LOLLEX- The LOLland offshore Lidar EXperiment

A novel approach to collect data for the investigation of wind farm flow and measure entrainment inside a finite wind farm

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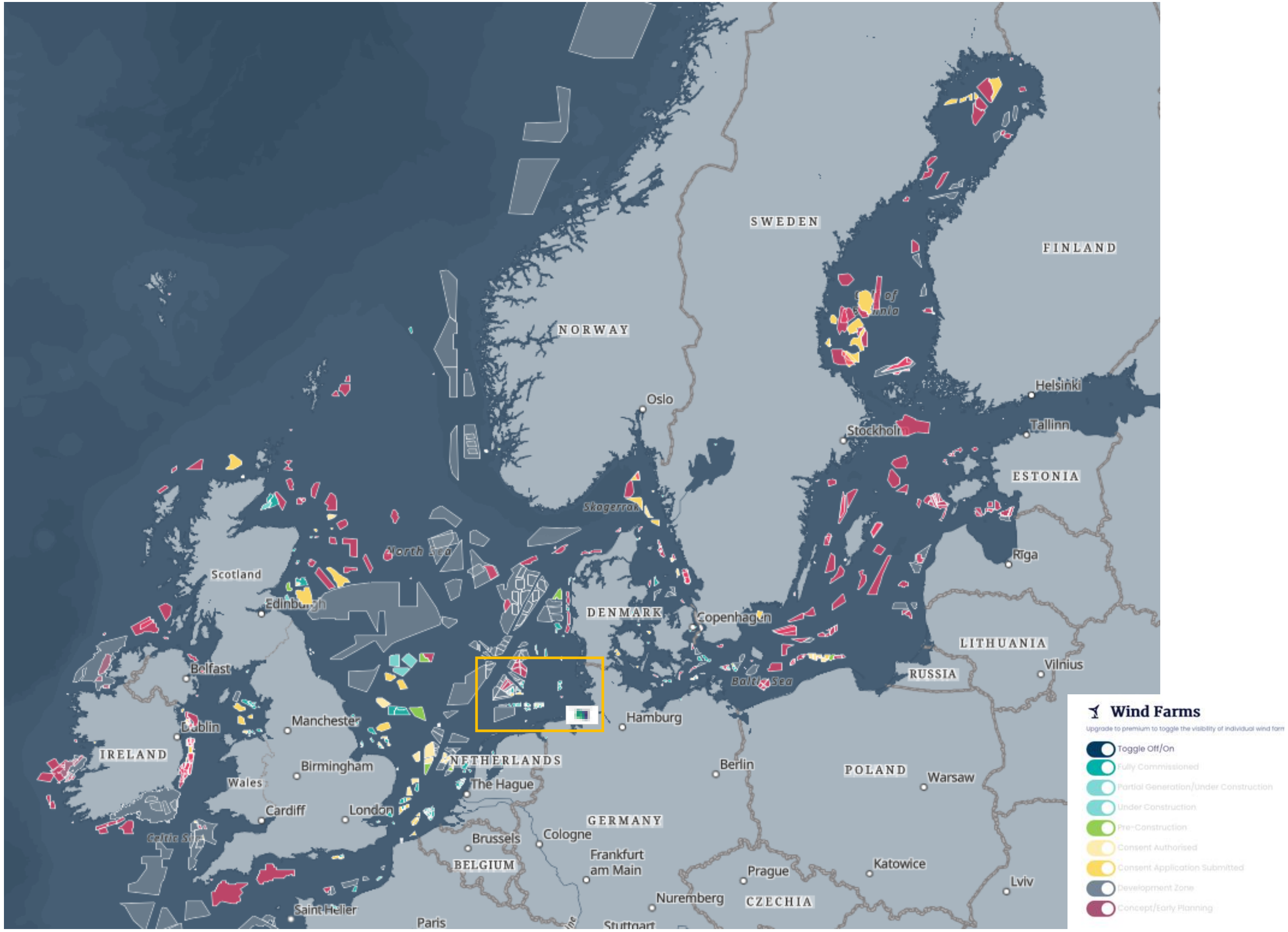
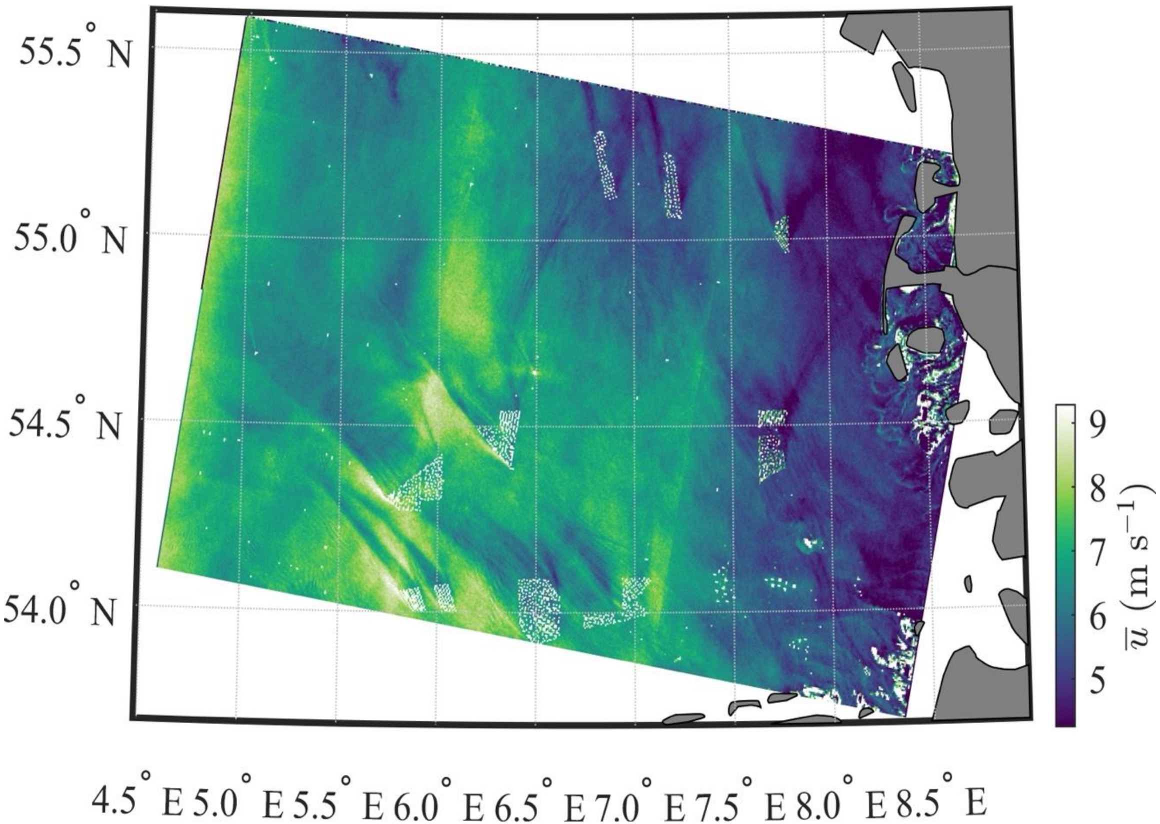
Offshore wind farms density in northern Europe



