Final Report for

Task 2.0 Extreme Wind Events & Design Parameters

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The final report submitted to the University of Delaware. This report is based on the following tasks:

**Task 2.0 Extreme Wind Events & Design Parameters**
Extreme wind events like hurricanes and ‘northeasters’ create extreme stress on offshore structures and sub-sea power cable systems.

**2.1 Assemble data**
Decades of existing data will be assembled from buoys and appropriate coastal stations. Concurrently, data from the 50m meteorological tower on the Lewes campus will be used to generate a better wind profile of the turbine site.

**2.2 Parameterization**
The assembled data will be used to determine the statistical probabilities of 50 and 100 years for wind and wave extreme events on a spatial basis. For the wind extreme events Monthly Extreme Wind Speeds method (Simiu and Scanlan 1986) will be used. The Peak-Over-Threshold (POT analysis) (Kamphuis, 2000) will be used wave extreme events analysis.
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1. Methodology

1.1. Assemble data

Wind

Wind data from 13 stations (Figure 1 and Table 1) that represent the Mid-Atlantic area, were obtained from the National Data Buoy Center (NDBC). The hourly averaged data was available for an approximate 20-year period (1990 to 2011) (Refer to: http://www.ndbc.noaa.gov/measdes.shtml). All that data was included in the data base file. Analysis of wind, waves and extreme events was included in this report only for 4 stations (44009, 44014, 44025 and CHLV2).

Figure 1.- Location of NDBC Buoys and C-Man stations
Table 1.- NDBC Buoys and C-MAN stations included in the database

<table>
<thead>
<tr>
<th>Number</th>
<th>STATION_ID</th>
<th>TTYPE</th>
<th>NAME</th>
<th>State</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41001</td>
<td>6-meter NOMAD buoy</td>
<td>150 NM East of Cape Hatteras</td>
<td>NC</td>
<td>34.704</td>
<td>-72.734</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>41002</td>
<td>6-meter NOMAD buoy</td>
<td>Hatteras - 250 NM East of Charleston</td>
<td>SC</td>
<td>32.382</td>
<td>-75.415</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>41025</td>
<td>3-meter discus buoy</td>
<td>Diamond Shoals</td>
<td>NC</td>
<td>35.006</td>
<td>-75.402</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>44004</td>
<td>6-meter NOMAD buoy</td>
<td>Hotel 200NM East of Cape May</td>
<td>NJ</td>
<td>38.484</td>
<td>-70.433</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>44005</td>
<td>6-meter NOMAD buoy</td>
<td>Gulf of Maine 78 NM East of Portsmouth</td>
<td>NH</td>
<td>43.189</td>
<td>-69.140</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>44009</td>
<td>3-meter discus buoy</td>
<td>Delaware Bay 26 NM Southeast of Cape May</td>
<td>NJ</td>
<td>38.464</td>
<td>-74.702</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>44011</td>
<td>6-meter NOMAD buoy</td>
<td>Georges Bank 170 NM East of Hyannis</td>
<td>MA</td>
<td>41.111</td>
<td>-66.580</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>44014</td>
<td>3-meter discus buoy</td>
<td>Virginia Beach 64 NM East of Virginia Beach</td>
<td>VA</td>
<td>36.611</td>
<td>-74.836</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>44017</td>
<td>3-meter discus buoy</td>
<td>23 Nautical Miles Southwest of Montauk Point</td>
<td>NY</td>
<td>40.691</td>
<td>-72.046</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>44018</td>
<td>3-meter discus buoy</td>
<td>SE Cape Cod 30NM East of Nantucket</td>
<td>MA</td>
<td>41.259</td>
<td>-69.294</td>
<td>5</td>
</tr>
<tr>
<td>11</td>
<td>44025</td>
<td>3-meter discus buoy</td>
<td>Long Island 33 NM South of Islip</td>
<td>NY</td>
<td>40.250</td>
<td>-73.166</td>
<td>5</td>
</tr>
<tr>
<td>12</td>
<td>chlv2</td>
<td>C-MAN Station</td>
<td>Chesapeake Light Tower</td>
<td>VA</td>
<td>36.910</td>
<td>-75.710</td>
<td>43.3</td>
</tr>
<tr>
<td>13</td>
<td>fpsn7</td>
<td>C-MAN Station</td>
<td>Frying Pan Shoals</td>
<td>NC</td>
<td>33.485</td>
<td>-77.590</td>
<td>43</td>
</tr>
</tbody>
</table>

File and data description

A file containing 13 NOAA NDBC stations mentioned in Table 1 was created as a structured data file that can be read in MATLAB. The data was downloaded from the NOAA NDBC web page and standardized by time frequency and variables. The file “buoy.mat” can be downloaded from: http://www.ccpo.odu.edu/~jlblanco/wind/data/. The file structure is included in Annex 1.

In the present report we characterize the wind main condition in the MAB area and use the information to get the values for the extreme conditions.

Waves

Ocean surface waves usually result from local wind or remote effects and may travel thousands of miles before striking land. There is little actual forward motion of individual water particles in a wave, despite the large amount of energy and momentum it may carry forward. The faster the wind, the longer the wind blows, and the bigger the area over which the wind blows, the bigger the waves. The basic wind and wave statistics contain their characteristic height over a period of time and is usually expressed as significant wave height and their period. Table 2 shows the wave data and number of years at selected NDBC buoys).

