~~The impact of low-level~~ Low-level jets' influence on the power ~~generated by~~ conversion efficiency of offshore wind turbines

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Abstract. Low-level jets (LLJ) are local maxima in the vertical wind speed profile. They are frequently observed at heights of approximately 50 m to 500 m above sea level in offshore regions. The influence of ~~low-level jets~~ LLJs on the power ~~production~~ conversion of the energy flux through the rotor swept area and loads of wind turbines has not been researched thoroughly. In this paper we investigate the influence of ~~low-level jets on wind turbine performance~~ LLJs on wind turbines in an offshore wind farm located approximately 15 km from the coast. We derive vertical wind profiles up to heights of 350 m from lidar plan position indicator scans with different elevation angles~~at the wind farm Nordergründe in the German Bight, located approximately 15 from the coast~~. We detect LLJs with a frequency of occurrence between 2.4 % to 22.6 %, based on different definitions used in literature at the observed location. We analyse their influence on the power production of the turbines using operational wind farm data. We observe a negative influence on ~~power production~~ the power conversion efficiency and increased power fluctuations in ~~low-level jet~~ LLJ situations compared to situations with equal wind-veer-corrected rotor equivalent wind speed (REWS) but without LLJs. Further, we conduct aeroelastic simulations for a set of wind profiles with varying veer, shear, turbulence intensity and shape of the LLJ core. ~~Increasing~~ Comparing situations with the same REWS, increasing veer and shear both have a negative impact on the simulated power ~~production~~conversion efficiency, while the shape of ~~a low-level jet~~ an LLJ only slightly alters the energy conversion process~~at the wind turbine for the same REWS~~. Thus, we conclude the main driver for the efficiency-lowering effect during the presence of ~~low-level jets~~ LLJs to be the combination of positive and negative shear, causing a high absolute shear across the rotor area as well as increased absolute veer.

1 Introduction

The massive expansion of offshore wind power requires an accurate assessment of the available wind resources for existing and future offshore wind projects. Industrial practice typically assumes stability-dependent logarithmic or power law wind profiles as inflow (Lopez-Villalobos et al., 2022). Situations with e.g. high shear or veer as well as local wind speed maxima with a subsequent fall-off towards higher altitudes in the vertical profile, so-called low-level jets (LLJ), are ~~are~~ typically not accounted for.

The general phenomenon of LLJ is well known; however, no consensus exists on their definition, detection method and the corresponding site-dependent frequency of occurrence. As occurrences are often ~~observed~~ found in the height band of the rotor, Emeis (2018) assumes the impact of LLJs on wind turbines - especially offshore - to grow with increasing turbine size.

~~Meteorological situations with LLJs are observed to extend to up to 100 in horizontal direction and last up to multiple hours (Schulz-Stellenfleth et al., 2022)~~Different formation mechanisms and types of LLJs have been described in the literature. They occur when one layer of the atmosphere, i.e. the boundary layer, decouples from the friction at the surface and thus experiences an increase in wind speed. This frictional decoupling can be triggered by several processes, e.g. by the sudden change from unstable to stable stratification when crossing the land-sea barrier or in onshore regions during nighttime when the surface temperature decreases due to radiative cooling (Emeis, 2018). Further, LLJs can also emerge during baroclinic situations, as in these cases the ~~thermal-driven winds at the surface~~ thermal wind vector may oppose the direction of the ~~thermal~~ geostrophic wind and thus cause a reverse shear flow (Guest et al., 2018). LLJs are observed to extend to up to 100 km in horizontal direction and last up to multiple hours (Schulz-Stellenfleth et al., 2022). Another type of LLJs are so-called frontal LLJs (FLLJ). This type of LLJ was first reported by Browning and Harrold (1970), describing regions of strong wind speeds travelling ahead of cold fronts. Recently, Baki et al. (2025) showed, that these FLLJs, which are followed by a sudden drop in wind speed and strong change in wind direction, can indicate a subsequent downward ramp in power production of offshore wind farms in the Belgian North Sea.

In the literature, several different definitions for an LLJ are used. Most are based on either the absolute or the relative fall-off of wind speed between the maximum and the minimum above, or a combination of both (e.g. Kalverla et al., 2019; Rubio et al., 2022; Wagn . The different definitions are applied to adjust the detection to the available measurement methodology and height restrictions. Other studies introduce further criteria, such as specific height bands in which LLJs are expected or a particular relation to the ground-level wind speed (e.g. Ranjha et al., 2013). Further definitions rely on detection based on the characteristics of the wind profile below the jet core (Emeis, 2014). Recently, Hallgren et al. (2023) introduced a new definition particularly intended for wind energy applications, which is based on the local shear around the LLJs' core.

Several studies have been carried out to characterise the frequency of occurrence of LLJs as well as their meteorological characteristics using measurement data. Schulz-Stellenfleth et al. (2022) provide an overview of the meteorological characteristics of LLJs and discuss their possible impacts on offshore wind turbines. However, studies show large differences in the occurrence of LLJs depending on the location and the definition of an LLJ event. Onshore, ~~LLJ detections range between~~ LLJs were observed in around 20% of all nights at a near coastal location derived from metmast and wind profiler measurements with a maximum height of 1420 m (Baas et al., 2009)~~and~~. At a different location close to Hannover, Germany, where SODAR measurements up to a maximum height of 800 m were available~~(Emeis, 2014). (Lampert et al., 2016)~~, Emeis (2014) observed LLJs during slightly more than 20 % of all night across different weather patterns. Lampert et al. (2016) found LLJs during 52 % of all days close to Brunswick in Northern Germany using lidar measurements reaching altitudes of 500 m. Offshore, LLJs were observed around 11 % of the time at the east-Frisian island Norderney and 7 % of the time at the far offshore island Heligoland using lidar measurements with maximum measurement altitudes of 500 m (Rausch et al., 2022). Pichugina et al. (2017) even detected LLJs in about 63 % of all measured wind profiles in the Gulf of Maine from a measurement campaign in 2004. In this context, it is important to note that none of the before-mentioned locations lie in proximity to nearby wind farms, whose wake effects could alter the wind profile characteristics. The frequency of occurrence of LLJs in offshore conditions strongly depends on the ~~fetch length~~ current season as well as the ~~current season~~ fetch length and time of the day, with the highest occurrences during wintertime and night (Dörenkämper et al., 2015). Additionally, there are studies based on atmospheric simulations and reanalysis data with a focus on larger areas. Aird et al. (2022) used mesoscale simulations to analyse LLJ characteristics at the east coast of the US and detected LLJs up to a maximum of 12 % of all hours in summer time. Based on ERA-Interim reanalysis data, Ranjha et al. (2013) showed that the occurrence frequency of coastal LLJ events strongly depends on the ~~observed~~ examined location, climatic zone and the current season. This is further backed up by Barekzai et al. (2024), who showed dependencies of LLJ occurrence frequencies on the present season and wind direction. While Kalverla et al. (2019) pointed out, that the climatological characteristics of LLJs are represented quite well within reanalysis data, they also concluded that speed and height of single events are depicted rather poorly, as they appear smeared out due to the limited vertical resolution of the used models. Similarly, Bui et al. (2025) demonstrate that LLJ intensity is often underestimated by reanalysis data, by comparing them to lidar measurements gathered at the FINO1 offshore platform in the German North Sea. Kalverla et al. (2019) further noted, that LLJs should be regarded in the parametrisation of wind profiles to reduce uncertainties in the performance prediction of offshore wind farms.

~~Other studies used numerical methods to evaluate the~~ The impact of LLJs on the performance of offshore wind turbines is investigated by other studies using numerical methods. When analysing the power production and turbine loads, ~~however,~~ it is crucial which reference wind speed and atmospheric stability regime is applied for the comparison between different ~~scenarios.~~ wind profile conditions. This, however, is not consistent in the existing literature, as here hub height wind speeds (e.g. Gadde and Stevens, 2021) or the rotor equivalent wind speed (e.g. Zhang et al., 2019) are not comparable between the different cases examined in the studies. Gadde and Stevens (2021) studied the influence of LLJs on the power output of wind turbines using large-eddy simulations (LES). As the LLJs' core height and atmospheric stratification are controlled via the surface cooling rate, ~~the~~ but the geostrophic wind speed is kept constant, the hub height wind speeds as well as the rotor equivalent wind speeds differ between the different cases. ~~The authors~~ Gadde and Stevens (2021) found a positive influence of the simulated LLJs on the turbines' power production during free inflow, compared to non-LLJ situations, as the entrained energy in the wind is increased due to the LLJs' presence. Further, they observed improved wake recovery for the first five to six turbine rows in a wind farm during a stable boundary layer with LLJ events present, compared to a turbulent neutral boundary layer. For the rows of turbines in the rear part of the wind farm, wake recovery is influenced negatively in stably stratified conditions with LLJs present. ~~Roy et al. (2022) analysed the power production during nocturnal LLJ and non-LLJ conditions without comparing situations with corresponding wind speeds, but showing overall increased wind speeds during LLJ events.~~ On the other hand, Zhang et al. (2019) reported from aeroelastic simulations, that turbines perform worse during LLJ events compared to situations with logarithmic wind profiles with the same hub height wind speed. In a different study, Schepers et al. (2021) derived highly resolved wind fields for aeroelastic simulations from LES simulations driven by mesoscale simulations representative for one year. Subsequently, they investigated the loads ~~,~~ experienced during an exemplary LLJ ~~event~~ with a core approximately at hub height ~~compared to reference loads using reference wind speeds from a one-year-long~~

~~LES simulation~~and four extreme meteorological events for a comparison with the design load cases. Applying simulations with blade-element momentum theory and a free vortex wake model of a 10 MW offshore turbine, the authors observed a decrease in damage equivalent and extreme blade root flapwise bending moments during the presence of the LLJ compared to ~~standard~~ design conditions. They attributed this decrease in experienced loads partly to the lower turbulence intensity observed during LLJs, and partly to the "non-extreme" shear compared to the observed design load cases defined by the International Electrotechnical Commission (IEC). Similarly, Gutierrez et al. (2017) observed decreases in tower and nacelle motions from aeroelastic simulations, when turbines are exposed to negative wind shear above the LLJ core, with increasing benefits, the more of the rotor area is covered by the negative shear profile.

During a two-month-long onshore campaign using Doppler wind lidar data, Weide Luiz and Fiedler (2022) ~~observed~~ showed that nocturnal LLJs shift the mean wind speed at hub height to higher values, compared to nights without LLJs present. ~~In turn, they also increased~~ The authors concluded that LLJs increase the average power production. However, the authors also reported that increased shear across the rotor area negatively impacts the turbines' power production. Further, their study mainly focused on probability distributions and mean values~~. It does not provide~~ , instead of providing a comparison between LLJ and non-LLJ situations with the same hub height wind speeds or the same rotor equivalent wind speeds. Roy et al. (2022) used metmast data and machine learning methods to detect and characterise LLJ events. The authors analysed the power production during nocturnal LLJ and non-LLJ conditions without comparing situations with corresponding wind speeds, but showing overall increased wind speeds during LLJ events. Murphy et al. (2020) report about impacts of high shear and veer events, also present during LLJ events, on wind turbine power production at an onshore location in the North American plains. The authors found a negligible influence of the shear exponent, while a high total directional veer across the rotor area coincides with decreased power production. Also, they showed that during these events, large differences between hub height wind speed and rotor equivalent wind speed (REWS) lead to discrepancies in the observed power production.

~~Although many studies focused on the occurrence of LLJs,~~ In summary, many studies analysed the occurrence and characterisation of LLJs. Also, using numerical studies, the importance of shear and veer and the presence on LLJs on turbine power performance and loads has been assessed. However, experimental insight into the influence of LLJs on the performance of commercially operating offshore wind turbines, including the systematic analysis of operational data of several turbines, concerning the produced power and experienced loads, is largely missing. ~~This is crucial since LLJs need to be regarded in the parametrisation of wind profiles to reduce uncertainties in the performance prediction of wind farms (Kalverla et al., 2019)~~Also, the application of different LLJ definitions makes the comparison of existing studies very difficult. Further, the way LLJ profiles are compared to reference inflow cases is not consistent in the literature. While some studies compare inflow situations with similar hub height wind speeds, others generate LLJs with a similar ratio of the core speed to the geostrophic wind speed by varying the surface cooling rate. Thus, the energy contained within the wind over the rotor swept area is not comparable between LLJ and non-LLJ situations. Therefore, more detailed research on LLJ occurrence and their impact on wind turbines, compared to situations with stability corrected logarithmic wind profiles with equal REWS is necessary for a refined wind resource assessment and understanding of wind turbine operation~~, especially for upcoming large~~ . This is especially important for upcoming turbine generations with even larger rotor diameters.

The objective of this study is to experimentally and numerically assess the impact of LLJs on the power ~~production~~ conversion efficiency of offshore wind turbines. To achieve this goal we derive vertical wind profiles from lidar measurements, estimate the atmospheric stability from local meteorological measurements and analyse the occurrence frequency and characteristics of LLJs at an offshore wind farm~~, using lidar measurements, meteorological data, operational data and aeroelastic simulations.~~

~~In the literature, several different definitionsfor an LLJ are used. Most are based on either the absolute or the relative fall-off of wind speed between the maximum and the minimum above, or a combination of both (e.g. Kalverla et al., 2019; Rubio et al., 2022; Wagn~~ ~~. The different definitions are applied to adjust the detection to the available measurement methodology and height restrictions. Other studies introduce further criteria, such as specific height bands in which LLJs are expected or a particular relation to the ground-level wind speed (e.g. Ranjha et al., 2013). Further definitions rely on detection based on the characteristics of the wind profile below the jet core (Emeis, 2014). Recently, Hallgren et al. (2023) introduced a new definition based on the local shear around the LLJs' core. In the present study, we first compare the different definitions, before focussing on the~~ . Here, we first compare the different definitions, before focussing on the shear-based LLJ ~~definition introduced by Hallgren et al. (2023)~~ definition introduced by Hallgren et al. (2023). Subsequently, the conversion efficiency of the offshore wind turbines is analysed by investigating operational data and comparing situations with and without LLJs with the same rotor equivalent wind speed (REWS), ensuring same energy flux through the rotor area. To further deepen our understanding of the underlying processes we carry out aeroelastical simulations of different LLJ profiles.

