Wind Energy

WIND ENERGY
Wind Energ. 2016; **19**:1151–1159
Published online 30 July 2015 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/we.1881

SHORT COMMUNICATION

The creation of a comprehensive metocean data set for offshore wind turbine simulations

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ABSTRACT

A database of meteorological and ocean conditions is presented for use in offshore wind energy research and design. The original data are from 23 ocean sites around the USA and were obtained from the National Data Buoy Center run by the National Oceanic and Atmospheric Administration. The data are presented in a processed form that includes the variables of interest for offshore wind energy design: wind speed, significant wave height, wave peak-spectral period, wind direction and wave direction. For each site, a binning process is conducted to create conditional probability functions for each of these variables. The sites are then grouped according to geographic location and combined to create three representative sites, including a West Coast site, an East Coast site and a Gulf of Mexico site. Both the processed data and the probability distribution parameters for the individual and representative sites are being hosted on a publicly available domain by the National Renewable Energy Laboratory, with the intent of providing a standard basis of comparison for meteorological and ocean conditions for offshore wind energy research worldwide. Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS
offshore wind energy; meteorological and ocean conditions

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Received 15 July 2014; Revised 29 April 2015; Accepted 13 June 2015

1. INTRODUCTION

Offshore wind turbines (OWTs) operate in a complex environment, undergoing loading from a variety of sources such as wind, waves and current. These external 'metocean' conditions play a critical role in the design and analysis of OWTs. Whether one is conducting research on OWTs, e.g. analysing the aerodynamic performance of a rotor or assessing the effectiveness of a particular control strategy, or one is performing a loads analysis, e.g. simulating design load cases specified by the International Electrotechnical Commission (IEC) offshore design standards (IEC 61400-3[1]), the metocean conditions that are utilized have a significant influence on the resulting outputs and conclusions. It is therefore crucial to have realistic metocean conditions available that accurately characterize the physical behavior of the offshore environment and that may be utilized across a wide range of OWT research, design and analysis activities.

While using metocean data from the specific site of interest is required for design loads analysis of a future installation, there are many research projects and preliminary design studies that could benefit from the realistic and freely available data presented in this paper. This database contains both site-specific and geographically averaged data (Section 3.2) for the waters surrounding the USA.

Design load case analyses that are utilized to estimate fatigue loading on an OWT are particularly important instances for which accurate metocean data are necessary. In such fatigue analyses, OWT simulations are performed over a wide range of metocean conditions, and the short-term fatigue loads of important outputs (e.g. blade-root flapwise bending moment or tower-base fore-aft bending moment) for each simulation are calculated, often using a rainflow counting algorithm.[2,3] To then estimate the lifetime fatigue, a weighted summation of the short-term fatigue is performed, where the weighting of each simulation corresponds to the probability of that particular metocean condition occurring. This is just one important instance in which accurate metocean data have a significant effect on the results of OWT analysis.

The objective of this technical note is to present a metocean data set created by researchers at the University of Massachusetts Amherst and the National Renewable Energy Laboratory (NREL) that can be utilized by the research community and industry for the design and analysis of OWTs. Specifically, this paper details the following:

- The source of a comprehensive set of metocean data and the subsequent post-processing.
- The processing of these data for the creation of conditional probability density functions (PDFs) for the mean wind speed, significant wave height, wave peak-spectral period, wind direction and wave direction of selected sites.
- The creation of 'generic' regional offshore sites in the USA, which characterize the East Coast, West Coast and Gulf of Mexico.
- The archiving of the data set and analysis in a free, publicly available database that can serve as a resource to the research community and industry.

Our goal is for this metocean data set to serve as a resource for future research and development by enabling realistic simulations of OWTs across a range of potential offshore sites. Ocean current speed and direction are not included in this database, and because of the lack of data extrapolation, the included data are more useful for normal conditions than for extreme events.