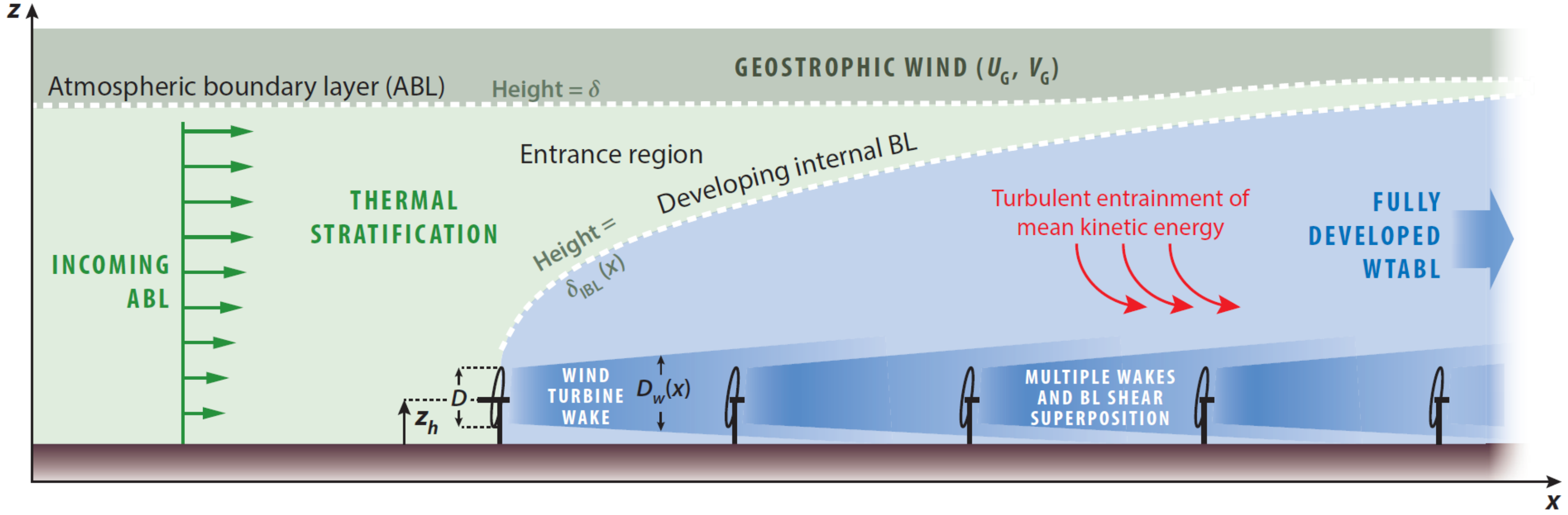
Source: https://map.4coffshore.com/offshorewind/

Farm-induced wakes spanning dozen of kilometres



Source: Finserås, E., Anchustegui, I. H., Cheynet, E., Gebhardt, C. G., & Reuder, J. (2024). Gone with the wind? Wind farm-induced wakes and regulatory gaps. Marine Policy, 159, 105897.

Complexity of flow physics in wind farms



Source: Stevens and Meneveau: Flow Structure and Turbulence in Wind Farms. AnnRevFluidDyn, 2017

Motivation

- Flow physics of (offshore) large wind farms is fundamentally different from a single wind turbine (Luzzatto et al., 2018)

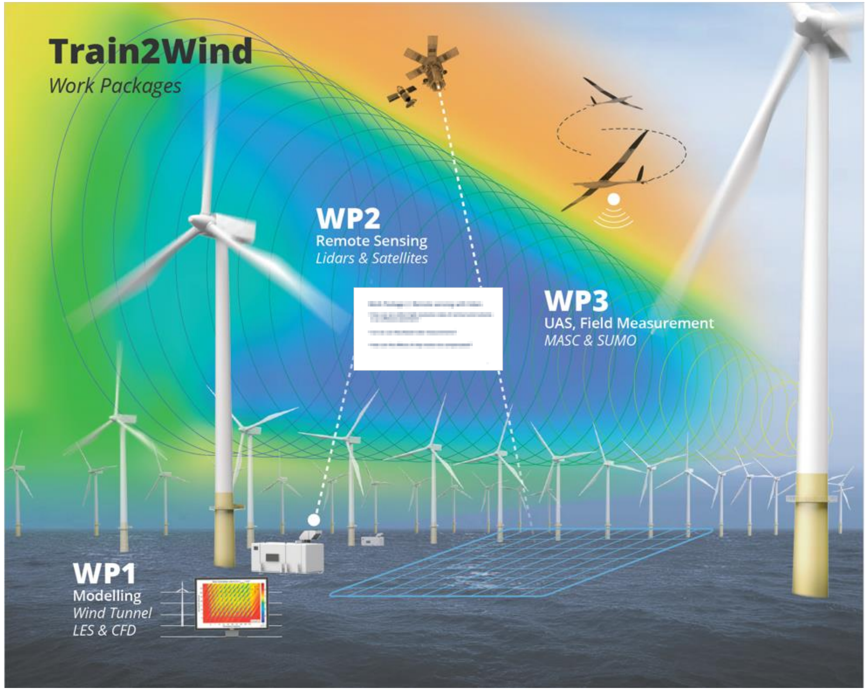
- Grand Challenges in Wind Energy Science calls for improved understanding of atmospheric physics in wind farms (Veers et al., 2019)

- Need for novel measurement strategies to analyse wind farm wakes and performance-enhancing parameters such as vertical momentum entrainment.

- Luzzatto-Fegiz, Paolo, and Colm-cille P. Caulfield. "Entrainment model for fully-developed wind farms: effects of atmospheric stability and an ideal limit for wind farm performance." *Physical Review Fluids* 3.9 (2018): 093802.
- Veers, Paul, et al. "Grand challenges in the science of wind energy." Science 366.6464 (2019): eaau2027.

Train2Wind ITN Project

- A measurement campaign at a full-scale offshore wind farm.
- A high-intensity measuring period using UAS, lidars, and collect information from satellites.
- Measuring the transition between the undisturbed air and the atmospheric boundary layer in the presence of the wind farm.



Source: Giebel, Gregor, et al. "Train2Wind: An Overview of the Lollex Experiment." *7th International Conference Energy & Meteorology: Towards climate-resilient energy systems*. 2023.

Work Package 2: Remote sensing with lidars

- How can we collect high resolution data of vertical wind velocity in an offshore wind farm?
- Can we use Ship-Based Lidar measurements?
- How can the effects of ship motion be compensated?

Lollex Campaign

September 2022-August 2023

Photo by Shokoufeh Malekmohammadi

Campaign site

- Rodsand2 wind farm
- Location: Baltic sea, south of Lolland
- Number of Turbines: 91
- Hub height: 68.5m
- Rotor blade diameter: 93m

