C2Wind

WindEurope 2025

Wake Modelling White Paper

Benchmark study

REPORT

Date: 2025-04-07
Doc. No: 2-000-002-06-01
Revision: 1

C2Wind ApS | Vesterballevej 5 | 7000 Fredericia | Denmark

C2WIND

Document information and change log.

Revision	Date	Status / Reason for Issue	Author	Checker
0	2025-03-21	Issued for internal review	RGA	JOG
1	2025-04-07	Issued for publication	RGA	CBM

Section	Summary of Changes (latest revision only)

C2WIND

Table of Contents

C2WIND

Executive Summary

This document presents the results of a validation study where three wake models are compared against offshore wind speed measurements near wind farm clusters. The study concludes with recommendations regarding model selection for Energy Yield Assessments.

What are wake effects? Wind turbines extract energy from the wind, reducing wind speeds downstream of the rotor. In a wind farm these cumulative effects need to be accounted for, as they decrease the power production of the downstream turbines compared with turbines facing the undisturbed flow.

What drives wake effects? Wake effects are primarily driven by the aerodynamic efficiency of each turbine, and the structure of the atmospheric turbulence which affects wake recovery. Both large scale (0.1-10km) and small scale (.01-100m) turbulence motions matter, making modelling wake effects challenging.

What is the rationale for writing this white paper? For at least a decade, academic studies have been pointing deficiencies in the current engineering practice relying on analytical models. However, prior to 2024 there was no cost-effective commercial tool available for modelling wake effects in a time-varying fashion, capturing both small- and large-scale turbulence. When such commercial models became available, C2Wind engaged with two model providers, Veer Renewables and Whiffle (each of them proposing a different modelling approach), with the idea to carry out the present validation study.

What are the main conclusions of the study? Validation results against high quality wind measurements show that these models work satisfactorily and capture the variations in wake effects attributed to wind farm aerodynamics and atmospheric turbulence, which engineering model do not. In other words, based on this validation exercise, and the other validation tests brought forward by the model providers, C2Wind does not consider that there is a reason to exclude these models from the Energy Yield Assessment toolbox. Condensed results are provided in Table 0-1 below (see Section 5.1 for more information).

mean deficits [%] – all stabilities, wind speed in [4; 12 m/s]		
	Borssele	**Kriegers Flak FLS2/FLS1**
Wind dir. [°N]	*[200;270[*	*[120;150[*
Meas.	14.9	3.5
Veer	14.3	2.3
Whiffle	17.1	4.9
TurbOPark	13.8	8.2
mean deficits [%] – all stabilities, wind speed in [4; 30m/s]		
	Borssele	**Kriegers Flak FLS2/FLS1**
Wind dir. [°N]	*[0;360[*	*[0;360[*
Meas.	5.4	-2.1
Veer	4.8	-1.8
Whiffle	6.6	-0.7
TurbOPark	4.1	-0.3

Table 0-1: Mean relative differences in mean wind speed between the selected floating lidars.

What should be the next steps? We recommend the following:

- The structure of the boundary layer varies greatly from region to region. Therefore, for every site, it is important to finely characterise atmospheric turbulence via an analysis of atmospheric stability and boundary layer dynamics and assess the risk of engineering (analytical) wake models operating outside their validity range.

- Commercial wake models of the type of Veer Renewables (Weather Research and Forecasting model with Wind Farm Parametrisation) and Whiffle (LES) should be used alongside engineering models. The type and extent of the datasets to be procured depend on the project location, configuration, and maturity.

- Wake modelling will remain difficult. High(er) fidelity models which can prove to accurately capture the main drivers of wake dynamics should not be discarded. Instead, their adoption should be favoured, followed with additional validation and fine tuning.

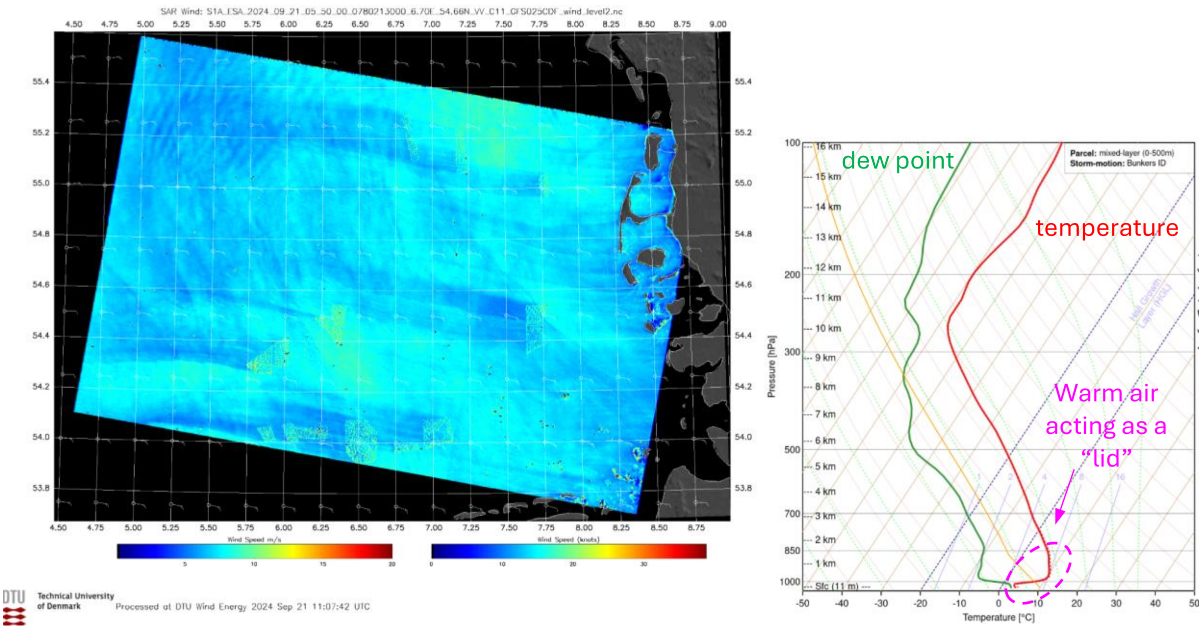

Figure 0-1: Illustration of a typical flow case (warm easterly winds over cold water in the North Sea) leading to long-lasting wake effects downstream of large wind farms. Left: satellite-derived 10 mASL wind speeds, source: https://science.globalwindatlas.info/#/map/satwinds. Right: corresponding air temperature profile from ERA5. Source: https://rawinsonde.com/ERA5_Europe/

1. Introduction

Wake effects often constitute the major energy loss that needs to be accounted for when assessing the energy yield of an offshore wind farm. This brief report outlines C2Wind's wake modelling approach for Energy Yield Assessments, with a focus on long-range wake effects. It begins with a brief discussion on the state of the art in engineering wake modelling, followed by a description of the wake models used in this study. Validation results are then presented, using floating lidar measurement pairs near two wind farm clusters. The report concludes with a discussion on model selection and offers recommendations.

Wake effect modelling was extensively discussed and debated at the WindEurope Technology Workshop 2024[1], with a focus on long-range wake effects, i.e. wake effects in between wind farms separated by tens of kilometres. Several approaches were presented:

- Analytical wake models.
- Steady state Reynolds-Averaged Navier Stokes (RANS).
- Mesoscale modelling combined with Wind Farm Parameterisation (WFP).
- Large Eddy Simulation (LES).

This palette of options, from very simple to very complex, has been known for more than a decade, see [OURO25] and [STEVENS17]. However, cloud-based, flexible and cost-effective solutions for providing WFP and LES datasets have been available since 2024 only. This represents a significant change for engineering wake modelling.

Up until cloud-based solutions were available, C2Wind had relied on analytical models only. The availability of WFP and LES cloud-based solutions, together with the wealth of high-quality floating lidar datasets near large wind farm clusters, represented an opportunity to run a validation study where two commercial models (WFP from Veer Renewables www.veer.eco and LES from Whiffle www.whiffle.nl) using the same reanalysis (ERA5) are compared against the same measurement dataset and using the same methodology. The study aimed as well at providing guidance on workflows and model selections for commercial Energy Yield Assessments.

This work was carried out in partnership with Veer Renewables and Whiffle. C2Wind initiated the study, processed and curated the measurements, defined the test cases and provided the input to the calculations, carried out the analysis and wrote the first draft of the report. Whiffle and Veer provided the simulations, comments and suggestions on the interpretation of the results, and edited sections of the final report.

A poster (PO.122) has been produced together with this study at the occasion of the WindEurope 2025 conference. It is publicly available on C2Wind's publications webpage https://c2wind.com/p/our-experience/publications.

[1] See https://windeurope.org/tech2024/programme/.

2. Datasets and test cases

2.1 Models description

Three models have been used for all analyses in this study:

- Ørsted's TurbOPark.
- Veer Renewables WakeMap (WFP).
- Whiffle Wind (LES).

Additionally, a PARK2 model implemented by C2Wind has been used in Section 5.2. A high-level description of these models is provided in Table 2-1. Veer Renewables and Whiffle have provided two sets of simulations for each test case: one with wakes, and one without wakes (using a thrust-free turbine model).

Model	Category	References
TurbOPark	Analytical	[NYGAARD20], [PEDERSEN22], [TPGIT]
PARK2	Analytical. C2Wind's implementation includes TI-dependent wake decay constant, as well as boundary-layer height refraction.	[PARK2]
WakeMap	Mesoscale (WRF) with WFP	[VEER2023]
Whiffle Wind	LES	[BAAS23], [POSTEMA24]

Table 2-1: High-level description of the wake models used in this study.

2.1.1 Analytical models: TurbOPark and C2Wind PARK2

The TurbOPark model released at [TPGIT] has been used without modification. C2Wind uses an internal implementation of PARK2, following the description in [PARK2] and the guidance from [EMD19] regarding the derivation of the wake decay constant (a function of turbulence intensity). C2Wind's PARK2 implementation also includes an option where mirror turbines are placed symmetrically above the boundary layer, to mimic the effect of shallow boundary layers on wake dispersion (a common method in pollution dispersion studies).

When comparing with pairs of floating lidar measurements, only TurbOPark has been used, as the PARK2 implementation became available only in the later part of the study. Future updates of this document will include PARK2 results, these will be presented at the WindEurope Technology Workshop 2025.

For both PARK2 and TurbOPark, time series were created using Park Power Curves for every degree bin and the Veer Renewable time series at a reference location from the thrust-free dataset. In an attempt to adjust TurbOPark results for the presence of coastal mesoscale wind speed gradients at Kriegers Flak, mean directional speed-up factors between the reference location and each turbine location were computed and used to correct the freestream wind speeds (i.e. one factor per turbine/lidar, per direction using 12 sectors).

2.1.2 Veer Renewables WakeMap

WakeMap is based on the Fitch WFP parameterization in the WRF model [FITCH12], using a turbulent kinetic energy generation factor of 1.0 and with turbulence advection turned on. WakeMap uses the ERA5 reanalysis as boundary forcing. In this study, an innermost domain at 700-m spatial resolution was used, which was nested by 2.1-km and 6.3-km outer domains. To speed up computations, the validation period was split into separate 3-day simulation periods, each with 6-hour spin up, and the resulting timeseries concatenated in post-processing.

WakeMap also uses the recent WRF WFP correction proposed in [VOLLMER2024]. In this study, the authors identify that the standard WFP implementation uses waked wind speeds in a grid cell containing a turbine to calculate thrust and power, whereas in principle the free stream wind speed should be used. Adjusting for this results in slightly lower thrust coefficients (i.e., less wake) and higher power output from the turbine.

