

The LOLland offshore Lidar EXperiment (LOLLEX): A novel observational approach for the study of wind farm flow and entrainment

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Abstract.

Vertical momentum entrainment above offshore wind farms plays a key role in the recovery of wind turbine and ~~wind-farm wakes~~wind-farm wakes, but remains poorly documented by field measurements. The LOLland offshore Lidar EXperiment (LOLLEX) campaign introduced a novel measurement approach to address this knowledge gap. The primary objective of this campaign was to develop a new atmospheric measurement strategy to characterise and quantify the vertical momentum entrainment inside and outside an offshore wind farm using Doppler wind lidar technology. LOLLEX was conducted from September 2022 to ~~September~~August 2023 in Denmark, in and around the Rødsand II wind farm, just south of the island of Lolland. During this campaign, two pulsed Doppler wind lidars, a scanning ~~and a profiling instrument~~lidar (WindCube100S) and a lidar wind profiler (WindCubeV2), were deployed onboard a crew transfer vessel (CTV) commuting daily between the harbour and the Rødsand II offshore wind farm~~Rødsand-II~~. Additionally, a scanning pulsed Doppler wind lidar (Halo Photonics) was mounted on a transformer platform north of the wind farm to perform range height indicator scans across the farm. ~~Motion-corrected mean Horizontal~~ wind speed data were collected up to 300 m above the sea surface by the ~~profiler-lidar~~lidar wind profiler. The scanning lidar on the CTV collected data up to 2.5 km, alternating between the wind profiling mode and vertical stare mode. The latter scan operated ~~with~~at a sampling frequency of 1 Hz and along-beam spatial resolution of 10 m, allowing for the study of the turbulent vertical wind velocity component. The dataset includes several thousand hours of vertical scans. As a result of the moving vessel, many of the observations occurred inside or ~~in the close vicinity of the~~near the wind farm, providing insight into the near and far wakes of individual and multiple turbines. The potential and limitations of the new measurement strategy ~~is~~are illustrated using four case studies: (1) the observation of a ~~Kelvin-Helmholtz~~Kelvin-Helmholtz instability above the wind farm, examined further in a companion paper; (2) turbulent mixing propagating downward from the top of the boundary layer, enhancing momentum entrainment; (3) internal atmospheric waves and (4) wake characterisation inside the wind farm using the range-height indicator scans from the lidar deployed on the platform. This work demonstrates a novel methodology integrating remote sensing with a mobile offshore platform to measure turbulence at unprecedented altitudes.

The dataset offers valuable data for wind energy research, boundary-layer meteorology, and further development of atmospheric measurement techniques.

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1 Introduction

The European Union aims to commission at least 300 GW of offshore wind capacity by 2050, compared to 19 GW in 2023 (European Commission, 2023). Achieving this target requires a significant increase in the speed and scale of turbine deployment.

30 Due to limited available space in the North and Baltic Seas, wind farms are being built in increasingly dense configurations, intensifying turbine interactions and wake ~~effects~~ losses (Borgers et al., 2025). Wake losses refer to the reduction in power output caused by turbine interactions within a wind farm or between farms. Within a farm, downstream turbines operate in the slower, more turbulent air generated by upstream turbines. These wake effects reduce annual energy production (~~AEP~~), complicate farm layout design, and thus increase the levelized cost of energy (~~LCOE~~) (Akhtar et al., 2021; Pryor et al., 2021; Minz et al., 2025).
35 They may also ~~influence legal frameworks~~ pose legal challenges (Finserås et al., 2024) and affect electricity market integration (Kenis et al., 2023). Coupled mesoscale-microscale wind models and analytical wake models (~~AWMs~~) have been widely used to quantify wake losses, assess wake extent, and support AEP and LCOE optimisation (Sanz Rodrigo et al., 2017; Pryor et al., 2021; Haupt et al., 2023; Wang et al., 2024).

~~Beyond a certain scale,~~

40 Wake recovery is governed by momentum entrainment, encompassing both vertical and lateral contributions, and referring to the turbulent transport of momentum into the wake. This process replenishes the kinetic energy extracted by turbines and is therefore a key mechanism controlling wake recovery. Following van der Laan et al. (2023), momentum entrainment can be expressed as the divergence of the Reynolds shear stresses. Under this definition, wake recovery is ~~governed primarily by vertical momentum entrainment from~~ driven mainly by the lateral and vertical gradients of these stresses.

45 Momentum entrainment has been quantified using computational fluid dynamics and associated bulk formulations based on velocity differences across an interface and entrainment coefficients (Bempedelis et al., 2023), with further support from Large Eddy Simulations and limited field data (Calaf et al., 2010; Luzzatto-Fegiz and Caulfield, 2018). This process is sustained by turbulent transport from the atmospheric boundary layer (ABL) into the internal boundary layer (IBL), which replenishes the kinetic energy within the farm (~~Frandsen, 1992; Abkar and Porté-Agel, 2013; Calaf et al., 2010; Porté-Agel et al., 2020; Meneveau, 2019; I~~
50 ~~, as sketched in Fig. ??). However, current wind farms seem not to have reached this scale and cannot be considered infinite (Syed et al., 2023). Vertical momentum entrainment has been modelled for both finite and idealised (infinite) wind farms, with validation from Large Eddy Simulations (LES) and limited field data (Calaf et al., 2010; Luzzatto-Fegiz and Caulfield, 2018; ?)~~ . However, direct observations of this process in offshore environments remain (~~Frandsen, 1992; Abkar and Porté-Agel, 2013; Porté-Agel et~~

However, the quantification of the momentum entrainment from field measurements, particularly above offshore wind farms, remains scarce (Meneveau, 2019; Giebel et al., 2021; Syed et al., 2023; Krishnamurthy et al., 2025).

~~Schematic of vertical momentum entrainment from the ABL into the IBL of a wind farm.~~

~~Accurately capturing entrainment and wake recovery processes requires advanced observational tools. Remote sensing has played a key role, with Doppler wind lidar~~ Commercial Doppler wind lidars (DWL) (Käsler et al., 2010; Krishnamurthy et al., 2017), ~~Doppler radar~~ (Hirth et al., 2015; Ahsbahs et al., 2020), airborne measurements (Syed et al., 2023), and synthetic aperture radar (Platis et al., 2018; Ahsbahs et al., 2020; Finserås et al., 2024) all providing valuable data.

In wind energy science, commercially available DWL profilers and scanners are commonly used. Profiler lidars are primarily deployed have increasingly been used in wind energy since the 2000s (Peña et al., 2013; Slinger and Harris, 2013; Gottschall et al., 2017). To the authors' knowledge, however, DWLs have seldom been used to observe and quantify momentum entrainment in the ABL. Lidar wind profilers are primarily used to measure mean wind speed profiles in the first 300 m above the surface (Hasager et al., 2008). In contrast, long-range-long-range scanning lidars can provide additional insights into mean and turbulent flow characteristics with ranges extending several kilometres (Lothon et al., 2006; Cheynet et al., 2017c). The scanning DWLs can operate in various modes, including Doppler beam swinging (DBS) for wind profiling, range-height indicator scans (RHI), plan-position indicator (PPI), and fixed line-of-sight scans. Yet most offshore DWL deployments rely on fixed platforms like met masts or substations (Krishnamurthy et al., 2017), limiting Most offshore DWLs are deployed on fixed offshore infrastructure such as substations or platforms supporting bottom-fixed meteorological masts (Krishnamurthy et al., 2017), which limits spatial coverage. Although profiler lidars lidar wind profilers have been deployed on floating buoys or vessels (Gottschall et al., 2017, 2018; Kelberlau and Mann, 2022; Rubio et al., 2022), they are generally often used to measure the mean wind speed at limited heights. Scanning lidar deployments and direction only, and scanning lidars are rarely deployed on vessels or buoys are rare, despite their potential to capture the structure of the atmosphere above offshore wind farms, including vertical momentum entrainment (Abkar and Porté-Agel, 2013; Luzzatto-Fegiz and Caulfield, 2018; Syed et al., 2023).

To address this gap, we present a new measurement strategy using two DWLs mounted on a crew transfer vessel (CTV). This dual-lidar approach combines a lidar wind profiler and a scanning wind lidar in vertical stare mode. This mobile setup allows flexible positioning near or inside the wind farm, providing wind speed profiles and high-resolution-high-resolution vertical velocity measurements. This combination provides enhanced capability for studying the offers the possibility to study atmospheric boundary layer physics, including wake recovery and vertical momentum entrainment compared to a fixed lidar or a ship-based lidar wind profiler, inside and above offshore wind farms.

This paper This study provides an overview of the LOLand-offshore Lidar EXperiment (LOLLEX) LOLLEX campaign, conducted from September 2022 to September-August 2023 at the Rødsand II wind farm in Denmark and presents the potential of the collected dataset in the form of collected dataset through selected case studies. It Motion-compensated Doppler wind lidar measurements from moving platforms have been demonstrated in recent studies (e.g. Duscha et al., 2022; Pichugina et al., 2026). The LOLLEX campaign constitutes an independent offshore implementation in which two pulsed Doppler wind lidars operated simultaneously on a routinely transiting crew transfer vessel. This allowed repeated in-motion profiling of wind speed and turbulence within and around an active offshore wind farm to investigate vertical momentum entrainment.

This paper starts with the campaign description in Section 2, including site characterisation, instrumentation and the selected
90 lidar measurement setup. Section 3 ~~describes then describes the methods used in this study, including data processing and~~
~~quality control, motion correction, and the data-processing-workflow, including motion compensation, data filtering, and the~~
~~complementary use of the mesoscale wind database NORA3 alongside remote sensing observations~~approach developed to
quantify vertical momentum entrainment. Furthermore, Section 4 summarises the collected ~~data-dataset~~ and its availability, ~~and~~
Section 5 presents the motion correction results for the overall campaign and four case studies, ~~three based on the scanning~~
95 ~~lidar-lidars~~ mounted on the CTV and one from the scanning lidar installed on the transformer platform. Finally, Section 6
~~evaluates-discusses~~ the potential and limitations of the current measurement setup in comparison with DWLs deployed on fixed
platforms or buoys.

2 Campaign description

The LOLLEX measurement campaign was carried out between September 2022 and ~~September~~-August 2023 as a collaborative
100 effort between the MSCA-ITN project Train²Wind, funded by the EU Horizon 2020 scheme, and the RWE group. The main
goal of Train²Wind was to advance the understanding of entrainment processes relevant for large offshore wind farms. The
choice of Rødsand II was mainly guided by logistical considerations, such as the accessibility of a well-suited CTV and the
well-positioned transformer platform. Its proximity to the land was an additional factor, as the initial experiment plan also
included considerable complementary measurement activities using various uncrewed aerial systems. However, most of these
105 activities could not be performed as intended due to regulatory ~~challenges~~constraints.

2.1 Experiment site

The Rødsand II wind farm (54.5799[°]N, 11.8903[°]E), in operation since 2010, is located in the shallow ~~Danish~~-waters of the
Baltic Sea, south of the island of Lolland ~~and close to the German border~~ (Fig. 1). The farm consists of 90 Siemens SWT-2.3-93
turbines, each with a nominal capacity of 2.3 MW, a hub height of 68.5 m, and a rotor diameter (D) of 93 m. The farm is
110 arranged in five curved rows of 18 turbines each, with ~~inter-turbine-inter-turbine~~ spacing ranging between 5D and 8D (see also
the bottom panel of Fig. 4). Approximately 3 km to the east lies the Nysted wind farm, commissioned in 2003, comprising 72
Bonus 2.3 MW turbines with a spacing ranging from 6D to 10D. The nearest landmass, the island of Lolland, is characterised by
low-lying, flat terrain with sandy beaches, coastal dunes, agricultural fields, small settlements, and patches of forest. The region
experiences high average wind speeds of about 9.6 m s⁻¹ at 100 m, predominantly from the west to the south-west, influenced
115 by weather systems passing over the North Sea and Baltic Sea (Davis et al., 2023, see also <https://globalwindatlas.info/en/>).

During more than a decade, Rødsand II and Nysted have been used for studies on the interaction between atmospheric
flow and wind farm arrays, in particular wind turbine wakes and wind farm interactions, also called cluster effect (Hansen
et al., 2015). Previous studies focusing on wake loss for these two farms used simulations alone (Nygaard and Hansen, 2016),
combined SCADA data and numerical simulations (Hansen et al., 2015; Fischereit et al., 2022) or simulation and mast-based
120 measurements (Cleve et al., 2009).

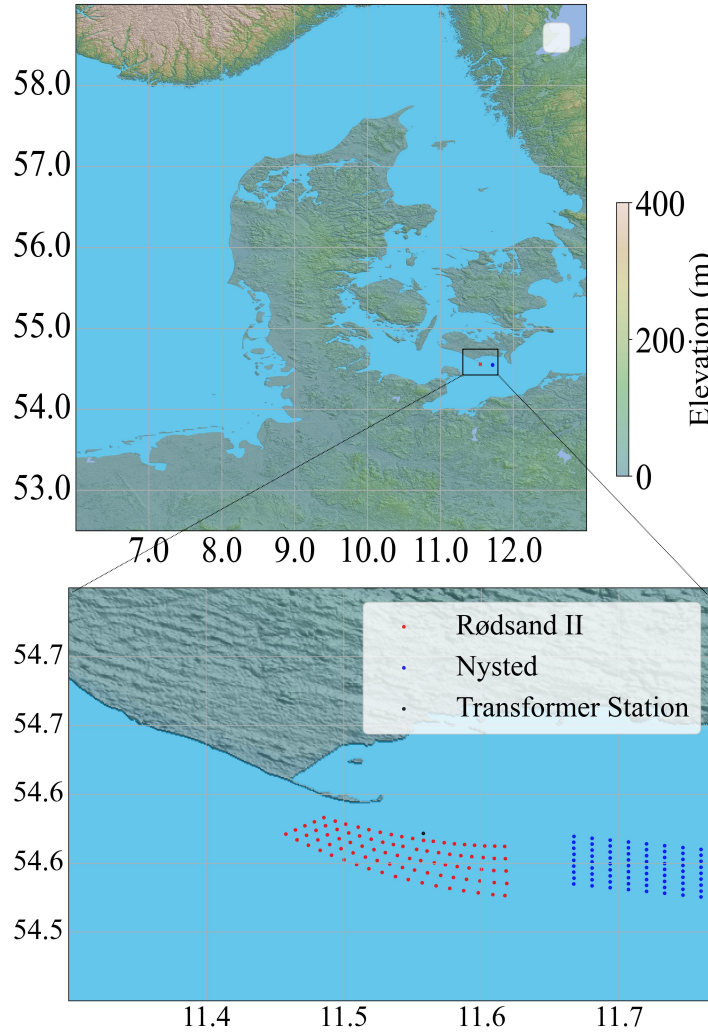


Figure 1. The location of the Rødsand II wind farm in the shallow waters of the Baltic Sea, south of Denmark, near the island of Lolland. This wind farm is located adjacent to the Nysted wind farm. This map was created using Rasterio (an open-source Python library by MapBox) version 1.4.2 (<https://rasterio.readthedocs.io/>). The digital elevation model was obtained from SRTM data V4, provided by the International Centre for Tropical Agriculture (CIAT), available at <https://srtm.csi.cgiar.org> (Jarvis et al., 2008).

There have, however, been only a few measurement campaigns that have focused on wake flow characteristics and the structure of the ABL above Rødsand II. In 2013–2014, a scanning lidar campaign under the lead of the Carbon Trust Offshore Wind Accelerator program was performed. It was aimed at investigating wake flow and boundary layer dynamics at Rødsand II. Only a limited portion of the results from this campaign has, however, been openly published (Adams, 2015).

125 The LOLLEX campaign builds on these foundations and introduces several novel and complementary elements: a **long-range** long-range scanning lidar deployed on the offshore transformer platform north of the wind farm and a dual **seanning–profiling**

scanning-profiling lidar setup mounted on a CTV as an observational platform of opportunity. ~~The WindCube lidars were provided by the national Norwegian research infrastructure OBLO (Offshore Boundary Layer Observatory) operated by the University of Bergen (UiB), and the lidar on the transformer platform was supplied by the Technical University of Denmark (DTU Wind and Energy Systems).~~

To complement the lidar data, high-resolution mesoscale wind speed data from the 3-km Norwegian Hindcast Archive (NORA3) (Haakenstad et al., 2021) were used. NORA3 is a ~~state-of-the-art~~ state-of-the-art hindcast dataset produced by dynamically downscaling ERA5 reanalysis data (Hersbach et al., 2020). It provides hourly wind conditions over Northern Europe at a horizontal resolution of 3 km. The dataset has been validated against both in-situ observations (Solbrekke et al., 2021) and remote sensing data (~~(?)~~) (Cheynet et al., 2025), demonstrating excellent performance in coastal and offshore environments.

During the LOLLEX campaign, a specific subset of the NORA3 database, containing wind speed data at seven vertical levels from 10 m to 750 m, was used in combination with the lidar observations above the wind farm, as shown in Malekmohammadi et al. (2025). It was also used to complement the Range Height Indicator (RHI) scans from the lidar installed on the transformer platform (see ~~section~~ Section 5).

2.2 Instrumentation

The backbone of the campaign was the installation of two DWLs onboard a CTV serving the Rødsand II wind farm, using it as an observational platform of opportunity. This mobile measurement ~~set-up~~ set-up over several months was complemented by the shorter fixed deployment of an additional scanning lidar system on the transformer platform of the wind farm.

2.2.1 Lidar deployment on the CTV

In September 2022, the WindCubeV2 was installed on the stern of a 27 m long and 10 m wide CTV, which operated nearly daily between Rødby harbour and the Rødsand II offshore wind farm for the transport of personnel and material for maintenance purposes. The vessel operations are typically performed between 7:00 am and 7:00 pm, providing up to 12 hours of wind field observations offshore, inside and around the farm. The lidar was installed with its ~~east-facing~~ east-facing side oriented toward the bow ~~-(see Fig. 2)~~. From September 2022 to January 2023 the WindCube100S remained onshore, deployed in the parking area of RWE Wind Services Denmark at the quay in Rødbyhavn, allowing for ~~night-time co-located~~ night-time co-located measurements while the CTV was in harbour. The second phase of the LOLLEX campaign started in the last week of January 2023 with the installation of the WindCube100S on the CTV side-by-side with the WindCubeV2 (Fig. 2).

