Uncertainties in offshore wind turbulence intensity

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Abstract. In the development, design and operation of wind farms the knowledge of wind turbulence intensity is of paramount importance, particularly at hub height. Given that measurements are rare, turbulence intensities are often determined using simplified formulations. These formulations only account for a dependence on wind speed and include a neutral stability assumption. There are, therefore, large uncertainties associated with the results of such formulations. In order to quantify these uncertainties we determine the dependence of turbulence intensity at different heights on the surface wind velocity, wave conditions and vertical temperature gradients from offshore LiDAR wind observations in the North Sea. The turbulence intensity is shown to depend strongly on the atmospheric stability and less strongly on the sea surface roughness. The lower turbulence intensity values are observed under stable atmospheric conditions. The dependence of the turbulence intensity on the surface roughness is higher at the lower levels, with the significant wave height being the sea surface roughness parameters with the stronger correlation with the turbulence intensity.

1. Introduction

One of the important variables for the development, design and operation of wind farms is the Turbulence Intensity at a given vertical level h, which is defined as the ratio between the standard deviation and the mean of the 10-minute wind speed [1]. Given that measurements are rare, turbulence intensities are often determined using simplified formulations. These formulations only account for a dependence on wind speed and include a neutral atmospheric stability assumption. However, the turbulence intensity is expected to depend on the vertical atmospheric stability and offshore to also depend on the surface roughness, see [2]. Atmospheric stability and surface roughness assumptions are also made when transforming wind speed to the height it is available into another height, such as hub height, implying that the accuracy of the applied turbulence intensities is affected twice by these assumptions.

Recent days demand for renewable energy and the expansion of the offshore wind energy use has motivated further research into the dependences of wind speed means and variations [2, 3, 4, 5] and the financing of measurement campaigns to support it. Wind velocities at several height and on varying time scales being currently observed offshore using masts, floating devices and, more recently, remote sensing¹. In order to support the development, design and operation of the planned wind farms in the Dutch waters in the North Sea the Dutch Ministry of Economic Affairs (rvo) has been financing detailed observations of metocean in the planned wind farm zones, see Figure 1. Fugro has taken the lead in these field measurement campaigns and presently there are metocean datasets available from de

¹ https://www.esa.int/Our_Activities/Observing_the_Earth/Aeolus/Aeolus_wows_with_first_wind_data
Borssele, Hollandse Kust (zuid) (HKZ) and Hollandse Kust (noord) (HKN) Farm Zones (https://offshorewind.rvo.nl/windwaterzh). In these field measurement campaigns Fugro has deployed and maintained for a period of up to two years a redundant arrangement of two, referred to as Station A and Station B, SEAWATCH Wind LiDAR (SWL) buoys and associated bottom water level and temperature sensors.

In this study we take advantage of the data compiled by Fugro to study the dependence of the turbulence intensity at sea on the atmospheric stability and the sea surface roughness. In the next section we provide a summary of the relevant instrumentation and variables being observed by the SWL buoys. In Section 3 the data analysis and results are presented, which are further discussed in Section 4. The article ends with some concluding remarks.

Figure 1. Overview of existing and planned Dutch wind farm zones with a zoom in the location of the HKZB station. Credits: EMK2017.

2. Observations
Observations of wind, waves and temperature from SWL buoys deployed by Fugro at Station B in the Hollandse Kust (zuid) (HKZ) Farm Zone, referred to as HKZB, from June 2016 until May 2018 are used in the analyses. The 10 minute data of the following variables are considered:
the Turbulence intensity (TI), defined as the ratio between the standard deviation and the mean of the 10-minute wind speed, at all levels 4, 30, 40, 60, 80, 100, 120, 140, 160, 180 and 200 m;
• the air ($T_{air}$) and the water ($T_{water}$) temperature;
• the (10-min mean) wind speed ($U$) and direction at all levels 4, 30, 40, 60, 80, 100, 120, 140, 160, 180 and 200 m;
• the significant wave height ($H_s$) and
• the peak wave period.

In order to collect these data, the SWL buoys are equipped with a Wavesense 3 directional wave sensor, a motion sensor, a Gill Windsonic M acoustic wind sensor measuring 1Hz winds at 4 m above water level, an air pressure sensor, an air temperature and humidity sensor, a water temperature sensor measuring the temperature 1 m below the sea surface, a current profiler and a ZephIR 300 LiDAR measuring winds at 30 to 200 m above water level, see Figure 2.

