Evaluation of A 3D PBL Parameterization For Simulations of A Flow Over Complex Terrai

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1 – Nataional Center for Atmospheric Research,
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DOE EERE: DE-EE0006898 & NCAR ASD

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Evaluation of Large-Eddy Simulations of A Flow Over Complex Terrain

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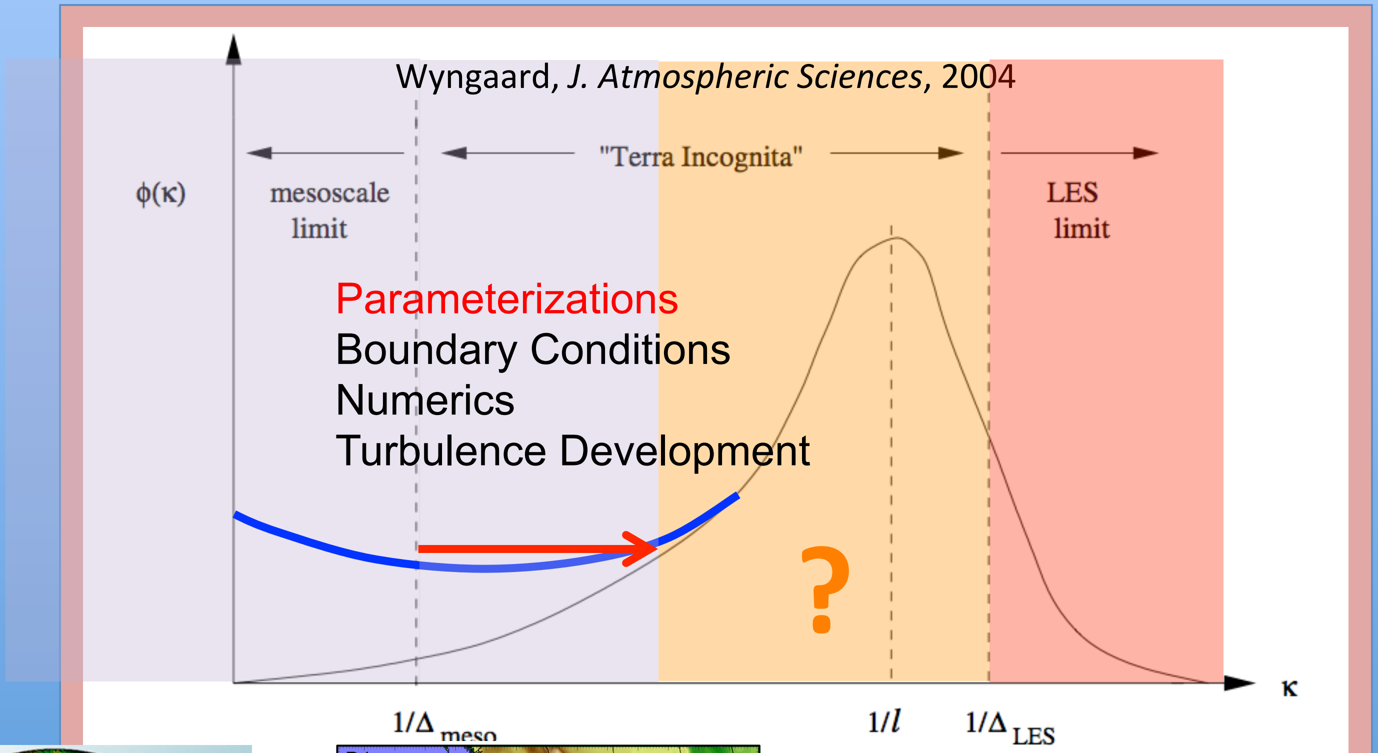
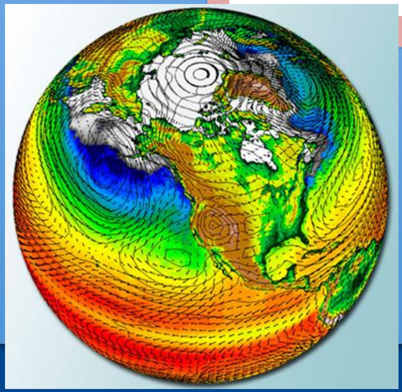
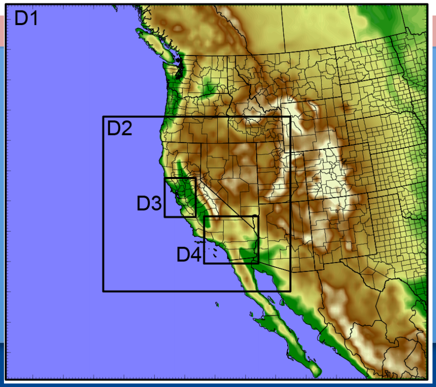
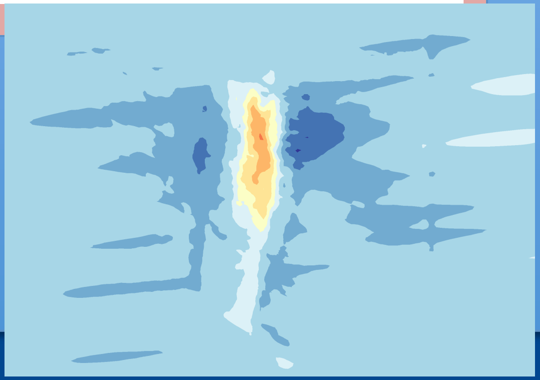
What is the effective approach to simulating mesoscale-microscale interactions?









