Ship-Based Doppler Wind Lidar can be used to observe Kelvin-Helmholtz Billows

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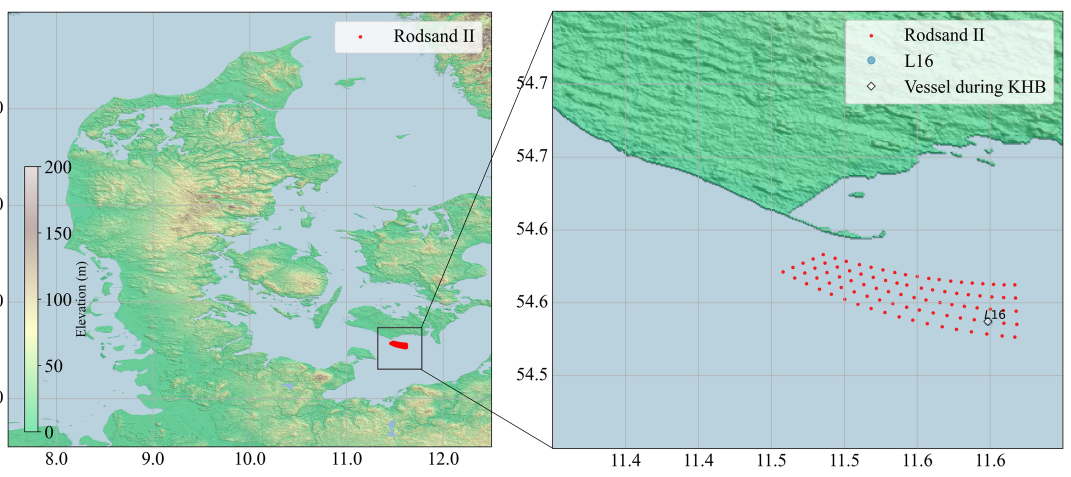
Introduction

Background: Kelvin-Helmholtz billows (KHBs) form from vertical shear in stable conditions, causing turbulence and vertical mixing. This can aid the wake recovery in offshore wind farms.
Novelty: This study uses a ship-borne Doppler wind lidar with high temporal resolution (1-second) and carrier-to-noise ratio (CNR) data to capture KHB structures abvoe an offshore wind farm.
Objectives: The study aims to characterise KHB-induced vertical turbulence, and discuss their potential influence on wind energy systems.

The LOLLEX campaign

The Lollex campaign, conducted from September 2022 to August 2023, was a collaboration between Train2Wind and the RWE group at the Rødsand 2 wind farm in Denmark:



