Appendix 5.2-B

Coastal Engineering Design Parameter Analysis Phase I - Preliminary

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Phase I – Preliminary

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1.0 Introduction

1. INTRODUCTION

This report presents the results from the Phase I investigation of coastal engineering design parameters for the wind farm project proposed by Cape Wind Associates, LLC. The Phase I investigation was completed based on existing data and analytical models. No new data were collected, nor were numerical models applied for the investigation. Design parameters related to wave height, water level, currents, and wind speed were developed for preliminary design purposes. Parameters were estimated at the Horseshoe Shoal site, and ocean wave conditions were estimated for comparison purposes at an alternative site southeast of Nantucket Island. Conservative assumptions were incorporated where appropriate, and parameters were estimated for extreme conditions corresponding to the 2-, 10-, 50-, and 100-year storms. **The information presented in this report is not intended for final design purposes.** Parameters need to be refined as the design process proceeds to gain more certainty in the estimates. The work was requested and authorized by Cape Wind Associates, LLC.

The report is organized as follows:

- Section 1. Introduction
- Section 2. Overall Technical Approach – reviews the technical procedure and three technical methods that were applied for the analysis
- Section 3. Engineering Analysis – provides the technical approach and results
- Section 4. Summary and Recommendations

2.0 Overall Technical Approach

2. OVERALL TECHNICAL APPROACH

2.1 Technical Procedure

Existing data were obtained and analyzed and computer-based analytical models were applied to predict the extreme storm surge, wind, current, and locally-generated wave conditions at the Horseshoe Shoal site, as well as ocean wave conditions at an offshore site southeast of Nantucket Island. The models were based on existing water level, wind, tidal current, and ocean wave data, as well as theory governing wind wave generation and extremal analysis. An overview of the technical approach is illustrated by Figure 2-1. A preliminary planning step was completed to refine the project scope to meet the project needs. Existing data were then compiled and reformatted to provide input data for the analytical programs that were applied to examine ocean waves, local waves and storm surge. Wind data were manipulated, and a subset was extracted for input to the extremal analysis program. The most suitable wind data for estimating locally-generated waves also were selected and modeled in a computer-based wind generated wave model. The results of the locally-generated wave analysis and the sub-sampled wind data and ocean wave data were then run through an extremal analysis. From the extremal analysis results, the extreme storm wave was calculated for local and ocean waves.

2.2 Analysis Techniques

The engineering analyses presented in Section 3 utilized analytical computer models to:

- simulate waves generated by local winds within Nantucket Sound;
- compute extreme conditions for storm events; and
- calculate the extreme storm wave (ESW).

These three analysis techniques are described below as the basis for later sections of the report.

2.2.1 Wind-Generated Wave Model

There is no extensive source of measured wave data in Nantucket Sound. Therefore, the locally-generated wave heights were calculated using available wind data and an analytical model for wind generated waves.

Wind blowing in any direction across Nantucket Sound generates waves that potentially impact the proposed Horseshoe Shoal site. Due to the restricted nature of the Sound there are three main factors affecting the height and length (period) of the waves: the fetch length; average water depth; and wind speed. Local, historic wind data collected at Nantucket Airport (1986-2001) were used as a basis for the wind-generated wave modeling.

Wind-generated waves were simulated using a computer model developed by the US Army Corps of Engineers (USACE). The model is part of the Automated Coastal Engineering System (ACES), published by the Coastal Engineering Research Center (USACE, 1992). The program is entitled *Wind Speed Adjustment and Wave Growth*, and

