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Characterization of offshore vertical wind shear conditions in Southern New England

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Abstract
Vertical wind shears could have a significant effect on the energy produced by a wind turbine and on its loads. Although the development of several wind farms has been planned on the East Coast of the United States, there are no studies that characterize the vertical wind shear over this area. This study focuses on characterizing wind shears in the marine boundary layer in Southern New England and along the East Coast of the United States. The analysis looks at the statistical distribution of vertical wind shear values and at their associated meteorological conditions. The analysis relies on remote-sensing wind measurements and other meteorological data recorded at the Woods Hole Oceanographic Institution Air–Sea Interaction Tower located 3 km to the South of Martha’s Vineyard, together with buoy measurements and ERA5 reanalysis data. This work shows that large vertical wind shear values (>0.05 m/s/m) calculated using wind measurements at 60 and 53 m were often observed (~25.3% of all the valid wind profiles analyzed) for South-Westerly winds within a range of positive bulk Richardson numbers 0–0.1. These large-shear values are the result of the presence of a strong high-pressure system (Bermuda-Azores High) over the North Atlantic basin and low pressures over land, which result in warm Southerly winds flowing over the cold waters of the Labrador current. The power density computed considering the vertical wind shear by means of the rotor equivalent wind speed is 5.5% smaller than that considering wind speed measurements at 110 m only.

KEYWORDS
atmospheric stability, offshore wind, US east coast, vertical wind shear, wind energy

1 | INTRODUCTION

Most of the offshore wind farms are located, as of 2019, in Northern Europe, where dozens of projects have been developed and constructed in the North, Irish and Baltic Sea. The United Kingdom, Germany, and Denmark host the largest installed offshore wind power capacities.1 There is only one offshore wind farm in operation in the United States: the 30-MW Block Island Wind Farm demonstration project, located in Rhode Island state waters. Yet the US national and federal targets for future installed capacity are ambitious, and about 25 GW are currently under development.2 It is expected that the first large-scale projects will be located in Southern New England, off the coast of Massachusetts and Rhode Island.
As part of project development, site conditions studies need be carried out before designing and constructing an offshore wind farm. They include detailed wind resource and yield assessments, which estimate the long-term net energy production of the park. They also include studies of the combined wind, waves, currents, and water level conditions that are used for designing wind turbines and substructures. Along with the analysis of the wind speed, the study of the turbulence intensity, atmospheric stability, and vertical wind shears plays an important role for the net energy and loads estimation of a wind farm. Atmospheric stability affects the wake recovery of the wind farm, and in the case of turbulence intensity and vertical wind shear, both have an influence on the rotor fatigue loads. Additionally, the vertical wind shear has a significant influence on the energy produced by a wind turbine. Normally, the studies for analysing these variables are based typically on a variety of in situ and remote-sensing wind and metocean measurements, complemented by model data.

Ground-based vertical-profiling lidars are widely used for evaluating wind conditions. They provide accurate and precise measurements of mean wind speed and direction at several heights above the surface (these measurements were included in the second version of the IEC 61400-12-1 standard) and are thereby well suited for the study of wind conditions, as hub heights often exceed 100 m (all heights are here referred to the mean sea level), and rotor diameters are often larger than 150 m. Since October 2016, a vertical-profiling lidar has been measuring at the Woods Hole Institute’s (WHOI) Air–Sea Interaction Tower (ASIT), as part of the Massachussets Clean Energy Center Metocean Data Initiative. It forms, together with other preexisting datasets, an important source of information for site condition studies in the region.12

Much research, engineering and standardization work has enhanced the importance of characterizing in detail wind speed and direction vertical profiles in order to accurately and precisely characterize wind turbine power curves. Previous studies showed that large vertical wind shears occur in New England; however, no comprehensive studies aiming on characterizing the vertical wind shear in this area have been carried out. Archer et al. studied the atmospheric conditions at the Cape Wind meteorological tower, located in the Nantucket Sound (approximately 27 km North-East to the ASIT’s location) and found that unstable conditions prevail in general. Additionally, Pichugina et al. found that low level jet (LLJ) events at the Gulf of Maine (100 km North to the ASIT location) occur with a high frequency. Finally, Bodini et al. studied the turbulence dissipation rate using wind measurements at ASIT and found that low turbulence is expected to be present close to the ASIT. This study aims at investigating the characteristics of the vertical wind shears in Southern New England and in the mid-Atlantic Bight and at comparing their magnitude and frequency with observations at the North Sea. Additionally, this study investigates the synoptic and atmospheric conditions present under the largest vertical wind shear events and the implications of these large vertical wind shears for estimations of the power density. Also, an analysis of the LLJs measured at the ASIT location was carried out. This work uses the ASIT profiling lidar measurements as primarily data source, combined with observations from meteorological buoys and reanalysis data. Together, they provide general and site specific information about microscale and mesoscale and regional weather patterns in these areas. Finally, considerations on the impact of these conditions on energy yield and design work are provided at the end of this study.

