

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 “

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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 3:

*The manuscript gives an impressive overview of airborne measurements. Unfortunately, it is too much descriptive. This may be fine with respect to meteorology, for the wind energy community (wind farm developers, wind turbine designers, wind energy researchers) more specifications are required, e.g. with respect to the airborne measurements:*

We would like to thank the reviewer for the judgement. We are happy to improve the manuscript based on the comments below, and include more quantitative information.

• *what is the averaging period of the wind speed (e.g. as shown in Fig. 2)? And what is the typical distance travelled by the aircraft during this time interval?*

The wind data are generally available at 100 Hz. For Figure 2 and 4, the wind speed is averaged over 15 s to reduce fluctuations. The aircraft is operated at an air speed of 65 m/s. Therefore, the aircraft travels a distance of around 1 km for each measurement point.

We added in the figure caption: “Wind speed measurements along the flight path perpendicular to the main wind direction are colour coded and plotted for every 15 s, corresponding to a displayed horizontal resolution of around 1 km.”

• *How accurate are these measurements? (e.g. on basis of the calibration of the instruments and/or comparing with sonic measurements on a static met-mast, when the aircraft has been flown close to it)*

We included a paragraph about sensors and accuracies:

“The meteorological instrumentation for measuring the high resolution (100 Hz) wind vector, temperature and humidity is installed in the nose boom. For the wind vector, this includes a five-hole probe (Rosemount, USA) and sensors for differential and total pressure (Setra, USA) to determine the airflow angles. The position and orientation of the aircraft are determined with a combination of an inertial measurement unit (IMU, different systems for the Dornier128: iNAV-RQH-1003, iMAR, Germany, and for the CessnaF406: iNAT-RQT-4001, iMAR, Germany) and a Global Navigation Satellite

System (GNSS, receiver OEM6, NovAtel, Canada). The wind vector can then be derived by subtracting the air speed vector from the ground speed vector. The temperature is measured by two complementary sensors, one with high accuracy, but slower response time (102DB1AG, Rosemount, USA), one with lower accuracy, but higher response time (102E4AL, Rosemount, USA). Humidity is measured with three different sensors: A capacitive sensor Humicap H233 (Vaisala, Finland), a dew point mirror TP 3-S (Meteolabor, Switzerland), and a fast, but drifting optical sensor (for the Dornier128: Lyman-alpha sensor L-6/HMS-2, Buck Research, USA, and for the CessnaF406: KH-20, Campbell Scientific, USA).

Additional instruments for measuring surface temperature, sea state and solar and terrestrial radiation are installed in the aircraft cabin: an infrared radiation thermometer (KT15.82D in the Dornier128 and KT19.85 in the CessnaF406, Heimann, now Heitronics, Germany), a laser scanner VZ-1000 (Riegl, Austria, only for the Dornier128), two pyranometers for measuring upward and downward solar irradiance (CMP22, Kipp and Zonen, The Netherlands), and two pyrgeometers for measuring upward and downward terrestrial irradiance (CGR4, Kipp and Zonen, The Netherlands). The radiation sensors are only available for the CessnaF406. More details on the sensors and the accuracies are provided in Lampert et al. (2020) and Lampert et al. (2024)."

- *How is the turbulence intensity determined? (what is the sampling rate?)*

Actually we do not use the parameter turbulence intensity in the manuscript. We now added information on the sampling rate and measurement uncertainty for the wind vector:

"The meteorological instrumentation for measuring the high resolution (100 Hz) wind vector, temperature and humidity is installed in the nose boom."

"the wind speed error of the 100 Hz data is  $\pm 0.35$  m/s on flight legs perpendicular to the prevailing wind direction"

- *How is the stratification (heat flux) obtained?*

We added in the text: "Latent heat fluxes were calculated based on the eddy covariance method, correlating the fluctuations of the vertical wind speed component and the fluctuations of the mixing ratio based on measurements of the Lyman-alpha fast humidity sensor. More details of the averaging method are explained in Platis et al. (2023)."

*Line 161: 'These include the ability to directly validate satellite-derived wind speed at hub height'; so, specify the (typical) mean and standard deviation of the difference between the SAR and airborne wind speed (Fig. 3)*

We thank the reviewer for the comment. Please see the response to the previous comments from reviewer 1 (on the quantification of agreement). For transects T6–T8, the estimated bias between the SAR-derived and airborne wind speeds is about 0.7 m/s. The standard deviation of the difference is about  $0.3 \text{ m s}^{-1}$ , with an rms of  $0.8 \text{ m s}^{-1}$  and a correlation coefficient of 0.8.

*Line 164: 'Airborne measurements also complement'; how?*

We changed the sentence to: "Airborne measurements also extend the spatial coverage provided by long-range scanning wind lidar systems, which are typically fixed at a single location and can retrieve wind field data over distances of up to approximately 15 km, depending on atmospheric conditions"

*Line 187: 'all models showed reduced performance further downstream'; specify*

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."

