5. JENNETTE'S PIER WAVE ENERGY TEST CENTER

5.1. Site Description

Jennette's Pier, owned by the State of North Carolina and managed by the NC Aquarium Division, is a unique public facility that provides education and outreach including displays of experimental data and monitoring equipment. The University of North Carolina Coastal Studies Institute (UNC CSI) began a partnership with Jennette's Pier in 2004 to foster research, ocean energy device testing and monitoring, outreach, and education. Part of this partnership is the Jennette's Pier Wave Energy Test Center. The site was used for the first time in December 2011 by Resolute Marine Energy.

The Jennette's Pier Wave Energy Test Facility has two test berth locations, one approximately 80 m north of the pier structure at 6 m water depth (35.9119 N, 75.5933 W) that is called the 'nearshore berth' and one approximately 600 m east of the seaward end of the pier at 11 m depth (35.9123 N, 75.5863 W) that is called the 'offshore berth.' The seabed is sandy at both locations. Figure 33 shows the gently sloping bathymetry around the site, which consists of a wide shelf.

The wave climate at the test site varies seasonally, with calmer seas in the summer compared to more energetic seas in the winter. The wave environment at Jennette's Pier is characterized by an annual average power flux of about 6.08 kW/m at 12.6 m depth.

The nearby University of North Carolina (UNC) Coastal Studies Institute (CSI) offers a wide range of technical and testing infrastructure support services for WEC developers. Jennette's Pier has small scale, shallow water wave energy resources, and is suited for scaled devices.

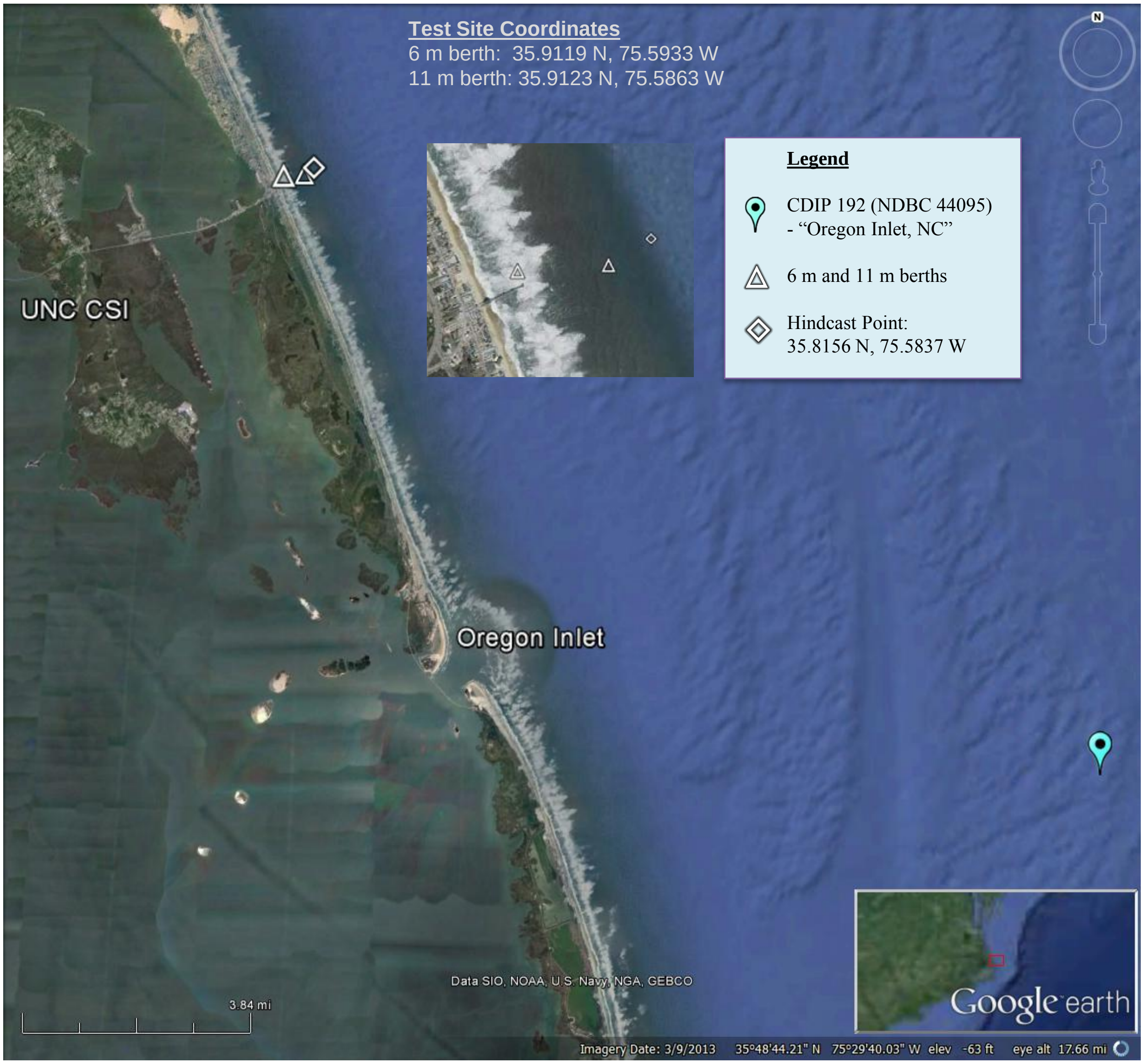


Figure 32: Jennette's Pier is located in the coastal waters of North Carolina in the town of Nags Head. The test site is 0.08 – 0.3 km off-shore in 6 – 11 m depth water. One National Data Buoy Center (NDBC) buoy is southeast of the site (see Table 3). The nearby UNC CSI is shown. Image modified from Google Earth (Google Earth 2015).

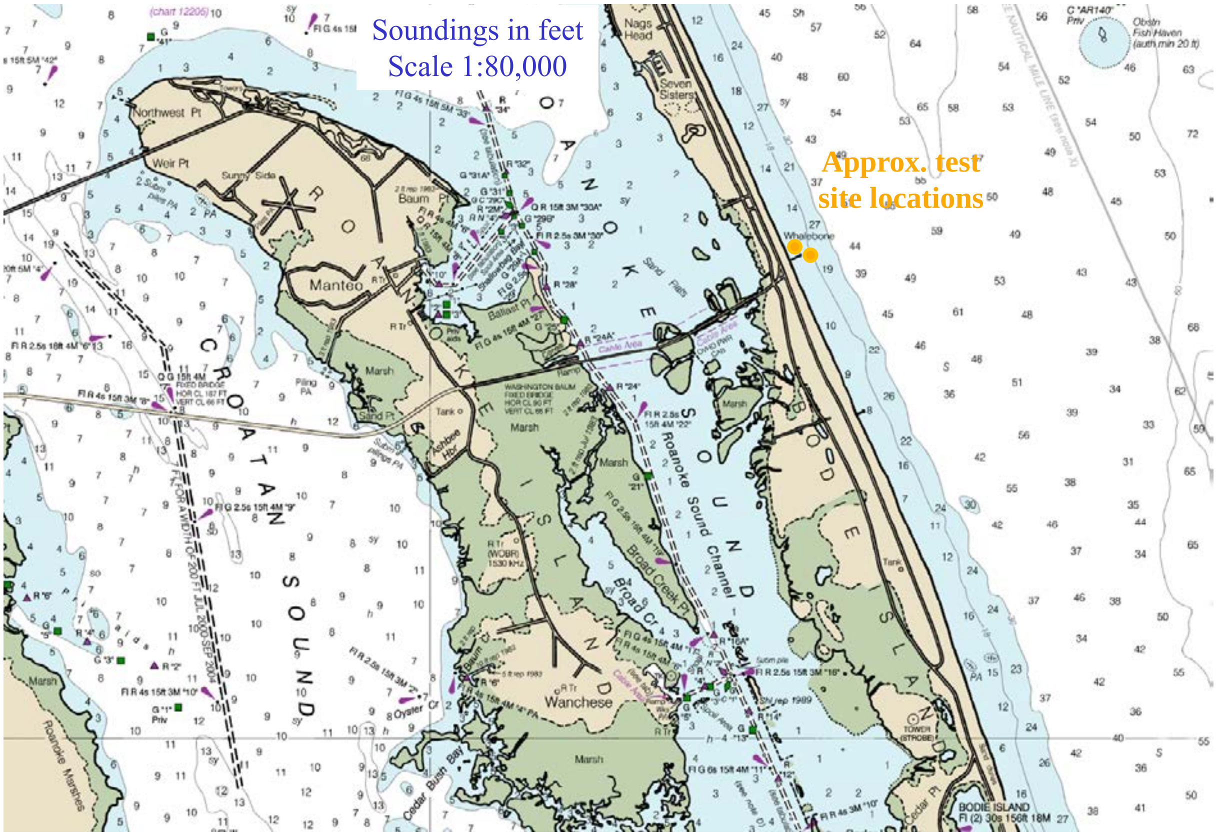


Figure 33: Nautical chart of Nags Head Island and the surrounding area shows the gradually sloping bathymetry off Jennette's Pier. Soundings in feet (1 foot = 0.3048 m). Image modified from nautical chart #12204 (Office of Coast Survey 2015).

5.2. WEC Testing Infrastructure

5.2.1. Mooring Berths

Moorings for wave energy devices will be temporary. Energy generated and monitoring instrumentation will be cabled to Jennette's Pier where there is a cable trough that protects cables running from the seabed to the research building at the seaward end of the pier and then to the pier house.

5.2.2. Electrical Grid Connection

Several renewable energy technologies are built into Jennette's Pier, including solar panels and three 10 kW wind turbines. The turbines are net metered and feed into the Pier substation (they do not feed into the grid). The Pier is exploring the possibility of similarly net metering wave energy devices tested at the site.

5.2.3. *Facilitating Harbor*

The Jennette's Pier Wave Energy Test Center can be accessed by boat via Oregon Inlet (∼10 miles from the Pier). Several harbors are within 10 miles of the inlet, including harbors and marinas at UNC CSI and Wanchese, from which service vessels and commercial divers are available. UNC CSI also has a Zodiac that can be beach-launched to support launch and recovery operations.

5.2.4. *On-Shore Office Space*

Office space is available for rent at UNC CSI, which is about 5 miles west of Jennette's Pier in Wanchese, NC. The Jennette's Pier research building is equipped with computers, which are cabled to the pier house. The pier house offers fiber optic connectivity, generator backup power, and a server that provides remote telemetric access to instrument data. In addition, the UNC CSI campus serves as a fiber hub for the MCNC NCREN network, resulting in upload and download speeds faster than T3 connections and latency of only 2 – 8 milliseconds.

5.2.5. *Service Vessel and Engineering Boatyard Access*

UNC CSI vessels are available for use, along with a vessel Captain, research technicians, and dive operations support for additional fees. Services from the UNC CSI fabrication shop including equipment rental and research equipment are available for a fee.

5.2.6. *Travel and Communication Infrastructure*

The Norfolk International Airport (ORF) is approximately a two hour drive from UNC CSI and Jennettes Pier. Raleigh Durham International Airport (RDU) is approximately a three hour drive from UNC CSI and Jennettes Pier. Cellular service offers consistent coverage; there are several Federal Communication Commission (FCC) registered cell phone towers located in and around Nags Head, NC.

5.2.7. *Met-Ocean Monitoring Equipment*

There is one Coastal Data Information Program (CDIP) buoy (Figure 34a) that measures and collects ocean data (see Figure 32 for location). There is also an Acoustic Wave and Current Gauge (AWAC) co-located at the 11 m berth (Figure 34b). Instrument and data specifications for this monitoring equipment are summarized in Table 3. Buoy data is accessible online at the CDIP and NDBC databases, and AWAC data is available through the U.S. Army Corps of Engineers Field Research Facility website. The land based meteorological station is north of the site. Other met stations are nearby with shorter periods of record. In addition, there are many measurements at Duck, NC (∼34 km northwest of Jennettes Pier), see Section 6.2.7.

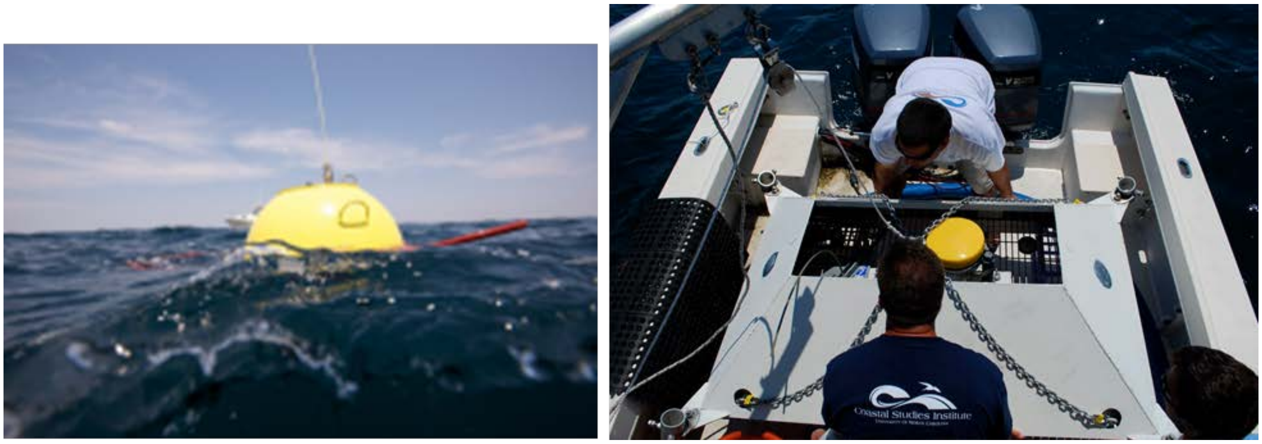


Figure 34: (a) CDIP 192 (NDBC 44095) located about 30 km southeast of the test site (Coastal Data Information Program 2013), (b) the AWAC being installed at the 11 m berth.

Table 3: Wave monitoring equipment in close proximity to Jennette's Pier.

<table>
<tr><th>Instrument Name (Nickname)</th><th colspan="2">NDBC 44095-CDIP 192 "Oregon Inlet, NC")</th><th colspan="3">Jennette's Pier AWAC (awac05)</th><th>KNCNAGSH4</th></tr>
<tr><td>Type</td><td colspan="2">Waverider Buoy</td><td colspan="3">Acoustic Wave and Current Gauge (AWAC)</td><td>Met station</td></tr>
<tr><td>Measured Parameters</td><td colspan="2">-std. met. data
-spectral wave density
-spectral wave direction</td><td colspan="3">-std. met. data
-spectral wave density
-spectral wave direction
-current speed and direction</td><td>meteorological data</td></tr>
<tr><td>Variables reported, including derived variables (Sampling interval)</td><td>Std Met.:
WVHT
DPD
APD
MWD
WTMP
(30 min sampling period)</td><td>-Spectral Wave Density
-Spectral Wave direction
(30 min sampling period)</td><td>Std Met.:
WVHT
DPD
MWD
(1 hr sampling period)</td><td>-Spectral Wave Density
-Spectral Wave direction
(1 hr sampling period</td><td>-Longshore current speed
-Cross-shore current speed
(1 hr sampling period)</td><td>AirTemp
DewPoint
Pressure
WDIR
WSPD
Humidity
Precip
(5 min sampling period)</td></tr>
<tr><td>Location</td><td colspan="2">~30 km southeast of Jennette's Pier; 7 miles off Oregon Inlet, NC</td><td colspan="3">Co-located at 11 m berth</td><td>Nags Head, NC</td></tr>
<tr><td>Coordinates</td><td colspan="2">35.750 N 75.330 W (35°45'0" N 75°19'48" W)</td><td colspan="3">35.9123 N 75.5868 W (35°54.74' N 75°35.205' W)</td><td>35°56'54" N, 75°37'37" W</td></tr>
<tr><td>Depth</td><td colspan="2">18.3 m</td><td colspan="3">11.3 m</td><td>Elevation: 10 ft</td></tr>
<tr><td>Data Start</td><td colspan="2">4/2012</td><td colspan="3">consistent data since 9/2012 (sporadic data collection from 2009-2012)</td><td>11/25/2007</td></tr>
<tr><td>Data End</td><td colspan="2">present</td><td colspan="3">3/16/2014</td><td>present</td></tr>
<tr><td>Period of Record</td><td colspan="2">~3.5 yrs</td><td colspan="3">~1.5 yrs</td><td>~8 yrs</td></tr>
<tr><td>Owner/ Contact Person</td><td colspan="2">USACE, CDIP/UNC

"Information Submitted by Scripps"
http://cdip.ucsd.edu/themes/s?un=0&tz=UTC&pb=1&wp=0&hl=1&r=999&bl=s?d2=p70:s:128:st:1&d2=p9&u2=s:192:st:1

http://www.ndbc.noaa.gov/station_page.php?station=44095</td><td colspan="3">Field Research Facility, Coastal Observations & Analysis Branch, US Army Corps of Engineers, Duck, North Carolina
http://www.frf.usace.army.mil/awac05/realtime.shtml</td><td>National Weather Service; data available on wunderground.com
http://www.wunderground.com/personal-weather-station/dashboard?ID=KNCNAGSH4</td></tr>
</table>

5.2.8. Environmental Monitoring

Jennettes Pier has the capability to monitor environmental conditions using CTDs (measuring Conductivity, Temperature, and pressure which can be related to Depth), water quality monitors, and an optical backscatter. Two Nortek Aquadopp current meters can be deployed with devices to measure the local wave and current environment. Two Multi-Electronique hydrophones for passive acoustic monitoring can be deployed with devices as well. Photographic and videographic documentation of colonization and response of marine organisms to devices can be recorded by UNC CSI divers (open and closed circuit rebreather certified), ROVs, or stationary cameras. UNC CSI has extensive photography and videography capabilities via still cameras rated to up to 450 ft, Digital Cinema cameras for Ultra-HD capture at depths to 450 ft, GoPros rated to 1000 ft, and a Deepsea Power and Light 0.01 lux lighting, 170 degree field of view camera rated to almost 2000 m with 1100 ft of cable and a sea-light sphere capable of emitting 4000 lumens.

5.2.9. Permitting

The 6 m and 11 m test berths are permitted by the U.S. Army Corps of Engineers. Notice will be given to mariners via the Coast Guard when specific devices are tested. Information on berth leasing charges, personnel fees, equipment hire, etc., can be requested from Jennettes Pier or UNC CSI. A well-defined work plan must be submitted 60 days before the proposed start date, and settled on 30 days before operations begin. The Jennettes Pier Operations Committee must approve the work plan prior to the research partner beginning operations. Operations must be respectful to the recreational use of Jennettes Pier, and peak season for public activities is April – October.

5.3. Data used

Researchers at the UNC CSI produced a 31 year hindcast dataset for the area offshore of North Carolina (UNC CSI 2015). This dataset was used to calculate statistics of interest for the wave resource characterization at the Jennette's Pier and USACE FRF sites. The hindcast data at the grid point shown in Figure 32.

In addition to the hindcast data set, historical data from AWAC05 was used to calculate representative spectra. Because the AWAC05 only has consistent data for about three years, historical data from a USACE FRF waverider buoy (NDBC 44056 / CDIP 433) was used to calculate extreme sea states. Wind data was available from a met station on-shore. However, to be consistent with the other sites, Climate Forecast System Reanalysis (CFSR) winds were used, as explained in Section 2.3. As with the other sites, current data was downloaded from OSCAR. See Figures 32 and 35 for data locations.

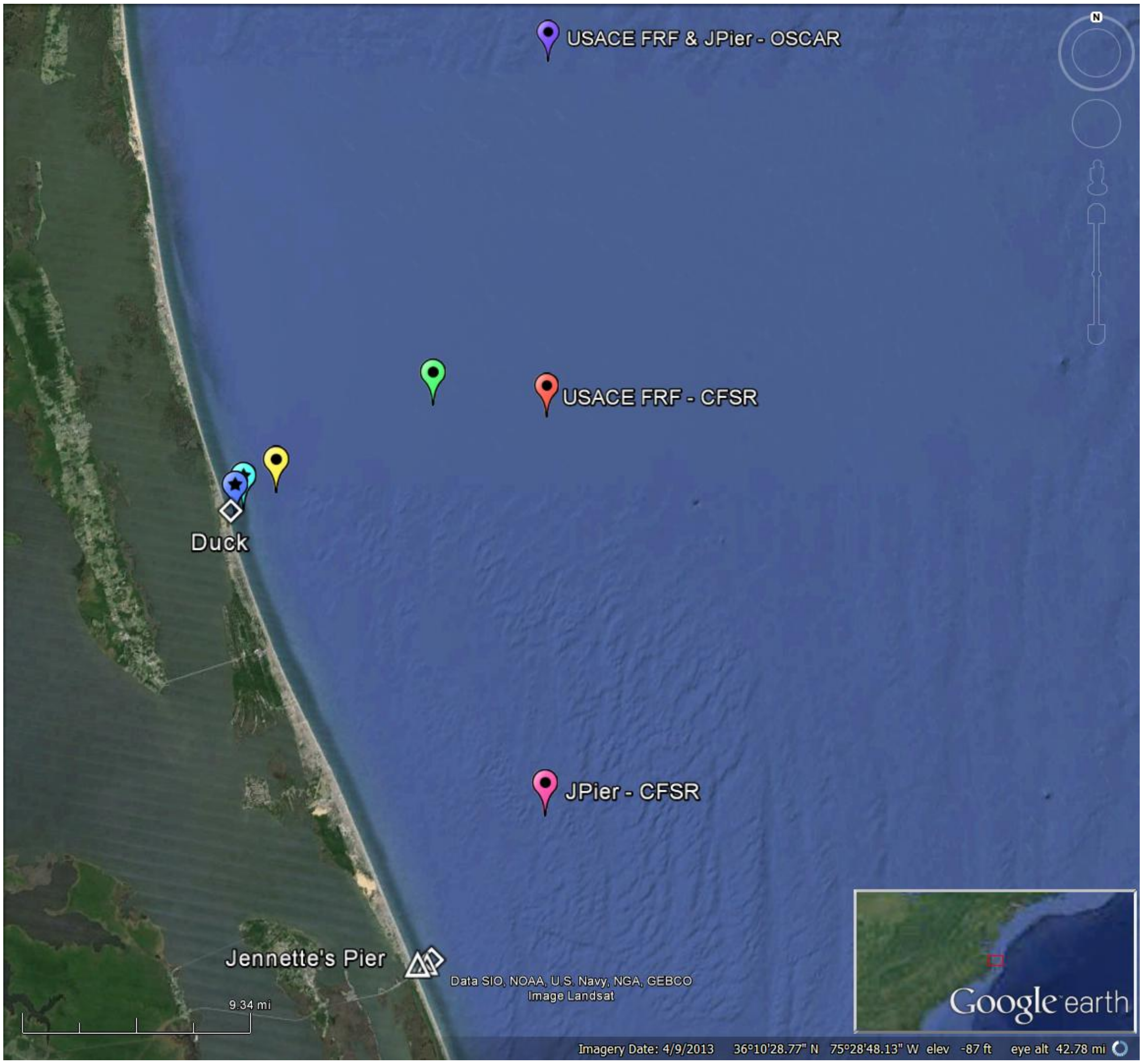


Figure 35: Jennette's Pier & USACE FRF (see Chapter 6) location map showing CSFR wind and OSCAR surface current data points (Google Earth 2015).

5.4. Results

The following sections provide information on the joint probability of sea states, the variability of the IEC TS parameters, cumulative distributions, weather windows, extreme sea states, and representative spectra. This is supplemented by wave roses as well as wind and surface current data in Appendix C. The wind and surface current data provide additional information to help developers plan installation and operations & maintenance activities.

5.4.1. Sea States: Frequency of Occurrence and Contribution to Wave Energy

Joint probability distributions of the significant wave height, H_{m0}, and energy period, T_e, are shown in Figure 36. Figure 36 (top) shows the frequency of occurrence of each binned sea state and Figure 36 (bottom) shows the percentage contribution to the total wave energy. Figure 36 (top) indicates that the majority of sea states are within the range 0 m $< H_{m0}$ $<$ 2 m and 4 s $< T_e <$ 9 s. Jennette's Pier experiences a minimal amount of extreme sea states, which rarely exceed 5 m. The site is well suited for testing WECs at smaller scales, especially those that are bottom mounted because the depth is only 11 m at the 'offshore berth.'

As mentioned in the methodology (Section 2.2), previous studies show that sea states with the highest frequencies of occurrence do not necessarily correspond to those with the highest contribution to total wave energy. The total wave energy in an average year is about 53,300 kWh/m, which corresponds to an average annual omnidirectional wave power of 6.08 kW/m. The most frequently occurring sea state is within the range 0.5 m $< H_{m0} <$ 1 m and 5 s $< T_e <$ 6 s, while the sea state that contributes most to energy is within the range 1.5 m $< H_{m0} <$ 2 m and 6 s $< T_e <$ 7 s. Several sea states occur at a similar frequency, and sea states within 0.5 m $< H_{m0} <$ 3 m and 5 s $< T_e <$ 10 s contribute a similar amount to energy.

Frequencies of occurrence and contributions to energy of less than 0.01% are considered negligible and are not shown for clarity. For example, the sea state within 0 m $< H_{m0} <$ 0.5 m and 9 s $< T_e <$ 10 s has an occurrence of 0.03%. The contribution to total energy, however, is only 0.004% and, therefore, does not appear in Figure 36 (bottom). Similarly, the sea state within 6 m $< H_{m0} <$ 6.5 m and 10 s $< T_e <$ 11 s has an occurrence of 0.0001%, but the contribution to total energy is 0.05%.

Curves showing the mean, 5^{th} and 95^{th} percentiles of wave steepness, H_{m0}/λ, are also shown in Figure 36. The mean wave steepness at the Jennette's Pier site is 0.0180 ($\approx 1/56$), and the 95^{th} percentile is about 1/29.

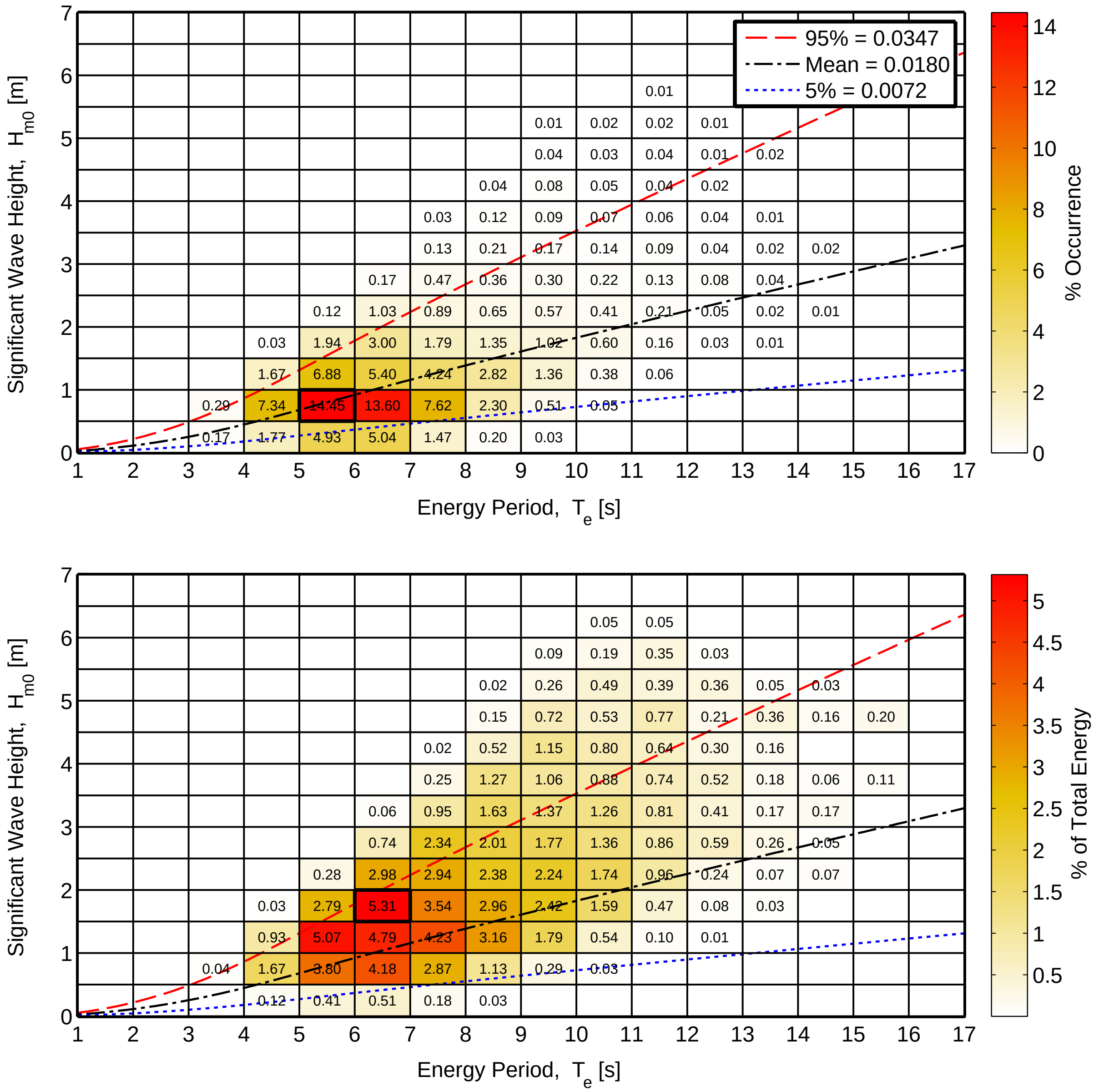


Figure 36: Joint probability distribution of sea states for the Jennette's Pier site. The top figure is frequency of occurrence and the bottom figure is percentage of total energy, where total energy in an average year is 53,300 kWh/m.

