Understanding parameter sensitivities in mesoscale and microscale models

Colleen Kaul, Pacific Northwest National Laboratory

With thanks to Larry Berg and Yun Qian of PNNL and featuring results fromYang et al., 2017, Boundary-Layer Meteorology
Berg et al., 2019, Boundary-Layer Meteorology
Yang et al., 2019, JGR-Atmospheres
Motivation

- Use Uncertainty Quantification (UQ) techniques to identify important parameters in atmospheric models
  - Effort focused on understanding how sensitivity arises through the modeling assumptions of selected closures
  - How are the results affected by the underlying flow conditions? Are the sensitivity results physically interpretable?
- Identify key parameter sensitivities of models in order to
  - Determine the best deployment of observational resources to constrain sensitivities
  - Downselect parameters to allow future studies to be performed more efficiently and enable ensemble modeling
  - Develop insights to improve parameterizations
- I will present our basic approach and highlights of UQ studies of mesoscale and coupled LES models
UQ Methodology Overview

- Target widely used schemes that are relevant to research and industry and identify their parameters (WRF implementations)
  - Mesoscale: Mellor-Yamada-Nakanishi-Niino (MYNN) Level 2.5 PBL scheme (12), Yonsei University (YSU) PBL scheme (15), and MM5 Surface Layer scheme (14)
  - Microscale: Deardorff 1.5 order TKE-based turbulence closure (5 +1)

- Define ranges of parameter values based on literature, theoretical limits, or scientific intuition

- Run an ensemble of simulations using perturbed values selected via quasi-Monte Carlo or Latin Hypercube sampling to explore parameter space efficiently

- Construct models of the responses of the full simulations to allow statistical analysis (Generalized Linear Model, Random Forest, etc.)
Mesoscale UQ Experimental Design

- Identified periods in two contrasting seasons with high data quality during the Columbia Basin Wind Energy Study (CBWES)—WFIP 2 still ongoing at the time
  - February 2011: MYNN
  - May 2011: MYNN and YSU

- 10 km WRF parent simulation nested down to 3.3 km

- 256 ensemble members for each parameterization and case period
Sensitivity of 80-m Winds to BL Parameters: Daytime

- **Similar**
  - PBL $D_1$
  - PBL $Pr$
  - PBL $\alpha_5$
  - PBL $\beta$

- **Different**
  - PBL $D_1$
  - PBL $Pr$
  - PBL $\alpha_5$
  - PBL $\beta$

- **Colors:** Ensemble variance explained by each parameter
- **Subset of parameters from Yang et al. (2017)**
- **Recall flux predictions have the form:**
  \[ -\bar{u}\bar{w} = LqS_M \frac{\partial u}{\partial z} \]

Berg et al., 2019, Boundary-Layer Meteorology

Atmospheric Challenges for the Wind Energy Industry

February 12, 2021
Sensitivity of 80-m Winds to BL Parameters: Nighttime

- Patterns similar between February and May nighttime (and February daytime)
- Generally stable conditions at night regardless of the season

Berg et al., 2019, Boundary-Layer Meteorology
Ratio of buoyant suppression to shear production of turbulence

Directly impacts flux predictions via stability functions $S_M$, $S_H$, e.g.

$$- \bar{u} \bar{w} = L q S_M \frac{\partial u}{\partial z}$$

A key flow variable for understanding spatial and temporal patterns of sensitivity

- Can relate to terrain/land surface features, wind speed dependence etc.
Comparison of PBL Schemes

- Similar analysis performed with the YSU PBL Scheme
- Overall both MYNN and YSU schemes reproduced the diurnal cycle of wind speeds
- Inter-member variance is greater for MYNN scheme during the night, and for YSU scheme during the day
  - For both schemes, most variance is attributable to a few parameters
- Daytime biases in MYNN results suggest presence of structural error
  - Use of ensemble helps us separate structural error from calibration issues