Section 2 describes the study area, including the main synoptic conditions and the main ocean currents. The data and methods are described in Section 3. Section 4 shows the results of the analysis of the vertical wind shear values observed at the ASIT, in addition to a description of the synoptic and atmospheric stability conditions that are present when the largest vertical wind shears are observed, and the link between the vertical wind shear and the power density. Finally, conclusions are provided in Section 5.

2 STUDY AREA AND ITS WIND CLIMATE

The ASIT is located about 3 km to the South of Martha’s Vineyard island, Massachusetts. Figure 1 (left) shows the location of the offshore wind lease areas over the Mid-Atlantic Bight, in addition to the location of the ASIT and the buoys that are used in this study. The closest lease area is located 23 km to the South of the ASIT.

In the Mid-Atlantic Bight, the wind climate is driven in part by the Bermuda-Azores high-pressure system, also referred to as the North Atlantic Subtropical anticyclone, or Azores High. During summer, it induces a South-Westerly wind flow along the East coast of the United States. In winter, this pressure system is located closer to Europe, and the wind conditions over New England are being mainly driven by the polar vortex. This is illustrated in Figure 2, where the mean synoptic conditions over the North Atlantic, derived from ERA5 reanalysis data, are provided for July 2017 and January 2018. This seasonal behavior of the wind flow pattern was also confirmed by Archer et al. using wind measurements collected at the Cape Wind Tower located 31.5 km North-East to the ASIT location.

Two main ocean currents are present in Southern New England. First is the Gulf stream, characterized by a northward-going flow of warm surface water. This current flows between Florida and the Bahamas, and then northward along the East coast up to Cape Hatteras (North Carolina), where it changes course towards the North-East. The second current is the cold water Labrador current flowing southward along the North-Eastern coast of Canada. At Grand Banks, off Newfoundland, this current splits into two: a branch of the current goes back North, while the other continues south-westwards along Nova Scotia and down to New England.

Both currents are visible from the mean sea surface temperature (SST) obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua platform, as illustrated in Figure 3 for the months of July and January between 2002 and 2019. The Gulf Stream appears
FIGURE 1 Location of the WHOI Air–Sea Interaction Tower (ASIT), National Data Buoy Center (NDBC) buoys, and offshore wind lease areas (left). Nominal bathymetry contour lines are showed in blue and are labelled in metres. Up-right and bottom-right plots show Martha’s Vineyard island in two larger scales with the elevation represented in colors obtained from the Shuttle Radar Topography Mission (SRTM) [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 2 Mean synoptic conditions during July 2017 (left) and January 2018 (right) from the ERA5 reanalysis dataset: 100-m wind vectors are shown with red arrows, and grey contour lines show isobars (at the surface) in hPa. ASIT, Air–Sea Interaction Tower [Colour figure can be viewed at wileyonlinelibrary.com]
distinctly flowing towards the North-East, with SST values larger than 20°C during both winter and summer months. In addition, there is a clear South-to-North positive SST gradient in the Mid-Atlantic Bight, which is stronger during winter with SST values ranging from 10°C to 25°C.

3 | DATA AND METHODS

ASIT, the primary data source, is described in Section 3.1.1, data from reanalysis ERA5 used for studying the synoptics conditions at the ASIT are detailed in Section 3.1.2, and buoy measurements used to complement the synoptical analysis are described in Section 3.1.3. Finally, wind measurements over the North Sea, used for the comparison of the vertical wind shears observed at that location with those observed at the ASIT, are detailed in Section 3.1.4.

The vertical wind shears observed at ASIT are related to the atmospheric stability conditions; therefore, Section 3.2.1 includes a description of the method used for estimating the atmospheric stability conditions. The methodology for the LLJs identification is described in Section 3.2.2. The power-law and the rotor equivalent wind speed (REWS) are introduced in Sections 3.2.3 and 3.2.4. Finally, the power density is computed using different approaches as explained in Section 3.2.5.

