Estimation of Extreme Wave and Wind Design Parameters for Offshore Wind Turbines in Gulf of Maine Using a POT Method

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Revision 2

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1 Acronyms, Symbols, and Abbreviations:

2 ABS = American Bureau of Shipping

3 ASCE = American Society of Civil Engineers

4 GoM = Gulf of Maine

5 GP = Generalized Pareto

6 H_s = significant wave height

7 IEC = Internationale Electrotechnical Commission

8 ISO = International Standards Organization

9 NERACOOS = North-eastern Regional Association of Coastal and Ocean Observing Systems

10 NOAA = National Oceanic and Atmospheric Administration

11 NREL = National Renewable Energy Laboratory

12 POT= peaks over a threshold

13 th = threshold used for POT analysis

14 T_p = wave peak spectral period

- 15 UMaine = University of Maine
- 16 US = United States
- 17 V = wind speed
- 18 V_{ref} = wind speed at sensor height
- 19 V_z = wind speed at height z
- 20 w = time window
- 21 z = height above sea level
- 22 z_{ref} = referenced sensor height above sea level
- 23 α = wind shear power law exponent
- 24 k = number of standard deviations above mean value
- 25 μ = mean

1. Introduction

Offshore wind turbines in the Gulf of Maine (GoM) offer important advantages as a source of abundant and steady wind in close proximity to dense New England population centres while reducing land use issues encountered by land-based wind. The US Department of Energy's National Renewable Energy Laboratory (NREL) has identified the Gulf of Maine as having Class 6 and 7 winds and an estimated 157 GW of wind power available within 95 km of the coast (Musial & Ram, 2010).

Extreme environmental conditions such as significant wave height with mean associated peak period and wind speeds are required for design of offshore wind turbine support structures. There are no buoy data based estimates of these conditions available for the GoM. To that end, predictions of extreme design conditions for five sites in the GoM based on buoy data collected by the University of Maine (UMaine) and the National Oceanic and Atmospheric Administration (NOAA) are presented. Calculations include extreme waves with mean associated wave peak periods, 8-minute average wind speeds and 5-second average gust wind speeds. Extreme significant wave height results are compared to predictions made in past studies. Extreme wind speed values are compared to the American Society of Civil Engineers (ASCE, 2010) 3-second average gust wind speeds for on land coastal structures. In addition, wind shear coefficients and gust factors are estimated and compared to the ASCE (2010) estimates.

2. Material and methods

2.1 Buoy Data

The data were obtained from two sources: (1) UMaine manufactured and operated buoys deployed over the past ten years which are part of the North-Eastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS) (Pettigrew, Wallinga, Neville, & Schlenker, 2005) (UMaine, 2009) and (2) NOAA Buoys, operated by the National Data Buoy Centre with over twenty years of data (NOAA, 2011). The locations of buoys used as data sources are shown in **Figure 1** and listed in **Table 1**. All buoys measured significant wave height, wave peak period, 8-minute average and 5-second average gust wind speeds at four or five meters above sea level. Data can be downloaded from appropriate online sites found within the reference section. Statistical parameters for the buoy wave and data sets are provided in **Table 2**. The mean significant wave height from the buoy data ranges from 0.6m to 1.6m and the mean for 8-minute average wind speed at 4m above sea level range from 4.7m/s to 6.6m/s. The standard deviation, skewness, and kurtosis of each of these data sets are also provided. Some of the buoy data

records are short (e.g. seven years) and extrapolating using this data can present uncertainty for long return period estimates. However, no other buoy data is available for this region at this time and there is a need for these estimates immediately.

2.2 Extreme Value Analysis Methods

Two methods were used to estimate extreme significant wave heights and wind speeds. The first method fits a Gumbel Distribution to all of the data collected or daily, weekly, monthly or yearly maxima. This method is called the “historical method” by ISO (2005) and it is often used to predict extreme significant wave heights. The second method fits a Generalized Pareto Distribution to Peaks over a Threshold (POT). The POT method is a more recent approach and employs techniques to identify and select non-serially correlated data points. Both methods were used to provide alternative ways of analysing the data and are compared in this study. Given, the increased ability to identify non-serial correlated data points, the POT method is the preferred method and is recommended for design.

The historical analysis is well known and was performed following the methodology of Sorenson (1993) with a Gumbel Distribution (Gumbel, 1958). The Gumbel distribution has been widely applied to the estimation of extreme wind speeds and significant wave heights (Castillo, 1988). With this method, there is not a clear rationale for choosing independent data points. The wind industry often uses only the annual maxima (Gross J. L. et al., 1995). Similarly, Coles (2001) used only annual maxima and fitted them to the Generalized Extreme Value Distribution (GEV). Including only annual maxima leaves little data for fitting to statistical models. Burton et al. (2001) found that there are about 160 independent extreme values per year for waves. We analysed data sets that include: all of the recorded buoy data (one or two samples every hour), daily maxima, weekly maxima, monthly maxima, and annual maxima. This provided a way to disaggregate the data from correlated weather patterns. The data set which produced the best fit was determined from a least squares linear regression analysis of the reduced variate data. There are five buoys each with a wave data set and wind speed data set. Each data set was investigated using all of the recorded buoy data (one or two samples every hour), daily maxima, weekly maxima, monthly maxima, and annual maxima resulting in fifty different R^2 values computed (5bouys x 2data channelsx5maxima types). **Figure 2** shows an example reduced variate plot for Buoy E01 significant wave height data that gave the best fit (R^2 value) using a plot of reduced variate and significant wave height, H_s . This particular fit used all of the data.