Yang et al., 2019, JGR-Atmospheres

Diurnal cycle of wind speed at Butler Grade

OBS
MYNN
YSU
LES UQ Experimental Design

- Selected two periods during WFIP2 with high westerly winds and large surface heat fluxes: 22 July 2016, 21 Aug. 2016

- LES domains include Physics-site 12 with sonic anemometers at 50 m and 80 m elevations

- WRF 1.35 km mesoscale domain nested to 150 m and 50 m resolution LES domains

- Perturbed 5 parameters of the Deardorff TKE-based subgrid scale turbulence closure + roughness length, 64 ensemble members per period
LES Parameter Sensitivity

- Sensitivity of most quantities of interest is dominated by eddy viscosity coefficient $c_k$, with some complexities:
  - Sensitivities of quantities related to turbulent fluctuations are much weaker to nonexistent over $c_k < \sim 0.15$

- Example: Turbulent kinetic energy
  - Within the “insensitive” range, we can obtain agreement with obs
  - The wrong parameter choice can be disastrous!

$E = \text{TKE at timescales shorter 10 min} $

Blue dots are ensemble members
LES Parameter Sensitivity

- Sensitivity of most quantities of interest is dominated by eddy viscosity coefficient $c_k$, with some complexities:
  - Sensitivities of quantities related to turbulent fluctuations are much weaker to nonexistent over $c_k \approx 0.15$

- Example: Turbulent kinetic energy
  - Within the “insensitive” range, we can obtain agreement with obs
  - The wrong parameter choice can be disastrous!
  - Aside: Numerics matter for LES!

\[ E = \text{TKE at timescales shorter 10 min} \]

**Blue dots** are ensemble members

**Orange dots** are a subset of simulations using same parameters but different advection schemes

$E$ = TKE at timescales shorter 10 min

*Blue dots* are ensemble members

*Orange dots* are a subset of simulations using same parameters but different advection schemes
LES Parameter Sensitivity

- Sensitivity of most quantities of interest is dominated by eddy viscosity coefficient $c_k$, with some complexities:
  - Sensitivities of quantities related to turbulent fluctuations are much weaker to nonexistent over $c_k < \sim 0.15$
  - Other quantities are more sensitive at low $c_k$

- Example: Wind Shear
  - Computed between 50 m and 80 m levels
  - Sensitivity levels off at $c_k > \sim 0.2$
  - Better agreement with obs at $c_k$ below defaults

Good news: Despite the dependence of parameter sensitivity on the particular quantity of interest (and on numerics), we generally see that we can capture relevant flow characteristics with $c_k \sim 0.1$

Blue dots are ensemble members
Orange dots are a subset of simulations using same parameters but different advection schemes
LES Parameter Sensitivity

- Sensitivity of most quantities of interest is dominated by eddy viscosity coefficient $c_k$, with some complexities:
  - Sensitivities of quantities related to turbulent fluctuations are much weaker to nonexistent over $c_k < \sim 0.15$
  - Other quantities are more sensitive at low $c_k$

- Example: Wind Shear
  - Computed between 50 m and 80 m levels
  - Sensitivity levels off at $c_k > \sim 0.2$
  - Better agreement with obs at $c_k$ below defaults

Blue dots are ensemble members
Orange dots are a subset of simulations using same parameters but different advection schemes
Summary and Conclusions

- UQ techniques can be used to understand the parametric sensitivity of wind-energy relevant quantities simulated with WRF and identify possible structural errors.

- Sensitivities can be large, of practical importance, and show complex spatial and temporal dependence.

- Sensitivities are dominated by a few parameters and these sensitivities can be related to flow physics we know, especially for mesoscale models.

