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

Cheynet et al.

1 Authors' Response to Reviewer 3

1.1 General comment

General Comments. The submitted paper, "Tall Wind Profile Validation Using Lidar Observations and Hindcast Data" by Etienne Cheynet et al., analyses the accuracy of three different wind atlases (NEWA, NORA3 and ERA5) by comparing them to long-range wind lidar measurements.Various error metrics such as bias, RMSE, EMD, R^2 are evaluated for five different sites including offshore (FINO1, FINO3), coastal onshore (Sola, Lista) and complex terrain (Bjerkeim).The study focuses on wind conditions at heights between 100 m and 500 m, a range not feasible for traditional met masts or short-range lidar profilers, making it directly applicable to tall wind turbines and airborne wind energy (AWE) systems. Additionally, the authors assess the estimated capacity factors of reference wind turbines (NREL 5 MW, NREL 18 MW, and IEA 15 MW) and AWE systems (3 MW fixed-wing and 100 kW EnerKíte semi-rigid), comparing simulated and measured wind data as a further quality metric. The authors conclude that all three wind atlases perform well offshore, with NORA3 and ERA5 showing slightly better performance above 200 m. Onshore, NORA3 consistently outperforms ERA5 and NEWA at all heights, emphasizing that the choice of a suitable wind model depends on specific application, location, and height requirements. The paper addresses important topics, such as the adequate choice of wind data for initial wind resource assessment, validation of wind models at heights relevant for future wind energy systems, and the need to develop DWL profilers to reliably measure these heights over the long term.
Here are some general comments I would like to see addressed before publishing the paper. However, some of these comments are a matter of personal preference, and I would appreciate hearing the authors' opinion if they choose not to implement them.

Response:

We sincerely thank the reviewer for their thorough and detailed review of the manuscript. We greatly appreciate the considerable effort and valuable insights, which we believe have significantly strengthened the quality of the manuscript.

Comment 1

Please rethink the title "Tall Wind Profile Validation Using Lidar Observations and Hindcast Data". This title sounds like you are validating tall wind profiles using lidar and hindcast data. I am not familiar with the term Hindcast, but it is my understanding that only NORA3 is Hindcast data, ERA5 is climate reanalysis data and NEWA derived from WRF and WAsP with boundary conditions from ERA5. Are you using Hindcast and reanalysis interchangeably? It would good if the title would reflect that you are validating and comparing lidar measurements with different wind models up to higher altitudes.

Response:

We agree with the reviewer. As stated in our reply to reviewer 1, we have now changed the title into: "Tall wind profile validation of ERA5, NORA3 and NEWA, using Lidar observations". Only the mesoscale ouput of NEWA were used as the microscale output are not available as time series.

Comment 2

Please clarify the writing. Several sentences are difficult to understand or can be understood in various ways. See attached commented document..

Response:

We have carefully revised the manuscript based on the detailed comments provided in the attached document to improve readability and reduce ambiguities.

Comment 3

Appendix: Why was the section moved to the appendix? It is my understanding that while this approach delivers good interpolation, it is not used because the improvement doesn't justify the increased afford? I think you could remove it for clarity and only focus on the approach you took, but I am open to hearing your opinion.

Response:

Yes, that is correct. We did not observe a substantial improvement with the more complex non-linear regression compared to the simpler and more robust linear interpolation. However, we chose to include these results in the appendix to document that alternative approaches were considered. We believe this adds transparency to our methodology and demonstrates that the chosen approach is not the only viable option. Additionally, presenting these results as figures in the appendix is more effective and concise than a textual explanation, as visualizations often provide clearer insights than lengthy descriptions.

Comment 4

You determine bias, R^2, RMSE and EMD only in terms of horizontal wind speed. Did you also investigate the directional difference between the models and measurements and are they meaningful or significant?

Response:

Yes, we did investigate directional differences between the models and measurements. In an earlier version of the manuscript, we included this information, replacing the EMD metric with the Circular EMD to discuss error metrics for the wind direction. However, the manuscript became excessively lengthy and heavy. Thus we had to remove this part to streamline the presentation. We acknowledge that wind direction, particularly veering, is an important topic for large offshore wind turbines and AWE systems. Nonetheless, we made the decision to focus on horizontal wind speed to keep the paper concise and accessible.

