Responses to Reviewers' Comments for Manuscript
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Tall Wind Profile Validation Using Lidar Observations and Hindcast Data

Addressed Comments for Publication to

Wind Energy Science (ISSN 2045-2322)

by

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1 Authors' Response to Reviewer 1

1.1 General comment

General Comments. In this manuscript three model-based datasets (NORA3, NEWA and ERA5) are validated using Doppler wind lidar data obtained from five locations, including North Sea (FINO1, FINO3) and coastal and complex terrain locations in Norway. Emphasis is given to long-range scanning Doppler wind lidars, providing wind profiles far above the atmospheric surface layer that are relevant for modern wind turbine designs and airborne wind energy (AWE) systems. These altitudes that are not feasible for in- situ wind measurements in tall masts (especially offshore) or the more extensively used short-range Doppler lidar wind profilers that are limited to 200-300m. The validation focuses on altitudes between 100m and 500m, using various error metrics, and their corresponding capacity factors, based on power curves for various wind turbines and AWE systems. The authors claim an increasing agreement between the models and the measurements with height, and argue that those models are valuable R&D on AWE systems.

In general, the manuscript addresses an important point, namely the need to validate models at altitudes relevant for future wind energy systems, and the lack of continuous, long-term measurement campaigns to do so. The authors point to the need of dedicated Doppler wind lidar profilers with sufficient height range, which are indeed lacking commercially right now. The manuscript also highlights the complexity of comparing the performance of various models, and that the best choice really depends on their actual application (type of location, relevant height range, . . .).

Response:

We thank the reviewer and appreciate the positive feedback and constructive comments on our article. We address the comments below and updated the manuscript adequately.

Comment 1

I have some objection to the term “tall wind profile”. Tall is used for physical structures, like masts or wind turbines, but a wind profile cannot be tall. I am not aware that “tall wind profile” is a commonly used term in our community, however, if I am wrong in this (i.e. it is used in more papers), I will drop my objection.

Response:

We acknowledge the reviewer’s concern regarding the term "tall wind profile" and agree that it is important to use precise terminology. There is a need for a term to describe wind speed profiling over several hundred metres, distinguishing it from traditional wind profiling. While no universally accepted label exists for this specific context, the term "tall wind profile" has been used in boundary-layer meteorology as by Peña et al. (2014) and Kelly et al. (2014). Given this precedent, we believe the term is appropriate for the present case.

We have updated the following sentence to the manuscript: *Tall wind profiles, as defined here, cover the entire atmospheric boundary layer (ABL) or at least the initial 500 m above the surface. The term ‘tall wind profile’ is in line with its use in boundary-layer meteorology (e.g. Peña et al., 2014; Kelly et al., 2014).*

Comment 2

The FINO1 measurements are not suitable for validation due to the presence of an operating wind farm (and the models do not include that). Therefore it should be not be included here, also because FIN03 is already available to cover the offshore situation. Only if the data could be filtered to minimize the effect of the wind farm (for instance, if the influence is only present for certain wind directions), its inclusion would make sense.

Response:

The reviewer raises a valid point about the potential influence of the surrounding wind farm on the FINO1 data. However, we believe it is important to include the FINO1 data to demonstrate how the presence of a wind farm can impact its agreement with the lidar data. This issue is explicitly addressed in the manuscript, as it highlights a key takeaway: wind atlases should be applied with caution in areas near existing wind farms. We believe that incorporating both the FINO1 and FINO3 datasets adds significant value, particularly as, to our knowledge, few studies have utilized both. While the suggestion to filter the data to minimize the wind farm's influence could serve as a topic for a master's thesis, such an analysis lies beyond the scope of this study.

we have added the following lines in the manuscript

The measurement data were collected by reference DWL instruments within the area covered by ERA5, NORA3, and NEWA. Two lidar campaigns were conducted in the marine ABL at the FINO1 and FINO3 locations, two others at coastal sites (Sola and Lista airports in Norway), and one in complex terrain (Bjerkreim, Norway). This diverse set of locations—comprising offshore, coastal, and complex terrain sites—provides a robust basis for assessing the performance of wind atlases for tall wind profiling. The FINO1 and FINO3 platforms offer complementary datasets for analyzing wind conditions near offshore energy installations (Podein et al., 2022). FINO1's proximity to wind farms enables an examination of discrepancies between lidar measurements and wind atlases. Combining data from both platforms highlights the challenges of wind resource assessment in such areas and underscores the need for cautious application of wind atlases near offshore energy projects.

Comment 3

The authors note that the conclusions on the model performances for the different sites might be hampered by the quality of the different Doppler lidar instruments. However, those measurements have been validated with other measurements, as described in Section 2.2. Wouldn't it therefore not be possible to quantity whether the validation results are significant in terms of the measurement uncertainty or bias?

