Understanding parameter sensitivities in mesoscale and microscale models

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With thanks to Larry Berg and Yun Qian of PNNL and featuring results from

Yang et al., 2017, Boundary-Layer Meteorology

Berg et al., 2019, Boundary-Layer Meteorology

Yang et al., 2019, JGR-Atmospheres

Motivation

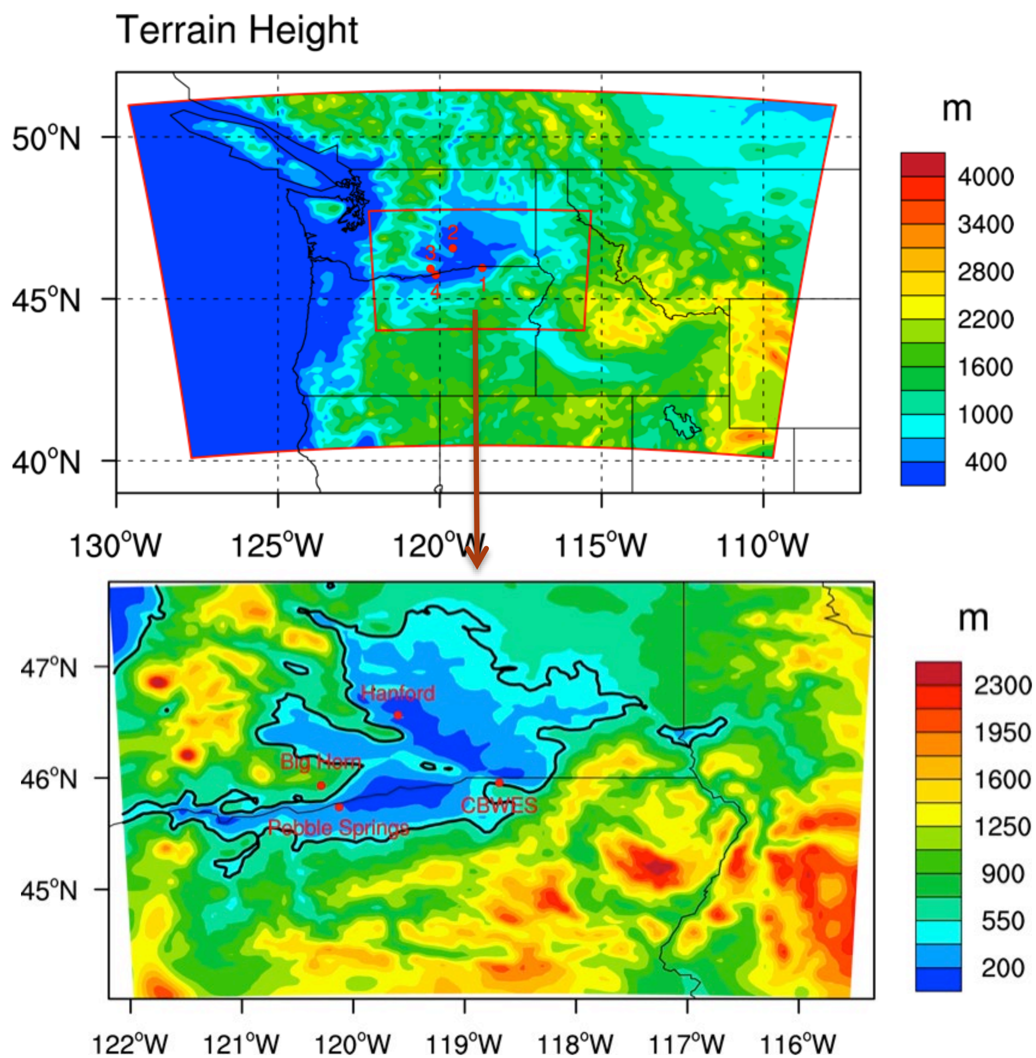
- Use Uncertainty Quantification (UQ) techniques to identify important parameters in atmospheric models
  - Effort focused on understanding how sensitivity arises through the modeling assumptions of selected closures
  - **How are the results affected by the underlying flow conditions? Are the sensitivity 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*

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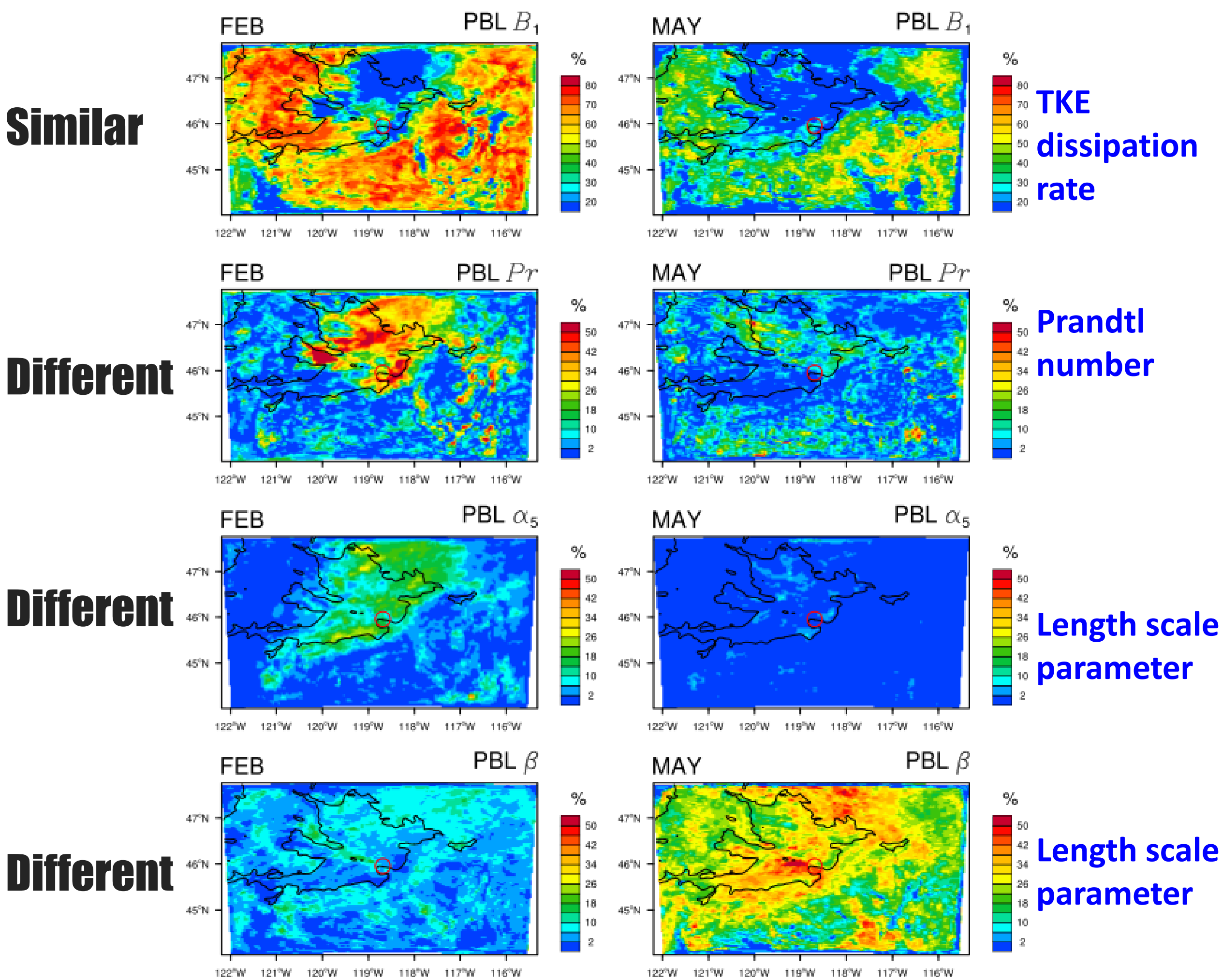

