LiDAR Measurements of Wind Shear Exponents and Turbulence Intensity Offshore the Northeast United States

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ABSTRACT

This paper presents wind speed shear exponents and turbulence intensity measurements collected from LiDARs measuring wind speeds from 40m to 200m above sea-level and provides comparisons to industry design guidelines. The high-altitude wind speed data are unique and represent some of the first measurements made offshore in this part of the country, which is actively being developed for offshore wind. The data is used to support the New England Aqua Ventus I Floating Offshore Wind Farm to be located 17km offshore the Northeast United States. Multiple LiDAR measurements were made using a DeepCLiDAR floating buoy and LiDARs located on a nearby island. The measured wind speed shear exponents are compared against industry standard mesoscale model outputs and offshore design codes including the American Bureau of Shipping, American Petroleum Institute, and DNV-GL guides. Significant variation in the vertical wind speed profile occurs throughout the year which is not addressed in design standards. Additionally, turbulence intensity measurements made from the LiDAR, although not widely accepted in the scientific community, are presented and compared against industry guidelines.

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1. INTRODUCTION

There is an increased need to characterize the high altitude wind conditions offshore as wind energy is developed to meet the increasing renewable energy demand in the Northeast US. Such measurement campaigns provide essential data to support project design activities while also generating unique measurements far offshore. This paper presents some of the first US measurements of wind shear exponents and turbulence intensity collected in support of offshore wind development. The data was collected by a floating light imaging, detection and ranging instrument (LiDAR) buoy, and a nearby land-based LiDAR, located 17km offshore the coast of Maine in the Northeast United States. The measurements were taken near the site of the US Department of Energy Advanced Offshore Wind Technology Project called New England Aqua Ventus I. The data represents one of the first high altitude data sets collected in the US. Wind shear exponents and turbulence intensity measurements made by the LiDAR devices are compared with published design guides for offshore wind turbines and differences are highlighted. These early offshore measurements provide useful insights into the behavior of the wind speed exponents far-offshore in the Northeast US and will help, as more data becomes available from other projects, support increased understanding and aid improvement of design methods and standards.

The paper first presents theory and background information useful in the understanding of the presented data and post-processing methods. Additional background on other offshore measurements of wind speed is also discussed briefly. The measurement set-up is then explained for both the LiDAR buoy and land-based

LiDAR measurement programs. Next, the data is presented followed by comparisons to industry published values. Finally, the paper concludes with a discussion of the results.

2. THEORY AND BACKGROUND

2.1 THEORY AND REPRESENTATIVE MEASUREMENTS OF WIND SHEAR EXPONENTS

A brief discussion of wind shear and how it is typically represented in offshore wind design codes is now presented. Wind shear is the natural variation of the wind speed with the height above the earth's surface due to a variety of physical processes. This variation in wind speed is often represented with a power law model defined as:

$$u = u_r\left(\frac{z}{z_r}\right)^{\alpha} \tag{1}$$

Where the variables are as defined in the nomenclature section at the end of this paper. The power law wind shear extrapolation method is often used for engineering design purposes and exponents are generally in the range of 0.1 to 0.2 although wider ranges are in use. However, it is well known that a variety of wind shear profiles are possible due at a site due to different boundary layer conditions as shown in Figure 1. Two measurement heights (z) are needed to determine α from experimental data. Wind speed measurements (u), in meters per second, taken at 40 and 100 meters were used in this study from the LiDAR measurements. 100 meters was chosen because it represents the hub height for the proposed turbines. 40 meters was chosen because it offered the most available data out of the remaining measurement heights. This resulted in the power law being treated as such:

$$u_{100m} = u_{40m}\left(\frac{100}{40}\right)^{\alpha} \quad (2)$$

Using the data and this relationship, the wind shear exponent could be solved for each measurement record.

A brief summary of known offshore wind measurements and wind shear exponents to provide context to the new measurements made in this study is now presented. Although there is a wealth of near surface data collected from oceanographic buoys in the US, at this time there are few public data sets for offshore wind speed measurements at wind turbine hub heights (100+m) available in the US. The US Department of Energy (DOE) launched a Wind Sentinel LiDAR buoy off the coast of Virginia in 2016[1] and in in Atlantic City, New Jersey. The National Renewable Energy Laboratory (NREL) has published US offshore wind resource maps, which present mean annual wind speeds at a height of 90m. These plots have assumed an average wind shear exponent of 0.11 [2]. Similar studies of the great lakes have used shear coefficients of 0.10 in Lake Erie and Lake Ontario [3]. The University of Maine, with the use of metocean buoy data including surface level wind speed data and published mean wind speeds from NREL, estimated wind shear coefficients of 0.16 [4]. A short one-month campaign of ship mounted LiDAR measurements was performed off the coast of Maine in the summer of 2004 and showed a range of wind shear values between -0.02 and 0.06 [5].

In Europe more published information on wind shear exists, likely due to the number of offshore wind farms currently installed. It has been shown that with traditional methods for accounting for wind shear in the surface layer is often under

97 estimated. It was observed by Bernhard Lange in 2004 that wind shear is often larger
98 than predictions from traditional methods, especially in warmer air conditions [6]. This
99 suggests that traditional methods may need to be modified where atmospheric stability
100 is accounted for. Furthermore, the Technical University of Denmark (DTU) has
101 performed studies in the North Sea using LiDAR devices and concluded that "current
102 wind engineering commonly-used wind shear norms and standards seem to be far too
103 optimistic and not very conservative" [7]. The values from standards were generally
104 lower than measurements. As such, these commonly used wind shear norms can lead to
105 overestimation of long-term wind resource. Further studies performed by the DTU in
106 the North Sea comparing wind shear measurements between met-masts and wind
107 LiDARs show that the typically assigned offshore wind shear value of α=0.2, is only
108 accurate for a very slim set of atmospheric and marine conditions [8]. Rather, it has
109 been observed that wind shear values at 100m have a range between -0.2 to 0.8.

110 Some design standards use a Logarithmic wind shear model instead of the power
111 law model. To compare the measured values to published values, equivalent wind shear
112 power law exponents were calculated using equation 2.3.2.9 from the Recommended
113 Practice from Det Norske Veritas, DNV-RP-C205 [9]:

$$\alpha = \frac{\ln\left(\frac{\frac{z}{z_0}}{\frac{H}{z_0}}\right)}{\ln\left(\frac{z}{H}\right)} \tag{3}$$

114

115 This equation is a combination of logarithmic and power law wind profiles and is
116 height dependent. Here H is equal to 40 meters and z is equal to 100 meters to be

consistent with the power law wind shear exponent value calculation process. This equation allows a direct comparison of the two models for estimating variation of wind speed with height.

2.2 THEORY AND REPRESENTATIVE MEASUREMENTS OF WIND SPEED TURBULENCE INTENSITY

For the purposes of offshore wind turbine design, the wind speed turbulence intensity (TI) is defined as the standard deviation of the wind velocity (u') over the mean wind velocity (u_{avg}) typically taken over a 10-minute record of wind speeds sample with cup anemometers [10]:

$$TI = \frac{u'}{u_{avg}} \tag{3}$$

Public wind TI measurements offshore in the US at hub-height are also scarce. Europe has more data for wind turbulence, but most of this data is still proprietary. Two years of analyzed data is available from a costal measurement station in Norway. This analysis shows that offshore and costal environments tend to have a TI slightly less than the onshore sector. Furthermore, there is a distinct difference shown between seasons where the variations between these sectors is more pronounced in summer [11]. Multiple methods of predicting *TI* have been compared to measurements taken at the Greater Gabbard Offshore Wind Farm. This data set shows mean *TI* values between 0.07-0.10 between 3-25m/s wind speeds, when taking into account all wind directions [12].