The second extreme value method was a POT analysis following well known methods (Davison, A. C., and Smith, R. L., 1990; Mathiesen et al., 1994; Ferreira, J. A. and Soares, C. G., 1998). As stated by Tucker and Pitt (2001), this method involves selecting a threshold value and fitting a distribution to the data points. In this paper, the Generalized Pareto Distribution (GPD) was used. **Figure 3** illustrates the POT peak selection process used in this study. Data points selected for use in fitting to the GPD function are shown in green. The dark dashed horizontal line is the threshold. The highest peaks over the threshold in the time period marked by the triangles were selected. The steps used in this process can be summarized as:

1. Identify all data above the threshold.
2. Loop through the data above the threshold in steps equal to a specified time window.
3. Select one max for each time window.
4. Check to make sure the maximum selected in each time window did not occur within one half of the time window of the previous data point selected. If the data point is within this duration, the point is considered to be serially related and discarded. The next highest data point that exceeded the threshold and does not lie within one half of time window is then selected.
5. The GPD is then fitted using the MATLAB function gpfitt (MathWorks, 2011).

This POT analysis follows a process very similar to the work of Simiu (2011) and attempts to deal with sampling discrete maximum significant wave heights by selecting only significant wave heights above a specified threshold for a selected time window. Four, eight, twelve, and sixteen day time windows were considered. Similar techniques for identifying discrete storm or weather events have been employed by many such as Gibson et al. (2009).

Comparisons between the fits for different thresholds and time windows were made and a distribution was selected for prediction of extreme events. To select the appropriate threshold and time window, a sensitivity analysis was completed to study their effects on the extreme value analysis predictions. A sample case is now discussed. Figure 4 (a) shows sample results from a sensitivity study for buoy E01 showing the effects of time window duration and threshold selection on 100 year significant wave height predictions. Differences of up to a meter in significant wave height predictions were seen. The four time window traces agree well for low and high thresholds because this results in sampling very similar data sets. However, the low threshold predictions are based on many non-independent data points resulting in a heterogeneous data set which is difficult to fit to statistical distributions as expressed by Ragan and Manuel (2008) and Toft et al. (2011). These authors further recommend choosing as high a

threshold as possible. Thresholds greater than mean of the data plus 1.4 or 1.9 times the standard deviation or higher are recommended with the condition that there be enough data points to avoid sampling error. Naess similarly notes that only peaks over high thresholds are relevant for an extreme value analysis (1984). For Buoy E01, the significant wave height mean is 1.2m and the standard deviation 0.8m. Therefore, the two recommended minimum thresholds would be greater than 2.3m and 2.6m. For Buoy E01 a threshold of 3m was selected as it exceed these recommended targets and still provided sufficient data for fitting the GPD. The effect of time window duration is now examined. In general, a larger time window is preferred to remove the effects of serial correlation. However, larger time windows result in fewer data points. For this particular buoy with a seven year data record, the 4-day time window was selected in lieu of the 8, 12, and 16-day time windows. The 16 and 12-day windows generate too few data points for fitting the GPD. The 4-day time window provides a superior fit to the data as compared to the 8-day time window as evidenced by the individual fits of the GPD as shown in Figure 4 (b) and (c). Figure 4 (b) shows the selected fit for buoy E01 extreme significant wave height with a 4-day time window and a 3m threshold. Figure 4 (c) shows the fit with an 8-day time window and a 3m threshold. Figure 4 (b) provides more data, provided a tighter confidence window, and was selected for use. Similar examinations of the data were performed for the other buoys.

2.3 Mean Period Associated with Extreme Significant Wave Heights

The mean peak periods associated with the predicted extreme significant wave heights were estimated using a scatter plot of measured peak period versus significant wave height for each buoy. A sample scatter diagram is presented in **Figure 5** for the UMaine Buoy E01. The wave peak period data provided from the buoys is based on a fairly coarse spectral analysis. The resolution is a trade off with sampling variability of the spectral estimates. Raw buoy spectral data was not available for this study. To address this coarseness, a block average of the peak period was made using a significant wave height bin of 0.2m. A three-parameter power law fit was made to the block average data to predict the peak period associated with a given significant wave height.