- Colors: Ensemble variance explained by each parameter
- Subset of parameters from Yang et al. (2017)
- Recall flux predictions have the form:

$$-\overline{u'w'} = LqS_M \frac{\partial u}{\partial z}$$

Berg et al., 2019, Boundary-Layer Meteorology

Sensitivity of 80-m Winds to *BL Parameters: Nighttime*

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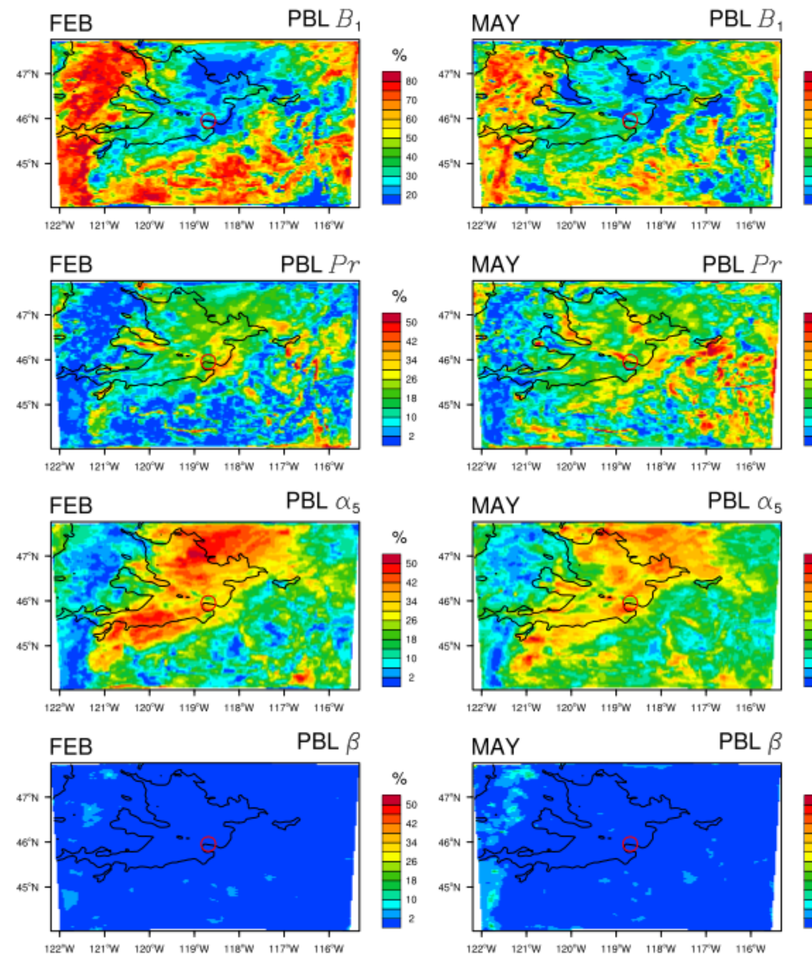
- Patterns similar between February and May nighttime (and February daytime)
- Generally stable conditions at night regardless of the season



Similar — TKE dissipation rate

Similar — Prandtl number

Similar — Length scale parameter

Similar — Length scale parameter

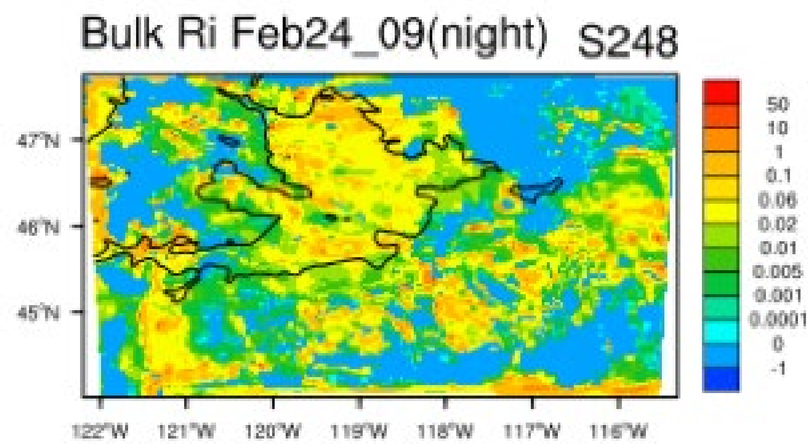
Berg et al., 2019, Boundary-Layer Meteorology

Interpretation via Richardson number

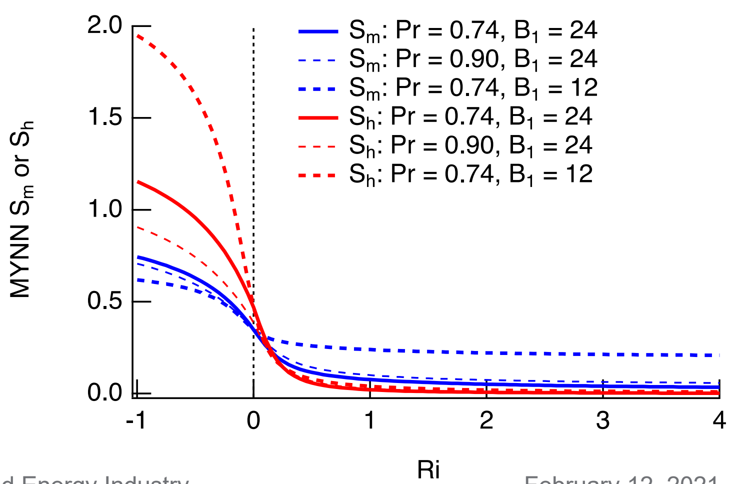
- Ratio of buoyant suppression to shear production of turbulence
- Directly impacts flux predictions via stability functions S_M, S_H, *e.g.*

$$-\overline{u'w'} = LqS_M \frac{\partial u}{\partial z}$$

- A key flow variable for understanding spatial and temporal patterns of sensitivity
  - Can relate to terrain/land surface features, wind speed dependence etc.



Unstable Stable



Comparison of PBL Schemes

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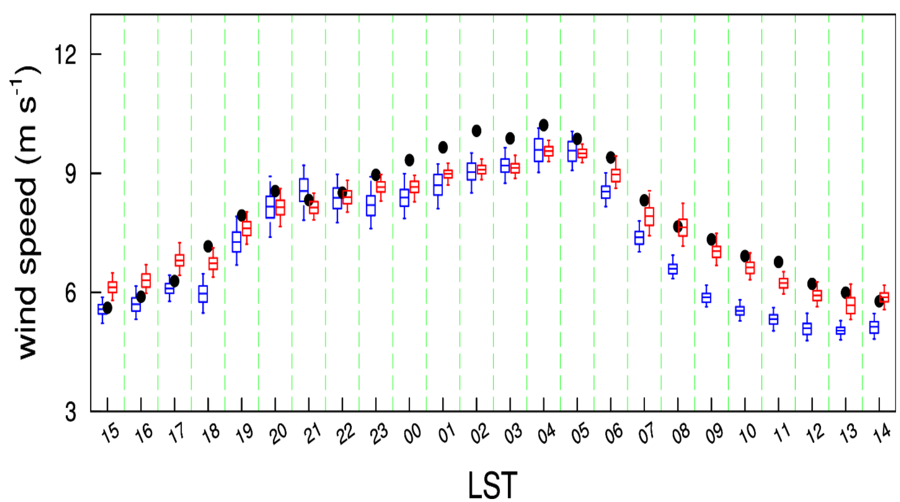
- Similar analysis performed with the YSU PBL Scheme
- Overall both MYNN and YSU schemes reproduced the diurnal cycle of wind speeds
- Inter-member variance is greater for MYNN scheme during the night, and for YSU scheme during the day
  - For both schemes, most variance is attributable to a few parameters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