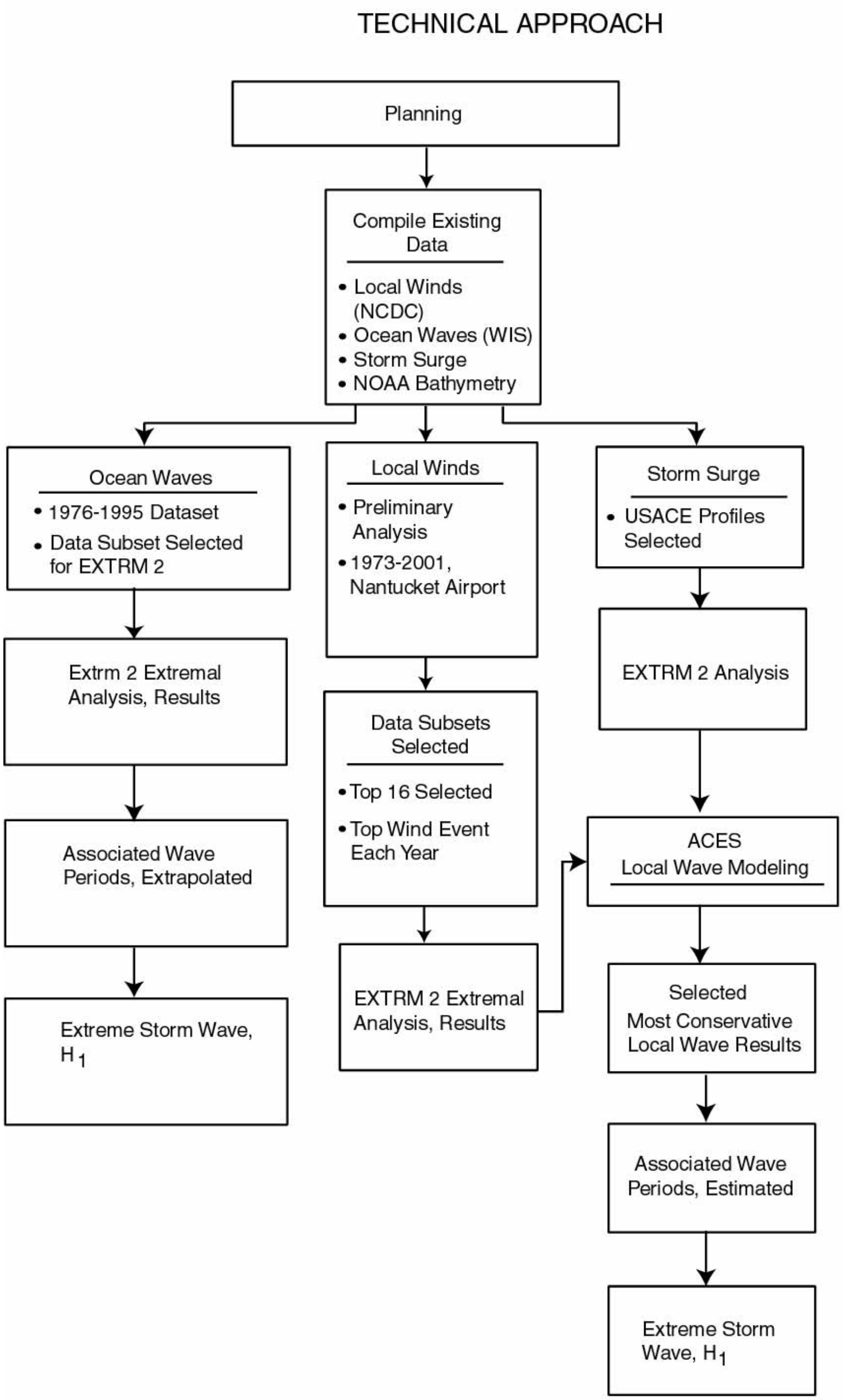

Figure 2-1. Schematic of the overall technical approach

provides simplified estimates for wave growth over open-water and restricted fetches, such as Nantucket Sound, in deep and shallow water. Although wind wave generation and growth incorporates complex physical processes that are not fully understood, simplified wave growth models provide useful and generally accepted estimates of wave heights and periods. Wind data, combined with estimates of fetch and depth from charts, were used to estimate wave height and period under selected conditions. The ACES model addresses only wind-generated waves, and does not account for the effects of refraction, diffraction and non-linear effects. In order to characterize these effects, a more detailed numerical model would be necessary, likely a spectral refraction and diffraction model such as STWAVE or REF/DIF-S. This level of modeling is not required for preliminary siting, project planning, and permitting purposes, but may be necessary to assist with final engineering and design at a later stage of project development. Detailed information regarding the theory of the analytical computer model used in this investigation can be found in the ACES users manual (USACE, 1992) and the Shore Protection Manual (USACE, 1984).

