Offshore Wind Turbines Will Encounter Very Low Atmospheric Turbulence

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Abstract.
Turbulence governs the development and erosion of wind farm wakes, which can deplete the offshore wind resource. Therefore, an accurate understanding of atmospheric turbulence is required to support the rapid growth of offshore wind energy. Using 13 months of lidar observations off the coast of Massachusetts, we find that offshore wind plants at the site will experience very low turbulence, quantified as lidar turbulence intensity, especially in summer, when the wind flows from the open ocean. Moreover, the lowest turbulence regimes are often associated with large wind veer conditions, which can impact the effectiveness of wake steering solutions.

1. Introduction

Offshore wind energy development is expanding, with many offshore wind projects being currently planned in different parts of the world. Offshore wind energy in Northern Europe currently accounts for a capacity of about 15 GW, with a planned increase to about 74 GW by 2030 [1]. In the US, while a single offshore wind farm has been already built [2], several other offshore wind farms will be built along the US Eastern Seaboard in the next few years, with the state of Massachusetts planning to produce about 11% of its overall electricity needs from offshore wind by 2027 [3].

The rapid growth of offshore wind energy requires a detailed modeling of the wind resource, which can be depleted by wind turbine and wind farm wakes. Offshore wakes can be particularly long-lived, with extensions greater than 45 km in some cases [4, 5, 6]. Turbulence represents the essential mechanism that controls the development and erosion of wakes, and the accuracy of its representation in numerical weather prediction models is responsible for the majority of the uncertainty in predicted wind speed at hub-height [7, 8]. Moreover, turbulence induce increased loads on the turbines, with possible premature failing [9, 10]. Therefore, a better knowledge of observed offshore turbulence conditions would contribute to the validation of model results, and allow for a better wind farm layout optimization offshore.

Here, we expand the analysis of offshore turbulence kinetic energy and turbulence dissipation rate shown in [11] to study the variability of turbulence intensity offshore using over one year of wind Doppler lidar measurements. We then relate our analysis of turbulence to the observed wind veer, which affects the structure of wind turbine wakes [12, 13], while also being an essential parameter in proposed wake steering solutions [14, 15].

2. Data and Methods

A "MetOcean Initiative" [16] surveyed the atmospheric boundary layer at the Woods Hole Oceanographic Institution's (WHOI) Air-Sea Interaction Tower (ASIT). The ASIT is a cabled, fixed platform located 3 km south of Martha's Vineyard, where water is about 17 m deep. The tower is in the vicinity of the Rhode Island and Massachusetts Wind Energy Areas (Figure 1), the largest region in the US where offshore wind energy projects are currently being planned.