2.1.3 Whiffle Wind

Whiffle Wind is a cloud-based, self-service platform for running LES developed by Whiffle. Whiffle Wind is built around Whiffle's in-house, GPU-resident atmospheric simulation platform. The current study uses Whiffle Wind's default simulation setup, with a 100 m resolution LES nested in a 2 km meso-scale model of which the boundaries are provided by ERA5. The Whiffle meso-scale model is also GPU-based and run concurrently with the LES to allow time-step coupling without writing large amounts of data to disk. The LES employs an actuator disk-based turbine model, of which the disk-based thrust and power coefficients are obtained from a separate, offline simulation. For more details about the Whiffle model see [BAAS23] and [POSTEMA24].

2.1.4 A note on RANS

RANS CFD models have not been considered in this study, primarily because these models are unable to account for mesoscale effects and site-specific, time-dependent variations in surface stability and boundary layer dynamics. Also, even for sites with uniform and simple conditions, they remain difficult to use for time series analysis due to the large number of flow cases which need to be simulated.

2.2 Measurement description and test cases

Pairs of floating lidar measurements near two wind farm clusters have been used:

- Two floating lidars deployed next to the Belgian wind farm cluster, prior to the construction of the Borssele wind farm.
- Three floating lidars (and a met mast) located in the Kriegers Flak area in the Baltic Sea, between Denmark, Sweden and Germany.

The measurements are described, with references to publicly available documents, in Table 2-2. A map of the measurement locations is provided in Figure 2-1.

Dataset	Location	Start date	Stop date	References
BWFZ FLS position 1	Dutch North Sea	2015-06-11	2017-08-27	[RVOFLS]
BWFZ FLS position 2	Dutch North Sea	2016-02-12	2016-07-07	[RVOFLS]
KFII-1-LB (FLS1)	Kriegers Flak (DK)	2023-09-03	2024-09-03	[C2WKFII] Appendix B
KFII-2-LB (FLS2)	Kriegers Flak (DK)	2023-09-03	2024-09-03	[C2WKFII] Appendix B
KFII-3-LB (FLS3)	Kriegers Flak (DK)	2023-11-01	2024-04-14	[C2WKFII] Appendix B
FINO2	Kriegers Flak (DE)	2023-11-01	2024-04-14	[C2WKFII] Appendix B

Table 2-2: High-level description of the measurement datasets used in this study.

Publicly available wind farm power time series from the ENTSO-E transparency platform have been used to make sure that all wind farms were operating during the timestamps considered for the validations.

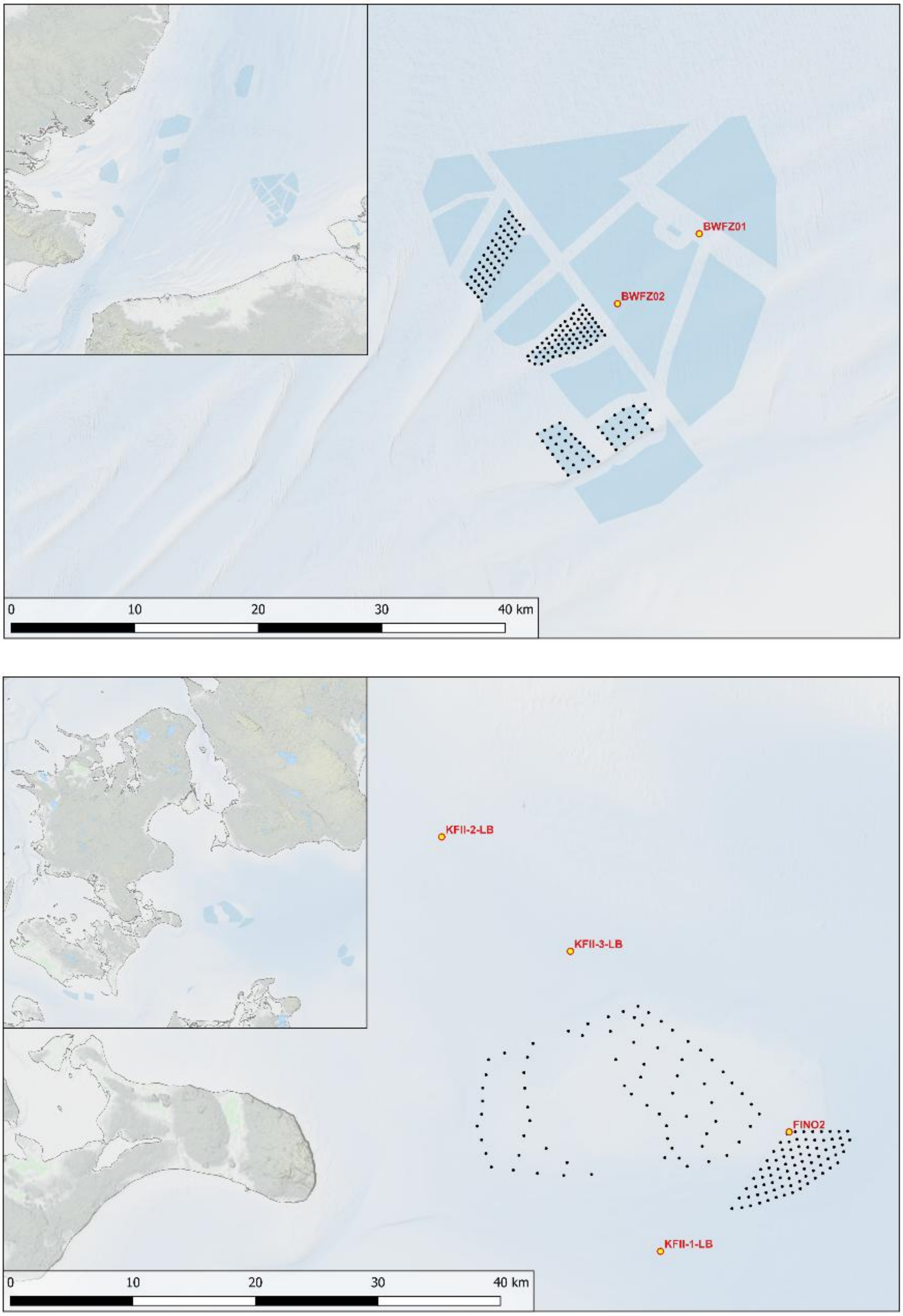

Figure 2-1: Maps of the measurement locations. Wind turbines are shown with black dots.

2.3 Wind farm layouts and turbine characteristics

Wind farm layouts and wind turbine characteristics (hub height, rotor diameter, power curve, thrust curve) have been obtained from C2Wind internal database and using publicly available information.

2.4 Analysis methods and guidelines

Prior to proceeding with wake calculations, systematically and carefully characterizing the atmospheric conditions that drive wake losses is essential. Offshore, atmospheric stability across the boundary layer (and above) is the main driver. C2Wind has authored several publicly available documents describing how atmospheric stability can be characterized at the surface and across the boundary layer, see [WE24], [WES24], [AMT25] and Appendix C of [C2WKFII].

Unless otherwise noted, atmospheric stability is characterised using the Obukhov length and the classification presented in [SATHE10], extended to include positive values smaller than 10 and negative values larger than -50 m. The Obukhov length has been computed from measurement datasets using the methodology outlined in [PEÑA08]. The Obukhov length is otherwise readily available from the Whiffle dataset, and for ERA5 it has been computed using the formulation recommended by the ECMWF[2]., The boundary layer height, for all model datasets, has been computed using the formulation outlined in Section 3.10.1 of [IFS41r2] and used in the ECMWF Integrated Forecast System for producing ERA5. Unless otherwise noted, the ERA5 Obukhov length time series has been used for classifying atmospheric stability.

When comparing measurement and model data, the following procedure was followed:

- 10-minute measurements and model time series were concatenated in a single dataset of concurrent data, including for each data the two lidar locations.
- For each dataset, wind speed at a reference elevation was derived by interpolating the time series at every timestamp using a power law fitted to the relevant section of the wind profile.
- A reference wind direction signal was chosen for each dataset: i.e. one reference signal for the two measurement timeseries, one for the two Whiffle time series, one for the Veer time series.
- A reference wind speed signal was chosen from the measurement dataset at the reference elevation.
- Ratios of wind speeds between the two lidar locations are then computed for every timestamp.
- Bin statistics are then computed using a rolling average with a given bin width (15 degrees).

[2] See https://confluence.ecmwf.int/display/CKB/ERA5%3A+How+to+calculate+Obukhov+Length.

3. Freestream validations

Comparisons of mean wind speed profiles as well as time series are provided against the FLS1 location (Baltic Sea) to serve as example in Figure 3-2 and Figure 3-3. They show that both Veer Renewables and Whiffle model datasets capture accurately freestream wind conditions.

When comparing the distribution of surface stability classes assessed using ERA5 and Whiffle data against values derived from the FLS measurements, it appears that the frequency of stable and very stable conditions may be overestimated in the Whiffle dataset, see Figure 3-5. Both models show significantly shallower boundary layers than the reanalysis in particular for stable conditions, see Figure 3-4. This is somewhat expected, given that ERA5 is known to overestimate boundary layer height, see [SINCLAIR22] and Section C.3 of [C2WFKII].

One thing to note is that Whiffle's model tend to predict shallower boundary layers than ERA5 also for unstable conditions. Also, as shown in Figure 3-1, for all stability classes Whiffle's turbulence intensity values delivered in the dataset are significantly smaller than what is typically observed offshore (see examples in [C2WKFII]).. Please note that this is here a TI diagnostic variable which does not include the sub-grid scale variance of the wind, but this variance is included when running the LES model and is present in the prognostic.

Take-away message: Carefully understanding and checking model behaviour reveals important information relevant for wake modelling.

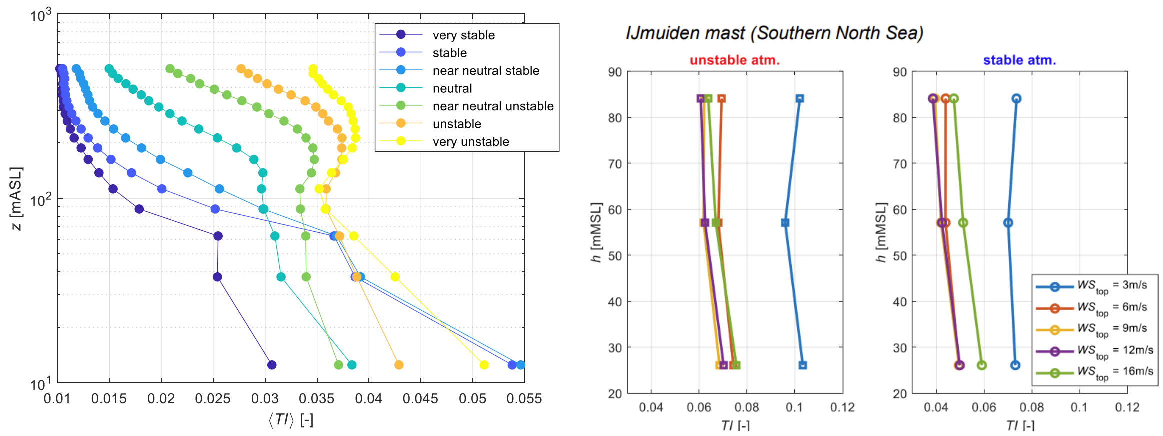

Figure 3-1: Left: mean turbulence intensity profiles from the Whiffle dataset, at the FINO2 location, as a function of elevation. Right: typical measured values offshore (reproduced from [C2W19]).

