DEVELOPMENT OF A WAVE ENERGY RESOURCE CLASSIFICATION SYSTEM

Kevin Haas[1] and Seongho Ahn
Georgia Institute of Technology
Civil and Environmental Engineering
Atlanta, GA USA

Vincent Neary and Sara Bredin
Sandia National Laboratories
Albuquerque, NM, USA

[1]Corresponding author: khaas@gatech.edu

INTRODUCTION

The success of wind energy resource and wind turbine classification systems has motivated interest in classification systems for the wave energy industry. Analogous to the wind energy resource classification system, a wave energy resource classification system would serve as a useful resource assessment tool that facilitates scoping studies and project planning at regional and national scales.

The wave energy resource classification system, as presented herein, is based on several wave climate statistics that broadly define opportunities for wave energy conversion and risks to the operation and survival of WEC devices. In comparison to wind energy resource classification, the wave energy resource classification system constrains the opportunity metric, power density, by peak period. It also introduces a risk metric, recognizing that energy resource assessments need to weigh both opportunities and risks for project development. Risks are characterized by the extreme significant wave height, with a 50-year recurrence interval as specified by current international design technical specifications for marine energy systems.

SOURCE OF WAVE DATA

The classification scheme developed herein is built on wave resource statistics derived using the phase II 30-year hindcast from the 3rd generation (3G) spectral wave, WaveWatch III® (WWIII) [1]. This hindcast was validated with point wave measurements at twenty-five NDBC buoy sites, which had at least 10 years of recorded data for continental US locations and at least 5 years for Alaska and Hawaii locations.

The model data used in this analysis have a spatial resolution of 4 min and include the spectral partitioned wave parameters at each grid point, which provide quantitative descriptions of partition wave height, peak period and the mean direction. These partitions are derived using an algorithm [2, 3] initially developed for watershed identification. Hourly spectral partition data are generated for 70,386 modeled wave sites. The locations of the partition data along with the depth are shown in Figure 1.

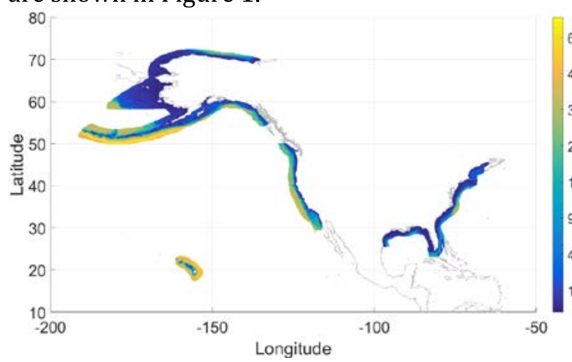

FIGURE 1. GEOGRAPHIC DISTRIBUTION OF PARTITION DATA. COLORS REPESENT WATER DEPTH (M).

CALCULATING WAVE RESOURCE ASSESSMENT DATA

The wave resource statistical data are derived using the partition data. The wave height (H) and energy period (T_e) are used to compute the wave power density (J) of that partition using

$$\mathrm{J} = \frac{\rho g}{16} H^2 C_g(T_e, h) \quad (1)$$

where C_g is the group velocity, which is a function of the energy period and the depth (h). The wave power density for each partition of the 30 year record is computed, and the joint probability of the partition wave power density and peak period is computed, $f(J, T_p)$.

In order to gain a high level wave classification scheme, annual available energy (AAE) density in MWh/m is used as a primary indicator of wave energy resources. The AAE density is analogous to

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annual energy production (AEP) without considering the energy conversion process. It can be thought of as the theoretical available wave energy resource for any particular location.

To compute AAE density as a function of peak period, the following summation of all power is used

$$\mathrm{AAE}(\mathrm{T_p}) = \mathrm{T}_{year} \sum J(T_p) f(J, T_p) \qquad (2)$$

where T_{year} is the number of hours in a year taken to be 8766 hours. The total AAE is taken as the following summation over all peak periods

$$\mathrm{AAE} = \sum \mathrm{AAE}(\mathrm{T_p}) \qquad (3)$$

Alternatively, the mean annual wave power density is computed as the AAE divided by the number of hours in a year.

This process is repeated for each location, and the geographic distribution of the total AAE/power density is shown in Figure 2 below. Not suprisingly, the largest AAE exceeding 500 MWhr/m^2 occurs on the West Coast and along the southern coast of Alaska. Hawaii has AAE on the order of 300 MWhr/m^2. The East Coast and the Gulf Coast have much more modest amounts of AAE, generally below 100 MWhr/m^2.