2.3 SUMMARY OF OFFSHORE WIND ENERGY DESIGN VALUES FOR WIND SHEAR EXPONENTS AND TURBULENCE INTENSITY FROM INDUSTRY STANDARDS

Wind shear exponents recommended design values are provided in offshore engineering design guides. In this paper, a review of the published values was completed including:

- American Bureau of Shipping (ABS) Guide for Building and Classing Floating Offshore Wind Turbine Installations [13]
- the International Electrotechnical Commission (IEC) International Standard IEC 61400-3 [14]
- DNV-RP-C205 Environmental Conditions and Environmental Loads [9]
- ASCE [15]

Table 1 presents a summary of the recommended wind shear exponents from these standards. The table shows that there is a significant difference between the standards for offshore wind designers. For example, the ABS guide differentiates between operational and extreme conditions while the other standards provide one value. The differences between the standards are significant. For example, a 5m/s wind speed at 4m above sea-level, when extrapolated to 100m hub height using equation 1 and the published wind shear exponents yields a wide range of wind speeds of 7.1, 9.5, 7.4, and 8.1m/s for the four standards listed in the order presented in Table 1.

Wind turbine design conditions, including wind shear and wind veer, are given by IEC 61400-1. ABS references this same set of conditions. The IEC models are based on 90% quantile turbulence measurement and provide turbulence intensity as a function of

wind speed for the purposes of load calculation and to provide conservative estimates for design of offshore wind systems.

3 EXPERIMENTAL METHODS

3.1 LIDAR MEASUREMENTS

Data were collected from a LiDAR on Monhegan Island and from a buoy approximately 1 km west of the Island as shown in Figure 2. Monhegan Island itself is roughly 17km form the mainland. The instruments and data collected are summarized in Table 2. Both LiDARs were Windcubes produced by Leosphere. The offshore measurements were collected using a Windcube V2 Offshore LiDAR, while the land-based data are comprised of measurements from both a Windcube V2 Offshore LiDAR and a Windcube V1 LiDAR deployed at different times. The V2 LiDAR is the next iteration of the V1 LiDAR and there are no significant difference in the data between the units after completing side-by- side comparisons on land and offshore as described by Viselli et al. [16]. The V2 Offshore LiDAR includes built in motion correction software to compensate for any motion experienced by the buoy while at sea. Both LiDARs delivered data points and average wind speeds based on a 10-minute averaging period. The data provided by the LiDARs include mean wind speeds, wind speed variance, signal to noise ratio to assess quality, and direction at nine programmable levels from 40m-200m above the system. Figure 3 shows the setup of a land-based measurement site, positioned at the Southern tip of the island, roughly 1.2km east from the deployment site of the DeepCLiDAR Buoy offshore, and provided a clear and open area for the LiDAR

to take measurements. The land-based LiDAR was positioned with a line-of-site to the LiDAR buoy with little obstruction. Additionally, surface level wind speed and wave data from an existing nearby UMaine buoy, E01, was also collected during this time [17]. This served as another reference point for the measurements and provided concurrent wave height data for the land-based LiDAR data discussed later.

Figure 4 shows the DeepCLiDAR deployed offshore south west of the Island. The water depth was roughly 95m and is approximately 1.26km from Monhegan Island. Due to the distance between Monhegan Island and Maine's coastline, the site offered an open-ocean environment generally upwind of the island. The buoy collected 30-minute significant wave height and peak period measurements, 1-minute current speeds and 1-minute directional data offshore. The buoy collected data for approximately seven months. A summary of sea state conditions at the buoy site is presented in Table 3.

3.2 ESTIMATES OF WIND SHEAR USING A MESOSCALE MODEL

Estimates of wind shear exponents at the site were also made using a mesoscale model and are presented in Table 8. The mesoscale model used is the Mesoscale Atmospheric Simulation System (MASS1), which was run in a series of nested grids, with the innermost grid having a spatial resolution of 1.2 km. The microscale model (WindMap) further refined this output to a horizontal grid spacing of 50 m. The source of topographic data was the National Elevation Dataset (NED), a digital terrain model produced on a 30 m grid by the US Geological Survey (USGS). The source of land cover data was the 30 m resolution National Land Cover Dataset (NLCD), which is produced by

the USGS and derived from Landsat imagery. While the majority of the mapped study area is open water, the land cover and topographic data was necessary to properly characterize wind flows over land features like Monhegan Island. In converting from land cover to surface roughness, the onshore roughness length values that were applied are believed to be typical of conditions in coastal Maine. However, the roughness could vary a good deal within each onshore class, potentially affecting the wind in the near shore environments.

The predictions of the model are compared to the measured average 10-minute wind shear measured by the land-based and offshore LiDARs. In general the measured wind shear is noticeably higher than the model predictions. The model was used to predict the monthly average wind shear exponent. The model estimates the wind shear for each hour of the day for each month. The values reported here are the average of the hourly average wind shear exponent predicted by the model for each day. The data shows a difference in mean wind shear throughout the year ranging from 0.05 to 0.19. Summer months exhibit the highest wind shear while winter typically experiences lower wind shear values.

3.3 WIND TURBULENCE INTENSITY MEASUREMENTS

Industry confidence in turbulence intensity values calculated using LiDAR measurements is not typically accepted. While turbulence characteristics of atmospheric flows can be derived from LiDAR measurements, it is not nearly as established other methods [18]. When using vertical profilers, such as LiDAR, turbulence measurements generally

226 experience two sources of difference from traditional measurements of TI. Variance is
227 reduced due to the volumetric averaging of radial velocity measurements. Furthermore,
228 variance is also effected by the cross contamination due to the scanning geometry of
229 the LiDAR [19]. Issues with variance from a Windcube LiDAR specifically have been
230 observed in a comparison of multi-LiDAR methods of measuring turbulence. Unstable
231 conditions further showed variance contamination in horizontal measurements from
232 the Windcube when compared to the multi-LiDAR setups [20]. Although the use of
233 LiDAR for turbulence has known limitations, the data collected here is useful given that
234 little if any turbulence data offshore the northeast US exists in the public domain. In this
235 study, the turbulence intensity was calculated directly from the LiDAR.
236
237 **4 RESULTS:**
238 4.1 *LiDAR MEASUREMENTS*
239 Table 4 summaries the basic wind measurements made by the land-based LiDAR
240 and DeepCLiDAR. The mean and standard deviation of the 10-minute wind speed
241 measurements is presented for each LiDAR using all data screened based on “data
242 availability” for each 10-minute record at 40m and 100m above the sea level. Data
243 availability is determined by the carrier-to-noise ratio (CNR) and helps flag low signal
244 strength, primarily due to insufficient particles in the air or other obstructions, which
245 leads to inaccurate measurements. This is a standard practice among LiDAR
246 measurements in the wind industry and helps lead to higher quality data collection and
247 analysis. Because the land-based measurement record is longer than the DeepCLiDAR

measurement record, concurrent land-based lidar measurements are also provided to facilitate comparison of the two data sets. These values are displayed in parenthesis below the full data values.

4.2 MEASURED WIND SHEAR EXPONENTS

Table 5, Table 6, and Table 7 show the measured wind shear values broken down into 2m/s bins for the all land-based measurements, concurrent land-based measurements, and the offshore buoy measurements respectively. Table 6 presents only the contemporaneous data measured by the Land-based LiDAR for the purposes of comparing with the offshore LiDAR measurements. Statistical data is provided for each bin. Both of the two LiDAR measurement campaigns generated over 24,000 10-minute wind speed samples (over 167 days). The final row includes data below 1m/s and above 27m/s and therefore an additional 221 and 271 data points are included. As expected based on the annual wind speed distribution, not all of the wind speed bins have an equal amount of data. For both the land-based and DeepCLiDAR measurements, about 90% of the data occurs when the average wind speed is below 17m/s.