3.1 | Data description

3.1.1 | ASIT dataset

A profiling wind lidar, Leosphere Windcube V2, has been measuring at the ASIT since August 10, 2016. To retrieve wind speed and direction from a profiling lidar, we need to assume flow homogeneity at the different azimuthal directions we measure as described in Peña et al. The campaign is managed by the Massachusetts Clean Energy Center as part of the Meteocean Data Initiative, in collaboration with the WHOI and UL

FIGURE 3   Monthly mean sea surface temperature over the North Atlantic basin during the period 2002–2019 from the Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua Satellite data for the months of July (left) and January (right) [Colour figure can be viewed at wileyonlinelibrary.com]
The wind speed and wind direction, estimated from the lidar measurements, are available at 11 height levels between 53 and 200 m above mean sea level, and the measurements heights are described in Table 1. The Leosphere Windcube V2 is a pulse lidar that uses combinations of five line of sight velocities to estimate the wind speed and wind direction. The backscattered signal along each line of sight is measured at all distances simultaneously and the length of the probe volume at each level is 30 m. Additional meteorological and oceanographic measurements at the ASIT were used in this study and are described in Table 1. All data available correspond to 10-min statistics of the measured parameters, and only the concurrent 10-min periods of lidar, meteorological and oceanographic measurements were used. The period of measurements considered in this study is 2016-12-01 to 2018-09-04. Further details about this dataset can be found in the installation reports provided by the Metocean Data Initiative and in the work preluding to this article. The anemometers and the Windcube V2 were respectively calibrated and validated before deployment at the ASIT.

Due to the proximity of the ASIT to the Martha’s Vineyard island, as illustrated in Figure 1 (bottom-right), the wind and meteorological conditions at this location differ in at least three aspects from most of the offshore wind lease areas. First, during winter, when cold air flows from the North-West, the lidar measurements are not representatives of the far-offshore conditions, as they measure a mix of developing marine boundary layer (close to the surface) and onshore wind conditions (at larger heights). Second, the ASIT is located close to the Muskeget Channel in shallow waters (Figure 1, top right); thereby, the tidal current conditions (and the SST conditions) at this location differ from the ones at the lease areas (see Figure 3). This means that the differences between the air and water temperatures (the main driver of atmospheric stability) obtained from the ASIT measurements might not be the same farther offshore. Lastly, the ASIT is located in shallow waters close to the coast (approx. 2.6 km); therefore, the wave conditions at this location differ from the offshore conditions, in particular during strong wind conditions with breaking waves possibly inducing winds that are characterized by a larger roughness close to shore. The analysis presented in this work focuses on large-shear conditions for South-Westerly summer winds. In these conditions, winds at the ASIT are not disturbed by the Martha’s Vineyard island, but the two other aspects (variations in SST and shallow water) should be kept in mind.

### 3.1.2 ERA5 reanalysis

Synoptic conditions were analyzed using the ERA5 reanalysis dataset. The data used in this study have an horizontal resolution of approximately 31 km, a temporal resolution of 1 h, and cover the period 2017-01-01 to 2018-06-30. The single level products at 10 and 100 m zonal and meridional wind components, mean sea level pressure, air temperature at 2 m, and SST were selected over a domain covering most of the North Atlantic, spanning latitudes 70°N to 0°N and longitudes 88°W to 1°W.

### 3.1.3 Buoy measurements

Buoy measurements from the National Data Buoy Center (NDBC) were downloaded from eight locations along the East Coast (see Figure 1, left). The measurement time series span the same period as for the ERA5 subset described in Section 3.1.2. These data include 8-min averages of wind speed and direction reported hourly, as well as atmospheric pressure, air temperature, sea temperature, and dew point temperature measurements. The NDBC buoys 41002 and 41025 are located in the Gulf Stream warm waters, while the other buoys are located further North in the Mid-Atlantic Bight.

### 3.1.4 Wind measurements in the North Sea

In this study, we compare vertical wind shear statistics observed in the North Sea and at the ASIT. The wind measurements in the North Sea come from a variety of publicly available sources including the London Array and Greater Gabbard met masts, the FINO3 met mast, the

### Table 1 Sensors installed at the Air–Sea Interaction Tower (ASIT) used in the present study (10-min averages)

| Instrument | Variable          | Height [m] |
|------------|-------------------|------------|
| Wind P2546A (cup anemometer) | Wind speed | 26.7 |
| RNRG 200P (wind vane) | Wind direction | 23.5 |
| SeaBird SBE37 | Water temperature | -4.4 |
| Vaisala | Air temperature | 17.6 |
|           | Air pressure |  |
|           | Relative humidity |  |
| Leosphere Windcube (lidar wind profiler) | Wind speed | 53, 60, 80, 90, 100, 110, 120, 140, 160, 180, 200 |
|           | Wind direction |  |
Europlatform lidar, and the IJmuiden met mast.\textsuperscript{33} We only used data before the start of operation of the neighboring farms near these locations. The height of the measurements selected for the wind shear comparison was chosen to be as close as possible to the ASIT lidar measurement heights. The location of all North Sea measurements can be observed in Figure 4.

