METOCEAN CRITERIA FOR VIRGINIA OFFSHORE WIND TECHNOLOGY ADVANCEMENT PROJECT (VOWTAP)

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This report is not to be used for contractual or engineering purposes unless described as 'Final' in the approval box below

Prepared for: Dominion Resources Services, Inc
Alternative Energy Solutions

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0	Draft Report	Manuel Medina Jon Molina	Shejun Fan	Shejun Fan	17 July 2013
Rev	**Description**	**Prepared**	**Checked**	**Approved**	**Date**

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SUMMARY OF TABLES AND FIGURES

1 INTRODUCTION

Fugro GEOS are pleased to provide this metocean criteria report to support the Client's Virginia Offshore Wind Technology Advancement Project (VOWTAP). The VOWTAP project is located approximately 24 miles off the coast of Virginia Beach (in the blue aliquots), as shown in Figure 1-1 below. The latitude and longitude coordinates for the two turbine sites are as follows; 36.885˚N, 75.4875˚W and 36.8925˚N, 75.486667˚W. The derived metocean criteria are applicable to these offshore locations.

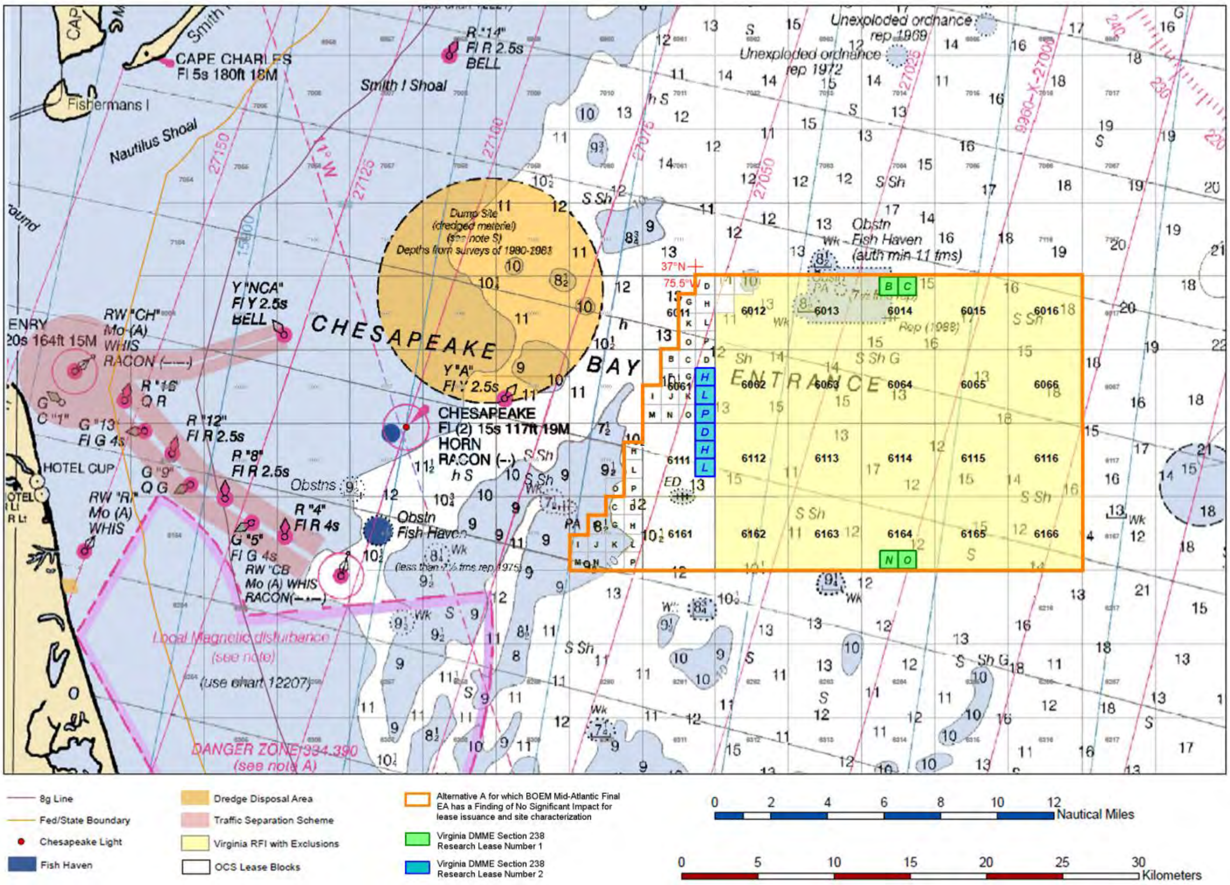

Figure 1-1 Study Area and VOMTAP Proposed Location

The major metocean processes expected to influence the study area are hurricanes and strong Northeasters winds and associated wave and currents, tides and tidal currents, and river discharge.

In December 2012, the Virginia Offshore Wind Technology Advancement Project (VOWTAP) was among seven projects selected by the U.S. Department of Energy (DOE) for an initial engineering, design, and permitting period. At the end of this period, in mid May 2014, the DOE will select up to three projects from the initial seven for follow-on phases that focus on detailed design, construction, installation, and data collection. During the follow-on phases, Dominion will deploy a floating LiDAR to collect site specific metrological and atmospheric data. Therefore, the Metocean report is based on data received from Oceanweather and NDBC bouys near the target site. See Section 3 of this report for additional information on data sources.

1.1 Units and Conventions

Unless explicitly stated otherwise, the following list outlines the units and conventions adopted in this report.

- Wind speeds are expressed in meter per second (m/s).
- Wind direction is expressed in compass points or degrees, relative to true North, and describes the direction from which the winds were blowing.
- Wave heights are expressed in meters (m).
- Wave periods are expressed in seconds (s).
- Wave direction is expressed in compass points or degrees, relative to true North, and describes the direction from which the waves were travelling.
- Current speed is expressed in meter per second (m/s).
- Current direction is expressed in degrees clockwise from true North and describes the directions towards which the current was flowing.

Table 1-1 Directional Sectors

DIRECTIONAL SECTOR	N	NE	E	SE	S	SW	W	NW
RANGE (° T)	337.5 -< 22.5	22.5 -< 67.5	67.5 -< 112.5	112.5 -< 157.5	157.5 -< 202.5	202.5 -< 247.5	247.5 -< 292.5	292.5 -< 337.5

1.2 Abbreviations

The following list outline the abbreviations adopted in this report.

- GEOS Global Environmental & Ocean Sciences
- MSL Mean Sea Level
- TMD Tide Model Driver
- DOE U.S. Department of Energy

1.3 Parameter Descriptions

The following table provides summary descriptions of the primary metocean parameters.

Parameter	Abbreviation	Comments	Units
Wind Speed	Ws	Mean wind speed at 10m above sea level. By default 1 hour average unless otherwise stated.	m/s
Significant Wave Height	Hs	Estimated from the wave energy spectrum, Hs = $4\sqrt{m_0}$. Equivalent to the mean height (from wave crest to trough) of the highest one-third of the waves in a sea-state.	m
Peak Period	Tp	The period associated with the peak in the wave energy spectrum.	s
Mean zero crossing Wave Period	Tz		s
Current Speed	Cs	Current speed	m/s
Crest Height	Hc	Height difference between maximum wave crest and succeeding trough.	m
Maximum Wave Height	Hmax	Height difference between the wave crest and trough of the largest wave in a sea-state.	m
Storm Surge Height	Hsur	Height of strom surges. Defined as the water level elevation due to sea surface pressure.	m

Table 1-2 Parameter Descriptions

2 METOCEAN CRITERIA

2.1 Wind Criteria

Extreme value analysis was carried out on a subset of peak wind speed events from the Oceanweather hindcast data. The analysis only considered winter storm events from 1957 to 2003 and hurricane storm events from 1924 to 2005. The 1-year criteria are derived from 26-years (1980 to 2005) of Oceanweather operational hindcast data. Data is also presented as including and excluding hurricanes for operational use only, this has no importance to design.

Section 2.1.7 depics the highest extreme values for return periods 1-, 50-, 100-, 500-, 1000-, and 10000-year return periods.

Hub height is 100 m above MSL.

2.1.1 Omni-Directional 1-Year Extreme Wind Values

Omnidirectional Wind Speeds at Hub Height 100 m Above MSL						
	1-hr (m/s)	10-min (m/s)	1-min (m/s)	15-sec (m/s)	5-sec (m/s)	3-sec (m/s)
1-year	30.60	33.23	36.61	38.65	40.27	41.02

Table 2-1 Omni-Directional 1-Year Extreme Wind Speed at Hub Heigh

2.1.2 1-Year Wind Fitting Parameters

The independent omni-directional 1-hr wind cases are given in Table 2-1 and detailed descriptions of the calculations are given below. The analysis considered 26-years (1980 to 2005) of Oceanweather operational hindcast data.

Cumulative frequency extrapolation involves grouping all the parameter values in the data set using specified class intervals and then forming a cumulative frequency distribution (cfd) by summing the number of observations greater than or equal to the lower bound of the class interval. This method was then employed to derive the 1-year criteria.

The Exponential (EXP), Fisher-Tippett 1 (FT1), Fisher-Tippett 2 (FT2), Fisher-Tippett 3 (FT3), Weibull 2 (W2) and Weibull 3 (W3) distributions were tested for goodness-of-fit to the data using the method of least squares (LS). The best fits for the 1-year wind speed are summarised in Table 2-2.

	Distribution	Fit	Threshold	# Peaks	Extreme Values
					1-yr
Ws (m/s)	FT2	LS	5.00	10707	30.69
	FT2	LS	5.00	10707	30.51
	FT2	LS	5.00	10707	30.67
	FT2	LS	10.00	21217	30.55
	FT2	LS	10.00	17079	30.67
	FT2	LS	10.00	21217	30.50
	AVERAGE				30.60

Table 2-2 Extreme Omni-directional Wind Speed Fitting Parameters for 1-year Extreme

2.1.3 Omni-Directional Winter Storm Extreme Wind Values at Hub Height

Winter Storm Omnidirectional Wind Speeds at Hub Height 100 m Above MSL						
	1-hr (m/s)	10-min (m/s)	1-min (m/s)	15-sec (m/s)	5-sec (m/s)	3-sec (m/s)
50-years	33.88	36.95	40.90	43.27	45.16	46.03
100-years	36.52	39.96	44.38	47.04	49.15	50.13
500-years	42.62	46.99	52.61	56.00	58.68	59.93
1000-years	45.25	50.05	56.23	59.95	62.89	64.27
10000-years	53.97	60.35	68.55	73.48	77.39	79.21

Table 2-3 Omni-Directional Winter Storm Extreme Wind Speeds at Hub height

2.1.4 Wind Fitting Parameters for Winter Storm

The independent omni-directional 1-hr wind cases are given in Table 2-3 and detailed descriptions of the calculations are given below.

Extreme value analysis was carried out on a subset of peak wave heights from the Oceanweather data. The analysis only considered winter storm events from 1957 to 2003.

The Peaks Over Threshold (POT) method consisted of declustering the data by selecting peak events to produce a set of independent and identically distributed observations. This method was then employed to derive the 50-, 100-, 500-, 1000-, and 10000-year criteria. The number of peaks exceeding a given level, divided by the number of years of record, gave the rate of exceedance which could then be used to find the expected number of occurrences in a specified period of time.

The Exponential (EXP), Fisher-Tippett 1 (FT1), Fisher-Tippett 2 (FT2), Fisher-Tippett 3 (FT3), Generalised Pareto (GP), Weibull 2 (W2) and Weibull 3 (W3) distributions were tested for goodness-of-fit to the Oceanweather data using the method of least squares (LS), maximum likelihood (MLE), and the method of moments (MoM). The best fits for 50-, 100-, 500-, 1000-, and 10000-year wind speed are summarised in Table 2-4.

	Distribution	Fit	Threshold	# Peaks	Extreme Values				
					50-yr	100-yr	500-yr	1000-yr	10000-yr
Ws (m/s)	EXP	MoM	9.91	72	35.26	38.42	45.76	48.92	59.43
	EXP	MoM	10.20	70	34.58	37.27	43.49	46.17	55.06
	EXP	MoM	10.53	64	33.08	35.52	41.17	43.60	51.67
	FT1	LS	9.91	72	33.34	35.82	41.56	44.02	52.21
	FT1	LS	10.20	70	35.11	38.24	45.49	48.61	58.98
	FT1	LS	10.53	64	34.49	37.15	43.31	45.95	54.74
	FT1	MLE	9.91	72	32.96	35.36	40.92	43.31	51.26
	FT1	MLE	10.20	70	33.25	35.70	41.36	43.80	51.89
	FT1	MLE	10.53	64	34.69	37.70	44.67	47.68	57.66
	FT1	MoM	9.91	72	34.22	36.79	42.74	45.29	53.79
	FT1	MoM	10.20	70	32.61	34.90	40.21	42.49	50.08
	FT1	MoM	10.53	64	32.99	35.34	40.79	43.13	50.91
	AVERAGE				33.88	36.52	42.62	45.25	53.97

Table 2-4 Extreme Omni-directional Wind Speed Fitting Parameters for Winter Storm

2.1.5 Omni-Directional Hurricane Extreme Wind Values at Hub Height

Hurricane Omnidirectional Wind Speeds at Hub Height 100 m Above MSL						
	1-hr (m/s)	10-min (m/s)	1-min (m/s)	15-sec (m/s)	5-sec (m/s)	3-sec (m/s)
50-years	45.57	50.44	56.68	60.44	63.42	64.81
100-years	50.34	56.04	63.37	67.78	71.27	72.90
500-years	61.39	69.27	79.39	85.49	90.32	92.57
1000-years	66.14	75.06	86.53	93.43	98.90	101.44
10000-years	81.92	94.74	111.23	121.15	129.01	132.67

Table 2-5 Omni-Directional Hurricane Extreme Wind Speeds at Hub height

2.1.6 Wind Fitting Parameters for Hurricanes

The independent omni-directional 1-hr wind cases are given in Table 2-5 and detailed descriptions of the calculations are given below.

Extreme value analysis was carried out on a subset of peak wave heights from the Oceanweather data. The analysis only considered hurricane storm events from 1924 to 2005.

The Peaks Over Threshold (POT) method consisted of declustering the data by selecting peak events to produce a set of independent and identically distributed observations. This method was then employed to derive the 50-, 100-, 500-, 1000-, and 10000-year criteria. The number of peaks exceeding a given level, divided by the number of years of record, gave the rate of exceedance which could then be used to find the expected number of occurrences in a specified period of time.

The Exponential (EXP), Fisher-Tippett 1 (FT1), Fisher-Tippett 2 (FT2), Fisher-Tippett 3 (FT3), Generalised Pareto (GP), Weibull 2 (W2) and Weibull 3 (W3) distributions were tested for goodness-of-fit to the data using the method of least squares (LS), maximum likelihood (MLE), and the method of moments (MoM). The best fits for 50-, 100-, 500-, 1000-, and 10000-year wind speed are summarised in Table 2-6.

	Distribution	Fit	Threshold	# Peaks	Extreme Values				
					50-yr	100-yr	500-yr	1000-yr	10000-yr
Ws (m/s)	EXP	MLE	10.55	99	44.57	49.01	59.28	63.70	78.37
	FT1	LS	10.01	103	47.00	51.88	63.17	68.02	84.14
	FT1	MoM	10.01	103	44.62	49.06	59.33	63.75	78.42
	FT1	MoM	9.80	106	46.10	51.42	63.77	69.09	86.75
	AVERAGE				45.57	50.34	61.39	66.14	81.92

Table 2-6 Extreme Omni-directional Wind Speed Fitting Parameters for Hurricanes

2.1.7 Omni-Directional Extreme Wind Values

Table 2-7 depics the highest extreme values for return periods 1-, 50-, 100-, 500-, 1000-, and 10000-year return periods. The data is optained from the heighst values between hurricanes and winterstorms.

Omnidirectional Wind Speeds at Hub Height 100 m Above MSL						
	1-hr (m/s)	10-min (m/s)	1-min (m/s)	15-sec (m/s)	5-sec (m/s)	3-sec (m/s)
1-year	30.60	33.23	36.61	38.65	40.27	41.02
50-years	45.57	50.44	56.68	60.44	63.42	64.81
100-years	50.34	56.04	63.37	67.78	71.27	72.90
500-years	61.39	69.27	79.39	85.49	90.32	92.57
1000-years	66.14	75.06	86.53	93.43	98.90	101.44
10000-years	81.92	94.74	111.23	121.15	129.01	132.67

Table 2-7 Omni-Directional Extreme Wind Values

2.1.8 Wind Speed Excluding and Including Hurricane Data

This sections illustrates data excluding and including hurricane data for operational use only. This has no importance for the design of the wind turbine.

2.1.8.1 Omni-Directional Monthly Average and Maximum Wind Speed Excluding Hurricanes

COMBINED PERIOD (1980 to 2005)	1hr Wind Speed at Hub Height 100m (m/s)	
	MEAN	MAX
All Year	8.41	35.38
January	10.77	26.68
February	10.12	27.69
March	9.62	31.78
April	8.26	27.11
May	6.81	23.55
June	6.15	20.83
July	6.20	25.84
August	6.45	35.38
September	7.39	33.83
October	8.71	32.04
November	9.60	26.48
December	10.66	29.17

Table 2-8 Omni-Directional Month Average and Maximum Wind Speed Excluding Hurricanes at Hub Height

2.1.8.1 Wind Speed Distribution at Hub Height Excluding Hurricanes

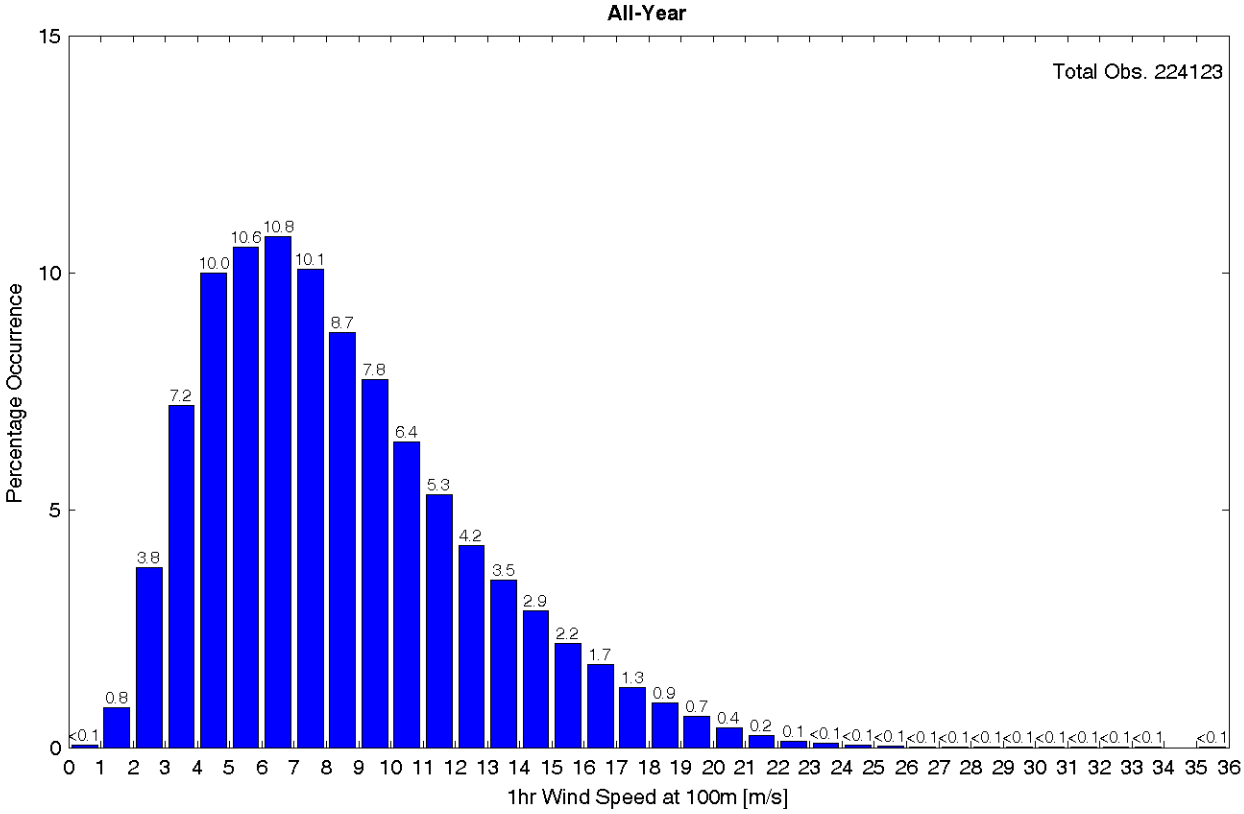

Figure 2-1 All Year Percentage Occurrence of Wind Speed at Hub Height Excluding Hurricanes

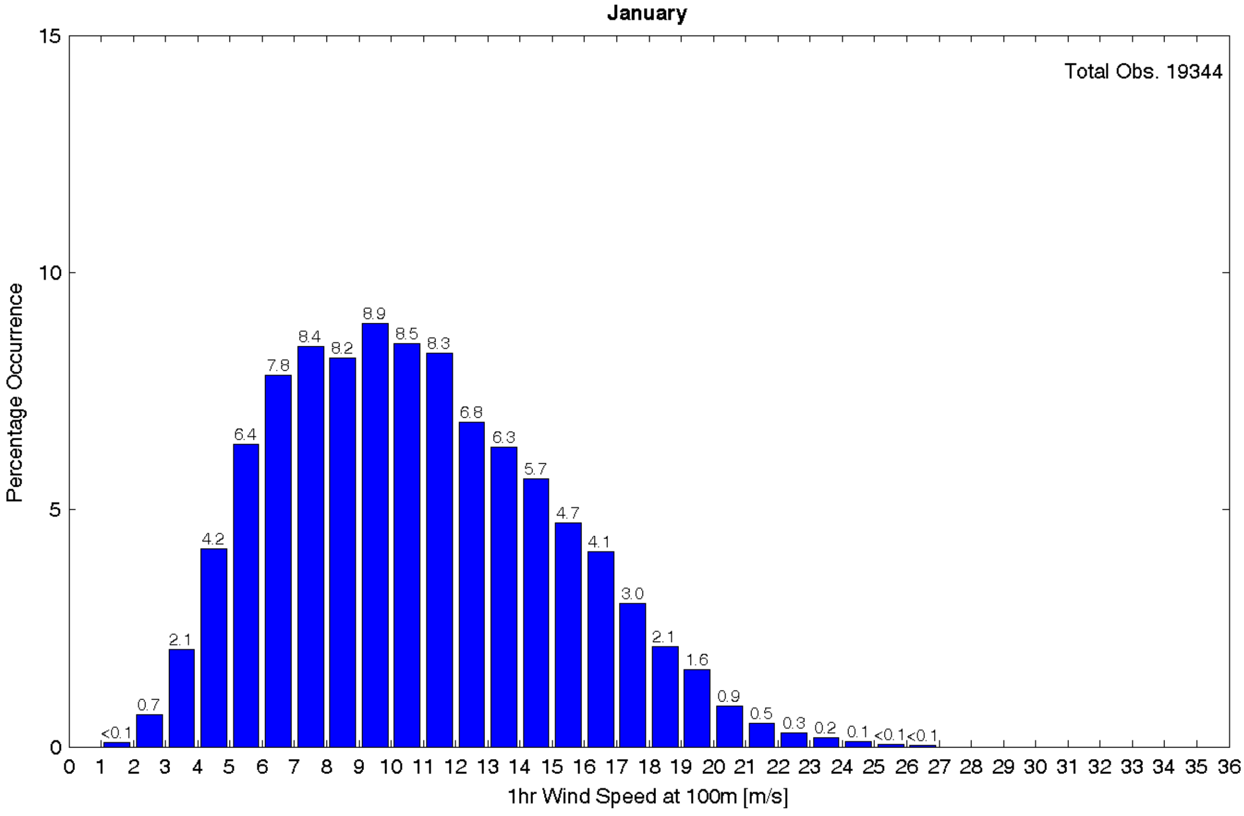

Figure 2-2 Percentage Occurrence of Wind Speed at Hub Height Excluding Hurricanes – January

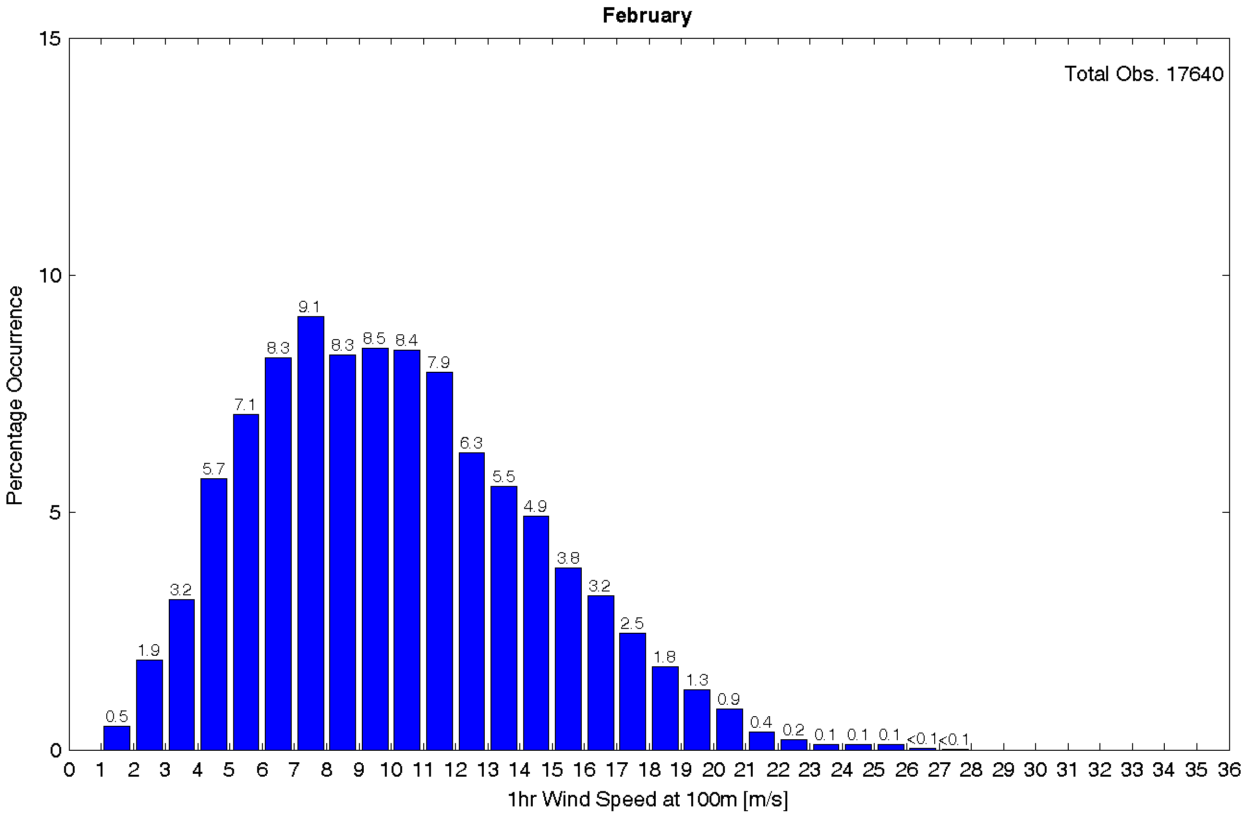

Figure 2-3 Percentage Occurrence of Wind Speed at Hub Height Excluding Hurricanes – February

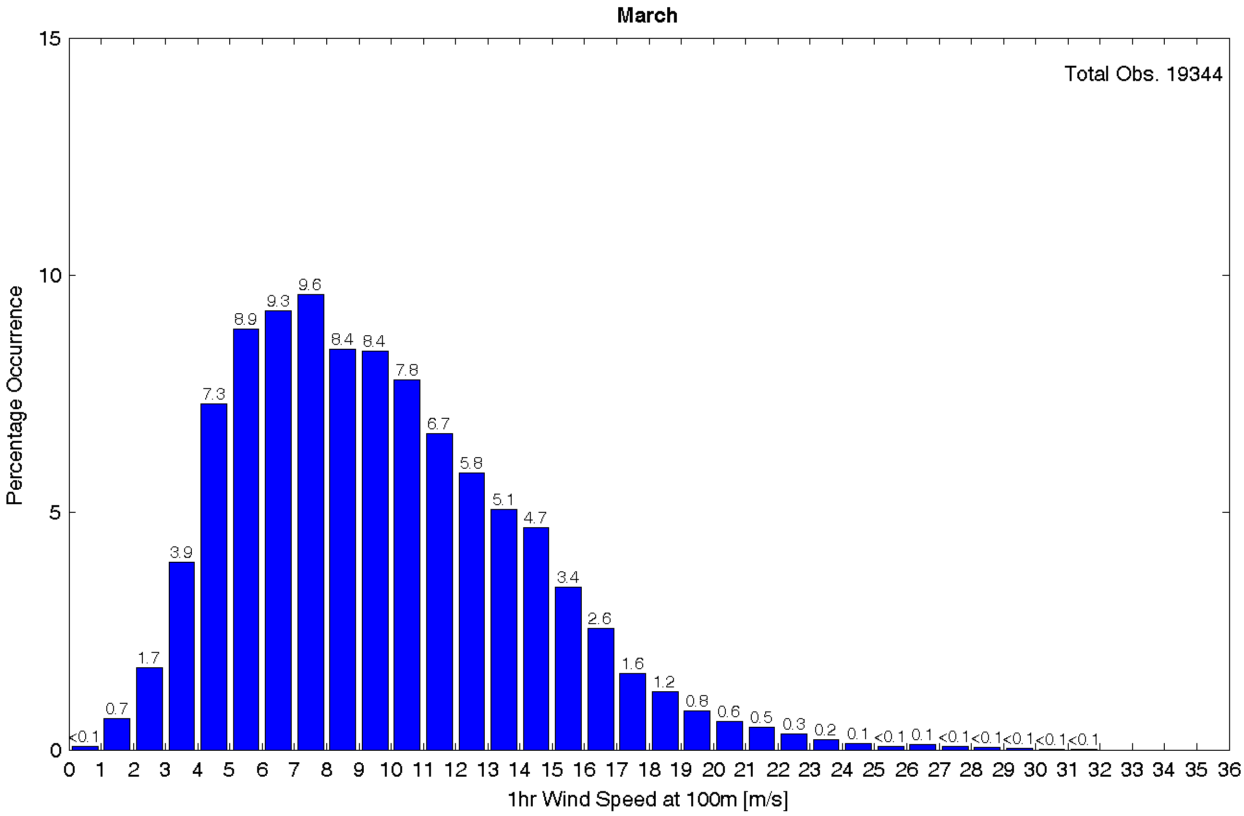

Figure 2-4 Percentage Occurrence of Wind Speed at Hub Height Excluding Hurricanes – March

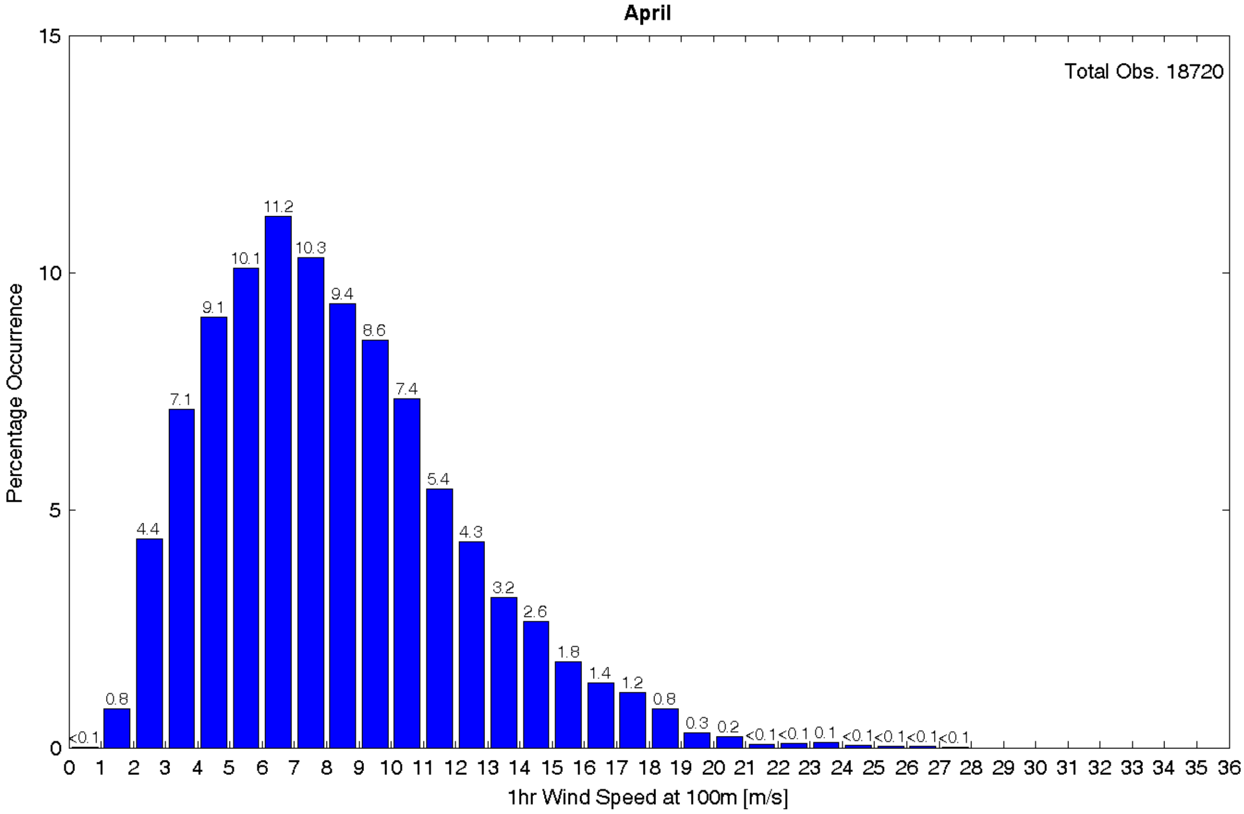

Figure 2-5 Percentage Occurrence of Wind Speed at Hub Height Excluding Hurricanes – April

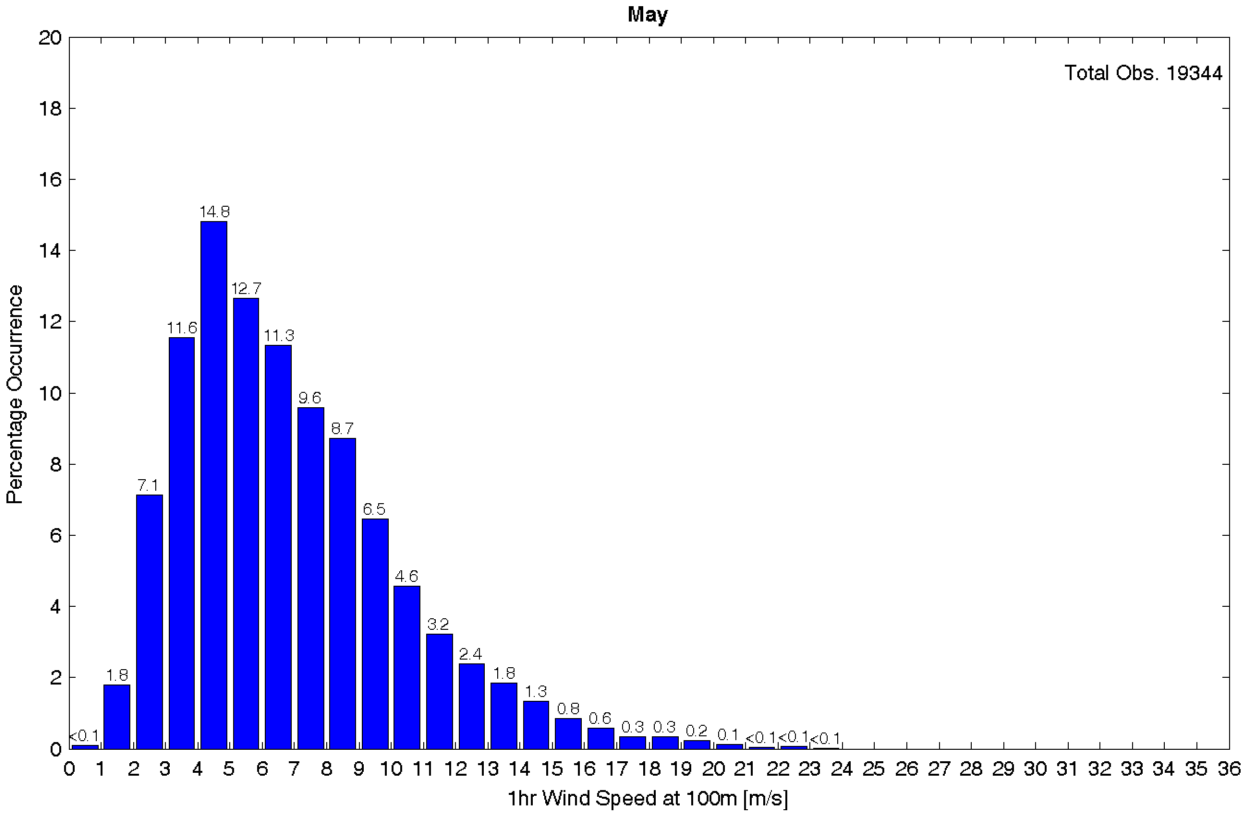

Figure 2-6 Percentage Occurrence of Wind Speed at Hub Height Excluding Hurricanes – May

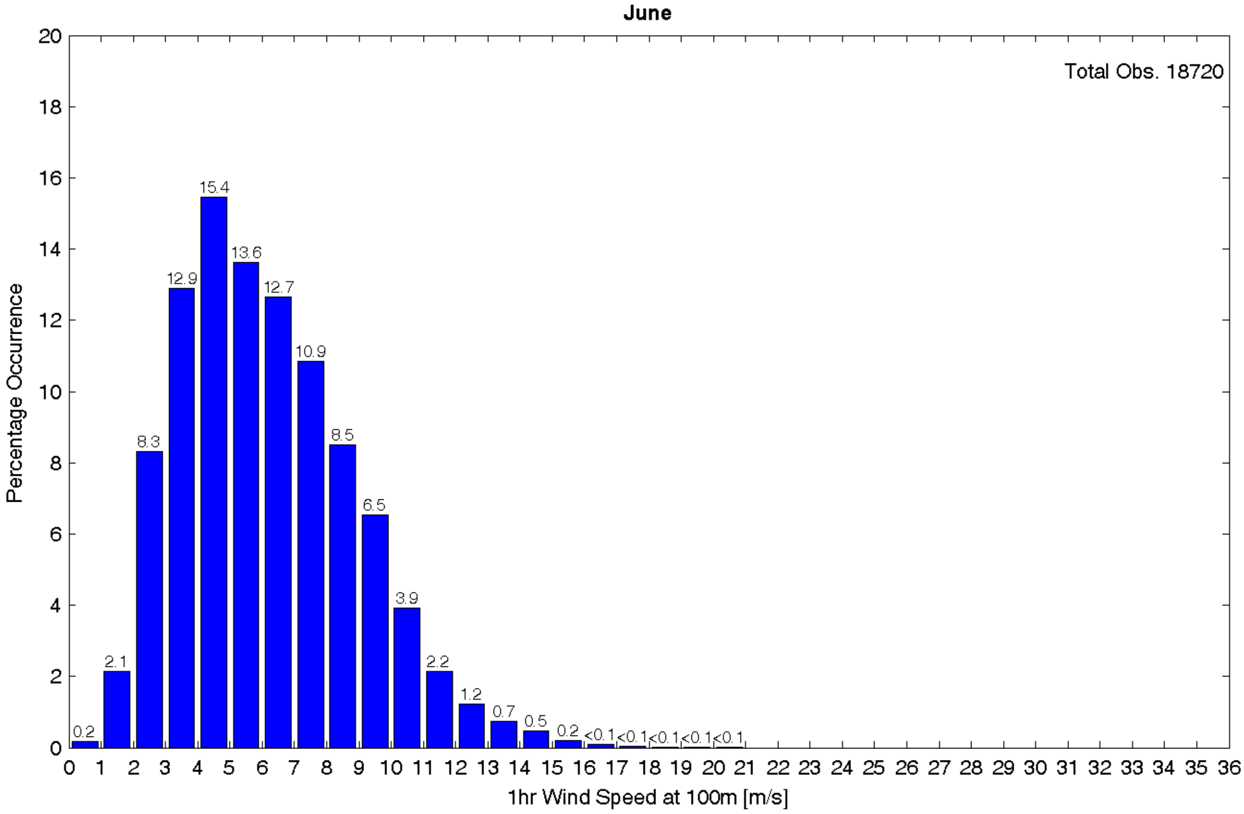

Figure 2-7 Percentage Occurrence of Wind Speed at Hub Height Excluding Hurricanes – June

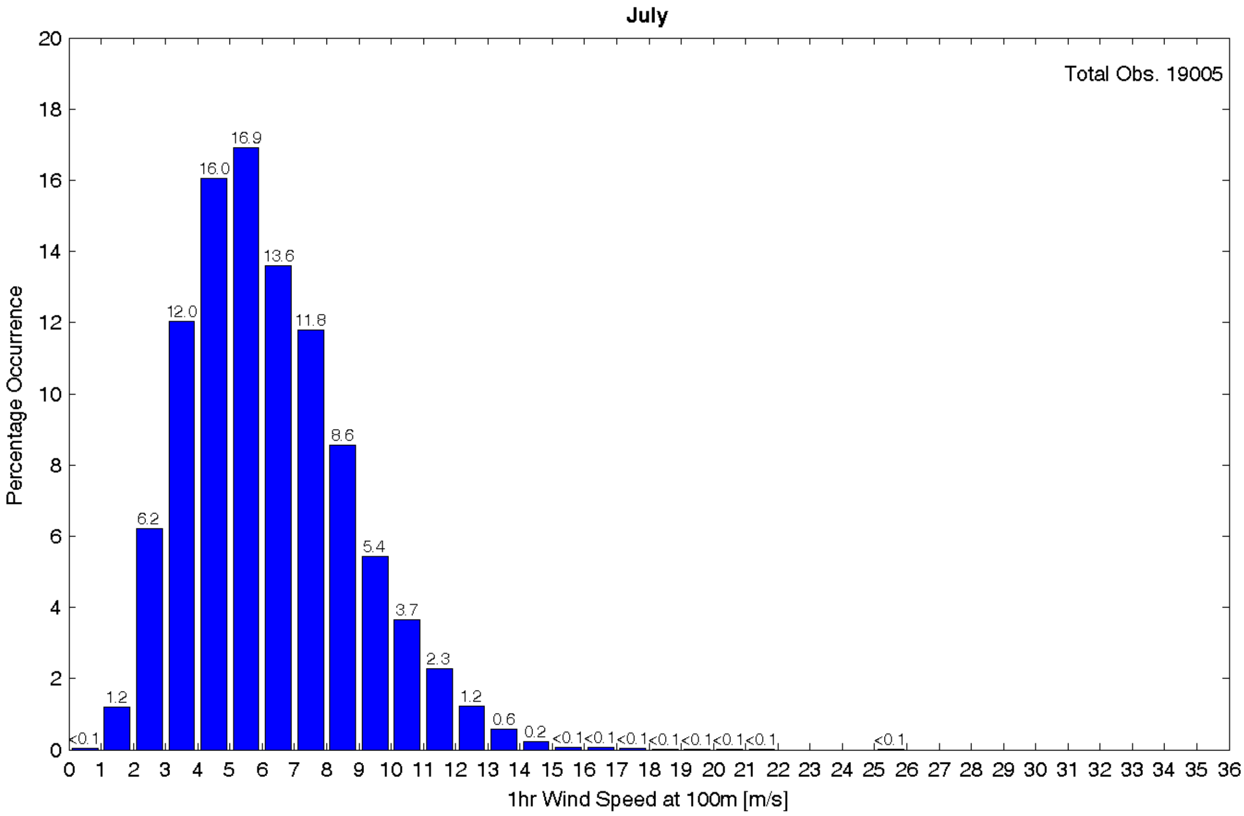

Figure 2-8 Percentage Occurrence of Wind Speed at Hub Height Excluding Hurricanes – July

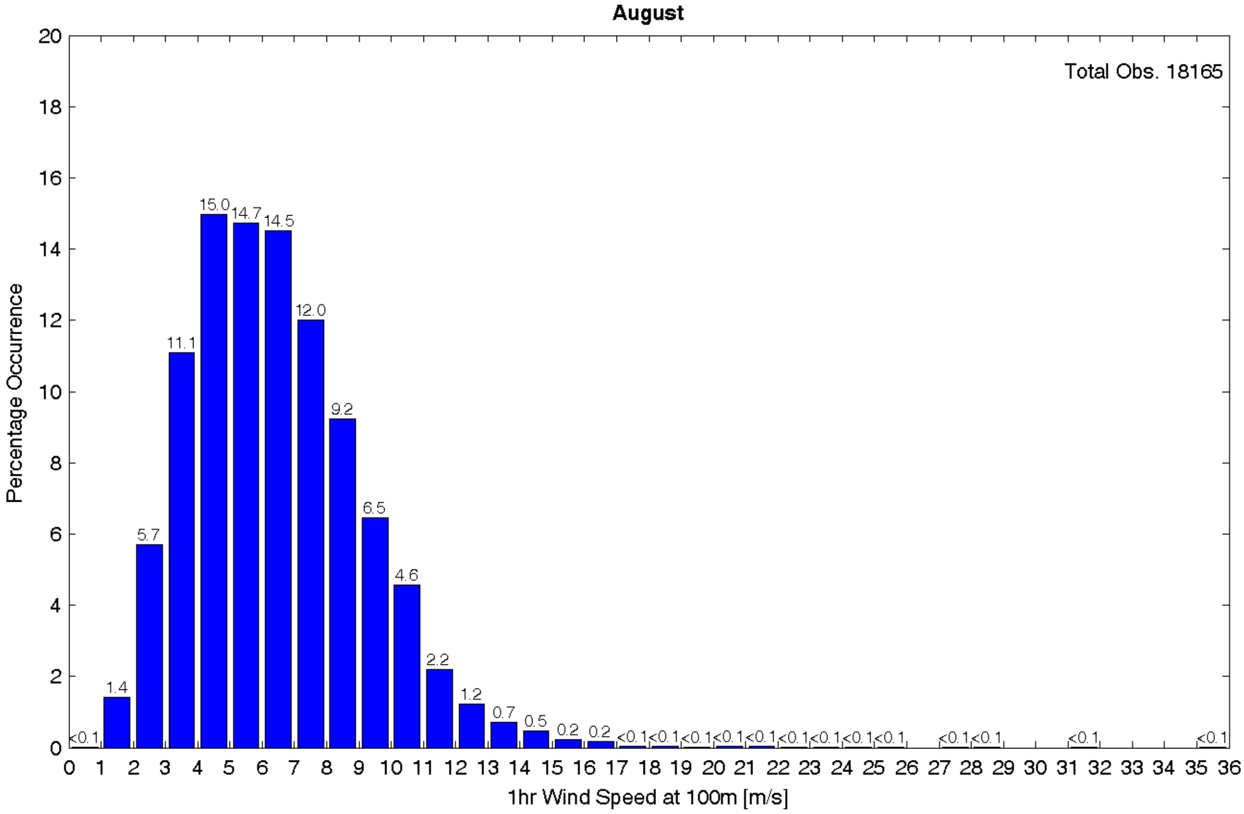

Figure 2-9 Percentage Occurrence of Wind Speed at Hub Height Excluding Hurricanes – August

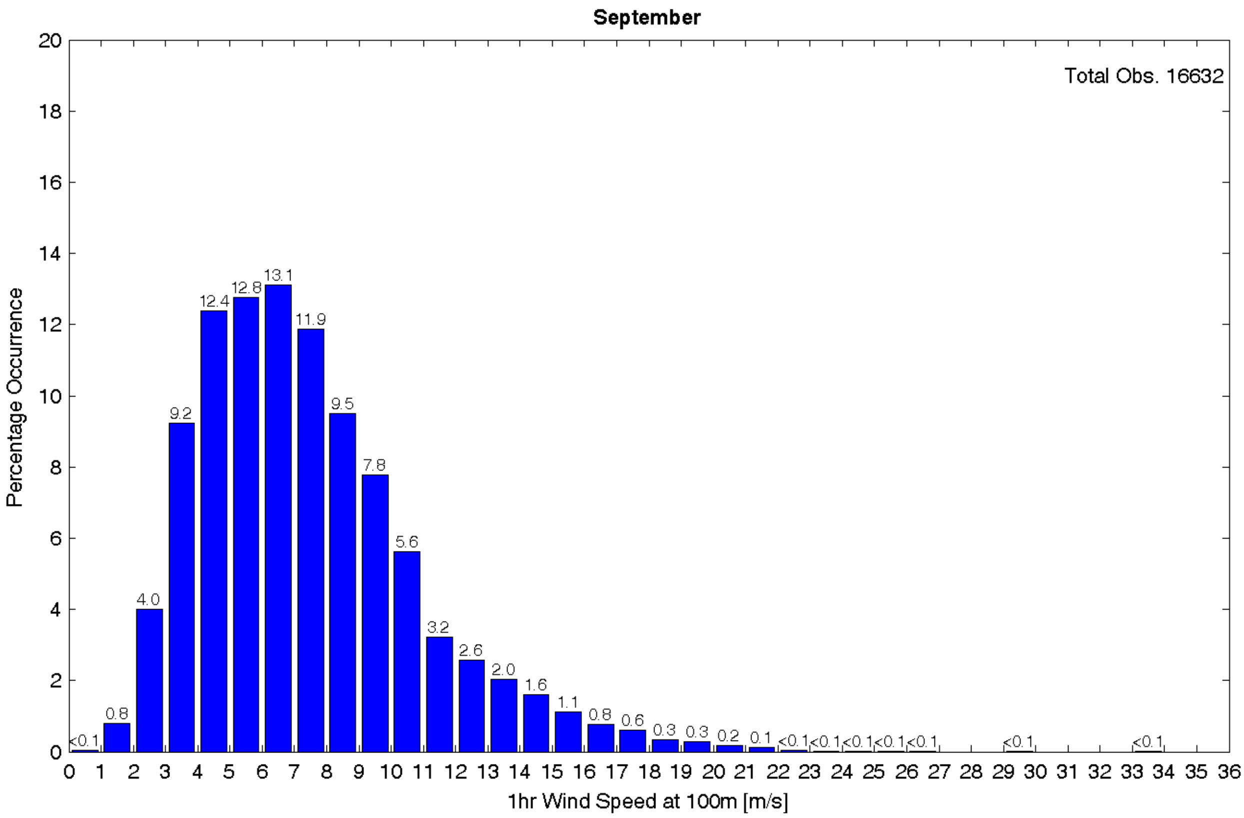

Figure 2-10 Percentage Occurrence of Wind Speed at Hub Height Excluding Hurricanes – September