This paper consists of five main sections. Following the introduction, Section 2 introduces the applied methodology. Section 3 shows the results of the study, followed by a discussion in Section 4 and a brief conclusion including an outlook for future research in Section 5. Further, the methodology for the atmospheric stability assessment in a near coastal region is elaborated on in Appendix A. Appendix B provides the calculations, on which the uncertainty estimation ~~for~~ of the rotor equivalent wind speed is based on.

2 Methods

This section describes the measurement site and methodology (Sect. 2.1), the processing of the lidar data and wind profile generation (Sect. 2.2), the detection of LLJs (Sect. 2.3) and the process of analysing the influence of LLJs on offshore wind turbine performance (Sect. 2.4).

2.1 Measurement campaign at the offshore wind farm Nordergründe

The lidar data we use for this study are obtained from a measurement campaign at the Nordergründe (NG) wind farm in the German Bight from October 2021 to September 2022. Figure 1a provides the position of the measurement site together with the deployed wind farms in the German North Sea as of time of the measurement campaign. The wind farm is located near the coast with the closest distance to the German mainland being $15\,\mathrm{km}$ in south-westerly direction. The farm features 18 bottom-fixed turbines of the type Senvion 6.2M126 with a rotor diameter $D = 126\,\mathrm{m}$, a hub height $z_{\mathrm{hh}} = 84\,\mathrm{m}$ above mean sea

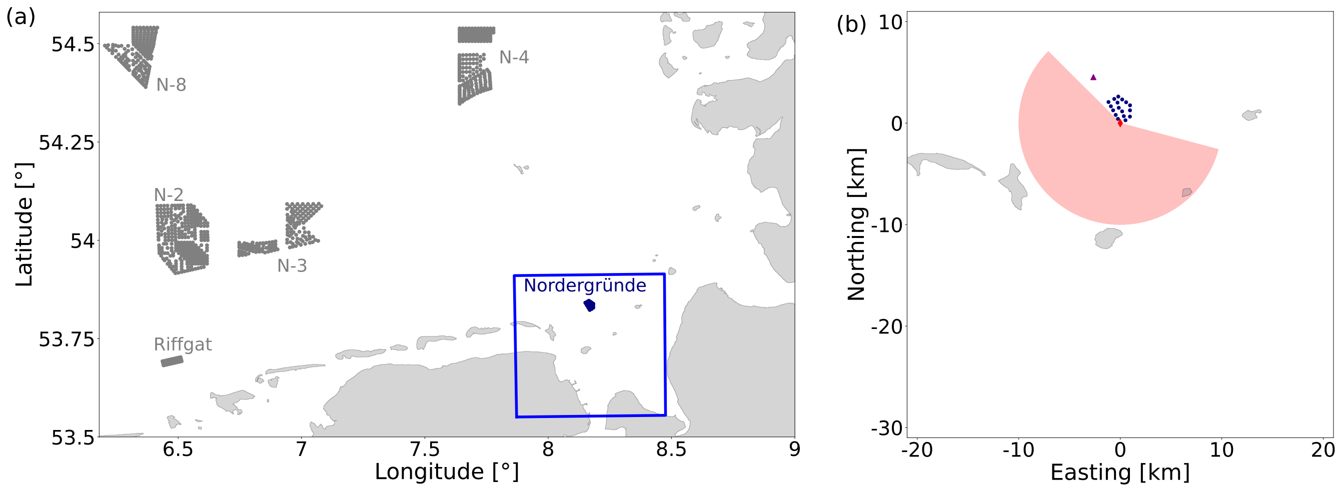

Figure 1. (a) Overview of the German North Sea with operational German offshore wind farms, as of the time of the end of our study (October 2022), depicted in grey. The wind farm Nordergründe where the measurements were conducted, is marked in blue. (b) Layout of NG, also including the nearby coastline ~~, and the~~ (blue square in (a)). The unobstructed lidar scan sector is marked in red. Further, the position of the lighthouse Alte Weser is depicted (purple ▲).

level (MSL), a rated wind speed $v_\mathrm{r} = 14\,\mathrm{ms}^{-1}$ and a rated power $P_\mathrm{r} = 6.15\,\mathrm{MW}$. We use data from ~~a~~ the long-range scanning lidar Vaisala Windcube 400S (serial no. 192), which was installed on the transition piece (TP) of turbine NG17~~. The chosen turbine~~ , roughly $16.5\,\mathrm{m}$ above MSL. The turbine NG17 is located at the south-western corner of the wind farm and thus experiences free inflow for south-easterly to north-westerly wind directions (Fig. 1b).

The lidar at NG17 measures a set of azimuthal scans (plan-position indicator, PPI) with increasing elevations, similar to Goit et al. (2020) and Visich and Conan (2025). The measurement sector is aligned with the prevailing wind direction at lidar height according to Theuer et al. (2024) ~~.~~ and each PPI covers an azimuthal range, i.e. has an opening angle, of 80°. For each azimuthal angle, the lidar is able to process wind speed information at 159 ranges along the beam, also called range gates. At each range gate, the line-of-sight velocity v_LOS and carrier-to-noise ratio (CNR) as a quality measure are stored. One set of PPI scans with increasing elevation takes around $75\,\mathrm{s}$ to finish, including the measurement reset time after each consecutive PPI scan. Table 1 provides more details of the scanning characteristics ~~.~~ and Fig. 2a depicts a vertical slice of the scanning pattern including the rotor swept area and lidar positioning on the TP $16.5\,\mathrm{m}$ above mean sea level. Further, the lidar also was equipped with two inclination sensors (Micro-Epsilon INC5701), which measure the pitch and roll movement of the lidar in a resolution of $2\,\mathrm{Hz}$.

Table 1. Details about the scan settings of the lidar mounted on turbine NG17. Elevation angles and range gates are listed as minimal value : spacing : maximal value.

Lidar height (MSL) [m]	16.5
Visible lidar sector for free inflow at NG17 [°]	105 to 315
PPI opening angle [°]	80
Azimuthal resolution [°]	2
Scanning speed (azimuthal direction) [°/s]	20
Elevation angles [°]	-0.2, 0 : 0.15 : 2.1
Accumulation time [ms]	100
Range gates [m]	300 : 60 : 9780

Meteorological measurements are available at the wind turbine NG17. We use a Vaisala HMP155 sensor to measure air temperature and humidity and a Vaisala PTB330 to measure air pressure. Both sensors are installed near the lidar system at 16.5 m above MSL and provide measurements at a frequency of 1 Hz. To assess the sea-surface temperature (SST) we use a system of two infrared (IR) sensors Heitronics CT09 and CT15, measuring at a resolution of 1 Hz, which apply an internal correction for sky radiation. As this system was only installed in April 2022, we use a water temperature measurement at the lighthouse Alte Weser, providing data in one minute intervals, for the previous period. Further information on the SST and water temperature measurements is found in Appendix A. Table 2 shows the available periods of the different data sources. The meteorological measurements are used to estimate the prevailing stability regime at the measurement location, ~~following Schneemann et al. (2020). For the investigation of the performance of the wind turbines, we use SCADA data of selected turbines in the wind farm during free inflow situations~~via the Obukhov length L following Schneemann et al. (2021). First, the bulk Richardson number

$$Ri_b = \frac{g}{T_\mathrm{v}} \frac{0.5 z_\mathrm{TP} \left(\Theta_\mathrm{TP} - \Theta_0\right)}{u_\mathrm{li}^2} \quad (1)$$

is calculated using the gravitational acceleration g, the virtual temperature at the sea surface T_v, the transition piece height z_TP, the virtual potential temperatures at transition piece height and sea surface Θ_TP and Θ_0, respectively, and the wind speed at transition piece height as measured at the closest range gate of the lidar u_li. Second, the bulk Richardson number is used to compute the dimensionless stability parameter

$$\zeta = \begin{cases} \frac{10 Ri_b}{1 - 5 Ri_b} & Ri_b > 0 \\ 10 Ri_b & Ri_b \leq 0. \end{cases} \quad (2)$$

Finally, we compute the Obukhov length

$$L = \frac{0.5 z_\mathrm{TP}}{\zeta}. \quad (3)$$

Due to our measurements of meteorological parameters at sea surface level and transition piece height, the estimation of L is strictly valid only between these two heights.

Table 2. Overview of used data for atmospheric stability estimates. The data from the Alte Weser lighthouse is publicly available at WSV (2023).

Quantity	Symbol	Location	Sensor	Usage period
Air temperature	T_{air}	TP NG17	HMP155	01/10/2021 - 30/09/2022
Relative humidity	Φ	TP NG17	HMP155	01/10/2021 - 30/09/2022
Air pressure	p_{air}	TP NG17	PTB330	01/10/2021 - 30/09/2022
Wind speed	v_{LOS}	TP NG17	Windcube 400S	01/10/2021 - 30/09/2022
Sea surface temperature	$T_{\text{SST, NG17}}$	NG17	Heitronics CT09/CT15	01/04/2022 - 30/09/2022
Water temperature	$T_{\text{AlteWeser}}$	Alte Weser lighthouse	WTW TetraCon 700 IQ SW	01/10/2021 - 31/03/2022

2.2 Lidar data processing and ~~uncertainty estimation~~wind profile generation

Lidar data processing consists of three main steps. First, we filter the data using a predefined quality flag provided by the lidar manufacturer based on the carrier-to-noise ratio of the measurements as well as a range availability filter. Second, applying the velocity azimuth display (VAD) algorithm the horizontal wind speed is computed from the measured line-of-sight velocities v_{LOS} (Werner, 2005). Here, we assume a spatially homogeneous wind direction across each range gate and a negligible influence of the vertical wind speed component due to the small elevation angles. ~~Thus, the~~ To obtain the wind direction at each range gate, we perform a least-squares fit using a cosine-function to fit the measured v_{LOS}. The phase offset of the obtained fit determines the wind direction for the particular subset of the data. Next, the horizontal wind speed v_{hor} can be computed as

$$v_{\text{hor}}(\theta, r) = \frac{v_{\text{LOS}}}{\cos(\theta - \chi(r))\cos(\alpha)} \tag{4}$$

with the azimuth angle θ, the wind direction $\chi(r)$ at each range r and the elevation angle α.

Third, measurements gathered at azimuth angles approximately perpendicular to the mean wind direction, i.e.

$$75° < |\theta - \chi| < 105° \tag{5}$$

are removed from the analysis, due to the high uncertainty associated with these measurements. Further, we exclude scans recorded from north-easterly wind directions, i.e. between wind directions of 320° and 100° to filter out measurements of the wind farm wake, which could lead to false detections of LLJ events in the further analysis.

For the lidar measurements, several uncertainties regarding the tilt of the lidar due to the turbine movement and the earth's curvature are introduced during the measurement process (Schneemann et al., 2021). First, there are uncertainties regarding the pitch and roll angles of the lidar which dynamically change due to platform movement of the TP, which is mainly caused by the thrust of the wind turbine rotor (Rott et al., 2022). To account for this, we use ~~measurements of motion sensors~~ tilt measurements of inclinometers placed in the lidar and correct the ~~measurement height . This approach is based on a method~~ height of the lidar probe volume. During periods without inclinometer measurements, we use a different method introduced by Rott et al. (2022). ~~It~~). This method estimates the platform tilt without any motion sensor measurements and instead relies on the ~~operational parameters~~ yaw position and power production of the turbine. ~~The procedure is implemented for situations where data gaps are present in the inclinometer measurements.~~ Second, a systematic variation of the measurement height above mean sea level is introduced due to the earth's curvature. We account for this variation by correcting the height of all measurements according to Osterman (2012). Note that variations of the water surface elevations with respect to mean sea level to the tides (tidal range approx. $3\,\mathrm{m}$) or other meteorological conditions are not considered.

To derive vertical wind profiles from lidar data, the computed horizontal wind speeds from the lidar PPI scans with different elevation angles are averaged spatially for different height bands with a vertical resolution of $10\,\mathrm{m}$. Spatial averaging in this case incorporates the complete measurement range of the lidar from 300 m to 9780 m, across the entire azimuth sector of the scan.

Following the generation of the vertical wind profiles, the data from different scans is resampled to 10-minute intervals by averaging the wind speeds and taking the vector average of the wind directions at their respective heights. Further, the wind profiles are slightly smoothed using a rolling average with a window size of $30\,\mathrm{m}$.

2.3 LLJ definition and detection

Figure 2b shows an exemplary depiction of a wind profile containing an LLJ. Here, important nomenclature, such as the core ~~height and core speed~~ speed and core height of the jet, i.e. the maximum wind speed and the height at which it occurs are illustrated. The fall-off for this particular jet is depicted as well. For reference, a logarithmic wind profile with the same ~~wind speed at the LLJ core height~~ REWS is displayed.

We detect LLJs from 10-minute average lidar wind profiles and use different LLJ definitions found in the literature (Table 3). Except for one definition, all use the wind speed fall-off for LLJ characterisation. The definition used by Ranjha et al. (2013) introduces the core height and relation to the wind speed at the lowest available height as further thresholds. In contrast to this, Hallgren et al. (2023) chose to define an LLJ event based on the maximum shear above and below the jet core.

Table 3. Different LLJ definitions applied in this study.