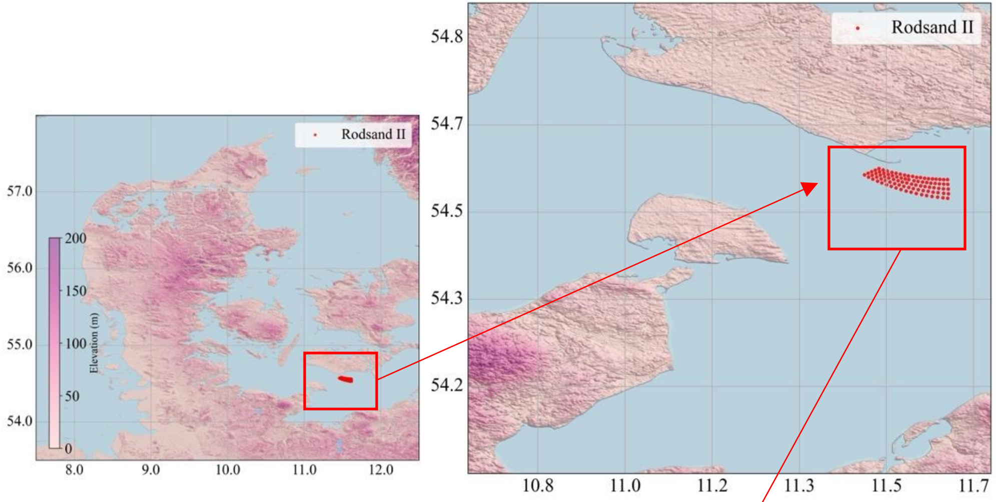


Photo source: https://gsseacon.com/realisation/roedsand-2-offshore-wind-farm/

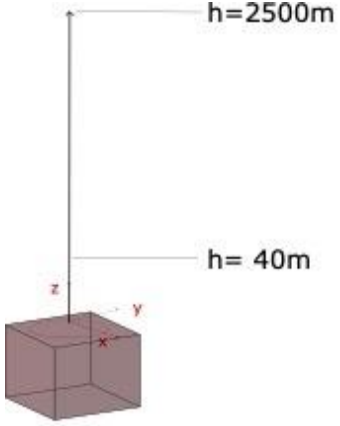
Instrumentations

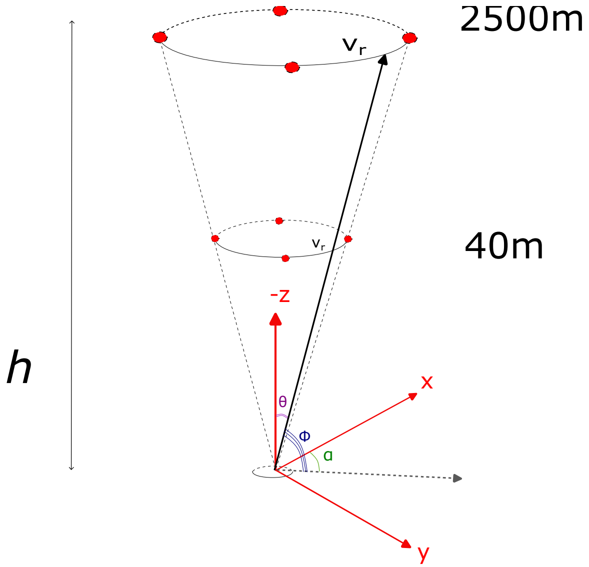
Wind Cube 100S

- Vertical scanning mode for 25 minutes
- Vertical wind velocity
- Resolution 10 m , 1 Hz

- DBS mode for 5 minutes
- Wind velocity profile

Picture source: https://www.nrgsystems.com/assets/resources/NRG-Windcube-Lidar-Scanning-Doppler-Lidar-Brochure.pdf

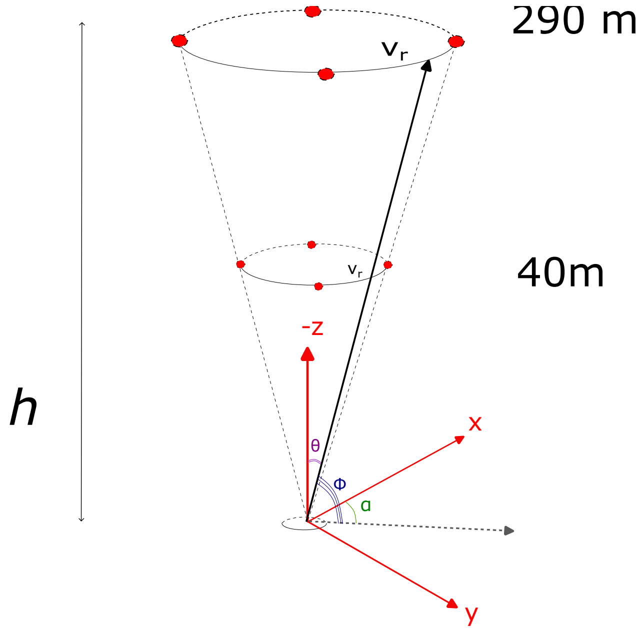




Wind Cube V2

- Measuring wind speed profile from 40m up to 300m

- IMU measuring the motion details (rotations, translational speed, heading, GPS location)



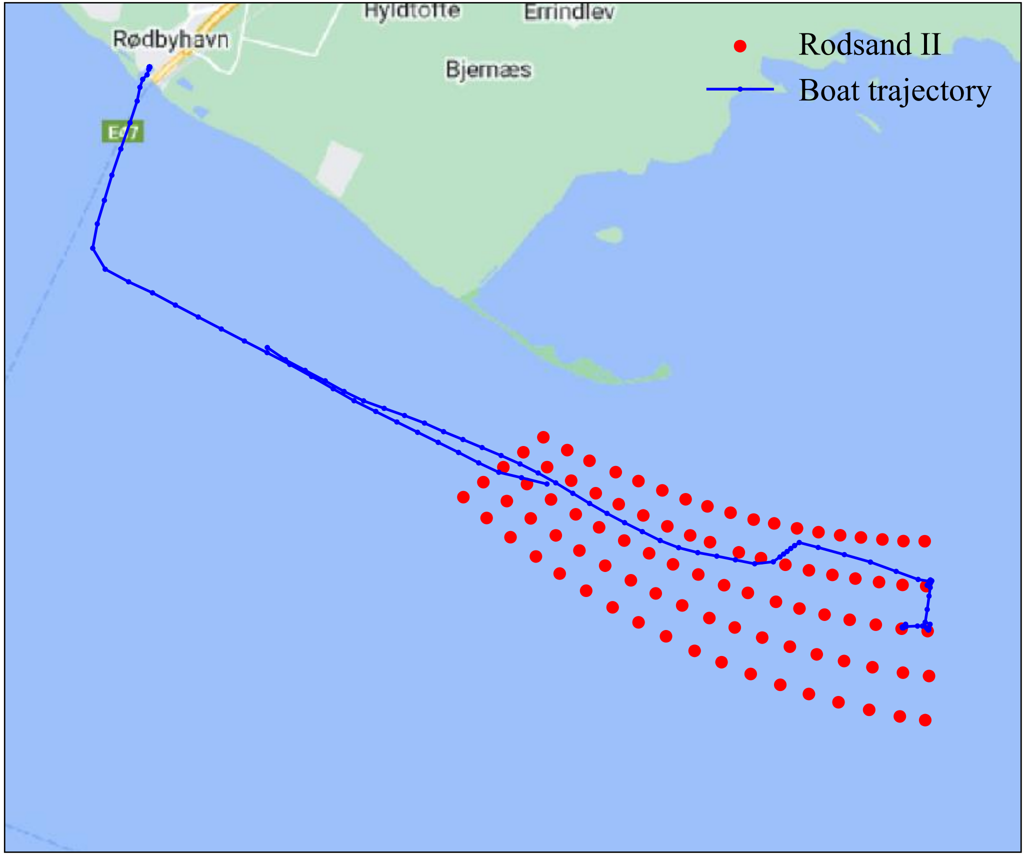
Picture source: http://www.windup.pt/resources/newsletter3pdf19av.pdf