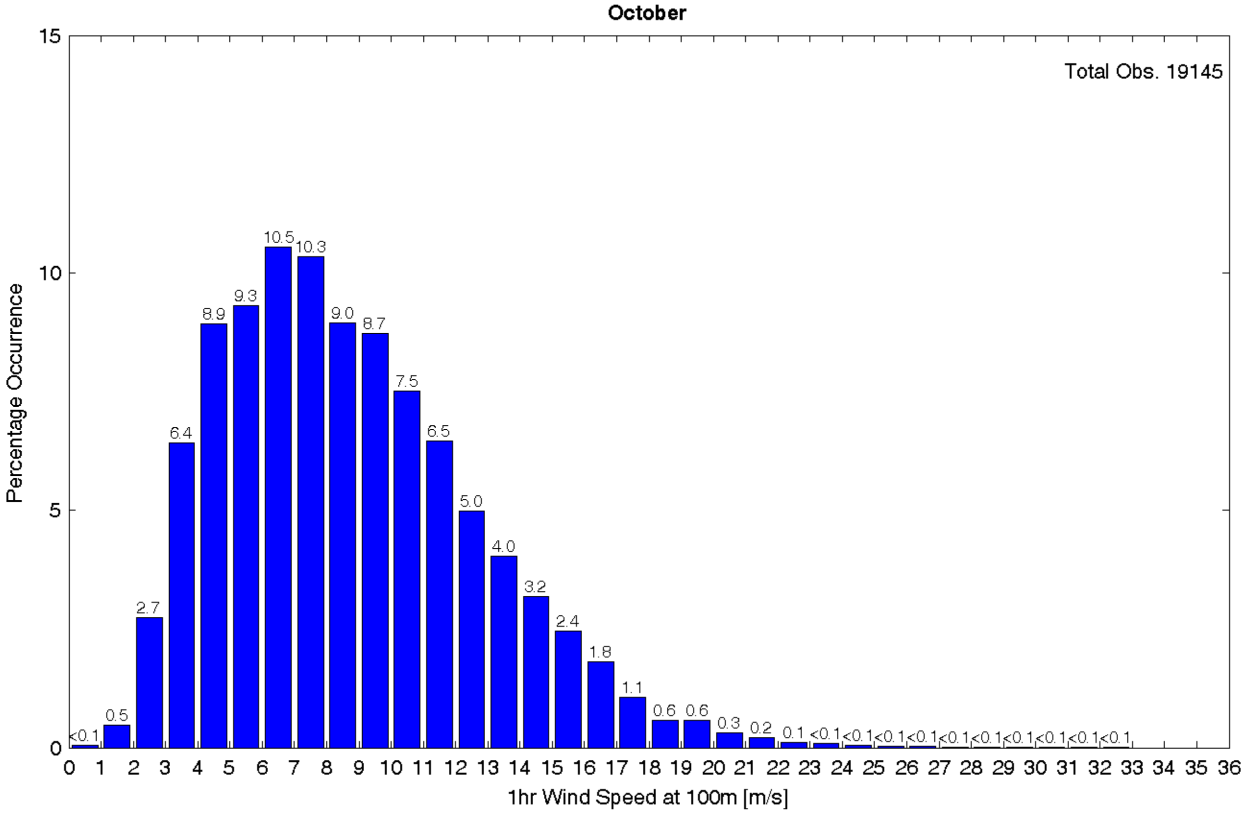

Figure 2-11 Percentage Occurrence of Wind Speed at Hub Height Excluding Hurricanes – October

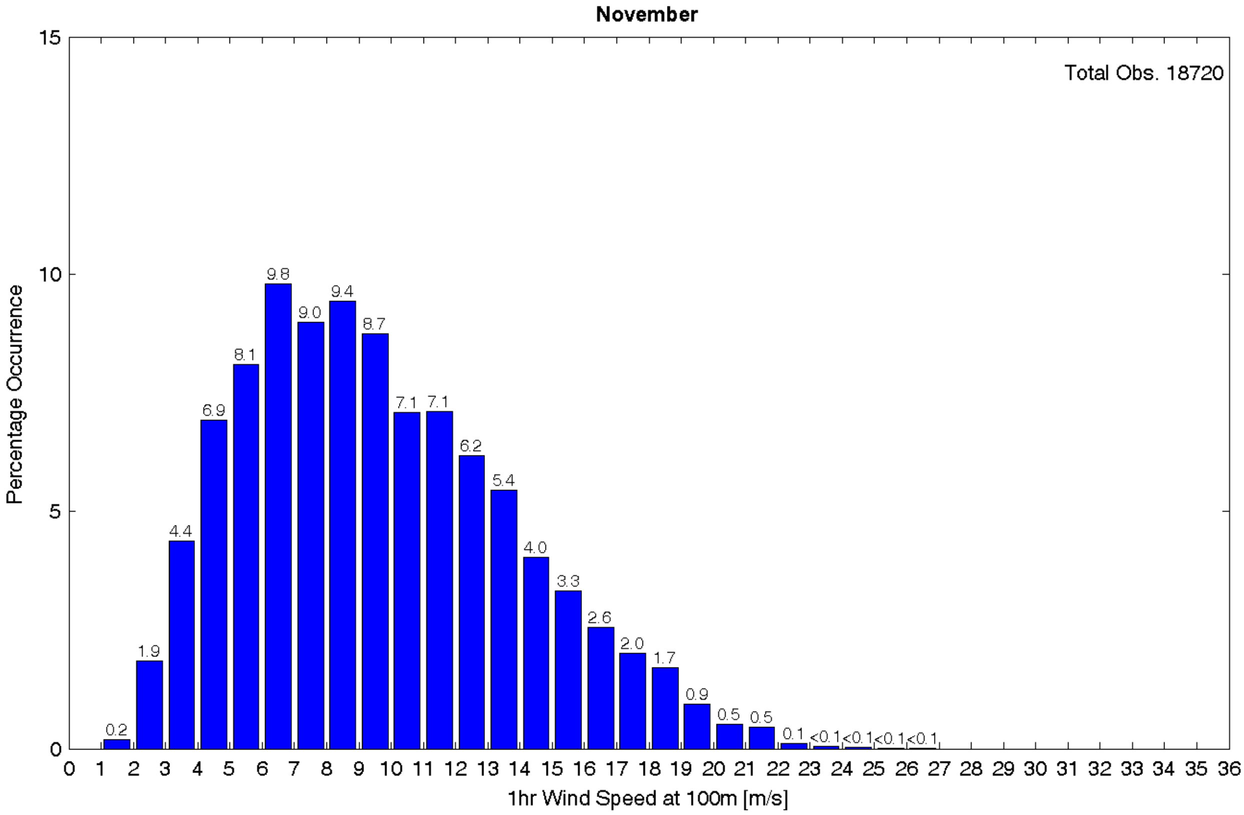

Figure 2-12 Percentage Occurrence of Wind Speed at Hub Height Excluding Hurricanes – November

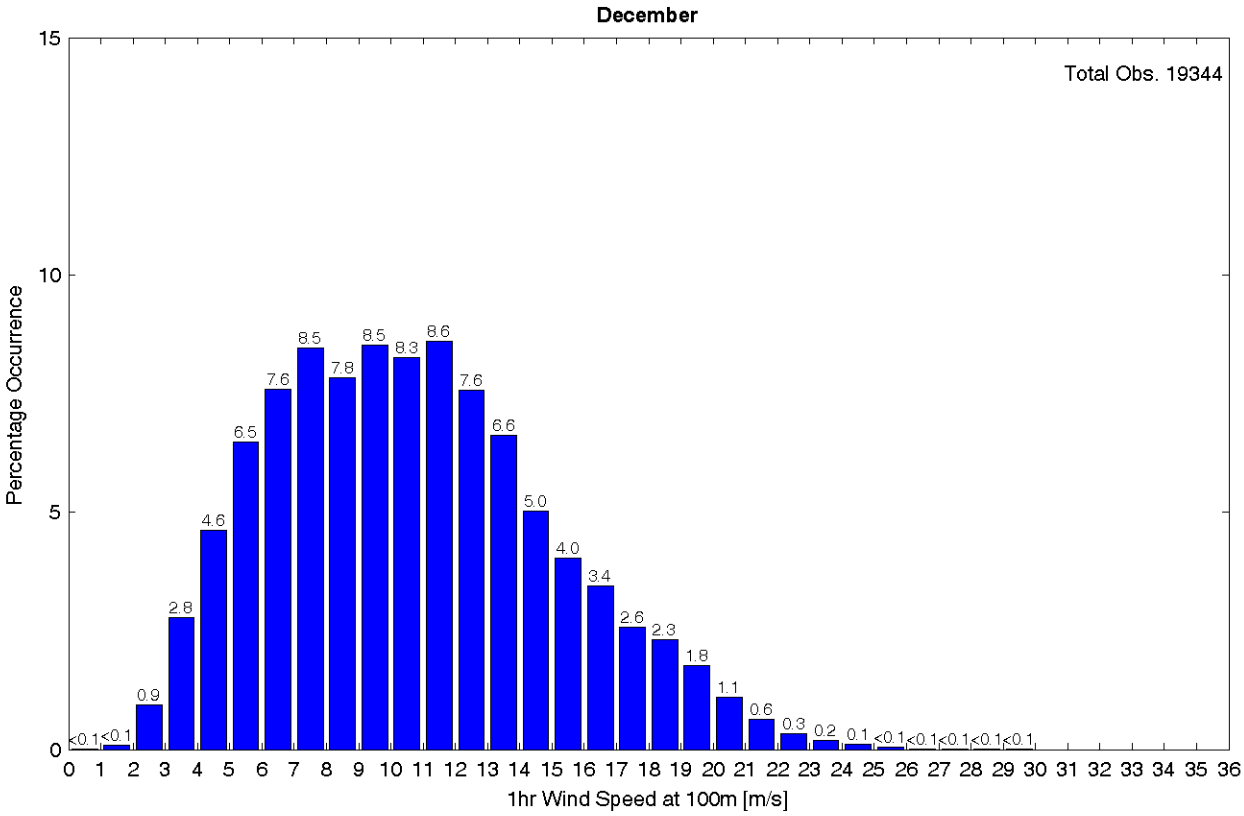

Figure 2-13 Percentage Occurrence of Wind Speed at Hub Height Excluding Hurricanes – December

2.1.8.2 Omni-Directional Monthly Average and Maximum Wind Speed Including Hurricanes

COMBINED PERIOD (1980 to 2005)	1hr Wind Speed at Hub Height 100m (m/s)	
	MEAN	MAX
All Year	8.44	41.78
January	10.77	26.68
February	10.12	27.69
March	9.62	31.78
April	8.26	27.11
May	6.81	23.55
June	6.15	20.83
July	6.24	30.12
August	6.62	35.38
September	7.73	71.78
October	8.75	32.04
November	9.60	26.48
December	10.66	29.17

Table 2-9 Omni-Directional Month Average and Maximum Wind Speed Including Hurricanes at Hub Height

2.1.8.3 Wind Speed Distribution at Hub Height Including Hurricanes

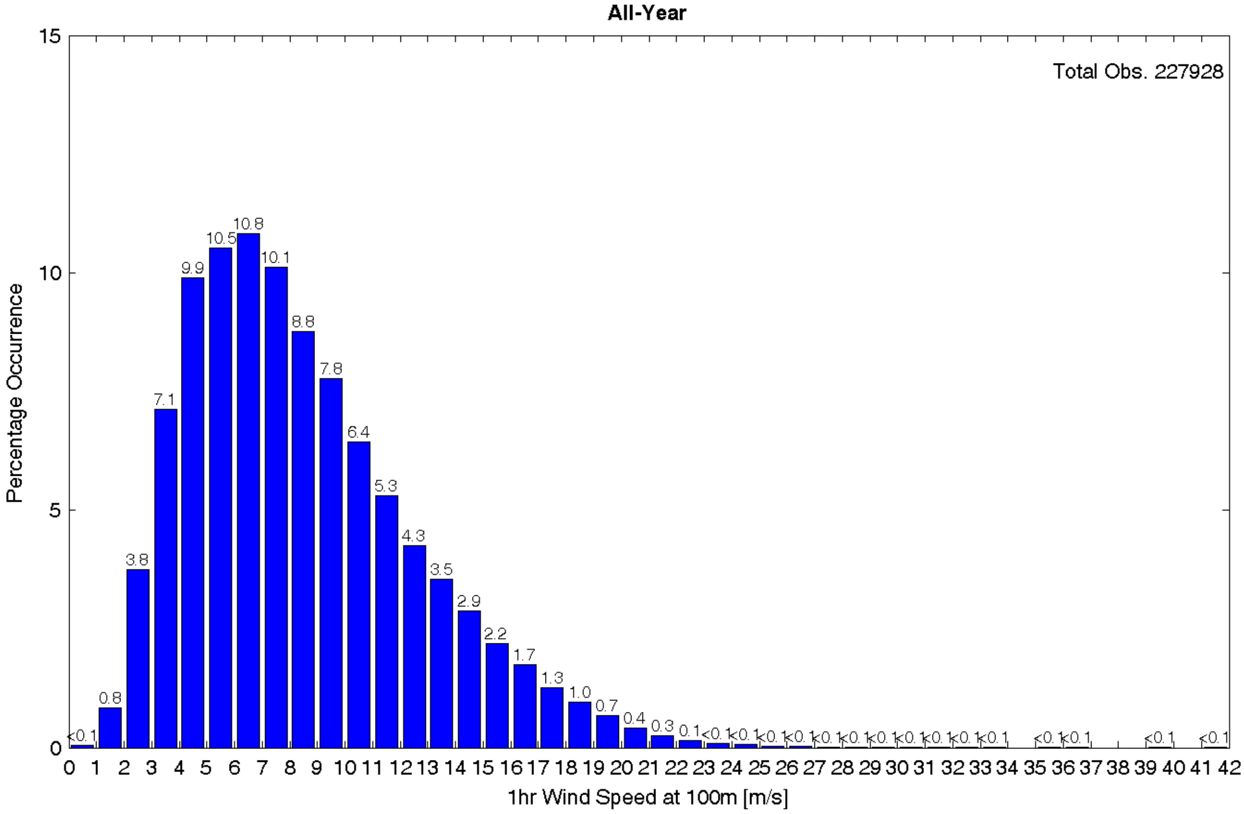

Figure 2-14 All Year Percentage Occurrence of Wind Speed at Hub Height Including Hurricanes

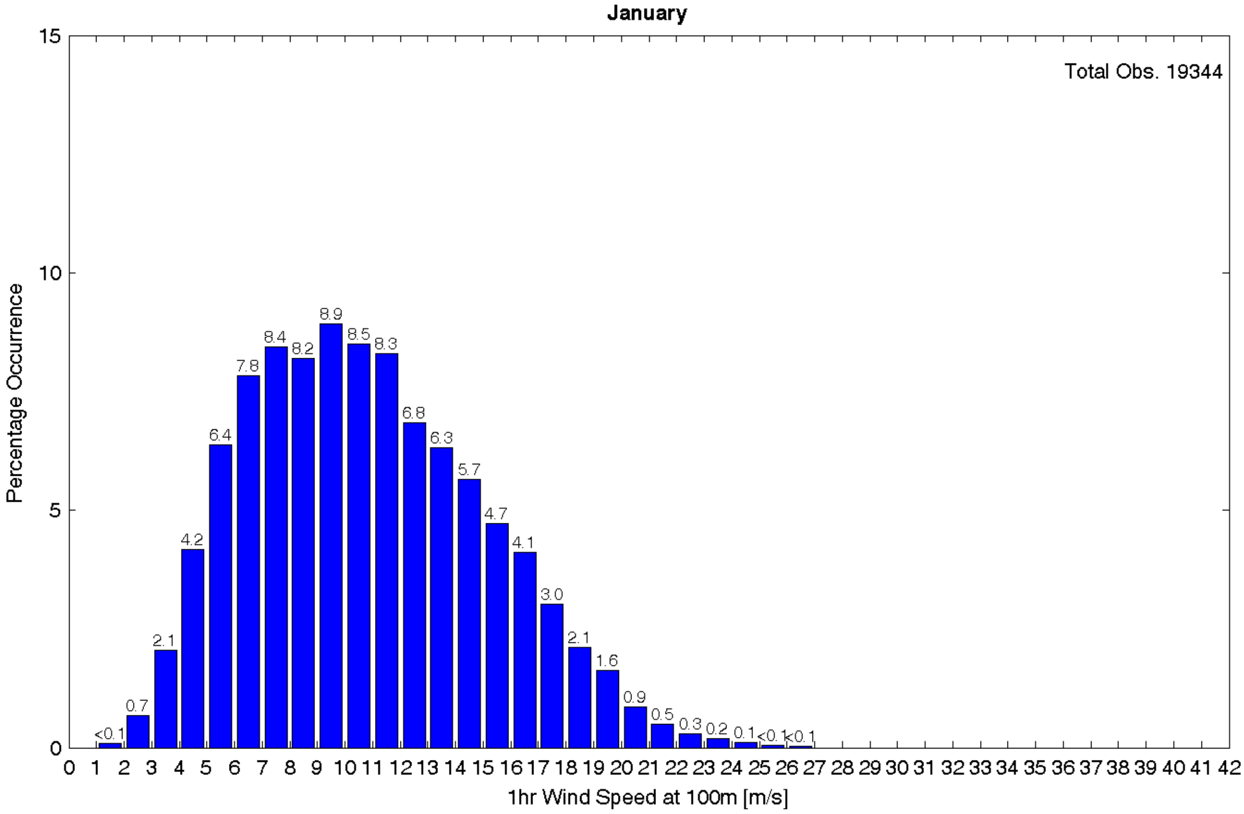

Figure 2-15 Percentage Occurrence of Wind Speed at Hub Height Including Hurricanes – January

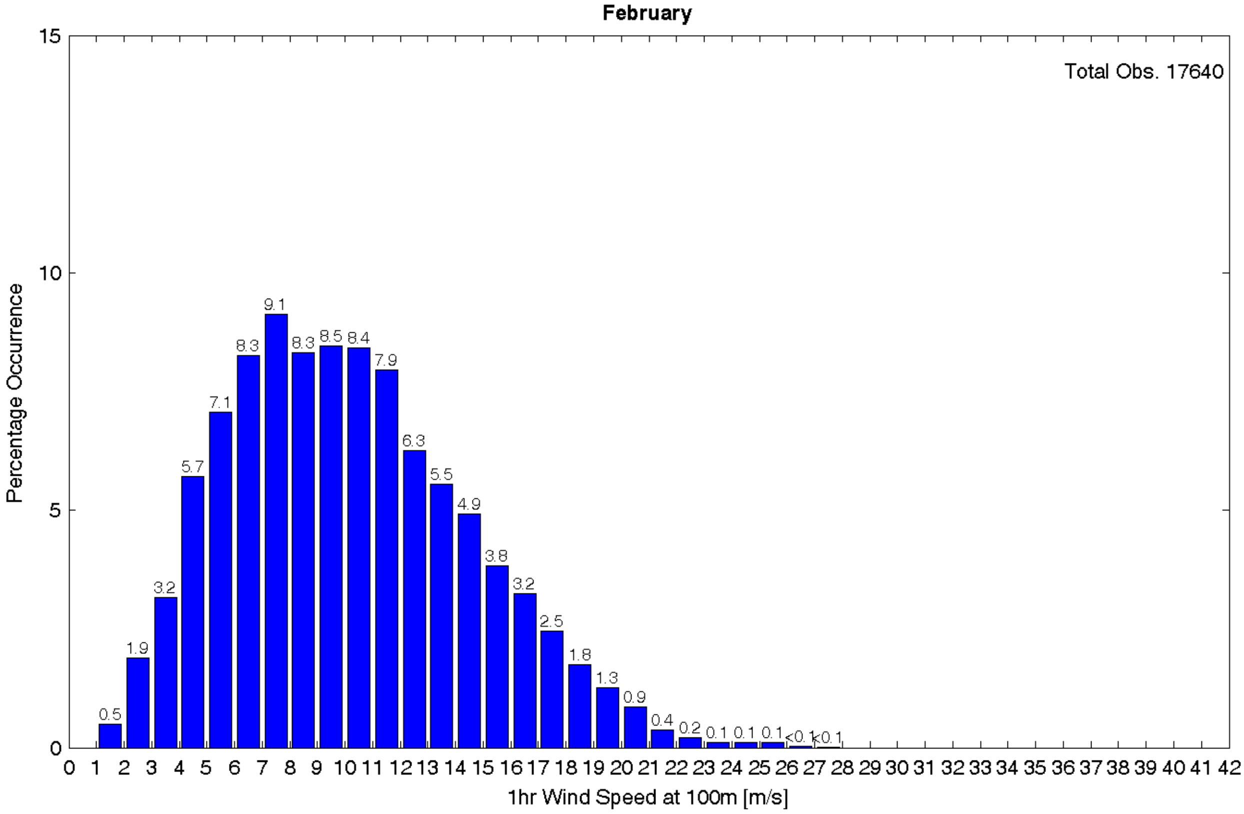

Figure 2-16 Percentage Occurrence of Wind Speed at Hub Height Including Hurricanes – February

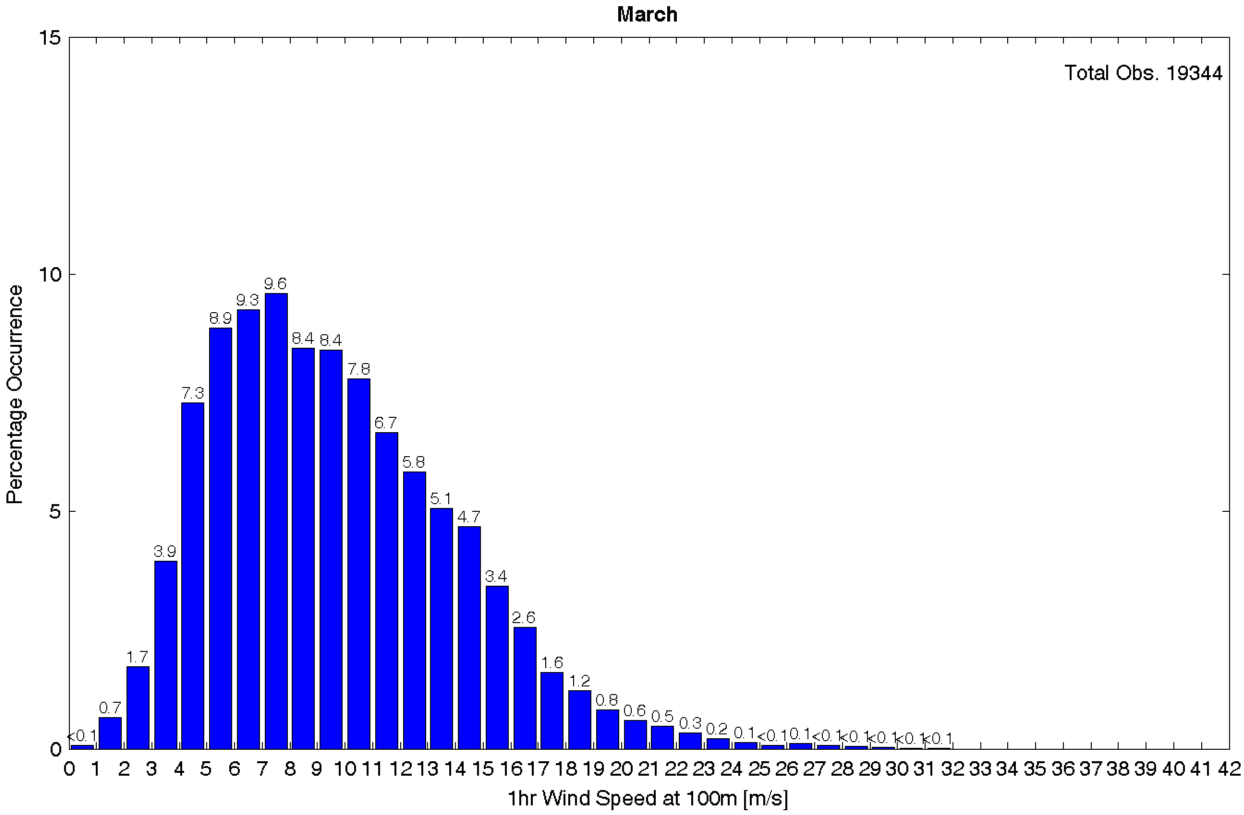

Figure 2-17 Percentage Occurrence of Wind Speed at Hub Height Including Hurricanes – March

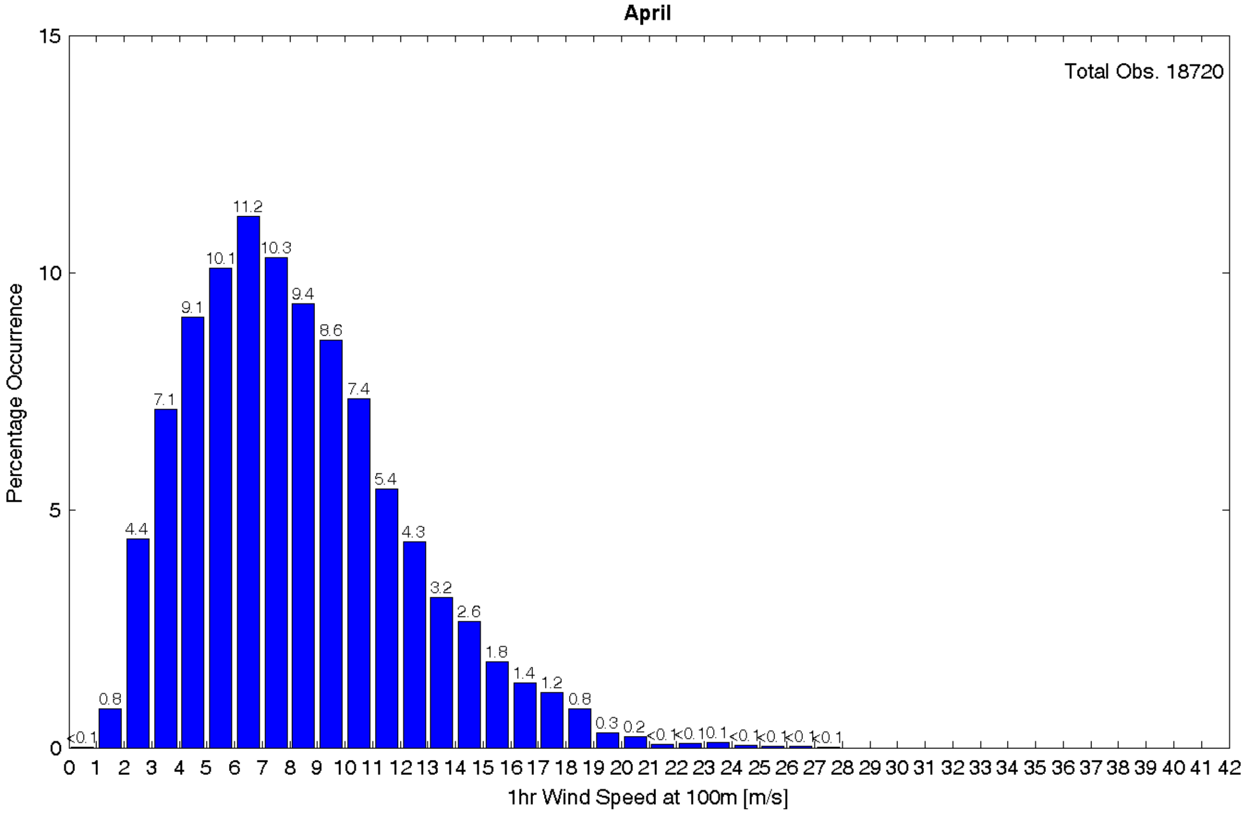

Figure 2-18 Percentage Occurrence of Wind Speed at Hub Height Including Hurricanes – April

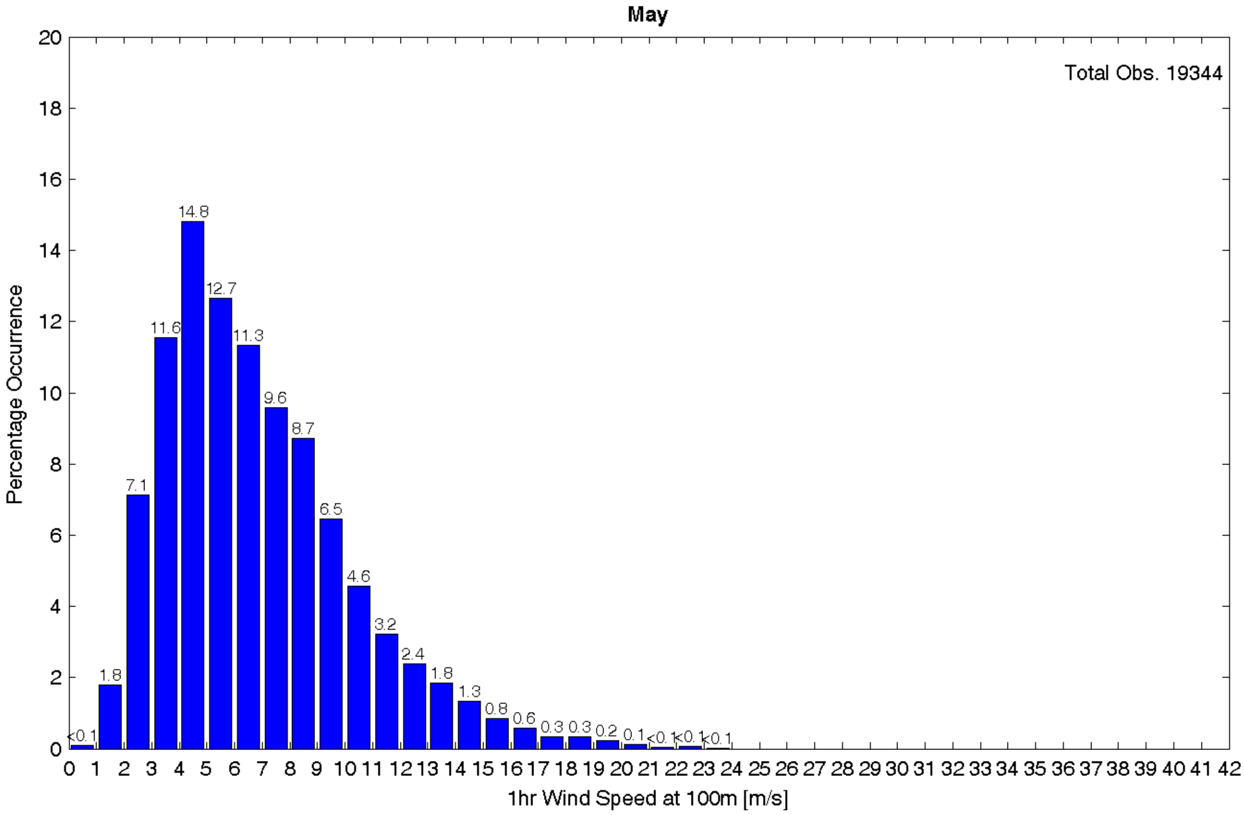

Figure 2-19 Percentage Occurrence of Wind Speed at Hub Height Including Hurricanes – May

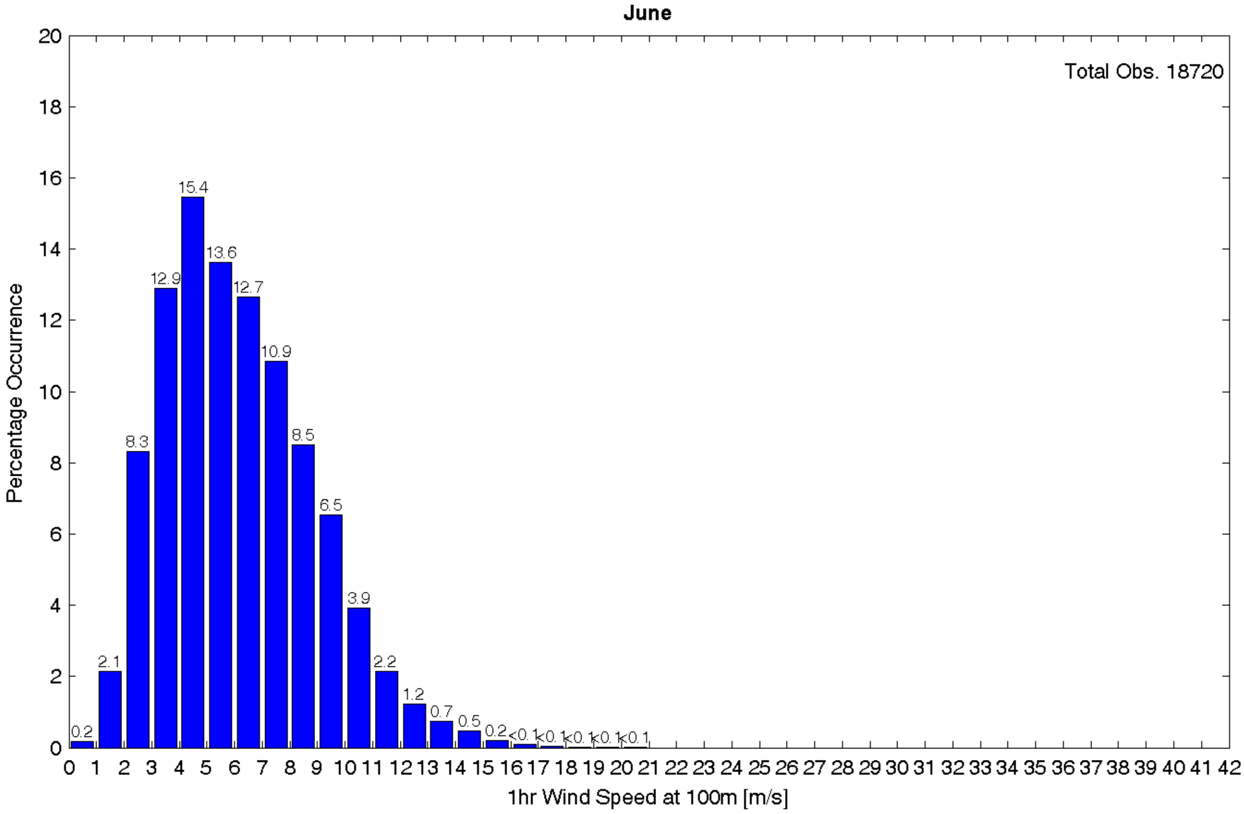

Figure 2-20 Percentage Occurrence of Wind Speed at Hub Height Including Hurricanes – June

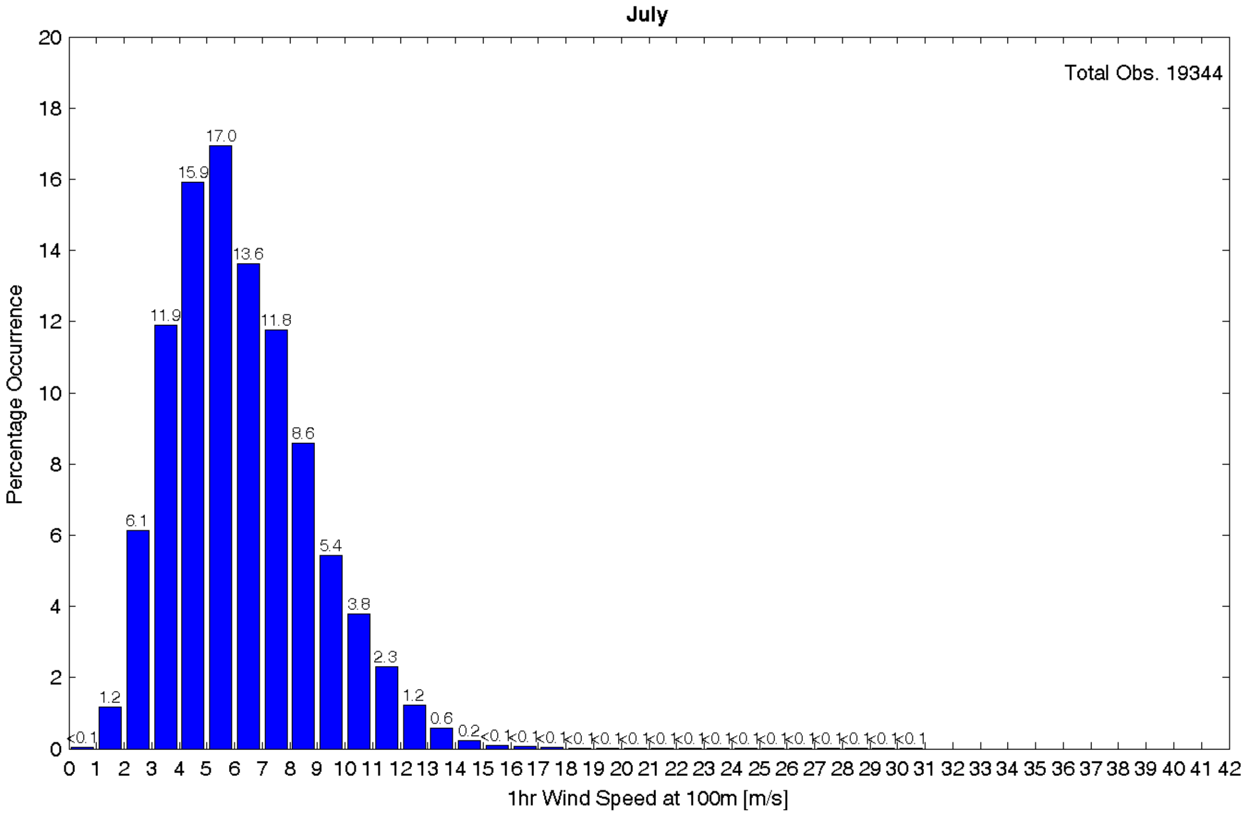

Figure 2-21 Percentage Occurrence of Wind Speed at Hub Height Including Hurricanes – July

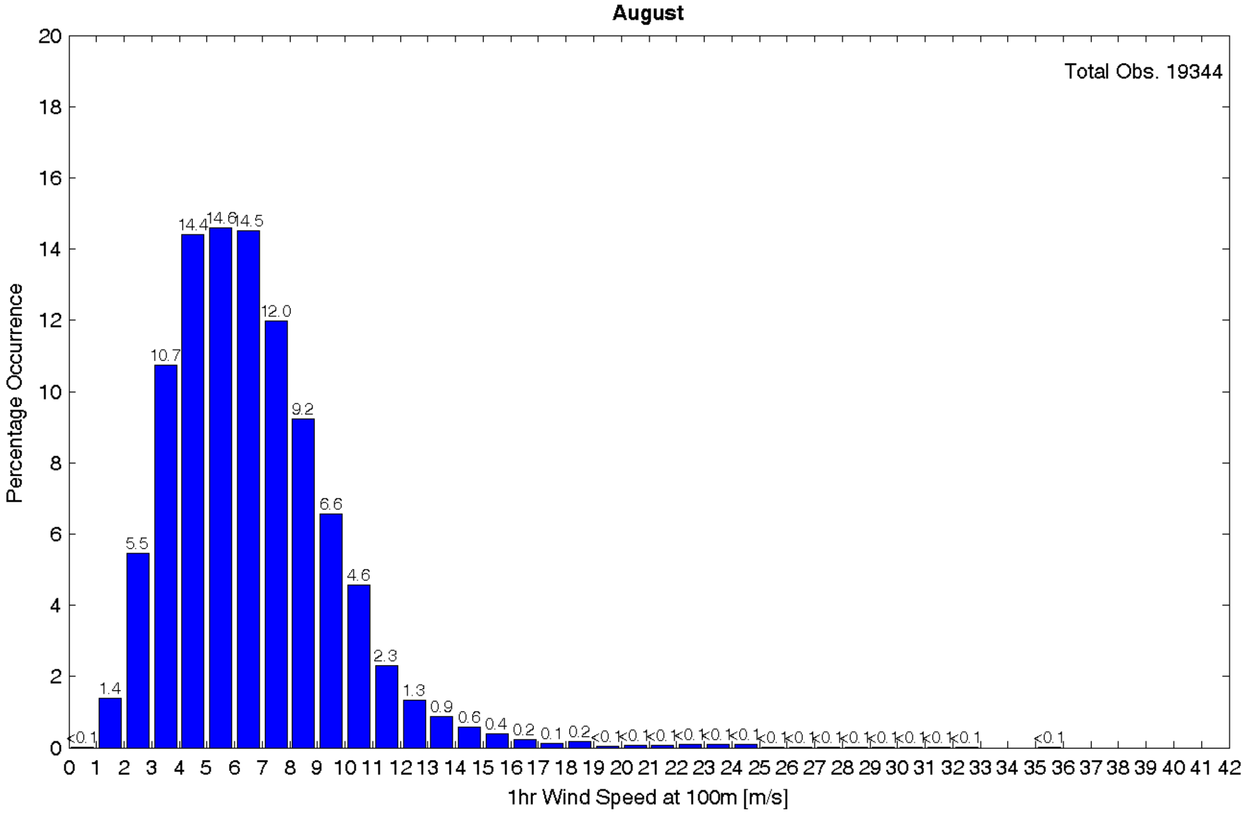

Figure 2-22 Percentage Occurrence of Wind Speed at Hub Height Including Hurricanes – August

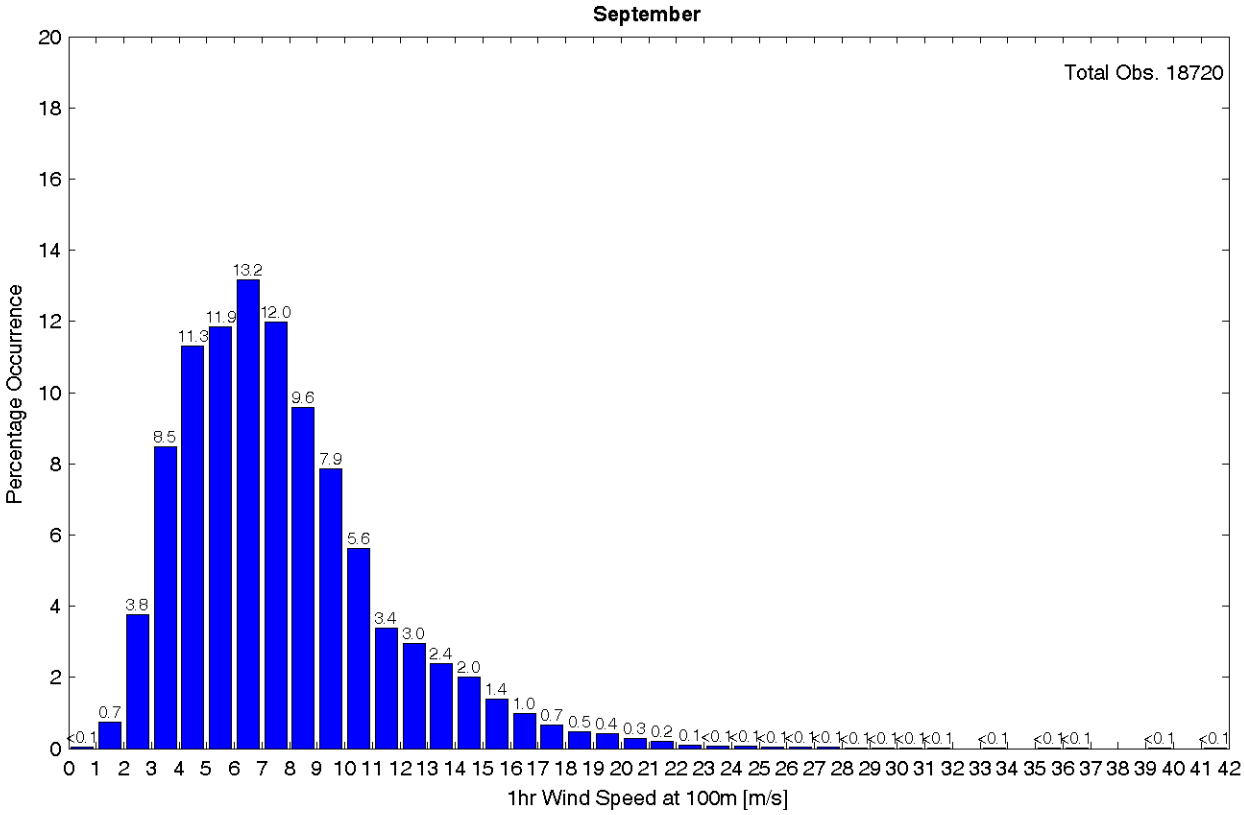

Figure 2-23 Percentage Occurrence of Wind Speed at Hub Height Including Hurricanes – September

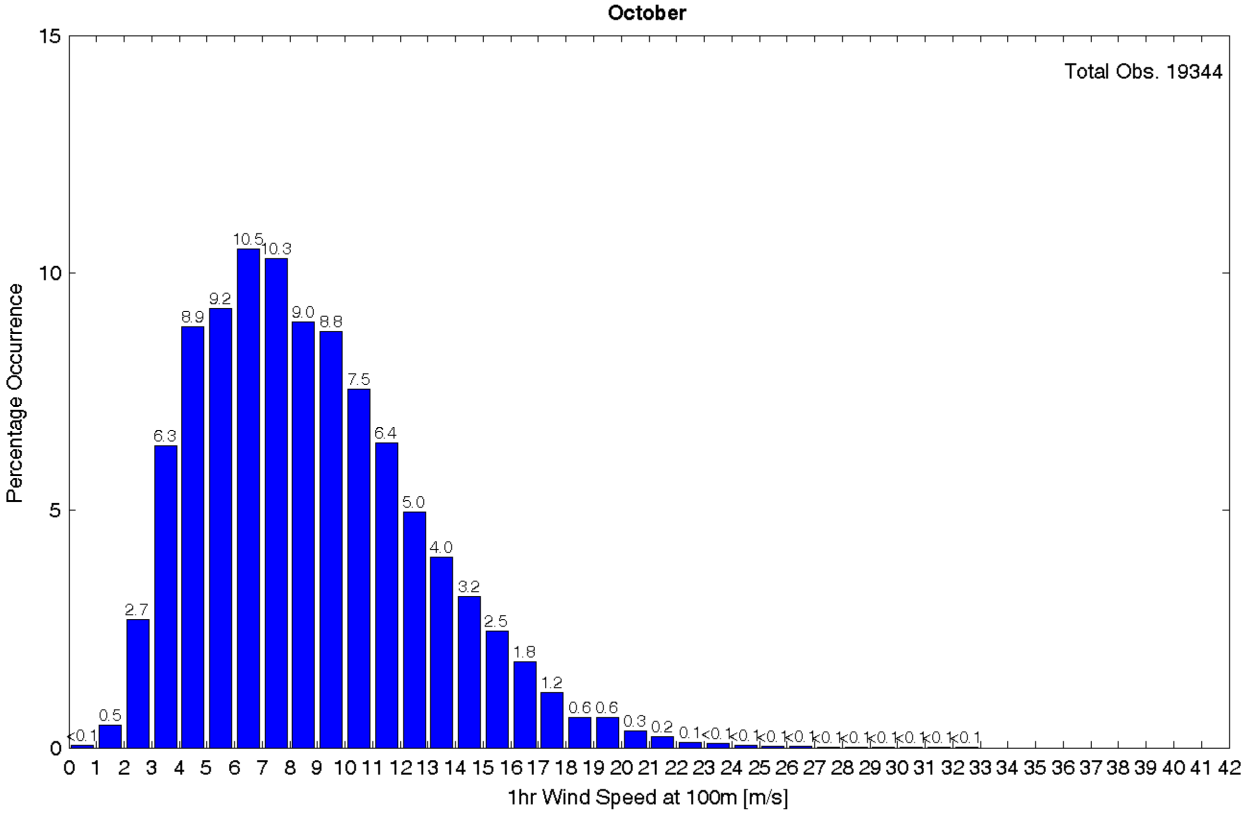

Figure 2-24 Percentage Occurrence of Wind Speed at Hub Height Including Hurricanes – October

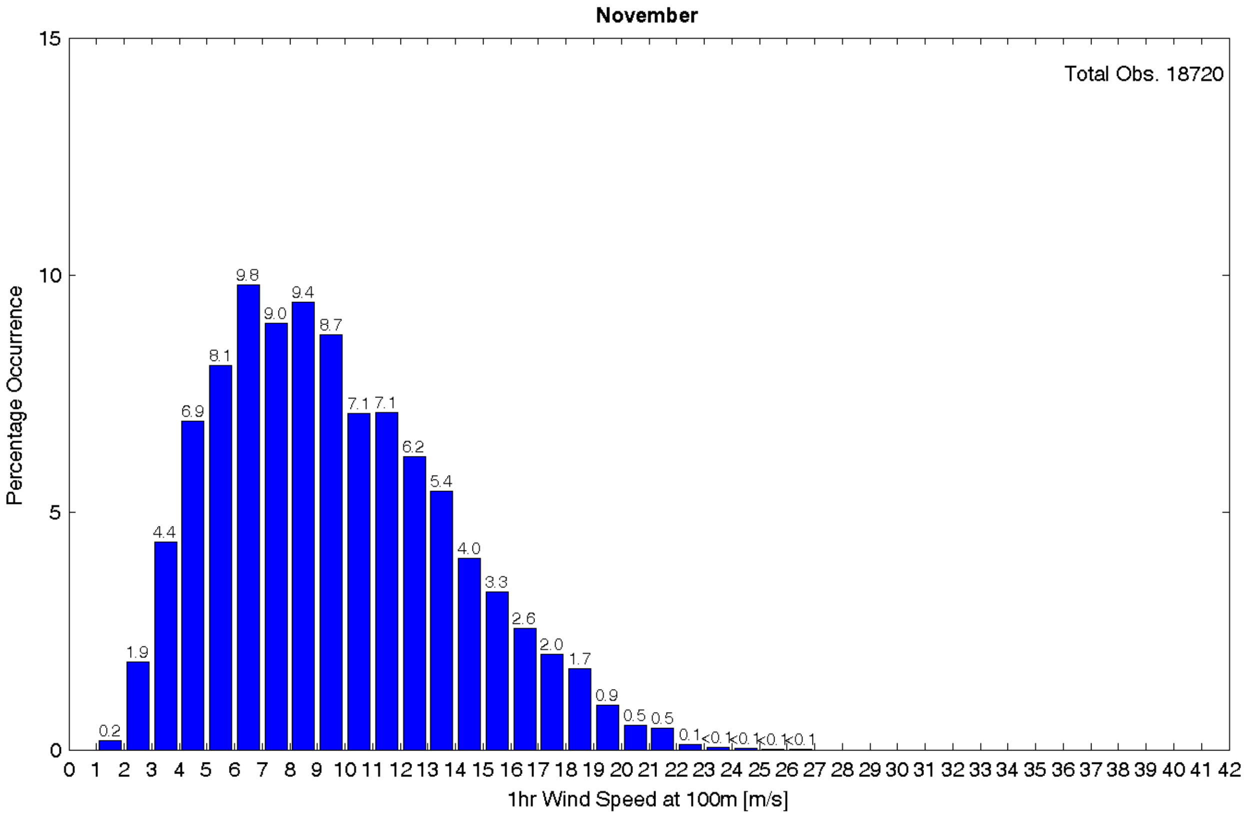

Figure 2-25 Percentage Occurrence of Wind Speed at Hub Height Including Hurricanes – November

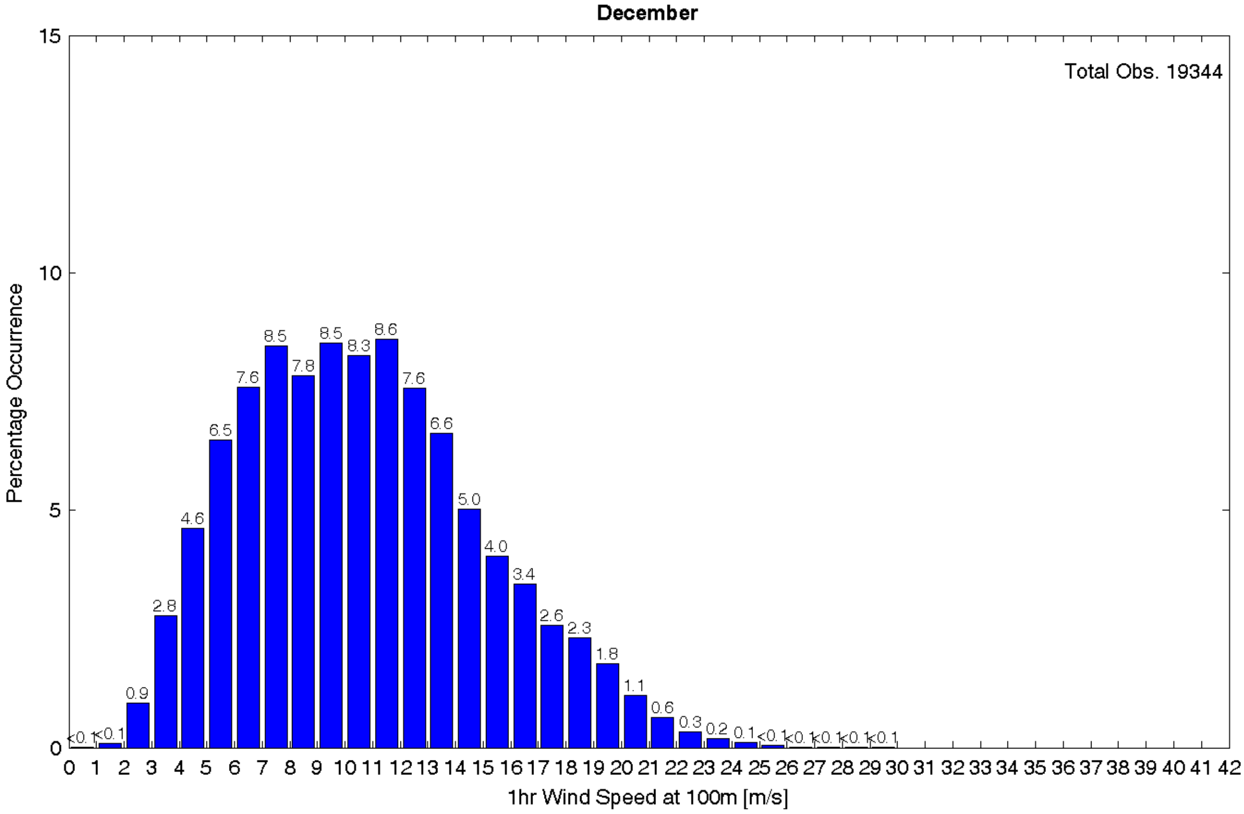

Figure 2-26 Percentage Occurrence of Wind Speed at Hub Height Including Hurricanes – December

2.1.9 Wind Speed Turbulence

The equation used for calculating turbulence standard diviation, normal turbulence model, was obtained from IEC 61400-3[1]. The equation reads as follows,

$$\sigma_1 = \frac{V_{hub}}{\ln\left(\frac{z_{hub}}{z_0}\right)} + 1.28 * 1.44 * I_{\text{ref}}$$

Where:
σ_1 turbulence standard deviation.
I_{ref} values are presented in table 2-10.
V_{hub} is the 10-min average wind speed at hub height.
σ_1/ V_{hub} turbulence intensity
z_{hub} is hub height, 100 meters.
z_0 is the roughness parameter, can be solved implicitly from the following equation;

$$z_0 = \frac{A_c}{g} * \left(\frac{k * V_{hub}}{\ln \frac{z_{hub}}{z_0}}\right)^2$$

Where:
g is the acceleration due to gravity.
k is 0.4, von Karman's constant.
A_c 0.011 for open sea and 0.034 may be use for near-coastal locations.
For coastal areas z_0 is between 0.001-0.01.[2]

I_{ref}	
Higher Turbulance Characteristics	0.16
Medium Turbulance Characteristics	0.14
Lower Turbulance Characteristics	0.12

Table 2-10 I_{ref} Values

No measurements of standard deviation of wind are available close to the site so the scaled 10min mean wind speed with occurrence period of 50 and 100 years was used from Tabke 2-7. The turbulence intensity will be recalculated after the measurement phase.