Diurnal cycle of wind speed at Butler Grade

OBS
MYNN
YSU

Yang et al., 2019, JGR-Atmospheres

LES UQ Experimental Design

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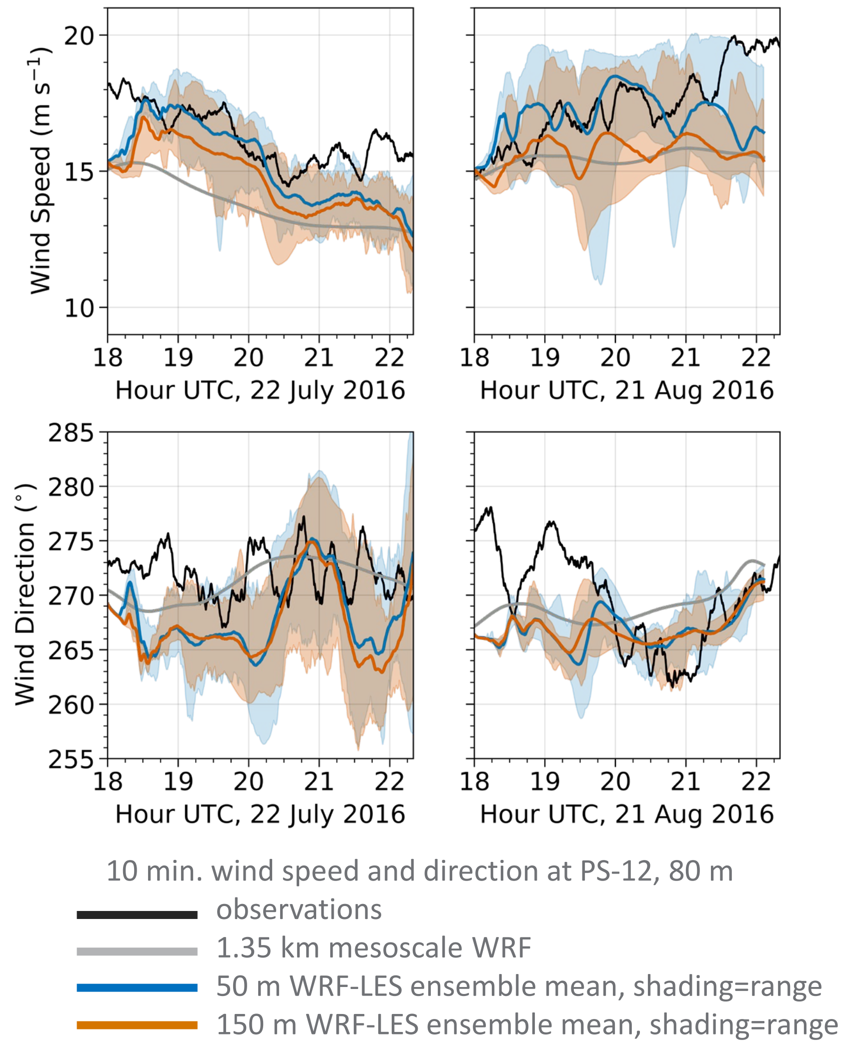
- Selected two periods during WFIP2 with high westerly winds and large surface heat fluxes: 22 July 2016, 21 Aug. 2016
- LES domains include Physics-site 12 with sonic anemometers at 50 m and 80 m elevations
- WRF 1.35 km mesoscale domain nested to 150 m and 50 m resolution LES domains
- Perturbed 5 parameters of the Deardorff TKE-based subgrid scale turbulence closure + roughness length, 64 ensemble members per period



LES Parameter Sensitivity

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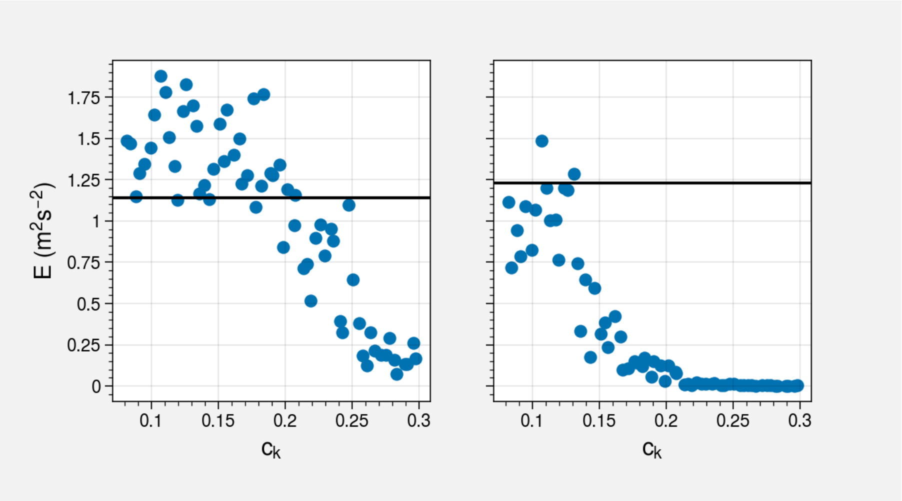
- Sensitivity of most quantities of interest is dominated by eddy viscosity coefficient c_k, with some complexities:
  - Sensitivities of quantities related to turbulent fluctuations are much weaker to nonexistent over c_k <~0.15



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

E = TKE at timescales shorter 10 min
Blue dots are ensemble members

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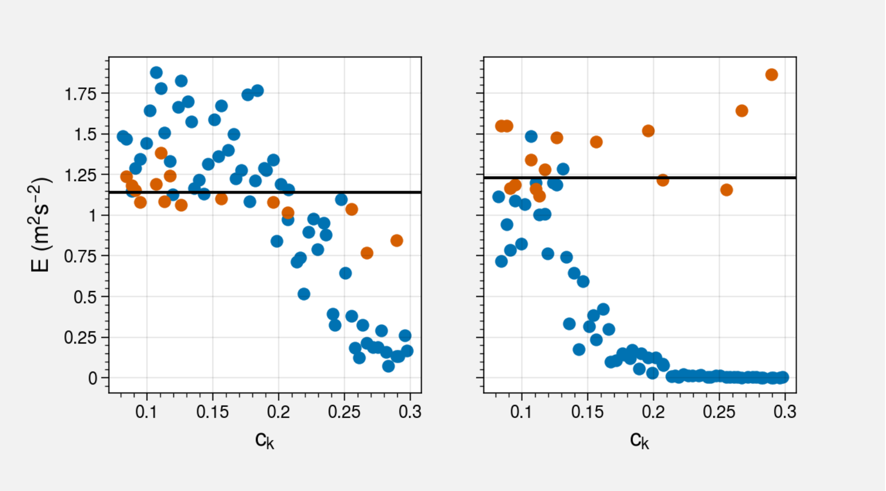

- Example: Turbulent kinetic energy
  - Within the “insensitive” range, we can obtain agreement with obs
  - The wrong parameter choice can be disastrous!
  - Aside: Numerics matter for LES!

E = 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

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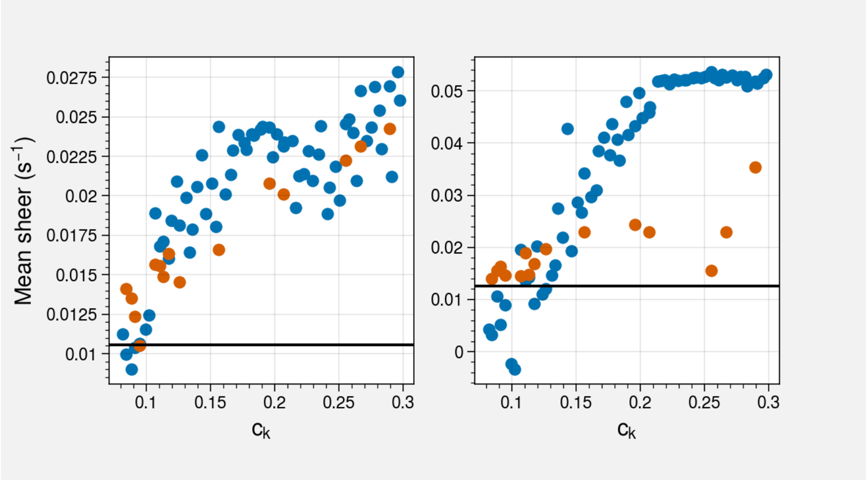
- Sensitivity of most quantities of interest is dominated by eddy viscosity coefficient c_k, with some complexities:
  - Sensitivities of quantities related to turbulent fluctuations are much weaker to nonexistent over c_k <~0.15
  - **Other quantities are more sensitive at low c_k**
- Example: Wind Shear
  - Computed between 50 m and 80 m levels
  - Sensitivity levels off at c_k >~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~0.1

