

Assessment of the Southern New England Offshore Wind Energy Resource

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ABSTRACT

This paper presents a summary of ongoing work on the assessment of the wind energy resource off the coast of southern New England. This work is being undertaken to determine the potential for the near term development of offshore wind energy projects in that region. The work summarized here consists of four aspects: 1) a review of existing offshore wind data, 2) the measurement of new data at an offshore site, 3) correlation and prediction of long term data at a new offshore site by reference to a longer term island site and 4) assessment of the overall coastal resource through the use of the MesoMap system.

1.0 INTRODUCTION/BACKGROUND

The concept of offshore wind for the U.S. was first proposed for New England. In the 1970's there was considerable background work that included detailed design work and cost analysis of far offshore wind systems for the eastern coast of the U.S. (Heronemus, 1972). Between the early 1980's and the late 1990's, little consideration has been given to offshore wind in the U.S., although it was pursued actively in Europe. At the present time, inspired by recent developments in Europe, there is renewed interest in the possibilities of offshore wind energy development in the U.S. (see Smith and Hagerman, 2001), especially off the coast of New England (Rogers, et al, 2000; Manwell, et al., 2001).

There is a growing general interest in the potential for wind energy development in southern New England, especially along its coastline and offshore. For example, developers have recently proposed a windfarm of at least 100 MW several miles offshore in Nantucket Sound. Due to the absence of meteorological data at this, and similar attractive locations in coastal southern New England, a wind resource measurement and assessment study is a critical need for providing the basis for appropriate windfarm designs, power generation projections and, eventually, project financing. A detailed wind resource study is therefore needed before this potential can be quantified and realized.

This paper summarizes the ongoing work of an offshore wind assessment for southern New England carried out by the University of Massachusetts and AWS Scientific, Inc. This work is sponsored by the Connecticut Clean Energy Fund, the Massachusetts Technology Park Corporation, and Northeast Utilities Service Company. This project has

two major objectives: (1) to define and map the wind resource characteristics of southern New England, including its offshore areas, to support the evaluation and planning of future wind energy development opportunities in this region, and (2) to collect new wind measurements and to design appropriate measurement platforms, in and adjacent to Nantucket Sound that can be used as the basis for the planning, design and financing of offshore wind projects in the vicinity. The present work, as described in this paper, consists of four aspects: 1) review of existing offshore wind data, 2) measurement of new data at an offshore site, 3) correlation and prediction of long term data at this offshore site by reference to a longer term island site and 4) assessment of the overall coastal resource through the use of the MesoMap software.

2.0 REVIEW OF EXISTING OFFSHORE WIND DATA

Under this phase of the work, a comprehensive study of existing sources for available wind measurement data for the New England coastal region is in progress. These sources include the following:

- National Data Buoy Center
- U.S. Navy and Coast Guard facilities
- Mean Sea Surface Index
- Ship data
- Surface and upper air observations from National Weather Service-affiliated weather stations
- State agencies
- Reanalysis data
- Maritime research
- Other government and private sources.

Available data sets have been identified and defined by period of record, latitude/longitude coordinates, tower height(s), physical setting, and organization originally responsible for gathering the data. From this inventory, digital time series and summarized data sets have been obtained for the sites. The data are in the process of being screened for completeness and reasonableness and reformatted into a standard format. Finally, the data are also being analyzed and a set of standard meteorological statistics is being produced. This includes: mean speed; diurnal, seasonal, and interannual variability; turbulence intensity; speed frequency distribution; wind shear; peak gusts; wind direction frequency roses (standard & energy weighted); and air temperature. The data statistics are then summarized into tables and graphs.

The initial work has concentrated on offshore data collected from the National Data Buoy Center (NDBC). This data archive consists of hourly wind and direction data from 12 locations in New England (see Figure 1), ranging from Maine (Mt. Desert Rock) to New York (Ambrose Light). Each data site has on record between 4 and 21 years wind data ranging from 1975 to 1998, with an average of 15 years for each location. Half of the twelve data measuring stations are located on islands or directly on the coastline, while the other half are floating buoys out on the water. The floating stations are located between 12 and 170 nautical miles

from the shore, and range in water depth from 19 to 88 meters deep. Though the location of the buoys are excellent for offshore wind data gathering, the potential value of the data is reduced because the anemometers are located only 5 m above sea level. This low elevation creates a questionable level of confidence when extrapolating data up to a typical hub height, perhaps 60 meters tall. The six non-buoy based data collection sites in comparison have their anemometry mounted between 13.8 and 49.1 meters above the ground.

