Wake effects of large offshore wind farms on the mesoscale atmosphere

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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, which has significantly lower computational requirements 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 than 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 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 (Blaak 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:

\[ T_k = \frac{C_{T_i} A_i \Delta U_{i,k}}{2} \]

\( N_j \) is the number of turbines located in grid-cell \( i \), \( \Delta x \) the horizontal grid-spacing, and \( \Delta v_{k} \) the horizontal velocity. It has been assumed that the turbulence kinetic energy inside a turbine effected grid-cell will experience an entrainment from the free atmospheric flow into the wake region, thereby addressing the efficiency issue. From the diffusion equation we can obtain:

\[ \phi = \frac{C_{T_i} A_i \Delta v_k}{2 \Delta x} \]

\[ T_k = \frac{C_{T_i} A_i \Delta v_k}{2} \]

\( \Delta v_k \) has been determined as the sum of all the grids that contain turbines up to distance \( 2 \Delta x \) from the horizontal grid spacing. This gives us \( \phi \) from (2) and we obtain for the total thrust:

\[ T_{\text{total}} = \sum \phi \]

The r.h.s. will be applied to all model levels \( k \). The up-stream velocity \( U_{k} \) comes from the wind farm parametrization, which take into account turbine-turbine interaction using (1) and (2) to transport the velocities.

**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 \( \ell \) and one velocity scale \( U_s \) (maximum velocity deficit). Since the horizontal distance in the model is several times larger than 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 grid-cell, thereby addressing the efficiency issue. From the diffusion equation we can obtain:

\[ \phi = \frac{C_{T_i} A_i \Delta v_k}{2 \Delta x} \]

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

\[ T_{\text{total}} = \sum \phi \]

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 total 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 bottom 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.

**Validation at Hornsrev**

We used the following 10-min averaged data from top mounted cup anemometers M2 (63m), M3 (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 between \( 255° < \theta < 285° \). The up-stream wind speed interval was selected in the range of \( 8\text{ms}^{-1} < \bar{U}_k \leq 10\text{ms}^{-1} \), so that the corresponding average time wind speed at 70m was 3.9ms\(^{-1}\) / 8ms\(^{-1}\). The model consists of 60x50 horizontal levels, had in total 60 vertical levels and \( \Delta z = 1400\text{m} \). The mesoscale model was initialized with a constant geostrophic wind \( \bar{U}_0 = 11\text{ms}^{-1} \) and \( V_0 = 2\text{ms}^{-1} \) such that it converged to a wind profile with a hub-height velocity of 9.3ms\(^{-1}\) with an angle of 270\(^\circ\).

The wind farm was placed in 5x4 grid-cells, each of them containing 4 turbines. For both schemes we used the G2 thrust from the curve thrust.