2. METOCEAN DATA SOURCE AND POST-PROCESSING

High-quality metocean data with high temporal resolution are difficult to find. The data source for this project is the National Oceanic and Atmospheric Administration (NOAA). This organization maintains an extensive network of floating data-collection buoys scattered throughout US and international waters. Data from these buoys can be found at the National Data Buoy Center.[4]

The first step in this work was to download the data from the NOAA website. To ensure statistical significance of the data, only sites with at least 5 years of data were selected for processing. The selected sites also needed to include the five measurement signals that were deemed necessary for offshore wind energy applications: mean wind speed, significant wave height, wave peak-spectral period, wind direction and wave direction. The requirement for a wave direction measurement proved to be the most limiting, but 23 sites met all criteria. Figure 1 shows the location and name of the sites downloaded from the NOAA database.

The data were collected differently for the different sensors. The wind speed data were averaged over 8 min and reported hourly. The wind direction was the average direction over the same 8 min averaging period. The significant wave height was measured as the average height of the highest one-third of waves over a 20 min period, also reported every hour. Peak-spectral period was the wave period with the maximum wave energy over this same 20 min wave measurement period. Wave direction was reported as the direction from which the waves at the dominant period arrived. The data from the

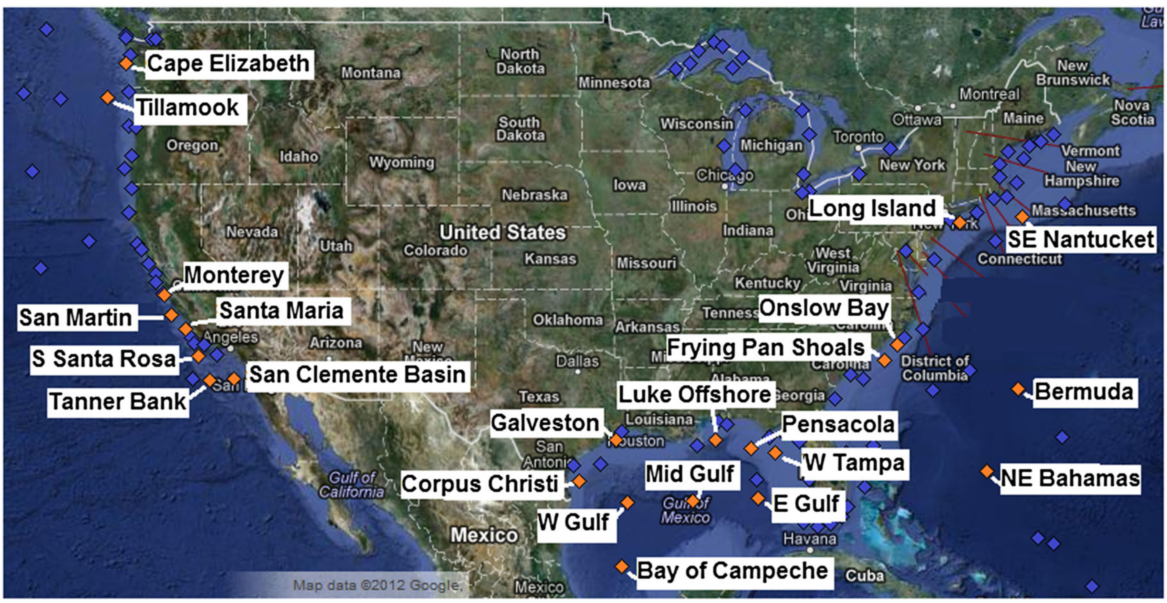

Figure 1. Map depicting names and locations of the data buoys used for this study (orange dots).

Wind Energ. 2016; **19**:1151–1159 © 2015 John Wiley & Sons, Ltd.
DOI: 10.1002/we

NOAA buoys contained missing entries for various sensors, and post-processing was required for each site to eliminate the impact from these missing data. While a number of interpolation schemes could be used to approximate the missing data, this was deemed unnecessary because of the large volume of clean data available for each site and the possible biasing that interpolation would introduce. Instead, any hour with missing entries for at least one of the important data channels (mean wind speed, significant wave height, wave peak-spectral period, wind direction and wave direction) was discarded.

