WAVE ENERGY RESOURCE CHARACTERIZATION AT THE US NAVY'S WAVE ENERGY TEST SITE, HAWAII

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INTRODUCTION

The US Navy's Wave Energy Test Site (WETS) is the first such grid-connected facility in the United States. It is located off Marine Corps Base Hawaii at Kaneohe on the windward (east) side of Oahu. The Naval Facilities Engineering Command (NAVFAC) has funded the infrastructure, including moorings, cables to shore, and onshore office space and grid interconnection hardware, as well as the environmental assessments required for site development. The location of the site, which consists of 3 berths at 30, 60, and 80 m water depth, is shown in Figure 1. Each berth includes a three-point mooring system for the connection of wave energy conversion (WEC) devices, as well as an undersea cable and junction box for transmission of power and data to shore. The pre-permitted site is capable of hosting WEC devices up to 1-MW. Through a cooperative effort between NAVFAC and the Department of Energy (DOE), the site is hosting companies for the testing of their pre-commercial devices in an operational setting in order to advance their technology readiness level. The Hawaii Natural Energy Institute (HNEI), at the University of Hawaii (UH), is supporting DOE and Navy objectives at WETS in a variety of ways. In this paper, we present one such category of support – numerical wave forecasting and hindcasting.

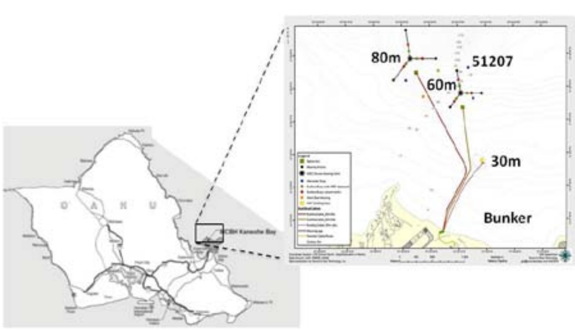

FIGURE 1. LOCATION OF WETS AND NDBC BUOY #51207, AND THE CONFIGURATION OF THE THREE TEST BERTHS.

Hawaii has complex wave climate related to its unique mid-Pacific location and the substantial effects of the archipelago [1]. The main wave regimes in Hawaii are shown in Figure 2. The persistent trade winds generate waves from the northeast to east throughout the year. Extratropical storms near the Kuril and Aleutian Islands generate swells toward Hawaii from the northwest to north in winter. The south facing shores experience moderate swells from the year-round Southern Hemisphere Westerlies that are augmented by mid-latitude cyclones in summer. Subtropical storms during winter and passing cold fronts can generate waves from all directions.

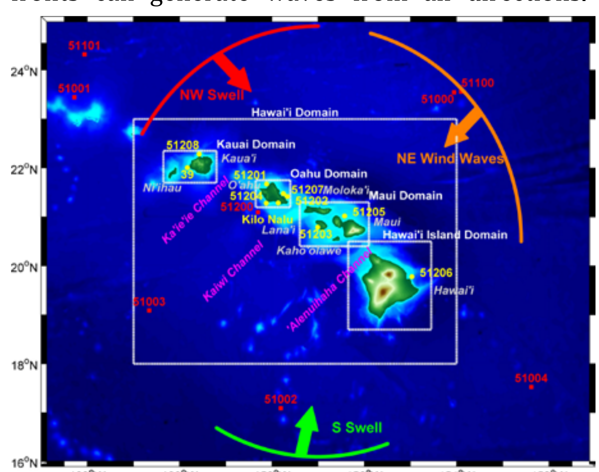

FIGURE 2. HAWAII WAVE CLIMATE, LOCATIONS FOR OFFSHORE BUOYS (RED SQUARES) AND NEARSHORE BUOYS (YELLOW DOTS), AND MODEL COVERAGE (WHITE BOXES).

WETS, which is sheltered from the low-energy south swells and the more extreme northwest swells, is exposed to trade wind waves throughout the year and north swells in the winter months. The persistent waves and multi-modal sea states provide a wide range of wave conditions for the testing of WEC devices.