**Reasons for optimism!**
Conclusion
Wind speed and wind power predictions are highly sensitive to the values of PBL Parameters.
Comparison of PBL Schemes

Ensemble mean and inter-member variance from the May period

**Mean**
- **Daytime**
- **Nighttime**

**Variance**
- **Daytime**
- **Nighttime**
Sensitivity of 80-m Winds to Boundary-Layer Parameters to Terrain Slope

Daytime
Nighttime

Closure Constants

Length Scales

TKE dissipation rate
TKE Diffusion
Pr Number

\[ C_2 \]

\[ C_3 \]

\[ \gamma_1 \]

\[ \alpha_1 \]

\[ I_s = \begin{cases} 
\frac{kz}{3.7} & \zeta \geq 1 \\
\frac{kz}{1 + 2.7\zeta} & 0 \leq \zeta < 1 \\
\frac{kz(1 - 100\zeta)}{2} & \zeta < 0 
\end{cases} \]
Response of 80-m wind to PBL parameters at CBWES

Daytime
Nighttime

Anomaly wind speed: Difference from average over the study period

TKE Dissipation Rate

Pr Number

Variability associated with other parameters

Variability associated with parameter

Length Scale Factor

Length Scale Exponent

\[
k_{z}/3.7 \quad \zeta \geq 1
\]

\[
k_{z}/(1+2.7\zeta) \quad 0 \leq \zeta < 1
\]

\[
k_{z}(1-100\zeta^{0.2}) \quad \zeta < 0
\]
Response of 80-m wind to PBL parameters at all sites

<table>
<thead>
<tr>
<th>TKE Dissipation Rate</th>
<th>Pr Number</th>
<th>Length Scale Factor</th>
<th>Length Scale Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) CBWES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) Hanford</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c) Big Horn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(d) Pebble Springs</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Daytime
Nighttime

Consistent Results for All Locations
Sensitivity of 80-m Winds to Surface Parameters: Relative Contribution

Main factors: $z_0$ and $k$

**Daytime**

**Nighttime**

Elevation
Sensitivity of 80-m Winds to Surface Parameters: Relative Contribution

Main factors: $z_0$ and $k$

Daytime (6-18 LST)
Sensitivity of 80-m Winds to Surface Parameters: Relative Contribution

- Main factors: $z_0$ and $k$

Daytime (6-17 LST)

Relative Contribution: $z_0$

Relative Contribution: Von Karman

Atmospheric Challenges for the Wind Energy Industry
Sensitivity of 80-m Winds to Surface Parameters: Relative Contribution

Main factors: $z_0$ and $k$, increased dependence on M-O functions

Nighttime (18-5 LST)
### Identification of Surface Parameters

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>description</th>
<th>default value</th>
<th>estimated range</th>
</tr>
</thead>
<tbody>
<tr>
<td>x1</td>
<td>X=(1.-16.*zolf)**(1/4) Used for the calculation of psim_unstable</td>
<td>16</td>
<td>(14, 18)</td>
</tr>
<tr>
<td>x2</td>
<td>X=(1.-16.*zolf)**(1/4)</td>
<td>4</td>
<td>(3.5, 4.5)</td>
</tr>
<tr>
<td>y1</td>
<td>Y=(1.-16.*zolf)**(1/2) Used for the calculation of psih_unstable</td>
<td>16</td>
<td>(14, 18)</td>
</tr>
<tr>
<td>y2</td>
<td>Y=(1.-16.*zolf)**(1/2)</td>
<td>2</td>
<td>(1.5, 2.5)</td>
</tr>
<tr>
<td>ym1</td>
<td>YM=(1.-10.*zolf)**(1/3) Used for the calculation of psim_unstable</td>
<td>10</td>
<td>(9.7, 11.6)</td>
</tr>
<tr>
<td>ym2</td>
<td>YM=(1.-10.*zolf)**(1/3)</td>
<td>3</td>
<td>(2.5, 3.5)</td>
</tr>
<tr>
<td>yh1</td>
<td>YH=(1.-34.*zolf)**(1/3) Used for the calculation of psih_unstable</td>
<td>34</td>
<td>(26, 42)</td>
</tr>
<tr>
<td>yh2</td>
<td>YH=(1.-34.*zolf)**(1/3)</td>
<td>3</td>
<td>(3.0, 3.5)</td>
</tr>
<tr>
<td>ms1</td>
<td>psim_stable=-6.1*log(zolf+(1+zolf<strong>2.5)</strong>(1./2.5))</td>
<td>6.1</td>
<td>(4.8, 9.4)</td>
</tr>
<tr>
<td>ms2</td>
<td>psim_stable=-6.1*log(zolf+(1+zolf<strong>2.5)</strong>(1./2.5))</td>
<td>2.5</td>
<td>(1.1, 2.5)</td>
</tr>
<tr>
<td>hs1</td>
<td>psih_stable=-5.3*log(zolf+(1+zolf<strong>1.1)</strong>(1./1.1))</td>
<td>5.3</td>
<td>(4.5, 9)</td>
</tr>
<tr>
<td>hs2</td>
<td>psih_stable=-5.3*log(zolf+(1+zolf<strong>1.1)</strong>(1./1.1))</td>
<td>1.1</td>
<td>(1.1, 2.5)</td>
</tr>
<tr>
<td>znt_factor</td>
<td>znt_new=znt*znt_factor</td>
<td>1</td>
<td>(1.0, 2.0)</td>
</tr>
<tr>
<td>karman</td>
<td>Von Karman constant</td>
<td>0.4</td>
<td>(0.35, 0.4)</td>
</tr>
</tbody>
</table>