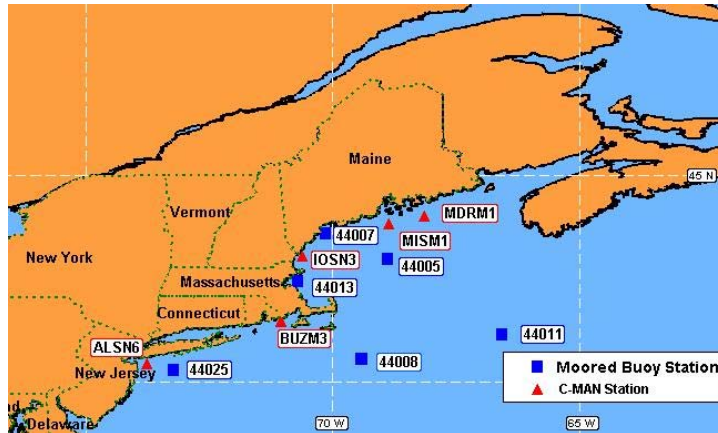


Figure 1 NDBC Data Sites

The next step using this data was to construct data sets that represented complete annual hourly profile for each of these sites. This consisted of a series of calculations that filled in some gaps in data sets (while preserving the basic statistics of the original file) and extrapolating the results at the station’s measured height to a height of 60 m. For the extrapolation the well-known log law was used. A nominal roughness height of 0.2 mm was used for sites in open water and 0.5 mm was used for sites on land. A summary of this work is given in Table 1.

Table 1 Summary of Data from NDBC Sites

SITE	NAME	Measured Height, m	Ave. Wind Speed at Meas. Height, m/s	Estimated Ave. Wind Speed at 60m, m/s
44005	Gulf of Maine	5	6.7	8.3
44007	Portland	5	5.6	7.0
44008	Nantucket	5	6.4	8.0
44011	George’s Bank	5	6.1	7.6
44013	Boston	5	6.1	7.6
44025	Long Island	5	6.4	7.9
44028	Buzzard’s Bay	13.8	6.9	7.8
ALSN6	Ambrose Light	49.1	7.6	7.7
BUZM3	Buzzard’s Bay	24.3	7.7	8.3
IOSN3	Isle of Shoals	32.3	7.0	7.4
MDRM1	Mt Desert Rock	31.7	7.9	8.4
MISM1	Matinicus Rock	32.7	7.9	8.3

In addition to this data, coastal wind resource data has been obtained from the National Renewable Energy Laboratory (NREL), the National Climatic Data Center (NCDC), and the Massachusetts Division of Energy Resources (DOER). That data is being analyzed as described above.

3.0 COLLECTION OF DATA IN NANTUCKET SOUND

As previously indicated there is a shortage of data taken at prospective sites for offshore wind turbine installations. In particular, there is no offshore data available from heights close to that of modern wind turbines, and no sites where there is anemometry at multiple levels. In an effort to partly rectify that situation, a monitoring project at Bishop and Clerk's Light in Nantucket Sound was initiated.

3.1 Site Details: Bishop and Clerk's Light

The site (Figure 2) is a rocky shallows located about 2.5 miles south of Yarmouth in Nantucket Sound. For a number of years there was a lighthouse at the site, but it fell into disrepair and was demolished. It was replaced by a smaller structure, upon which a navigation light is mounted. The light station is operated by the U.S. Coast Guard (U.S. Coast Guard #14490). A 36 m tower will be installed at the site. This will allow monitoring of the wind at 3 elevations, with the highest being at 40 m. Permitting delays have prevented the tower from being erected as of the time of this writing. Nonetheless, it was possible to install a temporary wind resource monitoring station at the end of November, 2000. This station includes 2 anemometers and 2 wind vanes, together with solar photovoltaic power supply, battery, and cell phone. The sensors are located at 15 m above mean sea level. This station has been supplying data continuously since that time. A summary of that data follows.