Two key input parameters to the ACES program are the basin geometry and the average water depth of the fetch. The fetch around Horseshoe Shoal is restricted by Nantucket Island, Cape Cod, Monomoy Island, Martha's Vineyard and surrounding shallow shoals. In order to be consistent with previous studies, the basin geometry and average depths used in this analysis were the same as those used in the existing conditions report (WHG, 2003). This information is summarized in Table 2-1 and Figure 2-2. Water depths are tabulated with reference to the mean low lower water (MLLW) tidal datum, which is 0.7 ft below NGVD 29.

ACES model output includes significant wave height (H_s), peak period (T_p), and peak direction. Significant wave height is statistically defined as the average height of the highest one-third waves in a sea state, and is a typical statistic used for coastal engineering applications. The spectral peak period is the wave period that characterizes the majority of the waves in a sea state (i.e., the frequency at which the most energy resides).

2.2.2 Extremal Analysis Program

The longer period return values in this study were approximated using a computer model developed by Offshore & Coastal Technologies, Inc. (OCTI), and published in 1985. The program is entitled "EXTRM2: Extremes Program," and provides simplified estimates of extremes for most problems. The program contains several distribution types (e.g., Weibull) but encourages the use of the Generalized Extreme Value (GEV) method, which is thought to provide reliable estimates of extremes without assuming the distribution type is known. The program requires the input data set to consist of a set of maxima drawn from a large sample, which is the basis for the sub-sampling of wind and wave data described in Sections 3.2 and 3.5. The GEV method uses asymptotic methods to fit sampled maxima to the tail of the parent distribution. The parent distribution itself is characterized by distribution parameters, which are estimated from the original sample. The maximum likelihood method 'fitting technique' is generally recognized as providing the optimal estimation of these parameters (Resio, 1989). More detailed information on the theoretical basis for the program can be found in the EXTRM2 user's manual (Resio, 1989).

The EXTRM2 model, using the GEV analysis will examine the sample and using a three standard deviation criterion will search for possible outliers. If found, outliers can be included or excluded from the analysis. The output consists of Gumbel and GEV extremes estimates and comparisons to the original data.

2.2.3 Extreme Storm Wave (ESW)

For the purposes of this project, the extreme storm wave was defined as the average height of the highest 1% (H_1) of all the waves in the spectrum based on discussions with Cape Wind engineers. The ACES wave growth model and the WIS hindcast wave data both give data in terms of the significant wave height (H_s), which represents the average height of the highest one-third waves in the spectrum. Assuming that the wave spectrum for the irregular waves approximately fits a Rayleigh distribution, a probability density function of wave height is obtained directly from statistical theory:

$$p(\mathrm{H})\, d\mathrm{H} = \mathrm{H}/4m_o \exp[-\mathrm{H}^2/8m_o]d\mathrm{H},$$

where H is the wave height and m_o is the zero-th spectral moment. Inherent to this equation are the assumptions that the maxima of the wave profile occur at the wave crests, and that the wave crests and troughs are symmetric. Based on this probability density function, values for H_{10} and H_1 can be calculated using numerically evaluated wave height relationships. The extreme storm wave (H_1) is approximately 1.67 times the significant wave height (H_s), and the average of the highest one-tenth waves in the spectrum ($H_{1/10}$) is approximately 1.31 times the significant wave height (Goda, 1985).