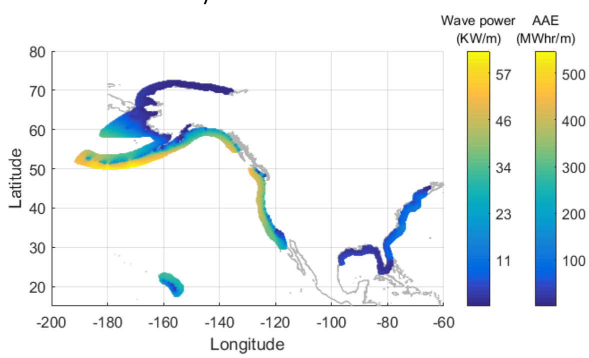

FIGURE 2. GEOGRAPHIC DISTRIBUTION OF TOTAL AAE AND WAVE POWER DENSITY.

To better characterize the wave resource, the AAE/power density can be viewed as a function of peak period as shown in Figure 3. This is an example for a single location off the coast of Hawaii. Interestingly, the AAE distribution here has two separate peaks, around 9 seconds and 14 seconds.

To aggregate all the AAE/power density data as a function of peak period, four different period bands are defined as shown in Table 1. These period bands correspond to local wind seas, short period swell, moderate period swell and long period swell. The $\mathrm{AAE}(\mathrm{T_p})$ within each band are summed up to produce a new AAE estimate for that particular band.

The geographic distributions of AAE/power density for each of the period bands are shown in Figure 4. Period band 1 has very little AAE density throughout the US coastal waters. For the East Coast, period band 2 has the highest level of AAE. On the West Coast and Alaska, period band 3 contains the most energy, although the West Coast still has significant energy for the long period swell in band 4. Hawaii has significant energy in bands 2-4.

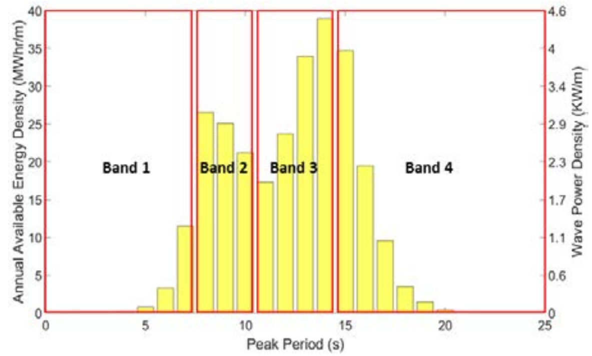

FIGURE 3. EXAMPLE OF SPLITTING AAE AND WAVE POWER DENSITY DISTRIBUTION INTO DIFFERENT PERIOD BANDS FOR A PARTICULAR LOCATION.

TABLE 1. CLASSIFICATION OF PERIOD BANDS.

Bands	Band 1	Band 2	Band 3	Band 4
Period (s)	$T_p < 7$	$7 < T_p < 10$	$10 < T_p < 14$	$14 < T_p$

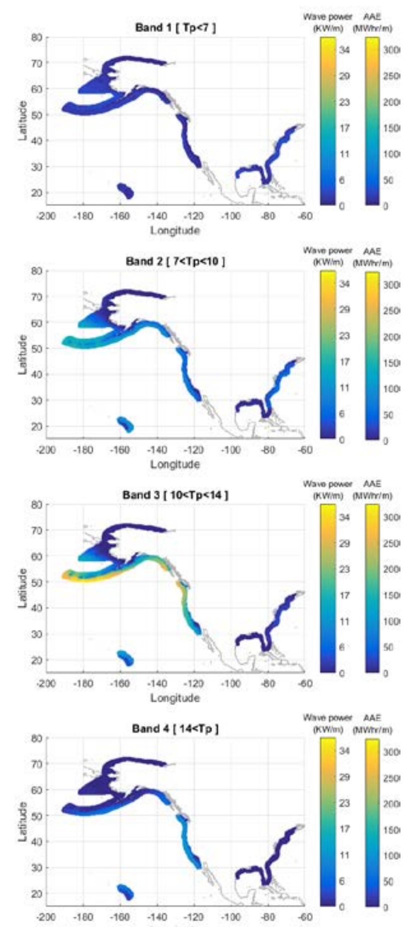

FIGURE 4. GEOGRAPHIC DISTRIBUTION OF AAE AND WAVE POWER DENSITY FOR EACH PERIOD BAND.

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AAE density is classified according to Table 2. Class 0 sites are locations which have consistently low power and would not facilitate utility scale wave energy development. Class 1 sites are generally low power and associated with small, localized applications. Class 2 and 3 sites are associated with progressively higher power and are capable of supporting utility scale applications.

