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

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Wake effects of large offshore wind farms on the mesoscale atmosphere

Patrick J.H. Volker, Jake Badger, Andrea Hahman and Søren Ott
DTU Wind Energy, Risø Campus, Roskilde, Denmark

DTU Wind Energy
Department of Wind Energy

Abstract

We present a new approach, which allows us to simulate the flow distortion caused by the thrust of wind farms in a mesoscale model. The atmospheric flow is simulated with the WRF mesoscale model, since it has significantly lower computational costs compared to higher 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, the total energy extracted by the wind farm and its velocity deficit distribution. In the considered parametrization the individual turbines apply a thrust dependent on a local sub grid scale velocity, which is influenced by the up-stream turbines. For the sub-grid scale velocity deficit, the entrainment from the free atmospheric flow into the wake region, 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 model includes a wind farm parametrization option (Fitch-Scheme). 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 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 to the flow. The validity of both wind farm parametrizations has been verified against observational data. We use met. mast measurements and power measurements from wind turbines, at HornsRev. The wind farm measurements have been used to compare the total thrust produced by both types of parametrization, as well as the down-stream velocity recovery in the first 6km after the wind farm.

Fitch-scheme

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

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

New Appoach

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 down-stream turbine, thereby addressing the efficiency issue. From the diffusion equation we can obtain

$$\ell^2 = \left(\frac{2\,K_m}{U_0}\right) x + \ell_0^2 \qquad (1)$$

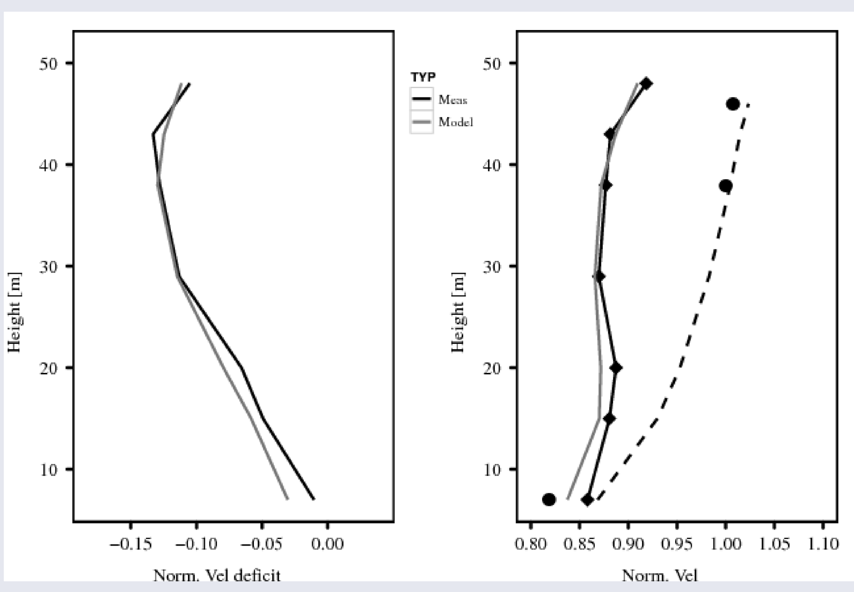
Eq. (1) describes the down-stream evolution of the velocity deficit region due to entrainment processes. U_0 is the hub-height velocity, K_m turbulence coefficient for momentum and ℓ_0 the initial length scale, which has to be determined from measurements.
Following the literature (e.g. Tennekes and 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

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

(1) and (2) form the full set of equations that describe the velocity deficit completely.
For the mesoscale field we used $\overline{\ell}$ from (1) and assume that the wake width is equal to the horizontal grid spacing. This gives us $\overline{U_s}$ from (2) and we obtain for the total thrust

$$\frac{C_T A_0 U_0^2}{2\,V} = \frac{1}{V} W \int_{-\infty}^{\infty} \overline{U}_s f\,(U_0 - \overline{U}_s f)\; dz = \frac{1}{V}\sum_{k=1}^{kmax} T_k \qquad (3)$$

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 (1) and (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.



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).

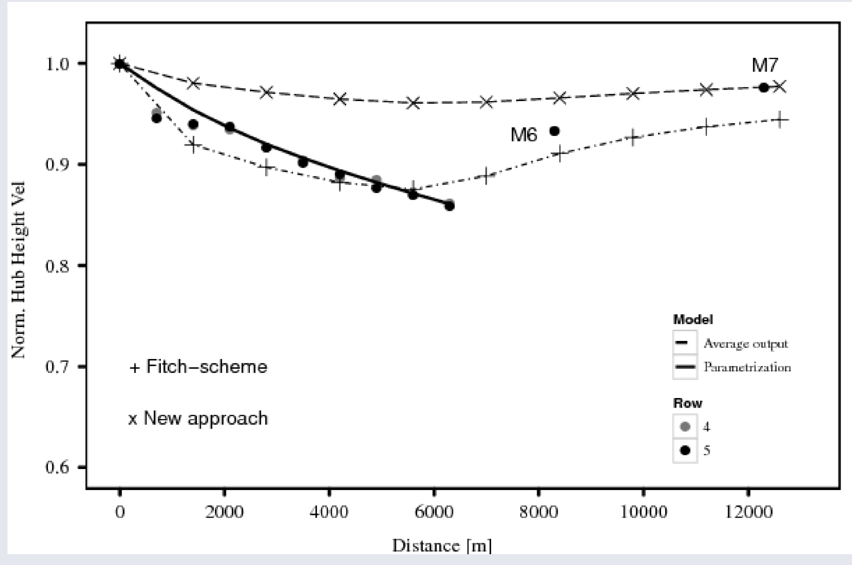
Validation at Hornsrev

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 8m/s $\leq U_{63} \leq$10m/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 Δx =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.