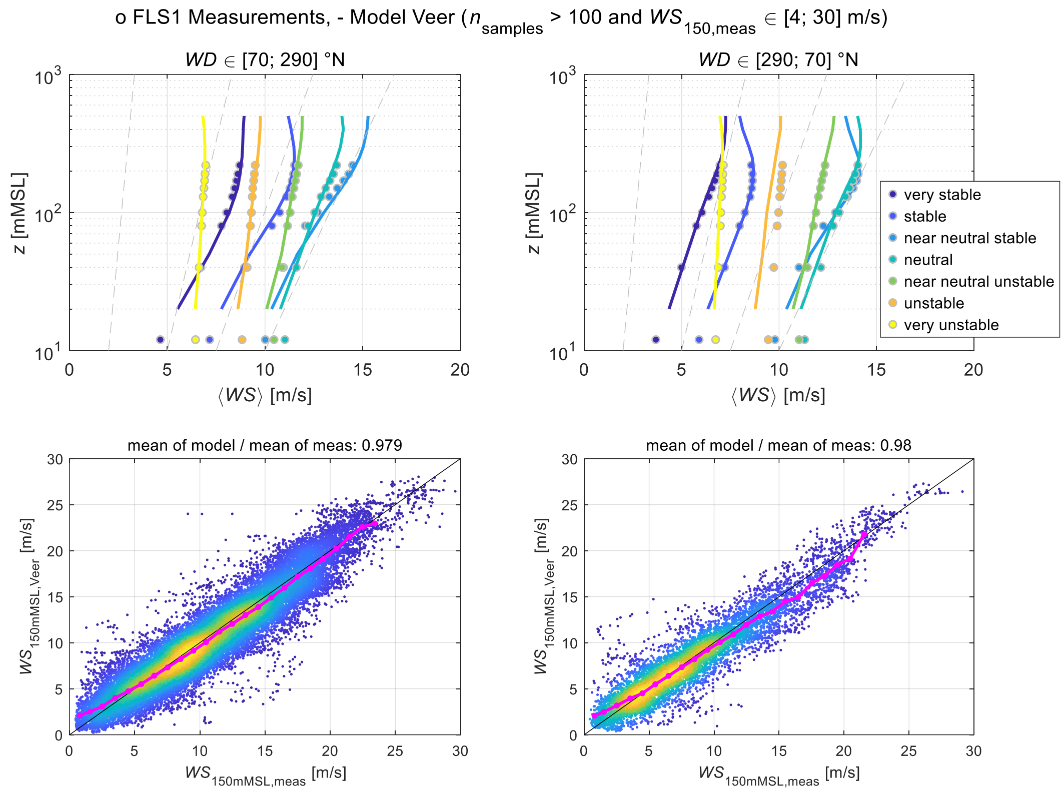

Figure 3-2: Comparison of modelled (Veer Renewables) and measured data at the FLS1 location in the Baltic Sea, for two wind directional bins (left: freestream, right: in wake).

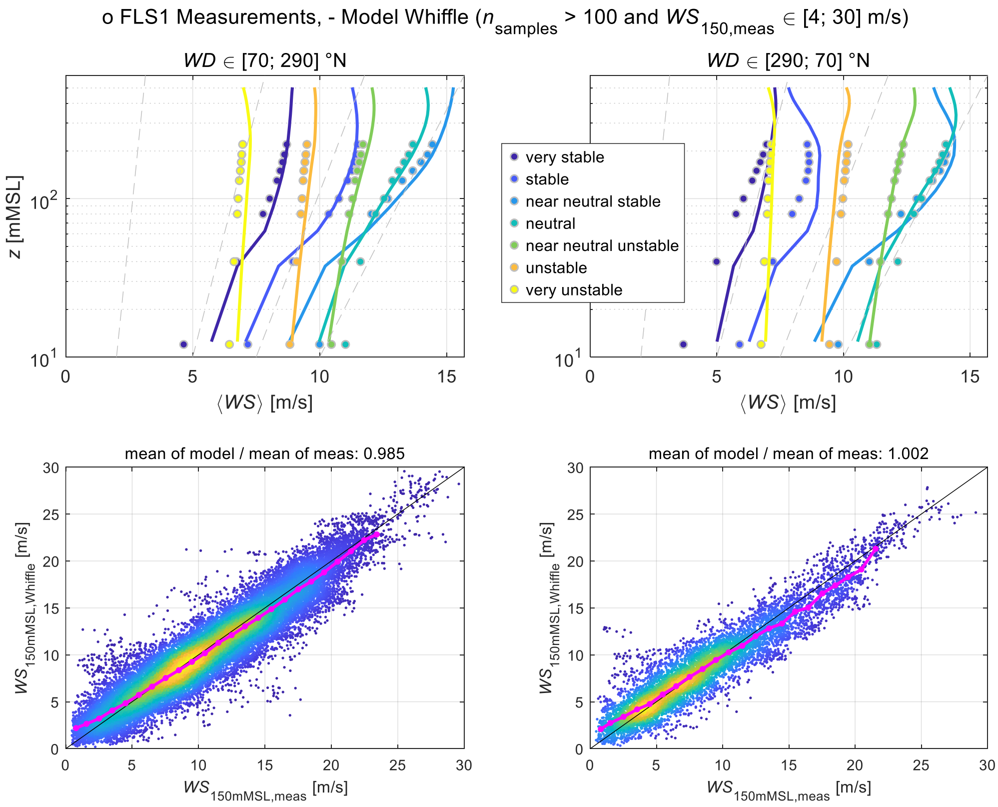

Figure 3-3: Comparison of modelled (Whiffle) and measured data at the FLS1 location in the Baltic Sea, for two wind directional bins (left: freestream, right: in wake).

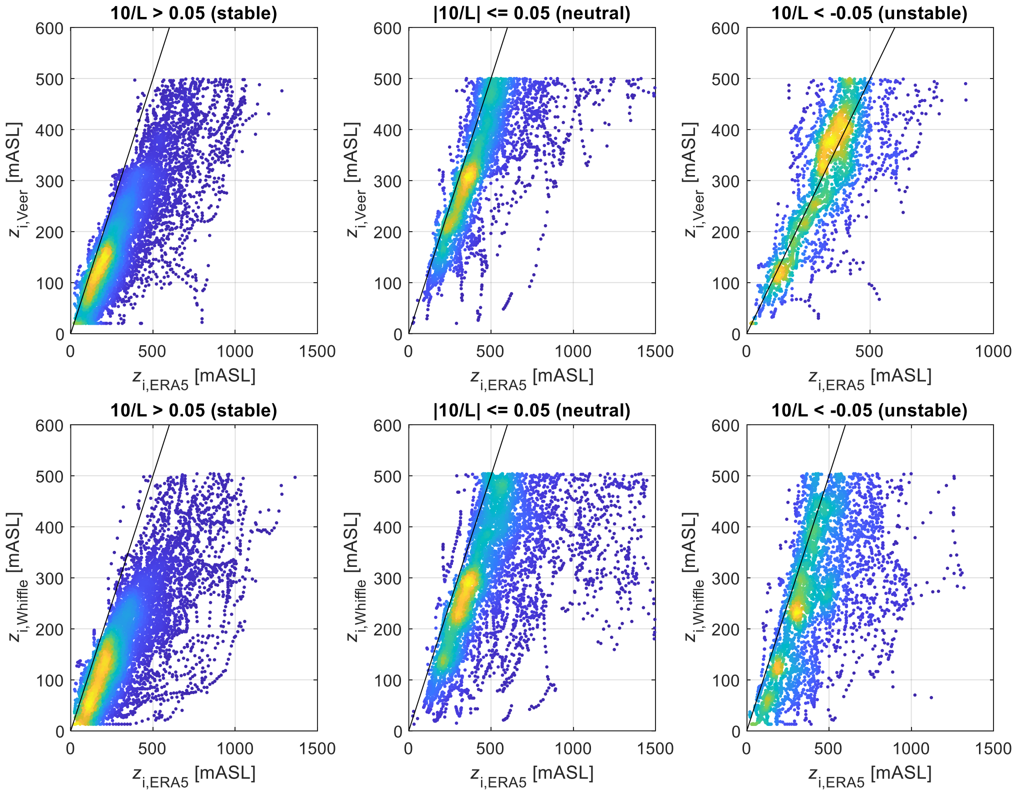

Figure 3-4: Comparison of atmospheric boundary layer height derived from Veer Renewables (top) and Whiffle (bottom) with that from ERA5 at the FINO2 location. Note: the comparison is shown for Veer Renewables and Whiffle data up to 600 mASL only (the highest model elevation available in the datasets), ERA5 values often exceed this value.

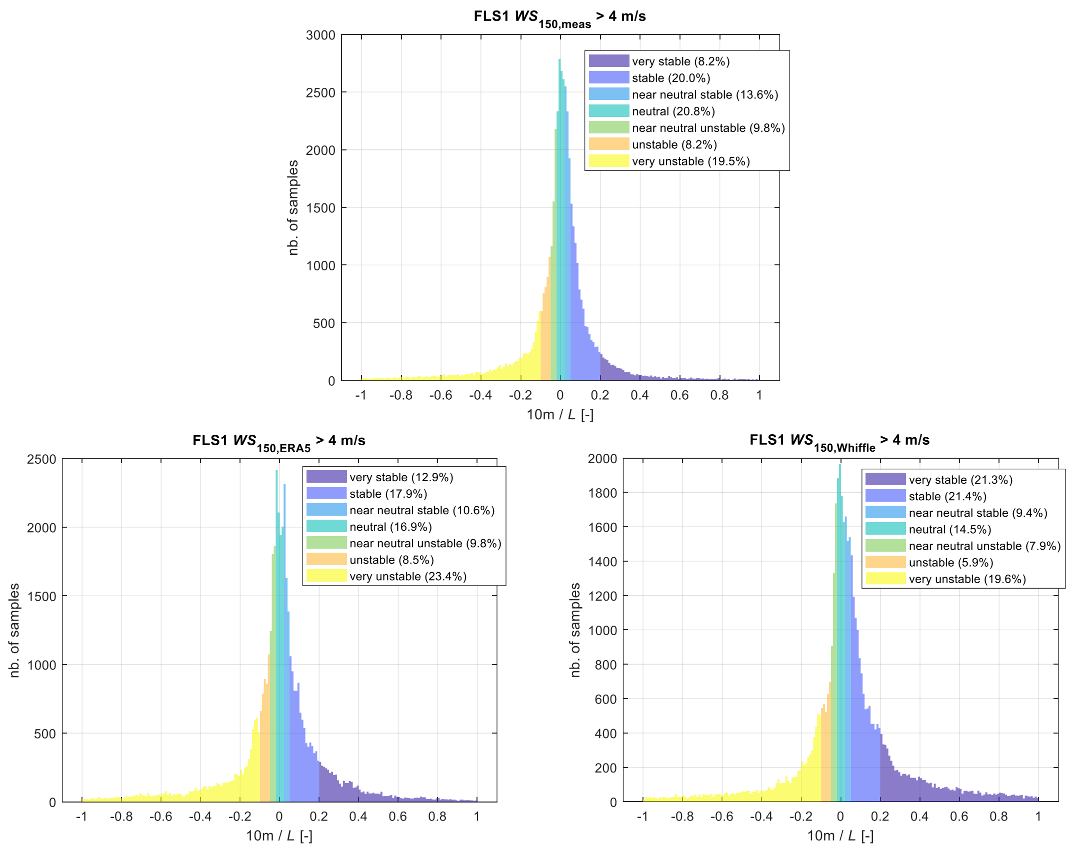

Figure 3-5: Comparison of atmospheric stability classification between model (left: ERA5, right: Whiffle) and measurements at the FLS1 location.