Defined by	Criteria (Conjunctive)
Hallgren et al. (2023)	• Shear above above core height $\leq -0.01\,\mathrm{s}^{-1}$ • Shear below the core $\geq 0.01\,\mathrm{s}^{-1}$
Kalverla et al. (2019)	• Absolute fall-off $\geq 2\,\mathrm{ms}^{-1}$
Ranjha et al. (2013)	• Relative fall-off $\geq 20\,\%$ • Core wind speed at least $20\,\%$ higher than wind speed at lowest available model or measurement height • Core height below $2\,\mathrm{km}$
Rubio et al. (2022)	• Absolute fall-off $\geq 1\,\mathrm{ms}^{-1}$
Wagner et al. (2019)	• Absolute fall-off $\geq 2\,\mathrm{ms}^{-1}$ • Relative fall-off $\geq 25\,\%$

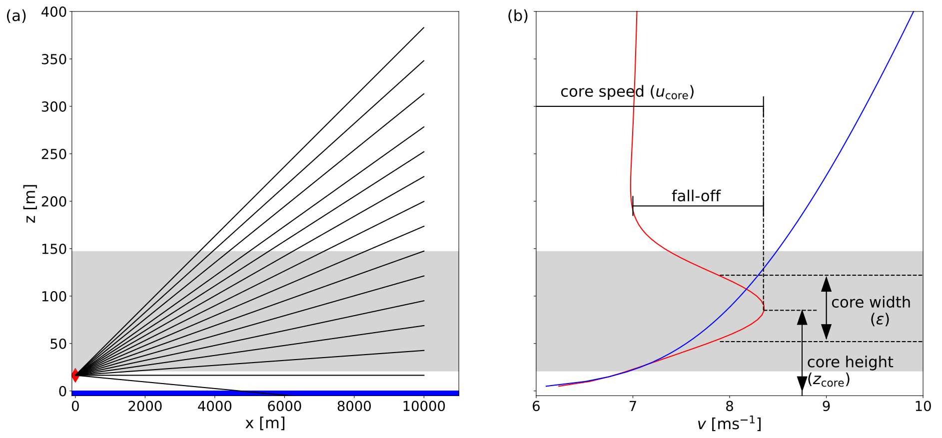

Figure 2. (a) Exemplary scanning pattern for the lidar measurement campaign, with the position of the lidar displayed at the height of the transition piece (red ♦), the lidar beams as black lines and the height range of the rotor swept area marked as a gray background. (b) Exemplary LLJ profile in red, with the important terminology defined. For reference, a logarithmic wind profile with ~~similar wind speed at core height~~ the same REWS of $8\,\mathrm{ms}^{-1}$ is shown in blue.

By applying the described LLJ definitions we systematically analyse the gathered wind profiles for the occurrence of LLJs within the given time frame. ~~For further analysis, we choose the definition introduced by Hallgren et al. (2023), as the authors show that a shear-based definition is more suitable for wind energy applications, because it is less sensitive towards the measurement method and available measurement heights. Further, the authors also show that this definition is less sensitive towards the measurement method and available measurement heights.~~

2.4 Wind turbine performance analysis via an equal REWS framework

To investigate the performance of offshore wind turbines under the influence of LLJs, we calculate wind turbine power curves from lidar based REWS and compare them in LLJ and non-LLJ situations. Therefore, we use operational data of the wind farm Nordergründe~~is used. We chose~~. The data from the Supervisory Control and Data Acquisition (SCADA) system contains various parameters that describe the turbine condition, such as the generated power, the yaw direction, blade pitch and operational status as well as meteorological parameters derived at hub height, i.e. wind speed and direction. We choose turbines in undisturbed inflow for a south-easterly to north-westerly wind direction sector. Subsequently, we filter the SCADA data for the different turbines with respect to the wind directions to only include data featuring undisturbed inflow (Figure 3). For the first row facing in south-westerly direction (green ■ in Fig. 3), the included sector spans from 185° to 315° and for the first row facing in south-easterly direction (magenta ♦ in Fig. 3) the sector spans from 105° to 190°. As NG17 is located at the south-westerly corner it is included in the analysis of both sectors.

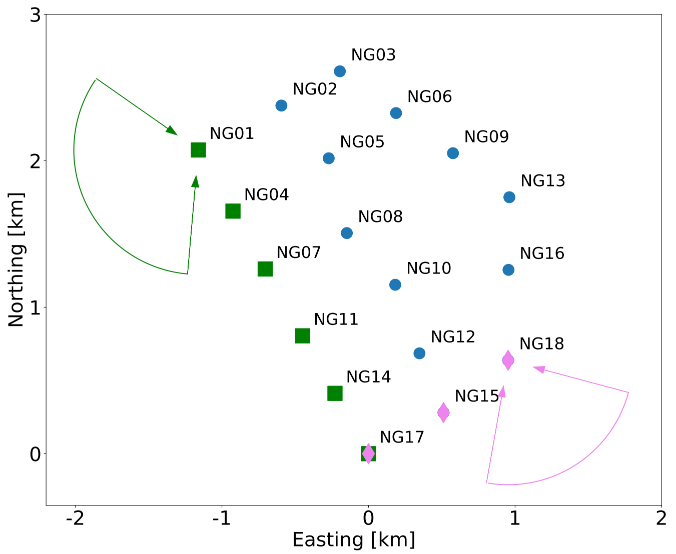

Figure 3. Layout of wind farm NG with turbine names. The turbines selected for further analysis are marked in green and magenta respectively and their corresponding wind direction sectors are specified as arrows with matching colours.

We use SCADA data of the turbines with a resolution of 0.2 Hz. First, we filter the data according to the wind turbine's operational status, such that cut-in, breaking and curtailment situations are not considered. Further, situations where the turbines are not operating at their optimal operating points, e.g. when the yaw angle of the nacelle is misaligned with respect to the wind direction measured by the lidar by more than 45°, are discarded. Subsequently, the operational data is resampled to 10-minute averages. In addition to the mean apparent power μ_P we also quantify the normalised power fluctuations

$$\mathrm{PO_{TI}} = \frac{\sigma_P}{\mu_P} \tag{6}$$

using the standard deviation of the apparent power σ_P normalised by the mean apparent power μ_P (Mittelmeier et al., 2017).

Next, the data is filtered for LLJ situations, where only LLJs with a core height between the upper and lower tip of the rotor are included. ~~Also, we applied a filter neglecting all situations where the hub height wind direction deviates more than 45from the yaw position of the nacelle, to ensure a reasonable alignment of the turbines with the wind direction.~~

Subsequently, the rotor equivalent wind speed (REWS) is calculated from the wind profiles derived in Section 2.2. We use the REWS to estimate the flux of kinetic energy through the rotor-swept area under consideration of wind veer as done in power performance measurements according to IEC 61400-12-1 (IEC, 2017). This is more meaningful than a simple wind speed measurement at hub height when analysing the power output of a wind turbine, as it also considers the wind shear across the swept area. Figure 4 shows exemplary wind speed and direction profiles stressing the importance to include wind veer in the analysis.

~~Next~~To begin with, we perform a density correction of the measured wind speed as done in power performance measurements according to IEC 61400-12-1 (IEC, 2017). To this end, we first compute the air pressure p at different heights z as in

$$p(z) = p_0 \left(1 + \frac{\Gamma}{T_0}(z - z_{\mathrm{TP}})\right)^{-\frac{g}{L\,R_0}} \tag{7}$$

with the air pressure and temperature at TP height p_0 and T_0, the lapse rate $\Gamma = 6.5\,\mathrm{K\,km^{-1}}$, the TP height z_{TP}, the gravitational acceleration $g = 9.81\,\mathrm{ms^{-2}}$, the Obukhov length L and the universal gas constant for dry air $R_0 = 287.05\,\mathrm{J\,kg^{-1}\,K^{-1}}$. Secondly, we extrapolate the measured temperatures to the desired height via

$$T(z) = T_0 - \Gamma(z - z_{\mathrm{TP}}). \tag{8}$$

Third, we compute the density

$$\rho(z) = \frac{1}{T(z)}\left(\frac{p(z)}{R_0} - \Phi(z) P_{\mathrm{W}}\left(\frac{1}{R_0} - \frac{1}{R_{\mathrm{W}}}\right)\right) \tag{9}$$

with the relative humidity $\Phi(z)$, the vapour pressure $P_{\mathrm{W}} = 2.05 \cdot 10^{-5} \exp(0.06312\ T_0)\,\mathrm{Pa}$ and the gas constant of water vapour $R_{\mathrm{W}} = 461\,\mathrm{J\,kg^{-1}\,K^{-1}}$. Finally, the density-corrected wind speed

$$v_{\mathrm{corr}}(z) = v(z)\left(\frac{\rho(z)}{\rho_0}\right)^{1/3} \tag{10}$$

is calculated with the standard air density $\rho_0 = 1.225\,\mathrm{kg\,m^{-3}}$.

Subsequently, we calculate the REWS

$$v_{\mathrm{eq}} = \left(\sum_{i=1}^{n_h} \left(v_{i,\mathrm{corr}} \cdot \cos(\phi_i)\right)^3 \frac{A_i}{A}\right)^{1/3} \tag{11}$$

with the total number of chosen height sections n_h, the density corrected wind speed in the i-th height segment $v_{i,\mathrm{corr}}$, the difference between hub height wind direction and wind direction within the i-th segment ϕ_i, the area of the i-th segment A_i, and the total rotor swept area A. The different segments are spanned around each of the 13 measurement heights of the wind profile within the rotor area. Thus, the REWS is computed from 13 wind speeds and directions across the rotor plane.

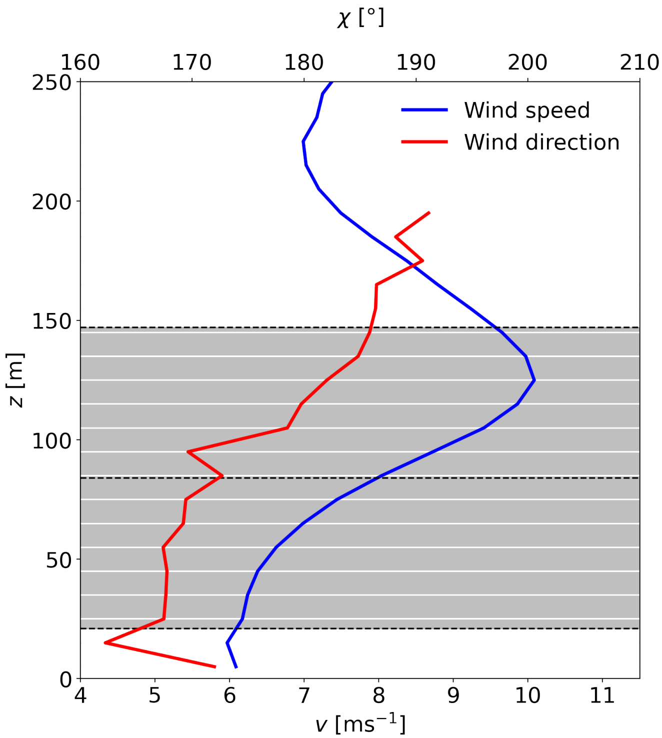

Figure 4. Exemplary measurement of a vertical wind speed profile (blue) and direction profile (red). Additionally, the lower tip, upper tip and hub height of the turbine are represented as dashed lines and the segments used for the determination of the REWS are shaded in grey.

Further, we also computed an uncertainty estimation for the REWS Δv_{eq} at each individual timestamp, which is further elaborated on in Appendix B.

Finally, we generate a power curve following the IEC 61400-12-1 (IEC, 2017), by classifying the data into wind speed bins based on the REWS of $0.5\,\mathrm{ms}^{-1}$ and averaging the apparent power obtained from SCADA within each bin. Here, only bins containing at least 30 minutes (i.e. 3 different 10 minute averaged measurements) of data are considered. We generate an uncertainty interval around this first power curve, by adding and subtracting ~~the determined uncertainties in the REWS~~ Δv_{eq} from the the measured time series and repeating the power curve calculation. While following the IEC 61400-12-1 (IEC, 2017) in most parts~~when generating~~, the power curves ~~, they~~ generated for this study are not fully compatible with the standard. Other criteria, such as e.g. measuring the vertical wind profile two to four rotor diameters in front of the turbine are not met.

2.5 Aeroelastic simulation of LLJ events

To support our experimental analysis we perform aeroelastic simulations with openFAST v3.5.0 to compare the energy conversion process during LLJ and non-LLJ situations (National Renewable Energy Laboratory, 2023). As a basis for these simulations we define 156 different vertical wind profiles, each with different combinations of veer, shear, Obukhov length L and turbulence intensity TI. The different quantities varied for the respective profiles are portrayed in Table 4. We include 12 uniform inflow profiles with varied veer and TI, 36 logarithmic wind profiles with different veer, shear and TI and 108 wind profiles including LLJs with varying veer, TI, core height and ~~vertical extensions.~~ core widths. While a maximum veer across the rotor area ($\Delta\Theta$) of 40° seem large even for stable conditions, these extreme events are present in our own measurements as well as observed in the literature (e.g. Olsen et al., 2025; Murphy et al., 2020).

We compute stability corrected logarithmic wind profiles

$$v_{\log}(z) = \sqrt{\frac{z_0 g}{\alpha_c}} \frac{1}{\kappa} \left(\ln\left(\frac{z}{z_0}\right) - \Psi\left(\frac{z}{L}\right) \right) \tag{12}$$

following Schneemann et al. (2021) with the height z, the gravitational constant $g = 9.81\,\mathrm{ms^{-2}}$, the von Kárman constant $\kappa = 0.4$, the Charnock parameter for offshore environments $\alpha_c = 0.011$ and the stability correction term

$$\Psi = \begin{cases} 2\ln\left(\frac{1+x}{2}\right) + \left(\frac{1+x^2}{2}\right) - 2\arctan(x) + \frac{\pi}{2} & \text{, for } L < 0 \\ -\beta \frac{z}{L} & \text{, for } L \geq 0 \end{cases} \tag{13}$$

where $x = \left(1 - \gamma \frac{z}{L}\right)^{1/4}$, γ = 19.3 and β = 6.

