PROBABILISTIC WAVE PARAMETERS FOR WEC SURVIVAL ANALYSIS AT US NAVY'S WAVE ENERGY TEST SITE IN HAWAII

Ning Li[1,2,*], Kwok Fai Cheung[2], Patrick Cross[1], and Luis Vega[1]
[1]Hawaii Natural Energy Institute
[2]Department of Ocean and Resources Engineering
University of Hawaii, HI 96822, USA

*Corresponding author: ningli@hawaii.edu

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 and the permitting process. The site consists of 3 berths at 30, 60, and 80 m water depth as shown in Figure 1. Each berth includes a three-point mooring system for connection of wave energy converters (WECs), as well as an undersea cable and a junction box for transmission of power and data to shore. The pre-permitted site is capable of hosting WECs of up to 1 MW. Through a cooperative effort between NAVFAC and the Department of Energy (DOE), the site is currently hosting NWEI and Fred. Olsen for testing of their pre-commercial devices in an operational setting.

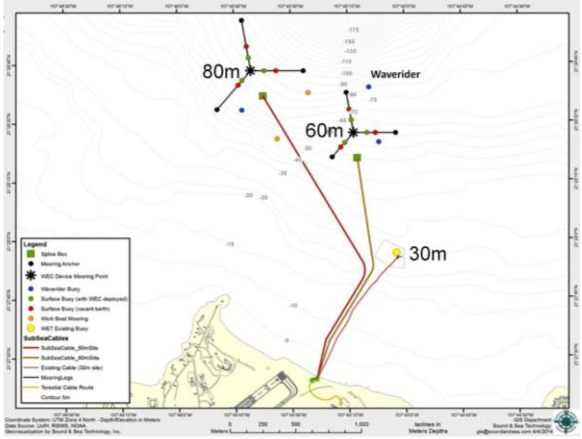

FIGURE 1. CONFIGURATIONS OF THE THREE TEST BERTHS AT WETS OFF KANEOHE, OAHU.

Hawaii has a complex wave climate due to its mid-Pacific location and massive archipelago [1]. Extratropical storms near the Kuril and Aleutian Islands generate swells toward Hawaii from the northwest to north during the boreal winter. The year-round Southern Hemisphere Westerlies augmented by mid-latitude cyclones in the boreal summer bring modest south swells to south-facing shores. Persistent trade winds generate waves from the northeast to east throughout the year, while subtropical cyclones during the winter and passing cold fronts can generate waves from all directions. The steep volcanic islands modulate the wind fields to create regional wave patterns with large spatial variation.

WETS, strategically located off the east shore of Oahu, is subject to persistent trade wind waves and intermittent north swells with power reaching 160 kW/m, but sheltered from the most energetic northwest swells and the year round south swells by headlands. Despite the favorable wave conditions for testing of WECs, the site is also subject to tropical cyclones, which may generate severe seas, requiring survival analysis for the devices.

HISTORICAL HURRICANES IN HAWAII

Historical accounts of hurricane events in Hawaii date back to 1832 [2], but the National Hurricane Center best track data is only available from 1949 onward. Figure 2 plots the available storm tracks in the North Central Pacific from 1949 to 2016. The strong vertical wind shear around Hawaii and a subtropical high-pressure ridge to the northeast tend to weaken approaching hurricanes and deflect their paths to the south. Notable exceptions are Hurricanes Dot, Iwa, and Iniki, which veered north from the tropics toward Kauai in 1959, 1982, and 1992. Several storms in recent years approached the islands from the east and brought sizeable waves to WETS. The waverider buoy at 80-m water depth recorded significant wave heights reaching 4.4 m, when Hurricane Lester passed within 180 km in 2016. A direct landfall or even a closer approach would produce much more severe wave conditions, putting the WECs at risk.