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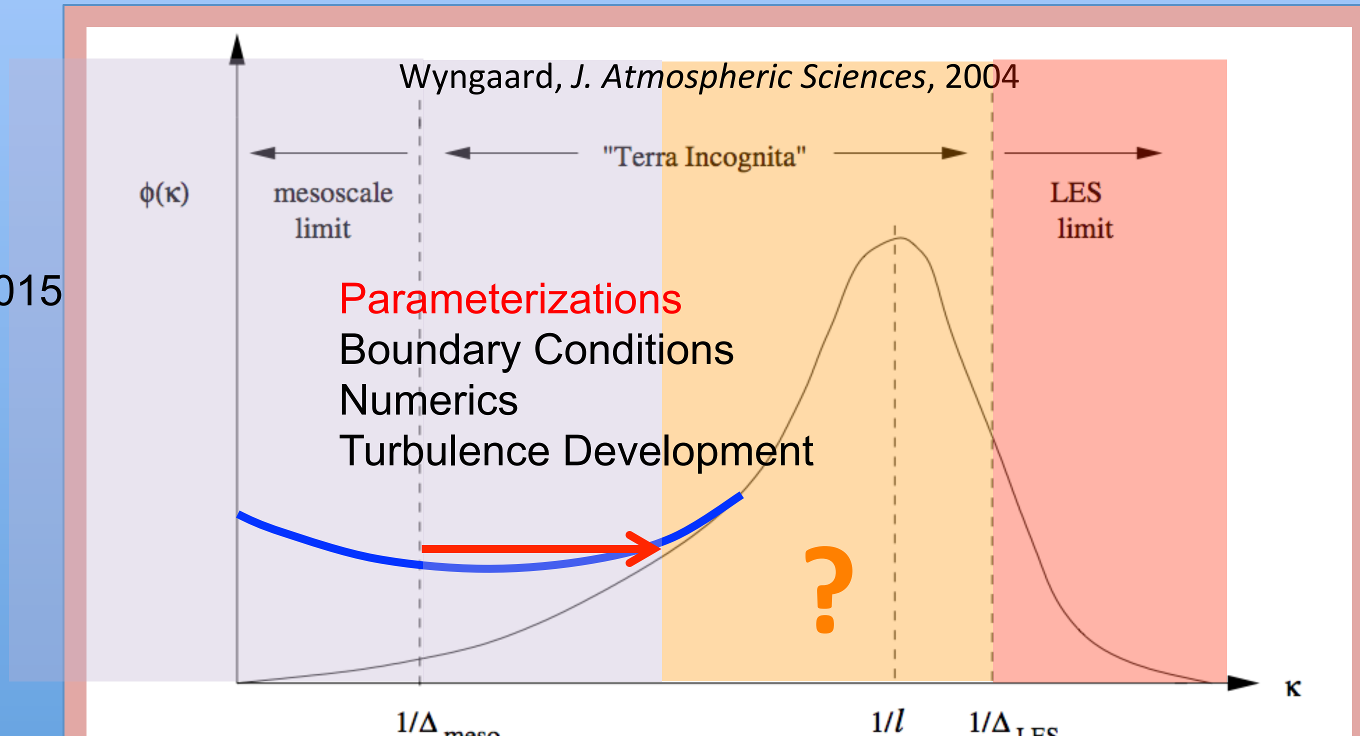
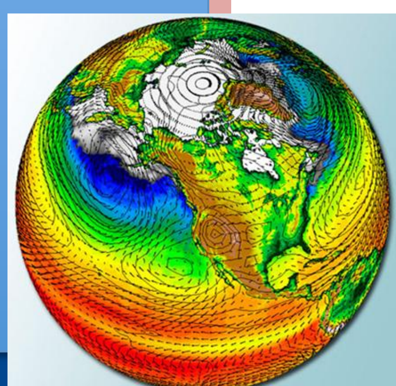
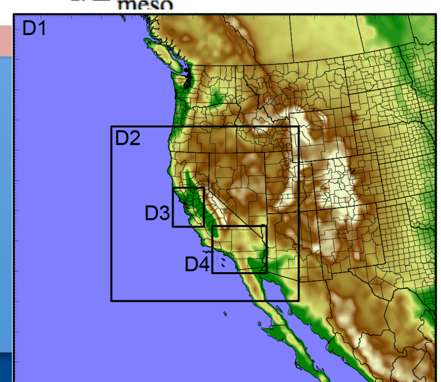
Adapted from Mirocha (LLNL)

