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Comparison of large-eddy simulations of wakes with wind farm wake parametrizations using the Weather Research and Forecasting model

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Abstract. Wind farm parametrizations are nowadays commonly used to predict the output of wind farms in real-time numerical weather prediction mesoscale models. However, their accuracy both to reproduce the wind speed and turbulent kinetic energy fields behind turbines is a matter of debate. Here, and to the authors knowledge for the first time for a single turbine, the in-built wind farm parametrization of the Weather Research and Forecasting model is evaluated using detailed large-eddy simulations of the wake performed with a generalized actuator disk model that was implemented in the same modeling system. Thus, a fairer evaluation is achieved compared to previous works, as we try to set the simulations as similar as possible within the same modeling framework. We find that both types of simulations can be used to provide similar inflow conditions to the turbine. Most importantly, by comparing the detailed-wake results, within the area where the turbine is placed, with the mesoscale results at the analogous position, velocity deficits can differ up to 50%. However, within the same area, the vertical profile of turbine-generated TKE is nearly identical between the two types of simulations. Our findings demonstrate that the generalized actuator disk implementation can provide us with a solid foundation for evaluation of wind farm parametrizations within weather models.

1. Introduction

A number of wind farm parametrizations have been implemented in numerical weather prediction models, e.g., in the Weather Research and Forecasting (WRF) mesoscale model \cite{1, 2}. These parametrizations are a combination of resolved and subgrid-scale effects, and aim at assessing the impact of a wind turbine or wind farm on the regional wind climatology. Since the WRF model is now often used within the wind energy community to reproduce the wind climatology of a region and since it incorporates a wind farm parametrization, the so-called ‘Fitch’ parametrization \cite{1}, which is widely used within the community \cite{3, 4}, it is important to evaluate its goodness with more advanced and detailed wake simulations.

On the other hand, a generalized actuator disk (GAD) model was implemented to simulate turbine wakes using the large-eddy simulation (LES) capability of the WRF model. This GAD implementation, which is detailed in \cite{5}, basically computes tangential and normal forces at the different blade sections using the aerodynamic blade specifications, which are then transformed into local forces aligned with the WRF coordinates and applied to the tendencies of the WRF’s velocity components. Having such an implementation provides us with the opportunity to perform evaluations and intercomparisons between models and parametrizations.
The Fitch parametrization basically models wind turbines as sinks of momentum and turbulent kinetic energy (TKE) sources. For an isolated wind turbine, it computes the wind turbine power output $P$ from the simulated hub-height wind speed $U_h$ via the manufacturer’s power curve, which is an input to the model. The power coefficient is then computed as

$$C_P = \frac{P}{(1/2)\rho AU_h^3},$$

(1)

where $A$ is the wind turbine swept rotor area and $\rho$ the air density (the WRF’s open-release version assumes it to be constant). A TKE coefficient is then computed as

$$C_{TKE} = c_f (C_T - C_P),$$

(2)

where $C_T$ is the thrust coefficient, which as $P$ is an input to the model (it should be provided by the manufacturer via the thrust curve), and $c_f$ a correction factor, which was recently introduced into the parametrization to account for mechanical and electrical losses (see [6] for details). $C_{TKE}$ is then used to compute the added TKE tendency, while $C_T$ is used to compute the tendencies that reduce both horizontal velocity components.

Here, we aim at evaluating wake simulations outputs of the open-release in-built WRF wind farm Fitch parametrization run in a mesoscale fashion, i.e., in the kilometer range, against those performed using the GAD model, which is run within the LES capability of the WRF model, i.e., in the meter/tens of meters range. This evaluation has the advantage, among similar studies (e.g., [6]), that both type of simulations are performed with the same model, i.e., the same basic physics and numerical recipes, which we expect provide the community with a fairer comparison and thus higher value for the results than previous comparisons. Section 2 introduces both the mesoscale and the LES simulations, as well as the methods we use to intercompare the results of both types of simulations. Section 3 presents the results, first, by looking at the inflow conditions of both types of simulations before the turbine is modelled, second, by looking at time-averaged hub-height cross sections of the simulated wind speed and TKE, and, third, by looking at spatial-averaged and temporal-averaged vertical profiles of the wind speed deficit and TKE generated by the turbine within different areas/grid points of the simulations. Conclusions are provided in the last section.