To incorporate LLJs into this definition, we added a Gaussian Bell curve

$$v_{\mathrm{LLJ}}(z) = \mathrm{SF} \cdot \frac{1}{\varepsilon\sqrt{2\pi}} \exp\left(\frac{1}{2} \left(\frac{z - z_{\mathrm{core}}}{\varepsilon} \right)^2 \right) \tag{14}$$

with an empirical scaling factor SF = $200\,\mathrm{m^2s^{-1}}$ to control the strength of the LLJ, the desired core height z_{core} and the ~~vertical extension~~ core width of the LLJ ~~core~~ ε. For all LLJ profiles, we choose ~~an unstable atmospheric stability of~~ unstable atmospheric conditions with L = -100 m, to keep the shear outside of the jet core as low as possible and isolate the effects of the jet core from other shear related effects.

To ensure similar energy flux through the rotor for all different simulations we compute the REWS v_{eq} for every profile and subsequently normalise to a REWS $v_{\mathrm{eq,\,ref}} = 8\,\mathrm{ms^{-1}}$. Thus in total, the LLJ profiles are designed as

$$v(z) = \left(v_{\log}(z, L) + v_{\mathrm{LLJ}}(z, SF, z_{\mathrm{core}}, \varepsilon)\right) \cdot \frac{v_{\mathrm{eq}}}{v_{\mathrm{eq,\,ref}}}. \tag{15}$$

Similarly, the logarithmic and uniform wind profiles are normalised to a wind veer-corrected REWS $v_{\mathrm{eq,\,ref}} = 8\,\mathrm{ms^{-1}}$. Figure 5 shows exemplary profiles used for the aeroelastic simulations.

Table 4. Parameters for the generation of artificial wind profiles used to simulate the turbine response in openFAST. The varied parameters include the turbulence intensity TI, veer across the rotor area $\Delta\Theta$, Obukhov length L, core height z_{core} and ~~vertical extension of the~~ core width ε.

Profile shape	TI [%]	$\Delta\Theta$ [°]	L [m]	z_{core} [m]	ε [m]
Uniform	0, 5, 10	0, 10, 20, 40	/	/	/
Logarithmic	0, 5, 10	0, 10, 20, 40	-100, 100, 1000	/	/
LLJ	0, 5, 10	0, 10, 20, 40	-100	27, 85, 143	20, 40, 60

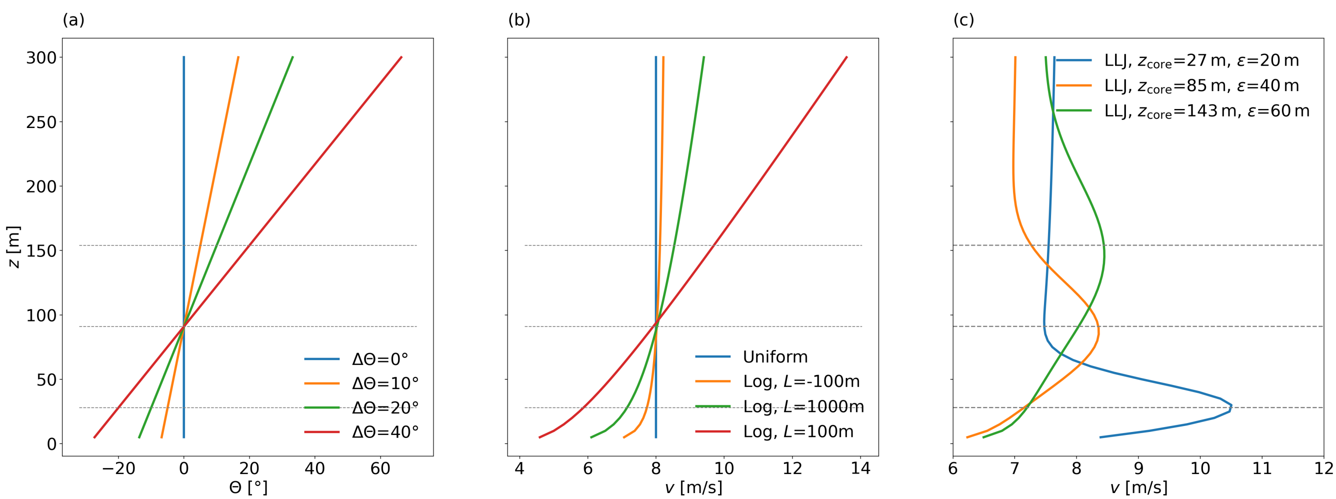

Figure 5. Exemplary inflow profiles used for the aeroelastic simulations normalised to $v_{\mathrm{eq}} = 8\,\mathrm{ms}^{-1}$. (a) provides the used wind direction profiles for all the different wind speed profiles, while (b) shows exemplary uniform and logarithmic profiles. In (c) exemplary LLJ profiles with different core heights and ~~vertical extents~~ core widths are shown.

Using TurbSim (Jonkman and Buhl, 2005), we generate ~~four dimensional wind fields~~ three-dimensional wind fields (width, height and time) containing all three wind speed components for each combination of employed wind speed and direction profiles.

We use the NREL-5MW reference turbine (Jonkman et al., 2009) in our simulations, as it features similar dimensions as the Senvion 6.2M126 turbines installed at NG. We include a model of the turbine installed on a monopile without hydrodynamic loading and use a simulation time of 600 s with time steps $dt = 0.005$ s. To exclude artefacts from the initialisation process, we remove the first 100 s from our simulation. Further, structural dynamics (ElastoDyn), sub-structural dynamics (SubDyn), control and electrical-drive dynamics (ServoDyn) as well as aerodynamic loads (AeroDyn) are computed using ~~the ElastoDyn, SubDyn, ServoDyn and AeroDyn~~ different subroutines within the openFast framework.

3 Results

In this section, we characterise the observed LLJs at the offshore wind farm Nordergründe ~~and compare hub height wind speeds from the derived wind profiles with same REWS during LLJ and non-LLJ situations~~(Section 3.1) and compare the apparent power production of the wind turbines during situations with the same REWS with and without LLJs present (Section 3.2) as well as the fluctuation in the power production (Section 3.3). Further, we analyse ~~aerodynamic~~ the aeroelastic simulations of the ~~power production~~ turbines with and without LLJ events present and show the change in turbine performance during LLJ events (Section 3.4).

3.1 Characterisation of LLJ events

To begin our analysis, we evaluate the occurrence statistics of LLJ events at the NG wind farm. For the characterisation of this location all detected LLJs independent of their core height are included. After ~~applying the LLJ detection algorithm and removing situations with north-easterly wind direction, i.e. including wakes of the NG turbines in the lidar measurement area, or insufficient data quality and availability,~~ excluding measurements with insufficient data quality or wind farm wakes inside the lidar scanned area, we apply the LLJ detection algorithm. Following all these steps 30,698 10-minute intervals remain, amounting to 5,116.33 h of available data. The availability at the highest altitudes is quite good, given the fewer measurement points in these regions, with over 30 % of all considered profiles reaching heights over 340 m. More than 66 % of all profiles contain data at altitudes larger than 250 m and more than 85 % of all profiles contain data up to 150 m, thus spanning ~~across~~ the entire rotor swept area.

Table 5 shows the amount of time we detect LLJs in the lidar wind profiles based on the different definitions ~~we applied~~ applied in this study. Using the definition adapted from Rubio et al. (2022) we observe a relatively high value with LLJs present at 9.1 % of the analysed time. The other definitions provide LLJ detections at a very similar rate, around 2.4 %-3.1 %, thus detecting less than half as many LLJs as the Rubio2022 definition. The shear definition introduced by Hallgren et al. (2023) shows by far the largest occurrence probability with 22.6 %. ~~It is used for our main analysis later on.~~ For all further analysis carried out in this study, we use this definition. We choose the shear based LLJ definition for two reasons. First, its decreased sensitivity to the available range of the vertical wind profile (Hallgren et al., 2023). Secondly, the shear definition is able to capture the change of wind speed across smaller height differences, thus taking factors impacting the wind turbine performance directly into account, whereas the fall-off can also be realised across several tens or hundreds of meters.

Table 5. Occurrence frequency of LLJs, as well as the absolute time of detected events and the relative occurrence frequency, for all valid measurements with a total duration of 5,116.33 h.

Definition	Absolute detected time [h]	Relative amount of time [%]
Wagner2019	124.3	2.4
Kalverla2019	146.7	2.9
Ranjha2013	157.17	3.1
Rubio2022	467.5	9.1
Hallgren2023	1,155.17	22.6

We analyse LLJ occurrence in dependency of several quantities, namely wind direction, time of the day and atmospheric stratification as well as the distribution of the observed core heights.

~~From the operational data of the wind farm, we obtain the wind direction and speed distribution at hub height of the turbines.~~

Figure 6a shows the frequency of occurrence of LLJ situations in the different wind direction sectors, while Figure 6b displays the wind rose at the NG site generated from nacelle anemometer data captured at NG17, where the majority of all situations display north-westerly to south-westerly wind directions. The lowest probability of occurrence are present for northerly to easterly wind directions. Thus, the inflow directions we are not able to observe from our measurements are the least frequent ones.

For the further analysis, we separated the accessible wind direction sector into land sectors, i.e. wind directions with short fetch lengths and sea sectors, i.e. directions, where the wind travels larger distances over the sea before reaching the wind farm. The land sectors are defined from 155° to 175° and 180° to 218° (20.1% of all profiles), while the remaining directions are classified as sea sectors (79.9 % of all profiles).

We notice that the occurrence frequency of LLJs for land and sea sectors respectively are quite similar. LLJs are detected in 24.0 % of all recorded situations in the land sector, while they are detected in 22.2 % of the profiles for the sea sectors.

Figure 6a shows, that LLJs most frequently occur for southerly wind directions, especially in situations where the flow comes from the direction of the mouth of the Weser river. Here, a distinct peak is observed at the border between land and sea sectors, where the wind travels directly along the coastline for a long distance.

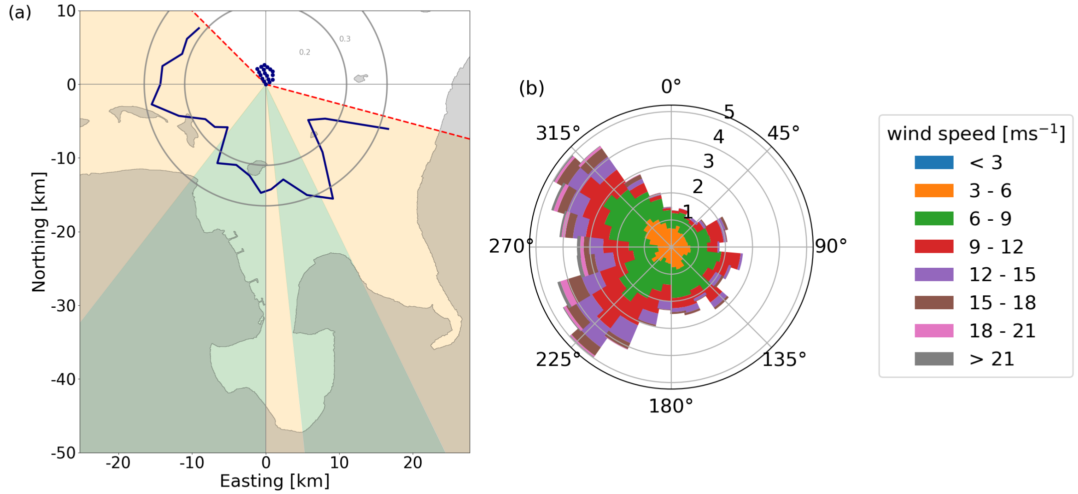

Figure 6. (a) Polar plot of the probability density of LLJ occurrences dependent on the wind direction (blue line) in the analysed wind direction sector (red dashed sector). For reference, the wind farm NG (blue markers) and coastlines (black) are shown. Further, the land and sea sectors are coloured in green and orange respectively. (b) Distribution of wind direction and corresponding wind speeds at hub height at the NG wind farm calculated from the nacelle anemometers of turbine NG17.

Figure 7 displays the diurnal cycle of LLJ occurrence at the NG wind farm for land and sea sectors. For the time of the day at which LLJs are observed, a clear pattern is present in the data. More LLJs are detected during the early morning hours, while very few are detected around noon. Although this behaviour is similar for both ,land and sea sectors it is more pronounced for the land sectors.

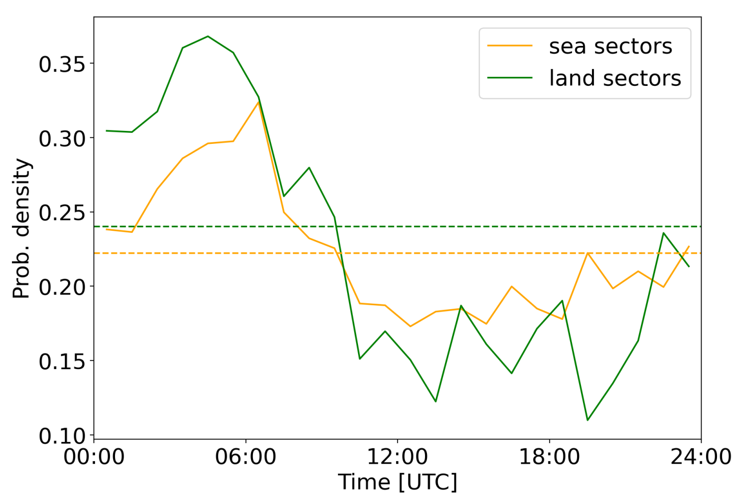

Figure 7. Daily cycle of LLJ detections for wind directions from land (green) and sea (orange) respectively (shown in Figure 6a). The dotted dashed lines represent the mean occurrence frequency across the entire day.