The data show a wide range of mean-wind shear values for the different wind-speed bins and significant variation within each bin as indicated by the standard deviation and 10^{th}/ 90^{th} percentile values. The lower wind-speed bins have low wind shear exponents and the exponent generally increases with the average 10-minute wind speed bin. For the lowest wind speed bin of 1-3m/s, the wind shear exponent is highly variable and the mean is negative. About 13% of the Land-based and 19% of the LiDAR

buoy wind shear exponent data was negative. However, these speeds are typically not too relevant for design of offshore wind systems since the cut in speed for most turbines is 4m/s. The average wind shear exponent for wind speed bins above 11m/s fall above 0.26 and 0.21 for the land-based and DeepCLiDAR data sets respectively. These values are higher than the recommended industry standards in Table 1. The overall average wind shear exponent using the contemporaneous data for the land-based and DeepCLiDAR buoy are 0.20 and 0.15. Figure 5, Figure 6, and Figure 7 present a scatter diagram of the measured wind shear exponents for the Land-based and buoy LiDAR measurements versus 10-minute mean wind speed at 100m above Mean Sea-Level. The mean wind shear exponent for each 2m/s bin and the 10^{th} and 90^{th} percentile for each bin are also plotted. The data shows an increase in wind shear exponent as wind speed increases, up until roughly 24m/s, however, it is unclear whether this drop is due to a physical phenomenon or due to a lack of data measurements at these higher wind speeds.

4.3 WIND TURBULENCE INTENSITY MEASUREMENTS

Table 9, Table 10, and Table 11 present the turbulence intensity data made from the Land-based and DeepCLiDAR wind speed measurements at 100m. When considering the concurrent data, the onshore LiDAR generally showed smaller turbulence intensity for all wind speeds. This is possibly due to the motion of the buoy, although there is motion correction applied to the measurements by the manufacturer. Additionally, the difference could also be due to the geographical location and topography of the two sites.

5 DISCUSSION: COMPARISON OF DATA WITH INDUSTRY DESIGN GUIDES

A comparison of the measured wind shear exponents against industry recommended design values is now presented. Table 12 presents a comparison of the measured exponents from the two LiDARs against industry design standards, the mesoscale model estimates, and a previous study.

The API estimates for power law exponent and log profile roughness parameter were calculated following standard APR RP 2MET [21] for a 1-hour wind speed of 20 m/s, and converted to a ten-minute mean wind speed. The API logarithmic wind shear model is different from the DNV model. The one year mean wind speed at 4m above sea level is equal to 21.4m/s at the location of this experiment which, when converted to 1-hour averaging period, is equivalent to 20m/s. This wind speed was used for the purposes of comparison of the values estimated here. An equivalent roughness coefficient and wind shear exponent were calculated between 40m and 100m elevations for the purposes of comparing with the other standards. The API model is representative of offshore conditions, in strong, nearly neutrally stable atmospheric wind conditions during storms.

Several wind shear parameters are presented for each data set and industry standard when available based on the roughness of the sea surface, which is characterized by the significant wave height conditions. The DeepCLiDAR buoy provides both wind and wave measurement instrumentation, which allows for the data to be screened and a separate mean wind shear to be reported for different significant wave height, Hs, ranges. In this study waves were considered to be Low, Medium or Large to

be below 1m, between 1m-3m, or above 3m significant wave height respectively. The majority of the waves were classified as Low: 62% Low, 36% Medium, and 2% Large. The land-based LiDAR was similarly treated except concurrent significant wave height data was taken from the other nearby reference buoy, E01. E01 is roughly 5.5km southwest from the land-based collection site. The majority of waves at E01 fall under 3m: 46% Low, 50% Medium, and 4% Large. These alternate wind shear values are presented and allow for comparison against industry standards, which provide typical wind shear values for different sea conditions.

DNV RP-C205 presents a wide range of wind shear values for offshore and coastal conditions based on the wave conditions. The other standards do not present explicit wind shear conditions based on wave heights. ABS and IEC present a normal and extreme wind shear only. The normal wind shear is likely more typical of a low to medium wave environment and the extreme wind shear could be considered more close to the larger wave environmental conditions.

The offshore LiDAR average shear exponent of 0.15 exceeds the offshore DNV range of 0.08 to 0.13, the ABS values of 0.11 to 0.14, the previous study by Viselli et al and the Mesoscale model prediction. This data is less than both the 0.2 value recommended by IEC 61400-3 and the 0.16 value proposed by ASCE-7. As compared to API, the measured wind shear in the 19-21m/s wind speed bin is equal to 0.27, which is significantly more than the API value.

The land-based LiDAR average shear exponent of 0.20 exceeds the offshore DNV range of 0.08 to 0.13, the ABS values of 0.11 to 0.14, the previous study by Viselli et al

and the Mesoscale model prediction. This data matches the 0.2 value recommended by IEC 61400-3 and exceeds the 0.16 value proposed by ASCE-7. As compared to API, the measured wind shear in the 19-21m/s wind speed bin is equal to 0.28, which is significantly more than the API value.

Differences in these comparisons could be due to lack of multiple complete years of data as well as site specific conditions not specifically addressed by the standards and past studies. Differences in winds shear has been observed to be diurnal and seasonal, as shown in Table 8, and is due to “the stability of the atmosphere, which is governed by vertical temperature distribution from radiative heating or cooling of the earth’s surface and the subsequent convective mixing of the air adjacent to the surface” [22]. This is especially true for offshore environments where there is a difference in sea and air temperature, which affects the lower boundary layer. Thus wind speeds and therefore wind profiles are effected. Previous findings have shown that the stratification of the lower boundary layer is mainly unstable in the fall while stable in the spring [23].

The DeepCLiDAR was deployed for approximately 8 months from February to the end of October of 2016. Considering the mesoscale model outputs, averaging this partial year data set would tend to result in higher average wind shear considering that the majority of the winter months were not included in the average. This could explain the differences with the DNV, ABS, prior study, and the mesoscale model but would likely widen the gap against the IEC 61400-3 standard. The land-based LiDAR was deployed considerably longer for 21 months. However, the result of this additional data record is an increase in wind shear as compared to the offshore LiDAR, which is not expected

based on the mesoscale model, which would expect a lower average wind shear to occur when more of the data from the winter months is considered. When considering specific data points considerably more deviation from the standards exists. The spread on the data for wind shear is highly variable and the values can increase or decrease significantly from the reported averages. In some cases, a negative wind shear occurs, which is not well discussed in current offshore standards. This data set includes a number of negative wind shear values as mentioned.

A comparison of the measured turbulence intensity against IEC standards is now presented. Figures 8, 9, and 10 present the measured turbulence from the land-based LiDAR and DeepCLiDAR. In addition to the measured data, the 90% percentile/ quantile of the measurements is provided for comparison against the IEC 61400-1 industry turbulence class turbulence intensity curves for Class A and Class C site conditions. The Land-based and DeepCLiDAR 90% quantiles fall below the Class C curve for all wind speed bins above about 2m/s.

6. SUMMARY AND CONCLUSIONS

A unique high altitude (40-200m) wind speed data set has been analyzed and provided in this paper. The data was collected in the Northeast US in support of the development of the first floating offshore wind project in the US planned for grid-connection by 2023. There is currently a lack of wind speed data at high altitudes in the US making these first measurements useful for understanding the wind conditions offshore in the US for future research and wind developments. This testing campaign

consisted of two LiDAR wind measurement devices collecting data simultaneously. One was positioned on land and other offshore on a DeepCLiDAR buoy.