5.4.2. IEC TS Parameters

The monthly means of the six IEC TS parameters, along with the 5^{th} and 95^{th} percentiles, are shown in Figure 37. The months, March – February, are labeled with the first letter (e.g., March is M). The values in the figure are summarized in Table 18 in Appendix C.

Monthly means of the significant wave height, H_{m0}, and the omnidirectional wave power density, J, show the greatest seasonal variability compared to the other parameters. Values are smallest and vary the least during the summer months, while the rest of the year is fairly consistent. The same trend is observed for the monthly mean energy period, T_e, but its variation is less pronounced. These observations are consistent with the relationship between wave power density, significant wave height and energy period, where wave power density, J, is proportional to the energy period, T_e, and the square of the significant wave height, H_{m0}.

The direction of maximum directionally resolved wave power is typically from the east at $\sim 90°$ during the summer and from east/northeast at $\sim 70°$ during the rest of the year. Seasonal variations of the remaining parameters, ϵ_0 and d_θ, are much less than J, H_{m0}, T_e, and θ_J, and are barely discernable. Monthly means for spectral width, ϵ_0, remain nearly constant at ~ 0.34. Similarly, monthly means for the directionality coefficient, d_θ, remains at ~ 0.87. In summary, the waves at the Jennette's Pier site, from the perspective of monthly means, have a fairly consistent spectral width, are predominantly from the east / northeast, and exhibit a wave power that has a narrow directional spread.

Wave roses of wave power and significant wave height, presented in Appendix C, Figure 132 and 133, also show the predominant direction of the wave energy at the Jennette's Pier site, which is east, with frequent but small shifts to the north. Figure 132 shows two dominant wave direction sectors, east (at 90°) and east/northeast (ENE) at 60°. Along the predominant wave direction, 90°, the omnidirectional wave power density is at or below 35 kW/m about 22% of the time, and greater than 35 kW/m about 0.37% of the time. Along the east/northeast direction (60°), wave power density is at or below 35 kW/m about 18% of the time, and greater than 35 kW/m about 1% of the time.

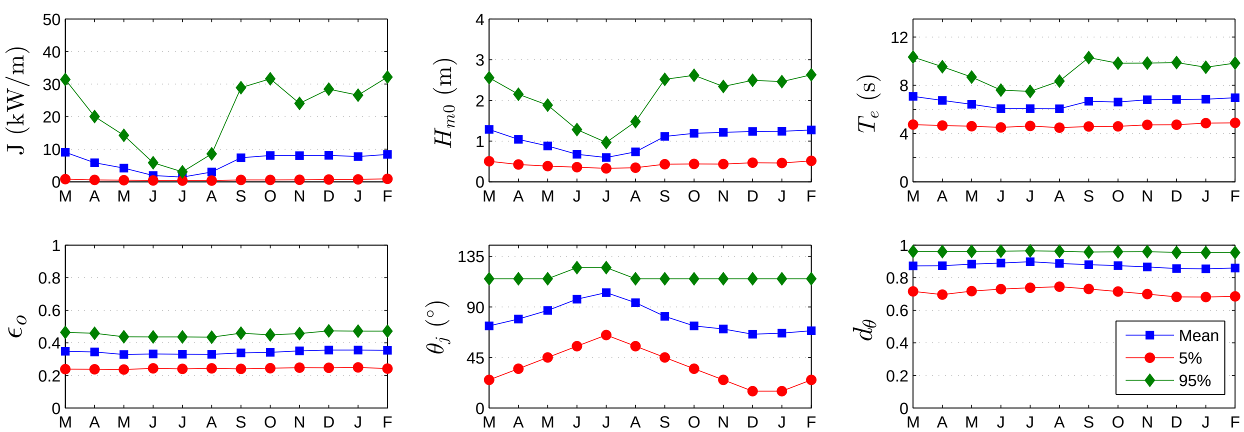


Figure 37: The average, 5th and 95th percentiles of the six parameters at the Jennette's Pier site.

Monthly means, however, smear the significant variability of the six IEC parameters over small time intervals as shown in plots of the parameters at 1-hour intervals in Figure 38 for a representative year. While seasonal patterns described for Figure 37 are still evident, these plots show how sea states can vary abruptly at small time scales with sudden changes, e.g., jumps in the wave power as a result of a storm.

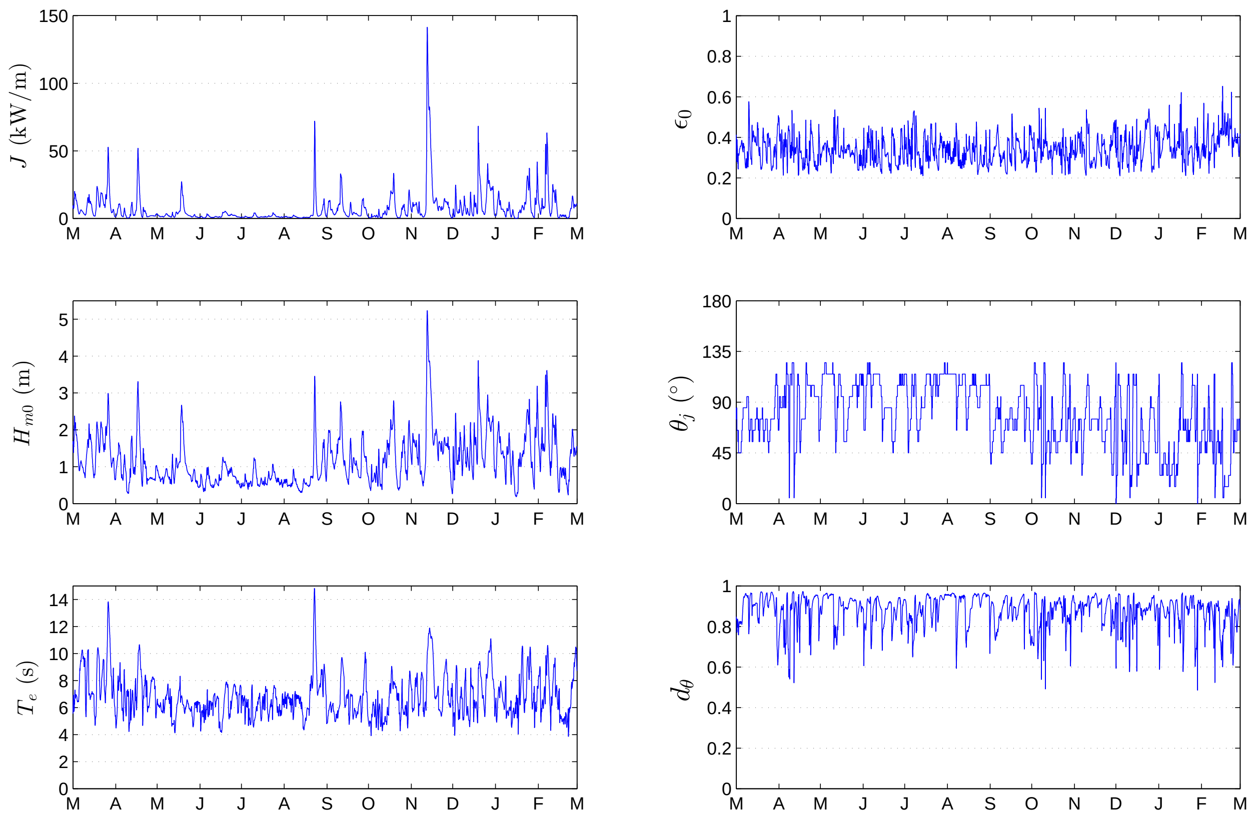


Figure 38: The six parameters of interest over a one-year period, March 2009 – February 2010 at the Jennette's Pier site.

5.4.3. Cumulative Distributions

Annual and seasonal cumulative distributions (a.k.a., cumulative frequency distributions) are shown in Figure 39. Note that spring is defined as March - May, summer as June - August, fall as September - November, and winter as December - February. The cumulative distributions are another way to visualize and describe the frequency of occurrence of individual parameters, such as H_{m0} and T_e. A developer could use cumulative 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 1 m for installation and recovery, according to Figure 39, this condition occurs about 60% of the time on average within a given year. If significant wave heights need to be less than or equal to 2 m for emergency maintenance, according to Figure 39, this condition occurs nearly 93% of time on average within a given year. Cumulative distributions, however, do not account for the duration of a desirable sea state, or weather window, which is needed to plan deployment and servicing of a WEC device at a test site. This limitation is addressed with the construction of weather window plots in the next section.

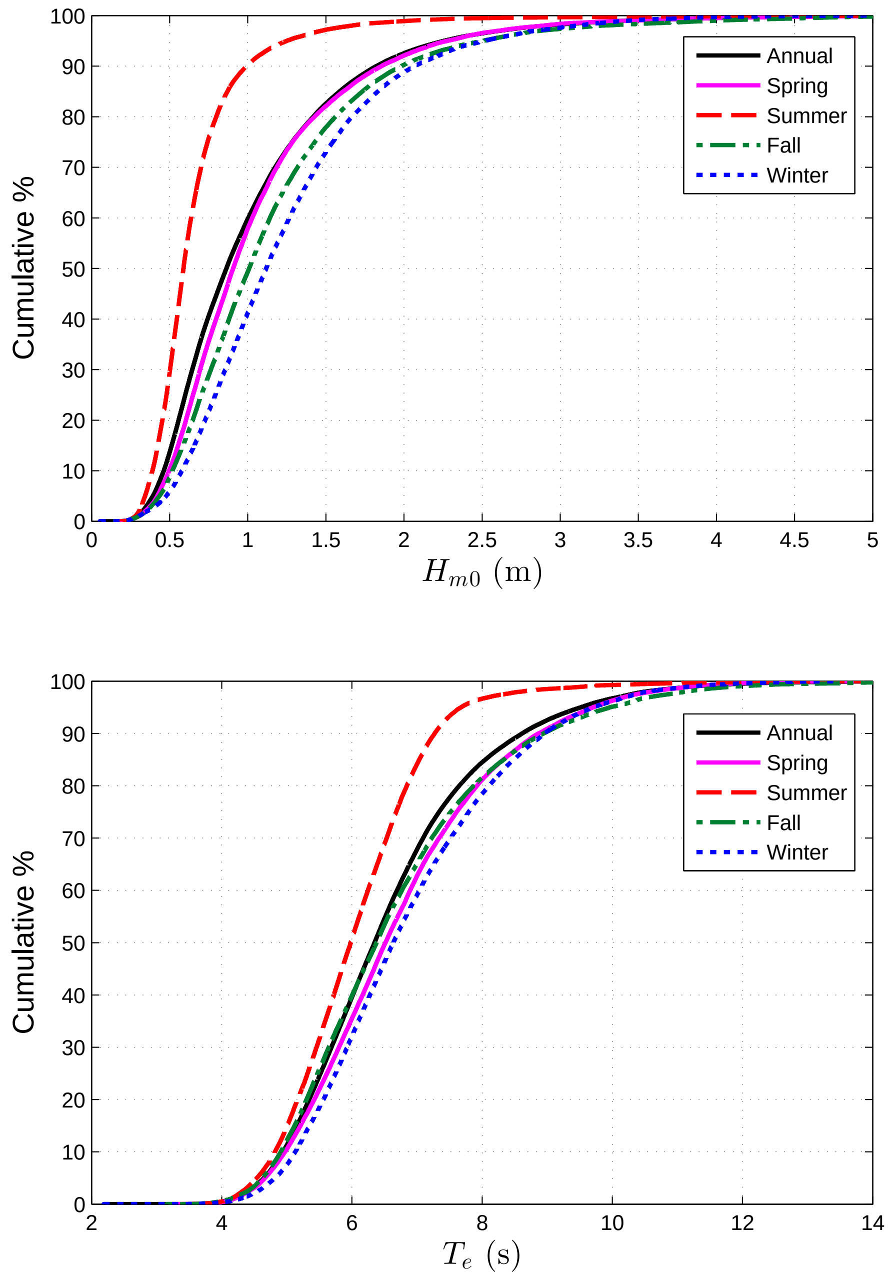


Figure 39: Annual and seasonal cumulative distributions of the significant wave height (top) and energy period (bottom) at the Jennette's Pier site.

5.4.4. Weather Windows

Figure 40 shows the number of weather windows at the Jennette's Pier site, when significant wave heights are at or below some threshold value for a given duration, for an average winter, spring, summer and fall. In these plots, each occurrence lasts a duration that is some multiple of 6-hours. The minimum weather window is, therefore, 6-hours in duration, and the maximum is 96-hours (4 days). The significant wave height threshold is the upper bound in each bin and indicates the maximum significant wave height experienced during the weather window. Note that the table is cumulative, so, for example, an occurrence of $H_{m0} \leq 0.5$ m for at least 66 consecutive hours in the fall is included in the count for 60 consecutive hours as well. In addition, one 12-hour window counts would count as two 6-hour windows. It is clear that there are significantly more occurrences of lower significant wave heights during the summer than winter, which corresponds to increased opportunities for deployment or operations and maintenance.

Weather window plots provide useful information at test sites when planning schedules for deploying and servicing WEC test devices. For example, if significant wave heights need to be less than or equal to 0.5 m for at least 12 consecutive hours to service a WEC test device at the Jennette's Pier site with a given service vessel, there would be, on average, forty-six weather windows in the summer, but only seven in the winter. When wind speed is also considered, Figure 41 shows the average number of weather windows with the additional restriction of wind speed, $U < 15$ mph. The local winds (which are not necessarily driving the waves) are used in these weather windows, and are given in Appendix C.4. That wind data was not available from the hindcast, so data from CFSR was used (see Section 2.3, Appendix C.4). For shorter durations (6- and 12-hour windows), daylight is necessary. Windows with $U < 15$ mph and only during daylight hours are shown in Figure 42. Daylight was estimated as 5am – 10pm Local Standard Time (LST).

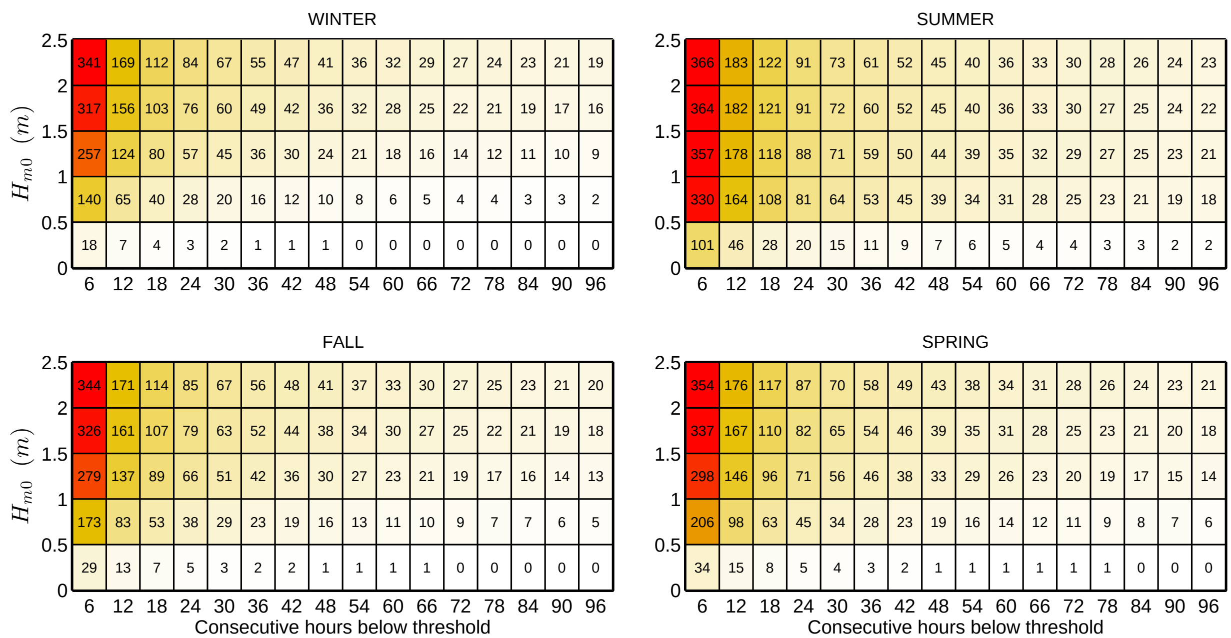


Figure 40: Average cumulative occurrences of wave height thresholds (weather windows) for each season at the Jennette's Pier site. Winter is defined as December – February, spring as March – May, summer as June – August, and fall as September – November.

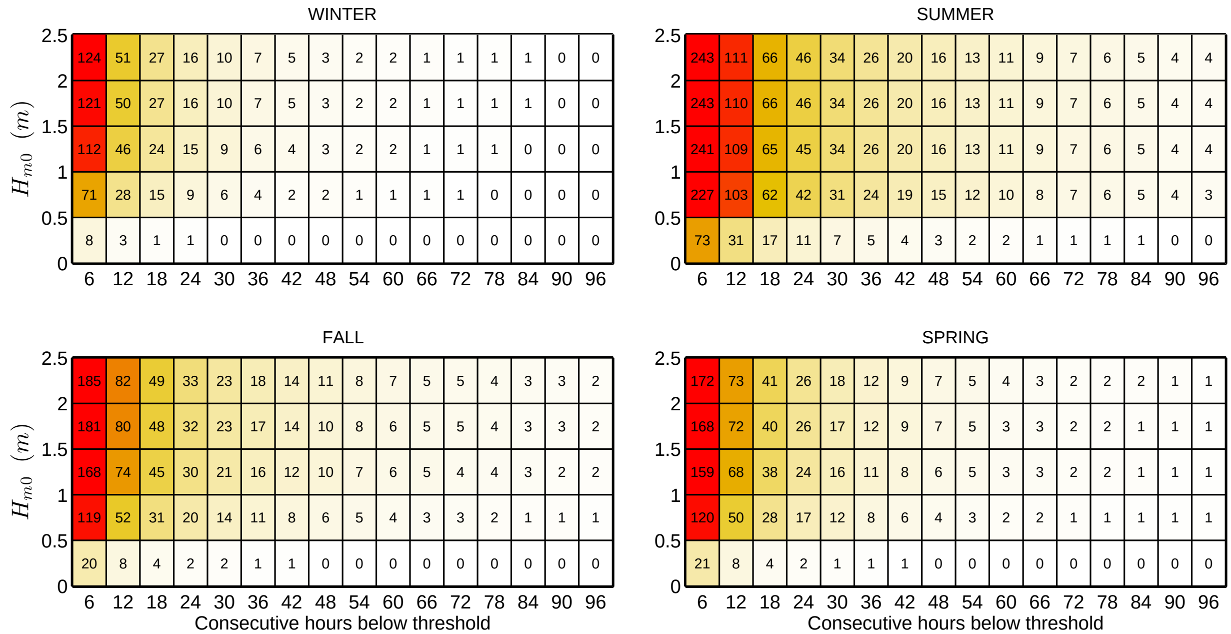


Figure 41: Average cumulative occurrences of wave height thresholds (weather windows) for each season at the Jennette's Pier site with an additional restriction of U < 15 mph.

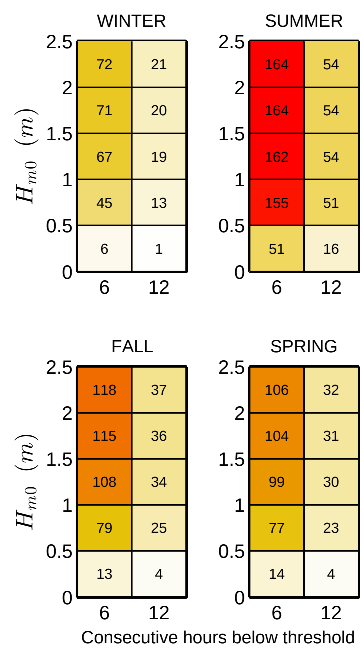


Figure 42: Average cumulative occurrences of wave height thresholds (weather windows) for 6- and 12-hour durations with $U < 15$ mph and only during daylight hours (5am – 10pm LST) at the Jennette's Pier site.

5.4.5. *Extreme Sea States*

As mentioned in 2.2, the way IFORM and the modified IFORM are currently implemented, they do not work well for datasets whose variables (H_{m0} and T_e) are bimodally distributed. The NDBC 44056 dataset is not well suited for IFORM, and therefore only the extreme significant wave height is estimated here using extreme value theory.

The generalized extreme value distribution (GEV) was fit to the annual significant wave height maximum in order to generate estimates of extreme values under the annual maximum method (AMM) (Rugerio et al. 2010). The peak over threshold (POT) method was also applied to the entire dataset in order to generate estimates of extreme values based on significant wave height exceedances over a certain threshold. Based on the application of this method as described by Ruggerio et al. (2010), the 99.5^{th} percentile of significant wave height was used as a threshold value. These methods were applied using the WAFO matlab toolbox (Brodtkorb et al. 2000). The bootstrapping method (Efron and Tibshirani 1993) was applied in order to generate a 95% confidence interval around the CDFs derived using both of the extreme value distribution methods utilized in this analysis.

The 100-year H_{m0} is estimated as 7.55 m and 8.46 m using the GEV and POT methods, respectively, as shown in Figures 43 and 44. The 10-, 25-, and 50-year values are shown in the figures. It should be noted that conditions at the NDBC44056 buoy (at 17 m depth) may differ significantly from the conditions at the test site berths (at 6 m and 11 m depths).

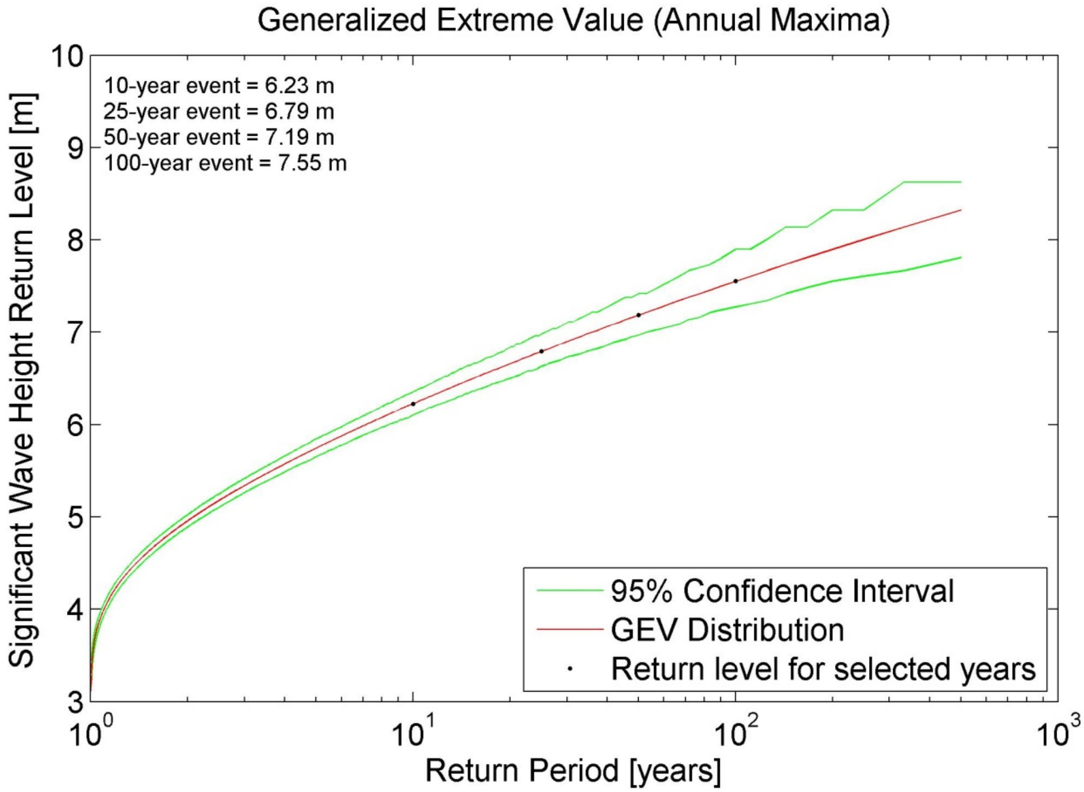


Figure 43: The generalized extreme values distribution was fit to annual maximum of significant wave height from NDBC44056 to generate estimates of extreme values. The 95% confidence interval is shown as well.

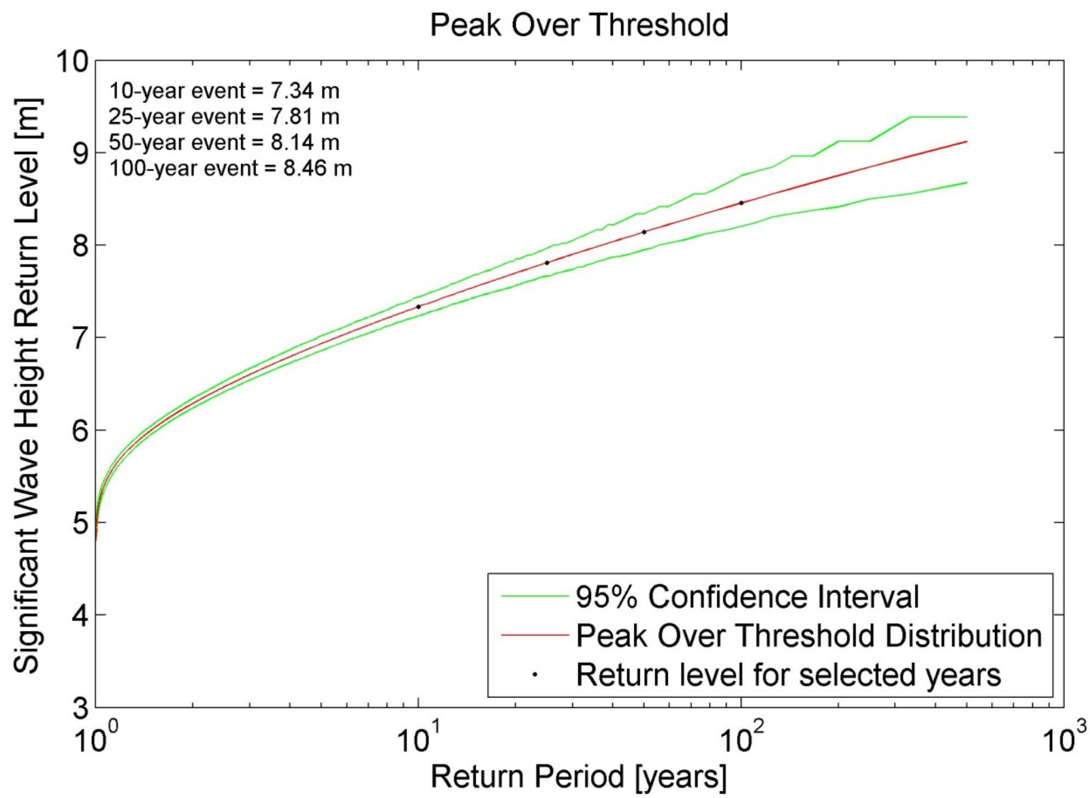


Figure 44: The peak over thresholds method was used with a threshold value of the 99.5^{th} percentile of significant wave height from NDBC44056. The 95% confidence interval is shown as well.

5.4.6. Representative Wave Spectrum

All hourly discrete spectra measured at AWAC05 for the most frequently occurring sea states are shown in Figure 45. The most frequently occurring sea state, which is within the range 0.5 m $< H_{m0} <$ 1 m and 7 s $< T_e <$ 8 s, was selected from a JPD similar to Figure 36 in Section 5.4.1, but based on the AWAC05 data. As a result, the JPD, and therefore the most common sea states, generated from the measured wave data are slightly different from that generated from hindcast data. For example, the most frequently occurring sea state for the JPD generated from hindcast data is in the same range for H_{m0} (0.5 m $< H_{m0} <$ 1 m), but two seconds lower on bounds for T_e (5 s $< T_e <$ 6 s). Often several sea states will occur at a very similar frequency, and therefore plots of hourly discrete spectra for several other sea states are also provided for comparison. Each of these plots includes the mean spectrum and standard wave spectra, including Bretschneider and JONSWAP, with default constants as described in Section 2.2.

For the purpose of this study, the mean spectrum is the 'representative' spectrum for each sea state, and the mean spectrum at the most common sea state, shown in Figure 45 (bottom-left plot), is considered the 'representative' spectrum at the site. The hourly spectra vary considerably about this mean spectrum, but this is partly reflective of the bin size chosen for H_{m0} and T_e. Comparisons of the representative spectra in all plots with the Bretschneider and JONSWAP spectra illustrate why modeled spectra with default constants, e.g., the shape parameter $\gamma = 3.3$ for the JONSWAP spectrum, should be used with caution. Using the constants provided in Section 2.2, the Bretschneider spectra are, at best, fair representations of the mean spectra in Figure 59. There is some evidence of bimodal spectra in the four sea states displayed, which is not captured by the modeled spectra. The mean measured spectra is the best representation of the conditions, however, if these modeled spectra were to be used at this site, it is recommended that the constants undergo calibration against some mean spectrum, e.g., the representative spectrum constructed here. A better alternative may be to explore other methods or spectral forms to describe bimodal spectra (e.g., Mackay 2011) if it is known that the shape is not unimodal.