Figure 8 presents the dependence of LLJ occurrence on the locally present atmospheric stratification. We use the Obukhov length as obtained from the temperature difference between the SST and the temperature at TP height (cf. Sec. 2.1) and divide our data into bins of atmospheric stability regimes (Table 6). ~~A more detailed method on how we calculate the Obukhov length is found in Schneemann et al. (2021).~~

We observe that for the land sectors, the unstable regimes are recorded particularly frequent, while the stability regimes for the sea sector are distributed quite evenly across the measurements. Here, the major exception are very stable conditions, which are recorded only 6.61 % of the time.

Table 6. Stability regime classification based on the Obukhov length L, as proposed by Sathe et al. (2022). Further the occurrence frequency for the different stability regimes within the land sectors (20.1 % of all profiles) and sea sectors (79.9 % of all profiles) are shown.

Stability regime	L [m]	Frequency of occurrence	
		Land sectors	Sea sectors
very stable (vs)	$10 < L \leq 50$	8.3 %	6.6 %
stable (s)	$50 < L \leq 200$	15.5 %	16.8 %
near neutral / stable (nns)	$200 < L \leq 500$	5.9 %	12.0 %
neutral (n)	$\|L\| > 500$	9.3 %	17.0 %
near neutral / unstable (nnu)	$-500 \leq L < -200$	9.9 %	12.5 %
unstable (u)	$-200 \leq L < -100$	24.9 %	16.3 %
very unstable (vu)	$-100 \leq L < -50$	26.3 %	18.9 %

For the sea sectors, we observe a slight increase in frequency of LLJ occurrence towards very stable and very unstable stratification, respectively. In contrast, for the land sectors, LLJs are observed more often during extreme stratification with an especially pronounced peak for a very stable atmosphere, where LLJs are detected for more than 50 % of all situations. However, Table 6 shows, these very stable situations only occur quite rarely compared to other stability regimes. When comparing the land and sea sectors directly, it becomes obvious that land sectors show a higher occurrence frequency of LLJs during stable regimes, while the occurrence frequency is higher for sea sectors during unstable regimes.

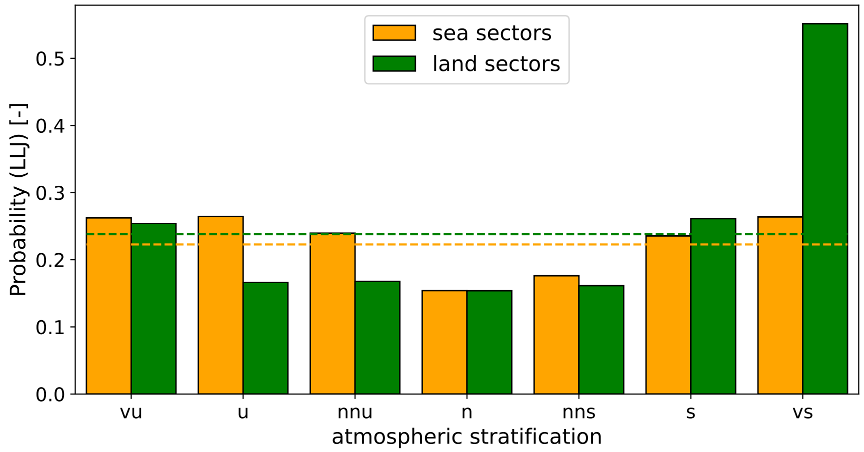

Figure 8. LLJ occurrence frequency across different stability regimes from very unstable towards very stable for land (green) and sea (orange) sectors respectively. The occurrence frequency is computed as a subset of the distribution of stratification events shown in Table 6.

Figure 9a shows the distribution of the LLJ core heights, while Figure 9b depicts the distribution of LLJ core speeds with core heights in- and outside of the rotor swept area. Further, the distribution of hub height wind speeds as recorded by the nacelle anemometer of NG17 is presented.

Regarding the height of the LLJ cores, we notice a steep increase of occurrence frequency at lower heights and throughout the rotor area. Just above the upper tip, at $165\,\mathrm{m}$ the maximum occurrence frequency is observed and a slight decrease of observed LLJs follows to higher altitudes. The average core height across all detected events is $188\,\mathrm{m}$.

The core speeds are distributed quite unevenly across all wind speeds. For lower wind speeds a steep increase is observed, leading to a peak wind speed followed by a rather shallow decrease, resembling a Weibull distribution. We find, that for LLJs within the rotor area, the distribution is shifted to slightly lower values, while the distribution across all heights is very similar to the distribution of hub height wind speeds.

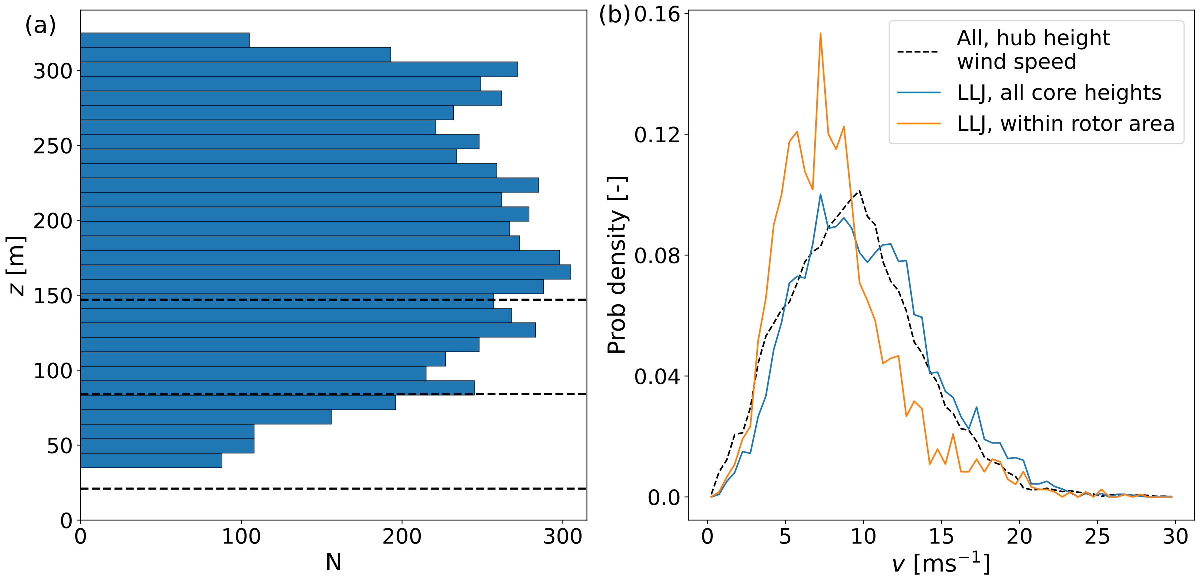

Figure 9. (a) Distribution of measured LLJ core heights. Lower tip, upper tip and hub height are marked by dashed lines. (b) Distributions of core speeds for all observed LLJs (blue), the data subset with core heights within the rotor area (orange) together with the hub height wind speed distribution of the whole data set (black dashed line).

3.2 LLJs' influence on wind turbine ~~power~~energy conversion efficiency

To analyse LLJs' influence on the energy conversion process at the wind turbines, we take a look at the variability of wind speed and direction across the rotor area. To also include the effects of the different negative and positive shears and veers within the profile, we analyse the average of the absolute differences of wind speed and direction across the rotor swept area:

$$\overline{|\Delta v|} = \frac{\sum_i |v(z_{i+1}) - v(z_i)|}{D} \quad \text{and} \quad \overline{|\Delta \Theta|} = \frac{\sum_i |\Theta(z_{i+1}) - \Theta(z_i)|}{D}; \quad \text{where}: z_{\text{low}} \leq z_i \leq z_{\text{up}} \tag{16}$$

with the upper and lower tip height z_{up} and z_{low} respectively and the rotor diameter $D = 126\,\text{m}$.

Figure 10 shows the average veer (a) and shear (b) across the rotor area for profiles with and without LLJs respectively. Here, we notice a skew of the LLJ profiles towards higher veer and shear values. This is also represented in the mean values of wind shear and veer which are both observed to be larger during LLJ events (cf. Table 7).

Table 7. Average wind shear and veer for LLJ and non-LLJ situations respectively.

	~~Shear~~ $\overline{\lvert\Delta v\rvert}$ [~~s^{-1}~~ s^{-1}]	~~Veer~~ $\overline{\lvert\Delta\Theta\rvert}$ [~~m^{-1}~~ $^\circ\, m^{-1}$]
non-LLJ	0.019	0.189
LLJ	0.037	0.318

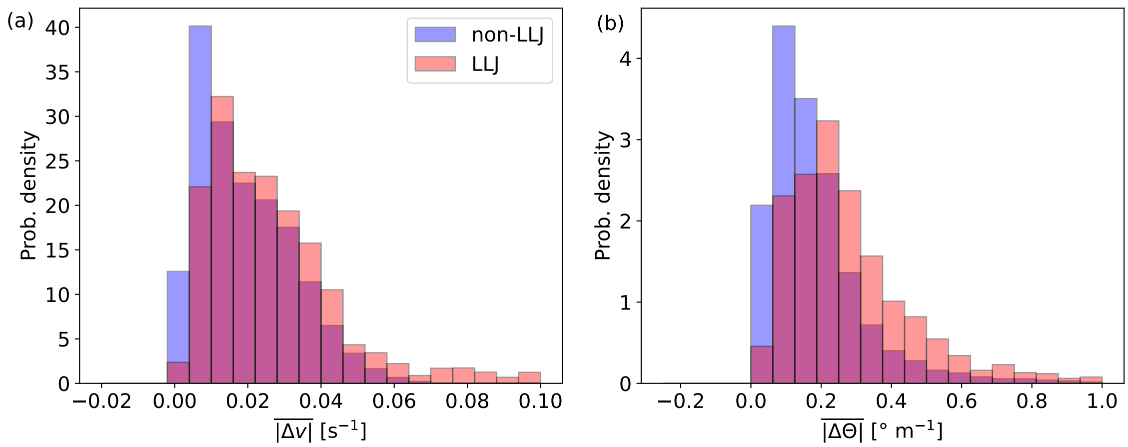

Figure 10. (a) Average wind shear and (b) veer across the rotor swept area for all measured profiles not containing LLJs shaded in blue and those containing LLJs in red.

Figure 11a shows the averaged apparent power production within the respective wind speed bins during free inflow situations (cf. Sec. 2.4). While the apparent power production is lower ~~for~~ during LLJ events throughout all ~~wind speeds~~REWS bins, we observe larger differences between the two in the upper partial load range. As the number of detected events decreases towards higher wind speeds, the uncertainty associated with these wind speed bins is observed to increase as well. A maximum difference between LLJ and non-LLJ cases of 8.9 % of the rated power is observed at 13 ms^{-1}.

Our analysis also shows that most LLJs within the rotor area are observed at REWS in the middle of the partial load range, with a maximum at around 7 ms^{-1} (Fig. 11b).

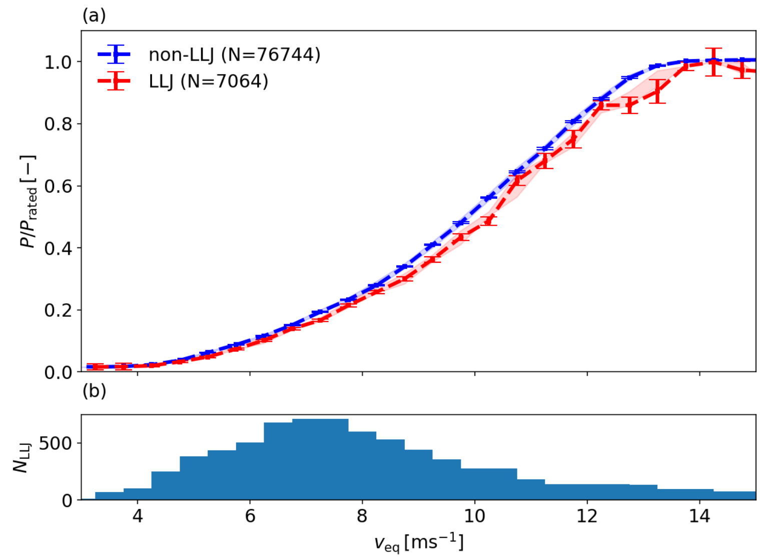

Figure 11. (a) Average apparent power production per binned REWS v_{eq} (cf. Average apparent power production Eq. 11) during non-LLJ situations (blue) and LLJ situations (red). Error bars depict the standard error of the mean of the apparent power within each wind speed bin. Shaded areas depict the corresponding uncertainty intervals obtained by computing power curves with added and subtracted uncertainty estimations respectively (cf. Section 2.4). (b) Number of LLJs per wind speed bin.

3.3 Analysis of the fluctuations in power production

To investigate the fluctuation of the power production during LLJ situations, we calculate its fluctuation $\mathrm{PO_{TI}}$ according to Eq. 6. Moreover, to make the results more representative we separate the data based on the present stability regime.

Figure 12 shows the distribution and box plots and the median of the $\mathrm{PO_{TI}}$ per 10-minute interval over the prevailing stability regime. Here, we observe that the fluctuations in apparent power production are higher for LLJ situations across almost all the different stability regimes, except for near-neutral unstable (nnu) and unstable (u) conditions. We observe a general trend towards higher $\mathrm{PO_{TI}}$ for increasingly unstable stratification for non-LLJ situations, while we observe similar median $\mathrm{PO_{TI}}$ during stable and (very) unstable situations with LLJs present. We also observe a slight increase of the median $\mathrm{PO_{TI}}$ for non-LLJ situations from neutral towards very stable stratification.