TABLE 2. AAE DENSITY CLASSES.

Class	Class 0	Class 1	Class 2	Class 3
AAE density (MWhr/m²)	AAE<10	10<AAE<50	50<AAE<200	200<AAE
Wave power density (KW/m)	J<1.1	1.1<J<5.7	5.7<J<22.8	22.8<J

As shown in Figure 5, the wave energy resource classes are applied to both the total AAE density as well as for each period band. Therefore, each location may fall into different classes for each band as well as for the total AAE density. For example in Figure 5, this location is class 3 for the total AAE density, but class 0 in band 1 and class 2 for bands 2-4.

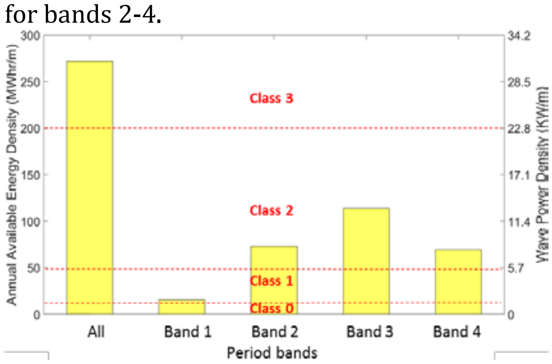

FIGURE 5. DEFINITION OF WAVE CLASSES.

Figure 6 shows the geographic distribution of the wave energy resource classes for the total AAE density. Following from the distribution of the AAE in Figure 3, the West Coast and portions of the Alaska Coast have the class 3 sites, along with portions of the Hawaii Coast. The East Coast is mostly class 2 whereas the Gulf Coast is class 1.

Finally, the geographic distribution of the wave energy resource classes for each period band is shown in Figure 7. Along the northern part of the West Coast, band 3 has class 3 sites with the other period bands falling into class 2. This indicates that the largest waves fall into the moderate period swell range.

The Aleutian Islands of Alaska have significant wave energy resources as seen by the class 3 sites within band 3 and class 2 sites in band 2, but mostly class 1 sites in band 3. This indicates that the Aleutian Islands tend to have higher energy in the small to moderate period swell range.

The East Coast has class 2 sites within band 2, the smaller period swell. Band 1 and 3 contains class 1 sites whereas band 4 contains class 0 sites. This indicates that the short period swell contains the most energy for the East Coast. For the Gulf Coast, the wind sea (band 1) is class 1, whereas the rest of the bands are mostly class 0.

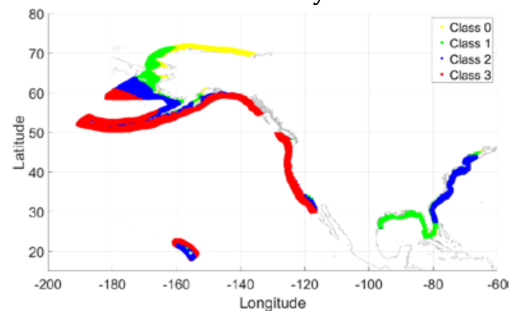

FIGURE 6. GEOGRAPHIC DISTRIBUTION OF WAVE ENERGY RESOURCE CLASSES.

Hawaii tends to have class 2 sites on the northern side for all swell bands (2-4). This indicates that the wave energy resource in Hawaii is distributed across a broader range of frequencies compared to other U.S. regional wave climates.

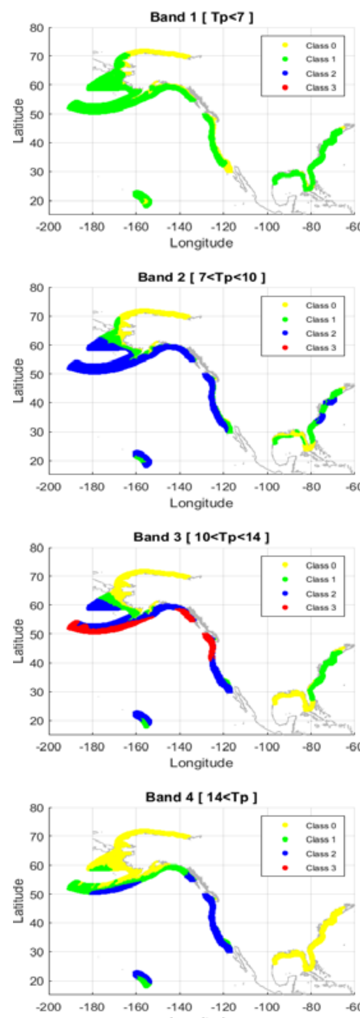

FIGURE 7. GEOGRAPHIC DISTRIBUTION OF WAVE CLASSES FOR EACH PERIOD BAND.