Post-processing of the data then continued with the extrapolating of the wind speed to a typical OWT hub height of 90 m. Most of the buoys had anemometers at 5 m above sea level, with a few at 10 m. Most engineering approaches use either log law or power law wind shear equations for the extrapolation, which can be seen in Equations (1) and (2), respectively:

$$U(z) = U(z_r)\frac{ln(z) - ln(z_0)}{ln(z_r) - ln(z_0)} \tag{1}$$

$$U(z) = U(z_r)\left(\frac{z}{z_r}\right)^{\alpha} \tag{2}$$

where $U(z)$ is the wind speed at height z, $U(z_r)$ is the reference wind speed at height z_r, z_0 is the surface roughness length and α is the power law exponent. Typically, the surface roughness length and the power law exponent are empirically fit to measure wind speed data over different surfaces. For offshore wind, z_0 varies from 0.20 mm for calm open seas to 0.50 mm for blown seas, and α is usually between 0.07 and 0.15. These two shear laws are simplifications of actual shear profiles, which depend on boundary-layer stability as well as surface roughness and other factors. NOAA has developed the COARE, (Coupled Ocean-Atmospheric Response Experiment), model that includes a modified log law and uses wave height to estimate the ocean surface roughness, air temperature, water temperature and humidity as an indicator of atmospheric boundary-layer stability.[5] Because the data buoys included sensors that report the needed inputs for the COARE model, a more accurate hub-height wind speed prediction was determined using the conditions at each data entry. These models are compared to examine the difference between extrapolated hub-height wind speed. When implementing the COARE model, the average value was used for data points that were missing information for a certain sensor (air temperature, water temperature and humidity). Figure 2 shows a comparison of average hub-height wind speeds for two power law approximations and the COARE model for all of the sites. Note that Figure 2 is sorted by descending average wind speed from the COARE model. Interestingly, the power laws over-predict the wind speed for some sites compared with the COARE model and under-predict for others. Both the power law and the COARE model may introduce errors into the hub-height wind speed. Because the COARE model takes atmospheric stability into account, it was used for the creation of the probability distributions. The processed data also include the extrapolated wind speeds from the two power laws for comparison.

To reduce the environmental variables, the wind direction and wave direction were combined into one measure: wind/wave misalignment angle, defined as the difference between the wind direction and the wave direction, while ensuring that the difference is always between −180°and 180°. The processed data include both wind and wave directions independently and the combined wind/wave misalignment value.

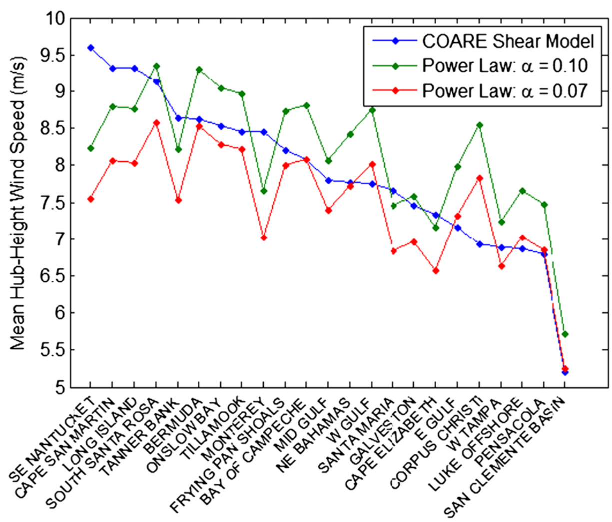

Figure 2. Comparison of COARE model prediction to two power law approximations of hub-height wind speed for all sites.