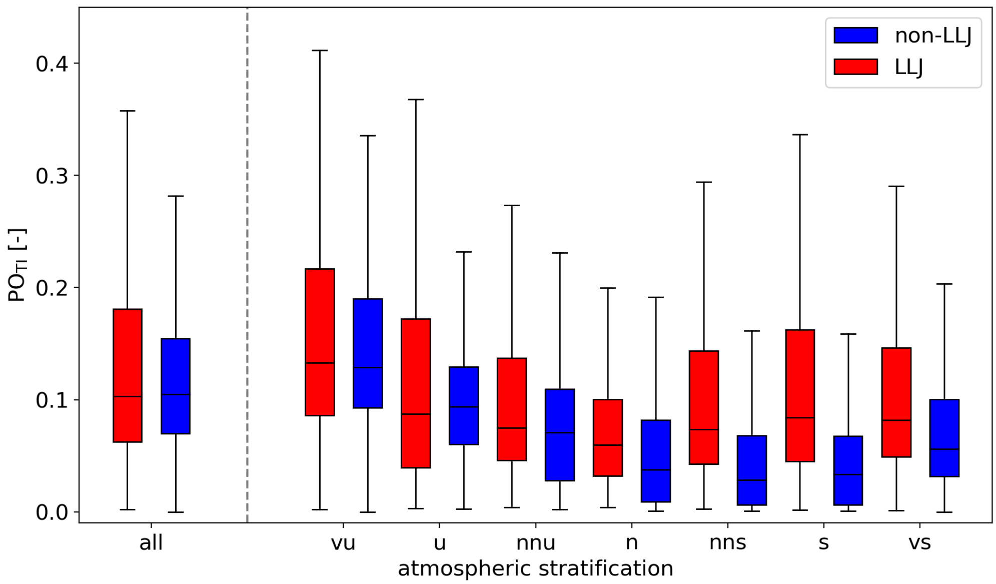

Figure 12. Box plots of the normalised standard deviation of the power production $\mathrm{PO_{TI}}$ for LLJ and non-LLJ situations, respectively, across all the different stability regimes. The boxes are limited by the first (Q1) and third quartile (Q3) respectively, with the whiskers representing $Q_1 - 1.5\,IQR$ and $Q_3 + 1.5\,IQR$, with IQR the interquartile range. The horizontal black lines represent the median $\mathrm{PO_{TI}}$.

3.4 Aeroelastic simulation of wind turbine performance

To further deepen our understanding of how LLJs affect ~~power production of wind turbines~~wind turbine performance, we analyse the results of 156 aeroelastic simulations, each with a different type of vertical wind speed profile, but the same veer-corrected REWS of the NREL 5MW offshore reference turbine (cf. Sec. 2.5).

Table 8 lists the average power production and $\mathrm{PO_{TI}}$ during the aeroelastic simulation of the turbine response to the generated inflow profiles. When analysing the average power production across all simulations, we observe a slightly ~~higher power production~~ increased power for the uniform inflow profiles. The average power production between LLJ and logarithmic profiles, however, is very similar. Concerning the $\mathrm{PO_{TI}}$, our simulations show the highest power fluctuation for LLJ profiles, while it decreases for logarithmic profiles and is lowest for the uniform inflow profiles.

Table 8. Average power production and $\mathrm{PO_{TI}}$ across all simulations for the different types of profiles. Further, the number of simulations for each profile type is displayed.

	uniform	logarithmic	LLJ
$\overline{P}$ [kW]	1642	1619	1619
$\mathrm{PO_{TI}}$ [-]	0.0091	0.0101	0.1112
N	12	36	108

One important factor, assumed to have a major influence on the observed power production is the absolute shear of the wind speed across the rotor area. Within our simulations, we observe a similar result.

Figure 13a shows the relation between the absolute shear in the profile and the temporally averaged power production of the turbine for each of the simulated inflow profile. Here, we observe that with increasing shear the ~~power production~~ generated power decreases. Further, we also observe, that this relation is quite linear for logarithmic wind profiles, whereas a more spread picture is seen for the LLJ profiles. Here, the minimum power production is not observed at the highest average shear of $0.064\,\mathrm{s}^{-1}$ across the rotor area, but already at $0.035\,\mathrm{s}^{-1}$.

A similar effect is observed concerning the veer across the rotor area (Fig. 13a). Again, a strong relation between increasing shear and ~~decreasing~~ decreased power production is found in the data. In contrast to the shear analysis, the decrease in observed power production for LLJ profiles seems to follow a linear trend~~here as well~~.

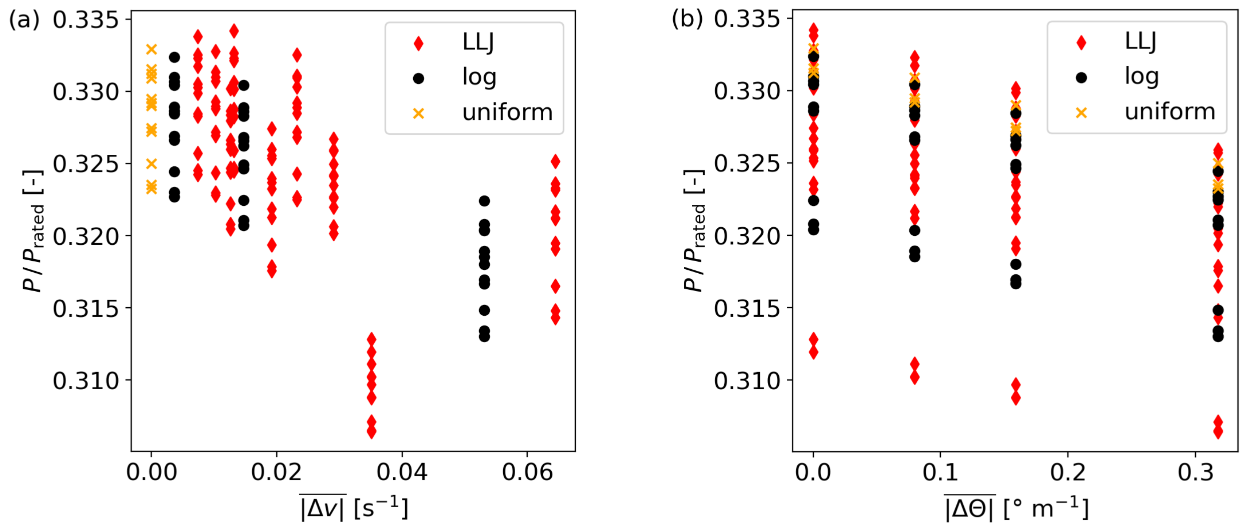

Figure 13. Simulated normalised power production over the shear (a) and veer (b) of the wind profiles across the rotor swept area for each of the simulated inflow profiles. Uniform wind profiles are depicted as orange crosses~~(x)~~, logarithmic profiles as black circles ~~(•)~~ and the LLJ profiles as red diamonds~~(♦)~~.

~~Further~~Next, we also analyse the relation between TI and average power production. Here, only a very small difference between the different simulated TIs is observed. From the data, we see a slight increase in power production with increasing TI. However, as Figure 14 shows, the fluctuations within the three TI regimes are quite high and only a slight increase in the median power is seen.

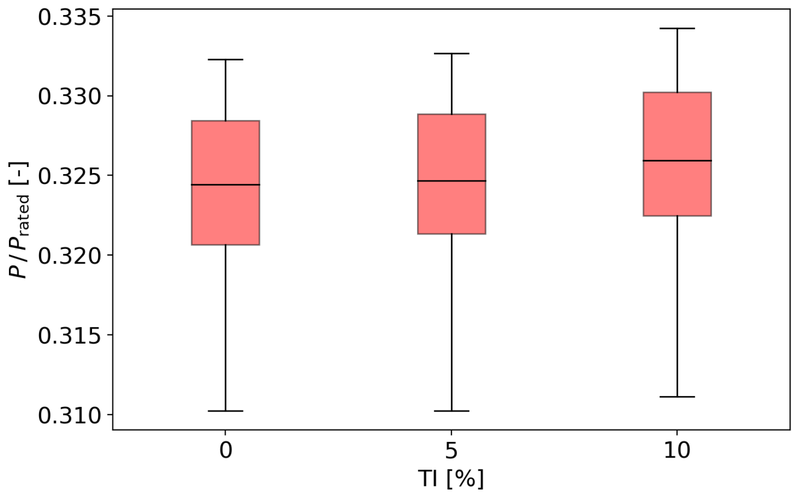

Figure 14. Boxplot of the power production for all simulated profiles with respect to the chosen TI. The black lines represent the median for each regime, while the box edges show the limits of the first and third quartile of the data.

In the following, we want to highlight the different characteristics of LLJ profiles, i.e. fall-off, width and core height and how they influence the power production of the turbines.

Figure 15a shows the average power production over the magnitude of the fall-off and the height of the LLJ core. We notice a decreasing trend for the power with increasing fall-off of the LLJ profiles. Also, we see lower power production for LLJs with their core height at the upper tip of the turbine. The opposite trend is observed for the LLJ core width ε (Fig. 15ab). Here, an increase of power is observed for wider LLJ cores. Also, the distribution of power production is far broader for very narrow LLJ cores compared to larger ε.

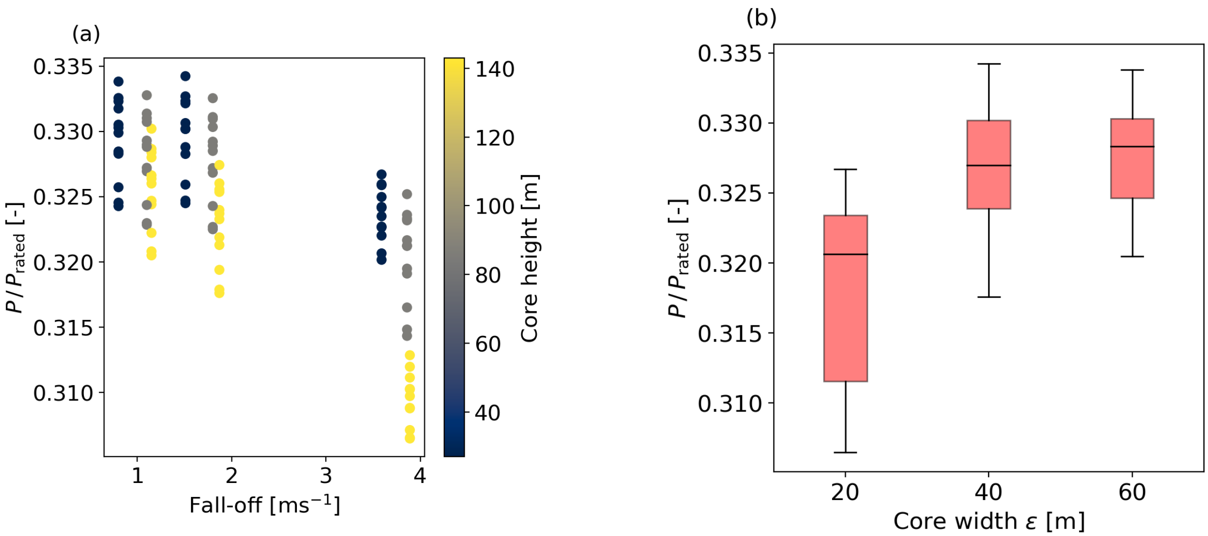

Figure 15. Average power production during simulations with LLJ wind profiles plotted over the fall-off and the core height as colour code (a) and the width of the LLJ core in (b) where the box represents the limits from first and third quartile and the black line the median value.

4 Discussion

Analysing LLJs in an offshore environment relies on the lidar sensing of vertical wind profiles and thus the several sources of uncertainty have to be considered. Previous studies relied on the measurement using the Doppler-beam-swing (DBS) and velocity-azimuth display (VAD) methods. The commonly used DBS technique retrieves a wind profile above the lidar in a comparably small measurement volume. As we performed multiple PPI scans at different elevations, our measurements encompassed a larger area with considerable variability in the wind field. However, generating the wind profiles from the volumetric 3D wind field, our results at hub height showed a good agreement with the wind speed obtained from the ~~wind farms' SCADA system~~ operational data of the turbine NG17~~, thus establishing the~~ . The correlation coefficient between the two variables lies at R^2=0.97. Further, we also compared vertical wind profiles retrieved using our volumetric approach to more localized wind profiles obtained via a method similar to Visich and Conan (2025) for one month of data. Here, we observe average absolute differences between the two methods below 1 ms^{-1} across almost all heights. The LLJ detection rate for the two different methods increases from 33.1 % using the volumetric approach to 36.6 % using the metmast approach, despite a considerably lower data availability of the metmast style profiles, dropping from 99.5 % obtained from the volumetric approach to 79.9 %. This establishes the multi-elevation lidar measurements as a valuable asset for the wind profile generation. Further, we accounted for several uncertainties like the earth's curvature and the tilt and roll of the lidar in post-processing, increasing the pointing accuracy of the positions of our measurements. Further uncertainties, such as measurement uncertainties of the wind speed and direction caused by the lidar, have been included in the analysis using the Gaussian uncertainty propagation. While the method applied in this study is not used often, it provides valuable results and proves to be well suited for this specific application.