There are 9 offshore and 7 nearshore wave buoys around the Hawaiian Islands. In support of WETS, NDBC #51207 (CDIP #198), which is directional Waverider™ buoy, was deployed in October 2012 to provide wave measurements at 80 m water depth within the site. The three years of records provide basic in-situ information. In addition, we operate a system of high-resolution models to provide long-term hindcast and 7.5-day operational forecast of the wave conditions at WETS. In this paper, we provide an overview of the numerical model system, the wave hindcast and forecast, and the validation with measurements from buoy #51207 at WETS.

NUMERICAL MODEL SYSTEM

Third generation spectral wave models, such as WAVEWATCH III [2] and SWAN (Simulating WAves Nearshore) [3] are proven tools in describing the multi-modal sea states around Hawaii [4]. Filipot and Cheung [5] adapted SWAN with the optimal wave breaking parameterization of Battjes and Janssen [6] and additional bottom friction scheme of Lowe et al. [7] to better describe the energy dissipation in the fringing reef environment of Hawaii. We built the wave model system from WAVEWATCH III and SWAN on a hierarchy of nested grids with increased spatial and temporal resolution from the global to island scale. Figure 2 shows the coupled Hawaii WAVEWATCH III within the global grid and the nested SWAN grids for the major islands or island groups.

High-quality global and regional wind data is crucial for modeling the multi-modal seas in Hawaii. The NOAA NCEP Global Forecast System (GFS) provides a 7.5-day wind forecast at 0.5° resolution four times daily, while the more

TABLE 1. NESTED COMPUTATIONAL GRIDS FOR SPECTRAL WAVE AND MESOSCALE ATMOSPHERIC MODELING.

Model	Grid	Longitude	Latitude	Resolution
WAVE WATCH III	global	180°W-180°E	77.5°S-77.5°N	0.5 arc-degree
WAVE WATCH III	Hawaii	161° - 154°W	18°N-23°N	3 arc-minute
SWAN	Oahu	158.35°°W -157.6°W	21.2°N - 21.75°N	0.3 arc-minute
WRF	Central Pacific	175.67°W ~136.26°W	6.35°N ~37.98°N	18 km
WRF	Hawaii	167.22°W ~149.30°W	15.39°N ~26.69°N	6 km

comprehensive Climate Forecast System Reanalysis (CFSR) produces assimilated surface winds for the entire globe at 0.5° resolution from 1979 to 2011 and 0.205° afterward [8,9]. We utilize the CFSR and GFS global winds as well as downscaled Hawaii regional winds from the Weather Research and Forecasting (WRF) model for wave hindcasting and forecasting [10]. Table 1 provides the coverage and resolution of the model grids for WAVEWATCH III, SWAN, and WRF. The coupled global and Hawaii WAVEWATCH III hindcast model produced significant wave height, peak wave period and peak direction at each grid point and wave spectra at buoy locations and along boundaries of the SWAN grids at hourly intervals. The nesting of SWAN in WAVEWATCH III produces higher resolution wave conditions over the shallow insular shelves and reefs for coastal wave studies and energy assessment.

Li et al. [1] provided a detailed assessment of the hindcast from February 1979 to May 2013. For example, as seen in Figure 3, there is good agreement between the computed wave parameters and buoy #51207 measurements during the period from Nov 2012 to May 2013, when the two datasets overlap. The hindcast captures the full range of wave conditions from north swells in the winter to predominant trade wind waves in the summer. The 34-year hindcast dataset has been thoroughly validated by measurements from the 7 offshore and 9 nearshore buoys for 1981 to 2013 (see Figure 2 for location map). In addition, altimeter measurements from GlobWAVE allow validation of the spatial pattern around the Hawaiian Islands for 1991 to 2009. The hindcast allows characterization of interannual and long-term

