Dear editor,

We thank the reviewer for their comments on the manuscript. The reviewer raises a number of concerns related to the resolution of our simulations. We will address the specific comments below, but we first would like to make a few more general points.

While there may be a justified discussion about the resolution of the model, this is beside the main point of the paper. We could have presented exactly the same method for long-term correction based on 10 m LES runs, a mesoscale simulation or even another model, as long as a self-consistent dataset of 10 years is available. The contribution of our paper is not to present or validate our LES model. It is the statistical correction method. Because LES is gaining popularity in WRA, however, we think that demonstrating the statistical correction method using LES output increases the relevance of the method. Then, being able to present two 10-year simulations driven by real-weather data outweighs the drawbacks of simulating on a relatively coarse resolution.

Secondly, since the resolution was also a concern of the first community comment, we have provided a document with supplementary analyses (at the bottom of this document), which will also serve as supplementary material to the manuscript. We believe this complement addresses a lot of the concerns raised by the reviewer.

Thirdly, there seems to be some confusion on the origin of the ASPIRE model, and its relation to GRASP (GPU-Resident Atmospheric Simulation Platform). ASPIRE is the name for our entire modelling suite; which encompasses the LES core, called GRASP, as well as various other components (e.g. the turbine calculations, the land-surface calculations). Previously, work using our model often referred to it as GRASP. Here, we choose to refer to the entire modelling suite. We indeed understand the confusion, and will clarify the manuscript.

The reviewer's comments are in italics, our responses in normal font.

<u>General remarks</u>

While the numerical study presented in the manuscript is unique because it uses a long-term (10-year) LES, the authors did not present a convincing motivation and justification for their numerical study that uses coarse LESs to estimate offshore wind speed and simulate wind farm power production by representing operating wind turbines with an actuator disk model. It is not clear that a coarse LES can deliver any benefit in estimating hub height or rotor equivalent wind speed compared to significantly less costly mesoscale simulations. The LES at resolution of 120 m does not improve wind speed prediction compared to mesoscale simulations (> 1 km) or even ERA5 reanalysis as shown in the manuscript. Coarse LES does not resolve turbulent eddies in the inertial range considering: offshore conditions, effective resolution, and the need for inflow turbulence development not described in the manuscript.

A motivation and justification for the use of coarse LES for wind energy purposes is that it is a computationally feasible approach for estimating AEP or the wind climate in a certain location. Current approaches to estimating wind climate or AEP for offshore wind farms include engineering wake/flow models, mesoscale models, RANS and LES. Each of the methods has its advantages and limitations. While many LES studies presented in the scientific literature use a much higher resolution, they are then usually limited to a small number of cases. To estimate AEP, however, either a large set of flow cases or a large set of days needs to be modeled, to include all prevailing wind conditions that the wind farm will encounter. So coarse resolution LES for wind resource AEP assessment provides a viable alternative and is now used routinely in the wind energy sector. We have added a number of extra references to make this point clearer. Specifically, the references to work with ASPIRE, including validation, for wind energy now are: the work by Williams et al. (2024), Oldbaum (2019), Baas et al. (2023) (wind farm modelling); Schepers et al. (2021), Taschner et al. (2023) (turbine physics and loads); Gilbert et al. (2020), Alonzo et al. (2022) (wind forecasting); and Kantharaju et al. (2023), Storey and Rauffus (2024) (wind climate modelling).

The study presents a Bayesian downscaling approach that combines LES and reanalysis output. While this approach is interesting and the use of LES can be considered as something that has not been explored before, similar methodologies have been used extensively for regional climate downscaling (e.g., Holthuijzen et al., 2021, J. App. Meteorolo. Climat. and references therein). The authors did not provide any references to research that preceded their study, so based on the way the approach is presented, it would seem that this approach is completely novel. The novel part is exploring three scenarios for long-term correction, and this is possibly the most relevant contribution.

We thank the reviewer for pointing this out and for providing a reference with similar correction methods. At the same time, we feel that our method is different in a number of ways from e.g. the methods described in Holthuijzen. Namely, rather than refining a coarser simulation (i.e. downscaling), our method estimates the long-term probability distribution of a variable obtained from a short-term fine-scale simulation. Nevertheless, we do agree that it is useful to position our method compared to other methods in the introduction, so we have added the following to the manuscript:

"Correcting or downscaling weather- or climate model data to better match observed reality is a widespread practice in environmental science. In this field, two main types can be distinguished (e.g. Ekström et al., 2015; Holthuijzen et al., 2021): dynamical downscaling, in which a more accurate model is used to refine results from an often coarser model; and statistical downscaling, in which statistical relationships between the modelled and observed variable are used to correct the modelled variable. These methods generally produce corrected timeseries, but can include spatial dimensions as well (Holthuijzen et al., 2021). The current study uses aspects of both the dynamical and statistical type. Firstly, the data to be corrected itself come from an LES downscaling of ERA5. Secondly, and this is the core message of the study, the probability distributions are then corrected for the difference in weather conditions between the simulation period and the long-term climate. This is done by estimating the conditional probability density between the variable of interest and ERA5 wind from the short simulation, and then using this relationship to modify the probability density of the variable of interest to represent the long term. In this sense, the long-term correction method is most related to statistical downscaling, but instead of correcting for a model deficiency, the long-term correction method corrects for non-representative simulation periods."

The study uses an actuator disk model that is not appropriate for the coarse LES resolution used in the study, i.e. 120 m in horizontal and 30 m in vertical taking, with the effective resolution that is even coarser. For example, Calaf et al. (2010, also Meyers and Meneveau, 2010, cited in the paper) resolved the rotor with 10 vertical grid cells. Baas et al. (2023) conducted a sensitivity study with grid cell size of 120 m and 60 m and similar vertical grid as present study and argued that the 120 m grid cell size is adequate, however, their estimates of aerodynamic losses were about 20% larger with coarser resolution – this is significant. In addition, the actuator disk model was implemented in the ASPIRE LES model, a version of a commercial, GPU-based model, which is not publicly available. It is not clear how ASPIRE differs from other versions of the GPU model (e.g., GRASP used in Baas et al., 2023, study) and if ASPIRE was validated in any way.

The use of an actuator disk model at this resolution is indeed a relevant topic of discussion, and to provide more context, the supplementary material shows how wind farm dynamics depend on resolution. Indeed, like in Baas et al. (2023), we find that a coarser resolution results in higher losses. This is mainly due to opposing responses of power production to resolution in the free-stream and realistic runs. However, for the purposes of this study, the response of the actuator disc model to resolution is not important: presenting and validating the long-term correction methods is the main message. In order to validate them with 10 years of LES data, therefore, a trade-off between accuracy and computational cost had to be made. Given the computational resources, one has to balance resolution, horizontal domain size, and vertical domain size. The latter two are important for representing global blockage and gravity waves (respectively). Making this trade-off resulted in the choice of a 120 m resolution, horizontal domain size of 10 km, and vertical domain size of 3 km.

As for the last point about validation of ASPIRE, please see the references in our reply to the first general remark.

Although, to achieve greater realism and therefore relevance, the numerical study includes coupling between coarse reanalysis and LES simulated is a hypothetical wind farm which means that the results of the study cannot be validated. The use of a hypothetical wind farm is of a very limited value considering that it is now possible to obtain wind power production data for existing wind farms in the North Sea (see, e.g., https://rave-offshore.de/en/data.html).

We agree that the validation and quantification of uncertainty of AEP calculations based on LES with actuator disk is important and deserves more research. However, we feel that validation would be widening the scope of the paper too much. Furthermore, applying the long-term correction methods to actual wind power production data could be a relevant route for further research. Here however, to present and validate the methods, we chose to use LES data, because it fits well with current WRA practices. In WRA, studying hypothetical wind farms is a very wide-spread practice.

Specific remarks

Abstract – The abstract is confusing and poorly written, e.g., no motivation for the use of LES is provided.

We will rephrase the abstract to provide more motivation for the use of LES.

Line 28 – It is stated that "'real- weather' LES has been demonstrated to be viable... to explicitly model the interactions between wind farms and the atmosphere (Baas et al., 2023)" however the cited study by Bass et al. (2023) does not include a validation that would demonstrate viability.

and

Line 68 – ASPIRE model is used in the study and a reference is made to the Dutch Atmospheric Large Eddy Simulation (DALES) model and the GPU version, however, there are no previous references to the ASPIRE model and its validation.

We have clarified that we have adopted ASPIRE as the new name to refer to our entire modelling suite, and have added a number of extra references about its origins, use, and validation (see the reply to the first general comment).

Line 119 – It is stated that "In the practice of LES modelling, it is often found that the wind speed displays a mean bias of O(0.1 m/s)..." but no reference is provided for this statement.

This statement is indeed not well-supported, it stems from our own practical experience of the model. We have added two references that support it (Storey and Rauffus (2024) and Kantharaju et al. (2023)).

Line 121 – The sentence: "Such a free stream run has no turbines included, or it has turbines that exert no force on the flow, and therefore leave it undisturbed." can be removed since is nonsensical. Turbines that exert no force on the flow are not turbines, since even turbines at rest exert force on the flow.