SIMULATED HURRICANES IN HAWAII

To reduce damage caused by ocean waves, engineers select design conditions based on annual exceedance probabilities or return periods according to acceptable risk levels. Due to the limited number of recorded hurricanes over the vast expanse of Hawaii waters, a probabilistic analysis can be realized through numerical simulation. Global climate models, when forced by historical and projected greenhouse gas concentrations, can describe synoptic weather patterns for downscaling of hurricanes using a stochastic-deterministic approach [3]. Through this method, hurricanes are initiated through random seeding across the source regions and steered by a weighted mean of the 250 and 850 hPa flows plus the beta-drift correction [4]. Hurricane intensity is computed by a one-dimensional, axisymmetric atmosphere-ocean model. Depending on the conditions, many of the seeds do not result in hurricanes. The seeding rate is calibrated to match the recorded average number of annual events.

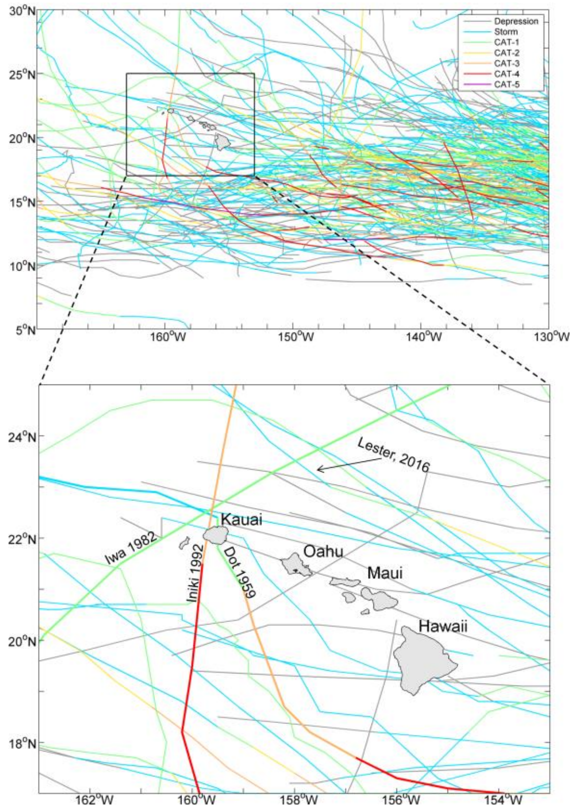

FIGURE 2. INSTRUMENTALLY RECORDED TROPICAL STORMS AND HURRICANES IN THE NORTH CENTRAL PACIFIC AND NEAR HAWAII FROM 1949 TO 2016.

We utilize 50 downscaling simulations from the NCAR-CCSM4 model over the North Central Pacific for the 1980-1999 period. This quasi 1000-year dataset includes 2436 simulated hurricane events as shown in Figure 3. The pattern follows the historical records with general migration from east to west and severe landfalls from north-tracking hurricanes. Among the simulated hurricanes, there are 252 events with category-1 strength or above when passing within 200 km off WETS that may bring severe wave conditions to the site. These events as shown in Figure 4 have radii of maximum winds ranging from 19 to 70 km, central pressure from 945 to 999 hPa, and maximum sustained wind speed from 29 to 69 m/s at the nearest approach. The 252 events provide adequate coverage of hurricane scenarios for probabilistic analysis of the storm wave conditions at WETS.

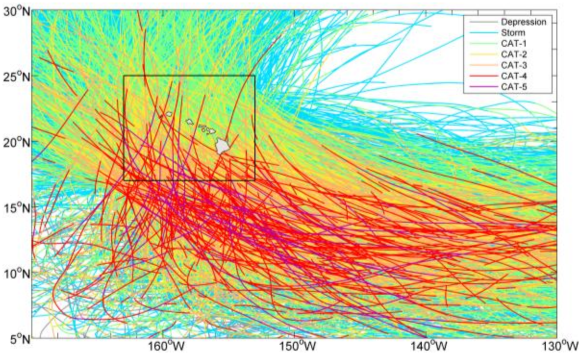

FIGURE 3. HURRICANES PASSING NEAR HAWAII (BLACK RECTANGLE) FROM 50 DOWNSCALING SIMULATIONS OF THE PERIOD 1980 TO 1999.