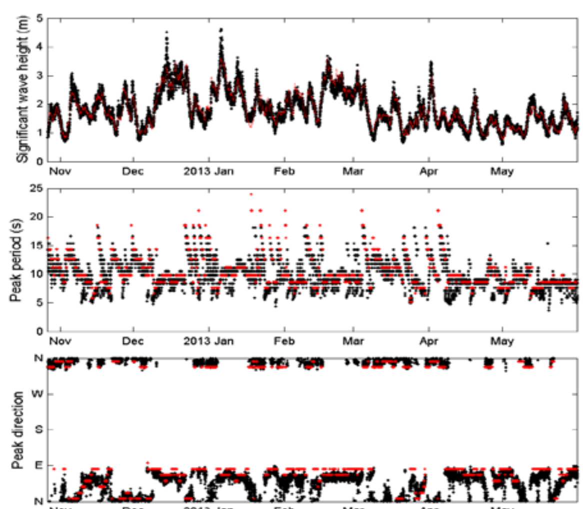

FIGURE 3. COMPARISON OF HINDCAST AND MEASURED SIGNIFICANT WAVE HEIGHT, PEAK PERIOD, AND DIRECION AT BUOY #51207 FROM NOV 2012 TO MAY 2013.

wave climate as well as the spatial variation of the wave conditions across the site.

The daily wave forecast provides 7.5 days of predictions at an hourly interval on the same system of grids as the hindcast. We provide daily updates of the wave forecast as well as its real-time validation with buoy measurements on oceanforecast.org. The nowcast data provide a backup for real-time operating conditions during waverider buoy maintenance or unexpected downtime. The daily wave forecast complements the long-term hindcast to support operational planning, deployment, and testing of WEC devices at WETS.

WAVE ENERGY CHARACTERIZATION

The long-duration hindcast provides a comprehensive dataset on the Hawaii wave climate for characterization of the wave energy resources at WETS. The wave conditions have strong seasonal variation. The mean significant wave height and peak direction in the summer months of June, July, August 2012 and the winter months from December 2012 to February 2013 are shown in Figure 4. Trade wind waves occur throughout the year and become dominant in summer months with an average height of 2 m approaching Hawaii. Heightened wave conditions can be seen in channels between islands due to local acceleration of the winds. Shadows of the dominant wind waves develop leeward of the islands. In contrast, the average wave height reaches 3.5 m in the winter due to energetic north swells. The year-round south swells, which have low energy levels, are masked by the trade wind waves and north swells.

The seasonal wave conditions around Oahu from SWAN are shown in Figure 5. The east-facing shores are exposed to the persistent wind waves throughout the year and the north swells in the winter months. The north shore is relatively calm during the summer, but open to the energetic swells during the winter. The west and south shores, which are sheltered from wind waves and north swells, have mild conditions throughout the year. WETS, located on the east shore, primarily experiences shorter-period wind waves from the east to northeast, with intermittent longer-period north swells, primarily in winter. The records from Figure 3 show wide ranges of significant wave height from 1 to 5 m and peak period from 6 to 24 s. These diverse wave conditions make WETS well suited for testing a range of WEC devices.

We utilize the 34 years of hindcast and the methodology proposed by Lenee-Bluhm et al. [11] to characterize the wave energy resources at

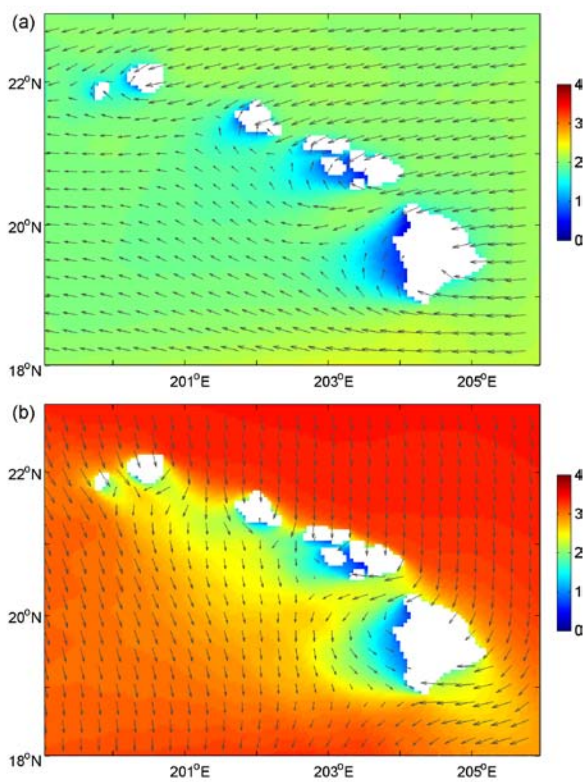

FIGURE 4. AVERAGE SIGNIFICANT WAVE HEIGHT FROM HAWAII WAVEWATCH III. (A) JUNE, JULY, AND AUGUST 2012. (B) DECEMBER 2012 TO FEBRUARY 2013.