Figure 2 Bishop and Clerk's Light

3.2 Initial Data from Site

As of the present time, just over 5 months of data has been acquired (12/1/00-5/12/01) at Bishop and Clerk's Light. During that time the wind speed has averaged 7.5 m/s. A frequency distribution plot of that data is shown in Figure 3.

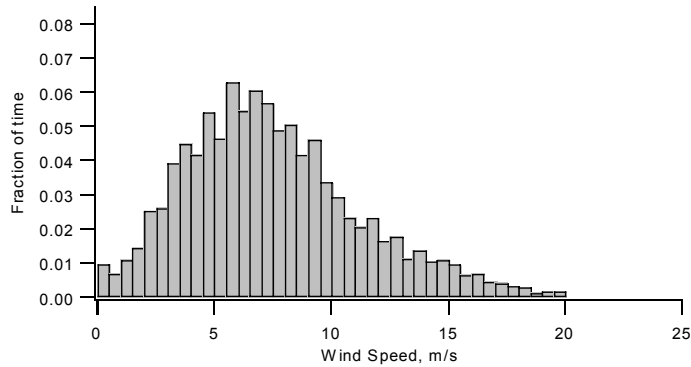


Figure 3 Frequency Distribution of Winds at Bishop and Clerk's Light

A wind rose of the first three months of the data is shown in Figure 4. The actual directions should be considered tentative, however. Accurate determination of true north (using a compass) at the site was hampered by the presence of the existing steel structure. A more exact determination will be made at the next opportunity, using more appropriate equipment. In any case, it is apparent that the prevailing wind directions in the winter months are from the northwesterly directions.

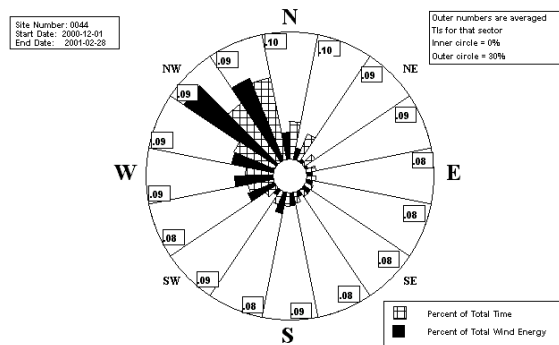


Figure 4 Wind Rose at Bishop and Clerk's Light (12/1/00-2/28/01)

One characteristic of particular interest for wind power development is the turbulence intensity. This is shown in Figure 5, as a function of wind speed. As expected the turbulence intensity decreases from high values at low winds to relatively low levels (on the order of 0.10) at wind speeds during which turbines would be operating. Such levels are typical of offshore sites.

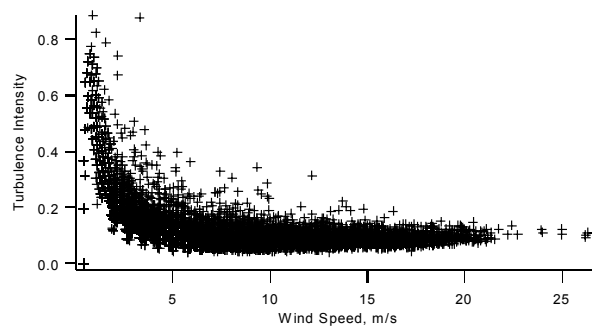


Figure 5 Turbulence Intensity at Bishop and Clerk's Light

4.0 LONG TERM ESTIMATES OF THE WIND RESOURCE AT NEW SITE (BISHOPS AND CLERK'S)

With only 5 months of data available, and that from a relatively low height, the data alone is insufficient to quantify the long term resource. In order to begin to make such an estimate, a two step method has been applied to estimate the long term resource at the hub height of a typical wind turbine at the site. This includes: 1) application of the Measure Correlate Predict (MCP) method to estimate the long term wind data at the height of the sensors and 2) extrapolation of the wind data to a greater height using the log law.