Table 2-1. Fetch geometry input to the wave model

Angle Start	Angle End	Fetch Length (mi)	Average Depth (MLLW) (ft)
0	22.5	8.6	19.3
22.5	45	9	21.3
45	67.5	20.4	22.3
67.5	90	18.2	27.3
90	112.5	17.7	37.3
112.5	135	20.4	28.3
135	157.5	16.5	20.3
157.5	180	11.2	19.3
180	202.5	12.2	31.3
202.5	225	6.9	26.3
225	247.5	10.8	25.3
247.5	270	10.2	33.3
270	292.5	13	18.3
292.5	315	6.9	11.3
315	337.5	7.1	13.3
337.5	360	7.2	17.3

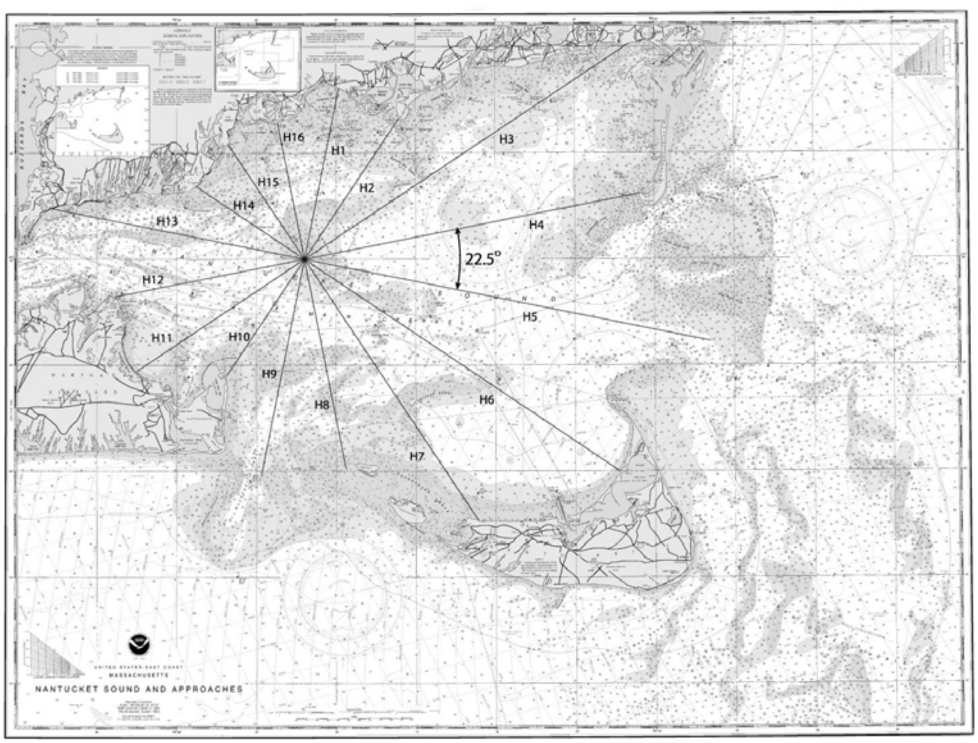

Figure 2-2. Fetch directions for Horseshoe Shoal

3.0 Engineering Analysis

3. ENGINEERING ANALYSIS

Based on the technical procedures outlined in Section 2, engineering analysis were conducted to estimate preliminary design parameters for:

- storm surge;
- winds;
- tidal currents;
- locally-generated waves in the Sound; and
- ocean waves.

Calculation procedures and results are described in the following subsections.

3.1 Storm Surge

Water level data were obtained from Tidal Flood Profiles for the New England Coastline (USACE, 1988) for the southern Cape Cod and northern Nantucket coastlines. Water level data also were obtained from the Federal Emergency Management Agency (FEMA) Flood Insurance Studies (FIS) for the Towns of Barnstable, Yarmouth, and Nantucket, MA. Based on a review of these sources of information, it was determined that the extreme water levels presented by the USACE for the southern Cape Cod coastline are most conservative. Since no information was available for the 2-year storm, the EXTRM2 program was applied to estimate the 2-year event based on input data for the 1-, 10-, 50-, and 100-year events. Results are presented in Table 3-1. The results likely overestimate actual storm surge at Horseshoe Shoal (where the full storm surge has not yet developed since it is some distance offshore from the southern Cape Cod coastline).

