Influences of offshore environmental conditions on wind shear profile parameters in Nantucket Sound

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ABSTRACT

Simultaneous wind resource and oceanographic data are available from an offshore monitoring tower in Nantucket Sound, off the coast of Massachusetts. These data provide an excellent opportunity to investigate how oceanographic data can be used to aid offshore wind resource assessment evaluations. This study considered whether wave height and/or tide height data could be used to improve the wind speed profile predictions of the 'log law' model at this site. In the shallow, protected waters of Nantucket Sound, tidal variations were found to have little affect on the predicted mean wind profile. Standard roughness length models under-predicted the mean wind profile.

INTRODUCTION

At onshore locations, the height of a sensor above the ground surface is assumed to remain constant. This is not the case, however, in offshore environments where instantaneous sensor height depends on the tide and wave heights.

This study is based on offshore data collected for the Cape Wind project in Nantucket Sound, off the coast of Massachusetts. This dataset, which was made available recently to the University of Massachusetts, is rare in the USA since it contains simultaneous measurements from both a traditional wind resource monitoring tower and an Acoustic Current Doppler Profiler (ADCP). Thus, this was an opportunity to study the effects of the ocean surface on the predictions typically made during wind resource evaluation, then compare the results to those of previous work, e.g. [1] and [2]. In this study, cup anemometer and wave height and period data from May through December 2003 were analyzed. Ultrasonic anemometer data were also taken, but tilted sensors rendered them unusable.

SITE AND DATA

The data [3] used in this project were taken at a tower owned by Cape Wind Associates and operated by the Woods Hole Group. The tower is located approximately 19 km south of Hyannis, MA. The water depth at the tower site is approximately 6.6 m. The installed instrumentation includes cup anemometers at 20, 40, and 60 m above the mean low water level, direction vanes at 20, 38, and 58 m, 3D ultrasonic anemometers at 21, 41, and 60 m, and temperature and barometric pressure sensors at 10 and 55 m. An ADCP is installed on the seafloor 90 m from the tower. The ADCP records significant wave height, peak wave period, tide height, water temperature near the seafloor, and current speed and direction.

Hourly wind and wave data were used in this analysis. Simultaneous wind and wave data were available for the period May 14 to

December 31, 2003. Of the 5,558 hours of data available, 2% of the wind data and 10% of the wave data were missing due to sensor or logger error, leaving 5012 points for which both the wind and wave data were acceptable.

It should be noted that it was not possible to correct the data for either stability or tower shadow effects. Only one anemometer was installed at each height, so tower shadow effects could not be determined. Faulty ultrasonic anemometers prevented determination of stability. Determining stability using a Richardson number also proved impossible—the temperature data are suspected of being of inadequate resolution. Without knowledge of the stability for each measurement, the wind speed was used as a rough proxy. When the wind speed exceeded some threshold, adequate mixing of temperature and humidity were assumed. In this study, two different thresholds were considered: 3.5 m/s (the typical 'cut-in' speed for modern wind turbines) and 10 m/s (suggested in [4]). For similar reasons, measurements for which the wind speed at the bottom of the tower, U_{20}, was greater than the speed at the top, U_{60}, were also excluded.

Between May and December of 2003, the mean wind speeds at 60, 40, and 20 m were, respectively, 8.4, 8.0, and 7.4 m/s, with the prevailing winds from the southwest. The Weibull shape factor, k, and scale factor, c, at 60 m were 2.14 and 9.61 m/s, respectively. The water surface elevation typically varied by 1 to 1.5 m between the minimum low tide and maximum high tide, and the largest significant wave height recorded was 2.0 m.

ANALYSIS

Roughness Length

The log law can be written to relate the wind speeds at the measured and target heights, z_m and z:

$$U(z) = U(z_m)\frac{\ln(z/z_0)}{\ln(z_m/z_0)} \qquad (1)$$

where z_0 is the roughness length. With speeds measured at two heights, z_0 can be determined directly:

$$z_0 = \exp\left(\frac{U_2\ln(z_1) - U_1\ln(z_2)}{U_2 - U_1}\right) \qquad (2)$$

The measured values of z_0 were not in the typical range expected at offshore locations. The mean value, determined using Eq. (2), was 0.50 m, with a standard deviation about this mean of 0.81 m. The value with the mean wind speeds, $\bar{U}_{60} = 9.5$ and $\bar{U}_{20} = 7.9$ m/s (for speeds greater than 3.5 m/s) was 0.10 m. Typical values of z_0 that are assumed for offshore sites are between 0.0002 and 0.0005 m [5]. The distribution of measured z_0 values is shown in Figure 1.