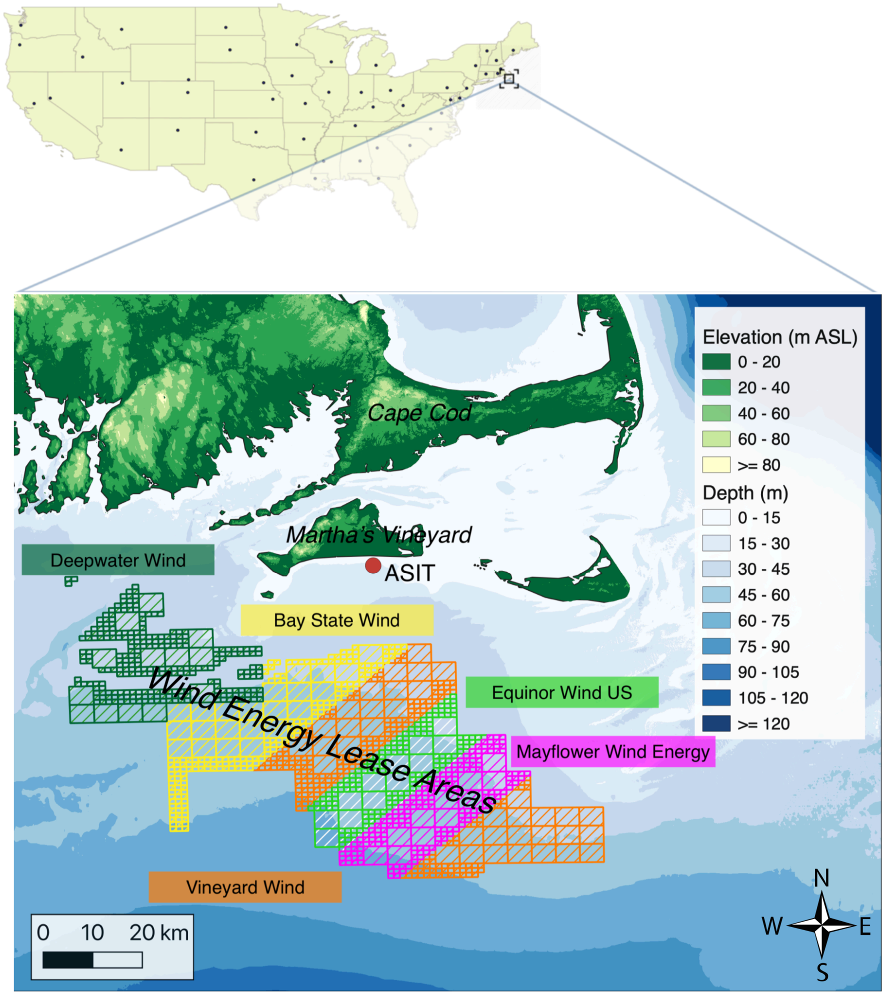

Figure 1. Map of the area where the MetOcean Initiative analyzed in this study took place. The WINDCUBE lidar was deployed on the Air-Sea Interaction Tower (ASIT).

A WINDCUBE version 2 (v2) lidar was deployed on the ASIT platform. This profiling lidar measures line-of-sight velocity along the 4 cardinal directions, with an additional line-of-sight velocity measurement along the vertical, with approximately 5 s required to complete a full measurement cycle. The lidar took measurements at 10 heights: 53, 60, 80, 90, 100, 120, 140, 160, 180, and 200 meters above sea level. Here, we analyze the first 13 months of observations, from 7 October 2016 through 29 October 2017. Data during precipitation periods were excluded from the analysis.

We quantify atmospheric turbulence at the site by calculating 2-min average turbulence intensity (TI) from the lidar observations as

$$TI = \frac{\sqrt{\sigma_u^2 + \sigma_v^2}}{U} \tag{1}$$

where σ_u^2 is the variance of the flow u-component, σ_v^2 the variance of the v-component, and U the mean horizontal wind speed. We acknowledge that the capability of lidars to fully resolve wind variances is subject of ongoing research [17], because of their limited temporal frequency and spatial averaging. However, since no sonic anemometers at the heights of interest were available, we calculate TI using lidar data, and will refer to it as lidar TI [18].

To relate offshore turbulence conditions with other atmospheric variables which impact the operations of wind turbines, we determine 2-min average wind veer as the difference in wind direction between 40 m and 200 m ASL, typical vertical limits for the rotor disk of modern offshore wind turbines.

3. Results

3.1. Turbulence intensity

Turbulence intensity at the site shows small average values (< 0.15) throughout the year (Figure 2), with little variability among the sampled heights. Similar to what was found in [11] for turbulence kinetic energy and turbulence dissipation rate, TI reveals a clear annual cycle, with maxima in winter and minima in summer. This pattern in turbulence intensity is determined