Table 3-1. Storm surge at Horseshoe Shoal

Parameter	1-year	2-year	10-year	50-year	100-year
Storm Surge (ft-MLLW)	4.5	4.8	6.5	9.6	11.7

3.2 Winds

Wind data were obtained from the National Climatic Data Center (NCDC) at Hyannis Airport and Nantucket Airport. These data sets spanned 1973-2001 at Hyannis and 1986-2001 at Nantucket. Hourly averages of wind speed and direction were obtained along with wind gust information. This wind data provided input information for the Wind-Generated Wave Model described in Sections 2.2.1 and 3.4.

A preliminary screening of the data was undertaken to select the appropriate data set for further analysis. After excluding outliers (major gust events) it was found that wind speeds recorded at Nantucket were of approximately the same magnitude as those measured at Hyannis. In addition, the Nantucket site was preferable due to its more open water location and presumed similarity to the wind farm site. Given these factors it was decided that the Nantucket wind data would be used as input for the extremal analyses.

For the wind speed extremal analysis, the top 16 wind speeds (mph) from the record were selected as one data set, and the top wind speed each of the 16 data years were selected as a second data set. Each wind measurement represents an hourly average. Both data sets were run through the extremal analysis program, EXTRM2, which prefers an annual data series (i.e., for the 1986-2001 period of wind speed data the top wind speed for each year should be used). Input parameters for the analysis were chosen based on the optimal methods of extremal analysis available in the program. These include an asymptotic method, (the Generalized Extreme Value (GEV) method), to equate the sampled maxima to the tail of the corresponding parent distribution. As part of the GEV procedure, the maximum likelihood method (MLM) was chosen to estimate the distribution parameters from the wind speeds sample provided.

EXTRM2 model output for both data sets is summarized in Table 3-2, including the GEV estimates of wind speed for the 2-yr, 10-yr, 50-yr and 100-yr return periods. A comparison of the data shows that the second data set, highest wind speed per year, yielded the most conservative extremal results (i.e., highest wind speeds). This was due to the slope of the data (smaller minima to the same maxima) as opposed to the top 16 wind speeds which had less variation and therefore gave smaller values for the longer return periods (e.g., 50- and 100-year).

Table 3-2. Extreme wind speeds at Horseshoe Shoal

Parameter	1-year	2-year	10-year	50-year	100-year
Wind Speed (mph)[1]	NA	56	59	67	70
Wind Speed (mph)[2]	NA	47	59	69	74

[1] Based on extremal analysis of top 16 hourly average wind events in the 16-year record
[2] Based on extremal analysis of top annual wind event

3.3 Tidal Currents

Tidal currents at the Horseshoe Shoal site were estimated by comparing the speed of tidal currents measured during an Acoustical Doppler Current Profiler (ADCP) survey (WHG, 2002) with the range of tidal oscillations of sea level, as measured at the Nantucket Island sea level station. The sea level data for the year 2002 were then analyzed to determine the range of sea level variability, and a ratio was established to estimate tidal currents from sea level. Tidal harmonic analysis of sea level data revealed dominance of the following tidal harmonics: O1, K1, N2, M2, S2, M4. Periods and amplitudes of the primary tidal harmonics are shown in Table 3-3.

