DTU Library

Wind Farm parametrization in the mesoscale model WRF

Volker, Patrick; Badger, Jake; Hahmann, Andrea N.; Ott, Søren

Link back to DTU Orbit

Wind Farm parametrization in the mesoscale model WRF

Patrick Volker[1], Jake Badger[1], Andrea Hahman[1], Søren Ott[1]

[1] DTU Wind Energy

Frederiksborgvej 399

DK-4000 Roskilde

Denmark

Submitted abstract

The project's objective is to investigate and develop methods for prediction of mesoscale climate, wake effects and atmospheric feedbacks, for scenarios where large portions of the sea are covered with wind farms. The atmospheric flow is simulated with the WRF mesoscale model, since it has significantly lower computational costs compared to high resolution models. Due to the fact that its typical horizontal grid spacing is on the order of 2km, the energy extracted by the turbine, as well as the wake development inside the turbine- containing grid cells, are not described explicitly, but are parametrized as another sub-grid scale process.

In order to appropriately capture the wind farm wake recovery and its direction, two properties are important, among others, the total energy extracted by the wind farm and its velocity deficit distribution. In the considered parametrization the individual turbines produce a thrust dependent on the background velocity. For the sub-grid scale velocity deficit, the entrainment from the free atmospheric flow into the wake region, which is responsible for the expansion, is taken into account. Furthermore, since the model horizontal distance is several times larger then the turbine diameter, it has been assumed that the generated turbulence and dissipation are balanced.

From version 3.2.1 onwards, the WRF (Weather Research and Forecast) model includes a wind farm parametrization option (Fitch Scheme). In contrary to the above described parametrization where the wind turbines are positioned explicitly, the wind farms in the default scheme are treated as a density distribution, which limits the description of the internal wind farm velocity deficit development and its related efficiency. In the Fitch Scheme the wind turbines act as drag devices, where the extracted force is proportional to the turbine area interfacing a grid cell. The sub-grid scale wake expansion is achieved by adding turbulence kinetic energy (proportional to the extracted power) to the flow. The validity of both wind farm parametrizations has been verified against observational data. We use

Synthetic Aperture Radar (SAR) satellite data, as well as mast measurements from meteorological masts and power measurements from wind turbines, at Horns Rev and Nysted. From the SAR satellite data the wake extension can be derived. The wind farm measurements have been used to compare the total thrust produced by both types of parametrization. In case studies the wake deficit has been estimated by the deflection of the wake due to the slowing down of the wind speed.

The results of the wind farm parametrization will be used to investigate eventual climate impacts of large wind farms. Furthermore it will develop techniques for up-scaling the effects simulated by wind farm wake models into mesoscale atmospheric planetary boundary layer (PBL) parameterisations and perform simulations using these parameterisations to understand the feedbacks between the wind farms and the regional wind climate. The work will extend the current knowledge about wake effects from observations and small-scale models to potential feedbacks in the PBL atmosphere.

1   Introduction

From the mid-nineties onwards several off-shore wind farms have been installed. In the coming years at least two larger clusters, one in the German Bight and the other in the Dogger bank (`http://www.forewind.co.uk/`) will arise. Therefore Cluster optimization as function of e.g. wind farm design, grid structure, electricity supply and/or wind-farm interaction (see e.g. the EERA-DTOC project[1])) became a topic of interest. In the presented study we concentrate on the description of a single wind farm wake, which later-on can be used for the study of wind farm interaction. With the actual tools and computer resources the most reasonable candidates to analyze the wind farm interaction and possible regional climate impacts are Mesoscale- and linearized CFD-Models (see e.g. FUGA ren et al., 2011). Both methods have there disadvantages. The first option is not able to describe the individual turbine wakes explicitly, whereas the second option, generally, can not take into account the atmospheric conditions, which are important in the far wake regime. In this paper we will focus on the first alternative and present a new wind farm parametrization approach. In first place we will aim to extract the right amount of energy and to take the sub-grid scale development of the velocity deficit into account. The typical horizontal grid spacing is of the order of kilometers and the vertical spacing in our simulations will be around 10 meters in the near surface region. Due to the coarse horizontal grid spacing the energy extracted by the turbine, as well as the wake development inside the turbine-containing grid-cells, cannot be described explicitly and is parametrized just as other sub-grid scale processes. In the following section we will motivate the physics behind the new wind farm parametrization approach, then its implementation and the verification will be discussed. For our study we used the mesoscale model WRF (Weather Research and Forecast Model) (Skamarock et al., 2008). From WRFV3.2.1 onwards it contains a wind farm parametrization option (Fitch), which will be used as reference in the verification. This option is dependent on the MYNN Planetary Boundary

---

[1]European Energy Research Alliance-Design Tools for Off-shore wind farm Clusters

Layer (PBL) scheme (Nakanishi and Niino, 2009), whereas the new parametriation is PBL-scheme independent. For consistency reasons the MYNN-scheme has been used during our analysis. Before we introduce the new approach we will first describe shortly the WRF Wind Farm option and the motivation for a new approach. Thereafter both parametrizations will be compared to in-situ and remote measurements.