3. METOCEAN DATA ANALYSIS

Once the metocean data were downloaded and post-processed, they were analysed to create the full long-term joint probability distributions in terms of conditional PDFs and then combined to create 'generic sites'. As Section 3.2 discusses, three generic sites were created: a West Coast site, an East Coast site and a Gulf of Mexico site. Because of geographic features of these locations, the West Coast site has the highest waves, the Gulf of Mexico site has the lowest waves and the East Coast site is in the middle (Figure 6). For the design of a real project, measured metocean data from the specific site should be used. For research purposes, however, these generic sites use realistic data, and the results can be generalized for an entire region. In this way, design loads for a specific turbine configuration using a generic site from the East Coast of the USA, for example, may be compared with the design loads from the same turbine at a site from another region.

3.1. Creation of conditional PDFs

With the post-processing complete, including scaling the wind speed to hub height, the data were used to create conditional PDFs based on analytical functions, which can then be used to assign probabilities to combinations of conditions. Analytical function conditional PDFs are useful because the probability of any combination of metocean conditions can be specified simply from the parameters of the PDFs, independent of the number of instances of the particular metocean conditions.

Because metocean conditions were not independent of each other, certain conditionalities were used to characterize the PDFs at each site. For this study, the following conditionalities are used, as defined in the design standards:[1]

- Wind speed was considered as an independent parameter.
- Wind/wave misalignment was conditioned by wind speed.
- Significant wave height was conditioned by wind speed and wind/wave misalignment.
- Peak-spectral period was conditioned by wind speed and significant wave height.

The conditioning of the wind/wave misalignment is not defined in the IEC standard. As the wind speed increases, the probability of aligned wind/waves also increases because of a higher likelihood that waves at a site are caused by the local wind, so an assumption was made that it is only conditioned on wind speed. Figure 3 depicts this concept. Using the foregoing conditionalities, the full joint probability function is expressed as follows:

$$P(U, H_s, T_p, \beta) = P(U)\,P(\beta|U)\,P(H_s|U,\beta)\,P(T_p|U,H_s) \tag{3}$$

In Equation (3), the $P()$ operator denotes the cumulative probability distribution (CDF), U is the wind speed, β is the wind/wave misalignment angle, H_s is the significant wave height and T_p is the peak-spectral period. It is clear that if one of the conditional probabilities is small, then the total probability will be very small, as each conditional probability is less than one by definition.

The analytical distributions fit to the measured data were chosen based on the literature and best fit to the data.[6,7] A two-parameter Weibull distribution was used for wind speed, gamma distributions were used for significant wave height and peak-spectral period and a von Mises distribution was used for the wind/wave misalignment. The von Mises distribution is also known as the circular normal distribution and was used because it was the most well-documented circular distribution

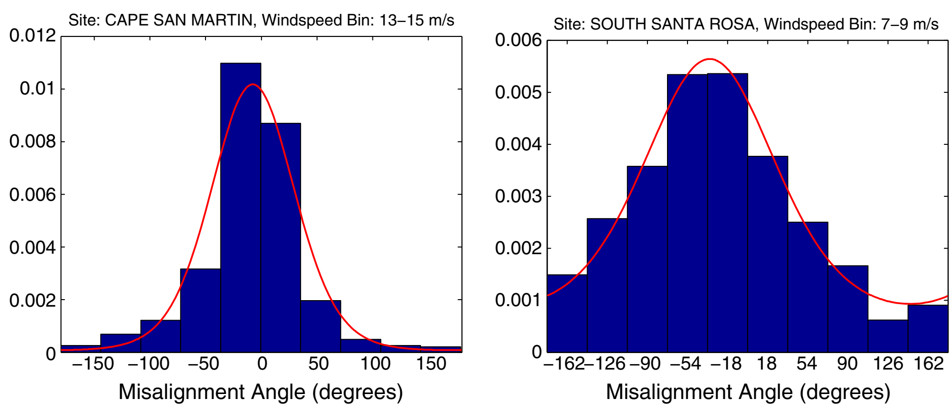

Figure 3. Wind/wave misalignment von Mises distribution fit examples.