2. Methods

The simulations are performed using the capability of the WRF model (version 3.7.1) to perform idealized simulations. Two types of idealized simulations are performed: those aiming at using the Fitch parametrization are setup in a mesoscale-like fashion, whereas the GAD simulations are performed using the LES capability of the WRF model. The same vertical grid and levels with 120 grid points (with constant spacing of $\approx 5$ m within the first 250 m) are used for both types of simulation with a model top at 2000 m. We simulate the same dry atmosphere, i.e., neutral atmospheric conditions with a constant potential temperature of 289.5 K up to 700 m where an inversion of $10$ K km$^{-1}$ is applied upwards. The initial $u$- and $v$-velocities, in the $x$- and $y$-horizontal directions, are set to 12 and 0 m s$^{-1}$ at all vertical levels in both types of simulations; thus these values correspond to the geostrophic velocity components. Also for both, we use the in-built WRF surface-layer scheme, which is based on Monin-Obukhov similarity theory [7], a constant surface roughness of 0.25 m, and the latitude is set to 43.45°. We use the same wind turbine: the DTU 10-MW reference turbine [8], which has a hub height of 119 m and a rotor diameter of 178.3 m. Specific details of the two types of simulations are given in the following subsections.
2.1. Mesoscale simulations

The simulations are performed with one domain with an horizontal resolution $\Delta x$ of 1 km and $100 \times 100$ horizontal grid points. We use the MYNN2 planetary boundary layer (PBL) scheme [9], which is the only PBL scheme that works together with the Fitch parametrization in the standard WRF distribution. We first run without the turbine during 10 h utilizing periodic lateral boundary conditions to develop the atmospheric boundary layer. Then, we perform two runs: one restarting the simulation without and one with the turbine in the middle of the domain using open lateral boundary conditions. These two simulations are run for 6 h and we time-average the results within the last hour.

Since we are not using the latest WRF model distribution, we had to apply the bug fix encountered by [6], which basically enables TKE to be horizontally advected. Note that this problem does not originate from the Fitch parametrization, but from the WRF module that updates the TKE from the turbine(s). Although the $\text{bl}\_\text{mynn}\_\text{tkeadvect}$ flag was set to true in the namelist.input of the WRF model, which allows TKE to be horizontal advected when using the MYNN2 PBL scheme for simulations without turbines, when the Fitch parametrization was turned on, the TKE horizontal advection was bypassed (see [6] for details). We also implemented the TKE correction factor in Eqn. (2) to the Fitch parametrization as in [6], who suggested $c_f = 0.25$.

As mentioned, for the Fitch parametrization, both the power and thrust curves are used as input. Figure 1 illustrates both of these curves. Note that we use the “mechanical” power curve [8], which has power values larger than 10 MW beyond rated.

![Power and thrust curves of the DTU 10-MW reference turbine][8]

2.2. Large-eddy simulations

The simulations are performed using two domains. First, we run a LES outer domain with $\Delta x = 30$ m and $500 \times 500$ horizontal grid points without the GAD utilizing periodic lateral boundary conditions to develop the atmospheric turbulent flow. After the outer domain runs for 10 h (in this domain turbulence is triggered after $\approx 2$ h and the jet speed shows maxima between hours 10 and 12, similarly to the LES in [10]), we perform two runs. One with a LES inner one-way nested domain with $\Delta x = 10$ m and $502 \times 502$ horizontal grid points with the GAD at the position (1000, 1000) m from the left-right corner of the innermost domain so that the analysis can be performed in different downwind areas (see Fig. 2). The other is an identical run but without the GAD. For these two high-resolution runs, the domain starts at
(5000, 5000) m from the outermost domain left-right corner. All LES runs are performed using the subgrid-scale model of [11] with the prognostic equation for the subgrid TKE.

Similarly to [6], we select five 1 km × 1 km areas downwind the turbine (see Fig. 2) to spatially average the LES results and directly intercompare vertical profiles of the velocity deficit and of the turbine-generated TKE, here defined as the difference between the simulation without and with the turbine, with those of the 1-km resolution mesoscale results on the correspondent 5 grid points.

3. Results

3.1. Inflow turbine conditions

Figure 3 illustrates the spatial-averaged vertical profiles of the instantaneous potential temperature Θ, horizontal wind speed $U = \sqrt{u^2 + v^2}$, and TKE for both the mesoscale and the LES run after 10 h of spinup, i.e., just before the turbine is placed in the simulation. As illustrated, the inflow potential temperature vertical profiles between the mesoscale and LES runs match very well both depicting neutral conditions within the PBL.