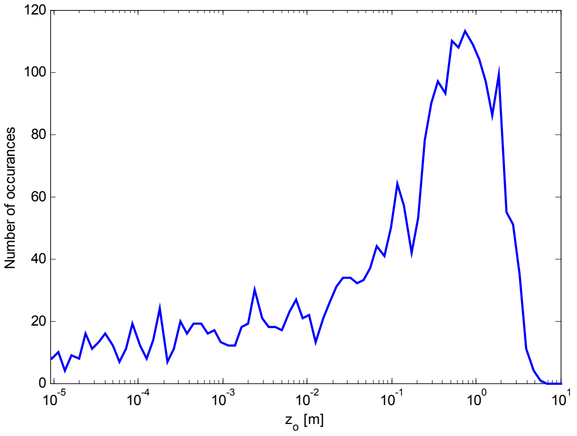

Figure 1 - Distribution of z_0 derived from the data using Eq. (2)

Tide Height

Deviations in tide height from the mean water level are analogous to changes in the ground surface elevation. With this tidal deviation, Δh, Eq. (1) can be rewritten:

$$U(z) = U_m \frac{\ln[(z - \Delta h)/z_0]}{\ln[(z_m - \Delta h)/z_0]} \qquad (3)$$

If z_0 is assumed to be constant with the value at mean wind conditions, 0.10 m, Eq. (3) suggests that the ratio (U_2 / U_1) will increase from 1.21 at $\Delta h = 0$ m to 1.22 at $\Delta h = \pm 1$ m, or by about 0.7% (Figure 2).

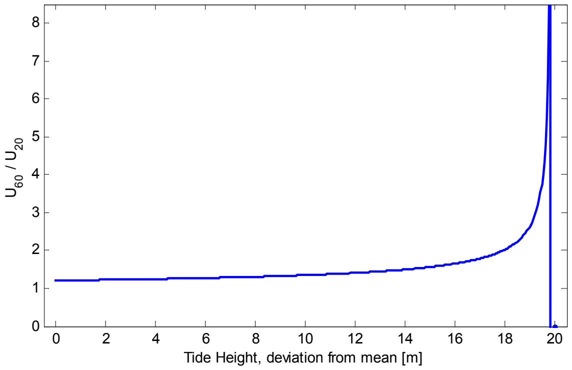

Figure 2 - Dependence of the ratio (U_2 / U_1) on tide height deviation, as suggested by Eq. (3)

In a recent study of North Sea data, Khan et al. [1] observed a slight but noticeable dependence of the ratio (U_2 / U_1) on tidal variation. For comparison with the Khan et al. study, the Nantucket Sound data were analyzed by binning the ratio (U_{60} / U_{20}) by tide height. The mean values of this ratio are plotted in Figure 3 (only values for which the number of binned points was greater than 100 are plotted). Also shown are the predicted ratios calculated with Eq. (3), with and without accounting for tidal variation. For this plot, $z_0 = 0.10$ m. The data are observed to follow the slight increasing trend of the prediction. However, the data also show that the 0.7% change due to the small tidal range is difficult to detect.

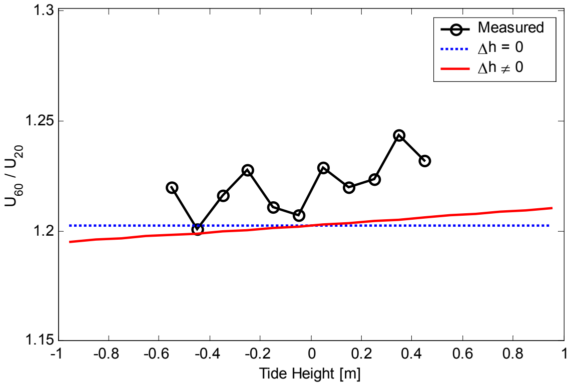

Figure 3 - Ratio of wind speeds at 60 and 20 m plotted against tide height deviation, for U > 3.5 m/s

Wave Height

Several models have been proposed in the literature to relate z_0 to different wave characteristics. For examples of these models, the reader is encouraged to consult Ueno and Deushi [6], Zhao and Lou [7], or Lange et al. [2]. This study investigated models which relate z_0 to wave height. The three most relevant models considered here are briefly described below.

- In the simplest models, z_0 is assumed to be constant, with a value, depending on mean sea surface conditions, between 0.2 mm (calm sea) and 0.5 mm (wind-blown sea) [5].

- The Charnock model [8] relates z_0 to the mean wave state by way of a constant:

  $$z_0 = A_C \frac{u_*^2}{g} \qquad (4)$$

  where u_* is the friction velocity and g is the gravitational acceleration. The Charnock constant, A_C is a site-specific constant ranging from 0.01 to 0.05 or greater. The value 0.0185 used here is an average from the literature.