3.2 | Methods

3.2.1 | Atmospheric stability analysis

Atmospheric stability was assessed at the ASIT via the bulk Richardson number $R_b$. This parameter has been used in many studies for the atmospheric stability characterization at offshore sites.\textsuperscript{34-36} Here, the $R_b$ was computed using the method suggested by Grachev and Fairall,\textsuperscript{37}

$$R_b = \frac{-gz - \Delta \theta + 0.6T \Delta q}{UT^2},$$

where $U$ is here the wind speed at the vertical level $z = 26.7$ m, $T$ is the air temperature at $z = 17.6$ m, $g$ is the gravitational acceleration ($9.8$ m/s\(^2\)), $\Delta \theta$ is the difference in potential temperature between the air and the water (measured respectively at $17.6$ m and $-4.4$ m), and $\Delta q$ is the difference of specific humidity between these two layers. The sign of $R_b$ is thus mainly given by the difference between air and water temperature. When the water is warmer than the air, $R_b$ is negative (unstable surface conditions), and positive values of $R_b$ occur when the water is colder than the air (stable surface conditions).

3.2.2 | LLJ characterization

LLJs are characterized by large vertical wind speed shear in the lower part of the boundary layer and a wind speed maximum between 100 and 500 m.\textsuperscript{38} These events have been studied over land, where nocturnal LLJs are common in stable conditions,\textsuperscript{38,39} and over sea.\textsuperscript{40} According to Emeis,\textsuperscript{41} the mechanism for a LLJ formation is a sudden transition of a flow from unstable to stable atmospheric conditions. The magnitude of the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Location of the North Sea measurements used in this study [Colour figure can be viewed at wileyonlinelibrary.com]}
\end{figure}
vertical wind shear underneath the peak of the LLJ depends on the vertical temperature gradient of the sub-jet layer, and it reaches a maximum when the flow undergoes a large synoptic pressure gradient. The change from unstable to stable conditions experienced by the flow leads to larger wind speeds because the frictional force is reduced. Under these conditions, the surface layer is very shallow, and the wind flow above this layer is mainly under the influence of the pressure-gradient and Coriolis forces.

In the present study, an analysis of LLJs was carried out with the methodology outlined by Baas et al. using the ASIT measurements up to 200 m. In that study, a LLJ is defined when the lowest maximum wind speed is at least 2 m/s and 25% larger than the next minimum above. This methodology classifies a mean wind profile as a LLJ if the mean wind profiles observed in the preceding and consecutive 30-min periods satisfy the criteria for a LLJ as well. In order to consider wind profiles with wind speeds larger than the cut-in wind speed of the current commercial wind turbines, the methodology described by Baas et al. was modified in order to ensure that the lowest wind speed maximum has to be larger than 6 m/s.

### 3.2.3 Power-law and vertical wind shear

The vertical wind speed profile can be described by a power-law for some engineering purposes,

$$U_z = U_H \left( \frac{z}{H} \right)^\alpha,$$

where $U_H$ is the wind speed measured at height $H$, $\alpha$ is the power-law or wind shear exponent, and $U_z$ is the wind speed at height $z$. The relationship between $\alpha$ and the vertical wind shear $dU/dz$ is given by

$$\alpha = \frac{dU}{dz} \frac{H}{U_H}.$$<ref>

### 3.2.4 Rotor equivalent wind speed

The REWS accounts for the vertical variation of the wind speed across a wind turbine rotor. It is defined as

$$\text{REWS} = \left( \sum_{i=1}^{n} (U_i \cos(\phi_i))^3 \frac{A_i}{A} \right)^{\frac{1}{3}},$$

where $A_i$ are horizontal segments of the rotor disk area $A$ and $\phi_i$ is the angle between wind direction and the rotor axis. In this study, the wind veer effect was not considered; therefore, $\phi_i$ was assumed equal to 0.

### 3.2.5 Power density estimation

The power density $E$ can be estimated as

$$E = \frac{1}{2} \rho \frac{1}{N} \sum_{i=1}^{N} U_i^3,$$

where $\rho$ is air density, which is here for simplicity assumed to be constant and equal to 1.225 kg/m$^3$ and $N$ is the number of realizations (number of 10-min mean records). In this study, the power density at the ASIT is estimated using four approaches. The first considers $U = \text{REWS} (E_{\text{REWS}})$. The second uses the wind speed measured at 110 m only ($E_{U_{110}}$). The third is based on the extrapolation of the wind speed measured at 26.7 to 110 m using the power-law ($E_{U_{110}}^\text{PL}$). In this approach, the vertical wind shear exponent is calculated for each 10-min period wind profile measured by the lidar from 53 to 200 m by computing the slope from the fit of a linear regression between log($z$) and log($U$). The fourth approach uses the wind speeds at 10 and 100 m from ERA5 to estimate that at 110 m and then estimate the power density ($E_{\text{ERA5}}$). This vertical extrapolation of wind speed is performed following the latter approach (via a power-law fit). Only timestamp records when valid data from lidar, anemometer, and ERA5 are available are considered for the power density calculation. Since $E_{\text{REWS}}$ considers the variation of wind speed with height, the power density computed using this approach is used as reference.
4  |  ANALYSIS AND RESULTS