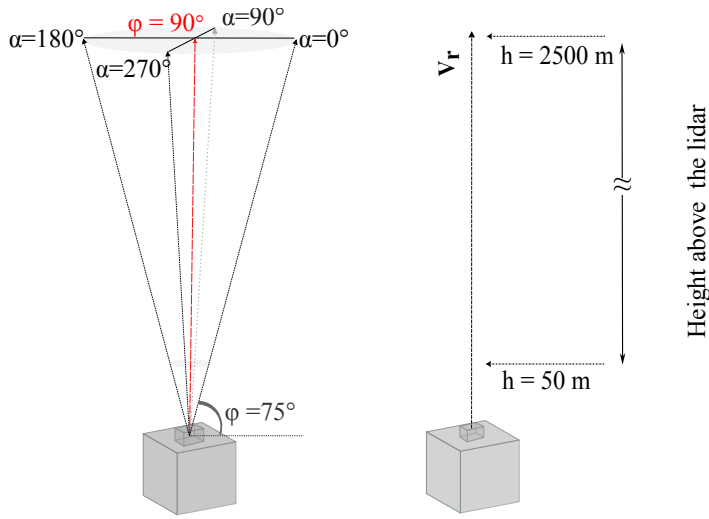
The WindCubeV2 measured wind speed and direction at 11 heights, ranging from 40 m to 290 m, ~~with~~ at a sampling frequency of 0.25 Hz. The system included a motion sensor and an Inertial Measurement Unit (IMU) that recorded attitude data at 10 Hz. The IMU tracked pitch, roll, yaw, and translational velocities in the x , y , and z directions, as well as GPS coordinates (latitude, longitude, altitude). ~~It~~ The IMU also provided the vessel's heading using GPS True Heading. In the WindCube V2, the IMU is part of an integrated unit linked to a differential GPS (GNSS). This configuration indicates that the reported position and attitude are not based on a purely inertial solution; instead, the inertial measurements are constrained by GPS, which limits the accumulation of low-frequency drift over time.



Figure 2. Location of the WindCubeV2 and WindCube100S lidars mounted on the stern of the CTV. Azimuth angles were defined relative to the vessel's heading and corrected using GPS true heading from the IMU.

160 The WindCube100S is a scanning lidar with a scanner head possessing hemispherical scanning capability. ~~It operated at~~
~~1-Hz sampling frequency, at ranges between 50 m and about 2500 m. The instrument followed a 30-minute~~
~~The instrument~~
~~operated on a 30-min~~ scan cycle alternating between two modes. ~~At full and half hour, it performed:~~ 5 minutes of ~~Doppler~~
~~Beam Swinging (DBS) → DBS~~ for wind profiling (~~right-left~~ panel in Fig.3), ~~in-between it collected for 3) and~~ 25 minutes the
~~vertical-velocity component of vertical velocity measurements~~ in vertical stare mode (~~left-right~~ panel in Fig. 3). ~~This schedule~~
165 ~~provided an appropriate balance between robust turbulence statistics and reliable mean wind profiles with sufficient temporal~~
~~resolution. In DBS mode, the WindCube100S retrieved wind profiles up to 2 km above the surface, clearly exceeding the range~~
~~of the continuous profiling. The 5-min DBS duration, shorter than the 10-min averaging period commonly used in the wind~~
~~industry, was selected to maximise the duration of vertical stare measurements used for turbulence and entrainment analysis.~~
~~A comparison between 5-min and 10-min averages derived from the~~ WindCubeV2 ~~lidar showed only minor differences in~~
170 ~~mean wind speed, apart from the expected increase in statistical uncertainty for the shorter averaging period.~~

In vertical stare mode, ~~it measured vertical wind velocity by emitting a beam at a~~ which corresponds to a line-of-sight (LOS)
~~configuration with an elevation angle of $\varphi = 90^\circ$ elevation angle.~~ The range gate length was set to 25 m with 60% geometric
~~overlap, resulting in an effective range resolution of 10 m,~~ the lidar operated at a sampling frequency of 1 Hz at ranges between
50 m and about 2500 m. In DBS mode, the lidar operated using a five-beam scanning configuration. Four oblique beams were
175 ~~sequentially emitted at an elevation angle of $\varphi = 75^\circ$ and azimuth angles of $\alpha = (0^\circ, 90^\circ, 180^\circ, 270^\circ)$, followed by a vertically~~
~~pointing beam with an elevation angle of $\varphi = 90^\circ$ at ranges between 50 m and about 2500 m (Fig. 3). During each 5-min DBS~~
~~period, approximately 80 individual samples were collected, corresponding to an effective sampling frequency of 0.3 Hz. In~~
~~wind profiling mode, the lidar retrieves wind speed and wind direction. Both instantaneous estimates and 5-min time-averaged~~
~~products were computed in post-processing (see Section 3.3).~~



The scanning pattern of WindCube100S in vertical stare mode (left) and DBS-mode (right).

Figure 3. Schematic of the WindCube100S scanning configurations used in this study. Left: five-beam DBS mode with inclined beam with the elevation angle (φ) of 75° and four azimuth angles (α), plus a vertical beam with the elevation angle (φ) of 90° . Right: vertical stare mode with the elevation angle (φ) of 90° .

Both instruments were remotely accessible, and the lidar data were uploaded to a server daily. Field inspections and basic maintenance took place regularly, and during inspections, wind and motion data were also collected directly from the lidar software. As the scanning lidar does not support near real-time motion correction, motion correction algorithms were applied during post-processing using the IMU data for both systems (see Section 3.3).

2.2.2 Scanning lidar on transformer platform

To complement the ship-based measurements, a Halo Photonics by Lumibird StreamLine XR+ scanning Doppler lidar was deployed on the transformer platform located north of the wind farm from April to July-August 2023 (Fig. 4). The lidar was mounted at a height of approximately 25 m above sea level. It operated in RHI mode with at a fixed azimuth angle of 206° and elevation angles increasing from -1° to $+10^\circ$, at a range gate length of 12 m. With an angular speed of $1^\circ/\text{s}$ and an accumulation time of typically 0.5 s. The range gate length was 12 m, and a full RHI scan, including a fast return, took about 16 seconds.

The scan sector extended from north to south across the wind farm. This allowed for the observation of wake propagation during both westerly and easterly wind events. When the wind direction was in the plane where the ship-based lidars travelled, facilitating the interpretation of those measurements as well as providing a continuous data set for studies of intra-farm turbulence. For wind directions approximately perpendicular to the lidar's line of sight, the nearest turbine was

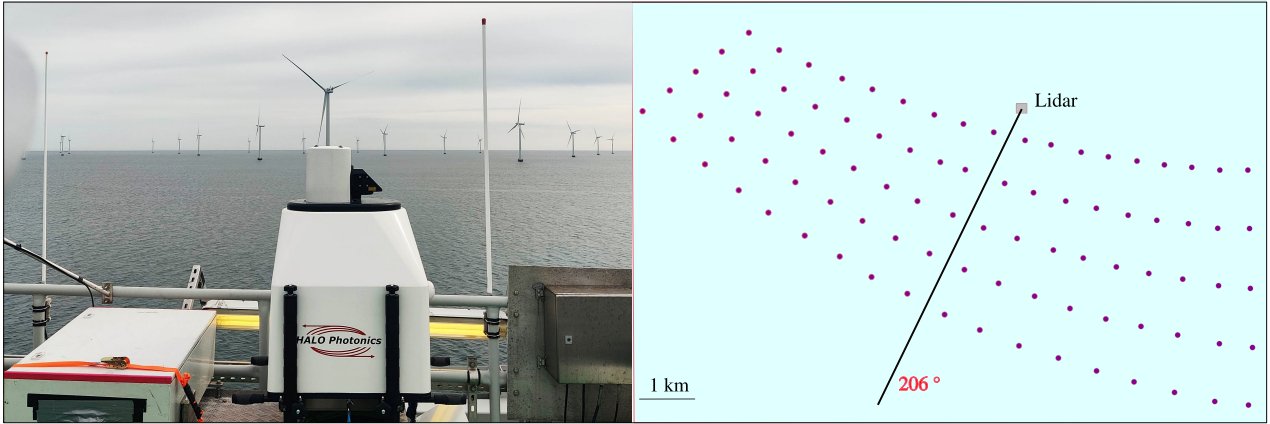


Figure 4. Left panel: The scanning lidar Halo Photonics by Lumibird StreamLine XR+ installed on the substation (view toward South). Right panel: Sketch of the lidar line of sight (top view) with an azimuth angle of 206° and a scanning range of 6 km.
~~Top panel: The scanning lidar Halo-Photonics by Lumibird StreamLine XR+ installed on the substation (view toward South). Bottom panel:~~
~~Sketch of the lidar line of sight (top view) with an azimuth angle of 206° and a scanning range of 6 km:~~

195 about 0.7 km away. ~~At that distance, and at that location~~ the lidar beam intersected the rotor area around 20 times per scan, yielding a vertical resolution of approximately 6 m within the wake. The farthest turbine was located 3.8 km away, where the beam crossed the rotor area only three times per scan direction, resulting in a vertical resolution of about 38 m (~~Fig. 5~~).

Fig. 5). At longer distances, ~~this the~~ decrease in vertical resolution reduced the accuracy of wake characterisation. The exact wake position and shape also varied with the wind direction and ~~turbine operating conditions~~ the operating conditions of the
 200 turbine, such as yaw misalignment and rotor tilt.

The RHI scan was selected to support the campaign’s focus on vertical momentum entrainment. The choice of only one RHI scan was made with the purpose of providing sufficient statistics of continuous data in the targeted plane. Nevertheless, since a DWL only measures the LOS speed component, this configuration imposes some limitations on the wind directions for which the wakes can be observed. In most cases, wake signatures are detectable, except when the wake’s lateral cross-section
 205 is exactly aligned with the RHI plane. In that case, the lidar cannot detect any component of the axial wake flow.

3 Methods

This section describes the motion correction algorithm applied to the data collected by the lidar wind profiler WindCubeV2 deployed on the CTV. It also introduces a new method to correct for the static tilt angle error of the WindCube100S in vertical stare mode. Finally, it details the pre-processing steps for filtering the data and dismissing the erroneous data.

210 3.1 Data processing and quality control

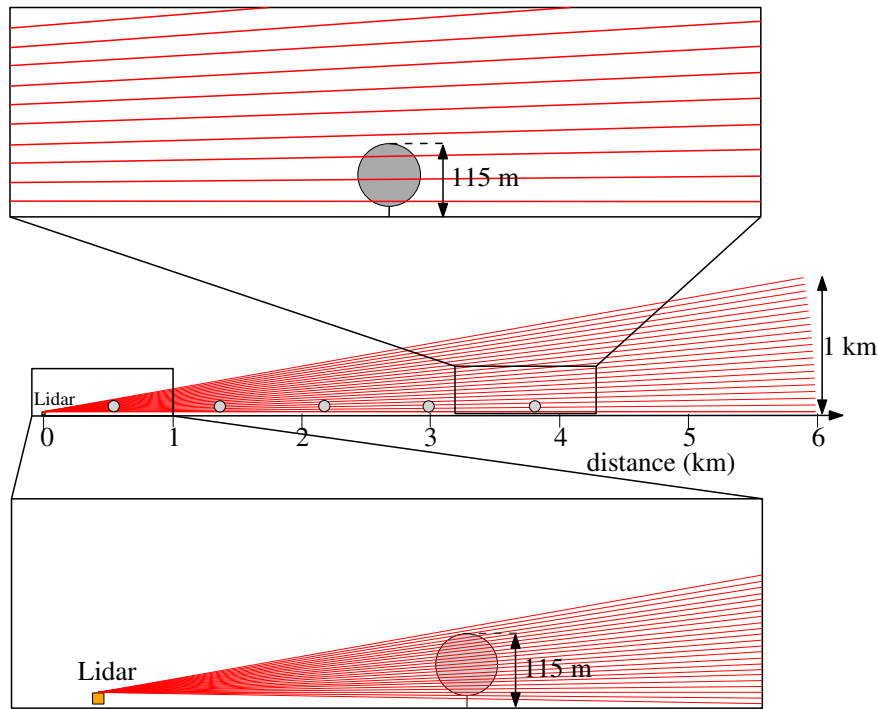


Figure 5. Sketch of an RHI scan in the case where the wake direction is perpendicular to the azimuth. The turbine rotors are indicated as grey circles. The inset sketches the lidar beams crossing the rotor plane at different distances: at around 3.8 km (top inset) and 0.7 km (bottom inset) from the lidar.

~~In a first processing step, all~~ The WindCube100S occasionally produced short or incomplete scans when deployed on the vessel, likely due to its sensitivity to rapid translation and acceleration. This can be attributed to its mechanically rotating scanning head for beam steering, in contrast to the WindCubeV2 Offshore, which operates without moving parts and is designed for dynamic buoy deployments. For the vertical staring mode conducted between 2023-01-25 and 2023-08-28 (approximately 9,900 scans), 65% of the WindCube100S scans were flagged as incomplete (scan duration < 10 min) and excluded, while 30% achieved the full 25-min duration.

~~All~~ lidar measurements were ~~subject to standard quality control procedures, as signal-to-noise filtering and outlier removal, to identify~~ subjected to a two-step quality control procedure to ensure high-quality data for further analysis. ~~For the ship-based lidar systems, additional motion correction was performed.~~

Both, the WindCubeV2 and WindCube100S lidars provide a Carrier-to-Noise ~~In the first step, a signal-quality filtering was applied using the Carrier-to-Noise~~ Ratio (CNR), which is commonly used to assess signal quality. ~~Measurements were filtered using a CNR threshold provided by both the WindCubeV2 and WindCube100S. A fixed CNR threshold was applied at each location and time step~~ time and range gate to remove low signal-to-noise measurements. Following earlier studies (Kumer et al., 2014; Cheynet et al., 2017c; Suomi et al., 2017), ~~a threshold of -24 dB was used~~ thresholds of -24 dB for the WindCubeV2

225 ~~-, and -27 and -27 dB for the WindCube100S. When deployed on the vessel, the WindCube100S occasionally produced short or incomplete scans, likely due to its sensitivity to rapid translation and acceleration. Unlike the WindCubeV2, which is designed for dynamic conditions on buoys, the WindCube100S is not optimised for mobile offshore deployments. Despite these limitations, a large number of high-quality scans were obtained, providing valuable measurements within the wind farm. Outlier removal was accomplished by were used.~~

230 ~~In the second step, statistical outliers were removed using a moving median absolute deviation filter, following the recommendation by (MAD) filter with 3 MADs away from the median, following Starkenburg et al. (2016) and Leys et al. (2013). Following filtering and,~~ to eliminate spurious values that passed the CNR threshold but were inconsistent with local temporal variability.

~~After signal-quality filtering and statistical outlier removal, data availability was range-dependent. That is, within a given scan, valid data could be retained at lower ranges while being filtered out at higher ranges. Therefore, data availability could not~~

235 ~~be represented by a single campaign-wide percentage. After quality control,~~ motion correction was applied to the WindCubeV2 data and to the ~~DBS-mode DBS-mode~~ scans of the WindCube100S, as described in Section 3.2. ~~Unless otherwise stated, all results presented in this manuscript are based on motion-corrected wind speed data.~~

~~The Following Päsche et al. (2015), a signal-to-noise ratio (SNR) threshold of -20 dB is commonly recommended for radial velocity data from the Halo Photonics StreamLine XR+ operating in RHI mode is filtered using the signal-to-noise ratio (SNR) percentiles and the velocity distribution. First, values with SNR above the 99th percentile or below the 1st percentile are removed. Then, a probability density function of the remaining velocity data is estimated. In the present case, this threshold appeared overly conservative. The lidar data were used solely for mean wind speed estimation, and the beam was frequently oriented at angles close to 90° relative to the mean wind direction, resulting in generally low SNR values. In addition, the SNR was originally provided on a linear scale, with a substantial fraction of values being negative, preventing a consistent~~

245 ~~conversion to dB.~~

~~For case study 4, a moderate correlation ($\rho \approx -0.63$) was found between the SNR and $|v_r - v_0|$, where v_r is the along-beam (radial) velocity and v_0 denotes the most probable radial velocity. However, substantial overlap between low- and high-deviation data across the SNR range indicates that SNR alone is not a reliable indicator of data quality. Consequently, no SNR-based filtering was applied. Radial velocity data were first filtered to remove implausible values by discarding samples with $|v_r| > 30 \text{ m s}^{-1}$.~~

250 ~~The most frequent (peak) velocity is identified from the probability density function. Only velocity values within a band around this peak are kept. The bandwidth is set to $\pm 8 \text{ m s}^{-1}$ around the peak velocity. All data outside this range are set to NaN and excluded from further analysis. probable radial velocity v_0 was then estimated as the mode of the v_r distribution. Only samples satisfying $|v_r - v_0| < k \text{ MoAD}$ were retained, where $\text{MoAD} = \text{median}(|v_r - v_0|)$ denotes the median absolute deviation about the modal radial velocity v_0 , and $k = 3$ is a dimensionless threshold parameter.~~

255 3.2 Motion correction for ~~lidar wind profiler~~DBS scans

A lidar wind profiler mounted on a moving platform, such as a buoy or ship, is subject to six degrees of freedom (DOF) of motion. These include translational movements, such as surge, sway, and heave along the platform's x , y , and z axes, as well as rotational movements, such as roll (β), pitch (φ), and yaw (ψ) around these respective axes. These motions alter the measurement

260 geometry and introduce artificial velocity components that affect both the observed radial wind ~~speed~~ (v_r velocity (v_r)) and the reconstructed three-dimensional wind vector ($\hat{u}$).