Table 2.- Wave data in the NDBC buoys

<table>
<thead>
<tr>
<th>station</th>
<th>years data</th>
<th># of years</th>
</tr>
</thead>
<tbody>
<tr>
<td>44014</td>
<td>1990-2011</td>
<td>18.9</td>
</tr>
<tr>
<td>chlv2</td>
<td>1984-2004</td>
<td>13.8</td>
</tr>
<tr>
<td>44009</td>
<td>1986-2011</td>
<td>23.2</td>
</tr>
<tr>
<td>44025</td>
<td>1991-2011</td>
<td>18.9</td>
</tr>
</tbody>
</table>

In the present report we characterize the wave main condition in the MAB area and use the
information to get the values for the extreme conditions.

Wind profile at Lewes turbine site

A dataset for a single 50m meteorological tower was provided by the University of Delaware. The met-tower is located on the Lewes campus of the University of Delaware. We used approximately 3.5 years of observed data recorded between May 2008 and November 2011.

Table 3.- Geographic coordinates, elevation and period of record of the Lewes met-tower station.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>N 38° 47.700''</td>
</tr>
<tr>
<td>Longitude</td>
<td>W 75° 9.43.600''</td>
</tr>
<tr>
<td>Elevation</td>
<td>1.8 m</td>
</tr>
<tr>
<td>Start date</td>
<td>5/8/2008 00:00</td>
</tr>
<tr>
<td>End date</td>
<td>11/14/2011 11:00</td>
</tr>
<tr>
<td>Duration</td>
<td>3.5 years</td>
</tr>
<tr>
<td>Length of time step</td>
<td>10 minutes</td>
</tr>
</tbody>
</table>

Table 4.- Information on the anemometers, wind vanes and temperature sensor for all the heights available at the Lewes met-tower station.