σ_1	50-year		100-year	
Roughness Parameter	z_0=0.001	z_0=0.01	z_0=0.001	z_0=0.01
High	4.6761	5.7714	5.1625	6.3794
Medium	4.6392	5.7345	5.1256	6.3425
low	4.6023	5.6976	5.0888	6.3056

Table 2-11 Turbulence Standard Deviation σ_1

σ_1/V_{hub}	50-year		100-year	
Roughness Parameter	z_0=0.001	z_0=0.01	z_0=0.001	z_0=0.01
High	0.0927	0.1144	0.1023	0.1265
Medium	0.0920	0.1137	0.1016	0.1257
low	0.0912	0.1130	0.1009	0.1250

Table 2-12 Wind Turbulence Intensity σ_1/ V_{hub}

2.1.10 Wind Speed Formula for Adjusting to Different Elevations

The equation used for adjusting wind speed at different elevations, was optained from IEC 61400-3[1]. The equation reads as follows;

$$V(z) = V_{hub} * (\frac{z}{z_{hub}})^{\propto}$$

Where:
V(z) is the wind speed at height z.
z is the height above mean sea level, 10 meters.
V_{hub} is the wind speed at hub height.
z_{hub} is hub height, 100 meters.
α power law exponent, 0.14.

Example: V(z) = 10; z = 10; z_{hub} = 100; V_{hub} = 10 $(100/10)^{0.14}$; V_{hub} = 13.8 m/s

2.1.11 Wind Speed Shear Model

The wind shear model was obtained from IEC 61400-3[1] document, the logarithmic and power law profile. The equations and parameters read as follows;

Logarithmic:

$$V(z) = V(z_r) * \frac{\ln(\frac{z}{z_0})}{\ln(\frac{z_r}{z_0})}$$

Power:

$$\mathrm{V(z)} = \mathrm{V(z)} * \left(\frac{z}{z_r}\right)^{\propto}$$

Where:
V(z) is the wind speed at height z.
z is the heigh above mean sea level, 10 meters.
z_r is hub height, 100 meters.
α is the wind sheat (or power law) exponent.
z_0 is the roughness length, can be solved implicitly from the following equation;

$$z_0 = \frac{A_c}{g} * \left(\frac{k * V_{hub}}{\ln \frac{z_{hub}}{z_0}}\right)^2$$

Where:
g is the acceleration due to gravity.
k is 0.4, von Karman's constant.
A_c 0.011 for open sea and 0.034 may be use for near-coastal locations.
V_{hub} is the wind speed at hub height.
z_{hub} is hub height, 100 meters.

2.1.12 Weibull Parameters

The weibull parameters are derived from fitting the Weibull probability density function to the distribution of the 26-years (1980 to 2005) of Oceanweather operational wind speed hindcast data converted to hub height, using equation in Section 2.1.21. Weibull formula used is as follows.

$$f(x;\alpha,\beta) = \frac{\alpha}{\beta^{\alpha}} * x^{\alpha-1} * e^{-(\frac{x}{\beta})^{\alpha}}$$

x: value at which to evaluate the function
α,β: parameters to the distribution

Figure 2-27 shows the Weibull fitting to the hourly wind speed distribution at hub height, with alpha and beta being 2.11 and 9.53. The average wind speed and wind power throughout the entire time series is 8.44 m/s and 668.98 W/m^2.

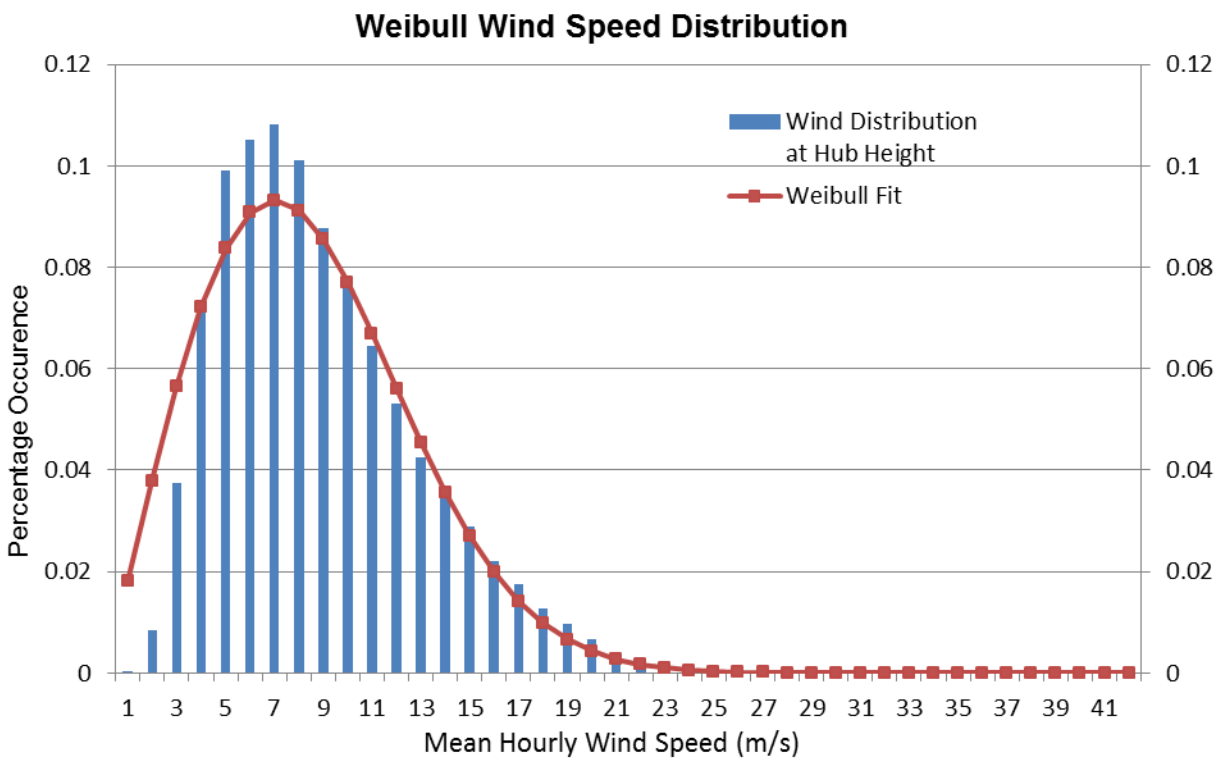

Figure 2-27 Weibull Wind Speed Distribution at Hub Height

2.2 Wave Criteria

Extreme value analysis was carried out on a subset of peak wind speed events from the Oceanweather hindcast data. The analysis only considered winter storm events from 1957 to 2003 and hurricane storm events from 1924 to 2005. The 1-year criteria are derived from 26-years (1980 to 2005) of Oceanweather operational hindcast data.

Section 2.2.23 depicts the highest extreme values for return periods 1-, 50-, 100-, 500-, 1000-, and 10000-year return periods.

2.2.1 Omni-Directiona 1 Year Extreme Values

Return Period	Hs	Tz	Tp	Hc	Hmax	THmax Low	THmax Mid	THmax High	Wave Length
	[m]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]
1-Year	5.34	6.5	9.9	6.22	10.01	8.8	10.0	10.9	128.0

Table 2-13 Omni-Directional 1 Year Extreme Values for All Waves

2.2.2 Directional 1 Year Extreme Values

Return Period	Hs	Tz	Tp	Hc	Hmax	THmax Low	THmax Mid	THmax High
Direction [from]	[m]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
1-Year	**5.34**	**6.5**	**9.9**	**6.22**	**10.01**	**8.8**	**10.0**	**10.9**
North	3.76	6.1	8.4	4.38	7.05	7.4	8.4	9.2
North-east	4.26	6.3	8.9	4.96	7.98	7.9	8.9	9.7
East	5.34	6.5	9.9	6.22	10.01	8.8	10.0	10.9
South-east	5.14	6.5	9.7	5.99	9.64	8.6	9.8	10.7
South	4.35	6.3	9.0	5.07	8.16	7.9	9.0	9.8
South-west	3.88	6.2	8.5	4.52	7.27	7.5	8.5	9.3
West	3.31	6.0	7.9	3.86	6.21	7.0	7.9	8.6
North-west	3.24	6.0	7.8	3.78	6.08	6.9	7.8	8.5

Table 2-14 Directional 1 Year Extreme Values for All Waves

2.2.3 1-Year Wave Fitting Parameters

The independent omni-directional wave cases are given in Table 2-13 and detailed descriptions of the calculations are given below. The analysis considered 26-years (1980 to 2005) of Oceanweather operational hindcast data.

Cumulative frequency extrapolation involves grouping all the parameter values in the data set using specified class intervals and then forming a cumulative frequency distribution (cfd) by summing the number of observations greater than or equal to the lower bound of the class interval. This method was then employed to derive the 1-year criteria.

The Exponential (EXP), Fisher-Tippett 1 (FT1), Fisher-Tippett 2 (FT2), Fisher-Tippett 3 (FT3), Weibull 2 (W2) and Weibull 3 (W3) distributions were tested for goodness-of-fit to the data using the method of least squares (LS). The best fits for the 1-year wind speed are summarised in Table 2-15.

	Distribution	Fit	Threshold	# Peaks	Extreme Values 1-yr
Hs (m)	EXP	LS	90.00	116297	5.37
	EXP	LS	10.00	22529	5.34
	FT1	LS	95.00	214551	5.34
	FT2	LS	95.00	214551	5.34
	FT2	LS	10.00	22529	5.33
	FT3	LS	95.00	214551	5.33
	FT3	LS	90.00	116297	5.33
	FT3	LS	50.00	52040	5.33
	FT3	LS	10.00	22529	5.33
	FT3	LS	5.00	8776	5.34
	AVERAGE				5.34

Table 2-15 Extreme Omni-directional All Wave Fitting Parameters for 1-year Extreme

2.2.4 Omni-Directional Winter Storm Extreme Values

Return Period	Hs	Tz	Tp	Hc	Hmax	THmax Low	THmax Mid	THmax High	Wave Length
	[m]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]
50-years	6.25	7.3	10.6	7.35	11.69	9.4	10.6	11.6	140.62
100-years	6.83	7.6	11.0	8.03	12.77	9.8	11.1	12.1	149.32
500-years	8.16	8.0	12.0	9.60	15.28	10.7	12.1	13.2	168.74
1000-years	8.74	8.2	12.4	10.28	16.36	11.0	12.5	13.6	176.97
10000-years	10.65	8.8	13.7	12.53	19.94	12.1	13.8	15.0	203.32

Table 2-16 Omni-Directional Winter Storm Extreme Values for All Waves

2.2.5 Directional Winter Storm Extreme Values

Return Period	Hs	Tz	Tp	Hc	Hmax	THmax Low	THmax Mid	THmax High
Direction [from]	[m]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
50-Years	**6.25**	**7.3**	**10.6**	**7.35**	**11.69**	**9.4**	**10.6**	**11.6**
North	4.49	6.6	9.0	5.28	8.40	8.0	9.0	9.9
North-east	6.25	7.3	10.6	7.35	11.69	9.4	10.6	11.6
East	4.88	6.7	9.4	5.74	9.13	8.3	9.4	10.3
South-east	5.98	7.2	10.3	7.03	11.19	9.2	10.4	11.3
South	5.19	6.9	9.7	6.10	9.71	8.6	9.7	10.6
South-west	4.60	6.6	9.1	5.41	8.61	8.1	9.2	10.0
West	3.57	6.1	8.1	4.20	6.69	7.1	8.1	8.8
North-west	3.72	6.1	8.2	4.37	6.96	7.3	8.3	9.0
100-Years	**6.83**	**7.6**	**11.0**	**8.03**	**12.77**	**9.8**	**11.1**	**12.1**
North	4.90	6.8	9.4	5.77	9.17	8.3	9.4	10.3
North-east	6.83	7.6	11.0	8.03	12.77	9.8	11.1	12.1
East	5.33	7.0	9.8	6.27	9.97	8.7	9.8	10.7
South-east	6.53	7.5	10.8	7.68	12.22	9.6	10.8	11.8
South	5.67	7.1	10.1	6.67	10.61	8.9	10.1	11.0
South-west	5.03	6.8	9.5	5.91	9.41	8.4	9.6	10.4
West	3.90	6.3	8.4	4.59	7.31	7.5	8.5	9.2

North-west	4.06	6.3	8.6	4.78	7.60	7.6	8.6	9.4
500-Years	**8.16**	**8.0**	**12.0**	**9.60**	**15.28**	**10.7**	**12.1**	**13.2**
North	5.86	7.2	10.2	6.90	10.97	9.1	10.3	11.2
North-east	8.16	8.0	12.0	9.60	15.28	10.7	12.1	13.2
East	6.37	7.4	10.7	7.50	11.93	9.5	10.7	11.7
South-east	7.81	7.9	11.8	9.19	14.62	10.4	11.8	12.9
South	6.78	7.5	11.0	7.98	12.69	9.7	11.0	12.0
South-west	6.01	7.2	10.4	7.07	11.25	9.2	10.4	11.4
West	4.67	6.6	9.2	5.49	8.74	8.1	9.2	10.1
North-west	4.86	6.7	9.3	5.71	9.09	8.3	9.4	10.2
1000-Years	**8.74**	**8.2**	**12.4**	**10.28**	**16.36**	**11.0**	**12.5**	**13.6**
North	6.28	7.4	10.6	7.38	11.74	9.4	10.6	11.6
North-east	8.74	8.2	12.4	10.28	16.36	11.0	12.5	13.6
East	6.82	7.6	11.0	8.03	12.77	9.8	11.1	12.1
South-east	8.36	8.1	12.2	9.84	15.65	10.8	12.2	13.3
South	7.26	7.7	11.4	8.54	13.58	10.1	11.4	12.5
South-west	6.44	7.4	10.7	7.57	12.05	9.5	10.8	11.7
West	5.00	6.8	9.5	5.88	9.36	8.4	9.5	10.4
North-west	5.20	6.9	9.7	6.12	9.73	8.6	9.7	10.6
10000-Years	**10.65**	**8.8**	**13.7**	**12.53**	**19.94**	**12.1**	**13.8**	**15.0**
North	7.65	7.9	11.7	9.00	14.32	10.3	11.7	12.8
North-east	10.65	8.8	13.7	12.53	19.94	12.1	13.8	15.0
East	8.32	8.1	12.1	9.78	15.56	10.8	12.2	13.3
South-east	10.19	8.7	13.4	11.99	19.08	11.9	13.5	14.7
South	8.85	8.3	12.5	10.41	16.56	11.1	12.6	13.7
South-west	7.85	7.9	11.8	9.23	14.68	10.5	11.9	12.9
West	6.09	7.3	10.4	7.17	11.40	9.2	10.5	11.4
North-west	6.34	7.4	10.6	7.46	11.86	9.4	10.7	11.7

Table 2-17 Directional Winter Storm Extreme Values for All Waves

2.2.6 All Wave Fitting Parameters for Winter Storm

The independent omni-directional wave cases are given in Table 2-16 and detailed descriptions of the calculations are given below.

Extreme value analysis was carried out on a subset of peak wave heights from the data. The analysis only considered winter storm events from 1957 to 2003.

The Peaks Over Threshold (POT) method consisted of declustering the data by selecting peak events to produce a set of independent and identically distributed observations. This method was then employed to derive the 50-, 100-, 500-, 1000-, and 10000-year criteria. The number of peaks exceeding a given level, divided by the number of years of record, gave the rate of exceedance which could then be used to find the expected number of occurrences in a specified period of time.

The Exponential (EXP), Fisher-Tippett 1 (FT1), Generalised Pareto (GP), Weibull 2 (W2) and Weibull 3 (W3) distributions were tested for goodness-of-fit to the data using the method of least squares (LS), maximum likelihood (MLE), and the method of moments (MoM). The best fits for 50-, 100-, 500-, 1000-, and 10000-year significant wave height are summarised in Table 2-18.

	Distribution	Fit	Threshold	# Peaks	Extreme Values				
					50-yr	100-yr	500-yr	1000-yr	10000-yr
Hs (m)	EXP	MLE	2.69	50	6.54	7.21	8.75	9.42	11.63
	EXP	MoM	2.69	50	6.05	6.60	7.89	8.44	10.27
	EXP	MoM	1.54	85	6.46	7.13	8.69	9.35	11.57
	FT1	LS	2.69	50	6.07	6.56	7.69	8.18	9.79
	FT1	LS	1.54	85	6.27	6.84	8.15	8.71	10.57
	FT1	MoM	0.74	99	6.33	6.93	8.32	8.91	10.90
	FT1	MoM	1.09	96	6.24	6.82	8.16	8.74	10.65
	FT1	MoM	1.54	85	6.03	6.55	7.76	8.28	10.01
	FT1	MLE	1.09	96	6.48	7.10	8.53	9.15	11.19
	FT1	MLE	1.54	85	6.00	6.52	7.72	8.24	9.96
	AVERAGE				6.25	6.83	8.16	8.74	10.65

Table 2-18 Extreme Omni-directional All Wave Fitting Parameters for Winter Storm

2.2.7 Wave Height and Length for Winter Storms for Site 1 and 2

Wave Length is calculated using the omni-directional winter storm extreme values found in Table 2-13 and Table 2-16 with the associated depths for each site.

Extreme Wave Criteria at Site 1		Return Period					
		1-year	50-year	100-year	500-year	1000-year	10000-year
Significant Wave Height (m)		5.34	6.25	6.83	8.16	8.74	10.65
Peak Period (s)		9.9	10.57	11.03	12.03	12.44	13.69
Wave Length (m)	Total Water Depth 24.7m	130.59	143.59	152.53	172.34	180.69	207.29

Table 2-19 Extreme Wave and Associated Wave Length for Winter Storms at Site 1

Extreme Wave Criteria at Site 2		Return Period					
		1-year	50-year	100-year	500-year	1000-year	10000-year
Significant Wave Height (m)		5.34	6.25	6.83	8.16	8.74	10.65
Peak Period (s)		9.9	10.57	11.03	12.03	12.44	13.69
Wave Length (m)	Total Water Depth 25.4m	131.60	144.75	153.79	173.78	182.19	208.91

Table 2-20 Extreme Wave and Associated Wave Length for Winter Storms at Site 2

2.2.8 Wave Orbital Velocity at 1m Above Seabed for Winter Storms for Site 1 and 2

Orbital velocity at 1 m above seabed is calculated using the omni-directional winter storm extreme values found in Table 2-13 and Table 2-16 with associated depths at each site. Table 2-22 and Table 2-24 show wave orbital velocity using Hmax and Tp associated with Hmax (THmax high). We are unable to compute wave orbital velocity for the 10000 year event because the wave is a breaking wave.

Extreme Wave Criteria at Site 1		Return Period					
		1-year	50-year	100-year	500-year	1000-year	10000-year
Significant Wave Height (m)		5.34	6.25	6.83	8.16	8.74	10.65
Peak Period (s)		9.9	10.57	11.03	12.03	12.44	13.69
Wave Orbital Velocity (m/s) at 1m above seabed	Total Water Depth 24.7m	1.12	1.41	1.60	2.04	2.23	2.86

Table 2-21 Extreme Wave and Associated Wave Orbital Velocity at 1m Above Seabed for Winter Storms at Site 1

Extreme Wave Criteria at Site 1		Return Period				
		1-year	50-year	100-year	500-year	1000-year
Hmax (m)		10.01	11.69	12.77	15.28	16.36
Peak Period Associated with Hmax (s)		10.9	11.6	12.1	13.2	13.6
Wave Orbital Velocity (m/s) at 1m above seabed	Total Water Depth 24.7m	2.26	2.75	3.04	3.61	3.73

Table 2-22 Extreme Hmax and Associated Wave Orbital Velocity at 1m Above Seabed for Winter Storms at Site 1

Extreme Wave Criteria at Site 2		Return Period					
		1-year	50-year	100-year	500-year	1000-year	10000-year
Significant Wave Height (m)		5.34	6.25	6.83	8.16	8.74	10.65
Peak Period (s)		9.9	10.57	11.03	12.03	12.44	13.69
Wave Orbital Velocity (m/s) at 1m above seabed	Total Water Depth 25.4m	1.09	1.37	1.55	1.99	2.18	2.80

Table 2-23 Extreme Wave and Associated Wave Orbital Velocity at 1m Above Seabed for Winter Storms at Site 2

Extreme Wave Criteria at Site 2		Return Period				
		1-year	50-year	100-year	500-year	1000-year
Hmax (m)		10.01	11.69	12.77	15.28	16.36
Peak Period Associated with Hmax (s)		10.9	11.6	12.1	13.2	13.6
Wave Orbital Velocity (m/s) at 1m above seabed	Total Water Depth 25.4m	2.22	2.69	2.99	3.58	3.74

Table 2-24 Extreme Hmax and Associated Wave Orbital Velocity at 1m Above Seabed for Winter Storms at Site 2

2.2.9 Fatigue Waves for Winter Storms

Extreme all-year omni-directonal and directional fatigue individual wave heights and periods for winter storms are provided in the attached Excel spreadsheet "Virgina_Extreme_Fatigue_WinterStorm." Directional scatter table of individual fatigue wave heights and periods scaled to an interval of 20 years at 45 degree intervals for winter storms are provided in the Excel spreadsheets "Virginia_Fatigue_20years_WinterStorm." Directional tables of mid height, median period, and 15 and 85 percentile period limits for fatigue waves at 45 degree intervals for winter storms are provided in the Excel spreadsheets "Virginia_Fatigue_Tables_WinterStorm."

2.2.10 Joint Frequency Distribution of Significant Wave Height and Direction for Winter Storms

All-Year

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	11.26	28.16	24.74	8.62	5.21	4.96	5.97	11.08	100.00	
> 6.0		0.20							0.20	0.20
5.5 – 6.0		0.29		0.14					0.43	0.63
5.0 – 5.5		0.48		0.08	0.10				0.66	1.29
4.5 – 5.0		0.42	0.15	0.08	0.08	0.03			0.77	2.06
4.0 – 4.5	0.18	0.90	0.28	0.27	0.21	0.14			1.98	4.03
3.5 – 4.0	0.76	1.22	1.18	1.12	0.42	0.18	0.03	0.70	5.60	9.64
3.0 – 3.5	1.25	3.10	2.48	0.99	0.88	0.29	0.88	1.33	11.21	20.85
2.5 – 3.0	1.70	3.19	3.11	1.15	1.15	0.45	1.32	1.64	13.70	34.55
2.0 – 2.5	1.95	4.31	4.96	0.95	0.99	0.78	2.09	3.26	19.31	53.85
1.5 – 2.0	2.54	4.62	2.87	1.08	0.49	1.68	1.16	2.40	16.84	70.69
1.0 – 1.5	2.12	4.83	5.17	1.19	0.46	0.74	0.38	1.47	16.36	87.06
0.5 – 1.0	0.71	3.99	4.29	0.97	0.13	0.29	0.11	0.28	10.77	97.83
0.0 – 0.5	0.07	0.60	0.25	0.59	0.29	0.36			2.17	

Mean Wave Direction (°T From)

Figure 2-28 All Year Percentage Occurrence of Significant Wave Height and Direction for Winter Storms

January

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	10.52	20.52	33.26	6.22	4.00	2.89	7.93	14.67	100.00	
> 6.0										
5.5 – 6.0										
5.0 – 5.5										
4.5 – 5.0										
4.0 – 4.5					0.37				0.37	0.37
3.5 – 4.0	0.52	2.22		0.15	0.81	0.52	0.07	1.04	5.33	5.70
3.0 – 3.5	1.41	3.63	2.30	0.22			1.93	0.96	10.44	16.15
2.5 – 3.0		7.04	6.37	1.78			1.26	0.37	16.81	32.96
2.0 – 2.5	1.26	1.04	8.44	0.44	1.33	0.52	3.26	1.93	18.22	51.19
1.5 – 2.0	5.19	4.44	3.41	0.74			0.30	3.04	17.11	68.30
1.0 – 1.5	0.89	0.37	8.15	0.22			1.11	6.67	17.41	85.70
0.5 – 1.0	0.96	1.63	4.59	0.07				0.67	7.93	93.63
0.0 – 0.5	0.30	0.15		2.59	1.48	1.85			6.37	

Mean Wave Direction (°T From)

Figure 2-29 Percentage Occurrence of Significant Wave Height and Direction for Winter Storms – January

February

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	14.75	35.39	21.05	7.52	5.08	3.74	3.01	9.47	100.00	
5.5–6.0		0.57							0.57	0.57
5.0–5.5		0.77							0.77	1.34
4.5–5.0		0.73							0.73	2.07
4.0–4.5		0.69		0.04					0.73	2.80
3.5–4.0	0.61	0.93	1.71	1.02	0.49	0.08		0.73	5.57	8.37
3.0–3.5	1.87	3.74	2.89	0.53	0.85	0.16	0.65	2.44	13.12	21.50
2.5–3.0	3.13	2.89	1.26	1.38	1.83	0.28	0.20	2.44	13.41	34.90
2.0–2.5	3.21	8.21	2.32	1.34	1.30	0.65	0.81	1.22	19.06	53.96
1.5–2.0	2.19	5.40	1.71	1.58	0.41	2.52	1.34	2.48	17.64	71.60
1.0–1.5	3.45	6.46	6.22	0.85	0.16			0.16	17.31	88.91
0.5–1.0	0.28	4.23	4.51	0.49					9.51	98.42
0.0–0.5		0.77	0.45	0.28	0.04	0.04			1.58	

Mean Wave Direction (°T From)

Figure 2-30 Percentage Occurrence of Significant Wave Height and Direction for Winter Storms – February

March

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	4.55	32.03	31.34	7.03	3.86	1.79	4.44	14.98	100.00	
		0.81							0.81	0.81
5.5–6.0		0.40		0.58					0.98	1.79
5.0–5.5		0.86		0.35	0.40				1.61	3.40
4.5–5.0		0.69	0.63	0.12	0.35	0.12			1.90	5.30
4.0–4.5		0.81	1.15	0.35		0.58			2.88	8.18
3.5–4.0	1.27	0.75	1.96	1.15		0.23	0.06	0.69	6.11	14.29
3.0–3.5	0.17	4.09	2.25	1.44	0.12	0.23	0.92	0.69	9.91	24.19
2.5–3.0	0.17	2.88	3.74	0.52	1.38	0.17	0.58	2.71	12.15	36.35
2.0–2.5	0.46	4.03	8.01	1.32	0.40		1.15	6.85	22.24	58.58
1.5–2.0	0.52	3.86	4.49	0.46	0.58		1.04	3.40	14.34	72.93
1.0–1.5	1.50	5.59	2.48	0.75	0.63	0.46	0.69	0.63	12.73	85.66
0.5–1.0	0.46	6.74	6.62						13.82	99.48
0.0–0.5		0.52							0.52	

Mean Wave Direction (°T From)

Figure 2-31 Percentage Occurrence of Significant Wave Height and Direction for Winter Storms – March

June

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	1.04	4.15	4.50	51.90		33.91	3.81	0.69	100.00	
5.5–6.0										
5.0–5.5										
4.5–5.0										
4.0–4.5										
3.5–4.0			0.35	2.77					3.11	3.11
3.0–3.5			2.08	2.08					4.15	7.27
2.5–3.0		2.08	2.08	4.50			3.81		12.46	19.72
2.0–2.5	1.04	2.08		2.08		4.50		0.69	10.38	30.10
1.5–2.0				6.92		11.76			18.69	48.79
1.0–1.5				16.61		10.38			26.99	75.78
0.5–1.0				16.96		7.27			24.22	100.00
0.0–0.5										

Mean Wave Direction (°T From)

Figure 2-32 Percentage Occurrence of Significant Wave Height and Direction for Winter Storms – June

October

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	0.52	38.34	23.83	5.70	5.18	5.70	20.73		100.00	
5.5–6.0										
5.0–5.5										
4.5–5.0										
4.0–4.5										
3.5–4.0										
3.0–3.5			9.84	5.70	5.18	1.04			21.76	21.76
2.5–3.0			7.25			4.66	6.74		18.65	40.41
2.0–2.5		3.63	6.74				6.74		17.10	57.51
1.5–2.0		22.80					7.25		30.05	87.56
1.0–1.5		5.18							5.18	92.75
0.5–1.0		4.66							4.66	97.41
0.0–0.5	0.52	2.07							2.59	

Mean Wave Direction (°T From)

Figure 2-33 Percentage Occurrence of Significant Wave Height and Direction for Winter Storms – October

November

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	11.57	27.00	19.29	1.48	17.21	1.48	16.91	5.04	100.00	
> 6.0										
5.5 – 6.0										
5.0 – 5.5										
4.5 – 5.0										
4.0 – 4.5					2.97				2.97	2.97
3.5 – 4.0					2.08				2.08	5.04
3.0 – 3.5					1.19	1.48	1.19		3.86	8.90
2.5 – 3.0	0.30	0.59	2.37		1.48		10.39	1.48	16.62	25.52
2.0 – 2.5		0.30	4.15		1.48		4.15	1.48	11.57	37.09
1.5 – 2.0	0.30		1.78		2.97		1.19	2.08	8.31	45.40
1.0 – 1.5	6.82	16.62	8.90		3.56				35.91	81.31
0.5 – 1.0	4.15	6.82		1.48	1.48				13.95	95.25
0.0 – 0.5		2.67	2.08						4.75	

Mean Wave Direction (°T From)

Figure 2-34 Percentage Occurrence of Significant Wave Height and Direction for Winter Storms – November

December

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	22.93	16.71	16.97	7.51	7.51	10.10	7.77	10.49	100.00	
> 6.0										
5.5 – 6.0										
5.0 – 5.5										
4.5 – 5.0				0.52					0.52	0.52
4.0 – 4.5	1.68	4.27		1.55					7.51	8.03
3.5 – 4.0	1.30	2.72	0.91	3.24				0.78	8.94	16.97
3.0 – 3.5	2.72	1.17	1.42	1.68	3.37	0.78	0.13	1.30	12.56	29.53
2.5 – 3.0	5.18	0.52	1.55	0.26	1.04	1.68	0.39		10.62	40.16
2.0 – 2.5	4.15	1.04	2.20		1.17	2.59	4.92	6.61	22.67	62.82
1.5 – 2.0	6.09	3.37	4.27		0.65	3.11	1.30	0.39	19.17	81.99
1.0 – 1.5	0.65	2.33	4.27		0.78	1.94			9.97	91.97
0.5 – 1.0	1.17	1.30	2.33	0.26	0.52		1.04	1.42	8.03	100.00
0.0 – 0.5										

Mean Wave Direction (°T From)

Figure 2-35 Percentage Occurrence of Significant Wave Height and Direction for Winter Storms – December

2.2.11 Joint Frequency Distribution of Significant Wave Height and Zero Up-Crossing Period for Winter Storms

All-Year

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	0.0–0.5	0.5–1.0	1.0–1.5	1.5–2.0	2.0–2.5	2.5–3.0	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	8.0–8.5	8.5–9.0	Total %	Exceed %
Total							0.80	5.34	19.66	24.39	18.77	16.80	7.41	3.42	1.64	0.95	0.46	0.36	100.00	
6.0–6.5																0.20			0.20	0.20
5.5–6.0															0.34	0.10			0.43	0.63
5.0–5.5														0.20	0.28	0.18			0.66	1.29
4.5–5.0													0.06	0.46	0.17	0.08			0.77	2.06
4.0–4.5												0.03	0.88	0.91	0.15				1.98	4.03
3.5–4.0												2.44	2.70	0.31	0.15				5.60	9.64
3.0–3.5											1.44	6.82	2.16	0.43	0.31	0.04			11.21	20.85
2.5–3.0										0.39	7.28	4.34	0.78	0.22	0.13	0.29	0.17	0.08	13.70	34.55
2.0–2.5									0.03	9.51	5.86	1.86	0.59	0.78	0.04	0.06	0.29	0.28	19.31	53.85
1.5–2.0									4.85	9.81	1.49	0.45	0.08	0.10	0.07				16.84	70.69
1.0–1.5								1.44	9.96	2.56	2.05	0.28	0.07						16.36	87.06
0.5–1.0							0.36	3.25	3.94	1.91	0.66	0.57	0.08						10.77	97.83
0.0–0.5							0.43	0.64	0.88	0.21									2.17	

Figure 2-36 All Year Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period for Winter Storms

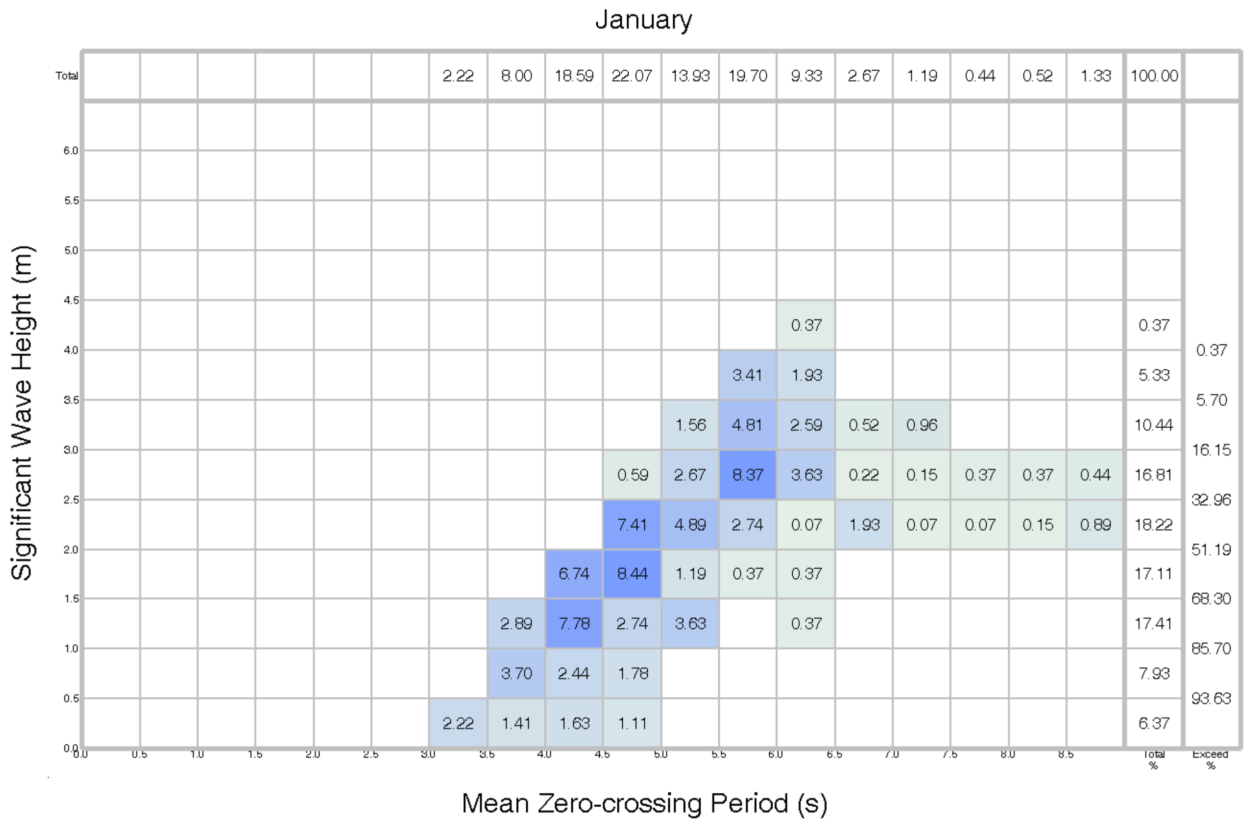

Figure 2-37 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period for Winter Storms – January

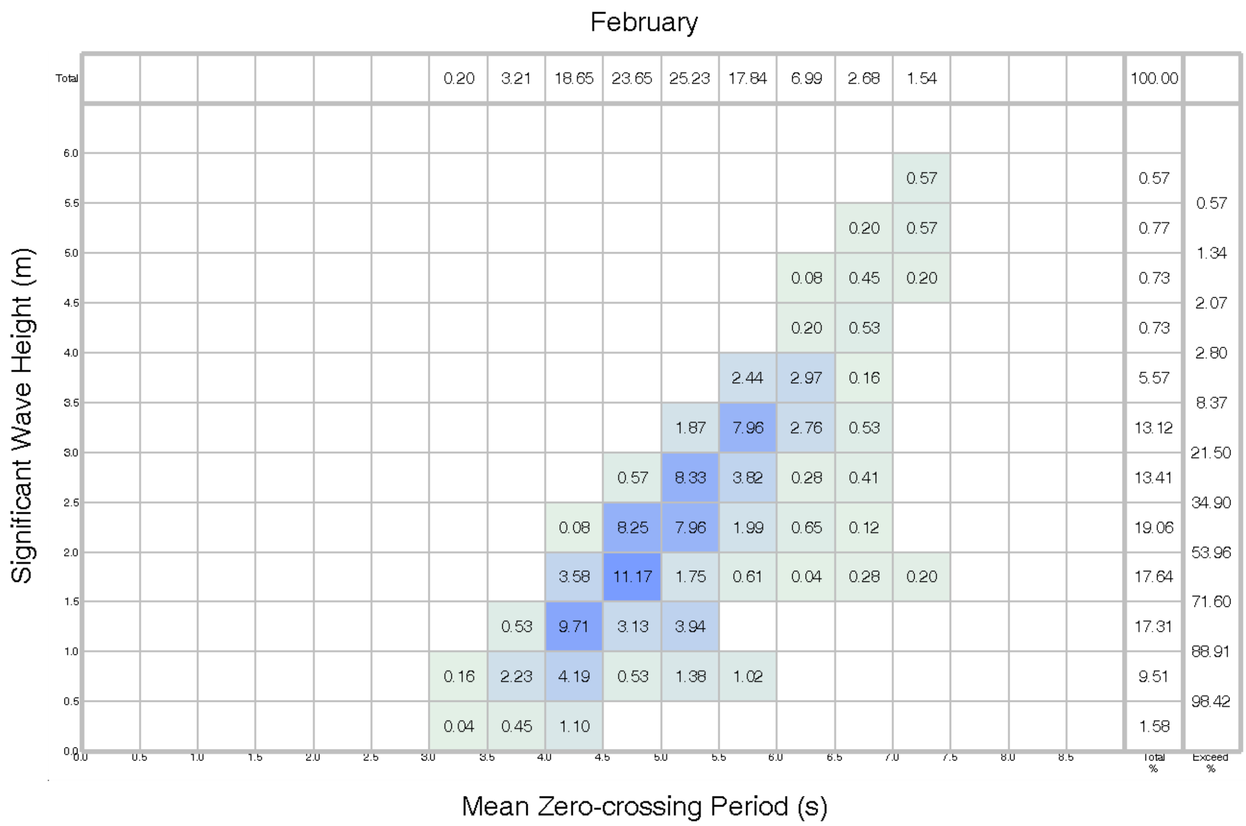

Figure 2-38 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period for Winter Storms – February

March

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	0.0–0.5	0.5–1.0	1.0–1.5	1.5–2.0	2.0–2.5	2.5–3.0	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	8.0–8.5	8.5–9.0	Total %	Exceed %
Total							0.29	3.23	19.01	22.70	15.73	17.74	6.28	5.88	3.63	3.57	1.50	0.46	100.00	
6.0–6.5																0.81			0.81	0.81
5.5–6.0															0.58	0.40			0.98	1.79
5.0–5.5														0.52	0.35	0.75			1.61	3.40
4.5–5.0													0.12	1.04	0.40	0.35			1.90	5.30
4.0–4.5													1.21	1.04	0.63				2.88	8.18
3.5–4.0												2.59	1.96	0.92	0.63				6.11	14.29
3.0–3.5											1.15	6.22	1.21	0.63	0.52	0.17			9.91	24.19
2.5–3.0											6.05	4.21		0.17	0.40	0.92	0.40		12.15	36.35
2.0–2.5										9.50	5.70	2.19	1.44	1.56	0.12	0.17	1.09	0.46	22.24	58.58
1.5–2.0									3.34	8.47	2.07	0.46							14.34	72.93
1.0–1.5								0.58	9.79	1.21		1.15							12.73	85.66
0.5–1.0							0.29	2.19	5.82	3.51	0.75	0.92	0.35						13.82	99.48
0.0–0.5								0.46	0.06										0.52	

Figure 2-39 Percentage Occurrence of Significant Wave Height and Peak Period Zero Up-Crossing Period for Winter Storms – March

June

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	0.0–0.5	0.5–1.0	1.0–1.5	1.5–2.0	2.0–2.5	2.5–3.0	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	8.0–8.5	8.5–9.0	Total %	Exceed %
Total								5.54	25.95	46.02	12.80	5.88	3.81						100.00	
6.0–6.5																				
5.5–6.0																				
5.0–5.5																				
4.5–5.0																				
4.0–4.5																				
3.5–4.0												1.04	2.08						3.11	3.11
3.0–3.5												2.42	1.73						4.15	7.27
2.5–3.0										0.69	9.34	2.42							12.46	19.72
2.0–2.5										6.92	3.46								10.38	30.10
1.5–2.0									10.03	8.65									18.69	48.79
1.0–1.5								1.73	8.65	16.61									26.99	75.78
0.5–1.0								3.81	7.27	13.15									24.22	100.00
0.0–0.5																				

Figure 2-40 Percentage Occurrence of Significant Wave Height and Peak Period Zero Up-Crossing Period for Winter Storms – June

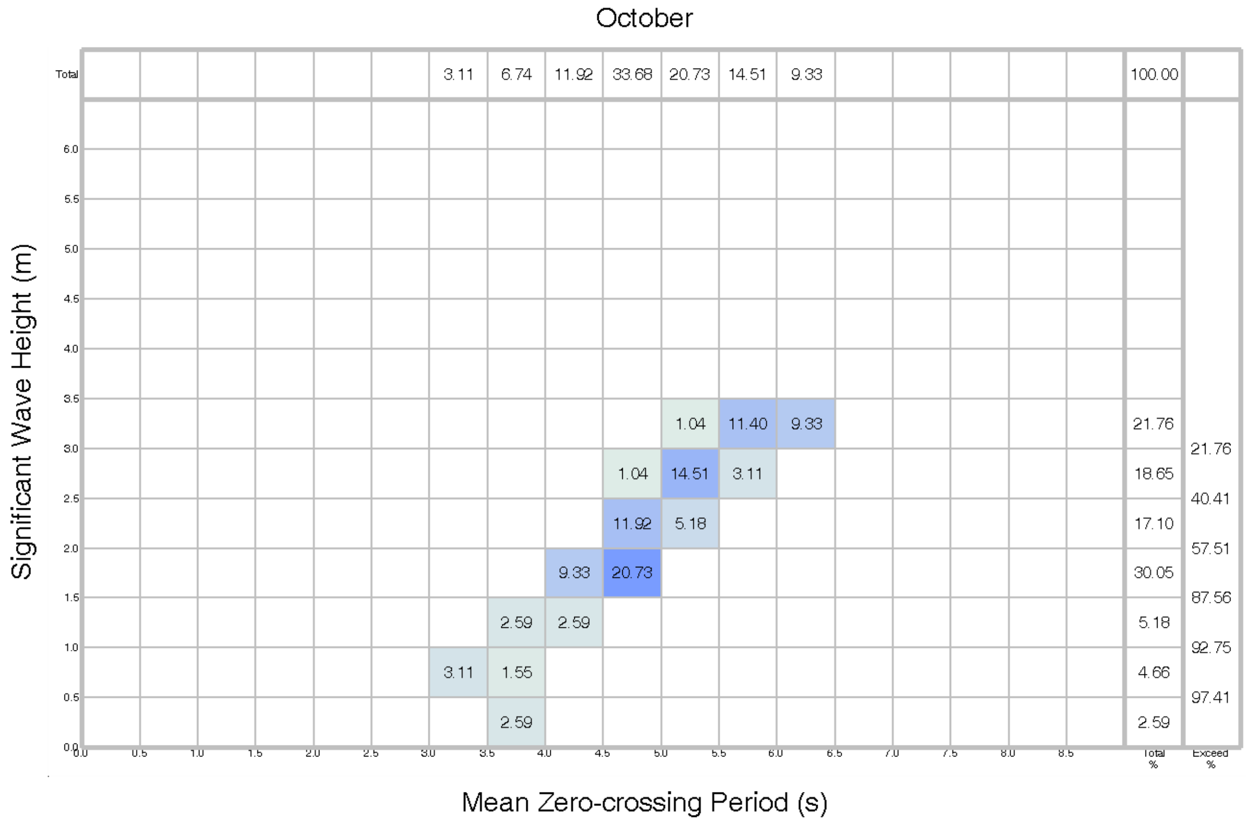

Figure 2-41 Percentage Occurrence of Significant Wave Height and Peak Period Zero Up-Crossing Period for Winter Storms – October

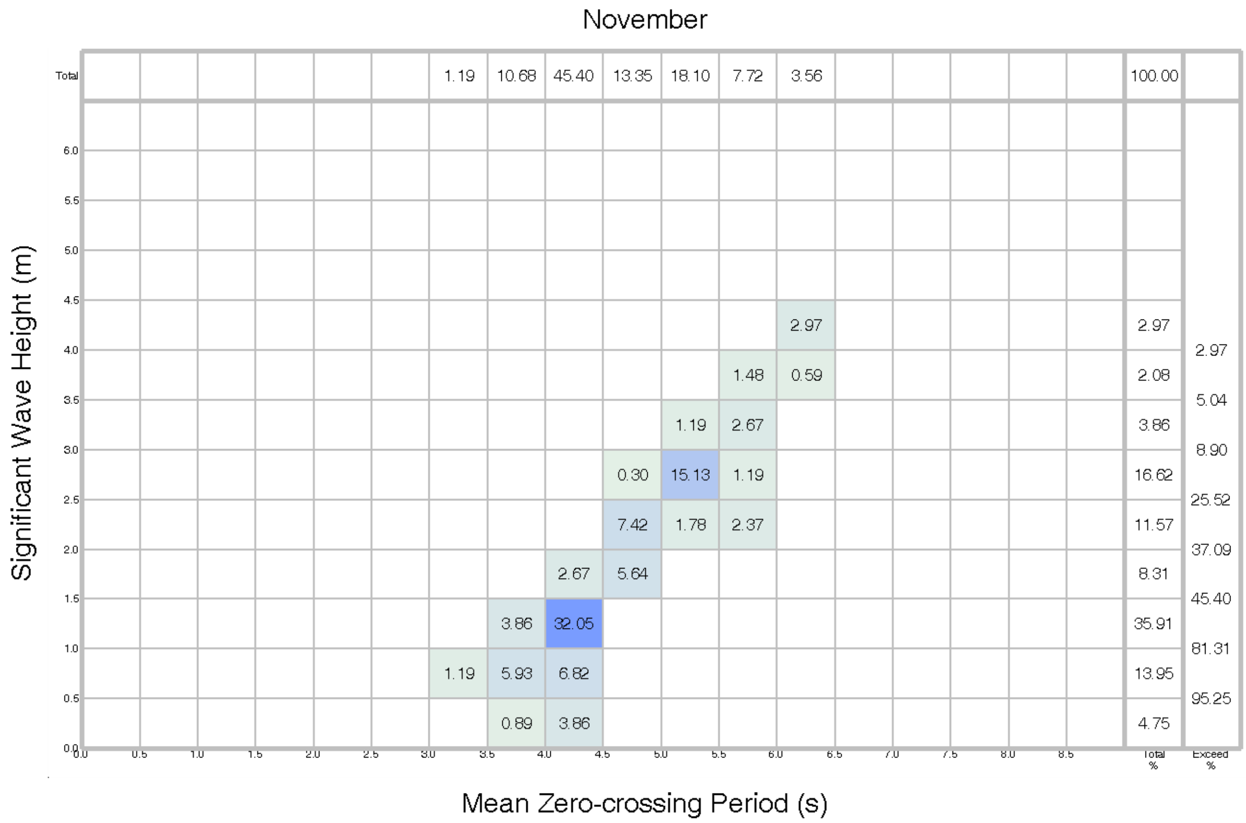

Figure 2-42 Percentage Occurrence of Significant Wave Height and Peak Period Zero Up-Crossing Period for Winter Storms – November