Response:

The performance of the lidar can vary over time due to calibration drift, maintenance needs, and transport-induced shocks. Although systematic calibration could, in theory, ensure consistent performance across WindCube 100S units, practical constraints like deployment schedules make this difficult. These factors introduce uncertainties that cannot be fully quantified in this study.

Comment 4

For the wind measurements at the relevant altitudes the authors immediately jump to Doppler lidar in the introduction. But there are also other remote sensing instruments that can measure wind between 200 and 500m, like radar wind profilers and sodar. In fact, for this validation study, their temporal and vertical resolution would be more than sufficient. The choice of Doppler lidar should be given a bit more context and motivation.

Response:

We agree with the reviewer. We have added the following lines in the introduction:

Tall wind speed profiles can in general be measured using remote sensing technologies (Emeis, 2011), including Doppler wind radar (Lehmann & Brown, 2021), sodar (Bianco, 2011), and lidar (Pichugina et al., 2012). As commercial Doppler wind lidars (DWLs) have become the standard instrumentation for wind energy applications, we have based our study on corresponding available lidar data sets.

Comment 5

The conclusion that there is an increasing agreement between models and lidar measurements, as stated in the abstract, is not explicitly stated in the main text, including the conclusion. Either the main text is underselling the results, or the abstract is overselling it.

Response:

Thank you for pointing this out. An increasing agreement between models and lidar measurements is indeed a finding of this study. We have updated the manuscript to explicitly emphasize the increasing agreement between models and lidar measurements in the main text, while being fairly nuanced. We have reformulated this sentence in the abstarct. The following sentence has been added in the main text:

In most cases, the agreement between the models and lidar measurements improves with height. However, this trend is not consistently observed at coastal and complex terrain sites, where deviations can occur, depending on the error metric and model database.

and in the conclusion:

While the agreement between the models and lidar measurements generally improves with height, this trend is less consistent at coastal and complex terrain sites, where deviations occur, especially for ERA5 and NEWA.

Comment 6

I was a bit surprised that although the paper emphasis the need for wind profile beyond what can be reached by traditional masts and (floating) short-range wind lidars, still most of the presented results are at an altitude of 150m (for which, by the way, there are much more lidar data available, including offshore). Why this particular choice?

Response:

The choice of 150 m reflects the hub height of the 15 MW wind turbine analysed in Fig. 10, enabling a more direct connection between the wind profile results and the turbine's capacity factor. Additionally, Fig. 7 should be interpreted alongside Fig. 8, which provides the profiles of the error metrics to offer a more comprehensive view of the model's performance across altitudes. We acknowledge that the focus on this altitude might seem limiting given the availability of lidar data at similar heights, but we believe that it is relevant for the context of this study (offshore wind energy). In the revised manuscript, we include a similar bar plot at a height of 300 m, which may be more relevant for airborne wind energy systems. However, merging these two figures was not feasible, as we prioritized achieving a balance between clarity and the concise presentation of information.

1.2 Specific comments

Comment 7

Title: “validation using lidar observations and hindcast data”. Are you not validating hindcast data using lidar observations?

Response:

This is correct. Following the comments from the other reviewers, we have reformulated the title as "Tall wind profile validation of ERA5, NORA3 and NEWA, using Lidar observations"

Comment 8

Table 1, why this table is in the manuscript? To make the point that there are very limited amount of tall towers with in-situ wind measurements, such a table is not required.

Response:

The table serves two purposes: (1) to illustrate the scarcity of tall masts with wind measurements, and more importantly, (2) to document where these masts are located and provide a resource for readers seeking more information. We believe this table offers valuable context for the study and helps orient readers, especially those interested in understanding the availability and characteristics of these rare measurement sites. None of the other reviewers raised objections to the inclusion of the table.

Comment 9

Section 3.3: It is not explained how the wind profile is used in the calculation of CF for wind turbines. Is this wind speed at hub height taken or a rotor average. Table 4 provides hub height and rotor diameter of the various wind turbine types, but nowhere it written how this information is used. This is in contrast to the extension discussion on the AWE system.

Response:

We agree that this aspect should be clarified. We used the wind speed at hub height rather than rotor-averaged wind speed for the calculation of capacity factors (CF). While rotor-averaged (or rotor-equivalent) wind speed, which accounts for effects such as shear, turbulence intensity, and wind veer (Wagner et al., 2009; Antoniou et al., 2009; Murphy et al., 2019), could provide more accurate capacity factor estimates, this level of detail is beyond the scope of the current study. Assessing its impact would ideally require output data from a full-scale large offshore wind turbine for validation. To clarify this, we have added the following lines to the manuscript:

In this study, capacity factor calculations are based on wind speed at hub height. Modelling the rotor-averaged (or equivalent) wind speed, which accounts for shear, turbulence intensity, and wind veering (Wagner et al., 2009; Antoniou et al., 2009; Murphy et al., 2019) may yield more realistic capacity factor estimates and further justify the modelling of tall wind profiles for the design of large offshore wind turbines. However, such an analysis falls beyond the scope of the present work.