We respectfully disagree that this is a nonsensical statement. It is common in wake studies to calculate what is sometimes called 'gross power', by using the undisturbed wind speeds as if no turbines were present. Of course this is a theoretical concept, but nonetheless useful and widely accepted.

Line 131 - It is stated that "... because of explicit representation of all fluid dynamical... effects..." First, it is not true that all fluid dynamical effects are represented since the rotation of the turbine is not accounted for, and second, at the coarse resolution used in the study it cannot be said that the fluid dynamical effects are represented well.

We agree that not all fluid dynamics is explicitly represented, and will change this in the text. However, we do believe that the key processes that govern real-weather boundary layer-flow and wind park power production are represented adequately. Again, we refer to the supplementary material for a more thorough discussion of this.

Line 160 – How is ASPIRE different from or related to GRASP. Has it been validated?

See our previous remarks about ASPIRE and GRASP. Concerning validation, we have added a number of studies (see reply to the first general comment).

Line 164 – Given the resolution, it is not clear how turbulence develops on the inner LES domain.

More information on turbulence generation is indeed a valid request, since it is an essential part of real-weather LES modelling. Turbulence is generated by adding fluctuations to the inflow conditions from the mesoscale simulations. These fluctuations are themselves produced by a smaller periodic precursor LES that is driven by the mesocale field at the LES boundaries. Hence, these added fluctuations are consistent with atmospheric conditions (Storey and Rauffus, 2024). We have added this information to the manuscript.

Line 165 – It is stated that "...the core LES domain is nested in a coarser mesoscale-type simulation with a resolution of 1.5 km,..." and "This coarser simulation has the same model formulation as the LES...," however, it is not clear what is the exact model formulation. It is only mentioned that the turbulence parameterization is different, but not how is it different, what other parameterizations were used: radiative transfer, microphysics, land surface, etc. For the study to be reproducible this information should be provided.

We agree that we have been unclear about the other parametrizations, and have adapted this in the manuscript.

Line 185 – If turbines do not exert any force they are not included in the simulation, so there is no need to mention turbine.

See our earlier remark about the use of free-stream turbines.

Line 221 (also Figure 2) – It is not clear what is the benefit of LES offshore when it results in larger errors and turbulence is not resolved with 120 m grid cell size.

See our introductory remark.

Line 230 – As shown by Baas et al. (2023) a coarse LES result in overestimation of aerodynamic losses.

This is indeed a known effect, which is also demonstrated in the supplementary material. However, it does not affect the core message of the paper: presenting and validating the long-term correction methods with a 10-year run.

References

Alonzo, B., Cassas, M., Raynaud, L., Verzijlbergh, R., Houf, D., Baas, P., and Dsouza, B.: Smart4RES: Report on improved NWP with higher spatial and temporal resolution, https://www.smart4res.eu/wp-content/uploads/2023/01/Smart4RES_Deliverable_D2.2.pdf (last accessed 9-8-2024), 2022.

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

Ekström, M., Grose, M. R., and Whetton, P. H.: An appraisal of downscaling methods used in climate change research, Wiley Interdisciplinary Reviews: Climate Change, 6, 301–319, https://doi.org/10.1002/wcc.339, 2015.

Gilbert, C., Messner, J. W., Pinson, P., Trombe, P. J., Verzijlbergh, R., van Dorp, P., and Jonker, H.: Statistical post-processing of turbulence-resolving weather forecasts for offshore wind power forecasting, Wind Energy, 23, 884–897, https://doi.org/10.1002/we.2456, 2020.

Holthuijzen, M. F., Beckage, B., Clemins, P. J., Higdon, D., and Winter, J. M.: Constructing High-Resolution, Bias-Corrected Climate Products: A Comparison of Methods, Journal of Applied Meteorology and Climate, 60, 455–475, https://doi.org/10.1175/JAMC-D-20, 2021.

Kantharaju, J., Storey, R., Julian, A., Delaunay, F., and Michaud, D.: Wind resource modelling of entire sites using Large Eddy Simulation, in: Journal of Physics: Conference Series, vol. 2507, Institute of Physics, ISSN 17426596, https://doi.org/10.1088/1742-6596/2507/1/012015, 2023.

Oldbaum: Wind Resource Assessment Hollandse Kust (noord) Wind Farm Zone, https://offshorewind.rvo.nl/files/view/9717fb65-79ab-4966-92e2-a73c856c18c9/hkn_20191022_oldbaum_wra-oct19-f.pdf (last accessed 9-8-2024), 2019.