For a ~~stationary platform~~ lidar mounted on a buoy, the 10-minute average wind speeds are only marginally impacted (typically by 1–2%) due to averaging over ~~wave-induced periodic~~ quasi-random motion (Malekmohammadi et al., 2024; Kelberlau et al., 2020). However, instantaneous measurements can be significantly affected. Therefore, ~~robust~~ motion correction is essential when ~~high-resolution high-resolution~~ wind data is required, especially in offshore environments ~~or for applications such as wake studies or entrainment characterisation.~~

Several motion correction algorithms have been developed to compensate for the ~~motion-induced distortions~~ motion-induced errors in lidar measurements from floating platforms (Peña et al., 2013; Kelberlau et al., 2020; Wolken-Möhlmann et al., 2014; Bischoff et al., 2015). These efforts primarily target periodic wave-induced motions, typically observed in buoy-based systems. However, ~~ship-based ship-based~~ systems experience both rotational and ~~non-periodic non-periodic~~ translational motion patterns that can be challenging to correct with standard correction techniques.

In this study, we adopt the correction method described by Duscha (2024) and Malekmohammadi et al. (2024), which is suitable for periodic and aperiodic motion conditions. The algorithm corrects each lidar beam’s line-of-sight (LOS) velocity in two steps: (1) ~~Translational Motion Correction~~ translational motion correction: The platform’s instantaneous translational velocity vector $\mathbf{u}_T \mathbf{u}_t$, comprising surge, sway, and heave, is projected onto the beam direction and subtracted from the measured $v_r \mathbf{v}_r$; (2) ~~Rotational Motion Correction~~ rotational motion correction: At each time step, the platform’s orientation is used to construct a ~~composite~~ rotation matrix $\mathbf{R}$ based on the roll, pitch, and yaw angles. ~~This matrix transforms the wind vector into the lidar’s moving coordinate frame as~~

In the absence of motion, $\mathbf{u}$ at one altitude can be reconstructed using the $\mathbf{v}_r$ obtained from one full DBS scan of WindCube lidar and the beam direction matrix $\mathbf{N}$ as

280
$$\mathbf{v}_r = \mathbf{R}\mathbf{N}(\mathbf{N}^T\mathbf{u}), \quad (1)$$

~~where $\mathbf{v}_r$ is the vector of observed radial velocities, where $\mathbf{u}$ is the true wind vector in the inertial frame, $\mathbf{u}_T$ is the translational motion vector.~~ For a WindCube wind lidar operating with a 5-beam DBS setup, $\mathbf{v}_r$ and $\mathbf{R}\mathbf{N}$ is the product of $\mathbf{N}$ are defined as

$$\underline{\mathbf{v}}_r = \begin{pmatrix} v_r(\alpha = 90^\circ) \\ v_r(\alpha = 180^\circ) \\ v_r(\alpha = 270^\circ) \\ v_r(\alpha = 0^\circ) \\ v_r(\phi = 90^\circ) \end{pmatrix}, \quad (2)$$

$$\underline{\mathbf{N}} = \begin{pmatrix} \cos \phi & 0 & \sin \phi \\ 0 & \cos \phi & \sin \phi \\ -\cos \phi & 0 & \sin \phi \\ 0 & -\cos \phi & \sin \phi \\ 0 & 0 & 1 \end{pmatrix}, \quad (3)$$

with α being the azimuth angle and ϕ the beam elevation angle.

In the presence of motion, considering the translational and rotational motion, Eq. 1 can be rewritten as

$$\underline{\mathbf{v}}_r - \underline{\mathbf{v}}_{r,t} = \underline{\mathbf{N}} \underline{\mathbf{R}}(\underline{\mathbf{u}}), \quad (4)$$

where $\underline{\mathbf{R}}$ is the rotation matrix ~~$\underline{\mathbf{R}}$ and the beam direction matrix $\underline{\mathbf{N}}$. The~~, and $\underline{\mathbf{v}}_{r,t}$ is the projection of translational speed $\underline{\mathbf{u}}_t$ to the beam as

$$\underline{\mathbf{v}}_{r,t} = \underline{\mathbf{N}} \underline{\mathbf{R}}(\underline{\mathbf{u}}_t). \quad (5)$$

The rotation matrix $\underline{\mathbf{R}}$ is computed from the ~~time-resolved~~ time-resolved attitude data using standard Euler rotations ~~÷~~

$$\underline{\mathbf{R}}_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \beta & \sin \beta \\ 0 & -\sin \beta & \cos \beta \end{pmatrix}, \quad (6)$$

$$\underline{\mathbf{R}}_y = \begin{pmatrix} \cos \varphi & 0 & -\sin \varphi \\ 0 & 1 & 0 \\ \sin \varphi & 0 & \cos \varphi \end{pmatrix}, \quad (7)$$

$$\underline{\mathbf{R}}_z = \begin{pmatrix} \cos \psi & \sin \psi & 0 \\ -\sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (8)$$

~~These where~~ β , φ , and ψ correspond to roll, pitch, and yaw in the inertial coordinate system. These matrices are combined as $\underline{\mathbf{R}} = \underline{\mathbf{R}}_z \underline{\mathbf{R}}_y \underline{\mathbf{R}}_x$ to account for the platform's full attitude. The best estimate of the corrected wind vector ($\underline{\mathbf{u}}$) is then obtained by ~~least-squares inversion:~~ using the least-squares method:

$$\hat{\mathbf{u}} = [(\underline{\mathbf{R}}\underline{\mathbf{N}})^T \underline{\mathbf{R}}\underline{\mathbf{N}}]^{-1} (\underline{\mathbf{R}}\underline{\mathbf{N}})^T (\underline{\mathbf{v}}_r - \underline{\mathbf{v}}_{r,t}). \quad (9)$$

300 where $v_{r,T} = \mathbf{R} \mathbf{N} u_T$.

Unlike earlier approaches limited to sinusoidal or low-frequency oscillations, the method applied here accommodates the erratic and multi-directional motions typical of ship-based lidar deployments. The efficacy of this algorithm has been validated under controlled conditions using a six-DOF motion platform (Malekmohammadi et al., 2024). Thus, this motion correction approach is well-suited for the deployment of DWLs on CTV or other vessels. In practice, the motion correction is implemented at each synchronised time step. For the WindCubeV2, one beam is recorded per second (5 s per complete five-beam scan), whereas for the WindCube100S, one beam is recorded every 3 s (15 s per scan). To ensure temporal consistency, both radial velocities and motion signals (translational velocities and attitude angles) are interpolated onto a common 1 Hz time base. This enables temporal collocation and synchronisation of the five beams forming each scan. The correction is then applied simultaneously to each synchronised beam set using the corresponding rotation matrix and translational velocity vector, and the wind vector is retrieved via Eq. 9. Although wind vectors are computed at 1 Hz after interpolation, this upsampling does not introduce additional physical information and is used only for subsequent statistical aggregation (e.g., mean estimates).

3.3 Static tilt correction for scanning lidar vertical staring scans

In this study, lidars operating on a moving platform the WindCube100S operates in DBS mode emit four to twice per hour using five beams, which result in four to yielding five equations for the three unknown wind components (u , v , and w). Due to this redundancy, which enables dynamic motion correction of the retrieved wind speed scan be corrected for motion. Nevertheless, a correction of this type is not possible in the. When operating in vertical stare modes since there is, however, only one equation with three unknowns in the system of equations.

It is available, making such dynamic correction impossible.

Hereinafter, u , v , and w denote the along-wind, across-wind, and vertical velocity components in a streamline coordinate system as defined by Kaimal and Finnigan (1994). In Malekmohammadi et al. (2025), a method to correct for static tilt angle error was outlined presented and applied to a single 30-minute record. In the present study 30-minute scan. Here, we extend this method to multiple records static tilt correction to the full campaign duration to assess its robustness. We compare it (Fig. 6). We compare this correction to a simpler tilt angle correction method based on the assumption of a mean horizontal flow at 400 m above the surface, as well as to the case where no correction is applied and to the uncorrected case. For completeness, the method is summarised in the following below, and its performance is discussed.

In vertical stare mode, the LOS velocity component closely approximates the vertical velocity component, unless non-zero tilt angles are present tilt angles differ significantly from zero. The static (time-averaged) tilt angle can be estimated and used to correct the lidar-retrieved vertical velocity component. The method is inspired by the double rotation algorithm commonly used for tilt correction of sonic anemometers. In the present case, the equation is given by

330
$$\overline{w}_c = -\overline{u} \cdot \text{sign}(\overline{w}_{\text{uncor}}) \cdot \sin(\theta) + \overline{w}_{\text{uncor}} \cdot \cos(\theta),$$

where $\overline{w}_c$ is the corrected (Wilczak et al., 2001; Foken and Mauder, 2008). Prior to applying this correction, the horizontal wind components are rotated into a coordinate system aligned with the mean horizontal wind direction. In this wind-aligned

frame, yaw misalignment is removed, and the projection of the mean flow onto the vertical axis depends only on the inclination angle θ . The following formulation therefore represents a physically prescribed static tilt correction rather than a statistical double- or triple-rotation enforcing $\overline{w}$ to be zero. Hereinafter, the overline denotes temporal averaging; for example, $\overline{u}$ and $\overline{w}$ denote the mean along-wind and vertical velocity component, respectively.

The tilt-corrected vertical component $\overline{w}_c$ at height z is given by

$$\overline{w}_c = -\overline{u} \cdot \text{sign}(\overline{w}_{\text{uncor}}) \cdot \sin(\theta) + \overline{w}_{\text{uncor}} \cdot \cos(\theta), \quad (10)$$

where $\overline{u}$ is the mean horizontal wind speed at the same height, $\overline{w}_{\text{uncor}}$ is the uncorrected mean vertical velocity component recorded by the lidar (i.e., the along-beam velocity), and θ is the static tilt angle. Depending on the application, the equation can be solved for $\overline{w}_c$, $\overline{u}$, or the height-independent tilt angle θ , the latter being independent of height. The angle θ can be determined either through visual inspection of the lidar's inclinometer or estimated using $\overline{w}_c$ and $\overline{u}$ from the lidar wind profiler WindCubeV2, as done in Malekmohammadi et al. (2025). Both visual inspection and the application of eq. (10) using data from WindCubeV2 yielded, on average, a static tilt angle of $\theta = 2.7^\circ \approx 2.7^\circ$.

Figure ?? compares the vertical wind velocity from The tilt angle derived from visual inspections represents the initial geometric alignment. During operation, quasi-static changes in vessel attitude (e.g. due to varying mass distribution) may occur and introduce a vertical velocity bias of approximately $\overline{w}_{\text{bias}} \approx \overline{u} \sin \theta$. In principle, the effective static tilt angle can be estimated for each measurement period using the Eq. 10. In this study, however, a constant value of 2.7° is used for simplicity and to preserve high data availability.

Figure 6 presents the probability density function (PDF) of the vertical velocity difference between the WindCube100S and the WindCubeV2, using three different methods for tilt correction: no correction, a correction assuming $\overline{w} = 0$ at 400 m, and tilt correction with $\theta = 2.7^\circ$ ($\theta = 2.7^\circ$ derived from Eq. 10). The case from 21 February 2023 was selected because both the corrected WindCubeV2 and is used as the reference instrument due to its dedicated wind-profiling configuration, continuous DBS operation, lower mechanical complexity, and consequently higher robustness and lower measurement uncertainty compared to the scanning WindCube100S provided high-quality data, with excellent agreement in mean wind speed at 150 m. Five-minute moving average of the vertical (top) and horizontal (bottom) wind velocity components measured by the WindCubeV2 and WindCube100S at 150 m above the surface. The top panel compares three tilt correction approaches for the vertical component: a correction using $\theta = 2.7^\circ$ (Eq. 10), a method assuming zero mean vertical velocity at 400 m, and no correction.

The method based on Eq. 10 shows the best match with the mean vertical velocity measured by the WindCubeV2 lidar. The approach assuming zero PDF is computed from all available high-quality data collected between 2023-01-01 and 2023-07-12 (> 6000 samples). Without correction, the vertical wind velocity from the scanning lidar exhibits a positive bias, with a median of 0.28 m s^{-1} and values reaching up to 1 m s^{-1} . Applying a constant correction based on the assumption of zero mean vertical velocity at 400 m performs less well but still significantly reduces the bias. Without any correction, the vertical velocity from the scanning lidar shows a bias of up to 1 but over-corrects, resulting in a negative median of -0.20 m s^{-1} . The WindCube100S lidar is used here instead of the tilt-correction method based on Eq. 10 yields the lowest absolute bias (-0.05 m s^{-1}), the lowest root-mean-square error relative to the WindCubeV2 because it samples five times faster and measures up to 2.5 km, compared

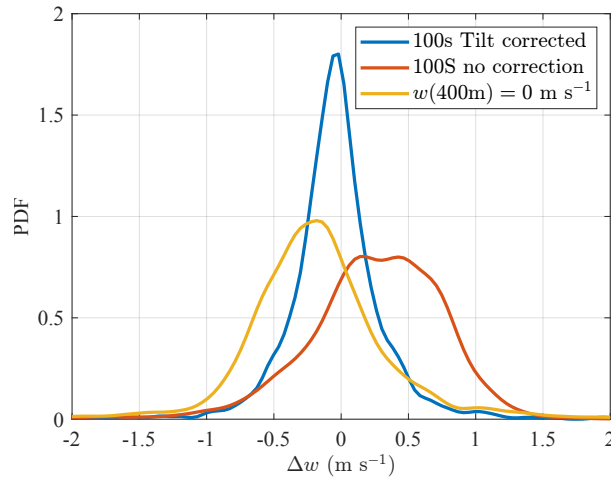


Figure 6. Probability density function (PDF) of the vertical velocity difference between the WindCube100S and the WindCubeV2 using data collected between 2023-01-01 and 2023-07-12 (> 6000 samples).

to 300 m for the WindCubeV2, thus producing a noticeably narrower PDF, indicating improved accuracy and precision compared to the other approaches. It should be noted that in turbulence analysis, velocity components are decomposed into mean and fluctuating parts using Reynolds decomposition

$$i = \bar{i} + i', \quad (11)$$

where $i = \{u, v, w\}$.

The static tilt correction is therefore applied to obtain an unbiased estimate of the mean vertical velocity without assuming it to be zero. This correction does not affect the turbulence statistics, as these are computed from the fluctuating component, which by definition has zero mean. Hereinafter, the scanning lidar data are shown with tilt correction using Eq. 10. While the mean velocity component is typically removed in turbulence analysis, correcting for static tilt bias is still essential hereto avoid misinterpreting physically meaningful vertical motions, such as those caused by entrainment or convection.

Periods with precipitation can occasionally introduce spurious vertical velocity signals in Doppler lidar measurements due to backscatter from falling hydrometeors (Aitken et al., 2012). Such events were rare in the dataset and were not analysed here, as this study focuses on mean flow and vertical turbulence in the marine atmospheric boundary layer and the associated momentum entrainment under typical atmospheric conditions.

3.4 Vertical momentum entrainment quantification from lidar measurements

In wind energy, momentum entrainment is defined as the divergence of Reynolds stresses that transports high-momentum fluid from the freestream into the wake and drives wake recovery (van der Laan et al., 2023). Denoting u', v', w' as the along-wind, across-wind, and vertical fluctuating velocity components, respectively, the streamwise, lateral, and vertical momentum entrainment

385 terms are defined as

$$\underline{\underline{E_x}} = - \frac{\partial \overline{u'u'}}{\partial x} \quad (12)$$

$$\underline{\underline{E_y}} = - \frac{\partial \overline{u'v'}}{\partial y} \quad (13)$$

$$\underline{\underline{E_z}} = - \frac{\partial \overline{u'w'}}{\partial z} \quad (14)$$

390 where $\underline{\underline{E_y}}$ (lateral entrainment) and $\underline{\underline{E_z}}$ (vertical entrainment) represent the dominant wake recovery mechanisms through spanwise and vertical stress divergence, while $\underline{\underline{E_x}}$ (normal stress divergence) represents streamwise turbulent diffusion and is typically much smaller than the combined lateral and vertical contributions.

In this study, $\underline{\underline{E_z}}$ is estimated from vertical profiles of the vertical velocity variance $\overline{w'w'}(z)$ and the mean wind speed $\overline{u}(z)$ using a turbulence closure in which the eddy viscosity is expressed as a function of turbulent kinetic energy and a mixing length. The momentum flux $\overline{u'w'}$ is first parametrised using a first-order flux-gradient relationship,

$$\underline{\underline{395}} \quad \overline{u'w'}(z) = -K_m(z) \frac{\partial \overline{u}}{\partial z}, \quad (15)$$

where K_m is the eddy viscosity for momentum and $\overline{u}$ denotes the mean along-wind velocity. The eddy viscosity is expressed in terms of the turbulent kinetic energy (TKE) and a mixing length as by Deardorff (1980); Mellor and Yamada (1982):

$$\underline{\underline{K_m(z)}} = c_\mu l(z) \sqrt{e(z)}, \quad (16)$$

400 where c_μ is a dimensionless constant and $l(z)$ is the mixing length. In the implementation used here, $c_\mu = 0.1$ (Deardorff, 1980; MacDonald). The mixing length $l(z)$ is specified using an asymptotic boundary-layer formulation with von Kármán constant $\kappa \approx 0.4$ following Blackadar (1962),

$$\underline{\underline{l(z)}} = \frac{\kappa z}{1 + \kappa z/l_\infty}, \quad (17)$$

$$\underline{\underline{l_\infty}} = ah, \quad (18)$$

405 where the parameter l_∞ represents the asymptotic mixing length; h is the atmospheric boundary-layer (ABL) height estimated using the CNR of the scanning lidar in vertical stare mode and $a \approx 0.085$ (Grenier and Bretherton, 2001; Cheng et al., 2020).