Installation of lidars on the CTV

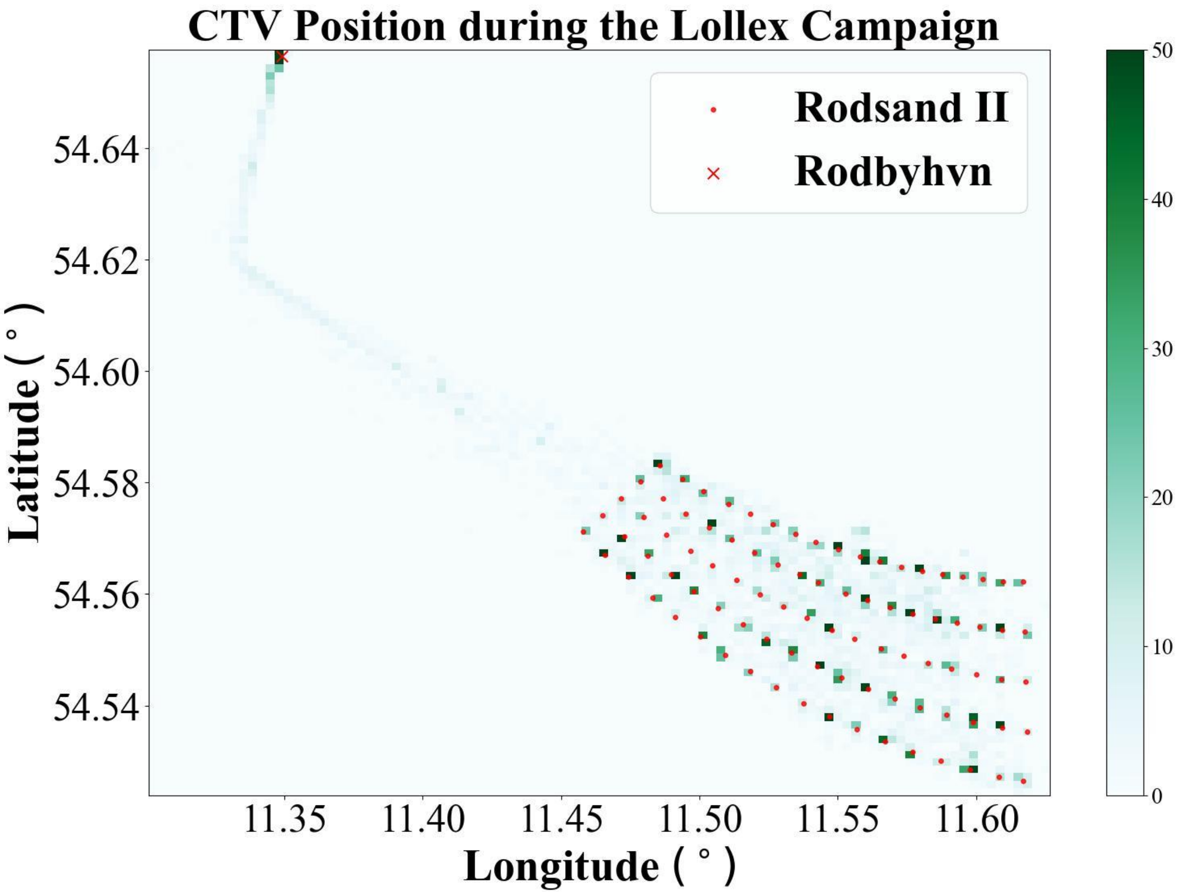
Photo by Christiane Duscha

Photo by Shokoufeh Malekmohammadi

Example of the CTV trajectory



- CTV did one round trip per day, leaving the harbour at around 7 am and returning around 6 pm.

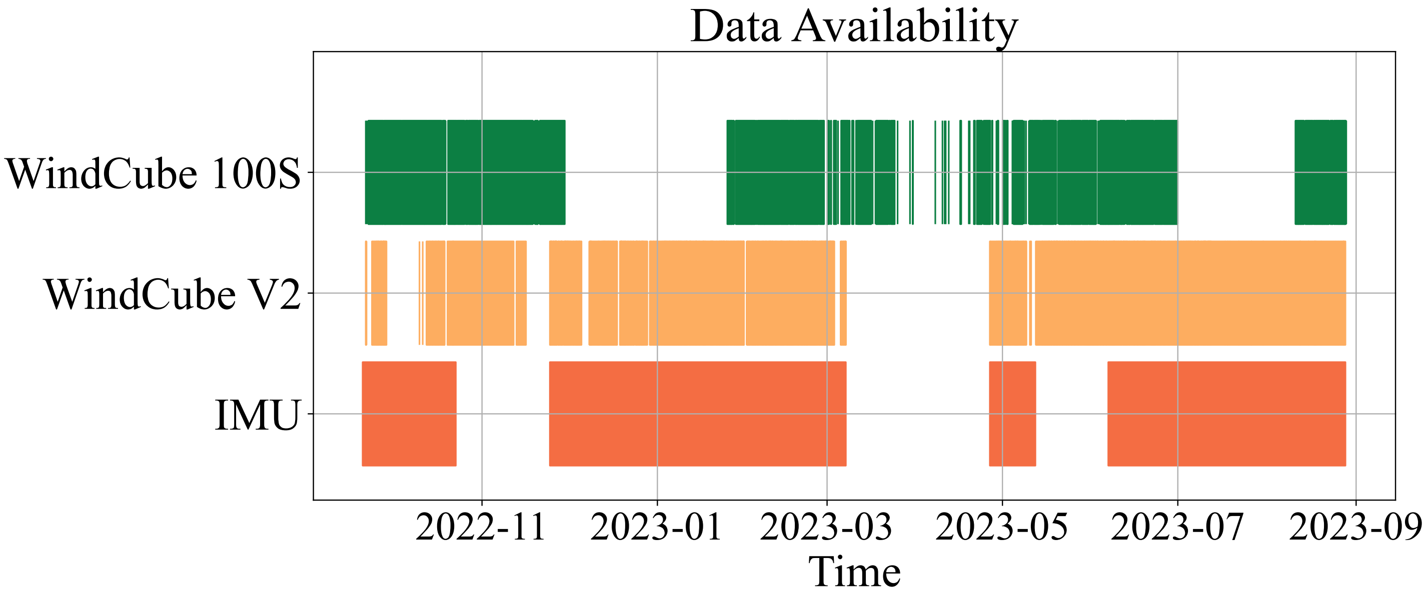


Duration : September 2022 – August 2023

CTV is not moving most of the time

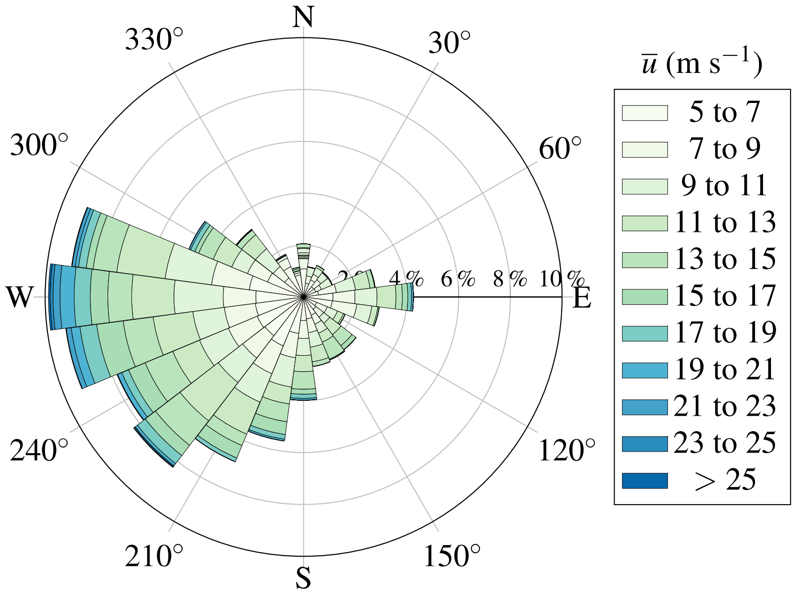
CTV is in vicinity of wind turbines most of the time

