RESPONSES POINT BY POINT TO REFEREE N°2 OF WIND ENERGY SCIENCE DISCUSSIONS

Brief communication: Enhanced representation of the power spectra of wind speed in Convection-Permitting Models

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Dear Referee No.2,

We thank you for your review work and the valuable comments, which helped to improve our paper. Our responses are reported in blue, and all the modified or new text is reported in *italics and red*. Line numbering refers to the original version of the paper that was available for the open discussion.

General comments

The paper deals with the issue of use of reanalysis data for wind-energy purposes. In particular, it is known that power spectrum of wind speed resulting from numerical methods suffer of energy loss at high frequencies, leading to an underestimation of extreme wind speeds needed for the structural design of wind turbine. In the manuscript, the authors evaluate the possibility of use Convenction-Permitting Models to better reproduce the theoretical -5/3 slope in wind power spectrum as alternative to the most used datasets like, e.g., ERA5. The study is very interesting and contributes significantly to the important open debate on the reliability of reanalysis data for structural design purposes. The brief communication is suggested to be published after minor revision.

Thank you very much for your positive insights about our work. We will respond to each of your specific comments in the following section.

Specific comments

Comment #1 - Page 3, Lines 81-83 *"Originally recorded at 10-minute intervals, these data were subsequently aggregated to hourly values by arithmetic averaging to facilitate direct comparison with the simulations of the CPM models."* Please explain whether the hourly sampled CPM data are representative of 10-min average wind speed or 1-hour average wind speed. Indeed, e.g., in ERA5 dataset the provided parameters are available hourly, and they are defined as either instantaneous value referring to a specific point-in-time (thus not averaged) or mean rate value averaged over a given time period. If the case is the first, then the "arithmetic averaging" of field measurements seems to be wrong.

We thank the referee for pointing out this relevant detail about the time window definitions of our datasets. We provide the following specifications for each dataset:

- CORDEX-FPS CPMs: Instantaneous hourly values showing the model state at each hourly timestep.
- ERA5: Instantaneous values (with an implicit 30-minute average of elapsed time).

• NEWA: Output at 30-minute temporal resolution (Hahmann et al., 2020), aggregated to hourly values for this analysis.

• Observations: Initially recorded every 4 seconds and aggregated to 10-minute means (Kohler et al., 2018), later combined into hourly mean values for comparison.

However, it is essential to note that our study examines how each dataset performs in the relevant frequency range, spanning from a few hours to ~ 1 hour, for spectral analysis. Here, we do not use this data for direct extreme wind calculations, as we stated in the introduction. At these temporal scales, different definitions of temporal windows do not greatly change our main conclusions about spectral slope behaviour.

This is because the processes that create the theoretical -5/3 slope in the mesoscale range (1-6 day^-1) work at characteristic timescales of about 4-24 hours that are much longer than the differences between instantaneous hourly values and 10-minute averages. Additionally, we confirmed this by comparing the spectral slopes between the original 10-minute observational data and the hourly-aggregated values, and found no significant differences in spectral behaviour at frequencies of ≥1 hour^-1, confirming that our comparative spectral analysis remains valid for the frequency range of interest in our study.

Therefore, while we acknowledge these methodological differences, they do not impact our primary findings regarding the superior spectral representation in CPMs compared to nudged simulations, such as NEWA, and reanalysis products, like ERA5. In this sense, we will aggregate the following paragraph in line 109:

"All datasets are analysed at an hourly frequency for consistency and comparison, but they have different time window definitions. CPMs represent instantaneous model states. ERA5 offers instantaneous values, averaging them over 30 minutes. NEWA provides 30-minute resolution data, grouped into hourly values. Observations are collected from 10-minute averages and converted to hourly values. These differences in time windows do not influence spectral analysis in our frequency range of interest, which is from 1 to 6 day^{-1}, because the atmospheric processes that generate the -5/3 spectral slopes operate at much longer timescales (4-24 hours) than these methodological differences."