<table>
<thead>
<tr>
<th>Label</th>
<th>Units</th>
<th>Height</th>
<th>Possible Records</th>
<th>Valid Records</th>
<th>Recovery Rate (%)</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed 49 m A</td>
<td>m/s</td>
<td>49 m</td>
<td>195,106</td>
<td>173,041</td>
<td>96.72</td>
<td>5.99</td>
<td>4.49</td>
<td>25.2</td>
</tr>
<tr>
<td>Speed 49 m A</td>
<td>m/s</td>
<td>49 m</td>
<td>195,106</td>
<td>173,041</td>
<td>96.72</td>
<td>5.73</td>
<td>0.00</td>
<td>6.70</td>
</tr>
<tr>
<td>Speed 49 m A</td>
<td>m/s</td>
<td>49 m</td>
<td>195,106</td>
<td>173,041</td>
<td>96.72</td>
<td>7.62</td>
<td>0.00</td>
<td>34.7</td>
</tr>
<tr>
<td>Speed 49 m A</td>
<td>m/s</td>
<td>49 m</td>
<td>195,106</td>
<td>173,041</td>
<td>96.72</td>
<td>4.07</td>
<td>0.00</td>
<td>19.6</td>
</tr>
<tr>
<td>Speed 49 m B</td>
<td>m/s</td>
<td>49 m</td>
<td>195,106</td>
<td>175,847</td>
<td>95.54</td>
<td>5.68</td>
<td>0.39</td>
<td>24.9</td>
</tr>
<tr>
<td>Speed 49 m B</td>
<td>m/s</td>
<td>49 m</td>
<td>195,106</td>
<td>175,847</td>
<td>95.54</td>
<td>0.736</td>
<td>0.00</td>
<td>6.69</td>
</tr>
<tr>
<td>Speed 49 m B</td>
<td>m/s</td>
<td>49 m</td>
<td>195,106</td>
<td>175,847</td>
<td>95.54</td>
<td>7.74</td>
<td>0.39</td>
<td>34.9</td>
</tr>
<tr>
<td>Speed 49 m B</td>
<td>m/s</td>
<td>49 m</td>
<td>195,106</td>
<td>175,847</td>
<td>95.54</td>
<td>3.99</td>
<td>0.39</td>
<td>19.3</td>
</tr>
<tr>
<td>Speed 49 m B</td>
<td>m/s</td>
<td>42 m</td>
<td>195,106</td>
<td>173,041</td>
<td>96.72</td>
<td>5.67</td>
<td>0.39</td>
<td>23.5</td>
</tr>
<tr>
<td>Speed 49 m B</td>
<td>m/s</td>
<td>42 m</td>
<td>195,106</td>
<td>173,041</td>
<td>96.72</td>
<td>0.750</td>
<td>0.00</td>
<td>6.30</td>
</tr>
<tr>
<td>Speed 49 m B</td>
<td>m/s</td>
<td>42 m</td>
<td>195,106</td>
<td>173,041</td>
<td>96.72</td>
<td>7.55</td>
<td>0.39</td>
<td>35.3</td>
</tr>
<tr>
<td>Speed 49 m B</td>
<td>m/s</td>
<td>42 m</td>
<td>195,106</td>
<td>173,041</td>
<td>96.72</td>
<td>3.73</td>
<td>0.39</td>
<td>17.6</td>
</tr>
<tr>
<td>Speed 49 m B</td>
<td>m/s</td>
<td>42 m</td>
<td>195,106</td>
<td>176,754</td>
<td>95.50</td>
<td>5.66</td>
<td>0.39</td>
<td>24.0</td>
</tr>
<tr>
<td>Speed 49 m B</td>
<td>m/s</td>
<td>42 m</td>
<td>195,106</td>
<td>176,754</td>
<td>95.50</td>
<td>0.762</td>
<td>0.00</td>
<td>6.40</td>
</tr>
<tr>
<td>Speed 49 m B</td>
<td>m/s</td>
<td>42 m</td>
<td>195,106</td>
<td>176,754</td>
<td>95.50</td>
<td>7.56</td>
<td>0.39</td>
<td>36.2</td>
</tr>
<tr>
<td>Speed 49 m B</td>
<td>m/s</td>
<td>42 m</td>
<td>195,106</td>
<td>176,754</td>
<td>95.50</td>
<td>3.69</td>
<td>0.39</td>
<td>18.3</td>
</tr>
<tr>
<td>Speed 30 m A</td>
<td>m/s</td>
<td>30 m</td>
<td>195,106</td>
<td>178,842</td>
<td>96.62</td>
<td>5.16</td>
<td>0.39</td>
<td>21.8</td>
</tr>
<tr>
<td>Speed 30 m A</td>
<td>m/s</td>
<td>30 m</td>
<td>195,106</td>
<td>178,842</td>
<td>96.62</td>
<td>0.777</td>
<td>0.00</td>
<td>6.10</td>
</tr>
<tr>
<td>Speed 30 m A</td>
<td>m/s</td>
<td>30 m</td>
<td>195,106</td>
<td>178,842</td>
<td>96.62</td>
<td>7.13</td>
<td>0.39</td>
<td>36.4</td>
</tr>
<tr>
<td>Speed 30 m A</td>
<td>m/s</td>
<td>30 m</td>
<td>195,106</td>
<td>178,842</td>
<td>96.62</td>
<td>3.18</td>
<td>0.39</td>
<td>15.9</td>
</tr>
<tr>
<td>Speed 30 m B</td>
<td>m/s</td>
<td>30 m</td>
<td>195,106</td>
<td>176,633</td>
<td>95.42</td>
<td>5.12</td>
<td>0.39</td>
<td>21.8</td>
</tr>
<tr>
<td>Speed 30 m B</td>
<td>m/s</td>
<td>30 m</td>
<td>195,106</td>
<td>176,633</td>
<td>95.42</td>
<td>0.768</td>
<td>0.00</td>
<td>6.30</td>
</tr>
<tr>
<td>Speed 30 m B</td>
<td>m/s</td>
<td>30 m</td>
<td>195,106</td>
<td>176,633</td>
<td>95.42</td>
<td>7.12</td>
<td>0.39</td>
<td>36.1</td>
</tr>
<tr>
<td>Speed 30 m B</td>
<td>m/s</td>
<td>30 m</td>
<td>195,106</td>
<td>176,633</td>
<td>95.42</td>
<td>3.12</td>
<td>0.39</td>
<td>15.9</td>
</tr>
<tr>
<td>Temperature 45 m</td>
<td>°C</td>
<td>45 m</td>
<td>195,106</td>
<td>184,961</td>
<td>93.92</td>
<td>7.6</td>
<td>0.00</td>
<td>122.0</td>
</tr>
<tr>
<td>Temperature 45 m</td>
<td>°C</td>
<td>45 m</td>
<td>195,106</td>
<td>184,961</td>
<td>93.92</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Temperature 45 m</td>
<td>°C</td>
<td>45 m</td>
<td>195,106</td>
<td>184,961</td>
<td>93.92</td>
<td>14.31</td>
<td>0.00</td>
<td>359.0</td>
</tr>
<tr>
<td>Temperature 45 m</td>
<td>°C</td>
<td>45 m</td>
<td>195,106</td>
<td>184,961</td>
<td>93.92</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Temperature 45 m</td>
<td>°C</td>
<td>45 m</td>
<td>195,106</td>
<td>184,961</td>
<td>93.92</td>
<td>0.00</td>
<td>0.00</td>
<td>30.6</td>
</tr>
<tr>
<td>Temperature Max</td>
<td>°C</td>
<td>195,106</td>
<td>184,961</td>
<td>93.92</td>
<td>14.31</td>
<td>0.00</td>
<td>359.0</td>
<td></td>
</tr>
<tr>
<td>Temperature Min</td>
<td>°C</td>
<td>195,106</td>
<td>184,961</td>
<td>93.92</td>
<td>0.00</td>
<td>0.00</td>
<td>30.6</td>
<td></td>
</tr>
</tbody>
</table>
The data were recorded using an NRG Symphony data logger in raw binary data. The files included 10-minute averages of wind speed, direction and temperature records along with their respective standard deviations. Table 3 presents basic information about the met-tower, including its geographic coordinates, elevation, period of record, and environmental conditions. Table (4) presents information on the anemometers, wind vanes and temperature sensor for all the heights available. The anemometers used in the measurement program were calibrated NRG #40. The data quality was done using the NRG # 40 specification sheet and also the tower distortion analysis was conducted before proceeding further. The file “wprofile.mat” can be downloaded from: http://www.ccpo.odu.edu/~jlblanco/wind/data/. The file structure is included in Annex 2.

Wind profile

The mean wind profile, i.e. measurements of wind speed as a function of height, averaged over periods of 10 - 60 minutes, is often described using a power law equation,

\[ \frac{U(z_1)}{U(z_2)} = \left( \frac{z_1}{z_2} \right)^p \]

where \(U(z_1)\) and \(U(z_2)\) are the wind speeds at heights \(z_1\) and \(z_2\), respectively, and \(p\) is the power law exponent, with a typical value of 0.14 onshore and 0.11 offshore (NOAA recommendations) that correspond to the near-neutral stability conditions that prevail at sea (Hsu et al., 1994). Considering that buoys collect wind data at 5 m over the sea level, and Chesapeake Light Tower at 43 m, for all the further analysis we will standardize all the wind data to the level of 50 m using the power law with the exponent of 0.11.

Joint distribution

"Joint distribution of X and Y is the distribution of the intersection of the events X and Y, that is, of both events X and Y occurring together". In that case this analysis was performed for the wave height and wind speed.