Schepers, G., Dorp, P. V., Verzijlbergh, R., Baas, P., and Jonker, H.: Aeroelastic loads on a 10 MW turbine exposed to extreme events selected from a year-long large-eddy simulation over the North Sea, Wind Energy Science, 6, 983–996, https://doi.org/10.5194/wes-6-983-2021, 2021.

Storey, R. and Rauffus, R.: Mesoscale-coupled Large Eddy Simulation for Wind Resource Assessment, in: Journal of Physics: Conference Series, vol. 2767, Institute of Physics, ISSN 17426596, https://doi.org/10.1088/1742-6596/2767/5/052040, 2024.

Taschner, E., Folkersma, M., Martínez-Tossas, L. A., Verzijlbergh, R., and van Wingerden, J. W.: A new coupling of a GPU-resident large-eddy simulation code with a multiphysics wind turbine simulation tool, in: Wind Energy, John Wiley and Sons Ltd, ISSN 10991824, https://doi.org/10.1002/we.2844, 2023.

Williams, S., Dubreuil-B, C., and Seim, K. S.: Multi-fidelity wake model validation at the Arkona offshore wind farm, conference session at Wind Europe Technology Workshop, https://windeurope.org/tech2024/programme/proceedings/sessions/the-impact-of-resource-on-performance/ (last accessed 9-6-2024), 2024.

Supplementary Material: A Resolution Study on Large Eddy Simulation of the Horns Rev Wind Farm

August 2024

1 Introduction

In this supplementary study, we present additional LES runs of the Horns Rev offshore wind farm, at varying resolutions. The goal is show the effect of LES resolution on wind farm power production, and profiles of wind, turbulence kinetic intensity, and the fraction of subgrid-scale and resolved turbulence kinetic energy. By performing both realistic runs (with active turbines) and free-stream runs (without active turbines), we can investigate the representation of wind-farm dynamics and boundary layer meteorology separately.

2 Methods

Like in the main text, the ASPIRE model is employed; with an LES with open boundaries nested in a coarser mesoscale-type simulation that does not resolve turbulence. The domains are centered at the Horns Rev wind farm (55.49°N, 7.48°E), and the run period consists of 10 days[1]. These 10 days were chosen by applying a k-means algorithm on the daily mean 100 m horizontal components of the ERA5 wind speed at that location, during 2015—2016.

The domain size of the coarser simulation is 256 km by 256 km, with a horizontal resolution of 2 km, and the 64 vertical levels start with a spacing of 40 m and stretch exponentially to the domain top at 8 km. Figure 2 shows the simulation setup. The LES domains vary in resolution and number of grid points as shown in Table 2, but all have a horizontal size of 15360 m by 15360 m. This ensures that all LES runs have same lateral inflow conditions. Above 200 m, the LES runs use an exponentially stretched vertical grid, which varies for the different resolutions. For each resolution, both a realistic (active turbines) and free-stream run (turbines leave the flow undisturbed) are performed.

The simulated wind farm is the well-studied Horns Rev offshore wind farm, which has 80 turbines of the V80-2.0MW type, and a total rated power of 160 MW. The details of the wind farm modelling are discussed in the main text and in Baas et al. (2023).

3 Results

The results from free-stream runs, providing insight into the effects of LES resolution on lower boundary-layer dynamics, are discussed in subsection 3.1. Then, subsection 3.2 presents the effects of LES resolution on wind farm dynamics. Here, results from both the free-stream and realistic runs are used to quantify the aerodynamic effects of the wind farm.

3.1 Effects of resolution on boundary layer dynamics

For all different resolutions, Fig. 3.1 presents vertical profiles of horizontal wind (M), its 10-minute standard deviation (σ_M), turbulence intensity ($\mathrm{TI} = \sigma_M/M$), turbulence kinetic energy (tke) as resolved by the model, and its subgrid-scale (sgs) value, and finally the ratio of resolved to subgrid-scale tke.

[1] 2015-01-13, 2015-02-14, 2015-06-11, 2015-08-31, 2015-09-01, 2015-10-29, 2016-02-21, 2016-07-26, 2016-10-18, 2016-12-21.