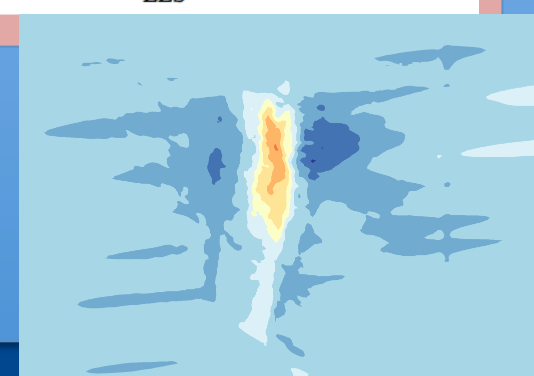
What is the effective approach to simulating mesoscale-microscale Interactions?

Fiori et al. 2010, 2011
Beare 2013
Boutle et al. 2014
Shin and Hong 2013, 2015
Shin and Dudhia 2016
etc.









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Improving forecast in complex terrain focusing on the Columbia River Gorge

- High spatial resolution is required to achieve more accurate wind forecasting in complex terrain, however…
- Currently NWP models use one-dimensional planetary boundary layer (PBL) parameterizations that are based on the assumption of horizontal homogeneity
- The assumption of horizontal homogeneity is not valid in high resolution simulations in complex terrain
- The goal is to develop and implement a three-dimensional planetary boundary layer scheme

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We need to develop a three-dimensional parameterization of turbulent mixing in PBL

Conservation equation for the horizontal wind components:

$$\frac{\partial U}{\partial t} + U_j \frac{\partial U}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x} - fV - \frac{\partial \langle uw \rangle}{\partial z}$$

$$\frac{\partial V}{\partial t} + U_j \frac{\partial V}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + fU - \frac{\partial \langle vw \rangle}{\partial z}$$

- The vertical turbulent fluxes are parameterized by the PBL scheme
- The horizontal turbulent fluxes are parameterized using Smagorinsky type (2D) diffusion scheme (Smagorinsky 1963)
- Different closure assumptions between PBL and diffusion schemes

Objective:

Incorporate a more consistent formulation of the turbulent fluxes based on first principles.

We need to develop a three-dimensional parameterization of turbulent mixing in PBL

Conservation equation for the velocity components:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + 2\epsilon_{ijk}\Omega_j U_k - \frac{\partial \langle u_i u_j \rangle}{\partial x_j}$$

- 3D PBL scheme includes (diagnostic) parameterization of all six turbulent stress components and computation of stress divergence (Mellor and Yamada 1974,1982; Yamada and Mellor 1975)
- Consistent closure assumption for all stress components

Objective:

Incorporate a more consistent formulation of the turbulent fluxes based on first principles.