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Table I. PDF and CDF equations for the three probability distributions used in this research.

Distribution	Data	Parameters	PDF	CDF
Weibull	Wind speed	λ, k	$\begin{cases} k\lambda^{-k}x^{k-1}e^{-(\frac{x}{\lambda})^k}, & x \geq 0 \\ 0, & x < 0 \end{cases}$	$\begin{cases} 1 - e^{-(\frac{x}{\lambda})^k}, & x \geq 0 \\ 0, & x < 0 \end{cases}$
Gamma	Significant wave height and peak-spectral period	k, θ	$\frac{1}{\Gamma(k)\theta^k} x^{k-1} e^{-\frac{x}{\theta}}$	$\frac{1}{\Gamma(k)\theta^k} \int_0^x t^{k-1} e^{-\frac{t}{\theta}} dt$
von Mises	Wind and wave misalignment angles	μ, κ	$\frac{e^{\kappa \cos(x-\mu)}}{2\pi I_0(\kappa)}$	$\frac{1}{2\pi I_0(\kappa)} \int_0^x e^{\kappa \cos(t-\mu)} dt$

Table II. Bin ranges and widths for the four metocean parameters.

Parameter	Bin width	Range
Wind speed (m s^{-1})	2	3–25
Wind/wave misalignment (°)	15	−180 to 180
Significant wave height (m)	0.5	0–13
Peak-spectral period (s)	0.5	0–27

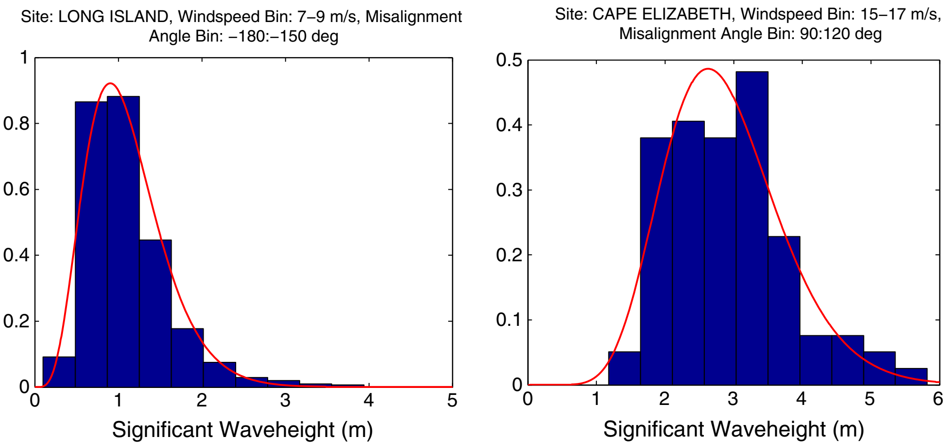

Figure 4. Significant wave height gamma distribution fit examples.

found by the authors.[8] The equations for the PDFs and CDFs of each function can be seen in Table I. In Table I, Γ is the gamma function, and I_0 is the modified Bessel function of order zero.

To construct the conditional probability distribution fits for significant wave height, the data were separated into bins of wind speed and wind/wave misalignment, and probability distribution parameters were fit to the significant wave height for each bin in a least squares sense. The binning scheme used to create the conditional probability distributions can be seen in Table II. These bins were chosen based on the recommended bin size from the IEC offshore design standard.

Figures 3–5 show examples of the probability distribution fits for various bins and sites. One difficulty with this approach was that many bins (for example, bins with high wind speed and low wave heights) were very unlikely and may have only a few occurrences in all of the downloaded data. There were a few ways to handle this issue, including lumping many unlikely events into one bin and using a functional fit to approximate the probability of events that do not occur in the data using similar events that do occur. The approach taken in this research, however, was to simply assume that the probability of any bin with five or fewer data points was zero.