2.4 Wind Design Parameters

The wind turbine industry requires several key design parameters. Preliminary estimates are made for these parameters. Due to differences in measurement conventions between the buoy instrumentations systems and standard wind engineering practices, corrections are required. Annual average power law wind shear exponents for

each buoy were estimated from the 8-minute average buoy wind speed data and published 10-minute wind speed data at 90m above sea-level from NREL. A power law wind shear model is recommended in the primary wind design standard, International Eletrotechnical Commission 61400-3 (2009). To calculate the power law wind shear exponent, a correction is needed to match the time averaging periods. IEC 61400-3 does not provide a general method for converting from one averaging period to another. The 8-minute average wind speed measured by the buoy was first converted to match the NREL reported 10-minute wind speeds with guidance from ISO 19901-1 (2005). Following ISO guidance, to convert from eight-minute wind speeds to 10-minute wind speeds, one must multiply the 8-minute wind speed by a factor of 0.99. The power law wind shear exponent is α in equation (1).

$$V_z = V_{ref} \left(\frac{z}{z_{ref}} \right)^\alpha \quad (1)$$

where V_z is the wind speed at the desired height, V_{ref} is the known wind speed at the buoy sensor height, z is the height of interest, z_{ref} is the height of the buoy measurement above sea level. The annual average wind shear power law exponent was estimated for each site by solving equation (1) for α using the annual mean of the 10-minute wind speed calculated from the buoy data for V_{ref} at 4m and the annual mean 90m 10-minute wind speed published by the NREL (2010) for V_z . NREL developed these estimates for Maine using best practices for modelling offshore wind. The NREL Maine wind models have been validated against ocean buoys, marine automated stations, Coast Guard stations, lighthouses, and satellite-derived wind speeds 10m over the ocean. In addition to wind shear exponents, the mean wind speed characteristics at each buoy were calculated at the sensor height and 90 m using the new wind shear power law exponent. The annual mean gust factor near sea level was also calculated by dividing the annual mean gust wind speed by the annual mean 8-minute average wind speed.

3. Results

3.1 Extreme Value Analysis

The results of the extreme values analysis for significant wave height are shown in **Table 3** for the five buoys considered in this study for 1, 5, 10, 25, 50, and 100-year return periods. For each buoy, two estimates of the extreme significant wave height were made based on the historical and POT methods. The POT results are recommended for design. For the historical method, the data sampling that gave the best fit as determined from a least squares analysis is given. For the POT method, the time window, w , in days and the significant wave height threshold, th , in meters, that gave the best fit as described above are provided. The mean, μ , and the number of

standard deviations above the mean required to reach the selected threshold, k , are also provided. The shape and scale parameters for the GP distribution are also provided for the POT method. The 90% confidence intervals for the POT method for the predicted extreme significant wave heights are also provided. The 50-year significant wave height, a critical design parameter for offshore wind turbines per the American Bureau of Shipping (ABS) Guide for Building and Classing Floating Offshore Wind Turbines (2013) and IEC 61400-3 (2009), for the buoys considered ranged from approximately from 4.7m to 9.8m for near shore and far offshore buoys.

A comparison of the confidence intervals shown in Table 3 for the 50-year return period significant wave height is now presented. The 50-year return period event is of particular interest because it is specified by the offshore wind turbine design standards such as ABS (2013) and IEC (2009). These intervals were estimated using a parameterized bootstrap method recommended for extreme value estimates by Kysely (2007) and Coles and Simiu (2003). The confidence intervals for the 50-year estimate of significant wave height for the longer buoy records from NOAA (27-31-year data record) are +20%/-15% different from the estimated value for NOAA 44005 and +28%/-22% different for NOAA 44007. The confidence intervals for 50-year estimate for significant wave height for the shorter record buoy records from UMaine (7-year data record) have larger confidence intervals. For buoy E01, the range is +49%/-31%. For Buoy F01 the range is +30%/-23%. For Buoy I01 the range is +42%/-15%. The confidence values are larger for the UMaine buoys as expected given the shorter seven year data records.

The predicted extreme 8-minute average wind speeds and 5-second average gust wind speeds are shown in **Table 4** and **Table 5**. The extreme gust wind speeds were estimated using the results from the POT method multiplied by the annual mean gust factor for each buoy shown in **Table 6**. The threshold, th , mean, μ , and number of standard deviations above the mean required to reach the threshold, k , are provided in meters per second. The UMaine buoy wind speeds are at an elevation of 4m and the NOAA wind speeds are at an elevation of 5m. The 50-year 8-minute average wind speeds ranges from 22.2m/s to 25.2m/s for all of the buoys. The 50-year five second gust wind speed ranged from 28.5m/s to 30.7m/s for all of the buoys. Confidence intervals are also provided for the 8-minute and gust wind speeds using the same parametric bootstrap procedure completed for the extreme significant wave height estimates. Similar to the wave heights, the estimates made with longer data records are noticeably smaller.

Estimates for extreme significant wave height and wind speed using standard thresholds equal to μ plus $1.4k$ and μ , plus $2.0k$ are provided in the appendix in **Table 8** and **Table 9**. The preferred time windows shown in Table 3 and

Table 4 were used to generate the results in Table 8 and 9. These estimates compare well with those presented in the Tables 3 and 4.

3.2 Mean Associated Period

The mean associated wave peak periods for the extreme significant wave height estimates made with the POT method given in Table 2 are shown in **Table 5**. The parameters a, b, and c in Table 5 correspond to the following equation for the fitted power law equation given by:

$$T_p = a \cdot Hs^b + c, \quad (2)$$

where T_p is the peak spectral period. The numbers in parentheses indicate the parameters that define the lower and upper bounds of the 95% confidence interval. A three parameter power law fit was selected based on a comparison of the R^2 value from a three parameter fit and two parameter fit. A two parameter fit was also considered as it is often used for offshore design (e.g. DNV, 2010). For the buoy data sets considered here a three parameter power law fit gave better results as indicated by the R^2 value of the two fits.