DATA availability



Wind conditions during the campaign

- Wind rose based on NORA3 data
- Mean wind at a height of 100 m
- Westerly winds dominate
- Median wind speed 8.5 m/s



Data processing

Data Filtering and noise treatment

- Data with CNR lower than -24 dB (WindCube V2), -27 dB (WindCube 100S) filtered

- Despiked data using the median absolute deviation filter

- Applied motion correction

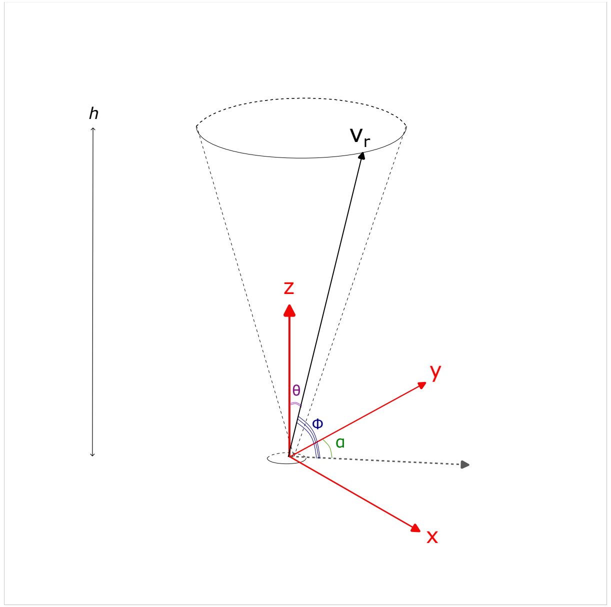
Retrieval of wind velocity for DBS mode

- LOS velocity is linked to wind velocity vector as

$$v_r = u\ sin\theta cos\alpha + \mathrm{v}\ \sin\theta\sin\alpha + \mathrm{w}\ \cos\theta$$

- Using the four LOS velocities the linear system of equations is solved:

$$\overrightarrow{v_r} = \boldsymbol{N}.\vec{u},$$



Motion Correction

- If lidar is experiencing motion:

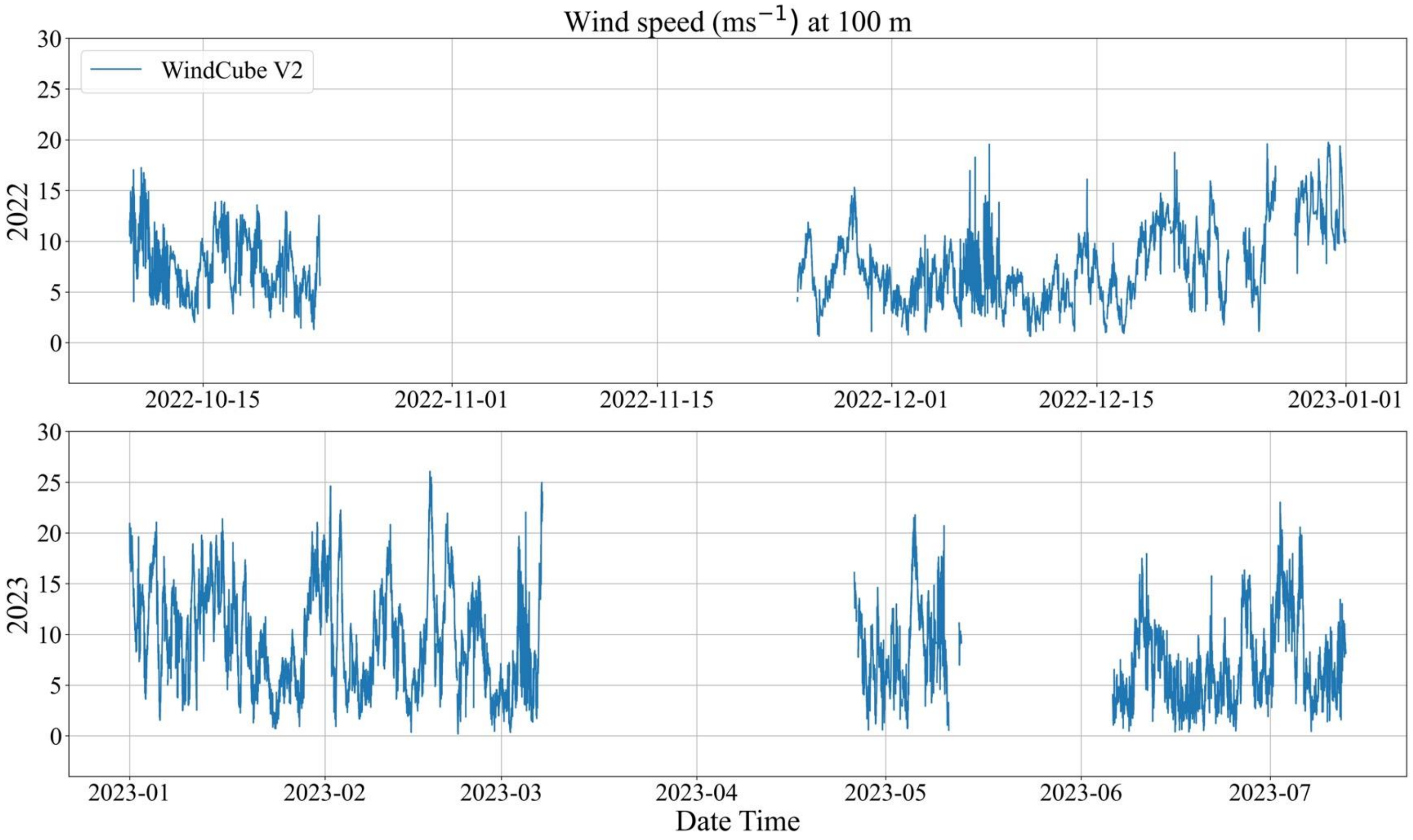
$$\overrightarrow{v_r} = \boldsymbol{RN}(\vec{u} + \overrightarrow{u_T}),$$