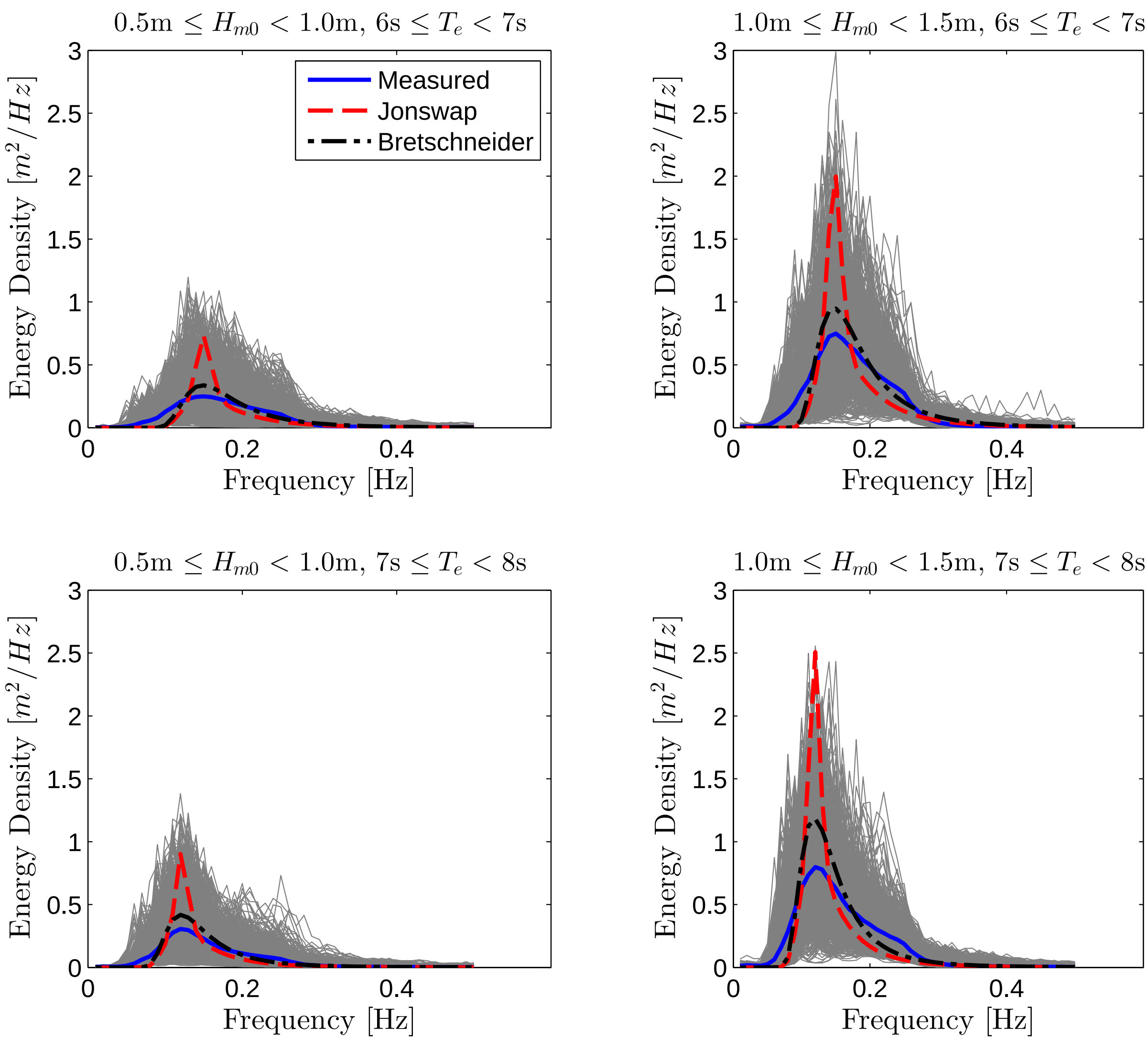


Figure 45: All hourly discrete spectra and the mean spectra measured at AWAC05 within the sea state listed above each plot. The JONSWAP and Bretschneider spectra are represented by red and black dotted lines, respectively.

6. U.S. ARMY CORPS OF ENGINEERS (USACE) FIELD RESEARCH FACILITY (FRF)

6.1. Site Description

The Field Research Facility (FRF) located on the Atlantic Ocean in Duck, NC was established by the U.S. Army Corps of Engineers in 1977 as part of the Coastal and Hydraulics Laboratory to support the Corps coastal engineering research requirements. The facility consists of a 560 m (1840-ft) long research pier, a main office building, field support buildings, and a 40 m (130-ft) observation tower. Since its creation, the FRF has maintained a comprehensive, long-term monitoring program of the coastal ocean including waves, tides, currents, local meteorology, and the concomitant beach response. The monitoring program is supported by a small, highly skilled field staff and several unique vehicles that permit successful operations in the turbulent surf zone.

At the site, the bathymetry is gently sloping, and the sea bed is sandy. Figure 47 shows the bathymetry around the site, and consists of a wide shelf. For the purpose of this catalogue, hindcast data at 36.1858 N, 75.7486 W at 4.8 m depth was used to represent the site. The wave climate at the test site varies seasonally, with calmer seas in the summer compared to more energetic seas in the winter. The wave environment at USACE FRF is characterized by an annual average power flux of about 3.29 kW/m at 4.8 m depth.

The USACE FRF offers a wide range of technical and testing infrastructure support services for WEC developers. The site has small scale, shallow water wave energy resources, and can accommodate scaled devices. The research pier can serve as a cable conduit through the surf zone to locations on land.

The FRF was utilized as an off-grid WEC test site in 2012 by Resolute Marine Energy (RME). RME located their device approximately 25 m south of the pier and in 6 m water depth. The FRF is capable of deploying devices past the pier in state waters. Locations past the pier would have higher wave power compared to the data presented in this chapter at 4.8 m depth, and presumably wave characteristics would be similar to the Jennette's Pier Wave Energy Converter Test Facility in Chapter 5, which uses hindcast data in 12.6 m depth and is ~34 km southeast of the FRF.

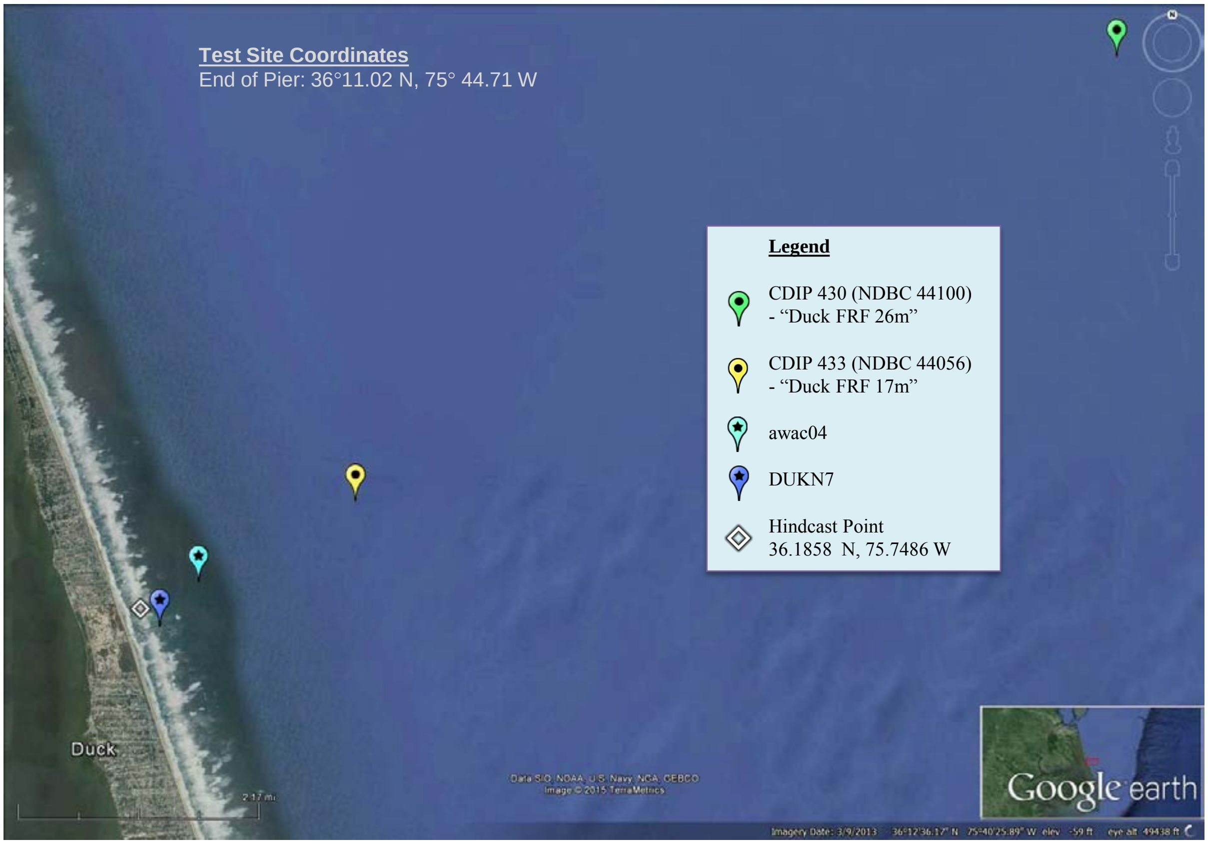


Figure 46: The USACE FRF is located in the coastal waters of North Carolina in the town of Duck. Three buoys, one AWAC, and one water level observation network close to the site are shown (see Table 4). Image modified from Google Earth (Google Earth 2015).

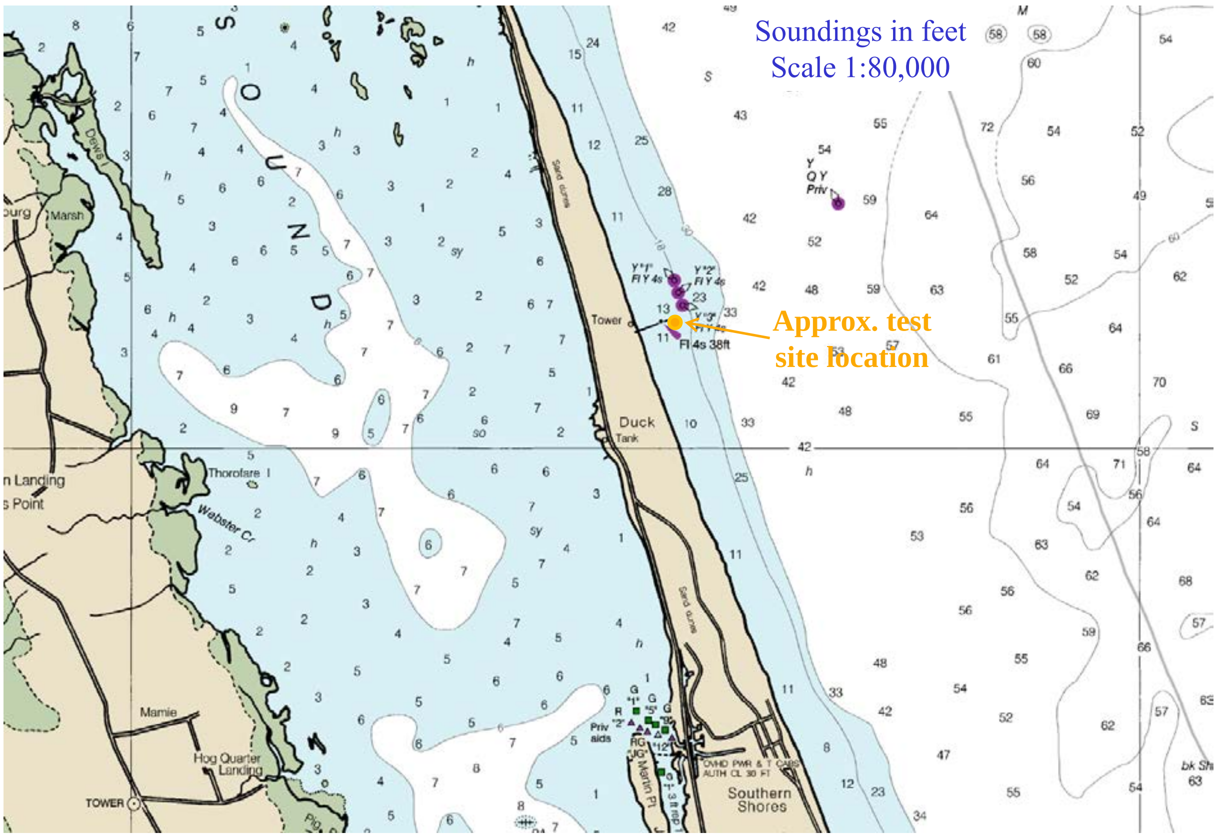


Figure 47: Nautical chart of Duck, NC and the surrounding area shows the gradually sloping bathymetry off Duck Pier. Soundings in feet (1 foot = 0.3048 m). Image modified from nautical chart #12204 (Office of Coast Survey 2015). End of Pier Coordinates: 36°11.02 N, 75°44.71 W.

6.2. WEC Testing Infrastructure

6.2.1. Mooring Berths

Mooring systems are not provided and would need to be installed according to the developer's design (FRF staff have extensive experience deploying moored equipment at this site). Energy generated and monitoring instrumentation will be cabled to the FRF communications trailer located at the seaward end of the pier or along the pier to a landward location.

6.2.2. Electrical Grid Connection

There are no special provisions for interfacing with the electrical grid (for the purpose of exporting power).

During the RME experiment, access to the grid was provided via a 3 phase outlet located on the pier. Their wave-driven generator was an induction machine (off-the-shelf induction motor driven as a generator) and was "plugged in" to this outlet. A load bank was setup to absorb any additional power generated to eliminate the export of power. The combination of their generator and load bank "looked" to the grid as a conventional motor consisting of a "real" load component (kW) equal to the net of generator output and load bank absorption, as well as a "reactive component" (kVAR) to excite the field of the generator. The load power factor was probably not less than 80%.

All aspects of the power flow to the grid connection were measured via a multi-function power transducer supplied by Ohio Semitronics. Measurements included real power, reactive power, apparent power (vector sum of real and reactive components) and power factor = real/apparent. The line-line voltages and line currents were also monitored. As a protective measure the system was provided with a frequency transducer and programmed to disconnect the apparatus in the event of an unusual deviation from 60 Hz.

6.2.3. Facilitating Harbor

The USACE FRF can be accessed by boat via Oregon Inlet (∼30 miles from the Pier). Several harbors are within 10 miles of the inlet, including harbors and marinas at UNC CSI and Wanchese, from which service vessels and commercial divers are available. ARMY Lighter Amphibious Resupply Cargo (LARC) vessels are also available at the FRF. These 10.6 m amphibious crafts are capable of driving off the beach and operating on the ocean within 3 nm of the coast.

6.2.4. On-Shore Office Space

Office space is available at the FRF although schedule dependent.

6.2.5. Service Vessel and Engineering Boatyard Access

A USACE FRF vessel and amphibious craft are available for support, along with a vessel Captain, research technicians, and dive operations support for additional fees.

6.2.6. Travel and Communication Infrastructure

The Norfolk International Airport (ORF) is approximately a one and a half hour drive from the USACE FRF. Raleigh Durham International Airport (RDU) is approximately a three and a half hour drive from the USACE FRF. Cellular service offers consistent coverage; there are several Federal Communication Commission (FCC) registered cell phone towers located in and around Duck, NC.

6.2.7. Met-Ocean Monitoring Equipment

There are many instruments located near the USACE FRF site. The most prominent ones are listed here, and additional information can be found on the FRF website. There is one National Buoy Data Center (NDBC) buoy (Figure 48(a)) that measures and collects ocean data, along with two CDIP buoys (Figure 48(b)) operated by the USACE FRF. There is an AWAC just northeast of the end of the pier, and a water level observation network on the pier (see Figure 46 for location). Instrument and data specifications for this monitoring equipment are summarized in Table 4. As noted above, not all measurements are listed here, and it is recommended to check the FRF website (http://www.frf.usace.army.mil/frf_data.shtml) for all available data. In addition, there are several measurements nearby at Jennettes Pier, NC (∼34 km southeast of the FRF), see Section 5.2.7.

Figure 48: (a) NDBC 44014 located 93 km northeast of the test site (National Data Buoy Center 2015), (b) CDIP 430 located 15 km northeast of the site (Field Research Facility, 2015).

Table 4: Wave monitoring equipment in close proximity to the USACE FRF.

<table>
<tr><th>Instrument Name (Nickname)</th><th colspan="3">NDBC 44014 (“Virginia Beach”)</th><th colspan="2">NDBC 44100 - CDIP 430 - (“Duck FRF 26m, NC”)</th><th colspan="2">NDBC 44056 - CDIP 433 (“Duck FRF 17m, NC”)</th></tr>
<tr><td>Type</td><td colspan="3">3-meter discus buoy</td><td colspan="2">Waverider Buoy</td><td colspan="2">Waverider Buoy</td></tr>
<tr><td>Measured parameters</td><td colspan="3">-std. met. data
-continuous winds
-spectral wave density
-spectral wave direction</td><td colspan="2">-std. met. data
-spectral wave density
-spectral wave direction</td><td colspan="2">-std. met. data
-spectral wave density
-spectral wave direction</td></tr>
<tr><td>Variables reported, including derived variables (Sampling interval)</td><td>Std Met.:
WDIR
WSPD
GST
WVHT
DPD
APD
PRES
ATMP
WTMP
(1 hr sampling period)</td><td>Contin. Winds:
WDIR
WSPD
GDR
GST
GTIME
(10 min sampling period)</td><td>-Spectral Wave Density
-Spectral Wave direction
(1 hr sampling period)</td><td>Std Met.:
WVHT
DPD
APD
MWD
WTMP
(30 min sampling period)</td><td>-Spectral Wave Density
-Spectral Wave direction
(30 min sampling period)</td><td>Std Met.:
WVHT
DPD
APD
MWD
WTMP
(30 min sampling period)</td><td>-Spectral Wave Density
-Spectral Wave direction
(30 min sampling period)</td></tr>
<tr><td>Location</td><td colspan="3">~93 km northeast of the end of FRF Duck Pier</td><td colspan="2">~15 km northeast of the end of FRF Duck Pier</td><td colspan="2">~3 km northeast of the end of FRF Duck Pier</td></tr>
<tr><td>Coordinates</td><td colspan="3">36.611 N 74.842 W (36°36’41” N 74°50’31” W)</td><td colspan="2">36°15.461 N 75°35.479 W (36°15’27.66” N 75°35’28.74” W)</td><td colspan="2">36.200 N 75.714 W (36° 11.993N 75°42.843W)</td></tr>
<tr><td>Depth</td><td colspan="3">47.6 m</td><td colspan="2">26 m</td><td colspan="2">17.4 m</td></tr>
<tr><td>Data Start</td><td colspan="3">std met: 10/1/1990
contin winds: 12/31/2002
spect wave dens: 01/23/1996
spect wave dir: 04/14/1998</td><td colspan="2">5/22/2008</td><td colspan="2">spectral wave data: 1987
directional spectra: 1997</td></tr>
<tr><td>Data End</td><td colspan="3">present</td><td colspan="2">present</td><td colspan="2">present</td></tr>
<tr><td>Period of Record</td><td colspan="3">std met: ~25 yrs
contin winds: ~13 yrs
spect wave dens: ~20 yrs
spect wave dir: ~17 yrs</td><td colspan="2">~7 yrs</td><td colspan="2">spectral data: ~28 yrs
directional spectra: ~18 yrs</td></tr>
<tr><td>Owner / Contact Person</td><td colspan="3">Funding provided by the US Army Corps of Engineers, Coastal Hydraulics Laboratory Owned and maintained by National Data Buoy Center http://www.ndbc.noaa.gov/station_history.php?station=44014</td><td colspan="2">Field Research Facility, Coastal Observations & Analysis Branch, US Army Corps of Engineers, Duck, North Carolina http://www.frf.usace.army.mil/wvrdr430/archive.shtml

http://cdip.ucsd.edu/?units=metric&tz=UTC&pub=public&map_stati=1,2,3&nav=historic&sub=data&stn=430&stream=p1</td><td colspan="2">Field Research Facility, Coastal Observations & Analysis Branch, US Army Corps of Engineers, Duck, North Carolina http://www.frf.usace.army.mil/wvrdr630/realtime.shtml

http://cdip.ucsd.edu/?units=metric&tz=UTC&pub=public&map_stati=1,2,3&nav=recent&sub=observed&stn=433&stream=p1&xitem=info</td></tr>
</table>

Instrument Name (Nickname)	11m AWAC (awac04) – Duck Field Research Facility	DUKN7 - 8651370 - Duck Pier, NC
Type	Acoustic Wave and Current Gauge (AWAC)	Water Level Observation Network
Measured parameters	std. met. data spectral wave density spectral wave direction current speed and direction	wind dir & speed gust pressure air temperature water temperature
Variables reported, including derived variables (Sampling interval)	*Std Met.:* WVHT DPD MWD (1 hr sampling period) Spectral Wave Density Spectral Wave direction (1 hr sampling period) Longshore current speed Cross-shore current speed (1 hr sampling period)	WDIR WSPD GST PRES ATMP WTMP (6 min sampling period)
Location	~0.8 km northeast of the end of FRF Duck Pier	on FRF Duck Pier
Coordinates	36.189 N 75.739 W (36°11.36' N 75°44.36' W)	36.183 N 75.747 W (36°11'1" N 75°44'44" W)
Depth	11.4 m	site elevation: 7.7 m above mean sea level air temp height: 8 m above site elevation anemometer height: 9.9 m above site elevation barometer elev: 9.1 m above mean sea level
Data Start	6/1/2008	7/1/2008
Data End	Currently down plans to restore data collect are underway	present
Period of Record	~7.5 yrs	~7.5 yrs
Owner / Contact Person	Field Research Facility, Coastal Observations & Analysis Branch, US Army Corps of Engineers, Duck, North Carolina http://www.nortekusa.com/usa/news/real-time-awac-data-from-duck-field-research-facility http://www.frf.usace.army.mil/awac04/realtime.shtml	NOAA's National Ocean Service, Tides & Currents http://www.ndbc.noaa.gov/station_page.php?station=dukn7 http://www.wunderground.com/MAR/buoy/DUKN7.html?

6.2.8. Environmental Monitoring

No monitoring has been required in previous deployments and tests.

6.2.9. Permitting

The site is permitted by the U.S. Army Corps of Engineers. Notice will be given to mariners via the Coast Guard when specific devices are tested.

6.3. Data used

Researchers at the UNC CSI produced a 31 year hindcast dataset for the area offshore of North Carolina (UNC CSI 2015). This dataset was used to calculate statistics of interest for the wave resource characterization at the Jennette's Pier and USACE FRF sites. The hindcast data at the grid point shown in Figure 46.

In addition to the hindcast data set, historical data from AWAC04 was used to calculate representative spectra. Because the AWAC04 only has data for about seven years, historical data from a USACE FRF waverider buoy (NDBC 44056 / CDIP 433) was used to calculate extreme sea states. Wind data was available from a water level observation network on the USACE FRF Duck pier. However, to be consistent with the other sites, Climate Forecast System Reanalysis (CFSR) winds were used, as explained in Section 2.3. As with the other sites, current data was downloaded from OSCAR. See Figures 46 and 49 for data locations.

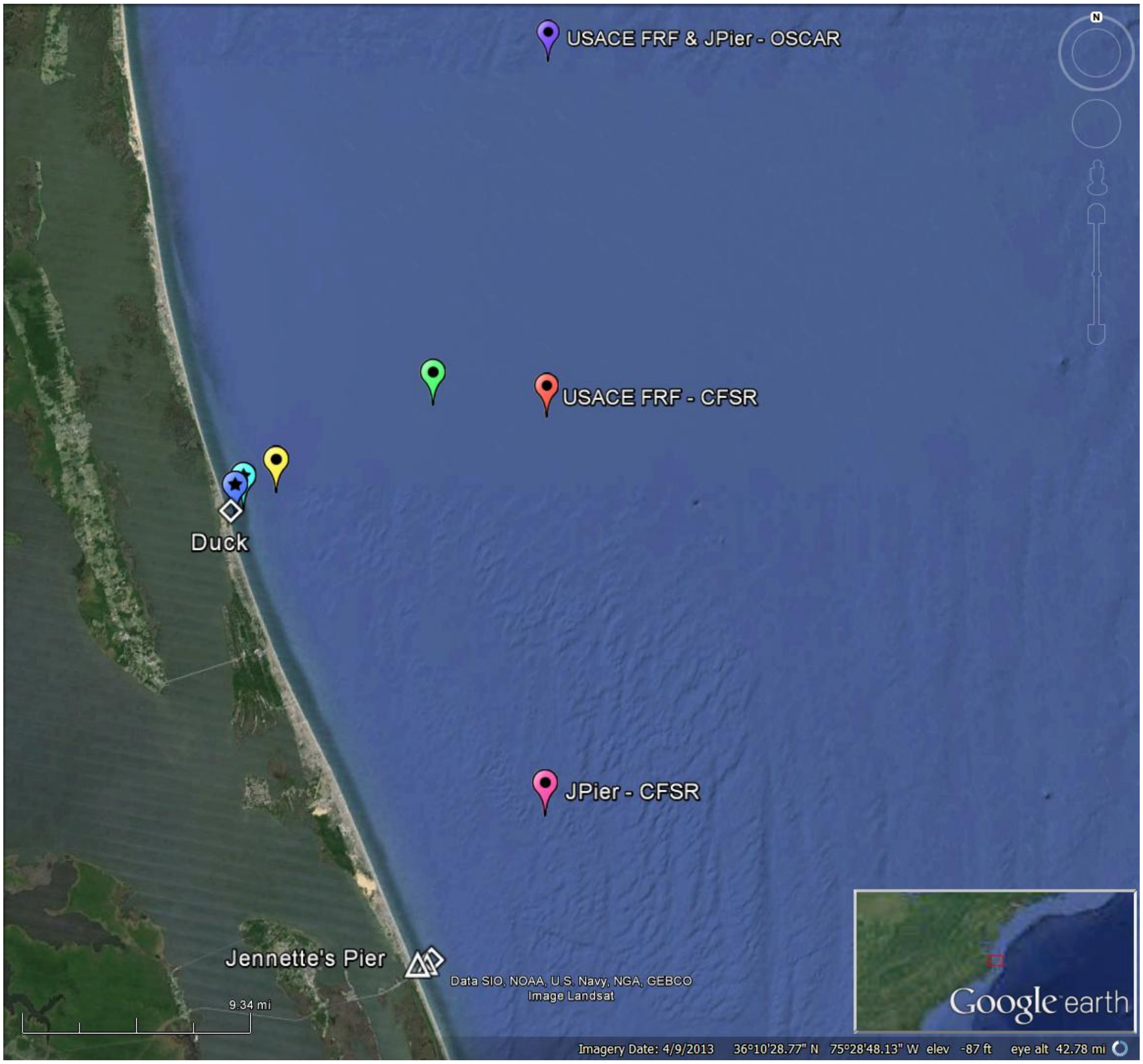


Figure 49: Jennette's Pier (see Chapter 5) & USACE FRF location map showing CSFR wind and OSCAR surface current data points (Google Earth 2015).

6.4. Results

The following sections provide information on the joint probability of sea states, the variability of the IEC TS parameters, cumulative distributions, weather windows, extreme sea states, and representative spectra. This is supplemented by wave roses as well as wind and surface current data in Appendix D. The wind and surface current data provide additional information to help developers plan installation and operations & maintenance activities.

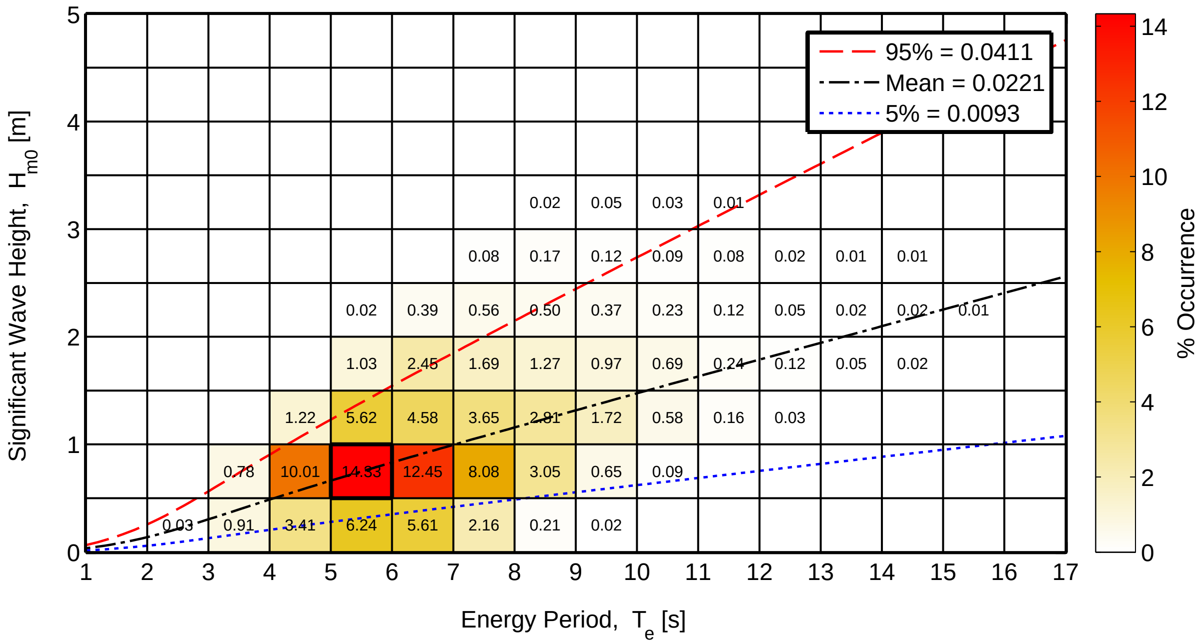
6.4.1. Sea States: Frequency of Occurrence and Contribution to Wave Energy

Joint probability distributions of the significant wave height, H_{m0}, and energy period, T_e, are shown in Figure 50. Figure 50 (top) shows the frequency of occurrence of each binned sea state and Figure 50 (bottom) shows the percentage contribution to the total wave energy. Figure 50 (top) indicates that the majority of sea states are within the range 0 m < H_{m0} < 2 m and 4 s < T_e < 9 s; very few occurrences of H_{m0} greater than 3 m occur because the data is taken from a depth of 4.8 m. The site is well suited for testing WECs at smaller scales, especially those that are bottom mounted because the depths only reach about 25 m at the end of the pier.