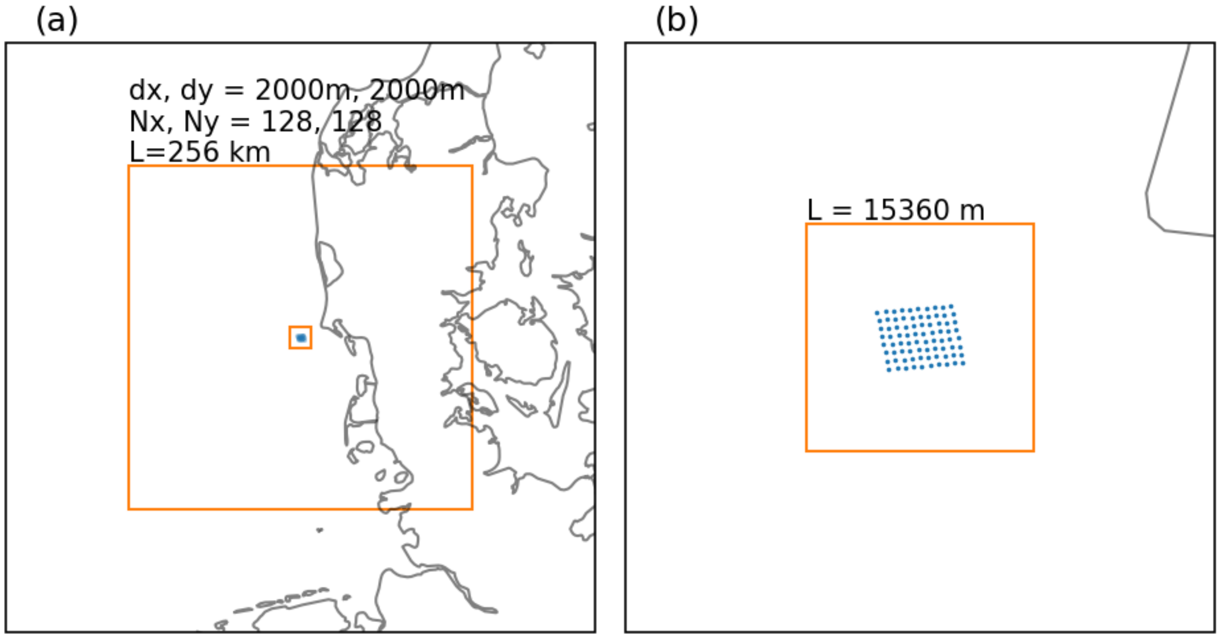

Figure 1: The simulation setup. a) the LES (small orange square) is nested in a coarser simulation (large orange square) on the North Sea. b) The LES domain with the wind farm layout (dots).

All these quantities show their expected mean vertical profile in the (lower) boundary layer. In general, there are small differences between the resolution, which decrease with height. For mean horizontal wind, the differences between the resolutions become negligible above approximately 100 m. Below that, they are of the order of 0.1 m s^{-1}. In the rotor layer, σ_M varies between approximately 0.5 m s^{-1} and 0.7 m s^{-1}. Combined with a wind speed between 9 m s^{-1} and 10 m s^{-1}, this gives a mean TI of about 0.04 to 0.07. For both these quantities, the variation with height is larger than the variation between the resolutions.

The total tke in the rotor layer varies between approximately 0.35 m^2 s^{-2} and 0.55 m^2 s^{-2}. Of this total tke, more than 92% is resolved for all resolutions.

The presented turbulence quantities show a resolution-dependence that might be counter-intuitive. Namely, they often increase with decreasing resolution. This is a result of the choice of subgrid turbulence parameterization used in this study. The ASPIRE model in its current set-up uses an anisotropic minimum dissipation subgrid turbulence parametrization. In this parametrization, the subgrid scheme becomes less diffusive (i.e.: there will be a more turbulent flow) when the aspect ratio of the grid boxes is higher. The simulations with a coarser resolution have a higher aspect ratio, and therefore a less active subgrid scheme, and hence a higher resolved tke.

These profiles presented until now are averaged over the whole simulation period, which might obscure a mean diurnal cycle. However, Fig. 3.1 shows that, as is common over sea, there is only a weak mean diurnal cycle in wind and turbulence quantities. The peak in hourly mean tke at 21:00 can be traced back to one strong wind ramp event on August 31st 2015, related to the passage of the core of a low pressure system very close to the wind farm. This wind ramp caused a roughly 4 m s^{-1} spike in wind speed (at hub height) over the course of a few minutes. Since this variability on the sub-10-minute scale, it causes an strong increase in the 10-minute tke.