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We have implemented an algebraic 3D PBL scheme for turbulent stresses and fluxes

Solving system of linear algebraic equations requires TKE and a "master" length scale (Mellor and Yamada 1974, 1982; Yamada and Mellor 1975).

$$
\begin{bmatrix}
\frac{q}{2\ell_1}+2\frac{\partial U}{\partial x} & -\frac{\partial V}{\partial y} & -\frac{\partial W}{\partial z} & 2\frac{\partial U}{\partial y}-\frac{\partial V}{\partial x} & 2\frac{\partial U}{\partial z}-\frac{\partial W}{\partial x} & -\frac{\partial V}{\partial z}-\frac{\partial W}{\partial y} & 0 & 0 & \beta g & 0 \\
-\frac{\partial U}{\partial x} & \frac{q}{2\ell_1}+2\frac{\partial V}{\partial y} & -\frac{\partial W}{\partial z} & 2\frac{\partial V}{\partial x}-\frac{\partial U}{\partial y} & -\frac{\partial U}{\partial z}-\frac{\partial W}{\partial x} & 2\frac{\partial V}{\partial z}-\frac{\partial W}{\partial y} & 0 & 0 & \beta g & 0 \\
-\frac{\partial U}{\partial x} & -\frac{\partial V}{\partial y} & \frac{q}{2\ell_1}+2\frac{\partial W}{\partial z} & -\frac{\partial U}{\partial y}-\frac{\partial V}{\partial x} & 2\frac{\partial W}{\partial x}-\frac{\partial U}{\partial z} & 2\frac{\partial W}{\partial x}-\frac{\partial V}{\partial z} & 0 & 0 & -2\beta g & 0 \\
\frac{\partial V}{\partial x} & \frac{\partial U}{\partial y} & 0 & \frac{q}{3\ell_1}+\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y} & \frac{\partial V}{\partial z} & \frac{\partial U}{\partial z} & 0 & 0 & 0 & 0 \\
\frac{\partial W}{\partial x} & 0 & \frac{\partial U}{\partial z} & \frac{\partial W}{\partial y} & \frac{q}{3\ell_1}+\frac{\partial U}{\partial x}+\frac{\partial W}{\partial z} & \frac{\partial U}{\partial y} & -\beta g & 0 & 0 & 0 \\
0 & \frac{\partial W}{\partial y} & \frac{\partial V}{\partial z} & \frac{\partial W}{\partial x} & \frac{\partial V}{\partial x} & \frac{q}{3\ell_1}+\frac{\partial V}{\partial y}+\frac{\partial W}{\partial z} & 0 & -\beta g & 0 & 0 \\
\frac{\partial \Theta}{\partial x} & 0 & 0 & \frac{\partial \Theta}{\partial y} & \frac{\partial \Theta}{\partial z} & 0 & \frac{q}{3\ell_2}+\frac{\partial U}{\partial x} & \frac{\partial U}{\partial y} & \frac{\partial U}{\partial z} & 0 \\
0 & \frac{\partial \Theta}{\partial y} & 0 & \frac{\partial \Theta}{\partial x} & 0 & \frac{\partial \Theta}{\partial z} & \frac{\partial V}{\partial x} & \frac{q}{3\ell_2}+\frac{\partial V}{\partial y} & \frac{\partial V}{\partial z} & 0 \\
0 & 0 & \frac{\partial \Theta}{\partial z} & 0 & \frac{\partial \Theta}{\partial x} & \frac{\partial \Theta}{\partial y} & \frac{\partial W}{\partial x} & \frac{\partial W}{\partial y} & \frac{q}{3\ell_2}+\frac{\partial W}{\partial z} & -\beta g \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{\partial \Theta}{\partial x} & \frac{\partial \Theta}{\partial y} & \frac{\partial \Theta}{\partial z} & \frac{q}{\Lambda_2}
\end{bmatrix}
\begin{bmatrix}
\overline{u^2} \\ \overline{v^2} \\ \overline{w^2} \\ \overline{uv} \\ \overline{uw} \\ \overline{vw} \\ \overline{u\theta} \\ \overline{v\theta} \\ \overline{w\theta} \\ \overline{\theta^2}
\end{bmatrix}
=
\begin{bmatrix}
\frac{q^3}{6\ell_1}+3C_1q^2\frac{\partial U}{\partial x} \\
\frac{q^3}{6\ell_1}+3C_1q^2\frac{\partial V}{\partial y} \\
\frac{q^3}{6\ell_1}+3C_1q^2\frac{\partial W}{\partial z} \\
C_1q^2\left(\frac{\partial V}{\partial x}+\frac{\partial U}{\partial y}\right) \\
C_1q^2\left(\frac{\partial W}{\partial x}+\frac{\partial U}{\partial z}\right) \\
C_1q^2\left(\frac{\partial W}{\partial y}+\frac{\partial V}{\partial z}\right) \\
0 \\ 0 \\ 0 \\ 0
\end{bmatrix}
$$

At each grid cell this system of algebraic equations is solved using either Gaussian elimination or sequential over-relaxation method.