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EXTREME SIGNIFICANT WAVE HEIGHT

Project risks at wave energy sites can be characterized by the extreme significant wave height with a 50-year recurrence interval, $H_{s_{50}}$, which is used in current international design technical specifications for specifying design wave loads in marine energy systems [4]. Mean values of $H_{s_{50}}$ for different regional wave climates, as well as the distribution of values (minimum, first-quartile, median, third quartile and maximum), are shown in Figure 8. Mean values of $H_{s_{50}}$ for most wave climates fall between six and seven meters, e.g., the Gulf Coast, the East Coast, the St. Lawrence Island of Alaska, and Hawaii. Mean values exceed seven meters in energetic wave climates, including the West Coast, the southern coast of Alaska, and the Aleutian Islands; and are less than six meters along the central and northern coasts of Alaska where wave energy resources are low.

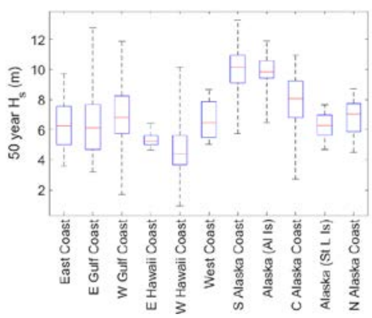

FIGURE 8. REGIONAL VARIATION OF EXTREME SIGNIFICANT WAVE HEIGHT $H_{s_{50}}$.

Normalizing $H_{s_{50}}$ by its mean value $H_{s_{mean}}$ provides a relative measure of risks to opportunities, analogous to the turbulence intensity parameter used in wind power classification, [5]. Scatter plots presented in Figure 9 indicate strong correlations between $H_{s_{50}}$ and $H_{s_{mean}}$ for the individual coastal regions.

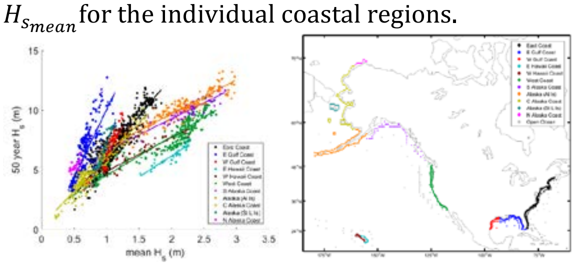

FIGURE 9. REGIONAL SCATTER PLOTS OF $H_{s_{50}}$ VS. $H_{s_{mean}}$ (LEFT) WAVE CLIMATE REGIONS (RIGHT).

For each region, a unique linear relationship governs

$$H_{s_{50}}/H_{s_{mean}} = m + b/H_{s_{mean}} \quad (4)$$

Because the intercepts for these different regional relations are nonzero, the ratio $H_{s_{50}}/H_{s_{mean}}$ is not constant for each regional wave climate. However, the normalized intercept in this relationship only changes $H_{s_{50}}/H_{s_{mean}}$ slightly over the range of observed $H_{s_{mean}}$ for each region; hence, the $H_{s_{50}}/H_{s_{mean}}$ classes given in Table 3 are sufficiently robust.

TABLE 3. EXTREME WAVE HEIGHT RATIO CLASSES.

Subclass	Low	Medium	High
Ratio	$H_{s_{50}}/H_{s_{mean}} \leq 5$	$5 < H_{s_{50}}/H_{s_{mean}} < 7$	$7 \leq H_{s_{50}}/H_{s_{mean}}$
Region	Hawaii, West Coast	Alaskan Coast, East Coast	Gulf Coast

CONCLUSIONS

A preliminary (strawman) wave energy resource classification scheme is developed based on the opportunity parameter of average wave site conditions (AAE or annual wave power density, constrained by the technology operational period bandwidth), and one risk metric (extreme significant wave height ratio). This classification scheme is expected to provide significant benefits to the WEC industry, from data reduction for site characterization and assessment, to standardizing and streamlining design and manufacturing of WEC technologies. The classification scheme provides information relevant for the operation of specific WEC technologies, e.g., the operating period bandwidth that links a WEC technology design performance parameter with the period band representing a population of waves in a given wave climate site. Providing information about the AAE associated with each operating period bandwidth provides information about how much energy is available specifically for devices that operate within those bands. However, the classification scheme itself maintains no inherent assumptions based on any specific devices and therefore is considered to be device agnostic.

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