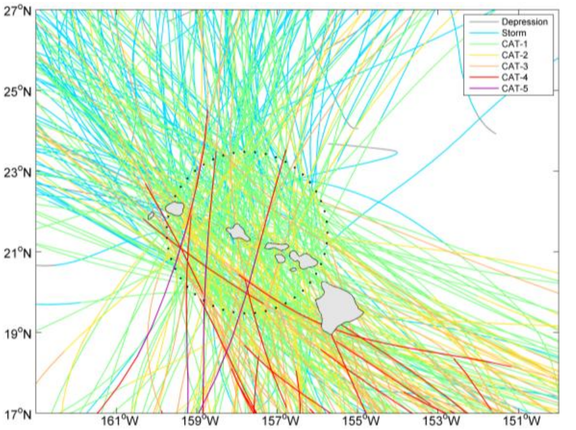

FIGURE 4. HURRICANES PASSING WITHIN 200 KM OFF WETS (INSIDE THE BLACK DOTTED CIRCLE).

HURRICANE WAVES

We utilize the third-generation spectral wave models, WAVEWATCH III [5], to describe wave generation and propagation from wind forcing. Figure 5 shows the nested computational grids covering the Hawaiian Islands and Oahu with 5.5 km and 550 m resolution. Wind forcing was computed from the track, maximum sustained wind speed, and radius of maximum winds by a parametric hurricane model [6]. A gust factor from [7] converts the sustained wind speed from 1-min to 20-min average for wave modeling.

Hurricane 1144, which makes landfall on Oahu from the southeast, produces the most severe wave conditions at WETS among the 252 modeled events. Figure 6 shows the simulated waves at landfall with 975 hPa central pressure and 45 km radius of maximum winds. The hurricane forward speed of 6.3 m/s augments the winds in the right quadrants to produce the asymmetric wave pattern. The spatial variation of the wave field is further modulated by the island. The heightened seas with a maximum significant wave height of 10 m attenuate toward the shore due to transformation over the insular shelf and nearshore reefs. This hurricane is not the strongest among the 252 events, but generates a significant wave height of 8.1 m at WETS, which is much higher than the 4.4 m from the 2016 Hurricane Lester.

The same wave modeling was conducted for the 252 selected hurricanes, which represent a diverse set of scenarios within 200 km of WETS over a 1000-year period. The model results cover a wide range of wave conditions from moderate to severe for the probabilistic analysis. Figure 7 plots the maximum significant wave height versus the corresponding peak period at WETS. The scatter alludes to the competing influence of factors such as hurricane intensity, size, and approach as well as the distance to the site. The upper bound of the significant wave height represents the breaking limit for the given peak period. Figure 8 plots the

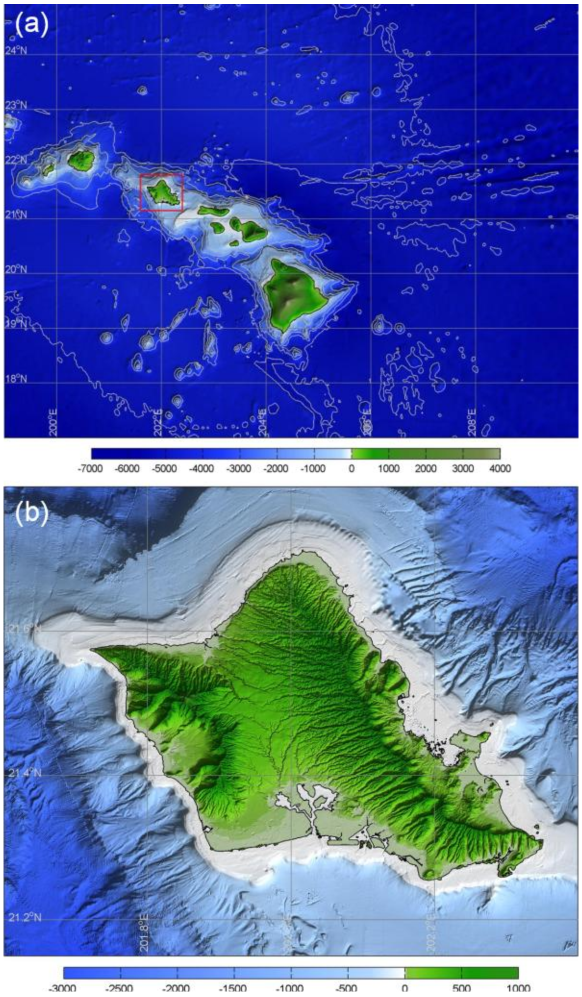

FIGURE 5. NESTED COMPUATIONAL GRIDS. (A) HAWAII. (B) OAHU.

