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Characterizing the wave energy resource of the US Pacific Northwest

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ABSTRACT

The substantial wave energy resource of the US Pacific Northwest (i.e. off the coasts of Washington, Oregon and N. California) is assessed and characterized. Archived spectral records from ten wave measurement buoys operated and maintained by the National Data Buoy Center and the Coastal Data Information Program form the basis of this investigation. Because an ocean wave energy converter must reliably convert the energetic resource and survive operational risks, a comprehensive characterization of the expected range of sea states is essential. Six quantities were calculated to characterize each hourly sea state: omnidirectional wave power, significant wave height, energy period, spectral width, direction of the maximum directionally resolved wave power and directionality coefficient. The temporal variability of these characteristic quantities is depicted at different scales and is seen to be considerable. The mean wave power during the winter months was found to be up to 7 times that of the summer mean. Winter energy flux also tends to have a longer energy period, a narrower spectral width, and a reduced directional spread, when compared to summer months. Locations closer to shore, where the mean water depth is less than 50 m, tended to exhibit lower omnidirectional wave power, but were more uniform directionally. Cumulative distributions of both occurrence and contribution to total energy are presented, over each of the six quantities characterizing the resource. It is clear that the sea states occurring most often are not necessarily those that contribute most to the total incident wave energy. The sea states with the greatest contribution to energy have significant wave heights between 2 and 5 m and energy periods between 8 and 12 s. Sea states with the greatest significant wave heights (e.g.>7 m) contribute little to the annual energy, but are critically important when considering reliability and survivability of ocean wave energy converters.

1. Introduction

Nearly everything on earth begins with the sun, and ocean waves are no exception. The sun heats the earth unevenly, giving rise to the wind. As the wind blows across vast stretches of sea, ocean waves are generated. The origins of fossil fuels also lie with the sun. However, their availability is the result of millions of years of accumulation and their use constitutes a significant contribution to global climate change. While relatively inexpensive and energy dense fossil fuels account for the majority of the global energy supply today, it is clear that carbon-free, renewable sources must supplant much, if not all, of this. Wind and solar energy conversion technologies have matured over recent decades, and are being installed around the world at an accelerating rate. While ocean wave energy conversion is still unproven on a commercial scale, significant advances in research, design and testing continue to be made. Success will mean access to a resource whose rate of renewal has been estimated to be on the order of 1–10 TW (1 TW $= 10^{12}$ W) [1]. Although at most between 10 and 25% of this can likely be converted to electricity [2], this represents a substantial portion of the present global electricity consumption of approximately 2 TW [3].

If we are to harvest energy from ocean waves, we must first understand the resource. While the energy flux of winds or tides involves the gross transport of the medium, the energy flux of ocean waves (to first order) propagates through the oscillation of the medium. In deep water this energy can travel great distances nearly undiminished, and at any given time and place there may be waves generated from local winds as well as swell arriving from distant storms. The complexity of a sea state lends itself to being approached as a random process, and under the assumptions of linearity, stationarity and ergodicity the surface of the sea can be accurately described as the superposition of a large number of long-crested harmonic waves, densely distributed over frequency and

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direction [4]. While initial stages of ocean wave energy conversion development tend to assume unidirectional, monochromatic waves, the conditions in which the system must eventually operate are random, irregular and directionally spread.

To effectively design a robust and survivable ocean wave energy converter (OWEC), the waves should be seen simultaneously as a resource and a risk; it is imperative that the expected range of conditions be considered when designing and siting OWECs. It is within this harsh, stochastic environment that an OWEC must not only operate efficiently, but also survive. The wave energy resource is highly variable on a scale of months, days or hours; yearly averages tend to oversimplify this reality. Additionally, an OWEC's performance may be sensitive to a number of quantities characterizing the energy flux, such as wave height or direction. As for the risks, they are both long-term (e.g. fatigue and wear) and acute (e.g. catastrophic failure during an extreme sea state). Also, seasonal trends in wave conditions may limit the times in which OWECs can be accessed or retrieved for maintenance or repairs. To succeed, an OWEC should operate reliably between available maintenance windows, survive infrequent but extreme storm events, and harvest energy over a broad range of sea states sufficient to recover expenses.

Wave energy resource assessments have been carried out for various regions of interest including Europe [5], the UK [6], Portugal [7,8], Sweden [9], Belgium [10], Spain [11,12], Australia [13], Canada [14] and a recently published global assessment [15]. In the US, wave energy assessments include those of California [16–18], Oregon [19], Washington [20] and the Atlantic coast of the south-eastern US [21]. The problem of resource assessment and characterization has been approached in a variety of ways. The resource is typically assessed using wave propagation models [22,23], satellite altimetry or *in situ* measurements [24]. At a minimum, the resource has been characterized by the energy flux per unit crest length, or wave power, but additional information may be calculated and reported regarding wave heights, periods and direction.