2   Fitch WRF Wind-Farm Parametrization

From version 3.2.1 onwards, the WRF model includes a wind farm parametrization option (Fitch Scheme) adapted from Blahak et al., 2010. In this parametrization the wind turbines are treated as a density function. All turbines will experience the same up-stream velocity, equal to the grid-cell velocity. The implemented equation for the thrust reads

$$T_k = \frac{C_t N_{ij} A_k v_{h,k}^2}{2 (\Delta x)^2 \Delta z_k}$$

$N_{i,j}$ is the number of turbines located in grid-cell (i,j), A_k the turbine blade segment intersecting with the model level k, Δx the horizontal grid-spacing and $v_{h,k}$ the horizontal velocity. It has been assumed that the turbulence kinetic energy inside a turbine effected grid-cell will experience apart from the increased shear an additional source proportional to the cube of the wind speed. The influence on the turbulence length scale, the dissipation as well as the stability function has not been considered. In the model we find for the $qke = \overline{u_i'^2}$, $i = 1, 2, 3$, which is equal to twice the turbulence kinetic energy

$$qke_{(\text{model+wake})} = qke_{(\text{model})} + \alpha \frac{N_{ij} A_k v_{h,k}^3 \Delta t}{(\Delta x)^2 \Delta z_k} \quad \text{where } \alpha = C_t - C_p$$

3   New approach

The new approach is following the classical far wake theory see e.g. Tennekes and Lumley (1972), which assumes that the far velocity deficit region can be described by one characteristic length scale ℓ and one velocity scale U_s (maximum velocity deficit). Since the horizontal distance in the model is several times larger then the turbine diameter, it has been assumed that the generated turbulence and dissipation are balanced. In this way it is possible to determine explicitly the influence of each turbine on any downstream turbine, thereby addressing the efficiency issue. From the diffusion equation we can obtain

$$\ell^2 = \left(\frac{2 K_m}{U_0} \right) x + \ell_0^2 \tag{3.1}$$

Eq. (3.1) describes the down-stream evolution of the velocity deficit region due to entrainment processes. U_0 is the hub-height velocity, K_m turbulence coefficient for momentum and ℓ_0 the initial length scale, which has to be determined from measurements. Following the literature (e.g. Tennekes and Lumley, 1972) we can write for small velocity deficits $U = U_0 - U_s f(z, \ell)$ From the definition of the thrust, we can obtain for the velocity deficit

$$U_s = \frac{U_0}{\sqrt{2}} \left(1 - \left(1 - \frac{C_t A_0^2}{\sqrt{\pi} W \ell} \right)^{\frac{1}{2}} \right) \tag{3.2}$$

(3.1) and (3.2) form the full set of equations that describe the velocity deficit completely.

For the mesoscale field we used $\overline{\ell}$ from (3.1) and assume that the wake width is equal to the horizontal grid spacing. This gives us $\overline{U_s}$ from (3.2) and we obtain for the total thrust

$$\frac{C_T A_0 U_0^2}{2V} = \frac{1}{V} \overline{W} \int_{-\infty}^{\infty} \overline{U}_s f \left(U_0 - \overline{U}_s f \right) dz = \frac{1}{V} \sum_{k=1}^{k_{max}} T_k \tag{3.3}$$

The r.h.s. will be applied to all model levels k. The up-stream velocity U_0 comes from the wind farm parametrization, which take into account turbine-turbine interaction using (3.1) and (3.2) to transport local (unresolved for the mesoscale model) wakes.

The constants ℓ_0 and α were obtained from a comparison between a "standalone" version of the model and Vindeby fast measurement data. We obtained $\alpha = 1$ and $\ell_0 = 0$m. In the figure below the result for a single wake at Vindeby has been plotted.
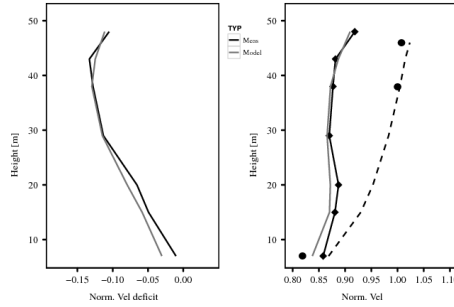

Figure 3.1: Left: Normalized velocity deficit $U_{wake}(k) - U(k)/U_0$ for the measurements (black line) and the model (grey line). Right: Measured upstream velocity (dots) and the logarithmic fit (dotted line), the downstream measurements (squares) and the measurement interpolation (black line) plus the model wake velocity (grey line).