Comment 10

In correct usage of term “In-situ” throughout the manuscript. Doppler lidar is a remote- sensing instrument and definitely not “in-situ”! However, in distinguishing between model and measurement data, in several parts of the manuscript the term “in-situ” is used for Doppler lidar, which is wrong. This needs to be corrected.

Response:
We agree with the reviewer and have removed the term "in-situ" throughout the manuscript, as it is not necessary and partly redundant.

Comment 11

The distinction coastal and complex locations from Figure 2 is not clear (at least for the non- Norwegian reader). Would a zoom-in of the map help to clarify the difference between the Sola and Lista as coastal/non-complex, and Bjerkeim as complex terrain?

Response:
We agree with the reviewer, we have added a topographic map of the area, which better highlight the difference between the sites as well as the following updated lines:

Figure 2 summarises the locations and measurement periods of the five campaigns selected for the validation of wind atlases while figure 3 provides a close-up of the three onshore locations. The offshore sites are situated in open waters, whereas the coastal sites are only a few kilometres from the shore, characterised by sharp roughness changes as the terrain transitions from open water to flat, agricultural land with sparse vegetation. These abrupt roughness changes introduce an internal boundary layer, which can be challenging to capture accurately in hindcast and reanalysis wind speed models. The complex site is mountainous, with steep slopes and limited vegetation or trees. While distinct from the fjord-like landscapes found in other parts of Norway, the complex terrain features significant elevation changes that contribute to non-homogeneous wind conditions, particularly within the atmospheric surface layer.

Comment 12

Section 5.2: Could you be more explicit, or give examples, on what you mean with “microscale models”

Response:
We have revised Section 5.2 and added the following explanation at the beginning of the section:

In wind energy, wind simulations are typically performed using two types of models: mesoscale models, which provide wind speed data over spatial scales ranging from a few kilometres to hundreds of kilometres, and microscale models, which operate at smaller scales, from a few metres to approximately one kilometre. While these models are complementary, microscale models are particularly useful in capturing wind flow in complex terrain, where topographic features significantly influence wind conditions, or near structures such as buildings and wind farms.
This study primarily focuses on mesoscale-derived wind speed data, which can be limited in capturing fine-scale flow features in complex terrains or near coastal sites. For offshore sites like FINO3, microscale effects are likely negligible. However, for coastal sites such as Sola and Lista, and for the complex terrain at Bjerkreim, microscale modelling may enhance the agreement between simulated and measured wind speeds. At Bjerkeim, computational fluid dynamics (CFD) models could help capture complex phenomena, such as flow recirculation and detached downslope flow, which are prevalent in mountainous terrain like South-eastern Norway.
At FINO1, microscale flow simulations may also be needed to model wake effects on in-situ measurements. Future studies should investigate the benefits of coupling mesoscale and microscale models to enhance performance metrics at coastal and complex sites. We anticipate this coupling could shift the near-zero bias of NORA3 to slightly negative or positive values, while potentially reducing the current bias of NEWA and ERA5 towards zero. However, such an analysis lies outside the scope of the present study.

Comment 13

Section 5.2: At the end of this section the issue of Doppler lidar wind profiling measurements in complex terrain is mentioned. This is a relevant point, but doesn't belong to this section (which is about the models). Maybe this issue should be discussed much earlier in the paper. Are there solutions to this issue, or would validation in complex terrain remain problematic?

Response:

We agree with the reviewer and have moved the discussion on Doppler lidar wind profiling measurements in complex terrain to just before Section 4.3, where it fits more appropriately. We have slightly shortened the content to better align with the context and added a reference to Klaas-Witt & Emeis (2022):

The discrepancy between modelled wind speed data and lidar-based measurements at the complex site Bjerkreim and the coastal sites Sola and Lista is influenced by the higher occurrence of non-homogeneous flow fields at onshore sites compared to offshore locations. These effects, particularly within the first 300 m above the surface, can exacerbate the measurement uncertainties of lidar retrievals using DBS or velocity-azimuth display scanning (Klaas-Witt & Emeis, 2022).

Higher measurement errors in complex terrain are a recognised challenge for Doppler wind lidar (DWL) profilers, as they rely on fundamental assumptions about homogeneous flow. However, advancements such as the use of a 5-beam DBS scanning mode, instead of the traditional 4-beam mode, have significantly improved DWL profiler performance in complex terrain for the past 10 years.

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