The TKE is defined as

$$\underline{\underline{e(z)}} = \frac{1}{2} (\overline{u'u'} + \overline{v'v'} + \overline{w'w'}), \quad (19)$$

where u , v , and w denote the instantaneous velocity components in the along-wind (x), cross-wind (y), and vertical (z) directions, respectively, and primes indicate turbulent fluctuations about the mean defined through Reynolds decomposition

410 (e.g., $u = \bar{u} + u'$). The TKE can be approximated as

$$e(z) \approx \frac{3}{2} \overline{w'w'}(z), \quad (20)$$

under the assumption of local isotropy. Under anisotropic conditions ($\overline{w'w'} \approx 0.3 \overline{u'u'}$ and $\overline{w'w'} \approx 0.6 \overline{v'v'}$), Eq. (20) remains of the same order of magnitude. Such anisotropy ratios are consistent with empirical atmospheric surface-layer (ASL) turbulence models based on Kaimal et al. (1972) and values reported by Solari and Piccardo (2001). In the present analysis, Eq. (20) is adopted for simplicity.

Substituting Eq. (20) into Eq. (16) yields

$$K_m(z) \approx c_\mu l(z) \sqrt{\frac{3}{2} \overline{w'w'}(z)}. \quad (21)$$

Finally, combining Eqs. (15) and (21), the turbulent momentum flux is estimated as

$$\overline{u'w'}(z) \approx -c_\mu l(z) \sqrt{\frac{3}{2} \overline{w'w'}(z)} \frac{\partial \bar{u}}{\partial z}, \quad (22)$$

420 from which the vertical momentum entrainment $E(z)$ is obtained using Eq. (14).

This formulation implicitly depends on the atmospheric state through the boundary-layer depth h , the turbulent kinetic energy e , and the vertical wind shear $\partial \bar{u} / \partial z$. In practice, Eq. (22) can be evaluated using different lidar configurations. In the dual-lidar setup, the WindCube100S in vertical stare mode provides $\overline{w'w'}(z)$, while the WindCubeV2 profiler delivers frequent and robust estimates of the mean wind profile and its vertical gradient $\frac{\partial \bar{u}}{\partial z}$. This configuration allows nearly simultaneous turbulence and shear measurements, improving the robustness of the entrainment estimate. Its limitation is the vertical range of the WindCubeV2, which is restricted to about 300 m.

Alternatively, the WindCube100S alone can be used by alternating between vertical stare mode (for $\overline{w'w'}$) and DBS mode (for $\bar{u}$ and $\frac{\partial \bar{u}}{\partial z}$). This extends the vertical coverage to about 1–1.5 km and enables entrainment estimates throughout a larger fraction of the ABL. However, the measurements are not simultaneous, and the DBS wind profiles are obtained less frequently than with the WindCubeV2, which may increase uncertainty under non-stationary conditions. The choice of sensor reflects, therefore, a trade-off between vertical spatial coverage and temporal resolution.

4 Data overview

This section provides an overview of the data collected during the LOLLEX measurement campaign. The campaign lasted about one year and produced approximately 6090 hours of WindCubeV2 measurements and 4500 hours of WindCube100S measurements, as shown in Figure 7. The dataset includes periods when the CTV was located in the harbour, in transit to or from the wind farm, and during mobile and stationary operations inside the wind farm. Approximately nine thousand RHI scans of 14 min were collected by the scanning lidar on the transformer platform, yielding over 2100 hours of data.

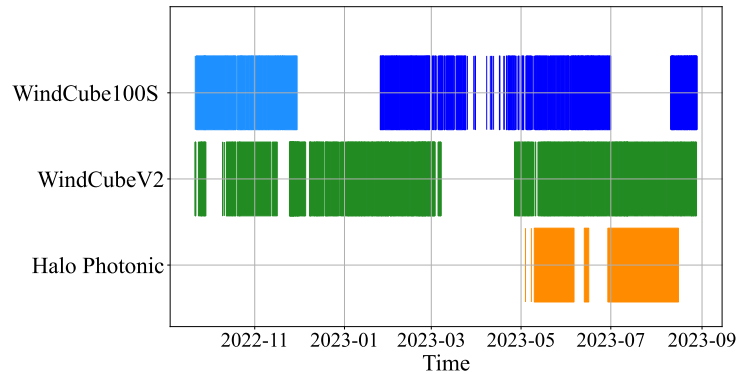


Figure 7. Periods of available data for the three lidars during the LOLLEX campaign: the WindCube100S scanning lidar (light blue when onshore, dark blue when on the CTV), the WindCubeV2 lidar ~~lidar~~ on the CTV (green), and the Halo Photonics StreamLine XR+ scanning lidar on the transformer platform (orange).

4.1 Data availability

Figure 7 shows the data availability of the WindCube100S, the WindCubeV2, and the Halo Photonics ~~by Lumibird StreamLine~~ XR+ (scanning lidar on the transformer platform) throughout the campaign. In 2022, the WindCube100S lidar was located in the harbour but had not yet been installed on the vessel. In January 2023, the WindCube100S was mounted on the CTV, allowing for direct measurements within the wind farm. For the WindCube100S, high data availability was recorded from September 2022 to July 2023, except during the period between December 2022 and January ~~2023 when the lidar was being installed on the CTV.~~ 2023. The WindCubeV2 exhibited even higher availability, with only one significant gap in April 2023. The scanning

445 lidar on the platform recorded reliable data from May to August 2023. As a result, overlapping measurements from all lidar systems were available between May and July 2023 and again at the end of August 2023.

~~In 2022, both lidars were located in the harbour but had not yet been installed on the vessel. Beginning in January 2023, the WindCubeV2 and WindCube100S were mounted on the CTV, allowing for direct measurements within the wind farm. From January to August 2023, the CTV operated~~ The CTV was located primarily in the harbour during the night and inside the wind

450 farm during ~~daytime~~ the day, as illustrated by ~~the vessel density map in~~ Fig. 8. This figure uses a pseudocolour plot to visualise the number of hours the CTV spent ~~in at~~ in at each location. The map reveals several high-density clusters, some exceeding 50 hours, near individual wind turbines and the transformer platform. These high-density areas correspond to the turbines most frequently visited for operation and maintenance, as well as offshore idle time. Most turbines were visited at least once, ensuring that lidar measurements were collected across the entire wind farm during stationary periods. This widespread spatial coverage is a clear

455 advantage of the vessel-based lidar setup. Such extensive spatial sampling would not have been achievable using wind lidars mounted only on buoys or fixed platforms.

Figure 9 ~~presents the wind rose based on~~ shows a comparison between the wind roses from NORA3 and WindCubeV2 data at 150 meters above sea level. To improve clarity, only wind ~~speeds~~ energy-relevant wind speeds (above 5 ~~meters per second~~

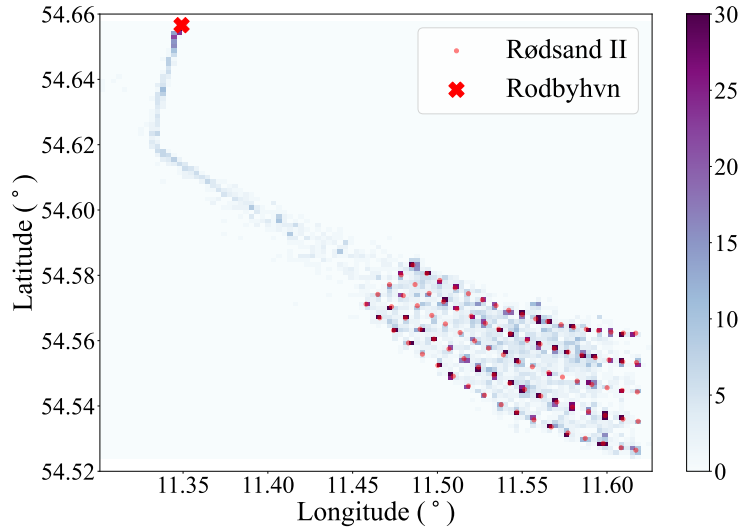


Figure 8. Spatial density map of the CTV's position during the LOLLEX campaign. The colour scale indicates the [frequency-cumulated time spent \(in hours\)](#) of recorded positions, with darker areas representing locations where the CTV spent more time. Red circles mark the Rødsand II wind turbines. The cross marks the approximate location of Rødbyhavn harbour. The map is based on data recorded by the WindCubeV2's internal IMU.

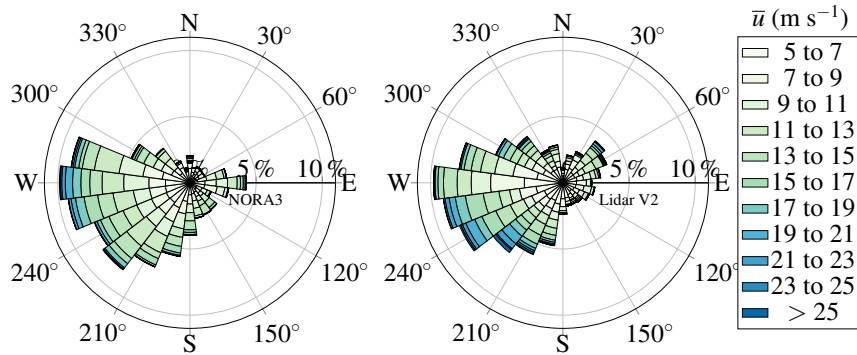


Figure 9. [Wind rose for the mean wind speed at 150 m obtained with NORA3 \(left\) and WindCubeV2 \(right\) during the Lollex measurement campaign, from 2022-10-09 to 2023-07-12 \(6624 h of data\).](#)

[m s⁻¹](#)) are included. The wind rose is based on 5623 hours of data. Both NORA3 and the WindCubeV2 show that westerly winds dominate, with a median wind speed between 8 and 9 m s⁻¹ at 150 meters altitude. The WindCubeV2 data indicate more frequent north-easterly winds and stronger winds from the sector between 210 and 260 degrees than NORA3 suggests. Differences in wind direction between the NORA3 dataset and the WindCubeV2 measurements can be explained by two factors. First, the CTV carrying the lidar was not fixed in space and often remained near the harbour or inside the wind farm,

while NORA3 data corresponds to a fixed offshore grid point. Second, the NORA3 model does not represent the effects of the
465 Rødsand II and Nysted wind farms on the local wind field.

~~Wind rose for the mean wind speed at 150 m obtained with NORA3 (left) and WindCubeV2 (right) during the Lollex measurement campaign, from 2022-10-09 to 2023-07-12 (6624 h of data).~~

5 Results

5.1 Time series analysis

470 This section compares the wind speed data from the two lidars mounted on the CTV with the NORA3 reanalysis before and after applying motion correction. The goal is to assess the overall quality of the lidar measurements and evaluate the performance of the motion correction method in addition to the evaluation of the consistency between the lidar data and NORA3. This comparison is important to build confidence in for the case studies presented later in the paper. Further, four selected case studies are presented, each highlighting the potential and limitations of the chosen measurement setup. The first three case studies rely
475 on the dual-lidars deployment on the CTV, focusing on a detailed characterisation of the marine atmospheric boundary layer and its potential interaction with a wind farm, while the fourth focuses on the lidar deployed on the transformer platform and its potential for wake detection and characterisation.

~~Time series of wind speed at 100 m above the surface during the LOLLEX campaign, comparing the ship-based lidar measurements with the NORA3 reanalysis data. The blue line represents 10-minute averaged wind speeds from the WindCubeV2
480 lidar wind profiler. The orange line shows 5-minute averaged DBS wind speed data from the WindCube100S scanning lidar. The green line corresponds to hourly wind speed from NORA3. The top panel shows data from 2022, and the bottom panel shows data from 2023.~~

5.1 Motion correction results

~~Figure ?? shows the time series of wind speed at 100 m above the surface from~~ Motion correction was applied to the full dataset,
485 including WindCubeV2 measurements and WindCube100S DBS data. The corrected and uncorrected results are compared with NORA3 ,the in Fig. 10. For the WindCubeV2 profiler, and the, the correction increases the regression slope from 0.85 to 0.91 and bias value from 0.1 ms^{-1} to 0.24 ms^{-1} , improves R^2 from 0.797 to 0.892, and reduces the RMSE from 1.9 ms^{-1} to 1.5 ms^{-1} . For the WindCube100S scanning lidar for the years 2022 and 2023. The average wind speed across all datasets at 100 m height is close to 10 m s^{-1} . The, the correction increases the bias from -0.19 ms^{-1} to 0.03 ms^{-1} , R^2 from 0.737 to
490 0.814, and slightly reduces the RMSE from 2.2 ms^{-1} to 2.1 ms^{-1} , with the regression slope moving closer to unity.

~~For the WindCubeV2 shows greater variability, as it provides wind speed values every 10 minutes, while lidars, the error metrics relative to NORA3 outputs wind speed only once per hour, even though it represents a 10-minute average centred around the full hour. The WindCube100S collected DBS measurements every 30 minutes, based on 5-minute scan periods, leading to irregular time series sampling, are similar to those reported in Cheynet et al. (2025), which were obtained using~~

Comparison between the NORA3 reanalysis data and ship-based Doppler wind lidar measurements at various heights during the LOLLEX campaign. Left: Mean bias between NORA3 and the WindCube100S scanning lidar (blue) and WindCubeV2 lidar wind profiler (orange); based on 10-minute averaged wind speed. Right: Root mean-square error (RMSE) between NORA3 and the two lidar systems, showing the typical deviation in wind speed at each height.

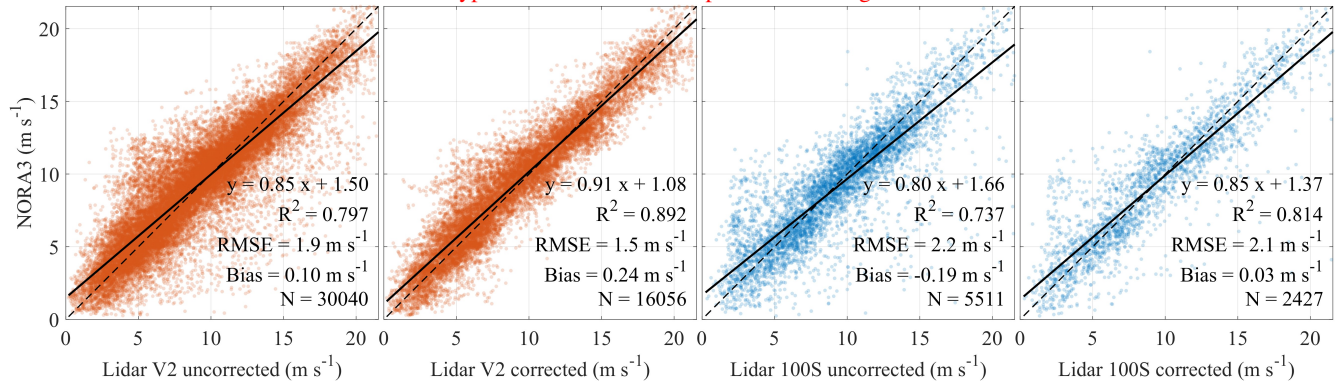


Figure 10. Scatter plots of 10-min mean wind speed from the WindCubeV2 (left two panels) and 5-min mean wind speed from the WindCube100S (right two panels) against NORA3 reference data for the entire campaign. Uncorrected data are shown in the first and third panels, and motion-corrected data in the second and fourth panels. The dashed line indicates the 1:1 relationship, and the solid orange line the linear regression fit. Motion correction improves agreement with NORA3, reflected in regression slopes closer to unity, increased R^2 , reduced RMSE, and reduced bias.

fixed lidar instruments. This suggests that the motion correction leads to performance comparable, in terms of these statistics, to that of fixed lidars. However, this does not imply that the motion correction is successful in all cases.

To perform a fair comparison, all data must be expressed using the same averaging time. Figure 11 shows the ensemble-averaged bias and RMSE between NORA3 and WindCubeV2 already use 10-minute averages. The WindCube100S uses 5-minute averages, which must be adjusted. To account for this difference, we apply a scaling factor based on the Durst curve (Durst, 1960; ASCE, 2000), which relates mean wind speed across different averaging intervals. We use an empirical approximation of the least-squares fitted Durst curve:-

$$\Gamma = 1.30 + 0.32 \tanh \left[0.79 \log \left(\frac{38}{\Delta_t} \right) \right]$$

where Δ_t is the averaging time in minutes. The parameters of these equations are close to those provided in Resio et al. (2002). Using this equation, a scaling factor $\Gamma = 0.96$ is applied to convert 5-minute mean wind speed to an equivalent 10-minute average.

After standardising the averaging time, we calculate the bias and root-mean-square error (RMSE) between the NORA3 and lidar data. Outliers are removed by excluding points where the difference between NORA3 and lidar exceeds 10 m s^{-1} ship-based lidars' wind profiles during the campaign before and after motion correction. The WindCubeV2 and WindCube100S both show a positive bias below $150\text{--}200 \text{ m}$, indicating that NORA3 tends to overestimate overestimates wind speed at lower heights.

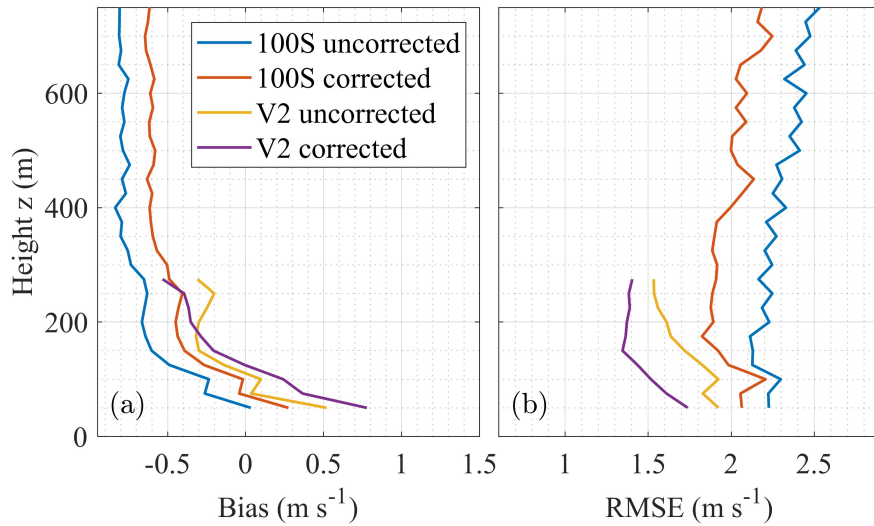


Figure 11. Ensemble-averaged bias (left) and root mean square error (RMSE; right) between NORA3 and ship-based Doppler wind lidar measurements at multiple heights during the LOLLEX campaign. Results are shown for the WindCube100S scanning lidar (uncorrected: blue; corrected: orange) and the WindCubeV2 wind profiler (uncorrected: yellow; corrected: purple), based on 10-minute averages for the WindCubeV2 and 5-minute averages for the WindCube100S.