Comment 5

Wind data: Please clarify how you compared the model and measurement data. You mention a spatial and temporal interpolation of model data to the lidar location, height and time. How did you interpolate between 30 or 60 min modeled wind data to 10 min increments as the measurements? Is it a linear interpolation? Considering how quickly the wind changes that leads to significant differences. I think it would be better if you averaged the 10 min measurements to 30 min or 60 min instead.

Response:

Thank you for your comment. As explained in the manuscript, we tested both approaches: interpolating the model data to 10-minute intervals and downsampling lidar data to match the model's 30- or 60-minute resolution. The differences between the two methods were minimal. However, downsampling the lidar data introduced challenges, particularly due to irregular sampling (e.g., at FINO1, only two 10-minute scans were conducted per hour) and data gaps that required additional processing, such as gap-filling. These steps added complexity and potential errors. Given the limitations and the fact that 10-minute averaging is a standard in wind energy studies, we chose to interpolate the model data to 10-minute intervals for consistency and simplicity. While we acknowledge that this approach may slightly increase errors due to rapid wind changes, the alternative would also introduce errors from data processing and manipulation.

Comment 6

Measurement campaigns: The duration of measurement campaigns, particularly at Sola and Bjerkreim are very short and seems to have a lot of data missing (Figure: 6). Please comment on what the reason for this is and add a brief statement in Section 2.2. that these measurements are not representative of the typical, annual wind variations at these sites.

Response:

The measurements at Bjerkreim and Sola were conducted using early prototype versions of commercial Doppler wind lidars, which were less reliable than the instruments available today. This led to significant data gaps and shorter campaign durations. Additionally, logistical constraints and the limited objectives of these campaigns contributed to their brevity. We have now added a statement in Section 2.2 to clarify that these measurements are not representative of the typical, annual wind variations at these sites. The added text reads:

It should be noted that the measurements at Bjerkreim and Sola were conducted over short time periods and are therefore not representative of the typical, annual wind variations at these sites. Instead, the data should be interpreted within the context of this study, which aims to compare tall wind speed profiles from wind atlases with lidar observations.

Comment 7

Why are you comparing wind data "at the range gate nearest to 150 m"? Why this height and not 200 m or 300 m which is closer to operating heights of tall wind turbines and AWEs? Why did you not interpolate to a specific height to compare them better?

Response:

To complement the error bar at 150 m, we have added a new figure showing similar error bars at 300 m. The operating height of tall wind turbine is typially the hub height (150 m) , altough he tip top height can/will reach indeed 200-300 m. As elaborated in our reply to reviewer 2, we use the height of 150 m for consistency with the description fo the capacity factor. Note that Figure 8 shows the profiles of these error metrics, so the error metrics at the other heigths are still provided in the manuscript. we have added the following description for these figures:

Figure 7 and Fig. 8 compare four error metrics describing the discrepancies between measurements and modelled mean wind speed data across the five sites at range gates closest to 150 m and 300 m, respectively. These results complement the profiles shown in Fig. 9. Notably, the variability in these metrics across the models observed in Fig. 7 and Fig. 8 aligns with trends at other altitudes, reinforcing the consistency of our findings.

Comment 8

Please introduce the Taylor diagrams a bit more and the what conclusions you can draw from them.

Response:

We have expanded the description of Taylor diagrams to improve clarity in the method section, which reads as

To complement these metrics, the Taylor diagram (Taylor, 2001) provides a summary of model performance by integrating the correlation coefficient, standard deviation, and RMSE into a single plot. This graphical representation is particularly useful for comparing multiple models against observed data in a visually intuitive way.

Comment 9

Do you really need section 5? I think you could merge it with section 6, but I would like to hear your opinion too.

Response:

We recognize that there are different approaches to structuring academic papers, with some preferring to merge the discussion and conclusion sections, while others advocate for keeping them separate. Both approaches are acceptable, and in this case, we opted to keep them distinct for the sake of clarity.

Comment 10

Please spend a few sentences introducing the different AWE models. Introduce the system design, size, soft-kite, rigid-wing or semi-rigid wing, operating conditions, limitations and model assumptions.

Response:

We have reformulated the paragraph in the introduction presenting airborne wind energy (AWE) systems as below. Note that we must remain concise as the paper is not a review paper or focusing solely about AWE.