Where

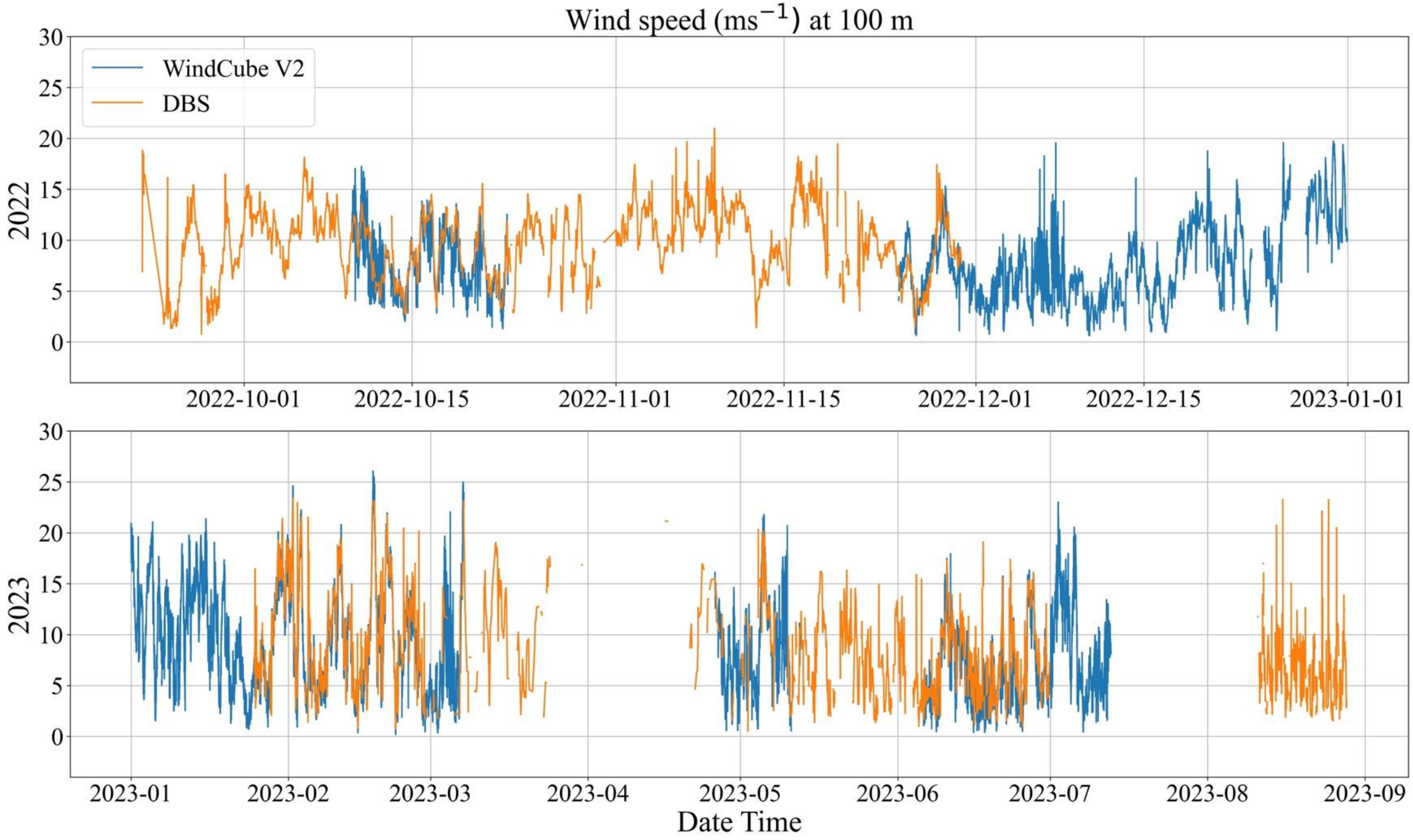
- $\boldsymbol{R}$ is the rotational matrix
- $\overrightarrow{u_T}$ is the translational motion vector

Results

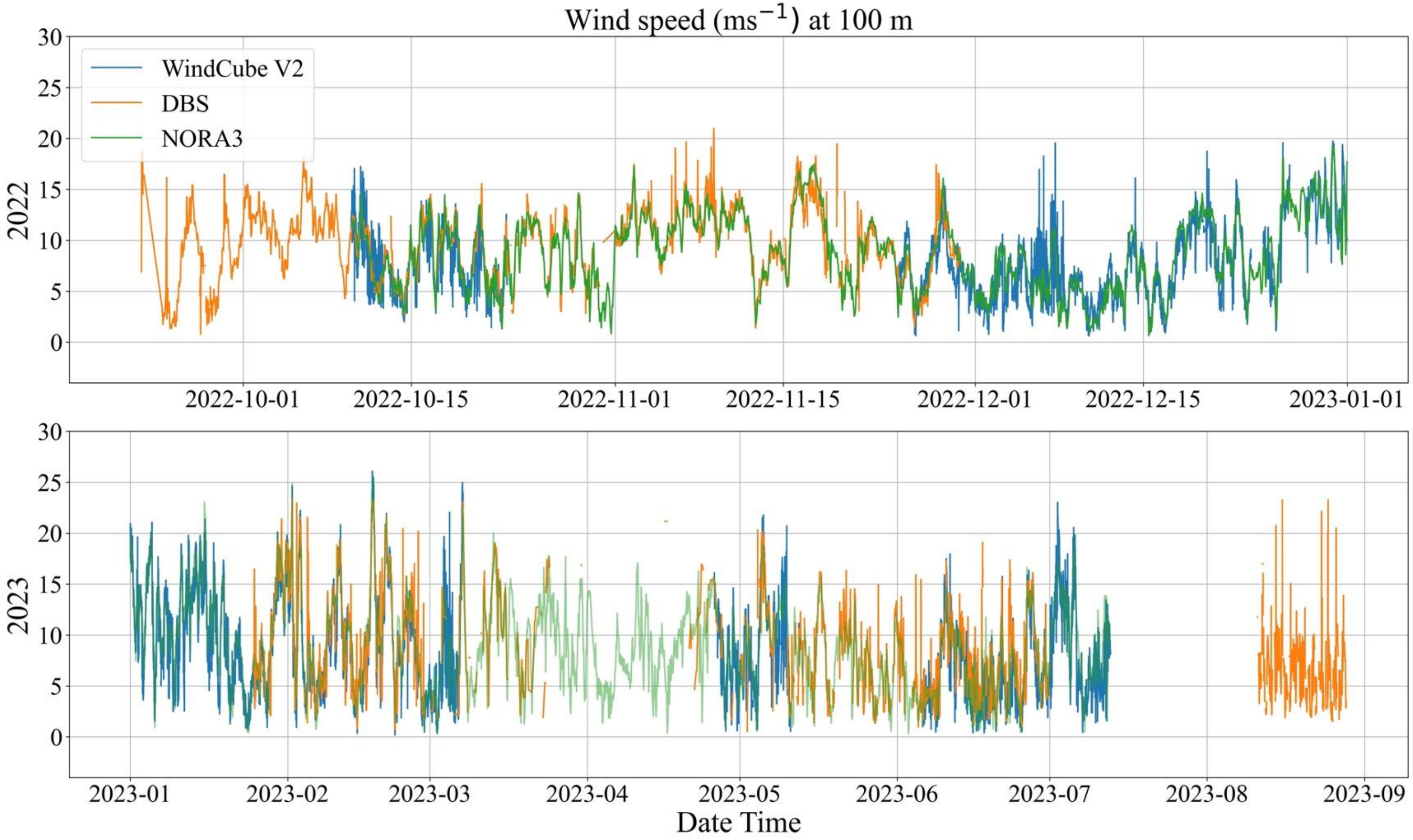
Wind speed timeseries (Wind profiler)



Wind speed timeseries (two lidars)