![Figure 2. Illustration of the wind and current profile measurements from the SEAWATCH Wind LiDAR Buoy. Heights ref. sea surface.](image-url)
The HKZB data are described and validated in [6], where the quality of the data is shown to be high. However, before proceeding with the analysis of the data, it is relevant to note that The Gill Windsonic is an ultrasonic wind sensor measuring the wind along the two horizontal axes defined by the sensor transmitting and receiving elements. The travel time difference of ultrasound emitted in opposite directions along the two perpendicular axes is used to calculate the wind speed components along those axes. From the components the 1Hz wind speed and direction relative to the instruments x-axis is computed. Then the wind direction relative to magnetic North is calculated using the measurement of buoy heading from the internal compass. The ZephIR LiDAR is a Continuous Wave (CW) LiDAR system. The continuous beam emitted from the window at the top of the LiDAR is slanted at an angle from the vertical and rotates with a period of 1 second around the central axis to continually scan a cone in the air. The return is focused to a particular elevation using an optical focus stage and samples individual line of sight points around the circle. The magnitude of the Doppler shift of the backscattered individual line of sight samples is used to reconstruct the 1 second wind field at a particular elevation. The LiDAR focuses each of the 10 selected elevations in sequence sampling the wind profile. Before going back to another profile, the LiDAR spends some time doing other tasks, such as looking for precipitation, fog and cloud base, and measuring at the reference height of 38 m above the laser. The effective interval between each profile is about 17 s. The profiles collected at 17 s intervals are averaged to give a time series of 10-minute average horizontal and vertical wind. Wind directions are checked in real-time against the data from the Gill wind sensor to resolve the 180 ambiguity in the results due to the ambiguity in the magnitude of the Doppler shift. Validation of LiDAR 10-minute average wind speed and directions against traditional cup anemometers show that the data are reliable [7]. On the other hand, the validation of LiDAR turbulence intensity indicate that the LiDAR values are biased high [7] and lack accuracy [8]. These discrepancies in terms of turbulence intensity are expected given that standard deviations are conventionally based on 1Hz data (not 1/17 Hz data). Although it is important to state this caveat, given that in this study the focus is on data dependences and not on absolute values, we consider the quality of the data enough for the purposes of this study.

3. Analysis and results
The analyses of the HKZB 10-min data from June 2016 until May 2018 are presented next. Given that for low wind speeds there is much scatter in the data and that these data are not relevant, all observations for which the observed wind speeds are below 5 m/s are excluded in the analyses.

We start by presenting an overview of the considered data. Figure 3 shows the observed timeseries of the TI and wind speed at the 30 m, 100m and 200 m levels, the differences between the air and the water temperature and the significant wave height. Figure 3 shows that during the measurement campaign the most extreme wind speeds are above 28 m/s and significant wave heights above 7m. Furthermore, the differences in temperature vary mostly between -5 and 5 degrees and the turbulence intensity is generally lower than 0.2.
**Figure 3.** Timeseries of HKZB turbulence intensity, wind speed, temperature gradient and significant wave height.
Figure 4. Density scatter of the turbulence intensity versus the wind speed at 30 m (top panel), 100 m (middle panel) and 200 m (bottom panel). The full (dashed) magenta line show the mean (5th and 95th percentiles) of the data considering bins of 1 m/s.

Figure 4 shows density scatter between the TI and the wind speed at levels 30, 100 and 200. The figure also shows the evolution with wind speed of the mean value, 5th and 95th percentiles of the TI. As can be seen in the figure, when – as done in practice - using solely the wind speed to determine the turbulence intensity, the uncertainties associated with the estimates can be large.

In order to explain some of the scatter is Figure 4, we have analysed how the dependence of the TI on the wind speed compares with its dependence on the atmospheric stability.

To analyse the dependence of the TI on the wind speed, the data were filtered using as criteria the exceedance of the Beaufort 6, 7 and 8 thresholds, namely 10.8, 13.9 and 17.2 m/s.

To analyse the dependence of the TI on the atmospheric stability, the differences between the observed air and water temperatures were used as a proxy for the atmospheric stability. The data were filtered according to the differences between the observed air and water temperatures

- between -1.5 °C and 1.5 °C,
- of more than 1.5 °C and
- of less than -1.5 °C,

considered to represent neutral, stable and unstable conditions, respectively. An additional temperature induced meteorological feature (or anomalous events [5]) in the North Sea are the low-level jets, in which the wind speed at 100 m is generally higher than above, where it falls off, i.e. there is a higher
wind speed jet around the 100 m level. We have tried to roughly identify such events with a simple algorithm [6].

Figure 5 shows the variation of the turbulence intensity with wind speed and atmospheric stability. The percentages of the data falling in the considered atmospheric stability criteria are printed in the legend of the figure. The wind speed threshold criteria is applied per level and the percentages increase with height, varying between 35% and 52% for the threshold of 10.8 m/s, 12% and 27% for the threshold of 13.9 m/s and 3% and 10% for the threshold of 17.2 m/s.