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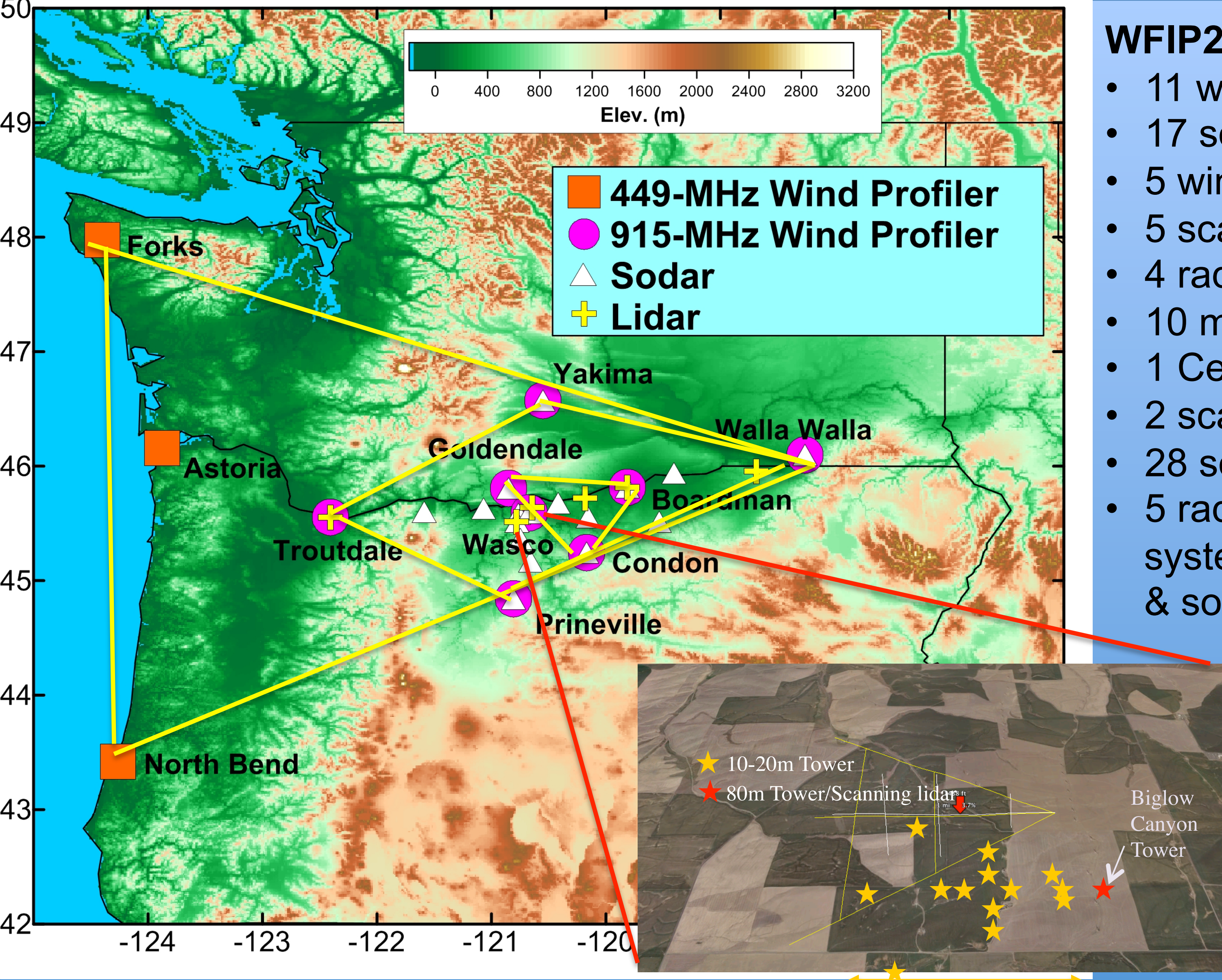
The fist step in development of a new 3D PBL scheme is based on LEVEL 2 scheme

Level 2 model is an algebraic model where TKE and a length scale are diagnosed (Mellor and Yamada 1974, 1982; Yamada and Mellor 1975).