Table 3-3. Periods and amplitudes of the O1, K1, N2, M2, S2, M4 tidal harmonics

Constituent	Period (hours)	Amplitude (feet)
O1	25.82	0.27
K1	23.93	0.30
N2	12.66	0.38
M2	12.42	1.42
S2	12.00	0.16
M4	6.21	0.09

A spatially-averaged tidal current speed (over the area encompassed by Horseshoe Shoal) was extracted from the survey data and compared to the water level data to reduce uncertainty in estimating the current speed for a specific location that may stem from spatial heterogeneity of tidal flow in the area. Although measured tidal current speeds at various locations on the Shoal were not highly variable (maximum current speed varied within 5%), the averaging improved the final estimate. The ratio between maximum current speed (ft/s) and sea level range (ft) was estimated to be 0.6 (0.59 for the flood tide and 0.61 for the ebb tide). Consequently, the range of tidal variability of ocean currents was estimated to be 0.9 ft/s (M2, N2, and diurnal harmonics are out-of-phase, long return periods) to 3.0 ft/s (when these harmonics are in-phase, long return periods). The range of current speed variability within one lunar cycle was from 1.2 ft/s to 2.6 ft/s. The estimated maximum speed of the tidal current for the year 2002 was 2.85 ft/s.

3.4 Locally-Generated Waves

In order to test the relative importance of fetch length and depth on wave height the highest wind speed in the Nantucket data set, excluding obvious outliers, was selected for a preliminary analysis. This speed was run through the ACES wave height prediction model for each directional bin using the direction specific fetch and depth parameters. The wave modeling methodology is summarized in detail in the Existing Conditions report (Woods Hole Group, 2004). This analysis determined that winds blowing from anywhere within the 0-22.5° and 292.5-360° angle bands would not produce high magnitude wave heights even with the maximum wind speed. In addition, a second ACES run was performed using a wind speed of 40 mph from each direction, which showed that wind speeds equal to 40 mph would only produce significant wave heights for winds blowing from the 90°-135° directions. A sensitivity analysis also was conducted on wind duration. Because of the restricted fetch length, seas fully develop rapidly and the model was relatively insensitive to wind direction. As such, both the observed and final durations were set to 3 hours. Using these criteria, the 16 years of wind data from Nantucket were screened to identify the top three or four unique wind speed events likely to produce the largest wave heights in each year. These 73 events were then run through the ACES model, using their specific wind directions and average fetch depth, to find the largest wave events. From this larger data set, two subsets of wind-generated wave heights were determined: the top 16 modeled wave events in the record and the top wave event modeled each year.

Extremal analysis on the two wind-generated wave height data sets was performed using EXTRM2. Within this program the GEV and MLM methods were utilized, as described in Section 3.2. The results were similar to the extremal analysis for the wind data in that the top wind-generated wave event each year produced more conservative estimates for the longer period returns. The results of the extremal analysis on the highest annual wave events are summarized in Table 3-4, including the GEV estimates of wind-generated wave heights for a 2-yr, 10-yr, 50-yr and 100-yr return period. Wave periods were not calculated for these events, but were instead calculated for the more conservative conditions presented in Table 3-5.

Table 3-4. Significant heights at Horseshoe Shoal generated by local winds within Nantucket Sound

Parameter	1-year	2-year	10-year	50-year	100-year
Locally-Generated Sound Significant Wave Height (ft)	NA	5.3	6.7	8.0	8.5

To investigate a potentially more conservative estimate of locally generated waves the 2-, 10-, 50- and 100-year extreme wind speeds (Table 3-2) were run through the ACES wave prediction model using the wind/fetch direction that produces the largest wave heights (101.25°), and adding the 2-yr, 10-yr, 50-yr and 100-yr storm surge elevation to the average water depth. The model results for significant wave height and spectral peak wave period are shown in Table 3-5, and are larger than the results on Table 3-4. Consequently, Table 3-5 results are more conservative, and are recommended for the preliminary design process.

