RESPONSES POINT BY POINT TO REFEREE N°1 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.1,

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 authors present an analysis of the wind speed power spectra from four regional convection-permitting models (three from the CORDEX Flagship Pilot Project and the New European Wind Atlas, NEWA). The wind speed power spectra are compared with theoretical expectations, and an observed spectrum from mast data, and contrasted with a reanalysis dataset that parameterizes convection (ERA5). The key finding of the work is that the convection-permitting models from the CORDEX project produce a wind speed power spectrum for high frequency variations (sub-daily) that matches with observations, offering an improved representation compared with the NEWA and ERA5. This has implications for wind resource and extreme wind assessments using model datasets. The improvement in representation over the NEWA is suggested to be a result of not using large-scale nudging in the model configuration. Although this is not shown in the paper, and I have a comment related to this theory, below. Overall, this a nice analysis that is well-written, and I think it is suitable for publication in Wind Energy Science after minor revisions (see comments below).

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

Specific comments

Comment #1. The authors have demonstrated the improved power spectrum of wind in the CORDEX CPMs. It is suggested that this is a result of the models being free-running and not nudged towards the large-scale. But I wonder if this improvement is balanced by other aspects becoming less accurate than the nudged simulations. What about the wind speed distribution, for example? This will also affect estimations of U50. There are some biases in the CORDEX model wind speed suggested in Figure 1, as acknowledged by the authors. I know the authors may not be able to provide any further analysis of this in this brief communication, but maybe this could be mentioned or relevant references cited?

We thank the reviewer for this clarification. We agree that our study focuses specifically on wind speed variability over short time frames, from a few hours to about one hour. This is one of the crucial factors for correctly calculating U50. However, we acknowledge that we are not examining all the factors that can influence the accuracy of U50 estimation.

Relevant literature indicates that improved wind speed data at high frequencies directly enhances the estimation of extreme wind speed (Larsén et al., 2012; Bastine et al., 2018), since realistic high-frequency variability is essential for calculating the spectral moments that are key to extreme value statistics. Yet, U50 accuracy relies on multiple factors beyond spectral features, including the accuracy of wind speed distribution, biases in mean wind speed, and the methods used for extreme values.

While the CPMs display biases in Figure 1, our analysis shows that their improved spectral quality eliminates the need for applying additional post-processing corrections typically required for nudged simulations, such as NEWA, and reanalysis products, like ERA5. This provides a significant advantage for wind energy applications.

We will clarify in the manuscript that our study addresses one critical aspect of U50 estimation: the representation of high-frequency wind variability, while acknowledging that a further validation of all wind energy factors is important for future research.

We will add this clarification in the introduction Line 54: *"Here, we specifically study wind speed variability at temporal scales from a few hours to ~1 hour, which is crucial for accurate U50 estimation as high-frequency variability directly affects extreme value statistics (Larsén et al., 2012), but this brief communication does not address all factors that influence extreme wind speed estimation accuracy in different modelling approaches.*

We examine the power spectra of the wind speed simulated by three CPMs at 100 …".

And we will also highlighted this issue at the end of the Discussion section in Line 203:

"While literature indicates that enhanced spectral characteristics directly improve extreme wind estimates through spectral correction methods (Bastine et al., 2018; Larsén and Ott, 2022), further validation across wind speed distributions, mean wind biases, and extreme value methodologies represents an important research priority for wind energy applications."

Moreover, thanks to the review made for this comment, we realised that Line 213 of the current text should be corrected to state that *" …NEWA employs multi-day simulations with spectral nudging (8-day runs). On the other hand… "* rather than *frequent restarts every 36 hours*, to clearly show the methodological differences between the above sets which, according to previous literature, influence the spectral characteristics of winds.

Comment #2. Line 5: I don't think ERA5 is a "mesoscale" model.

We thank the referee for pointing out that we need to make this clearer in the abstract. We recognise that ERA5 is a global reanalysis product, not a mesoscale model. Line 5 should be changed to reflect this difference. We are going to correct the text in the abstract (lines 5 and 6) with: *"…contrary to other mesoscale simulations and global reanalysis used by the wind community (NEWA and ERA5, respectively), which exhibit steepened spectral slopes…"*

We appreciate the reviewer for this clarification about the correct classification of atmospheric products.

Comment #3. Some more background could be useful in the Introduction. For example, I am not sure what the second-order spectral moment is, and how it relates to estimating extreme winds. Same for Nyquist frequency on line 20.