4

4 Validation

We used for the validation 10-min averaged data from top mounted cup anemometers M2 (63m), M6 (70m) and M7 (70m), the wind vane at 60m on M2 and the power measurements from the turbines in row 4 and 5 at Hornsrev. We selected only data from the met. masts in the up-stream wind directions betweeen $255° \leq \theta \leq 285°$. The up-stream wind speed interval was selected in the range of $8\text{m/s} \leq U_{63} \leq 10\text{m/s}$, so that the corresponding time average wind speed at 70m was 9.3m/s (equal to the model hub-height wind speed).

The model consists of 60×50 horizontal levels, had in total 60 vertical levels and $\Delta x =$1400m. The mesoscale model was initialized with a constant geostrophic wind $U_g =$11m/s and $V_g =$ -2m/s such that it converged to a wind profile with a hub height velocity of 9.3m/s with an angle of 270°. The wind farm was placed in 5×4 grid-cells, each of them containing 4 turbines. For both schemes we used the C_t from the thrust curve.

4.1 Velocity deficit recovery

We normalized the wake measurements of M6 (8300m) and M7 (12300m) with the corrected (logarithmic extrapolation to 70m) wind speed from M2. From the power measurement we derived the corresponding hub-height wind speeds via the power curve. To be data consistent the derived velocities were normalized by the wind speed of the first row.
The abscissa in fig.(4.1) indicates the down-stream distance from the first turbine onwards. The dots up to 6300m represent the averaged normalized hub-height velocities from row 4 and 5 and the dots at 8300m and 12300m are the averaged normalized velocities at hub-height from M6 and M7 respectively. The solid line is a part of the parametrization of the new approach and represents the local hub-height velocities of the turbines. The dashed lines are the model outputs, whereas the symbols mark the model output position. The Fitch-scheme produces a deeper wake then the new approach. Inside the wind farm it reaches the measured local turbine velocities.

4.2 Total Thrust

In this section we will compare the total modeled thrust with the measured thrust. This gives us for the total thrust of grid-cell (i, j) in the Fitch-scheme simply

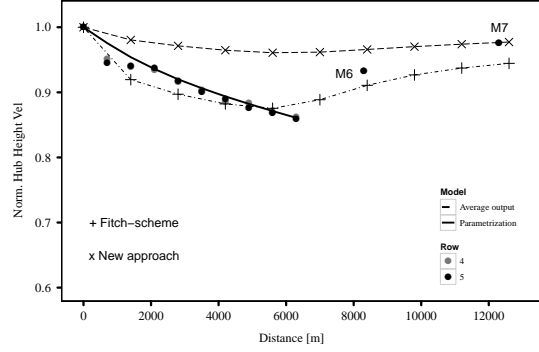$$T_{i,j} = \sum_{k=1}^{k_{max}} \frac{C_t N_{ij} A_k v_{h,k}^2}{2 (\Delta x)^2 \Delta z_k},$$

Figure 4.1: Velocity deficit recovery at the Hornsrev windfarm.

since the turbines are not resolved explicilty. Whereas the total thrust applied to grid-cell (i, j) for the new approach is

$$T_{i,j} = \frac{\overline{W}}{V} \sum_{n=1}^{n_{\text{turb}}} \sum_{k=1}^{k_{max}} \left((U_{0,n} - \overline{U}_{s,n} f_k) \overline{U}_{s,n} f_k \right) \Delta z_k$$

For the measurements, we use the power and thrust curve to achieve the thrust per turbine. We sum up groups of four turbines to measure the equivalent total thrust per grid-cell:

$$T_{i,j} = \sum_{n=1}^{4} 0.5 C_{t,n} A_0^2 U_n^2 / V \quad \text{where } V = D_0 \left(\Delta x \right)^2$$

Since the turbine hub-height velocity deviates from the met. mast up-stream velocity, we selected $8\text{m/s} \leq U_0 \leq 11\text{m/s}$ to achieve an average velocity of 9.2m/s at the first turbine (compared to 9.3m/s of the model).