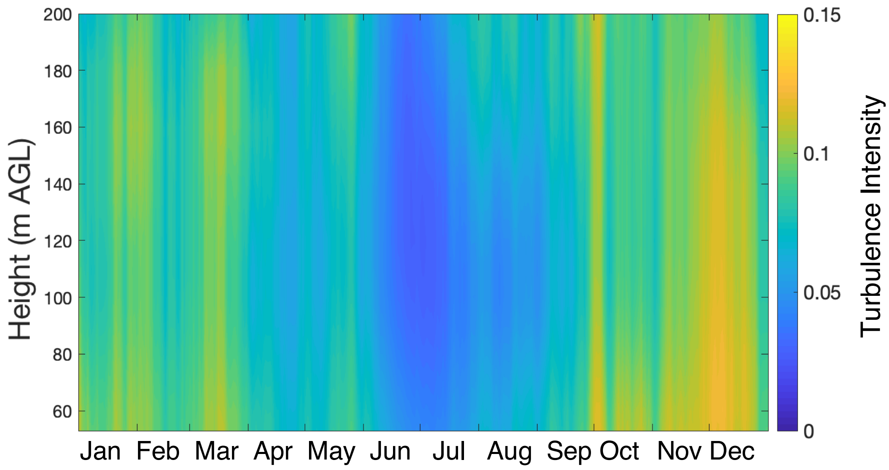

Figure 2. Annual cycle of lidar turbulence intensity as measured by the WHOI ASIT lidar. At each height, data have been smoothed using a 30-day running mean. Data from the overlapping calendar days in October 2016 and 2017 have been averaged.

by different wind regimes at the site. In the winter, the wind mainly flows from the north-northwest, therefore interacting with the land before being measured by the offshore lidar. In addition, northerly winds will generally be colder than the surface water, thus leading to locally unstable conditions. On the other hand, in summer, the wind is mostly from the southwest, where the lower friction surface of the open ocean causes a lower turbulence regime. Also, this southerly flow will be on average warmer than the surface water, causing stable conditions, typically associated with lower turbulence regimes.

The impact of the annual variability of TI can also be considered in terms of its average diurnal cycles in different seasons. Figure 3 shows the average diurnal cycle of lidar TI in winter

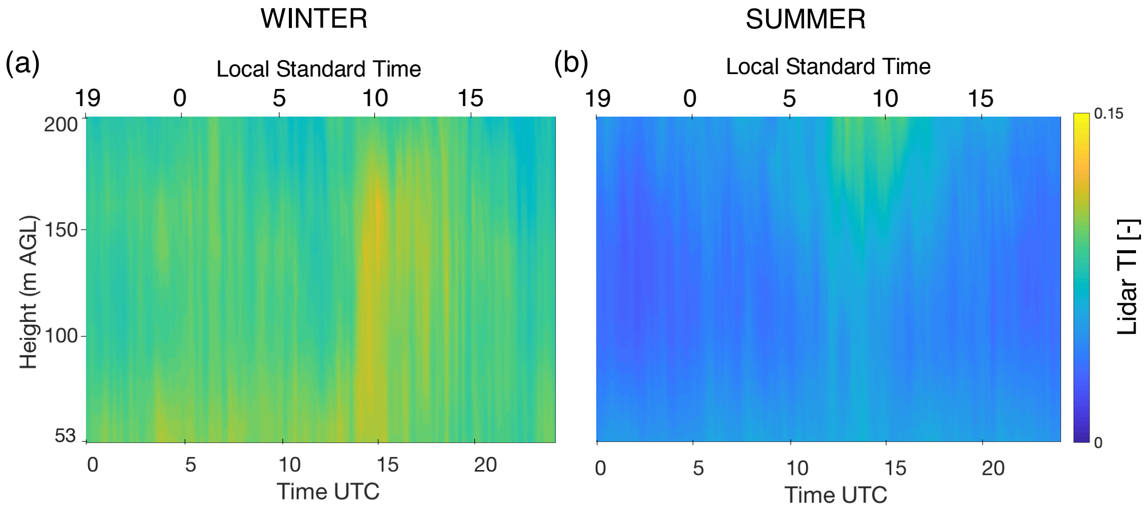

Figure 3. Average diurnal cycle of lidar turbulence intensity for December, January, and February (panel a) and June, July, and August (panel b) as measured by the WHOI ASIT lidar.

and summer. The cycles of TI resemble those of TKE and TKE dissipation rate in [11]. The contrast between low turbulence in summer and a relatively larger TI in winter clearly emerges, with little dependency of the results with height. Subtle diurnal cycles are found, with a slightly larger variability in the summer (as found for wind speed in [11]), when TI is largest in the morning.