As mentioned in the methodology (Section 2.2), previous studies show that sea states with the highest frequencies of occurrence do not necessarily correspond to those with the highest contribution to total wave energy. The total wave energy in an average year is 28,815 kWh/m, which corresponds to an average annual omnidirectional wave power of 3.29 kW/m. The most frequently occurring sea state is within the range 0.5 m < H_{m0} < 1 m and 5 s < T_e < 6 s, while the sea state that contributes most to energy is within the range 1 m < H_{m0} < 1.5 m and 5 s < T_e < 6 s. Several sea states occur at a similar frequency, and sea states within 0.5 m < H_{m0} < 2 m and 5 s < T_e < 8 s contribute a similar amount to energy.

Frequencies of occurrence and contributions to energy of less than 0.01% are considered negligible and are not shown for clarity. For example, the sea state within 0 m < H_{m0} < 0.5 m and 2 s < T_e < 3 s has an occurrence of 0.03%. The contribution to total energy, however, is only 0.002% and, therefore, does not appear in Figure 50 (bottom). Similarly, the sea state within 2.5 m < H_{m0} < 3 m and 15 s < T_e < 16 s has an occurrence of 0.001%, but the contribution to total energy is 0.01%.

Curves showing the mean, 5^{th} and 95^{th} percentiles of wave steepness, H_{m0}/λ, are also shown in Figure 50. The mean wave steepness at the USACE FRF site is 0.0221 ($\approx 1/45$), and the 95^{th} percentile is about 1/24.



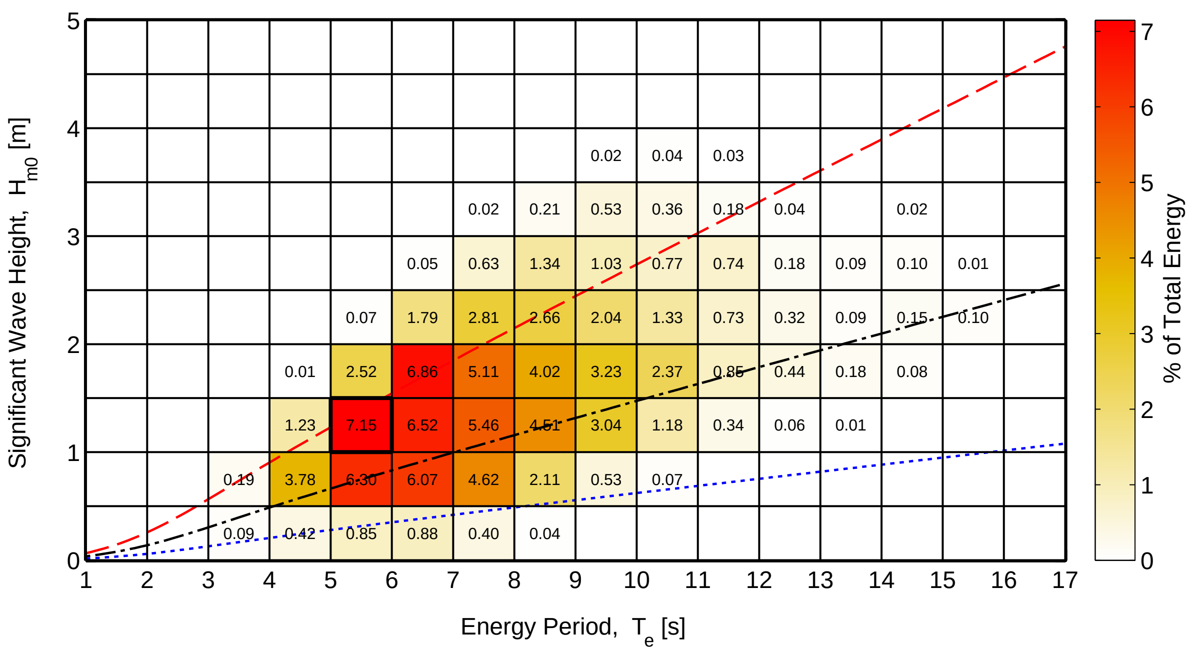


Figure 50: Joint probability distribution of sea states for the USACE FRF site. The top figure is frequency of occurrence and the bottom figure is percentage of total energy, where total energy in an average year is 28,815 kWh/m.

6.4.2. IEC TS Parameters

The monthly means of the six IEC TS parameters, along with the 5^{th} and 95^{th} percentiles, are shown in Figure 51. The months, March – February, are labeled with the first letter (e.g., March is M). The values in the figure are summarized in Table 23 in Appendix D.

Monthly means of the significant wave height, H_{m0}, and the omnidirectional wave power density, J, show the greatest seasonal variability compared to the other parameters. Values are smallest and vary the least during the summer months, while the rest of the year is fairly consistent. The same trend is observed for the monthly mean energy period, T_e, but its variation is less pronounced. These observations are consistent with the relationship between wave power density, significant wave height and energy period, where wave power density, J, is proportional to the energy period, T_e, and the square of the significant wave height, H_{m0}.

The direction of maximum directionally resolved wave power is typically from the east at $\sim 90°$ during the summer and from east/northeast at $\sim 70°$ during the rest of the year. Seasonal variations of the remaining parameters, ϵ_0 and d_θ, are much less than J, H_{m0}, T_e, and θ_J, and are barely discernable. Monthly means for spectral width, ϵ_0, remain nearly constant at ~ 0.37. Similarly, monthly means for the directionality coefficient, d_θ, remains at ~ 0.9. In summary, the waves at the USACE FRF site, from the perspective of monthly means, have a fairly consistent spectral width, are predominantly from the east / northeast, and exhibit a wave power that has a narrow directional spread.

Wave roses of wave power and significant wave height, presented in Appendix D, Figure 138 and 139, also show the predominant direction of the wave energy at the USACE FRF site, which is east, with frequent but small shifts to the north. Figure 138 shows two dominant wave direction sectors, east (at 90°) and east/northeast (ENE) at 60°. Along the predominant wave direction, 90°, the omnidirectional wave power density is at or below 35 kW/m about 35% of the time, but greater than 35 kW/m about 0.02% of the time. Along the east/northeast direction (60°), wave power density is at or below 35 kW/m about 23% of the time, and greater than 35 kW/m about 0.04% of the time.

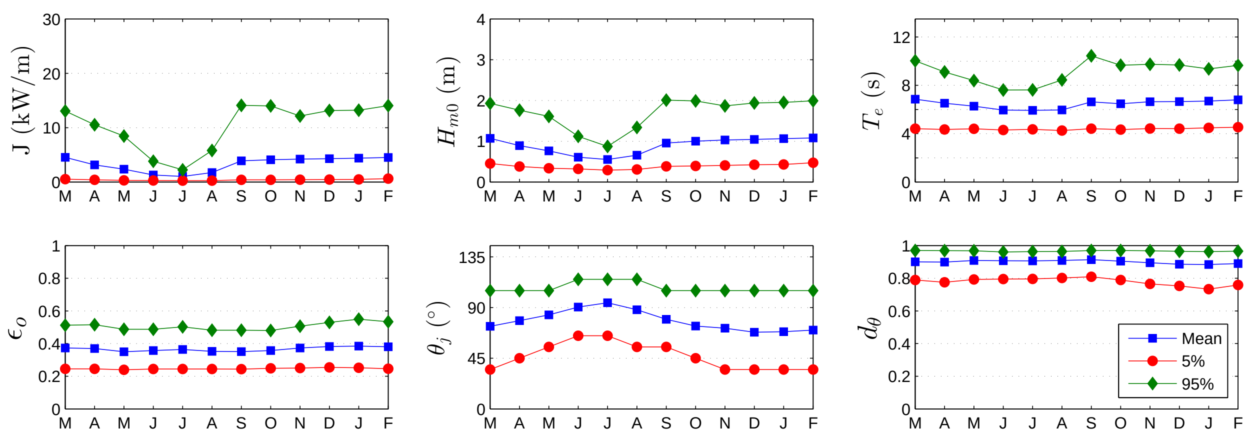


Figure 51: The average, 5^{th} and 95^{th} percentiles of the six parameters at the USACE FRF site.

Monthly means, however, smear the significant variability of the six IEC parameters over small time intervals as shown in plots of the parameters at 1-hour intervals in Figure 52 for a representative year. While seasonal patterns described for Figure 51 are still evident, these plots show how sea states can vary abruptly at small time scales with sudden changes, e.g., jumps in the wave power as a result of a storm.

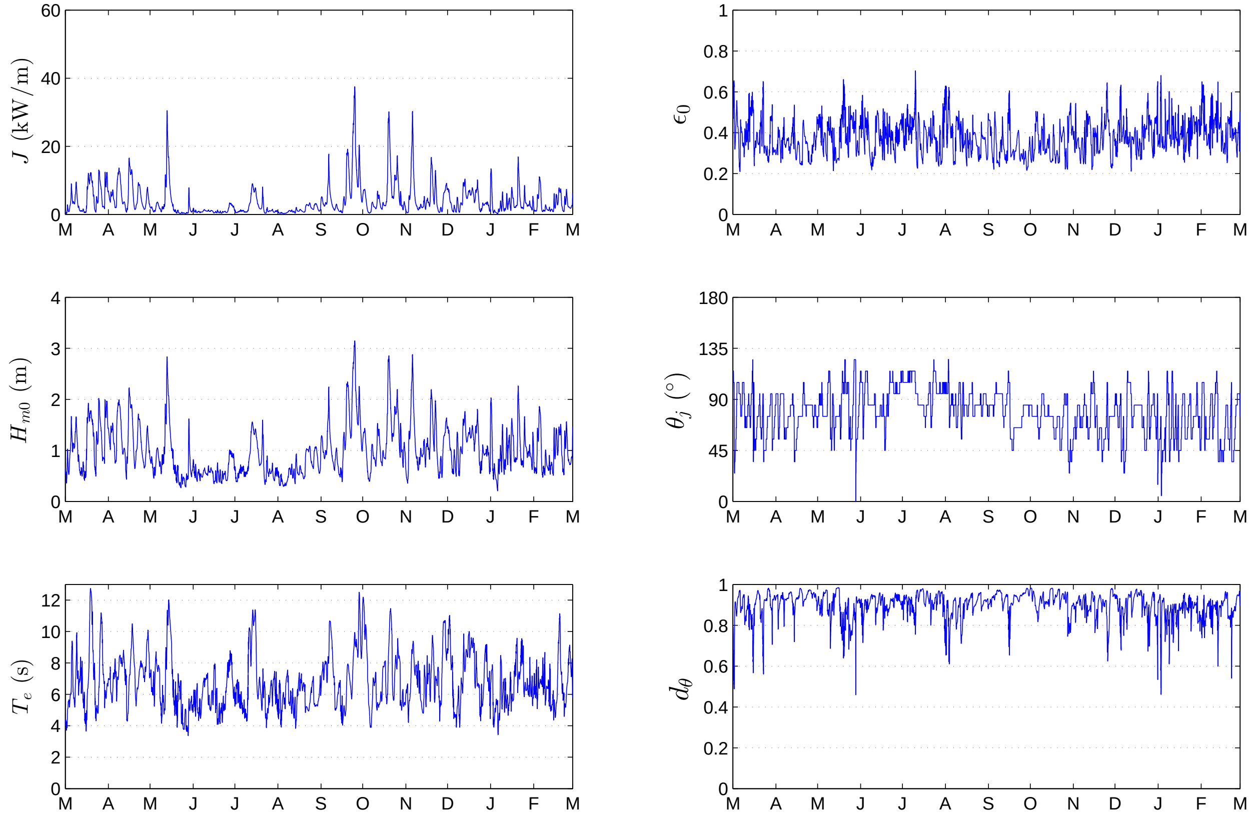


Figure 52: The six parameters of interest over a one-year period, March 2008 – February 2009 at the USACE FRF site.

6.4.3. Cumulative Distributions

Annual and seasonal cumulative distributions (a.k.a., cumulative frequency distributions) are shown in Figure 53. Note that spring is defined as March May, summer as June - August, fall as September - November, and winter as December - February. The cumulative distributions are another way to visualize and describe the frequency of occurrence of individual parameters, such as H_{m0} and T_e. A developer could use cumulative 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 1 m for installation and recovery, according to Figure 53, this condition occurs about 68% of the time on average within a given year. If significant wave heights need to be less than or equal to 2 m for emergency maintenance, according to Figure 53, this condition occurs nearly 97% of time on average within a given year. Cumulative distributions, however, do not account for the duration of a desirable sea state, or weather window, which is needed to plan deployment and servicing of a WEC device at a test site. This limitation is addressed with the construction of weather window plots in the next section.

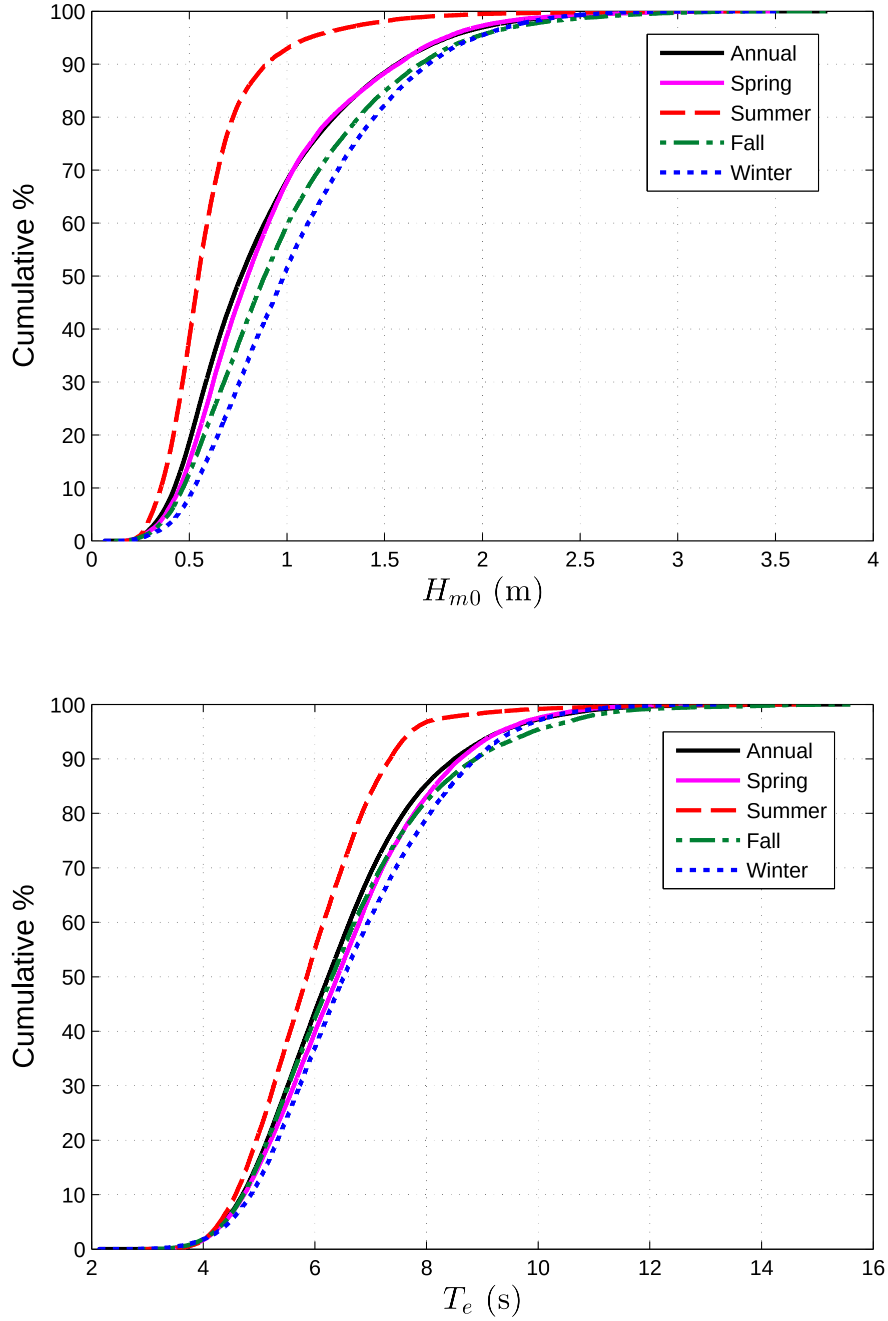


Figure 53: Annual and seasonal cumulative distributions of the significant wave height (top) and energy period (bottom) at the USACE FRF site.

6.4.4. Weather Windows

Figure 54 shows the number of weather windows at the USACE FRF site, when significant wave heights are at or below some threshold value for a given duration, for an average winter, spring, summer and fall. In these plots, each occurrence lasts a duration that is some multiple of 6-hours. The minimum weather window is, therefore, 6-hours in duration, and the maximum is 96-hours (4 days). The significant wave height threshold is the upper bound in each bin and indicates the maximum significant wave height experienced during the weather window. Note that the table is cumulative, so, for example, an occurrence of $H_{m0} \leq 0.5$ m for at least 66 consecutive hours in the fall is included in the count for 60 consecutive hours as well. In addition, one 12-hour window counts would count as two 6-hour windows. It is clear that there are significantly more occurrences of lower significant wave heights during the summer than winter, which corresponds to increased opportunities for deployment or operations and maintenance.

Weather window plots provide useful information at test sites when planning schedules for deploying and servicing WEC test devices. For example, if significant wave heights need to be less than or equal to 0.5 m for at least 12 consecutive hours to service a WEC test device at the USACE FRF site with a given service vessel, there would be, on average, sixty weather windows in the summer, but only ten in the winter. When wind speed is also considered, Figure 55 shows the average number of weather windows with the additional restriction of wind speed, $U < 15$ mph. The local winds (which are not necessarily driving the waves) are used in these weather windows, and are given in Appendix D.4. That wind data was not available from the hindcast, so data from CFSR was used (see Section 2.3, Appendix D.4). For shorter durations (6- and 12-hour windows), daylight is necessary. Windows with $U < 15$ mph and only during daylight hours are shown in Figure 56. Daylight was estimated as 5am – 10pm Local Standard Time (LST).

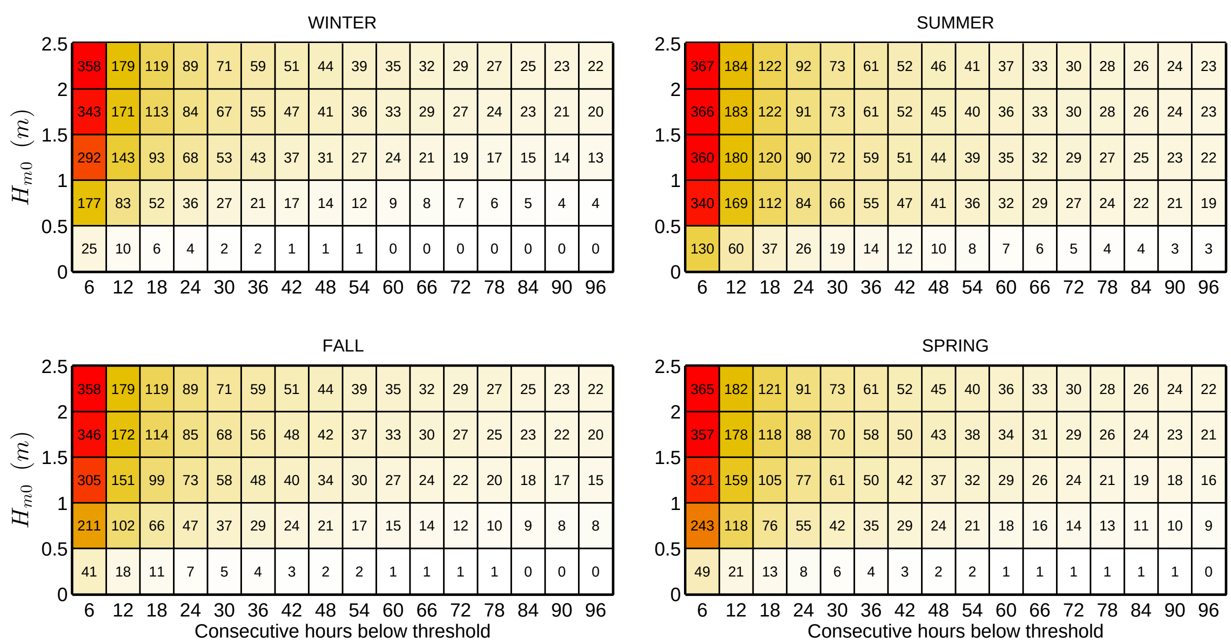


Figure 54: Average cumulative occurrences of wave height thresholds (weather windows) for each season at the USACE FRF site. Winter is defined as December – February, spring as March – May, summer as June – August, and fall as September – November.

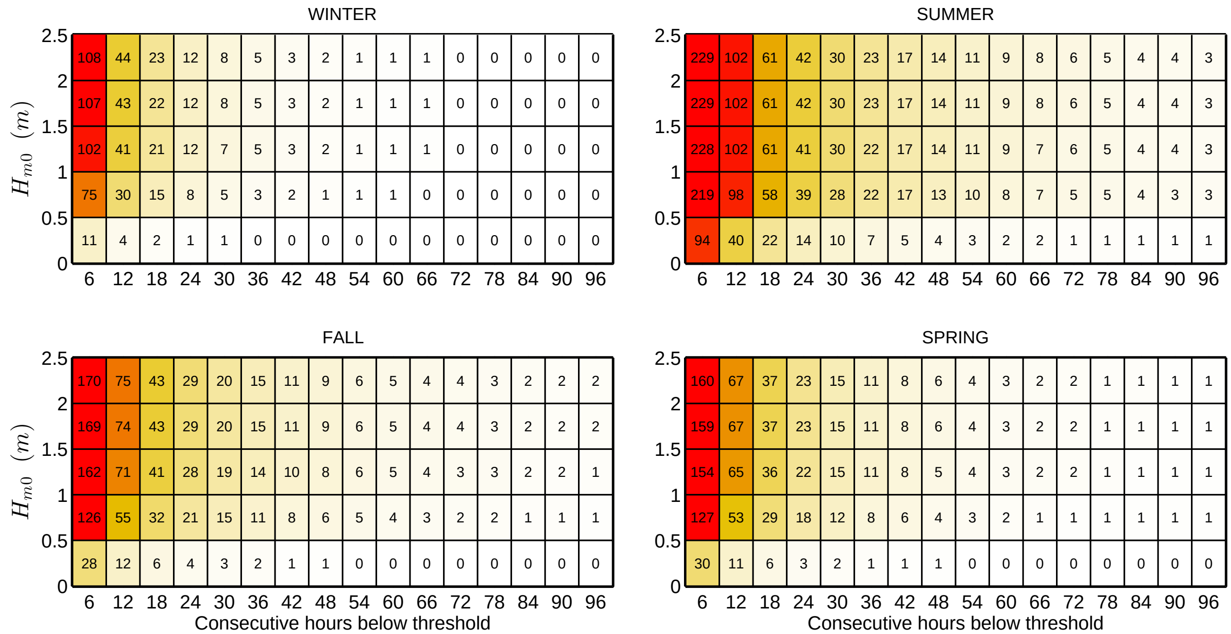


Figure 55: Average cumulative occurrences of wave height thresholds (weather windows) for each season at the USACE FRF site with an additional restriction of U < 15 mph.

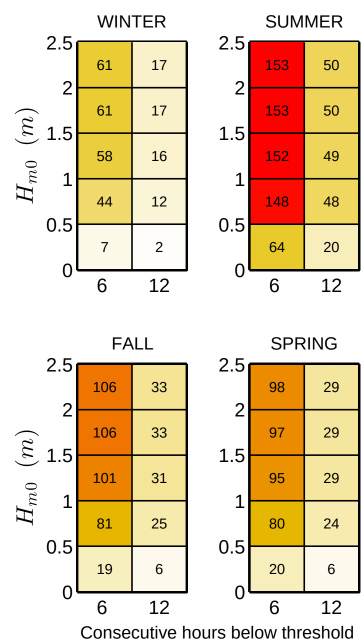


Figure 56: Average cumulative occurrences of wave height thresholds (weather windows) for 6- and 12-hour durations with $U < 15$ mph and only during daylight hours (5am – 10pm LST) at the USACE FRF site.

6.4.5. *Extreme Sea States*

As mentioned in 2.2, the way IFORM and the modified IFORM are currently implemented, they do not work well for datasets whose variables (H_{m0} and T_e) are bimodally distributed. The NDBC 44056 dataset is not well suited for IFORM, and therefore only the extreme significant wave height is estimated here using extreme value theory. Note this is the same dataset used for the Jennette's Pier site, but the text and figures are repeated here for completeness.

The generalized extreme value distribution (GEV) was fit to the annual significant wave height maximum in order to generate estimates of extreme values under the annual maximum method (AMM) (Rugerio et al. 2010). The peak over threshold (POT) method was also applied to the entire dataset in order to generate estimates of extreme values based on significant wave height exceedances over a certain threshold. Based on the application of this method as described by Ruggerio et al. (2010), the 99.5th percentile of significant wave height was used as a threshold value. These methods were applied using the WAFO matlab toolbox (Brodtkorb et al. 2000). The bootstrapping method (Efron and Tibshirani 1993) was applied in order to generate a 95% confidence interval around the CDFs derived using both of the extreme value distribution methods utilized in this analysis.

The 100-year H_{m0} is estimated as 7.55 m and 8.46 m using the GEV and POT methods, respectively, as shown in Figures 57 and 58. The 10-, 25-, and 50-year values are shown in the figures. It should be noted that conditions at the NDBC44056 buoy (at 17 m depth) are a good representative of locations available for testing, but for the location of the hindcast data (at 4.8 m depth) conditions may differ significantly.

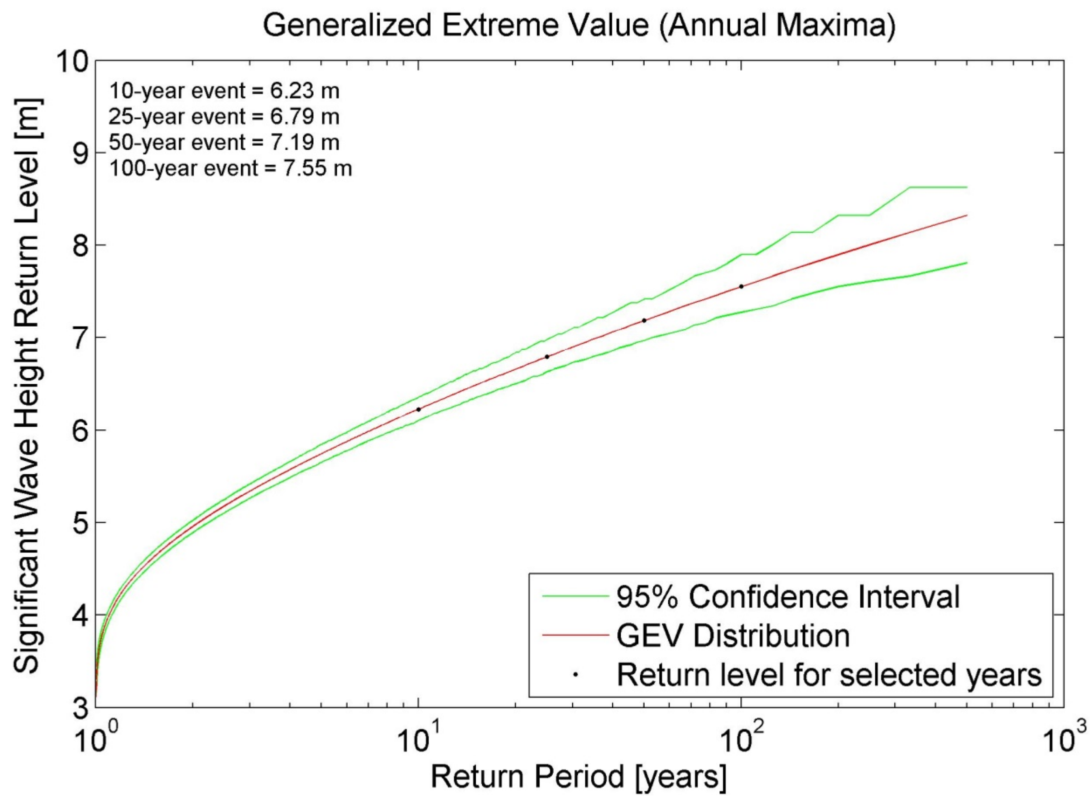


Figure 57: The generalized extreme values distribution was fit to annual maximum of significant wave height from NDBC44056 to generate estimates of extreme values. The 95% confidence interval is shown as well.