We appreciate the referee's suggestion. Although the manuscript already defines the second-order spectral moment $m2$ and mentions the Nyquist frequency (lines 17-21). We have now added some explanation for explicit clarity. First, we will add, in the manuscript version, line 19: *"…cause substantial underestimation of extreme winds. This moment quantifies the contribution of short-timescale fluctuations to total wind variance, and is particularly relevant for estimating wind extremes (Frehlich & Sharman, 2004; Larsén et al., 2012). Therefore, spectral correction methods are…"* to improve the conceptualisation of the second-order moment. Then, we will add the following to line 21 of the original manuscript: *"...extending to the Nyquist frequency of 10-minute data (72 day^-1). The Nyquist frequency represents the maximum resolvable frequency given the data's sampling interval; for hourly and 10-minute time series, this corresponds to 12 and 72 day^-1, respectively (Skamarock, 2004; Larsén et al., 2012)."*

Comment #4. The authors say that hourly wind data is used, but do not mention how the temporal window of these data are defined. For example, do the wind speeds represent 10-minute averages, hourly averages, or instantaneous wind speeds at the hourly model time step? I imagine that this could impact the high-frequency variations assessed in this study, especially if they differ between datasets.

We thank the referee for pointing 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 closer 10-minute observational data to the hour and the hourly-averaged 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 110:

"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 #5. Figure A1: I assume the CPMs cover a much larger area than this? It would be useful to see the points in relation to the CPM domain (in case any points are close to the boundary, for example).

We appreciate this comment. The CPM simulations do indeed cover a wider domain (the total extension of the elevation model shown in Figure A1a) than the one outlined in red in Figure A1a. This red box was conservatively defined within the full CPM domain to avoid boundary effects in the selection of evaluation points. The points themselves were generated through a spatially uniform random sampling within this reduced area to minimise spatial bias. As a result, some points appear close to the red box edges, though still well within the CPM domain and within the margin to avoid edge effects.

We also note that the plotted markers/tags are larger than the actual CPM grid cells (3 km × 3 km), which can visually exaggerate proximity to boundaries. We will improve the description of what we define as 'Study Domain' in the caption of Figure A1a: *"Study Domain: is an internal domain within the total extent of the CPMs, which has been established to avoid edge effects in the random selection of points. Note that the label of the selected locations has a visible size but exceeds the 3 km x 3 km spatial resolution."*

Comment #6. Figure 1: Could fc be indicated to show where the slopes have been corrected? And why aren't the observations shown on panel d?

Thank you for your comment. However, during the development of the research, although the *fc* is calculated, it was decided to remove it from the graphs because the intention is to preliminarily illustrate spectral correction, as a general context in model data, but not to open a debate on the cut-off frequency (*fc*), since in this discussion it is not relevant and the focus of attention on the subject matter could be lost, in addition to exceeding the scope and extent of the work.

On the other hand, the observations in panel d were not included because they were intended to be used as a reference for the three CPMs (a-c), since previous studies had already shown that ERA 5 and NEWA have an energy deficit at high frequencies, so this is not a new finding.

For clarity, we will add to line 129: *"...and fc is the frequency where the slope deviates from the theoretical one."*

Comment #7. Line 116: I was slightly confused by "de-trended" as I usually would interpret this to mean that a long-term trend was subtracted from the time series. But it sounds like the wind speed anomalies from the mean were calculated?

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 #8. Line 145: Is "almost identical" a correct assessment? The two lines appear to diverge significantly at the upper tail.

We appreciate the comment and have corrected the text from the current lines 144 and 146 to adequately describe what is presented in the results of Figure 1, explaining concisely but rigorously the causes of the divergences in the very high frequency limits (frequencies > 10 day^-1). The text will be modified as follows:

"…As can be seen in Fig. 1, the corrected and raw spectra from the CPMs show good agreement in the mesoscale frequency range (1-10 day^-1), confirming that CPMs adequately represent spectral behaviour at these frequencies. However, divergence occurs at frequencies > 10 day^-1 (periods < 2.4 hours), approaching the effective temporal resolution limit of hourly model output, where the representation of sub-daily atmospheric variability becomes increasingly uncertain. The CMCC model, however, shows slightly…"

Comment #9. Do the spectrum correction methods preserve the diurnal and semi-diurnal wind cycle? Some of these peaks appear to disappear in Figure 1 (but not all). This is not crucial to the paper, but I am curious.