4.1 Summary and Application of the Measure Correlate Predict Method

The Measure Correlate Predict (MCP) method has been described by Derrick (1992, 1993). A summary of that is presented below. The fundamental principle behind MCP is that the wind at a new "test site" can be predicted based on comparisons with data from a long term "reference" site, which is located somewhere in the general vicinity. The reference site used in this paper is Thompson Island, in Boston Harbor, where the authors have been collecting data on a 40 m tower for the last 3 years. Among other reasons, this site was used because the data was immediately available. Similar archived data from NOAA sites will eventually be obtainable, but after a delay, and so was less applicable to this study.

In the MCP method both wind speed and direction time series data are assumed to be available for the reference site, and wind speed time series data is available for the test site. The wind speed at the reference site is binned into direction sectors (typically 12 sectors of 30 degrees each). A straight line is fit is made for each sector, between the wind speeds at the reference site and the test site. Note that it is not necessary to consider the direction at the test site. The equation for a straight line in sector j is: $y = m_j x + c_j$

For this paper, the x values are of Thompson Island, and the y values are at Bishop and Clerk's. The method of determining the slope, m , and intercept, c , using a least squares approach is outlined in the Appendix. The question also arises as to how good the fit is to the data. In other words, what would be the effect on the estimate of y due to changing the values of m or c ? This can be considered by finding the standard deviation of the y estimates, which correspond to particular values of x . The MCP method assumes that the confidence in the estimate can be found from the standard deviations of all the estimates, by appropriately considering the probability of occurrence of the various x values. The latter are determined from the long term data. The standard deviation of an estimate of y , $\sigma(y)$, given an x , is found from the variance of the intercept (σ_c^2), the variance of the slope (σ_m^2) and a covariance term ($\sigma_{m,b}$) as follows:

$$\sigma(y) = \sqrt{\sigma_c^2 + x^2 \sigma_m^2 + 2\sigma_{m,c} x}$$

Determining these terms is discussed in the Appendix.

The mean wind speed in each sector is:

$$Y = \sum_{i=1}^N p_i y_i$$

where p_i is the probability of y being in the i^{th} wind speed bin and N is the number of bins. The standard deviation of the estimate within a sector is found from:

$$\sigma(Y) = \sqrt{\sum_{i=1}^N (p_i \sigma(y_i))^2 + \sum_i \sum_j 2p_i p_j \text{covar}(y_i, y_j)}$$

where:

$$\text{covar}(y_i, y_j) = x_i x_j \sigma_m^2 + (x_i + x_j) 2p_i p_j \sigma_{m,c}^2 + \sigma_c^2$$

The overall predicted mean speed is:

$$V = \sum_{j=1}^{N_s} P_j Y_j$$

where P_j = probability of being in the j^{th} sector, N_s = number of sectors

4.2 Application of MCP to Bishop and Clerk's Data

The long term data site is taken to be Thompson Island. The data from the two sites appears to be visually fairly well correlated as seen in Figure 6, which gives a sample time series

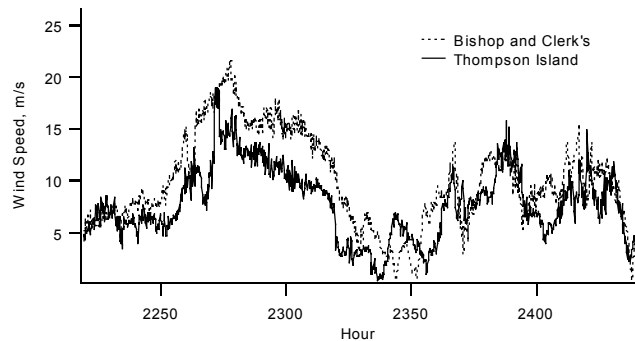


Figure 6 Time Series Comparison between Thompson Island and Bishop and Clerk's

When ten minute averaged Thompson Island data is plotted against that from Bishop and Clerk's, the trend is clear, but there is also a substantial amount of scatter, as can be seen in Figure 7.

