Effect of Wind Turbine Wakes on the Performance of a Real Case WRF-LES Simulation

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Wind farm drag parameterization\textsuperscript{[1,2]} for grid sizes $\geq 5$ D

How does the absence of a wind farm parameterization, or of any wind turbine model, affect the simulation performance?

\textsuperscript{*}Performed by VORTEX
\textsuperscript{[1]} Fitch (2016)
\textsuperscript{[2]} Volker et al. (2015)
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Methodology

Climate Forecast System Reanalysis

\[ \Delta = 9 \text{ km} \quad \Delta = 3 \text{ km} \quad \Delta = 1 \text{ km} \quad \Delta = 333 \text{ m} \]

\[ \Delta = 38 \text{ km} \]

Meteorological Mast (MET)
Northern Wind Turbine (NWT)
Southern Wind Turbine (SWT)

Model Performance

Free Stream
Wake
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Methodology

- **Constant wake expansion**
  \[
  \text{width}(x) = D + 2kx
  \]
  
  \[k = \text{expansion factor} = 0.05^{[3]}\]
  
  \[x = \text{downstream distance}\]
  
  \[D = \text{rotor diameter}\]

- **NWT**
  - waked when \(\gamma_{\text{SWT}} \in [140^\circ, 169^\circ]\)
  - 11% of data
  
  \(\gamma = \text{nacelle position}\)

- **MET**
  - waked when \(\gamma_{\text{SWT}} \in [140^\circ, 182^\circ]\)
  - 16% of data

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Measurements (PEIWEE[4])

- Turbines
  - 10’ means at z = 80 m
    - nacelle position, horizontal wind speed, power
- Met. mast
  - 10’ means from 10 Hz meas. at z = 60 m
    - horizontal wind speed and direction

Simulation

- WRF, two-way nesting
- Time series at three grid points closest to measurement sites
- 10’ means from 4 Hz output

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Expected wind speed over-estimation is only seen at MET
Wind speed at NWT was under-estimated on average ($\delta_{\text{avg}} \sim -0.1 \text{ m s}^{-1}$)
Larger under-estimation of turbulence intensity at MET ($\delta_{\text{avg}} \sim -0.15$ vs. $\delta_{\text{avg}} \sim -0.06$ at NWT)
Wind direction errors similar at both sites, and can also be due to:
  - topographically forced directional turning $^{[4]}$
  - roughness elements, IBLs, displacement height $^{[5]}$

$\delta = x_{\text{sim}} - x_{\text{obs}}$ at coinciding 10’ mean time stamps

$^{[4]}$ Barthelmie et al. (2016)
$^{[5]}$ Benson (2005)
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Results -- Model Performance Under "Waked" vs. "Free" Conditions

- $\delta_w$ consistently larger than $\delta_f$
  - Especially at MET where wind speed $\delta_w \sim 35\%$ higher than $\delta_f$
- Model performance at NWT less affected by wake
  - Note: ~15 m escarpment adds to flow complexity
- Other phenomena not (or mis-) represented by model, e.g.
  - Surface layer treatment
  - Spatial resolution of BCs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>MET</th>
<th>NWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Speed $U$</td>
<td>[m s$^{-1}$]</td>
<td>3.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Wind Direction $\beta$</td>
<td>[deg]</td>
<td>35.5</td>
<td>40.2</td>
</tr>
<tr>
<td>Turbulence Intensity $I$</td>
<td>[-]</td>
<td>0.16</td>
<td>0.08</td>
</tr>
<tr>
<td>Power $P$</td>
<td>[kW]</td>
<td>495.4</td>
<td>385.8</td>
</tr>
</tbody>
</table>

Table: Temporal mean of model absolute errors.
Model consistently underestimated turbulence (waked and free)

- At both sites, better performance under free conditions
- High turbulence in measurements coincides with waked periods (large std. dev. over 10 minutes)
Model underestimated $\beta$ differences between the two turbines

Similar error magnitudes in free vs. waked: not from wake-induced meandering but other surface phenomena
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Results -- Post-Simulation Wake Correction

- **Jensen**\(^[6]\) wake
  \[
  VD(t) = \frac{1 - \sqrt{1 - C_T(t)}}{(1 + \frac{kx}{R})^2}
  \]
  \[
  U = U_\infty (1 - VD)
  \]

- **Advantages:**
  - easy to implement
  - avoids costly CFD + SFD

- **Disadvantages**
  - only wind speed (no TI/direction)

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\([6]\) Jensen (1983)
WRF-LES real case short validation exercise

(separately for "free" vs. "waked" conditions)

Clear impact of wake only appears on measurement site that is further onshore

Dangers of blindly applying a post-processing tool

(other error sources e.g. complex terrain, terra incognita)

Not there yet -- before worrying about turbine-induced turbulence, ensure adequate meso-micro coupling and high accuracy free stream ABL simulation