Von Karman constant
## Identification of Boundary-Layer Parameters

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Description</th>
<th>Default Value</th>
<th>Estimated Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_1$</td>
<td>TKE dissipation rate</td>
<td>24</td>
<td>(12, 36)</td>
</tr>
<tr>
<td>$sqfac$</td>
<td>TKE Diffusion factor</td>
<td>2</td>
<td>(1.5, 4.5)</td>
</tr>
<tr>
<td>$pr$</td>
<td>Turbulent Prandtl number</td>
<td>0.74</td>
<td>(0.5, 2)</td>
</tr>
<tr>
<td>$c_3$</td>
<td>Closure constant</td>
<td>0.34</td>
<td>(0.33, 0.5)</td>
</tr>
<tr>
<td>$c_5$</td>
<td>Closure constant</td>
<td>0.2</td>
<td>(0.1, 0.3)</td>
</tr>
<tr>
<td>$g_1$</td>
<td>Closure constant</td>
<td>0.229</td>
<td>(0.1768, 0.2395)</td>
</tr>
<tr>
<td>$alp_1$</td>
<td>Used in calculation of the turbulence length scale (LT)</td>
<td>0.23</td>
<td>(0.115, 0.345)</td>
</tr>
<tr>
<td>$alp_2$</td>
<td>Used in calculation of the turbulence length scale (LB)</td>
<td>0.65</td>
<td>(0.5, 1.0)</td>
</tr>
<tr>
<td>$alp_3$</td>
<td>Used in calculation of the turbulence length scale (LB)</td>
<td>3</td>
<td>(2.5, 7.5)</td>
</tr>
<tr>
<td>$alp_4$</td>
<td>Used in calculation of the turbulence length scale (LS)</td>
<td>20</td>
<td>(20, 100)</td>
</tr>
<tr>
<td>$cns$</td>
<td>Used in calculation of the turbulence length scale (LS)</td>
<td>2.1</td>
<td>(1.35, 4.05)</td>
</tr>
<tr>
<td>$ls_{exp}$</td>
<td>Exponent on equation to determine LS that is based on results from LES</td>
<td>0.2</td>
<td>(0.1, 0.3)</td>
</tr>
</tbody>
</table>

### Closure Constants

- $b_1$: TKE dissipation rate
- $sqfac$: TKE Diffusion factor
- $pr$: Turbulent Prandtl number

### Length Scales

- $alp_1$: Used in calculation of the turbulence length scale (LT)
- $alp_2$: Used in calculation of the turbulence length scale (LB)
- $alp_3$: Used in calculation of the turbulence length scale (LB)
- $alp_4$: Used in calculation of the turbulence length scale (LS)
- $cns$: Used in calculation of the turbulence length scale (LS)
- $ls_{exp}$: Exponent on equation to determine LS that is based on results from LES