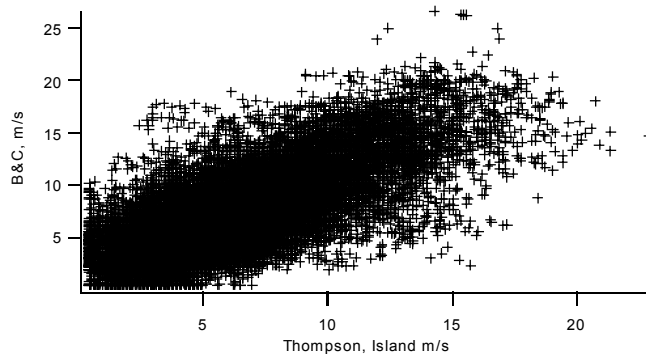


Figure 7 Scatter Plot: Wind Speeds at Thompson Island and Bishop and Clerk's

A computer code was written in Visual Basic 3.0 to implement the MCP technique. Twelve wind direction sectors were used in the analysis. Slopes and offsets for each of the sectors were generated using five months of concurrent data as described above. The code was checked by verifying that the mean wind at Bishop and Clerk's for the concurrent time period (7.51 m/s) could be predicted from that at Thompson Island (6.36 m/s). This could in fact be done to within 0.01 m/s. On the other hand, the prediction of the wind speed frequency distribution at Bishop and Clerk's did not match as closely to that obtained directly from the data, as illustrated in Figure 8. This reflects the observation that the best fit lines for most sectors resulted in offsets larger than one, and slopes less than one. Such parameters would tend to contract the frequency distribution, as was the case.

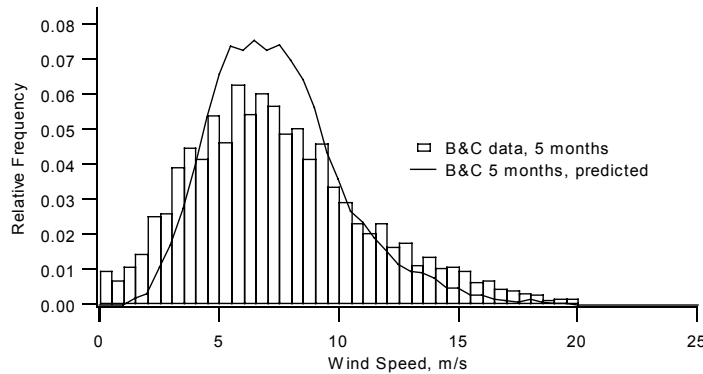


Figure 8 Wind Speed Frequency Distributions at Bishop and Clerk's (5 Month)

The parameters derived from the MCP method were then used to predict both the mean wind speed and the wind speed frequency distribution at Bishop and Clerk's. For this, a frequency distribution based on 3 years of wind speed measurements at Thompson Island was used. The measured mean at Thompson Island for this period was 5.8 m/s. This resulted in a predicted long term average of 7.0 m/s at Bishop and Clerk's. The measured distribution at Thompson Island and the predicted long term distribution at Bishop and Clerk's are shown in Figure 9.

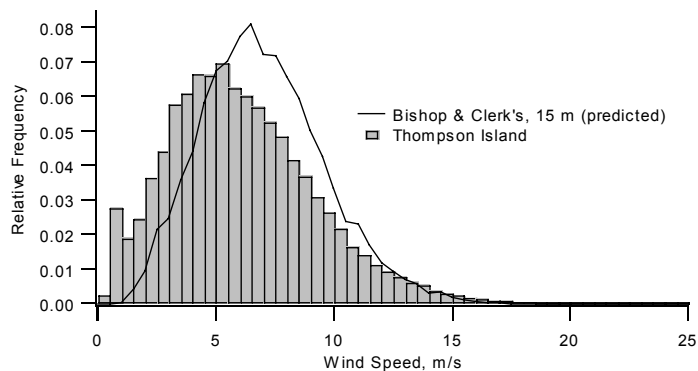


Figure 9 Predicted Long Term Wind Speed Frequency at Bishop and Clerk's

4.3 Predicted Variation of Wind Speed with Height

The wind resource at a height greater than that for which the wind speed was measured can be predicted at Bishop and Clerk's using the well known log law, which is expressed as:

$$V_1 / V_2 = \ln(h_1 / z_0) / \ln(h_2 / z_0)$$

where V refers to velocity, h is height above sea level, and z_0 is the roughness length