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 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.

Total Thrust

Comparison of the total modeled thrust with the measured thrust.
For the Fitch-scheme:

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

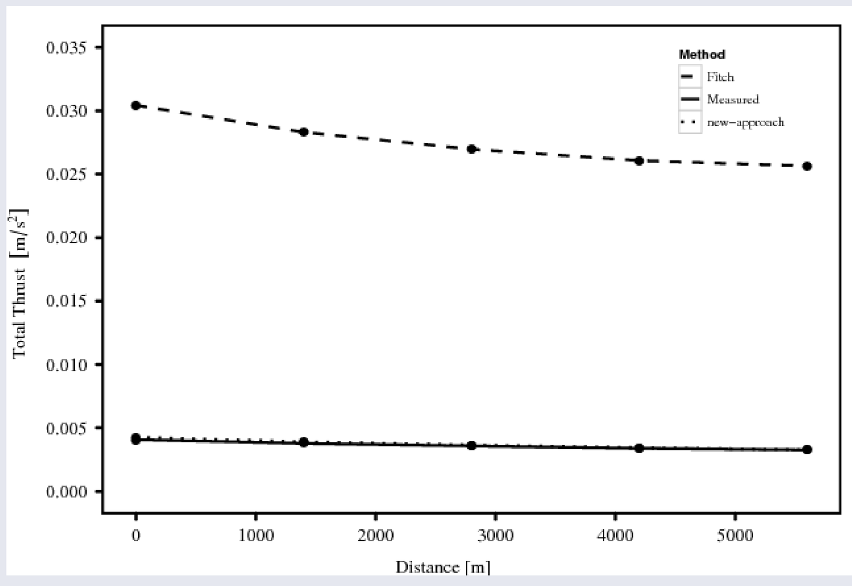
For the new approach we have:

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

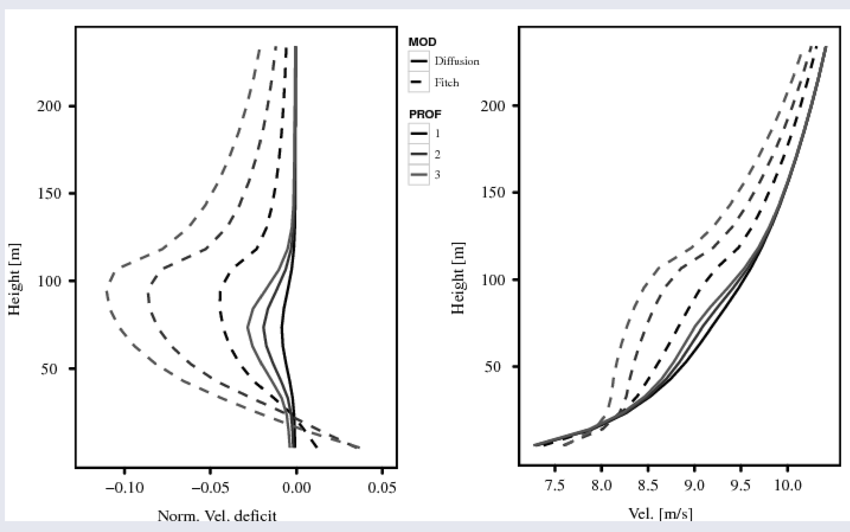
For the measurements, we use the power and thrust curve to achieve the thrust per turbine. We sum up groups of four turbines to measure the equivalent total thrust per grid-cell:

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

Since the turbine hub-height velocity deviates from the met. mast up-stream velocity, we selected 8m/s $\leq U_0 \leq$11m/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. 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 one order of magnitude. The new-approach follows the measured thrust.



For instance, we see that in the graph on the left side, where the normalized velocity deficit $(U_{down} - U_{up})/U_0$ has been plotted, the velocity deficit of the Fitch scheme penetrates from the first grid-cell on deep in the PBL. We notice also that the maximum velocity deficit due to the enhanced turbulence has been transported upwards. Furthermore no large positive velocity deficits at the lower boundary are obtained due to the high turbulence mixing.

Conclusions

In this paper we present a new approach which allows to simulate the flow distortions caused by wind farms in a mesoscale model. We compared 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 at the west coast of Denmark. The results showed that the thrust applied to the flow is overestimated by almost one order of magnitude in the Fitch-scheme. Furthermore we found that the created turbulence kinetic energy diffuses the velocity deficit deep into the boundary layer and causes unnaturally high positive 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. With the new approach we applied the same thrust to the flow as has been measured. Since the recovery of the velocity deficit matched with the at 6km down-stream located met. mast M7 measurements, we can conclude the vertical distribution of the velocity deficit is well described by the new approach.

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