3.2 Effects of resolution on wind farm dynamics

The inclusion of wind turbines in the simulations allows us to study the effect of LES resolution on wind farm dynamics, and in particular, power production. Also, by comparing this realistic run to the free stream

Table 1: Domain setup of the LES runs. dx and dy are the horizontal grid spacing, dz the vertical grid spacing below 200 m, Lz is the domain height, and Nx and Ny are the number of grid points in the horizontal direction. Lz and Nx and Ny are chosen such that the horizontal domain size is 15360 m for all runs.

simulation id	realistic / free stream	dx, dy (m)	dz (m) (surface)	Lz (m)	Nx, Ny
000	free stream	120	30	2515	128
001	free stream	80	20	2547	192
002	free stream	40	20	2547	384
003	free stream	20	20	2547	768
010	realistic	120	30	2515	128
011	realistic	80	20	2547	192
012	realistic	40	20	2547	384
013	realistic	20	20	2547	768

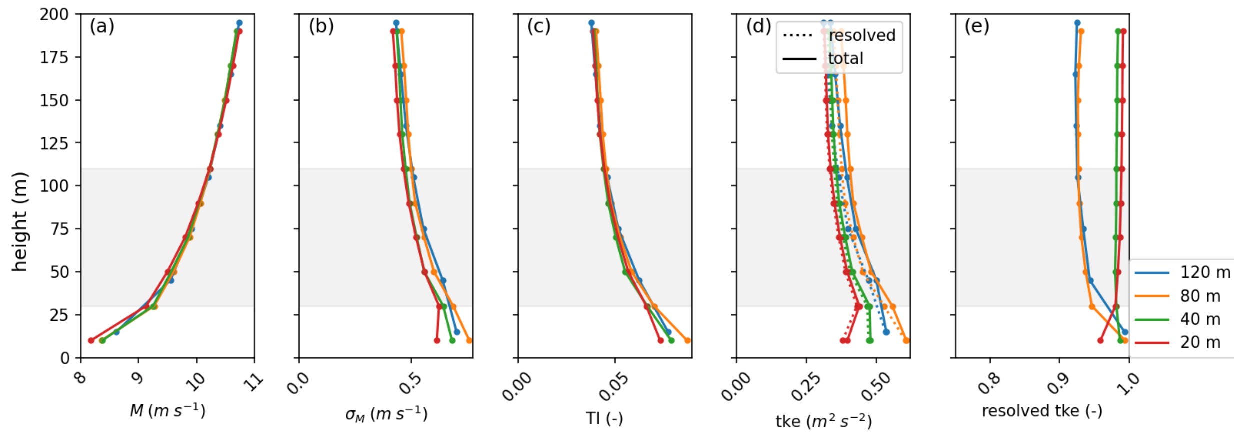

Figure 2: Time-mean vertical profiles of horizontal wind (a), its standard deviation (b), TI (c), resolved and total tke (d), and the ratio of resolved to subgrid-scale tke (e), for the different resolutions. The dots indicate model levels, and the rotor layer is shaded.

run, aerodynamic losses can be quantified.

Figure 4 shows probability density functions (PDFs) of wind at hub height in the center of the domain, and total power production, for all resolutions, and for the realistic and free stream run. The wind PDFs resemble a Weibull-shape, but due to the relatively short simulation period of 10 days, and the day-selection technique, it is not completely smooth. The power production PDFs peak at rated power. The PDFs of both wind and power production are similar for the different resolutions, which is reflected in the mean wind and power production values, shown in Table 3.2. The mean values in both total power production and wind differ by a few percent between the different resolutions. For the realistic runs, power production decreases with coarser resolution; whereas for the free-stream runs, it increases with coarser resolution. These opposing trends cause the aerodynamic losses to differ between the resolutions (ranging between 7 % and 11 %). A similar effect was reported in Baas et al. (2023).

However, besides this difference in mean value between the different resolutions, the general shapes of the wind- and power PDFs agree. This indicates that the basic physical processes that govern the lower-boundary layer and wind farm dynamics are well-represented at all presented resolutions.

To illustrate the effect of realistic inclusion of wind turbines in the simulation on the wind field, Fig. 5 shows maps of the mean wind, filtered to wind directions between 225°— 255°. Also, the velocity deficit with respect to the free-stream runs are shown. In general, there is a pronounced effect of the park on the