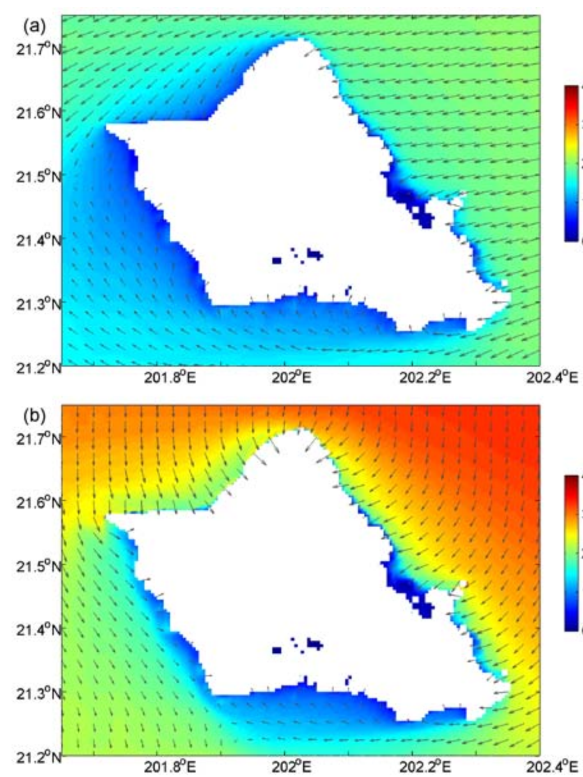

FIGURE 5. AVERAGE SIGNIFICANT WAVE HEIGHT FROM OAHU SWAN. (A) JUNE, JULY, AND AUGUST 2012. (B) DECEMBER 2012 TO FEBURARY2013.

WETS. The long-term hindcast can provide wave energy parameters directly at the test berths. The location of buoy #51207 is representative of the overall site conditions. In Figure 6, the hourly wave power at the location of buoy #51207 for 1985 and 1995 indicates a broad range of wave power within a given year, as well as substantial interannual variability. The wave power reaches a peak of 167 kW/m in 1985, but just 88 kW/m in 1995. These years are representative of higher and lower energy cycles associated with climate variations [12].

Short-term wave hindcasts introduce bias in wave energy resource assessments. The use of the full 34-year dataset eliminates such effects induced by inter-annual climate cycles. The 5th, 50th, and 95th percentiles of wave power and energy period at WETS are plotted in Figure 7. The median wave power flux increases from 6.8 kW/m in August to 16.7 kW/m in December associated with the north swells, while the monthly median energy period decreases from 9.5 s in January to 6.5 s in July due to the predominance of trade wind waves. These monthly parameters highlight seasonal wave

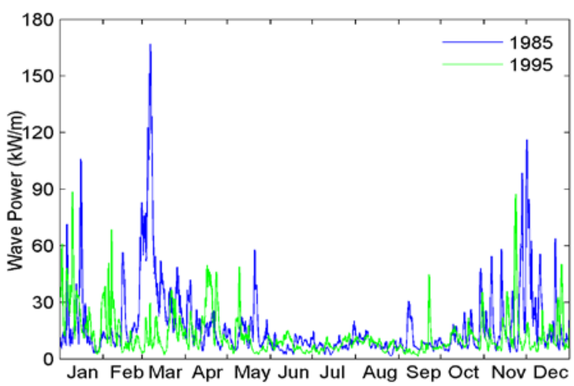

FIGURE 6. HOURLY WAVE POWER AT WETS DURING 1985 AND 1995.