For the vertical profile of wind speed, the differences between both types of simulation are more evident. Within the lowest ≈200 m, the LES run overpredicts the wind shear when compared to the mesoscale run; this is due to the tendency of the specific subgrid-scale model to overpredict the dimensionless shear of the LES [12, 10]. Above ≈200 m, the LES run shows lower wind speeds than those of the mesoscale run, the latter showing a more prominent jet close to the boundary-layer height, which is a feature from a number of PBL parametrizations [13]. The resolved TKE from the LES run matches well that of the mesoscale model within the bulk of the boundary layer. The subgrid-scale TKE of the LES, as expected, decreases quickly with height and above the lower-tip height, it is much lower than the resolved TKE of the LES.

3.2. Horizontal cross sections

The left frames in Fig. 4 show hub-height cross sections (on a small portion of the domain) of both the horizontal velocity and the TKE, which are time-averaged over the last hour of the

Figure 2. (left) Configuration of the LES domains. (right) A cross section of the instantaneous wind speed at hub height on the LES innermost domain with the GAD after 2 h of simulation. The black squares indicate the areas where LES outputs are spatially averaged. The colorbar indicates the wind speed in m s$^{-1}$.
Figure 3. Spatial-averaged vertical profiles of the potential temperature $\Theta$, wind speed $U$, and turbulent kinetic energy (TKE) for both the mesoscale (PBL) and the LES runs at 10 h. For the LES run, the subgrid-scale TKE is shown in the dashed line. Grey lines illustrate the turbine’s hub height, and upper- and lower-tip heights simulation, of the mesoscale run using the Fitch parametrization. As illustrated, at the turbine position, which is at (50, 50) km, the TKE increases (up to more than 1 m$^2$s$^{-2}$) and the wind speed decreases ($\approx$0.3–0.4 m s$^{-1}$) compared to the background values ($\approx$0.75 m$^2$s$^{-2}$ and $\approx$9 m s$^{-1}$, respectively). The presence of the turbine appears to be affecting the simulated fields more than 30 and 40 km downwind in case of the TKE and wind speed, respectively. This is probably an artifact of the idealized simulations and the differences are quite small at those distances; at hub height, the velocity deficit is below 2% already at 5 km downstream of the turbine.

The right frames in Fig. 4 show hub-height cross sections (on nearly the full innermost domain) of both the horizontal velocity and the resolved TKE, which are time-averaged over the last hour of the simulation, of the LES run using the GAD. As illustrated, around the turbine position, which is at (1000, 1000) m, the resolved TKE increases (up to nearly 5 m$^2$s$^{-2}$) and the wind speed decreases ($\approx$7 m s$^{-1}$) compared to the background values ($\approx$0.75 m$^2$s$^{-2}$ and $\approx$9 m s$^{-1}$, respectively). The presence of the turbine appears to be affecting the simulated fields more than 2 and 3 km downwind in case of the resolved TKE and wind speed, respectively.

3.3. Vertical profiles

Here we intercompare the mesoscale and the LES runs. As already mentioned, simulation outputs on five grid points of the mesoscale run are compared with spatial-averaged LES outputs within five areas correspondent to the size of the mesoscale resolution at those five positions. Figure 5 illustrates this comparison for the vertical profiles of velocity deficit where both LES and mesoscale outputs are time-averaged within the last hour of simulation. Starting with the area where the turbine is placed (1), we can see differences (here between mesoscale and LES results) in velocity deficit as great as 0.3 m s$^{-1}$, i.e., about 50%, which was also found using a different LES [6]. Note also that in this latter study the turbine used was the NREL 5 MW. For area 2, the differences in velocity deficit are comparable at hub height but increase the farther
Figure 4. (Left frames) Time-averaged hub-height cross section of TKE (top frame, colorbar in $m^2 \, s^{-2}$) and horizontal velocity (bottom frame, colorbar in $m \, s^{-1}$) for the mesoscale simulation using the Fitch wind-farm parametrization. (Right frames) Similar to the left frames but for the LES using the GAD. In the top-right frame, the TKE only accounts for the resolved part from this level. For area 3, the turbine seems to have little effect in the LES, whereas the velocity deficit in the mesoscale is the second highest. For area 4, the turbine does not seem to have as much effect in the LES compared to the mesoscale result, whereas for area 5 (the furthest downwind from the turbine), both mesoscale and LES show a significant impact of the turbine and similar deficits between hub height and upper-tip height.