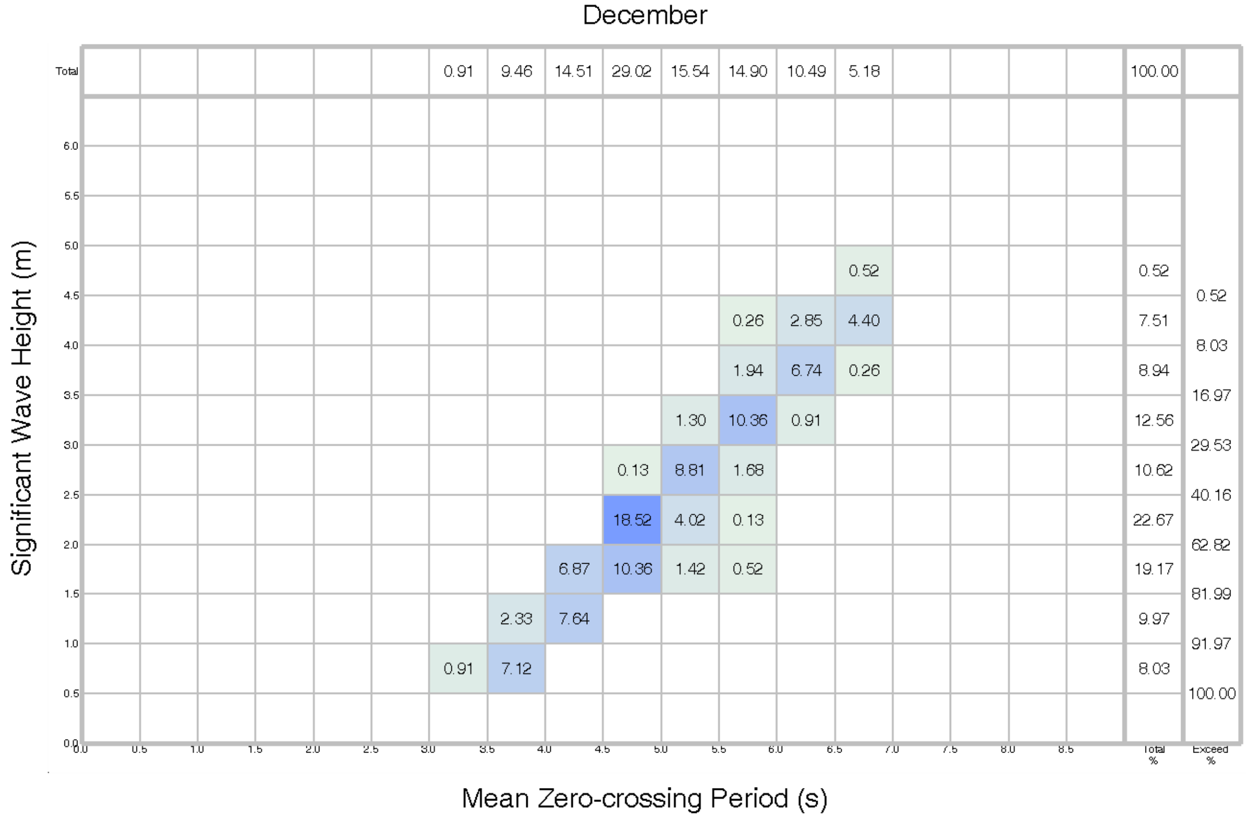

Figure 2-43 Percentage Occurrence of Significant Wave Height and Peak Period Zero Up-Crossing Period for Winter Storms – December

2.2.12 Joint Frequency Distribution of Significant Wave Height and Peak Period for Winter Storms

All-Year

Significant Wave Height (m) \ Peak Period (s)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	14–	Total %	Exceed %
Total				2.30	9.54	19.29	24.26	11.15	5.51	6.57	8.59	1.36	3.43	5.16	2.84	100.00	
6.0–											0.03	0.03	0.04	0.10		0.20	0.20
5.5–6.0										0.04	0.28	0.06			0.06	0.43	0.63
5.0–5.5									0.04	0.11	0.18		0.14		0.18	0.66	1.29
4.5–5.0								0.08	0.08	0.36			0.11		0.13	0.77	2.06
4.0–4.5								0.20	0.63	0.32	0.03	0.03	0.28	0.34	0.15	1.98	4.03
3.5–4.0							0.52	1.63	1.36	0.80	0.31	0.41	0.06	0.28	0.25	5.60	9.64
3.0–3.5							3.42	1.86	1.13	0.87	1.64	0.43	1.30	0.29	0.25	11.21	20.85
2.5–3.0						0.39	5.38	2.65	0.59	0.67	1.32	0.15	0.80	1.02	0.73	13.70	34.55
2.0–2.5					0.03	4.44	7.55	0.97	0.91	0.94	2.17	0.15	0.35	1.05	0.74	19.31	53.85
1.5–2.0					0.14	10.31	2.69	0.52	0.20	0.53	1.41	0.10	0.07	0.87		16.84	70.69
1.0–1.5				0.06	6.65	3.14	2.24	2.02	0.31	0.97	0.34			0.62	0.03	16.36	87.06
0.5–1.0				1.58	2.14	0.46	2.47	1.23	0.25	0.71	0.73		0.28	0.59	0.32	10.77	97.83
0.0–0.5				0.66	0.57	0.55				0.24	0.15					2.17	

Figure 2-44 All Year Percentage Occurrence of Significant Wave Height and Peak Period for Winter Storms

January

Significant Wave Height (m) \ Peak Period (s)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	14–	Total %	Exceed %
Total				3.56	9.85	19.85	19.70	12.52	4.89	9.33	6.67	1.93	4.44	3.70	3.56	100.00	
6.0–																	
5.5–6.0																	
5.0–5.5																	
4.5–5.0																	
4.0–4.5									0.37							0.37	0.37
3.5–4.0							0.81	2.52	0.67		0.22	1.04	0.07			5.33	5.70
3.0–3.5							3.78	0.67	0.37	0.52	1.70	0.89	2.52			10.44	16.15
2.5–3.0							2.59	2.30	2.07	2.07	1.85		1.85	1.93	2.15	16.81	32.96
2.0–2.5						1.85	7.19	1.63	1.41	1.41	1.56			1.78	1.41	18.22	51.19
1.5–2.0					0.15	11.63	2.07	1.48		0.81	0.96					17.11	68.30
1.0–1.5					7.93	1.41	2.81	3.78		1.11	0.37					17.41	85.70
0.5–1.0				0.59	1.26	2.07	0.44	0.15		3.41						7.93	93.63
0.0–0.5				2.96	0.52	2.89										6.37	

Figure 2-45 Percentage Occurrence of Significant Wave Height and Peak Period for Winter Storms – January

February

Significant Wave Height (m) \ Peak Period (s)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	14–15	Total %	Exceed %
Total				1.38	8.25	15.40	29.54	11.05	5.97	5.65	15.20	0.89	2.48	4.19		100.00	
6.0+																	
5.5–6.0											0.41	0.16				0.57	0.57
5.0–5.5										0.12	0.24		0.41			0.77	1.34
4.5–5.0										0.41			0.33			0.73	2.07
4.0–4.5									0.16	0.04			0.53			0.73	2.80
3.5–4.0							0.61	0.77	1.91	1.46	0.37			0.45		5.57	8.37
3.0–3.5							4.39	2.03	1.99	1.14	2.97		0.16	0.45		13.12	21.50
2.5–3.0						0.24	6.18	2.93	0.37	0.28	2.19	0.16	0.57	0.49		13.41	34.90
2.0–2.5					0.08	2.76	8.09	1.58	0.41	0.81	4.02	0.37	0.49	0.45		19.06	53.96
1.5–2.0					0.12	9.55	3.37			0.24	2.76	0.20		1.38		17.64	71.60
1.0–1.5					5.69	2.84	3.45	2.80	0.53	0.24	0.77			0.98		17.31	88.91
0.5–1.0				1.30	1.54		3.45	0.93	0.61	0.20	1.46					9.51	98.42
0.0–0.5				0.08	0.81					0.69						1.58	

Figure 2-46 Percentage Occurrence of Significant Wave Height and Peak Period for Winter Storms – February

March

Significant Wave Height (m) \ Peak Period (s)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	14–15	Total %	Exceed %
Total				1.27	7.78	19.70	18.09	11.41	6.45	6.11	5.13	0.40	5.30	9.45	8.93	100.00	
6.0+											0.12	0.12	0.17	0.40		0.81	0.81
5.5–6.0										0.17	0.58				0.23	0.98	1.79
5.0–5.5									0.17	0.29	0.40				0.75	1.61	3.40
4.5–5.0								0.35	0.35	0.69					0.52	1.90	5.30
4.0–4.5								0.63	0.81	0.69	0.12				0.63	2.88	8.18
3.5–4.0							0.63	1.96	1.15	0.75	0.40		0.17		1.04	6.11	14.29
3.0–3.5							1.84	1.73	0.92	0.06	0.92	0.17	2.82	0.40	1.04	9.91	24.19
2.5–3.0						0.58	3.51	2.76	0.12		0.86		0.98	2.02	1.32	12.15	36.35
2.0–2.5						6.97	5.99	0.29	1.61	1.38	1.73			2.30	1.96	22.24	58.58
1.5–2.0					0.17	8.24	2.53	0.98	0.81	0.75		0.12		0.75		14.34	72.93
1.0–1.5					4.72	3.63	0.63	0.63	0.52	1.32				1.15	0.12	12.73	85.66
0.5–1.0				1.27	2.36	0.29	2.94	2.07					1.15	2.42	1.32	13.82	99.48
0.0–0.5					0.52											0.52	

Figure 2-47 Percentage Occurrence of Significant Wave Height and Peak Period for Winter Storms – March

June

Significant Wave Height (m) \ Peak Period (s)	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	Total %	Exceed %
Total	1.04	9.69	18.69	24.57	19.38	2.77	16.96	6.92	100.00	
3.5–4.0					0.35	2.77			3.11	3.11
3.0–3.5					2.08		2.08		4.15	7.27
2.5–3.0			1.04	5.19	3.11		3.11		12.46	19.72
2.0–2.5			1.73	8.30			0.35		10.38	30.10
1.5–2.0			13.49				2.77	2.42	18.69	48.79
1.0–1.5	0.69	7.27	2.42	3.46	4.50		8.65		26.99	75.78
0.5–1.0	0.35	2.42		7.61	9.34			4.50	24.22	100.00
0.0–0.5										

Figure 2-48 Percentage Occurrence of Significant Wave Height and Peak Period for Winter Storms – June

October

Significant Wave Height (m) \ Peak Period (s)	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	Total %	Exceed %
Total	6.74	4.66	16.06	49.22	8.81	5.70	6.22	2.59	100.00	
3.0–3.5				6.74	0.52	5.70	6.22	2.59	21.76	21.76
2.5–3.0				11.40	7.25				18.65	40.41
2.0–2.5			1.04	15.03	1.04				17.10	57.51
1.5–2.0			13.99	16.06					30.05	87.56
1.0–1.5		4.15	1.04						5.18	92.75
0.5–1.0	4.15	0.52							4.66	97.41
0.0–0.5	2.59								2.59	

Figure 2-49 Percentage Occurrence of Significant Wave Height and Peak Period for Winter Storms – October

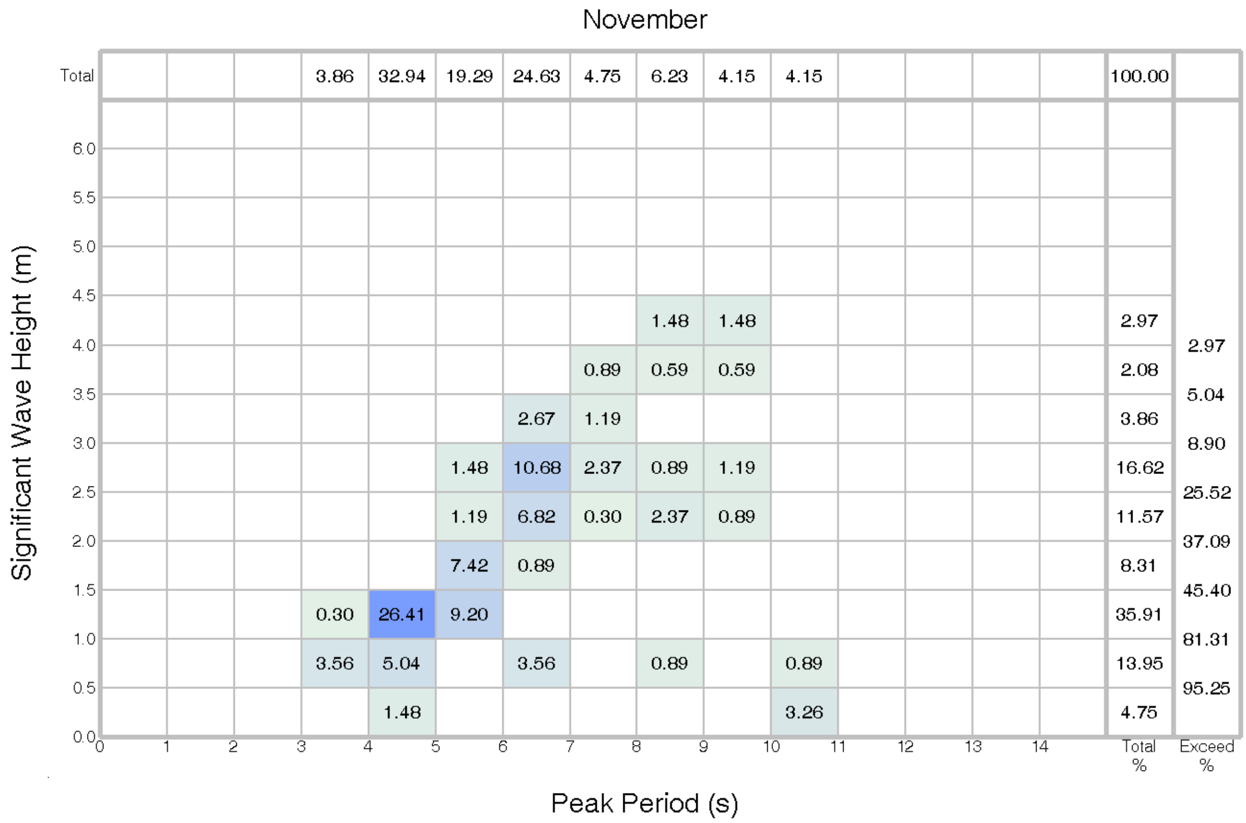

Figure 2-50 Percentage Occurrence of Significant Wave Height and Peak Period for Winter Storms – November

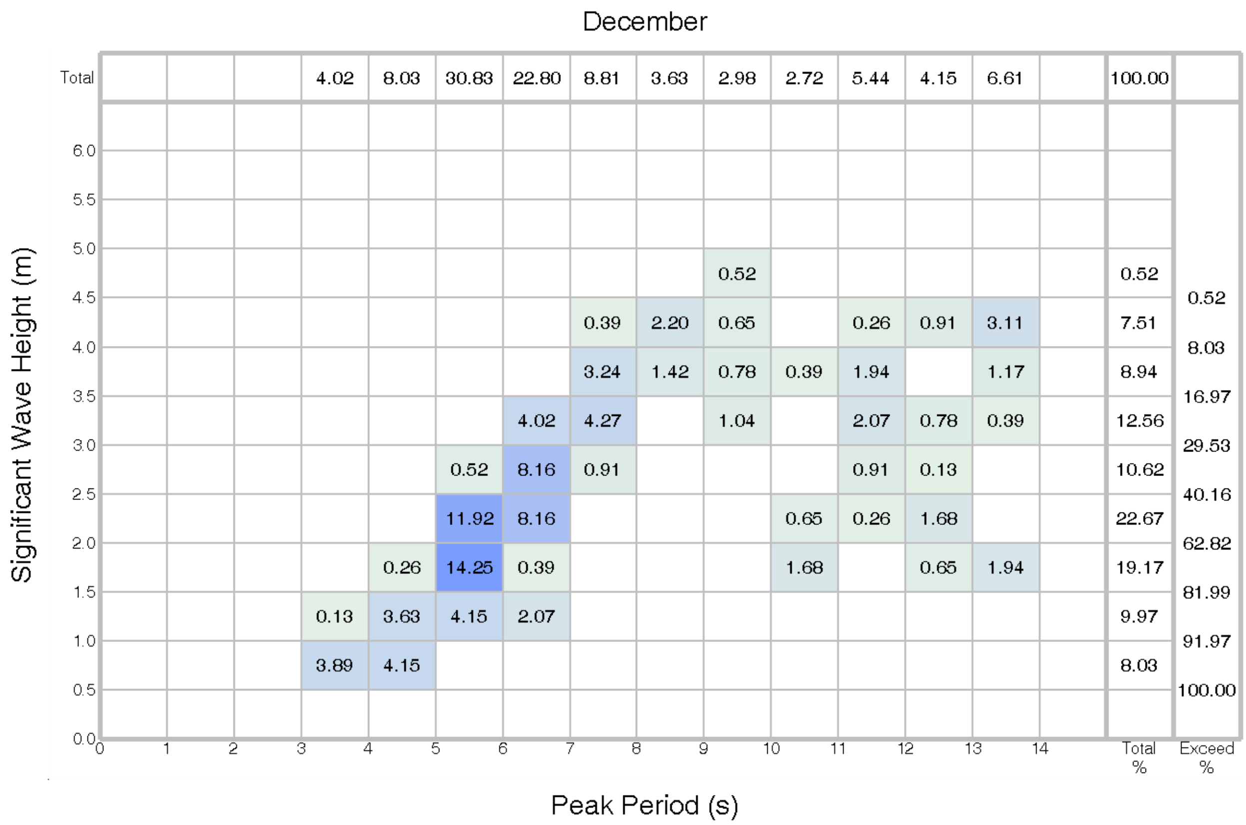

Figure 2-51 Percentage Occurrence of Significant Wave Height and Peak Period for Winter Storms – December

2.2.13 All Waves for Hurricanes

Extreme value analysis was carried out on a subset of peak wave heights from the Oceanweather hindcast data. The analysis only considered hurricane storm events from 1924 to 2005.

2.2.14 Omni-Directional Hurricane Extreme Values

Return Period	Hs	Tz	Tp	Hc	Hmax	THmax Low	THmax Mid	THmax High	Wave Length
	[m]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]
50-years	8.16	8.0	12.0	9.49	14.72	10.6	12.0	13.1	167.52
100-years	9.13	8.3	12.6	10.61	16.46	11.2	12.7	13.8	180.72
500-years	11.38	8.9	14.0	13.23	20.52	12.4	14.1	15.3	210.58
1000-years	12.35	9.1	14.5	14.35	22.26	12.9	14.6	15.9	223.23
10000-years	15.57	9.8	16.2	18.09	28.06	14.4	16.3	17.8	263.17

Table 2-25 Omni-Directional Hurricane Extreme Values for All Waves

2.2.15 Directional Hurricane Extreme Values

Return Period	Hs	Tz	Tp	Hc	Hmax	THmax Low	THmax Mid	THmax High
Direction [from]	**[m]**	**[s]**	**[s]**	**[m]**	**[m]**	**[s]**	**[s]**	**[s]**
50-Years	**8.16**	**8.0**	**12.0**	**9.49**	**14.72**	**10.6**	**12.0**	**13.1**
North	4.77	6.8	9.3	5.54	8.59	8.2	9.3	10.2
North-east	6.45	7.4	10.7	7.50	11.63	9.5	10.8	11.7
East	8.16	8.0	12.0	9.49	14.72	10.6	12.0	13.1
South-east	8.13	8.0	11.9	9.45	14.65	10.6	12.0	13.1
South	5.36	7.0	9.8	6.23	9.66	8.7	9.9	10.8
South-west	3.94	6.4	8.5	4.58	7.11	7.5	8.5	9.3
West	3.74	6.3	8.3	4.35	6.75	7.3	8.3	9.1
North-west	3.70	6.3	8.2	4.30	6.67	7.3	8.3	9.0
100-Years	**9.13**	**8.3**	**12.6**	**10.61**	**16.46**	**11.2**	**12.7**	**13.8**
North	5.33	7.0	9.8	6.20	9.61	8.7	9.8	10.7
North-east	7.21	7.7	11.3	8.38	13.01	10.0	11.3	12.4
East	9.13	8.3	12.6	10.61	16.46	11.2	12.7	13.8
South-east	9.09	8.3	12.6	10.57	16.39	11.2	12.6	13.8
South	5.99	7.3	10.3	6.97	10.81	9.2	10.4	11.3
South-west	4.41	6.6	9.0	5.12	7.95	7.9	9.0	9.8
West	4.19	6.5	8.7	4.87	7.55	7.7	8.8	9.6
North-west	4.14	6.5	8.7	4.81	7.46	7.7	8.7	9.5
500-Years	**11.38**	**8.9**	**14.0**	**13.23**	**20.52**	**12.4**	**14.1**	**15.3**
North	6.64	7.5	10.9	7.72	11.98	9.6	10.9	11.9
North-east	8.99	8.2	12.5	10.45	16.21	11.1	12.6	13.7
East	11.38	8.9	14.0	13.23	20.52	12.4	14.1	15.3
South-east	11.33	8.8	14.0	13.17	20.42	12.4	14.0	15.3
South	7.47	7.8	11.5	8.68	13.47	10.2	11.5	12.6
South-west	5.50	7.1	9.9	6.39	9.91	8.8	10.0	10.9
West	5.22	7.0	9.7	6.06	9.41	8.6	9.7	10.6
North-west	5.16	6.9	9.6	5.99	9.30	8.5	9.7	10.6
1000-Years	**12.35**	**9.1**	**14.5**	**14.35**	**22.26**	**12.9**	**14.6**	**15.9**
North	7.21	7.7	11.3	8.38	13.00	10.0	11.3	12.4
North-east	9.76	8.4	13.0	11.34	17.59	11.5	13.1	14.3

East	12.35	9.1	14.5	14.35	22.26	12.9	14.6	15.9
South-east	12.29	9.1	14.5	14.29	22.16	12.9	14.6	15.9
South	8.11	8.0	11.9	9.42	14.61	10.6	12.0	13.1
South-west	5.96	7.2	10.3	6.93	10.75	9.1	10.4	11.3
West	5.66	7.1	10.1	6.58	10.21	8.9	10.1	11.0
North-west	5.60	7.1	10.0	6.50	10.09	8.9	10.1	11.0
10000-Years	**15.57**	**9.8**	**16.2**	**18.09**	**28.06**	**14.4**	**16.3**	**17.8**
North	9.09	8.3	12.6	10.56	16.38	11.1	12.6	13.8
North-east	12.30	9.1	14.5	14.29	22.16	12.9	14.6	15.9
East	15.57	9.8	16.2	18.09	28.06	14.4	16.3	17.8
South-east	15.50	9.7	16.2	18.01	27.93	14.3	16.3	17.7
South	10.22	8.6	13.3	11.87	18.42	11.8	13.4	14.6
South-west	7.52	7.8	11.5	8.73	13.55	10.2	11.6	12.6
West	7.14	7.7	11.2	8.29	12.86	9.9	11.3	12.3
North-west	7.05	7.6	11.2	8.20	12.72	9.9	11.2	12.2

Table 2-26 Directional Hurricane Extreme Values for All Waves

2.2.16 All Wave Fitting Parameters for Hurricanes

The independent omni-directional wave cases are given in Table 2-25 and detailed descriptions of the calculations are given below.

Extreme value analysis was carried out on a subset of peak wave heights from the Oceanweather data. The analysis only considered hurricane storm events from 1924 to 2005.

The Peaks Over Threshold (POT) method consisted of declustering the data by selecting peak events to produce a set of independent and identically distributed observations. This method was then employed to derive the 50-, 100-, 500-, 1000-, and 10000-year criteria. The number of peaks exceeding a given level, divided by the number of years of record, gave the rate of exceedance which could then be used to find the expected number of occurrences in a specified period of time.

The Exponential (EXP), Fisher-Tippett 1 (FT1), Generalised Pareto (GP), Weibull 2 (W2) and Weibull 3 (W3) distributions were tested for goodness-of-fit to the data using the method of least squares (LS), maximum likelihood (MLE), and the method of moments (MoM). The best fits for 50-, 100-, 500-, 1000-, and 10000-year significant wave height are summarised in Table 2-27.

	Distribution	Fit	Threshold	# Peaks	Extreme Values				
					50-yr	100-yr	500-yr	1000-yr	10000-yr
Hs (m)	EXP	LS	1.00	367	7.98	8.91	11.06	11.99	15.07
	EXP	LS	1.50	201	8.39	9.41	11.79	12.81	16.20
	EXP	MoM	1.50	201	8.07	9.03	11.28	12.25	15.46
	EXP	MoM	2.20	101	8.25	9.27	11.63	12.65	16.03
	EXP	MLE	2.20	101	8.20	9.20	11.54	12.55	15.89
	FT1	LS	2.20	101	8.11	8.98	10.99	11.86	14.74
	AVERAGE				8.16	9.13	11.38	12.35	15.57

Table 2-27 Extreme Omni-directional All Wave Fitting Parameters for Hurricanes

2.2.17 Wave Height and Length for Hurricanes for Site 1 and 2

Wavelength is calculated using the omni-directional hurricane extreme values found in Table 2-13 and Table 2-25 with the associated depths for each site.

Extreme Wave Criteria at Site 1		Return Period					
		1-year	50-year	100-year	500-year	1000-year	10000-year
Significant Wave Height (m)		5.34	8.16	9.13	11.38	12.35	15.57
Peak Period (s)		9.9	11.96	12.61	13.99	14.54	16.21
Wave Length (m)	Total Water Depth 24.7m	130.59	171.08	184.46	214.56	227.28	268.26

Table 2-28 Extreme Wave and Associated Wave Length for Hurricanes at Site 1

Extreme Wave Criteria at Site 2		Return Period					
		1-year	50-year	100-year	500-year	1000-year	10000-year
Significant Wave Height (m)		5.34	8.16	9.13	11.38	12.35	15.57
Peak Period (s)		9.9	11.96	12.61	13.99	14.54	16.21
Wave Length (m)	Total Water Depth 25.4m	131.60	172.51	185.97	216.17	228.92	270.14

Table 2-29 Extreme Wave and Associated Wave Length for Hurricanes at Site 2

2.2.18 Wave Orbital Velocity at 1m Above Seabed for Hurricanes for Site 1 and 2

Wave orbital velocity at 1 m above seabed is calculated using the omni-directional hurricane extreme values found in Table 2-13 and Table 2-25 with the associated depths for each site. Table 2-31 and Table 2-33 show wave orbital velocity using Hmax and Tp associated with Hmax (THmax high). We are unable to compute wave orbital velocity for the 500-, 1000,- and 10000 year event because the wave is a breaking wave.

Extreme Wave Criteria at Site 1		Return Period					
		1-year	50-year	100-year	500-year	1000-year	10000-year
Significant Wave Height (m)		5.34	8.16	9.13	11.38	12.35	15.57
Peak Period (s)		9.9	11.96	12.61	13.99	14.54	16.21
Wave Orbital Velocity (m/s) at 1m above seabed	Total Water Depth 24.7m	1.12	2.02	2.35	3.07	3.36	4.12

Table 2-30 Extreme Wave and Associated Wave Orbital Velocity at 1m Above Seabed for Hurricanes at Site 1

Extreme Wave Criteria at Site 1		Return Period		
		1-year	50-year	100-year
Hmax (m)		10.01	14.71	16.46
Peak Period Associated with Hmax (s)		10.9	13.1	13.8
Wave Orbital Velocity (m/s) at 1m above seabed	Total Water Depth 24.7m	2.26	3.53	3.76

Table 2-31 Extreme Hmax and Associated Wave Orbital Velocity at 1m Above Seabed for Hurricanes at Site 1

Extreme Wave Criteria at Site 2		Return Period					
		1-year	50-year	100-year	500-year	1000-year	10000-year
Significant Wave Height (m)		5.34	8.16	9.13	11.38	12.35	15.57
Peak Period (s)		9.9	11.96	12.61	13.99	14.54	16.21
Wave Orbital Velocity (m/s) at 1m above seabed	Total Water Depth 25.4m	1.09	1.98	2.30	3.01	3.30	4.10

Table 2-32 Extreme Wave and Associated Wave Orbital Velocity at 1m Above Seabed for Hurricanes at Site 2

Extreme Wave Criteria at Site 2		Return Period		
		1-year	50-year	100-year
Hmax (m)		10.01	14.71	16.46
Peak Period Associated with Hmax (s)		10.9	13.1	13.8
Wave Orbital Velocity (m/s) at 1m above seabed	Total Water Depth 25.4m	2.22	3.49	3.78

Table 2-33 Extreme Hmax and Associated Wave Orbital Velocity at 1m Above Seabed for Hurricanes at Site 2

2.2.19 Fatigue Waves for Hurricanes

Extreme all-year omni-directonal and directional fatigue individual wave heights and periods for hurricanes are provided in the attached Excel spreadsheet “Virgina_Extreme_Fatigue_Hurricane.” Directional scatter table of individual fatigue wave heights and periods scaled to an interval of 20 years at 45 degree intervals for hurricanes are provided in the Excel spreadsheets “Virginia_Fatigue_20years_Hurricane.” Directional tables of mid height, median period, and 15 and 85 percentile period limits for fatigue waves at 45 degree intervals for hurricanes are provided in the Excel spreadsheets “Virginia_Fatigue_Tables_Hurricane.”

2.2.20 Joint Frequency Distribution of Significant Wave Height and Direction for Hurricanes

All-Year

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	2.16	8.60	30.48	36.71	10.40	6.27	3.96	1.43	100.00	
> 8.5			<0.01	<0.01					0.02	0.02
8.0 – 8.5			0.03	<0.01					0.03	0.05
7.5 – 8.0			0.05	<0.01					0.06	0.10
7.0 – 7.5		<0.01	0.03	0.02					0.06	0.16
6.5 – 7.0		<0.01	0.07	0.03					0.11	0.27
6.0 – 6.5		<0.01	0.08	0.04					0.12	0.39
5.5 – 6.0		0.02	0.10	0.03	<0.01				0.16	0.55
5.0 – 5.5	<0.01	0.03	0.20	0.06	0.02				0.31	0.86
4.5 – 5.0	0.02	0.29	0.24	0.06	0.02				0.63	1.49
4.0 – 4.5	0.07	0.18	0.44	0.10	0.04	<0.01	<0.01	<0.01	0.85	2.34
3.5 – 4.0	0.02	0.49	0.79	0.11	0.06	0.01	<0.01	0.01	1.50	3.84
3.0 – 3.5	0.06	0.89	1.63	0.20	0.06	0.06	0.02	0.04	2.96	6.80
2.5 – 3.0	0.22	0.95	2.40	0.91	0.33	0.08	0.13	0.06	5.09	11.89
2.0 – 2.5	0.14	1.39	4.12	1.40	0.39	0.15	0.12	0.21	7.92	19.81
1.5 – 2.0	0.71	1.21	6.77	7.47	1.88	0.72	0.20	0.38	19.33	39.14
1.0 – 1.5	0.73	1.97	8.21	15.71	4.49	3.61	2.80	0.59	38.11	77.25
0.5 – 1.0	0.17	1.13	5.21	10.09	3.09	1.63	0.69	0.14	22.14	99.40
0.0 – 0.5		0.02	0.10	0.47	<0.01				0.60	

Mean Wave Direction (°T From)

Figure 2-52 All Year Percentage Occurrence of Significant Wave Height and Direction for Hurricanes

May

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	5.47	11.39	43.28	28.70			8.20	2.96	100.00	
> 8.5										
8.0 – 8.5										
7.5 – 8.0										
7.0 – 7.5										
6.5 – 7.0										
6.0 – 6.5										
5.5 – 6.0										
5.0 – 5.5										
4.5 – 5.0										
4.0 – 4.5										
3.5 – 4.0		0.23	4.10						4.33	4.33
3.0 – 3.5		3.19	1.37						4.56	8.88
2.5 – 3.0		2.73	1.82	0.23					4.78	13.67
2.0 – 2.5		3.87		2.28					6.15	19.82
1.5 – 2.0	5.01	1.37	12.07	3.87					22.32	42.14
1.0 – 1.5	0.46		6.83	16.63			5.24	2.96	32.12	74.26
0.5 – 1.0			17.08	5.69			2.96		25.74	100.00
0.0 – 0.5										

Mean Wave Direction (°T From)

Figure 2-53 Percentage Occurrence of Significant Wave Height and Direction for Hurricanes – May

June

Significant Wave Height (m) vs. Mean Wave Direction (°T From)

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	2.43	10.62	17.04	7.96	32.52	3.54	23.67	2.21	100.00	
8.5										
8.0										
7.5										
7.0										
6.5										
6.0										
5.5										
5.0										
4.5										
4.0										
3.5		1.55	5.97						7.52	7.52
3.0		1.77	4.87						6.64	14.16
2.5		1.55	3.98						5.53	19.69
2.0	0.44	2.21	2.21	3.10					7.96	27.65
1.5	1.55	0.44		2.65	0.88		0.66	1.99	8.19	35.84
1.0	0.44	3.10		2.21	20.35	1.77	14.16	0.22	42.26	78.10
0.5					11.28	1.77	8.85		21.90	100.00
0.0										

Figure 2-54 Percentage Occurrence of Significant Wave Height and Direction for Hurricanes – June

July

Significant Wave Height (m) vs. Mean Wave Direction (°T From)

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	1.36	1.30	16.93	57.97	11.99	3.65	5.32	1.48	100.00	
8.5										
8.0										
7.5										
7.0										
6.5										
6.0										
5.5										
5.0				0.37					0.37	0.37
4.5				0.43	0.06				0.49	0.87
4.0				0.19	0.25				0.43	1.30
3.5				0.25	0.25				0.49	1.79
3.0				0.31	0.25				0.56	2.35
2.5			0.12	0.99	0.06	0.25			1.42	3.77
2.0		0.43	0.37	0.80		0.37			1.98	5.75
1.5	1.05	0.25	6.98	4.26	1.05	0.31			13.91	19.65
1.0	0.25		2.60	37.39	9.95	2.29	5.25	1.48	59.21	78.86
0.5	0.06	0.62	6.55	10.44	0.12	0.43	0.06		18.29	97.16
0.0			0.31	2.53					2.84	

Figure 2-55 Percentage Occurrence of Significant Wave Height and Direction for Hurricanes – July

August

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	0.10	5.95	18.84	49.10	13.08	8.99	3.72	0.23	100.00	
8.5			0.04	0.02					0.06	0.06
8.0			0.07	0.01					0.09	0.15
7.5			0.11	0.01					0.12	0.27
7.0			0.05	0.02					0.07	0.34
6.5			0.06	0.05					0.11	0.45
6.0			0.07	0.05					0.12	0.57
5.5			0.07	0.02	0.02				0.12	0.69
5.0			0.27	0.02	0.06				0.35	1.05
4.5		0.58	0.30	0.01	0.06				0.96	2.01
4.0		0.16	0.41	0.05	0.07				0.69	2.70
3.5		0.40	1.25	0.10	0.09				1.84	4.54
3.0	0.04	0.97	1.18	0.30	0.09			0.04	2.62	7.16
2.5		0.71	1.85	1.40	0.58	0.13	0.05	0.07	4.80	11.96
2.0		0.91	3.14	2.03	0.49	0.32	0.16		7.05	19.02
1.5	0.06	0.52	3.02	10.60	1.85	1.45	0.43	0.04	17.97	36.99
1.0		1.40	2.64	17.17	4.12	5.14	2.36	0.09	32.92	69.91
0.5		0.28	4.28	15.85	5.62	1.95	0.72		28.69	98.60
0.0				1.36	0.04				1.40	

Mean Wave Direction (°T From)

Figure 2-56 Percentage Occurrence of Significant Wave Height and Direction for Hurricanes – August

September

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	2.15	10.54	35.98	34.58	8.26	4.49	2.64	1.37	100.00	
8.5										
8.0			0.02						0.02	0.02
7.5			0.05						0.05	0.07
7.0		<0.01	0.04						0.05	0.12
6.5		0.02	0.11						0.12	0.24
6.0		0.02	0.12	0.02					0.16	0.41
5.5		0.04	0.16	0.04					0.24	0.64
5.0	0.01	0.06	0.26	0.04	<0.01				0.38	1.02
4.5	0.04	0.29	0.33	0.05	0.01				0.72	1.74
4.0	0.15	0.26	0.67	0.14	0.01	0.01	<0.01	<0.01	1.26	3.00
3.5	0.05	0.65	0.59	0.12		0.02	0.02	0.02	1.48	4.48
3.0	0.08	0.86	1.56	0.16	0.03	0.04	0.02	0.06	2.81	7.29
2.5	0.24	1.18	2.84	0.78	0.32	0.04	0.15	0.06	5.62	12.91
2.0	0.18	1.66	5.47	0.97	0.36	0.06	0.14	0.19	9.02	21.93
1.5	0.60	1.56	7.31	7.53	2.07	0.55	0.11	0.48	20.20	42.14
1.0	0.72	2.58	10.56	15.17	3.16	2.92	2.06	0.55	37.73	79.86
0.5	0.07	1.36	5.76	9.57	2.28	0.84	0.14		20.02	99.88
0.0			0.12						0.12	

Mean Wave Direction (°T From)

Figure 2-57 Percentage Occurrence of Significant Wave Height and Direction for Hurricanes – September

October

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	4.52	9.43	35.28	22.46	9.97	9.71	6.35	2.29	100.00	
8.0–8.5										
7.5–8.0										
7.0–7.5				0.08					0.08	0.08
6.5–7.0				0.12					0.12	0.20
6.0–6.5				0.08					0.08	0.28
5.5–6.0				0.06					0.06	0.34
5.0–5.5				0.06					0.06	0.40
4.5–5.0				0.04					0.04	0.44
4.0–4.5		0.08		0.08					0.16	0.60
3.5–4.0		0.24	0.22	0.10	0.14	0.02			0.72	1.31
3.0–3.5	0.06	0.96	3.02	0.08	0.06	0.22	0.04		4.44	5.75
2.5–3.0	0.64	0.80	2.23	0.58	0.14	0.08	0.28	0.06	4.80	10.55
2.0–2.5	0.30	1.45	2.92	1.59	0.54	0.16	0.06	0.76	7.78	18.32
1.5–2.0	1.53	1.65	11.14	4.52	1.87	0.42	0.18	0.54	21.85	40.17
1.0–1.5	1.55	1.85	11.12	10.62	4.85	4.54	4.08	0.76	39.38	79.55
0.5–1.0	0.44	2.25	4.48	4.46	2.37	4.28	1.71	0.18	20.16	99.70
0.0–0.5		0.16	0.14						0.30	

Mean Wave Direction (°T From)

Figure 2-58 Percentage Occurrence of Significant Wave Height and Direction for Hurricanes – October

November

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total			84.32	1.69	13.56			0.42	100.00	
8.0–8.5										
7.5–8.0										
7.0–7.5										
6.5–7.0										
6.0–6.5										
5.5–6.0										
5.0–5.5										
4.5–5.0										
4.0–4.5										
3.5–4.0										
3.0–3.5										
2.5–3.0			11.02						11.02	11.02
2.0–2.5			11.44						11.44	22.46
1.5–2.0			16.53						16.53	38.98
1.0–1.5			45.34	1.69	13.56				60.59	99.58
0.5–1.0								0.42	0.42	100.00
0.0–0.5										

Mean Wave Direction (°T From)

Figure 2-59 Percentage Occurrence of Significant Wave Height and Direction for Hurricanes – November

December

Significant Wave Height (m)	N	NE	E	SE	S	SW	W	NW	Total %	Exceed %
Total	25.31	0.83	1.66	13.69	34.02			24.48	100.00	
8.5										
8.0 – 8.5										
7.5 – 8.0										
7.0 – 7.5										
6.5 – 7.0										
6.0 – 6.5										
5.5 – 6.0										
5.0 – 5.5										
4.5 – 5.0										
4.0 – 4.5										
3.5 – 4.0										
3.0 – 3.5				2.90					2.90	2.90
2.5 – 3.0				3.73					3.73	6.64
2.0 – 2.5		0.41	1.66	4.56					6.64	13.28
1.5 – 2.0	1.66	0.41		2.49	3.32			2.07	9.96	23.24
1.0 – 1.5	14.52				30.71			8.30	53.53	76.76
0.5 – 1.0	9.13							14.11	23.24	100.00
0.0 – 0.5										

Mean Wave Direction (°T From)

Figure 2-60 Percentage Occurrence of Significant Wave Height and Direction for Hurricanes – December

2.2.21 Joint Frequency Distribution of Significant Wave Height and Zero Up-Crossing Period for Hurricanes

All-Year

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	0.0–0.5	0.5–1.0	1.0–1.5	1.5–2.0	2.0–2.5	2.5–3.0	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	8.0–8.5	Total %	Exceed %
Total							0.15	8.47	20.97	28.27	19.54	13.45	5.05	2.28	1.11	0.63	0.08	100.00	
8.5–9.0																	0.02	0.02	0.02
8.0–8.5																	0.03	0.03	0.05
7.5–8.0																0.02	0.03	0.06	0.10
7.0–7.5																0.05	<0.01	0.06	0.16
6.5–7.0															0.02	0.09		0.11	0.27
6.0–6.5															0.08	0.05		0.12	0.39
5.5–6.0														0.01	0.12	0.02		0.16	0.55
5.0–5.5													<0.01	0.16	0.14			0.31	0.86
4.5–5.0													0.05	0.51	0.07			0.63	1.49
4.0–4.5												0.02	0.48	0.34	0.02			0.85	2.34
3.5–4.0												0.28	1.11	0.10	0.01			1.50	3.84
3.0–3.5											0.10	2.04	0.77	0.04	0.01			2.96	6.80
2.5–3.0										0.03	1.98	2.80	0.20	0.04	0.02	0.01		5.09	11.89
2.0–2.5									0.02	1.44	4.70	1.42	0.10	0.12	0.05	0.06		7.92	19.81
1.5–2.0								0.02	1.46	10.72	4.73	1.75	0.38	0.19	0.05	0.02		19.33	39.14
1.0–1.5							<0.01	3.99	12.92	11.20	4.46	2.66	1.68	0.69	0.41	0.09		38.11	77.25
0.5–1.0							0.15	4.46	6.44	4.65	3.41	2.37	0.28	0.08	0.10	0.21	<0.01	22.14	99.40
0.0–0.5								<0.01	0.13	0.21	0.15	0.11						0.60	

Figure 2-61 All Year Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period for Hurricanes

May

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	0.0–0.5	0.5–1.0	1.0–1.5	1.5–2.0	2.0–2.5	2.5–3.0	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	8.0–8.5	Total %	Exceed %
Total								5.24	14.35	35.54	18.45	21.18	5.24					100.00	
8.5–9.0																			
8.0–8.5																			
7.5–8.0																			
7.0–7.5																			
6.5–7.0																			
6.0–6.5																			
5.5–6.0																			
5.0–5.5																			
4.5–5.0																			
4.0–4.5																			
3.5–4.0												0.23	4.10					4.33	4.33
3.0–3.5												3.42	1.14					4.56	8.88
2.5–3.0											1.59	3.19						4.78	13.67
2.0–2.5											6.15							6.15	19.82
1.5–2.0										21.87	0.46							22.32	42.14
1.0–1.5								2.28	11.62	11.85	6.38							32.12	74.26
0.5–1.0								2.96	2.73	1.82	3.87	14.35						25.74	100.00
0.0–0.5																			

Figure 2-62 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period for Hurricanes – May

June

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	Total %	Exceed %
Total	4.65	23.89	31.42	14.82	7.74	7.96	9.51				100.00	
3.5–4.0							7.52				7.52	7.52
3.0–3.5						4.65	1.99				6.64	14.16
2.5–3.0					2.21	3.32					5.53	19.69
2.0–2.5				2.43	5.53						7.96	27.65
1.5–2.0			2.65	5.53							8.19	35.84
1.0–1.5		13.50	21.90	6.86							42.26	78.10
0.5–1.0	4.65	10.40	6.86								21.90	100.00

Figure 2-63 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period for Hurricanes – June

July

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	Total %	Exceed %
Total		6.61	31.15	41.35	9.33	5.50	2.72	2.16	0.56	0.62	100.00	
5.0–5.5								0.37			0.37	0.37
4.5–5.0							0.06	0.43			0.49	0.87
4.0–4.5							0.43				0.43	1.30
3.5–4.0						0.31	0.19				0.49	1.79
3.0–3.5						0.56					0.56	2.35
2.5–3.0					1.30	0.12					1.42	3.77
2.0–2.5				1.17	0.80						1.98	5.75
1.5–2.0			0.80	8.47	0.56	1.92	0.74	0.68	0.25	0.49	13.91	19.65
1.0–1.5		2.35	22.62	23.42	5.81	2.60	1.30	0.68	0.31	0.12	59.21	78.86
0.5–1.0		4.26	6.49	7.54							18.29	97.16
0.0–0.5			1.24	0.74	0.87						2.84	

Figure 2-64 Percentage Occurrence of Significant Wave Height and Peak Period Zero Up-Crossing Period for Hurricanes – July

August

Significant Wave Height (m) vs. Mean Zero-crossing Period (s)

Hs (m) \ Tz (s)	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	8.0–8.5	Total %	Exceed %
Total	9.02	22.78	30.03	16.41	12.26	5.42	2.38	0.94	0.52	0.24	100.00	
8.5–9.0										0.06	0.06	0.06
8.0–8.5										0.09	0.09	0.15
7.5–8.0									0.04	0.09	0.12	0.27
7.0–7.5									0.06	0.01	0.07	0.34
6.5–7.0									0.11		0.11	0.45
6.0–6.5								0.06	0.06		0.12	0.57
5.5–6.0								0.12			0.12	0.69
5.0–5.5							0.23	0.12			0.35	1.05
4.5–5.0						0.02	0.94				0.96	2.01
4.0–4.5						0.41	0.28				0.69	2.70
3.5–4.0					0.32	1.35	0.17				1.84	4.54
3.0–3.5				0.11	1.23	1.25	0.02				2.62	7.16
2.5–3.0			0.07	1.69	2.34	0.69					4.80	11.96
2.0–2.5		0.02	1.02	3.79	2.22						7.05	19.02
1.5–2.0		1.54	10.27	3.75	1.79	0.38	0.21	0.04			17.97	36.99
1.0–1.5	3.97	12.06	11.96	1.33	1.43	0.93	0.40	0.58	0.26		32.92	69.91
0.5–1.0	5.04	9.04	6.27	5.31	2.51	0.38	0.12	0.01			28.69	98.60
0.0–0.5		0.12	0.43	0.43	0.43						1.40	

Figure 2-65 Percentage Occurrence of Significant Wave Height and Peak Period Zero Up-Crossing Period for Hurricanes – August

September

Significant Wave Height (m) vs. Mean Zero-crossing Period (s)

Hs (m) \ Tz (s)	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	8.0–8.5	Total %	Exceed %
Total	5.46	17.41	26.50	23.91	15.73	5.71	2.86	1.51	0.87	0.04	100.00	
8.5–9.0												
8.0–8.5										0.02	0.02	0.02
7.5–8.0									0.03	0.02	0.05	0.07
7.0–7.5									0.05		0.05	0.12
6.5–7.0								0.03	0.09		0.12	0.24
6.0–6.5								0.11	0.06		0.16	0.41
5.5–6.0							0.02	0.17	0.04		0.24	0.64
5.0–5.5						<0.01	0.17	0.21			0.38	1.02
4.5–5.0						0.09	0.48	0.15			0.72	1.74
4.0–4.5					0.03	0.67	0.52	0.04			1.26	3.00
3.5–4.0					0.24	1.11	0.10	0.02			1.48	4.48
3.0–3.5				0.12	2.10	0.51	0.06	0.02			2.81	7.29
2.5–3.0			0.02	2.18	3.24	0.03	0.08	0.05	0.02		5.62	12.91
2.0–2.5		0.01	1.27	5.65	1.42	0.20	0.25	0.09	0.12		9.02	21.93
1.5–2.0	0.01	1.28	9.94	6.16	2.09	0.46	0.21	0.06			20.20	42.14
1.0–1.5	3.33	10.20	10.72	6.20	3.75	2.27	0.87	0.37	0.03		37.73	79.86
0.5–1.0	2.12	5.90	4.45	3.60	2.86	0.37	0.10	0.19	0.42	<0.01	20.02	99.88
0.0–0.5		0.02	0.10								0.12	

Figure 2-66 Percentage Occurrence of Significant Wave Height and Peak Period Zero Up-Crossing Period for Hurricanes – September

October

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	Total %	Exceed %
Total	0.54	15.76	23.56	28.13	16.00	11.10	3.14	0.97	0.58	0.22	100.00	
8.0–8.5												
7.5–8.0												
7.0–7.5										0.08	0.08	0.08
6.5–7.0										0.12	0.12	0.20
6.0–6.5									0.06	0.02	0.08	0.28
5.5–6.0									0.06		0.06	0.34
5.0–5.5								0.02	0.04		0.06	0.40
4.5–5.0								0.04			0.04	0.44
4.0–4.5							0.10	0.06			0.16	0.60
3.5–4.0						0.40	0.30	0.02			0.72	1.31
3.0–3.5					0.10	3.38	0.96				4.44	5.75
2.5–3.0				0.04	2.09	2.65	0.02				4.80	10.55
2.0–2.5			0.06	2.81	3.96	0.96					7.78	18.32
1.5–2.0		0.06	2.11	14.27	4.22	1.01	0.16	0.02			21.85	40.17
1.0–1.5	0.02	5.75	16.43	8.12	4.26	1.95	1.61	0.82	0.42		39.38	79.55
0.5–1.0	0.52	9.93	4.80	2.79	1.37	0.76					20.16	99.70
0.0–0.5		0.02	0.16	0.12							0.30	

Figure 2-67 Percentage Occurrence of Significant Wave Height and Peak Period Zero Up-Crossing Period for Hurricanes – October