510 This overestimation may be due to the influence of the wind farm, which decelerates the flow but is not represented in the The NORA3 model. At higher altitudes, the bias becomes nearly constant at around -0.5 m s^{-1} hindcast does not consider wind-farm wakes, while the lidar measurements are affected by the flow deceleration caused by the farm, a phenomenon also documented at the FINO1 site (Podein et al., 2022; Cheynet et al., 2025). It is worth mentioning that NORA3 has a horizontal resolution of 3 km and represents boundary-layer flows more realistically than the earlier 10 km NORA10 hindcast (Haakenstad et al., 2021).
 515 Nevertheless, uncertainties in the representation of near-surface wind processes may remain. Evaluations of similar high-resolution wind atlas datasets (3 km) show that they reproduce near-surface wind characteristics fairly well, although certain aspects of boundary-layer dynamics, such as the structure of low-level jets, may still be imperfectly represented (Kalverla et al., 2020; Rubio et al., 2020).

As shown in Fig. 11a, the bias of the motion-corrected WindCubeV2 data becomes slightly more negative with increasing altitude. The variations in bias remain within $\pm 0.2 \text{ m s}^{-1}$ across the profile. For the WindCube100S, the bias is more positive below approximately 100 m, and its magnitude decreases, approaching -0.5 m s^{-1} above 200 m after correction.

The RMSE between the WindCubeV2 and NORA3 decreases with height for both uncorrected and motion-corrected data, with the corrected data showing systematically lower values (Fig. 11 b). Above approximately 150 m, however, the RMSE increases again. In contrast, the RMSE between the WindCube100S and NORA3 is relatively constant increases slightly with height, with typical values around 2 m s^{-1} after correction. The magnitude of the bias and RMSE is consistent with earlier validation studies of NORA3 in offshore and coastal regions (Cheynet et al., 2025). A local maximum appears near the near

turbine tip height, possibly due to may reflect increased flow variability, not captured by NORA3. The ~~RMSE is slightly higher for the WindCubeV2, which may be caused by uncertainties introduced during motion correction. Unlike the WindCubeV2, the contrasting RMSE trends suggest that part of the height dependence reflects measurement characteristics rather than changes~~
530 ~~in model performance, with increasing uncertainty for the~~ WindCube100S does not undergo full motion correction, except for static tilt correction during vertical stare mode.

~~Overall, both lidars show consistent performance compared to at higher altitudes. This interpretation is consistent with previous findings that NORA3, especially above the rotor layer. These results support the use of NORA3 as a reference dataset and provide the necessary foundation for the case studies in the next section. performance generally improves slightly with~~
535 height above the surface (Cheynet et al., 2025).

6 First results

~~This section presents four selected case studies, each highlighting the potential and limitations of the chosen measurement setup. The first three case studies rely on the dual-lidars deployment on the CTV, focusing on a detailed characterisation of the marine atmospheric boundary layer and its potential interaction with a wind farm, while the fourth focuses on the lidar deployed on the transformer platform and its potential for wake detection and characterisation.~~
540

5.1 Case study 1 – ~~Kelvin-Helmholtz~~ Kelvin-Helmholtz billows observations

This case study was presented in detail in Malekmohammadi et al. (2025), but the analysis was limited to the period between 12:35 and 13:00 UTC on 22 February 2023. Here, we expand upon that work to highlight the influence of CTV motion on velocity retrieval and to provide recommendations for the use of a scanning DWL on a moving vessel. For completeness,
545 we summarise below the context in which ~~Kelvin-Helmholtz~~ Kelvin-Helmholtz billows (KHBs) were observed, but refer the reader to Malekmohammadi et al. (2025) for further details.

KHBs are ~~wave-like~~ wave-like structures caused by shear instability between air layers moving at different speeds (von Helmholtz, 1868; Stull, 1988). They typically form under hydrostatically stable conditions when vertical wind shear exceeds a critical threshold. This leads to dynamic instability and enhanced turbulent mixing, particularly vertical momentum transport.
550 During the LOLLEX campaign, the scanning DWL on the CTV observed KHBs on several occasions. One of the clearest events occurred on 2023-02-22, between 12:30 and 13:00. The KHBs were captured in both the CNR and ~~radial-vertical~~ velocity data, as shown in Fig. 12. The time series reveals distinct KHB structures between 12:46 and 12:56 at altitudes ranging from 550 to 750 m. These structures evolved from small ~~wave-like~~ wave-like perturbations into billows that grew, overturned, and eventually dissipated. In the vertical velocity field, they appear as alternating zones of upward and downward motion.

Before the event, a bright and persistent CNR maximum ~~around is observed near 600 m indicates m~~ (Fig. 12 top panel). This maximum corresponds to aerosol accumulation beneath the capping inversion, a common precursor to shear-driven instabilities, at the top of the stable boundary layer. Strong temperature inversions can suppress vertical turbulent mixing and limit dispersion, leading to the accumulation of aerosols below the inversion (Zhang et al., 2024). Vertical wind shear due to

the change from typical sub-geostrophic wind speeds in the BL towards geostrophic winds in the free atmosphere above can create favourable conditions for Kelvin-Helmholtz instabilities.

The KHBs were advected across the lidar beam over approximately 11 minutes, and their passage caused vertical mixing. This mixing is visualised by the broadening and dimming of the CNR maximum, which progressively descended downward to around 400 m by 13:00. However, a local maximum in the CNR remained visible until 13:30, suggesting that elevated aerosol concentrations persisted at around 400 m altitude, even after the dissipation of the KHBs.

~~Time-series of the Carrier-to-Noise-ratio (CNR) and vertical-velocity-component w recorded by the WindCube100S in vertical-stare mode from 12:35 to 13:30 on 2023-02-22. The bottom-panel shows the CTV-absolute speed, roll and pitch angles during the observational period. The red-box indicates the period during which the KHBs were observed.~~

Coincidentally, the lidar ~~instruments also captured the near-wake of a wind-turbine measurements,~~ located approximately 37 ~~m-upstream. The wake appeared in the~~ m downstream of the turbine, captured the effect of the turbine on the local flow field. This appears in the vertical velocity time series as a band of enhanced positive vertical velocity between 100 ~~m and 200 m-m height,~~ visible between 12:35 and 13:12, ~~indicating a flow-distortion effect by the turbine, potentially from the signature of blade-tip-vortices~~ 12. The spatial extent of the enhanced vertical velocity band indicates a rotor-induced streamline deflection in the near-wake region. This interpretation is consistent with previous ~~LES-based~~ studies of near-wake dynamics (e.g., Lanzilao and Meyers, 2024) ~~(Whale et al., 2000; Hong et al., 2014; Dasari et al., 2019; Lanzilao and Meyers, 2024).~~ SCADA data confirm that the turbine was operational during the observation period, with a nacelle orientation of approximately 167° , placing the lidar nearly directly downstream of the rotor.

~~It is important to remember that DWL-measurement-uncertainties generally increase in the near-wake of turbines, as the Doppler-spectrum broadens, complicating the accurate wind-speed-retrieval (Cheynet et al., 2017b). For the determination of wind-profiles from subsequent measurements along different line-of-sight beams, the algorithms also rely on the assumption of homogeneous flow conditions, which are violated in regions of strong flow-heterogeneity, such as the near-wake of a wind turbine. As such, the observed variability in the lower 200 m of the profile likely reflects increased uncertainty, and results within this region should be interpreted with caution, particularly in the context of turbulence-analysis.~~

The bottom panel of Fig. 12 shows the vessel speed, roll, and pitch angles. Between 12:35 and 13:10, the CTV remained stationary with minimal roll and pitch. After 13:12, the vessel began moving away from the turbine, which led to a negative velocity bias in the WindCube100S data and the disappearance of the near-wake signature. The vessel speed increased to approximately 4 m s^{-1} before becoming stationary again near 13:20, after which it resumed motion to a new location.

When the CTV is in motion, the along-beam velocity data retrieved by the WindCube100S becomes significantly noisier, likely due to the combination of high translational speed and varying pitch and roll angles. This limits the instrument's ability to capture accurate velocity measurements and reduces the amount of usable data during periods of vessel motion. Consequently, operating the CTV in stationary mode is preferable when using scanning lidar for turbulence analysis, as it improves both the quality and availability of the retrieved data. Interestingly, the CNR data appear to be less affected by vessel motion. For instance, the dissipation of the KHBs into smaller ~~wave-like~~ wave-like patterns after 13:00 remains detectable beyond 13:10,

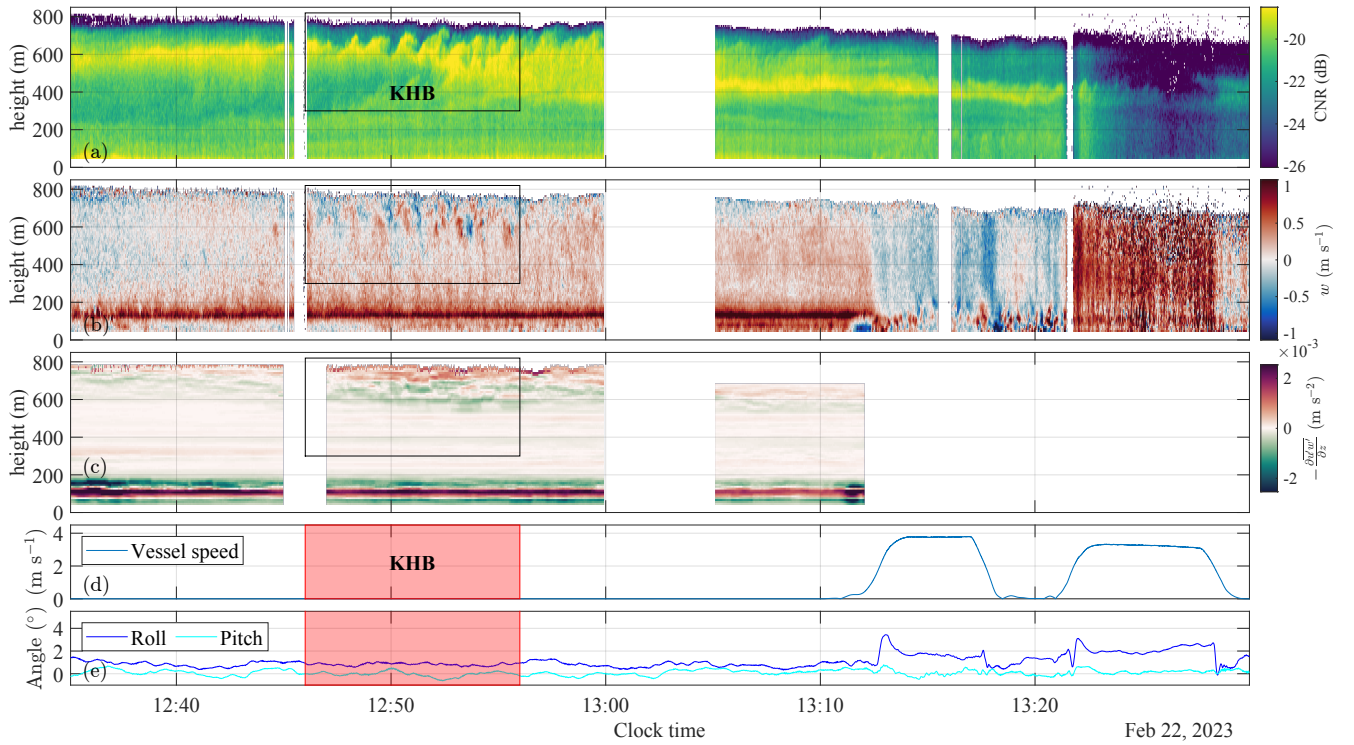


Figure 12. Time series of the Carrier-to-Noise ratio (CNR, panel a), instantaneous vertical velocity component w (panel b) and vertical stress divergence estimate (panel c) obtained using the WindCube100S data in vertical stare mode from 12:35 to 13:30 on 2023-02-22. Panel (d) and (e): CTV absolute speed, roll and pitch angles during the observational period.

even though the vessel was moving and the [velocity](#) data were considerably noisier. This highlights the utility of the CNR as a complementary data source, particularly under non-ideal motion conditions, for tracking coherent structures like KHBs.

595 The observation of this KHB event revealed a significant increase in the variance of the vertical velocity component within a 400-m thick atmospheric slab, well above the region influenced by the turbine near-wake. In this case, no direct interaction between the KHBs and the wake was observed. However, such interactions may occur under different conditions, e.g. in a shallower ABL, within large wind farms where the internal boundary layer reaches the ABL top, or when KHBs form at lower altitudes, as briefly documented by [?Radiünz et al. \(2025\)](#). As highlighted by Malekmohammadi et al. (2025), the enhanced
600 vertical mixing associated with KHBs, indicated by elevated vertical velocity variance, could accelerate wake recovery by entraining higher-momentum air downward. We therefore hypothesise that if KHBs overlap more directly with wind turbine wakes, they may enhance wake recovery under stable stratification. This hypothesis warrants further investigation.

5.2 Case study 2–2 – Entrainment observations

The second case study documents observation of vertical momentum entrainment during-on the same day (2023-02-22), but
605 through a different mechanism, i.e., significant downward turbulence motion likely through a mechanism different from KHB,
namely buoyancy-driven downward turbulent motions from the top of the ABL at ea. (around 1000 m height to the lowest m)
reaching down to approximately 200 m above the surface. Such-These measurements were collected before the vessel entered
the wind farm , under south-east wind conditions. The CNR profiles indicate a local CNR-CTV was stationary at the beginning
of the case study and started moving at 07:12 UTC. The CNR profiles show a local maximum between 950 m and 1000m,
610 suggesting an ABL depth of m at the beginning of the scan, indicating that the ABL depth is approximately 1000 m. The m
(Fig. 13 a). Within this layer, the WindCubeV2 and WindCube100S lidar DBS data revealed a local wind speed maximum of
5.9 mDBS measurements reveal a local wind speed maximum of 6 m s⁻¹ around near 200 m above the surface. Similarly, the
m, with NORA3 model captured a local maximum of around showing a similar maximum of about 5.5 m m s⁻¹ for wind speed
at approximately around 150 m m (Fig. 14). A strong negative wind-speed gradient occurs above this maximum. A significant
615 negative gradient in wind speed was observed above this local maximum. The lidar data in the top two panels of Fig. 13 reveal
large vertical coherence structures characterised by alternating positive (upward-) and negative (downward-) vertical motions,
indicative of significant vertical movements Consistent with this, the vertical wind velocity in Fig. 13 b shows coherent regions
of upward and downward motion emerging around 06:47 and persisting thereafter, indicating substantial vertical transport
within the ABL.