1.2. Extreme events analysis

Extreme events are often highly variable in terms of intensity and sequencing. By definition, they are rare. Thus, long-term statistical methods must deal with the problem of using a small, variable sample to estimate parameters that often have a major impact on design. Engineers are continually reminded that events such as the 100-year extreme storm can by chance occur during a much shorter data collection effort. Conversely, a 10-year record may not contain any events that equal or exceed the long-term 10-year extreme.
The preferred approach to data selection is to take the maximum value from each event to create a partial duration series of extreme values. Typically, the events are storms, ranging from small, weak events to the most severe storms of record. Small events can be difficult to identify. Further, they are of little interest if an adequate number of bigger storms is available in the record. Often the partial duration series will be censored to exclude data values less than some threshold value. Thus the extreme analysis can focus on a smaller series representing truly significant events. The threshold is often chosen so that the number of data values in the series is greater than the number of years of record (generally 1-3 times the number of years of record).

Long-term wind analysis

Extreme wind speeds can be analyzed with a simple approach using monthly extreme wind speeds (Simiu and Scanlan 1986). This analysis was performed to the hourly wind and gust information. (Gust: Peak 5 or 8 second gust speed (m/s) measured during eight-minute period).

\[ U_r = \bar{U}_m + 0.78 \sigma_m [\ln(12 T_r) - 0.577] \]

where

- \( U_r \) = wind speed with \( r \)-years return period
- \( \bar{U}_m \) = mean value of maximum monthly wind speed
- \( \sigma_m \) = standard deviation of maximum monthly wind speeds

Following the methodology described by CEM II.8 (2002) "Extreme conditions in coastal engineering are often described in terms of return values and return periods. The return period is the average time interval between successive events of the design wave being equaled or exceeded. For example, a 25-year significant wave height is that height that is equaled or exceeded an average of once during a 25-year time period. Return period is expressed as":

\[ T_r = \frac{t}{1 - P(H_s)} \]

Wave data registered every hour contain information that is calculated as the average of the highest one-third of all of the wave heights during 20-minute sampling period, depending of the precedent time. For make statistical analysis independent data points representing storm rather than individuals hourly waves are calculated. The wave data was separated in to storms using the Peak Over Threshold (POT) analysis (Kamphuis, 2000).

"The POT data was analyzed using different probability distributions. Each distribution was linearized into the form \( Y = AX + B \). Where \( Y \) is the transformed probability distribution, and \( X \) is the transformed wave height. The coefficients \( A \) and \( B \) are the slope and intercept of the straight-line relationship and are determined by linear regression." (CEM II.8, 2002)
**Probability distribution**

**Gumbel Distribution**

"The Gumbel distribution is used to find the minimum (or the maximum) of a number of samples of various distributions."

\[ P = \exp \left( - \exp \left( - \frac{H - \gamma}{\beta} \right) \right) \]

This equation can be linearized by taking logs of both sides and reduced to the form:

\[ Y = - \ln \left( \ln \left( \frac{1}{P} \right) \right) = G; \quad X = H; \quad A = \frac{1}{\beta}; \quad B = -\frac{\gamma}{\beta} \]

**Weibull Distribution**

The Weibull Distribution is a continuous probability distribution and is used to describe the size distribution of values.

\[ P = 1 - \exp \left( - \left( \frac{H - \gamma}{\beta} \right)^{\alpha} \right) \]

This equation can be linearized by taking logs of both sides and reducing to the form:

\[ Y = \ln \left( \frac{1}{Q} \right)^{1/\alpha} = W; \quad X = H; \quad A = \frac{1}{\beta}; \quad B = -\frac{\gamma}{\beta} \]

For this distribution the linear regression only provides two constants (\( \beta \) and \( \gamma \)) the constant \( \alpha \) is determined searching for the best regression.

**Extrapolation**

The wave height \( H \) for a return period of \( Tr \) years may be determined. For this calculation the number of events per year (\( \lambda \)) is determined and the exceedence probability (\( Q \)) of one event in \( Tr \) years would be: \( Q=1/ (\lambda \cdot Tr) \)

The probabilities for the different distributions are:

**Gumbel distribution**

\[ H_{Tr} = \gamma - \beta \ln \left( \ln \left( \frac{1}{P} \right) \right) = \gamma - \beta \ln \left( \ln \left( \frac{\lambda \cdot Tr}{\lambda \cdot Tr - 1} \right) \right) \]
Weibull distribution

\[ H_{Tr} = \gamma + \beta \left( \ln \frac{1}{Q} \right)^{1/\alpha} = \gamma - \beta (\ln(\lambda Tr))^{1/\alpha} \]

Additionally to the extreme analysis, we used a metric developed by Butman et al (2008) to identify windstorm events. A storm based on wind stress was defined as a period when wind stress exceeded 0.2 Pa (about 11 m/s, 22 knots, or 25 mph) for at least 6 h. Wind stress had to fall below 0.2 Pa for at least 12 h to initiate a new storm. Integrated wind stress (IWINDS) was defined as the sum of the magnitudes of the hourly wind stress for the duration of the storm (Butman et al, 2008).

2. Results and discussion

2.1. Wind

The wind roses (Figures 2 to 5) show the seasonal distribution of wind direction and wind speed during a period of almost 22 years of data analyzed for the NDBC station 44009, 44014, 44025 and CHLV2. For the buoys (44009, 44014 and 44025) the predominant wind direction in the area is along the coast toward S-SSE in spring and summer and toward NNW during winter in the case of the CHLV2 (Fig. 5) the main direction change to wind blowing toward SSE in spring and winter, a predominance of wind from the west during Fall and from the W during Winter. The frequency with wind speeds greater than 6 m/s in all these sites is around 60% of the time. The long-term average was 8.2, 7.8, 8.5 and 7.6 m/s respectively. Calms are present less than 1% of the time, with a 0.63, 0.75, 0.46 and 0.96% of the time respectively.
Figure 2.- 50 m wind rose at the buoy 44009 by season. Wind direction is “blowing from”. Average wind speed is 8.2 m/s. Calms frequency 0.63%. Colors scale correspond to wind speed in m/s.