4.1  |  Vertical wind shear

For a Windcube, the strength of the signal obtained when collecting measurements within a 10-min period is represented by the parameter ‘availability signal’. Only wind measurements, where the 10-min lidar availability signal was equal to 100% are used; these corresponds to 44% of all measured wind speed profiles, and these measurements are distributed homogeneously during the period of measurements. The distribution of vertical wind shear computed at all adjacent levels is shown in Figure 5 (see the nondimensional wind speed values $du/dz \approx \Delta U/\Delta z$). The distribution of the vertical wind shears computed between 60 and 53 m shows two peaks; the largest at $\approx 0.01$ m/s/m and the second largest at $\approx 0.06$ m/s/m. As the measurement height increases, wind shear values become smaller, as expected for flow over flat and homogenous land. In this study, large vertical wind shears values are defined as being larger than 0.05 m/s/m for levels between 60 and 53 m. This threshold is chosen, since this is the value at which the frequency of the vertical wind shears increases again, although for the other higher levels, frequencies of occurrence decrease at these shear levels. Additionally, vertical wind shears values larger than 0.05 m/s/m correspond to power-law shear exponent values larger than 0.30 for $U = 10$ m/s and $z = 60$ m in Equation (3). As shown in Peña et al,45 based on a number of measurements over the North Sea, power-law shear exponents larger than 0.30 have a rather low frequency.

A comparison between the vertical wind shear distribution at the ASIT and at FINO3 is illustrated in Figure 6, and histograms of the vertical wind shear between ASIT and the other North Sea measurement locations are shown in Figure A1 (Appendix B1). For all cases, the ASIT measurements show a larger occurrence of wind shears larger than 0.05 m/s/m than the wind shears measured at the positions in the North Sea. This is even clearer observed for those cases in which wind measurements closer to the surface are used for the wind shear calculation. For example, when comparing the ASIT and FINO3 datasets, vertical wind shears larger than 0.075 m/s/m are observed at the ASIT between 60 and 53 m more frequently. However, when comparing the ASIT and Ijmuiden mast (MMIJ) data, vertical wind shears larger than 0.075 m/s/m, although present at ASIT, are less frequent; this is because measurements at 110 and 140 m were used and at these levels, the wind does not increase so strongly with height.

**FIGURE 5**  Frequencies of occurrence of vertical wind shear values computed between different contiguous measurement heights at the Air–Sea Interaction Tower (ASIT) [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 6**  Histogram of vertical wind shear values observed at the ASIT and at FINO3. ASIT, Air–Sea Interaction Tower [Colour figure can be viewed at wileyonlinelibrary.com]
At the ASIT, most of the large vertical wind shears were found during spring and summer months, being June the month with the highest frequency of large vertical wind shears. Winter months showed a lower frequency of large wind shears in comparison with summer months.

4.2 Flow and stability conditions

South-Westerly winds are prevailing during the summer months (Figure 7, left), which is consistent with the results showed by Archer et al.\textsuperscript{17} Given our previous findings, this means that large vertical wind shears might appear more often under South-Westerly winds. Winds at the ASIT during winter months flow more homogeneously from all wind directions than during summer with a slightly higher frequency of southerly winds (Figure 7 right).

At the ASIT, most of the large vertical wind shears ($\Delta U/\Delta z > 0.05 \text{ m/s/m}$) computed between 60 and 53 m are observed under South-Westerly winds (summer conditions), as illustrated in Figure 8-top frame. The other populated wind direction (North-East) shows nearly no occurrences of large vertical wind shears. In the bottom panels of Figure 8, stability roses are split into two: on the bottom-left panel, positive $Ri_b$ values, i.e., stable atmospheric conditions, are displayed, whereas negative $Ri_b$ values, i.e., unstable atmospheric conditions, are displayed on the bottom-right panel. As clearly illustrated, South-Westerly winds are mostly observed under stable atmospheric conditions. For north and north-easterly winds, where large vertical wind shears are rare, unstable atmospheric conditions are most common.

We know so far that large vertical wind shears are observed mostly under the summer months and under the predominant South-Westerly winds, which are mostly characterized by a stable atmosphere. However, are large vertical wind shears truly associated with stable atmospheric conditions? To respond this, a histogram of $Ri_b$ values classified into ranges of vertical wind shears is shown in Figure 9. As illustrated, vertical wind shears between 0 and 0.02 m/s/m are the most frequent under unstable atmospheric conditions (negative $Ri_b$ values). Most of the large vertical wind shears appear under stable atmospheric conditions for a specific $Ri_b$ range of values (0.01–0.06). Under the latter specific range, the frequency of occurrence of these large vertical wind shear events is larger than that of any other vertical wind shear range. For $Ri_b > 0.1$, occurrences of large vertical wind shears are as often or less than those under other vertical wind shear ranges.