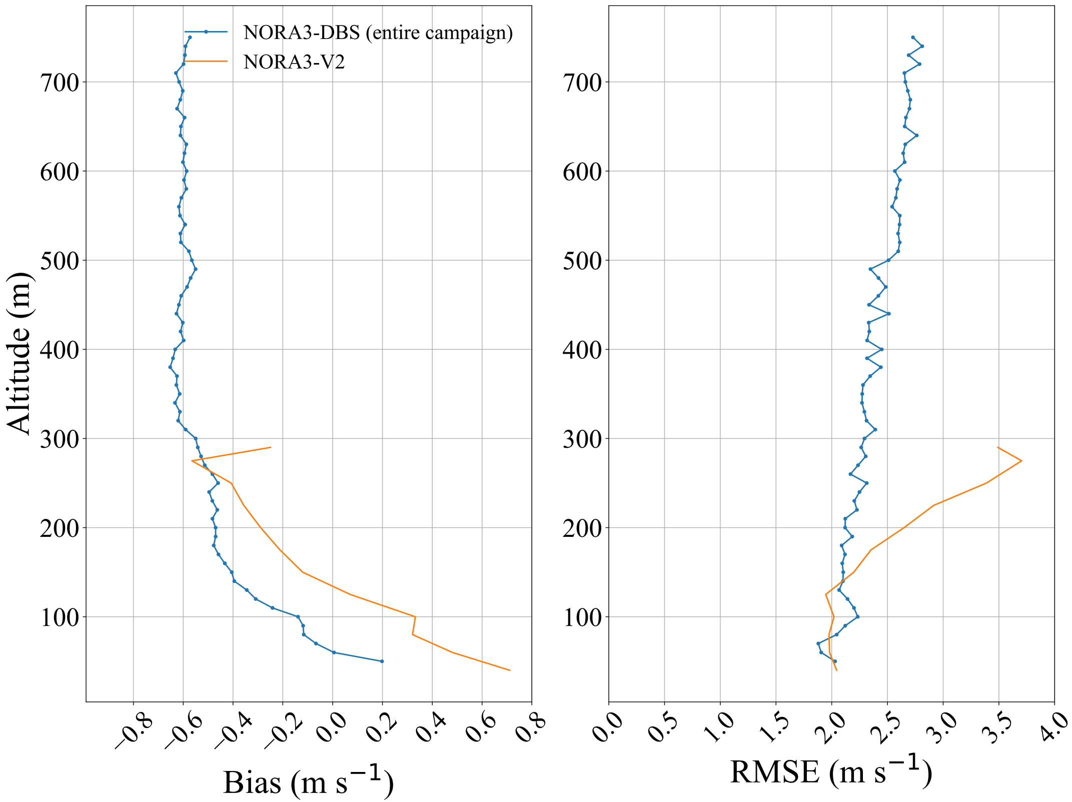


Wind speed timeseries (lidars vs NORA3)

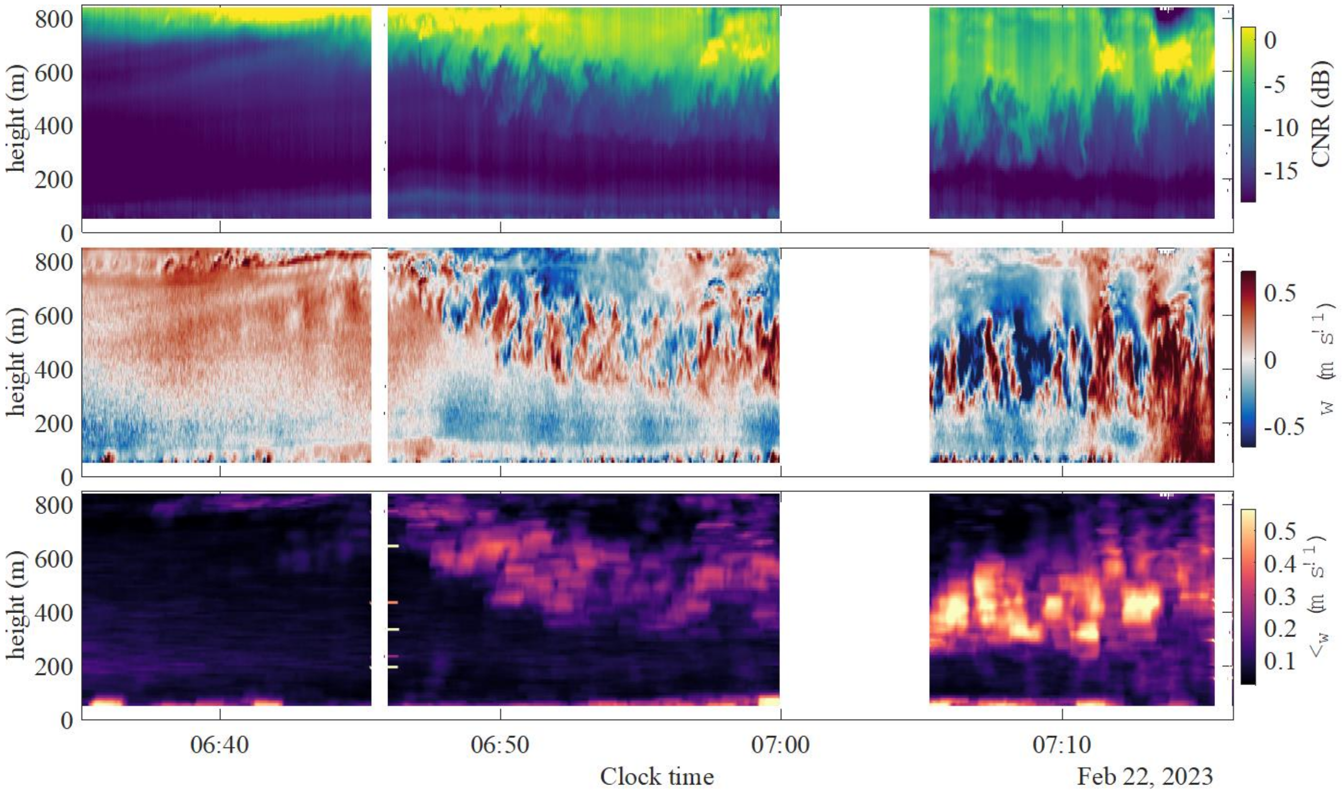


Errors profile

- Reasonable agreement between the NORA3 hindcast and observational data
- Absolute error range : 0-0.6 m/s
- NORA3 overestimates wind speed at height below 100 m
- RMSE is different for each lidar and needs more investigation



Case Study 1: Entrainment Observations



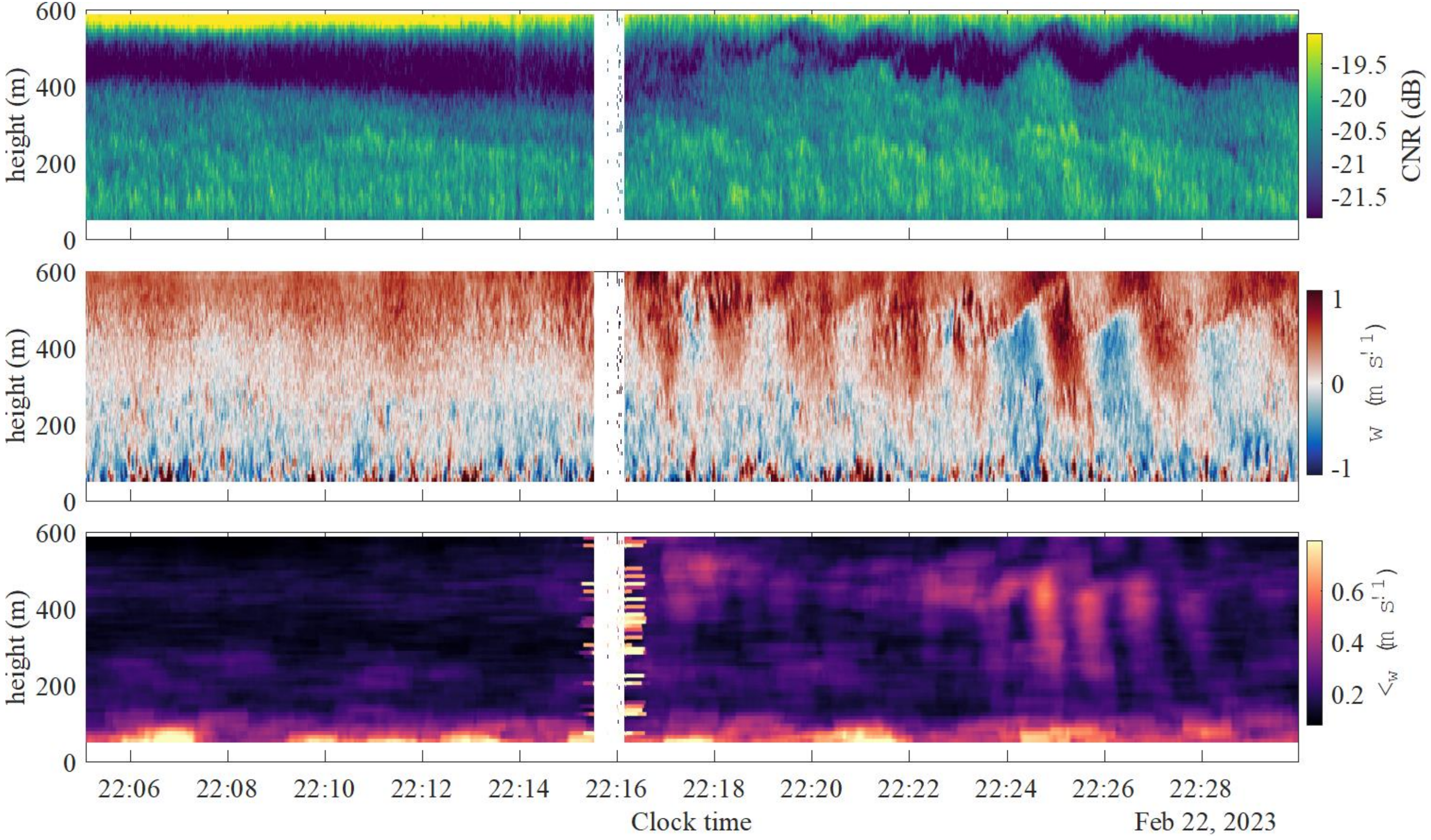
- Measurements in the morning under stable atmospheric conditions