The number of hours per year of wind speed at 50 m height (dotted line in Figure 6) for NDBC stations 44009, 44014, 44025 and CHLV2 for the period 1990 – 2011, shows that the wind speed follows the Weibull distribution (fitted curve, Figure 7) where the CHLV2 has maximum frequency of values in wind speed lower than 12 m/s, contrary to the other buoys that have higher frequency at wind speeds greater than 12 m/s. That distribution is better represented by the corresponding wind power density (solid line in Figure 6), were the maximum energy is found at buoy 44025 located off New Jersey.
Figure 3. - 50 m wind rose at the buoy 44014 by season. Wind direction is “blowing from”. Average wind speed is 7.8 m/s. Calms frequency 0.75%. Colors scale correspond to wind speed in m/s.

Figure 4. - 50 m wind rose at the buoy 44025 by season. Wind direction is “blowing from”. Average wind speed is 8.5 m/s. Calms frequency 0.46%. Colors scale correspond to wind speed in m/s.
Figure 5.- 50 m wind rose at the buoy CHLV2 by season. Wind direction is “blowing from”. Average wind speed is 7.6 m/s. Calms frequency 0.96%. Colors scale corresponds to wind speed in m/s.

Figure 6. - Number of hours per year of wind speed at 50 m height (dotted line) and the corresponding wind power density (solid line) on NDBC stations 44014, 44009, 44025 and CHLV2 for the period 1990 – 2011.
Average of wind speed by season and hour is shown in Figure 8. In all the cases we can see a diurnal pattern that changes by season, being smaller during fall. The wind speed decreases from the ocean to the coast and from north to south, with maximum values in winter and a minimum in summer. At the buoys 44009 and 44014 the highest wind speeds occur at midday during most of the year excepting winter, and the lowest during evening or night hours. The opposite pattern is observed during winter at all the stations.

In general, winter is much windier than summer. Wind speeds in the fall and spring are somewhere in between. Winter wind speed is flat throughout the day. Summer wind speed is at a minimum in the morning hours, between 8 am and noon and at a maximum in the evening hours between 8 pm and midnight.
Figure 8. Seasonal average of hourly wind speed distribution for the NDBC stations 44009, 44014, 44025 and CHLV2. Vertical lines represent one standard deviation of the hourly mean.
2.2. Waves

Wind wave height is dependent on a) wind speed; b) fetch length; and c) duration of time the wind blows consistently over the fetch. Wind ‘fetch’ is the distance the wind blows over water with similar speed and direction. High wind speeds blowing for long periods of time over long stretches of water result in the highest waves.

The wave information for the NDBC stations 44009, 44014, 44025 and CHLV2, were plotted as frequency of occurrence for wave height and wave period (Figure 9) (shown here only for the CHLV2) and the joint distribution of wave height and period (Figure 10).

Waves in the MAB region typically are 1 m in height with a period between 4 and 8 seconds (Figs 9 and 10). There is an increased occurrence of minor waves in summer. In fall and winter the distribution tends to increase the frequency of higher waves with higher periods. The highest peaks in the data correspond to wave heights up to 7 m with periods of up to 20 seconds (Figs 9 and 10).

Figure 9. Frequency of occurrence of wave height (left) and period (right) by month, at the NDBC station CHLV2.
Figure 10.- Joint distribution of waves height and wind speed at the NDBC stations 44009, 44014, 44025 and CHLV2.
2.3. Wind profile

Mean wind profile and extrapolation to 100m: In the figures below we show the wind shear profile that was calibrated using the 6 anemometers at 3 different heights of 49m, 42m and 30m respectively. The power law exponent for the entire dataset was 0.297 for the 10 minutes average and 0.231 for the 10 minutes maximum (black line in Figure 11 a) and b). Similarly, the roughness length was calculated for the entire dataset, getting 1.26m for the 10 minutes average and 1.38m for the 10 minute maximum, these values correspond to a sub-urban terrain according to Manwell et al. (2002) and is indicated as red in the figure.

![Figure 11](image)

Figure 11.- Annual and seasonal mean (circle) of Lewes met-tower wind profile (lines are power law best-fit curve): a) 10 minutes average; b)10 minutes maximum (gust); c) monthly mean of the power law exponent; and d) hourly mean of the power law exponent, plus and minus one standard deviation (dotted line).

The wind shear exponent using power law was calculated to understand its behavior over different months (Figure 11). The exponent has its lowest in winter, increases in summer and has its maximum in fall. It is behaving in the general trend with unstable conditions prevailing in winter and stable conditions prevailing in fall. The wind speed gradient is diminished during unstable conditions (heating of the surface, increased vertical mixing) and increased during stable conditions (cooling of
the surface, suppressed vertical mixing).

The diurnal variation of the power law exponent: The exponent has its maximum from late evening to early morning while it’s lowest around noon. This also follows the same trend: unstable conditions prevail at noon as more heating of surface and increased vertical mixing, and thus explaining the low power law exponent value.

2.4. Extreme events

In the MAB area, extreme events are produced by hurricanes, tropical storms or extra-tropical storms (‘northeasters’). During hurricanes, sustained winds must be at least 100 km/h, but may reach over 200 km/h in the strongest of these storms. The strong winds push the ocean's surface, building waves that can reach 12 m high in open water. Meteorologists consider the water off the MAB area too cool to support a Category 5 storm. Hurricane category 3 and 4 are possible. Hurricanes and tropical storms occur mainly during summer and fall months and northeasters usually in fall, winter and early spring.