620 The profile of the vertical Prior to 06:47, the moving standard deviation of the velocity component w , denoted as (σ_w) , is
shown in the bottom panel of Fig. 13. Between-) is relatively uniform between 100 m and 800 m, σ_w exhibits fairly uniform
values until m, with weak turbulence ($\sigma_w < 0.2 \text{ m s}^{-1}$) (Fig. 13 c). From 06:46 with a vertical turbulence intensity I_w under
2% at heights between 100 and 700 m above the surface. Starting at 06:47 , a local increase in onwards, σ_w becomes visible at
an altitude of approximately increases locally near 600 m. Over time, σ_w continues increases steadily, reaching a peak m and
625 subsequently reaches values of approximately 0.5 m m s⁻¹ between 400 m and 600 m. The corresponding vertical profile of σ_w
at 06:47-07:00 window shown in Fig. 15 a, also shows local increase of the vertical turbulent fluctuations at heights between
200 and 800 m above the surface. Between-

Figure 15 also presents the vertical profiles of kurtosis (b) and skewness (c) for three observational windows (06:35-06:47 and
07:00, $I_w \approx 0.05$ at 500 m and between 07:06:47-07:05-00, and 07:05-07:12), together with the corresponding power spectral
630 densities of w at 430 m (d). Prior to 06:47, the turbulence intensity has nearly doubled with $I_w \approx 0.09$ at 500 m. It should
be noted that the lidar beam spatial averaging leads to an underestimation of the turbulence intensity I_w by 20-30%. Thus,
the turbulence intensity increase within one hour is significant. Figure 13 illustrates that this phenomenon the power spectral
density S_w exhibits pronounced white noise at frequencies above 0.1 Hz, indicating that turbulence fluctuations are too weak
to be reliably resolved by the WindCube100S scanning lidar. Between 06:47 and 07:00, the S_w spectra indicate improved
635 detectability of turbulent fluctuations, although noise levels remain sufficiently high to partially obscure the effects of along-beam
spatial averaging. After 07:05, vertical velocity fluctuations peak near 430 m, and the corresponding S_w spectrum shows

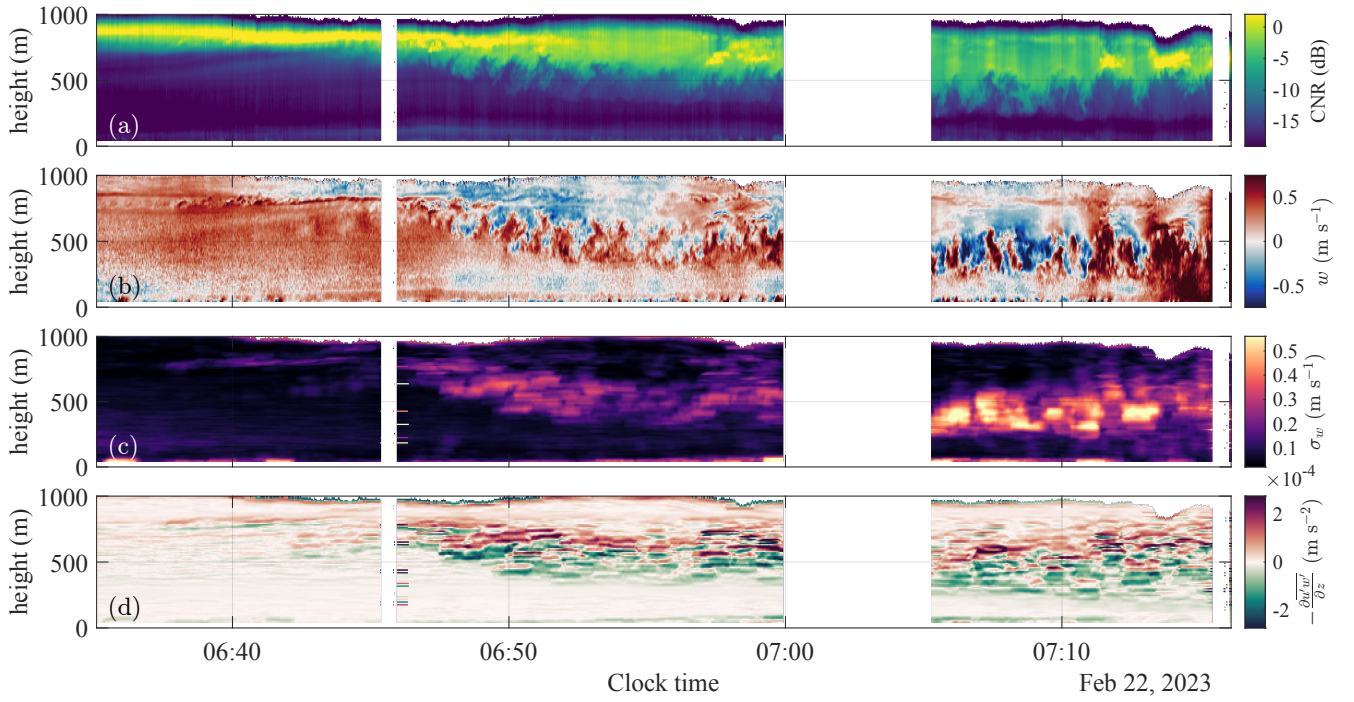


Figure 13. CNR (a), instantaneous vertical velocity component w (b), estimated moving standard deviation, σ_w , of the component w (c), and vertical stress divergence estimate (d) obtained using the WindCube100S on 22 February 2023 between 06:35 and 07:16 in the harbour.

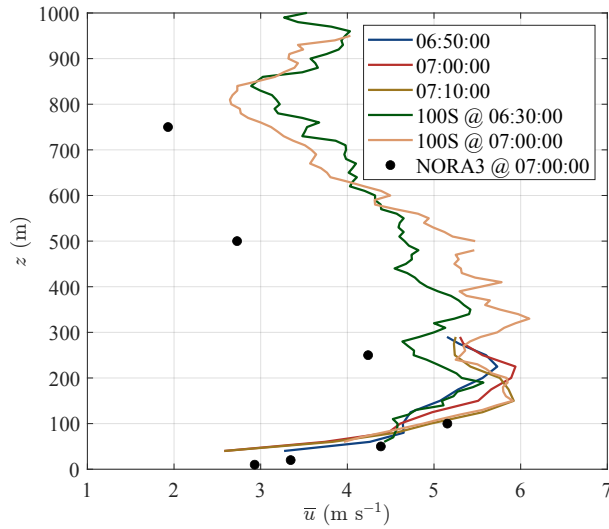


Figure 14. Profiles of the mean wind speed recorded by the WindCubeV2 and the WindCube100S on 22 February 2023 at multiple time windows between 06:30 and 07:10 in the harbour.

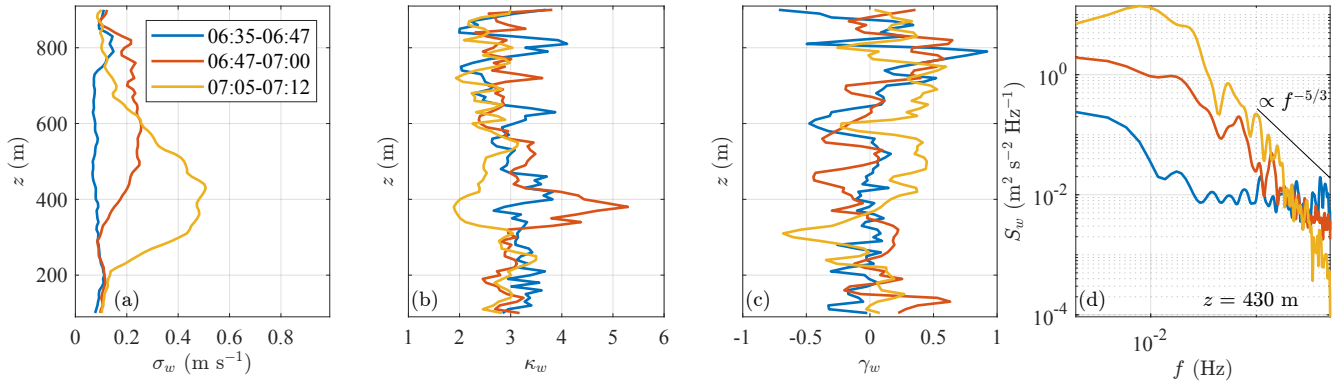


Figure 15. Profiles of the standard deviation σ_w (a), kurtosis κ_w (b), skewness γ_w of the vertical velocity component (c), and the power spectral density of S_w at 430 m (d). All panels are based on data recorded by the WindCube100S in the harbour on 22 February 2023 between 06:35 and 07:16.

reduced noise levels, with along-beam spatial averaging associated with the lidar probe-volume length becoming apparent at frequencies above 0.1 Hz, where the spectral slope steepens relative to the $-5/3$ inertial subrange. The pronounced spatial and temporal variability of σ_w reflects a non-stationary and non-homogeneous ABL with a negative vertical motion starting from the top of the ABL near vertically evolving boundary layer, suggesting the onset of downward transport from the boundary-layer top.

Further, Fig. 13 d shows that the vertical stress divergence increases after 06:47. Carrier-to-Noise Ratio (CNR, top panel) and measured vertical velocity component w (middle panel) recorded by the WindCube100S on 22 February 2023 between 06:35 and 07:16 in the harbour. The bottom panel shows the estimated moving standard deviation, σ_w , of the vertical velocity component w during the same period.

The instantaneous profiles of the vertical velocity and the CNR further suggest enhanced mixing due to turbulence. Measurements were conducted in the morning under stable atmospheric conditions, as indicated by the Profiles of Richardson Number (Ri_B) 47 around 500 m, with values between -0.004 and 0.004 m s^{-2} . These magnitudes are, however, smaller than the shear-driven stress divergence observed in case 1 (turbine wake) and case 3 (atmospheric wave). The increase in stress divergence coincides primarily with enhanced turbulence (see Malekmohammadi et al. (2025)). Despite the overall stability, the observed increase in turbulence intensity suggests that external factors may have triggered localised mixing events near the top of σ_w , although it remains proportional to the product of σ_w and the vertical shear $\partial \bar{u} / \partial z$. The enhanced entrainment, initially centred near 500 m after 06:50, expands vertically from about 200 m to 800 m after 07:10, indicating vertically distributed momentum redistribution across a large fraction of the ABL.

Although the strong vertical shear suggests that shear instabilities may develop, the observations do not display several characteristic signatures of KHB. In particular, the ABL around power spectral density of w does not exhibit the narrow-banded spectral peak and well-defined periodicity typically associated with KHB; instead, the spectra show a broader increase in

energy across a range of frequencies. Local increases in kurtosis have previously been used as indicators of coherent KHB structures (Blumen et al., 2001; Malekmohammadi et al., 2025). In the present case, a local kurtosis peak appears between 06:47–07:00. A plausible explanation for the enhanced turbulence observed near the ABL top is entrainment of momentum from the free atmosphere, potentially driven by shear instabilities or interactions with stratocumulus clouds. A strong negative wind speed gradient, recorded by the DWLs and the NORA3 model, supports the presence of shear-driven mixing and 07:00 but disappears during 07:05–07:12, even though σ_w continues to increase. This behaviour contrasts with the persistent kurtosis peak observed during the KHB event reported in Malekmohammadi et al. (2025). These features suggest that while shear-driven instability cannot be entirely excluded, the observed turbulence is more consistent with intermittent entrainment and mixing near the ABL top than with classical KHB.

Furthermore, radiative cooling at the top of stratocumulus clouds can trigger buoyancy-driven turbulence that may be a plausible mechanism for triggering the observed buoyancy-driven turbulence (Wood, 2012). The resulting turbulence propagates downward, contributing to enhanced entrainment near the top of the cloud-topped boundary layer (Wood, 2012). This region is typically characterised by strong gradients in humidity and temperature, which are known to support that favour mixing processes. Following Hogan et al. (2009), turbulence dominated by cloud-top influenced by cloud-top radiative cooling is typically often associated with negative skewness above the surface layer. In the present case, a negative skewness of vertical velocity w , reaching values as low as -0.8 – -0.7 at 300 m height (Fig. 15 c), is observed between 07:05 and 07:15. In contrast, this localised negative peak is not present in the data from absent before 06:35 to 06:45, before the local increase in the standard deviation, prior to the increase in σ_w . Between 06:47 and 07:00, the skewness profile is relatively noisy but shows slightly negative values, while skewness becomes moderately negative (down to -0.4 – -0.4) between 400 and 700 m. These observations are consistent with the findings of Hogan et al. (2009), supporting the interpretation that the turbulence is amplified from the top of the ABL due to radiative cooling during 06:47–07:00. However, a negative skewness peak was also observed during the KHB event documented in Malekmohammadi et al. (2025), indicating that this feature is not unique to turbulence driven by radiative cooling. Although the present observations are qualitatively consistent with turbulence initiated near the ABL top, the absence of thermodynamic measurements near the boundary-layer top prevents a definitive attribution to radiative cooling. Although we did not have access to humidity or temperature profiles during this event, the vertical velocity and mean wind speed profiles indicated the presence of strong shear. The exact mechanisms driving the observed entrainment and mixing remain uncertain and warrant further investigation. At the same time, the strong vertical shear suggests that shear-driven instabilities may also contribute, and the dominant mechanism therefore remains uncertain.

These observations document how turbulent entrainment processes demonstrate that turbulent entrainment can develop under stable morning conditions and how vertical momentum can be redistributed conditions and redistribute vertical momentum over several hundred meters, even in the absence of without convective forcing or clear classical coherent structures such as KHBs. The non-stationary nature of the non-stationary turbulence and its vertical extent suggest that entrainment at entrainment initiated near the ABL top was likely driven by shear instabilities and potentially cloud-top cooling. These findings further underscore and propagated downward through combined shear and buoyancy effects. Such vertically distributed entrainment may facilitate wake recovery in a wind farm by promoting the downward transport of higher-momentum air. These findings

highlight the value of ~~using a scanning Doppler wind lidar, complemented by a profiler DWL, combining scanning and profiling Doppler wind lidars~~ on vessels to ~~study entrainment under stable atmospheric conditions. Joint measurements of humidity and temperature profiles using a co-located passive microwave radiometer would be valuable for distinguishing between shear- and buoyancy-driven entrainment mechanisms. Additionally, ultrasonic anemometers could usefully complement the lidar data by providing near-surface turbulence measurements.~~ investigate entrainment processes.

5.3 Case study 3 – Internal wave observations

Case study 3 addresses observations of internal waves conducted in the harbour after the CTV returned from the offshore wind farm. The evening of 22 February was characterised by stable stratification, a wind speed of 10 m s^{-1} at 100 m, a strong ~~near-linear near-linear~~ shear of approximately $0.06 \text{ m s}^{-1} \text{ m}^{-1}$ between 40 m and 100 m (Fig. 16) and a cloud cover above 600 m as indicated by the CNR profiles. ~~The in Fig. 17 a. As shown in Fig. 16, the~~ WindCube100S detected the presence of a ~~low-level low-level~~ jet, with a maximum wind speed of 15 m s^{-1} between ~~420 300~~ m and ~~450 500~~ m above the surface. From 22:05 to 22:30, the lidar ~~system~~ recorded wind conditions suggestive of internal atmospheric waves below the cloud-topped ABL. Such waves are often associated with the presence of ~~low-level low-level~~ jets (Jia et al., 2019). In the present case, the observed ~~wave-like wave-like~~ motions may have been triggered by shear instability near the maximum of the ~~low-level low-level~~ jet, where vertical wind shear was strongest. Wave patterns began to form at 22:16 and became visible in both the CNR (above 400 m) and the vertical velocity fluctuations (from 200 m to 600 m). It should be noted that these waves were not generated by wind farms and are therefore distinct from the ~~so-called farm-generated so-called farm-generated~~ gravity waves (Allaerts and Meyers, 2018). When internal atmospheric waves, including gravity waves, form upstream of a wind farm and at a height low enough to interact with the farm's internal boundary layer, they may enhance wake recovery by amplifying mixing and wake meandering (?). ~~Vertical profile of the observed wave-like pattern on 22 February 2023. Top panel: Time series of the carrier-to-noise ratio; middle panel: instantaneous vertical velocity fluctuations; bottom panel: instantaneous standard deviation along the scanning beam. The wave-like pattern is visible between 200 m and 600 m altitude from 22:16 to 22:30.~~ (Feng et al., 2026).

Figure 17 shows the vertical structure of these oscillations, which span approximately 200 m in height. The ~~wave-like wave-like~~ motions are visible both in the instantaneous vertical velocity (~~middle-panel-panel b~~) and the corresponding standard deviation (~~bottom-panel-panel c~~). The internal wave structure coincides with the nose of the ~~low-level low-level~~ jet. A spectral analysis of the vertical velocity at 200, ~~300~~, 400, ~~500~~, and 600 m revealed a dominant periodic signal with a 2-minute cycle during the wave event, as shown in Fig. ~~??~~ 16 b and c. The observed phase shift between altitudes suggests that vertical wind shear strongly influences the wave structure. No distinct spectral peak is observed prior to the occurrence of the waves (Fig. 16 b), indicating the absence of wave activity during this earlier period. During the wave event (22:15–22:30), pronounced spectral peaks appear between approximately 200 and 600 m, consistent with the oscillations visible in the time series in Fig. 16 c. After 22:30, clear spectral peaks remain visible between approximately 350 and 600 m, while no pronounced peak is observed at 200 m, suggesting that the wave packet initially reaches 200 m but later remains confined to higher altitudes near the nose of the low-level jet.

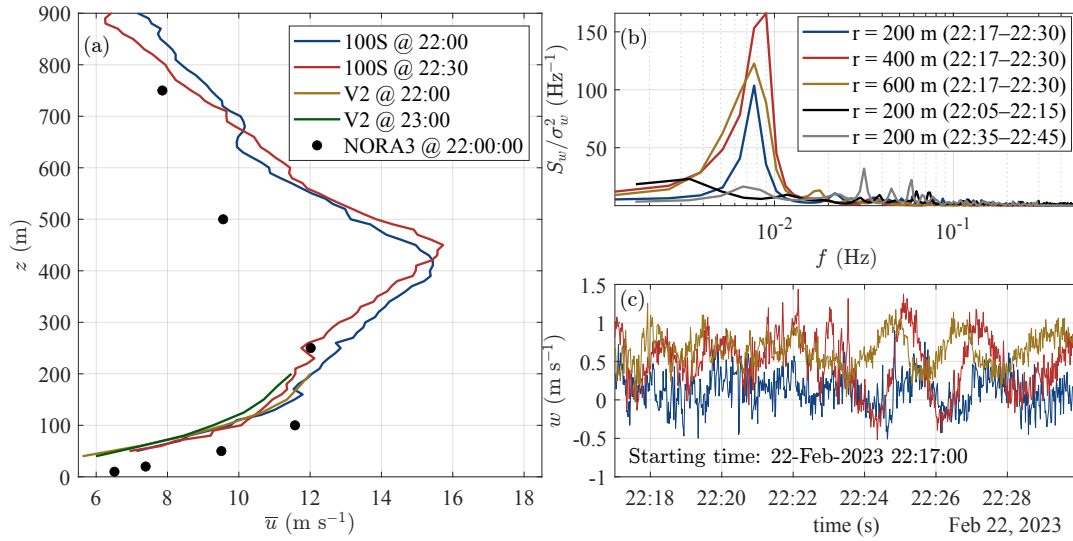


Figure 16. Power spectral densities (top-panel a): Profiles of the mean wind speed measured by the WindCubeV2 and associated time-series the WindCube100S on 22 February 2023 between 22:00 and 22:35 in the harbour. (bottom-panel b): Power spectral densities of the vertical velocity fluctuations from 200 to 600 m above the surface on 22-02-2023 from during the wave event (22:17–22:30). The black (grey) solid line shows the power spectral density at 200 m prior (after) to the observation of the waves for comparison. (c): Time series of vertical velocity corresponding to the PSD shown in panel (b) between 22:17 and 22:30.

The spectral peak falls within the mesoscale range, rather than the typical turbulence range, and is therefore more consistent with internal atmospheric waves rather than with turbulent eddies.

The observed period places these waves at the lower end of the internal gravity wave spectrum. For comparison, Banakh and Smalikho (2016) reported oscillation periods between 6.5 and 18 minutes in coastal terrain, while Jia et al. (2019) observed shear-driven gravity waves with periods exceeding 10 minutes. According to Sun et al. (2015), internal gravity wave periods typically range from 1 to 30 minutes, indicating that the 2-minute period observed here is short but still within the expected range.