The data from this campaign suggests that wind shear varies throughout the year with wind speed, and for different wave conditions. The mean measured wind shears exceeded those presented in most industry recommendations. It was not uncommon to see a wind shear exponent above 0.20 with wind speeds above 10m/s. Industry standards generally present only a one or two representative wind shear values for all design load cases. In reality, wind shear varies significantly. Higher wind shear could have significant effect on the fatigue life for a wind turbine and support structure. For example, the loading on the blade will vary more with increased wind shear as it rotates.

Both onshore and offshore LiDAR wind turbulence measurements are not currently used as a reliable measurement. The data is presented in this paper because there is little offshore turbulence measurements available in the US. The data shows that the offshore wind turbulence at 100m was below IEC 61400-1 Class C.

In summary, this data campaign and analysis suggest that wind shear may need to be considered carefully given the significant variation possible and the higher mean values recorded as compared to recommended industry values recommend for design of wind energy systems. Additional long term offshore wind data collection campaigns would help to confirm these findings and determine if these trends are typical for other regions in the Northeast US.

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411 **NOMENCLATURE**
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ABS	American Bureau of Shipping
API	American Petroleum Institute
ASCE	American Society of Civil Engineers
CNR	Carrier-to-Noise Ratio
DOE	US Department of Energy
DTU	Technical University of Denmark
Hub-height	Height of wind turbine rotor center above mean sea-level (m)
H	Reference height above sea-level
Hs	Significant Wave Height (m)
IEC	International Electrotechnical Commission
LiDAR	Light Imaging, Detection, and Ranging Instrument
MASS1	Mesoscale Atmospheric Simulation System
MSL	Mean Sea Level
NEAV	Sew England Aqua Ventus I Project
NED	National Elevation Database
NLCD	National Land Cover Dataset
NREL	National Renewable Energy Laboratory
STD	Standard Deviation

TI	Turbulence Intensity
USGS	United States Geological Survey
α	Wind shear power law exponent
H	Height (m)
u	Wind speed (m/s)
u_r	Reference or measured wind speed (m/s)
u’	Root-mean-square of velocity fluctuation (Standard deviation)
u_x	Wind speed (m/s) at height X (m)
z_r	Reference height (m)
z	Height (m)
z_o	Logarithmic wind shear law roughness parameter (m)

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501 **FIGURE CAPTIONS LIST**
502

Fig. 1 Possible Wind Shear Profiles Offshore

Fig. 2 LiDAR Deployment Test Sites

Fig. 3 View of Land Based LiDAR from North/Northeast Looking South/Southwest over Lobster Cove, Monhegan Island

Fig. 4 View Looking North of the DeepCLiDAR Buoy System

Fig. 5 Reference LiDAR Measured Wind Shear v. 100m Wind Speed Data for All Data

Fig. 6 Reference LiDAR Measured Wind Shear v. 100m Wind Speed Data for Contemporaneous Data Only

Fig. 7 DeepCLiDAR Measured Wind Shear v. 100m Wind Speed With Data

Fig. 8 Measured Land-Based Wind Turbulence Intensity v. 10-minute Mean Wind Speed at 100m

Fig. 9 Measured Land-Based Wind Turbulence Intensity v. 10-minute Mean Wind Speed at 100m Using Concurrent Data

Fig. 10 Measured Offshore Wind Turbulence intensity v. 10-minute Mean Wind Speed at 100m

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505 **TABLE CAPTION LIST**
506

Table 1 Comparison of offshore wind shear design values

Table 2 Summary of data collected and used in this study

Table 3 Campaign average and maximum 1 hour significant and maximum wave heights

Table 4 Summary of wind speed measurements taken by LiDAR systems on land and offshore (contemporaneous data is provided in parentheses for Land-based measurements.)

Table 5 Land-based reference LiDAR measured wind shear exponent α (all data is considered)

Table 6 Land-based reference LiDAR measured wind shear exponent α (only concurrent measurements with offshore LiDAR are considered)

Table 7 DeepCLiDAR measured wind shear exponent α

Table 8 Mesoscale model predicted wind shear exponents

Table 9 Land-based reference LiDAR wind turbulence intensity at 100m using all data

Table 10 Land-based reference LiDAR wind turbulence intensity at 100m using contemporaneous data

Table 11 DeepCLiDAR measured wind turbulence intensity at 100m

Table 12 Costal wave environment and its relation to wind shear exponent and

roughness parameter

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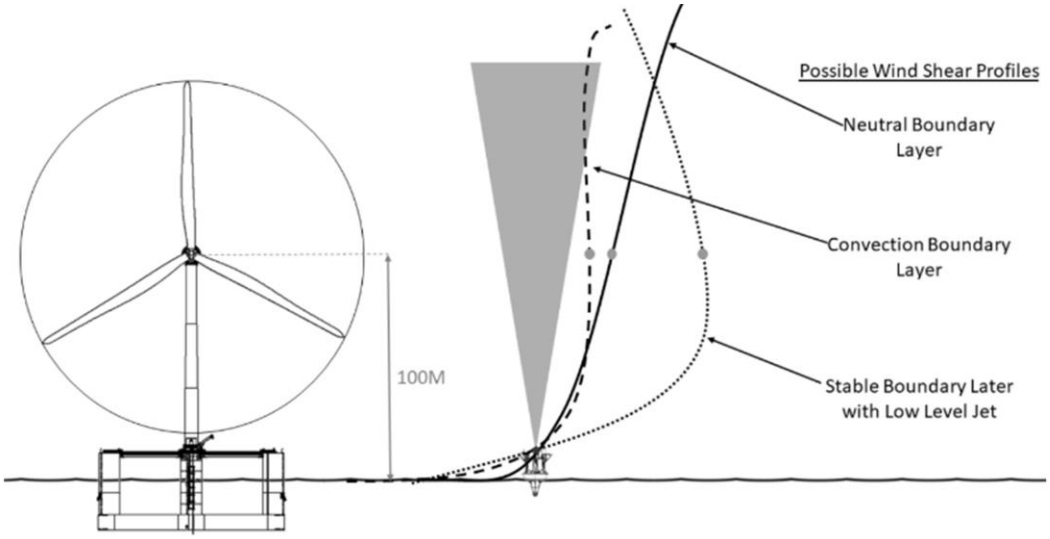

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511 **Figure 1 Possible wind shear profiles offshore**

