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Supplement of

Estimating long-term annual energy production from shorter-time-series data: methods and verification with a 10-year large-eddy simulation of a large offshore wind farm

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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 S1 shows the simulation setup. The LES domains vary in resolution and number of grid points as shown in Table S1, 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. S2 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.

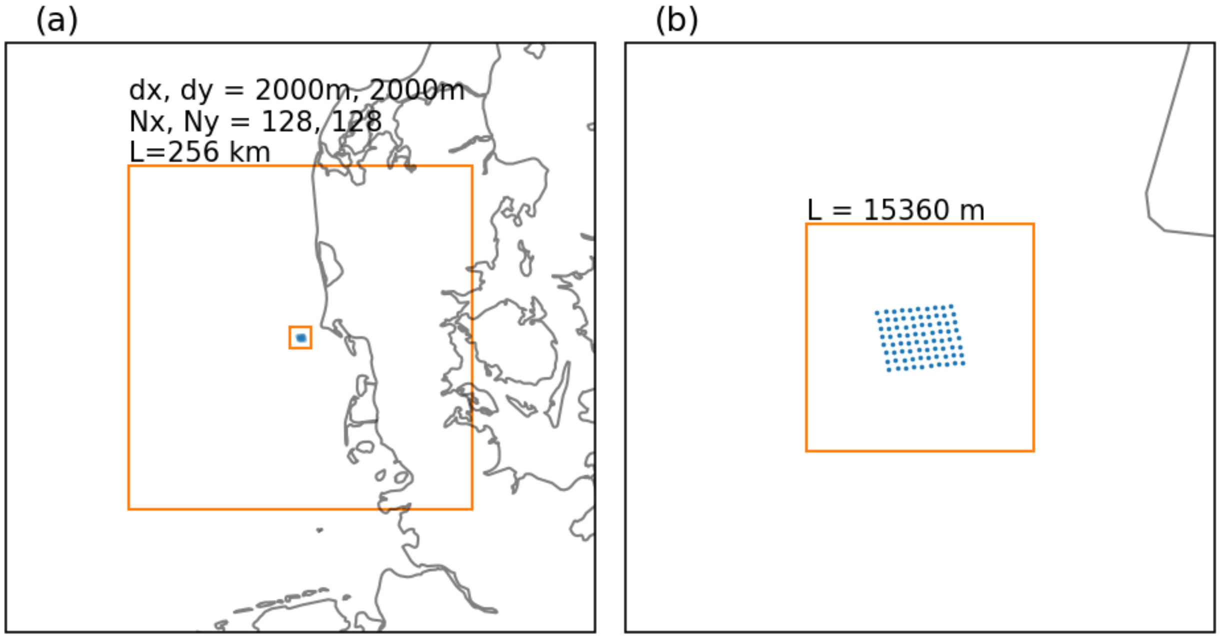

Fig. S1: The simulation setup. a) the LES (small orange square) is nested in a coarser simulation (large orange square) on the North Sea. b) The LES domain with the wind farm layout (dots).

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 S1: 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