It might be not that surprising that the large vertical wind shears are mostly observed within a range of positive $Ri_b$ values and do not frequently occur at higher $Ri_b$ values, as under such conditions, winds are generally low. To verify this, the relationship between the observed wind speeds at 53 m and $\Delta \theta$ is illustrated in Figure 10. The large vertical wind shear observations are color-coded according to the $\Delta U/\Delta z$ value computed using lidar wind measurements at 60 and 53 m. The isolines in the figure represent $Ri_b$ values computed for a range of $\Delta \theta$ and $U$ values, assuming, for simplicity of the $\Delta q$ computation, an air pressure of $P = 98$ kPa, a relative humidity of 98 % and $z = 26$ m. In general, the largest observed vertical wind shears appear under stable conditions, particularly for $0.01 < Ri_b < 0.06$. Most of the vertical wind shears within the range 0.05–0.07 m/s/m correspond to $\Delta \theta$ and wind speed values within the ranges 0°–4 °C and 5–10 m/s, respectively. The largest wind shear events ($\Delta U/\Delta z > 0.07 \text{ m/s/m}$) correspond to wind speed values larger than 10 m/s and for all ranges of positive values of $\Delta \theta$ but only few of these cases are above $Ri_b > 0.1$.

![Figure 7](https://example.com/figure7.png) Wind roses at 53 m from wind speed and wind direction measurements at Air–Sea Interaction Tower (ASIT) during summer (left) and winter (right) [Colour figure can be viewed at wileyonlinelibrary.com]
**FIGURE 8** (Top) Vertical wind shear rose computed from measurements at 60 and 53 m. (Bottom-left) Atmospheric stability rose for positive $Ri_b$ values. (Bottom-right) Atmospheric stability rose for negative $Ri_b$ values [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 9** Histogram of $Ri_b$ values for different ranges of vertical wind shears ($\Delta U/\Delta z$) computed from lidar wind measurements at 60 and 53 m [Colour figure can be viewed at wileyonlinelibrary.com]
4.2.1 | Synoptic conditions from ERA5

The mean synoptic conditions for periods corresponding to large vertical wind shear events observed at the ASIT can be observed in Figure 11. In this figure, $\Delta \theta$ (represented in colors) is computed as the mean difference between the air temperature at 2 m and the SST from ERA5; the mean velocity vectors at 100 m (represented with arrows) and the mean sea level pressure (represented as isolines) are also shown. For these events, the mean values of the ERA5 $\Delta \theta$ are in the order of 2.0 $^\circ$C between the North of Cape Hatteras and the Southern part of Nova Scotia. The figure also illustrates that the Bermuda High extends along the whole North Atlantic basin and over the East coast of North America and low pressures are present over the land of the East Coast, which are the prevailing synoptic conditions of summer months as illustrated in Figure 2 (left). Under these conditions, warm air flows over the cold waters of the Mid-Atlantic Bight area, leading to stable atmospheric conditions over the Mid-Atlantic Bight. The ERA5 data are consistent with the results illustrated in Figure 8, where it is shown that large vertical wind shears occur under South-Westerly winds, in which stable atmospheric conditions are predominant.

4.2.2 | ERA5 dataset evaluation at the Mid-Atlantic Bight

Given the qualitatively high agreement between the ASIT findings and the ERA5 data, an exploration of the accuracy of the ERA5 products is sought. The correlation coefficient and root-mean-square error (RMSE) from the comparisons between the SST, air temperature, $\Delta \theta$ and wind speed products from the ERA5 data and the observations at the eight buoys are shown in Table 2. The correlation for all variables is very high, and only the wind speed, as expected, shows lower correlations. The comparison of SST between buoy 41025 and ERA5 is low due to possible problems with the SST measurements.

$R_{ib}$ values computed from the observations of buoys 41002 and 41025 are always negative within the period of study, as they are located within the Gulf Stream area. The frequency of occurrence of positive $R_{ib}$ values gradually increases with the buoy's latitude.

4.2.3 | LLJ events

In total, 126 LLJ events are identified from the ASIT measurements, and they occur slightly more often between 07:00 and 15:00 local time. Most LLJs are observed in May, July, and August, which are also three of the months when most of the large vertical wind shear events are found.
However, during June, the month with the largest number of large vertical wind shear events, almost no LLJs are identified. We speculate that, if present, LLJs during June might occur above 200 m where we do not have observations. It is important to note that 76% of the detected LLJs show a relatively low jet nose, between 80 and 110 m, being the 80-m measurement the level with the largest frequency of the maximum wind speeds of the LLJs identified (39% of all LLJs). Only 15% of the LLJs that we detect are associated with jet noses at levels higher than 110 m.