3.3 Wind Design Parameters

Relevant industry wind design parameters estimated from the buoy data and NREL published data are shown in **Table 6**. The annual average 8-minute wind speed and ISO corrected 10-minute wind speed on the buoy is presented for each buoy. 10-minute averages are presented in addition to the eight-minute wind speed data to accommodate standard wind engineering practice of using 10-minute average wind speed. The annual mean wind shear power law coefficient uncertainty is not available. This is because only an annual mean wind speed was provided from NREL from which the coefficient was derived.

4. Discussion

The following discussion includes commentary on the differences between the two methods used to estimate extreme values as well as a comparison of the preferred estimation method with past work. Extreme wind speeds and wind shear power exponents are compared with ASCE published design standards for coastal onshore regions in Maine.

4.1 Comparison of Historical and POT Methods

The extreme value estimates for significant wave height, 8-minute average wind speed, and 5-second average gust wind speed shown in Tables 2, 3, and 4 indicate that for all three parameters, the historical method consistently predicted larger values than the POT analysis. For significant wave height, the historical method predicted values up to 30% larger and on average 13% larger. For 8-minute average wind speed, the historical method predicted values up to 27% larger and on average 11% larger. These differences are likely largely due to the inclusion of serially correlated data points in the historical method. This is the main drawback of the historical method. Analyses using the historical method have previously been shown to over predict extreme values even though the data showed a good fit in the probability plot (Buisand, 1984). Therefore, the POT predictions are expected to be more accurate. The POT method predictions are used for comparison with past extreme value estimates in the next section.

4.2 Comparison of Extreme Significant Wave Height Predictions to Public Data

There are several published studies presenting extreme significant wave height predictions. Neu (1976, 1982) produced several papers predicting extreme significant wave heights based on shipboard observations and wave probe measurements along the Atlantic coast for coarse $5^0 \times 5^0$ square regions. Godshall et al. (1980) published similar analyses based on shipboard observations for finer $1^0 \times 1^0$ square regions. Walker (1984) has also published predictions of extreme significant wave heights from shipboard observations in $5^0 \times 5^0$ squares. Estimates for extreme significant wave heights have also been produced by Panchang et al. (1990, 1999, 2006 and 2008) using a regional wave hindcast model. Comparisons are made with an early model with a grid spacing 27.4 nautical miles. Predictions of 100 year significant wave heights made using the POT method are compared with the work of Godshall et al. and Panchang et al. in **Table 7**. Walker and Neu were not compared due to the coarseness of their grids. For Buoy E01, the predictions from this study compared well with Panchang but differed significantly with Godshall. Godshall's prediction closest to Buoy E01 covers a large area including shallow water may have led to lower predictions for this point while Panchang's model data point closest to Buoy E01 resides in relatively open water free from the coast. For Buoy F01, significant differences exist between the POT method and Panchang and Godshall's results. This is attributable to Buoy F01's location within the mouth of Penobscot Bay which is on the very edge of both Panchang's and Godhsall's closest output points. Similar arguments can be made for Buoy I01. NOAA Buoy 44005 showed very good agreement between the POT method estimates and Panchang and

Godshall's results. This buoy is located far offshore and both Panchang's and Godshall's output areas do not include coastline and the water depth is relatively constant. The POT method predictions from NOAA buoy 44007 agreed within 10% of Panchang's estimates but are 30% different from Godshall's. These differences again are possibly due previous estimates' grid coarseness. In general, the predictions from this study compared favourably for open water locations. In regions closer to shore the predictions compare less favourably.

4.2 Comparison of Estimated Wind Design Conditions to ASCE-7

No extreme offshore wind speeds for the Gulf of Maine have been published. The American Society of Civil Engineers' publication, ASCE-7, (2010) estimates the 50-year return period 3-second gust for the entire Maine onshore coast at 10 m above sea level to be 45 m/s. Using the wind shear exponent estimated from the combined buoy and NREL data and correcting from 5-second to three second time average periods following ISO 19901-1, the estimated extreme wind speeds at the buoy locations were corrected for a 10m elevation and 3-second averaging period. The results are shown in **Table 8**. The extreme gust wind speeds from this study were found to be -20 to-26% less than ASCE. The wind shear exponents for each buoy are also compared with the recommended value of 0.15 from ASCE for coastal exposure conditions. The wind shear exponents provided from ASCE and determined in this study are relatively close to those recommended by IEC 61400-3, offshore wind turbine design standard which a value of 0.14 for normal offshore wind conditions. The wind shear exponents varied from 0.13 to 0.19 in this study with the 0.19 being an outlier. The values estimated in this study should be used carefully as they are based on utilizing two independent data sources.

4. Summary and Conclusions

This analysis presented in the paper presents key wave and wind design parameters required in the design of offshore wind turbines near several possible wind turbine locations. These design parameters were estimated based on buoy data records of seven to twenty-five years. We have calculated extreme wind speeds, extreme significant wave heights and mean associated peak periods for offshore Maine. This work is intended to provide a starting point for detailed engineering design specifications for future wind energy development throughout the Gulf of Maine with future data reducing estimate uncertainty. Site specific data will likely be required for a future project and values presented in this paper could be useful for initial planning, general understanding of the wave climate in the Gulf of Maine, and possible calibration of hindcast models for other sites.