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

LES Parameter Sensitivity

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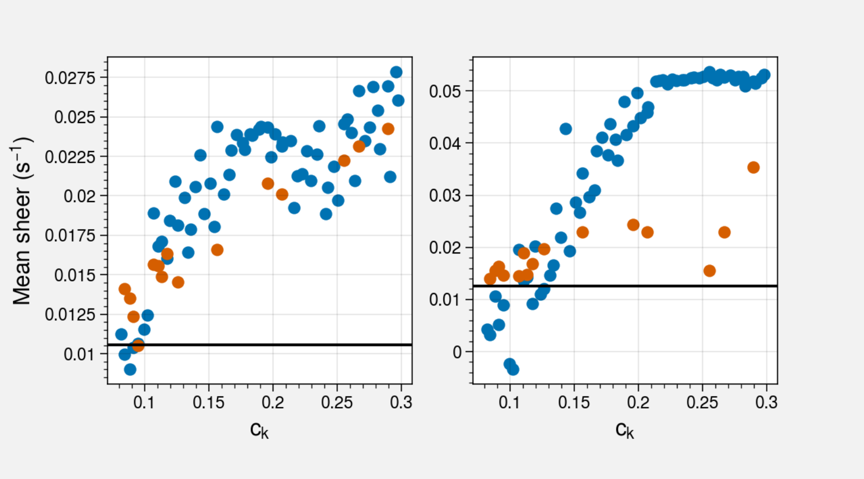

Blue dots are ensemble members
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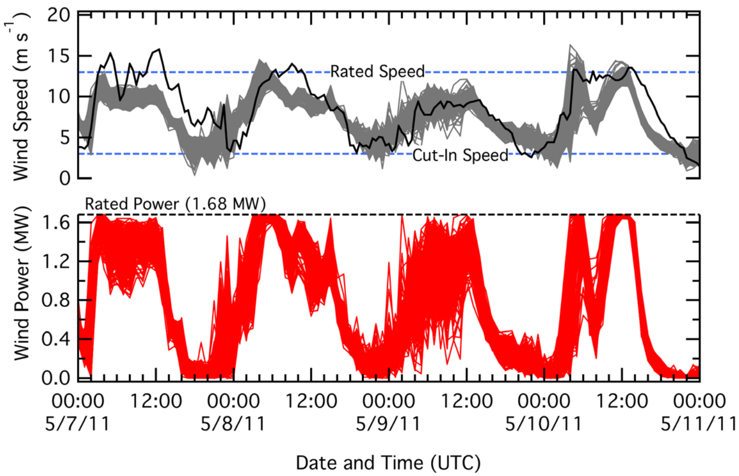
Summary and Conclusions

- 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

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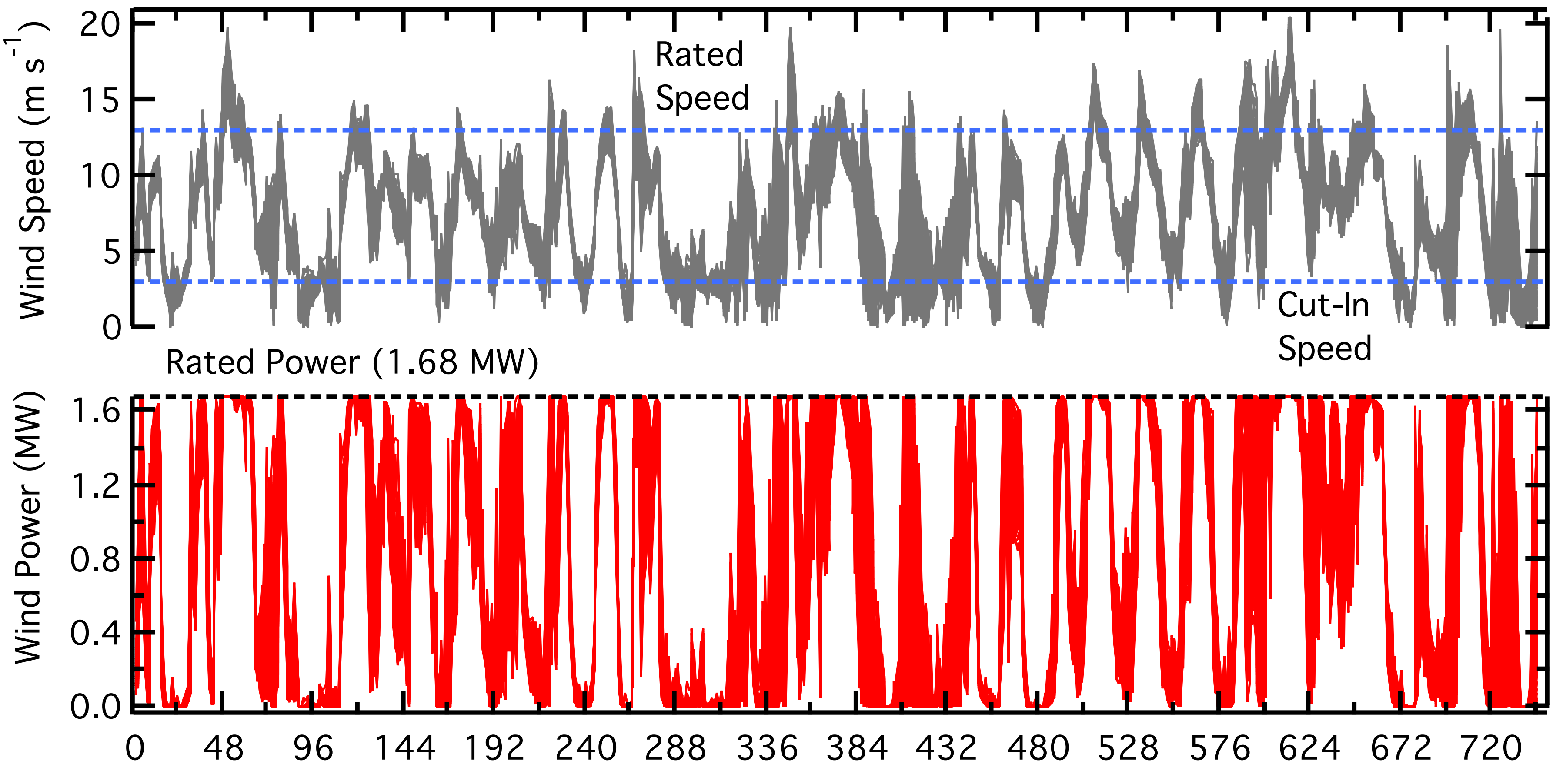
Impact on Wind Power

- Wind speed and wind power predictions are highly sensitive to the values of **PBL Parameters**