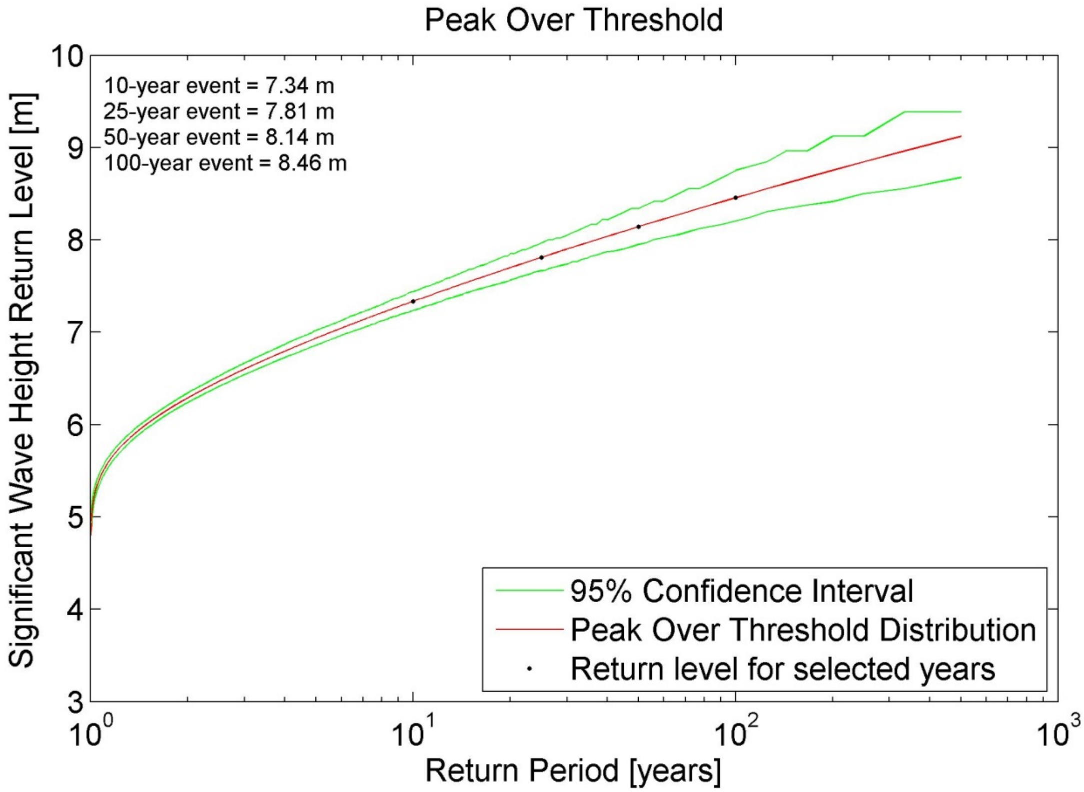


Figure 58: The peak over thresholds method was used with a threshold value of the 99.5th percentile of significant wave height from NDBC44056. The 95% confidence interval is shown as well.

6.4.6. Representative Wave Spectrum

All hourly discrete spectra measured at AWAC04 for the most frequently occurring sea states are shown in Figure 59. The most frequently occurring sea state, which is within the range 0.5 m $< H_{m0} <$ 1 m and 7 s $< T_e <$ 8 s, was selected from a JPD similar to Figure 50 in Section 6.4.1, but based on the AWAC04 data. As a result, the JPD, and therefore the most common sea states, generated from the measured wave data are slightly different from that generated from hindcast data. For example, the most frequently occurring sea state for the JPD generated from hindcast data is in the same range for H_{m0} (0.5 m $< H_{m0} <$ 1 m), but two seconds lower on bounds for T_e (5 s $< T_e <$ 6 s). Often several sea states will occur at a very similar frequency, and therefore plots of hourly discrete spectra for several other sea states are also provided for comparison. Each of these plots includes the mean spectrum and standard wave spectra, including Bretschneider and JONSWAP, with default constants as described in Section 2.2.

For the purpose of this study, the mean spectrum is the 'representative' spectrum for each sea state, and the mean spectrum at the most common sea state, shown in Figure 59 (bottom-left plot), is considered the 'representative' spectrum at the site. The hourly spectra vary considerably about this mean spectrum, but this is partly reflective of the bin size chosen for H_{m0} and T_e. Comparisons of the representative spectra in all plots with the Bretschneider and JONSWAP spectra illustrate why modeled spectra with default constants, e.g., the shape parameter $\gamma = 3.3$ for the JONSWAP spectrum, should be used with caution. Using the constants provided in Section 2.2, the Bretschneider spectra are, at best, fair representations of the mean spectra in Figure 59. There is some evidence of bimodal spectra in the four sea states displayed, which is not captured by the modeled spectra. The mean measured spectra is the best representation of the conditions, however, if these modeled spectra were to be used at this site, it is recommended that the constants undergo calibration against some mean spectrum, e.g., the representative spectrum constructed here. A better alternative may be to explore other methods or spectral forms to describe bimodal spectra (e.g., Mackay 2011) if it is known that the shape is not unimodal.

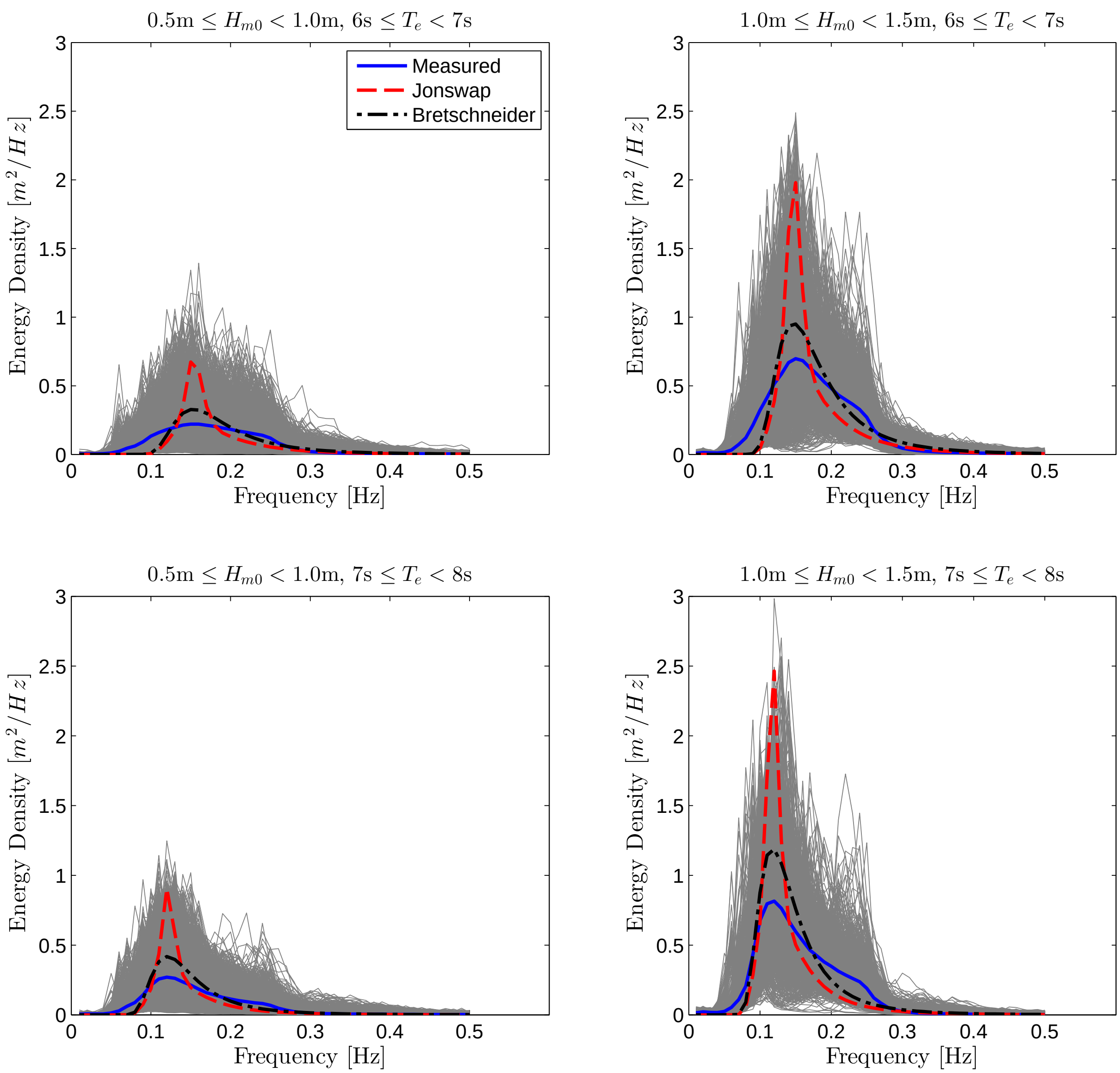


Figure 59: All hourly discrete spectra and the mean spectra measured at AWAC04 within the sea state listed above each plot. The JONSWAP and Bretschneider spectra are represented by red and black dotted lines, respectively.

7. PACIFIC MARINE ENERGY TEST CENTER (PMEC): LAKE WASHINGTON TEST SITE

7.1. Site Description

As described in the PMEC NETS chapter, the Pacific Marine Energy Center (PMEC) is the name of the Northwest National Marine Renewable Energy Centers (NNMREC) marine energy converter testing facilities located in the Pacific Northwest region. NNMREC is a Department of Energy funded entity designed to facilitate development of marine renewable energy technology. Ultimately PMEC will facilitate testing a broad range of technologies being produced by the marine energy industry (NNMREC 2014). The Lake Washington Test Site is an off-grid WEC test site that became operational in 2012. The most recent location used in winter 2012/2013 by Oscilla Power (Nair et al. 2013) will be designated the test location for the purpose of this catalogue. As shown in Figure 60, the Lake Washington site is at 47.6795 N, 122.2305 W. This site was chosen due to the long fetch from predominant southerly winds in winter and because the location is clear from barge traffic. Other locations in the lake may be available for testing, and it is encouraged to contact PMEC for recommendations.

The Lake Washington site is located in the northern portion of Lake Washington, northeast of Seattle, WA. At the test site, the water depth is approximately 51 m, the bathymetry is gently sloping, and the lake bed consists of soft mud. Figure 61 shows the bathymetry in the lake. The wave climate at the test site varies seasonally, with calmer conditions in the summer due to weak northerly winds, and more energetic conditions in the winter due to strong southerly winds. The wave climate is event driven by local winds, and there are periods of very low waves (nearly zero wave power) throughout the year. The wave environment at Lake Washington is characterized by an annual average power flux of about 0.04 kW/m.

NNMREC offers a wide range of technical and testing infrastructure support services for WEC developers. Lake Washington has small scale ('nursery') wave energy resources, and can accommodate scaled, prototype devices.

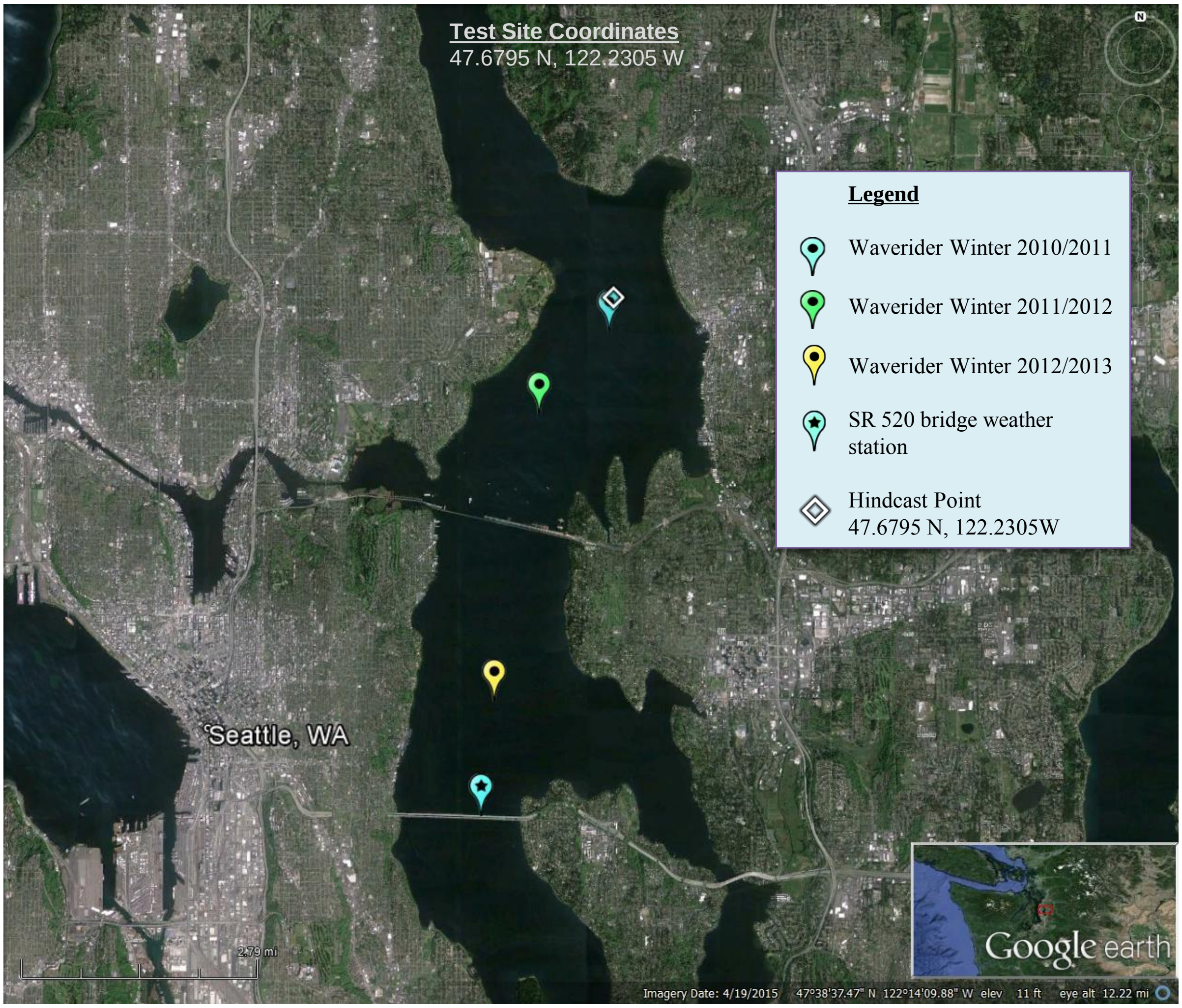


Figure 60: PMEC Lake Washington is located in the northern portion of Lake Washington northeast of Seattle. The test site is approximately 1.2 km off-shore in 56 m depth water. The fetch for predominant southerly winds in winter is about 5 km (from the Route 520 bridge). A Waverider buoy was deployed by APL-UW in three locations for short durations (see Table 5). Image modified from Google Earth (Google Earth 2015).

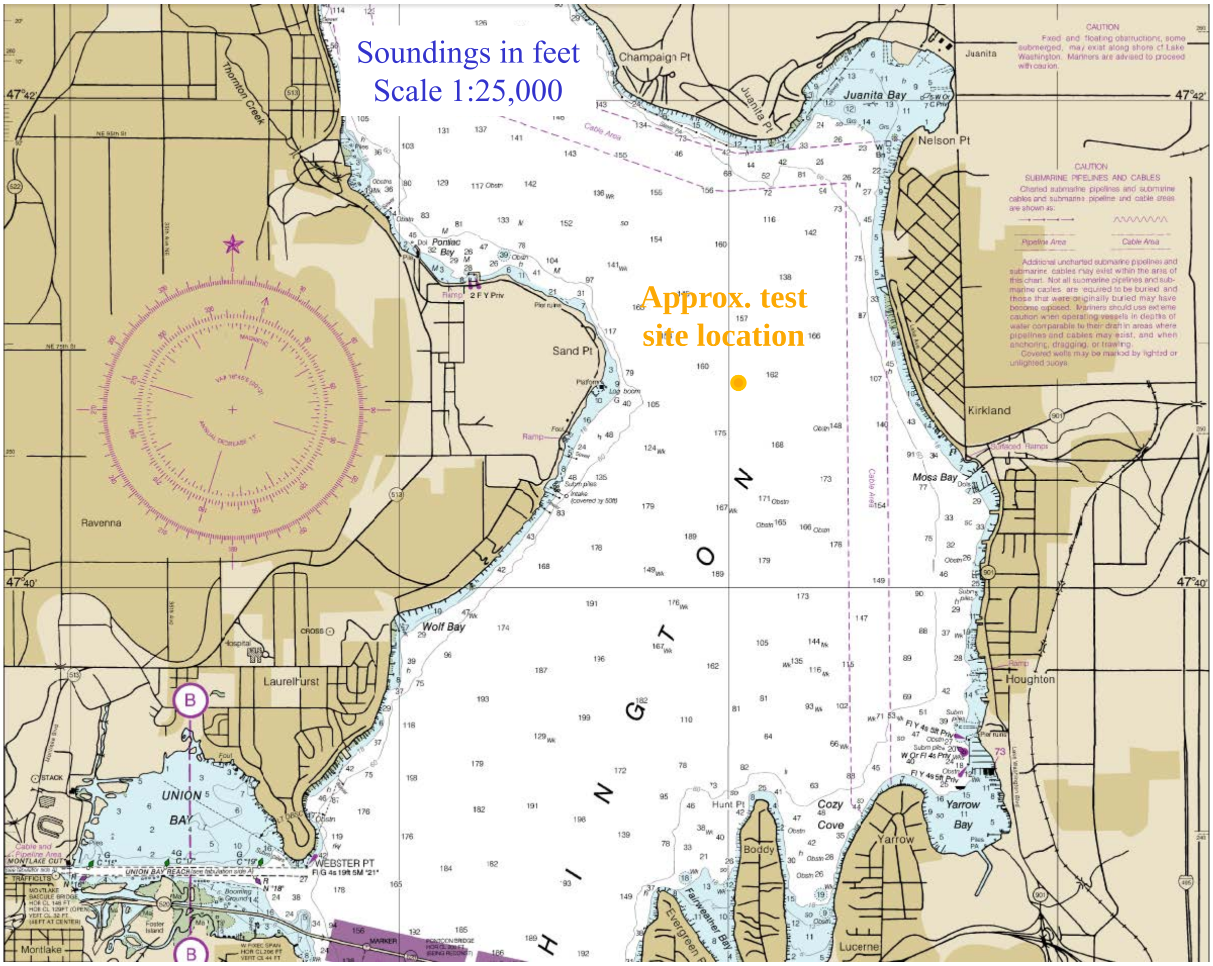


Figure 61: Nautical chart of part of Lake Washington shows the gradually sloping bathymetry around the test site. Soundings in feet (1 foot = 0.3048 m). Image modified from nautical chart #18447 (Office of Coast Survey 2012).

7.2. WEC Testing Infrastructure

7.2.1. Mooring Berths

PMEC Lake Washington does not have any mooring berths permanently installed. A temporary mooring system designed by the Advanced Physics Laboratory at the University of Washington (APL-UW) was used in the winter 2012/2013 testing (Nair et al. 2013).

7.2.2. Electrical Grid Connection

There is currently no electrical grid connection at PMEC Lake Washington, because it is a nursery / demonstration site. Testing typically consists of 'proof of concept' and is not ready for grid connection.

7.2.3. Facilitating Harbor

The APL dock facility is located 5 km east of Lake Washington, in Portage Bay at the western edge of the UW campus. The dock facility has room for staging, moorage for the APL vessels, and a 3 ton hoist.

7.2.4. On-Shore Office Space

Seattle is on the west side of Lake Washington, and several smaller cities are on the other surrounding sides. There is office space for rent as part of the APL "Collaboratory" in 909 Boat St, immediately adjacent to the APL dock facility.

7.2.5. Service Vessel and Engineering Boatyard Access

No dedicated service vessel is available at this time. The APL has a fleet of research vessels which can be reserved up to nine months in advance. The R/V Jack Robertson is the flagship at 56' LOA and with a 3 ton A-frame capacity. The R/V Henderson 54' LOA is a barge suitable to long-term operations (moored on the Lake for round-the-clock operations). Several smaller vessels are available.

In addition, private service vessels for hire are available in the Seattle area, from Foss Tugs, Norseman Maritime, Pacific Fisherman, and Island Tug & Towing.

7.2.6. Travel and Communication Infrastructure

Seattle-Tacoma International Airport (SEA) is in SeaTac, Washington, about 20 minutes south of downtown Seattle. Cellular service offers consistent coverage; there are several Federal Communication Commission (FCC) registered cell phone towers in and around Seattle, Washington.

7.2.7. Met-Ocean Monitoring Equipment

There were three separate deployments of a Waverider buoy by the Applied Physics Lab, at the University of Washington (APL-UW). Each deployment lasted for a few months and was located at different locations in the lake, each time at approximately 60 m depth. The first two locations corresponded to locations of interest for other wave projects (D'Asaro et al. 2014, Thomson et al. 2009). The third deployment of the APL-UW Waverider is less than a kilometer from the designated wave energy test site location used in winter 2012/2013. In addition, APL-UW has conducted numerous shorter deployments of SWIFT buoys to study the fetch dependence and whitecaps along the lake (Thomson 2012). There is also a monitoring buoy operated by King County that reports meteorological data. Instrument and data specifications for this monitoring equipment are summarized in Table 5. UW buoy data can be obtained from Jim Thomson by request, and King County wind data is available online. There are no NDBC buoys in Lake Washington.

Figure 62: Waverider buoy deployed by the University of Washington located less than 1 km from the test site.

Table 5: Wave monitoring equipment in close proximity to PMEC Lake Washington.

Instrument Name (Nickname)	University of Washington Waverider - Deployment 1	University of Washington Waverider - Deployment 2	University of Washington Waverider - Deployment 3
Type	Waverider buoy	Waverider buoy	Waverider buoy
Measured parameters	-std. met. data -spectral wave density -spectral wave direction	-std. met. data -spectral wave density -spectral wave direction	-std. met. data -spectral wave density -spectral wave direction
Variables reported, including derived variables (Sampling interval)	*Std Met.:* WVHT DPD APD MWD (30 min sampling period) -Spectral Wave Density -Spectral Wave direction (30 min sampling period)	*Std Met.:* WVHT DPD APD MWD (30 min sampling period) -Spectral Wave Density -Spectral Wave direction (30 min sampling period)	*Std Met.:* WVHT DPD APD MWD (30 min sampling period) -Spectral Wave Density -Spectral Wave direction (30 min sampling period)
Location	∼2.8 km southwest of the designated test site	∼8 km south/southwest of the designated test site	∼0.7 km south of the designated test site
Coordinates	47.6582 N 122.2498 W (47°39'29.52" N 122°14'59.28" W)	47.6097 N 122.2615 W (47°36'34.97" N 122°15'40.69" W)	47.6733 N 122.2313 W (47°40'23.88" N 122°13'52.68" W)
Depth	62 m	62 m	62 m
Data Start	11/18/2010	10/25/2011	12/22/2012
Data End	3/15/2011	1/11/2012	3/14/2013
Period of Record	∼4 months	∼2.5 months	∼3 months
Owner / Contact Person	University of Washington; contact Jim Thomson jthomson@apl.washington.edu	University of Washington; contact Jim Thomson jthomson@apl.washington.edu	University of Washington; contact Jim Thomson jthomson@apl.washington.edu

Instrument Name (Nickname)	**King County Lake Washington Buoy**	**Washington State Department of Transportation SR 520**
Type	Monitoring buoy	Weather station
Measured parameters	Meteorological data	Meteorological data
Variables reported, including derived variables (Sampling interval)	AirTemp Pressure WDIR WSPD Humidity Precip Solar radiation (1 hr sampling period)	AirTemp Pressure WDIR WSPD Humidity (5 min sampling period)
Location	In the center of Lake Washington	On SR 520 bridge
Coordinates	47.6122 N 122.254 W	
Depth	-anemometer height: ~2 m	
Data Start	1/1/2008	10/31/2007
Data End	present	present
Period of Record	~7 yrs	~8 yrs
Owner / Contact Person	King County; data available on https://green2.kingcounty.gov/lake-buoy/Data.aspx	Washington State Department of Transportation; data available on http://www.wsdot.wa.gov/traffic/bridges/WeatherHistory.aspx?bridge=SR+520

7.2.8. Environmental Monitoring

No monitoring has been required in previous deployments and tests.

7.2.9. Permitting

Each test requires its own permits. Everything works through the WA Joint Aquatic Resources Permit Application (JARPA), which is a single document used to request all permits. Previous deployments/tests have been required to avoid "fish windows", nominally the spring time.

7.3. Data used

Coast & Harbor produced a 10 year hindcast dataset for the Lake Washington site (Coast and Harbor 2015). This dataset was used to calculate parameters of interest for the characterization at this site. The hindcast data at the grid point shown in Figure 60 was analyzed.

In addition to the hindcast data set, short term data from a buoy deployment by APL-UW was used to calculate representative spectra. Because the buoy deployments were short term (less than a year), it was necessary to use hindcast data to calculated the extreme significant wave height. Wind data was available from the Washington State Department of Transportation weather station located on the SR 520 bridge south of the site. Climate Forecast System Reanalysis (CFSR) winds were only available over land near Lake Washington, and were not considered reliable data sources for wind on the lake, as mentioned in Section 2.3. In addition, OSCAR data is not available at this location, and no current measurements are available. Therefore the wind data from the SR 520 bridge was used for wind statistics, and to estimate surface current speeds (see Appendix E.5), so unfortunately this site cannot be consistent with the other sites in this manner.

7.4. Results

The following sections provide information on the joint probability of sea states, the variability of the IEC TS parameters, cumulative distributions, weather windows, extreme sea states, and representative spectra. This is supplemented by wave roses as well as wind and surface current data in Appendix E . The wind and surface current data provide additional information to help developers plan installation and operations & maintenance activities.

7.4.1. Sea States: Frequency of Occurrence and Contribution to Wave Energy

Joint probability distributions of the significant wave height, H_{m0}, and energy period, T_e, are shown in Figure 63. Figure 63 (top) shows the frequency of occurrence of each binned sea state and Figure 63 (bottom) shows the percentage contribution to the total wave energy. Note that because the waves are much smaller at this site compared to others in the catalogue, the JPD was broken into smaller bin ranges (0.1 m for H_{m0} and 0.2 s for T_e). Figure 63 (top) indicates that the majority of sea states are within the range 0 m $< H_{m0} <$ 0.4 m and 1 s $< T_e$ $<$ 2.2 s. A narrow range of sea states are experienced at the Lake Washington site, because they consist only of locally generated wind waves. The site is well suited for performing proof of concept testing for WECs at the beginning stages, and has scaled resources but relatively deep water ($\sim$50 m).

As mentioned in the methodology (Section 2.2), previous studies show that sea states with the highest frequencies of occurrence do not necessarily correspond to those with the highest contribution to total wave energy. The total wave energy in an average year is 177 kWh/m, which corresponds to an average annual omnidirectional wave power of 0.04 kW/m. The most frequently occurring sea state is within the range 0 m $< H_{m0} <$ 0.1 m and 1 s $< T_e <$ 1.2 s, while the sea state that contributes most to energy is within the range 0.4 m $< H_{m0} <$ 0.5 m and 2.2 s $< T_e <$ 2.4 s. Several sea states occur at a similar frequency, and sea states within 0.2 m $< H_{m0} <$ 0.5 m and 1.6 s $< T_e <$ 2.4 s contribute a similar amount to energy.

Frequencies of occurrence and contributions to energy of less than 0.01% are considered negligible and are not shown for clarity. For example, the sea state within 0.9 m $< H_{m0} <$ 1 m and 3 s $< T_e <$ 3.2 s contributes 0.23% to energy, but has an occurrence of only 0.007%, therefore it does not appear in Figure 63 (top).

Curves showing the mean, 5^{th} and 95^{th} percentiles of wave steepness, H_{m0}/λ, are also shown in Figure 63. The mean wave steepness at the Lake Washington site is 0.0463 ($\approx$ 1/22), and the 95^{th} percentile is approximately 1/18.