The inter-annual variability is governed mainly by the ENSO cycle. El Nino events cause stronger westerly winds in the atmosphere over the southeastern United States. These winds tend to shear hurricanes apart and help steer them away from the mainland. La Nina events bring cold waters over the equatorial Pacific, and there tends to be an increase in hurricane activity over the east coast of the U.S.

Using the integrated wind stress, we identified the storms in the MAB area for each wind data set. In Figures 12 and 13 we can see the storms distribution for the buoy 44009 and CHLV2 station, respectively. In the north area (44009), most of the storms occur mainly during the fall and winter season (most of them correspond to ‘Northeaster’ storms) with some exception during spring and summer that correspond to hurricanes (Table 5a). In the southern MAB area (CHLV2), the biggest storms occur mainly during summer that correspond to hurricanes (Figure 13 and Table 5b) but still present several storms during fall and winter season (that correspond to Northeaster’s). People unfamiliar with offshore weather often hear more about hurricanes and little about northeasters even though northeasters can create strong sustained winds over several days.
Figure 12.- Integrated wind stress distribution for the buoy 4409 by year and month.

Figure 13.- Integrated wind stress distribution for station CHLV2 (Chesapeake Light Tower) by year and month.
Table 5. - Date of the 20 biggest storms for a) buoy 44009 and 4) CHLV2

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Wind

Extreme wind speeds are similar at all stations in the Virginia coastal area, increasing towards the south (as we see in Figures 12 and 13), due to the greater prevalence of land falling hurricanes along the North Carolina Outer Banks.

Using the extreme wind event analysis at NDBC buoy 44009, we find that the monthly maximum values of wind speed and gust (Figure 14) have a clear seasonal cycle and some inter annual changes. The maximum values of gust are in general almost 10 m/s bigger than wind speed, showing maximum values between 25 and 30 m/s for wind speed and 30 to 42 m/s for wind gust. Similar values were observed in other locations.
Figure 14.- Monthly hourly wind speed and gust maximum at 50 m height in NDBC 44009 buoy

Extreme wind values at 50 m height wind speed and gust for 25, 50 and 100 years return period were calculated for NDBC station 44014, CHLV2, 44009 and 44025 (Table 6 on the next page, Figure 15, page 24). Extrapolated extreme values increase from north to south and coast to ocean, reaching a 100-year return period wind speed of 46.96 m/s at buoy 44014. The 100-year return period gust was 52.53 m/s.
Table 6. Return period of 50 m height wind speed and gust (m/s) (25, 50 and 100 years return period)

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Where:
Type : ws = hourly wind speed (eight-minute average on each hour)
gust= Peak 5 second gust speed (m/s) measured during eight-minute on each hour
Nm : Number of months of data
Um : Mean value of maximum monthly wind speeds
Ur(r) : Wind speed with r year return period (r=25, 50 and 100 years)
Sm : Standard deviation of maximum monthly wind speed
Srm : Standard deviation of the sampling error estimation Ur
CI(95): Confidence interval at 95% confidence level (+-)
Figure 15.- Return period of wind speed and gust from NDBC stations 44009, CHLV2, 44014 and 44025.
Waves

Probability distribution

For each place we did a wave probability distribution analysis using three different models (Gumbel, Weibull and Raleigh) that can fit the best solution for the wave distribution at different height thresholds (Figure 16). This analysis is critical to make the 100 years extrapolation and depends on the waves record's length. The Weibull and Rayleigh modes solution are very similar at each observation site but some differences were apparent with the Gumbel distribution. Considering that small differences can be found in each solution we show both (Figure 17, Tables 6 and 7).

Figure 16. - Wave height probability distribution analysis using three models Gumbel, Weibull and Raleigh for buoy 44009.

Wave Height predictions

The long-term distribution of significant wave height is more effectively simulated by the Weibull model than the other competing models (Satheesh, et al 2005). The design wave parameters predicted have reliable accuracy and hence the parametric relations derived from the Weibull model for maximum wave height distribution. The significant wave height predicted also is sufficiently accurate suggesting that the prediction derived from the Weibull model are most effective in shallow water (Satheesh, et al 2005).

Tables 6 and 7 show the 20, 50 and 100 years extrapolated wave height values for different thresholds and different methods.
Table 6.- Design wave height predicted for return period of 20, 50 and 100 years using Gumbel and Weibull model and different threshold at NDBC 44014 and CHLV2.

| 44014 - Wave Heights predictions (m) from grouped data - (1990 - 2011) dt=18.9 yr |
|-----------------------------------------------|-----------------------------------------------|
| a) Gumbel | Return Period(years) |
| Ht(m) | Events | lambda | alfa | beta | gamma | 20 | 50 | 100 |
| 2 | 2012 | 106.5 | 0.7 | 2.1 | 7.41 | 8.04 | 8.52 |
| 3 | 967 | 51.2 | 0.7 | 3.1 | 7.7 | 8.3 | 8.76 |
| 4 | 376 | 19.9 | 0.6 | 4.1 | 7.88 | 8.46 | 8.9 |
| 5 | 147 | 7.8 | 0.6 | 5 | 8.04 | 8.59 | 9.01 |
| 6 | 49 | 2.6 | 0.6 | 6 | 8.25 | 8.78 | 9.18 |
| 7 | 19 | 1 | 0.5 | 6.9 | 8.52 | 9.02 | 9.4 |
| b) Weibull |
| 2 | 490 | 35.4 | 1.2 | 1.1 | 1.5 | 7.41 | 7.99 | 8.42 |
| 3 | 119 | 8.6 | 0.5 | 2.9 | 5.57 | 6.05 | 6.41 |
| 4 | 38 | 2.7 | 0.5 | 3.8 | 5.95 | 6.45 | 6.83 |

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</table>
Table 7.- Design wave height predicted for return period of 20, 50 and 100 years using Gumbel and Weibull model and different threshold at NDBC 44009 and 44025.