Comparison of PBL Schemes

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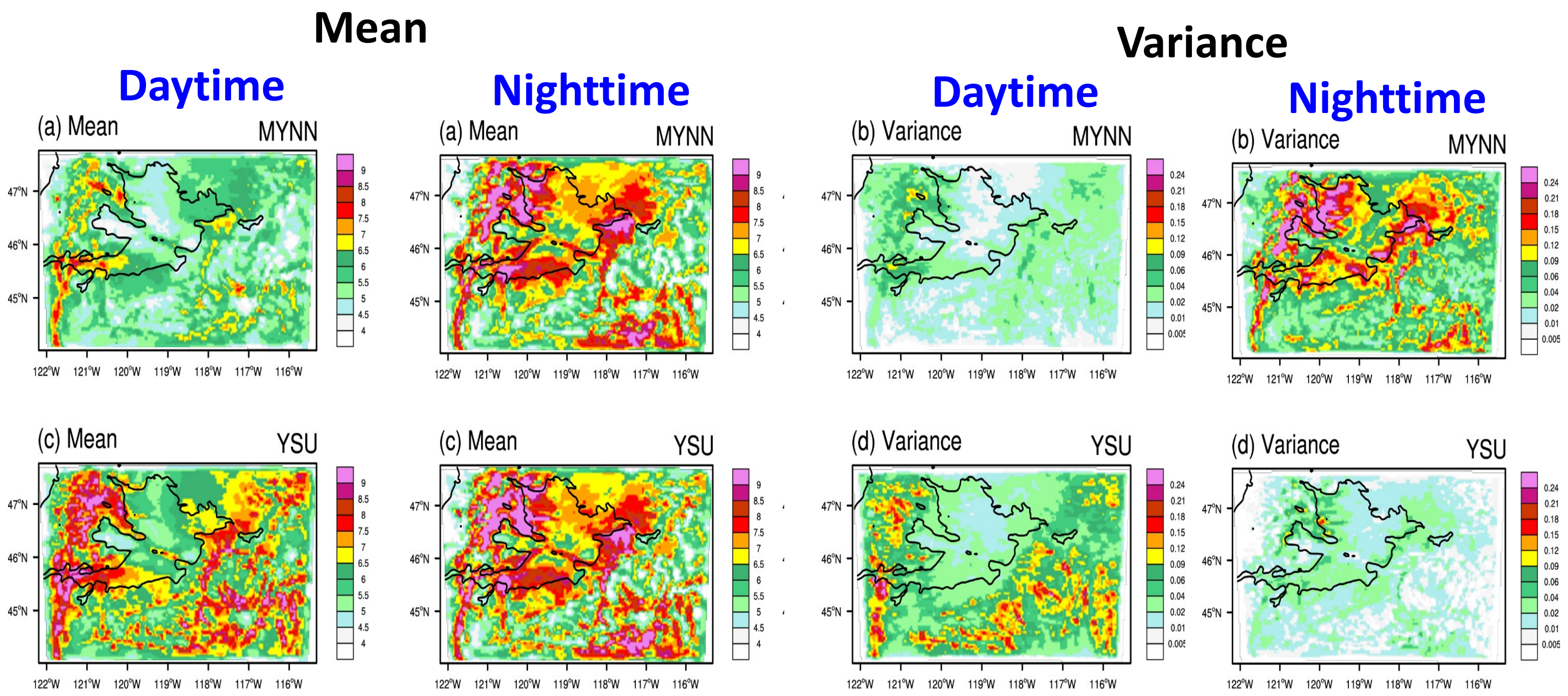
- Ensemble mean and inter-member variance from the May period



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

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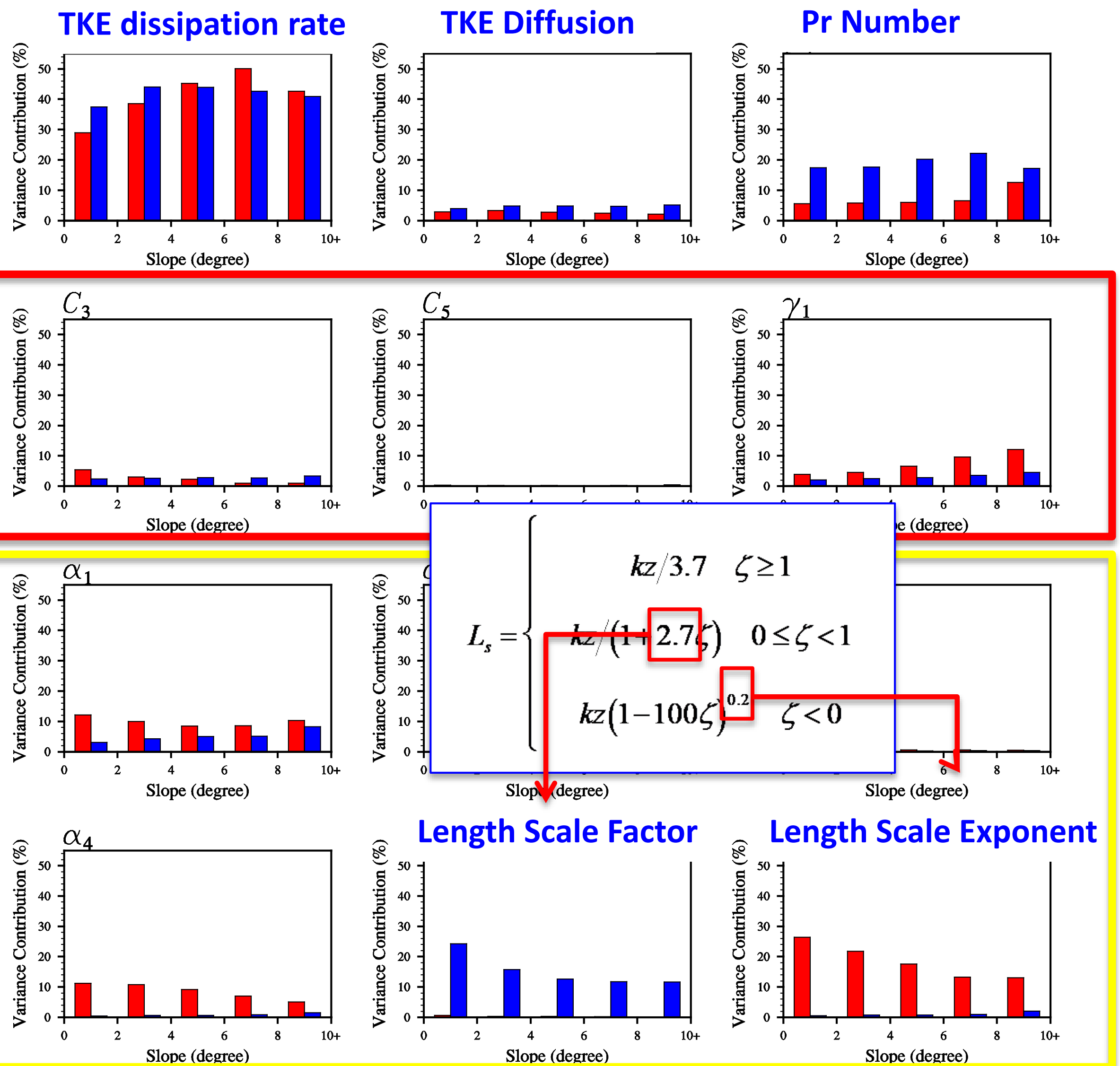
Daytime
Nighttime