November

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	Total %	Exceed %
Total	0.42	42.37	32.63	15.68	8.90	100.00	
2.5–3.0				2.12	8.90	11.02	11.02
2.0–2.5			0.85	10.59		11.44	22.46
1.5–2.0			13.56	2.97		16.53	38.98
1.0–1.5		42.37	18.22			60.59	99.58
0.5–1.0	0.42					0.42	100.00

Figure 2-68 Percentage Occurrence of Significant Wave Height and Peak Period Zero Up-Crossing Period for Hurricanes – November

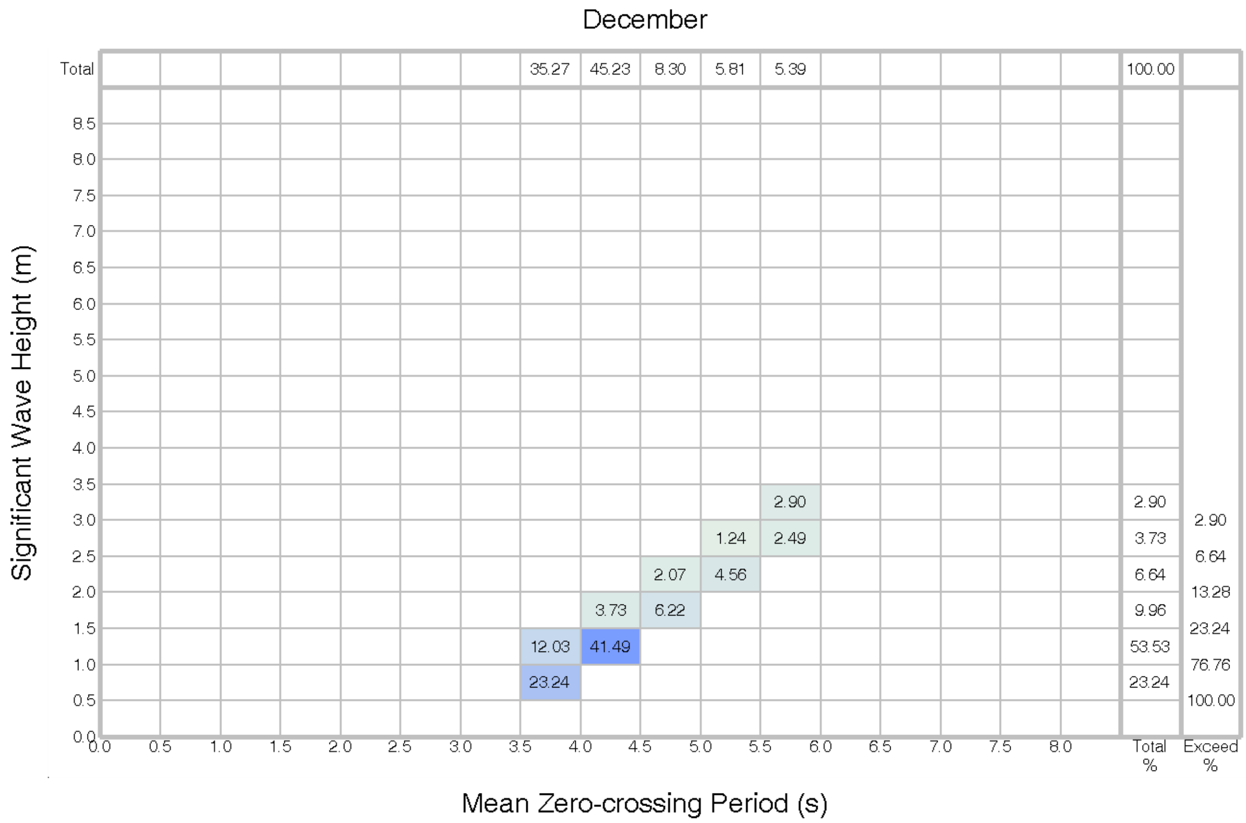

Figure 2-69 Percentage Occurrence of Significant Wave Height and Peak Period Zero Up-Crossing Period for Hurricanes – December

2.2.22 Joint Frequency Distribution of Significant Wave Height and Peak Period for Hurricanes

All-Year

Significant Wave Height (m) \ Peak Period (s)	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	Total %	Exceed %
Total				1.50	12.10	13.92	25.90	17.15	6.85	5.32	6.44	2.87	2.63	3.06	1.20	0.73	0.23	0.10	100.00	
8.5-9.0												0.02							0.02	0.02
8.0-8.5											0.02	0.02							0.03	0.05
7.5-8.0											0.03	0.02							0.06	0.10
7.0-7.5									<0.01	<0.01	0.02	0.02	<0.01						0.06	0.16
6.5-7.0									<0.01	<0.01	0.08	0.02							0.11	0.27
6.0-6.5									<0.01	0.02	0.08	0.02							0.12	0.39
5.5-6.0									<0.01	0.05	0.08	0.02							0.16	0.55
5.0-5.5								<0.01	0.02	0.17	0.09	<0.01	0.02						0.31	0.86
4.5-5.0							<0.01	0.02	0.07	0.23	0.19	0.06	0.04	<0.01	<0.01				0.63	1.49
4.0-4.5							0.02	0.07	0.34	0.12	0.08	0.16	0.05		0.01				0.85	2.34
3.5-4.0							0.03	0.20	0.57	0.16	0.16	0.27	0.10	0.03	<0.01				1.50	3.84
3.0-3.5						<0.01	0.18	1.15	0.66	0.12	0.21	0.23	0.21	0.11		0.09			2.96	6.80
2.5-3.0						0.05	0.95	2.20	0.66	0.30	0.28	0.22	0.09	0.18	0.12	0.01	0.02	<0.01	5.09	11.89
2.0-2.5					0.04	0.53	2.54	1.75	0.71	0.60	0.53	0.37	0.57	0.09	0.09	0.06	<0.01	0.03	7.92	19.81
1.5-2.0				0.02	0.34	3.39	6.95	2.50	0.99	0.84	1.48	1.01	0.79	0.61	0.08	0.16	0.13	0.04	19.33	39.14
1.0-1.5				0.28	8.68	6.27	9.73	4.30	1.92	1.36	1.99	0.32	0.43	1.70	0.80	0.29	0.03	0.02	38.11	77.25
0.5-1.0				1.20	3.00	3.69	5.50	4.80	0.75	1.09	1.12	0.10	0.33	0.33	0.07	0.12	0.05		22.14	99.40
0.0-0.5					0.03			0.16	0.14	0.26	<0.01								0.60	

Figure 2-70 All Year Percentage Occurrence of Significant Wave Height and Peak Period for Hurricanes

May

Significant Wave Height (m) \ Peak Period (s)	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	Total %	Exceed %
Total					5.69	16.40	19.36	32.35	5.01	3.87	11.62	5.47	0.23						100.00	
8.5-9.0																				
8.0-8.5																				
7.5-8.0																				
7.0-7.5																				
6.5-7.0																				
6.0-6.5																				
5.5-6.0																				
5.0-5.5																				
4.5-5.0																				
4.0-4.5																				
3.5-4.0								0.23	1.59			2.28	0.23						4.33	4.33
3.0-3.5								1.37				3.19							4.56	8.88
2.5-3.0							0.46	1.59			2.73								4.78	13.67
2.0-2.5							2.28				3.87								6.15	19.82
1.5-2.0						2.73	13.21			1.37	5.01								22.32	42.14
1.0-1.5					2.73	13.67	3.42	6.38	3.42	2.51									32.12	74.26
0.5-1.0					2.96			22.78											25.74	100.00
0.0-0.5																				

Figure 2-71 Percentage Occurrence of Significant Wave Height and Peak Period for Hurricanes – May

June

Significant Wave Height (m) \ Peak Period (s)	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	Total %	Exceed %
3.5–4.0						1.99	1.33	3.76	0.44	7.52	7.52
3.0–3.5					2.43	2.43		1.77		6.64	14.16
2.5–3.0				2.21	1.77	0.44	0.44	0.66		5.53	19.69
2.0–2.5		0.66	0.88	1.55	3.10	1.77				7.96	27.65
1.5–2.0			4.20	1.99	1.77	0.22				8.19	35.84
1.0–1.5		21.90	12.39	0.66	7.30					42.26	78.10
0.5–1.0	5.31	8.63	7.96							21.90	100.00
Total	5.31	31.19	25.44	6.42	16.37	6.86	1.77	6.19	0.44	100.00	

Figure 2-72 Percentage Occurrence of Significant Wave Height and Peak Period for Hurricanes – June

July

Significant Wave Height (m) \ Peak Period (s)	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	14–15	Total %	Exceed %
5.0–5.5							0.37						0.37	0.37
4.5–5.0						0.12	0.37						0.49	0.87
4.0–4.5						0.31	0.12						0.43	1.30
3.5–4.0					0.31	0.19							0.49	1.79
3.0–3.5				0.06	0.49								0.56	2.35
2.5–3.0				0.62	0.43	0.37							1.42	3.77
2.0–2.5			0.80	0.99	0.19								1.98	5.75
1.5–2.0		0.56	4.33	4.82	2.10			0.56	1.55				13.91	19.65
1.0–1.5		10.44	12.73	29.67	1.55		1.30	2.53	0.31		0.68		59.21	78.86
0.5–1.0	2.60	0.37	1.67	11.99	0.19	0.25					0.68	0.56	18.29	97.16
0.0–0.5						2.84							2.84	
Total	2.60	11.37	19.53	48.15	5.25	4.08	2.16	3.09	1.85		1.36	0.56	100.00	

Figure 2-73 Percentage Occurrence of Significant Wave Height and Peak Period for Hurricanes – July

August

Significant Wave Height (m) \ Peak Period (s)	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	Total %	Exceed %
Total				1.21	11.72	15.45	29.95	15.34	3.47	5.47	6.29	2.83	3.87	2.24	0.07	1.04	0.68	0.38	100.00	
8.5-9.0												0.06							0.06	0.06
8.0-8.5											0.04	0.05							0.09	0.15
7.5-8.0											0.09	0.04							0.12	0.27
7.0-7.5											0.04	0.04							0.07	0.34
6.5-7.0											0.07	0.04							0.11	0.45
6.0-6.5											0.10	0.02							0.12	0.57
5.5-6.0										0.05	0.07								0.12	0.69
5.0-5.5									0.02	0.27	0.06								0.35	1.05
4.5-5.0								0.01	0.05	0.35	0.49	0.06							0.96	2.01
4.0-4.5								0.04	0.29	0.26	0.10	0.01							0.69	2.70
3.5-4.0								0.27	0.50	0.18	0.06	0.65	0.18						1.84	4.54
3.0-3.5						0.01	0.11	0.97	0.24	0.07	0.21	0.37	0.35	0.17		0.11			2.62	7.16
2.5-3.0							1.13	2.08	0.33	0.18	0.58	0.22	0.12			0.05	0.07	0.02	4.80	11.96
2.0-2.5					0.04	0.35	2.36	1.40	0.22	0.50	0.80	0.06	0.94	0.06		0.15	0.04	0.13	7.05	19.02
1.5-2.0					0.34	3.85	8.05	1.01	0.40	0.58	1.06	0.51	0.88	0.58	0.05	0.23	0.27	0.15	17.97	36.99
1.0-1.5				0.24	8.86	6.06	9.20	1.89	1.07	0.56	1.72	0.33	0.87	1.43	0.02	0.50	0.11	0.07	32.92	69.91
0.5-1.0				0.96	2.49	5.18	9.09	7.26	0.34	1.46	0.80	0.38	0.54				0.19		28.69	98.60
0.0-0.5								0.40		1.00									1.40	

Figure 2-74 Percentage Occurrence of Significant Wave Height and Peak Period for Hurricanes – August

September

Significant Wave Height (m) \ Peak Period (s)	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	Total %	Exceed %
Total				0.63	8.67	12.02	23.38	20.85	8.27	6.50	7.20	2.68	2.46	4.45	1.91	0.86	0.12		100.00	
8.5-9.0																				
8.0-8.5											0.01	<0.01							0.02	0.02
7.5-8.0											0.02	0.02							0.05	0.07
7.0-7.5									<0.01	<0.01	<0.01	0.02	<0.01						0.05	0.12
6.5-7.0									<0.01	0.01	0.08	0.02							0.12	0.24
6.0-6.5									<0.01	0.02	0.09	0.04							0.16	0.41
5.5-6.0									<0.01	0.07	0.12	0.04							0.24	0.64
5.0-5.5								<0.01	0.04	0.14	0.14	0.02	0.03						0.38	1.02
4.5-5.0							<0.01	0.04	0.11	0.23	0.12	0.08	0.09	0.02	0.02				0.72	1.74
4.0-4.5							0.04	0.13	0.47	0.09	0.11	0.31	0.10		0.02				1.26	3.00
3.5-4.0							0.06	0.14	0.64	0.16	0.18	0.13	0.10	0.06	<0.01				1.48	4.48
3.0-3.5						<0.01	0.27	1.14	0.61	0.16	0.22	0.11	0.04	0.13		0.13			2.81	7.29
2.5-3.0						0.07	0.85	2.47	0.98	0.41	0.17	0.04	0.02	0.37	0.24				5.62	12.91
2.0-2.5					0.02	0.50	2.61	2.29	0.84	0.80	0.50	0.59	0.51	0.12	0.19	0.05			9.02	21.93
1.5-2.0				0.01	0.31	2.87	5.99	3.77	1.20	1.15	1.65	1.15	0.90	0.80	0.08	0.21	0.12		20.20	42.14
1.0-1.5				0.31	6.61	5.09	8.87	6.02	2.40	1.83	2.10	0.09	0.29	2.46	1.33	0.32			37.73	79.86
0.5-1.0				0.31	1.73	3.47	4.69	4.71	0.97	1.42	1.67		0.38	0.49	0.02	0.15			20.02	99.88
0.0-0.5								0.12											0.12	

Figure 2-75 Percentage Occurrence of Significant Wave Height and Peak Period for Hurricanes – September

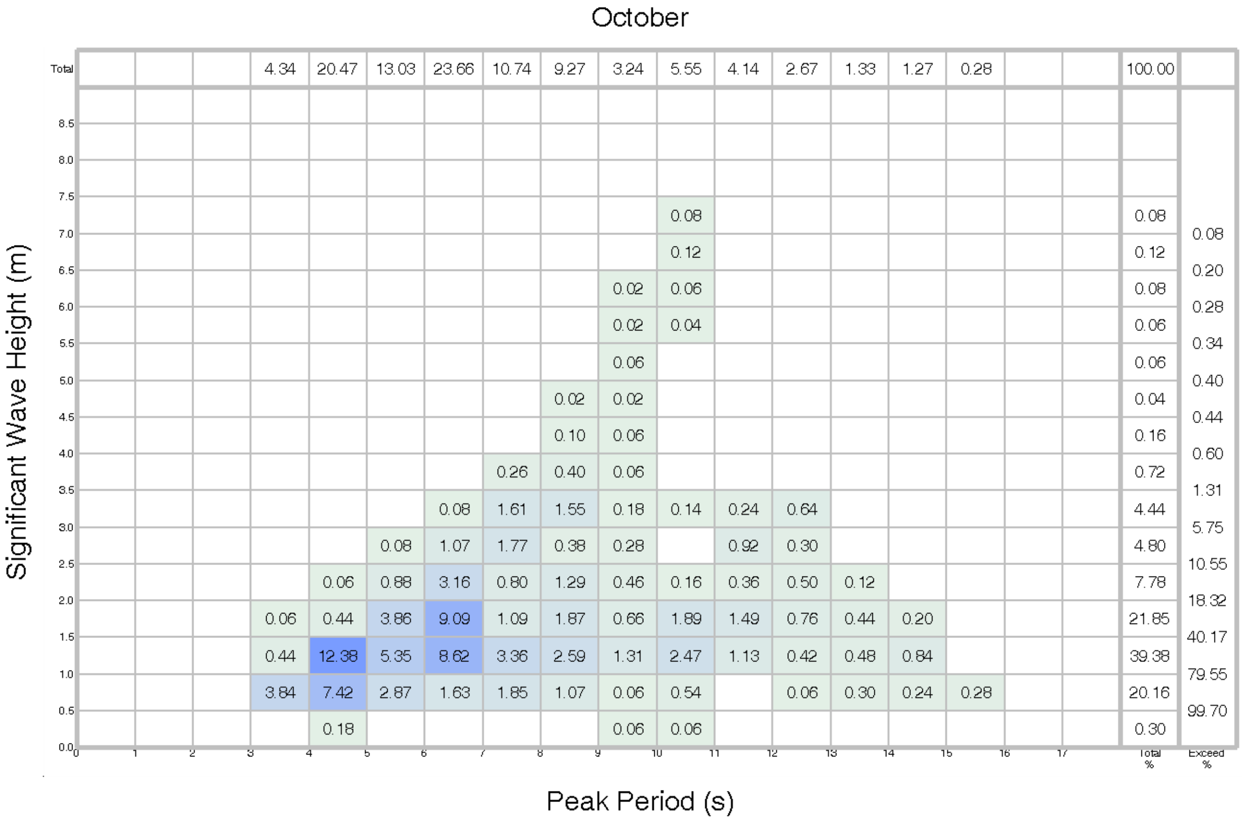

Figure 2-76 Percentage Occurrence of Significant Wave Height and Peak Period for Hurricanes – October

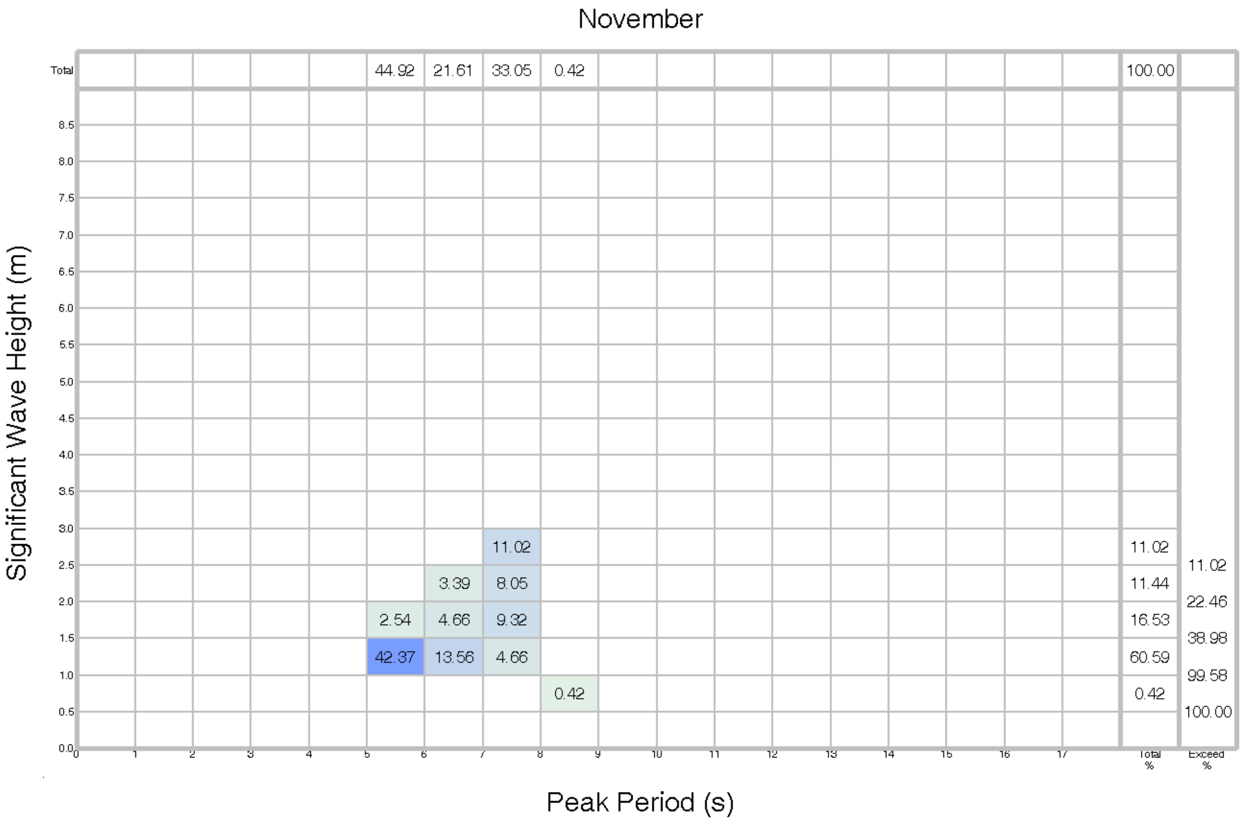

Figure 2-77 Percentage Occurrence of Significant Wave Height and Peak Period for Hurricanes – November

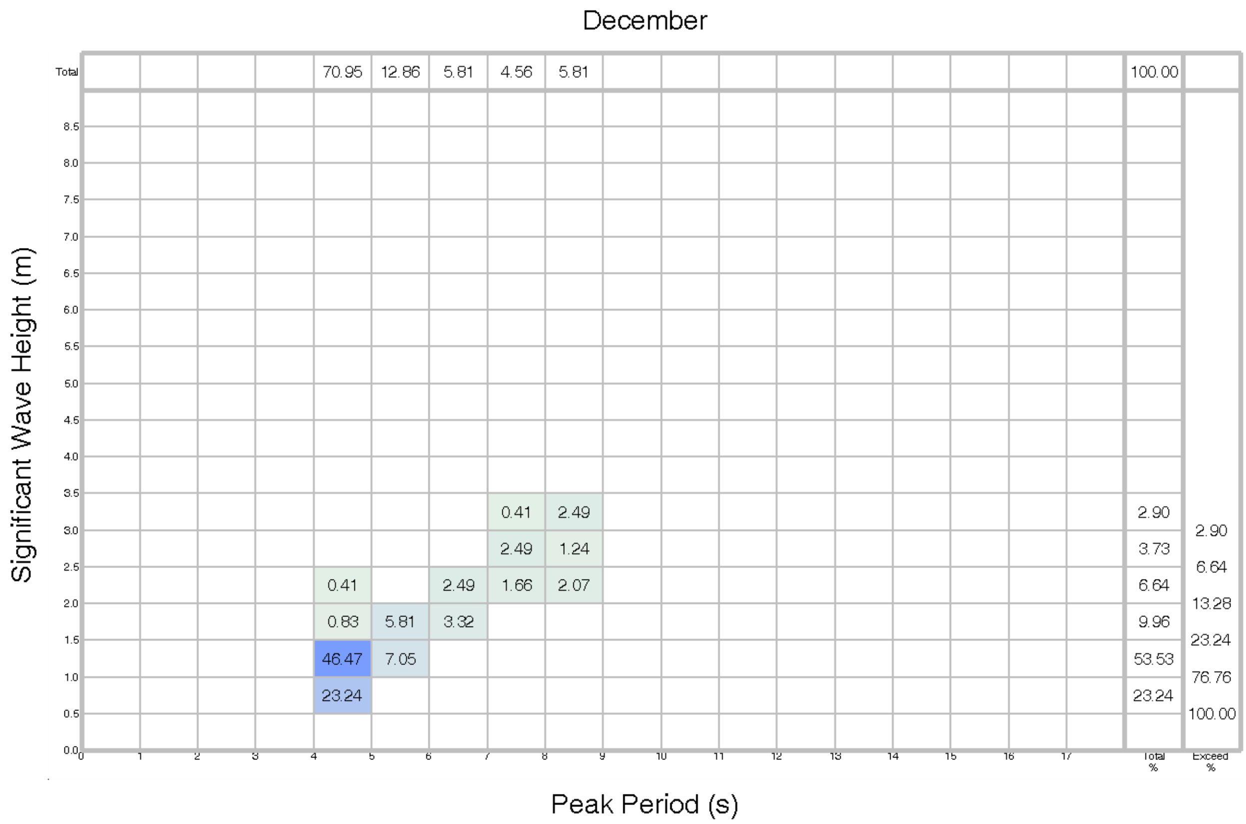

Figure 2-78 Percentage Occurrence of Significant Wave Height and Peak Period for Hurricanes – December

2.2.23 Extreme Wave Criteria All

This section depicts the highest extreme values for return periods 1-, 50-, 100-, 500-, 1000-, and 10000-year return periods. The data is optained from the heighst values between hurricanes and winterstorms for all parameters for both sites.

2.2.23.1 Omni-Directiona Extreme Values

Return Period	Hs	Tz	Tp	Hc	Hmax	THmax Low	THmax Mid	THmax High	Wave Length
	[m]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]
1-Year	5.34	6.5	9.9	6.22	10.01	8.8	10.0	10.9	128.0
50-years	8.16	8.0	12.0	9.49	14.72	10.6	12.0	13.1	167.52
100-years	9.13	8.3	12.6	10.61	16.46	11.2	12.7	13.8	180.72
500-years	11.38	8.9	14.0	13.23	20.52	12.4	14.1	15.3	210.58
1000-years	12.35	9.1	14.5	14.35	22.26	12.9	14.6	15.9	223.23
10000-years	15.57	9.8	16.2	18.09	28.06	14.4	16.3	17.8	263.17

Table 2-34 Omni-Directional Extreme Values

2.2.23.2 Directional Extreme Values

Return Period	Hs	Tz	Tp	Hc	Hmax	THmax Low	THmax Mid	THmax High
Direction [from]	[m]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
1-Year	**5.34**	**6.5**	**9.9**	**6.22**	**10.01**	**8.8**	**10.0**	**10.9**
North	3.76	6.1	8.4	4.38	7.05	7.4	8.4	9.2
North-east	4.26	6.3	8.9	4.96	7.98	7.9	8.9	9.7
East	5.34	6.5	9.9	6.22	10.01	8.8	10.0	10.9
South-east	5.14	6.5	9.7	5.99	9.64	8.6	9.8	10.7
South	4.35	6.3	9.0	5.07	8.16	7.9	9.0	9.8
South-west	3.88	6.2	8.5	4.52	7.27	7.5	8.5	9.3
West	3.31	6.0	7.9	3.86	6.21	7.0	7.9	8.6
North-west	3.24	6.0	7.8	3.78	6.08	6.9	7.8	8.5
50-Years	**8.16**	**8.0**	**12.0**	**9.49**	**14.72**	**10.6**	**12.0**	**13.1**
North	4.77	6.8	9.3	5.54	8.59	8.2	9.3	10.2
North-east	6.45	7.4	10.7	7.50	11.63	9.5	10.8	11.7
East	8.16	8.0	12.0	9.49	14.72	10.6	12.0	13.1
South-east	8.13	8.0	11.9	9.45	14.65	10.6	12.0	13.1
South	5.36	7.0	9.8	6.23	9.66	8.7	9.9	10.8
South-west	3.94	6.4	8.5	4.58	7.11	7.5	8.5	9.3
West	3.74	6.3	8.3	4.35	6.75	7.3	8.3	9.1
North-west	3.70	6.3	8.2	4.30	6.67	7.3	8.3	9.0
100-Years	**9.13**	**8.3**	**12.6**	**10.61**	**16.46**	**11.2**	**12.7**	**13.8**
North	5.33	7.0	9.8	6.20	9.61	8.7	9.8	10.7
North-east	7.21	7.7	11.3	8.38	13.01	10.0	11.3	12.4
East	9.13	8.3	12.6	10.61	16.46	11.2	12.7	13.8
South-east	9.09	8.3	12.6	10.57	16.39	11.2	12.6	13.8
South	5.99	7.3	10.3	6.97	10.81	9.2	10.4	11.3
South-west	4.41	6.6	9.0	5.12	7.95	7.9	9.0	9.8
West	4.19	6.5	8.7	4.87	7.55	7.7	8.8	9.6
North-west	4.14	6.5	8.7	4.81	7.46	7.7	8.7	9.5
500-Years	**11.38**	**8.9**	**14.0**	**13.23**	**20.52**	**12.4**	**14.1**	**15.3**

North	6.64	7.5	10.9	7.72	11.98	9.6	10.9	11.9
North-east	8.99	8.2	12.5	10.45	16.21	11.1	12.6	13.7
East	11.38	8.9	14.0	13.23	20.52	12.4	14.1	15.3
South-east	11.33	8.8	14.0	13.17	20.42	12.4	14.0	15.3
South	7.47	7.8	11.5	8.68	13.47	10.2	11.5	12.6
South-west	5.50	7.1	9.9	6.39	9.91	8.8	10.0	10.9
West	5.22	7.0	9.7	6.06	9.41	8.6	9.7	10.6
North-west	5.16	6.9	9.6	5.99	9.30	8.5	9.7	10.6
1000-Years	**12.35**	**9.1**	**14.5**	**14.35**	**22.26**	**12.9**	**14.6**	**15.9**
North	7.21	7.7	11.3	8.38	13.00	10.0	11.3	12.4
North-east	9.76	8.4	13.0	11.34	17.59	11.5	13.1	14.3
East	12.35	9.1	14.5	14.35	22.26	12.9	14.6	15.9
South-east	12.29	9.1	14.5	14.29	22.16	12.9	14.6	15.9
South	8.11	8.0	11.9	9.42	14.61	10.6	12.0	13.1
South-west	5.96	7.2	10.3	6.93	10.75	9.1	10.4	11.3
West	5.66	7.1	10.1	6.58	10.21	8.9	10.1	11.0
North-west	5.60	7.1	10.0	6.50	10.09	8.9	10.1	11.0
10000-Years	**15.57**	**9.8**	**16.2**	**18.09**	**28.06**	**14.4**	**16.3**	**17.8**
North	9.09	8.3	12.6	10.56	16.38	11.1	12.6	13.8
North-east	12.30	9.1	14.5	14.29	22.16	12.9	14.6	15.9
East	15.57	9.8	16.2	18.09	28.06	14.4	16.3	17.8
South-east	15.50	9.7	16.2	18.01	27.93	14.3	16.3	17.7
South	10.22	8.6	13.3	11.87	18.42	11.8	13.4	14.6
South-west	7.52	7.8	11.5	8.73	13.55	10.2	11.6	12.6
West	7.14	7.7	11.2	8.29	12.86	9.9	11.3	12.3
North-west	7.05	7.6	11.2	8.20	12.72	9.9	11.2	12.2

Table 2-35 Directional Extreme Values

2.2.23.3 Extreme Wave Height and Length

Extreme Wave Criteria at Site 1		Return Period					
		1-year	50-year	100-year	500-year	1000-year	10000-year
Significant Wave Height (m)		5.34	8.16	9.13	11.38	12.35	15.57
Peak Period (s)		9.9	11.96	12.61	13.99	14.54	16.21
Wave Length (m)	Total Water Depth 24.7m	130.59	171.08	184.46	214.56	227.28	268.26

Table 2-36 Extreme Waves and Associated Wave Length at Site 1

Extreme Wave Criteria at Site 2		Return Period					
		1-year	50-year	100-year	500-year	1000-year	10000-year
Significant Wave Height (m)		5.34	8.16	9.13	11.38	12.35	15.57
Peak Period (s)		9.9	11.96	12.61	13.99	14.54	16.21
Wave Length (m)	Total Water Depth 25.4m	131.60	172.51	185.97	216.17	228.92	270.14

Table 2-37 Extreme Waves and Associated Wave Length at Site 2

2.2.23.4 Extreme Wave Orbital Velocity

Extreme Wave Criteria at Site 1		Return Period					
		1-year	50-year	100-year	500-year	1000-year	10000-year
Significant Wave Height (m)		5.34	8.16	9.13	11.38	12.35	15.57
Peak Period (s)		9.9	11.96	12.61	13.99	14.54	16.21
Wave Orbital Velocity (m/s) at 1m above seabed	Total Water Depth 24.7m	1.12	2.02	2.35	3.07	3.36	4.12

Table 2-38 Extreme Wave and Associated Wave Orbital Velocity at 1m Above Seabed at Site 1

Extreme Wave Criteria at Site 1		Return Period		
		1-year	50-year	100-year
Hmax (m)		10.01	14.71	16.46
Peak Period Associated with Hmax (s)		10.9	13.1	13.8
Wave Orbital Velocity (m/s) at 1m above seabed	Total Water Depth 24.7m	2.26	3.53	3.76

Table 2-39 Extreme Hmax and Associated Wave Orbital Velocity at 1m Above Seabed at Site 1

Extreme Wave Criteria at Site 2		Return Period					
		1-year	50-year	100-year	500-year	1000-year	10000-year
Significant Wave Height (m)		5.34	8.16	9.13	11.38	12.35	15.57
Peak Period (s)		9.9	11.96	12.61	13.99	14.54	16.21
Wave Orbital Velocity (m/s) at 1m above seabed	Total Water Depth 25.4m	1.09	1.98	2.30	3.01	3.30	4.10

Table 2-40 Extreme Wave and Associated Wave Orbital Velocity at 1m Above Seabed at Site 2

Extreme Wave Criteria at Site 2		Return Period		
		1-year	50-year	100-year
Hmax (m)		10.01	14.71	16.46
Peak Period Associated with Hmax (s)		10.9	13.1	13.8
Wave Orbital Velocity (m/s) at 1m above seabed	Total Water Depth 25.4m	2.22	3.49	3.78

Table 2-41 Extreme Hmax and Associated Wave Orbital Velocity at 1m Above Seabed at Site 2

2.2.24 Air Gap

Wave forces are the principal environmental force acting on an offshore structure. As such they are designed so that the main facilities will not be impacted by wave loading, with the cellar deck generally being the lowest point considered in the air gap calculation. The maximum extreme water level comprises the following elements, which are illustrated in Figure 2-79.

- Tidal height
- Surge height (storm, seasonal)
- Crest height

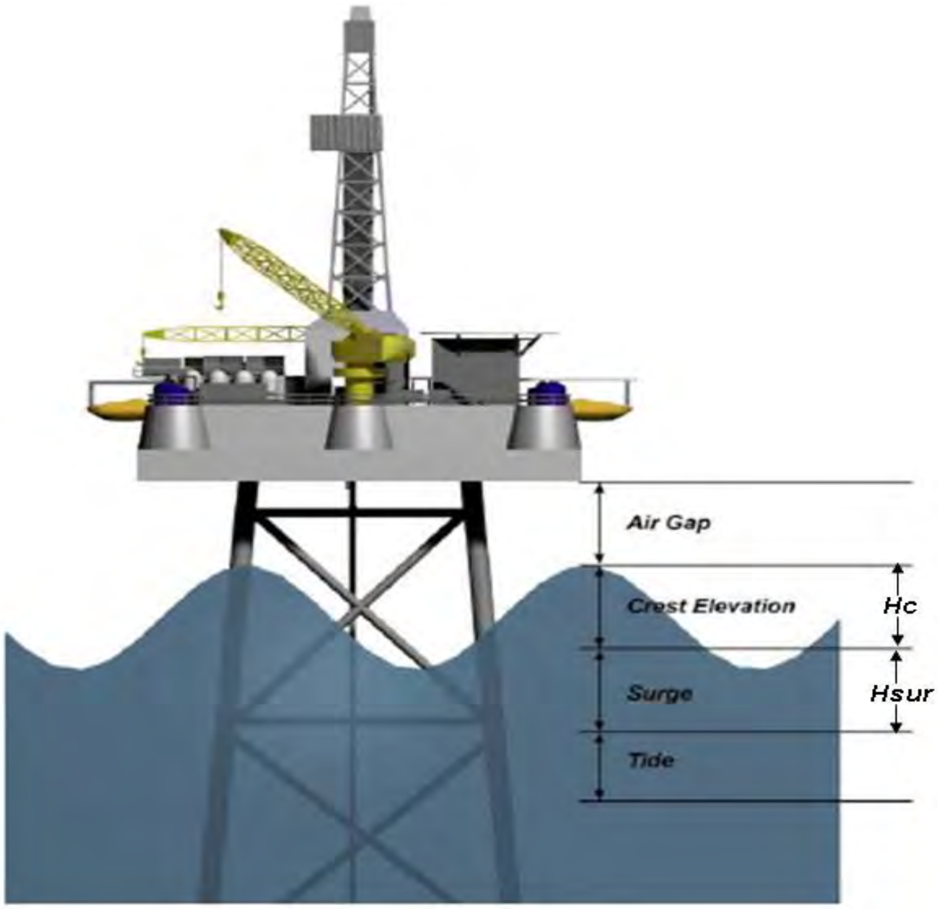

Figure 2-79 Air Gap Diagram

Platform elevation is defined as relative to the expected value of the highest crest elevation with a recurrence period of 50 years (Table 2-34), accounting for the highest astronomical tide, positive storm surge, the crest height of the extreme wave, and motion of the support structure.[1]

2.2.24.1 Water Levels

Storm surge and tide values are based on section 2.5.

2.2.24.2 Hmax and Hc

Maximum and crest wave height values were derived using in-house software (EXWAN – EXtreme Wave ANalysis).

The probability distributions of maximum wave or crest height for a storm are given by:

$$P(H_{max} < h) = exp\left\{ \int_0^T log\{F_{Hs(t)}(h)\} dt / T_{m02}(t) \right\}$$

where:

$P(H_{max} < h)$ is the non-exceedance probability of the maximum wave or crest height in a storm;
$F_{Hs(t)}(h)$ is the short-term non-exceedance probability of wave or crest height, h, for a significant wave height, Hs, at time, t;
$T_{m02}(t)$ is the spectral estimate of the mean zero up-crossing wave period at time, t;

T is the duration of the storm.

This approach was developed by Borgman (1973)[1] and has been adopted by the EXWAN software as a means of determining the maximum wave and crest height from each storm. The Oceanweather hindcast data contained an estimate of *Tp* and this parameter is used to derive T_{m02} by multiplying by 0.74.

In order to calculate $F_{Hs(t)}(h)$ for each time step within each storm the Forristall 3-D approach was used for crest height. This formulation is based on the 2-parameter Weibull distribution:

$$F_{Hs}(h) = 1 - exp\left\{-\frac{(4\,h/Hs)^A}{B}\right\}$$

where, A and B are parameters that were empirically fitted.

Forristall (2000)[2] derived estimates of extreme crest heights for given sea states in given water depths by using simulations of JONSWAP spectra and empirically fitted the following for *A* and *B*:

$$A = 2 - 1.7912S - 0.5302U_r + 0.2824U_r^2$$
$$B = \{4(0.3536 + 0.2568S + 0.0800U_r)\}^A$$

where:

$U_r = \frac{Hs}{k_1^2 d^3}$; is the Ursell number, and

$S = \frac{2\pi H_s}{g T_{m01}^2}$; is the wave steepness,

$T_{m01} = m_0/m_1$, the ratio of the zeroth to the first moments of the wave spectrum;
k_1 is the deep water wave number corresponding to T_{m01};
d is the water depth.

Time series data from Oceanweather was processed using the EXWAN program to produce a representative crest height for each individual storm. The ratio of crest heights to the highest Hs recorded in each storm was then calculated. The regression equation Hc = 1.1763*Hs was then developed and used to derive the respective crest heights for winter storms and equation Hc = 1.1622*Hs was then developed and used to derive the respective crest heights for hurricanes.

The maximum wave height was calculated using EXWAN and the 2-parameter Weibull distribution proposed by Forristall. The values used for A and B are 2.13 and 8.42, respectively. As with the crest heights, the ratio of maximum heights to the highest Hs recorded in each storm was then calculated. The regression equation Hmax = 1.8711*Hs for winter storms and Hmax = 1.8027*Hs for hurricanes, was then developed and used to derive the respective maximum wave heights in the Criteria Reference.

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[1] Borgman, L., 1973. *Probabilities for highest wave in hurricane*. J. Waterways, Harbors, and Coastal Eng, Div. ASCE **99**, 185-207.

[2] Forristall, G.Z. (2000). *Wave crest distributions: observations and second order theory*. J. Phys. Ocean, **30**, 1931-1943.

2.2.25 Wave Persistence

Total wave persistence values for Virginia are provided in the attached Excel spreadsheet "Virginia_wave_persistence." Persistence statistics are expressed as the percentage of hours in a month that windows of duration 6, 12, 18, 24, 36, 48, and 72 hours occur.

2.2.26 Wavelength Equation

Stream function wave theory was developed by Dean (1965)[3] to examine fully nonlinear water waves numerically. The method involves computing a series solution to the fully nonlinear water wave problem, involving the Laplace equation with two nonlinear free surface boundary conditions (constant pressure, and a wave height constraint (Dalrymple, 1974)[4]. Chaplin (1980)[5] reformulated the method to be able to predict correctly the behaviour of steep and near-breaking waves. The Stream Function Matlab package presented here is to calculate wave kinematics for non-linear regular waves on a uniform current with water depth d, wave height H and wave period T are known.

The StreamFunction Matlab package was converted to Matlab from FORTRAN code CW263.FOR. The original FORTRAN code by Dr. John Chaplin of Southampton University was downloaded from: http://www.civil.soton.ac.uk/hydraulics/download/downloadtable.htm

This wave Streamfunction package has the following features:
• Automatic selection of the order of the stream function. The order of the Stream function wave is a measure of how nonlinear the wave is. In deep water, the order can be low, 3 to 5 say, while, in very shallow water, the order can be as great as 30. A measure of which order to use is to choose an order and then increase it by one and obtain another solution. If the results do not change significantly, then you have the right order.
• Uniform background current
• For steep waves the solution advances in steps, in which the order and the wave height are progressively increased.

2.2.27 Wave Spectra and Parameters

The JONSWAP (Joint North Sea Wave Project) wave frequency spectrum is an extention of the Pierson-Moskowitz (PM) spectrum to include fetch limited situation. The PM spectrum was originally propose for a fully-developed sea.

$$S_{JS}(\omega) = F_n * S_{PM}(\omega) * \gamma^{e^{\left((-0.5)*\left(\frac{\omega-\omega_m}{\sigma*\omega_m}\right)^2\right)}}$$

Where
$S_{PM}(\omega)$ is the Pierson-Moskowitz spectrum:

$$S_{PM}(\omega) = \left(\frac{\alpha * g^2}{\omega^5}\right) * e^{\left(-1.25*\left(\frac{\omega_m}{\omega}\right)^4\right)}$$

g is the acceleration due to gravity
ω is the wave frequency in radians per second (rad/s)
ω_m is the peak frequency
α is 0.0081
γ is a non-dimensional peak shape parameter

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[3] Dean, R.G, 1965, Stream Function Representation of Nonlinear Ocean Waves, JGR, 70(18):4561-4572
[4] Dalrymple, R.A., 1974, A Finite Amplitude Wave on a Linear Shear Current, JGR, 79(30):4498-4504
[5] Chaplin, J.R., 1980, Developments of Stream-Function Wave Theory. Coastal Engineering, 3:179-205

σ is a numerical parameter
$\sigma=\sigma_a$ for $\omega \le \omega_m$
$\sigma=\sigma_b$ for $\omega > \omega_m$
F_n is a normalizing or scaling factor used to ensure that S_{JS} and S_{PM} have the same H_s. For σ_a=0.07 and σ_b=0.09 F_n becomes:

$F_n(1)=(0.78+0.22\gamma)^{-1}$ for $1\le \gamma \le 6$
$F_n(2)=[5*(0.065\gamma^{0.803}+0.135)]^{-1}$ for $1\le \gamma \le 10$

$F_n(1)$ was obtained by Ewing[3] and $F_n(2)$ by Yamaguchi[4]

In Xwaves, the default option in the spectrum fitting was used. According to the manual, default option uses a modified form of the JONSWAP that is based on significant wave height (H_s). peak period (T_p), and peak enhancement factor γ. σ_a and σ_b are held constant at 0.07 and 0.09, respectively. α is then computed independently based on H_s, T_p, and γ.

Example: For γ = 1, 2, and 3, σ_a = 0.07, σ_b = 0.09, ω_m = 0.5:

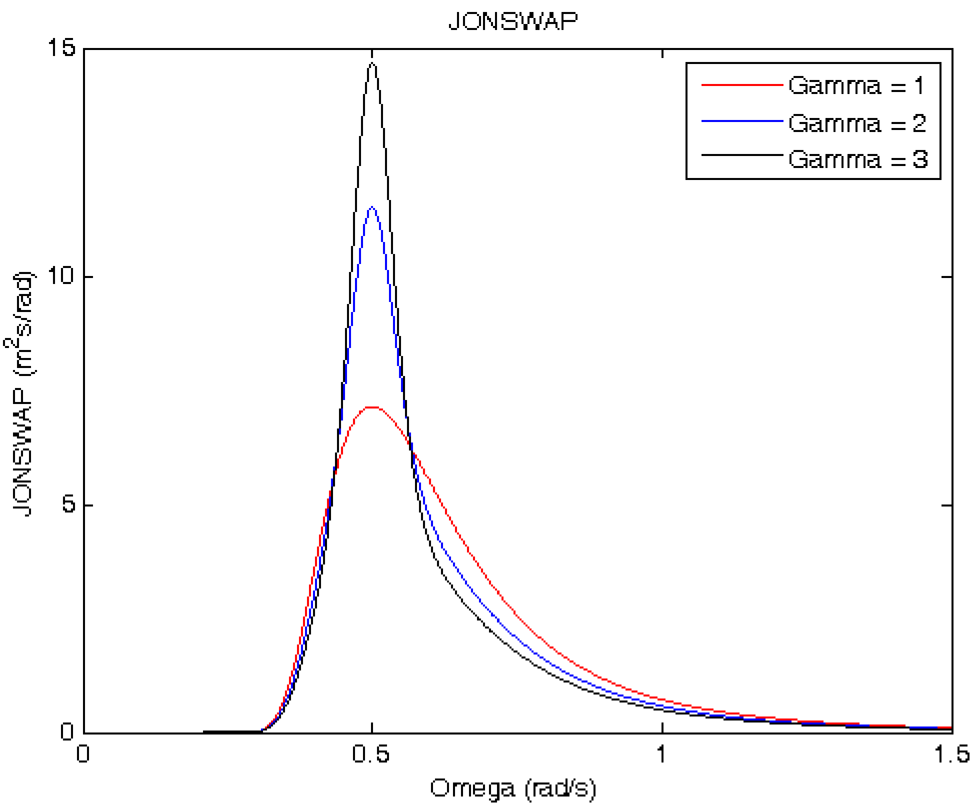

Figure 2-80 JONSWAP Example

2.2.28 Breaking Waves

To determine if a wave is a breaking wave, the relationship below was used obtained from ISO 19901-1[5]:

$H_s/H_d \geq 0.78$

Where H_s is Hmax and H_d is the water depth in meters.

Tables below show the H_s/H_d for both sites for winter storms and hurricanes. There are breaking waves in the area for return periods of 500- and 1000 years for hurricanes at both sites. The maximum sustainable wave heigh for site 1 is 19.27 m and 19.81 m for site 2.

Breaking waves are classified as spilling, plunging or surging. The first two types, spilling and plunging, are relevant for offshore wind turbines. The water depth, sea floor slope and wave period determine whether the breaking wave is spilling or plunging. Annex C in IEC 61400-3[1] provides guidance relating to shallow water hydrodynamics and the influence of site characteristics on the nature and dimensions of breaking waves. Annex D relates to the calculation of hydrodynamic loads for breaking waves.

Extreme Wave Criteria at Site 1		Return Period for Winter Storms			Return Periods for Hurricanes		
		100-year	500-year	1000-year	100-year	500-year	1000-year
Hmax (m)		12.77	15.28	16.36	16.46	20.52	22.26
H_s/H_d	Total Water Depth 24.7m	0.51	0.62	0.66	0.67	0.83	0.90

Table 2-42 H_s/H_d Values for Site 1 for Winter Storms and Hurricanes

Extreme Wave Criteria at Site 2		Return Period for Winter Storms			Return Periods for Hurricanes		
		100-year	500-year	1000-year	100-year	500-year	1000-year
Hmax (m)		12.77	15.28	16.36	16.46	20.52	22.26
H_s/H_d	Total Water Depth 25.4m	0.50	0.60	0.64	0.65	0.81	0.88

Table 2-43 H_s/H_d Values for Site 2 for Winter Storms and Hurricanes

Breaking waves was also determined by using equation 2-58 in the Shore Protection Manual.

$$\left(\frac{H}{L}\right)_{Max} = 0.142 * \tanh\left(\frac{2 * \pi * d}{L}\right)$$

$$L = \frac{g * T^2}{2 * \pi}\sqrt{\tanh\left(\frac{4 * \pi^2 * d}{T^2 * g}\right)}$$

Where:
T= THmax (s), d= depth (m), H= Hmax (m)

Table 2-44 and Table 2-45 illustrate the maximum wave steepness and the wave steepness for return periods 100-, 500-, and 1000-years. Once the maximum wave steepness is exceded the wave becomes unstable and breaks. There are breaking waves in the area for return periods of 500- and 1000 years for hurricanes at both sites.

Extreme Wave Criteria at Site 1		Return Period for Winter Storms			Return Periods for Hurricanes		
		100-year	500-year	1000-year	100-year	500-year	1000-year
(H/L)max (m)		0.10	0.09	0.09	0.09	0.08	0.08
Hmax/L	Total Water Depth 24.7m	0.07	0.08	0.08	0.08	0.09	0.09

Table 2-44 Maximum Wave Steepness for Site 1 for Winter Storms and Hurricanes

Extreme Wave Criteria at Site 2		Return Period for Winter Storms			Return Periods for Hurricanes		
		100-year	500-year	1000-year	100-year	500-year	1000-year
(H/L)max (m)		0.10	0.09	0.09	0.09	0.08	0.08
Hmax/L	Total Water Depth 25.4m	0.07	0.08	0.08	0.08	0.09	0.09

Table 2-45 Maximum Wave Steepness for Site 2 for Winter Storms and Hurricanes

2.2.29 Advice on Values for Normal, Sever, Extreme and Reduce Wave Data

The normal sea state and severe sea state are derived from 26-years (1980 to 2005) of Oceanweather operational hindcast data. As described in IEC 61400-3[1], the relationship between wind speed at hub height and significant wave height is $Hs=0.1272*Ws_{hub}+0.09342$, illustrated in Figure 2-81. The normal sea state parameters are presented in Table 2-46.

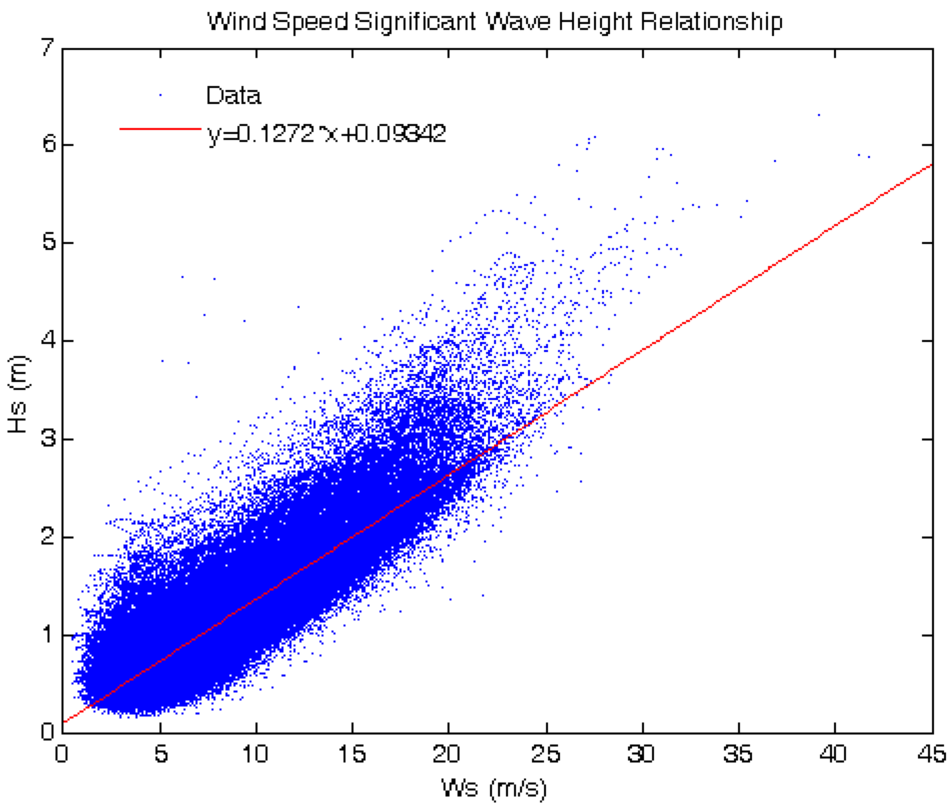

Figure 2-81 Relationship Between Wind Speed at Hub Height and Significant Wave Height

Normal Sea State	
Mean Wind Speed (m/s)	8.44
Significant Wave Height (m)	1.17
Wave Period, T (s)	3.83 < T < 4.93

Table 2-46 Normal Sea State Parameters

The severe sea state parameters are presented in Table 2-47. The severe wave height was calculated by extrapolating the significant wave heights that occur within 1 m/s of the mean wind speed at hub height, to a 50 year recurrence period. Wind speed with a 50 year recurrence period is derived from 26-years (1980 to 2005) of Oceanweather operational hindcast data.