### 44009 - Wave Heights predictions (m) from grouped data - (1986 - 2011) dt=23.2 yr

<table>
<thead>
<tr>
<th>Ht(m)</th>
<th>Events</th>
<th>lambda</th>
<th>alfa</th>
<th>beta</th>
<th>gamma</th>
<th>Return Period(years)</th>
<th>20</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1761</td>
<td>75.8</td>
<td>0.6</td>
<td>2</td>
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<td></td>
<td>6.74</td>
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<td>7.78</td>
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<tr>
<td>3</td>
<td>520</td>
<td>22.4</td>
<td>0.6</td>
<td>3.2</td>
<td></td>
<td></td>
<td>6.85</td>
<td>7.4</td>
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</tr>
<tr>
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<td>4.2</td>
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<td>7.01</td>
<td>7.51</td>
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<td></td>
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<td>7.43</td>
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**b) Weibull**

<table>
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<th>lambda</th>
<th>alfa</th>
<th>beta</th>
<th>gamma</th>
<th>Return Period(years)</th>
<th>20</th>
<th>50</th>
<th>100</th>
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<tbody>
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### 44025 - Wave Heights predictions (m) from grouped data - (1991 - 2011) dt=18.9 yr

<table>
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<th>Events</th>
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<th>alfa</th>
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<th>gamma</th>
<th>Return Period(years)</th>
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<th>100</th>
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<td></td>
<td>7.91</td>
<td>8.44</td>
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</table>

**b) Weibull**

<table>
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<th>Ht(m)</th>
<th>Events</th>
<th>lambda</th>
<th>alfa</th>
<th>beta</th>
<th>gamma</th>
<th>Return Period(years)</th>
<th>20</th>
<th>50</th>
<th>100</th>
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<td>6.82</td>
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<tr>
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<td>6.3</td>
<td></td>
<td>7.93</td>
<td>8.43</td>
<td>8.77</td>
</tr>
</tbody>
</table>

Note: lambda = number of events per year = Events / dt
In Figure 21, we show similar analysis of the design wave parameters predicted for return period up to 200 years, assuming a 3 m wave height threshold.

The biggest wave height is found in 44014 and can reach 10 m height at 100 year return period (Weibull).

Figure 17.- Design wave height predicted for return period up 200 years using Gumbel and Weibull model. Threshold 3 m.
3. Conclusions

Unfortunately there are limited data stations offshore of the coastal area of MAB and the length of the record is no longer than 25 years.

In general, wind speed is higher in the winter and lower in the summer. Wind speeds in the fall and spring are somewhere in between. Winter wind speed is flat throughout the day. Summer wind speed is at a minimum in the morning hours, between 8 am and noon and at a maximum in the evening hours between 8 pm and midnight. The low frequency of calms, the high frequency of wind class 3 and above, the low impact of hurricanes and the shallow of the coastal ocean, make the Virginia, Maryland and Delaware coastal ocean a unique place for offshore wind energy development.

The power law predicts 5-15% higher wind speeds at a 75 m hub height than the log law starting with a 5 to 30 m measurement height. The power law exponent for the entire dataset was obtained to be 0.294 and this value was used to create the profile as indicated in blue in the figures. Similarly, the roughness length was calibrated for the entire dataset and was obtained to be 1.26 m which indicates a sub-urban terrain.

Wind shear exponent using the power law calculated to understand their behavior in different months. The exponent has the lowest level in winter, increases in summer and has its maximum in fall. It behaves the trend in the unstable conditions that prevailed in the winter and stable conditions prevail in fall. As a reason, the wind speed gradient decreases in unstable conditions (heating of the surface, increasing the vertical mixing) and increased during stable conditions (surface cooling, suppresses vertical mixing). Diurnal variation of the exponent of the power law has its maximum late in the evening to early morning, while the lowest was observed at midday.

The wind rose (Figure 3) shows that during the 17 years of data analyzed, the predominant wind direction in the area is along the coast from N-NNW and from SSW with a frequency of 63% of the time with wind over 6 m/s. The long-term average for buoy 44014 was 7.1 m/s and calms are present only 0.78% of the time.

The values of extreme wind speeds are similar at all stations in the MAB area, increasing towards the south, due to the greater prevalence of land falling hurricanes along the North Carolina Outer Banks. At CHLV2, the extreme wind values at 50 m height for 25, 50 and 100 years return period are 35.4, 37.5 and 40.0 m/s respectively for mean wind speed and 40.0, 42.4 and 44.9 m/s for wind gust.
4. References


Annex 1

File and NDBC buoy data description

Table 1-1. - NDBC Buoys and C-MAN stations included in the database.