4. Gross power time series

Power time series computed using Veer Renewables and Whiffle models can be reproduced from the original power curve and freestream wind speed time series. In particular for the Whiffle dataset, this requires adjusting the wind speed (following Wind Resource Assessment good practices) for the combined effects of air density, rotor equivalent wind speed, and turbulence intensity (the prognostic variance is used) which are inherently captured in the model[3]. Air density and rotor equivalent wind speeds adjustments are here carried out using IEC standard methods (this is always done by default at C2Wind), and turbulence intensity adjustment is carried out using the guidance provided by Whiffle[4]; see Figure 4-1. The Veer Renewables model incorporates fewer adjustments, see Figure 4-2.

Take-away message: when comparing model power time series with actual power measurements, users should account for differences in mean hub height wind speed (as for any mesoscale model), but also for other, model-specific adjustments. Similarly, when integrating these novel model results into existing EYA workflows, the following is recommended:

- Run one wake simulation, and a simulation with zero thrust, wake losses should be estimated from the ratio of the two simulations.
- Derive park power curve for comparison with analytical (diagnostic) models.

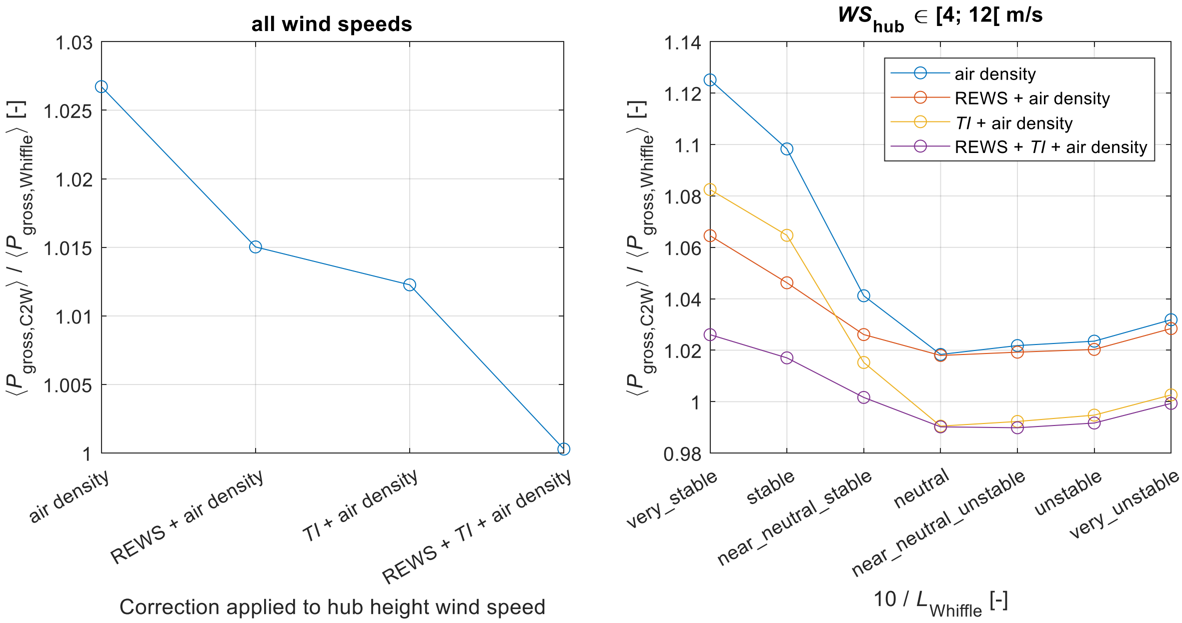

Figure 4-1: Ratio between C2Wind's and Whiffle gross power time series for Baltic 2, using different hub height correction methods and different stability classes. Left: all stability classes and all wind speeds, right: for wind speeds below rated power.

[3] See https://docs.whiffle.cloud/getting-started/adding-a-custom-turbine/best-practices-for-turbine-specs#reference-turbulence-intensity.

[4] C2Wind otherwise uses the IEC turbulence intensity renormalization method.

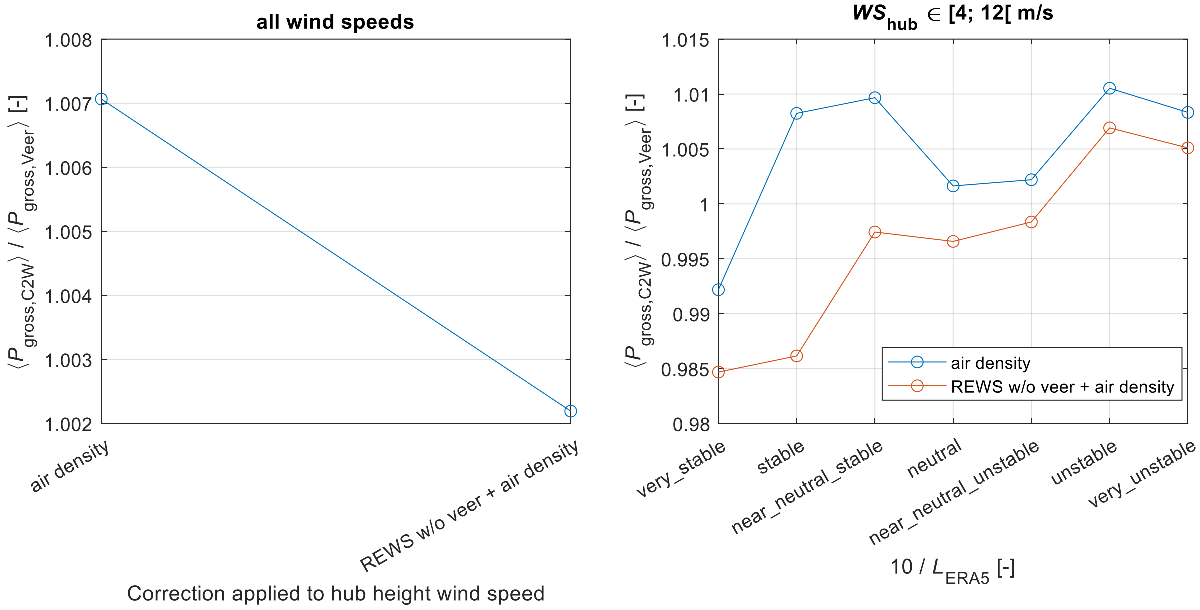

Figure 4-2: Same as for Figure 4-1, for the Veer Renewables model dataset.

5. Wake validation

5.1 Wake validation against wind speed measurements

Wake validations results are first presented in a synthetized fashion, with all mean binned ratios shown together, per stability classes (using the ERA5 time series), see Figure 5-1 for the Borssele cluster and Figure 5-2 to Figure 5-3 for the FLS2 / FLS1 pair at Kriegers Flak.

In a more complete fashion, results with both mean values as well as p10/p90 values are provided in Figure 5-4 for the Borssele cluster and in Figure 5-5 to Figure 5-7 for the FLS pairs at Kriegers Flak. In these figures measurements are shown in black.

All validation plots are shown for a reference elevation of 100 mMSL. A summary of some of the key results is provided in Table 5-1 (the wind directional bins with the largest wake effects have been selected).

Take-away messages:

- For the Borssele cluster, all models perform well and seem to predict well the mean ratio between the two lidars in the primary wake situation.

- For the Kriegers Flak cluster, wake effects appear to be, for some wind directional bins and some stability classes, overly dominated by mesoscale effects which are inherently better captured with Veer Renewables and Whiffle models than with TurbOPark (even if correcting TurbOPark using mean directional scaling factors as explained in Section 2.1.1).

mean deficits [%] – all stabilities, wind speed in [4; 12 m/s]		
	Borssele	**Kriegers Flak FLS2/FLS1**
Wind dir. [°N]	*[200;270[*	*[120;150]*
Meas.	14.9	3.5
Veer	14.3	2.3
Whiffle	17.1	4.9
TurbOPark	13.8	8.2
mean deficits [%] – all stabilities, wind speed in [4; 30m/s]		
	Borssele	**Kriegers Flak FLS2/FLS1**
Wind dir. [°N]	*[0;360[*	*[0;360[*
Meas.	5.4	-2.1
Veer	4.8	-1.8
Whiffle	6.6	-0.7
TurbOPark	4.1	-0.3

Table 5-1: Mean ratios between FLS locations, for different wind speed and wind directional bins (for Kriegers Flak, only the dataset with the longest concurrency period – 1 year – is considered in this table). For Kriegers Flak, the TurbOPark results include the directional mesoscale correction.

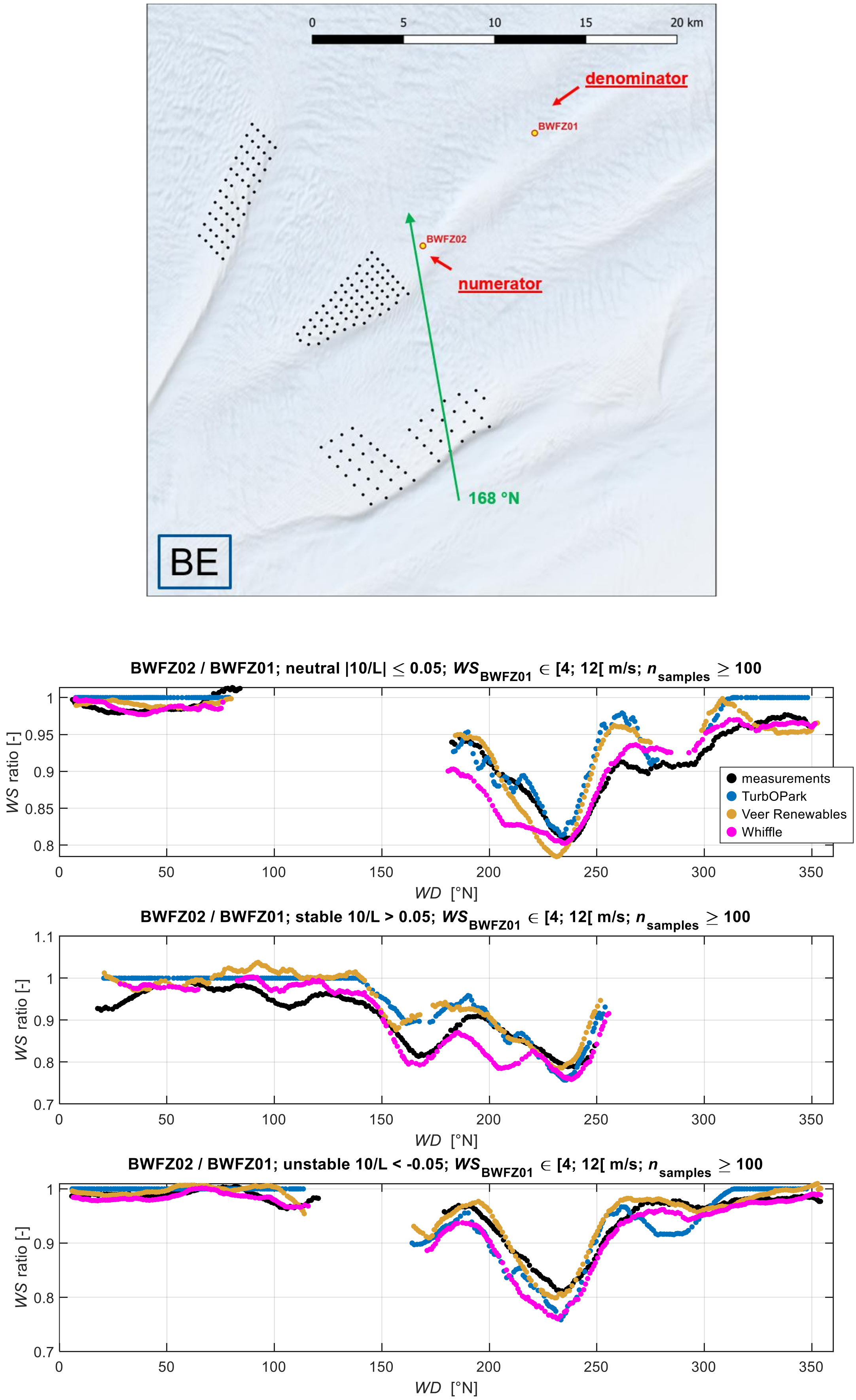

Figure 5-1: Validation at the Borssele cluster.

