

Answers to the comments of the reviewers for the manuscript

„Airborne measurements for investigating offshore wind farm wakes
and modifications of sea state - benefits and limitations “

Submitted to Wind Energy Science

by

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The authors would like to thank the three anonymous reviewers for their detailed comments and suggestions to improve the manuscript. In the following, the comments are provided in italic letters. Each point is answered in normal letters. Changes to the text are indicated by quotation marks. Lines refer to the original manuscript.

Review 2:

The manuscript summarizes flight measurements around wind farms. This is a highly relevant and exciting study program with clear added value for the scientific community.

The authors would like to thank the reviewer for this positive judgement.

Regarding the manuscript specifically, it states (lines 64-65) “that are already published, and adds new aspects, which have not yet been published so far.” However, it is not clear which results are new and which have been previously published (there is no central place where this is summarized).

It is unclear to what extent it should be seen as a review of the authors' previous work and how much is new.

For figures 5, 6, and 7, it is clearly stated that they are obtained from previous work. Is it correct to assume that Figures 1, 2, 3, 4, 8, and 9 have not been previously published?

We added in the text:

“It summarizes results that are already published, and adds new aspects, which have not yet been published so far: Such new material includes

- the direct comparison of almost simultaneous airborne and satellite-derived wind field in the wake of wind farms (Sect. 3.1)
- a study of changes of sea surface properties (Sect. 3.6)
- limitations in identifying the global blockage effect (Sect. 3.7)”

What does "Powered by Esri" in Figures 1,2, and 4 mean?

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** line 34: including a different visual appearance (Ladenburg, 2009),*

We do not understand this point. The mentioned text and reference are the same as in the manuscript, and it is not indicated what should be changed here.

** Line 115-116: Does the uncertainty depend on the main wind speed, and if so, how strong is this dependence?*

We changed the text to:

“The systematic wind speed correction was derived by analytically estimating wind speed perturbation caused by a static installation offset and a small angle-of-sideslip error using a first-order linearisation of the wind derivation equations. Assuming an absolute angular error of 0.3° on the angle of sideslip and a measurement speed of 65 m/s, the wind speed error of the 100 Hz data is ± 0.35 m/s on flight legs perpendicular to the prevailing wind direction.”

** Line 115-116: What is the uncertainty in the velocity fluctuations?*

The uncertainty for the wind speed is stated in the answer above.

** Figure 2/4: Can you indicate the main wind direction? Is it correct to assume the flight paths are always perpendicular to the shown flight paths?*

We added an arrow to indicate median wind direction in both Fig. 2 and Fig. 4.

We added in the figure captions: “Wind speed measurements along the flight path perpendicular to the main wind direction are colour coded and plotted for every 15 s.”

** Figure 2/4: Can you indicate some characteristic times of the measurements in the figure*

We added in the figure captions: “One flight leg of around 45 km length requires a flight time of around 12 min.”

** Figure 2/4: How much is the variation in the wind direction over the measurement duration of the flight? What is the potential impact of wind direction variations during the measurements?*

Wind direction variations are potentially affecting the wake, but this dynamic behaviour is beyond the presentation within this paper. The wind measurements therefore denote 4D in-situ data in the form of time series with all its inherent properties.

Basic statistics on wind direction and speed during the measurement legs were added in Fig. 2 and Fig. 4 to illustrate the variability of wind conditions during the flight.

We added in the figure captions: “The arrow indicates the main wind direction. The variability of the wind field during the measurement flight is illustrated by the standard deviations of wind speed and wind direction.”

** Figure 2/4: Can you also indicate the wind farm names in this figure? It is a bit confusing that the view of this figure differs from that in Figure 1.*

We added the wind farm names in Fig. 2 and Fig. 4.

** Line 162: Can you comment on the uncertainty in the SAR data due to the extrapolation towards hub-height?*

We thank the reviewer for the comment. We have added a short note on the uncertainty due to the extrapolation of SAR-derived 10 m wind speed to hub height. This uncertainty depends on the assumed wind profile, atmospheric stability, and surface roughness. Although it is reduced by using stability information from the airborne profiles, it remains relevant in and near wind-farm wakes, where turbulence, vertical shear, and sea-surface roughness can be modified.

“One should note that extrapolating from SAR-derived 10 m wind speed towards hub height introduces uncertainty related to atmospheric stability, surface roughness, and the vertical wind profile. This uncertainty is reduced here by using stability information from the flight profiles, but the stability functions used in the extrapolation are still idealised (Garraat, 1994) .”

** Figure 3: How long does each measurement (T6, T7, T8) individually take?*

We added in the figure caption: “One flight leg of around 45 km length requires a flight time of around 12 min.”

** Figure 3: Some SAR data seems missing; i.e. the yellow lines have some gaps. Can you comment and explain this?*

We thank the reviewer for pointing this out. The gaps in the SAR-derived curves are caused by quality filtering of unrealistic SAR wind-speed values. Some transects, especially T6, pass close to the Amrumbank West wind farm, where turbine-related SAR artifacts can affect the backscatter and produce unrealistic wind-speed spikes. These spikes were removed before the comparison, which leads to missing points in the SAR-derived curves.

We added in the figure caption: “The gaps in the SAR-derived data are caused by quality filtering of unrealistic SAR wind speed values due to turbine-related SAR artifacts close to the wind farm Amrumbank West.”