Airborne Wind Energy (AWE) systems harness wind energy using tethered aircraft operating at altitudes between 200 and 600 m. At these heights, wind speeds are generally stronger and steadier than near the surface. Since the 2010s, AWE systems have made significant advances (Vermillion et al., 2021; Fagiano et al., 2022; Eijkelhof & Schmehl, 2022). Prototypes with capacities exceeding 600 kW have been developed, and scaling to multi-megawatt systems has been proposed (Vermillion et al., 2021; Kruijff & Ruiterkamp, 2018). Despite this progress, AWE systems are still in the early stages of development compared to offshore wind turbines. Two main concepts dominate current AWE designs. Ground-generation systems, or "pumping power" systems, generate energy on the ground using a winch and generator. The tethered aircraft alternates between energy-generation and recovery phases.

Aircraft for this concept include soft kites, semi-rigid wings, and rigid wings. Each type offers trade-offs between adaptability and durability. Onboard generation systems, in contrast, produce energy in the air using onboard turbines and power is transmitted to the ground via conductive tethers. These systems typically use rigid-wing aircraft, quadrotors, or toroidal aerostats (Cherubini et al., 2015). While ground-generation systems are relatively efficient, they require advanced automation for continuous operation (Elfert et al., 2024). Onboard-generation systems are better at harnessing high-altitude winds but face challenges in weight optimization and tether design. Flexible wings are adaptable to varying wind conditions but are less durable. Conversely, rigid wings provide higher power output but come with greater mechanical complexity and costs (Fagiano et al., 2022). Key challenges remain for AWE systems, including managing wind variability, tether dynamics, and autonomous operation. A major limitation lies in the reliance on oversimplified wind speed approximations, due to the lack of detailed wind speed data at altitudes above 200 m (Sommerfeld et al., 2019). Addressing this gap through tall wind profiling is essential for optimizing AWE system design and unlocking their full potential for large-scale deployment.

Comment 11

Please revise the figures to improve readability and clarity (see comments in PDF document)!

Response:

We have addressed the reviewer's feedback to improve the readability and clarity of the figures. However, it is important to note that the figures were designed to align with the two-column format used by Wind Energy Science, which can result in a slightly unconventional layout in the single-column review format.

Comment 12

I believe that it is good practice not to have empty sections before a subsection title, e.g. Sections 3 or 5. Either remove the subsection titles or write a very brief summary of the section before the first subsection title.

Response:

We understand the viewpoint of the reviewer and have followed the recommendation where we found it relevant and useful to improve the manuscript. However, we have not applied this change in all cases, for the sake of conciseness and limit redundancy.

Comment 13

Try to formulate mote active voice sentences. Some are mentioned in the attached document.

Response:

We have followed the reviewer's recommendation and revised the manuscript addressing the specific instances highlighted in the attached document.

Comment 14

You can remove several unused abbreviations and introduce z for height or $\overline{u}$ for average horizontal wind speed

Response:
Following the the reviewer's suggestion and have removed unused abbreviations where appropriate. We have used ABL for atmospheric boundary layer more consistently. OWT is now replaced by offshore wind turbines for clarity. The abbreviation "WRF" is also removed as it was used only once. We have also introduced z for height and $\overline{u}$ for average horizontal wind speed as recommended:

Hereinafter, z denotes the height in meters above the surface, and $\overline{u}$ represents the horizontally averaged mean wind speed at height z.

Comment 15

Please add hyperlinks to the references, e.g. citation A, Tab.1, Fig.2, Eq. 3

Response:
We confirm that hyperlinks were used for reference and citation. We systematically use the cleveref and natbib packages in LaTeXwhich autmoatically format the reference style and create a hyperlink.

Comment 16

Capitalize "fig." and "table" in the entire the paper

Response:
We have adjusted the cleveref package to automatically capitalize references to figures and tables, following the reviewer's feedback.