Most LLJs occurred under similar wind directional and $R_i$ bins as those where the large vertical wind shear events are observed. For 62% of the LLJ events, a large vertical wind shear was observed within ±30 min of the LLJ event, as expected, since regions of large wind shear are found

**TABLE 2** Correlation coefficient ($R^2$) and root-mean-square error (RMSE)

| Buoy   | SST $R^2$ | SST RMSE | Air temperature $R^2$ | Air temperature RMSE | $\Delta \theta R^2$ | $\Delta \theta$ RMSE | Wind speed $R^2$ | Wind speed RMSE |
|--------|-----------|-----------|------------------------|-----------------------|---------------------|----------------------|-------------------|-----------------|
| 44020  | 0.99      | 0.71      | 0.99                   | 0.81                  | 0.92                | 0.97                 | 0.83              | 1.42            |
| 44008  | 0.96      | 0.93      | 0.98                   | 0.81                  | 0.93                | 0.88                 | 0.74              | 1.86            |
| 44025  | 0.99      | 0.51      | 0.99                   | 0.74                  | 0.96                | 0.77                 | 0.84              | 1.38            |
| 44066  | 0.99      | 0.58      | 0.98                   | 0.95                  | 0.94                | 0.98                 | 0.87              | 1.33            |
| 44009  | 0.99      | 0.69      | 0.98                   | 1.03                  | 0.89                | 1.08                 | 0.79              | 1.44            |
| 44014  | 0.97      | 0.98      | 0.99                   | 0.76                  | 0.91                | 1.10                 | 0.81              | 1.46            |
| 41025  | 0.63      | 1.64      | 0.97                   | 1.06                  | 0.82                | 1.87                 | 0.79              | 1.57            |
| 41002  | 0.98      | 0.37      | 0.98                   | 0.62                  | 0.91                | 0.70                 | 0.88              | 1.17            |
below the jet. Pichugina et al.\textsuperscript{18} studied LLJ events during July and August 2004 in the Gulf of Maine, 100 km North of Martha's Vineyard. There, LLJs were present in 63\% of the 15-min wind profiles analyzed. Helmis et al.\textsuperscript{40} studied LLJs during summertime at the Nantucket island, which is located approximately 30 km East to the ASIT location. There, most LLJs were found under South-Westerly winds, in agreement with our analysis.

In this study, large vertical wind shears and LLJ events occur both under similar synoptic conditions. In the study area, the transition of the flow from unstable to stable often occurs concurrently with a strong Bermuda-Azores high and a low pressure over the East coast, leading to a large synoptic pressure gradient. Southerly winds flow first above the Gulf stream, where unstable atmospheric conditions dominate most of the time, and then reach the relatively colder water of the Mid-Atlantic Bight, leading to the occurrence of stable conditions and the frequent occurrence of large vertical wind shears.

4.2.4 Vertical wind shear at different locations in the Mid-Atlantic Bight

The vertical wind shear computed using ERA5 wind speeds between 10 and 100 m was analyzed at the locations shown in Figure 12 (left). The distributions of those vertical wind shears (Figure 12, right) for selected southern locations (P1 to P3) show that large vertical wind shears only occur during approximately 2\% of all records within the considered period. The influence of the Gulf Stream in these three locations is clear by looking at the ERA5 $\Delta $ values in Figure 12 (left). Locations closer to the coast and further north show a steady increase of the occurrences of large vertical wind shears. However, when comparing the ERA5-based vertical wind shear distribution with that from the observations at the ASIT (computed using wind speed measurements at 100 and 26.7 m), it is clear that the ERA5 dataset does not reproduce accurately the distribution and that, although it captures the increasing trend of large vertical wind shear values (e.g., the frequency of occurrence of large vertical wind shear is between 6\% and 8\% for locations P5, P6, P7, and at the ASIT's location), it underestimates their frequency when compared to the ASTI measurements, which show a 20.8\% of large wind shear events.

4.2.5 Impact of the vertical wind shear on the power density estimation

The impact of the vertical wind shear on the power density observed at ASIT is evaluated considering a 164-m wind turbine rotor diameter with a hub height of 110 m. The $\text{REWS} (U_{\text{REWS}})$ was computed using Equation (4) and considering 11 segments over the rotor area to account for all the vertical levels measured by the lidar. The largest difference between the observed wind speed at hub height ($U_{\text{hub}}$) and the $U_{\text{REWS}}$ occur when large vertical wind shears are observed. For 3.9\% of the records, we observe differences between $U_{\text{hub}}$ and $U_{\text{REWS}}$ larger than 0.5 m/s, which coincide with wind shears larger than 0.05 m/s/m; differences larger than 0.5 m/s, which are associated to vertical wind shears lower than 0.05 m/s/m,
are found only 0.8% of the time. This is due to the asymmetry in the wind speed profile under stable atmospheric conditions with shallow surface layers, which are those conditions when most of the large vertical wind shears are found. The REWS is able to represent this asymmetry and a single measurement like that at hub height cannot.