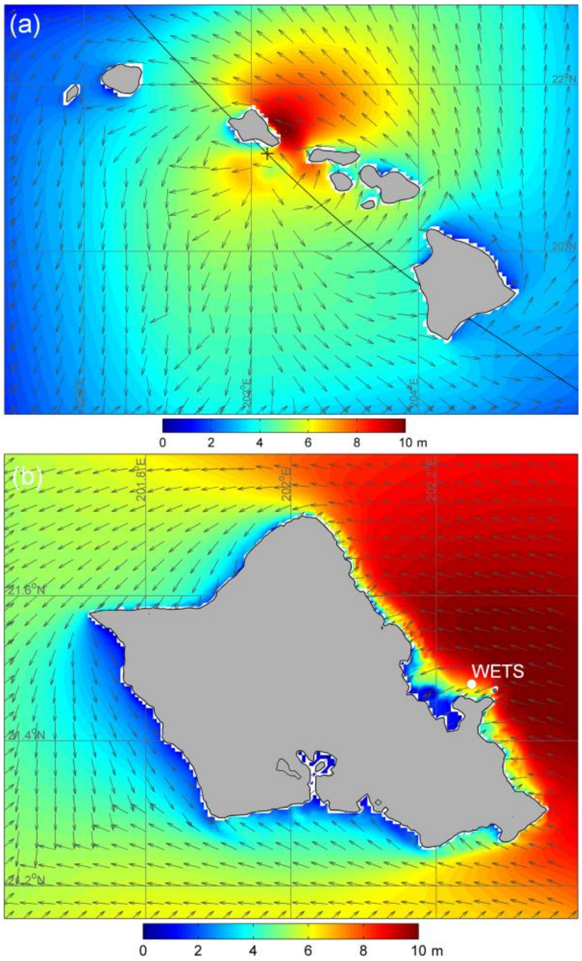

FIGURE 6. COMPUTED WAVE HEIGHTS FROM HURRICANE 1144. (A) HAWAII. (B) OAHU. BLACK LINE AND CROSS DENOTE THE HURRICANE TRACK AND EYE LOCATION.

significant wave height as a function of the annual exceedance probability. The distribution gives 5.1 and 5.9 m significant wave height for exceedance probabilities of 0.02 and 0.01 equivalent to the 50 and 100-year return period. The respective peak periods, from Figure 7, are in the range of 9-13 and 10-13 sec. The wave height from Hurricane Lester in 2016 represents a more frequent event with a return period of 20 years. The probabilistic approach is effective in providing design wave heights and periods based on risk levels accepted by the owner. In addition, north swells and mesoscale local events might bring severe conditions comparable to hurricane waves. The Waverider buoy recorded a maximum significant wave height of 5.3 m from a strong cold front in January, 2017. Severe wind waves or swells might become the design conditions for short return periods.

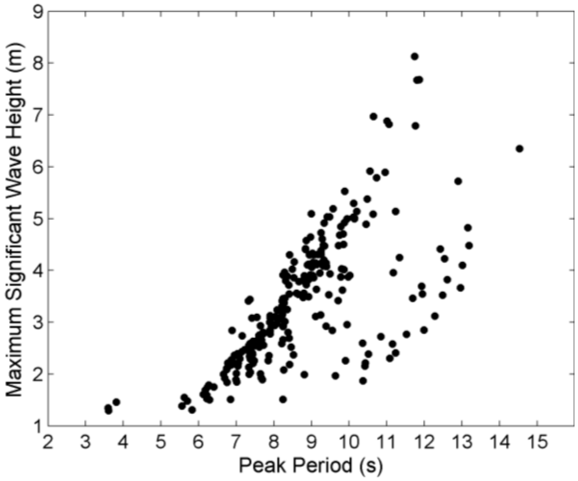

FIGURE 7. MAXIMUM WAVE HEIGHTS VERSUS PEAK PERIOD AT WETS FOR THE SELECTED HURRICANES.