*Line 188: 'The study underlines the value of high-resolution airborne data for benchmarking wake models in clustered offshore wind farm'; be more specific: what did airborne exactly add to the traditional way of wake measurements (in other words: what can be done with airborne measurements what is not possible with e.g. a lidar or met-mast).*

We changed the sentence to: "Unlike traditional met-masts, which only provide single-point time series, or Doppler lidars, which are limited to a scanning range of about 10 km, in-situ airborne measurements allow capturing the full, large-scale cluster wake developments that can extend beyond 50 km to 70 km under stable atmospheric conditions (Platis et al., 2020). By flying meandering patterns perpendicular to the wind direction at hub height across multiple locations, aircraft data uniquely provide high-spatial-resolution cross-sections of the wind field. This makes it possible to simultaneously evaluate wake deficits, lateral wake extent, and merged wake structures from multiple adjacent wind farm clusters across vast horizontal distances."

*Line 217: Typo: (?Djath et al.*

We corrected the latex citation error.

*Line 226-228: 'the dissipation of a land-based LLJ'; 'a breakdown of the LLJ'; clarify what the difference is.*

Thank you for this comment. We agree that the wording was ambiguous and could imply two distinct physical mechanisms. In this section, following the interpretation presented in Section 4.3 of Cañadillas et al. (2023), both expressions were intended to describe the gradual weakening and eventual erosion of the land-based low-level jet as the flow adjusts offshore under changing stability conditions and enhanced vertical mixing. To avoid confusion, we revised the wording and now consistently refer to the "weakening" or "gradual decay" of the LLJ throughout the manuscript.

We changed the text to: " Cañadillas et al. (2023) present two contrasting airborne measurement cases illustrating the offshore adjustment of low-level jets (LLJs) over the German Bight under offshore-flow conditions. In the first case (Fig. 5a; 23 July 2020), warmer sea-surface temperatures offshore (approximately 17,°C at FINO1 compared to about 13,°C over land during the early morning) reduced atmospheric stability over the sea and enhanced vertical turbulent mixing. This promoted the downward transport of momentum and led to a rapid weakening and gradual erosion of the land-based LLJ as the flow adjusted offshore, accompanied by increasing near-surface wind speeds with increasing fetch. In the second case (Fig. 5b; 23 September 2020), the flow over land was initially much more strongly stratified. Although the warmer sea surface gradually reduced the stability offshore, the boundary layer adjustment occurred more slowly, allowing the LLJ to persist farther offshore before weakening. As a consequence, the wind speed decreased with increasing distance from the coast."

*Line 237: 'high-resolution data in both horizontal and vertical directions'; specify*

We changed the text to: “Unlike many ground-based methods, they provide high-resolution data in the range of few cm in both horizontal and vertical directions”

*Line 250: 'it struggled to accurately reproduce the absolute wind speed'; specify*

Thank you for this comment. We agree that the original wording was too general and could suggest an overall poor model performance. However, Cañadillas et al. (2022) showed generally good agreement between the lidar observations and the WRF simulations including wind farm effects (WRF-WF), with mean wind speed differences of approximately 2%. Larger deviations were mainly observed under stable atmospheric conditions. To clarify this point, we revised the text accordingly.

The revised text now reads:

“The WRF model, using the wind farm parameterization by Fitch et al. (2012), was found to capture the horizontal extent of wakes well (Cañadillas et al., 2022). The agreement between lidar observations and WRF simulations including wind farm effects (WRF-WF) was generally good, with mean wind speed differences of approximately 2%, although larger deviations occurred under stable atmospheric conditions.”

*Line 254: 'The mechanism for creating turbulence for wind turbines does not seem to be constant with height to reproduce observations (Larsen et al., 2024)'; I do not understand this rather odd sentence; is it about ambient turbulence or wind turbine generated turbulence?*

Indeed it sounds odd – it is about the mismatch between simulated wind-turbine generated turbulence generation and observations. 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: Clarify 'roll mean' and 'running mean values'*

The terms 'running mean' and 'roll mean' refer to the same method in this study. Applying a rolling average filters the raw flight data and model outputs, making them highly comparable and significantly improving plot readability. We changed the wording in Fig. 7 accordingly.

*Figure 7 top left; it seems odd that the wind speeds in Leg 6 are smaller than in Leg 5;*

Specifically, as observed on Leg 6 in Fig. 7, the distinct drop in measured wind speed is not caused by the wind farms, but is rather due to the spatial variability and the closer distance to the coast and/or a temporal change in the weather situation (e.g., cloud or rain formation) during the multi-hour measurement flight, which the steady-state engineering models fail to capture. We added this information at the end of Sect. 3.5.2.

*several models (EM-BL, EM-LR and EM-TP) show the same. What is the reason?*

The models are initialized with a uniform, undisturbed free-stream wind speed for each flight leg, therefore they simply default to this baseline background velocity at the lateral edges of the flight

path or far downstream where the wake has dissipated. Since no wake effect is computed in these regions, the models output the exact same undisturbed background wind speed, causing their curves to overlap.

We added in the text: “Several models provide the same output for specific locations, and the corresponding lines overlap in Fig. 7. As the models are initialized with a uniform, undisturbed free-stream wind speed for each flight leg, they have the same background velocity at the lateral edges of the flight path or far downstream where the wake has dissipated. Since no wake effect is computed in these regions, the models provide the exact same undisturbed background