The power density computed using the approaches described in Section 3.2.5 is shown in Table 3. The $E_{\text{Urews}}$ is the smallest compared with $E_{U_{110}}$ and $E_{U_{110}}^U$ (6% and 18% smaller, respectively). The estimate using the ERA5 products, $E_{\text{ERA5}}$, is the smallest value; this is because, in general, the wind speeds from the ERA5 dataset at 110 m are smaller than the concurrent lidar wind speed measurements; the mean wind speeds at 110 m are 10.68 and 11.10 m/s for the ERA5 and lidar datasets, respectively.

### TABLE 3

| Power density computed from four different approaches, as described in Section 3.2.5 |
|-----------------|-----------------|-----------------|-----------------|
| $E_{\text{Urews}}$ | $E_{U_{110}}$ | $E_{U_{110}}^U$ | $E_{\text{ERA5}}$ |
| $E$ [W/m$^2$]    | 1.302.8         | 1.378.5         | 1.529.2         | 1.214.1         |
| $E_{\text{Urews}}/E$ | 1.00            | 1.06            | 1.18            | 0.93            |

5 | CONCLUSIONS

The vertical wind shears obtained using lidar measurements at the ASIT, in the Mid-Atlantic Bight, show frequent large values near the surface (>0.05 m/s/m) when using measurements at 60 and 53 m for their computation. The wind and oceanic conditions of the measurement location are relatively similar to that of the nearby offshore wind farms lease areas, in summer. These large vertical wind shears are more frequent at the ASIT than at a number of locations in the North Sea, where most of the installed offshore wind capacity is currently located. Most of the large vertical wind shears occur under South-Westerly winds and moderately stable atmospheric stability conditions ($0 < R_i < 0.1$). Large vertical wind shears are found more frequently during spring and summer months, June being the month with the highest frequency of large vertical wind shears.

Large vertical wind shears at the ASIT are associated with a strong Bermuda-Azores high and low atmospheric pressures over land near the East coast of the United States. Under these conditions, warm air masses from southern latitudes flow northward along the coast, leading to stable atmosphere conditions in the Mid-Atlantic Bight once they flow over the remains of the Labrador current. The flow experiences a sudden change from unstable (over the Gulf Stream) to stable conditions (observed at the Mid-Atlantic Bight), which favors the formation of LLJs. Since LLJ events are characterized by large vertical wind shears below their nose, one might expect that most of the large vertical wind shear events are associated with LLJs. Although most of the LLJs are found under similar atmospheric conditions as those where the large vertical wind shear events occur, not all the LLJs were associated with large vertical wind shear events. Since most of the LLJs are found at heights between 110 and 80 m, the vertical wind shear estimated from the measurements between 60 and 56 m is not necessarily large.

By using ERA5 reanalysis products, we show a consistent increase of the frequency of occurrence of large vertical wind shears with increasing latitudes over the Mid-Atlantic Bight. However, the distribution of vertical shear values derived using ERA5 products shows a smaller frequency of large vertical wind shears at the ASIT measurement location when compared with the ASIT wind measurements. This highlights the need for using meteorological models of higher resolution (to at least the mesoscale) when performing detailed studies of the wind and metocean conditions in the area. In general, wind speed, SST, and air temperature measurements from buoys located over the Mid-Atlantic Bight show good agreement with the ERA5 products and further highlight the conditions in which large vertical wind shears occur at the ASIT.

The power density computed when using one wind speed measurement at an assumed hub height of 110 m is 6% larger than the power density estimated when considering the vertical wind shear. The vertical wind shear should therefore be accounted when performing annual energy production estimates of future wind farm projects. The vertical wind shear should be derived using wind measurements along the rotor operating levels instead of using the power-law approach for vertical extrapolation of wind speed, since large deviations in power density can be obtained. The largest differences between the 110-m wind speed and the REWS were found when vertical wind shears larger than 0.05 m/s/m are observed.

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APPENDIX A: DISTRIBUTION OF VERTICAL WIND SHEAR VALUES OBSERVED AT THE ASIT AND AT DIFFERENT LOCATION IN THE NORTH SEA

**FIGURE A1** Histograms of vertical wind shear values observed at the ASIT and at different locations in the North Sea: London Array (Top-left), Greater Gabbard (Top-right), EPL (bottom-left) and MMJ (bottom-right) [Colour figure can be viewed at wileyonlinelibrary.com]