3.2. Wind veer

An annual cycle is also present in wind veer, which can greatly impact the structure of wind turbine wakes [12, 19, 13]. Figure 4 shows the annual cycle of 2-min average wind veer between 40 and 200 m ASL, in terms of monthly mean values. Wind veer shows maxima in the spring

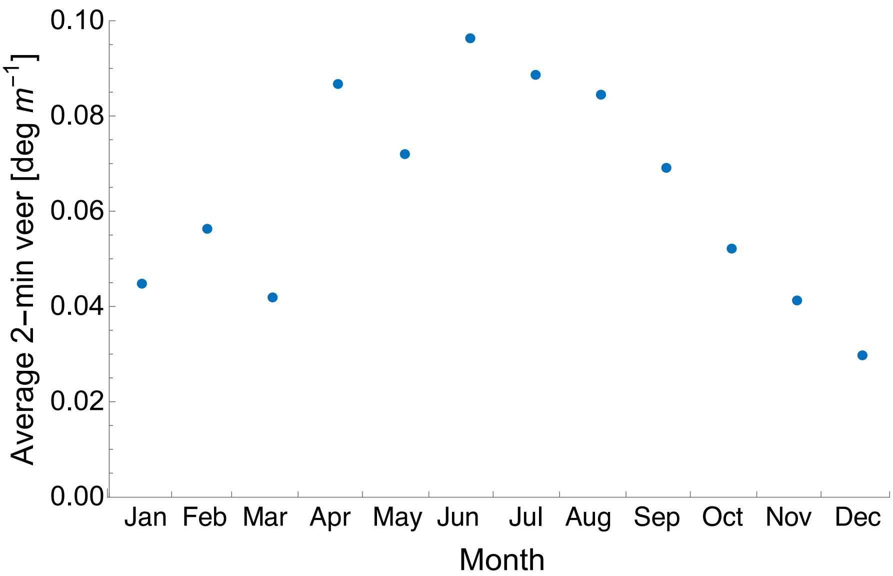

Figure 4. Mean 2-min wind veer between 40 and 200 m ASL for each calendar month.

and summer, with average values of $\sim 0.1^\circ$ m^{-1}, which would determine a $\sim 16^\circ$ change in wind direction for turbines with a 160-m wide rotor disk. In winter, veer is less than half of what found in summer, with average values as low as $\sim 0.03^\circ$ m^{-1} in December.

To further analyze the annual variability of wind veer at the considered location, as well as its relationship with the recorded wind speed, figure 5 shows empirical cumulative functions of 2-min average wind veer, for various wind speed bins, in winter and summer. Extremely large

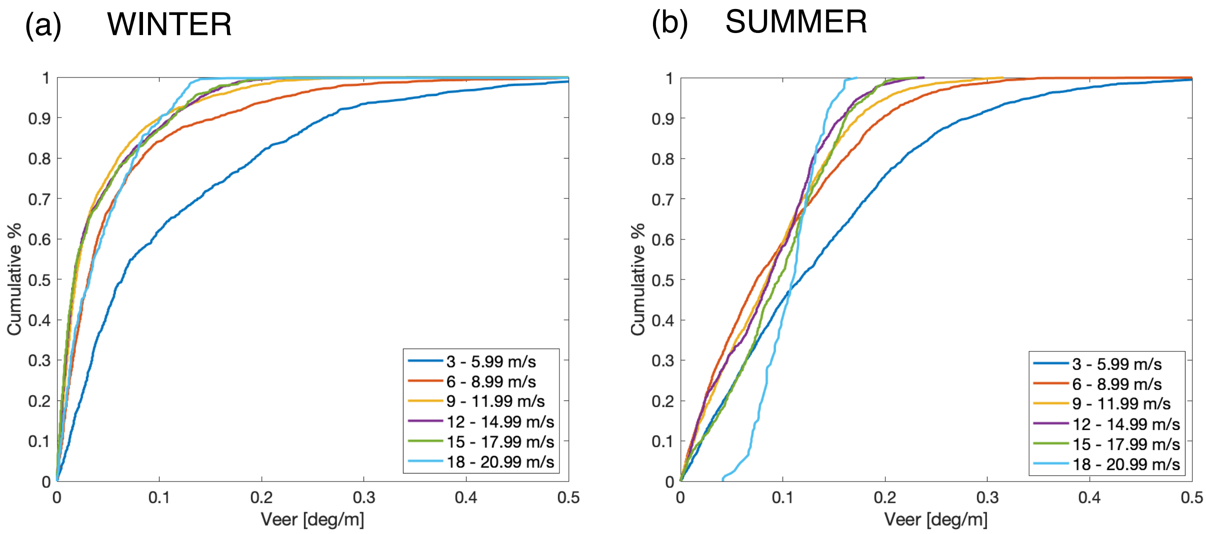

Figure 5. Empirical cumulative functions of 2-min average wind veer between 40 and 200 m ASL, for various wind speed bins, in winter and summer, as measured by the WHOI ASIT lidar.