$$\frac{q^3}{\Lambda_1} = -\overline{u^2}\frac{\partial U}{\partial x} - \overline{v^2}\frac{\partial V}{\partial x} - \overline{w^2}\frac{\partial W}{\partial x} - \overline{uv}\left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right) - \overline{uw}\left(\frac{\partial U}{\partial z} + \frac{\partial W}{\partial x}\right) - \overline{vw}\left(\frac{\partial V}{\partial z} + \frac{\partial W}{\partial y}\right) - \beta g \overline{w\theta}$$

Stresses (and heat fluxes are diagnosed quantities)

$$A\,x = B$$



Physics Site 2 km

WFIP2 measurements:

- 11 wind profiling radars
- 17 sodars
- 5 wind profiling lidars
- 5 scanning lidars
- 4 radiometers
- 10 microbarographs
- 1 Ceilometer
- 2 scanning radars
- 28 sonic anemometers
- 5 radiative flux systems & soil moisture

Adapted from Jim Wilczak

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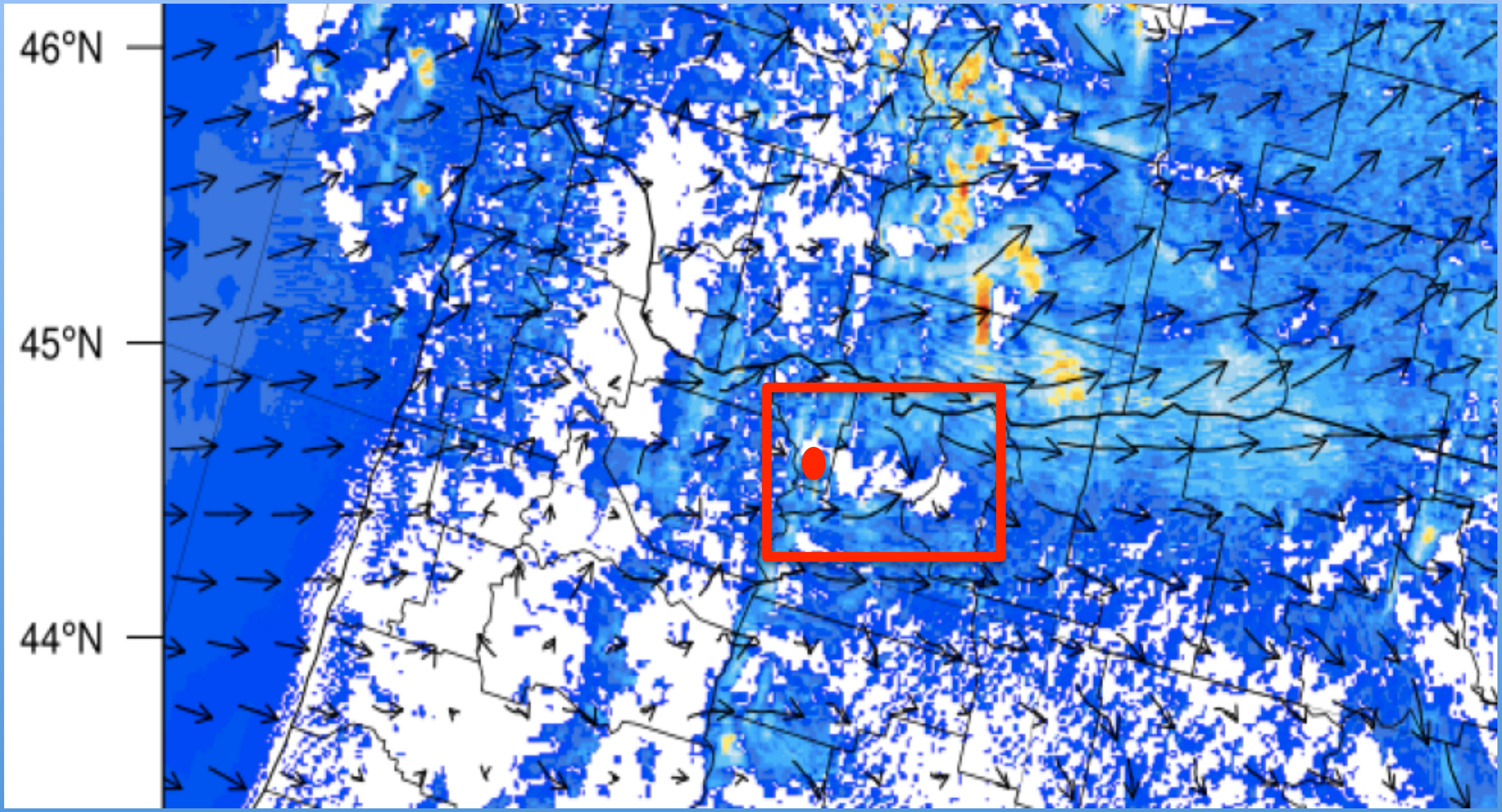
Mountain Hood Wake on March 7, 2016
WFIP2 HRRR nest – 750 m grid cell size