Table 3-5. Significant wave heights and periods at Horseshoe Shoal generated by local winds within Nantucket Sound (based on extreme winds)

Parameter	1-year	2-year	10-year	50-year	100-year
Locally-Generated Sound Significant Wave Height (ft)	NA	6.7	8.6	10.4	11.2
Spectral Peak Wave period (sec)	NA	5	5.6	6.2	6.4

3.5 Ocean Waves

For comparison to the locally-generated waves at the Horseshoe Shoal site, a preliminary investigation of offshore wave conditions at a site southeast of Nantucket Island was conducted. Wave data were available from Wave Information Studies (WIS) performed by the USACE. Hindcast wave data were obtained from the representative site southeast of Nantucket Island, WIS site 2089 (41.25N, 69.75W). The USACE WIS provided 20 years of hindcast significant wave height, peak period and direction for this site between 1976 and 1995, including the effects of coastal storms (which were not included in the previous WIS hindcast data set between 1956 and 1975).

By sorting the hindcast data based on significant wave height, the largest wave event from each year was selected and an extremal analysis was performed on this data set. As with the wind and locally-generated wave analysis, the GEV and MLM methods were used in the EXTRM2 program. The results of this analysis are presented in Table 3-6. Where possible, the associated wave period was estimated from similar wave height values in the WIS data set. For the larger wave height values this was not possible. In these cases the wave height-wave period relationship in the WIS data was used to extrapolate a wave period from a larger wave height.

Table 3-6. Extreme ocean wave heights southeast of Nantucket Island

Parameter	1-year	2-year	10-year	50-year	100-year
Offshore Significant Wave Height (ft)	NA	22	31	39	42
Offshore Wave Period (sec)	NA	14	16	21	24

Although there is potential for ocean waves to reach Horseshoe Shoal through the openings between Cape Cod and Nantucket Island and between Nantucket Island and Marthas Vineyard, ocean waves at Horseshoe Shoal were not estimated as part of this Phase I analysis. Estimating the complex refraction and diffraction processes that occur as waves propagate from the Ocean into the Sound would require numerical modeling and site-specific data. For preliminary design purposes, therefore, a conservative assumption can be made that ocean waves reach the Horseshoe Shoals site, that wave period would be similar to the wave periods observed in the Ocean, and that a maximum depth-limited wave height would occur.

3.6 Wind-Generated Currents

A wind-generated current model was developed for the existing conditions analysis (WHG, 2003) to characterize wind-generated currents within Nantucket Sound. The model was developed to estimate current speeds over an idealized elliptical shoal representative of Horseshoe Shoal within an idealized closed rectangular basin of similar spatial scale to Nantucket Sound. A linearized stream function equation was derived to calculate small-amplitude barotropic flow over the representative shoal system, balancing stresses and forces associated with constant wind stress, Coriolis, and bottom friction. Wind stress was formulated using an empirical parametrization for an unstratified atmosphere (Large and Pond, 1981). The model was designed to simulate wind blowing across the axis of the Sound, which exerts a stress on the sea surface that generates flow across Horseshoe Shoal balanced by a return flow on the deeper margins of the Sound.

The extreme wind conditions derived in Section 3.2 were simulated, and winds were assumed to blow from west to east along the long axis of the Sound. This is a conservative assumption (i.e., likely overestimates wind-generated current speeds), because it incorporates the highest wind speeds along the longest fetch, although the highest wind speeds tend to come from the N and NE directions. Model output included a current speed profile across the Shoal that varied with water depth. Current speed increased with decreasing water depth, and was likely overestimated in the shallowest portions of the shoal where the linear assumptions implicit to the model were most compromised. Nonetheless, model results provide a conservative first approximation of wind-generated currents for preliminary design purposes. Table 3-7 provides a range of current speeds output by the model at a depth of 10 – 20 ft for each extreme storm event.