The historical and POT extreme value estimation methods were used to predict extreme significant wave height, eight minute wind average speed, and five second average gust wind speed at five buoy sites. The results from these two methods were compared and the historical method was found to consistently over predict the extreme events likely due to serially correlated data points, a known limitation of the historical method. The predictions made by POT method are therefore recommended for design over the historical method.

Extreme significant wave height predictions using the POT method compared well with past estimates based on hindcast model output and shipboard observations for the open water sites. Extreme significant wave heights estimated from buoys closer to shore differed considerably from past work likely due to coastline distortion not captured in previous studies. Therefore, these new predictions are more useful for projects nearer to the coastline where data is scarce.

Extreme wind speeds and wind shear coefficients predicted from the POT method in this study were adjusted for elevation and time averaging period to agree with ASCE published onshore coastal values to allow for comparison as no other published data offshore Maine exists. The extreme wind speeds compared were up to 27% lower than the ASCE values. The wind shear values compared well with the ASCE published values.

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Figure

Figure 1: Gulf of Maine Buoys Considered in Study

Figure 2: Reduced Variate vs. Extreme Significant Wave Height Plot for Buoy E01

Figure 3: Buoy E01 POT Data Reduction Sample Plot

Figure 4: Sensitivity Study Results for Buoy E01 Significant Wave Height Data

(a) Comparison of threshold and time window on 100 year significant wave height

(b) Selected GPD Fit of data

(c) Sample Fit That Was Not Selected

Figure 5: Sample Scatter Diagram of Peak Period and Significant Wave Height

Table 1. Buoy characteristics

Buoy	Latitude	Longitude	Location	Depth (m)	Data Time Range	Length (yrs)
UMaine E01	43°42.86'N	69°21.35'W	Monhegan Island, ME	100	Jan. 8, 2002 - Sept. 9 th , 2009	7.8
UMaine F01	44°3.25'N	68°59.87'W	Penobscot Bay, ME	110	Jan. 8, 2002 - Sep. 17 th , 2009	7.8
UMaine I01	44° 6.35'N	68° 6.52'W	Acadia National Park, ME	100	Jan. 6 th , 2002 - Sep. 16 th , 2009	7.8
NOAA 44005	43°11.37'N	69°8.38'W	East of Portsmouth, NH	201	Dec. 16 th , 1978 - Dec. 31 st , 2009	32
NOAA 44007	43°31.88'N	70°8.65'W	Southeast of Portland, ME	24	Feb. 16, 1982 - Dec. 31 st , 2009	29

Table 2. Buoy data statistics

Buoy	significant wave height				8-minute wind speed at 4m			
	mean (m)	standard deviation (m)	skewness	kurtosis	mean (m/s)	standard deviation (m/s)	skewness	kurtosis
UMaine E01	1.2	0.8	1.9	9.0	5.6	3.2	0.6	2.8
UMaine F01	0.6	0.4	2.1	10.0	4.7	3.1	0.9	3.8
UMaine I01	1.3	0.8	1.9	8.2	5.9	3.5	0.6	2.8
NOAA 44005	1.6	1.0	1.7	7.1	6.6	3.6	0.6	3.1
NOAA 44007	0.9	0.6	2.5	13.0	5.6	3.2	0.6	3.2

Table 3. Extreme significant wave height in meters
(90% confidence intervals provided for POT method)

Return Period (yrs)	UMaine E01		UMaine F01		UMaine I01		NOAA 44005		NOAA 44007	
	Historical All data	POT w = 4 th = 3 $\mu = 1.2$ k= 4.0 shape = -0.0513 scale = 1.1389	Historical Daily max	POT w =4 th = 1 $\mu = 0.6$ k= 2.6 shape = -0.1391 scale = 0.7784	Historical Daily max	POT w = 4 th = 4 $\mu = 1.3$ k= 4.8 shape = -0.1830 scale = 1.2897	Historical All data	POT w = 8 th = 4 $\mu = 1.6$ k= 4.0 shape = -0.1667 scale = 1.4317	Historical All data	POT w = 8 th = 3 $\mu = 0.9$ k= 4.7 shape = -0.1605 scale = 1.4818
1	7.6	6.4 (5.3, 7.7)	3.5	3.4 (2.9, 3.9)	7.1	6.7 (5.8, 8.0)	9.1	7.0 (6.4,7.6)	7.0	5.8 (5.2, 6.6)
5	8.7	7.9 (6.1, 10.4)	4.2	4.0 (3.3, 4.9)	8.6	7.8 (6.3, 10.0)	10.4	8.3 (7.3, 9.5)	8.1	7.3 (6.1, 8.7)
10	9.2	8.5 (6.3, 11.6)	4.5	4.3 (3.4, 5.3)	9.3	8.2 (6.4, 10.8)	10.9	8.8 (7.6, 10.2)	8.5	7.8 (6.4, 9.5)
25	9.8	9.2 (6.6, 13.3)	4.9	4.6 (3.6, 5.8)	10.2	8.7 (6.6, 11.9)	11.7	9.3 (8.1, 11.0)	9.1	8.4 (6.7, 10.6)
50	10.3	9.8 (6.8, 14.6)	5.2	4.7 (3.6, 6.1)	10.8	8.9 (6.6, 12.6)	12.2	9.7 (8.2, 11.6)	9.6	8.8 (6.9, 11.3)
100	10.7	10.3 (7.0, 16.0)	5.5	4.9 (3.7, 6.4)	11.5	9.2 (6.7, 13.3)	12.8	10.0 (8.5,12.2)	10.1	9.2 (7.3, 12.0)