<table>
<thead>
<tr>
<th>Number</th>
<th>STATION_ID</th>
<th>TYPE</th>
<th>Description</th>
<th>State</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41001</td>
<td>6-meter NOMAD buoy</td>
<td>150 NM East of Cape Hatteras</td>
<td>NC</td>
<td>34.704</td>
<td>-72.734</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>41002</td>
<td>6-meter NOMAD buoy</td>
<td>Hatteras - 250 NM East of Charleston</td>
<td>SC</td>
<td>32.382</td>
<td>-75.415</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>41025</td>
<td>3-meter discus buoy</td>
<td>Diamond Shoals</td>
<td>NC</td>
<td>35.006</td>
<td>-75.402</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>44004</td>
<td>6-meter NOMAD buoy</td>
<td>Hotel 200NM East of Cape May</td>
<td>NJ</td>
<td>38.484</td>
<td>-70.433</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>44005</td>
<td>6-meter NOMAD buoy</td>
<td>Gulf of Maine 78 NM East of Portsmouth</td>
<td>NH</td>
<td>43.189</td>
<td>-69.140</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>44009</td>
<td>3-meter discus buoy</td>
<td>Delaware Bay 26 NM Southeast of Cape May</td>
<td>NJ</td>
<td>38.464</td>
<td>-74.702</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>44011</td>
<td>6-meter NOMAD buoy</td>
<td>Georges Bank 170 NM East of Hyannis</td>
<td>MA</td>
<td>41.111</td>
<td>-66.580</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>44014</td>
<td>3-meter discus buoy</td>
<td>Virginia Beach 64 NM East of Virginia Beach</td>
<td>VA</td>
<td>36.611</td>
<td>-74.836</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>44017</td>
<td>3-meter discus buoy</td>
<td>23 Nautical Miles Southwest of Montauk Point</td>
<td>NY</td>
<td>40.691</td>
<td>-72.046</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>44018</td>
<td>3-meter discus buoy</td>
<td>SE Cape Cod 30NM East of Nantucket</td>
<td>MA</td>
<td>41.259</td>
<td>-69.294</td>
<td>5</td>
</tr>
<tr>
<td>11</td>
<td>44025</td>
<td>3-meter discus buoy</td>
<td>Long Island 33 NM South of Islip</td>
<td>NY</td>
<td>40.250</td>
<td>-73.166</td>
<td>5</td>
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<tr>
<td>12</td>
<td>chlv2</td>
<td>C-MAN Station</td>
<td>Chesapeake Light Tower</td>
<td>VA</td>
<td>36.910</td>
<td>-75.710</td>
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<tr>
<td>13</td>
<td>fpsn7</td>
<td>C-MAN Station</td>
<td>Frying Pan Shoals</td>
<td>NC</td>
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<td>-77.590</td>
<td>43.3</td>
</tr>
</tbody>
</table>

The file “buoy.mat” is a structured data file that can be read in MATLAB and contain 13 NOAA NDBC stations mentioned in table 1. Data was downloaded from the NOAA NDBC web page and standardized by time, frequency and variables. Missing data or gaps were filled with NaN. The structure of the file is:

buoy(n).place : place or station ID
state : US state where the station is located
desc : Description of the station

type : Type of buoy or C-MAN station

lat : latitude
lon : longitude

aelev : anemometer elevation (m above site elevation)

hour : is the structured variable containing the hourly data.

mm: month
dd : day
hh : hour
dy : decimal year

w : hourly wind speed (eight-minute average on each hour)
dir : Wind direction (the direction the wind is blowing from in degrees clockwise from true N) during the same period used for w.
uw : U component of wind (East-West)
vw : V component of wind (North-South)
at : Air temperature (Celsius).
wt : Sea surface temperature (Celsius).
ap : Sea level atmospheric pressure (hPa). The recorded pressure is reduced to sea level using the method described in NWS Technical Procedures Bulletin 291 (11/14/80).
gst : Peak 5 second gust speed (m/s) measured during eight-minute on each hour
wht : Significant wave height (meters) is calculated as the average of the highest one-third of all of the wave heights during the 20-minute sampling period.

Dpd: Dominant wave period (seconds) is the period with the maximum wave energy.
apd : Average wave period (seconds) of all waves during the 20-minute period.
mwd: Mean wave direction corresponding to energy of the dominant period (DOMPD). The units are degrees from true North just like wind direction.
**Example:** if you are interested in the wind speed data from the buoy 44009 located off Delaware, the command for to get that information is: “buoy(6).hour.w”

The file “buoy.mat” can be downloaded from: http://www.ccpo.odu.edu/~jlblanco/wind/data/.
Annex 2

File and Lewes met-tower data description

Information from each sensor of the Lewes Meteorological tower and reading period was assembled into a structured data file.

The file has the following data:
Year (yr), month (mm), day (dd), hour (hh), minutes (mi), decimal year (dy) and channel for each sensor (ch).

Each channel has the following information: avg, sd, max, min, name, altitude.

Units:
Wind speed m/s.
Wind Direction degree (blowing from)
Temperature °C

Data description per channel
ch(1,1).name='wind speed A'; altitude=49;
ch(2,1).name='wind speed B'; altitude=49;
ch(3,1).name='wind speed A'; altitude=42;
ch(4,1).name='wind speed B'; altitude=42;
ch(5,1).name='wind speed A'; altitude=30;
ch(6,1).name='wind speed B'; altitude=30;
ch(7,1).name='wind direction'; altitude=48;
ch(8,1).name='wind direction'; altitude=29;
ch(9,1).name='temperature'; altitude=3;
ch(10,1).name='voltage';

Examples:
- Plot the wind speed A at 42 meters

plot(wpro.dy, wpro.ch(3,1).avg)

- Plot the wind profile of A sensors on one specific date

    selA=[5,3,1]; %index of selected levels ...down - up A
    for j=1:length(selA)
        x(:,j)=wpro.ch(selA(j)).avg;
        y(j,1)=wpro.ch(selA(j)).altitude;
    end
    nu=350; %specific date
    figure(1); clf
    plot(x(nu,:),y,'o-')
    xlabel('Wind speed (m/s)')
    ylabel('Altitude (m)')
    title(['Lewes Met Tower - Wind profile ' (datestr(wpro.dy(nu))))]
    ylim([0 50])
    xlim([0 6])

The file “wprofile.mat” can be downloaded from: http://www.ccpo.odu.edu/~jlblanco/wind/data/.