REFERENCE: Kohler, M., Metzger, J., & Kalthoff, N. (2018). Trends in temperature and wind speed from 40 years of observations at a 200-m high meteorological tower in Southwest Germany. *International Journal of Climatology*, *38*(1), 23-34.

Comment #2 - Page 45, lines 116-117 *"the hourly time series of CPMs, ERA5, and NEWA, were first detrended by subtracting their mean value, thus removing the constant component."* The detrending operation is usually made to remove low-frequencies oscillations that can introduce an unwanted mean component to short records. Please specify better what you mean by "detrend" in this case: is it perhaps to make time series zero-mean for the purpose of deriving power spectra?

We thank and agree with the referee's comment about the terminology. The referee is correct that 'detrended' is usually used to remove low-frequency oscillations and long-term trends over time. In our analysis, we calculated wind speed anomalies by subtracting the average of the time series. We do this to centre the data around zero and remove the constant component needed for spectral analysis while preserving the temporal trend. We will change the term in line 116 to *'mean-centred'* to better describe the preprocessing done before spectral analysis.

Comment #3 - Figure 1. It is shown that CPM simulations provide enhanced spectral contribution at larger frequencies. Is there a possible physical explanation for this phenomenon?

We thank the referee for this critical question about the physical mechanisms behind the improved spectral performance of CPMs.

As we discuss throughout the original manuscript, particularly in lines 174-184 and 207-218, the better spectral representation at high frequencies in CPMs comes from fundamental differences in simulation methods that preserve natural atmospheric processes. CORDEX-FPS CPMs use continuous, free-running simulations. This setup allows convective processes to develop their own spectral characteristics without large-scale limits (Coppola et al., 2020), preserving the natural energy flow processes that create mesoscale variability, especially in the high-frequency range (1-12 day^-1) where we see spectral improvements.

On the other hand, other high-resolution models, such as NEWA, employ spectral nudging and frequent restarts (8-day runs with spectral nudging) to ensure consistency with reanalysis forcing (Hahmann et al., 2020). Vincent and Hahmann (2015) showed that spectral nudging reduces wind speed variance across all wavelengths, even at the surface where nudging is not applied. This constraint may interfere the natural energy flow processes that generate mesoscale variability, which explains the steepened spectral slopes seen in Figure 1d.

In this sense, the key difference in simulation philosophy lies between fidelity to physical processes and large-scale constraints, which explains why CPMs naturally maintain realistic high-frequency wind variability. However, the disadvantage is that these continuous simulations are computationally very costly (Coppola et al., 2020; Fosser et al., 2024).

Comment #5 In addition to the KIT measurement site, the PSD of randomly-selected 10 locations are discussed. Since they can be relevant, please describe both roughness and orography conditions at KIT measurement site as well as at the 10 locations of Figure 2.

Thank you. To complement the information we presented in Figure A1, we will cite in line 80 the work of Kohler et al. (2018) for the description and details about the KIT mast point. In addition, we will include a table in the annexes with information on the roughness of the random points in the appendices:

Table 1A. *Characteristics of the 10 randomly selected locations for spectral analysis. Roughness length (z0) values from COSMO model and ranges based on CORINE Land Cover classifications (Demuzere et al., 2008).*

Point	Latitude	Longitude	Elevation [m a.s.l]	zo[m] Range	Description (Examples)
Serie 1	40.271	6.1286	0	0-0.0003	Very smooth (water, ice)
Serie 2	42.566	2.1006	1638.61	0.7-inf	Very rough (dense forests, urban centres)
Serie 3	42.566	15.5526	0	0-0.0003	Very smooth (water, ice)
Serie 4	44.213	2.7086	813.98	0.3-0.7	Rough (scattered forests, peri-urban areas)
Serie 5	46.805	1.0366	85.88	0.03-0.3	Moderate (shrubs, bareland)
Serie 6	44.024	3.0126	595.05	0.3-0.7	Rough (scattered forests, peri-urban areas)
Serie 7	47.426	4.4946	430.61	0.03-0.3	Moderate (shrubs, bareland)
Serie 8	45.239	6.0906	2349.68	0.7-inf	Very rough (dense forests, urban centres)
Serie 9	40.352	16.2746	287.52	0.03-0.3	Moderate (shrubs, bareland)
Serie 10	40.595	12.9686	0	0-0.0003	Very smooth (water, ice)

REFERENCES:

Demuzere, M., De Ridder, K., and van Lipzig, N. P. M.: Modeling the energy balance in Marseille: Sensitivity to roughness length parameterizations and thermal admittance, Journal of Geophysical Research: Atmospheres, 113, D16 120, https://doi.org/10.1029/2007JD009113,610 2008.