Sever Sea State	
50 Year Wind Speed (m/s)	43.59
Significant Wave Height (m)	6.10
Wave Period, T (s)	8.79 < T < 11.28

Table 2-47 Sever Sea State Parameters

The extreme conditions are the 1 year and 50 year recurrence Hmax values as described in Table 2-13 for 1 year extreme, Table 2-16 for winter storms and Table 2-25 for hurricane. The reduced conditions, presented in Table 2-48, consist of the extreme 3-sec wind speed at 10 m ASL with associated Hs and extreme Hs with associated 3-sec wind speed at 10 m ASL. Reduced values are calculated by dividing by 1.3.

Reduce Conditions		1-year	50-years	100-years	500-years	1000-years	10000-years
Winter Storm	3-sec Wind Speed (m/s)	29.72	33.35	36.32	43.41	46.56	57.38
	Reduced Hs (m)	4.11	4.81	5.25	6.28	6.72	8.19
	Hs (m)	5.34	6.25	6.83	8.16	8.74	10.65
	Reduced 3-sec Wind Speed (m/s)	22.86	25.65	27.94	33.39	35.82	44.14
Hurricane	3-sec Wind Speed (m/s)	29.72	46.95	52.81	67.06	73.49	96.11
	Reduced Hs (m)	4.11	6.28	7.02	8.75	9.50	11.98
	Hs (m)	5.34	8.16	9.13	11.38	12.35	15.57
	Reduced 3-sec Wind Speed (m/s)	22.86	36.12	40.62	51.58	56.53	73.93

Table 2-48 Reduced Values for Wind Speed and Significant Wave Height for Winter Storms and Hurricanes

2.3 Currents Criteria

Current criteria are derived from 7-years (2006 to 2012) Rutgers University's ESPreSSO (Experimental System for Predicting Shelf and Slope Optics) hindcast from gridpoint 36.8587°N, 75.5139°W.

2.3.1 Omni-Directional Extreme Near Surface Currents

Return Period	Current Speed (m/s)
1-year	1.08
50-years	1.46
100-years	1.53
500-years	1.69
1000-years	1.76
10000-years	1.99

Table 2-49 Omni-Directional Extreme Near Surface Current Speed

2.3.2 Directional Extreme Near Surface Currents

Return Period	Direction [towards]	Current Speed (m/s)
1-year	**Omni-directional**	1.08
	North	0.84
	North-east	0.90
	East	0.83
	South-east	1.07
	South	1.08
	South-west	0.90
	West	0.80
	North-west	0.67
50-years	**Omni-directional**	1.46
	North	1.14
	North-east	1.22
	East	1.12
	South-east	1.45
	South	1.46
	South-west	1.22
	West	1.09
	North-west	0.92
100-years	**Omni-directional**	1.53
	North	1.19
	North-east	1.28
	East	1.17
	South-east	1.52
	South	1.53
	South-west	1.28
	West	1.14
	North-west	0.96
500-years	**Omni-directional**	1.69
	North	1.31

	North-east	1.41
	East	1.29
	South-east	1.67
	South	1.69
	South-west	1.41
	West	1.26
	North-west	1.06
1000-years	**Omni-directional**	1.76
	North	1.37
	North-east	1.47
	East	1.35
	South-east	1.74
	South	1.76
	South-west	1.47
	West	1.31
	North-west	1.10
10000-years	**Omni-directional**	1.99
	North	1.55
	North-east	1.66
	East	1.52
	South-east	1.97
	South	1.99
	South-west	1.66
	West	1.48
	North-west	1.24

Table 2-50 Directional Extreme Near Surface Current Speed

2.3.3 Current Fitting Parameters

The independent omni-directional current cases are given in Table 2-49 and detailed descriptions of the calculations are given below.

Extreme value analysis was carried out on a subset of peak current speeds from the EXPreSSO data. The analysis runs from 2006 to 2012.

The Peaks Over Threshold (POT) method consisted of declustering the data by selecting peak events to produce a set of independent and identically distributed observations. This method was then employed to derive the 1-, 50-, 100-, 500-, 1000-, and 10000-year criteria. The number of peaks exceeding a given level, divided by the number of years of record, gave the rate of exceedance which could then be used to find the expected number of occurrences in a specified period of time.

The Exponential (EXP), Fisher-Tippett 1 (FT1), Fisher-Tippett 2 (FT2), Fisher-Tippett 3 (FT3), Generalised Pareto (GP), Weibull 2 (W2) and Weibull 3 (W3) distributions were tested for goodness-of-fit to the ESPreSSO data using the method of least squares (LS), maximum likelihood (MLE), and the method of moments (MoM). The best fits for 1-, 50-, 100-, 500-, 1000-, and 10000-year current speed are summarised in Table 2-51.

	Distribution	Fit	Threshold	# Peaks	Extreme Values					
					1-yr	50-yr	100-yr	500-yr	1000-yr	10000-yr
Cs (m/s)	EXP	LS	50.00	13283	1.08	1.46	1.53	1.69	1.76	1.98
	FT1	LS	95.00	41268	1.08	1.47	1.54	1.70	1.77	2.00
	FT1	LS	95.00	41268	1.08	1.47	1.54	1.69	1.76	1.99
	FT1	LS	50.00	22672	1.07	1.45	1.51	1.67	1.73	1.95
	FT2	LS	95.00	41268	1.08	1.47	1.54	1.70	1.76	1.99
	FT2	LS	10.00	3555	1.08	1.50	1.58	1.76	1.85	2.13
	FT2	LS	90.00	41268	1.07	1.46	1.52	1.68	1.75	1.97
	FT3	LS	50.00	13283	1.08	1.46	1.52	1.68	1.75	1.97
	FT3	LS	95.00	41268	1.08	1.44	1.50	1.64	1.70	1.90
	AVERAGE				1.08	1.46	1.53	1.69	1.76	1.99

Table 2-51 Extreme Omni-directional Near Surface Current Speed Fitting Parameters

2.4 Wind-Wave-Current Joint Probability

The wind-wave joint probability criteria in section 2.4.1 are derived from 26-years (1980 to 2005) of Oceanweather operational hindcast data.

The GROWFINE Eastcoast data from Oceanweather only have continuous wind and wave data from 1/1/1980 to 12/31/2005, while the current data from Rutgers University ESPreSSO model is from 2006 to 2012, there is no overlapping period for the three parameters to derive the joint probability between wind, wave, and current. An alternative method to derive the joint probability between wind, wave, and current is by using the following approach. NCEP WaveWatch III wind and wave data was obtained from 2000 to 2012 at a gridpoint (37N 75.5W) close to the sites. Comparisons of NCEP WaveWatch III wind and wave data against Oceanweather hindcast wind and wave data from 2000 to 2005 were undertaken. Figure 2-82 illustrates the wind speed relationship between WaveWatch III and Oceanweather and Figure 2-83 illustrates the significant wave height relationship between WaveWatch III and Oceanweather. WaveWatch III wind data was calibrated using the formula y=1*x-0.14, and formula y=1.1*x+0.086, to calibrate for significant wave height. Current data from Rutgers University ESPreSSO was interpolated to Wave Watch III to have the same time stamp. Overall a 7-year (2006-2012) calibrated WaveWatch III wind and wave, with interpolated ESPreSSO current data was used to derive the joint probability between wind, wave, and current. The wind, wave, and current joint probability are provided in the attached Excel spreadsheet "Wind_Wave_Current_Joint_Probability."

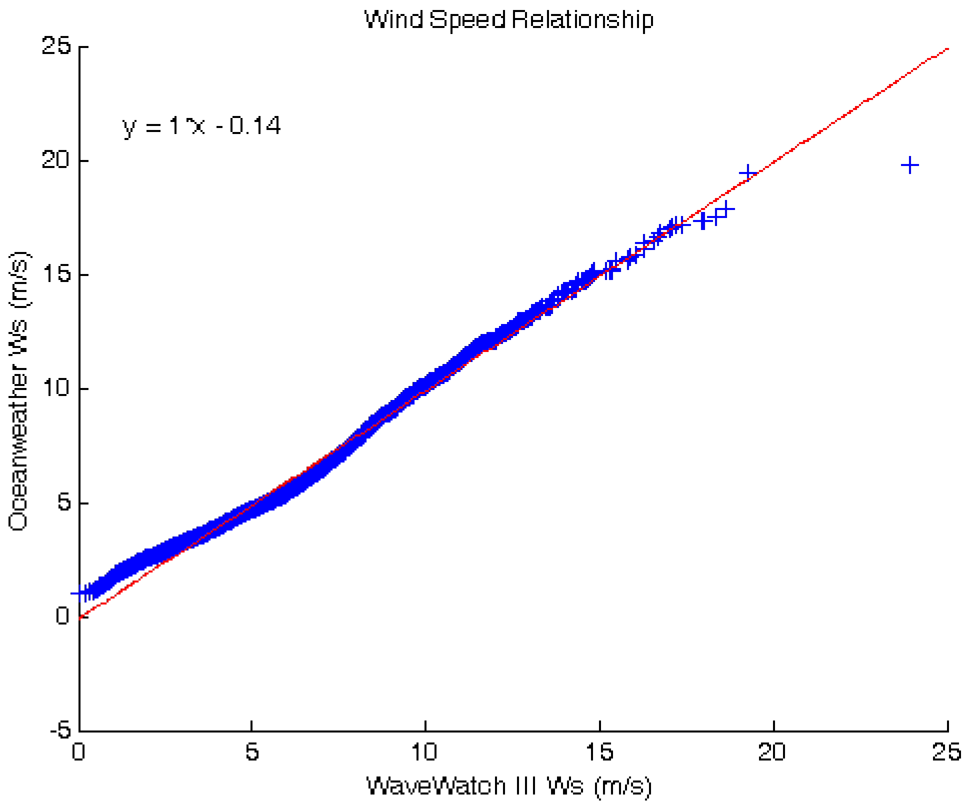

Figure 2-82 Relationship Between WaveWatch III Wind Speed with Oceanweather Wind Speed

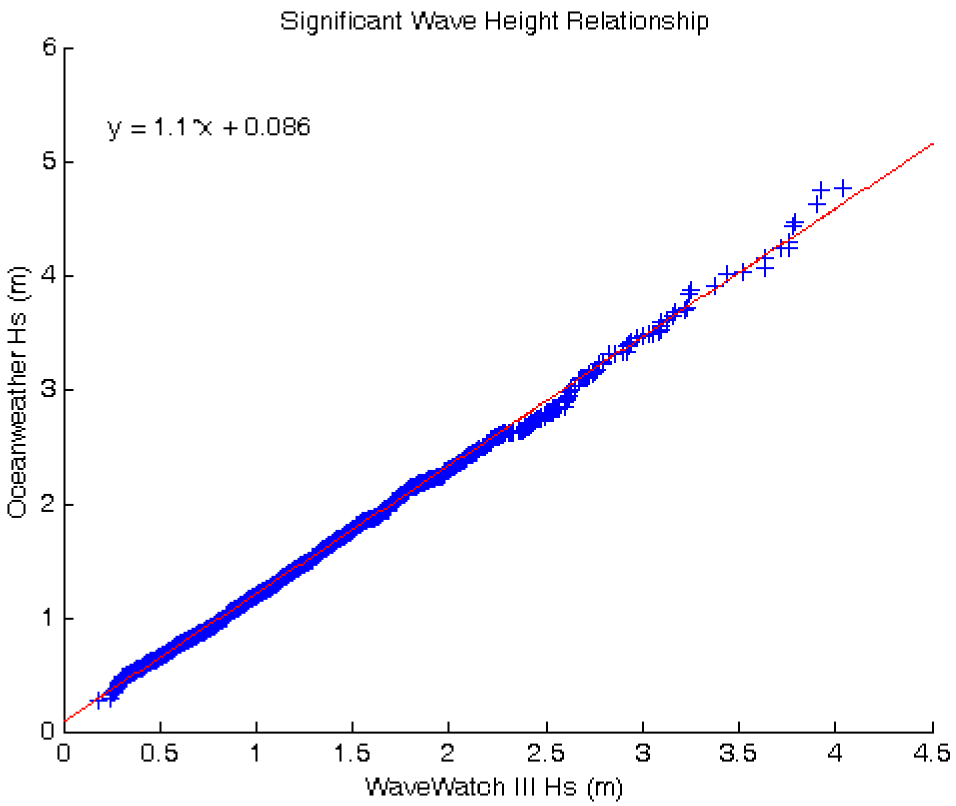

Figure 2-83 Relationship Between WaveWatch III Significant Wave Height with Oceanweather Significant Wave Height

2.4.1 Wind-Wave Joint Probability

All-Year

1hr Wind Speed at 100m [m/s] \ Significant Wave Height [m]	0.0–0.5	0.5–1.0	1.0–1.5	1.5–2.0	2.0–2.5	2.5–3.0	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–	Total %	Exceed %
Total	5.87	43.11	28.19	12.95	6.03	2.35	0.98	0.32	0.12	0.06	0.02	<0.01	<0.01	100.00	
40–												<0.01		<0.01	
38–40													<0.01	<0.01	
36–38												<0.01		<0.01	
34–36											<0.01			<0.01	
32–34										<0.01	<0.01			<0.01	
30–32										<0.01	<0.01	<0.01		<0.01	0.01
28–30								<0.01	<0.01	<0.01	<0.01			0.02	0.03
26–28						<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	0.04	0.07
24–26					<0.01	<0.01	0.03	0.03	0.02	0.01	<0.01	<0.01		0.10	0.17
22–24					<0.01	0.05	0.09	0.05	0.03	0.02	<0.01	<0.01		0.24	0.41
20–22			<0.01	<0.01	0.07	0.30	0.19	0.07	0.03	<0.01	<0.01			0.67	1.08
18–20			<0.01	0.03	0.63	0.53	0.32	0.11	0.01	<0.01				1.63	2.71
16–18			<0.01	0.48	1.65	0.63	0.21	0.03	<0.01					3.01	5.73
14–16		<0.01	0.13	2.68	1.67	0.50	0.10	0.01	<0.01					5.09	10.82
12–14		<0.01	2.08	4.33	1.12	0.22	0.03	<0.01	<0.01					7.79	18.61
10–12	<0.01	0.39	7.67	3.03	0.57	0.08	<0.01	<0.01						11.75	30.36
8–10	0.02	5.47	9.42	1.39	0.20	0.02	<0.01		<0.01					16.53	46.88
6–8	0.50	14.36	5.38	0.63	0.07	<0.01	<0.01	<0.01	<0.01	<0.01				20.94	67.82
4–6	2.57	14.98	2.56	0.26	0.04	<0.01		<0.01						20.41	88.23
2–4	2.52	7.35	0.89	0.11	0.01	<0.01								10.89	99.12
0–2	0.26	0.55	0.06	<0.01										0.88	

Figure 2-84 All Year Percentage Occurrence of Total Significant Wave Height and Wind Speed

2.4.2 Joint Frequency Distribution of Significant Wave Height and 30° Direction Bin

All-Year

Significant Wave Height (m) \ Mean Wave Direction (°T From)	000	030	060	090	120	150	180	210	240	270	300	330	Total %	Exceed %
Total	6.35	9.72	13.19	17.05	14.02	10.51	10.48	5.95	2.75	2.56	3.18	4.24	100.00	
> 6.0				<0.01	<0.01								<0.01	
5.5 – 6.0				<0.01	<0.01	<0.01							<0.01	
5.0 – 5.5			<0.01	<0.01	<0.01	<0.01	<0.01						0.02	0.03
4.5 – 5.0		0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01					0.06	0.08
4.0 – 4.5	<0.01	0.02	0.06	0.02	0.01	<0.01	<0.01	<0.01	<0.01				0.12	0.20
3.5 – 4.0	0.01	0.05	0.17	0.03	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.32	0.52
3.0 – 3.5	0.08	0.24	0.37	0.08	0.04	0.05	0.02	<0.01	0.01	0.01	0.03	0.05	0.98	1.50
2.5 – 3.0	0.26	0.47	0.61	0.21	0.07	0.15	0.10	0.04	0.04	0.06	0.12	0.22	2.35	3.85
2.0 – 2.5	0.86	0.99	1.03	0.63	0.18	0.25	0.37	0.18	0.15	0.22	0.44	0.74	6.03	9.88
1.5 – 2.0	1.77	2.06	1.71	1.62	0.51	0.57	1.01	0.74	0.44	0.53	0.83	1.15	12.95	22.83
1.0 – 1.5	2.11	3.17	3.78	5.20	2.27	1.91	3.40	2.25	0.99	0.87	0.96	1.28	28.19	51.02
0.5 – 1.0	1.17	2.51	4.82	8.29	9.30	6.06	5.14	2.52	1.05	0.81	0.72	0.72	43.11	94.13
0.0 – 0.5	0.09	0.18	0.62	0.97	1.61	1.50	0.42	0.20	0.06	0.07	0.08	0.07	5.87	

Figure 2-85 All Year Percentage Occurrence of Significant Wave Height and 30° Direction Bin

January

Significant Wave Height (m) \ Mean Wave Direction (°T From)	000	030	060	090	120	150	180	210	240	270	300	330	Total %	Exceed %
Total	13.15	14.88	13.23	8.98	4.52	6.08	5.44	5.74	5.09	5.97	7.19	9.72	100.00	
> 6.0														
5.5 – 6.0														
5.0 – 5.5														
4.5 – 5.0														
4.0 – 4.5														
3.5 – 4.0	0.04	0.14	0.01				<0.01	0.01			0.01	0.05	0.27	0.27
3.0 – 3.5	0.18	0.61	0.51	0.17		0.05	0.06	0.02		0.05	0.14	0.14	1.92	2.19
2.5 – 3.0	0.68	0.97	0.78	0.26	0.08	0.28	0.27	0.12	0.08	0.10	0.44	0.52	4.59	6.77
2.0 – 2.5	2.04	1.62	1.05	0.66	0.30	0.43	0.58	0.35	0.48	0.63	1.11	2.28	11.53	18.31
1.5 – 2.0	3.74	3.23	2.01	1.35	0.57	0.81	0.93	1.18	1.07	1.51	2.14	2.71	21.25	39.56
1.0 – 1.5	3.88	4.61	4.05	3.06	0.95	1.61	1.82	2.39	1.91	2.34	2.13	2.61	31.35	70.91
0.5 – 1.0	2.47	3.44	4.28	3.20	2.51	2.37	1.58	1.51	1.40	1.23	1.06	1.34	26.37	97.28
0.0 – 0.5	0.12	0.26	0.54	0.28	0.11	0.54	0.20	0.17	0.16	0.11	0.16	0.07	2.72	

Figure 2-86 Percentage Occurrence of Significant Wave Height and 30° Direction Bin - January

February

Significant Wave Height (m)	000	030	060	090	120	150	180	210	240	270	300	330	Total %	Exceed %
Total	12.45	15.20	15.83	12.41	7.46	5.17	6.79	5.15	3.51	3.56	4.89	7.56	100.00	
5.5–6.0														
5.0–5.5														
4.5–5.0														
4.0–4.5	0.05					<0.01							0.05	0.05
3.5–4.0	0.07	0.12	0.12	0.05		0.05					<0.01	0.06	0.47	0.52
3.0–3.5	0.27	0.49	0.73	0.18		0.06	0.02				<0.01	0.09	1.83	2.35
2.5–3.0	0.60	0.77	1.33	0.36	0.03	0.23	0.09	0.12	0.04	0.08	0.20	0.51	4.35	6.70
2.0–2.5	2.17	1.46	1.67	0.56	0.37	0.23	0.60	0.28	0.11	0.26	0.85	1.81	10.36	17.06
1.5–2.0	3.53	3.37	1.97	1.63	0.74	0.67	1.46	1.54	0.72	0.83	1.34	2.14	19.94	37.00
1.0–1.5	4.00	5.04	4.34	3.84	2.43	1.58	2.56	1.84	1.53	1.20	1.53	1.89	31.77	68.78
0.5–1.0	1.75	3.70	5.12	5.08	3.02	1.90	1.92	1.18	1.07	1.10	0.95	1.01	27.81	96.58
0.0–0.5	0.03	0.26	0.57	0.71	0.87	0.44	0.15	0.19	0.05	0.10	0.01	0.04	3.42	

Mean Wave Direction (°T From)

Figure 2-87 Percentage Occurrence of Significant Wave Height and 30° Direction Bin - February

March

Significant Wave Height (m)	000	030	060	090	120	150	180	210	240	270	300	330	Total %	Exceed %
Total	9.35	13.72	15.85	14.15	9.09	8.66	8.67	5.73	2.76	2.51	3.73	5.76	100.00	
5.5–6.0					0.02	<0.01							0.03	0.03
5.0–5.5					<0.01	0.02	0.01						0.03	0.06
4.5–5.0		0.06		0.03	0.01		0.01	0.01					0.11	0.17
4.0–4.5		0.17	0.04	0.05	0.02			0.02	0.01				0.30	0.47
3.5–4.0		0.18	0.23	0.04	0.08				0.02		0.04	0.01	0.59	1.06
3.0–3.5	0.02	0.32	0.38	0.18	0.06	0.17	0.04	0.03	0.03	0.03	0.11	0.10	1.46	2.52
2.5–3.0	0.26	0.71	0.64	0.28	0.14	0.37	0.31	0.10	0.06	0.12	0.18	0.55	3.74	6.26
2.0–2.5	1.49	1.32	1.23	0.90	0.36	0.62	0.92	0.21	0.21	0.30	0.58	1.17	9.31	15.56
1.5–2.0	2.88	3.36	2.48	1.47	0.70	1.10	1.89	1.17	0.44	0.67	1.02	1.57	18.76	34.32
1.0–1.5	3.00	4.06	4.25	4.23	2.10	2.63	2.71	2.53	1.00	0.72	1.04	1.70	29.97	64.29
0.5–1.0	1.62	3.31	6.01	6.50	5.15	3.39	2.55	1.54	0.92	0.62	0.64	0.62	32.86	97.16
0.0–0.5	0.08	0.23	0.59	0.47	0.44	0.37	0.24	0.12	0.07	0.05	0.13	0.05	2.84	

Mean Wave Direction (°T From)

Figure 2-88 Percentage Occurrence of Significant Wave Height and 30° Direction Bin - March

April

Significant Wave Height (m)	000	030	060	090	120	150	180	210	240	270	300	330	Total %	Exceed %
Total	5.06	8.86	15.61	16.08	10.48	12.26	14.78	5.23	2.02	2.98	3.07	3.58	100.00	
5.5–6.0														
5.0–5.5														
4.5–5.0			0.05										0.05	0.05
4.0–4.5			0.20										0.20	0.26
3.5–4.0	0.04		0.14									0.04	0.22	0.48
3.0–3.5	0.02	0.12	0.30	0.02		0.10	0.01				0.03	<0.01	0.59	1.07
2.5–3.0	0.04	0.73	0.56	0.06		0.26	0.10	0.04	0.01	0.05	0.04	0.05	1.94	3.01
2.0–2.5	0.40	1.07	1.11	0.45	0.15	0.41	0.53	0.14	0.07	0.21	0.26	0.42	5.22	8.23
1.5–2.0	1.36	1.35	1.74	1.44	0.37	0.96	1.91	0.67	0.30	0.50	0.62	1.03	12.25	20.48
1.0–1.5	2.08	2.86	4.24	4.78	2.49	3.48	5.91	2.26	0.86	1.04	0.97	1.29	32.26	52.74
0.5–1.0	1.03	2.53	6.09	7.78	6.04	5.45	6.06	1.95	0.68	0.96	0.98	0.68	40.22	92.96
0.0–0.5	0.10	0.19	1.18	1.55	1.43	1.61	0.26	0.17	0.10	0.22	0.17	0.06	7.04	

Mean Wave Direction (°T From)

Figure 2-89 Percentage Occurrence of Significant Wave Height and 30° Direction Bin - April

May

Significant Wave Height (m)	000	030	060	090	120	150	180	210	240	270	300	330	Total %	Exceed %
Total	2.64	6.19	13.84	21.99	17.59	15.04	13.04	5.12	1.04	0.94	1.34	1.22	100.00	
5.5–6.0														
5.0–5.5														
4.5–5.0														
4.0–4.5														
3.5–4.0		0.04	0.10										0.14	0.14
3.0–3.5		0.03	0.61	0.02									0.66	0.80
2.5–3.0	0.02	0.10	0.70	0.10		0.04	0.06	0.02					1.03	1.83
2.0–2.5	0.12	0.61	0.93	0.59		0.17	0.29	0.06	<0.01		0.02	0.01	2.80	4.63
1.5–2.0	0.55	1.08	1.51	1.80	0.03	0.27	0.93	0.34	0.12	0.06	0.11	0.15	6.93	11.56
1.0–1.5	1.17	1.95	3.75	4.95	1.69	2.25	4.31	2.14	0.35	0.39	0.48	0.35	23.76	35.33
0.5–1.0	0.62	2.24	5.60	13.22	12.90	9.63	7.05	2.39	0.52	0.45	0.64	0.55	55.80	91.13
0.0–0.5	0.16	0.14	0.65	1.31	2.97	2.69	0.41	0.18	0.06	0.04	0.10	0.16	8.87	

Mean Wave Direction (°T From)

Figure 2-90 Percentage Occurrence of Significant Wave Height and 30° Direction Bin - May

June

Significant Wave Height (m)	000	030	060	090	120	150	180	210	240	270	300	330	Total %	Exceed %
Total	1.45	3.56	7.67	16.53	25.06	15.99	16.86	9.27	1.42	0.68	0.72	0.79	100.00	
5.5–6.0														
5.0–5.5														
4.5–5.0														
4.0–4.5				0.02									0.02	0.02
3.5–4.0			<0.01	<0.01									0.01	0.03
3.0–3.5			0.01										0.01	0.04
2.5–3.0		0.02	0.14										0.15	0.19
2.0–2.5		0.04	0.55	0.05	0.04		0.04				0.01	0.01	0.74	0.93
1.5–2.0	0.17	0.42	0.92	0.88	0.19	0.11	0.35	0.19	0.02	0.03	0.10	0.02	3.38	4.31
1.0–1.5	0.51	1.55	1.91	3.93	1.57	1.34	4.55	2.94	0.21	0.15	0.24	0.24	19.12	23.43
0.5–1.0	0.62	1.44	3.51	10.07	19.19	11.03	10.72	5.82	1.12	0.45	0.30	0.44	64.70	88.13
0.0–0.5	0.15	0.11	0.61	1.59	4.07	3.52	1.22	0.32	0.07	0.05	0.07	0.09	11.87	

Mean Wave Direction (°T From)

Figure 2-91 Percentage Occurrence of Significant Wave Height and 30° Direction Bin - June

July

Significant Wave Height (m)	000	030	060	090	120	150	180	210	240	270	300	330	Total %	Exceed %
Total	0.77	2.35	6.44	13.35	20.51	19.40	20.17	12.21	2.49	1.00	0.77	0.54	100.00	
5.5–6.0														
5.0–5.5					<0.01	0.01							0.02	0.02
4.5–5.0			<0.01	0.01	0.01	0.01							0.04	0.05
4.0–4.5				<0.01	<0.01	<0.01	<0.01						0.02	0.07
3.5–4.0				<0.01	0.01		0.01						0.03	0.10
3.0–3.5				<0.01	0.02		<0.01	<0.01					0.03	0.13
2.5–3.0					0.03	<0.01		0.02					0.05	0.18
2.0–2.5			0.01		0.05	0.03	<0.01	0.08					0.17	0.35
1.5–2.0	0.04	0.05	0.62	0.39	0.18	0.14	0.61	0.44	0.03		<0.01	<0.01	2.51	2.86
1.0–1.5	0.23	0.69	0.96	1.84	1.02	1.16	4.92	3.93	0.47	0.18	0.15	0.14	15.68	18.54
0.5–1.0	0.45	1.50	4.06	9.31	15.18	13.31	13.34	7.09	1.91	0.77	0.56	0.30	67.79	86.33
0.0–0.5	0.05	0.11	0.79	1.78	4.01	4.74	1.27	0.65	0.08	0.06	0.05	0.09	13.67	

Mean Wave Direction (°T From)

Figure 2-92 Percentage Occurrence of Significant Wave Height and 30° Direction Bin - July

August

Significant Wave Height (m) vs. Mean Wave Direction (°T From)

Significant Wave Height (m)	000	030	060	090	120	150	180	210	240	270	300	330	Total %	Exceed %
Total	0.92	3.77	10.28	21.99	24.32	16.03	14.04	5.93	1.26	0.55	0.42	0.48	100.00	
>6.0														
5.5–6.0														
5.0–5.5				0.01	0.03								0.04	0.04
4.5–5.0			0.13	0.01	0.02	<0.01							0.16	0.20
4.0–4.5			0.05	0.01	0.02								0.07	0.27
3.5–4.0			0.20	0.02	0.02	0.01	<0.01						0.25	0.52
3.0–3.5			0.27	0.03	0.04	0.01	0.02	<0.01	0.01				0.38	0.89
2.5–3.0		0.07	0.25	0.13	0.11	<0.01		<0.01	0.01	0.01			0.59	1.49
2.0–2.5		0.19	0.49	0.23	0.10	0.03	0.04	0.01		0.03	0.02	<0.01	1.13	2.62
1.5–2.0	0.18	0.71	0.85	1.31	0.33	0.21	0.39	0.27	0.05	0.02	0.04	0.05	4.40	7.03
1.0–1.5	0.36	1.55	3.35	6.39	2.23	2.16	4.62	2.19	0.29	0.16	0.12	0.19	23.60	30.62
0.5–1.0	0.35	1.19	4.44	12.86	18.79	11.65	8.49	3.25	0.89	0.34	0.24	0.22	62.71	93.34
0.0–0.5	0.04	0.07	0.25	1.00	2.66	1.95	0.48	0.21				0.01	6.66	

Figure 2-93 Percentage Occurrence of Significant Wave Height and 30° Direction Bin - August

September

Significant Wave Height (m) vs. Mean Wave Direction (°T From)

Significant Wave Height (m)	000	030	060	090	120	150	180	210	240	270	300	330	Total %	Exceed %
Total	2.32	6.29	15.18	31.77	21.04	8.86	7.21	3.01	1.42	0.83	0.75	1.34	100.00	
>6.0				0.01	0.02								0.03	
5.5–6.0				0.03	0.01	<0.01							0.04	0.03
5.0–5.5				0.04	0.02	<0.01							0.06	0.07
4.5–5.0			0.06	0.03	0.02		<0.01						0.11	0.13
4.0–4.5			0.16	0.03	0.05	<0.01	<0.01	<0.01					0.26	0.24
3.5–4.0			0.28	0.02	0.03	0.02		<0.01	<0.01	0.01			0.36	0.49
3.0–3.5		0.19	0.46	0.19	0.04	0.03			0.02	<0.01			0.93	0.85
2.5–3.0	<0.01	0.40	0.78	0.60	0.20	0.11	0.05	0.01	0.02	0.03	<0.01		2.21	1.79
2.0–2.5	0.12	1.02	1.45	1.45	0.21	0.16	0.13	0.03	0.02	0.03	0.05	0.06	4.74	4.00
1.5–2.0	0.53	1.00	2.40	4.17	1.10	0.81	0.53	0.38	0.19	0.10	0.24	0.40	11.83	8.73
1.0–1.5	1.27	2.41	5.40	12.44	5.35	2.16	2.94	1.24	0.45	0.28	0.27	0.54	34.75	20.57
0.5–1.0	0.40	1.22	4.00	12.22	12.94	4.94	3.32	1.28	0.72	0.37	0.19	0.33	41.94	55.32
0.0–0.5		0.05	0.19	0.55	1.05	0.61	0.23	0.05	<0.01	<0.01	<0.01		2.75	97.25

Figure 2-94 Percentage Occurrence of Significant Wave Height and 30° Direction Bin - September

October

Significant Wave Height (m)	000	030	060	090	120	150	180	210	240	270	300	330	Total %	Exceed %
Total	6.56	12.61	18.74	22.86	13.38	6.79	5.39	2.84	2.19	2.38	2.26	3.99	100.00	
5.5–6.0														
5.0–5.5			0.04	0.03									0.07	0.07
4.5–5.0		0.06	0.10	0.01	<0.01								0.17	0.24
4.0–4.5		0.04	0.16	0.01	0.02								0.22	0.45
3.5–4.0		0.04	0.35	0.02	0.02								0.42	0.87
3.0–3.5	<0.01	0.49	0.63	0.07	0.05	0.02	0.02	0.01	0.03				1.32	2.19
2.5–3.0	0.21	0.69	1.33	0.20	0.04	0.12		0.01	0.02	0.06	0.05	0.10	2.82	5.01
2.0–2.5	0.66	1.58	2.66	1.16	0.22	0.21	0.20	0.07	0.06	0.14	0.08	0.17	7.21	12.22
1.5–2.0	1.66	2.93	2.88	2.27	0.78	0.57	0.58	0.30	0.31	0.54	0.62	1.18	14.62	26.85
1.0–1.5	2.86	4.01	5.04	9.32	2.72	1.77	2.03	1.48	0.94	0.75	0.82	1.74	33.46	60.31
0.5–1.0	1.12	2.65	5.11	9.08	8.77	3.65	2.50	0.90	0.81	0.77	0.65	0.71	36.72	97.03
0.0–0.5	0.04	0.14	0.46	0.69	0.76	0.45	0.07	0.07	0.03	0.13	0.04	0.09	2.97	

Mean Wave Direction (°T From)

Figure 2-95 Percentage Occurrence of Significant Wave Height and 30° Direction Bin - October

November

Significant Wave Height (m)	000	030	060	090	120	150	180	210	240	270	300	330	Total %	Exceed %
Total	10.39	14.29	12.60	14.33	10.14	6.37	6.76	5.17	4.39	4.02	5.35	6.20	100.00	
5.5–6.0														
5.0–5.5														
4.5–5.0			<0.01	0.01									0.02	0.02
4.0–4.5			0.02	0.06		0.02	<0.01						0.11	0.13
3.5–4.0			0.42	0.06	0.02	0.02	0.01						0.53	0.66
3.0–3.5	0.01	0.16	0.16	0.02	0.14	0.07	0.05	0.02	0.01	0.02	0.01	0.10	0.77	1.43
2.5–3.0	0.46	0.52	0.28	0.37	0.13	0.15	0.20	0.03	0.10	0.14	0.14	0.42	2.93	4.36
2.0–2.5	1.60	1.22	0.57	0.93	0.12	0.40	0.68	0.51	0.37	0.49	0.88	1.07	8.83	13.19
1.5–2.0	3.42	3.40	1.53	1.68	0.66	0.81	1.23	1.09	0.93	0.88	1.57	1.90	19.10	32.30
1.0–1.5	3.05	4.93	3.79	4.11	3.58	1.62	2.32	1.76	1.74	1.31	1.55	1.37	31.14	63.43
0.5–1.0	1.75	3.69	4.81	5.92	4.82	2.79	1.93	1.61	1.15	1.13	1.04	1.28	31.92	95.36
0.0–0.5	0.10	0.37	1.01	1.16	0.67	0.48	0.32	0.16	0.09	0.05	0.17	0.06	4.64	

Mean Wave Direction (°T From)

Figure 2-96 Percentage Occurrence of Significant Wave Height and 30° Direction Bin - November

December

Significant Wave Height (m)	000	030	060	090	120	150	180	210	240	270	300	330	Total %	Exceed %
Total	11.42	15.20	13.25	10.12	4.45	4.99	6.41	5.86	5.40	5.38	7.71	9.81	100.00	
>6.0														
5.5–6.0														
5.0–5.5														
4.5–5.0		0.03			0.01								0.04	0.04
4.0–4.5		0.03	0.08		0.02								0.13	0.17
3.5–4.0	0.01	0.13	0.14	0.18	0.04	0.03							0.53	0.70
3.0–3.5	0.42	0.50	0.39	0.05	0.11	0.07	0.05	0.03	0.06	0.02	0.02	0.17	1.89	2.59
2.5–3.0	0.83	0.73	0.55	0.16	0.08	0.19	0.17	0.07	0.12	0.13	0.37	0.54	3.94	6.53
2.0–2.5	1.80	1.80	0.75	0.52	0.22	0.37	0.43	0.39	0.43	0.56	1.45	1.86	10.60	17.13
1.5–2.0	3.31	3.86	1.60	1.17	0.49	0.44	1.38	1.38	1.17	1.21	2.14	2.69	20.83	37.97
1.0–1.5	3.02	4.57	4.34	3.49	1.25	1.16	2.16	2.24	2.19	1.89	2.31	3.27	31.88	69.85
0.5–1.0	1.86	3.31	4.78	3.99	1.95	2.26	2.03	1.65	1.36	1.53	1.38	1.21	27.30	97.15
0.0–0.5	0.17	0.23	0.61	0.57	0.28	0.48	0.19	0.10	0.07	0.04	0.05	0.06	2.85	

Mean Wave Direction (°T From)

Figure 2-97 Percentage Occurrence of Significant Wave Height and 30° Direction Bin - December

2.4.3 Joint Frequency Distribution of Significant Wave Height and Zero Up-Crossing Period

All-Year

Significant Wave Height (m)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	Total %	Exceed %
Total							1.30	18.61	34.88	24.19	12.28	5.66	2.01	0.69	0.23	0.09	0.04	0.01	<0.01	100.00	
>6.0															<0.01	<0.01				<0.01	
5.5–6.0															<0.01	<0.01				<0.01	
5.0–5.5														<0.01	<0.01	<0.01				0.02	0.03
4.5–5.0													<0.01	0.05	<0.01	<0.01				0.06	0.08
4.0–4.5													0.06	0.05	<0.01					0.12	0.20
3.5–4.0												0.08	0.21	0.03	<0.01					0.32	0.52
3.0–3.5											0.12	0.69	0.15	0.01	<0.01					0.98	1.50
2.5–3.0										0.09	1.54	0.64	0.06	0.02	<0.01	<0.01	<0.01	<0.01		2.35	3.85
2.0–2.5									0.02	3.43	2.03	0.39	0.09	0.03	0.02	<0.01	<0.01	<0.01	<0.01	6.03	9.88
1.5–2.0								0.04	4.27	6.55	1.21	0.40	0.20	0.13	0.08	0.04	0.02	<0.01		12.95	22.83
1.0–1.5							0.04	3.61	15.44	4.76	2.08	1.21	0.71	0.24	0.07	0.02	<0.01			28.19	51.02
0.5–1.0							0.99	13.51	13.45	8.07	4.57	1.95	0.42	0.11	0.02	0.01	<0.01			43.11	94.13
0.0–0.5							0.28	1.46	1.69	1.29	0.74	0.30	0.09	0.01	<0.01					5.87	

Mean Zero-crossing Period (s)

Figure 2-98 All Year Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period

January

Significant Wave Height (m) vs. Mean Zero-crossing Period (s)

Hs (m) \ Tz (s)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	8.0–8.5	8.5–9.0	9.0–9.5	Total %	Exceed %
Total	2.33	18.93	36.57	25.95	9.98	4.37	1.14	0.26	0.13	0.25	0.04	0.05		100.00	
3.5–4.0						0.20	0.07							0.27	0.27
3.0–3.5					0.36	1.31	0.17	0.05	0.03					1.92	2.19
2.5–3.0				0.22	3.24	0.94	0.13	0.01	<0.01	0.02	0.01	0.02		4.59	6.77
2.0–2.5			0.05	8.09	2.60	0.54	0.07	0.07	0.04	0.04	<0.01	0.03		11.53	18.31
1.5–2.0		0.05	8.60	10.68	1.22	0.26	0.20	0.01	0.02	0.19	0.02			21.25	39.56
1.0–1.5	0.09	5.91	19.05	3.64	1.40	0.78	0.35	0.07	0.04	0.02				31.35	70.91
0.5–1.0	1.69	11.89	8.04	3.19	1.14	0.28	0.09	0.04						26.37	97.28
0.0–0.5	0.55	1.07	0.83	0.11	0.04	0.06	0.05							2.72	

Figure 2-99 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period - January

February

Significant Wave Height (m) vs. Mean Zero-crossing Period (s)

Hs (m) \ Tz (s)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	8.0–8.5	8.5–9.0	9.0–9.5	Total %	Exceed %
Total	1.37	17.65	34.54	24.80	11.69	6.38	1.96	1.18	0.43					100.00	
4.0–4.5							0.05							0.05	0.05
3.5–4.0						0.26	0.22							0.47	0.52
3.0–3.5					0.15	1.34	0.31	0.03						1.83	2.35
2.5–3.0				0.24	2.73	1.18	0.10	0.09	0.02					4.35	6.70
2.0–2.5			0.03	6.47	2.77	0.67	0.22	0.14	0.05					10.36	17.06
1.5–2.0		0.05	6.94	10.21	1.53	0.53	0.23	0.26	0.19					19.94	37.00
1.0–1.5	0.06	4.30	18.92	4.34	2.18	0.79	0.57	0.50	0.12					31.77	68.78
0.5–1.0	1.13	11.78	7.77	3.38	2.05	1.24	0.27	0.15	0.05					27.81	96.58
0.0–0.5	0.19	1.52	0.88	0.16	0.28	0.37	<0.01	<0.01						3.42	

Figure 2-100 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period - February

March

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	Total %	Exceed %
Total	1.30	16.33	33.07	25.89	13.58	5.81	2.69	1.14	0.19	0.01	100.00	
5.5–6.0									0.02	0.01	0.03	0.03
5.0–5.5								0.02	0.01		0.03	0.06
4.5–5.0							0.01	0.09	0.01		0.11	0.17
4.0–4.5							0.24	0.06			0.30	0.47
3.5–4.0						0.11	0.45	0.03			0.59	1.06
3.0–3.5					0.26	0.93	0.25	0.02			1.46	2.52
2.5–3.0				0.11	2.46	1.04	0.07	0.04	0.02		3.74	6.26
2.0–2.5			0.02	5.09	3.36	0.69	0.12	0.02			9.31	15.56
1.5–2.0		0.05	5.63	10.11	1.90	0.51	0.30	0.22	0.05		18.76	34.32
1.0–1.5	0.06	3.89	16.00	5.26	2.41	1.20	0.66	0.44	0.05		29.97	64.29
0.5–1.0	0.98	11.24	10.42	5.19	3.12	1.21	0.50	0.17	0.04		32.86	97.16
0.0–0.5	0.26	1.15	0.99	0.14	0.07	0.11	0.08	0.02			2.84	

Figure 2-101 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period - March

April

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	Total %	Exceed %
Total	1.81	17.79	38.41	22.32	11.08	5.20	2.35	0.80	0.17	0.06	100.00	
4.5–5.0								0.05			0.05	0.05
4.0–4.5							0.09	0.12			0.20	0.26
3.5–4.0						0.09	0.09	0.04			0.22	0.48
3.0–3.5					0.03	0.48	0.05	0.03			0.59	1.07
2.5–3.0				0.03	1.36	0.51	0.02	0.02			1.94	3.01
2.0–2.5			0.03	2.52	2.10	0.42	0.09	0.02	0.02	0.02	5.22	8.23
1.5–2.0		0.07	4.04	6.27	0.87	0.34	0.30	0.19	0.13	0.04	12.25	20.48
1.0–1.5	0.02	3.01	18.72	5.77	2.18	1.28	0.98	0.26	0.02		32.26	52.74
0.5–1.0	1.16	13.26	13.33	6.14	3.78	1.85	0.65	0.06			40.22	92.96
0.0–0.5	0.63	1.45	2.28	1.59	0.77	0.23	0.08				7.04	

Figure 2-102 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period - April

May

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	Total %	Exceed %
3.5–4.0						0.05	0.09			0.14	0.14
3.0–3.5						0.65	0.02			0.66	0.80
2.5–3.0					0.54	0.43	0.06			1.03	1.83
2.0–2.5			0.01	0.99	1.43	0.32	<0.01	0.03	0.03	2.80	4.63
1.5–2.0		0.04	1.54	3.22	1.41	0.35	0.16	0.11	0.12	6.93	11.56
1.0–1.5	0.03	2.85	11.52	4.20	2.31	1.94	0.60	0.19	0.14	23.76	35.33
0.5–1.0	0.92	13.76	16.16	12.07	8.09	3.99	0.67	0.14	<0.01	55.80	91.13
0.0–0.5	0.31	1.58	1.88	2.47	1.81	0.58	0.23	0.02		8.87	
Total	1.25	18.23	31.10	22.94	15.57	8.30	1.84	0.48	0.29	100.00	

Figure 2-103 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period - May

June

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	Total %	Exceed %
4.0–4.5								0.02	0.02	0.02
3.5–4.0								0.01	0.01	0.03
3.0–3.5							0.01		0.01	0.04
2.5–3.0					0.15	<0.01			0.15	0.19
2.0–2.5				0.19	0.52	0.02	0.01		0.74	0.93
1.5–2.0		<0.01	0.75	1.82	0.53	0.20	0.07		3.38	4.31
1.0–1.5	0.04	2.70	11.29	3.02	1.32	0.45	0.29		19.12	23.43
0.5–1.0	0.73	18.37	19.72	13.51	9.03	2.98	0.36		64.70	88.13
0.0–0.5	0.13	2.43	2.97	2.54	2.33	1.03	0.44		11.87	
Total	0.90	23.50	34.74	21.08	13.88	4.68	1.19	0.03	100.00	

Figure 2-104 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period - June

July

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	Total %	Exceed %
Total	1.25	30.48	38.30	19.40	7.35	2.73	0.33	0.10	0.03	0.03	100.00	
5.5–6.0												
5.0–5.5								0.02			0.02	0.02
4.5–5.0							<0.01	0.02	0.01		0.04	0.05
4.0–4.5							0.02	<0.01			0.02	0.07
3.5–4.0						0.01	0.01	<0.01			0.03	0.10
3.0–3.5						0.03	<0.01				0.03	0.13
2.5–3.0					0.05	<0.01					0.05	0.18
2.0–2.5				0.09	0.08						0.17	0.35
1.5–2.0		<0.01	0.89	1.35	0.09	0.08	0.03	0.03	0.01	0.02	2.51	2.86
1.0–1.5	0.03	2.72	10.41	1.85	0.50	0.07	0.07	0.03	0.01	<0.01	15.68	18.54
0.5–1.0	1.05	24.97	22.67	11.92	5.19	1.87	0.12				67.79	86.33
0.0–0.5	0.18	2.78	4.33	4.19	1.45	0.67	0.07				13.67	

Figure 2-105 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period - July

August

Significant Wave Height (m) \ Mean Zero-crossing Period (s)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	Total %	Exceed %
Total	0.52	16.82	38.07	24.15	12.58	5.80	1.31	0.48	0.18	0.10	100.00	
5.5–6.0												
5.0–5.5								0.02	0.02		0.04	0.04
4.5–5.0								0.16			0.16	0.20
4.0–4.5							0.04	0.04			0.07	0.27
3.5–4.0						0.03	0.20	0.02	<0.01		0.25	0.52
3.0–3.5					0.04	0.15	0.19				0.38	0.89
2.5–3.0					0.21	0.31	0.08				0.59	1.49
2.0–2.5			<0.01	0.38	0.55	0.20					1.13	2.62
1.5–2.0		0.01	0.92	2.19	1.07	0.16	0.05	0.01			4.40	7.03
1.0–1.5	<0.01	2.19	13.08	4.85	1.90	1.08	0.20	0.07	0.11	0.10	23.60	30.62
0.5–1.0	0.31	13.69	22.09	14.83	7.66	3.55	0.52	0.06	<0.01		62.71	93.34
0.0–0.5	0.21	0.92	1.97	1.90	1.16	0.32	0.04	0.10	0.04		6.66	

Figure 2-106 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period - August

September

Mean Zero-crossing Period (s)

Significant Wave Height (m)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	8.0–8.5	8.5–9.0	9.0–9.5	Total %	Exceed %
Total	0.26	10.28	29.97	25.11	17.55	9.67	4.65	1.78	0.45	0.14	0.14			100.00	
6.0–6.5									<0.01	0.02				0.03	0.03
5.5–6.0									0.02	0.02				0.04	0.07
5.0–5.5								0.02	0.04					0.06	0.13
4.5–5.0							0.01	0.09	0.01					0.11	0.24
4.0–4.5							0.18	0.08						0.26	0.49
3.5–4.0						0.03	0.32		0.01					0.36	0.85
3.0–3.5					0.02	0.74	0.16	0.01	0.01					0.93	1.79
2.5–3.0				0.01	1.05	1.06	0.05	0.03	0.01					2.21	4.00
2.0–2.5			0.02	1.23	2.79	0.64	0.07							4.74	8.73
1.5–2.0		0.03	1.96	5.16	2.27	1.24	0.56	0.32	0.13	0.06	0.10			11.83	20.57
1.0–1.5	<0.01	2.17	13.85	8.04	4.54	2.86	2.13	0.94	0.14	0.04	0.04			34.75	55.32
0.5–1.0	0.26	7.38	13.20	10.08	6.53	3.02	1.11	0.29	0.07					41.94	97.25
0.0–0.5		0.70	0.95	0.59	0.36	0.09	0.06							2.75	

Figure 2-107 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period - September

October

Mean Zero-crossing Period (s)

Significant Wave Height (m)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	8.0–8.5	8.5–9.0	9.0–9.5	Total %	Exceed %
Total	0.95	13.95	33.10	25.58	14.85	6.97	2.88	0.90	0.35	0.22	0.13	0.06	0.06	100.00	
6.0–6.5															
5.5–6.0															
5.0–5.5									0.03	0.04				0.07	0.07
4.5–5.0							0.01	0.09	0.07	<0.01				0.17	0.24
4.0–4.5							0.08	0.13	0.01					0.22	0.45
3.5–4.0						0.07	0.32	0.04						0.42	0.87
3.0–3.5					0.03	0.96	0.33	<0.01						1.32	2.19
2.5–3.0				0.03	1.78	0.89	0.10	0.02						2.82	5.01
2.0–2.5			0.02	2.60	3.63	0.59	0.18	0.01	0.03	0.02	0.03	0.04	0.06	7.21	12.22
1.5–2.0		0.05	4.08	7.49	1.98	0.44	0.26	0.18	0.10	0.02	<0.01	0.02		14.62	26.85
1.0–1.5	0.03	3.02	16.94	7.31	3.15	1.71	0.92	0.22	0.04	0.08	0.06			33.46	60.31
0.5–1.0	0.68	9.95	11.12	7.62	4.03	2.26	0.65	0.22	0.08	0.07	0.04			36.72	97.03
0.0–0.5	0.24	0.93	0.94	0.52	0.25	0.06	0.04							2.97	

Figure 2-108 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period - October

November

Significant Wave Height (m) vs. Mean Zero-crossing Period (s)

Hs (m) \ Tz (s)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	8.0–8.5	8.5–9.0	9.0–9.5	Total %	Exceed %
Total	1.84	18.31	34.78	27.24	10.37	4.34	2.06	0.46	0.41	0.10	0.08			100.00	
5.5–6.0															
5.0–5.5															
4.5–5.0								0.02						0.02	
4.0–4.5							0.04	0.05	0.03					0.11	0.02
3.5–4.0						0.02	0.39	0.10	0.02					0.53	0.13
3.0–3.5					0.15	0.52	0.09		0.02					0.77	0.66
2.5–3.0				0.12	2.08	0.70	0.01	0.01	0.01					2.93	1.43
2.0–2.5			0.01	6.01	2.30	0.30	0.18	0.03	<0.01					8.83	4.36
1.5–2.0		0.04	7.14	9.95	0.95	0.37	0.18	0.13	0.20	0.07	0.08			19.10	13.19
1.0–1.5	0.05	4.49	17.17	4.62	1.91	1.50	1.13	0.11	0.13	0.03				31.14	32.30
0.5–1.0	1.36	12.12	9.13	5.61	2.76	0.85	0.05	0.03						31.92	63.43
0.0–0.5	0.43	1.66	1.32	0.93	0.22	0.07								4.64	95.36

Figure 2-109 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period - November

December

Significant Wave Height (m) vs. Mean Zero-crossing Period (s)

Hs (m) \ Tz (s)	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	6.5–7.0	7.0–7.5	7.5–8.0	8.0–8.5	8.5–9.0	9.0–9.5	Total %	Exceed %
Total	1.85	20.78	35.80	25.89	8.97	3.81	1.76	0.69	0.18	0.18	0.04	0.04	0.01	100.00	
5.5–6.0															
5.0–5.5															
4.5–5.0							<0.01	0.03						0.04	
4.0–4.5							0.04	0.09						0.13	0.04
3.5–4.0						0.07	0.37	0.09						0.53	0.17
3.0–3.5					0.36	1.26	0.26							1.89	0.70
2.5–3.0				0.27	2.86	0.67	0.12	0.02						3.94	2.59
2.0–2.5			0.04	7.59	2.27	0.26	0.16	0.09	0.09	0.03	0.03	0.04	0.01	10.60	6.53
1.5–2.0		0.04	8.88	10.43	0.74	0.36	0.11	0.13	0.04	0.09				20.83	17.13
1.0–1.5	0.06	5.99	18.66	4.29	1.28	0.84	0.64	0.13		<0.01				31.88	37.97
0.5–1.0	1.61	13.44	7.31	3.02	1.35	[illegible]	0.05	0.11	0.05	0.05	0.02			27.30	69.85
0.0–0.5	0.19	1.31	0.91	0.29	0.11	0.04								2.85	97.15

Figure 2-110 Percentage Occurrence of Significant Wave Height and Zero Up-Crossing Period - December

2.5 Water Levels

2.5.1 Storm Surge

Extreme storm surge (positive and negative) criteria were derived using the winter storm and hurricane Oceanweather data and subtracting the tides. Tides were calculated using the TMD (Tidal Model Driver) over the EastCoast2001 model. Table 2-54 depics the highest values for storm surge between winter storms and hurricanes.