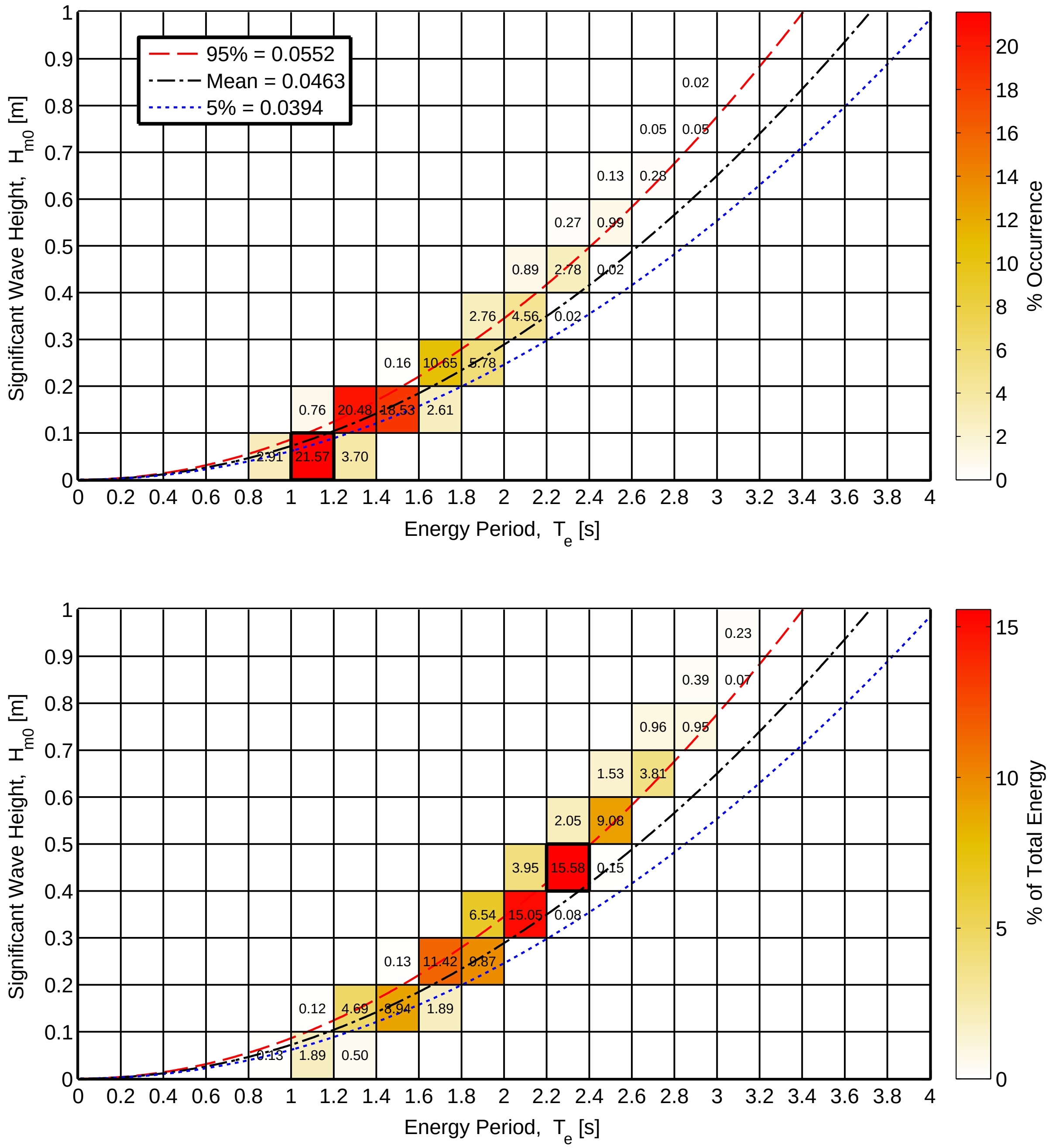


Figure 63: Joint probability distribution of sea states for Lake Washington. The top figure is frequency of occurrence and the bottom figure is percentage of total energy, where total energy in an average year is 177 kWh/m.

7.4.2. IEC TS Parameters

The monthly means of the six IEC TS parameters, along with the 5^{th} and 95^{th} percentiles, are shown in Figure 64. The months, March – February, are labeled with the first letter (e.g., March is M). The values in the figure are summarized in Table **??** in Appendix E.

Monthly means of the significant wave height, H_{m0}, and the omnidirectional wave power density, J, show the greatest seasonal variability compared to the other parameters. Values are largest and vary the most during the winter months. The same trend is observed for the monthly mean energy period, T_e, but its variation is less pronounced. These observations are consistent with the relationship between wave power density, significant wave height and energy period, where wave power density, J, is proportional to the energy period, T_e, and the square of the significant wave height, H_{m0}.

The direction of maximum directionally resolved wave power is typically from the south at $\sim 180°$, with some variaton in the mean in the summer months. There are frequent shifts of the direction to the north near 0° / 360°, which causes the 5th and 95th percentiles to be so wide. In some of the spring and fall months, the 5th percentile of direction changes because the northerly wind (and therefore waves) occur less often. The mean directionality coefficient is very consistent throughout the year, however, there are instances of lower d_θ in the summer (signified by the drop in the 5th percentile). Seasonal variation of the spectral width is indiscernible and appears to be nearly contant throughout the year at 0.24. In summary, the waves at the Lake Washington site, from the perspective of monthly means, have a fairly consistent spectral width, are predominantly from the south, and exhibit a wave power that has a narrow directional spread.

Wave roses of wave power and significant wave height, presented in Appendix E, Figures 144 and 145, also show the predominant direction of the wave energy at the Lake Washington site, which is south, with frequent shifts to the north/northeast. Figure 144 shows two dominant wave direction sectors, south (at 180°) and south/southwest (SSW) at 210°. Along the predominant wave direction, 180°, the omnidirectional wave power density is at or below 0.35 kW/m about 12% of the time, and greater than 0.35 kW/m nearly 0.2% of the time. Along the south/southwest direction (210°), wave power density is at or below 0.35 kW/m almost 8% of the time, and greater than 0.35 kW/m about 0.2% of the time.

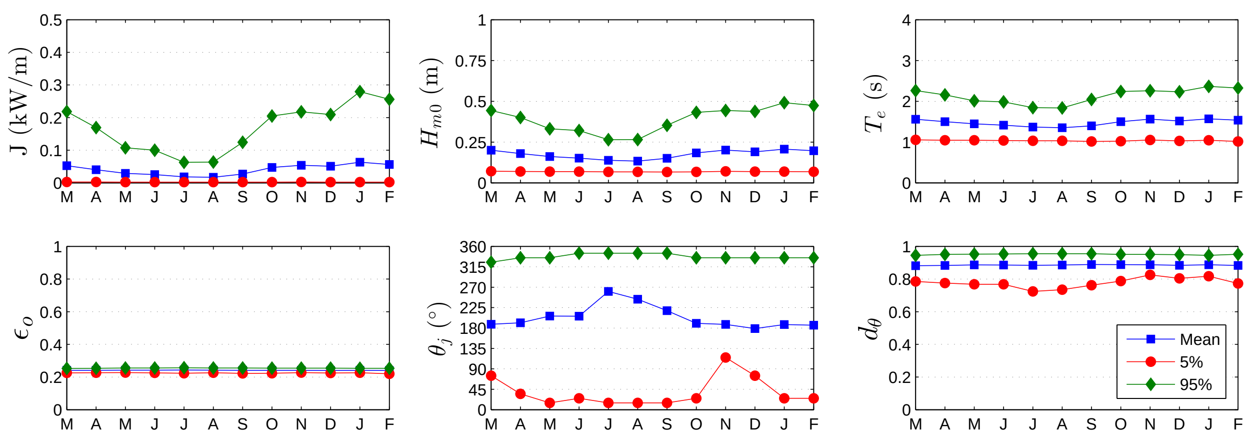


Figure 64: The average, 5^{th} and 95^{th} percentiles of the six parameters at the Lake Washington site.

Monthly means, however, smear the significant variability of the six IEC parameters over small time intervals as shown in plots of the parameters at 1-hour intervals in Figure 65 for a representative year. While seasonal patterns described for Figure 64 are still evident, these plots show how sea states can vary abruptly at small time scales with sudden changes, e.g., jumps in the wave power as a result of a storm. The frequent shifts in wind direction are also evident in this figure.

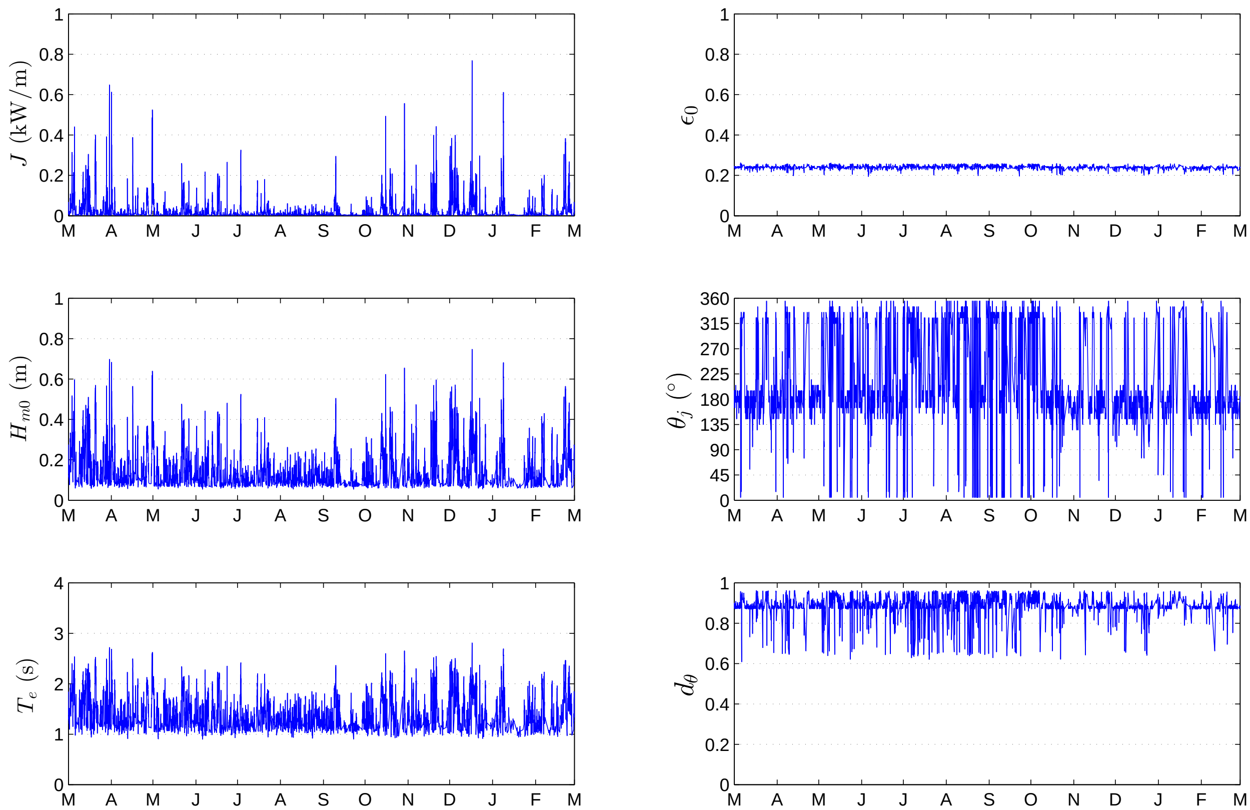


Figure 65: The six parameters of interest over a one-year period, March 2013 – February 2014 at the Lake Washington site.

7.4.3. Cumulative Distributions

Annual and seasonal cumulative distributions (a.k.a., cumulative frequency distributions) are shown in Figure 66. Note that spring is defined as March – May, summer as June – August, fall as September – November, and winter as December – February. The cumulative distributions are another way to visualize and describe the frequency of occurrence of individual parameters, such as H_{m0} and T_e. A developer could use cumulative 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 0.1 m for installation and recovery, according to Figure 66, this condition occurs nearly 28% of the time on average within a given year. If significant wave heights need to be less than or equal to 0.2 m for emergency maintenance, according to Figure 66, this condition occurs about 71% of time on average within a given year. Cumulative distributions, however, do not account for the duration of a desirable sea state, or weather window, which is needed to plan deployment and servicing of a WEC device at a test site. This limitation is addressed with the construction of weather window plots in the next section.

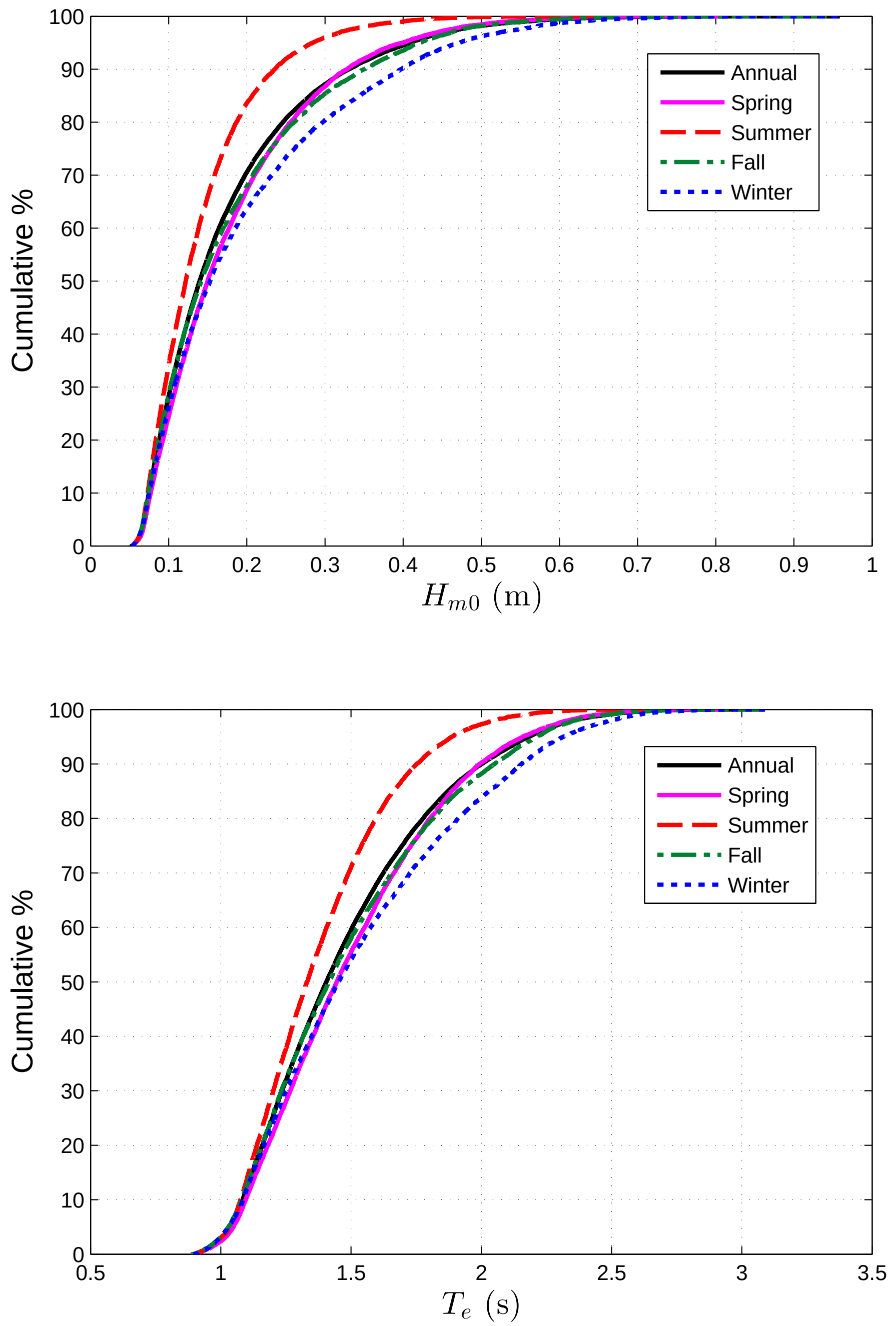


Figure 66: Annual and seasonal cumulative distributions of the significant wave height (top) and energy period (bottom) at the Lake Washington site.

7.4.4. Weather Windows

Figure 67 shows the number of weather windows at the Lake Washington site, when significant wave heights are at or below some threshold value for a given duration, for an average winter, spring, summer and fall. In these plots, each occurrence lasts a duration that is some multiple of 6-hours. The minimum weather window is, therefore, 6-hours in duration, and the maximum is 96-hours (4 days). The significant wave height threshold is the upper bound in each bin and indicates the maximum significant wave height experienced during the weather window. Note that the table is cumulative, so, for example, an occurrence of $H_{m0} \leq 0.2$ m for at least 72 consecutive hours in the fall is included in the count for 66 consecutive hours as well. In addition, one 12-hour window counts would count as two 6-hour windows. There are more occurrences of lower significant wave heights during the summer than winter, which typically corresponds to increased opportunities for deployment or operations and maintenance. For this particular test site, however, waves are so low during the summer that winter is a more likely deployment period because the frequent winter storms provide sufficient wave activity, but there are still many calm periods in the winter which would allow for deployment and maintenance (Nair et al. 2013).

Weather window plots provide useful information at test sites when planning schedules for deploying and servicing WEC test devices. For example, if significant wave heights need to be less than or equal to 0.2 m for at least 12 consecutive hours to service a WEC test device at the Lake Washington site with a given service vessel, there would be, on average, thirty-five weather windows in the winter. When wind speed is also considered, Figure 68 shows the average number of weather windows with the additional restriction of wind speed, $U < 15$ mph. The local winds (which for this site, do drive the waves) are used in these weather windows, and are given in Appendix E.4. That wind data was obtained from the SR 520 bridge weather station (see Section 2.3, Appendix E.4). For shorter durations (6- and 12-hour windows), daylight is necessary. Windows with $U < 15$ mph and only during daylight hours are shown in Figure 69. Daylight was estimated as 5am – 10pm Local Standard Time (LST).

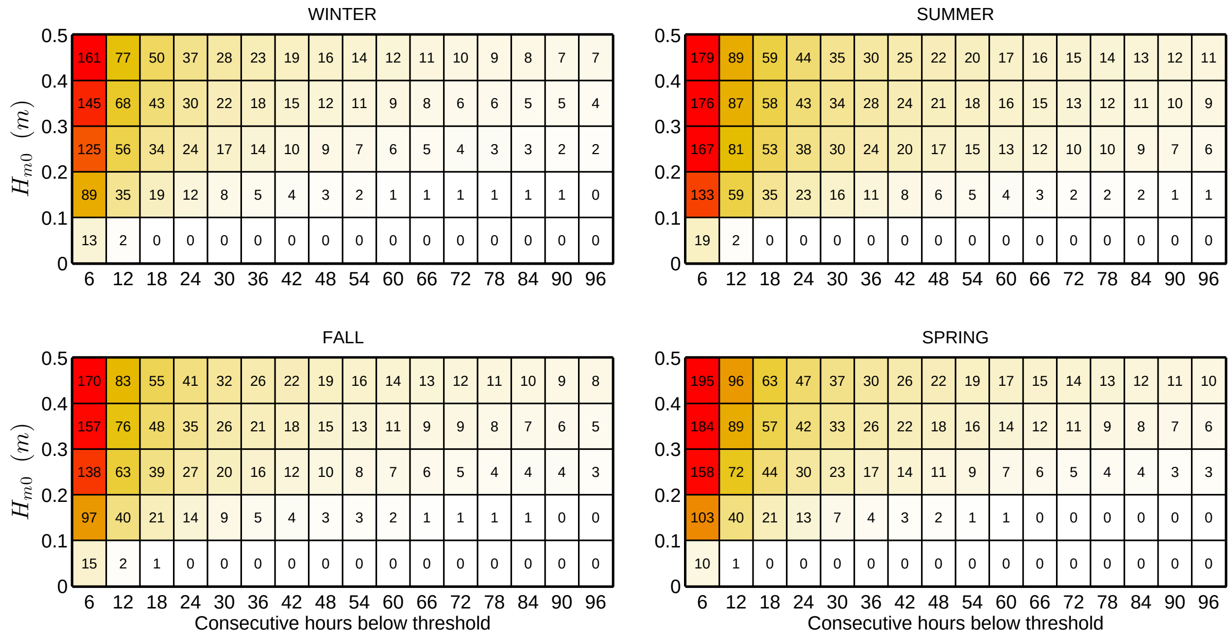


Figure 67: Average cumulative occurrences of wave height thresholds (weather windows) for each season at the Lake Washington site. Winter is defined as December – February, spring as March – May, summer as June – August, and fall as September – November.

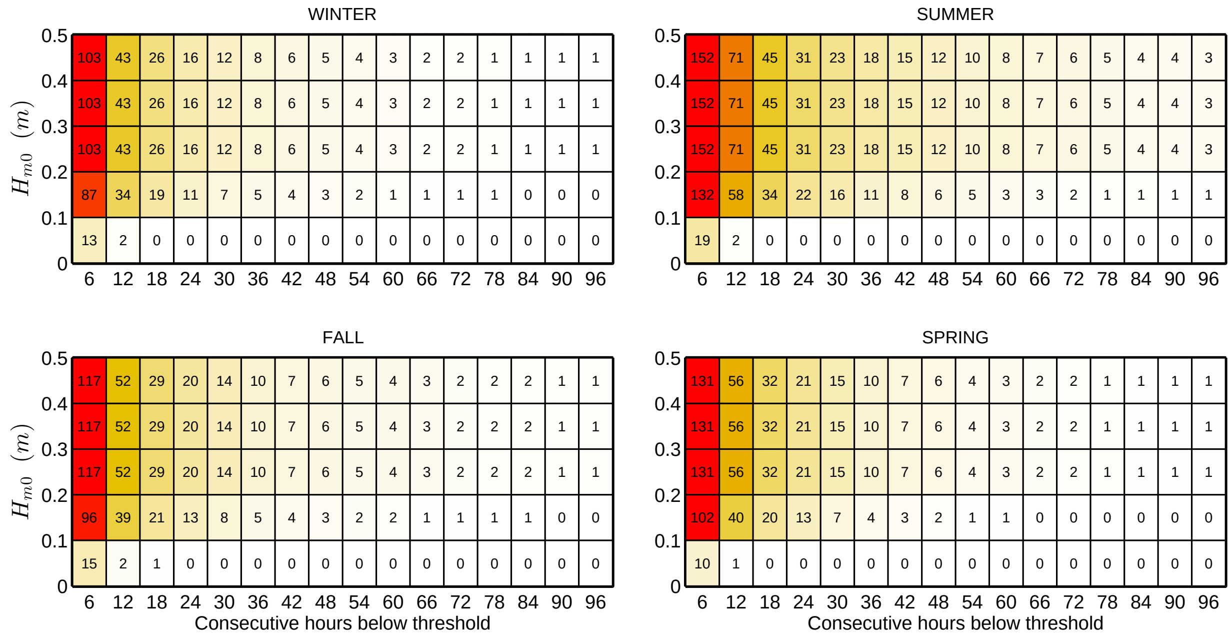


Figure 68: Average cumulative occurrences of wave height thresholds (weather windows) for each season at the Lake Washington site with an additional restriction of U < 15 mph.

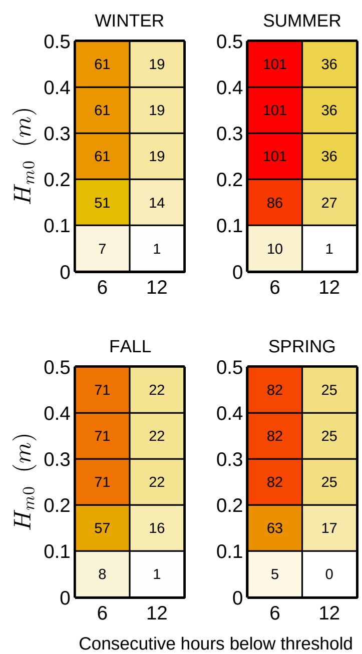


Figure 69: Average cumulative occurrences of wave height thresholds (weather windows) for 6- and 12-hour durations with $U < 15$ mph and only during daylight hours (5am – 10pm LST) at the Lake Washington site.

7.4.5. Extreme Sea States

Measured wave data at Lake Washington consists only of very short term deployment periods (less than a year), and is not an appropriate dataset for extreme sea state estimation. Hindcast data is therefore used for this site. In addition, as mentioned in 2.2, the Lake Washington dataset is not well suited for IFORM because the distribution is so narrow (see Figure 63) due to the waves being short fetched wind waves; so only the extreme significant wave height is estimated here using extreme value theory.

The generalized extreme value distribution (GEV) was fit to the annual significant wave height maximum in order to generate estimates of extreme values under the annual maximum method (AMM) (Rugerio et al. 2010). The peak over threshold (POT) method was also applied to the entire dataset in order to generate estimates of extreme values based on significant wave height exceedances over a certain threshold. Based on the application of this method as described by Ruggerio et al. (2010), the 99.5th percentile of significant wave height was used as a threshold value. These methods were applied using the WAFO matlab toolbox (Brodtkorb et al. 2000). The bootstrapping method (Efron and Tibshirani 1993) was applied in order to generate a 95% confidence interval around the CDFs derived using both of the extreme value distribution methods utilized in this analysis.

The 100-year H_{m0} is estimated as 1.13 m and 1.04 m using the GEV and POT methods, respectively, as shown in Figures 70 and 71. The 10-, 25-, and 50-year values are shown in the figures.

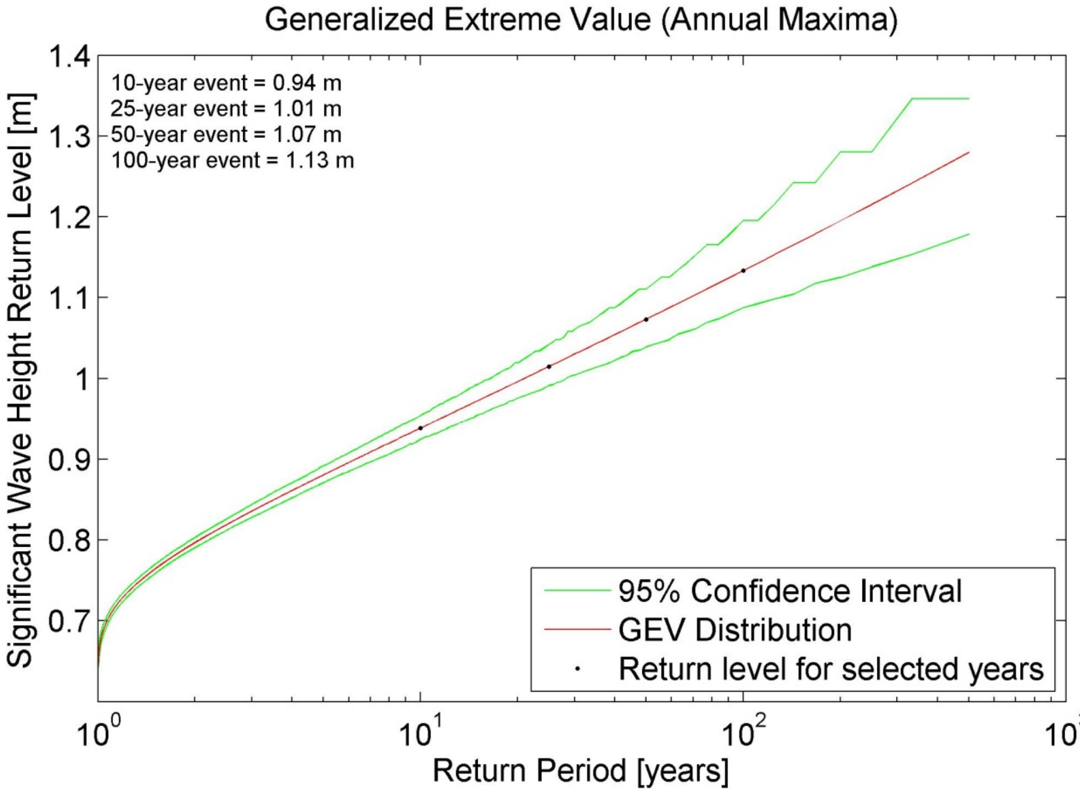


Figure 70: The generalized extreme values distribution was fit to annual maximum of significant wave height from the hindcast dataset to generate estimates of extreme values. The 95% confidence interval is shown as well.

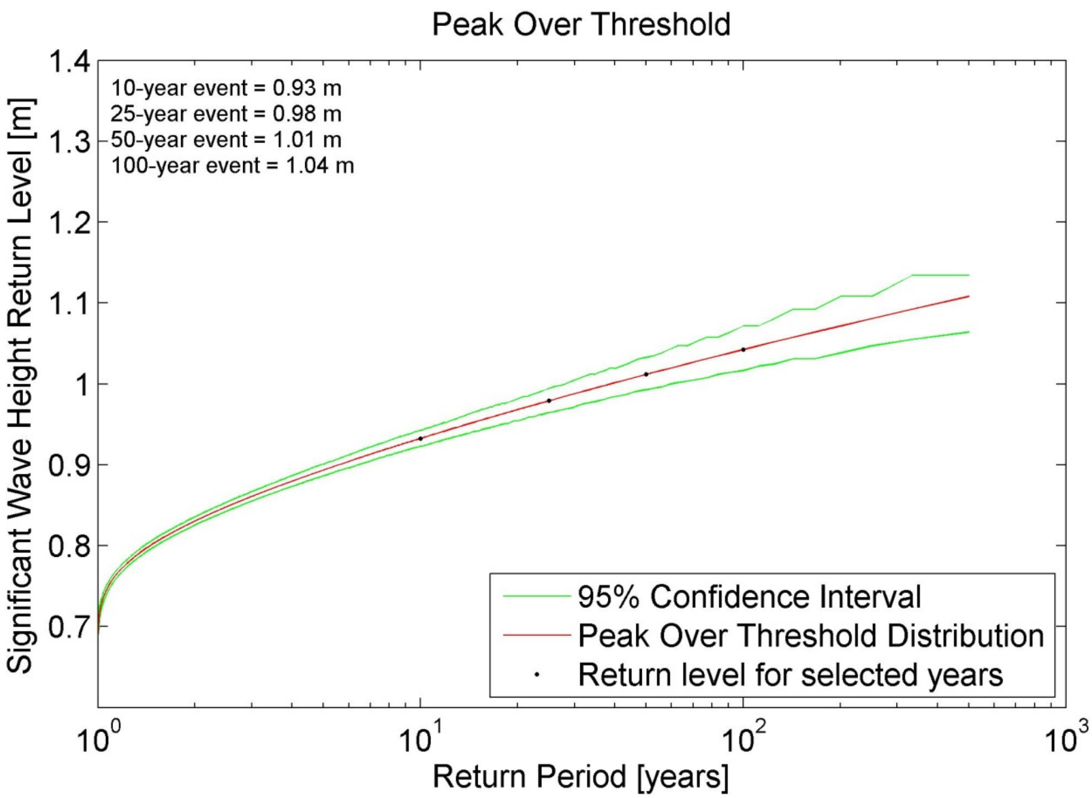


Figure 71: The peak over thresholds method was used with a threshold value of the 99.5th percentile of significant wave height from the hindcast dataset. The 95% confidence interval is shown as well.