Notes:

1. POT predicted values are recommended for design purposes. Historical method is provided for comparative purposes only.
2. 90% confidence intervals provided in parentheses for POT method predictions only

Table 4. Extreme 8-minute average wind speeds in m/s at 4-5m above sea level

Return Period (yrs)	UMaine E01		UMaine F01		UMaine I01		NOAA 44005		NOAA 44007	
	Historical All data	POT w = 4 th = 14 $\mu = 5.6$ k= 4.4 shape = -0.0309 scale = 1.6797	Historical Daily max	POT w =4 th = 13 $\mu = 4.7$ k= 4.2 shape = -0.1859 scale = 2.4854	Historical Daily max	POT w = 8 th = 14 $\mu = 5.9$ k= 4.0 shape = -0.1692 scale = 2.3806	Historical All data	POT w = 8 th = 15 $\mu = 6.6$ k= 4.1 shape = -0.2208 scale = 2.9581	Historical All data	POT w = 12 th = 14 $\mu = 5.6$ k= 4.4 shape = -0.2117 scale = 2.6368
1	21.4	18.4 (16.9, 20.5)	19.8	17.8 (16.4, 19.7)	21.3	18.6 (17.1, 20.5)	21.0	20.8 (19.7, 21.9)	21.8	18.9 (17.9, 20.2)
5	24.2	20.8 (18.0, 25.2)	23.6	20.0 (17.5, 23.5)	25.4	20.9 (18.2, 24.5)	24.9	23.0 (21.3 25.0)	24.6	21.1 (19.3, 23.3)
10	25.4	21.8 (18.3, 27.4)	25.3	20.8 (17.8, 24.9)	27.1	21.7 (18.5, 26.1)	26.6	23.8 (21.8 26.1)	25.8	21.8 (19.7, 24.4)
25	27.0	23.1 (18.7, 30.6)	27.4	21.7 (18.1, 26.8)	29.4	22.6 (18.8, 28.2)	28.9	24.6 (22.2 27.4)	27.4	22.7 (20.2, 25.7)
50	28.2	24.1 (19.0, 33.2)	29.1	22.2 (18.3, 29.3)	31.1	23.2 (19.0, 29.6)	30.6	25.2 (22.5 28.3)	28.6	23.2 (20.4, 26.7)
100	29.4	25.0 (19.2, 36.0)	30.7	22.7 (18.4, 31.8)	32.8	23.7 (19.1, 31.1)	32.3	25.6 (22.8 29.1)	29.8	23.6 (20.6, 27.5)

Notes:

1. POT predicted values are recommended for design purposes. Historical method is provided for comparative purposes only.
2. 90% confidence intervals provided in parentheses for POT method predictions only
3. UMaine buoys wind speeds measured at 4m above sea level. NOAA buoys wind speeds measured at 5m above sea level.

Table 5 Extreme 5-second gust wind speeds in m/s

Return Period (yrs)	UMaine E01	UMaine F01	UMaine I01	NOAA 44005	NOAA 44007
1	22.6 (20.8, 25.2)	23.5 (21.6, 26.0)	23.1 (21.2, 25.4)	25.4 (24.0, 26.7)	23.2 (22.0, 24.8)
5	25.6 (22.1, 31)	26.4 (23.1, 31.0)	25.9 (22.6, 30.4)	28.1 (26.0, 30.5)	26.0 (23.7, 28.7)
10	26.8 (22.5, 33.7)	27.5 (23.5, 32.9)	26.9 (22.9, 32.4)	29.0 (26.6, 31.8)	26.8 (24.2, 30.0)
25	28.4 (23.0, 37.6)	28.6 (23.9, 35.4)	28.0 (23.3, 35.0)	30.0 (27.1, 33.4)	27.9 (24.8, 31.6)
50	29.6 (23.4, 40.8)	29.3 (24.2, 38.7)	28.8 (23.6, 36.7)	30.7 (27.5, 34.5)	28.5 (25.1, 32.8)
100	30.8 (23.6, 44.3)	30.0 (24.3, 42.0)	29.4 (23.7, 38.6)	31.2 (27.8, 35.5)	29.0 (25.3, 33.8)

Notes:

1. Extreme gusts were calculated using POT predicted values from Table 3 multiplied by annual mean gust factor
2. UMaine buoys wind speeds measured at 4m above sea level. NOAA buoys wind speeds measured at 5m above sea level.
3. 90% confidence intervals provided in parentheses