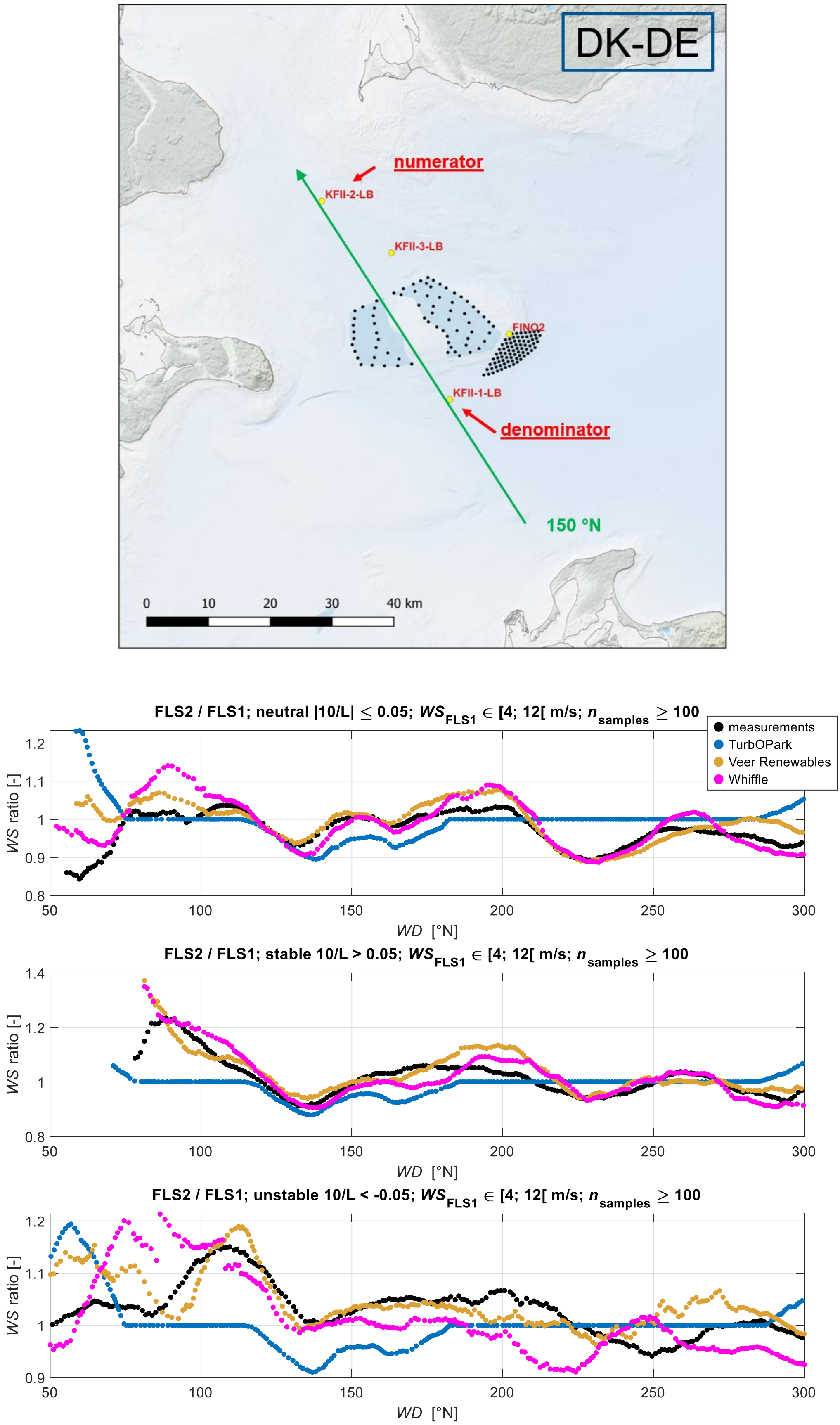

Figure 5-2: Validation at the Kriegers Flak cluster. Here, the TurbOPark results do **not** include any mean directional scaling to account for coastal effects.

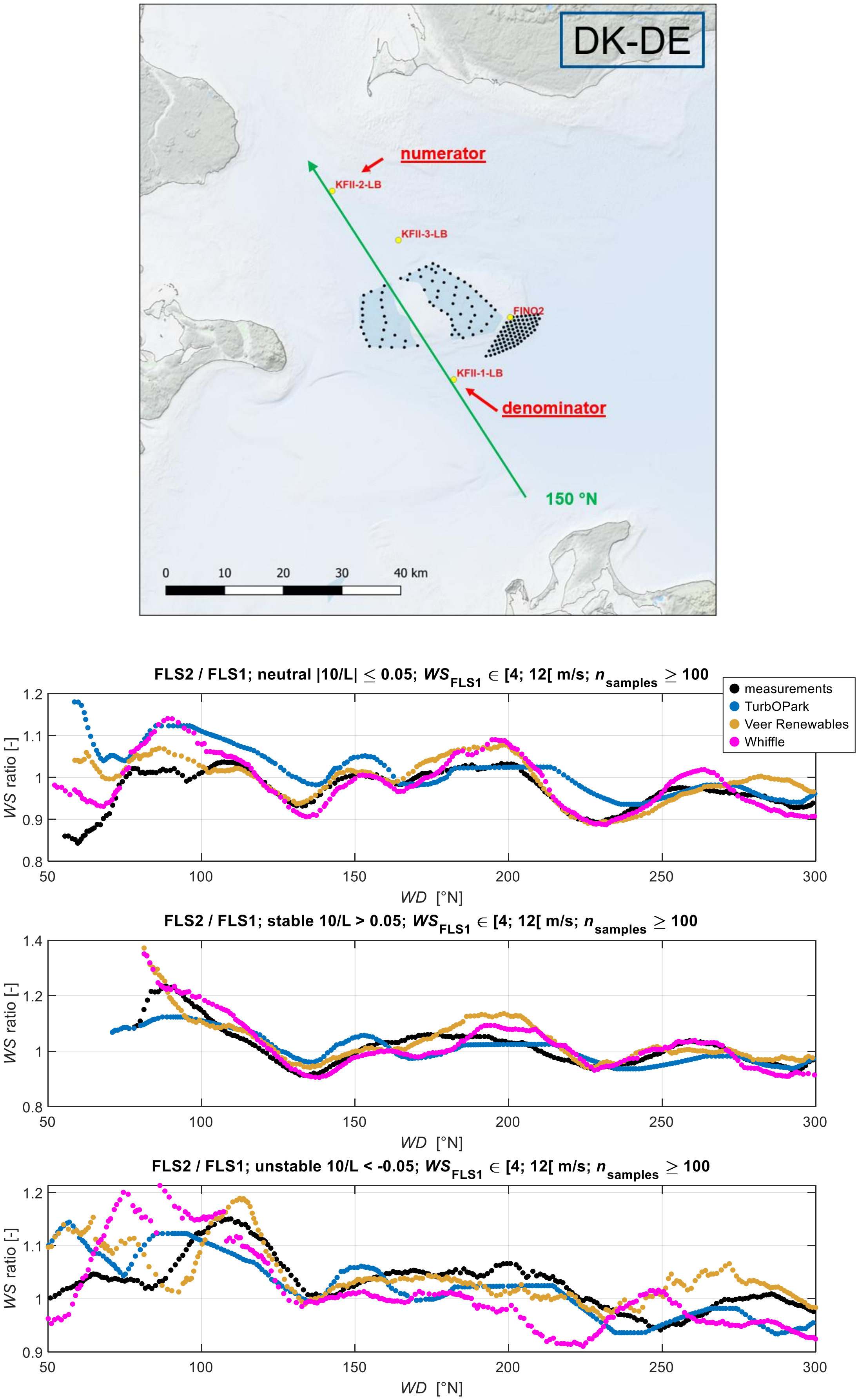

Figure 5-3: Validation at the Kriegers Flak cluster. Here, the TurbOPark results **do** include mean directional scaling to account for coastal effects.

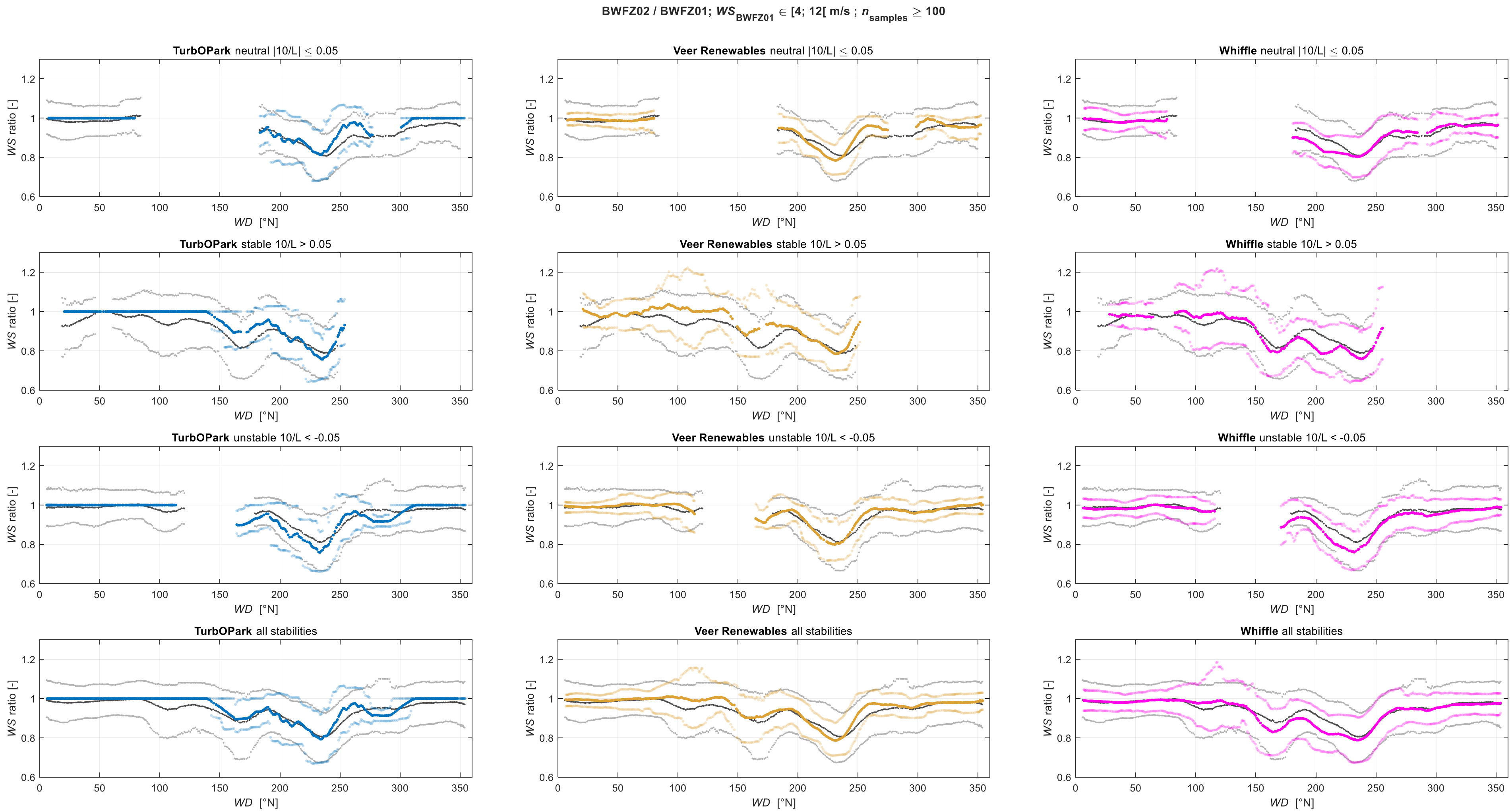

Figure 5-4: Validation at the Borselle cluster. Here, the TurbOPark results do **not** include any mean directional scaling to account for coastal effects.

