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Dynamical and statistical-dynamical modelling of wind farm flows with WRF

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A turbine can be described as a drag device. It effects the:

- **RANS equations** (ensemble average with overline)

  \[
  \frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}'_i u'_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \overline{p}}{\partial x_i} - \varepsilon_{i3k} f \overline{u}_k - \delta_{i3} g + \overline{f}_{di}
  \]

- **and TKE equation**

  \[
  \frac{\partial \overline{e}}{\partial t} + \overline{T} = \overline{p}_s + \overline{p}_b - \varepsilon + \overline{p}_t
  \]

Turbine relevant terms are:

\[
\begin{align*}
\overline{f}_{di} & \quad \text{Drag force} \\
\overline{p}_t & \quad \text{Turbine induced turbulence}
\end{align*}
\]
Discretisation implies spatial averaging $\langle \cdot \rangle$ of the RANS equations

- The drag force in spatial averaged RANS equations becomes $\langle f_d \rangle$

- The additional TKE term $\langle \bar{p}_t \rangle$ depends on the definition of fluctuations:

\begin{align*}
(1) & \text{ around spatial average: } \langle u'' f''_d \rangle \\
(2) & \text{ around ensemble average: } \langle u' f'_d \rangle
\end{align*}
Method (1) Implemented in WRF (WRF-WF)

At the turbine blade levels:

- it applies a local drag force:

  \[ \langle f_d \rangle = -\rho c_t A_0 \langle u \rangle^2 / 2 \]

- and injects:

  \[ \langle \vec{P}_t \rangle = \langle u'' f_d'' \rangle = \rho A_0 (c_t - c_p) \langle |u| \rangle^3 / 2 \]

\[
\begin{align*}
\text{\{ } & c_t \quad \text{Thrust coefficient} \\
& c_p \quad \text{Power coefficient} \\
& A_0 \quad \text{Rotor area}
\end{align*}
\]

Motivation for a different approach

- Within a grid-cell the wake expands
- TKE mostly generated by shear $\langle P_s \rangle$, which is part of the TKE equation

\[ \text{LES simulation: } \sigma_u/U_h \]


However: Horizontal resolution in the mesoscale model is too coarse to resolve the wake expansion

Approach: Explicit description of the unresolved wake
Motivation for a different approach

- Within a grid-cell the wake expands
- TKE mostly generated by shear $\langle \bar{p}_s \rangle$, which is part of the TKE equation

**LES simulation:** $\sigma_u/U_h$


**However:** Horizontal resolution in the mesoscale model is too coarse to resolve the wake expansion

**Approach:** Explicit description of the unresolved (SGS) wake
Method (2) Explicit wake Parametrisation (EWP)

- Applies a spatial averaged drag force (conserving the total drag):

\[
\langle f_d \rangle = -\sqrt{\frac{\pi}{8}} \frac{c_t}{\Delta x \Delta y} \frac{r_0^2 \bar{u}_0^2}{\sigma_e} \exp \left[-\frac{1}{2} \left( \frac{z-h}{\sigma_e} \right)^2 \right]
\]

Sketch of the wake development within a grid-cell:

\[
\sigma^2(x) = \frac{2K_m}{U_0} x + \sigma_0^2
\]

- \(\langle u'f'_d \rangle \ll \langle u''f''_d \rangle\). Thus TKE is only injected by shear \(\langle p_s \rangle\)

WRF-WF and EWP at Horns Rev I wind farm

- Wind farm: $80 \times 2$ MW with 560 m separation
- Measurements at 2 km and 6 km (70 m amsl)
- Wind Speed $8 \pm 0.5$ m/s, direction $270 \pm 15^\circ$

Model Set-up: Idealised case
- 1120 m grid $\Rightarrow$ 4 turbines per grid
- Seven wind directions between 255 and 285°

Velocity Deficit at Hub-height

**WRF-WF**

**EWP**

\[
\frac{\langle u_h \rangle}{\langle u_o, h \rangle}
\]
Normalised velocity deficit profile (neutral)

**WRF-WF scheme:**
- Accelerations at the lowest model level
- Lifting of the maximum deficit near to the upper blade tip

**EWP scheme:**
- Profile agrees with neutral LES simulations
- Less diffusive than WRF-WF scheme
**Turbulence kinetic energy difference (neutral)**

**WRF-WF**

**EWP**

**WRF-WF scheme:**
- Increased TKE from the lowest model level onwards due to $\langle P_t \rangle$ and $\langle P_s \rangle$
- Fast growing internal boundary layer

**EWP scheme:**
- Increased/decreased TKE above/below hub-height
- Slower internal boundary layer growth
Dynamical Modelling (EWP in wrf real)

WRF simulation after 2 days spin-up: From 00 UTC every 30 min the velocity deficit (Wind farm minus control) at 10 m.

Wake behind Belwind and Thornton wind farm 2013 July 1st 17:34 UTC (SAR image).

**Advantage:** WRF allows to study instantaneous flow (WS, T, Q)

**Disadvantage:** No analytical study possible due to always changing conditions
Statistical-Dynamical Modelling (wrf ideal)

Steady state simulations with Geostrophic wind forcing and neutral PBL
These simulations can be used to analyse the wind speed reduction analytically

Simulations for different wind speeds and roughness

Example: We can relate optimal turbine spacing to wind conditions and roughness
**Challenge: Irregular Wind farms**

**Rødsand II and Nysted layout**

Power production: $115^\circ$ and $U = 8 \text{ m/s}$

**WRF layout (1 km grid)**

Power production: $95^\circ$ and $U = 8 \text{ m/s}$
Conclusion

Possible

• Simulate flow reductions behind wind farms
• For simple turbine configurations we can estimate flow reductions inside wind farm

Challenges

• Flow reduction within irregular wind farms
• Power estimation (local wind may be different from spatial average)
• EWP: more measurements are needed for initial length scale