Closure Constants

Length Scales



Response of *80-m wind* to PBL parameters at CBWES

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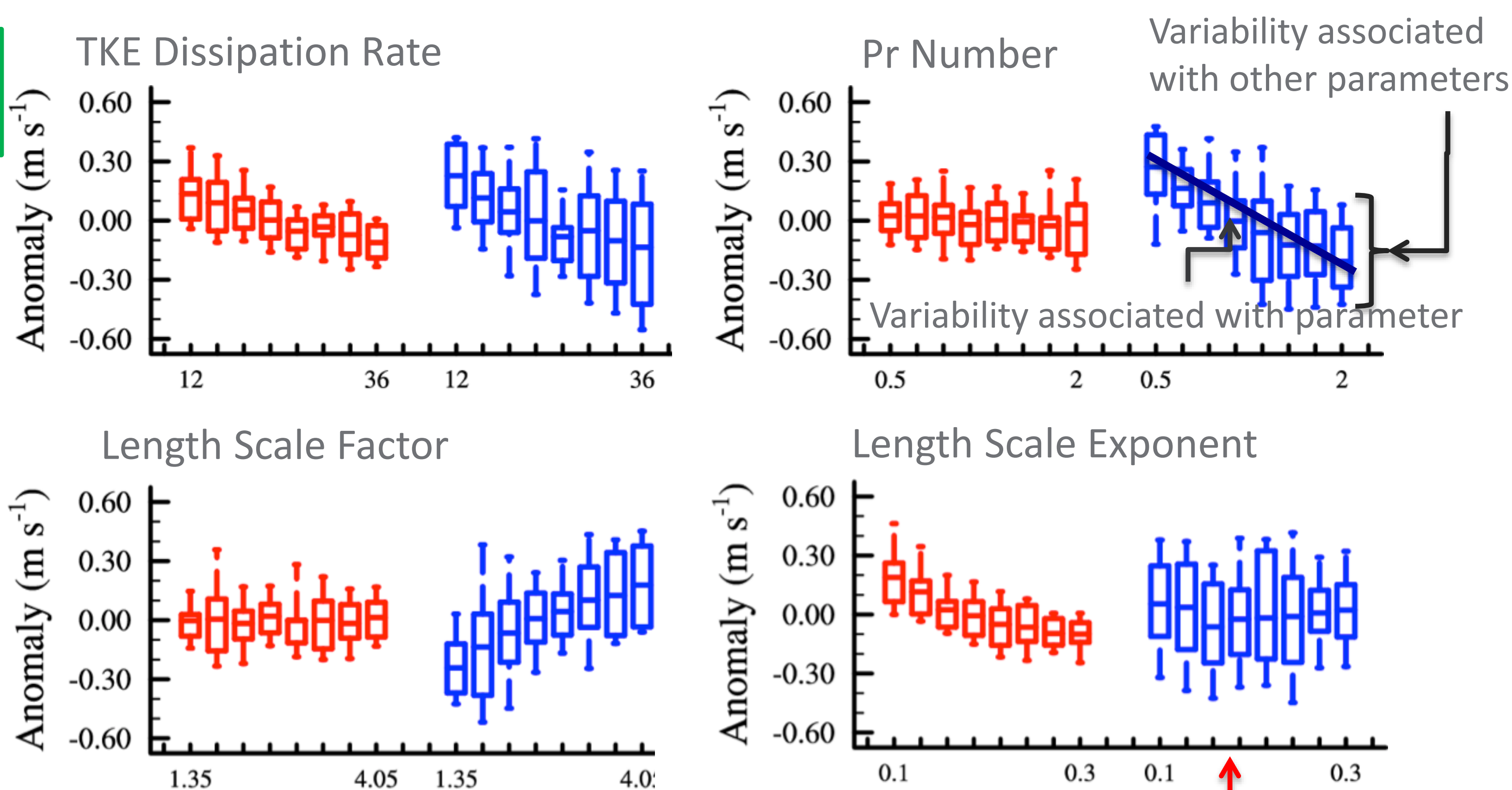
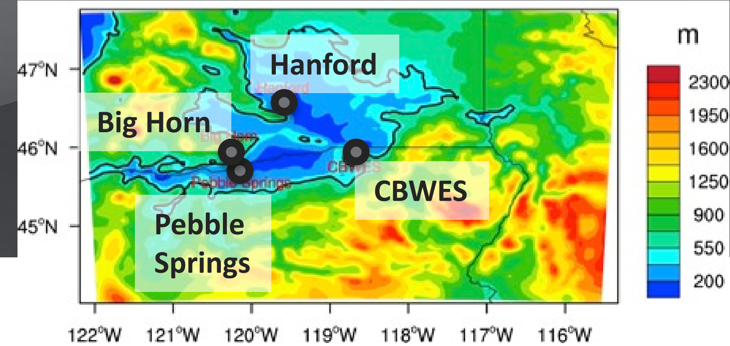
Daytime
Nighttime



$$L_s = \begin{cases} kz/3.7 & \zeta \geq 1 \\ kz/(1+2.7\zeta) & 0 \leq \zeta < 1 \\ kz(1-100\zeta)^{0.2} & \zeta < 0 \end{cases}$$

