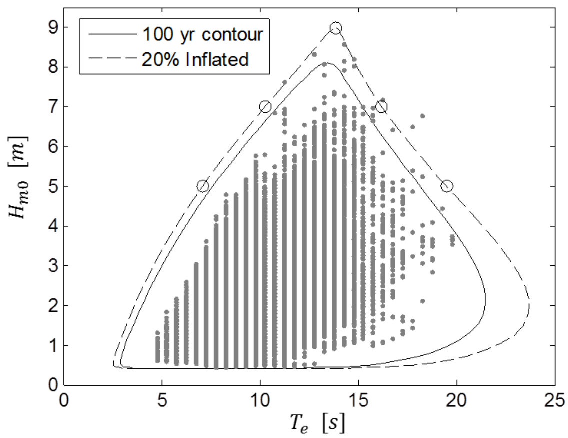

FIGURE 6. 100-YEAR CONTOUR (WITH SELECTED SEA STATES REPRESENTED BY OPEN CIRCLES) AT NDBC 46212 FROM 2004-2012.

TABLE 1. SEA STATES ALONG THE INFLATED 100-YEAR CONTOUR FOR NDBC 46212.

Significant wave height H_{m0} [m]	Energy period T_e [s]
5.0	7.1
7.0	10.3
9.0	13.8
7.0	16.2
5.0	19.5

CONCLUSIONS

For the wave resource catalogue at the selected U.S. test sites, we will follow the general guidelines in the IEC TS, and will also provide additional information about weather windows and extreme events. This paper provides examples of some of the information on wave characterization that will be presented in the catalogue, although the final version will use simulated hindcast data at the specific test site locations.

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