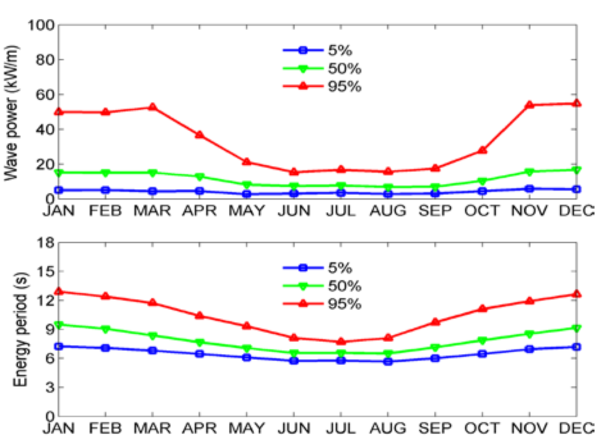

FIGURE 7. MONTHLY 5TH, 50TH, AND 95TH PERCENTILE WAVE POWER FLUX AND ENERGY PERIOD AT WETS.

variability useful for planning and operations of wave energy converters.

We sum the occurrences and energy for waves with significant wave height lower than specified thresholds at WETS, and plot the cumulative occurrence and energy distribution in Figure 8(a). Likewise, the distributions of occurrences and total energy for waves with power flux lower than a specified value are also plotted in Figure 8(b). Waves with heights smaller than 2.0 m occur approximately 75% of the time, but only contribute to 31% of the total energy. The cumulative distributions for the wave power flux and the associated wave energy follow a similar pattern. Waves with power flux under 15 kW/m occur 69% of the time, but those events contribute just 37% of the total energy. In contrast, waves with power flux exceeding 15 kW/m occur 31% of the time, but yield 63% of total energy at WETS.

CONCLUSIONS

Numerical wave modeling is an important aspect of HNEI's support to the operation of the Navy's Wave Energy Test Site (WETS). A system of third-generation spectral wave models has produced a 34-year wave hindcast dataset and is currently providing daily 7.5-day wave forecasts on a hierarchy of nested grids from global to

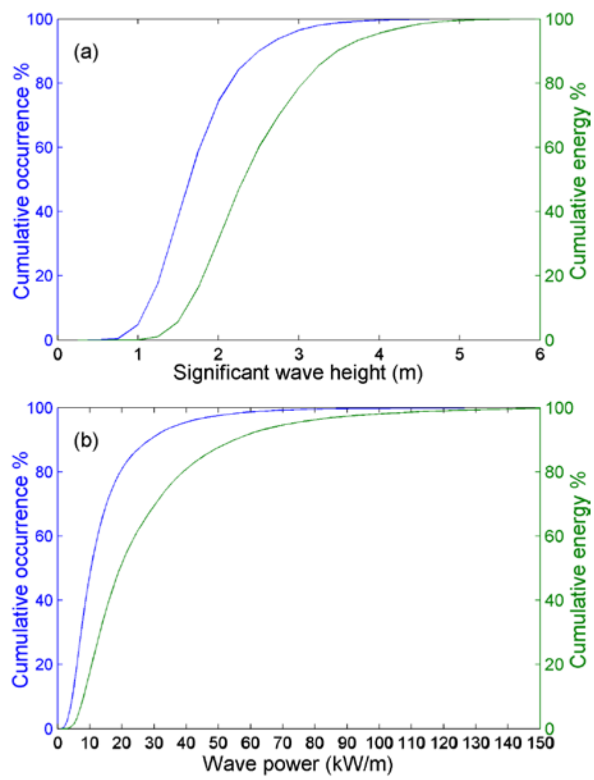

FIGURE 8. CUMULATIVE DISTRIBUTIONS OF OCCURRENCE AND ENERGY AT WETS. (A) SIGNIFICANT WAVE HEIGHT. (B) WAVE POWER.

island scales. The high-resolution wave hindcast around the Hawaiian Islands provides a wealth of information for characterization of wave resources in support of WEC developers, who may test at WETS. This dataset exhibits seasonal and interannual variability of wave conditions that make WETS quite well suited for testing of various WEC types. The daily 7.5-day wave forecast complements the buoy measurements to support planning of at-sea operations and day-to-day operation of WEC devices.

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