We thank the reviewer for their interest in the diurnal and semi-diurnal cycles. The cycles are visible in the raw spectra, which is consistent with the expected atmospheric behaviour. On the other hand, the preservation of diurnal (f = 1 day^-1) and semi-diurnal (f = 2 day^-1) cycles in spectral correction relies, indeed, on the choice of cutoff frequency (*fc*) relative to these characteristic frequencies. When *fc* is set below these frequencies, the cycles are preserved.

When *fc* is above them, the correction may smooth these peaks, as noted by Larsén et al. (2022) (https://doi.org/10.1002/we.2771).

Comment #10. Line 159: What is meant by large-scale offsets? I assume this relates to bias in the wind speed distribution in the models, including the mean wind speed?

Thank you for asking us to clarify this term. By "large-scale offsets," we mean the clear differences in absolute spectral energy levels among the three CPM models. These differences appear across all frequencies and locations (Figures 1 and 2). As you correctly assume, they show how the models represent wind speed distributions, including mean wind speeds and overall variability. The ETH model consistently has the highest spectral energy levels, followed by CMCC and CNRM.

These differences come from unique model setups, such as different parameterisation schemes, boundary layer representations, and numerical discretisations used inside each CPM. While these energy level differences impact the absolute size of wind variability estimates, the main point is that all models remain close to the theoretical -5/3 spectral slope. This shows that the basic physical representation of energy cascade processes stays intact despite these systematic biases.

In this sense, we will modify line 159 to: *"…models, with the ETH model generally showing the highest energy, followed by CMCC and CNRM. This is related to the large-scale offsets between the different models, that is,* differences in spectral energy levels*. While these energy levels…"*

Technical corrections

1. Acronyms should be defined throughout where they first appear, such as on lines 4 and 5. There are some acronyms that are not defined (HIRHAM, REMO,CFSR, MERRA)

A table with all the acronyms will be added to the annexes section to provide clarity and cleanliness to the main text. The table is as follows:

Table A1. *Acronyms used in the paper and their meanings*

Acronym	***Meaning***
CCLM	*Consortium for Small-scale Modelling – Climate Limited-area Modelling.*
CFSR	*Climate Forecast System Reanalysis.*
CMCC	*Euro-Mediterranean Center on Climate Change (Fondazione CMCC).*
CNRM	*Centre National de Recherches Météorologiques (Météo-France & CNRS).*

CNRM-ALADIN63	*CNRM configuration of the ALADIN limited-area model, version 63 (ALADIN = Aire Limitée Adaptation dynamique Développement InterNational).*
CNRM-AROME	*CNRM configuration of AROME (Applications of Research to Operations at Mesoscale).*
CORDEX-FPS	*Coordinated Regional Climate Downscaling Experiment – Flagship Pilot Studies.*
COSMO-crCLIM	*Climate (convection-resolving) version of COSMO for climate simulations.*
CPM/CPMs	*Convection-Permitting Model(s).*
ERA5	*ECMWF Reanalysis v5.*
ERA-Interim	*ECMWF Interim Reanalysis.*
ESGF	*Earth System Grid Federation.*
ETH	*ETH Zürich — Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology).*
FFT	*Fast Fourier Transform.*
HIRHAM	*Regional climate model combining HIRLAM (High-Resolution Limited Area Model) and ECHAM (ECMWF/Max-Planck model).*
IMK-TRO	*Institute of Meteorology and Climate Research – Troposphere (KIT).*
JRA-55	*Japanese 55-year Reanalysis (JMA).*
KIT	*Karlsruhe Institute of Technology.*

MERRA	*Modern-Era Retrospective Analysis for Research and Applications.*
NEWA	*New European Wind Atlas.*
NOAA GFS	*National Oceanic and Atmospheric Administration – Global Forecast System (run by NCEP/NWS).*
NWP	*Numerical Weather Prediction.*
PSD	*Power spectral density.*
RCM	*Regional Climate Model.*
REMO	*REgional MOdel.*
S(f)	*Power spectral density as a function of frequency f.*
SLHD	*Semi-Lagrangian Horizontal Diffusion.*
U50	*50-year return-period wind speed.*
WRF	*Weather Research and Forecasting Model.*

2. Line 20: Is 'climatological average' the correct term here?

Thank you for spotting this. We will change Line 20 this to *"…tail with the theoretically expected spectral slope of −5/3…"* to reflect its physical basis in a better way.

3. Line 91: Should be "3 km grid spacing"

Thank you for this comment. We will complement Line 91 with: *"…domain is also 3 km grid spacing, the NEWA…"*