For a more complete understanding of the considered conditions, Figure 6 shows the corresponding variation of the vertical wind profile (the ratio between the wind speed at a given level and at the lowest level) with wind speed and atmospheric stability and Figure 7 shows the roses of the 100 m wind velocity for the whole period and for the data falling in the considered atmospheric stability criteria, respectively.

The following conclusions ensue from the analysis of the figures:

- The most frequent atmospheric stability conditions are unstable conditions and the less frequent stable conditions, with stable conditions being often associated with on average stronger and more predominant winds from the Southwest (Figure 7).
- Under stable conditions (red line) the TI is the lowest and under unstable conditions (blue line) the TI is the highest, cf. Figure 5.
- Under stable (unstable) conditions the ratio between the wind speed at the highest and at the lowest level is the highest (lowest), cf. Figure 6.
The TI varies more in terms of the atmospheric stability than of the wind speed, in fact the mean TI values for considering a threshold of 10.8 m/s and 17.2 m/s are rather close especially at the higher levels, cf. Figure 5.

In the presence of low level jets the turbulence intensity (relative wind speed) show a large increase (decrease) from the 100 m to the 180 m level.

These results show that it is important to take the atmospheric stability into account when determining the turbulence intensity and the vertical wind profile.

**Figure 6.** Mean observed wind profiles at HKZB under different conditions.
Figure 7. Roses of the 100m wind velocity observed during the whole (top) measurement campaign at HKZB (June 2016 – May 2018) under Coastal Jet (middle left), stable (middle right), unstable (bottom left) and neutral (bottom right) conditions.

The turbulent intensity is expected to also depend on the time-varying sea surface roughness. Three proxies for the sea surface roughness are considered:
- The surface wind speed, $U_4$, i.e. the wind speed observations at 4m;
- The significant wave height, $H_s$, and
- The wave steepness, $s_0$, computed as the ratio between the significant wave height and the squared peak wave period.

Figure 8 shows the variation with height of the correlation between turbulence intensity with the considered sea surface roughness proxies. The figure shows that the stronger correlations are with the significant wave height and as expected decreasing with height. Although low, these correlations indicate that at the lower levels some of the TI variability depends on the sea surface roughness.

![Figure 8](image)

**Figure 8.** Correlation between observed turbulence intensity (TI) and the surface wind speed, significant wave height and wave steepness.

4. **Discussion**

In order to determine how close the measurement campaign period is matching the climatic average and whether the period is characterized by extraordinary conditions we have resorted to the ERA5 dataset (https://confluence.ecmwf.int/display/CKB/What+is+ERA5), the most recent reanalysis dataset from the European Centre for Medium-range Weather Forecasts (ECMWF). The strength of the ECMWF reanalysis datasets is that they come from the combination of one of the leading numerical weather prediction models (the ECMWF model) with an advanced data assimilation system. The ERA5 data are available from 1979 with a spatial resolution of 0.3° x 0.3° and a temporal resolution of 1 hour. Figure 9 shows the roses of the wind velocity from the ERA5 grid point closer to HKZB for the 1979 to 2018 period and for the measurement campaign period (from June 2016 until May 2018).
The figure shows that the wind distribution during the measurement campaign period is comparable to the long-term wind climate distribution, although there was a slightly higher than normal incidence of eastern wind during the campaign period. Furthermore, by comparing the ERA5 10 m wind rose (Figure 9, right panel) for the HKZ measurement campaign period with the observed 100 m wind rose (Figure 7, top panel) one can see that the distribution of the ERA5 data compares rather well with that of the observations, although as expected the ERA5 10 m wind speed are lower than the HKZB 100 m wind speeds.

In these analyses we have used simple proxies for atmospheric stability, namely the temperature gradient instead of the more precise Obukhov length scale [4], low level jets and surface roughness. Nevertheless, the obtained dependences are in line with those in the literature and as expected: stronger vertical wind speed gradients under stable conditions and lower gradients under unstable conditions and lower TI by higher average wind speeds. Furthermore, the obtained percentages of occurrence of low level jets is in line with those obtained by [5].

Lastly, it is important to note that the considered TI values are expected to be biased high and so the given values should be interpreted with care. On the other hand, we consider the given dependences of turbulence intensity of wind speed, atmospheric stability and surface roughness to be correct.

5. Final remarks
Two years of observation at a location on the Dutch North Sea were used to study the dependence of the turbulent intensity on the atmospheric stability and the sea surface roughness. The results show a strong dependence on these variables. Therefore, we recommend that at least atmospheric stability should also be considered when determining turbulence intensities. If not possible due to lack of data, the uncertainties that result from not accounting for these should be considered when determining turbulence intensities using the standard formulations, which only account for a dependence on wind speed and include a neutral stability assumption.

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