7.4.6. Representative Wave Spectrum

All hourly discrete spectra from the hindcast data for the most frequently occurring sea states are shown in Figure 72. Note that typically measured data is used in this catalogue, however, for this site, the measured data was very short term, and not representative of a full year. The most frequently occurring sea state, which is within the range 0 m $< H_{m0} <$ 0.1 m and 1 s $< T_e <$ 1.2 s, was selected from the hindcast JPD in Figure 63 in Section 7.4.1. Often several sea states will occur at a very similar frequency, and therefore a plot of hourly discrete spectra for one other sea state is also provided for comparison. Each of these plots includes the mean spectrum and standard wave spectra, including Bretschneider and JONSWAP, with default constants as described in Section 2.2.

For the purpose of this study, the mean spectrum is the 'representative' spectrum for each sea state, and the mean spectrum at the most common sea state, shown in Figure 72 (left plot), is considered the 'representative' spectrum at the site. The hourly spectra vary somewhat about this mean spectrum, but this is partly reflective of the bin size chosen for H_{m0} and T_e. Comparisons of the representative spectra in all plots with the Bretschneider and JONSWAP spectra illustrate why modeled spectra with default constants, e.g., the shape parameter $\gamma =$ 3.3 for the JONSWAP spectrum, should be used with caution. Using the constants provided in Section 2.2, the Bretschneider spectra are fair representations of the mean spectra in

Figure 72. If available, mean measured spectra (with a period of record of at least one year) would be the best representation of the conditions. In this case, the mean simulated spectra are considered the best representation, although short term measurements are still informative. If modeled standard spectra (Bretschneider or JONSWAP) were to be used at this site, it is recommended that the constants undergo calibration against some mean spectrum, e.g., the representative spectrum constructed here.

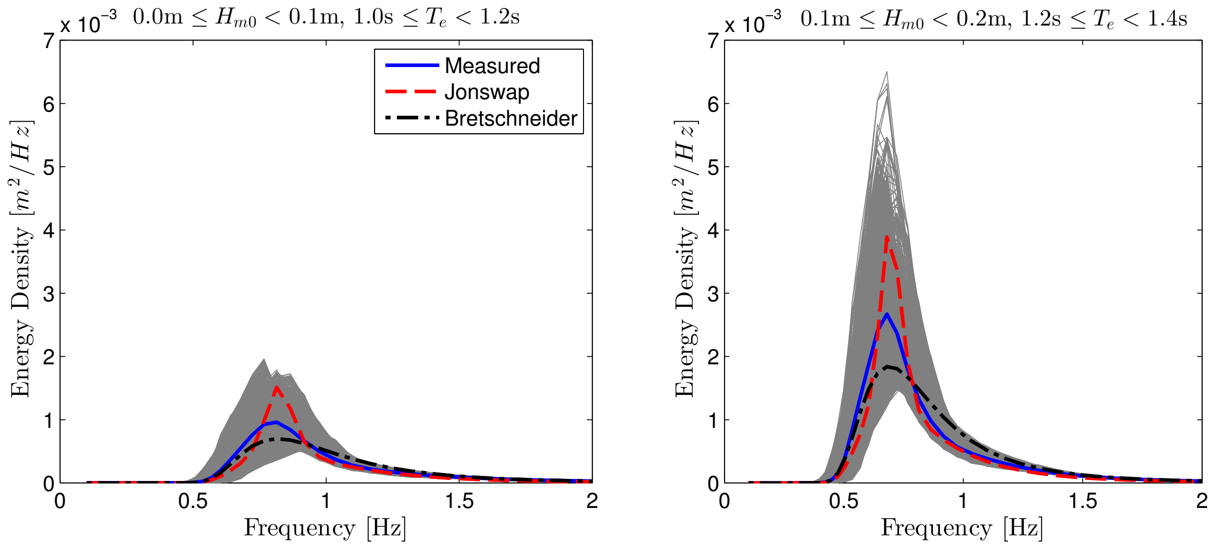


Figure 72: All hourly discrete spectra and the mean spectra from the hindcast dataset within the sea state listed above each plot. The JONSWAP and Bretschneider spectra are represented by red and black dotted lines, respectively.

8. PACIFIC MARINE ENERGY TEST CENTER (PMEC): SOUTH ENERGY TEST SITE (SETS)

8.1. Site Description

As described in the PMEC NETS chapter, the Pacific Marine Energy Center (PMEC) is the name of the Northwest National Marine Renewable Energy Centers (NNMREC) marine energy converter testing facilities located in the Pacific Northwest region. NNMREC is a Department of Energy funded entity designed to facilitate development of marine renewable energy technology. Ultimately PMEC will facilitate testing a broad range of technologies being produced by the marine energy industry (NNMREC 2015). NNMREC is currently in the permitting phase of developing a utility-scale, grid-accessible test site, the South Energy Test Site (SETS), which is planned to be operational in 2017. As shown in Figure 73, SETS will encompass an area of 2-square nautical mile (roughly 6.9 square kilometers) in the Outer Continental Shelf (outside state waters), centered at approximately 44.567 N, 124.229 W. Four grid-connected test berths, each with its own subsea cable, are planned.

SETS is located near the City of Newport, Oregon and Yaquina Bay. At the test site, the water depth is approximately 58-75 m (32-41 fathoms), the bathymetry is gently sloping, and the sea bed is predominantly sandy. Figure 74 shows the bathymetry surrounding the test site. The wave climate at the test site varies seasonally, with calmer seas in the summer compared to more energetic seas in the winter. The wave environment at SETS is characterized by an annual average power flux of about 40.7 kW/m, including a number of events with significant wave heights exceeding 7 m each winter.

NNMREC offers a wide range of technical and testing infrastructure support services for WEC developers as discussed in the PMEC NETS chapter. SETS has full scale wave energy resources, and will be able to accommodate utility scale devices and small arrays. NNMREC would like testing at this facility to allow certification to IEEE and other international standards, and ideally some of the devices will provide power to the local grid (NNMREC 2015), although this will depend on getting the necessary approvals and many other factors.

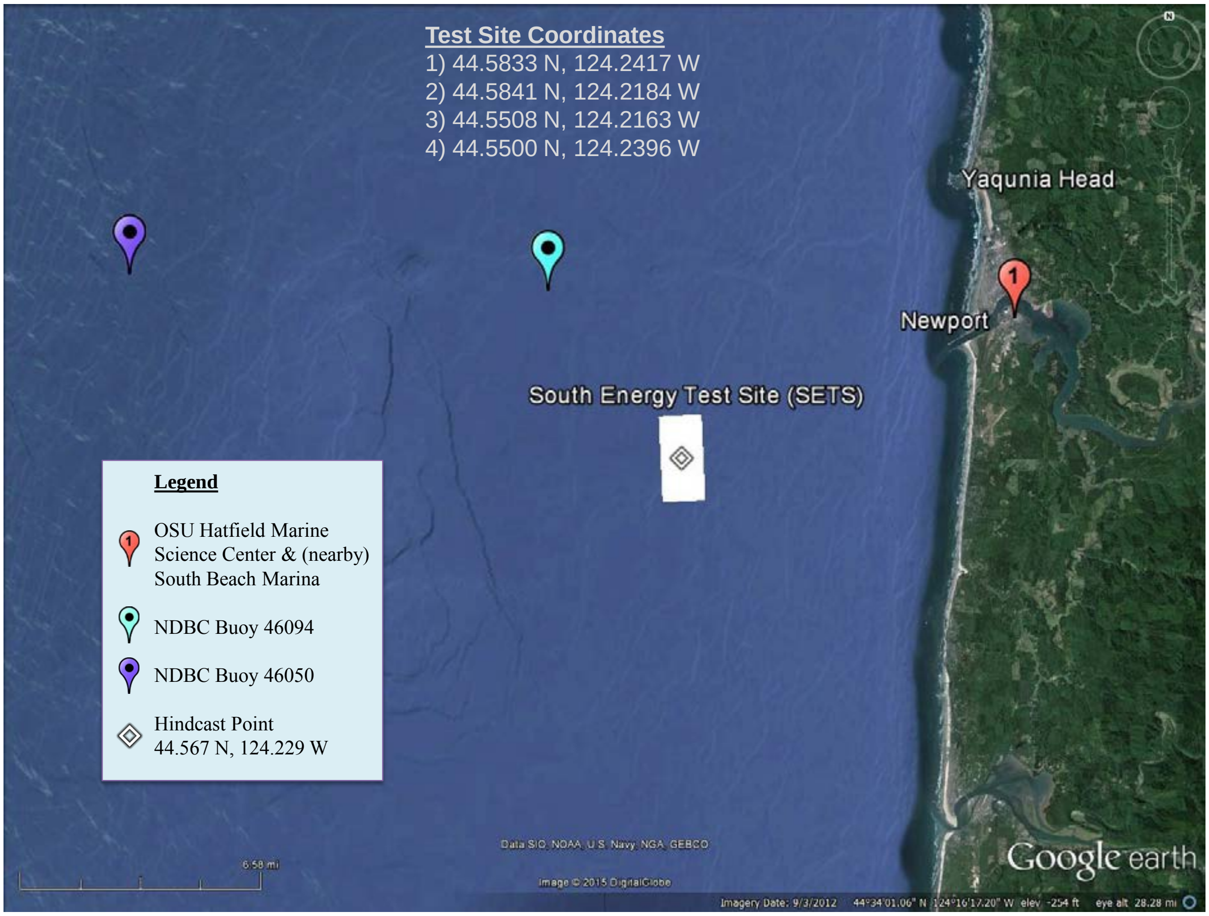


Figure 73: SETS is located in the coastal waters of Oregon near the City of Newport. The test site is approximately 11–13 km off-shore in 58–75 m depth water. One National Data Buoy Center (NDBC) ocean buoy and one NDBC meteorological station are close to the site (see Table 6). The South Beach Marina, Port of Toledo Yaquina Boatyard, and OSU Hatfield Marine Science Center offer services valuable for WEC testing. The point of reference for the hindcast simulation is in the center of SETS. Image modified from Google Earth (Google Earth 2015).

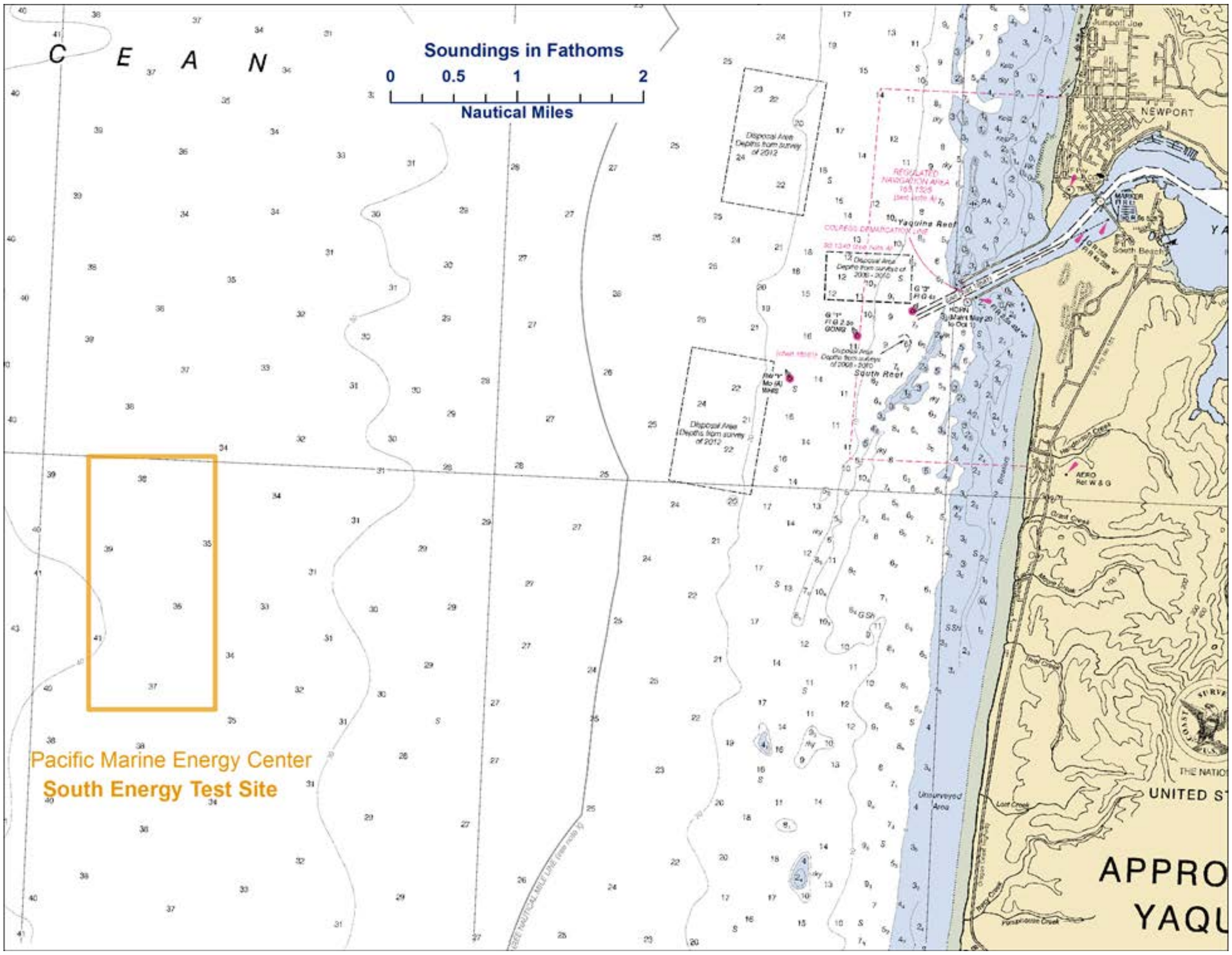


Figure 74: Nautical chart of Yaquina Head and surrounding area shows the gradually sloping bathymetry around SETS. Soundings in fathoms (1 fathom = 1.8288 m). Image modified from nautical chart #18561 (Office of Coast Survey 2011).

8.2. WEC Testing Infrastructure

8.2.1. Mooring Berths

SETS is planned to be permitted to test up to twenty WECs concurrently so that small arrays can be tested. Mooring systems will not be provided and would need to be installed according to the developer's design. Three- to four-point anchoring layouts are commonly used, but NNMREC is researching the feasibility of single point moorings. WEC testing can be done year around, and devices will likely be in the site for multiple years.

8.2.2. Electrical Grid Connection

SETS will be a utility scale grid connected facility. Four-grid connected test berths with their own buried subsea cable are planned. In addition to transmitting energy, the subsea cable will also be capable of transmitting performance and environmental data to an onshore control center.

8.2.3. Facilitating Harbor

SETS is approximately 13 km south/southwest of the entrance to Yaquina Bay, the mouth of the Yaquina River. The South Beach Marina is located near the outlet of Yaquina Bay and offers year-round boat mooring (near Waypoint #1 in Figure 73).

8.2.4. On-Shore Office Space

The fishing and tourist City of Newport, Oregon, where approximately ten thousand people live, is on the north side of Yaquina Bay (U.S. Census Bureau 2012). Meeting rooms and temporary office space through PMEC are planned to be available following the completion of SETS.

8.2.5. Service Vessel and Engineering Boatyard Access

No dedicated service vessel is available at this time, but following the completion of SETS, more resources may be available through PMEC. Service vessels for hire are likely available in the Newport/Toledo area. The Port of Toledos Yaquina Boatyard (Waypoint #2 in Figure 73) services boats and provides space for self-service. Yaquina Boatyard hauls boats up to 300 tons and has capabilities that include steel fabrication, carpentry, painting, haul-out, and project management (Port of Toledo 2014).

8.2.6. Travel and Communication Infrastructure

Portland International Airport (PDX) is a two and a half hour drive from Newport, Oregon. Eugene Airport is located closer and is a one hour and forty minute drive. Cellular service offers consistent coverage; three Federal Communication Commission (FCC) registered cell phone towers are located in and around Newport, Oregon.

8.2.7. Met-Ocean Monitoring Equipment

A buoy for measuring waves and currents is currently deployed for a 1 year period. Data may be available from OSU after deployment completion. NNMREC plans to deploy instrumentation in each berth when devices are testing. Specific instrumentation will depend on the device. If the site is empty of WECs under test, it is planned that one monitoring device will be deployed at all times.

In addition, there are two National Buoy Data Center (NDBC) buoys that measure and collect ocean data and one NDBC station reporting meteorological data (see Figure 73 for location). Instrument and data specifications for this monitoring equipment are summarized in Table 6. Buoy data is accessible online at the NDBC database. NDBC 46050 (Stonewall Bank) is located 25 km northwest of the test site and provides spectral wave data. NDBC

46094 (NH-10) is slightly closer to the site at about 9 km northwest and reports standard ocean wave data (Figure 75 (a)). The land based meteorological station is situated directly on the shoreline (Figure 75 (b)).

Figure 75: (a) Moored buoy NDBC 46094 located 9 km northwest of the test site, (b) meteorological station NWPO3 on the coastline 15 km northeast of the test site (National Data Buoy Center 2014).

Table 6: Wave monitoring equipment in close proximity to SETS. Note this is the same equipment provided for NETS in Table 1.

Instrument Name (Nickname)	**NDBC Station 46094 (also called NH-10)**	**NDBC Station 46050 (Stonewall Bank)**	**NWPO3**
Type	Moored buoy	3-meter discus buoy	C-MAN station (MARS payload)
Measured parameters	-std. met. data -continuous winds -sea surface temp, salinity, density -current measurements	-std. met. data -continuous winds -spectral wave density -spectral wave direction	-std. met. data -continuous winds
Variables reported, including derived variables (Sampling interval)	*Std Met.:* WDIR WSPD BAR ATMP (10 min sampling period)	*Std Met.:* WDIR WSPD GST WVHT DPD APD PRES ATMP WTMP (1 hr sampling period) *Contin. Winds:* WDIR WSPD GDR GST GTIME (10 min sampling period) -Spectral Wave Density -Spectral Wave direction (1 hr sampling period)	*Std Met.:* WD WSPD GST BAR ATMP DEWP (1 hr sampling period) *Contin. Winds:* WDIR WSPD GDR GST GTIME (10 min sampling period)
Location	directly west of Newport, 9 km northwest of SETS	20 nm (nautical miles, 1 nm = 1.852 km) directly west of Newport, 25 km northwest of SETS	on the shoreline, near Newport, 15 km northeast of SETS
Coordinates	44.633 N 124.304 W (44°38’0” N 124°18’13” W)	44.639 N 124.534 W (44°38’20” N 124°32’2” W)	44.613 N 124.067 W (44°36’48” N 124°4’0” W)
Depth	-depth: 81 m -air temp 2.5 m above site -anemometer 3 m above site	-depth: 128 m -air temp: 4 m above water -anemometer: 5 m above water -barometer: sea level -sea temp depth: 0.6 m below water	-site: 9.1 m above sea level -air temp: 6.4 m above site -anemometer: 9.4 m above site -barometer: 11 m above sea level
Data Start	2/5/2007	-std met: 11/16/1991 -contin winds: 09/07/1997 -spect wave dens: 01/01/1996 -spect wave dir: 03/05/2008	-std met: 1/10/1985 -contin winds: 1/12/1997
Data End	present; several winters missing data	present	present
Period of Record	∼8.5 yrs	-std met: ∼24 yrs -contin winds: ∼18 yrs -spect wave dens: ∼20 yrs -spect wave dir: ∼7.5 yrs	std met: ∼31 yrs contin winds: ∼19 yrs
Owner / Contact Person	Oregon Coastal Ocean Observing System/ National Data Buoy Center	National Data Buoy Center	National Data Buoy Center

8.2.8. Environmental Monitoring

Environmental conditions have been characterized at the site by Oregon State University, NOAA, and NNMREC. The information gathered includes baseline measurements of benthic habitat and organisms, marine mammal populations, and acoustics (Batten 2013). Developers can contract with NNMREC to monitor environmental effects of WEC deployments during testing. Required environmental monitoring of WEC deployments is yet to be determined, and will depend on permitting.

8.2.9. Permitting

NNMREC is in the process of permitting. More information will be available once SETS is completed.

8.3. Data used

Researchers at the Northwest National Marine Renewable Energy Center (NNMREC) produced a 7 year hindcast dataset for the area offshore of Oregon (García-Medina et al. 2014) in order to complement the study of temporal and spatial variability in the wave resource over the Pacific Northwest region by Lenee-Bluhm et al.(2011). This dataset was used to calculate statistics of interest for the wave resource characterization at SETS. The hindcast data at the grid point in the center of SETS was analyzed (see Figure 73). Although a 10 year hindcast would be preferred, García-Medina et al. (2014) showed that the probability density function (PDF) of significant wave height from their hindcast compared to NDBC 46029 buoy data were in agreement up to $\sim$7 m, and, therefore, the hindcast is at least representative of the twenty-seven years of buoy operation, 1985 – 2011.

In addition to the hindcast data set, historical data from buoy NDBC 46050 was used to calculate extreme sea states and representative spectra. Wind data was available from NDBC 46050 and a Coastal-Marine Automated Network (C-MAN) station, NWPO3 located just on-shore. However, to be consistent with the other sites, Climate Forecast System Reanalysis (CFSR) winds were used, as explained in Section 2.3. As with the other sites, current data was downloaded from OSCAR. See Figures 73 and 76 for data locations.

Figure 76: SETS location map showing the CFSR wind and OSCAR surface current data points, and NDBC buoy locations (Google Earth 2015).

8.4. Results

The following sections provide information on the joint probability of sea states, the variability of the IEC TS parameters, cumulative distributions, weather windows, extreme sea states, and representative spectra. This is supplemented by wave roses as well as wind and surface current data in Appendix F . The wind and surface current data provide additional information to help developers plan installation and operations & maintenance activities.

8.4.1. Sea States: Frequency of Occurrence and Contribution to Wave Energy

Joint probability distributions of the significant wave height, H_{m0}, and energy period, T_e, are shown in Figure 77. Figure 77 (top) shows the frequency of occurrence of each binned sea state and Figure 77 (bottom) shows the percentage contribution to the total wave energy. Figure 77 (top) indicates that the majority of sea states are within the range 1 m $< H_{m0}$ $<$ 3.5 m and 7 s $< T_e <$ 11 s; but a wide range of sea states are experienced at SETS, including extreme sea states caused by severe storms where H_{m0} exceeded 7.5 m. The site is well suited for testing WECs at various scales, including full-scale WECs, and testing the operation of WECs under normal sea states. Although the occurrence of an extreme sea state for survival testing of a full scale WEC is unlikely during a normal test period, the SETS wave climate offers opportunities for survival testing of scaled model WECs.

As mentioned in the methodology (Section 2.2), previous studies show that sea states with the highest frequencies of occurrence do not necessarily correspond to those with the highest contribution to total wave energy. The total wave energy in an average year is 350,391 kWh/m, which corresponds to an average annual omnidirectional wave power of 40.7 kW/m. The most frequently occurring sea state is within the range 1.5 m $< H_{m0} <$ 2 m and 8 s $< T_e$ $<$ 9 s, while the sea state that contributes most to energy is within the range 3.5 m $< H_{m0}$ $<$ 4 m and 10 s $< T_e <$ 11 s. Several sea states occur at a similar frequency, and sea states within 2 m $< H_{m0} <$ 5 m and 9 s $< T_e <$ 11 s contribute a similar amount to energy.

Frequencies of occurrence and contributions to energy of less than 0.01% are considered negligible and are not shown for clarity. For example, the sea state within 0.5 m $< H_{m0}$ $<$ 1 m and 5 s $< T_e <$ 6 s has an occurrence of 0.02%. The contribution to total energy, however, is only 0.001% and, therefore, does not appear in Figure 77 (bottom). Similarly, the sea state within 8.5 m $< H_{m0} <$ 9 m and 13 s $< T_e <$ 14 s has an occurrence of 0.005%, but the contribution to total energy is 0.07%.

Curves showing the mean, 5^{th} and 95^{th} percentiles of wave steepness, H_{m0}/λ, are also shown in Figure 77. The mean wave steepness at SETS is 0.0166 ($\approx 1/60$), and the 95^{th} percentile is approximately 1/34.

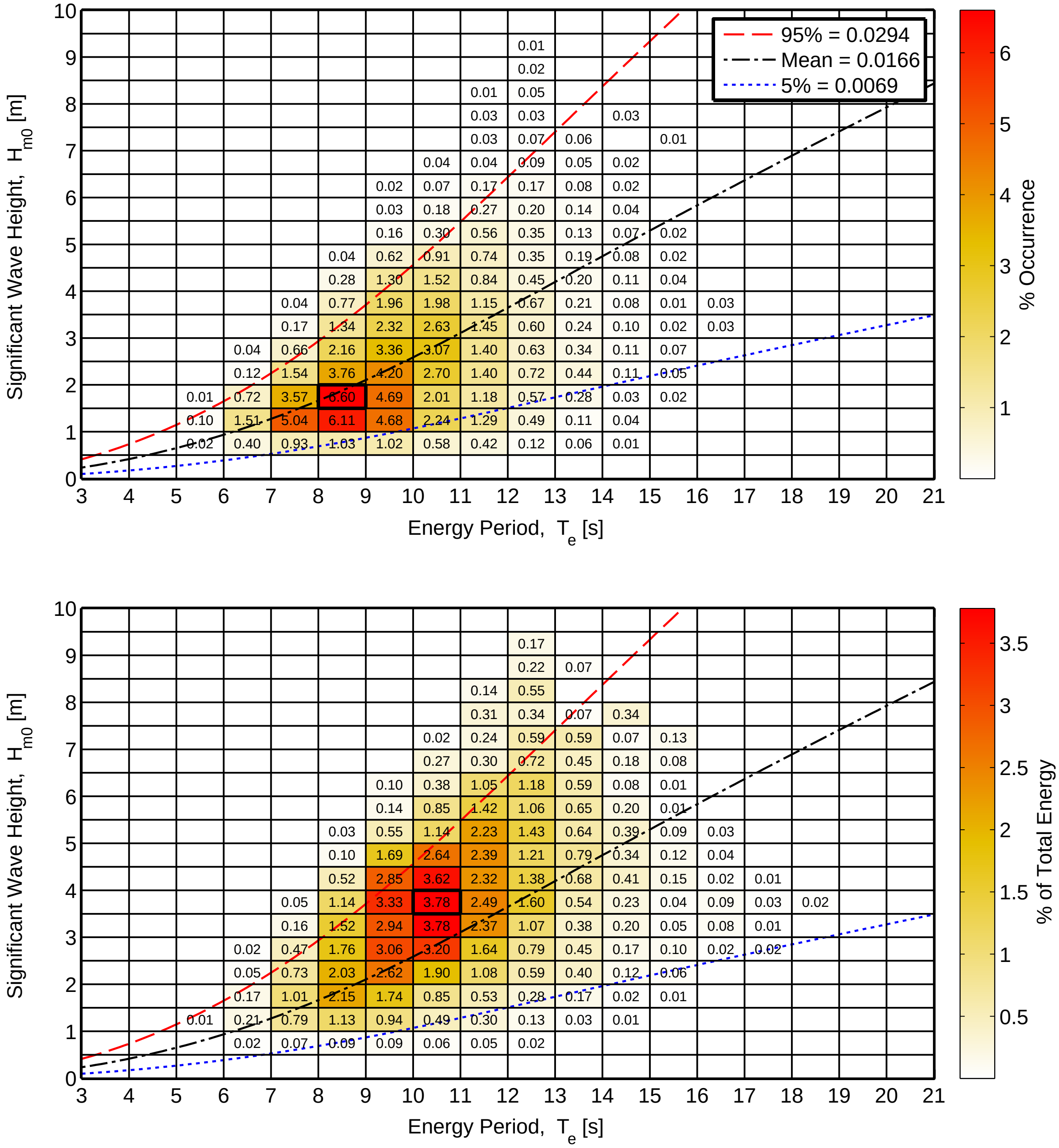


Figure 77: Joint probability distribution of sea states for SETS. The top figure is frequency of occurrence and the bottom figure is percentage of total energy, where total energy in an average year is 350,291 kWh/m.

8.4.2. IEC TS Parameters

The monthly means of the six IEC TS parameters, along with the 5^{th} and 95^{th} percentiles, are shown in Figure 78. The months, March – February, are labeled with the first letter (e.g., March is M). The values in the figure are summarized in Table **??** in Appendix F.