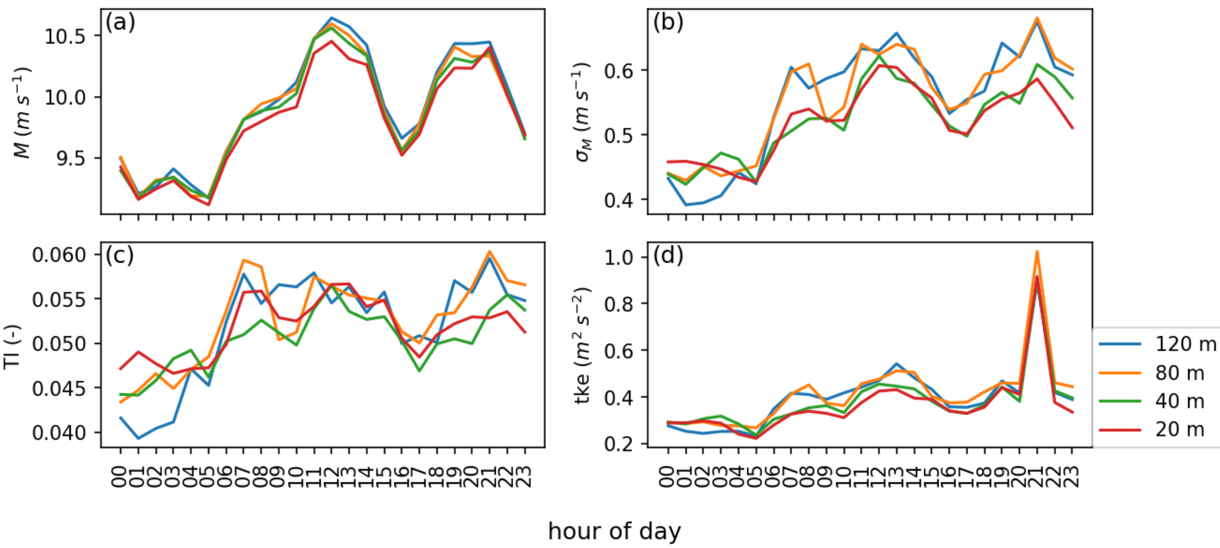

Figure 3: Mean diurnal cycles of (a) wind, (b) its standard deviation, (c) TI, and (d) resolved tke. The data are shown at the model levels closest to hub height, which is 75 m for the 120 m resolution run, and 70 m for the others.

Table 2: Mean total realistic and free stream power, their fraction, and mean realistic and free stream wind (at hub height, in the center of the domain), and their fraction.

resolution (m)	mean realistic power (MW)	mean free-stream power (MW)	realistic power / free stream power (-)	mean realistic wind (m s^{-1})	mean free-stream wind (m s^{-1})	realistic wind / free stream wind (-)
120	84.33	95.08	0.89	8.74	9.85	0.89
80	84.63	94.33	0.90	8.72	9.88	0.88
40	85.42	93.55	0.91	8.65	9.85	0.88
20	86.46	93.04	0.93	8.53	9.80	0.87

mean flow inside and downstream of the park. For the finest resolution, individual turbine wakes can be discerned, whereas for the coarser resolution, these individual wakes are less clear. Nevertheless, the general shape and magnitude of the wind park wake is captured by all resolutions.

4 Conclusion

In this supplementary study, the effect of LES resolution on lower boundary layer dynamics, and on the wind farm dynamics was shown. The resolution was varied between 20 m, enough to resolve individual turbines, to 120 m, the resolution used in the main text of this study.

Mean profiles of wind- and turbulence variables did not vary considerably between resolutions, and the differences between resolutions were smaller than the typical variations over the rotor layer. Also, differences between resolutions are likely smaller than the typical ASPIRE bias (for mean wind, this bias in the order of 0.1 m s^{-1}). The probability distribution of both wind and total power production were very similar between the resolutions, and the mean values of those quantities differed a few percent between resolution. The realistic and and free-stream runs show opposite trends with resolution, causing the aerodynamic losses to differ more between the different resolutions. This will remain an active area of research for the ASPIRE model.