In the literature ~~many~~ several different LLJ definitions are used, all coming with individual benefits and drawbacks. Within our work, we present the characterisation of the occurrence of LLJs and their properties. Further, to analyse wind turbine power under the influence of atmospheric LLJs we use long-range lidar and SCADA data from the wind farm Nordergründe. For our analysis, we mainly use the definition of an LLJ proposed ~~recently~~ by Hallgren et al. (2023). The main characteristic of this definition is ~~,~~ that instead of using the absolute and/or relative fall-off of the wind speed it makes use of the shear of the wind speed. Hallgren et al. (2023) show ~~,~~ that this makes the provided definition less sensitive to limited measurement heights. This is especially important in our case, as ~~the wind profiles generated~~ we generated wind profiles from multi-elevation PPI scans~~reach~~ , reaching maximum heights of around 350 m~~, while other~~ . Other studies using e.g. reanalysis data ~~show~~ make use of increased measurement heights, thus also showing occurrences of LLJs at higher altitudes (e.g. Kalverla et al., 2019). Also, the ~~Hallgren~~ shear-based definition is more ~~useful for~~ applicable to wind energy-related purposes, as it concentrates directly on the shear, a property which is shown to have a non-negligible influence on the conversion efficiency of a wind turbine ~~(Dörenkämper et al., 2014)~~(Dörenkämper et al., 2014; Murphy et al., 2020). Using this local property instead of a fall-off - which can in theory be realised over a large height difference - also allows a precise description of the inflow conditions across the rotor area. Further, we also observe large discrepancies between the shear definition and the fall-off-based definitions concerning the detected LLJ events, with the shear-based definition detecting ten times more LLJ events than the most restrictive criteria and double the amount compared to the least restrictive definition (cf. Table 5).

Our results show that LLJ occurrence frequency is highly dependent on many factors, as large differences emerge compared to other studies (e.g. Rausch et al., 2022; Baas et al., 2009), thus showing a strong dependence of LLJ occurrence on the measurement site, the applied measurement techniques and the measurement period. Next to the environmental conditions, our results also show a very strong difference based on the different LLJ definitions present in the literature (cf. Table 5). The difference in occurrence frequency for varying locations is further backed up by mesoscale simulations ~~who~~ which found a relation between distance to the coast and LLJ occurrence frequency (Barekzai et al., 2024). Also, as we are only able to observe a limited wind direction sector, LLJs from a north-easterly direction, i.e. fetch direction from the open sea, are not captured in this study. Also, the proximity of the measurement location to the Wadden Sea makes it a complex site, as this way, the sea surface temperature and thus the prevailing atmospheric stratification are strongly dependent on the current tide (Appendix A). Regarding the influence of the atmospheric stratification on the detection rate of LLJs, we observe a similar behaviour for both land and sea sectors as the occurrence frequencies increase towards both stable and unstable stratification. ~~However, while~~ While for unstable stratification they occur more frequently from sea sectors, LLJs show higher probabilities for stable stratifications when emerging from coastal directions. Our results also show that the amount of ~~LLJs~~ detected LLJ cores increases with height, up to a local maximum at 165 m. In our study, we observe an increased occurrence frequency during unstable conditions, compared to previous studies (e.g. Wagner et al., 2019). Based in the directional analysis of the occurrences, we assume these to be features advected from the land masses. Further, as we are only able to measure temperature differences between the TP of the turbine and the sea surface, the stability estimate allows us to draw conclusions about this region. For increased altitudes, the number of detected core heights seems to stagnate and even decrease. However, at these altitudes also the availability of measurements decreases notably, i.e. less wind profiles are available for LLJ detection. Further, within our measurements, we are only able to observe wind speeds up to heights of 350 m. Hallgren et al. (2023) show that extending this height up to 500 m leads to a significant increase of identified LLJs. ~~However, for~~ For some of the observed LLJ occurrence characteristics, such as e.g. the diurnal cycle, similarities to the literature are observed (e.g. Rausch et al., 2022), independent of the location and the distance to the mainland.

As the main finding, we observe a ~~decreased power production~~ less efficient power conversion efficiency of turbines in LLJ situations compared to non-LLJ situations, with a maximum difference of 8.9 %. ~~However, as~~ As this difference is observed directly below rated wind speed, it must be treated carefully. One driver for this decreased ~~power production~~ efficiency is the increased shear across the rotor area which is shown to be detrimental to the performance of wind turbines (Dörenkämper et al., 2014). This trend is further verified by aeroelastic simulations carried out within our study. The results show ~~,~~ that not necessarily the anomaly in the shape of the profile leads to a reduced apparent power production, but rather the increased absolute shear. This is also seen from the simulations with different shapes of LLJ profiles, where a lower production is observed for situations with higher absolute shear. Also, an increased veer across the rotor area is observed for LLJ profiles at NG, which according to the results of the aeroelastic simulations further decreases turbine efficiency, even when comparing situations with the same wind veer-corrected REWS. Moreover, Mortarini et al. (2018) observed a lower turbulence intensity below the LLJ core. This has a slightly negative effect on a wind turbine's power production (Dörenkämper et al., 2014). The trend we observe is further backed up by Zhang et al. (2019), who also ~~show~~ showed a decreased power production for LLJ-situations with the same hub height wind speed as for a logarithmic wind profile within their simulations, despite using rather weakly pronounced LLJs in their study. Here, ~~the authors also show~~ Zhang et al. (2019) also found that this deficit is highly dependent on the relative position of the wind speed maximum inside the rotor area, which is confirmed by our simulations. While the average apparent power decreased during LLJ events, we observed an increase in the fluctuation of the production, especially during stable stratification. One factor impacting this behaviour can be the rise of intermittent bursting of turbulence, which can be triggered by LLJs (Ohya et al., 2008) and may have an effect on the performance of the turbines.

~~We found, decreased power production~~ While in our study, we found decreased power conversion efficiency during LLJ situations~~. In contrast Gadde and Stevens (2021) found improved~~ , Gadde and Stevens (2021) found increased power production during LLJ-situations in a numerical study. However, their Large-Eddy Simulations compare wind profiles with different REWS, by deriving their wind profiles from varied meteorological parameters. As a result, LLJ situations show a higher availability of energy in the wind and thus the power production is increased. This further ~~emphasizes~~ emphasises the use of a different metric - like the REWS - to compare power ~~production~~ conversion efficiency for different wind profile shapes. We tried to evaluate the performance of turbines with similar energy availability and thus aimed to compare situations with similar REWS. This way we can show how the energy conversion process becomes less efficient during LLJ events, with the main drivers here being the increased shear and veer across the rotor area.

Despite the observed ~~power losses~~ efficiency decrease during LLJ situations, we cannot draw any indication on whether the effect on the annual energy production (AEP) is negative or positive due to several reasons. First, frequent LLJ situations affect the ~~the~~ wind speed distribution at hub height in addition to their effect on wind shear and REWS. Secondly, LLJ occurrence is correlated with atmospheric stratification and turbulence characteristics, both impacting the wind turbine wake development and AEP (St. Martin et al., 2016; Cañadillas et al., 2022). Finally, the influence of LLJs on wind farm wake losses is an open question. Nonetheless, our results suggest that the consideration of LLJs in the AEP calculation at sites with high occurrence frequencies of such situations could result in reduced uncertainties in predicted energy production in the future.

5 Conclusion

In this study, we investigate the influence of atmospheric low-level jets (LLJ) on offshore wind turbine power conversion efficiency based on scanning lidar measurements~~and~~ , wind farm operational data at the Nordergründe wind farm and aeroelastic simulations. We observe LLJs between 2.4% and 22.6% of the investigated time depending on the used definition, thus proving them to be a relevant phenomenon to be considered for wind power applications. Most LLJs observed at this location have core heights above the rotor-swept area. Thus, their importance for wind energy-related processes will increase in the future with larger turbines being installed. When compared to other studies, it becomes clear that the LLJ occurrence frequency is dependent on the observed location as well as the observed time frame and meteorological conditions, e.g. atmospheric stratification~~and wind direction~~ , wind direction and fetch. Concerning the location several factors ~~might~~ can play a role, e.g. the distance to the coast, predominant wind directions and other special features such as the proximity to the Wadden Sea, which has a large influence on the sea surface temperature, which in turn impacts the atmospheric stratification.

~~Moreover, our study showed that wind turbines are not able to convert the energy contained in the wind to the same extent during LLJs, as they can do during non-LLJ situations. Thus, we propose an incorporation of LLJs into the AEP calculations in strongly affected regions to possibly reduce uncertainties in the energy prediction. While previous~~ Previous studies relied on the hub height wind speed to compare different types of wind profiles and their influence on the energy conversion process in wind turbines~~, we opted to instead use the~~ . Instead, we explicitly use the wind-veer-corrected rotor equivalent wind speed (REWS) ~~. We explicitly use REWS~~ as our reference wind speed, thus following the guidelines provided by IEC 61400-12-1 (IEC, 2017)~~, as this~~ . This formulation - compared to just the hub height wind speed - incorporates the change of wind speed and direction across the rotor and thus is a more suitable measure for the energy flux through the rotor area. Applying REWS as a reference, our study showed that wind turbines are not able to harvest the energy contained in the wind to the same extent during LLJs, as they can do during non-LLJ situations. Thus, we propose an incorporation of LLJs into the AEP calculations in strongly affected regions to possibly reduce uncertainties in the energy prediction. For the variability of the power production, we observe higher fluctuations during LLJ situations throughout various stability regimes, with stronger differences emerging especially during stable stratification.

Although ~~,~~ a clear trend is observed for the considered performance parameters, i.e. the power production and its fluctuation from field measurements and aeroelastic simulations, more extensive research on larger datasets is required to further develop our understanding of the interactions between wind turbines and LLJs. This includes the wake recovery inside wind farms during LLJ situations as well as their possible impact on wind turbine loads due to the uneven distribution of the wind speed and especially direction over the rotor area.

Data availability. Wind farm operational data from Nordergründe are confidential and not published. Lidar and meteorological data are not published. Recent values of water level, water temperature and further quantities measured at the lighthouse Alte Weser are available at https://www.pegelonline.wsv.de, access to historical data is limited (WSV, 2023). The OSTIA dataset is publicly available via https://doi.org/10.48670/moi-00165 (Good et al., 2020).

Appendix A: Atmospheric stability and sea surface temperature

The main quantity to describe the static atmospheric stratification in the marine boundary layer is the difference between the air temperature at a given height and the sea surface temperature (SST). While the air temperature can be measured with manageable efforts, knowledge about the SST is harder to achieve. Using a measurement buoy is expensive and prone to damage. Previous studies used a buoy in a far offshore location to measure SST (e.g. Schneemann et al., 2020). In periods without the buoy measurement, the SST from the OSTIA data set providing one value per day (Good et al., 2020) proved useful. For the present study in a near coastal area with mud flats (Wadden Sea) and a large effect of tidal currents, we expect faster changes in the SST than being resolvable with OSTIA. Therefore we used a combination of two infrared sensors (Heitronics CT09 and CT15 with internal correction for sky radiance) installed on the transition piece of the wind turbine NG17.

Combining our SST measurements at NG17 with water level measurements from the Alte Weser lighthouse (AW), located roughly 5.2 km from the wind farm, we observe a clear dependency between the sea level and a change in the SST. At times of high tide, the SST decreases by up to 3 ~~C~~ °C compared to low tide. Figure A1a shows the water level at the lighthouse Alte Weser with level maxima detected and marked for one exemplary period of eleven days. Figure A1b depicts the SST measured with the IR sensors at the wind turbine NG17. This suggests that cooler water is transported by the rising tide towards the measurement location, while the opposite takes place at low tide.

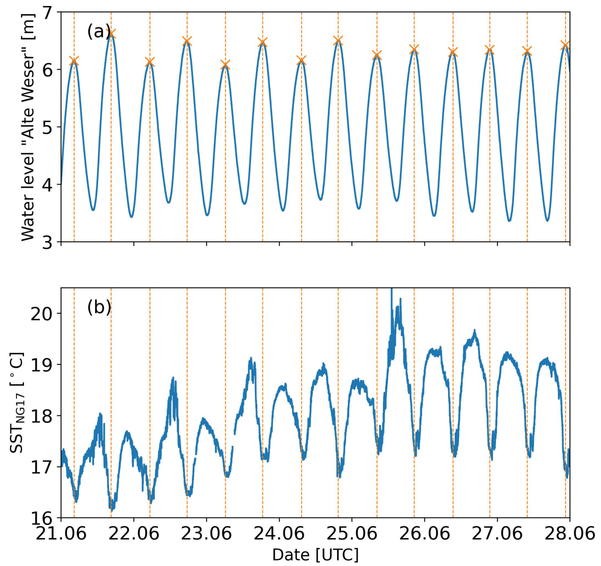

Figure A1. (a) Water level measured at the lighthouse Alte Weser (WSV, 2023). Maxima are detected with a peakfinder and marked ($\times$). (b) Sea surface temperature measured at the wind turbine NG17 in the offshore wind farm Nordergründe with approx. 5.2 km distance to Alte Weser. Times of high tide detected in (a) are marked by vertical dashed lines.

Figure A2 compares three different sources of the local water temperature. Aside from our IR-SST measurements at the turbine NG17 $\mathrm{SST}_{\mathrm{NG17}}$ we show two publicly available data sources, namely the water temperature measured at the lighthouse Alte Weser $T_{\mathrm{AlteWeser}}$ (WSV, 2023) and the SST from the OSTIA data set $\mathrm{SST}_{\mathrm{OSTIA}}$ (Good et al., 2020). The water temperature at Alte Weser is measured using a sensor WTW TetraCon 700 IQ SW. It is installed at the foundation of the lighthouse in north-westerly direction in a fixed position of approx. 1 m below mean tidal low water.

The OSTIA data set provides one SST value per day. Here we chose the values from the closest offshore grid point to the NG wind farm.

Both $\mathrm{SST}_{\mathrm{NG17}}$ and $T_{\mathrm{AlteWeser}}$ show a periodic temperature fluctuation with the tidal currents that can not be resolved by $\mathrm{SST}_{\mathrm{OSTIA}}$. Concerning the correlation between the different temperature measurements, we observe good agreement.