Table 6. Annual mean wind data and wind design parameters

Buoy	UMaine E01	UMaine F01	UMaine I01	NOAA 44005	NOAA 44007
Mean 8-minute wind speed at sensor height (m/s)	5.6	4.7	5.9	6.7	5.6
Mean 5-second gust wind speed at sensor height (m/s)	6.9	6.2	7.3	8.2	6.9
Mean gust factor	1.23	1.32	1.24	1.22	1.23
Wind shear power law exponent	0.16	0.19	0.14	0.13	0.13
Mean 10-minute wind speed at 90 m (m/s)	9.1	8.5	9.0	9.6	8.0
Mean 5-second gust wind speed at 90 m (m/s)	11.0	11.2	11.1	12.3	10.0
NREL predicted mean 10-minute wind speed (m/s) at 90 m (2010)	9.0-9.5	8.0-8.5	9.0-9.5	9.5-10.0	8.0-8.5

Table 7. Mean peak wave periods for predicted extreme significant wave heights in seconds
(95% confidence intervals provided for estimated power law parameters)

Return Period (yrs)	UMaine E01	UMaine F01	UMaine I01	NOAA 44005	NOAA 44007
1	11.7	9.7	11.2	12.3	13.0
5	12.8	10.4	11.7	14.1	15.4
10	13.3	10.7	11.9	14.1	16.2
25	13.8	11.1	12.1	15.6	17.2
50	14.2	11.2	12.2	16.2	18.0
100	14.6	11.4	12.3	16.7	18.7
a	1.353 (0.2348, 2.47)	1.224 (0.5207, 1.928)	2.238 (0.6027, 3.874)	0.2173 (0.2016, 0.233)	0.3989 (0.37, 0.4279)
b	0.7900 (0.4514, 1.129)	0.9785 (0.6473, 1.31)	0.5413 (0.2929, 0.7897)	1.656 (1.613, 1.7)	1.506 (1.453, 1.559)
c	5.730 (4.409, 7.052)	5.635 (4.911, 6.36)	4.904 (3.173, 6.635)	6.854 (6.831, 6.877)	7.406 (7.38, 7.432)

Table 8. 100 year return period significant wave heights predicted in this study as compared to other published values nearby each buoy.

Analysis Method	E01	F01	I01	44005	44007
POT method	10.3	4.9	9.2	10.0	9.2
Panchang et al. (1990)	10.6	11.1	11.7	10.8	10.1
Godshall et al. (1980)	7.11	12.89	NA	10.33	6.94
% Difference with Panchang	-3%	-56%	-21%	-7%	-9%
% Difference with Godshall	45%	-62%	NA	-3%	33%

Table 9. Comparison of wind shear exponents and 50yr 3-second gust wind speeds estimates to ASCE-7

Buoy	UMaine E01	UMaine F01	UMaine I01	NOAA 44005	NOAA 44007
50 year 5-second gust wind speed at sensor height (m/s)	29.6	29.3	28.8	30.7	28.5
Wind shear power law exponent from data	0.16	0.19	0.14	0.13	0.13
Wind shear power law exponent per ASCE-7coastal exposure conditions	0.15				
Wind shear power law exponent % difference from ASCE-7	7%	27%	-7%	-13%	-13%
ISO conversion from 5-second to 3-second wind speed	1.034				
50 year 3-second gust wind speed at 10m (m/s)	35.4	36.1	33.9	35.8	33.2
Maine coastal ASCE 50 year 3-second gust wind speed at 10m (m/s)	45.0				
50 year 3-second gust % difference from ASCE-7	-21%	-20%	-25%	-21%	-26%

Table 10. Extreme significant wave height in meters for thresholds ($\mu+1.4\sigma$) and ($\mu+2.0\sigma$)
(90% confidence intervals provided for POT method)