Extreme Winter Storm Surge	Return Period					
	1-year	50-years	100-years	500-years	1000-years	10000-years
Positive Surge [m]	0.44	0.96	1.03	1.22	1.30	1.57
Negative Surge [m]	-0.34	-1.06	-1.19	-1.49	-1.62	-2.04

Table 2-52 Extreme Winter Storm Surge (positive and negative)

Extreme Hurricane Surge	Return Period					
	1-year	50-years	100-years	500-years	1000-years	10000-years
Positive Surge [m]	0.24	1.39	1.58	2.02	2.21	2.84
Negative Surge [m]	-0.29	-0.55	-0.59	-0.7	-0.74	-0.89

Table 2-53 Extreme Hurricane Surge (positive and negative)

Extreme Surge	Return Period					
	1-year	50-years	100-years	500-years	1000-years	10000-years
Positive Surge [m]	0.44	1.39	1.58	2.02	2.21	2.84
Negative Surge [m]	-0.34	-1.06	-1.19	-1.49	-1.62	-2.04

Table 2-54 Extreme Surge (positive and negative)

2.5.2 Tides

To produce the tidal descriptors in Table 2-55, the water elevation time series obtained with TMD (Section 3.1.3). Tides are presented relative to lowest astronomical tide (LAT).

TIDAL LEVELS	LAT (m)
Highest Still Water Level (HSWL)	2.98
Highest Astronomical Tide (HAT)	1.46
Mean Higher High Water (MHHW)	1.22
Mean Sea Level (MSL)	0.67
Mean Lower Low Water (MLLW)	0.16
Mean Low Water Spring (MLWS)	0.06
Lowest Astronomical Tide (LAT)	0
Lowest Stil Water Level (LSWL)	-1.06

Table 2-55 Tidal Levels in Relative to LAT

2.5.3 Chart Datum vs Land Survey Datum

The nearest identified station between chart datums is Duck. Duck is located offshore North Carolina at 36° 11' N, 75° 44.8' W, and is approximately 81 km from the target sites. Based on comparisons, TMD and at Duck, we believe it is reasonable to use the relationship in Table 2-56 to relate offshore data to the North American Vertical Datum 1988 (NAVD 88). Table 2-56 is in relative to mean low low water (MLLW).

TIDAL LEVELS	Duck	TMD
	MLLW (m)	MLLW (m)
NAVD 88	0.67	-
Mean Higher High Water (MHHW)	1.12	1.06
Mean High Water (MHW)	1.03	0.98
Diurnal Tide Level (DTL)	0.56	0.53
Mean Sea Level (MSL)	0.54	0.51
Mean Tide Level (MTL)	0.54	0.50
Mean Low Water (MLW)	0.04	0.02
Lowest Astronomical Tide (LAT)	0	0

Table 2-56 Chart Datum Comparison

2.6 Air Temperature and Density

Air temperature and density were derived from 29-years (1984 to 2012) of measured NDBC Station CHLV2 data.

COMBINED PERIOD (1984 to 2012)	Air Temperature [C]			Air Density [kg/m^3]		
	MIN	MAX	STD DEV.	MIN	MAX	STD DEV.
All Year	-16.70	33.10	7.91	1.12	1.36	0.04
January	-16.70	21.20	4.91	1.18	1.36	0.03
February	-9.50	21.10	4.27	1.18	1.34	0.03
March	-6.50	24.90	4.23	1.17	1.34	0.03
April	0.00	29.10	3.86	1.16	1.28	0.02
May	8.00	31.30	3.54	1.16	1.26	0.02
June	12.10	32.20	2.85	1.14	1.22	0.01
July	17.20	33.10	1.99	1.14	1.21	0.01
August	16.50	32.30	1.89	1.12	1.20	0.01
September	12.60	30.80	2.39	1.14	1.23	0.01
October	5.90	29.30	3.44	1.15	1.28	0.02
November	-0.20	24.40	3.95	1.18	1.31	0.02
December	-8.80	23.00	4.59	1.18	1.33	0.03

Table 2-57 Air Temperature and Density

2.7 Seawater Temperature, Salinity and Density

Seawater temperature, salinity, and density were derived from 7-years (2006 to 2012) of Rutgers University's ESPreSSO (Experimental System for Predicting Shelf and Slope Optics) hindcast data from gridpoint 36.8587°N, 75.5139°W.

COMBINED PERIOD (2006 to 2012)	Seawater Temperature [C]			Seawater Salinity [PSU]			Seawater Density [kg/m^3]		
	MIN	MAX	STD DEV.	MIN	MAX	STD DEV.	MIN	MAX	STD DEV.
All Year	3.75	29.87	6.84	24.04	34.47	1.55	1014.92	1026.33	2.32
January	4.66	13.46	1.82	27.43	33.68	1.15	1020.72	1025.97	0.96
February	3.75	9.75	1.36	26.08	33.90	0.97	1020.24	1026.33	0.73
March	4.26	15.39	1.63	27.63	33.55	1.14	1021.21	1026.23	0.99
April	7.17	15.83	1.78	24.04	33.14	1.37	1018.04	1025.58	1.26
May	9.56	22.24	2.34	24.81	33.42	1.75	1017.59	1025.43	1.63
June	18.12	26.92	1.72	24.67	32.89	1.68	1015.95	1023.07	1.46
July	20.14	28.32	1.21	24.19	34.42	1.97	1014.92	1022.57	1.60
August	22.57	29.87	1.17	26.61	34.47	1.68	1016.32	1022.17	1.41
September	19.37	26.97	1.26	28.07	32.48	0.83	1017.91	1022.80	0.83
October	15.96	24.70	1.75	28.58	32.77	0.88	1019.20	1023.57	0.86
November	10.86	20.47	1.67	27.26	32.98	0.90	1020.55	1024.52	0.71
December	7.03	*15.83*	1.55	26.32	33.04	0.88	1019.53	1025.27	0.79

Table 2-58 Seawater Temperature, Salinity and Density at Near Surface

2.8 Seawater Mechanical and Thermal Properties

Overall statistics of kinematic viscosity, specific heat capacity and thermal conductivity of seawater (Table 2-59) were calculated following Sharqawy et al. (2010)[6] using the ESPreSSO modelled temperature and salinity data near the surface (~0.1MPa of pressure).

Property	MIN	MAX	MEAN	STD DEV.
Kinematic Viscosity [m^2/s]	8.3614e-07	1.6307e-06	1.1736e-06	2.0497e-07
Specific Heat Capacity [J/kg-K]	4001	4056.5	4018.9	9.1989
Thermal Conductivity [W/m-K]	0.5763	0.61563	0.5960	0.0103

Table 2-59 Thermal and Mechanical Properties of Seawater Near The Surface.

[6] Sharqawy, Mostafa H., John H. Lienhard V and Syed M. Zubair. "The thermophysical properties of seawater: A review of existing correlations and data." Desalination and Water Treatment, 16 (April 2010) 354–380.

2.9 Effects of Climate Change for The Next 25 Years

Climate-related changes have already been observed globally and in the United States. It has been well accepted that greenhouse gas concentrations in the atmosphere will continue to increase unless the billions of tons of our annual emissions decrease substantially. Continued emissions of greenhouse gases will lead to further climate changes. Future changes are expected to include a warmer atmosphere, a warmer and more acidic ocean, higher sea levels, and larger changes in precipitation patterns. The Global Climate Change Impacts in the United States report the U.S. Global Change Research Program (2009) indicated that likely future changes for the United States and surrounding coastal waters include more intense hurricanes with related increases in wind, rain, and storm surges (but not necessarily an increase in the number of these storms that make landfall), as well as drier conditions in the Southwest and Caribbean. These changes will affect human health, water supply, agriculture, coastal areas, and many other aspects of society and the natural environment. The effects to the wind farm projects for the next 25 years would be on extreme wind speed, wave height, currents and water level, which are associated with tropical cyclones in the area.

In response to future anthropogenic climate warming, tropical cyclones could potentially change in a number of important ways, including frequency, intensity, size, duration, tracks, area of genesis or occurrence, precipitation, and storm surge characteristics.

2.9.1 Change in Extreme Wind Speed due to Climate Change Over The Next 25 Years

The following is quoted from Weather and Climate Extremes in a Changing Climate report lead by William J. Gutowski, Jr. "In summary, theory and high-resolution idealized models indicate increasing intensity and frequency of the strongest hurricanes and typhoons in a CO2-warmed climate. Parts of the Atlantic basin may have small decreases in the upper limit intensity, according to one multimodel study of theoretical potential intensity. Expected changes in tropical cyclone intensity and their confidence are therefore assessed as follows: in the Atlantic and North Pacific basins, some increase of maximum surface wind speeds of the strongest hurricanes and typhoons is likely. We estimate the likely range for the intensity increase (in terms of maximum surface winds) to be about **1 to 8% per °C** tropical sea surface warming over most tropical cyclone regions. This range encompasses the broad range of available credible estimates, from the relatively low 1.3% per °C area average estimate by Vecchi (personal communication, 2007) of Vecchi and Soden (2007) to the higher estimate (5% per °C) of Emanuel (1987, 2005), and includes some additional subjective margin of error in this range. The ensemble sensitivity estimate from the dynamical hurricane modeling study of Knutson and Tuleya (2004) of 3.7% per °C is near the middle of the above range. Furthermore, the available evidence suggests that maximum intensities may decrease in some regions, particularly in parts of the Atlantic basin, even though sea surfaces are expected to warm in all regions." (Gutowski, 2008)[7]

During the past 30 years, annual sea surface temperature in the main Atlantic hurricane development region increased nearly 2°F. Projections are that sea surface temperatures in the main Atlantic hurricane development region will increase at even faster rates (see Figure 2-111), there is a good

[7] Gutowski, W.J., G.C. Hegerl, G.J. Holland, T.R. Knutson, L.O. Mearns, R.J. Stouffer, P.J. Webster, M.F. Wehner, and F.W. Zwiers, 2008: Causes of observed changes in extremes and projections of future changes. In: Weather and Climate Extremes in a Changing Climate: Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands [Karl, T.R., G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.)]. Synthesis and Assessment Product 3.3. U.S. Climate Change Science Program, Washington, DC, pp. 81-116.

chance that 1°C or 1.8°F temperature increase would happen in the next 25 years, so the extreme wind speed would increase by 1 to 8 percent. (Karl, 2008)[8]

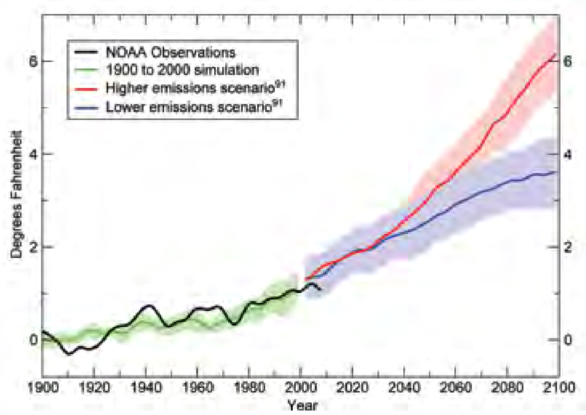

Figure 2-111 Observed (black) and projected temperatures (blue = lower scenario; red = higher scenario) in the Atlantic hurricane formation region. Increased intensity of hurricanes is linked to rising sea surface temperatures in the region of the ocean where hurricanes form. The shaded areas show the likely ranges while the lines show the central projections from a set of climate models. (Karl, 2008)[6]

2.9.2 Change in Extreme Wave Height due to Climate Change Over The Next 25 Years

The heights and periods of the waves generated are governed by the wind velocity and the duration or time that the wind blows. The third important factor is the fetch, the distance over which the wind blows. The fetch distance restricts the time during which individual waves are moving under the action of the wind and therefore governs the time during which energy can be transferred from wind to waves. For fetch limited condition, U.S. Army Corps of Engineers Shore Protection Manual (SPM) model gives:

$$Hs = 1.616 \times 10^{-2} U_A F^{1/2} = 1.616 \times 10^{-2} \times 0.71 U^{1.23} F^{1/2}$$

Where UA is an "adjusted wind speed", U is the actual wind speed and F is fetch. The significant wave height Hs would increase by 1.2% to 9.9% in the next 25 years give the 1 to 8% wind speed increase, assume wind fetch does not change.

2.9.3 Change in Extreme Currents due to Climate Change Over The Next 25 Years

The extreme currents would also increase due to increase of extreme wind speed. In deep water along open coastlines, API 2A-WSD recommended that surface storm current can be roughly estimated to have speeds up to 2-3 percent of the one-hour sustained wind speed during tropical storms and hurricanes and up to 1% of the one-hour sustained wind speed during winter storms or extratropical cyclones. As the storm approaches shallow water and the coastline, the current can increase.

[8] Karl, T.R., G.A. Meehl, T.C. Peterson, K.E. Kunkel, W.J. Gutowski Jr., and D.R. Easterling, 2008: Executive summary. In: *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands* [Karl, T.R., G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.)]. Synthesis and Assessment Product 3.3. U.S. Climate Change Science Program, Washington, DC, pp. 1-9.

2.9.4 Sea Level Rise due to Climate Change Over The Next 25 Years

Several recent studies (Boon, 2012; Ezer and Corlett, 2012a, 2012b; Ezer, Atkinson et al, 2013; Sallenger et al., 2012)[9][10][11][12][13] indicate that the rates of sea level rise (SLR) have been accelerating along the coastal mid-Atlantic region. Over the past few decades the pace of relative sea level rise in the Chesapeake Bay has been 2 to 3 times faster than that of the global average (from 1.8 mm/y for 1961-2003 to 3.1 mm/y for 1993-2003), a trend that may continue during the coming decades. As a result, low-lying coastal communities in the mid-Atlantic region, such as the Hampton Roads area in the Chesapeake Bay, have seen a significant increase in the frequency of flooding in recent years (Mitchell et al., 2013)[14]. Future projections of SLR depend on estimates of past SLR rates and potential SLR acceleration. For example, the U.S. Army Corps of Engineers introduces 3 SLR scenarios based on assessment of the National Research Council (NRC), they include SLR of 0.5m (NRC-I scenario), 1.0m (NRC-II) and 1.5m (NRC-III) between 1986 and 2100. In Figure 2-112, Ezer and Corlett compared various SLR projection scenarios for 4 Chesapeake Bay locations with long records, Baltimore and Annapolis in the northern Chesapeake Bay and Kiptopeke and Sewells Point in the southern Chesapeake Bay and close to the study area. Based on the projection, there will be 3 to 9cm sea level rise at the study site in the next 25 years.

[9] Boon, J. D. (2012) Evidence of sea level acceleration at U.S. and Canadian tide stations, Atlantic coast, North America, J. Coast. Res., 28(6), 1437–1445, doi:10.2112/JCOASTRES-D-12-00102.1.
[10] Ezer, T., and W. B. Corlett (2012a), Is sea level rise accelerating in the Chesapeake Bay? A demonstration of a novel new approach for analyzing sea level data, Geophys. Res. Lett., 39, L19605, doi:10.1029/2012GL053435.
[11] Ezer, T., and W. B. Corlett (2012b), Analysis of relative sea level variations and trends in the Chesapeake Bay: Is there evidence for acceleration in sea level rise? Proc. Oceans'12 MTS/IEEE, October 14–19, IEEE Xplore, doi:10.1109/OCEANS.2012.6404794.
[12] Ezer, T., L. P. Atkinson, W. B. Corlett and J. L. Blanco (2013), Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast, J. Geophys. Res. Oceans, 118, 685–697, doi:10.1002/jgrc.20091.
[13] Sallenger A.H., Doran K. S., and Howd, P., 2012, Hotspot of accelerated sea-level rise on the Atlantic coast of North America, Nature Climate Change 2: 884-888.
[14] Mitchell, M., C. Hershner, J. Herman, D. Schatt, E. Eggington, and S. Stiles (2013), Recurrent flooding study for Tidewater Virginia, Report SJR 76, 2012, 141 pp., Virginia Institute of Marine Science, Gloucester Point, Va.

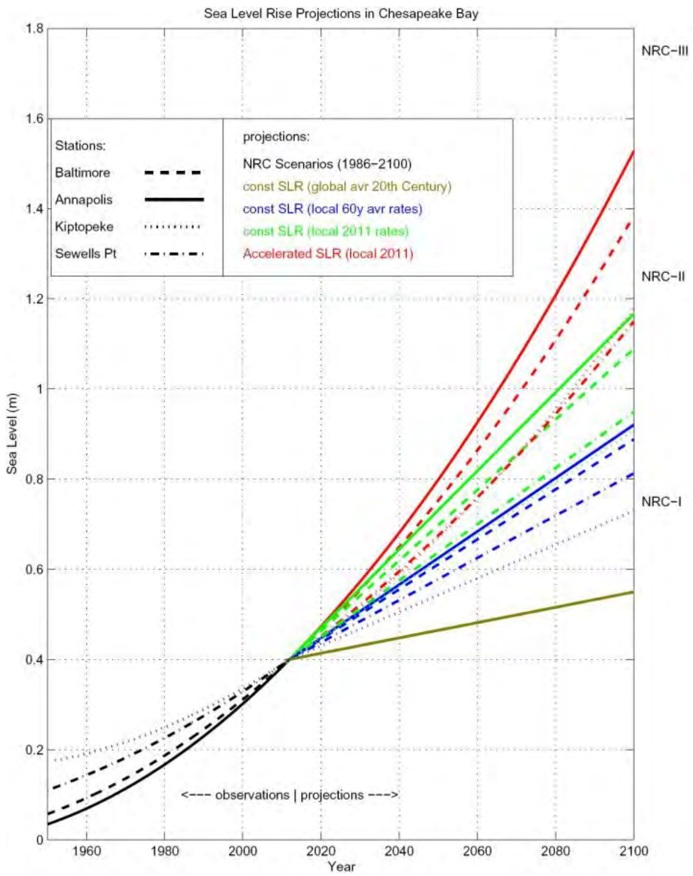

Figure 2-112 Sea Level Projections in Chesapeake Bay (from Ezer and Corlett, 2012b)

2.10 Snow and Sea Ice

Since the wind farm site is at such a low altitude, snow and ice would not be effecting design factors. For detail description with respect to ice loads follow IEC 61400-3[3], Annex E.

3 CRITERIA REVIEW

3.1 Data Sources

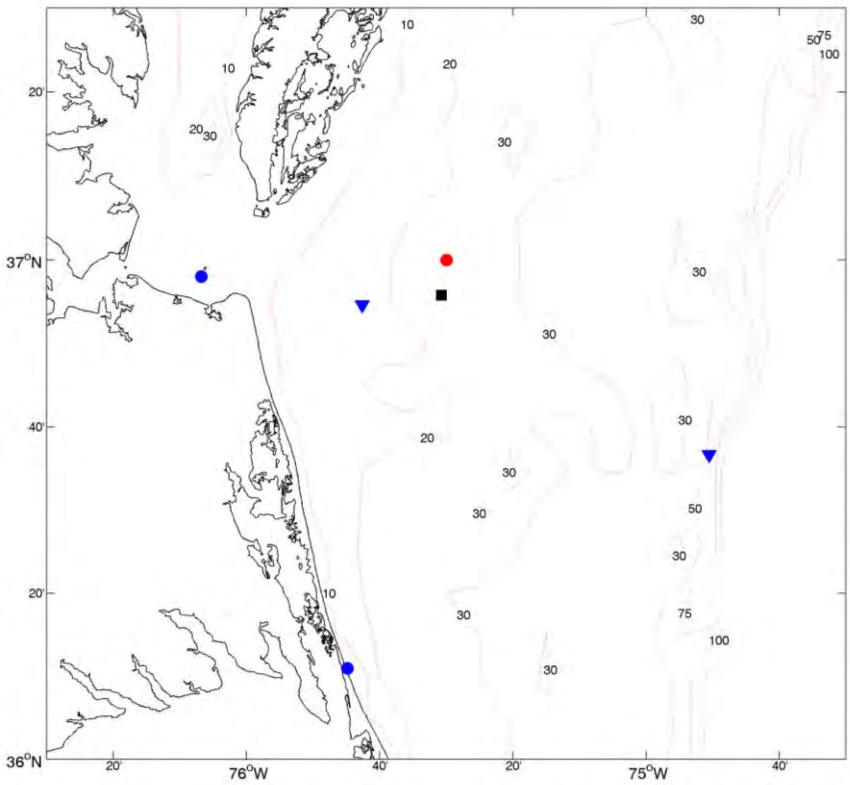

Figure 3-1 Data sources (blue triangles: NDBC Buoys; red dots: Oceanweather gridpoints; blue dot: tidal gauge) and target site (black square).

Table 3-1 Public Domain Metocean Data

Data Sources	Location	Wind	Wave	Current	Water Level	Air Temperature	Seawater
Oceanweather EE002791	37.000°N 75.500°W	1957~2003	1957~2003	N	1957~2003	N	N
Oceanweather EO002791	37.000°N 75.500°W	1980~2005	1980~2005	N	N	N	N
Oceanweather ET002791	37.000°N 75.500°W	1924~2005	1924~2005	N	1924~2005	N	N
NDBC Station 44014	36.611°N 74.842°W	1990~Present	1990~Present	3/1/97~3/31/97 3/1/10~present	N	1990~Present	Temperature 1990~Present
NDBC Station CHLV2	36.910°N 75.710°W	8/21/84~Present	1984~2004	N	N	8/21/84~Present	Temperature 8/21/84~Present
NDBC Tidal Gauge 8651370	36.183°N 75.747°W	6/1/91-Present	N	N	6/01/78-Present	6/1/91-Present	Temperature 11/12/92-Present
NOAA Tidal Gauge 8638863	36.967°N 76.113°W	6/1/91-Present	N	N	1/26/75-Present	6/1/91-Present	Temperature 6/1/91-Present
ESPreSSO	36.859°N 75.514°W	N	N	1/3/06-12/31/12	N	N	Temperature 1/3/06-12/31/12

3.1.1 Wind/Wave Data Sources

Wind and wave criteria would be derived from the Oceanweather hindcast database Global Reanalysis of Ocean Waves U.S East Coast (GROW-FINE EC28km) and measured wind and wave data at the NDBC stations in the area. The existing data in the area are shown in Figure 3-1 and Table 3-1. Cross checking and comparison would be performed.

The GROW-FINE EC28km hindcast model is Oceanweather's state of the art third generation wave model. It is both an update and an enhancement of existing GROW200. GROW-FINE EC28km serves to both update and improve upon GROW200 in the following ways:

- Decrease of grid spacing from 0.625 degrees latitude by 1.25 degrees longitude to a grid of 15-minute (~28km) spacing.
- The hindcast wave model incorporates shallow water third-generation physics.
- Inclusion of significant tropical and winter storms.
- Output from the ADCIRC hydrodynamical model for estimates of storm surge and vertically average currents in storm conditions.
- The grid points archived with spectra have been greatly expanded to every coastal point along the U.S. East Coast.

Extreme value analyses would be carried out on the hindcast and measured data sets of wind speed and significant wave height to produce extreme criteria associated with the specified return periods. Directional extremes would be derived by scaling the omni-directional values by relative severity factors for each directional sector.

Wind speeds at elevations greater than 10m ASL with duration other than 1hour will be derived using the equations recommended in ISO19901-1:2005.

The crest height and maximum wave height with a probability of exceedence of 63%, 50%, 10% and 1% would be derived from analysis fo storm events using our EXWAN software which addresses the short term probability distribution function for these parameters in the storm rather than an individual seastate which can lead to underestimation. Associated wave period parameters would be calculated from derived empirical relationships between wave height and period.

Near-bed horizontal wave orbital velocity will be derived from Hs and Tp using stream function wave theory.

The number of individual wave heights and periods that a structure is likely to encounter during a given return period will be derived by numerical simulation. A summary of the method is given below:

- Estimate the wave spectrum from Hs and Tp.
- Simulate a Gaussian time series from the wave spectrum.
- Transform the Gaussian time series to non-Gaussian using an appropriate transformation function.

Estimate individual wave heights and periods from the non-Gaussian time series.

3.1.2 Current Data

The currents criteria would be derived from the Rutgers University's ESPreSSO (Experimental System for Predicting Shelf and Slope Optics) hindcast from 2006 (http://www.myroms.org/espresso/). The ESPreSSO model covers the Mid-Atlantic Bight from the center of Cape Cod southward to Cape

Hatteras, from the coast to beyond the shelf break and shelf/slope front. The model domain is shown in Figure 3-2.

The prototype system is a 5-km horizontal, 36-level ROMS model with Incremental Strong Constraint 4DVAR assimilation of AVHRR and daily composite SST (remss) and along track altimeter SSH anomalies (RADS). The initial conditions were MOCHA Mid-Atlantic Bight climatology dynamically adjusted by ROMS IS4DVAR. Meteorological forcing is NCEP/NAM 12-km 3-hourly forecast data. Boundary conditions are from HYCOM NCODA forecast system. Tide boundary conditions are from the ADCIRC tidal model. River discharges from major rivers are also considered.

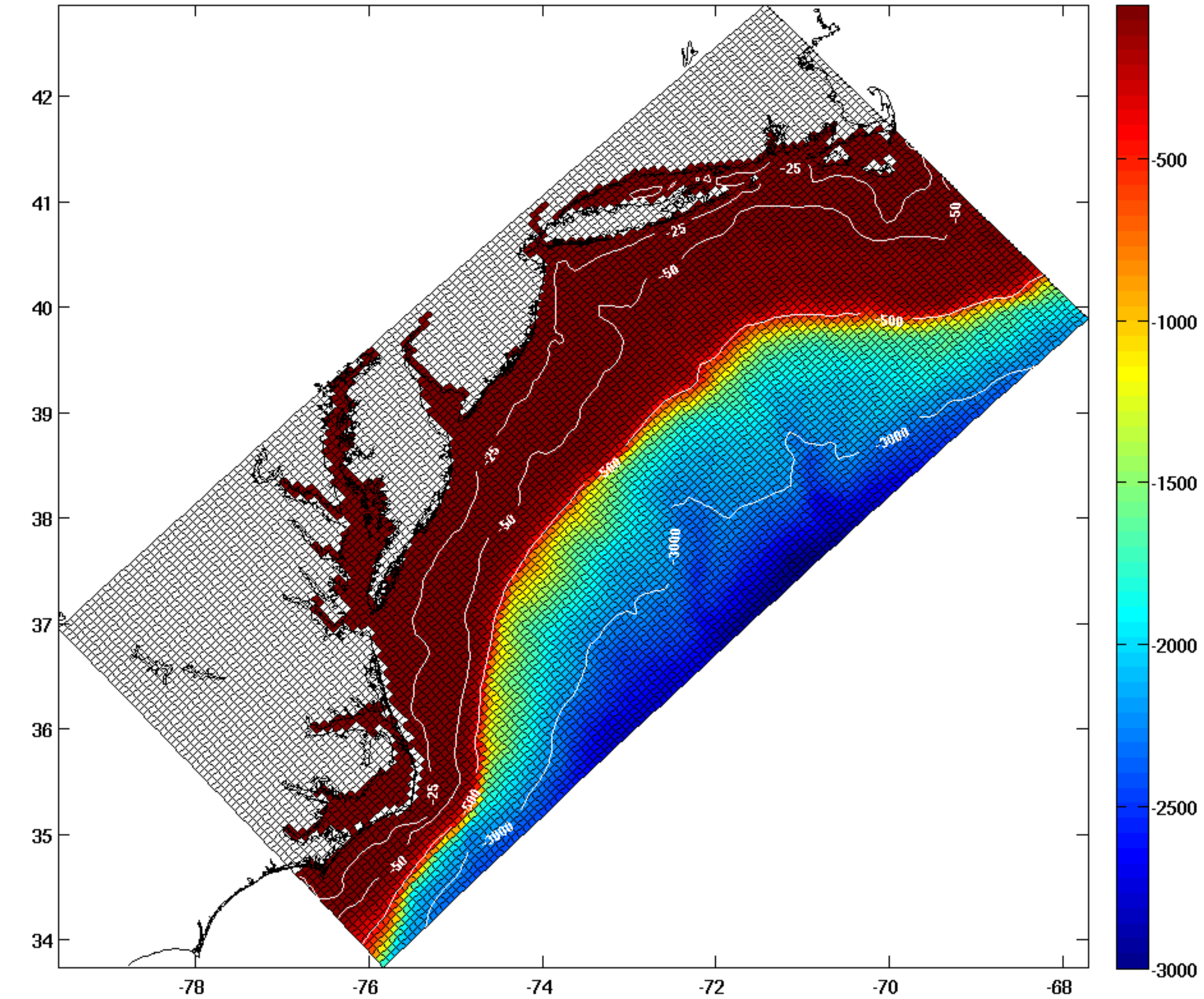

Figure 3-2 EXPreSSO Model Domain Grids

The model data would be verified/calibrated using the any available measurements in the area (HF Radar surface current measurement, near surface currents at NDBC buoy 44014, etc).

Extreme value analyses would be carried out on the hindcast current data to produce extreme criteria associated with the specified return periods. Directional extremes would be derived by scaling the omni-directional values by relative severity factors for each directional sector.

3.1.3 Water Level

Tidal information would be derived from Oregon State University East Coast 1/30° model. The harmonic constituents in this model were derived from TOPEX/POSEIDON satellite altimeter data which were inverted and assimilated into a global barotropic tidal model. The model has been validated using 179 shallow water tide gauge data. The model constituents would be accessed using TMD (Tide Model Driver), a MATLAB package that allows the user to create tidal predictions from the harmonic constituents for a specified location and duration. Surge would be derived from Oceanweather hindcast database Global Reanalysis of Ocean Waves U.S East Coast (GROW-FINE EC28km).

3.1.4 Air Temperature

Air temperature statistics would be derived from NDBC station CHLV2 measured data.

3.1.5 Seawater Temperature

Seawater temperature statistics would be derived from measured surface temperature data in the area and ESPreSSO model temperature hindcast through the depth. The existing measurements in the area are shown in Figure 3-1 and Table 3-1. Cross checking and comparison would be performed.

3.1.6 Seawater Salinity and Density

Seawater salinity statistics would be derived from ESPreSSO model temperature hindcast through the depth. The seawater density would be calculated from salinity and temperature and depth.

3.1.7 Effects of Climate Change

The effects of climate change would be quantified based on literature review and long term measurements in the tidal gauges in the study area.

4 DATA VALIDATION

The grid point from Oceanweather was selected due to the proximity and similar water depth to the target site. The grid point is located at 37°N 75.5°W with a water depth of 25 m. Oceanweather wind and wave hindcast data were compared to NDBC Station CHLV2, located at 36.91°N 75.71°W with a water depth of 19 m. Wind speed values have been converted to hub height using the equation in Section 2.1.10, with a power exponent value of 0.14. CHLV2 anemometer height is 43 m above mean sea level and significant wave height measured by fixed wave staff.

4.1 Data Comparison

Figure 4-1 below, shows 1 to 99% quantile-quantile plot of Oceanweather hindcast versus measured data. The black line in the graphs indicates a 1 to 1 ratio, which means that the distribution of the measured data is the same as that of the hindcast data. Model wind speeds are slightly higher than the measured which could be due to the difference in location and serve as a more conservative value. Significant wave height shows an almost 1 to 1 ratio, which would suggest that the distributios of significant wave heights at both locations are roughly the same. Figure 4-2 are scatter plots of the hindcast model data versus measured data. These graphs help to illustrate a near linear relationship between the two data sets. Again the black line illustrates a 1 to 1 ratio and the red line shows the best fit for the data. Based on these results, the hindcast data were used with no calibration.

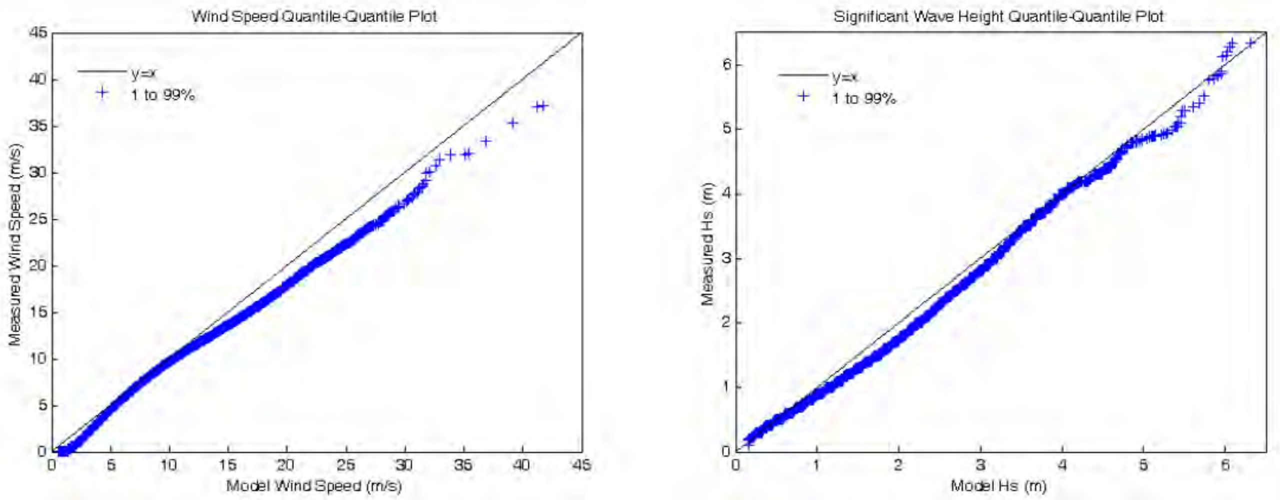

Figure 4-1 Wind Speed and Significant Wave Height Quantile-Quantile Plot

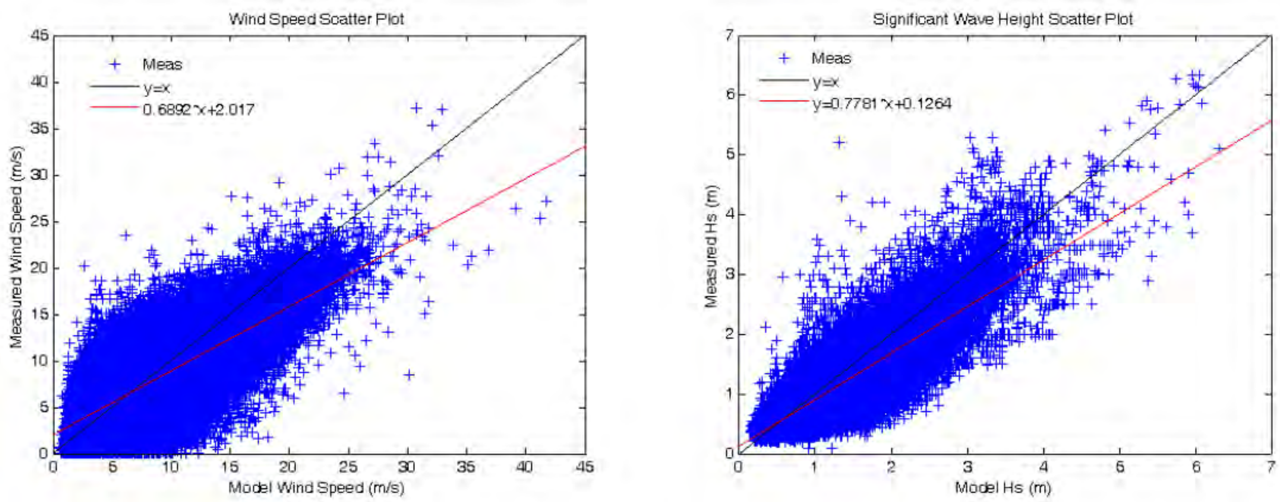

Figure 4-2 Wind Speed and Significant Wave Height Scatter Plot

4.2 Oceanweather Validation

Oceanweather provided their own validations for grid point located at 36.75°N 74.75°W, with a water depth of 137 m. This grid point was compared with NDBC Buoy 44014 located at 36.61°N 74.84°W, with a water depth of 95 m. The results of the comparison are shown below. (Oceanweather did not provided an explanation of the methodology used for this validation)

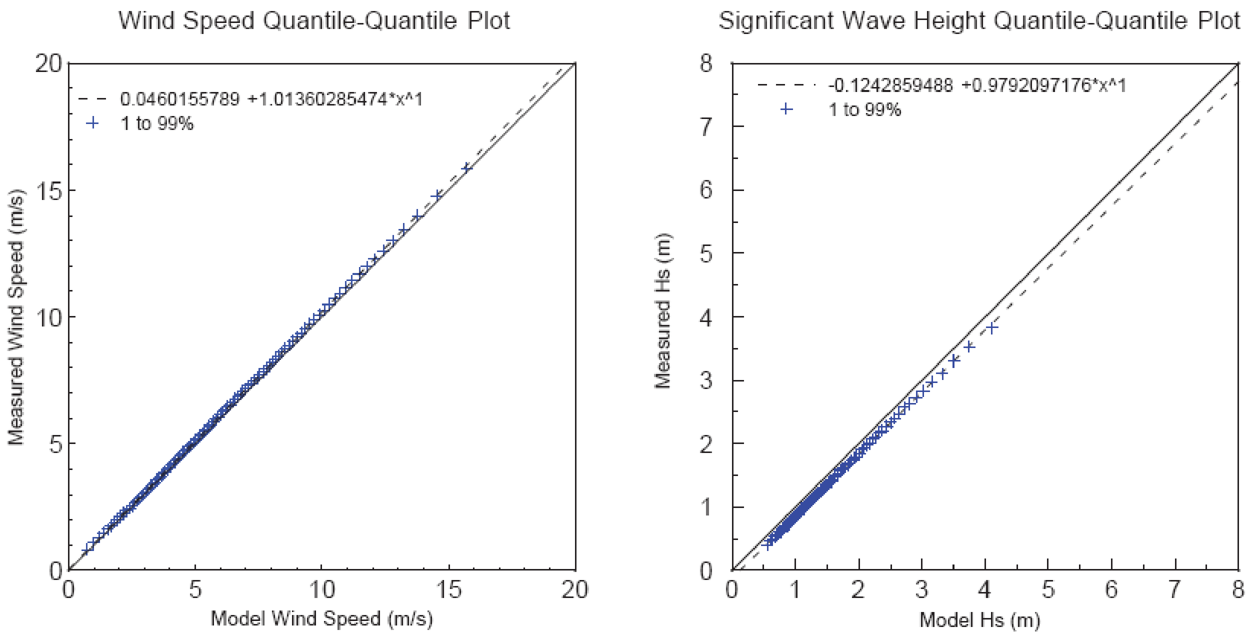

Figure 4-3 Wind Speed and Significant Wave Height Quantile-Quantile Plot

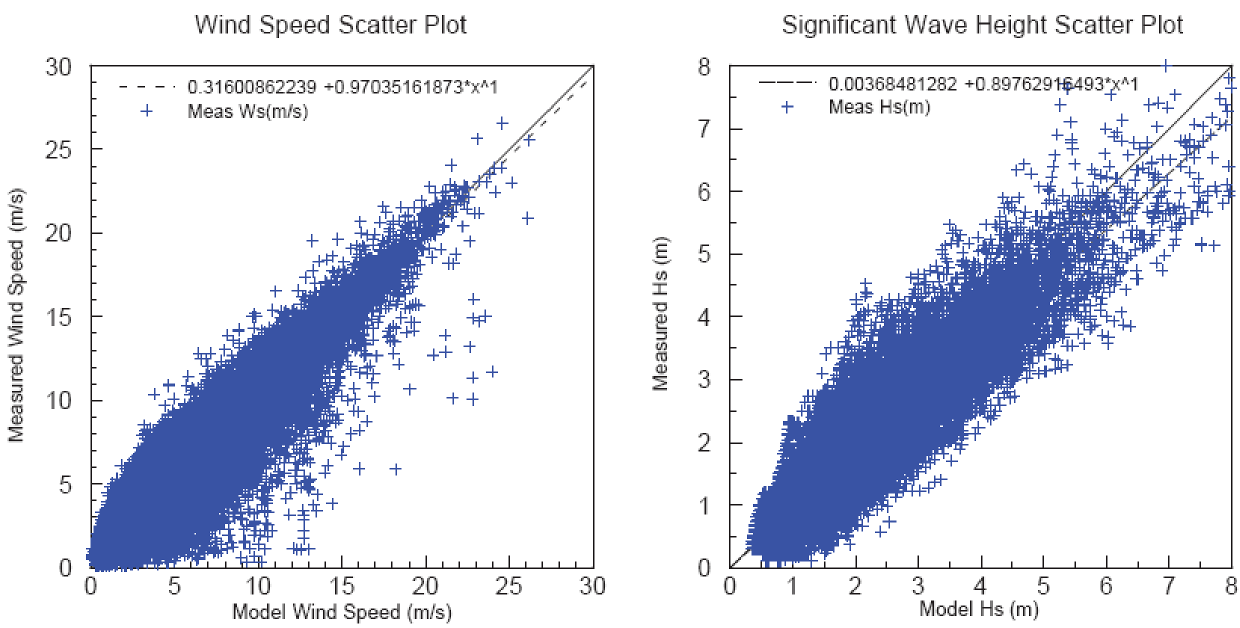

Figure 4-4 Wind Speed and Significant Wave Height Scatter Plot

5 HURRICANE STUDIES

Six storms have been identified as having a potential impact on the survey region. For each of these storms (the sixth storm is a tropical storm followed in quick succession by a hurricane), time series of the measured data and the Oceanweather modelled data have been presented. Measured wind speed and wave height from NDBC Station CHLV2 and Buoy 4401 were used (where available).

All wind data presented in this section have been converted to hub height (100m ASL). The power law equation was used as illustrated in Section 2.1.10, using a power law exponent of 0.081. CHLV2 anemometer height is 43 m above mean sea level and Buoy 44014 anemometer height is 5 m above sea level.

5.1 Hurricane Gloria 1985

Gloria developed to a tropical depression on September 16, 1985 south of Cape Verde. By September 21 Gloria reached hurricane wind speeds and continued to move northeast. Gloria reached a maximum intensity of 249 km/hr, category 4, (2008 preliminary reanalysis) northeast of the Bahamas on September 25. As Gloria continued to move north it began to weaken due to interactions with a ridge. Gloria past east of the site on September 27 as a category 2 hurricane. Gloria made land fall in Long Island and western Connecticut as a category two hurricane while weakening. Below are the wind (100m ASL) and wave height comparisons between Oceanweather data, NDBC Station CHLV2 and Buoy 44014 for the time period of 16 September to 01 October 1985.

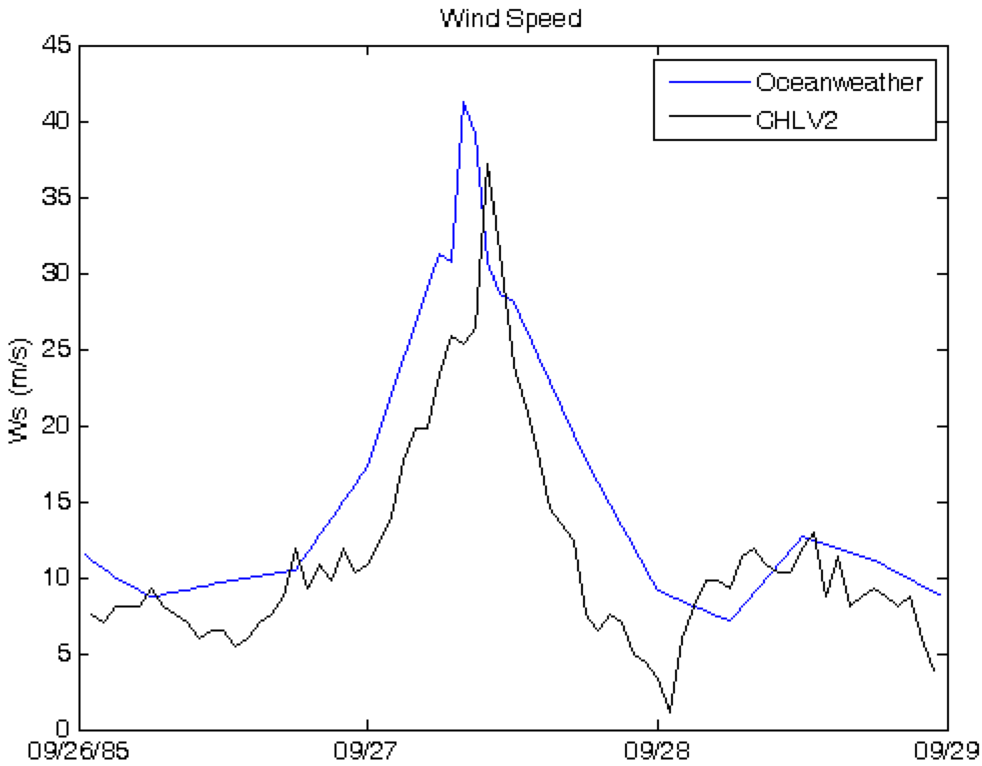

Figure 5-1 Wind Speed Comparison (m/s)

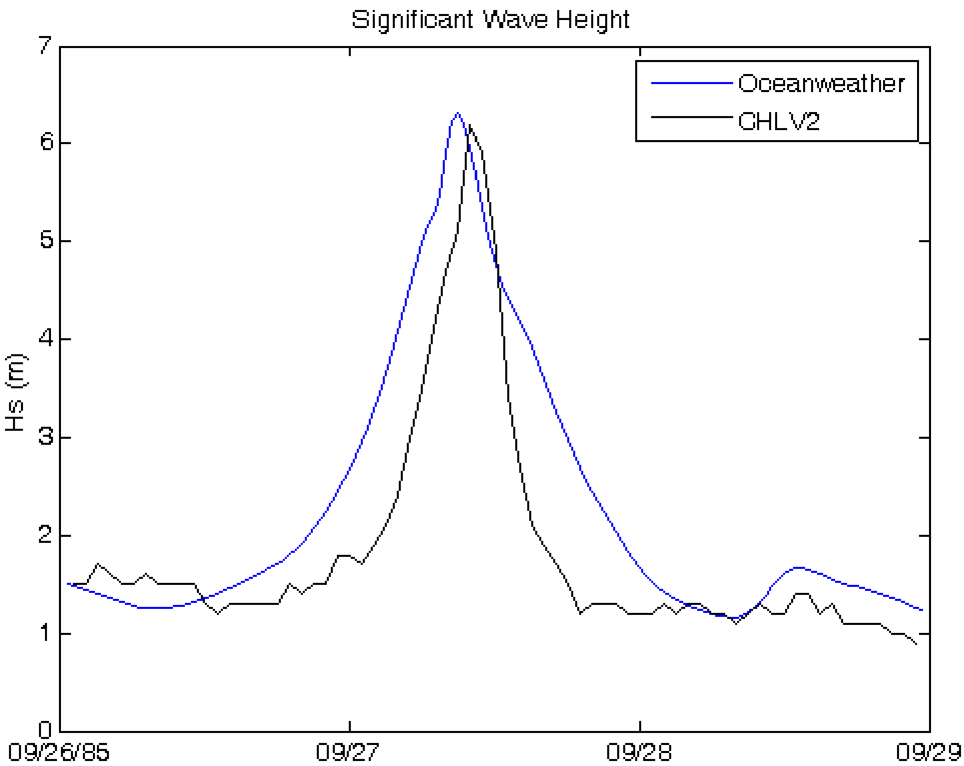

Figure 5-2 Significant Wave Height Comparison (m)

	Maximum Wind Speed (m/s)	Maximum Significant Wave Height (m)
CHLV2	35.38	6.20
Oceanweather	35.96	6.31

Table 5-1 Maximum Wind Speed and Significant Wave Height Comparison

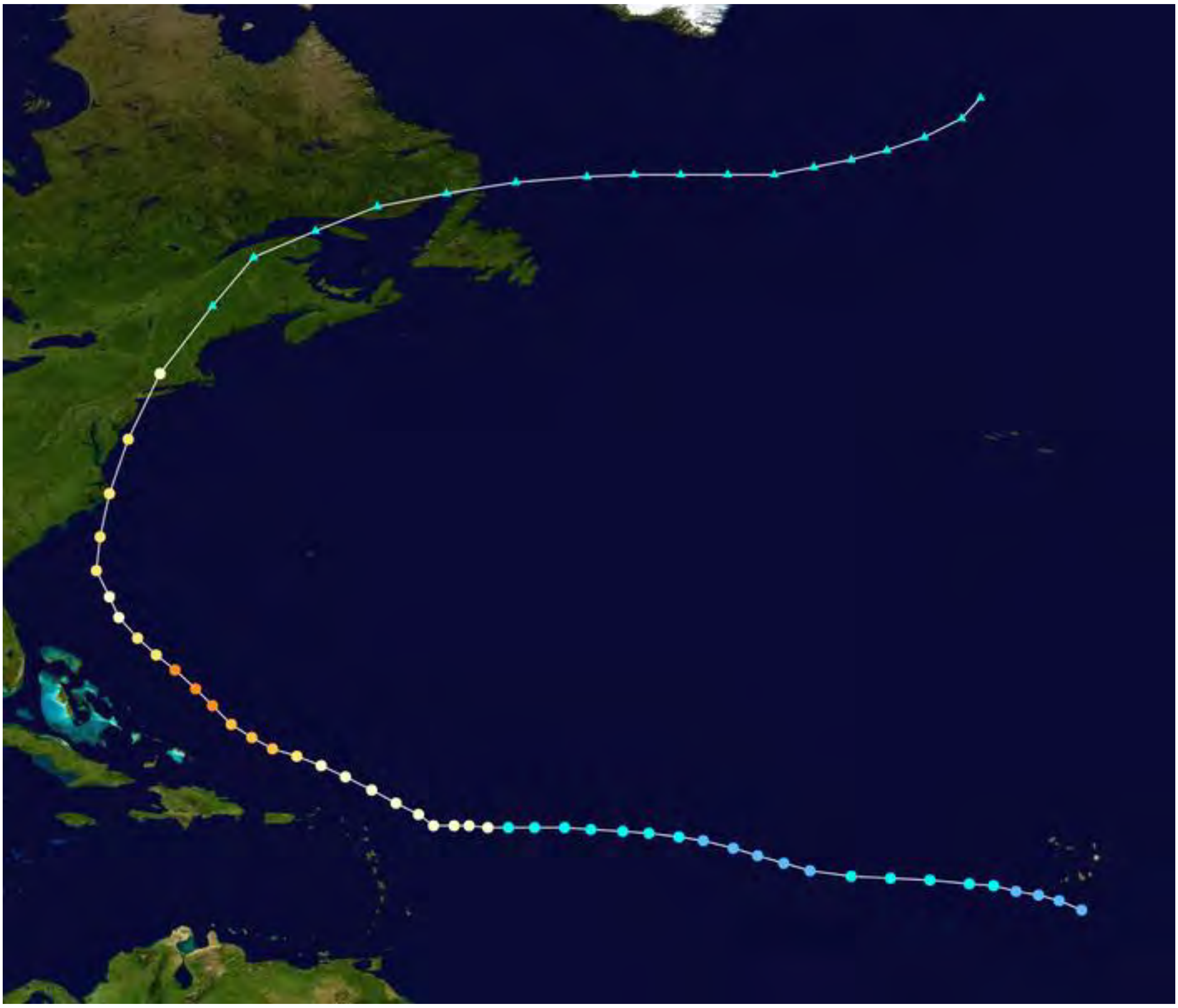

Figure 5-3 Hurricane Gloria 1985 Track TD TS 1 2 3 4 5 **(Saffir-Simpson Hurricane Scale)**

5.2 Hurricane Bonnie 1998

Bonnie developed into a tropical depression on August 19, 1998 moving eastward. Bonnie reached a maximum intensity of 185 km/hr, category 3, east of the Bahamas on August 23. Bonnie made landfall in North Carolina as a category 2 hurricane on August 27. As Bonnie made landfall, the storm turned to the east as a trough approached from the west. As the center reached open waters, Bonnie re-intensified into hurricane status on August 28. At this point Bonnie was just south east of the site as the storm continued to move to the northeast. Below are the wind (100m ASL) and wave height comparisons between Oceanweather data, NDBC Station CHLV2 and Buoy 44014 for the time period of 19-31 August 1998.