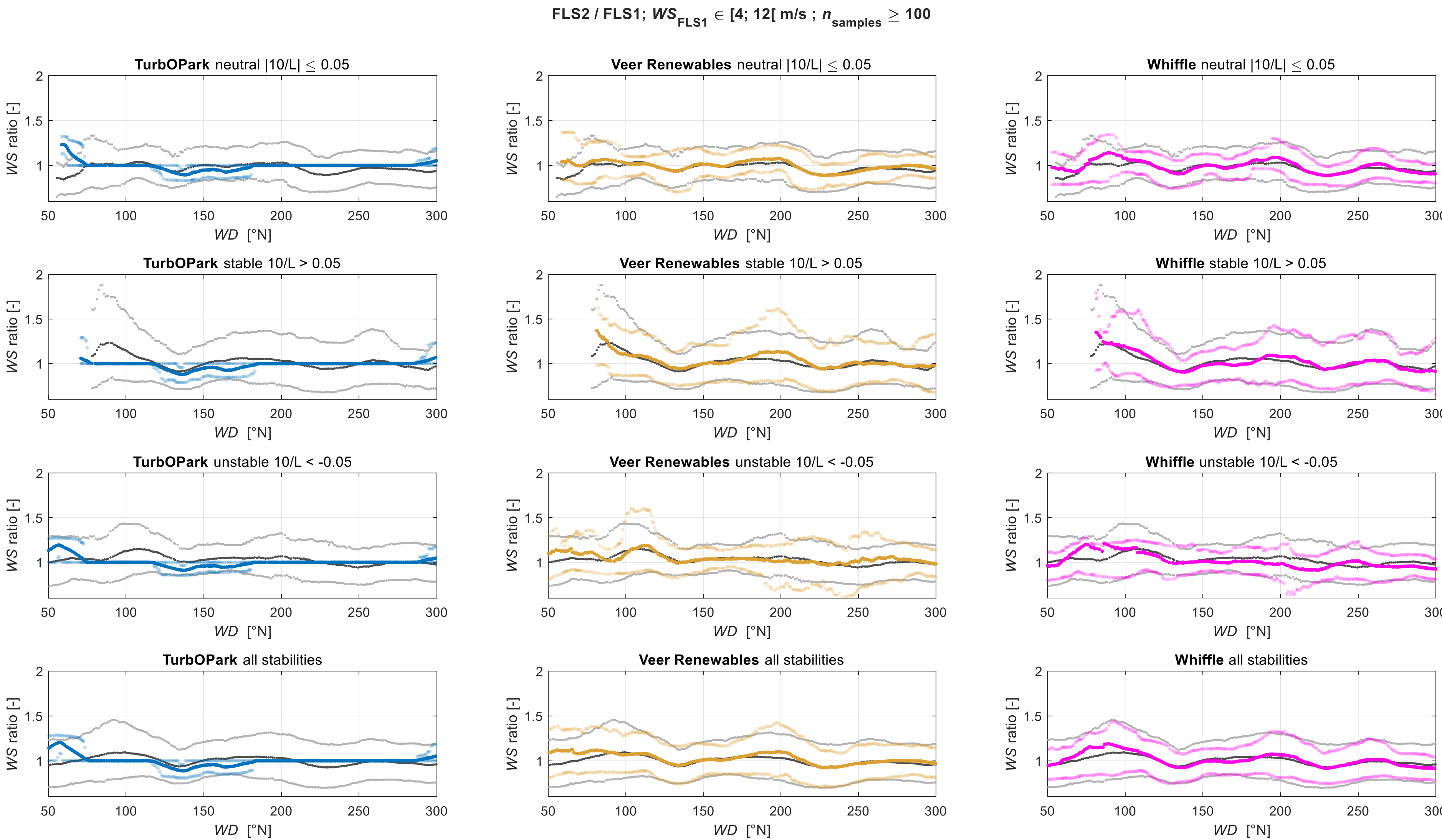

Figure 5-5: Validation at the Kriegers Flak cluster. Here, the TurbOPark results do **not** include any mean directional scaling to account for coastal effects.

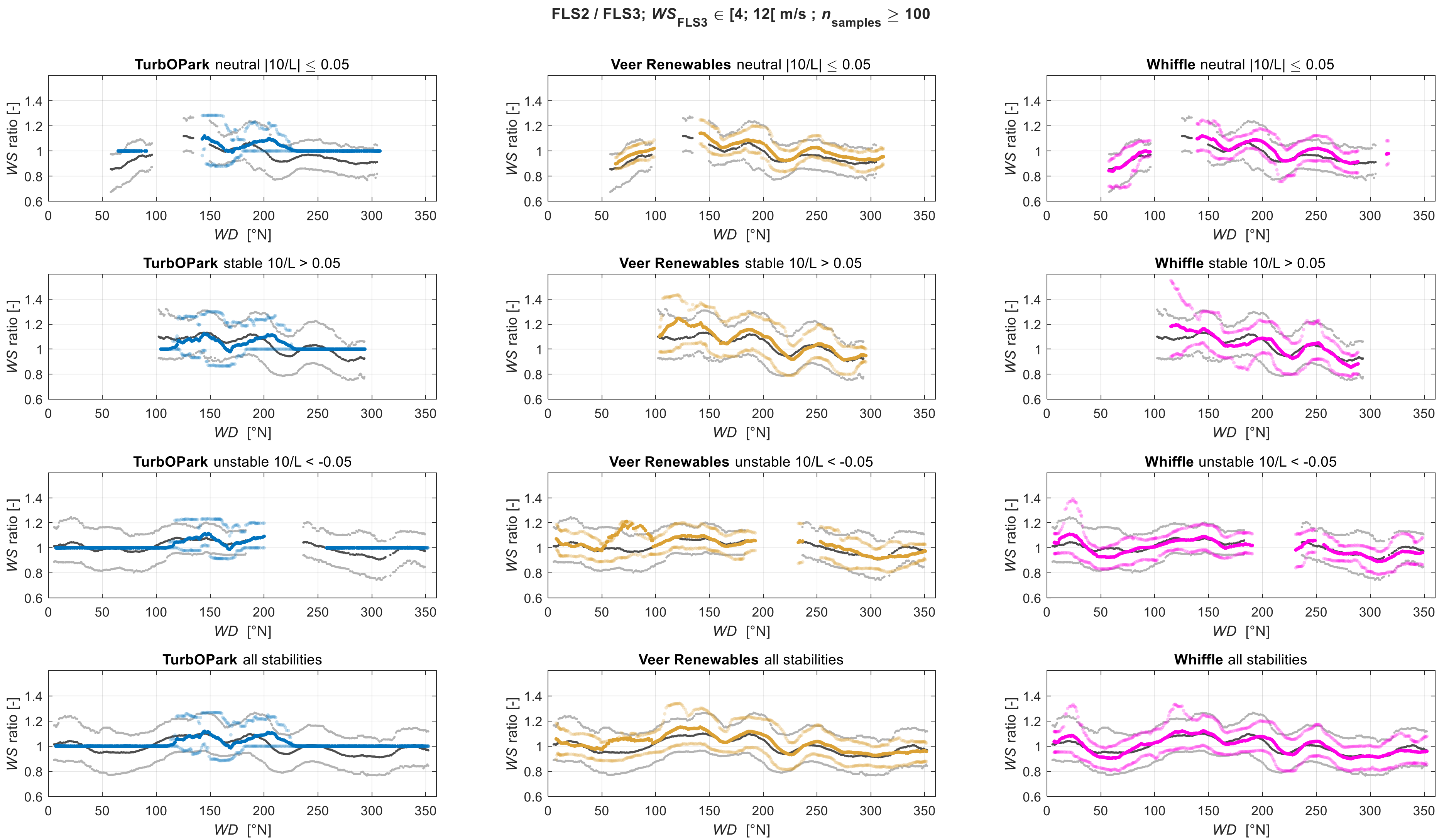

Figure 5-6: Validation at the Kriegers Flak cluster. Here, the TurbOPark results do **not** include any mean directional scaling to account for coastal effects.

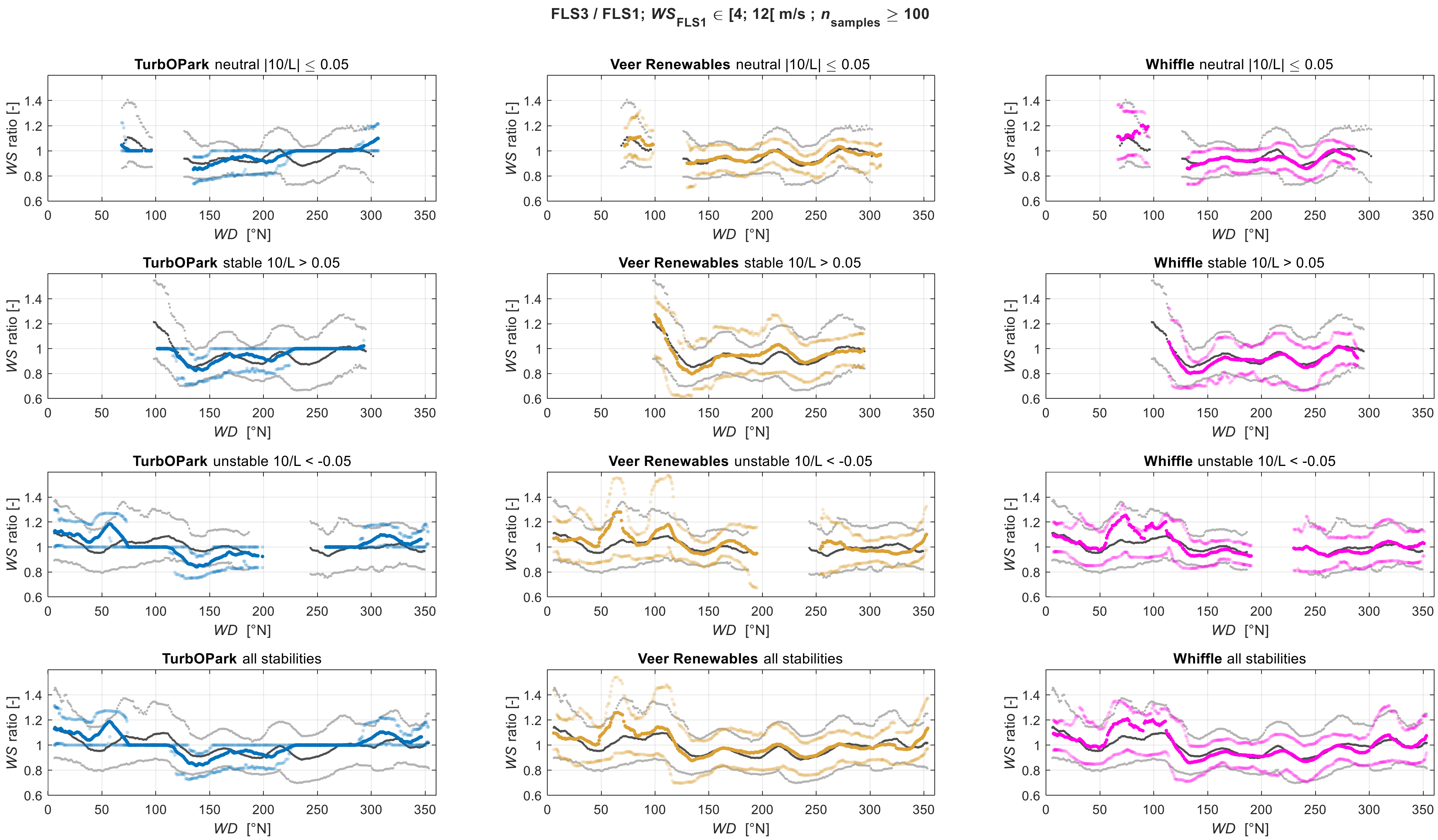

Figure 5-7: Validation at the Kriegers Flak cluster. Here, the TurbOPark results do **not** include any mean directional scaling to account for coastal effects.