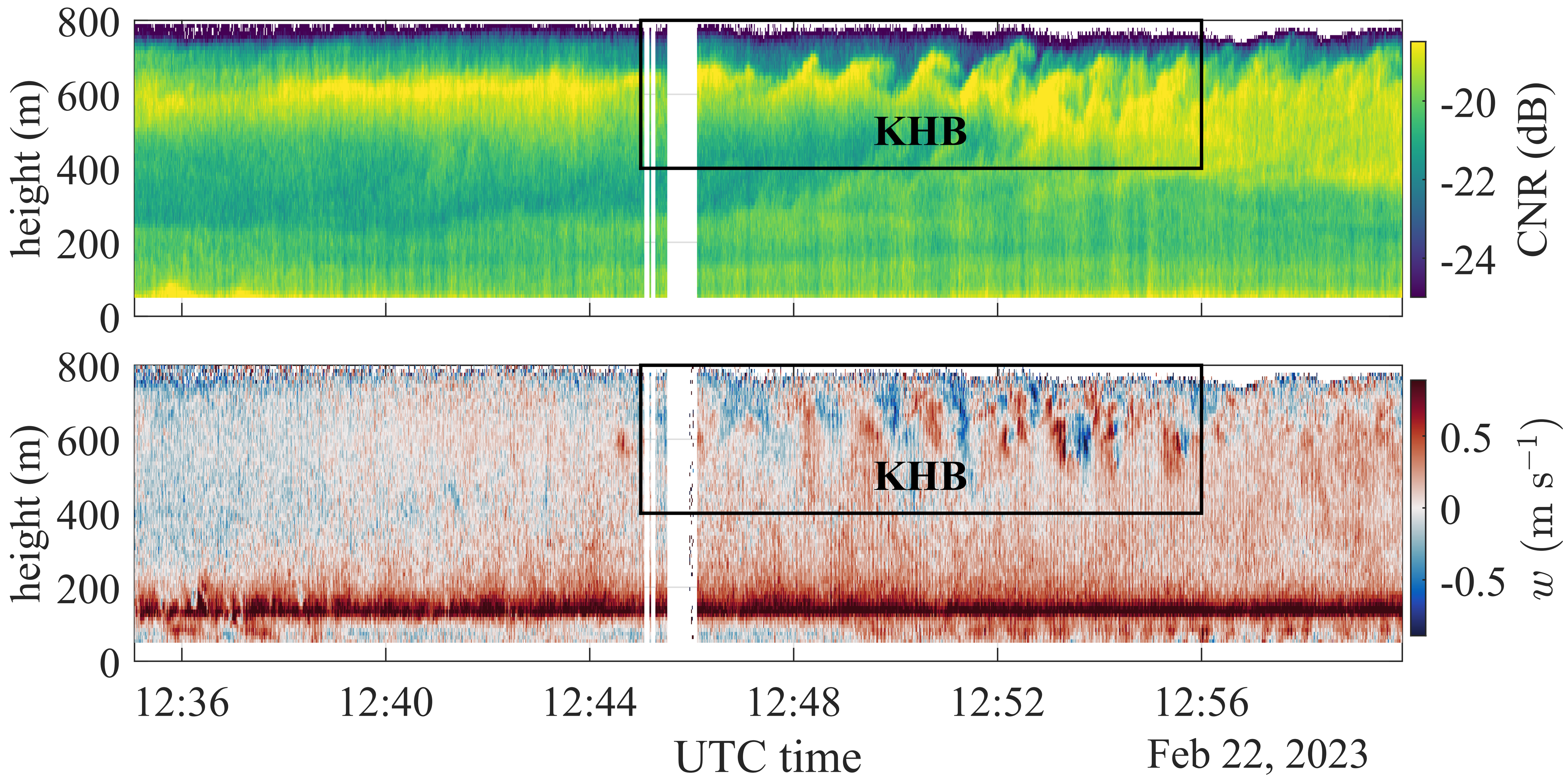
Two Doppler wind lidars, shown below, were installed on a crew transfer vessel to measure wind velocity within and around the wind farm. The WindCube V2 profiled wind speeds up to 300 m, while the WindCube 100S scanned the atmosphere up to 2 km. During the Kelvin-Helmholtz Billows observation on 22 February 2023, the vessel was stationary, capturing flow characteristics near a wind turbine's wake.

Data and methods

In this study, a scanning lidar was installed on a vessel without motion correction, leading to a tilt-dependent bias in the vertical velocity data. To correct this, we developed a new method to correct the vertical beam tilt based on the double rotation technique, typically used for correcting tilt angles in sonic anemometers. Velocity peaks above 6 m/s and data with CNR below -27 dB were disregarded. Turbulence was analysed using detrended data, with spectral density estimated by the Power Spectral Density (PSD).