Table 3-7. Extreme Wind-Generated Current Speeds

Parameter	1-year	2-year	10-year	50-year	100-year
Current Speed (ft/sec)	NA	1.5-2	3-3.5	4.5-5.5	5.5-7

4.0 Summary And Recommendations

4. SUMMARY AND RECOMMENDATIONS

This report documents the methods, data sources, and results of the Phase I Coastal Engineering Design Parameter Analysis for the proposed wind farm project. Table 4-1 summarizes the preliminary design parameters, including:

- Maximum annual tidal currents (ft/sec).
- Significant wave height (H_s), $H_{1/10}$, the extreme storm wave height (H_1), and the spectral peak period (sec) corresponding to waves at the Horseshoe Shoal site generated by local winds in the Sound.
- Significant wave height (H_s), $H_{1/10}$, the extreme storm wave height (H_1), and the spectral peak period corresponding to ocean waves southeast of Nantucket Island.
- Hourly-averaged wind speed (mph).
- Storm surge (ft) relative to mean lower low water (MLLW).

These design parameters are intended to support Cape Wind's preliminary design, but are not intended to be final design parameters. Final design parameters should be developed based on more detailed numerical modeling and site-specific data from Cape Wind's Scientific Measurement Devices Station (SMDS). In order to provide an indication of the level of accuracy associated with the preliminary design parameters, Table 4-1 also provides confidence intervals for parameters where possible.

Until data become available from the SMDS, the main recommendation to improve the design parameter analysis is application of a numerical wave model to characterize the extent to which ocean waves can propagate into the Sound to the Horseshoe Shoal site. A spectral refraction and diffraction model should be applied to simulate the transfer of wave energy from the Ocean into the Sound and onto Horseshoe Shoal. The spectral wave model also would provide a detailed characterization of the spatial variability of wave height and the potential for wave breaking across Horseshoe Shoal, which may allow for development of turbine-specific design conditions (or at least for groups of turbines that would be exposed to similar wave conditions). More detailed wave modeling may indicate the extent to which some turbine locations would be exposed to smaller waves than others, potentially allowing for a refined design and eventual construction cost savings. Absent more detailed wave modeling results, only one representative design wave height and period is available to characterize the entire shoal system, which may over- or underestimate actual conditions at individual turbine locations. In particular, design wave forces may be underestimated where there is potential for shallow water wave shoaling and breaking. A more detailed wave model also would simulate wave-current interactions, which have the potential to create higher, steeper waves, particularly where waves are travelling in a direction opposite the tidal currents. Such wave-current interactions may require modification of the design parameters.

Table 4-1. Summary of preliminary coastal engineering design parameters

Parameter	1-year	2-year	Confidence Interval	10-year	Confidence Interval	50-year	Confidence Interval	100-year	Confidence Interval
Tidal Currents (ft/sec)	2.85	NA	NA	NA	NA	NA	NA	NA	NA
Locally-Generated Significant Wave Height in Sound (ft)	NA	6.7	0.2	8.6	0.6	10.4	1.1	11.2	1.4
Locally-Generated Spectral Peak Period in Sound (sec)	NA	5	0.1	5.6	0.3	6.2	0.3	6.4	0.4
Locally-Generated H(1/10) in Sound (ft)	NA	8.5	0.3	10.9	0.8	13.2	1.4	14.2	1.8
Locally-Generated Extreme Storm Wave (ESW) Height in Sound (ft)	NA	11.2	0.3	14.3	1.0	17.3	1.8	18.7	2.3
Offshore Significant Wave Height (ft)	NA	22	1	31	3	39	5	42	6
Offshore Spectral Peak Period (sec)	NA	14	NA	16	NA	21	NA	24	NA
Offshore H(1/10) (ft)	NA	28	1	39	4	50	6	53	8
Offshore Extreme Storm Wave (ESW) Height (ft)	NA	37	2	52	5	65	8	70	10
Wind Speed (mph)	NA	47	1	59	4	69	7	74	8
Storm Surge (ft-MLLW)	4.5	4.8	NA	6.5	NA	9.6	NA	11.7	NA
Wind-Generated Currents (ft/sec)	NA	1.5-2	NA	3-3.5	NA	4.5-5.5	NA	5.5-7	NA

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