Anomaly wind speed: Difference from average over the study period

Response of *80-m wind* to PBL parameters at all sites

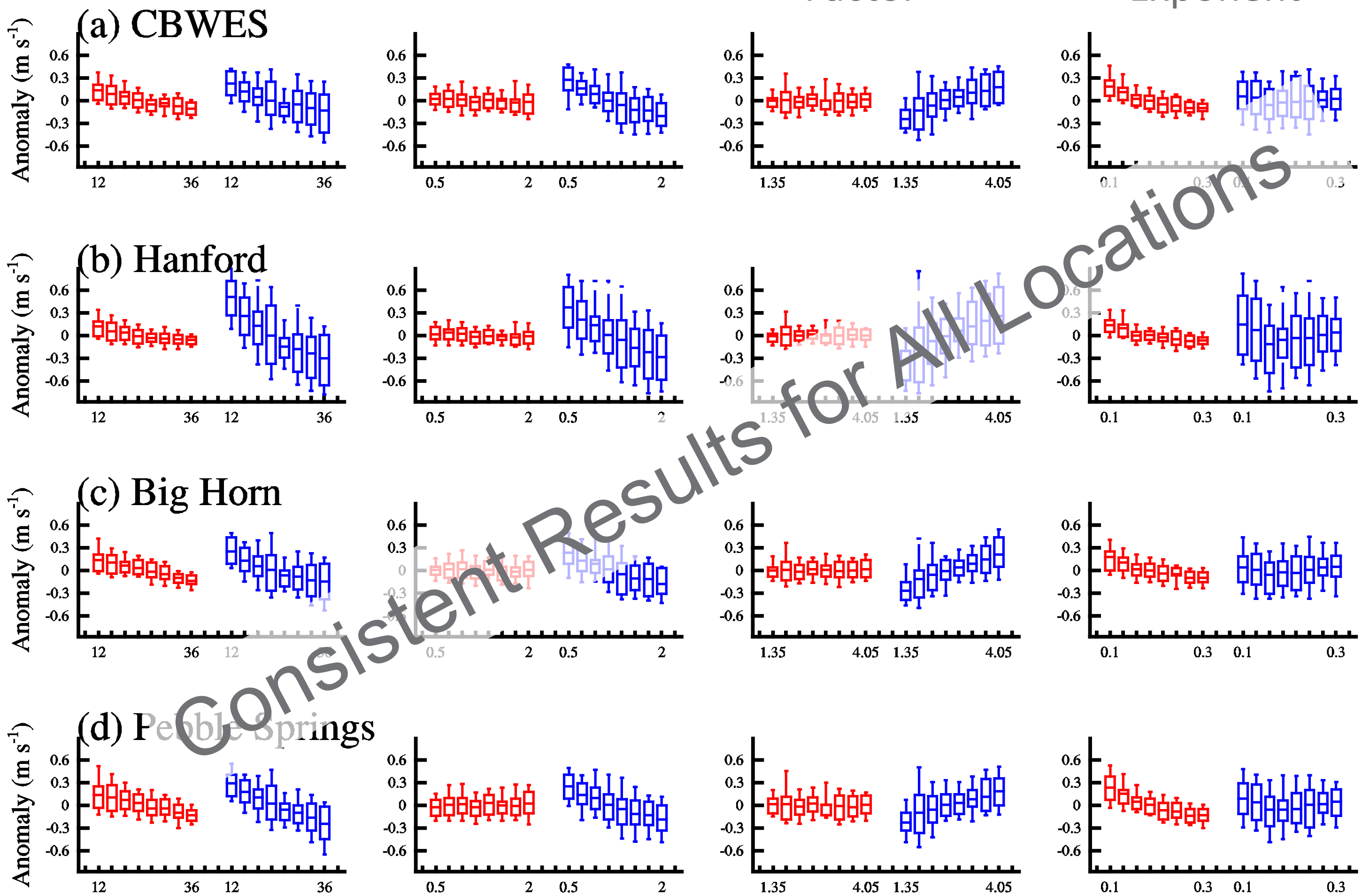


TKE Dissipation Rate

Pr Number

Length Scale Factor

Length Scale Exponent

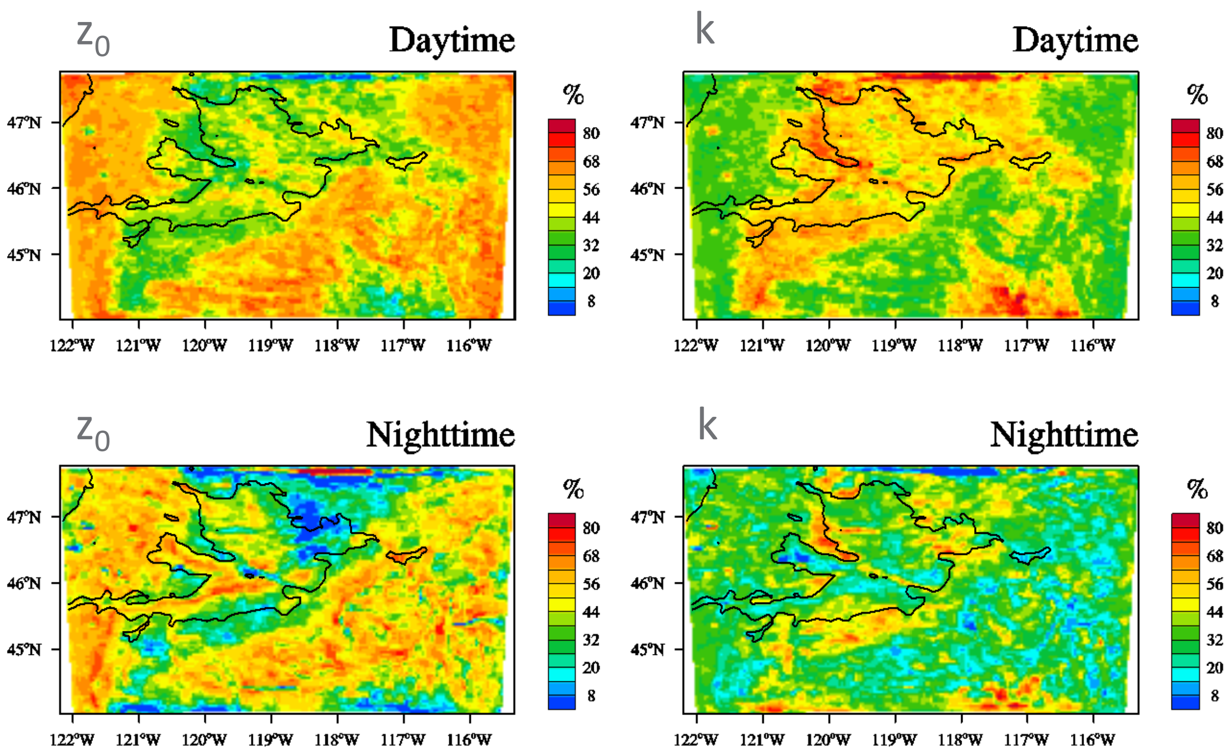


Consistent Results for All Locations

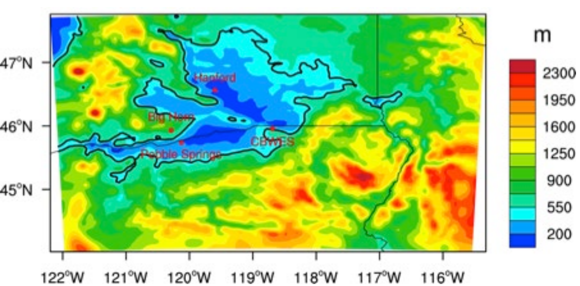
Daytime
Nighttime

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

- Main factors: z_0 and k



Elevation



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

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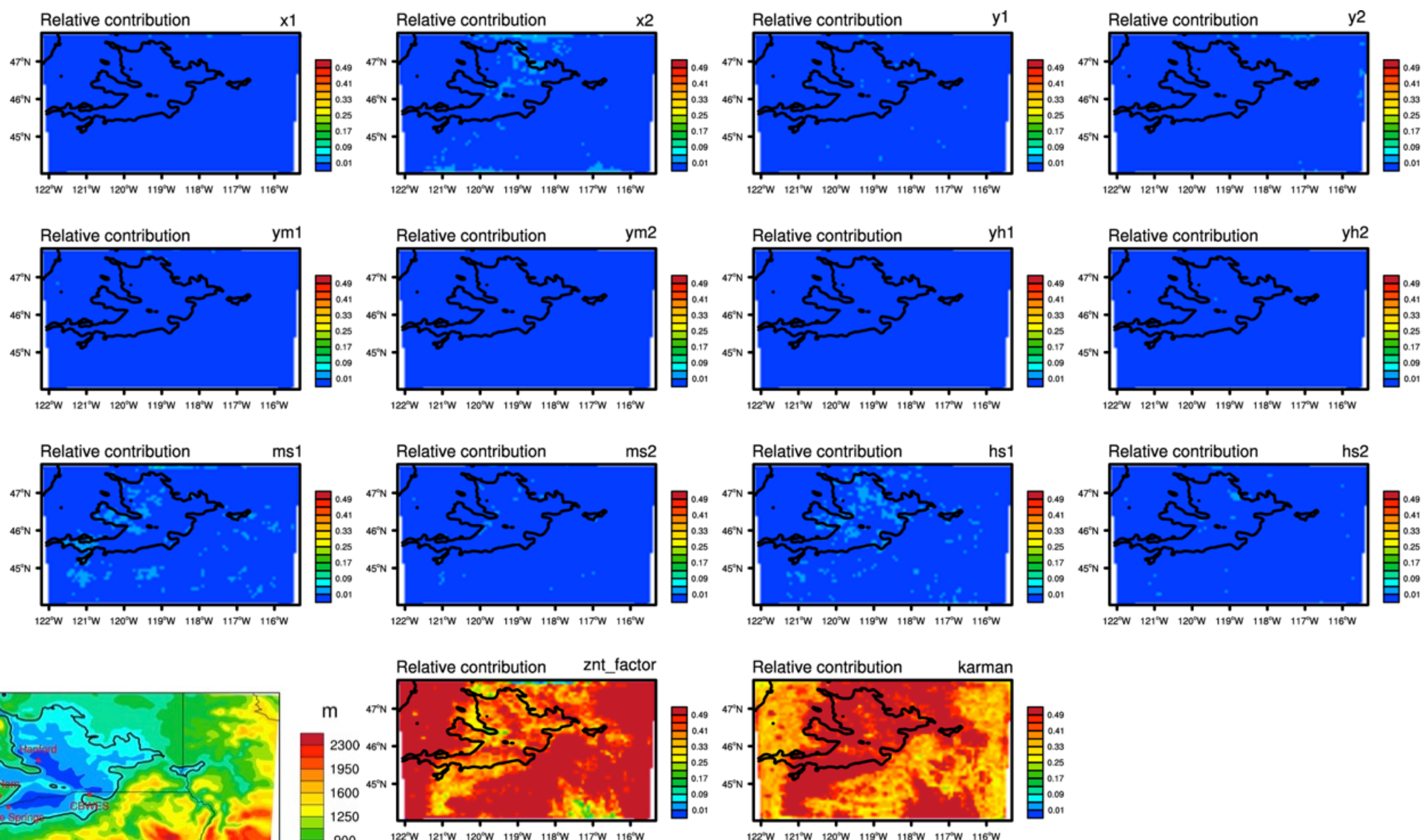
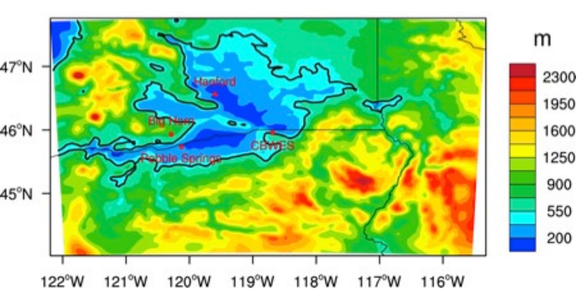
- Main factors: z_0 and k

Daytime (6-18 LST)