As an example, let us consider the creation of a probability distribution for peak-spectral period for the highest wind speed bin (23–25 m s^{-1}) and the lowest significant wave height bin (0–0.5 m s^{-1}). For a given site with 10 years of data, these conditions may have occurred five times. This corresponds to a probability of 6×10^{-5}. If we then create a probability distribution of the peak-spectral period of the waves for these five data points, the probability is further reduced as each combination of parameters must be multiplied by the probability of that peak-spectral period occurring. Equation (3) elucidates this point in more detail.

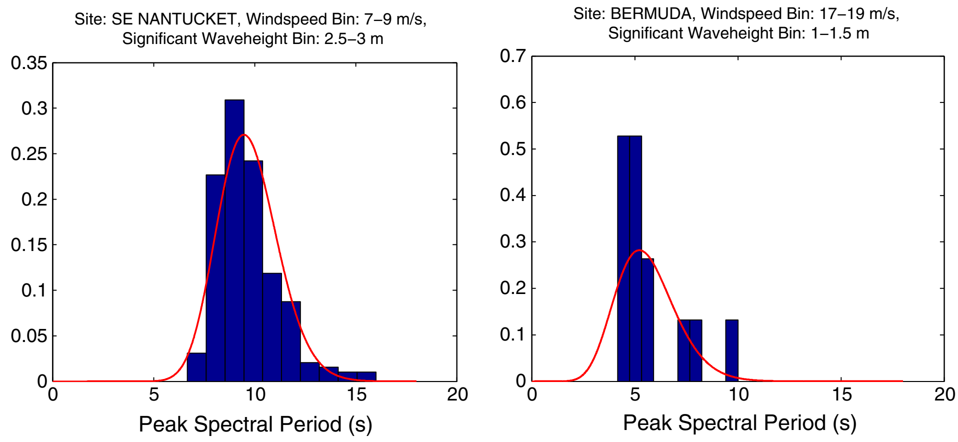

Figure 5. Peak-spectral period gamma distribution fit examples.

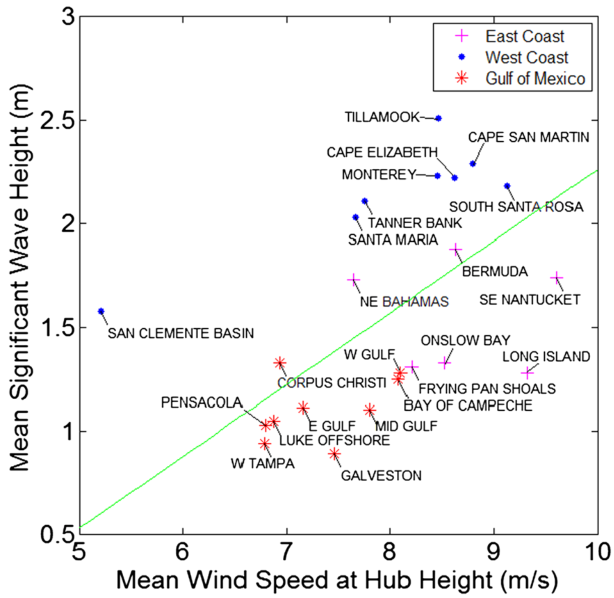

Figure 6. Mean wind speed and significant wave height for each site.

3.2. Creation of generic sites

Once all of the distributions were created for each site, the site information was combined to create three representative sites. Figure 6 shows a plot of the mean wind speeds and significant wave heights for each site (the San Clemente Basin site was removed from the study because of its low wind speed). Using this plot, a number of methods could be proposed to group the sites, and a geographical grouping as shown by the legend in Figure 6 was chosen as the most appropriate approach.