It is commonly assumed that the roughness length, z_0 , over open ocean is equal to 0.0002 m. Using that roughness length, it can be predicted that the winds at 60 m should be 1.123 times as high as at 15 m. Applying that value to scale the predicted wind speed distribution at Bishop and Clerk's results in a prediction of 7.9 m/s for Bishop and Clerk's. This predicted value is well within the range of the projected based on buoy and other coastal data, which were shown in Table 1. It is of note, however, that the projected value is less than that for BUZM3, which is located in Buzzard's Bay (see Figure 1)

That site has some similarities to Bishop and Clerk's and it could be expected that it would have a similar mean wind speed (projected to be 8.3 m/s at 60 m at BUZM3). There may be at least two reasons for this. First of all, some airport comparisons have indicated that the time period during which the wind has been monitored at Thompson Island may have been somewhat less windy than normal (on the order of 0.5 m/s). A lower than normal long term wind would skew the estimates at Bishop and Clerk's. Second, the projection for Buzzard's Bay is in fact higher than the projections for most of buoys, even those in the open ocean, which would be expected to be quite windy. The Buzzard's Bay data was taken at a greater height than any of the buoys or the existing sensors at Bishop and Clerk's. It may well be that the simple log law and the assumed roughness length is not sufficiently accurate to ensure confidence in the projection of wind speeds up to heights at which turbines will be operating. For example, it is known that the roughness length in the open ocean increases with wind speed, and can be on the order of 0.002 m for moderate winds. Using such a value would result in a prediction of a long term mean in excess of 8 m/s. These results reinforce the observation that it is of great value to obtain data at heights for which the data is relevant. The results also suggest that it would be of interest to perform MCP comparisons between B&C and other sites, particularly those for which longer data records are available.

5.0 ASSESSMENT OF THE OVERALL COASTAL WIND RESOURCE

In addition to examining data from existing sites, and installing new measurement stations, the overall wind resource of the region is to be assessed using an advanced computer model. A mesoscale weather modeling system—MesoMap—will be used to map the wind resources across the entire states of Connecticut, Massachusetts and Rhode Island, including all offshore waters out to 10 km from the coastline. MesoMap (Brower, et al., 2000) is an integrated set of atmospheric simulation models, global weather and geographical data bases, and computer and storage systems. It has been developed by TrueWind Solutions in the past three years with support from the New York State Energy Research and Development Authority and the U.S. Department of Energy. At the core of the MesoMap system is MASS (Mesoscale Atmospheric Simulation System), a state-of-the-art numerical weather prediction model developed since the

early 1980s by TrueWind Solutions partner MESO, Inc. MASS is similar to other weather models such as Eta and MM5. It embodies the fundamental physics of atmospheric motion including conservation of mass, momentum, and energy, as well as the moisture phases, and it contains a turbulent kinetic energy submodule which accounts for the effects of viscosity and thermal stability on wind shear. The MesoMap system uses historical atmospheric data at multiple levels in the atmosphere to establish the boundary conditions at the top and sides of the model domain, while all significant processes that determine winds near the surface (terrain and surface roughness effects, sea breezes, temperature inversions, low-level jets, etc.) are calculated internally by the model.

The MesoMap system uses a variety of geographical and meteorological inputs. The main geographical inputs are elevation, land cover, and vegetation greenness (normalized differential vegetation index, or NDVI). Both land cover and NDVI data are translated by the model into biophysical parameters such as surface roughness, albedo, emissivity, and others. The main meteorological inputs are reanalysis data, rawinsonde (upper air weather measurement) data, and land and sea surface temperature measurements. The most important is the reanalysis data base, a global set of gridded historical weather data produced by the U.S. National Center for Atmosphere Research. The data provide a description of atmospheric conditions around the world at all levels of the atmosphere in intervals of six hours. Along with the rawinsonde and surface temperature data, the reanalysis data establish the initial conditions as well as updated lateral boundary conditions for the MesoMap simulations. However, the model itself determines the evolution of atmospheric conditions within the region based on the interactions among different elements in the atmosphere and between the atmosphere and the surface. Because the reanalysis data are on a relatively coarse, 200 km grid, the MesoMap system is run in several nested grids of successively finer mesh size, each taking as input the output of the previous nest, until the desired grid scale is reached. The outermost grid typically extends several thousand kilometers.