The total thrust per grid-cell for the models and the corresponding measured thrust are plotted in fig.(4.2). The dots represent the down-stream grid-cell thrusts per volume. From this figure we can conclude that the Fitch scheme overestimates the energy extracted from the flow by almost an order of magnitude. The new-approach follows the measured thrust.
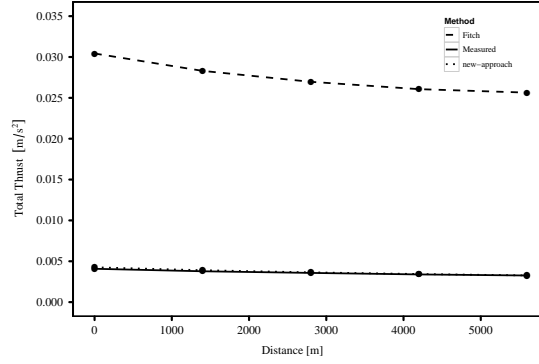
Figure 4.2: Total thrusts per grid volume versus the down-stream distance at Hornsrev

Finally we can see from fig.(4.2) that the velocity deficit of the Fitch-scheme penetrates from the first grid-cell on deep into the PBL. We notice also that the maximum velocity deficit probably due to the enhanced turbulence has been transported upwards. Furthermore large positive velocity deficits at the lower boundary are obtained due to the high turbulence mixing.
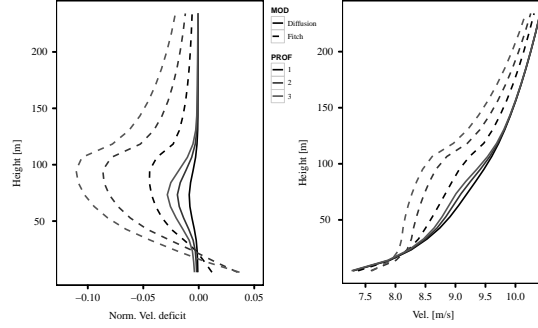

Figure 4.3: Left: normalized velocity deficit $(U_{down} - U_{up})/U_0$ inside the wind-farm, decreasing darkness when proceeding donwstream. Right: Horizontal velocity inside the wind farm

5 Conclusion

In this paper we present a new approach, which allows us to simulate the flow distortion caused by the thrust of wind farms in a mesoscale model. We compare the new approach and the wind farm parametrization implemented in the WRF mesoscale

model (Fitch-scheme) against 10-min averaged velocity data from the large wind farm Hornsrev off the west coast of Denmark. The results show that in the Fitch-scheme the thrust applied to the flow is overestimated by almost one order of magnitude. Furthermore we found that the modeled sub-grid turbulence kinetic energy in the Fitch-scheme diffuses the velocity deficit deep into the boundary layer, and causes unnaturally high positive (grid-cell averaged) velocity deficits at the lower boundary. Both deficiencies would have consequences on the analysis of the impact of wind farms on the atmosphere as well as its ocean feedbacks.

After correcting the Fitch-scheme (results are not shown here), its total thrust applied to the flow agreed with the measurements at the first up-stream turbine. However, since the scheme does not account for efficiency (turbine-turbine interaction), the down-stream thrust applied to the flow was therefore overestimated. Furthermore we noticed that the down-stream recovery of the velocity deficit in the corrected Fitch-scheme, due to its intensive mixing, is this time too fast. Finally we observed that it produced now even relatively higher positive velocity deficits (same order as the deficits) at the lower boundary. The new approach is able to follow, thanks to the internal turbine interaction, the reduced thrust applied to the flow. The recovery of the velocity deficit matches the (at 6km down-stream located met. mast M7) measurements.

References

U. Blahak, B. Goretzki, and J. Meis. A simple parametrization of drag forces induced by large wind farms for numerical weather prediction models. *EWEC Conference*, 2010.

M. Nakanishi and H. Niino. Development of an improved turbulence closure model for the atmospheric boundary layer. *Journal of the meteorological Society of Japan*, 87:895–912, 2009.

Ott Søren, Jacob Berg, and Morten Nielsen. Linearised cfd models for wakes. *Risø National Laboratory, Roskilde, Denmark*, Risø-R-1772(EN):01–41, 2011.

William C. Skamarock, Joseph B. Klemp, Jimy Dudhia, David O. Gill, Dale M. Barker, Michael G. Duda, Xiang-Yu Huang, Wei Wang, and Jordan G. Powers. *A Description of the Advanced Research WRF Version 3*. NCAR Technical note, 2008.

H. Tennekes and J.L. Lumley. *A first Course in Turbulence*. The MIT Pess, 1972.