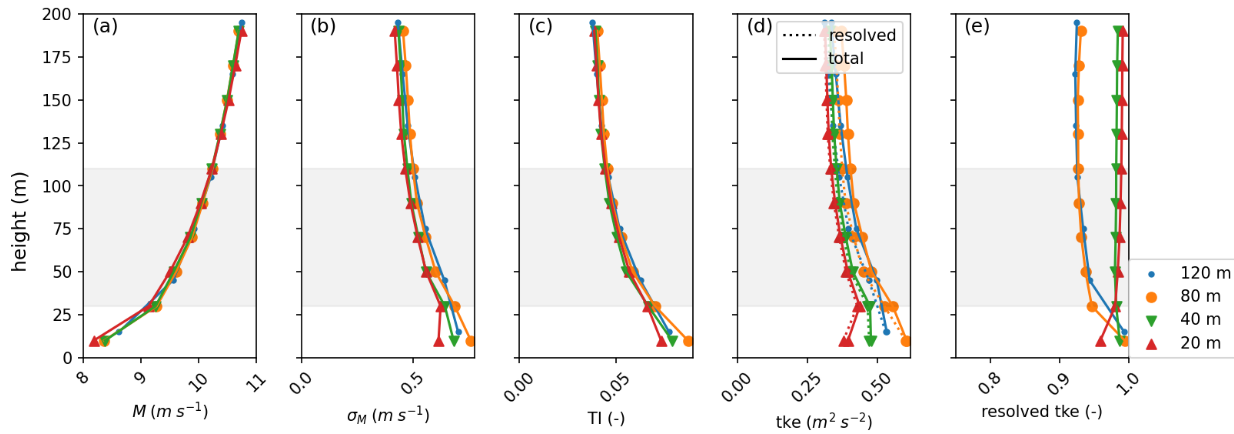

Fig. S2: Time-mean vertical profiles of horizontal wind (a), its standard deviation (b), TI (c), resolved and total tke (d), and the ratio of resolved to subgrid-scale tke (e), for the different resolutions. The dots indicate model levels, and the rotor layer is shaded.

run, aerodynamic losses can be quantified.

Figure S4 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 S2. 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. S5 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

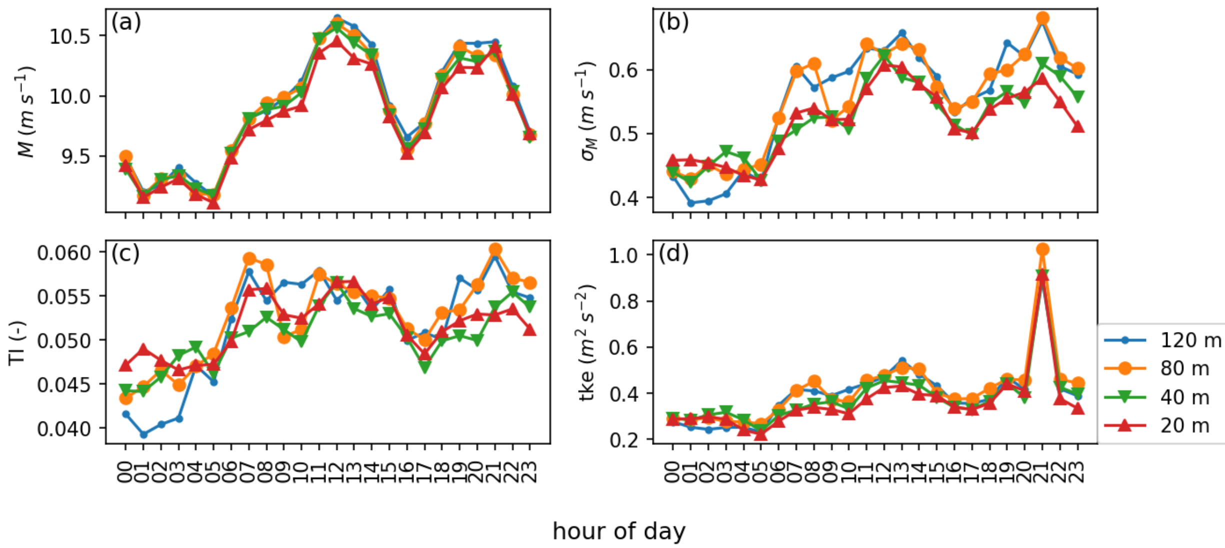

Fig. S3: Mean diurnal cycles of (a) wind, (b) its standard deviation, (c) TI, and (d) resolved tke. The data are shown at the model levels closest to hub height, which is 75 m for the 120 m resolution run, and 70 m for the others.

Table S2: 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.