** Figure 3: What is the turbulence intensity of the wind signal measured by the airborne measurements? What is the approximate uncertainty in this?*

The importance of this figure is to illustrate a comparison of satellite-derived wake data and airborne in-situ data. We further quantified: “For transects T6–T8, the SAR-derived and airborne wind speeds show an overall agreement with an rms of 0.8 m/s and a correlation coefficient of 0.8. The bias varies

between the individual transects (including a change in sign between T6 and T7/T8), indicating that the differences are not systematic across all transects and may depend on local atmospheric boundary-layer conditions. The standard deviation of the SAR and airborne wind-speed differences is about 0.3 m/s.”

** line 177-178: "In addition, a wind farm not in operation does induce downstream turbulence, even if the wind speed is not reduced significantly" --> This statement seems out of context here. Do you know how large the effect is?*

We agree that the statement does not substantially contribute to the topic. Therefore, we removed the sentence.

** Line 185: "Particularly, the engineering model coupled with WRF—" --> this is unclear: please specify further.*

We agree with the reviewer that this description was too brief. We have revised the text to explicitly clarify the coupling mechanism of the EM-WRF model:

"Particularly, the engineering model coupled with WRF (EM-WRF, Fig. 7) - where a heterogeneous, undisturbed WRF background simulation is used as input to initialize each turbine locally, and turbine wakes are propagated as passive scalars along the atmospheric flow streamlines derived from the WRF data (zum Berge et al., 2024) - proved to be most consistent with the airborne observations, especially under stable stratification."

** Line 188: Statements here are not really in a logical order.*

We changed the sentence to: "All models (see Fig. 7) showed a reduced accuracy in predicting wake position and strength at distances beyond 30 km from the wind farm cluster. Therefore, accurate inflow conditions and proper atmospheric stability characterization are required to improve the performance of all model results over such large scales."

** Section 3.2: This section overall can benefit from better structuring and division in some paragraphs, and some more details to provide context to the reader.*

We sharpened the focus of the section and organised the text as several paragraphs. In particular, we added in the text: "Airborne observations provide the opportunity to focus the measurement strategy on covering overlapping wake effects of multiple wind farms, and to confirm simulations of the wind field."

** Figure 5: Do you know why the effect is observed for only part of the x-range of the wind farm?*

We added in the text:

"The distance of the flight trajectory to the wind farms varies due to wind park geometry and wind direction, resulting in visible effects of the latent heat fluxes only for part of the areas indicated as downstream of the wind farms in Fig. 5."

** Line 217: A citation is missing.*

Thank you – we corrected the latex citation error.

** Line 232: "measurements are a suitable tool to study these effects of coastal transition." --> Can be removed here: This is more what is generally outlined in abstract, conclusion, and introduction, but does not need to be repeated throughout the manuscript.*

We modified the sentence and put it into the conclusion section: "Airborne measurements can resolve the complex and height-dependent phenomena of wind field modifications for coastal transitions, and such data can help to understand and properly simulate mesoscale processes in offshore wind assessments."

** Line 254-255: The two lines are very vague and do not form a proper paragraph.*

Thank you for the valuable point. We reviewed the sentence which now sounds as follows:

"Simulation progress has been achieved by coupling atmospheric and oceanic models. Nevertheless, current simulation approaches for representing wind-turbine generated turbulence do not fully reproduce observations, particularly regarding the vertical transport of turbulent kinetic energy and its impact on the sea surface (Larsen et al., 2024)"

** Figure 7: Please increase the font size of labels in this figure.*

Thank you for the hint – we increased the font size of the labels in Fig. 7.

** Figure 8: Can you explain the "red lines" at North displacements of 6 km (49 km panel), 8 km (70 km panel), and 22 km (76 km panel)*

The red lines visible at these three displacement positions are artifacts caused by intermittent disturbances captured during the LiDAR measurements — likely originating from passing vessels or similar moving objects in the field of view. The fact that similar disturbances appear across three different range panels (49, 70, and 76 km) at spatially consistent positions suggests that the source was advected or moving during the measurement period, leaving a coherent signature across the three multiple panels.

We changed the figure caption to: "The horizontal, narrow lines with high energy density can be attributed to boats or other disturbances near the sea surface. The fact that similar disturbances appear across three different range panels (49, 70, and 76 km) at similar spatial positions suggests that the source was advected or moving during the measurement period."

** Figure 8: What is the black in panels 70 and 76 km?*

The black regions in panels 70 and 76 km correspond to areas of very low spectral energy density, particularly at angular frequencies below approximately 1.5 rad/s. Overall, the spectra at these large distances from the wind park exhibit a more homogeneous distribution, with energy levels predominantly in the green range of the color scale, leaving low-energy regions appearing black due to the applied range.

We included in the text: "At downstream distances of 70 km and 76 km, very low spectral energy density are observed (black colour), particularly at angular frequencies below approximately 1.5 rad/s. Overall, the spectra at these large distances from the wind farm exhibit a more homogeneous distribution, with energy levels predominantly around $0.2 \text{ m}^2\text{rad}^3\text{s}^{-3}$ (green range of the color scale), leaving low-energy regions appearing black due to the applied range."

** Figure 9: What confuses me in this figure is the mismatch in locations shown in the first panels. I.e Panel (b) indicates latitudes: 54.2 to 54.65, which does not seem to clearly correspond to what is shown in panel (a). Similar for the longitudes in panel c, which do not correspond to panel a.*

Indeed - the mixing of decimal and deg/minute notation is confusing. We changed the tick format as well as the tick/grid positions to enhance readability.