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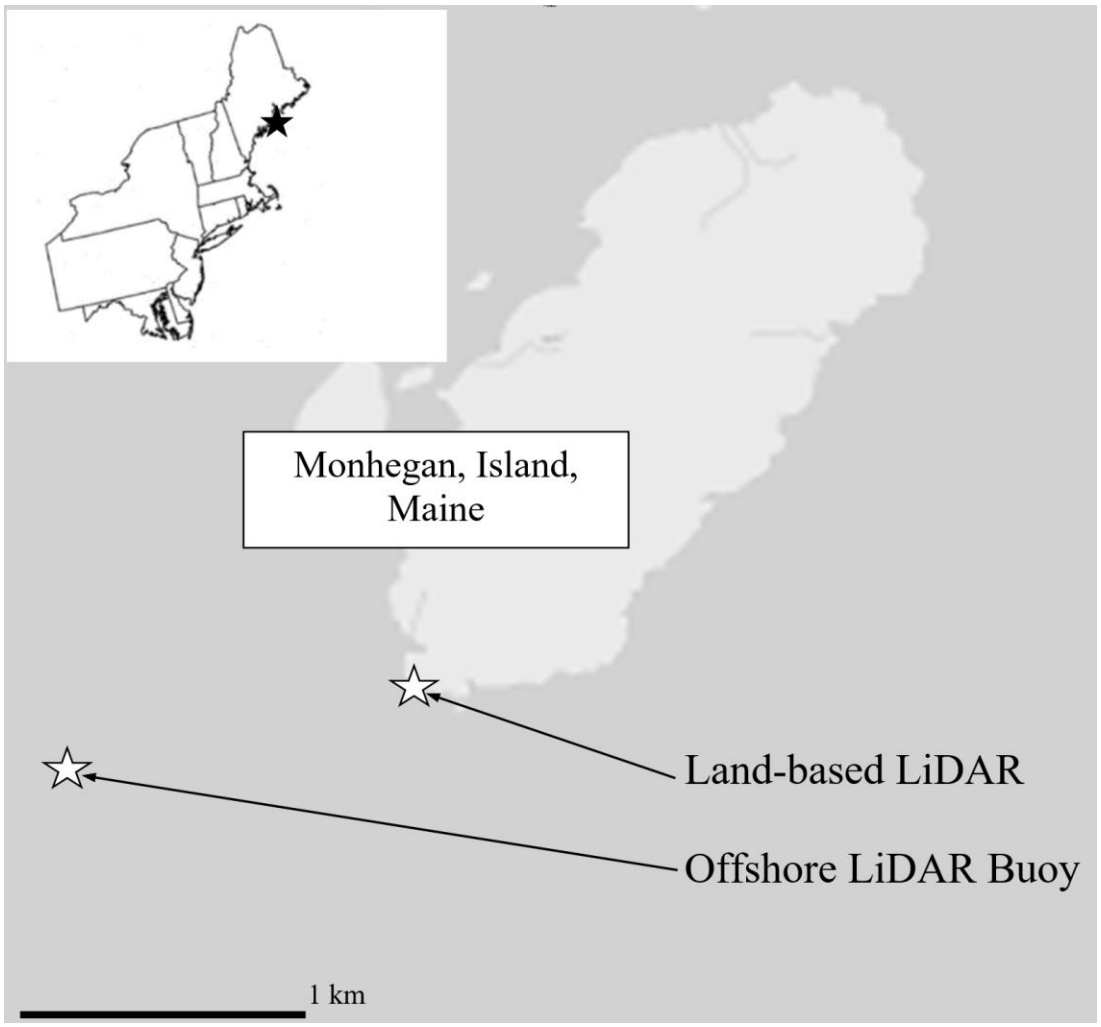

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515 **Figure 2 LiDAR deployment test sites**

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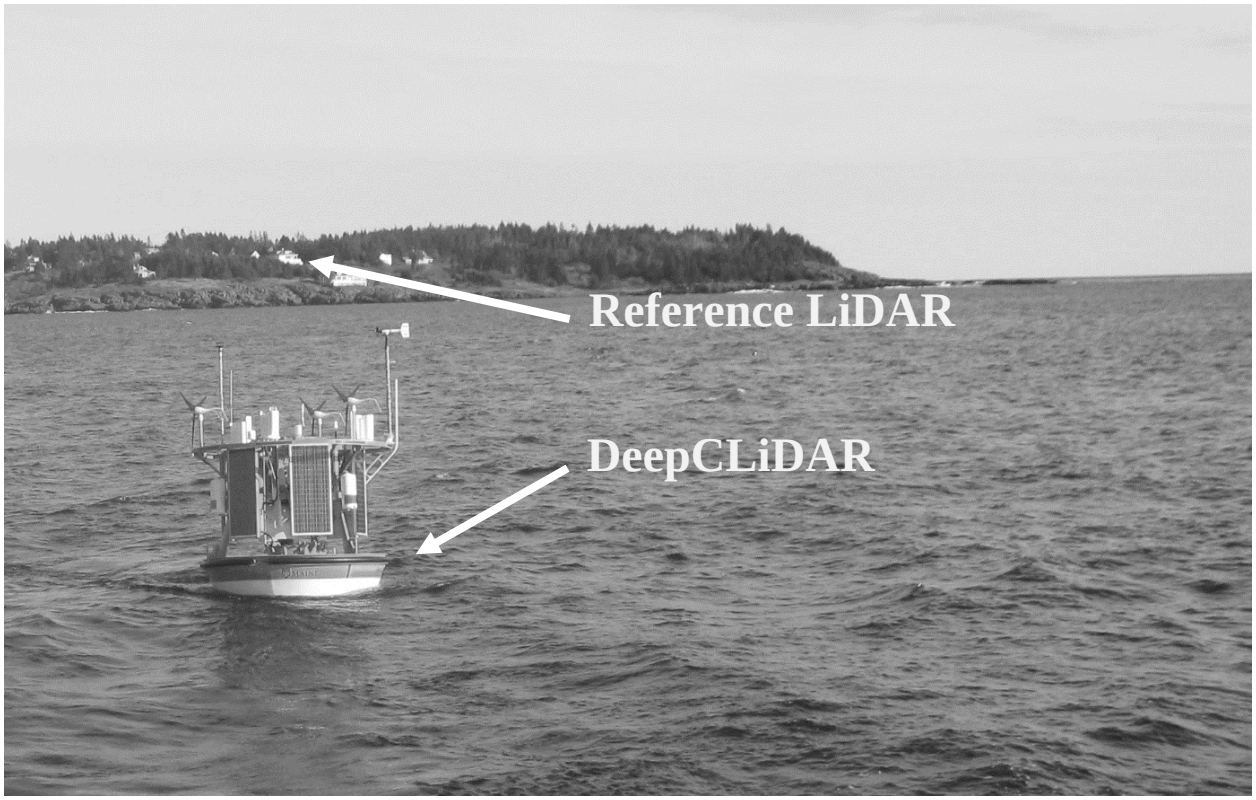
Figure 3 View of land based LiDAR from north/northeast looking south/southwest over Lobster Cove, Monhegan Island



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524 **Figure 4 View looking north of the DeepCLiDAR buoy system**

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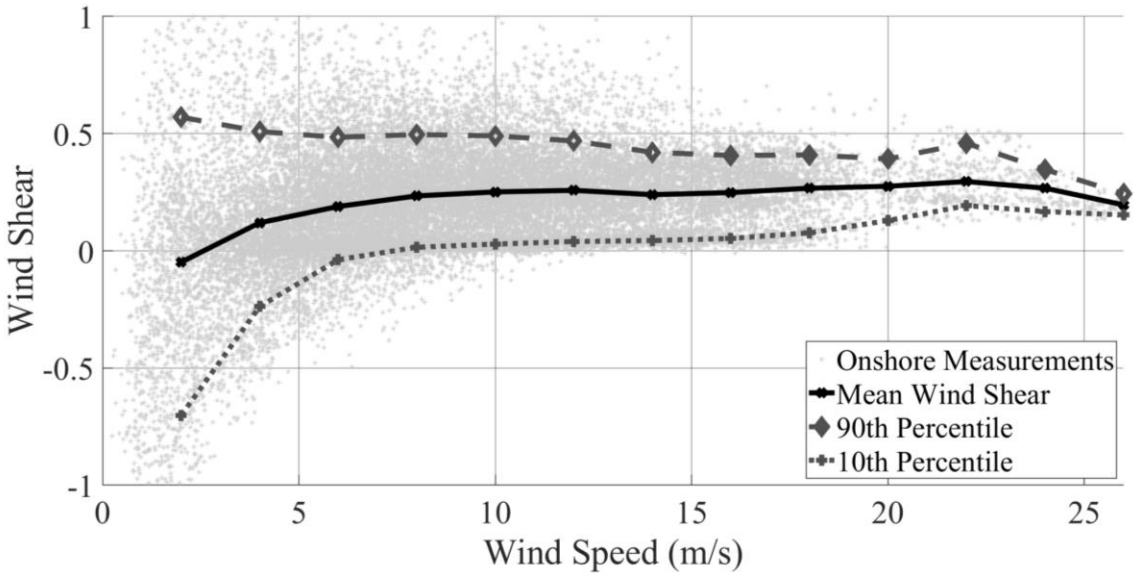