This study seeks to add to our understanding of the wave energy resource of US Pacific Northwest (Washington, Oregon and N. California). Archived spectral data from wave measurement buoys at ten locations of varying depths and distances from the coastline form the basis of a comprehensive characterization of the wave energy resource. We intend to detail the seasonal trends (as well as the variability on the scale of hours and days) of six characteristic quantities describing the wave energy flux, including measures of gross wave power, wave heights, characteristic period, spectral width, characteristic direction and directional uniformity. In addition to temporal variability, the distribution of total energy over these characteristic quantities will be presented. The range of conditions observed in this study reveal much of the character of the wave energy resource in the US Pacific Northwest.

2. Wave data

2.1. Sources of wave data

Under investigation is the wave energy resource off the coasts of Washington, Oregon and northern California, an area bounded by 40–49°N latitudes and 124–125°W longitudes. For the purpose of this characterization, the surface of the sea is regarded as a Gaussian random process under the assumptions of stationarity and ergodicity. This, along with an assumption of small amplitude linear wave theory, allows a descriptive analysis of sea states in the frequency domain.

Archived spectral records from wave measurement buoys were used in this assessment. The records were obtained from the websites of both the National Data Buoy Center (NDBC - www.ndbc.noaa.gov) and the Coastal Data Information Program (CDIP - cdip.ucsd.edu), each of which operates and maintains a network of wave measurement buoys. The locations of the buoys considered in this study are provided in Fig. 1. For consistency, all buoys are referred to using their NDBC station ID numbers. It has become standard practice to archive the variance spectral density as a discrete function of frequency, but prior to this NDBC simply reported a few quantities derived from the spectrum, such as significant wave height and peak period. Although these quantities can be used to estimate the energy flux, nothing is revealed about the distribution of this energy flux over frequency or direction. To examine the complexity of the sea states of the Pacific Northwest only those records which archived the variance spectral density were used, from their earliest availability through the end of 2008. For the 10 buoys used in this study, this provided over 700,000 hourly records of spectral density, with information on the distribution over direction provided for over 400,000 of these records. The names and locations of the buoys, as well as the availability of their spectral records, are provided in Tables 1 and 2.

All NDBC stations used in this study are currently taking directional wave measurements using a pitch-roll-heave payload housed in a 3 m discus buoy, and archive spectral records once every hour. CDIP archives spectral records every half an hour, and the buoys included in this study are 0.9 m directional Waverider buoys. Prior to 1998, CDIP records were processed and archived at

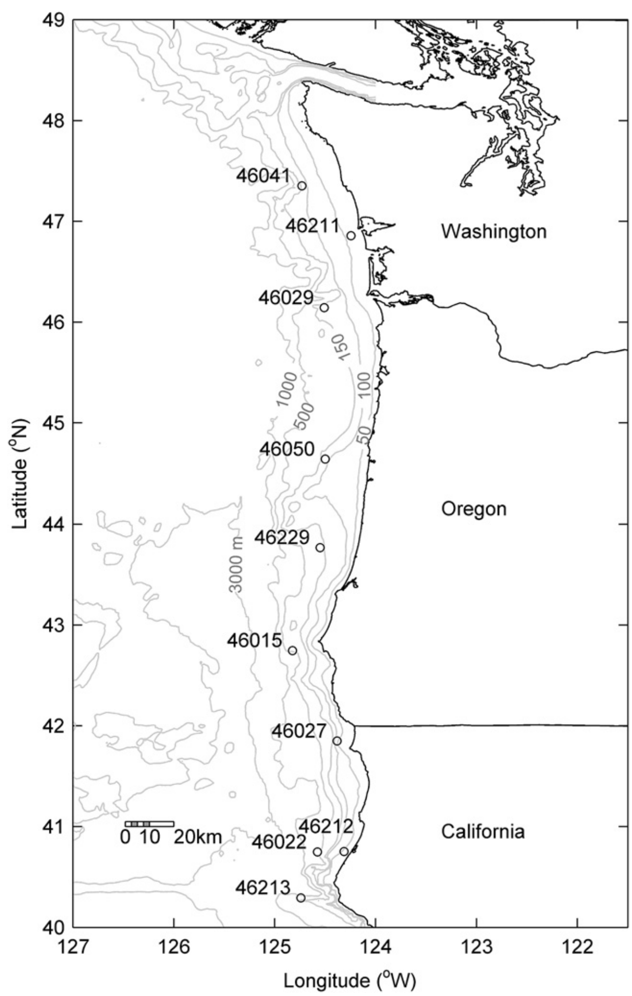

Fig. 1. Locations of wave measurement buoys providing spectral records for US Pacific Northwest wave energy resource assessment.