As shown in the bottom-panel of Fig. 17 c, the local increase in the standard deviation of vertical velocity extends to heights below 200 m, even though the CNR indicates that the wave-like pattern is strongest around 500 m. Given the proximity of the measurement site to the coast and its distance of about 20 km from the nearest offshore wind farm, it is possible that similar wave-like motions could occur above the wind farm itself. If so, such waves could enhance wake recovery by amplifying vertical momentum entrainment into the farm, especially considering that the internal boundary layer generated by the wind farm is likely confined to below 200 m. In Fig. 17 d, the vertical stress divergence is strongly negative near the nose of the low-level jet, where the wind-speed gradient is largest. Following the detection of atmospheric waves, it becomes more negative, indicating enhanced vertical momentum entrainment associated with strong wind shear and increased vertical velocity variance. This behaviour implies that the atmospheric wave intensifies downward transport of high-momentum air.

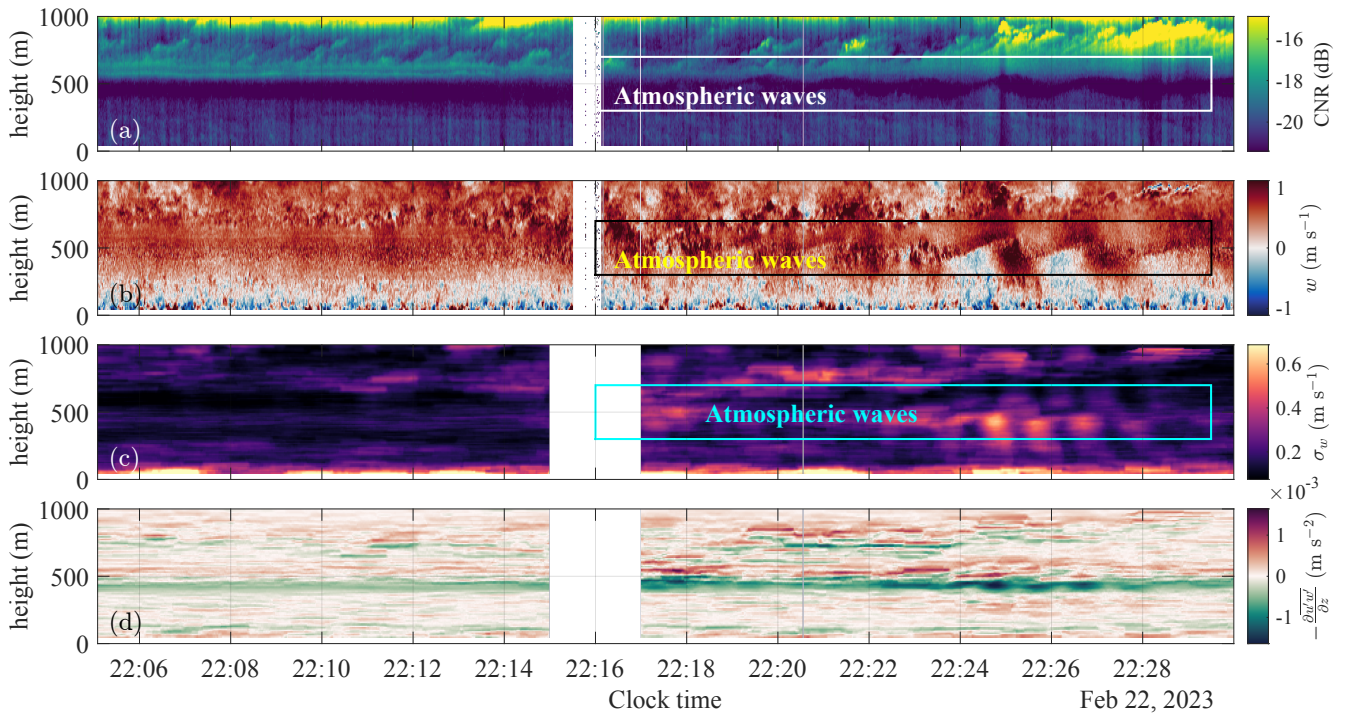


Figure 17. CNR (a), instantaneous vertical velocity component w (b), estimated moving standard deviation, σ_w , of the component w (c) and vertical stress divergence estimate (d) obtained using the WindCube100S on 22 February 2023 between 22:05 and 22:30 in the harbour.

The previous case studies, along with this one, demonstrate the ability of scanning and profiling DWLs to capture dynamic processes in the ABL, including momentum entrainment associated with internal waves. However, limitations remain for a complete characterisation of internal atmospheric waves. In particular, the absence of co-located temperature and humidity measurements restricts our ability to study the stratification of the atmosphere in detail and, therefore, to identify the dominant wave generation mechanisms. While wind speed profiles confirm the presence of a ~~low-level~~ low-level jet and support the interpretation of shear-induced wave activity, additional observations would be needed to distinguish between shear- and ~~buoyancy-driven~~ buoyancy-driven processes.

Moreover, although reanalysis products such as NORA3 could be used to estimate atmospheric stability (e.g., via the Bulk Richardson number), their temporal and spatial resolution is limited compared with the scales of the observed processes. A more robust assessment would require co-located, high-resolution profile measurements of temperature and humidity, e.g. by a passive microwave radiometer (Westwater et al., 2004; Rose et al., 2005), a Raman lidar (Lange et al., 2019; Wulfmeyer and Behrendt, 2020), or an infrared temperature profiler (Knuteson et al., 2004; Michaud-Belleau et al., 2025). To obtain such measurements, a HATPRO RG4 profiler was installed at Rødsand harbour at the beginning of the campaign. Unfortunately, the instrument was malfunctioning, and no usable data could be obtained.

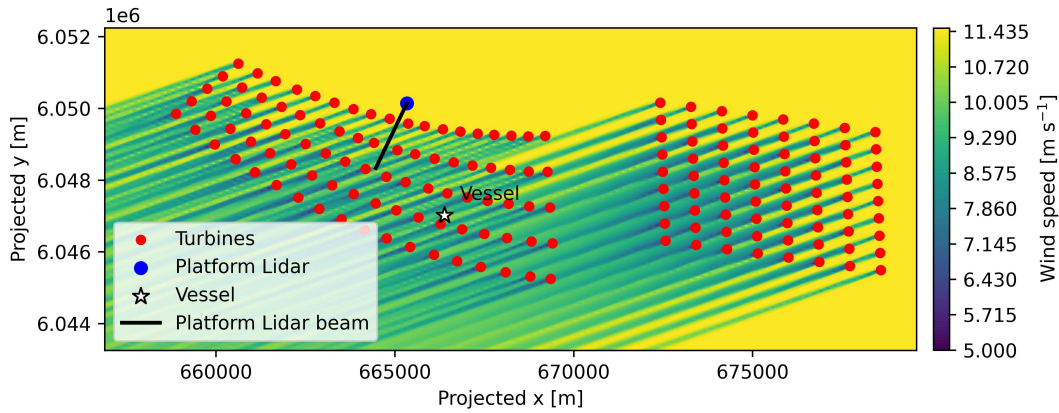


Figure 18. Horizontal cross-section of the mean wind speed at hub height for case study 4, with a free-stream wind speed of 12.1 m s^{-1} , a wind direction of 71° at 100 m, and a shear coefficient of 0.14 in the first 100 m above the surface. The TurboGaussian deficit model is used without blockage effects. The flow field is computed using PyWake with a downwind propagation scheme and a squared-sum superposition model, and is evaluated on a horizontal grid at hub height.

5.4 Case study 4 – Wake observations

This case study presents preliminary results from RHI scans performed by the long-range scanning ~~DWL~~ lidar installed on the transformer platform north of the Rødsand II wind farm. Two representative cases are shown: one with easterly winds and one with westerly winds. The limited joint data availability from the floating WindCubeV2 lidar and the platform-mounted lidar prevented a systematic analysis; however, a few representative cases can still be highlighted.

Case study 4 corresponds to an easterly mean flow observed by the platform-mounted lidar on 2023-06-13 between 12:11 and 12:25. According to NORA3, the wind speed and direction at 100 m were 12.1 m s^{-1} and 71° , respectively, whereas the WindCubeV2 lidar measured 9.2 m s^{-1} and 69° . Data from the WindCube100S were not available during this period. A least-squares fit to the NORA3 mean wind speed profile yields a shear exponent of 0.14. At the time of the observations, the CTV was located on the southeastern side of the wind farm (Fig. ??) and one with westerly winds (Fig. ??). Hereinafter, we focus on Fig. 18, implying that the area scanned by the platform-mounted lidar and the WindCubeV2 lidar were not collocated.

Wind speed, wind direction, and wind shear derived from NORA3 were used as input to the PyWake model (Pedersen et al., 2023) for wind-farm flow simulations. Since NORA3 does not account for the presence of the wind farm, it provides an estimate of the undisturbed upstream flow, whereas the V2 lidar measurements are affected by turbine and wind-farm wakes. PyWake was therefore used to simulate wind speed profiles at the location of the WindCubeV2 lidar using different wake deficit models. In addition, virtual RHI scans were generated to mimic the measurements from the scanning lidar on the transformer platform. These virtual scans reproduce vertical slices of the mean along-beam velocity component in the wind turbine wake. For comparison, virtual RHI scans were generated using PyWake as observed by the lidar.

775 The comparison serves two main purposes. First, it provides a novel approach to assess the reliability of the measurements. The PyWake simulations were initialised using mean wind speed and direction from NORA3, assuming undisturbed inflow conditions. For the easterly wind case, wind directions performance of wake deficit models implemented in analytical wake modelling frameworks. Second, it enables a qualitative evaluation of the lidar measurements, i.e. to verify whether the observed wake structures are consistent with simulations.

780 It should be noted that NORA3 does not necessarily provide a perfect estimate of the true upstream wind conditions. Discrepancies between model predictions and observations may therefore arise from several sources, including measurement noise, limitations of the wake models in representing real atmospheric conditions, or inaccuracies in the initial and boundary conditions derived from NORA3 and the lidar profiler (WindCube V2) on the CTV were in close agreement. However, for the westerly wind case, the lidar profiler data were not reliable enough to validate the. For the purpose of comparing wake deficit models, these sources of uncertainty are of secondary importance, as all simulations rely on the same NORA3 direction input and are evaluated against the same reference measurements.

785 In PyWake, the wind farm layout was modeled using the PropagateDownwind model combined with the TurboGaussianDeficit wake deficit model, which is similar to Ørsted's TurbOPark model. Our choice of this model is motivated by Fischereit et al. (2022), who found that analytical wake models (AWMs) tend to underestimate the wake deficit, i.e. they overestimate wake recovery between the PropagateDownwind wind farm model was adopted, in which wake effects are computed by propagating the influence of upstream turbines downstream and superimposing their wake deficits onto the undisturbed inflow. This formulation neglects upstream blockage effects, which were therefore not considered. A set of analytical wake deficit models was evaluated under identical inflow conditions, including NOJ (Jensen, 1983), TurboNOJ (Nygaard et al., 2020), BastankhahGaussian (Bastankhah and Porté-Agel, 2014), NiayifarGaussian (Niayifar and Porté-Agel, 2016), ZongGaussian Zong and Porté-Agel (2020), TurboGaussian (Ørsted, 2020), and GCL (Larsen, 2009). For Gaussian-based wake deficit models, a mirror ground model was used to account for sea-surface reflection. Wake superposition was treated using a squared-sum approach, and wake-added turbulence was modelled using the Crespo-Hernandez formulation (Crespo and Hernandez, 1996), assuming a uniform ambient turbulence intensity of 0.07, representative of typical offshore conditions (Cheynet et al., 2017a).

795 The inflow was prescribed using a UniformSite with power-law shear, defined by the NORA3 reference wind speed, wind direction, reference height, and shear exponent. Simulations were performed for the combined Rødsand II and Nysted wind farms. The TurboGaussianDeficit model, in contrast, typically produces significantly longer wakes than other Gaussian wake deficit models such as those by Zong and Porté-Agel (2020) or Niayifar and Porté-Agel (2016), and we consider it more suitable for the present case. We note that our results differ from those reported by Souaiby and Porté-Agel (2024), who did not use PyWake. These differences may reflect variations in how the analytical wake models were implemented and configured.

805 The simulations also included the GaussianOverlapModel for rotor-averaged wind speed, the mirror ground model, farm layouts, implemented from measured turbine position data. All turbines were represented using a generic Siemens SWT-2.3-93 turbine (rotor diameter 93 m, hub height 69 m), with power and thrust coefficients prescribed from tabulated curves. No yaw misalignment or wake deflection effects were considered.

For each wake deficit model, the Crespo-Hernandez turbulence model, and a hub-height turbulence intensity of 0.1. Finally, wake superposition was modeled using the squared-sum method. The simulated flow field was sampled in two configurations. First, vertical profiles of the mean wind speed were extracted at the position of the floating WindCubeV2 lidar. Second, virtual RHI scans were generated by sampling the flow field in a vertical plane aligned with the scanning geometry of the platform-mounted lidar. The along-beam velocity was reconstructed by projecting the simulated horizontal wind vector onto the lidar line-of-sight, thereby neglecting any mean vertical velocity component. Differences between the present results and those reported by Souzaiby and Porté-Agel (2024) may partly arise from differences in wake model selection, configuration, and the treatment of wake superposition and turbulence.

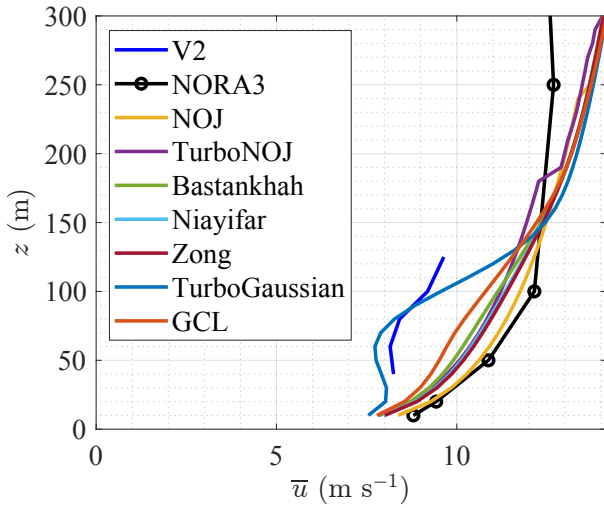
Figure ?? compares lidar and PyWake results for the case on 2023-05-20, between 05:13 and 05:28 UTC, with an azimuth of 206° . Figure 19 shows the vertical profile of the mean wind speed above the CTV during case study 4. The WindCubeV2 lidar profile exhibits negative wind shear below approximately 60 m and positive shear above, which is characteristic of waked flow. At 100 m, the WindCubeV2 lidar measures 9.2 m s^{-1} and 7.8 m s^{-1} , respectively, both with a direction of 76° at 100 m above the surface. Satellite data (Fig. ??) confirm a north-easterly flow, with surface wind speeds exceeding 8 m s^{-1} lower than the NORA3 estimate of 12.1 m s^{-1} upstream of the wind farm, indicating that the actual upstream wind speed may have been higher than measured by the lidar profiler, which was located inside the farm.

Figure ?? presents a similar comparison, but for a westerly flow with a wind speed of 9.0 m s^{-1} at hub height and a wind direction of 278° on 2023-06-01. In both cases, the direction was adjusted from the NORA3 wind direction by a value of -6° to better align the position of the first wake centreline with the lidar observation and to provide a comparable estimate of the along-beam velocity component. This is consistent with the horizontal flow field in Fig. 18, which places the vessel within a waked region.

The PyWake simulations in Fig. 19 show that most wake deficit models underestimate the observed wake losses, resulting in higher wind speeds than measured by the V2 lidar. Only the TurboGaussian model provides close agreement with the observations. Although based on a single case, this result is consistent with Fischereit et al. (2022), who reported that commonly used analytical wake models underestimate wake deficits and overestimate wake recovery between the Rødsand II and Nysted wind farms, but did not include the TurboGaussian model. The TurboGaussian model, closely related to Ørsted's TurbOPark concept, produces stronger far-wake effects; in the present simulations, it yields longer wake extents and larger velocity deficits than the other Gaussian-based models, leading to improved agreement with the lidar observations.

Comparison of 14-min mean along-beam wind speed on 2023-06-01 for an azimuth of 206° . Top panel: Measured by the scanning lidar (16:28–16:42). Bottom panel: Virtual RHI scan from PyWake, using inflow conditions of 9.0 m s^{-1} wind speed and 278° direction at 100 m altitude.

For easterly winds, the lidars can capture both Figure 20 compares the 14-min mean along-beam wind velocity measured by the platform-mounted scanning lidar during an RHI scan on 2023-06-13 at 12:11 with corresponding virtual RHI scans



Surface wind speed from SAR on 2023-05-20 at 05:33:25. Red dots indicate turbine locations in the wind farms near Lolland, taken from the database by Zhang et al. (2021). The image shows north-easterly flow with surface wind speeds exceeding 8 m s^{-1} upstream of Rødsand II.

Figure 19. Vertical profiles of mean wind speed above the CTV during case study 4 under easterly flow conditions (wind direction 71° , wind speed at $100 \text{ m } \bar{u} = 12.1 \text{ m s}^{-1}$, shear exponent $\alpha = 0.14$). The profiles are obtained from NORA3, the WindCubeV2 lidar, and PyWake simulations using different wake deficit models (NOJ, TurboNOJ, BastankhahGaussian, NiayifarGaussian, ZongGaussian, TurboGaussian, and GCL).

obtained from PyWake simulations. The comparison is performed using an averaged flow field, consistent with the steady-state assumption of the PyWake simulations. Both measurements and simulations reveal multiple turbine wakes.