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528 **Figure 5 Reference LiDAR measured wind shear exponent v. 100m wind speed data for**

529 **all data. The mean wind shear exponent for each 2m/s bin and the 10th and 90th**

530 **percentile for each bin are plotted.**

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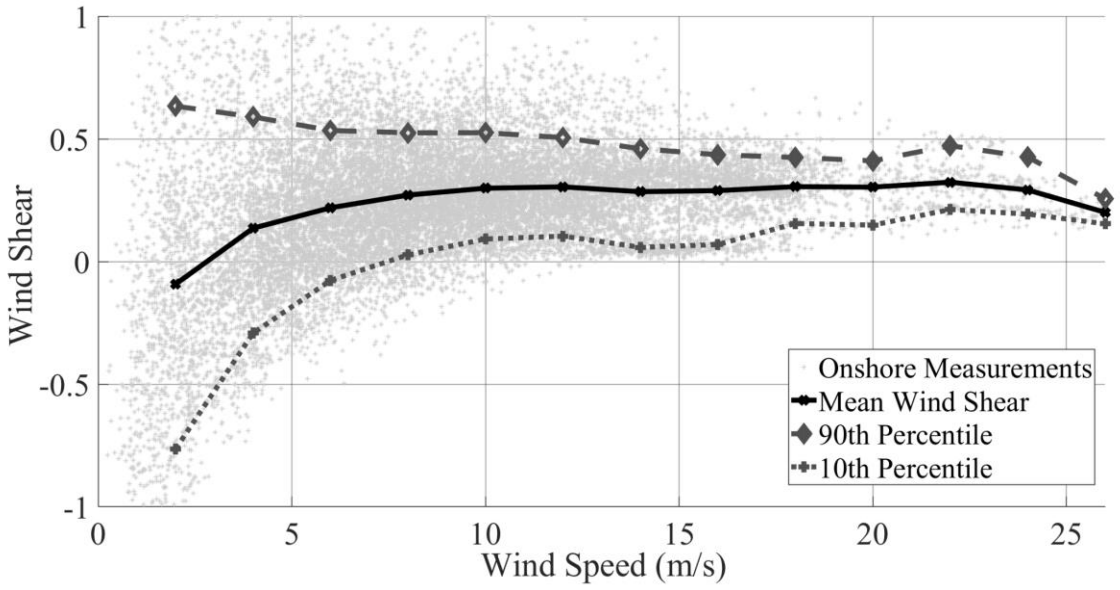

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533 **Figure 6 Reference LiDAR measured wind shear exponent v. 100m wind speed data for**

534 **contemporaneous data only. The mean wind shear exponent for each 2m/s bin and**

535 **the 10th and 90th percentile for each bin are plotted.**

536

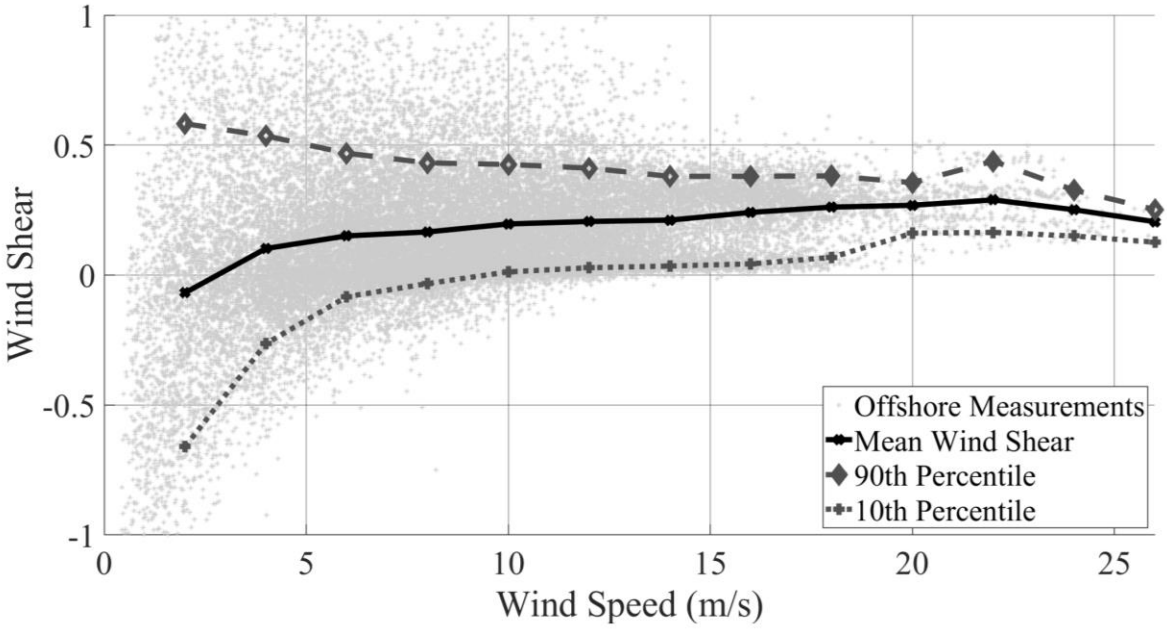
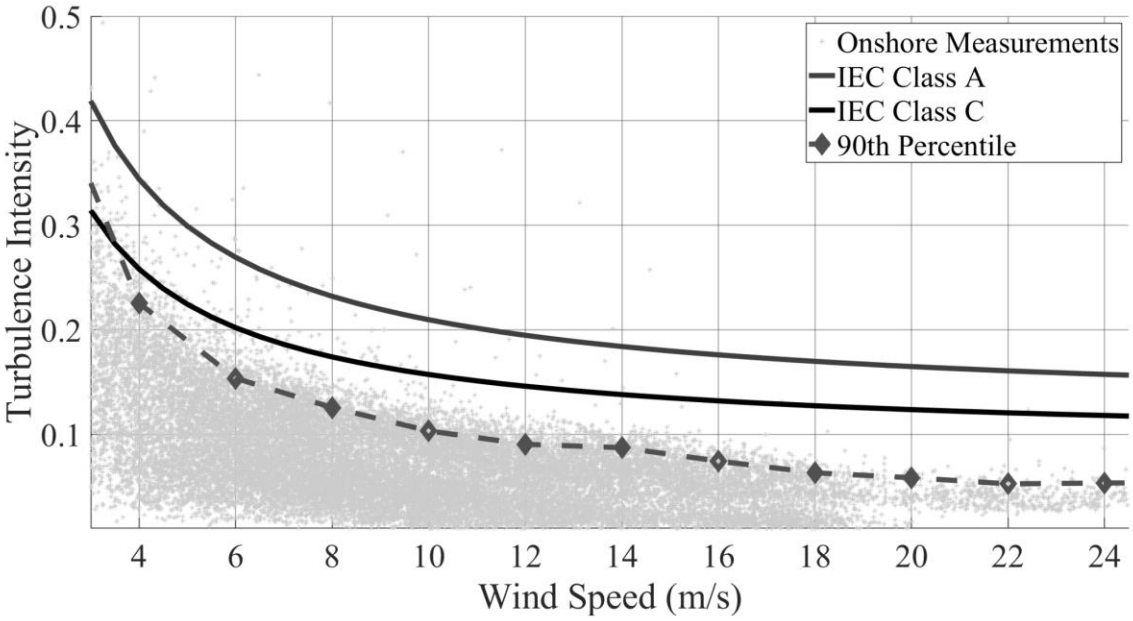


Figure 7 DeepCLiDAR measured wind shear exponent v 100m wind speed with data. The mean wind shear exponent for each 2m/s bin and the 10th and 90th percentile for each bin are plotted.