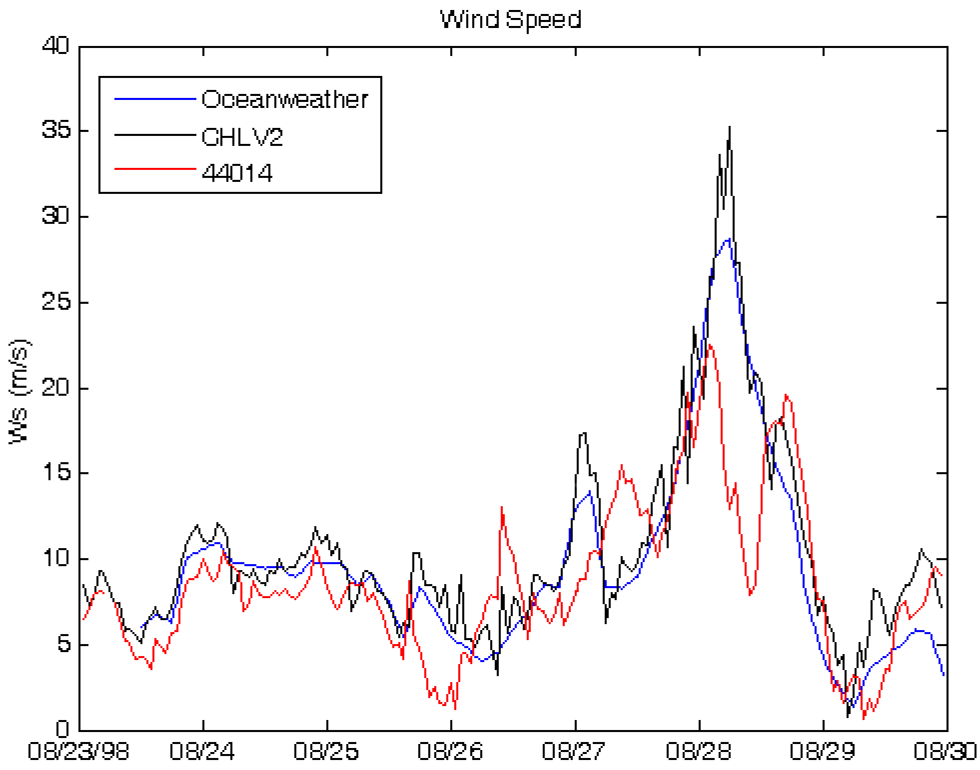

Figure 5-4 Wind Speed Comparison (m/s)

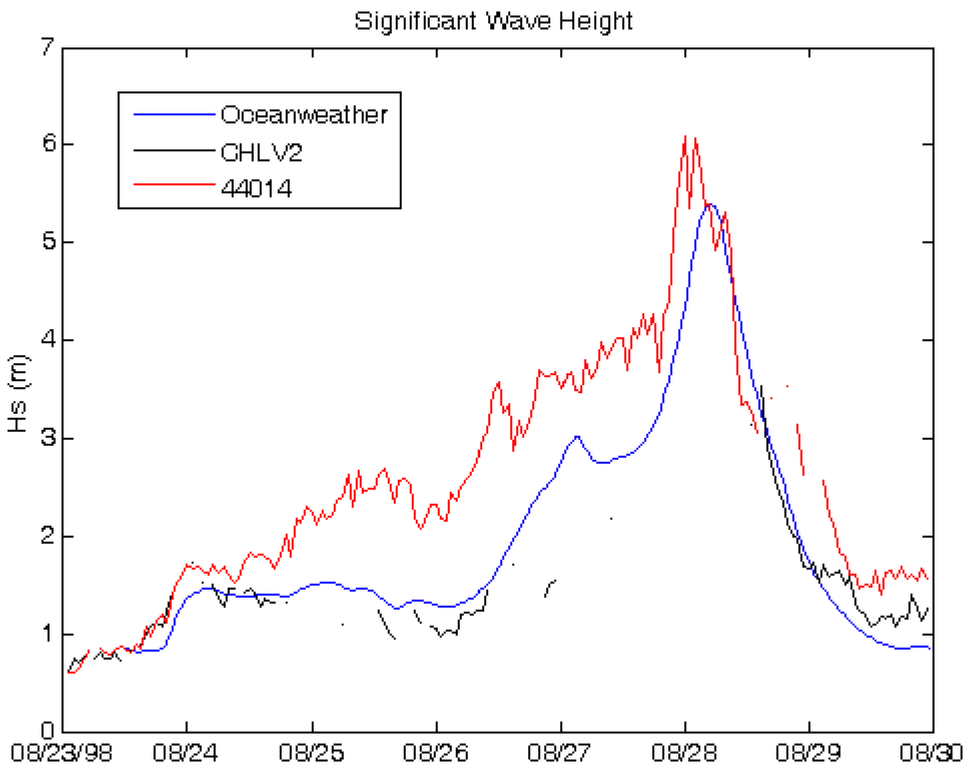

Figure 5-5 Significant Wave Height Comparison (m)

	Maximum Wind Speed (m/s)	Maximum Significant Wave Height (m)
CHLV2	35.30	-
44014	22.50	6.08
Oceanweather	28.75	5.39

Table 5-2 Maximum Wind Speed and Significant Wave Height Comparison

Figure 5-6 Hurricane Bonnie 1998 Track TD TS 1 2 3 4 5 **(Saffir-Simpson Hurricane Scale)**

5.3 Hurricane Dennis 1999

On August 24, 1999 Dennis developed into a tropical depression east of Grand Turk Island, strengthening into a tropical storm that same day. Dennis intensified to a hurricane on August 26 over the Bahamas. On August 28, Dennis reached a maximum intensity of 170 km/hr, category 2 hurricane. Dennis did not pass over the site but due to the interactions with a cold front, Dennis remained near the site just east of North Carolina. Dennis made landfall as a tropical storm on September 4 in North Carolina. Below are the wind (100m ASL) and wave height comparisons between Oceanweather data, NDBC Station CHLV2 and Buoy 44014 for the time period of 24 August to 07 September 1999.

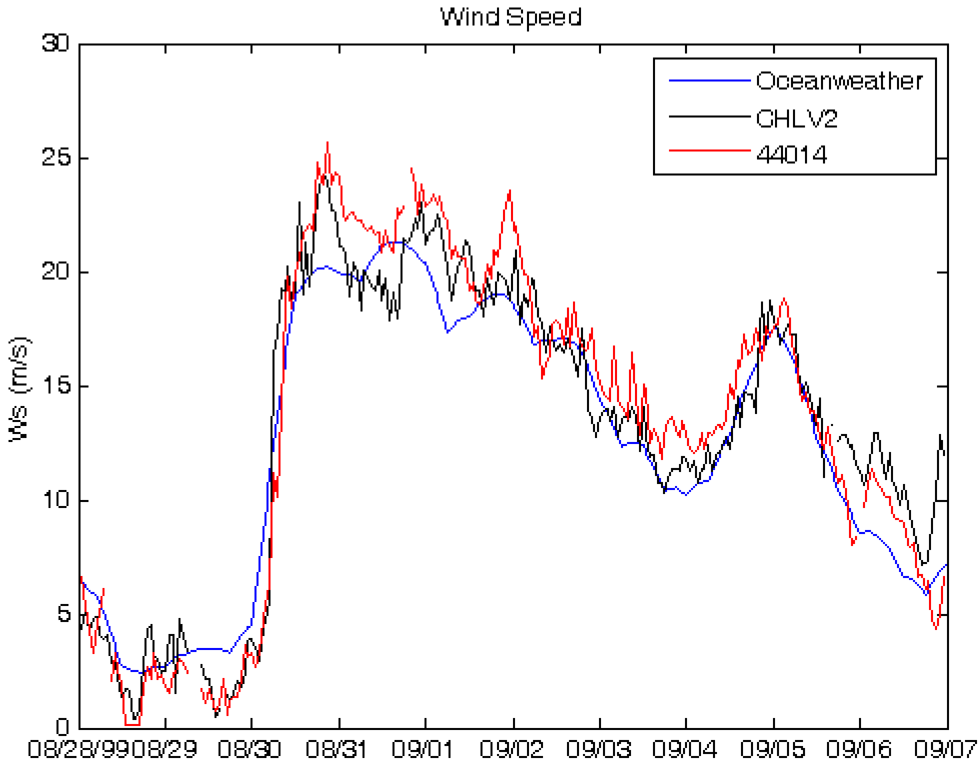

Figure 5-7 Wind Speed Comparison (m/s)

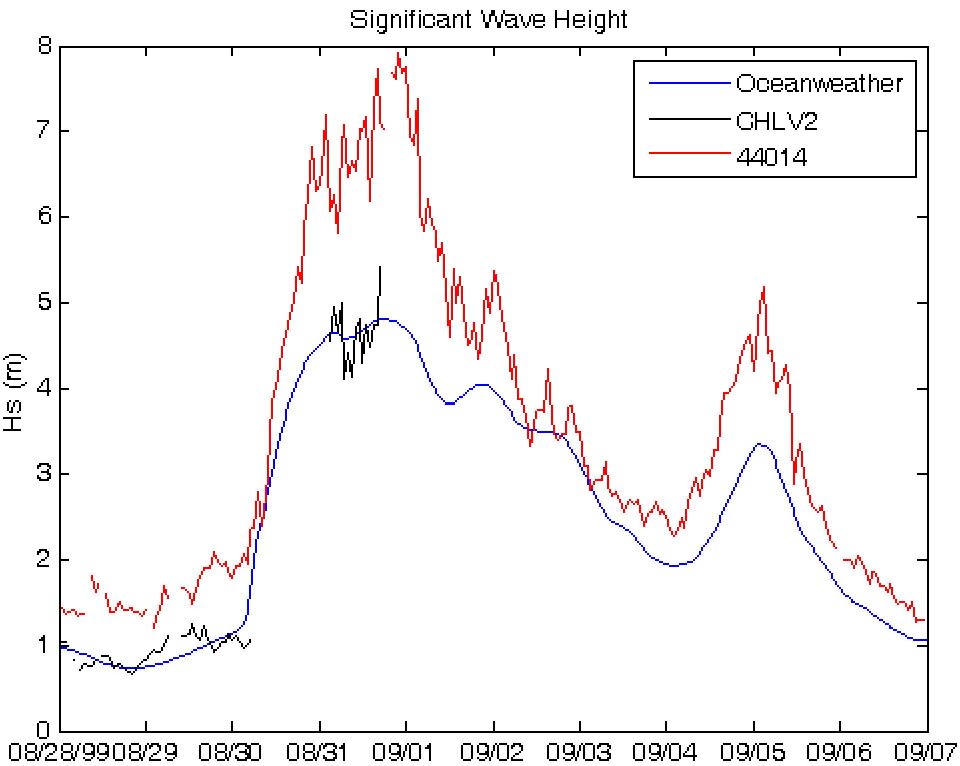

Figure 5-8 Significant Wave Height Comparison (m)

	Maximum Wind Speed (m/s)	Maximum Significant Wave Height (m)
CHLV2	24.27	-
44014	25.66	7.92
Oceanweather	21.28	4.81

Table 5-3 Maximum Wind Speed and Significant Wave Height Comparison

Figure 5-9 Hurricane Dennis 1999 Track TDTS 1 2 3 4 5 **(Saffir-Simpson Hurricane Scale)**

5.4 Hurricane Floyd 1999

Floyd developed in the Atlantic on 7 September 1999, reaching a maximum intensity of 250 km/h (category 4, just shy of becoming a category 5) east of the Bahamas. Floyd continued to move northwest then became parallel to the east coast making landfall in North Carolina as a category 2 hurricane on 16 September 1999. Hours later Floyd passed west of the site as a category 1 hurricane on 16 September 1999. Below are the wind (100m ASL) and wave height comparisons between Oceanweather data, NDBC Station CHLV2 and Buoy 44014 for the time period of 14-19 September 1999.

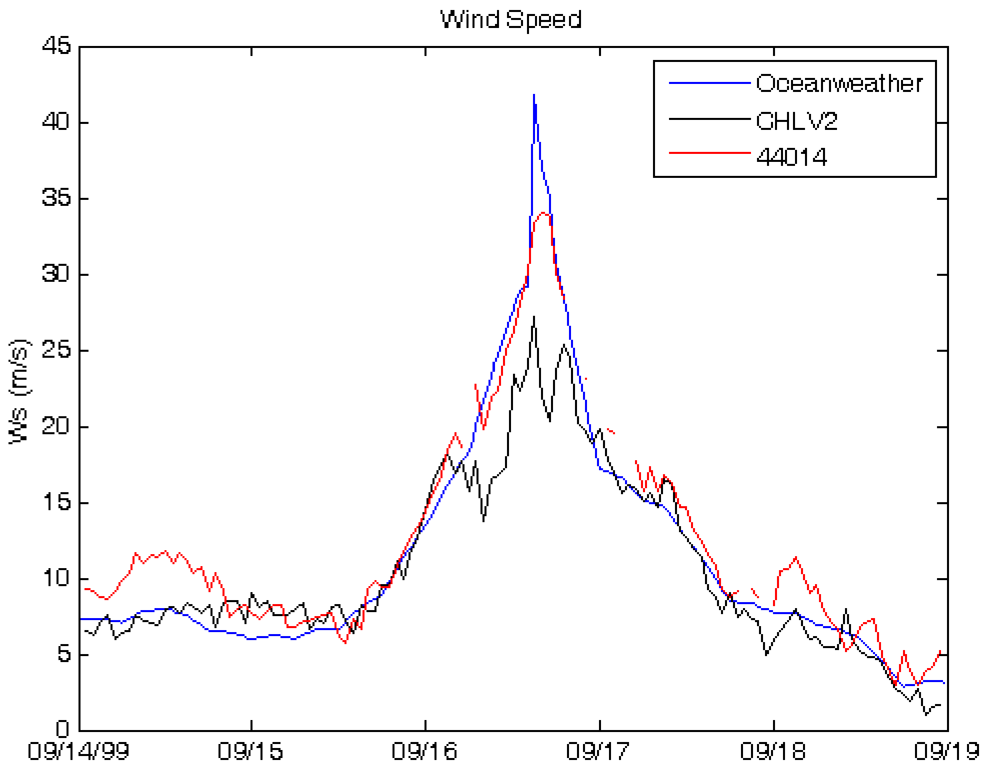

Figure 5-10 Wind Speed Comparison (m/s)

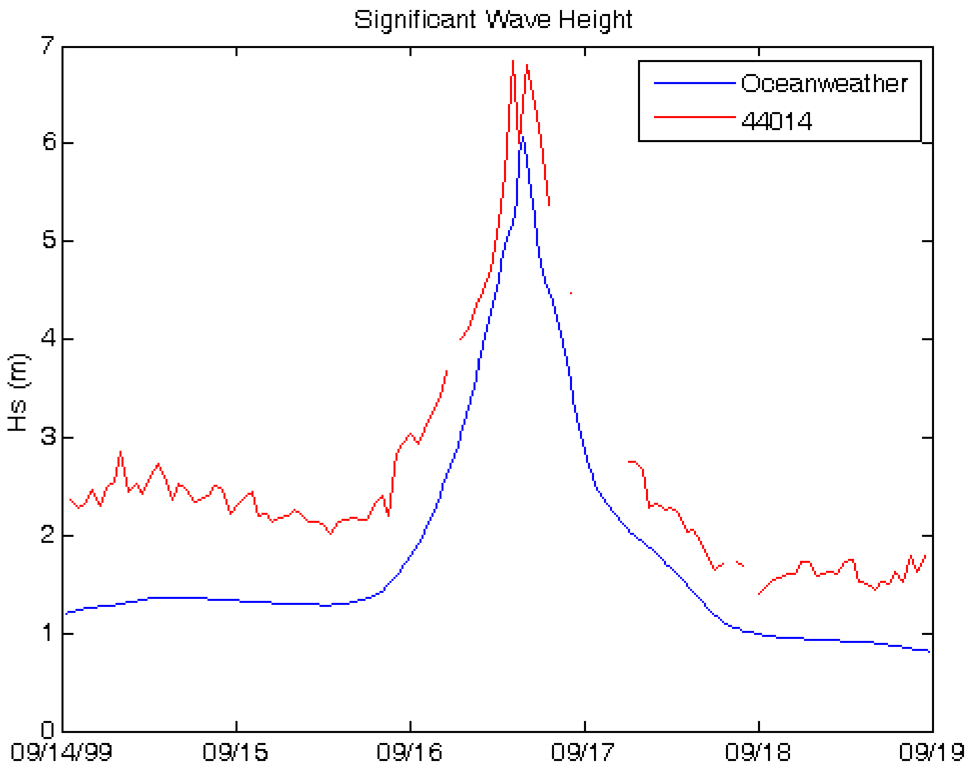

Figure 5-11 Significant Wave Height Comparison (m)

	Maximum Wind Speed (m/s)	Maximum Significant Wave Height (m)
CHLV2	25.85	-
44014	28.56	6.85
Oceanweather	36.48	6.06

Table 5-4 Maximum Wind Speed and Significant Wave Height Comparison

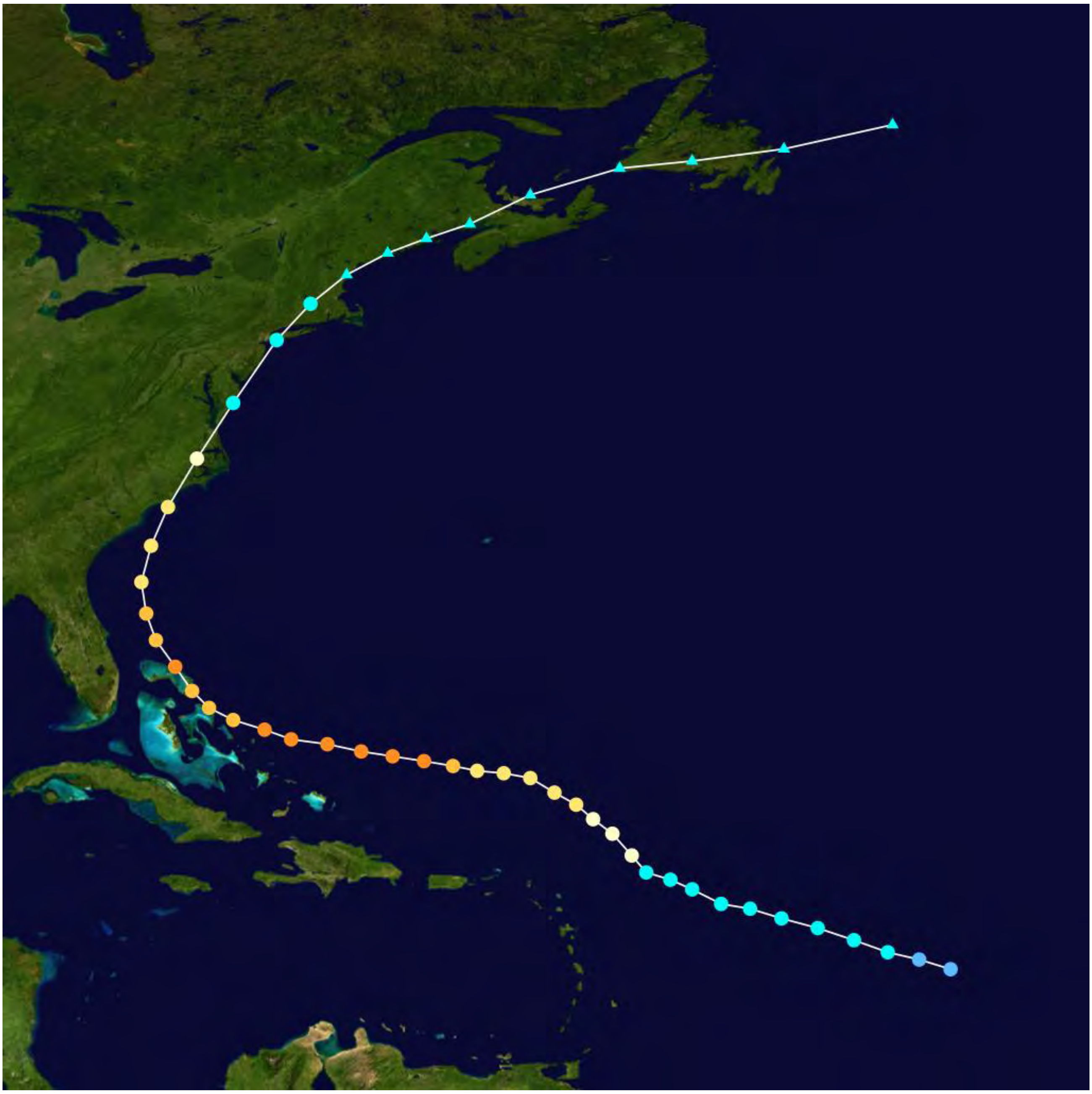

Figure 5-12 Hurricane Floyd Track 1999 TDTS 1 2 3 4 5 **(Saffir-Simpson Hurricane Scale)**

5.5 Hurricane Isabel 2003

On September 6, 2003 Isabel formed into a tropical depression and hours later into a tropical storm. Isabel reach a category 1 hurricane on September 7, moving towards the north east. Isabel reached a maximum intensity of 270 km/hr, category 5, east-northeast of Puerto Rico. Isabel weakened back to a category 4 hurricane due to an eyewall replacement cycle, reaching category 5 yet again in September 13. Isabel made landfall in North Carolina on September 18 as a category 2 hurricane, due to its fast motion Isabel maintained hurricane strength until reaching western Virginia on September 19. Below are the wind (100m ASL) and wave height comparisons between Oceanweather data, NDBC Station CHLV2 and Buoy 44014 for the time period of 6-19 September 2003.

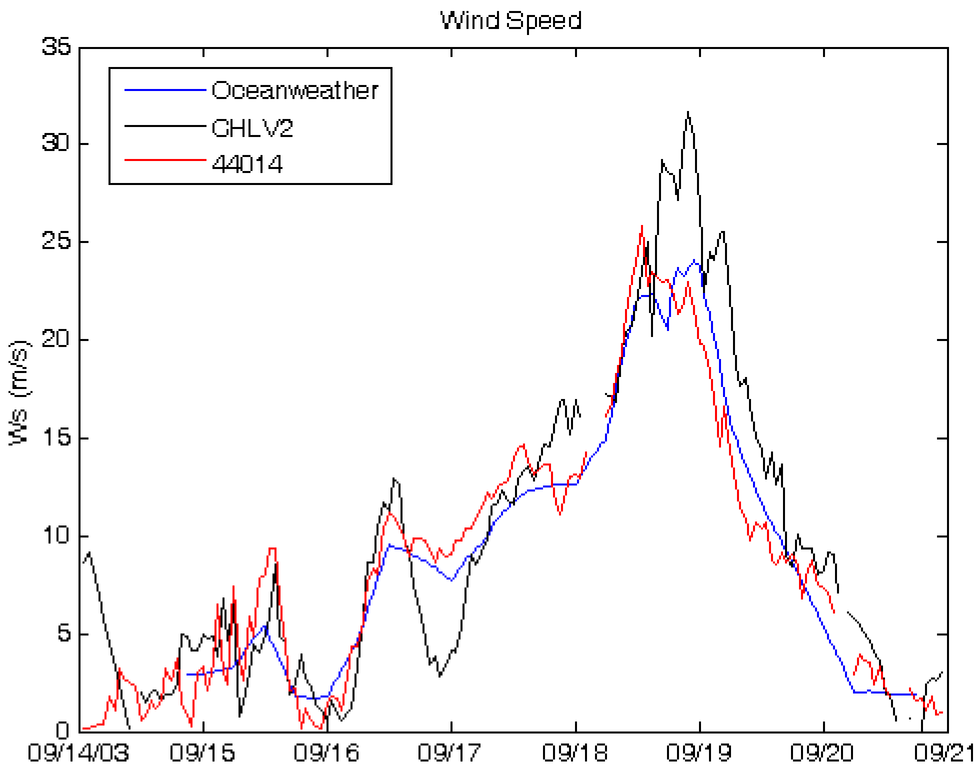

Figure 5-13 Wind Speed Comparison (m/s)

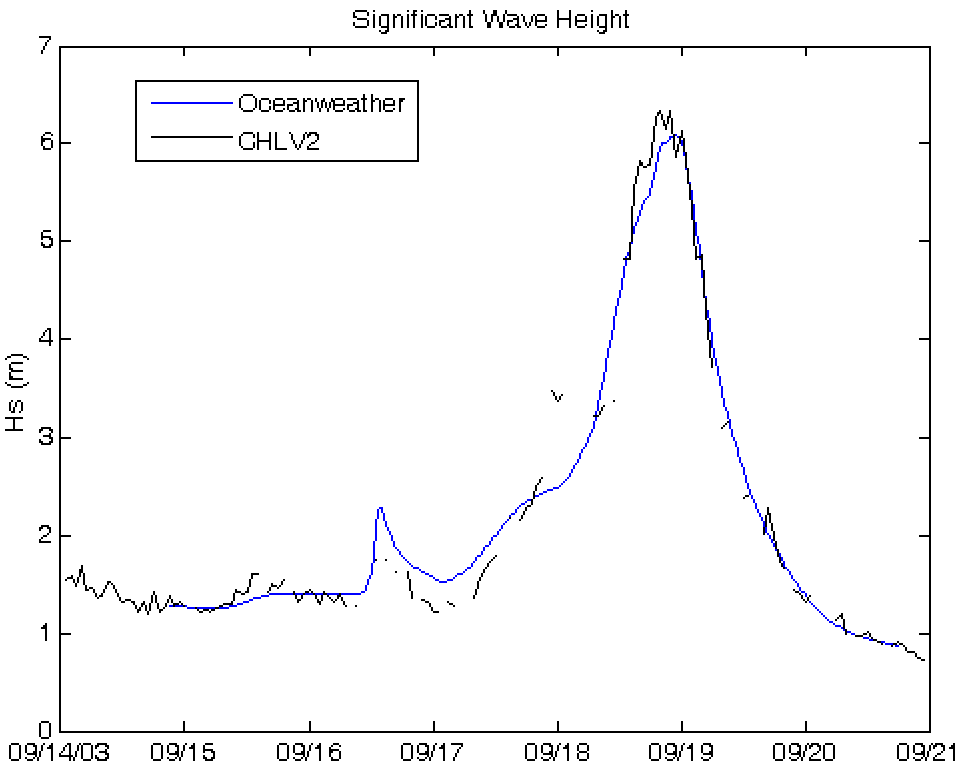

Figure 5-14 Significant Wave Height Comparison (m)

	Maximum Wind Speed (m/s)	Maximum Significant Wave Height (m)
CHLV2	31.71	6.34
44014	25.88	-
Oceanweather	24.08	6.08

Table 5-5 Maximum Wind Speed and Significant Wave Height Comparison

Figure 5-15 Hurricane Isabel 2003 Track TDTS 1 2 3 4 5 **(Saffir-Simpson Hurricane Scale)**

5.6 Tropical Storm Bonnie and Hurricane Charley 2004

Bonnie and Charley both developed in the Caribbean Sea just six days apart. Bonnie reached a maximum intensity of 100 km/h (tropical storm), as it passed over the Gulf of Mexico. Once it made landfall in Florida, Bonnie weakened to a tropical depression. Bonnie then entered the Atlantic just east of the site on 13 August 2004, before Bonnie interacted with an extratropical cyclone destroying the tropical depression. Charley had a very similar trajectory to Bonnie. Charley reached a maximum sustained wind of 240 km/h (category 4 hurricane), just before making landfall in Florida. Charley continued to move northeast making landfall for its third time in South Carolina. Charley passed just west of the site as a tropical storm on 14 August 2004 just hours before getting absorbed by an extratropical cyclone. Below are the wind (100m ASL) and wave height comparisons between Oceanweather data, NDBC Station CHLV2 and Buoy 44014 for the time period of 13-16 August 2004.

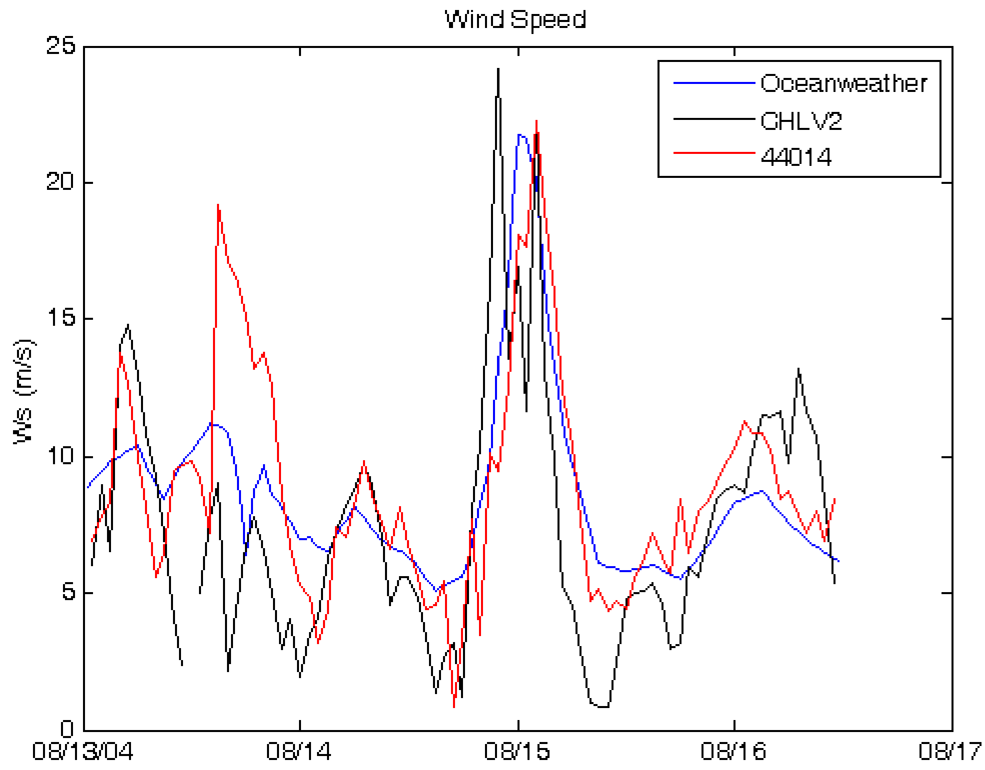

Figure 5-16 Wind Speed Comparison (m/s)

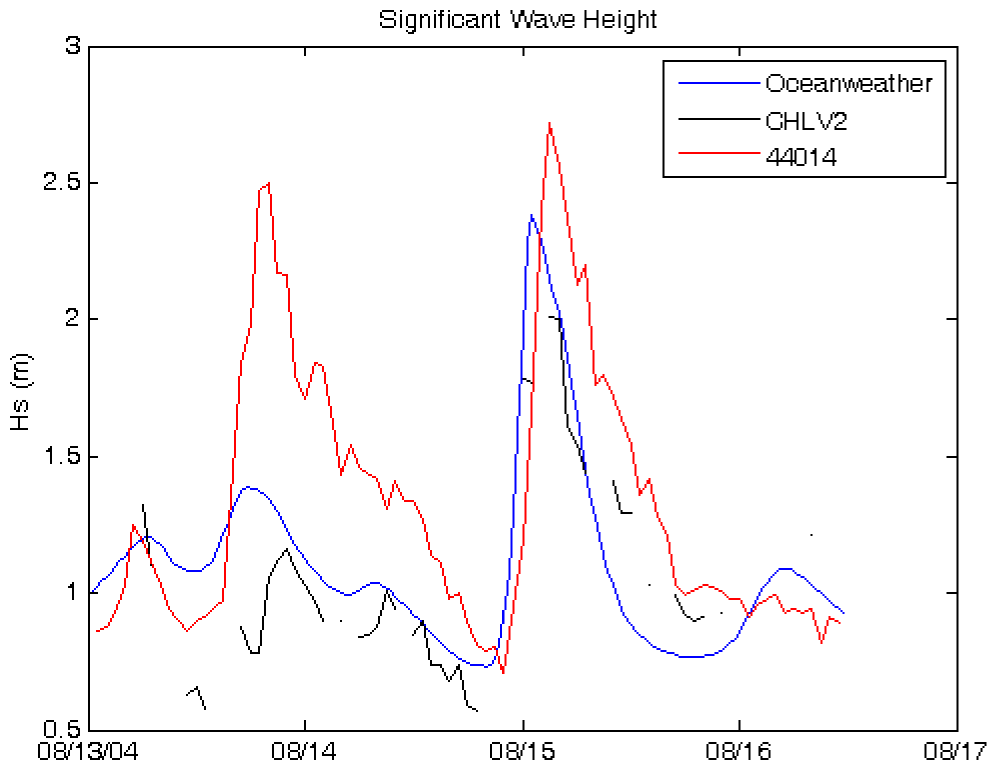

Figure 5-17 Significant Wave Height Comparison (m)

	Maximum Wind Speed (m/s)	Maximum Significant Wave Height (m)
CHLV2	22.96	2.01
44014	18.63	2.72
Oceanweather	19.02	2.39

Table 5-6 Maximum Wind Speed and Significant Wave Height Comparison

Figure 5-18 Tropical Storm Bonnie Track 2004 TD TS 1 2 3 4 5 **(Saffir-Simpson Hurricane Scale)**

Figure 5-19 Hurricane Charley Track 2004 TD TS 1 2 3 4 5 **(Saffir-Simpson Hurricane Scale)**

6 TECHNICAL REFERENCE

6.1 Extreme Value Analysis

Extreme omni-directional wind, wave and current speeds were derived using the Peaks-Over-Threshold (POT) Method. The POT values were derived by fitting the Weibull, Fisher-Tippett 1, and Exponential functions to the rate of exceedance using the method of least squares, Maximum Likelihood and Method of Moments. Extreme directional wind speeds were derived by scaling the omni-directional extreme values using relative severity factors derived from the relative magnitude of the maximum 1-hour mean wind speed in each direction sector.

6.1.1 Probability Distributions

The functions[15,16,17,18,19,20] used in this study for the estimation of extreme values are the:

- Fisher-Tippett distribution, Type 1.
- Weibull 3-parameter
- Exponential

The FT1 and Exponential functions are two parameter distributions. The Weibull function may be described by two or three parameters: α is the location parameter and the limiting value of the distribution, β is the scale parameter and defines the spread of the distribution, and γ is the shape parameter and describes the asymmetry of the distribution. The Generalised Pareto is also a three parameter distribution: a location parameter, x_t, a scale parameter, β, and a shape parameter, γ. The following paragraphs describe the distributions and present expressions for the moments estimators and for plotting on probability paper.

<u>Fisher-Tippett Type 1 Distribution</u>
This function is also known as a Gumbel, double exponential, Jenkinson Type 2, extreme value and extremal type 1 distribution.

$$P(x) = \exp \{-\exp [-(x - \alpha)/\beta]\} \qquad \beta > 0$$

where $P(x)$ is the cumulative probability that $X \leq x$ and α is the mode of the distribution.

The function may be re-arranged to give

$$x = \alpha - \beta [\ln(-\ln P(x))]$$

It can be seen that plotting $-\ln(-\ln P(x))$ against x will give a straight line.

The mean and variance of the F-T 1 distribution are as follows:

[15] Carter, D.J.T. and Challenor, P.G. (1981). *Estimating Return Values of Wave Height*. IOS Report No. 116.

[16] Carter, D.J.T. et al (1986). *Estimating Wave Climate Parameters for Engineering Applications*. Offshore Technology Report No. OTH 86 228. London: HMSO.

[17] Coastal Engineering Research Center, US Army Engineer Waterways Experiment Station (1985). *Computer Program: WAVDIST (MACE 17) Extremal Significant Wave Height Distributions*. Coastal Engineering Technical Note CETN-I-40, December 1985.

[18] Davison, A.C. and Smith, R.L. (1990). *Models for Exceedences over High Thresholds*. J. R. Statist. Soc. B, 52, No. 3, 393-442.

[19] Johnson, N.L. and Kotz, S. *Continuous Univariate Distributions - 1*.

[20] National Environmental Research Council (1975). *Flood Studies Report Volume 1: Hydrological Studies*.

mean = $\alpha + \gamma\beta$
variance = $\beta^2 \pi^2/6$

where γ = Euler's constant = 0.5772.

The moments estimators are therefore given by

$\boldsymbol{\alpha}$ = mean - $\gamma\boldsymbol{\beta}$
$\boldsymbol{\beta}$ = $\sqrt{\text{variance}}\sqrt{6}/\pi$

<u>Weibull Distribution</u>

$$P(x) = 1 - \exp\{-[(x - \alpha)/\beta]^{\gamma}\} \quad x > \alpha;\ \beta, \gamma > 0$$
$$P(x) = 0 \quad x < \alpha$$

where α is the lower limiting value of the distribution.

Re-arranging gives

$$x = \alpha + \beta[-\ln(1 - P(x))]^{1/\gamma}$$

$$\ln[-\ln(1 - P(x))] = \gamma\ln(x - \alpha) - \gamma\ln\beta$$

so a plot of $\ln[-\ln(1 - P(x))]$ against $\ln(x - \alpha)$ is a straight line.

For a three parameter Weibull distribution the mean, variance and skewness are given by

Mean = $\beta\Gamma(1 + 1/\gamma) + \alpha$
variance = $\beta^2[\Gamma(1 + 2/\gamma) - \Gamma^2(1 + 1/\gamma)]$
skewness = $\beta^3[\Gamma(1 + 3/\gamma) - 3\Gamma(1 + 2/\gamma) * \Gamma(1 + 1/\gamma) + 2\Gamma^3(1 + 1/\gamma)]$

where Γ is the gamma function and the moments estimators are obtained by

$\boldsymbol{\alpha}$ = mean - $[\boldsymbol{\beta}\Gamma((1 + 1/\gamma)]$
$\boldsymbol{\beta}$ = $\{\text{variance}/[\Gamma(1 + 2/\gamma) - \Gamma^2(1 + 1/\gamma)]\}^{0.5}$
Skewness = $[\Gamma(1 + 3/\gamma) - 3\Gamma(1 + 2/\gamma) * \Gamma(1 + 1/\gamma) + 2\Gamma^3(1 + 1/\gamma)] / [\Gamma(1 + 2/\gamma) - \Gamma^2(1 + 1/\gamma)]^{3/2}$
which is solved iteratively for γ

Note that skewness = coefficient of skewness * variance$^{3/2}$.

For a two parameter Weibull distribution, $\alpha = 0$ and the mean and variance are given by

mean = $\beta\Gamma(1 + 1/\gamma)$
variance = $\beta^2[\Gamma(1 + 2/\gamma) - \Gamma^2(1 + 1/\gamma)]$

and the moments estimators are obtained by

$\boldsymbol{\beta}$ = mean/$\Gamma(1 + 1/\gamma)$

variance/mean^2 = $[\Gamma(1 + 2/\gamma) - \Gamma^2(1 + 1/\gamma)]/[\Gamma(1 + 1/\gamma)]^2$
which is solved iteratively for γ

Exponential Distribution

$P(x) = 1 - \exp[-(x - \alpha)/\beta]$

The mean and variance are given by

Mean $= \alpha + \beta$
variance $= \beta^2$

The moments estimators are therefore

α = mean - β
$\beta = \sqrt{\text{variance}}$

6.1.2 Peaks Over Threshold Analysis

The peak over threshold technique (Coastal Engineering Research Center, 1985[2]) consists of declustering the data by selecting storm peak events that exceeded a predetermined threshold within a forty-eight hour moving window. The observations are assumed to be independent and identically distributed. The number of peaks exceeding a given level, divided by the number of years of record, gives the rate of exceedance which can then be used to find the expected number of occurrences in a period of specified length of time. The probability distribution of the peak values which depends on the threshold over which the peaks are counted is then combined with the rate of occurrence of peaks to give the unconditional distribution of peak values from which extreme values corresponding to given return periods can be calculated, i.e.

$P(x.y) = P(x/y)\,P(y)$

where $P(x.y)$ = the unconditional probability distribution of peak values with time.
$P(x/y)$ = the conditional probability distribution of peak values.
$P(y)$ = the probability distribution of storms with time.

The return periods of extreme values are calculated as follows:

$RP = 1 / \{ \lambda [1 - P(x/y)] \}$

where λ is the Poisson parameter and $P(x/y)$ the conditional probability distribution of peak values.

The number of storms occurring per unit time is assumed to be a random variable that may be represented by the Poisson distribution. The Poisson distribution is characterised by a mean value, λ, which is the average number of storms per year. The value of λ is calculated as the number of storms divided by the period of record in years. The probability density of the Poisson distribution is given by the following formula:

$p(i) = (\lambda^{i} \exp^{-i}) / i!$

where $i = 0, 1, 2, \ldots n$.

6.1.3 Cumulative Frequency Distribution

Cumulative frequency extrapolation involves grouping all the parameter values in the data set using specified class intervals and then forming a cumulative frequency distribution (cfd) by summing the number of observations greater than or equal to the lower bound of the class interval. The Fisher-Tippett distributions, Types 1 and 3 and the Weibull and Exponential distributions are then fitted to the data, using the method of least squares, in order to extrapolate to the required probability of non exceedence. The advantage of this method is that it can be used with as little as one year of data.

However, the probability levels calculated for the cumulative frequency method assume that the measurements used to form the distribution are independent. Therefore, by ignoring the correlation between consecutive values of the metocean parameter, this method may result in underestimation of extreme values. Note that in some cases the Fisher-Tippett 3 function has values of the location parameter (the upper limiting value of the distribution) which are very high. As the value of this parameter becomes larger the distribution tends more towards the F-T1, therefore, the function fitted to the cfd's represents a Fisher Tippett Type 1 rather than a Fisher-Tippett Type 3.

The relationship between probability of non-exceedence and return period is as follows:

$$P(x) = 1 - 1/(365.25mRP)$$

where P(x) = the probability of non-exceedence.
m = the number of observations in a day.
RP = the return period (years).

6.1.4 Associated Tp with Extreme Waves

Data from GFC were used to create an omni-directional joint frequency distribution of Tp, and Tz conditional on Hs. The mode of each conditional distribution was then estimated for each primary parameter class interval. A power law regression equation was then used to define the relationship between the two parameters.

6.1.5 Associated Hc and Hmax

Crest and maximum wave height were calculated using in-house software (EXWAN – EXtreme Wave ANalysis).

The probability distributions of maximum wave or crest height for a storm are given by:

$$P(H_{max} < h) = exp\left\{\int_0^T log\{F_{Hs(t)}(h)\}dt / T_{m02}(t)\right\}$$

where:

$P(H_{max} < h)$ is the non-exceedance probability of the maximum wave or crest height in a storm;
$F_{Hs(t)}(h)$ is the short-term non-exceedance probability of wave or crest height, h, for a significant wave height, Hs, at time, t;
$T_{m02}(t)$ is the spectral estimate of the mean zero up-crossing wave period at time, t;
T is the duration of the storm.

This approach was developed by Borgman[21] and has been adopted by the EXWAN software as a means of determining the maximum wave and crest height from each storm. The GOMOS data contained an estimate of *Tp* and this parameter was used to derive T_{m02} by multiplying by 0.74.

In order to calculate $F_{Hs(t)}(h)$ for each time step within each storm the Forristall 3-D approach was used for crest height. This formulation is based on the 2-parameter Weibull distribution:

[21] Borgman, L., 1973. *Probabilities for highest wave in hurricane*. J. Waterways, Harbors, and Coastal Eng, Div. ASCE **99**, 185-207.

$$F_{Hs}(h) = 1 - exp\left\{ -\frac{(4\,h/Hs)^A}{B} \right\}$$

where, A and B are parameters that were empirically fitted.

Forristall[22] derived estimates of extreme crest heights for given sea states in given water depths by using simulations of JONSWAP spectra by empirically fitted the following for *A* and *B*:

$$A = 2 - 1.7912S - 0.5302U_r + 0.2824U_r^2$$
$$B = \{4(0.3536 + 0.2568S + 0.0800U_r)\}^A$$

where:

the Ursell number, $U_r = \frac{Hs}{k_1^2 d^3}$;

the wave steepness, $S = \frac{2\pi H_s}{gT_{m01}^2}$;

$T_{m01} = m_0/m_1$, the ratio of the zeroth to the first moments of the wave spectrum;
k_1 is the deep water wave number corresponding to T_{m01};
d is the water depth.

The maximum wave height was calculated using EXWAN and the 2-parameter Weibull distribution proposed by Forristall. The values used for A and B were 2.13 and 8.42, respectively. As with the crest heights, the ratio of maximum wave height to the highest Hs recorded in each storm was calculated. The regression equation of Hmax vs. Hs and Hc vs. Hs were then developed and used to derive the respective maximum wave heights in the Criteria Reference.

[22] Forristall, G.Z. (2000). *Wave crest distributions: observations and second order theory*. J. Phys. Ocean, **30**, 1931-1943.

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[3] ISO 19901-1:2005, Petroleum and natural gas industries – Specific requirements for offshore structures – Part1: Metocean design and operating considerations

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[6] Computational Techniques for Tidal Datums Handbook, Silver Spring, September 2003

Annex A
(Marine Growth and Corrosion)

A.1 Marine Growth

There are two forms of marine growth, or fouling as well as seaweed and kelp. Hard fouling consists of mussels, barnacles and tubeworms and soft fouling consists of organisms such as hydroids, anemones and coral. Types of marine growth vary with depth and location.

Marine growth varies depending on the water body in the Lower Chesapeake Bay. Marine growth is typically about 1 to 3 inches thick and is thickest in the splash zone down to about -10ft. Within that zone, the growth is predominantly hard shells and barnacles, with some algae. Dense growth of barnacles and hard shells are typically in the upper 15ft of water and decrease to less dense hard shells below 15ft.

The marine growth varies from area to area. For reference, marine growth at three different locations are provided here, UK sector Table A.1-1 (API RP 2MET 1st Ed Ballot 2), Gulf of Mexico Table A.1-2 (Heideman and George), and offshore southern and central California Table A.1-3 (API RP 2MET 1st Ed Ballot 2).

Depth	Type of growth		
	Hard	Soft	Algae/Kelps
0 m to 15 m	0.2 m	0.07 m	3.0 m
15 m to 30 m	0.2 m	0.3 m	Unknown
30 m to sea floor	0.01 m	0.3 m	No growth

Table A.1-1 Terminal Thickness of Marine Growth UK sector

Depth	Thickness (mm)
MHHW	38
-10 m from MLLW	38
-50 m from MLLW	10
-100 m from MLLW	10
-140 m from MLLW	0

Table A.1-2 Hard Shell Marine Growth for Gulf of Mexico

Depth	Thickness (mm)
Unspecified	200

Table A.1-3 Marine Growth Offshore California

A.2 Corrosion

Offshore wind turbines are exposed to a very corrosive marine environment and require unique corrosion protection. The material selection, design, corrosion protection systems, and suitable inspection and repair programs should be kept in consideration. For more detail descriptions follow the specifications under EN ISO 12944-5 : 1998.