- Vertical coherent structures
- Increase in σ_w to 0.5 m/s

- $TI: 0.11 - 0.13$ ($TI = \frac{\sigma_w}{\bar{u}}$)

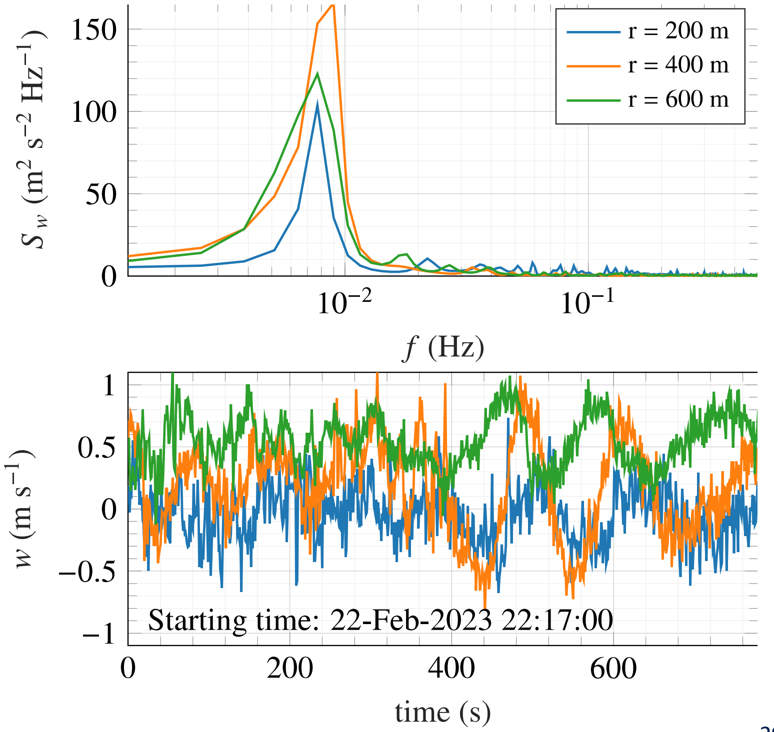
- Increase in TI due to external factors like shear instabilities or entrainment of momentum

Case Study 2: Atmospheric Wave Observations



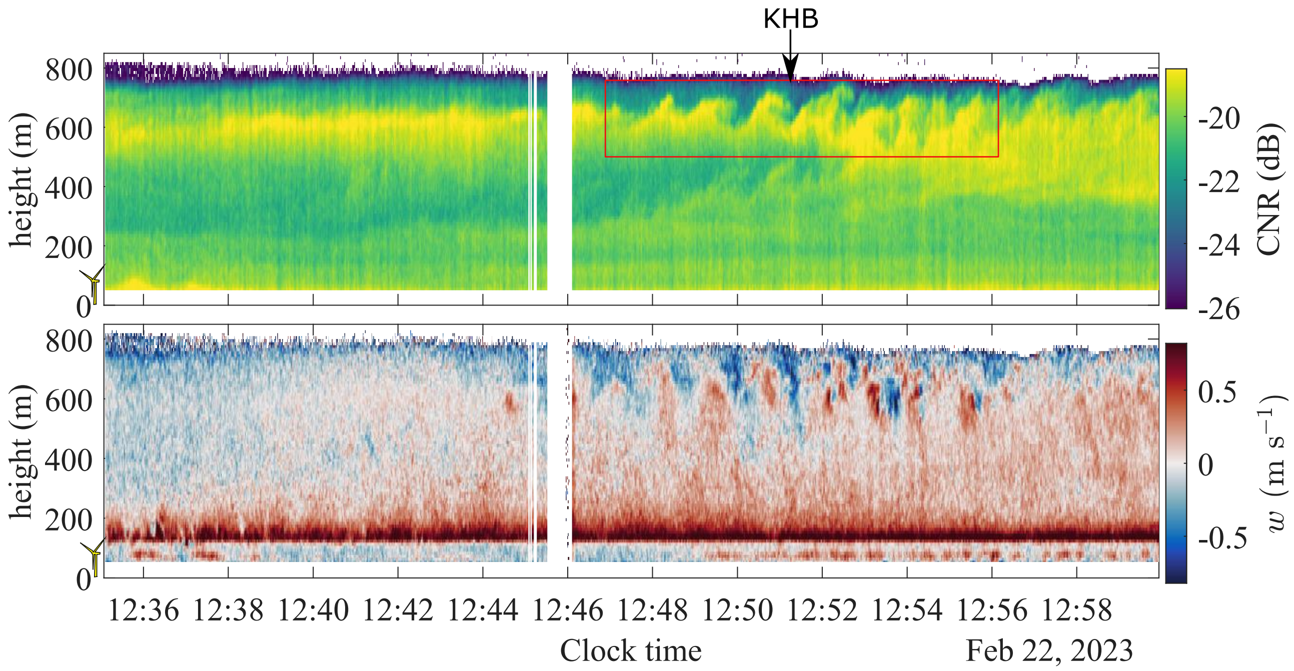
Case Study 2: Atmospheric Wave Observations on 22 February 2023

- Periodic motion with a 2-minute cycle
- Phase shift between altitudes indicating wind shear influence
- Wave Effects extends below 200 m
- Potential enhancement of wake recovery if occurring above wind farm



Case Study 3: Kelvin-Helmholtz billows (KHBs) above the wind farm

- KHBs between 600 m and 800
- Flow interactions with offshore wind turbines within the first 200 m.
- Rarity and brief appearance of KHBs make this observation significant



See our poster in the poster session

Conclusion

- Ship-based lidar measurements have (after appropriate motion correction) a great potential for offshore wind energy meteorology.

- Lollex campaign provides a novel and unique dataset for the investigation of complex wind farm flow and entrainment offshore.

- The combination of a lidar wind profiler with a scanning lidar in fixed staring mode, provides information on wind farm boundary layer with a unique spatial and temporal resolution.

Acknowledgement

- National Norwegian infrastructure project Offshore Boundary Layer Observatory (OBLO)
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- Technical University of Denmark (DTU)

EU no. 861291

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