Wind maps will be created by running MesoMap for several hundred simulated days drawn from a 15-year period. The days are chosen through a stratified random sampling scheme so that each month and season is represented with equal weight. Each simulation generates wind and weather variables (temperature, pressure, moisture, turbulent kinetic energy, heat flux, and others) throughout the model domain, and the variables are stored in data files at hourly intervals. When the runs are finished, the several thousand output files are processed and summarized in a variety of formats, including color-coded maps of mean wind speed and power density at various heights above ground, wind rose charts, and data files containing wind frequency distribution parameters. In addition, model predictions will be compared with reliable historical surface measurements (including buoys and satellite-based ocean surface readings) to establish model uncertainties. Based on prior model validations at over a dozen tall-tower sites in the northeastern U.S., the average model speed bias is anticipated to be less than 5%, which is within the normal measurement error of meteorological equipment (including allowances for sensor calibration, site representativeness, and climatological adjustment). The maps will have a gridded spatial resolution of 400 m and will be available in digital formats.

6.0 SUMMARY/ CONCLUSIONS

Based on the work to date, the following conclusions can be made:

- 1) Data collection from the various sources and the new site at Bishop and Clerk's light is proceeding as expected and yielding high quality long term data sets for a number of sites.
- 2) The wind speed projections at Bishop and Clerk's light, based on the Measure-Relate-Predict method are encouraging.
- 3) The long term wind speed averages at typical wind turbine hub height in Nantucket Sound are expected to be in the range of 8 m/s.
- 4) More offshore wind data is needed at greater heights. This emphasizes the need for the higher tower at the Bishop and Clerk's site.
- 5) The Measure-Relate-Predict method should be carried out between Bishop and Clerk's and more sites.
- 6) Closer attention should be given to the MCP's ability to predict wind speed distributions.
- 7) We anticipate using the results from Bishop and Clerk's as a means of further validating the MesoMap predictions.

7.0 ACKNOWLEDGMENTS

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Appendix: Measure-Correlate Predict Statistics

The essence of the least squares fit is to find the values of m and c which minimize the sum of the differences between the measured values of y and the predicted ones:

Suppose we call this sum Q :

$$Q = \sum_{i=1}^N (c + mx_i - y_i)^2$$

This gives:

$$\frac{\partial Q}{\partial c} = \sum_{i=1}^N -2(c + mx_i - y_i) = 0; \quad \frac{\partial Q}{\partial m} = \sum_{i=1}^N -2x_i(c + mx_i - y_i) = 0$$

This can be reduced to two equations in two unknowns (the coefficients),

$$Sc + S_x m = S_y; S_x c + S_{xx} m = S_{xy}$$

where

$$S = N; S_x = \sum_{i=1}^N x_i; S_{xx} = \sum_{i=1}^N x_i^2; S_y = \sum_{i=1}^N y_i; S_{xy} = \sum_{i=1}^N x_i y_i$$

The solution is:

$$c = \frac{S_y S_{xx} - S_{xy} S_x}{\Delta}; \quad m = \frac{S S_{xy} - S_x S_y}{\Delta}$$

where

$$\Delta = S S_{xx} - S_x S_x$$

The standard deviation of an estimate of y , given an x is found from:

$$\sigma(y) = \sqrt{\sigma_c^2 + x^2 \sigma_m^2 + 2\sigma_{m,c} x}$$

where:

$$\sigma_c^2 = \frac{S_{xx}}{\Delta}; \quad \sigma_m^2 = \frac{S}{\Delta}; \quad \sigma_{m,c}^2 = \frac{-S_x}{\Delta}$$