To create the East Coast, West Coast and Gulf of Mexico sites, averaging was performed for all of the distribution parameters for the sites in each group. For the Weibull distribution for wind speeds, simple averaging of the scale and shape parameters was used to create the generic distribution, as can be seen in Figure 7 for the East Coast.

While actual design standards contain language about the importance of using environmental data specific to the proposed site, in many research activities, site-specific data are not needed, rather a representative characterization of sites is sufficient. The value of these generic sites is their broad applicability to the three offshore regions in the USA.

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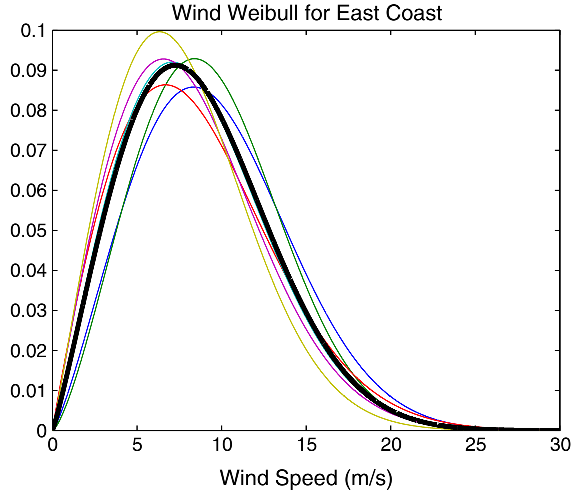

Figure 7. Wind Weibull distributions comparing individual sites (colored lines) to the mean East Coast distribution (black line).

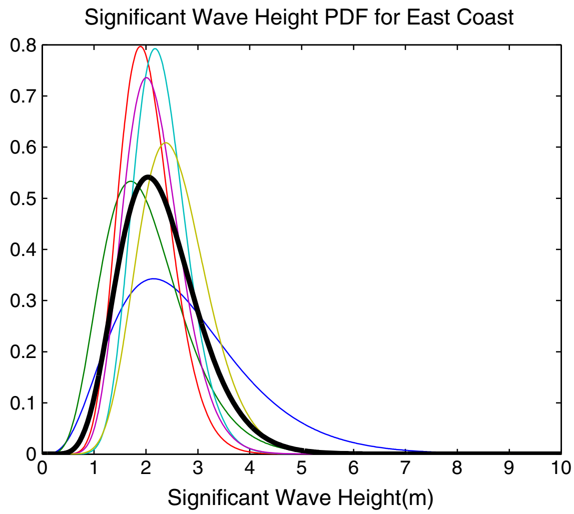

Figure 8. Significant wave height distributions comparing individual sites (colored lines) to the mean East Coast distribution (black line) for 12 m s^{-1} wind speed and −105° wind/wave misalignment.

4. METOCEAN DATABASE

An extensive online database has been created and is hosted by NREL at the following location: https://nwtc.nrel.gov/metocean. Included in this repository are the processed data from the 23 sites in both a MATLAB (MathWorks Inc., Natick, MA) '.mat' format and a simple text format, as well as a MATLAB script for downloading the data from the NOAA website. The binned and sorted data for each site are also included, in a MATLAB data structure format. Because of the multi-dimensional nature of these data, the MATLAB structure format lends itself well to the application. A table of the PDF parameters for the individual and generic sites is also included. Details on the formatting of the data structures are included in the repository but are omitted here for brevity.