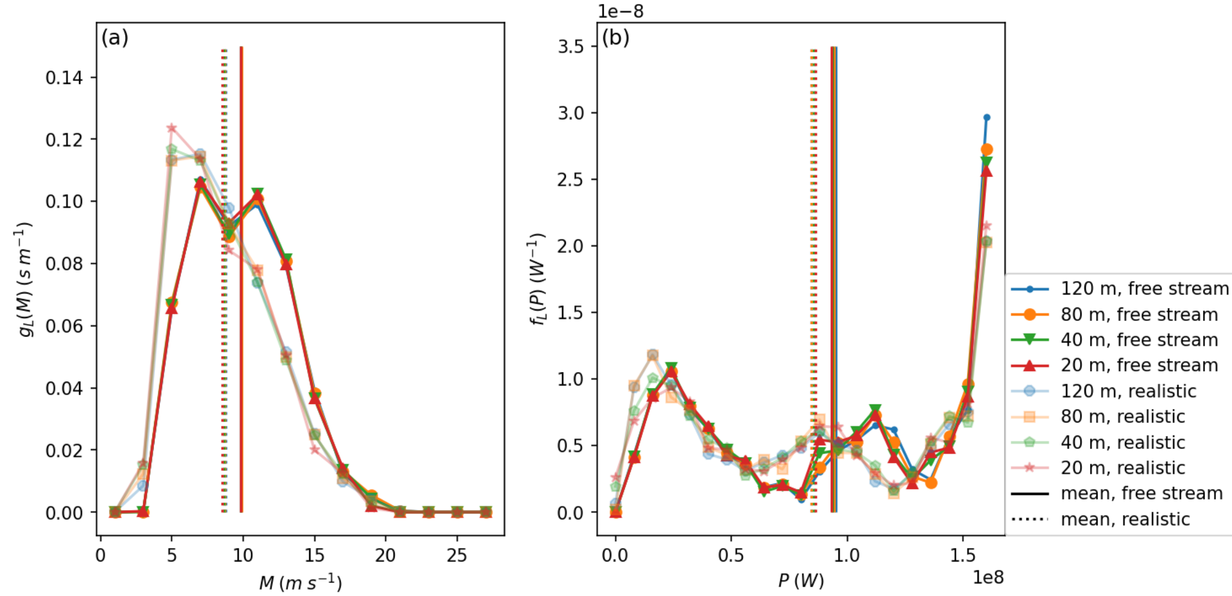

Fig. S4: PDFs of (a) wind at hub height in the center of the domain and (b) total power production. Vertical lines denote the mean values.

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.

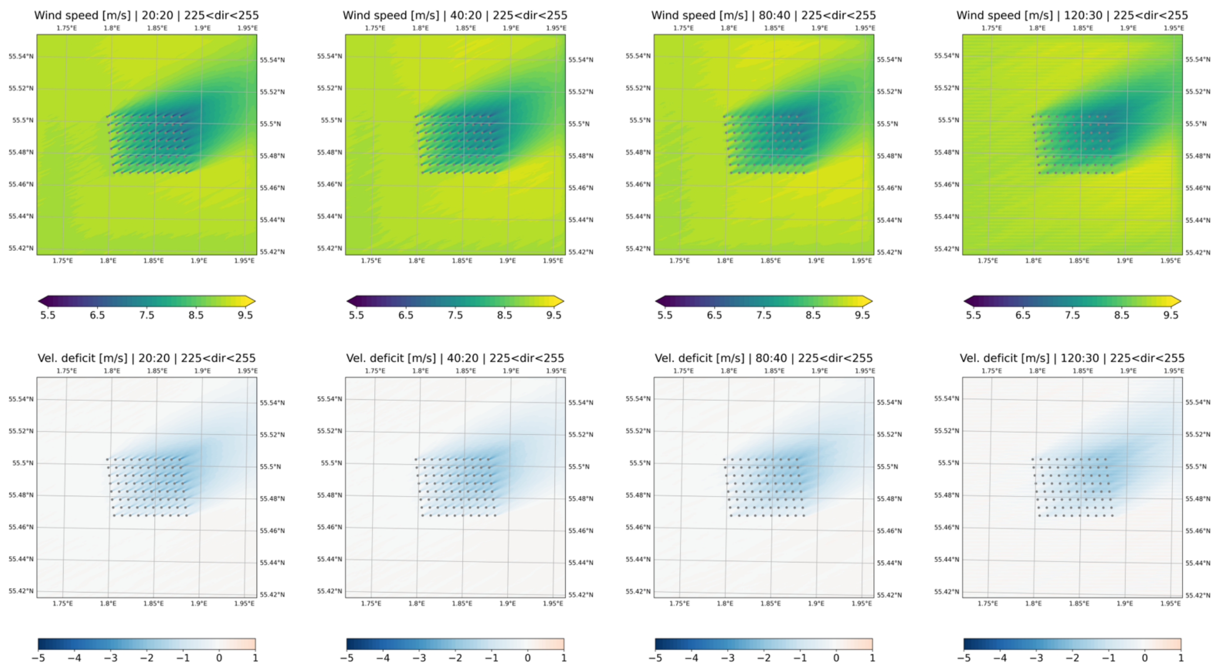

Fig. S5: Visualisation of wind park wakes at hub height for the different resolutions. Top row: maps of mean wind of the realistic runs, when the wind direction is in the sector 225°— 255°. Bottom row: velocity difference between the realistic and free-stream runs.