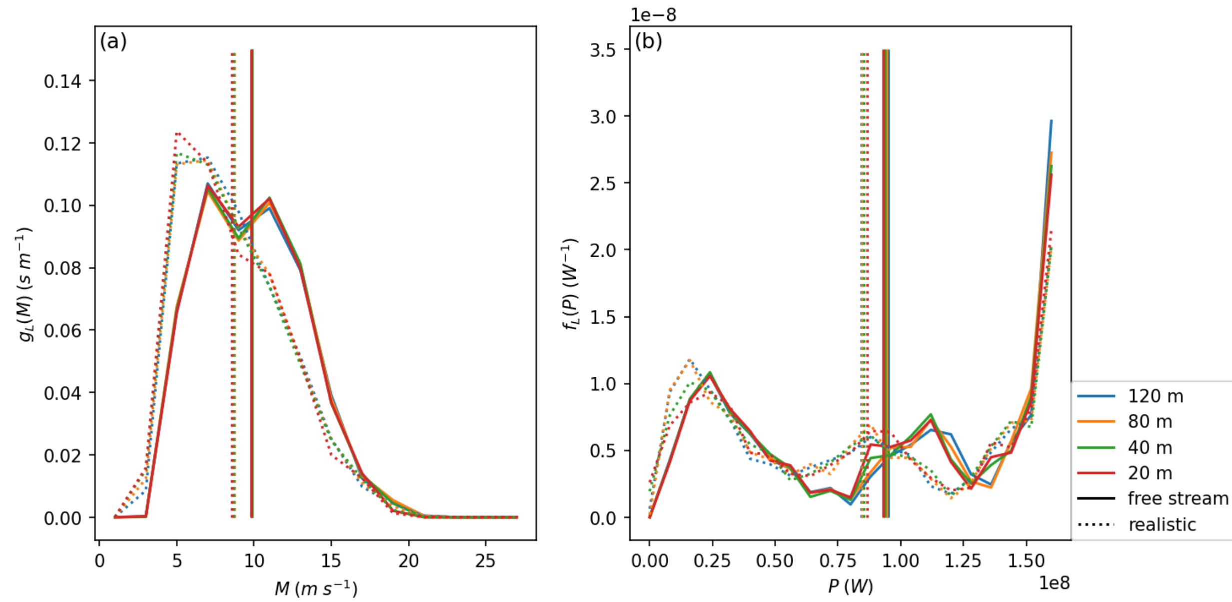

Figure 4: PDFs of (a) wind at hub height in the center of the domain and (b) total power production. Vertical lines denote the mean values.

Finally, maps of mean wind speed show the wake effect. Although for individual turbines, the wakes are not resolved at the coarsest resolutions, the bulk effect of the wind farm on the flow field is very similar between resolutions.

To conclude, this study showed that the essential physics of boundary layer meteorology and wind farm dynamics can be sufficiently captured at resolutions that do not resolve individual turbine wakes.

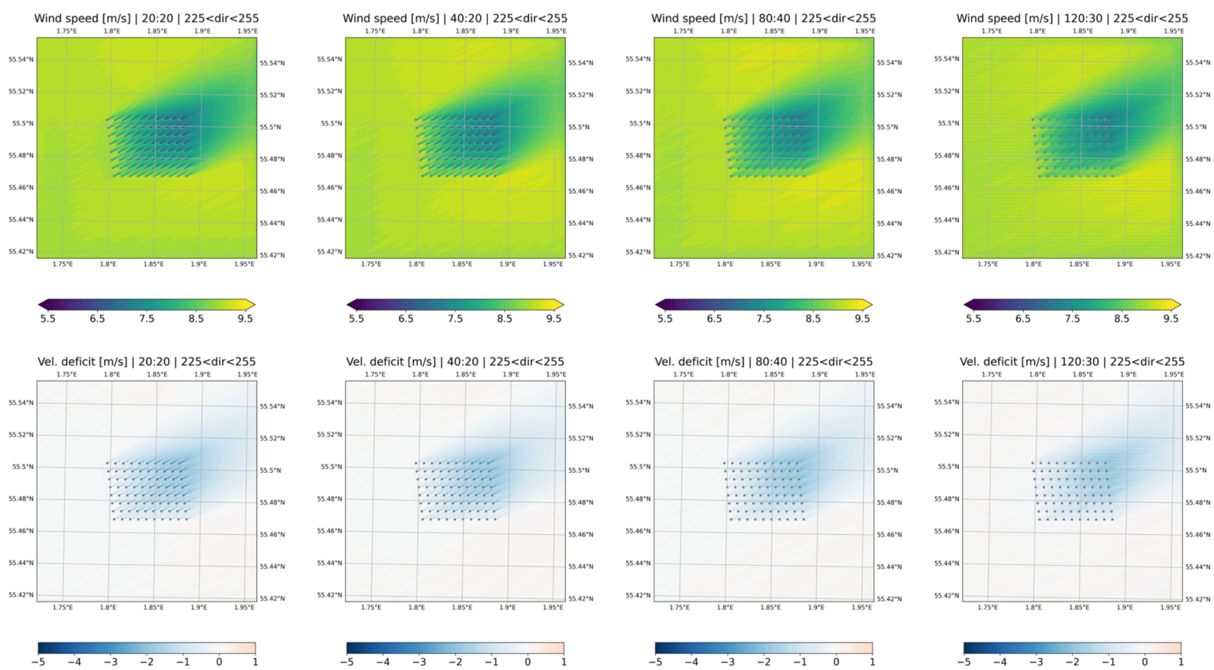

Figure 5: Visualisation of wind park wakes at hub height for the different resolutions. Top row: maps of mean wind of the realistic runs, when the wind direction is in the sector 225°— 255°. Bottom row: velocity difference between the realistic and free-stream runs.