For the significant wave height and peak-spectral period that used a gamma distribution, simple averaging of the shape and scale parameters led to erroneous results because the mean and standard deviation are functions of both parameters. To create the average parameters, therefore, the scale and shape parameters were converted to mean and variance values, which were averaged for the sites in the groups, and then converted back to scale and shape parameters. The definition of the mean value for a gamma distribution is $\mu = k\theta$, and the definition of variance is $\sigma^2 = k\omega^2$, so this process was a simple algebraic manipulation. The PDFs that were created in this way were then compared with the original sites. The von

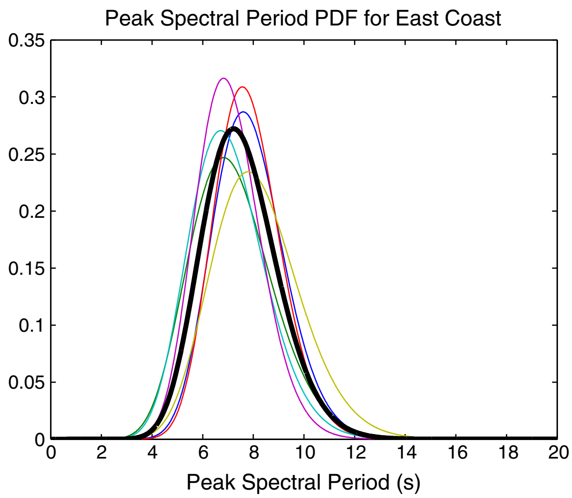

Figure 9. Peak-spectral period distributions comparing individual sites (colored lines) to the mean East Coast distribution (black line) for 12 m s^{-1} wind speed and 2.25 m significant wave height.

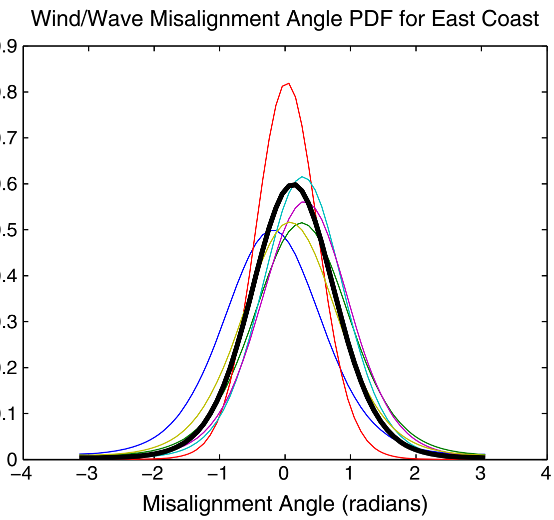

Figure 10. Wind/wave misalignment angle distributions comparing individual sites (colored lines) to the mean East Coast distribution (black line) for 24 m s^{-1} wind speed.

Mises distribution uses mean and variance as its parameters, so no manipulation was needed; the parameters were simply averaged across the sites for each geographic region. Figures 8–10 show examples of the comparisons for the East Coast site. An alternative method to create the generic sites, which was not taken here but could be performed using the database, was to combine and then average the raw data of the sites before binning and processing.

5. CONCLUSIONS

A database of metocean conditions for over 200 total years of data from 23 offshore sites across the USA has been processed from the original buoy data from NOAA into a form useful for offshore wind energy research. Various methods have been used to scale the wind speeds from surface winds to turbine hub height. These methods (two power laws and the COARE model) may introduce errors to the wind speed due to uncertainties in atmospheric stability. For future development of offshore wind, more research into upper-level wind measurements and reliable atmospheric stability estimates is important to reduce these errors. The database allows for alternative scaling laws to be implemented.

The processed data have then been analysed to form a joint probability distribution containing wind speed, significant wave height, wave peak-spectral period and wind/wave misalignment for each site. Three generic sites have been created by averaging the sites from the East Coast, the West Coast and the Gulf of Mexico. All of these data and associated analysis are included in a database for open use in research and development of offshore wind.

We believe that these data provide a useful resource for offshore wind energy research. The database has the potential to provide a common metocean basis for comparison for OWT design, similar to how the NREL 5 MW reference turbine is utilized. The inclusion of wind and wave directions enables further research into the effects of wind/wave misalignment, which can be an important driver of loads for OWTs. Currently, only sites in the USA have been analysed, but future work may expand this analysis to European and Asian sites, if the raw data can be obtained.

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