Monthly means of the significant wave height, H_{m0}, and the omnidirectional wave power density, J, show the greatest seasonal variability compared to the other parameters. Values are largest and vary the most during the winter months. The same trend is observed for the monthly mean energy period, T_e, but its variation is less pronounced. These observations are consistent with the relationship between wave power density, significant wave height and energy period, where wave power density, J, is proportional to the energy period, T_e, and the square of the significant wave height, H_{m0}.

Slight seasonal variation in the spectral width, ϵ_0, can be seen, where the spectral width is smaller in the winter, and has greater variation in the summer. The direction of maximum directionally resolved wave power, θ_J, is fairly consistent throughout the year from west, and slight variation throughout the year can be seen but it does not seem to correspond directly to season. Some seasonal variability of the directionality coefficient, d_θ, is evident, with lower values and more variation in the summer. In summary, the waves at SETS, from the perspective of monthly means, have a fairly consistent spectral width, although narrower in the winter, are predominantly from the west, and exhibit a wave power that has a narrow directional spread, especially in the winter.

Wave roses of wave power and significant wave height, presented in Appendix F, Figure 150 and 151, also show the predominant direction of the wave energy at SETS, which is west, with frequent but small shifts to the north and occasional but small shifts to the south. Figure 150 shows two dominant wave direction sectors, west (at 270°) and west/northwest (WNW) at 285°. Along the predominant wave direction, 285°, the omnidirectional wave power density is at or below 35 kW/m about 19% of the time, but greater than 35 kW/m nearly 15% of the time. Along the west direction (270°), wave power density is at or below 35 kW/m about 18% of the time, and greater than 35 kW/m about 11% of the time.

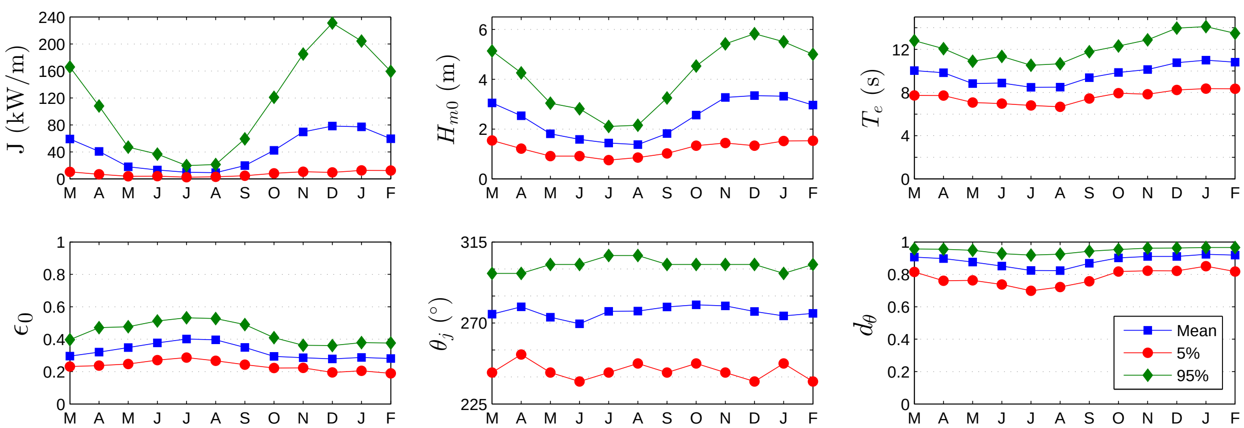


Figure 78: The average, 5^{th} and 95^{th} percentiles of the six parameters at SETS.

Monthly means, however, smear the significant variability of the six IEC parameters over small time intervals as shown in plots of the parameters at 1-hour intervals in Figure 79 for a representative year. While seasonal patterns described for Figure 78 are still evident, these plots show how sea states can vary abruptly at small time scales with sudden changes, e.g., jumps in the wave power as a result of a storm.

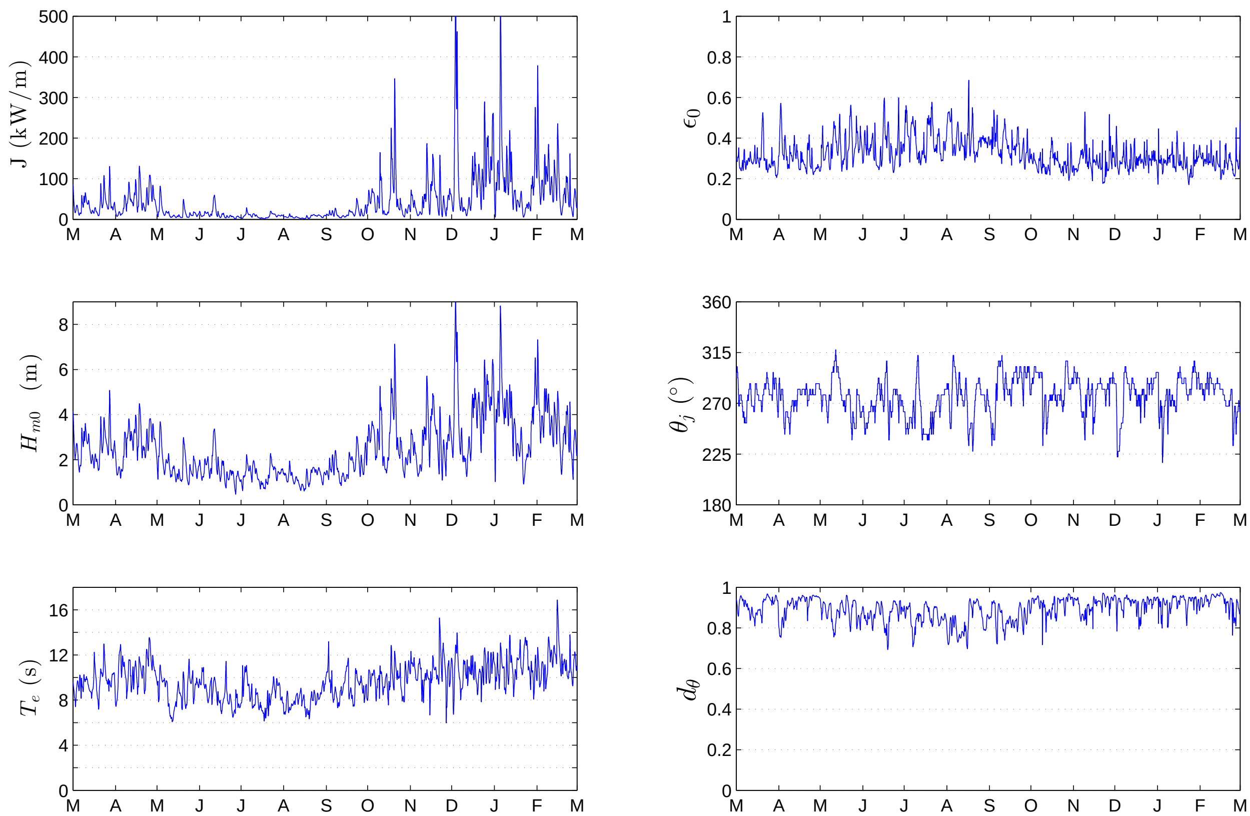


Figure 79: The six parameters of interest over a one-year period, March 2007 – February 2008 at SETS.

8.4.3. Cumulative Distributions

Annual and seasonal cumulative distributions (a.k.a., cumulative frequency distributions) are shown in Figure 80. Note that spring is defined as March – May, summer as June – August, fall as September – November, and winter as December – February. The cumulative distributions are another way to visualize and describe the frequency of occurrence of individual parameters, such as H_{m0} and T_e. A developer could use cumulative 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 1 m for installation and recovery, according to Figure 80, this condition occurs about 4.6% of the time on average within a given year. If significant wave heights need to be less than or equal to 2 m for emergency maintenance, according to Figure 80, this condition occurs about 46% of time on average within a given year. Cumulative distributions, however, do not account for the duration of a desirable sea state, or weather window, which is needed to plan deployment and servicing of a WEC device at a test site. This limitation is addressed with the construction of weather window plots in the next section.

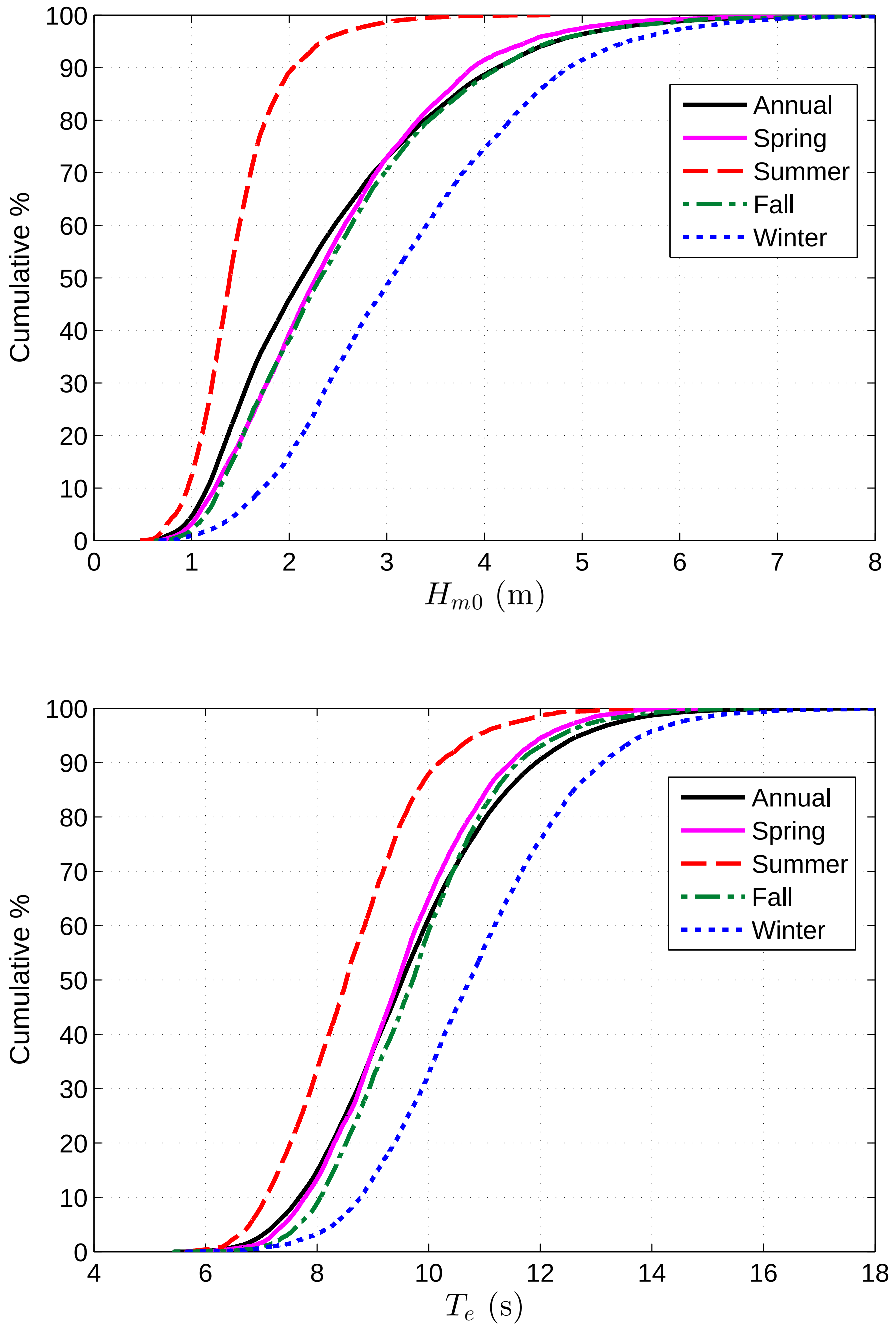


Figure 80: Annual and seasonal cumulative distributions of the significant wave height (top) and energy period (bottom) at SETS.

8.4.4. Weather Windows

Figure 81 shows the number of weather windows at SETS, when significant wave heights are at or below some threshold value for a given duration, for an average winter, spring, summer and fall. In these plots, each occurrence lasts a duration that is some multiple of 6-hours. The minimum weather window is, therefore, 6-hours in duration, and the maximum is 96-hours (4 days). The significant wave height threshold is the upper bound in each bin and indicates the maximum significant wave height experienced during the weather window. Note that the table is cumulative, so, for example, an occurrence of $H_{m0} \leq 1$ m for at least 30 consecutive hours in the fall is included in the count for 24 consecutive hours as well. In addition, one 12-hour window counts would count as two 6-hour windows. It is clear that there are significantly more occurrences of lower significant wave heights during the summer than winter, which corresponds to increased opportunities for deployment or operations and maintenance.

Weather window plots provide useful information at test sites when planning schedules for deploying and servicing WEC test devices. For example, if significant wave heights need to be less than or equal to 1 m for at least 12 consecutive hours to service a WEC test device at SETS with a given service vessel, there would be, on average, nineteen weather windows in the summer, but only one in the winter. When wind speed is also considered, Figure 82 shows the average number of weather windows with the additional restriction of wind speed, $U < 15$ mph. The local winds (which are not necessarily driving the waves) are used in these weather windows, and are given in Appendix F.4. That wind data was not available from the hindcast, so data from CFSR was used (see Section 2.3, Appendix F.4). For shorter durations (6- and 12-hour windows), daylight is necessary. Windows with $U < 15$ mph and only during daylight hours are shown in Figure 83. Daylight was estimated as 5am – 10pm Local Standard Time (LST).

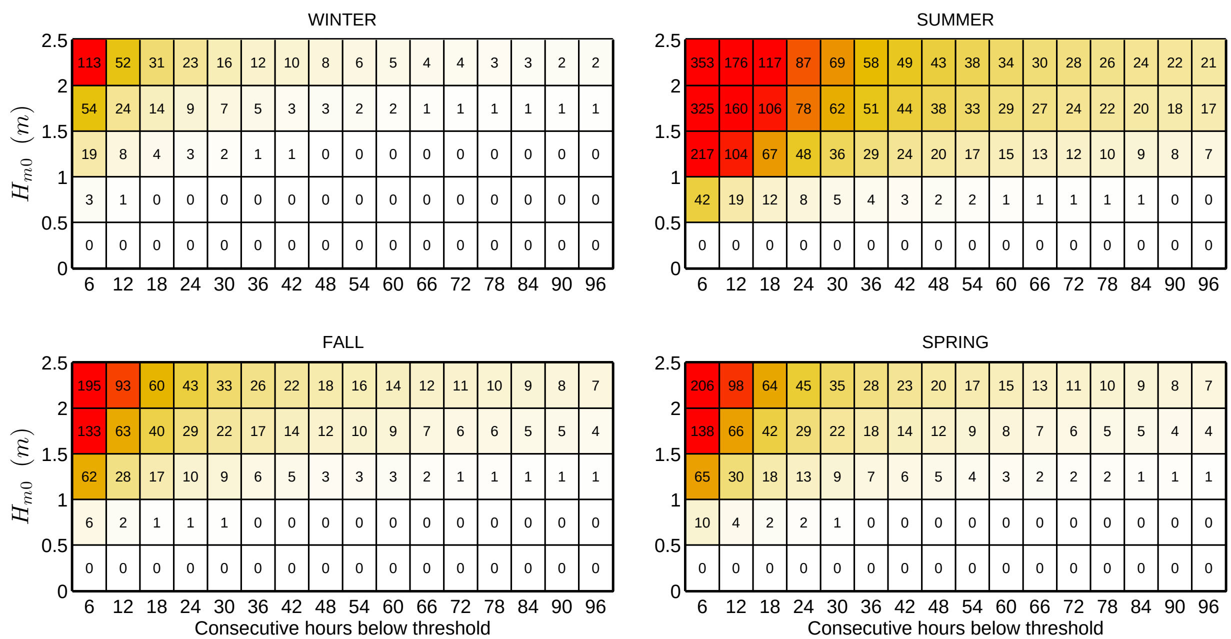


Figure 81: Average cumulative occurrences of wave height thresholds (weather windows) for each season at SETS. Winter is defined as December – February, spring as March – May, summer as June – August, and fall as September – November.

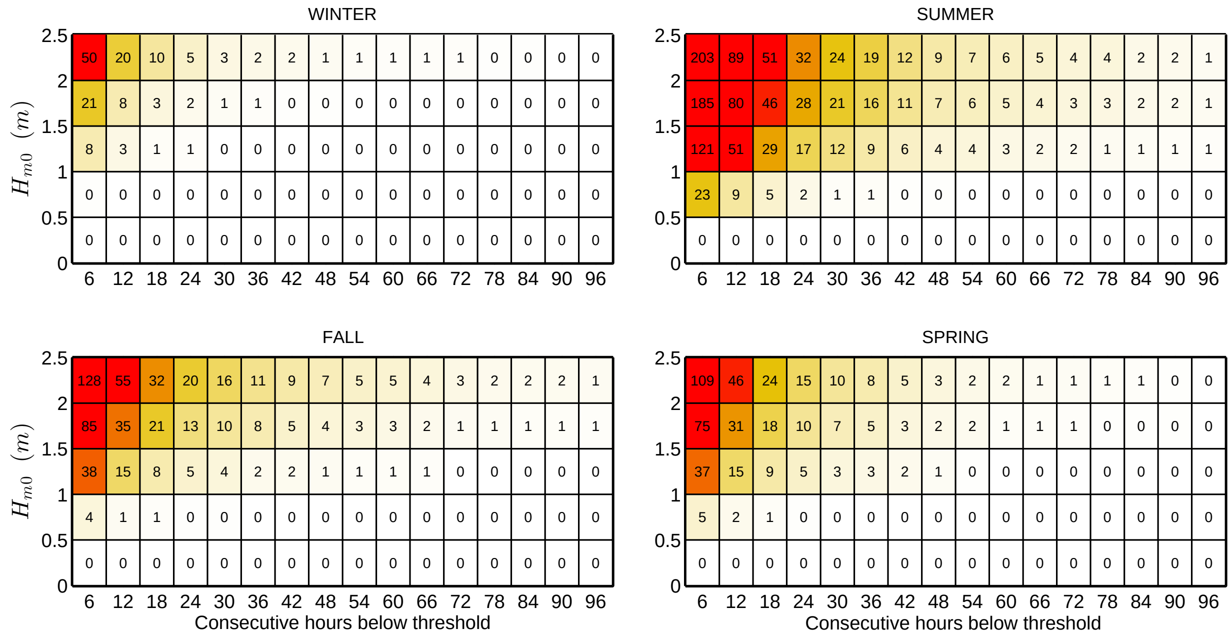


Figure 82: Average cumulative occurrences of wave height thresholds (weather windows) for each season at SETS with an additional restriction of U < 15 mph.

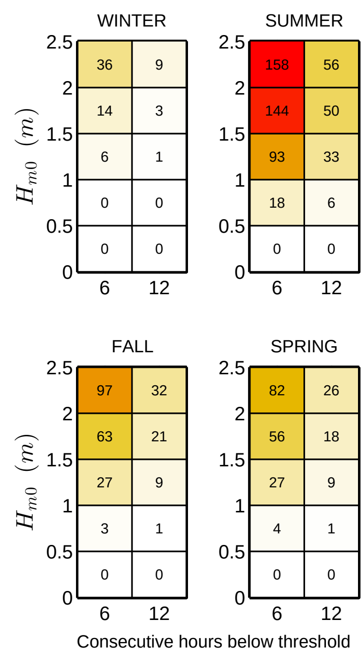


Figure 83: Average cumulative occurrences of wave height thresholds (weather windows) for 6- and 12-hour durations with $U < 15$ mph and only during daylight hours (5am – 10pm LST) at SETS.

8.4.5. Extreme Sea States

The modified IFORM was applied using NDBC 46050 data (see Table 6 for buoy information) to generate the 100-year environmental contour for SETS shown in Figure 84. Note this is the same data set used for NETS, but for completeness, the text and figure are repeated here. Selected sea states along this contour are listed in Appendix F, Table 34. As stated in Section 1.2, environmental contours are used to determine extreme wave loads on marine structures and design these structures to survive extreme sea states of a given recurrence interval, typically 100-years. For SETS, the largest significant wave height estimated to occur every 100-years is over 17.3 m, and has an energy period of about 16.6 s. However, significant wave heights lower than 17.3 m, with energy period less than or greater than 16.6 s, listed in Table 34, could also compromise the survival of the WEC test device under a failure mode scenario in which resonance occurred between the incident wave and WEC device, or its subsystem. For comparison, 50- and 25-year return period contours are also shown in Figure 84. The largest significant wave height on the 50-year contour is 16.3 m with an energy period of about 16.4 s, and on the 25-year contour is 15.4 m and 16.1 s. It should be noted that conditions at the NDBC46050 buoy (at 128 m depth) may differ significantly from the conditions at the test site (at depths of 58-75 m).

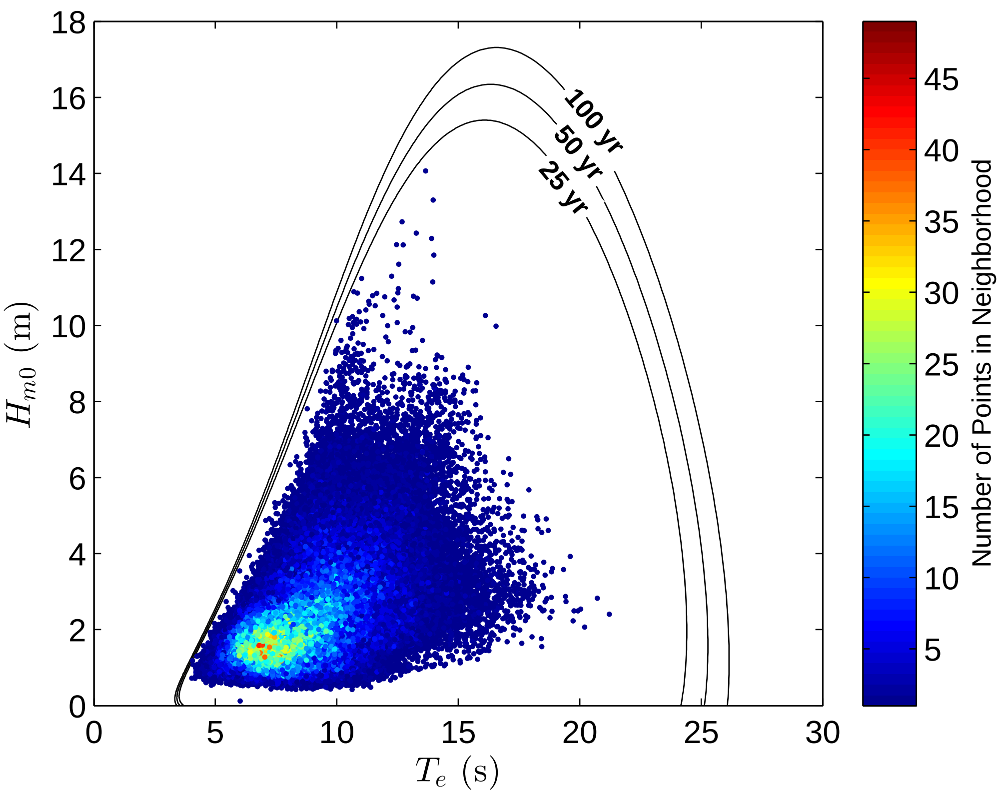


Figure 84: 100-year contour for NDBC 46050 (1996–2014).

8.4.6. Representative Wave Spectrum

All hourly discrete spectra measured at NDBC 46050 for the most frequently occurring sea states are shown in Figure 85. Note this is the same data set used for NETS, but for completeness, the text and figure are repeated here. The most frequently occurring sea state, which is within the range 1.5 m $< H_{m0} <$ 2 m and 7 s $< T_e <$ 8 s, was selected from a JPD similar to Figure 77 in Section 8.4.1, but based on the NDBC 46050 buoy data. As a result, the JPD, and therefore the most common sea states, generated from buoy data are slightly different from that generated from hindcast data. For example, the most frequently occurring sea state for the JPD generated from hindcast data is in the same range for H_{m0} (1.5 m $< H_m 0 <$ 2 m), but one second higher on bounds for T_e (8 s $< T_e <$ 9 s). Often several sea states will occur at a very similar frequency, and therefore plots of hourly discrete spectra for several other sea states are also provided for comparison. Each of these plots includes the mean spectrum and standard wave spectra, including Bretschneider and JONSWAP, with default constants as described in Section 2.2.

For the purpose of this study, the mean spectrum is the 'representative' spectrum for each sea state, and the mean spectrum at the most common sea state, shown in Figure 85 (bottom-right plot), is considered the 'representative' spectrum at the site. The hourly spectra vary considerably about this mean spectrum, but this is partly reflective of the bin size chosen for H_{m0} and T_e. Comparisons of the representative spectra in all plots with the Bretschneider and JONSWAP spectra illustrate why modeled spectra with default constants, e.g., the shape parameter $\gamma = 3.3$ for the JONSWAP spectrum, should be used with caution. Using the constants provided in Section 2.2, the Bretschneider spectra are fair representations of the mean spectra in Figure 85, however it does not capture the bimodal nature of the spectra. The mean measured spectra is the best representation of the conditions, however, if these modeled spectra were to be used at this site, it is recommended that the constants undergo calibration against some mean spectrum, e.g., the representative spectrum constructed here. A better alternative may be to explore other methods or spectral forms to describe bimodal spectra (e.g., Mackay 2011) if it is known that the shape is not unimodal.

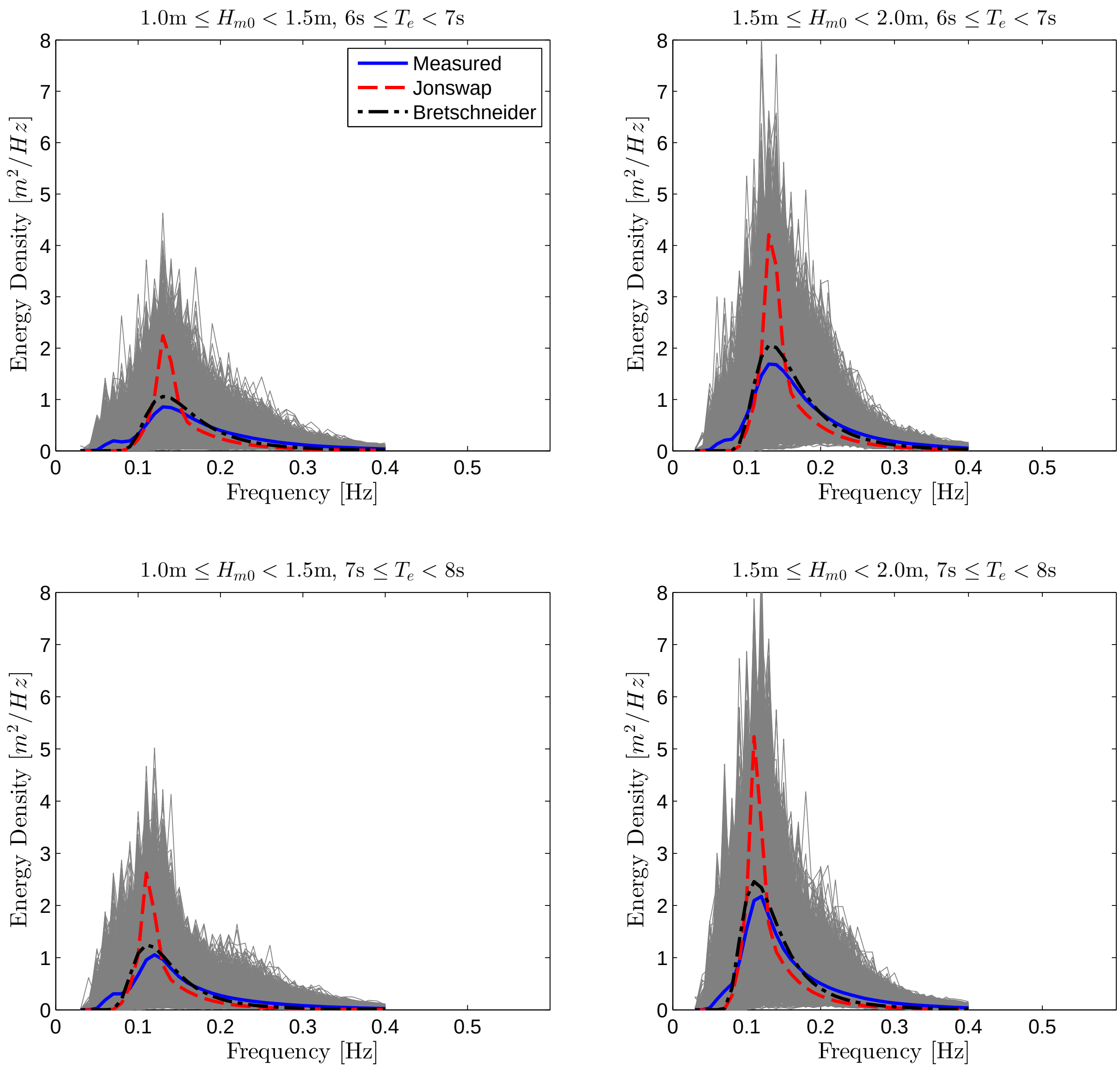


Figure 85: All hourly discrete spectra and the mean spectra measured at NDBC 46050 within the sea state listed above each plot. The JONSWAP and Bretschneider spectra are represented by red and black dotted lines, respectively.