5.2 Wake loss comparisons between models

For every timestamp and for each model, power time series including wake and gross power are available. For the Baltic 2 and Kriegers Flak wind farms, the ratio of the mean power of the two time series has been computed for every wind speed bin and every wind directional bin. Results are displayed in Figure 5-8 and Figure 5-10 for two subsets: deep boundary layers (full lines) and shallow boundary layers (dashed lines) where the threshold between deep and shallow is set to 3 times the hub height.

Beside TurbOPark, results from C2Wind's PARK2 implementation are provided as well. These have been computed using as input the hub height turbulence intensity and boundary layer height time series from the Whiffle dataset.

The same dataset is used for producing Figure 5-9, where the results are provided as a function of boundary layer height.

Take-away messages:

- For deep boundary layers, all models are in good agreement.

- For shallow boundary layers, Veer Renewables and Whiffle show significantly larger wake losses. In some situations (westerly winds), C2Wind PARK2 implementation seems to capture some of this effect, while for easterly directions this is not the case.

- Baltic 2 wind farm production data are not available to C2Wind, therefore model bias cannot be assessed. The total wake loss (i.e. including all wind speed) predicted by TurbOPark is smaller than the wake loss predicted by the Whiffle, Veer Renewables and C2Wind PARK2 models.

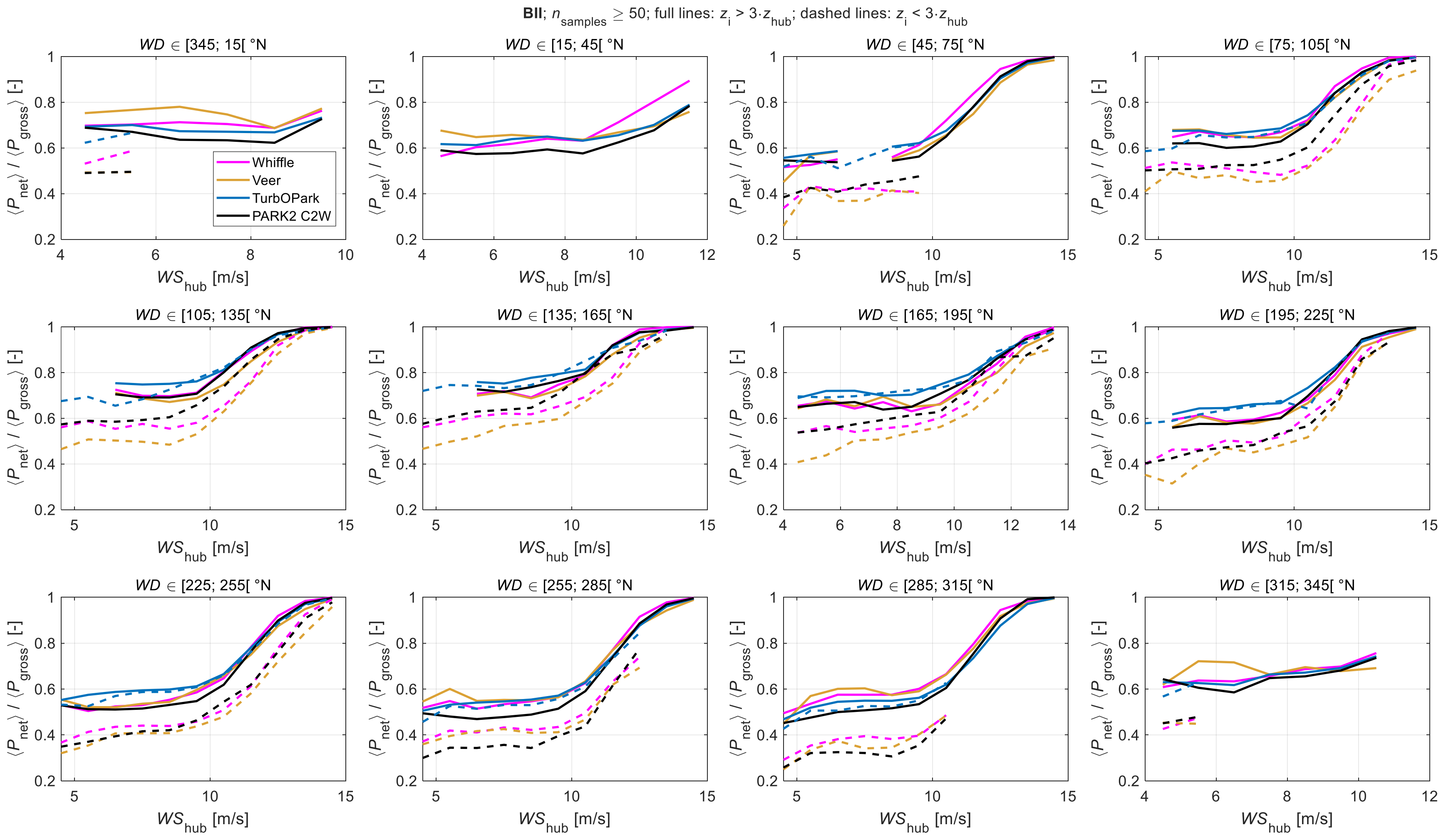

Figure 5-8: Ratio between waked- and gross mean power time series for the Baltic 2 wind farm. Results are displayed for two subsets: deep boundary layers (full lines) and shallow boundary layers (dashed lines) and are provided for every 30-degree wind directional bin and every wind speed below rated.

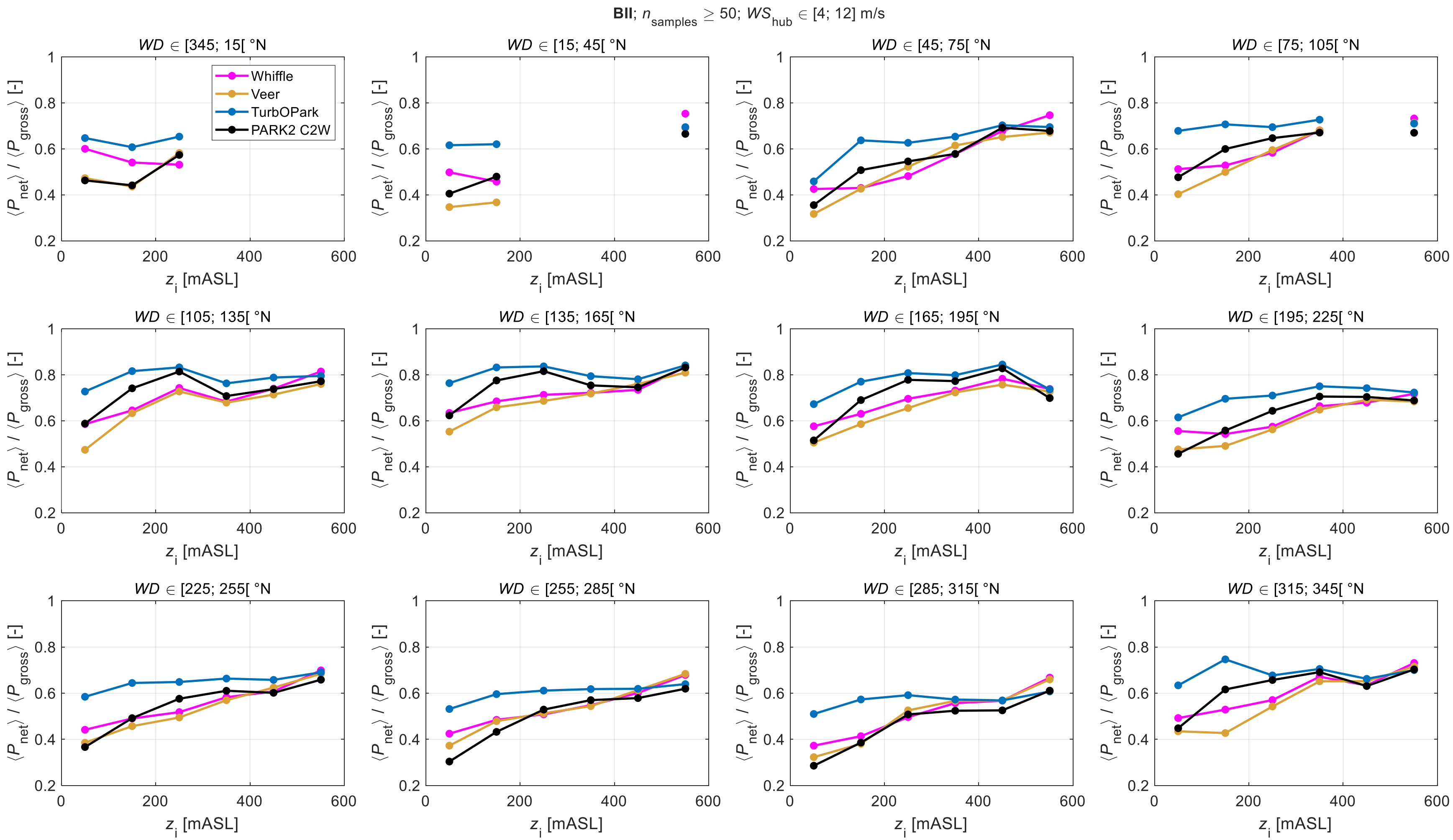

Figure 5-9: Ratio between waked- and gross mean power time series for the Baltic 2 wind farm, provided for every 30-degree wind directional bin and several boundary layer height bins for wind speeds below rated.