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547 **Figure 8 Measured Land-Based Wind Turbulence Intensity v. 10-minute Mean Wind**

548 **Speed at 100m**

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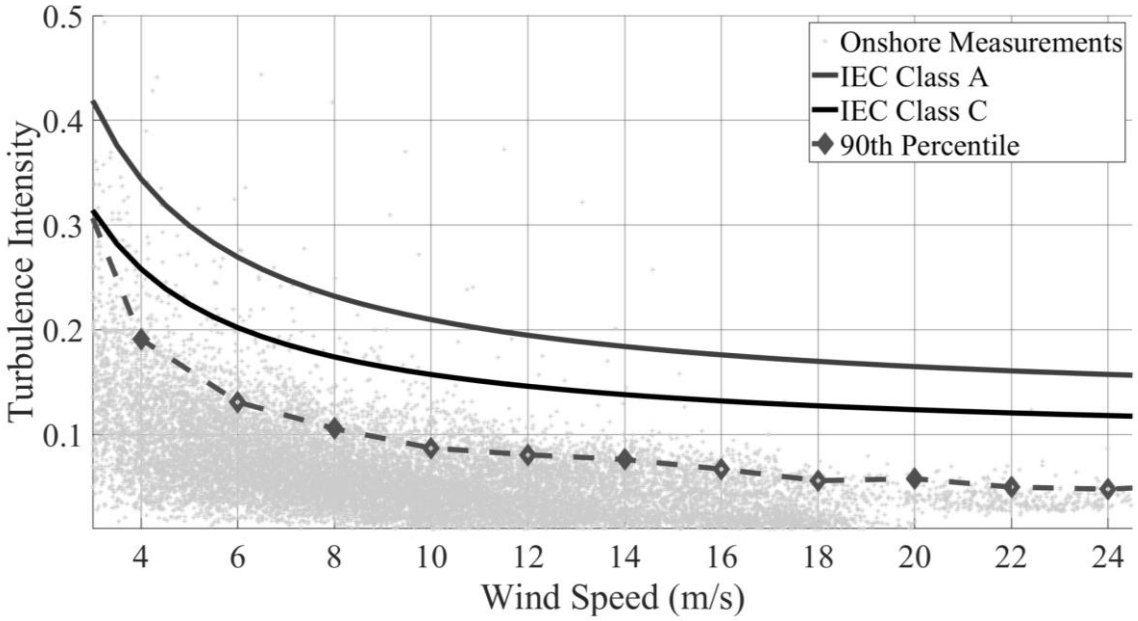
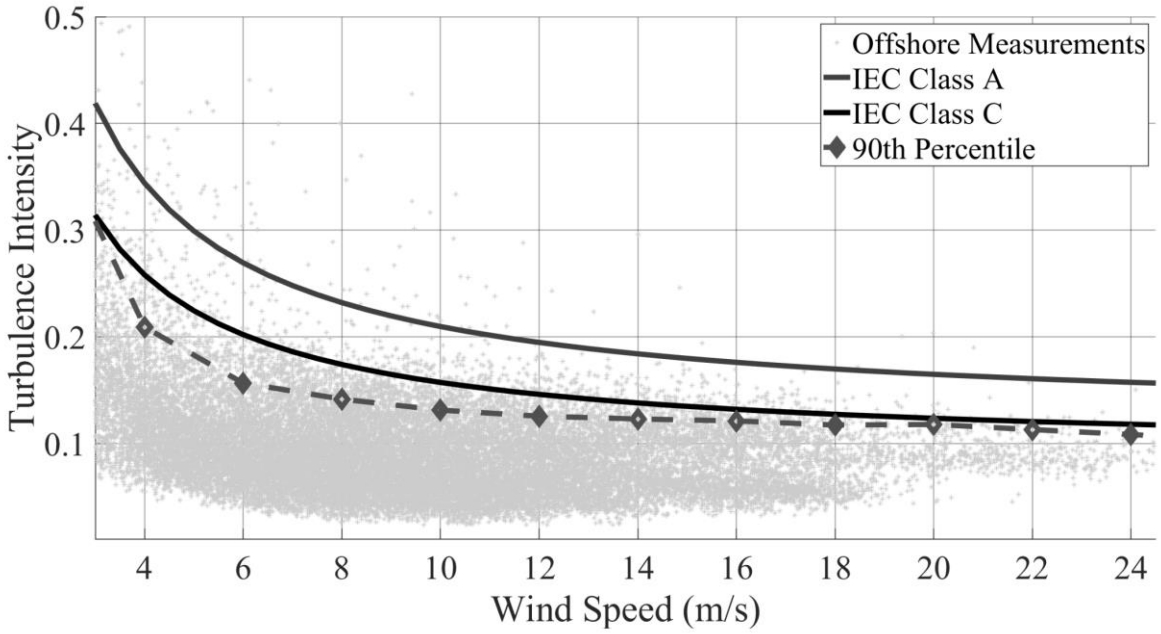


Figure 9 Measured Land-Based Wind Turbulence Intensity v. 10-minute Mean Wind Speed at 100m Using Concurrent Data



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558 **Figure 10 Measured Offshore Wind Turbulence Intensity v. 10-minute Mean Wind**

559 **Speed at 100m**

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561 **Table 1 Comparison of offshore wind shear exponents**

Reference	ABS (operational/ extreme)	IEC 61400-3	DNV- RP-C205	ASCE
Wind Shear Exponent	0.11/0.14	0.20	0.12	0.15

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564 **Table 2 Summary of data collected and used in this study**

Station	Sensor Type	Elevation above MSL	Lat. & Lon. (DD MM)	Date Range	Average Sampling Period
Offshore, UMaine DeepCLiDAR Buoy	Wave	Surface	43° 45′ 22.8”N 69° 20′ 21.0”W	2/19/2016 - 10/28/2016	30-min
	Wind Speed LiDAR	40-200m			10-min
Land-based, Monhegan Island	Wind Speed LiDAR	40-200m	43° 45’ 29.7” N 69° 19’ 19.1” W	3/18/2014 - 7/21/2014	10-min
				11/26/15 - 04/19/2017	
Offshore, Reference Buoy E01	Wave	Surface	43° 42’ 53.4”N 69° 21’ 18.0”W	7/9/2001- 6/29/2017	30-min

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Table 3 Campaign average and maximum 30-min significant and maximum wave heights

Measurement	Average (m)	Maximum (m)	Average Wave Peak Period (s)
Significant Wave Height	1.04	5.30	9.5
Max Wave Height	1.73	8.94	

572 **Table 4 Summary of wind speed measurements taken by LiDAR systems on land and**
573 **offshore (contemporaneous data is provided in parentheses for the land-based**
574 **measurements.)**
575

Measurement	Land-based LiDAR		Offshore DeepCLiDAR	
	Mean (m/s)	Std (m/s)	Mean (m/s)	Std (m/s)
40m Wind Speed: All Data	7.73 (7.28)	3.62 (3.68)	7.64	3.86
40m Wind Speed: Availability >90%	7.58 (7.35)	3.65 (3.63)	7.68	3.85
100m Wind Speed: All Data	8.96 (9.11)	4.40 (4.78)	9.21	4.62
100m Wind Speed: Availability >90%	9.00 (9.24)	4.52 (4.76)	9.35	4.82

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578 **Table 5 Land-based reference LiDAR measured wind shear exponent α (all data is**

579 **considered)**

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Wind Speed Bins (m/s)	Mean	Standard Deviation	10th Percentile	90th Percentile	Number of Data Points
1-3	-0.05	0.52	-0.70	0.57	1,722
3-5	0.12	0.33	-0.24	0.51	2,814
5-7	0.19	0.22	-0.04	0.48	3,875
7-9	0.23	0.20	0.02	0.50	3,909
9-11	0.25	0.18	0.03	0.49	3,519
11-13	0.26	0.18	0.04	0.47	2,776
13-15	0.24	0.15	0.04	0.42	2,153
15-17	0.25	0.13	0.05	0.41	1,716
17-19	0.27	0.12	0.08	0.41	913
19-21	0.28	0.11	0.13	0.39	210
21-23	0.30	0.10	0.19	0.46	251
23-25	0.27	0.09	0.17	0.35	136
25-27	0.20	0.04	0.15	0.24	66
All Data	0.20	0.28	-0.03	0.24	24,281