The same type of intercomparison is performed for the turbine-generated TKE and the results shown in Fig. 6. Starting with area 1 (where the turbine is located), and in contrast to the velocity deficit results for the same area, the mesoscale and LES vertical profiles closely resemble each other; a similar agreement was found in the work of [6] for the turbine area. For area 2, the LES results are the highest at all vertical levels and the mesoscale results are about half of them (similar results were found by [6] within the same area). For area 3, turbine-generated TKE is very little, whereas the mesoscale results clearly see the effect of the turbine. For area 4, the mesoscale and LES values are close within the hub height and upper-tip height, and for area 5 we see a much stronger effect of the turbine in the LES compared to the mesoscale.

4. Conclusions and discussion
Here we aim at intercomparing the in-built wind farm Fitch mesoscale wake parametrization in the WRF model with high-fidelity LES simulations using a GAD. In contrast to the work in [6], a ‘fairer’ intercomparison was performed, as the mesoscale simulation and LES were both carried out using the WRF model, and we tried to setup the simulations as similar as possible.

The PBLs developed in both the mesoscale and LES runs, before the turbine was placed in the simulation, closely resembled each other. Vertical profiles of potential temperature were nearly identical and TKE profiles were very close to each other within the bulk of the PBL,
Figure 5. Vertical profiles of the velocity deficit at five grid points of the mesoscale run (solid lines) and spatially-averaged LES run over five areas correspondent to the mesoscale grid points (markers). Both LES and mesoscale results are time-averaged. Grey lines illustrate the turbine’s hub height, and upper- and lower-tip heights.

Figure 6. Vertical profiles of the turbine-generated TKE at five grid points of the mesoscale run (solid lines) and spatially-averaged LES run over five areas correspondent to the mesoscale grid points (markers). Both LES and mesoscale results are time-averaged. For LES only the resolved TKE is shown. Grey lines illustrate the turbine’s hub height, and upper- and lower-tip heights.
with the largest differences below hub height. Wind speed profiles showed however differences close to the PBL height and in the wind shear within the turbine swept area. However, as the comparisons between LES and mesoscale runs were performed based on the differences between the results with and without the turbine, these differences are not likely to have arisen from differences in the inflow.

Within the area where the turbine was placed results are mixed. The velocity deficit of the LES was nearly as twice as high as that of the mesoscale simulation within the rotor swept area. However, the vertical profile of turbine-generated TKE is nearly identical between both LES and mesoscale results, in agreement with the findings in [6], which motivated their suggestion on reducing the TKE coefficient within the Fitch parametrization to a quarter of the value used until recently. Within the area just downwind that where the turbine is placed, the maximum velocity deficits were quite similar between the mesoscale and LES results, whereas for the turbine-generated TKE, the mesoscale result showed nearly half the values of the LES.

It is important to note that we did not study the effect on the results of the effective resolution inherent to the WRF model, surface roughness (we use a rather high value and the Fitch parametrization is normally used to model offshore wind farms), atmospheric stability, inversion strength and PBL height, grid resolution (both in the mesoscale and LES), and number of turbines within the averaging area. We plan to analyze these effects in the near future. Also important is that we assume that the wake of the Fitch parametrization and that of the GAD are in averaged aligned at the same relative wind direction and that some of the results within downwind areas from the turbine might be affected by any misalignment. This will also be studied in future work as well as the computations of the power and thrust coefficient within the range of wind speed values covered by the manufacturer’s correspondent curves (Fig. 1), and the sources of uncertainty of the results.

Further, one can notice that the turbulent rolls are qualitatively larger within the area 1 of the LES compared to those within area 5 (Fig. 2-right) and so we might require a longer fetch to develop the smaller turbulence structures. Figure 7 shows vertical profiles of $U$ and TKE, which are temporally-(during the last hour of simulation) and spatially-averaged within the five areas for the LES without the GAD. As illustrated, TKE differs the most below hub height between the values within area 1 and 5, with higher values the closer to the outer domain. We therefore also plan to investigate the effect of the position of the GAD in the LES on the results of the intercomparison with the mesoscale runs.

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Figure 7. Temporal and spatial averages of the vertical profiles of $U$ (left) and resolved TKE within the five areas for the LES run without the GAD. Grey lines illustrate the turbine’s hub height, and upper- and lower-tip heights.

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