- Taylor and Yelland's model [4] relates z_0 to the wave height and steepness:

$$\frac{z_0}{H_S} = A\left(\frac{H_S}{\lambda_p}\right)^B \qquad (5)$$

where (H_S / λ_p) is the wave steepness, and λ_p is the peak wavelength, which corresponds to the frequency at the spectral peak. Based on three measured data sets, Taylor and Yelland suggest values for the dimensionless constants, $A = 1200$ and $B = 4.5$.

The three models described above were used to determine whether knowledge of the wave height improved predictions of the wind speed profile. Four different sets of z_0 values were used: $z_0 = 0.2$ mm, $z_0 = 0.5$ mm, z_0 from Eq. (4) with $A_C = 0.0185$, and z_0 from Eq. (5). For this last model, values of λ_p were derived from the measured peak period, T_p, using $\lambda_p = c\, T_p$ (for shallow water of depth h, the wave speed, $c = (g\, h)^{1/2}$ [9]). Eq. (1) was used to extrapolate the profile from the measured U_{20}. For each height, the mean speed was calculated to create the predicted profiles, which are compared to the mean measured profile in Figure 4.

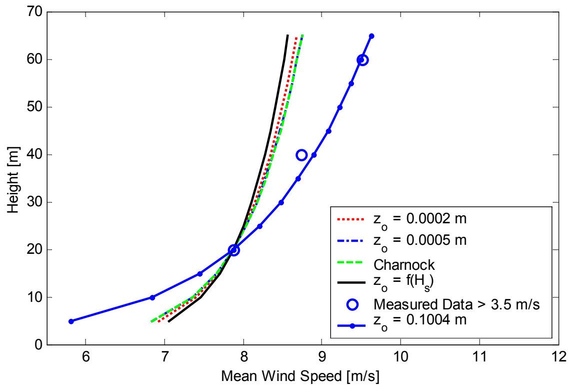

Figure 4 - Modeled and measured wind speed profiles

From the results in Figure 4, three observations are made. First, the mean measured profile is almost linear, and so is not well fitted by the log law. Second, the three models under-predict the mean speed at 60 m by an average of 1 m/s, or 11 %. Third, the four predicted profiles are very close in value, suggesting that the standard assumptions used in these models do not hold for this site.

The z_0 models with their standard constants do not seem to properly characterize the data. For comparison, an equivalent constant z_0 and Charnock constant, A_C, were calculated from the data.

As mentioned previously, the constant z_0 found from the mean data was 0.10 m. This constant z_0 model is shown in Figure 4.

With $z_0 = 0.10$ m, A_C was determined from Eq. (4), with the mean u_* calculated from

$$\overline{u}_* = \kappa \frac{\left(\overline{U}_{60} - \overline{U}_{20}\right)}{\ln\left(60/20\right)} \qquad (6)$$

where κ is von Kármán's constant ($\kappa = 0.4$). The value of A_C fitted to the data was 1.016.

The constants A and B in Eq. (5) could not be determined from the data. The data were restricted to wind speeds greater than 10 m/s, following the methods of Taylor and Yelland. Plotting (z_0 / H_S) against (H_S / λ_p) revealed that for these data, no one least-squares fit was correct. From Figure 5, however, it is clear that the Taylor and Yelland constants do not match the data.

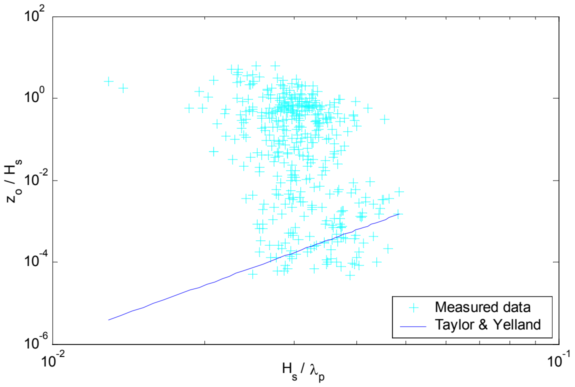

Figure 5 – Nantucket Sound data, with U > 10 m/s, compared to the Taylor and Yelland model

CONCLUSIONS

The Nantucket Sound data were used to evaluate the effects of tide and wave heights on extrapolation model predictions. The following conclusions were drawn:

- Over the ±1 m range of tidal variation, the data approximately followed the predicted ±0.7 % change in the ratio (U_{60} / U_{20}).
- Three roughness length models from the literature were used to predict the mean wind profile. All of these models under-predicted the mean profile by about 11 % at 60 m when the standard model constants were used. Site-specific constants were calculated for two of the models.
- The roughness length, z_0, at this site, under mean wind conditions, was 0.10 m, three orders of magnitude larger than is typically used to describe offshore sites.
- The Charnock constant was determined from the data to be $A_C = 1.016$.

ACKNOWLEDGEMENTS

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