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583 **Table 6 Land-based reference LiDAR measured wind shear exponent α (only**

584 **concurrent measurements with offshore LiDAR are considered.)**

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Wind Speed Bins (m/s)	Mean	Standard Deviation	10th Percentile	90th Percentile	Number of Data Points
1-3	-0.09	0.57	-0.76	0.63	1284
3-5	0.14	0.38	-0.29	0.59	2023
5-7	0.22	0.25	-0.08	0.53	2702
7-9	0.27	0.20	0.03	0.52	2837
9-11	0.30	0.18	0.09	0.53	2585
11-13	0.30	0.17	0.10	0.51	2048
13-15	0.28	0.16	0.06	0.46	1434
15-17	0.29	0.13	0.07	0.44	1126
17-19	0.31	0.10	0.15	0.42	631
19-21	0.30	0.10	0.15	0.41	153
21-23	0.32	0.10	0.21	0.47	189
23-25	0.29	0.09	0.19	0.43	97
25-27	0.20	0.04	0.15	0.26	32
All Data	0.23	0.31	-0.08	0.51	17306

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588 **Table 7 DeepCLiDAR measured wind shear exponent, α**

Wind Speed Bins (m/s)	Mean	Standard Deviation	10th Percentile	90th Percentile	Number of Data Points
1-3	-0.07	0.48	-0.66	0.58	2,120
3-5	0.10	0.35	-0.26	0.53	3,429
5-7	0.15	0.24	-0.08	0.47	4,521
7-9	0.17	0.20	-0.03	0.43	5,036
9-11	0.20	0.18	0.01	0.43	4,450
11-13	0.21	0.16	0.03	0.41	3,460
13-15	0.21	0.14	0.03	0.38	2,167
15-17	0.24	0.12	0.04	0.38	1,700
17-19	0.26	0.11	0.07	0.38	882
19-21	0.27	0.09	0.16	0.36	287
21-23	0.29	0.09	0.16	0.44	207
23-25	0.25	0.08	0.15	0.33	91
25-27	0.21	0.05	0.13	0.25	7
All Data	0.15	0.27	-0.09	0.42	28,628

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591 **Table 8 Mesoscale model predicted wind shear exponents**

	Average Wind Shear Exponent, α		
Month	**Mesoscale Model**	**Reference LiDAR Measurements**	**DeepCLiDAR Measurementsα**
Jan	0.05	0.12	NA
Feb	0.06	0.16	0.13
Mar	0.10	0.22	0.09
Apr	0.14	0.24	0.13
May	0.17	0.26	0.15
Jun	0.18	0.22	0.18
Jul	0.19	0.23	0.19
Aug	0.18	0.25	0.22
Sep	0.16	0.08	0.13
Oct	0.11	0.24	0.13
Nov	0.08	0.17	NA
Dec	0.06	0.12	NA
Yearly Average	**0.12**	**0.20**	**0.15**

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Table 9 Land-based reference LiDAR wind turbulence intensity at 100m using all data

Wind Speed Bins (m/s)	Mean	Standard Deviation	10th Percentile	90th Percentile	Number of Data Points
1-3	0.265	0.136	0.111	0.455	1722
3-5	0.139	0.067	0.057	0.225	2815
5-7	0.098	0.043	0.044	0.154	3878
7-9	0.077	0.036	0.033	0.126	3909
9-11	0.063	0.032	0.023	0.103	3519
11-13	0.056	0.027	0.021	0.090	2776
13-15	0.055	0.026	0.020	0.087	2153
15-17	0.045	0.021	0.017	0.074	1716
17-19	0.037	0.019	0.014	0.063	913
19-21	0.042	0.013	0.025	0.058	210
21-23	0.041	0.011	0.029	0.053	251
23-25	0.041	0.010	0.030	0.053	136
25-27	0.047	0.007	0.041	0.054	66
All Data	0.093	0.085	0.026	0.174	24285

597 **Table 10 Land-based reference LiDAR wind turbulence intensity at 100m using**

598 **contemporaneous data**

Wind Speed Bins (m/s)	Mean	Standard Deviation	10th Percentile	90th Percentile	Number of Data Points
1-3	0.235	0.129	0.098	0.422	1284
3-5	0.117	0.062	0.050	0.191	2024
5-7	0.082	0.039	0.039	0.131	2705
7-9	0.064	0.032	0.029	0.106	2837
9-11	0.052	0.029	0.021	0.087	2585
11-13	0.048	0.025	0.018	0.081	2048
13-15	0.045	0.025	0.018	0.076	1434
15-17	0.037	0.021	0.015	0.067	1126
17-19	0.030	0.017	0.013	0.056	631
19-21	0.039	0.013	0.016	0.058	153
21-23	0.039	0.011	0.029	0.050	189
23-25	0.039	0.009	0.030	0.048	97
25-27	0.045	0.005	0.038	0.052	32
All Data	0.080	0.078	0.022	0.090	17310

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601 **Table 11 DeepCLiDAR measured wind turbulence intensity at 100m**

Wind Speed Bins (m/s)	Mean	Standard Deviation	10th Percentile	90th Percentile	Number of Data Points
1-3	0.252	0.111	0.228	0.408	2127
3-5	0.138	0.063	0.124	0.209	3434
5-7	0.103	0.042	0.095	0.157	4523
7-9	0.091	0.037	0.085	0.142	5036
9-11	0.083	0.036	0.076	0.131	4450
11-13	0.081	0.032	0.076	0.126	3460
13-15	0.083	0.030	0.079	0.123	2167
15-17	0.082	0.028	0.077	0.121	1700
17-19	0.080	0.026	0.079	0.117	882
19-21	0.094	0.021	0.090	0.118	287
21-23	0.091	0.015	0.089	0.113	207
23-25	0.091	0.014	0.090	0.108	91
25-27	0.095	0.007	0.091	0.103	7
All Data	0.110	0.075	0.050	0.176	28642

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604 **Table 12 Coastal wave environment and its relation to wind shear exponent and**

605 **roughness coefficient**

Source	Terrain Type	α Wind Shear Exponent	Z_0 Wind Shear Roughness Coefficient
Land-based LiDAR Measurements	Coastal area with small waves (<1m)	0.20	0.190
	Coastal area with medium waves (1<Hs<3m)	0.19	0.144
	Coastal area with large waves (Hs>3m)	0.20	0.190
	All data	0.20	0.190
Offshore DeepCLiDAR Buoy Measurements	Open sea with small waves (<1m)	0.14	0.023
	Open sea with medium waves (1<Hs<3m)	0.18	0.108
	Open sea with large waves (Hs>3m)	0.19	0.144
	All data	0.15	0.035
DNV RP-C205	Offshore without waves	0.07	0.0001
	Offshore with large waves	0.07	0.010
	Coastal areas with onshore wind (low)	0.11	0.001
	Coastal areas with onshore wind (high)	0.09	0.010
ABS	Offshore- Normal winds	0.14	0.036
	Offshore- Extreme winds	0.11	0.003
API RP 2MET	20m/s wind speed at 10m above sea level	0.08	0.0004
IEC 61400-3	Offshore- Normal winds	0.20	0.190
	Offshore- Extreme winds	0.20	0.190
ASCE-7	Offshore- annual average	0.16	0.054
Viselli et al	Offshore- annual average	0.12	0.120
Mesoscale Model	Annual average	0.12	0.009

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