Large scale wind farm wakes and a wind-wave-wake coupled mesoscale modeling system

Patrick J.H. Volker, Jake Badger, Xiaoli G. Larsén, Jianting Du, Jesper N. Nissen, and Poul E. Sørensen

DTU Wind Energy and Vattenfall
Relevance

Wind farms will increase in size and wind farm clusters are expected to arise

- What is the influence of an up-stream wind farm?
- How strong are fluctuations when a wind farm is in or outside the wake of an up-stream wind farm?
Model choice

Large Eddy Simulation (LES) models:

7,500,000 Cells
Area ≈ 4.2 km$^2$


Mesoscale model:

2,750,000 Cells
Area ≈ 180,000 km$^2$

Source: Volker et al. (2012)
Mesoscale models consider:

- Velocity components \( (U_i) \), Temperature \( (\theta) \), Moisture \( (q) \), density \( (\rho) \)
- Turbulence Kinetic Energy (TKE), Geopotential height \( (\phi) \), and pressure \( (P) \)

Ensemble averaged velocity equation

\[
\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} - \varepsilon_{i3k} f U_k - \delta_{i3} g + F_{Di}
\]

and ensemble averaged TKE equation

\[
\frac{\partial E}{\partial t} + T = P_s + P_b - \epsilon + P_t
\]

Turbine relevant terms are
\[
\begin{cases}
  F_{Di} & \text{Drag force} \\
  P_t & \text{Turbine induced turbulence}
\end{cases}
\]
Discretisation of the model equations

Discretisation implies volume averaging of all ensemble averaged equations, with a:

1) coarse horizontal resolution, $\Delta x \approx \text{km’s}$
2) fine vertical resolution down to $\Delta z \approx 10 \text{ m’s}$

$\Rightarrow$ the turbine drag force $F_{Di}$ is

1) unresolved in the horizontal directions
2) fairly well resolved in the vertical direction
Wind Farm Parametrisations

WRF Wind Farm scheme (Fitch et al. 2012):
(1) Local drag force
(2) Additional TKE source term

EWP approach accounts for unresolved expansion and applies:
(1) Grid-cell averaged drag force

Concept:

Sketch of the wake development within a grid-cell

For both schemes turbulence shear is regulated by the PBL-Scheme
Mesoscale Model (Evaluation)

Horns Rev I (160 MW)  Model Wind farm (dx 1120 m):

Time and wind direction wind speed bias at Mast M6 and M7 (2 km and 6 km downstream)
Mesoscale Model (Evaluation)

Qualitative comparison with Synthetic Aperture Radar (SAR) images. They can retrieve wind speed from back-scatter (higher wind speeds are brighter):

RADARSAT-1/-2 from Data and Products ©MacDonald, Dettwiler and Associates Ltd are acknowledged.

SAR Image (17:34 UTC)          WRF-EWP (17:30 UTC)

1\textsuperscript{st} of July of 2013: Belwind & Thornton

⇒ Comparable extension and divergence
Challenges

Timing is important when simulating events. Offshore, we use the Charnock formulation for the roughness which is valid for the open sea.

Turbines have no specific position in the model. Interaction happens between grid-cells only.
Mesoscale Model (Evaluation cont’d)

30\textsuperscript{th} of April 2013: UK wind farms and Belwind & Thornton

⇒ Challenge in timing snap-shots
Irregular Wind Farms

Due to low horizontal resolution (≈ km) single turbine wakes remain unresolved by the model. In case of Rødsand II - Nysted:

Wind turbine density doesn't allow for resolving the interaction between individual turbines only between grid-cells
Power production: $77^\circ$ and $U = 8$ m/s
Power production: $97^\circ$ and $U = 8 \text{ m/s}$
Power production: 117° and $U = 8$ m/s
Current development for coastal areas

In coastal areas and at high wind speeds the charnock formulation is not valid anymore. 

**Option**: coupling between WRF (including wake scheme) and Wave model (e.g. SWAN)
Coupling of WRF and SWAN

The Wave Boundary Layer Model

Wind speed difference with/without coupling

- Storm center/strongest wind area, example:

  20:45, 2004-02-23

\[ \Delta U_{10}/U_{10} \text{ (\%)} \]

between coupled and not-coupled
Conclusions

- WRF+WF scheme is able to simulate the long-term averaged wind speed reduction behind regular wind farms.
- WRF+WF scheme allows to model the instantaneous velocity reduction behind wind farms.

Challenges

- The timing in the simulation of instantaneous flows.
- In irregular wind farms the wind speed reduction is not straightforward to model (possible solution coupling to microscale model).