Return Period (yrs)	UMaine E01		UMaine F01		UMaine I01		NOAA 44005		NOAA 44007	
	POT w = 4 k= 1.4 shape = -0.1058 scale = 1.338	POT w = 4 k= 2.0 shape = -0.0769 scale = 1.221	POT w = 4 k= 1.4 shape = -0.1619 scale = 0.7841	POT w = 4 k= 2.0 shape = -0.1543 scale = 0.7330	POT w = 4 k= 1.4 shape = -0.2485 scale = 1.8051	POT w = 4 k= 2.0 shape = -0.2400 scale = 1.657	POT w = 8 k= 1.4 shape = -0.1752 scale = 1.5262	POT w = 8 k= 2.0 shape = -0.1184 scale = 1.3163	POT w = 8 k= 1.4 shape = -0.0924 scale = 1.3538	POT w = 8 k= 2.0 shape = -0.0602 scale = 1.2713
1	6.4 (5.4, 7.6)	6.4 (5.4, 7.7)	3.4 (2.9, 4.0)	3.4 (2.9, 4.0)	6.8 (5.8, 7.9)	6.8 (5.8, 7.9)	7.0 (6.4, 7.7)	7.0 (6.4, 7.6)	5.5 (4.9, 6.2)	5.6 (4.9, 6.3)
5	7.7 (6.1, 9.7)	7.8 (6.1, 10.0)	4.0 (3.2, 4.9)	4.0 (3.2, 5.0)	7.7 (6.4, 9.4)	7.7 (6.3, 9.5)	8.2 (7.3, 9.3)	8.3 (7.4, 9.4)	7.0 (6.0, 8.3)	7.2 (6.0, 8.6)
10	8.2 (6.4, 10.6)	8.4 (6.4, 11.1)	4.2 (3.3, 5.3)	4.2 (3.3, 5.4)	8.0 (6.5, 9.9)	8.1 (6.5, 10.0)	8.6 (7.6, 9.8)	8.8 (7.7, 9.4)	7.6 (6.3, 9.1)	7.9 (6.4, 9.6)
25	8.8 (6.7, 11.7)	9.0 (6.7, 12.4)	4.5 (3.5, 5.7)	4.5 (3.4, 5.8)	8.4 (6.7, 10.4)	8.4 (6.6, 10.6)	9.1 (7.9, 10.4)	9.4 (8.1, 11.0)	8.3 (6.8, 10.2)	8.7 (6.9, 10.9)
50	9.3 (6.9, 12.5)	9.5 (6.9, 13.5)	4.6 (3.5, 6.0)	4.6 (3.5, 6.2)	8.6 (6.8, 10.8)	8.6 (6.7, 11.1)	9.4 (8.0, 10.8)	9.8 (8.4, 11.6)	8.8 (7.1, 11.0)	9.3 (7.2, 11.9)
100	9.6 (7.0, 13.3)	10.0 (7.0, 14.5)	4.8 (3.6, 6.3)	4.8 (3.6, 6.5)	8.7 (6.8, 11.1)	8.8 (6.8, 11.4)	9.6 (8.2, 11.2)	10.2 (8.6, 12.2)	9.3 (7.3, 11.7)	9.9 (7.5, 13.0)

Table 11. Extreme 8-minute wind speed in meters/s for thresholds ($\mu+1.4\sigma$) and ($\mu+2.0\sigma$)
(90% confidence intervals provided for POT method)

Return Period (yrs)	UMaine E01		UMaine F01		UMaine I01		NOAA 44005		NOAA 44007	
	POT w = 4 k= 1.4 shape = -0.4318 scale = 4.1377	POT w = 4 k= 2.0 shape = -0.1164 scale = 2.4394	POT w = 4 k= 1.4 shape = -0.3127 scale = 4.4331	POT w = 4 k= 2.0 shape = -0.1746 scale = 2.7652	POT w = 8 k= 1.4 shape = -0.3368 scale = 4.5908	POT w = 8 k= 2.0 shape = -0.2322 scale = 3.0087	POT w = 8 k= 1.4 shape = -0.3228 scale = 4.8548	POT w = 8 k= 2.0 shape = -0.2426 scale = 3.3821	POT w = 12 k= 1.4 shape = -0.3017 scale = 4.366	POT w = 12 k= 2.0 shape = -0.2318 scale = 3.1511
1	17.9 (16.6, 19.3)	19.0 (17.3, 21.1)	18.0 (16.1, 20.1)	17.7 (16.2, 19.5)	19.4 (17.4, 21.6)	18.8 (17.2, 20.8)	21.3 (20.1, 22.6)	20.8 (19.7, 22.0)	19.4 (18.2, 20.6)	18.9 (17.8, 20.1)
5	18.8 (17.2, 20.5)	21.4 (18.6, 24.9)	20.1 (17.4, 23.1)	20.0 (17.6, 22.9)	21.5 (18.7, 24.8)	21.0 (18.3, 24.4)	23.5 (21.7, 25.4)	23.1 (21.4, 25.0)	21.3 (19.7, 23.1)	21.0 (19.3, 22.8)
10	19.0 (17.3, 20.8)	22.3 (19.1, 26.5)	20.7 (17.8, 24.1)	20.7 (18.0, 24.1)	22.1 (19.0, 25.8)	21.7 (18.6, 25.7)	24.2 (22.2, 26.3)	23.8 (21.8, 26.0)	21.9 (20.1, 23.9)	21.6 (19.8, 23.7)
25	19.2 (17.4, 21.1)	23.4 (19.6, 28.5)	21.3 (18.1, 25.1)	21.6 (19.3, 26.8)	22.7 (19.3, 26.8)	22.5 (19.0, 27.2)	24.8 (22.7, 27.1)	24.6 (22.4, 27.1)	22.6 (20.5, 24.7)	22.4 (20.3, 24.8)
50	19.3 (17.5, 21.3)	24.1 (19.9, 29.9)	21.7 (18.3, 25.8)	22.2 (18.7, 26.8)	23.1 (19.4, 27.5)	23.0 (19.1, 28.3)	25.2 (22.9, 27.7)	25.1 (22.6, 27.9)	22.9 (20.8, 25.2)	22.9 (20.5, 25.5)
100	19.4 (17.5, 21.4)	24.8 (20.2, 31.3)	22.0 (18.4, 26.3)	22.7 (18.9, 27.8)	23.3 (19.5, 28.0)	23.4 (19.3, 29.2)	25.5 (23.1, 28.1)	25.5 (22.9, 28.5)	23.2 (21.0, 25.6)	23.3 (20.8, 26.1)