Both measurements and simulations capture wakes from individual turbines from within the Rødsand II wind farm but also the farm-induced wake from the. The simulations primarily resolve three distinct wakes, while Fig. 18 suggests that the flow may also be influenced by additional far-wake contributions from the upstream Nysted wind farm, which is known to lead to additional wake loss in. Such farm-to-farm interactions are known to enhance wake losses at Rødsand II (Hansen et al., 2015; van der Laan et al., 2015). For westerly winds, no farm clustering effect takes place. In both cases, however, this contribution cannot be unambiguously isolated in the RHI scans from the lidar and the simulations reveal multiple turbine wakes. For the easterly flow of the platform-mounted lidar. In Fig. 20, the wake of the first-nearest turbine, located about 0.8 approximately 0.7 km from the lidar, is captured. However, the alignment of the second and third wakes (clearly identified in both measurements and simulations. The alignment of subsequent wakes, around 1.0 km and 1.5 km away) between measurements and simulations is less accurate. This mismatch may result from minor km downstream, is slightly less consistent between simulations and observations. In particular, a third wake is predicted by the simulations but is not clearly visible in the measurements, likely due to measurement noise.

Discrepancies between simulated and observed wake structures can arise from several factors. Small variations in wind direction, which can significantly shift the wake centre in virtual scans wake positions in virtual RHI scans when NORA3

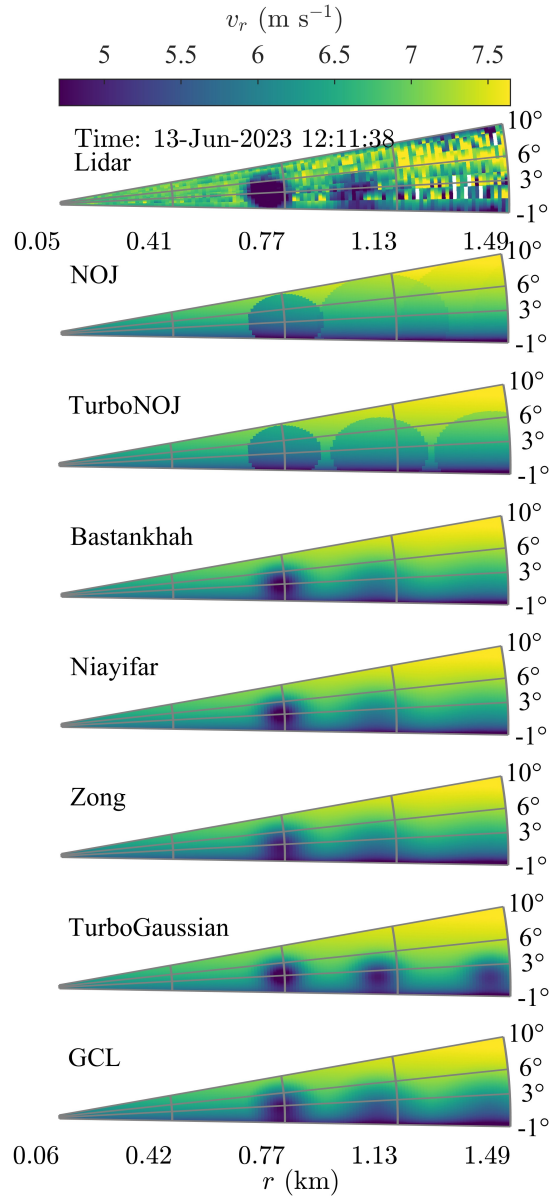


Figure 20. Comparison of 14-min mean along-beam wind speed on 2023-05-20 for velocity from an RHI scan on 2023-06-13 at 12:11 (azimuth of 206°). Top The top panel shows measurements from the scanning platform-mounted lidar (05:14–05:28). Bottom panel: Virtual The seven panels below show corresponding virtual RHI scan scans from PyWake simulations using inflow different wake deficit models (NOJ, TurboNOJ, BastankhahGaussian, NiayifarGaussian, ZongGaussian, TurboGaussian, and GCL). Simulations are performed under easterly flow conditions of 9.0 m s⁻¹ (wind speed and 70° direction 71°, wind speed at 100 m altitude $\bar{u} = 12.1$ m s⁻¹, shear exponent $\alpha = 0.14$).

is used to prescribe the inflow. Additional sources of ~~error may mismatch~~ include wind veering (Bodini et al., 2017), yaw misalignment due to turbine control ~~strategies and maybe the Coriolis force effect on the wake~~, and large-scale effects such as ~~the Coriolis-induced deflection~~ of the Nysted ~~wind farm~~ (van der Laan et al., 2015).

In the westerly flow case, two wakes are observed at approximately 500 m and 1.2 km. The wake at 1.2 km appears broader and may result from the superposition of multiple wakes, as indicated by the PyWake simulation. Between these two wakes, PyWake predicts additional far wakes that are not clearly visible in the measurements. As with the Easterly case, small changes in wind direction have a noticeable effect on the simulated wake position and velocity field.

~~farm wake~~ (van der Laan et al., 2015). Differences in wind speed between simulations and measurements ~~likely originate from both wind direction uncertainty and underestimated upstream wind speeds~~ are further influenced by uncertainties in the ~~upstream inflow~~. During the campaign, upstream conditions were not systematically measured, as ~~the vessel-mounted lidars were located in a sheltered harbour environment or inside the farm most of the time~~. ~~often located in sheltered harbour environments~~ or within the wind farm. Although NORA3 provides a practical inflow estimate, it may be less reliable under moderate and weak wind conditions. In periods of strong winds, when the vessel could not operate within the farm, wake validation relied solely on platform-based lidar observations.

Overall, several thousand RHI scans were collected during the campaign. ~~We believe this dataset is valuable for further validating AWMs in the~~, providing a unique dataset for the validation of analytical wake models at Rødsand II ~~wind farm~~. ~~Although a qualitative analysis~~. While the present qualitative comparison suggests that the ~~TurbOPark-TurboGaussian~~ (TurbOPark-type) model performs well ~~in our~~ for this case, further work is ~~needed to refine inflow conditions and identify possible yaw misalignment~~ required to better characterise inflow conditions, for example using SCADA data. ~~In particular, future studies should include a~~, and to extend the analysis to multiple cases. Future work should include systematic quantitative error analysis, using e.g. the metrics, such as root-mean-square error or bias ~~between the observed and virtual RHI scans~~. ~~Such a comparison would help~~, applied to both RHI scans and vertical wind speed profiles to identify the most suitable wake deficit models. Also, such RHI scans may complement nacelle-mounted lidars for wake analysis, which could be the topic of further study.

6 Discussion

~~CTV-based measurements are subject to operational limits. Measurements are only possible during~~
CTV-based wind lidar measurements overcome several key limitations of DWLs mounted on fixed platforms or buoys, while also introducing their own set of constraints. In this study, observations within the offshore wind farm were largely restricted to daytime working hours, ~~typically from~~ (typically 07:00 to 19:00. ~~This limits~~ 00), limiting the ability to capture ~~stable nighttime conditions and diurnal transitions~~. ~~nighttime conditions~~. Although measurements were continuously recorded, including during ~~nighttime in the harbour~~, no observations within the wind farm were obtained outside daytime operations.

In addition, safety regulations prohibit CTV operations when significant wave heights exceed 2 m or wind speeds surpass 12 m s^{-1} . ~~These thresholds reduce~~, reducing data availability during strong-wind or swell events. In contrast, buoy-based

lidars can operate continuously, including during high-wind conditions, though they lack the flexibility to capture different spatial locations. However, under severe wind and wave conditions, buoy motion can become too large for reliable wind measurements, leading to a significant degradation in data quality. In such cases, fixed platforms provide the most suitable approach for studying the atmosphere under strong wind and wave conditions.

895 The WindCubeV2 ~~lidar showed robust performance on the moving vessel. Its design for offshore conditions, including reduced mechanical complexity and compatibility with motion correction, contributed to stable operation.~~ maintained considerably higher data availability during the campaign compared to the WindCube100S (by a factor of about 3.5). The WindCube100S scanning lidar, in contrast, was more sensitive to translational motion. This sensitivity caused interruptions in some scans or led

900 ~~to incomplete datasets. Despite this,~~ showed a higher rate of scan interruptions, which we attribute not only to its mechanical configuration, specifically the relatively heavy two-axis external scanner head used to adjust both azimuth and elevation angles, but also to its sensitivity to platform motion. In particular, translational motions of the vessel appear to contribute to data loss and incomplete scans. In contrast, the system still produced many high-quality scans suitable for wake and turbulence analysis. WindCubeV2 uses optical switching without moving parts for beam steering (Peña et al., 2013), making it more robust

905 under dynamic conditions. For the vertical staring mode conducted between 2023-01-25 and 2023-08-28 (approximately 9900 scans), 65% of the WindCube100S scans were flagged as incomplete (scan duration < 10 min) and excluded, while only 30% reached the full 25-min duration.

~~Power~~ Moreover, power supply considerations are an important factor when installing lidar systems on offshore vessels. Each vessel has a different electrical configuration, which influences how equipment can be safely integrated. In this campaign, the

910 CTV required a daily power reset, which posed a risk to the WindCube100S due to its higher power demands and limited internal buffering. To address this, the lidar was connected to an external uninterruptible power supply (UPS) housed in a watertight enclosure. This configuration ensured stable operation during brief power interruptions. Future deployments can benefit from standardised power interface protocols and pre-tested UPS systems to improve installation efficiency and system robustness across different vessel types.

915 In principle, a dual-lidar setup like the one tested here could also be installed on a buoy. However, this would require careful consideration of platform stability and instrument design. Scanning DWLs are physically larger and more mechanically complex than ~~profiler lidars~~ lidar wind profilers, and most commercial models do not include active motion correction. Operation on a floating platform would therefore necessitate additional stabilisation measures or dedicated ~~post-processing~~ post-processing procedures. While motion correction is routinely applied to ~~profiler lidars~~ lidar wind profilers on buoys, extending this capability

920 to scanning ~~systems~~ lidars requires further development. Alternatively, vessels such as CTVs provide a more stable and spacious platform. Among available offshore platforms, the CTV offers a cost-effective and mobile solution for short-term campaigns in shallow coastal areas.

Finally, the success of this campaign was supported by favourable environmental conditions. The measurement site was located in a shallow-water region with low average wave heights. The surrounding coastal topography and the short distance to

925 the harbour enabled nearly daily access to the wind farm. These factors made it feasible to implement a mobile lidar strategy using a CTV. In deeper waters or more remote offshore locations, this approach would require significant adjustments. Vessels

may not be able to visit the site daily, resulting in fewer data collection opportunities. Harsher sea states would increase platform motion, leading to greater uncertainty in the retrieved wind velocities due to tilt and translation effects. The exposure to rough conditions may also increase the risk of contamination or damage to the lidar optics, for example, due to sea spray on the scanner head.

To address these challenges, future campaigns may consider integrating ~~real-time~~ real-time motion correction systems. One promising approach could involve gyroscopic ~~self-levelling platforms as discussed in Malekmohammadi et al. (2024)~~ self-stabilising platforms as shown in Achtert et al. (2015). Such systems could minimise the impact of platform tilt and reduce the reliance on ~~post-processing~~ post-processing corrections. While these systems may not be practical for small buoys due to size and power limitations, they could be feasible on larger vessels or semi-permanent floating platforms. Further investigation into active stabilisation methods for scanning lidars could help extend mobile measurement strategies to more demanding offshore environments.

7 Conclusions

The study presents new measurements of vertical momentum entrainment above an offshore wind farm, as well as observations of wind turbine wakes, collected during the LOLand offshore Lidar EXperiment (LOLLEX), resulting in a unique dataset for wind energy and boundary-layer research. The campaign introduced a novel dual-lidar setup ~~mounted~~ on a crew transfer vessel (CTV), combining a scanning ~~and a profiling Doppler wind lidar~~ Doppler wind lidar and a Doppler lidar wind profiler. This mobile platform enabled flexible sampling of the atmospheric boundary layer (ABL) at various positions and under different wind ~~directions~~ conditions. To complement these mobile observations, a long-range scanning lidar was installed on a transformer platform at the northern edge of the Rødsand II wind farm. This fixed lidar provided continuous, high-resolution ~~range-height~~ range-height indicator (RHI) scans along a fixed line of sight across the wind farm. ~~Together, the two systems allowed for the~~ The CTV-mounted scanning lidar enabled the study of entrainment processes ~~and wake recovery up to 3~~ up to about 2 km above the surface, while the platform-mounted scanning lidar provided detailed observations of wake structures within the lower 300-400 m of the atmosphere. The campaign lasted one year and produced several thousand hours of Doppler lidar data.

~~To illustrate the potential and limitations of this measurement setup, we presented~~ This study presents the potential of the measurement setup using four case studies. These examples highlight different entrainment-related processes and demonstrate the ~~value of combining scanning and profiling~~ complementarity of Doppler wind lidars ~~on both~~ deployed on mobile and fixed platforms:

1. ~~Kelvin-Helmholtz billows~~ Kelvin-Helmholtz billows (KHBs) were captured at altitudes between 550 and 750 m, indicating increased vertical mixing under stable conditions. This case illustrates how the vertical stare mode can be used to quantify turbulence statistics associated with shear instabilities (Malekmohammadi et al., 2025), but also reveals how vessel motion can significantly degrade the quality of scanning lidar data.

2. A case of downward turbulent mixing was observed during one morning, where momentum was transferred from the top of the ABL to lower levels ~~in the absence~~, with no clear signatures of classical structures ~~like KHBs~~, such as KHBs. This transient phenomenon, which may involve cloud-top cooling, shows that vertical entrainment can occur deeper into the boundary layer than documented in the first case study.
3. Internal atmospheric waves with a 2-minute period were detected near the nose of a ~~low-level~~ low-level jet. These shear-induced oscillations suggest that entrainment processes may not be limited to turbulence but also include wave-driven mechanisms, particularly under stable atmospheric conditions.
4. Wake profiles inside the wind farm were recorded using RHI scans from the platform-mounted lidar. These were compared with PyWake simulations, ~~offering~~ providing valuable data for wake model validation. For this case, the TurboGaussian wake deficit model showed the best agreement with the observations. This case demonstrates that the campaign was not limited to turbulence studies but also supports direct observations of wake deficits, which are an essential ~~part~~ component of understanding wake recovery.

Together, these results show that scanning lidars and lidar wind profilers can detect dynamic ABL processes relevant to wake recovery. They also demonstrate the value of mobile lidar systems for offshore measurements, especially when flexibility in spatial coverage is needed. Still, several limitations remain. The scanning lidar was highly sensitive to vessel motion, and data quality degraded significantly while the CTV was in transit. Motion correction was only applied in ~~post-processing to the profiler lidar~~. ~~No real-time correction was implemented. real-time stabilisation or onboard correction would likely improve performance, particularly if deployed on a larger, more stable platform.~~ post-processing to the lidar wind profiler. The use of a CTV also restricts operations to relatively calm sea states (significant wave height $H_s < 2$ m) and moderate wind speeds ($\bar{u} < 12$ m s⁻¹), limiting data availability. In addition, the lack of co-located temperature and humidity measurements prevented a full characterisation of atmospheric stratification, making it difficult to separate ~~buoyancy—and shear-driven buoyancy- and shear-driven~~ processes.

The dataset collected during the LOLLEX campaign represents, nevertheless, a valuable resource for wind energy science and boundary layer meteorology. Future studies using this dataset could explore the following:

- ~~Adding instruments such as microwave radiometers, radiosondes, or ultrasonic anemometers could help describe the vertical temperature structure and near-surface turbulence more accurately. This is important for understanding atmospheric stability and mixing over the sea.~~
- ~~Using real-time motion correction or stabilised platforms could increase the amount of usable lidar data and improve the quality of turbulence measurements from moving platforms. While stabilised platforms are challenging to implement on buoys due to size and power constraints, they may be more feasible on vessels thanks to greater space and onboard power supply.~~

- 990 3. A more detailed evaluation of near-wake measurements ~~is needed~~. Case study 1 showed that vessel-mounted lidars can detect near-wake structures. The LOLLEX campaign provides a unique opportunity to investigate this further, as it includes numerous high-resolution scans collected at varying distances and angles relative to turbine wakes.
4. Combining data from the fixed platform lidar and the vessel-mounted lidars. This could give a more complete picture to understand wind turbine wake recovery by using wind velocity data across the rotor plane, both in the horizontal and
- 995 vertical directions.
5. ~~Use~~ Using vertical stare scans from the scanning lidar to estimate the atmospheric surface layer depth. This approach can follow methods such as those proposed by Puccioni et al. (2024). Accurate estimation of ABL depth is important for ~~modeling~~ modelling wake recovery and vertical momentum entrainment in offshore wind farms. Comparing these lidar-based estimates with boundary layer depths from reanalysis datasets would help assess the reliability of reanalysis
- 1000 products in coastal regions of Northern Europe.
6. Adding instruments such as microwave radiometers, radiosondes, or ultrasonic anemometers could help describe the vertical temperature structure and near-surface turbulence more accurately.

Data availability. WindCubeV2 lidar wind profiler metadata are available in the Figshare repository: <https://doi.org/10.11583/DTU.22739729.v1>. The full datasets from both the WindCubeV2 and the WindCube100S scanning lidars are currently being processed. Due to the large

1005 volume of data, only the subsets used in the case studies presented in this paper will be made publicly available in the near future. The complete datasets are available from the authors upon request.

Author contributions. Conceptualisation of the campaign was done by JR, GG, CL, JM, MS, and SM. Data analysis and creation of figures were done by SM and EC. Model simulations with PyWake were performed and analysed by EC. Project management and funding was handled by GG and JR. The lidar deployment on the vessel was prepared and supervised by SM. The original draft was prepared by SM, EC

1010 and JR, with contributions by JM and MS and the review and editing were done by EC, JR, GG, CL, JM and MS.

Competing interests. The authors declare no conflict of interests.

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1015 ~~lidar instrumentation~~ lidars deployed on the CTV. The lidar on the transformer platform was supplied by the Technical University of Denmark (DTU Wind and Energy Systems). We gratefully acknowledge the owners of Rødsand II for the access to the wind farm and the support of

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