Kohler, M., Metzger, J., & Kalthoff, N. (2018). Trends in temperature and wind speed from 40 years of observations at a 200-m high meteorological tower in Southwest Germany. *International Journal of Climatology*, *38*(1), 23-34.

Comment #6 The study is limited to comparison of Power Spectrum. Evaluate the possibility of compare recorded and simulated yearly maxima at KIT measurement site, e.g. by showing their empirical distribution function or, at least, the right tail of the parent distribution.

We appreciate the comment, and although the suggestion is not entirely in line with the focus and central topic of our paper on the spectral characteristics of the compared datasets, for context, we provide statistical comparisons of the datasets evaluated at the KIT point in the appendix section as supplementary information.

In line 109, we will add: *"A statistical comparison of the time series from the different datasets at the KIT point is presented in Figure A2."*

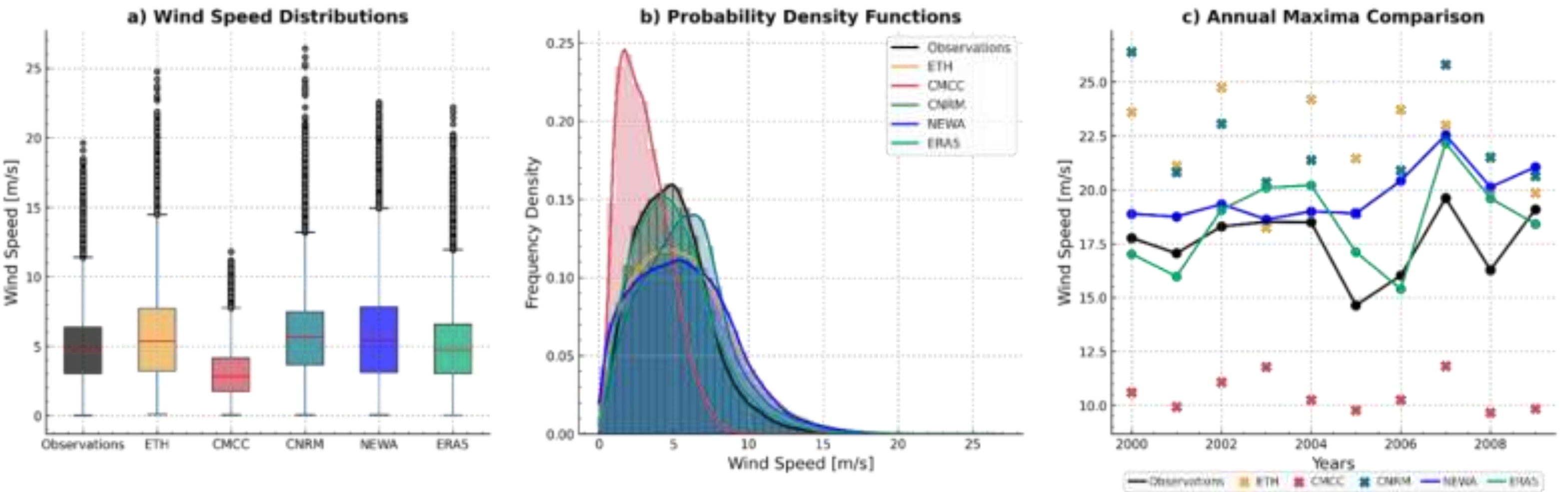

Figure A2. *Comparison of time series at the KIT point.*