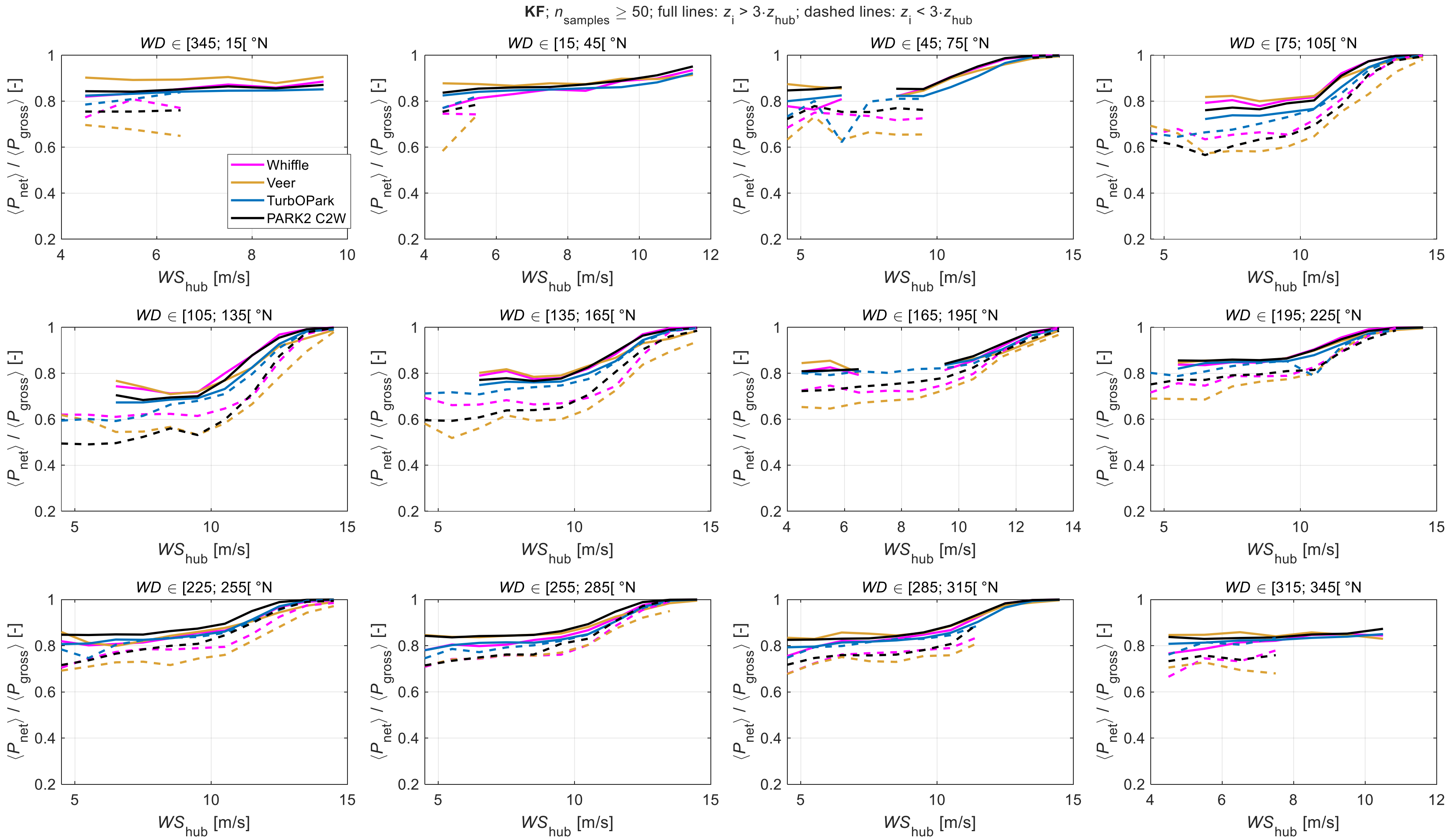

Figure 5-10: Ratio between waked- and gross mean power time series for the Kriegers Flak wind farm. Results are displayed for two subsets: deep boundary layers (full lines) and shallow boundary layers (dashed lines) and are provided for every 30-degree wind directional bin and every wind speed below rated.

6. Model guidance selection for EYA

From the results presented in this study, C2Wind considers that analytical engineering wake models cannot solely be used for assessing wake effects over regions where mesoscale effects and shallow boundary layers have a significant effect on wind farm performance.

The validations presented in this report show that commercially available Wind Farm Parametrisation and LES models show satisfactory results and capture wake dynamics otherwise impossible to model with analytical models only.

Similarly to mesoscale datasets used for long-term correction and micrositing, the type and extent of the computational datasets to be procured depend on the project location, configuration, and maturity. C2Wind recommends to carefully characterise site conditions prior to choosing a representative modelling time period and domain extent. This should be done primarily using atmospheric stability, at the surface and across the boundary layer. Combined with careful simulation planning (a full year of simulation is often not needed), this can result in time- and cost-effective ways to incorporate these novel modelling approaches into existing EYA workflows.

Wake modelling will remain difficult. Wind Farm Parametrisation and LES models, despite their limitations (which in great part are inherent limitations to mesoscale modelling, shared with any mesoscale model), provide a more physical insight into wake dynamics that analytical engineering models (that are in essence diagnostics models, requiring well defined flow case inputs). C2Wind sees no reason to not bring these models into the mix of already very diverse wake modelling strategies. In parallel, practitioners should keep using engineering models (accounting for atmospheric stability, these needs be reiterated) for fast- and preliminary estimates.

Regarding the additional cost of such models: in recent years, a great reduction in Energy Yield Uncertainty has been achieved with the vast adoption of floating lidar measurement campaigns, for a cost more than 2 orders of magnitude larger than the cost of the type of computational wake datasets discussed in the present report. Given the magnitude of the current uncertainty in wake modelling (often in the order of 20 to 25% of the wake loss), investing now in using, familiarising ourselves with- and validating these high-fidelity model results will provide industry-wide benefits.

C2WIND

7. References

[AMT25] **Cimini D., Gandoin R., Fiedler S., Acquistapace C., Balotti A., Gentile S., Geraldi E., Knist C., Martinet P., Nilo S. T., Pace G., Pospichal B. and Romano F.:** Atmospheric stability from microwave radiometer observations for on/offshore wind energy applications, Atmos. Meas. Tech. Discuss. [preprint, revised version accepted for publication].
Link: https://doi.org/10.5194/amt-2024-186, in review, 2024.

[BAAS23] **Baas, P., Verzijlbergh, R., van Dorp, P., and Jonker, H.:** Investigating energy production and wake losses of multi-gigawatt offshore wind farms with atmospheric large-eddy simulation, Wind Energ. Sci., 8, 787–805, https://doi.org/10.5194/wes-8-787-2023, 2023.

[C2W19] **C2Wind.** Model evaluation of downscaled ERA5 time series for British and Dutch offshore sites. WindEurope Wind Resource Workshop 2019 (2019-06).
Link: https://c2wind.com/f/content/windeurope_wra_workshop_20190627_c2w_rev4.pdf

[C2WKFII] **C2Wind.** Lot 2 (Kriegers Flak II). Wind Assessment. Doc. no. 23072-04-03 Revision 4 (2024-09-24).
Link: https://c2wind.com/f/content/23072-04-034---kriegers-flak-ii---wind-assessment.pdf

[EMD19] **EMD.** Recommendations for wake loss calculation for offshore wind farms (2019-03-22).
Link: https://www.emd-international.com/files/windpro/March-19_Revised%20offshore%20PARK%20WDC%20recommendations_v1.pdf

[FITCH12] **Fitch, A. C., Olson, J. B., Lundquist, J. K., Dudhia, J., Gupta, A. K., Michalakes, J., and Barstad, I.:** Local and mesoscale impacts of wind farms as parameterized in a mesoscale NWP model, *Mon. Weather Rev.*, **140**, 3017–3038 (2012). Link**:** https://doi.org/10.1175/MWR-D-11-00352.1

[IFS41r2] **ECMWF.** IFS Documentation CY41R2 - Part IV: Physical Processes (2016).
Link: https://doi.org/10.21957/tr5rv27xu

[NYGAARD20] **Nygaard N. G., Steen S. T., Poulsen L., Pedersen J. G.** Modelling cluster wakes and wind farm blockage. J. Phys.: Conf. Ser. 1618 062072 (2020).
Link: https://iopscience.iop.org/article/10.1088/1742-6596/1618/6/062072

[OURO25] **Ouro P., Ghobrial M., Ali K., Stallard T.** Numerical modelling of offshore wind-farm cluster wakes. Renewable and Sustainable Energy Reviews (2025).
Link: https://www.sciencedirect.com/science/article/pii/S1364032125001996

[PARK2] **Rathmann O. S., Hansen B. O., Hansen K. S., Mortensen N. G., Murcia Leon J. P.** The Park2 Wake Model - Documentation and Validation. DTU Wind Energy E Vol. 160 (2018).
Link: https://orbit.dtu.dk/en/publications/d527ae78-d931-450c-a1eb-1fc6c1989133

[PEDERSEN22] **Pedersen J. G, Svensson E., Poulsen L., Nygaard N. G.** Turbulence Optimized Park model with Gaussian wake profile. J. Phys.: Conf. Ser. 2265 022063 (2022)
Link: https://iopscience.iop.org/article/10.1088/1742-6596/2265/2/022063

[PEÑA08] **Peña A., Gryning S-E., Hasager C.B.** Measurements and Modelling of the Wind Speed Profile in the Marine Atmospheric Boundary Layer. Boundary-Layer Meteorology (2008-10).

[POSTEMA24] **Postema, B., Verzijlbergh, R., van Dorp, P., Baas, P., and Jonker, H.:** Estimating Long-Term Annual Energy Production of a Large Offshore Wind Farm from Large-Eddy Simulations: Methods and Validation with a 10-Year Simulation, Wind Energ. Sci. Discuss. [preprint], https://doi.org/10.5194/wes-2024-54, in review, 2024.

[RVOFLS] **RVO.** Borssele – Studies.
Link: https://offshorewind.rvo.nl/page/view/78f1a154-5b56-4ab0-a70f-d746a610179e/studies-borssele

[SATHE10] **Sathe A.** Atmospheric stability and wind profile climatology over the North Sea - Case study at Egmond aan Zee (2010).
Link: https://repository.tudelft.nl/file/File_1d863ca5-3e53-40ff-866f-b081e3c6cf09?preview=1

[SINCLAIR22] **Sinclair V. A. et al.** Boundary-layer height and surface stability at Hyytiälä, Finland, in ERA5 and observations (2022)
Link: https://amt.copernicus.org/articles/15/3075/2022/

[STEVENS17] **Stevens R., Meneveau C.** Flow Structure and Turbulence in Wind Farms. Annual Review of Fluid Mechanics (2017).
Link: https://www.annualreviews.org/content/journals/10.1146/annurev-fluid-010816-060206

[TPGIT] **Ørsted.** TurbOPark Gitub repository https://github.com/OrstedRD/TurbOPark. Last fetched: 2025-03-20.

[VEER2023] **Veer Renewables**. WakeMap: The Next Generation in Wind Resource Modelling.
Link: https://sway.cloud.microsoft/xXNw4LesRPw80JB9

[VOLLMER2024] **Vollmer, L., Sengers, B. A. M., and Dörenkämper, M.:** Brief communication: A simple axial induction modification to the Weather Research and Forecasting Fitch wind farm parameterization, *Wind Energ. Sci.*, **9**, 1689–1693 (2024).
Link: https://doi.org/10.5194/wes-9-1689-2024

[WE24] **Gandoin R., Juul Krogstrup M.** Addressing and Resolving Discrepancies in Wind Resource and Metocean Studies for Offshore Wind Farms. P.O.078. WindEurope Technology Workshop 2024.
Link: https://c2wind.com/f/content/po078_rev2.pdf

[WES24] **Gandoin, R. and Garza, J.:** Underestimation of strong wind speeds offshore in ERA5: evidence, discussion and correction, Wind Energ. Sci., 9, 1727–1745 (2024).
Link: https://doi.org/10.5194/wes-9-1727-2024.