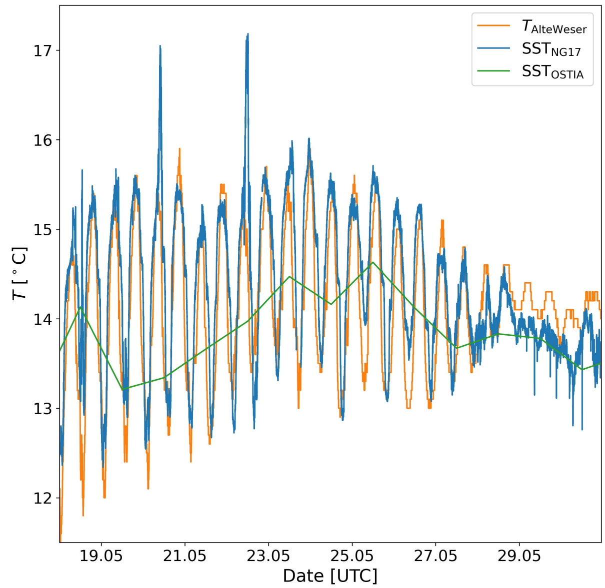

Figure A2. Water temperature at the lighthouse Alte Weser $T_{\mathrm{AlteWeser}}$ with a resolution of 1/60 Hz (WSV, 2023) (orange), sea surface temperature $\mathrm{SST}_{\mathrm{NG17}}$ measured with an infrared sensor from the transition piece of turbine NG17 in the offshore wind farm Nordergründe resampled to one minute (blue), and sea surface temperature from the OSTIA data set $\mathrm{SST}_{\mathrm{OSTIA}}$ (Good et al., 2020) at a grid point in the western vicinity of Nordergründe with one value per day (green).

Figure A3 shows the annual fluctuation of the SST as captured by the different data sources. Here, we average the data from the Alte Weser lighthouse and the local SST measurements at NG to daily values. The comparison shows that all three methods capture the daily fluctuations and the annual trend quite well.

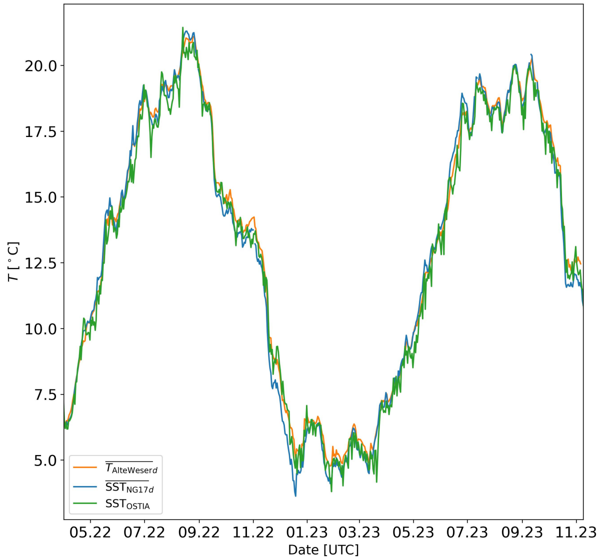

Figure A3. Water temperatures from Alte Weser, NG17 and OSTIA as in Figure A2 but data from Alte Weser and NG17 resampled to daily values. More ~~then~~ than one year of data is shown.

To provide a more statistically sound analysis, we performed orthogonal distance regressions (ODR) between the one minute averages of AW and NG as well as the OSTIA data and the daily average of the NG measurements. Figure A4 shows scatter plots of the SST measurements from different data sources, with Fig. A4a presenting the correlation between the high-resolution data at AW and NG and Fig. A4b displaying the correlation between NG and OSTIA. For both different combinations we observe a very high Spearman correlation coefficient of $R^2 > 0.99$. Further, we also observe a slope very close to one and small positive offsets for AW and OSTIA compared to the NG data.

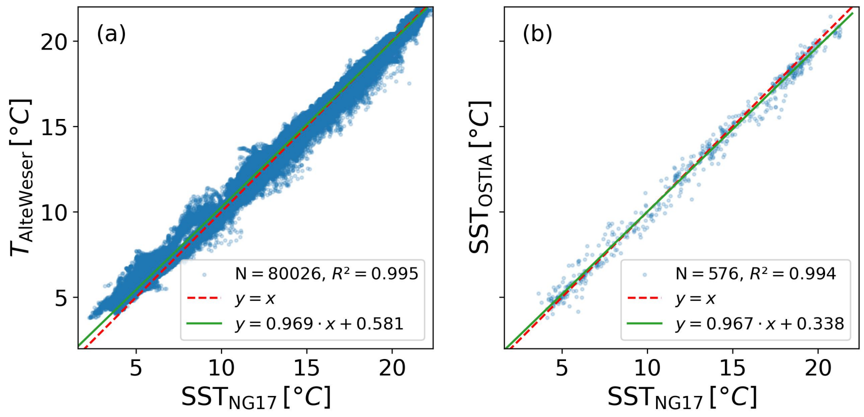

Figure A4. Scatter plots showing the correlation between the SST measurements at NG17 and water temperature measurement at the lighthouse Alte Weser (a) and the OSTIA data set (b), respectively. The $y = x$ curve is depicted as a ~~dotted~~ dashed red line and the regression line in green.

Finally, we compare the stability estimates obtained from the three different temperature measurements. Here, we use the dimensionless $\zeta = z_{\mathrm{TP}}\,/\,L$-parameter as no discontinuity around the zero crossing is present.

~~Figures~~Figure A5 shows the correlations between the different stability estimates.

~~All two~~ Both combinations show a Spearman correlation coefficient of $R^2 > 0.88$ and thus provide a quite good correlation. However, there is a visible difference between high-resolution data and the OSTIA data set. The correlation coefficient between AW and NG is considerably higher at $R^2 = 0.961$, compared to the correlation of the high-resolution data with OSTIA-based stability estimates at ~~$R^2 = 0.912$ and~~ $R^2 = 0.882$~~respectively. For all three~~. For both datasets, we perform an ODR and observe regression lines with almost negligible bias and a slope close to one.

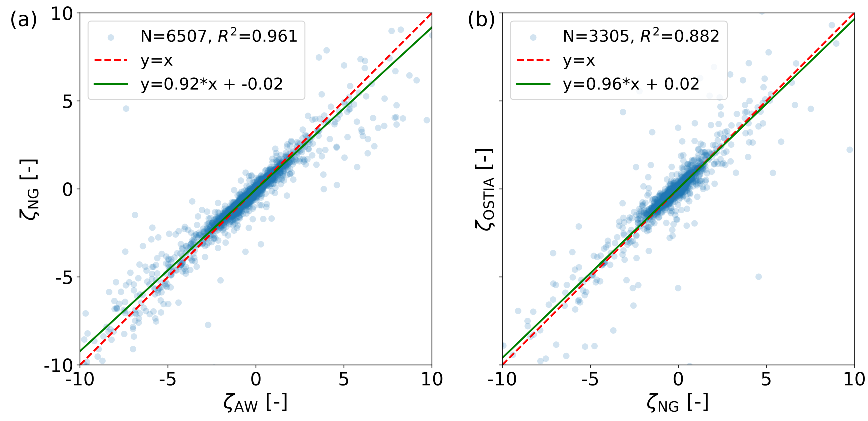

Figure A5. Scatter plots of the ζ-parameters derived from all three different temperature measurements. In (a) the correlation between Alte Weser and NG is shown, while (b) shows the correlation between between NG and OSTIA. A regression line determined via ODR is drawn in ~~red~~ green with the regression parameters shown in the legend. The $y = x$ curve is depicted as a dashed red line.

Appendix B: Estimation of measurement uncertainties and error propagation of the rotor equivalent wind speed

Some uncertainties from the scanning lidar wind speed measurements, such as the pitch and roll movement of the devices, can be directly accounted for by applying correction algorithms. Others, such as the uncertainty of the measured line-of-sight velocity v_{LOS} or estimated density $\rho(z)$, cannot. To perform an uncertainty estimation concerning these measurements we use Gaussian error propagation on the REWS defined in Equation 11. The total uncertainty of the REWS

$$\Delta v_{\mathrm{eq}} = \sqrt{\sum_i \left(\frac{\partial v_{\mathrm{eq}}}{\partial v_{i,\,\mathrm{corr}}}\Delta v_{i,\,\mathrm{corr}}\right)^2 + \sum_i \left(\frac{\partial v_{\mathrm{eq}}}{\partial \phi_i}\Delta \phi_i\right)^2} \tag{B1}$$

is thus calculated as the square root of the sum of squares of the individual uncertainty contributions, with the partial derivatives

$$\frac{\partial v_{\mathrm{eq}}}{\partial v_{i,\,\mathrm{corr}}} = \left(\sum_i \left((v_{i,\,\mathrm{corr}}\cos(\phi_i))^3 \frac{A_i}{A_{\mathrm{tot}}}\right)\right)^{-2/3} \cdot v_{i,\,\mathrm{corr}}\cos(\phi_i)^3 \frac{A_i}{A_{\mathrm{tot}}} \tag{B2}$$

$$\frac{\partial v_{\mathrm{eq}}}{\partial \phi_i} = -\left(\sum_i \left((v_{i,\,\mathrm{corr}}\cos(\phi_i))^3 \frac{A_i}{A_{\mathrm{tot}}}\right)\right)^{-2/3} \cdot v_{i,\,\mathrm{corr}}^2\cos(\phi_i)^2 \sin(\phi_i) \frac{A_i}{A_{\mathrm{tot}}}. \tag{B3}$$

The uncertainty in wind direction difference $\Delta\phi_i$ is assumed to be 1° according to Schneemann et al. (2021). The uncertainty of the density-corrected wind speed, however, is composed of the uncertainty of the measurement itself as well as the computed density. Thus the combined uncertainty reads

$$\Delta v_{i,\mathrm{corr}} = \sqrt{\left(\frac{\partial v_{i,\,\mathrm{corr}}}{\partial v_i}\cdot \Delta v_i\right)^2 + \left(\frac{\partial v_{i,\,\mathrm{corr}}}{\partial \rho}\cdot \Delta \rho\right)^2} \tag{B4}$$

with

$$\frac{\partial v_{\mathrm{corr}}}{\partial v_i} R \frac{\partial v_{\mathrm{i,corr}}}{\partial v_i} = \left(\frac{\rho(z)}{\rho_0}\right)^{1/3} \quad \text{and} \quad \frac{\partial v_{i,\,\mathrm{corr}}}{\partial \rho} = \frac{1}{3}\frac{\rho(z)}{\rho_0}^{-2/3} v_i \rho(z)^{-2/3} \rho_0{}^{-1/3}. \tag{B5}$$

Following Schneemann et al. (2021) we assume an uncertainty of the wind speed of $\Delta v_i = \pm 0.1\,\mathrm{ms}^{-1}$. The Gaussian propagated uncertainty for the density reads as

$$\Delta \rho = \sqrt{\left(\frac{\partial \rho}{\partial T}\Delta T\right)^2 + \left(\frac{\partial \rho}{\partial p}\Delta p\right)^2 + \left(\frac{\partial \rho}{\partial \Phi}\Delta \Phi\right)^2} \tag{B6}$$

with

$$\frac{\partial \rho}{\partial T} = -\frac{1}{T^2}\left(\frac{p(z)}{R_0} - \Phi P_{\mathrm{W}}\left(\frac{1}{R_0} - \frac{1}{R_{\mathrm{W}}}\right)\right), \tag{B7}$$

$$\frac{\partial \rho}{\partial p} = \frac{1}{RT} \quad \text{and} \tag{B8}$$

$$\frac{\partial \rho}{\partial \Phi} = \frac{P_{\mathrm{W}}}{T}\left(\frac{1}{R_0} - \frac{1}{R_{\mathrm{W}}}\right). \tag{B9}$$

For the humidity measurements an uncertainty of $\Delta\Phi = \pm 1\,\%$ is specified. As the height dependent temperature is obtained via the assumption of a simple linear decrease, the uncertainty is specified as $\Delta T(z) = \Delta T_0 = \pm 0.4\,°\mathrm{C}$. The height corrected pressure, however, is dependent on the pressure and temperature measured at the transition piece. Hence, its uncertainty is again obtained via Gaussian error propagation as

$$\Delta p(z) = \sqrt{\left(\frac{\partial p(z)}{\partial p_0}\Delta p_0\right)^2 + \left(\frac{\partial p(z)}{\partial T_0}\Delta T_0\right)^2} \tag{B10}$$

with

$$\frac{\partial p(z)}{\partial p_0} = \left(\left(1+\frac{L}{T_0}\right)(z-z_0)\right)^{g/LR_0} \tag{B11}$$

$$\frac{\partial p(z)}{\partial T_0} = -\frac{L}{T_0^2}\frac{gp_0}{(1+L/T_0)R_0}\left((z-z_0)\left(\frac{L}{T_0}+1\right)\right)^{-g/LR_0} \tag{B12}$$

and the measurement uncertainties $\Delta T_0 = \pm 0.4\,°\mathrm{C}$ and $\Delta p_0 = \pm 0.1\,\mathrm{hPa}$.

Author contributions. JP conducted the main research and wrote the majority of the manuscript. JS planned, conducted, executed and supervised the measurement campaign, provided extensive feedback on the data analysis and the manuscript, contributed to the scientific discussion and wrote parts of the appendix. GS provided significant feedback in reviewing the manuscript and on the data analysis and significantly contributed to the scientific discussion. FT supervised the measurement campaign, provided support by reviewing the manuscript and contributed to the scientific discussion. MK supervised the work, contributed to the scientific discussion and provided significant feedback in reviewing the manuscript.

Competing interests. The authors declare no competing interests.

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