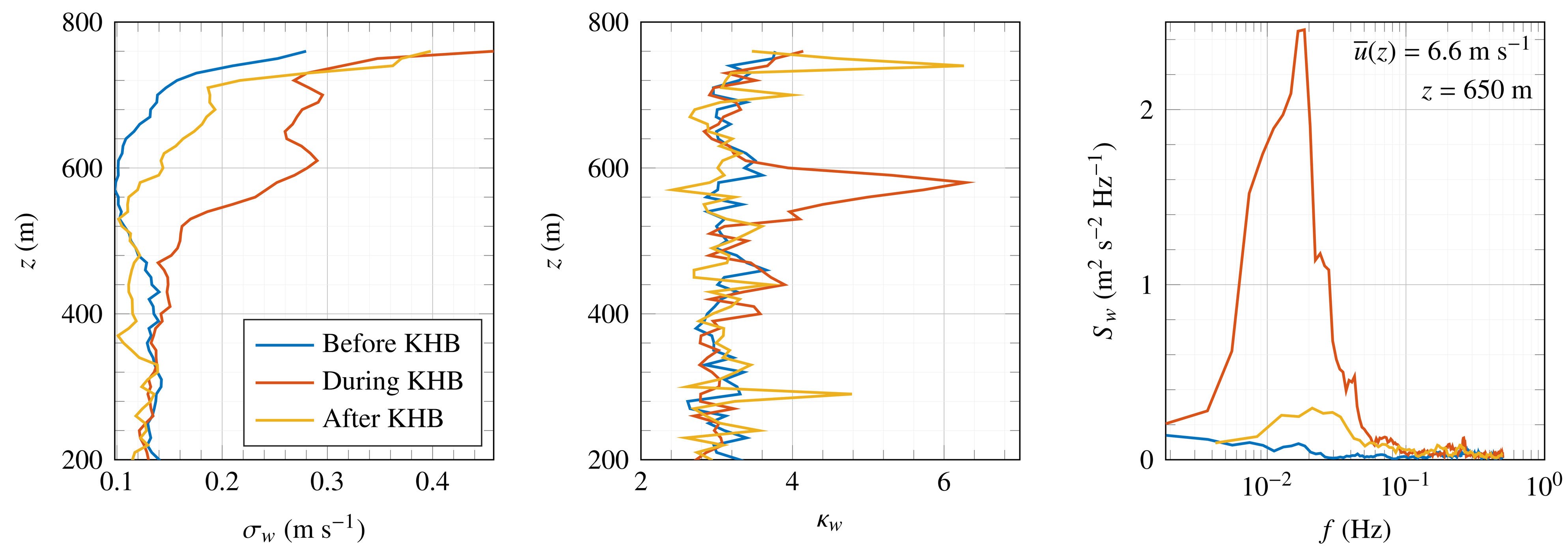
Mean wind speed and time series analysis

The figure below shows lidar measurements from 12:35 to 13:00, covering the Kelvin-Helmholtz Billows (KHB) event. The top panel displays the carrier-to-noise ratio (CNR), highlighting aerosols at different heights, with billows clearly visible between 550 m and 750 m from 12:45 to 12:56. The bottom panel shows vertical velocity, where alternating upward and downward motions correspond to the KHB formation. Aerosol accumulation at 600 m, beneath an inversion layer, indicates the presence of wind shear, which triggers the KHBs. The KHB causes notable mixing, reducing the CNR intensity and extending downward by 13:00. No interaction with the near wake of the wind turbine (below 200 m) is detected.



Fluctuating vertical velocity component analysis

This figure shows the profiles of the standard deviation σ_w (left) and kurtosis κ_w (middle) of the vertical velocity component, along with the power spectral density S_w (PSD) at 650 m (right) before, during, and after the KHB event. The standard deviation increases substantially during the KHB, reaching values 2.2 times higher than before, indicating enhanced turbulence. The kurtosis exceeds 6 at 575 m, suggesting strong intermittency near the KHB edges. The PSD reveals a sharp rise in energy during KHB, with a spectral peak around 0.02 Hz, almost 100 times larger than before. After the KHB, turbulence levels decrease, and the PSD returns to pre-event values. This indicates that the KHB event drives strong, short-lived mixing, significantly impacting vertical atmospheric dynamics.



Conclusions

This study demonstrates the successful use of a ship-based Doppler wind lidar to observe Kelvin-Helmholtz Billows (KHBs) in the marine atmospheric boundary layer above an offshore wind farm. The high-resolution measurements showed increased vertical turbulence and periodic velocity fluctuations during KHB events. No interaction between the KHBs and wind farm was observed in this study. However, we hypothesis that, under the right conditions, KHBs may improve wake recovery in stable conditions, benefiting wind farm performance. The dataset, collected between 2022 and 2023, provides valuable insights for future research in wind energy meteorology. It may also be relevant for airborne wind energy systems, potentially affecting energy efficiency, flight stability, and system load.

Acknowledgments

This work is funded by the European Union Horizon 2020 research and innovation program under grant agreement no. 861291 as part of the Train2Wind Marie Sklodowska-Curie Innovation Training Network (https://www.train2wind.eu/). The lidar instrumentation was provided by the OBLO (Offshore Boundary Layer Observatory) project funded by the Research Council of Norway (project number: 227777). We gratefully acknowledge the owners of Rødsand 2 for the access to the wind farm and the support of RWE for providing access to the crew transfer vessel "MV Carrier" from Northern Offshore Service, enabling the success of our campaign.