wind veer ($> 0.3^\circ$ m^{-1}) is reached throughout the year, with larger values for lower wind speeds, when wakes impact wind energy production the most as the turbine-produced power is more sensitive to wind speed. Larger average veer is detected in summer for all the considered wind speeds, with most of the wind speed bins showing, for a given quantile, a summer veer double than what is found in winter.

The weak diurnal cycle found for atmospheric turbulence is also detected in wind veer. Figure 6 shows the daily cycle of 2-min veer, expressed as hourly average values, for different seasons. Wind veer is larger in summer throughout the average day. Although the diurnal variability is limited, especially in winter, a peak in wind veer is found in the early morning in winter, while in summer the maxima are shifted a few hours later.

4. Discussion and Conclusions

Wind plant wakes undermine offshore wind energy production [20], as they can extend tens of km downwind in low-turbulence conditions [4, 5, 6]. To complement the turbulence characterization by [11], we quantified turbulence intensity (TI) from 13 months of observations from a profiling lidar deployed off the coast of Massachusetts, where most of the future U.S. offshore wind energy projects are being planned.

The small values of turbulence intensity reveal how wakes at this location would have an extended persistence, especially in summer, when TI is less than half of what is measured in winter. Summer winds at the site come from the open ocean, while in the winter the wind regime shifts, with dominant colder north-westerly winds that determine increased turbulence due to their upwind interaction with the land. Subtle diurnal variability for TI is found in

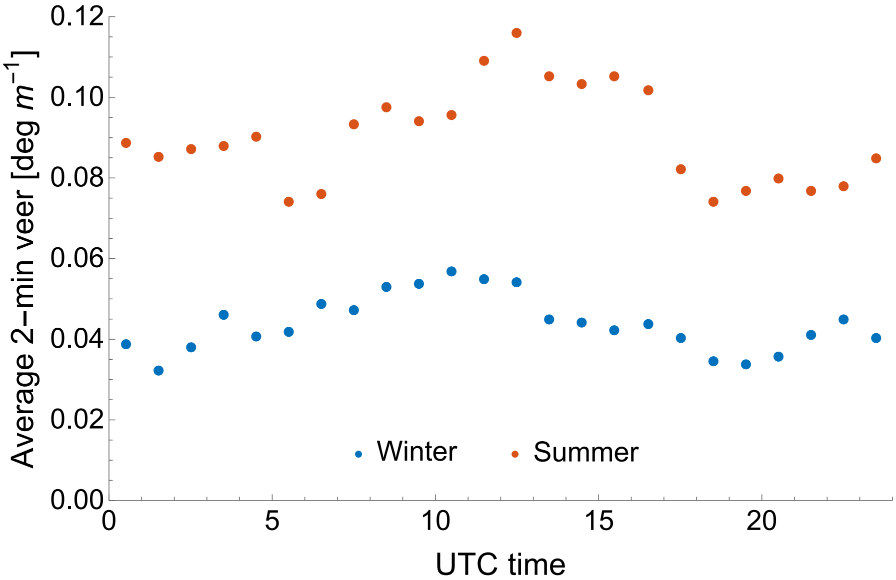

Figure 6. Daily cycle of 2-min wind veer between 40 and 200 m ASL, expressed as hourly average values, in summer (June, July, and August) and winter (December, January, and February).

both seasons. Summertime wakes would also be affected by large wind veer, with values greater than 0.3° m^{-1}. These large veer values can make the implementation of wake steering solutions [14, 15] challenging.

Both the turbulence and veer regimes should be considered when studying optimal layout solutions for the offshore wind farms currently being planned in the US Eastern Seaboard, to minimize wake losses and increase offshore wind energy production.

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