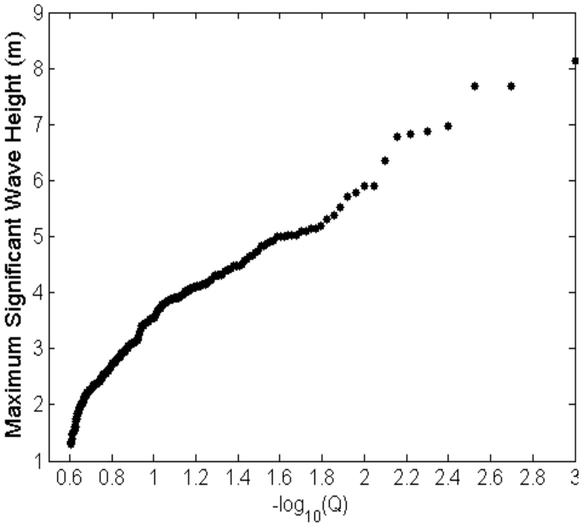

FIGURE 8. MAXIMUM SIGNIFICANT WAVE HEIGHT VERSUS ANNUAL EXCEEDANCE PROBABILITY.

CONCLUSIONS AND FUTURE WORK

The persistent and diversified wave conditions make WETS a suitable place for WEC testing. Hurricane waves, despite their infrequent occurrence, pose a challenge to the survivability of the devices. We utilize 252 hurricane scenarios within 200 km of WETS from downscaling simulations of a climate model and the third generation spectral model WaveWatch III to produce a range of severe wave conditions at WETS. The computed wave height presented as a function of annual exceedance probability enables a risk-based survival analysis of WECs. This study provides a proof-of-concept of the probabilistic approach and a baseline for analysis of hurricane wave conditions under the present and future climate projections. Further analysis of wind wave and swell data is needed to complement the design conditions for WECs at WETS.

ACKNOWLEDGEMENTS

NAVFAC provided support through contract no N00024-08-D-6323, via the Applied Research Laboratory at the University of Hawaii. We would like to thank Kerry Emanuel for the permission to use the 50 downscaling simulations of the NCAR-CCSM model in this research.

REFERENCES

[1] Li, N., Cheung, K.F., Stopa, J.E., Hsiao, F., Chen, Y.-L., Vega, L., and Cross, P., 2016,"Thirty-four years of Hawaii wave hindcast from downscaling of climate forecast system reanalysis," Ocean Modelling, 100, pp. 78-95.
[2] Shaw, S.L., 1981. "A History of Tropical Cyclones in the Central North Pacific and the Hawaiian Islands 1832-1979," Central Pacific Hurricane Center, National Weather Service Forecast Office, Honolulu, Hawaii.
[3] Emanuel, K.A., 2013, "Downscaling CMIP5 climate model shows increased tropical cyclone activity over the 21st century," Proceedings of the National Academy of Sciences, 110(30), pp. 12,219-12,224.
[4] Holland, G.J., 1983, "Tropical cyclone motion: Environmental interaction plus a beta effect," Journal of the Atmospheric Sciences, 40, pp. 328-342.
[5] Tolman, H. L., 2008, "A mosaic approach to wind wave modeling," Ocean Modelling, 25, pp. 35-47.
[6] Phadke, A.C., Martino, C.D., Cheung, K.F., and Houston, S.H., 2003, "Modeling of tropical cyclone winds and waves for emergency management," Ocean Engineering, 30(4), pp. 553-578.
[7] Krayer, W.R. and Marshall, R.D., 1992, "Gust factors applied to hurricane winds," Bulletin of American Meteorological Society, 73(5), pp. 613-618.