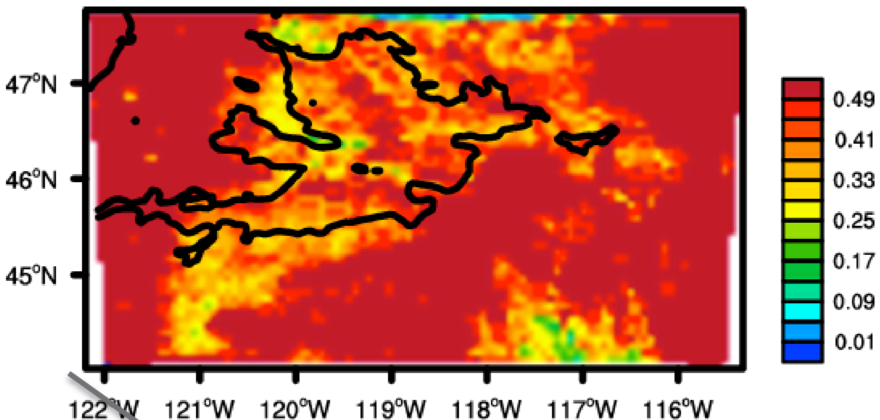


Sensitivity of 80-m Winds to *Surface* Parameters: Relative Contribution

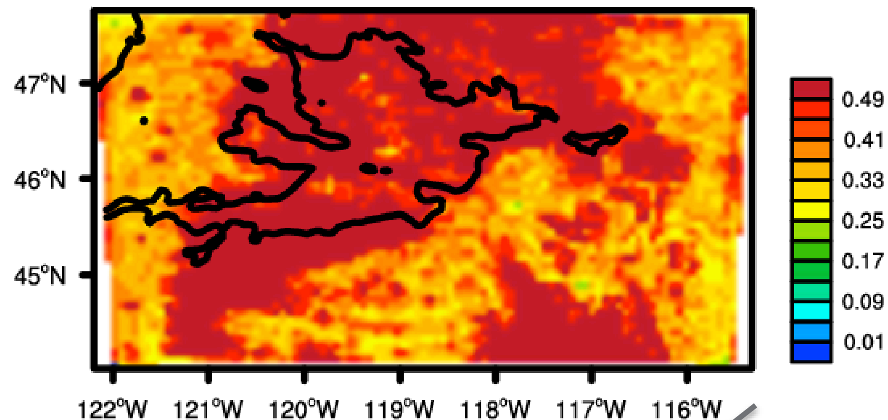
- Main factors: z_0 and k

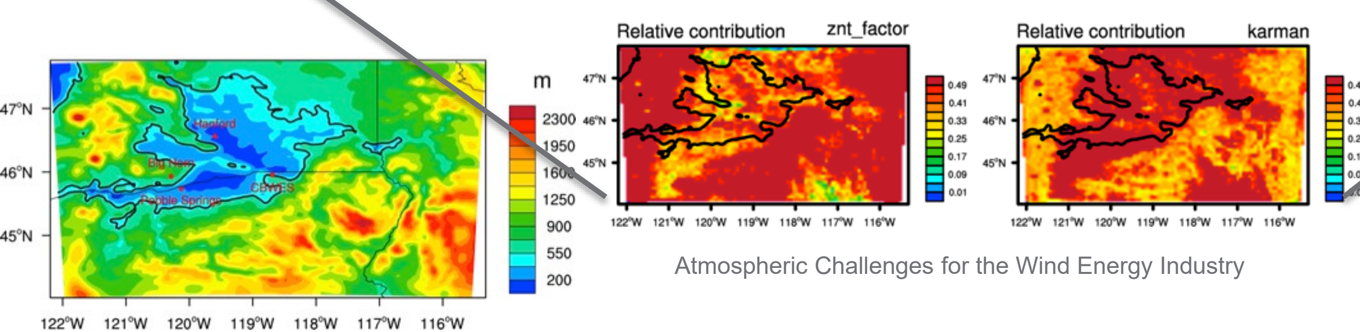
Daytime (6-17 LST)

Relative Contribution: z_0



Relative Contribution: Von Karman





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

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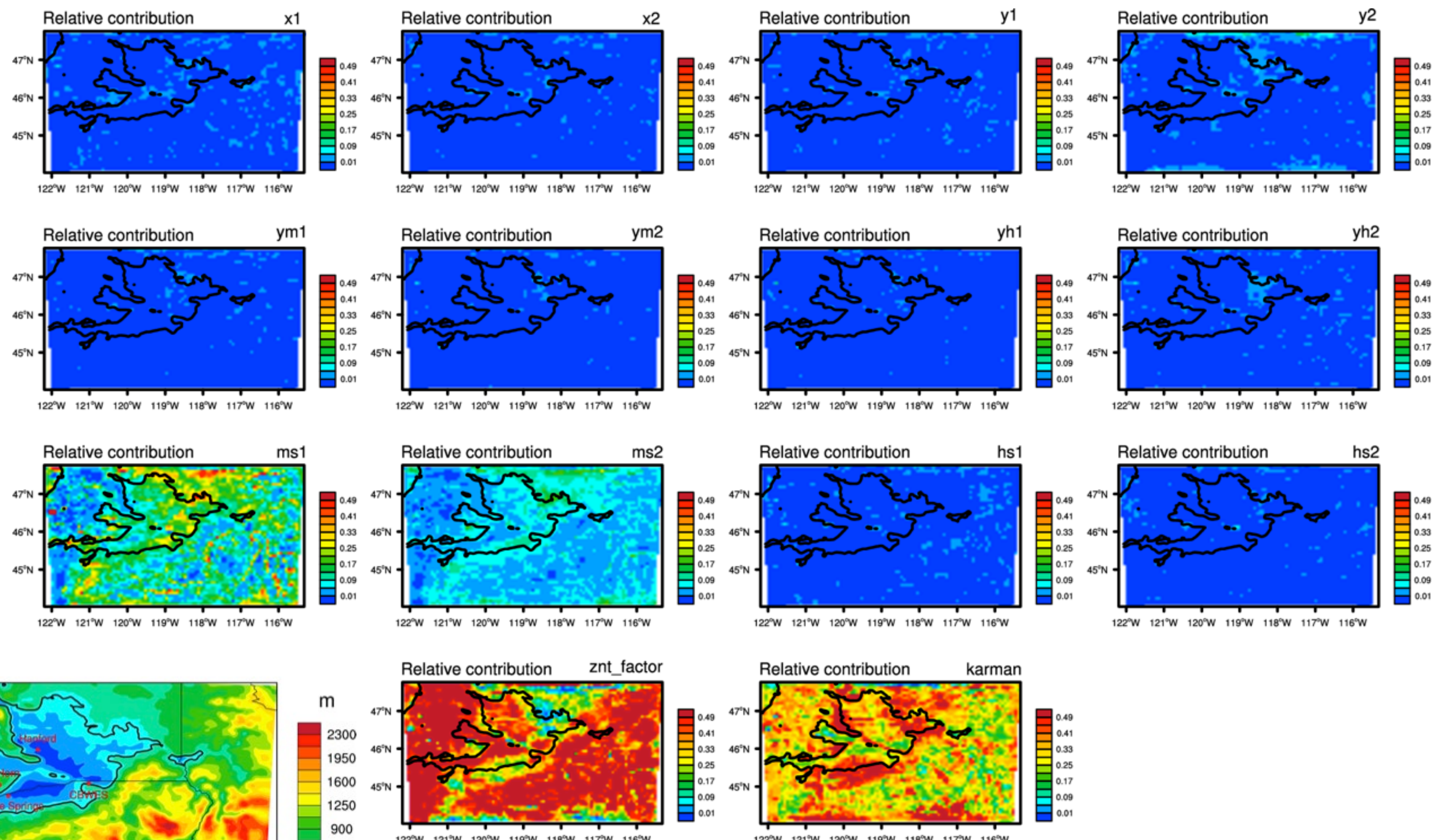
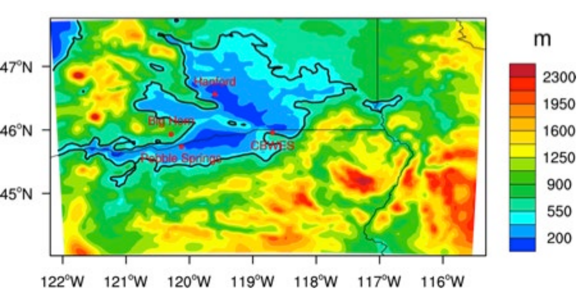
- Main factors: z_0 and k, increased dependence on M-O functions

Nighttime (18-5 LST)





Identification of Surface Parameters

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

Identification of Boundary-Layer Parameters

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TKE dissipation rate

TKE Diffusion

Pr Number

Parameter name	description	default value	estimated range
b1	...finition of the dissipation rates	24	(12,36)
sqfac	...on factor	2	(1.5, 4.5)
pr	...Prandtl number	0.74	(0.5, 2)
c3	closure constant	0.34	(0.33, 0.5)
c5	closure constant	0.2	(0.1, 0.3)
g1	closure constant	0.229	(0.1768, 0.2395)
alp1	Used in calculation of the turbulence length scale (LT)	0.23	(0.115, 0.345)
alp2	Used in calculation of the turbulence length scale (LB)	0.65	(0.5, 1.0)
alp3	Used in calculation of the turbulence length scale (LB)	3	(2.5, 7.5)
alp4	Used in calculation of the turbulence length scale (LS)	20	(20, 100)
cns	Used in calculation of the turbulence length scale (LS)	2.1	(1.35, 4.05)
ls_exp	Exponent on equation to determine LS that is based on results from LES	0.2	(0.1, 0.3)

Closure Constants

Length Scales