List of Main Changes in Response to the Reviewer's Comments

We have carefully reviewed all comments and implemented most of the suggested changes. Below, we summarize key modifications and provide specific responses to certain points:

- **Acronyms:** We have re-evaluated the use of acronyms. Unnecessary acronyms have been removed, and we have not introduced any new ones to maintain clarity.
- **Figures:** Figures 2, 4, and 5–12 have been updated to address the reviewer's comments wherever possible. In a few cases, suggestions did not improve clarity, so we opted for a compromise. For example, please see Figure 10.
- **Table 4:** Table 4 has been removed as we now use only three turbine models to enhance clarity, making such a table unnecessary.
- **Terminology ("above the surface"):** We have reduced the use of the phrase "above the surface."
- **Use of transitional words:** We have improved the logical flow of the manuscript by revisiting transitional words (e.g., "therefore") throughout the text.
- **Definitions of "hindcast" and "reanalysis":** Brief definitions of hindcast and reanalysis are now provided.
- **Consistency in writing style:** We recognize that writing styles can differ. Both the reviewer's and our chosen style are valid, as long as consistency is maintained.
- **Abstract and acronyms:** We regard the abstract as a separate entity. Therefore, acronyms and definitions introduced in the abstract are reintroduced in the main text.
- **Introduction:** The last paragraph of the introduction has been clarified.
- **4D-Var data assimilation reference:** We have added a reference to 4D-Var data assimilation. We believe that the reference is more suitable than an extensive explanation, which would be beyond the scope of this study.

- **URLs and references:** URLs have been removed and replaced by corresponding BibTeX references.
- **Clarification of ASL:** The distinction between ASL (atmospheric surface layer) and "above sea surface" has been clarified. We have removed the acronym for "above sea surface."
- **HARMONIE-AROME definition:** HARMONIE-AROME is defined as a numerical weather prediction model in the revised manuscript. For comparison, the Weather Research and Forecasting (WRF) model is also a numerical weather prediction model.
- **ERA5 wind speed data:** ERA5 provides wind speed data at pressure levels and two height levels (10 m and 100 m). These levels do not always overlap. Combining both datasets adds robustness to our analysis.
- **Marine ABL terminology:** We prefer "marine ABL" over "offshore" because the former is more precise and indicates flow characteristics above the sea, whereas "offshore" may include coastal or seaside measurements.
- **Pressure-to-height conversion:** The conversion from pressure level to height level depends on atmospheric conditions and varies over time. This is why we use geopotential height, which also varies with time.
- **Angle conventions:** Angle conventions differ for scanning lidars (elevation relative to horizontal) and profilers (opening angle). Referring to "opening angle" for scanning lidars would be confusing, in our opinion.
- **Geopotential vs geometric height:** The difference between geopotential height and geometric height is negligible (close to or below 1 cm at 500 m above the surface). For brevity, we believe this aspect does not require further elaboration in the manuscript.
- **Placement of appendix A:** Appendix A remains appropriately placed, as it is not directly used in the methods or results sections. It is necessary to demonstrate that spatial linear interpolation on vertical levels is appropriate.
- **Panel labeling:** We have labelled the subpanels of Figs 7,9,8,11,12 and the figure in appendix with letters for clarity.

- **AWE system parameters:** For brevity, we have not elaborated on additional AWE system parameters (e.g., operating height, size), as they are not directly relevant to the results section.
- **Interpolation of wind data:** Whenever possible, we interpolate wind atlas data to the lidar range gate height. When not possible (e.g., for capacity factor calculations), we interpolate both wind atlas and lidar data to the operational or hub height. This approach avoids data overprocessing. We tried to clarify this point in the revised manuscript.
- **Turbine types for capacity factor:** We now use only three turbine types to improve the clarity of our capacity factor results.
- **Capacity factor insight:** We confirm that a capacity factor of 10–20% represents a significant drawback for intermittent wind energy systems, as such systems are unlikely to be economically viable.
- **Figures 11 and 12:** We have merged Figures 11 and 12 (those showing the CF of AWE systems) for conciseness.
- **Revisions to sections 4.3 and 5:** Sections 4.3 and 5 have been partially rewritten.
- **Numerical model resolution:** A higher spatial resolution does not always improve numerical model outputs. For example, ERA5 performs as well as NORA3 offshore and outperforms NEWA, which is unexpected but plausible. Overly high resolution can distort grid elements in terrain-following grids, introducing numerical errors.
- **Non-linear regression (appendix A):** The non-linear regression in Appendix A uses least-squares fitting. Including height levels at 750 m could alter the results slightly.

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