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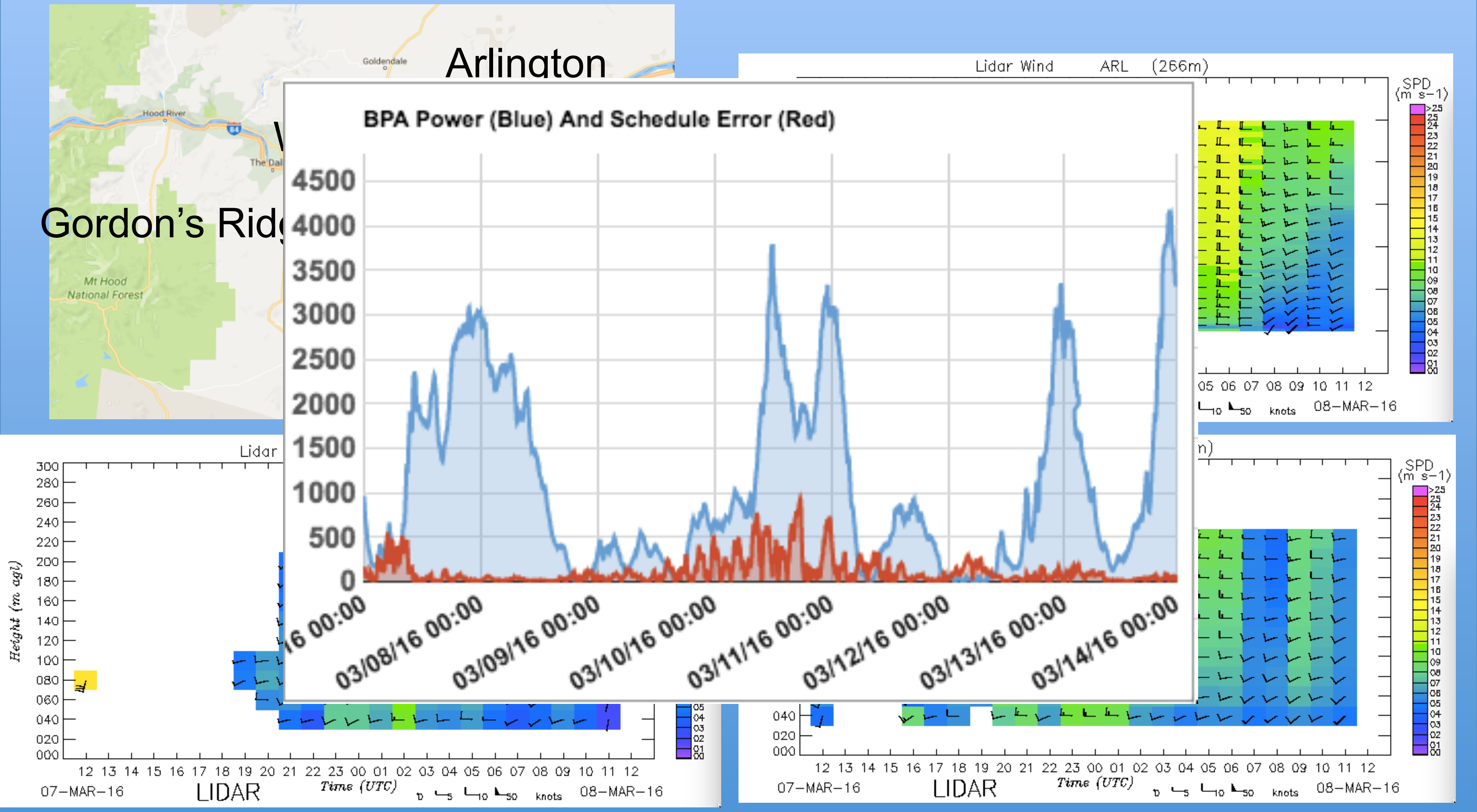
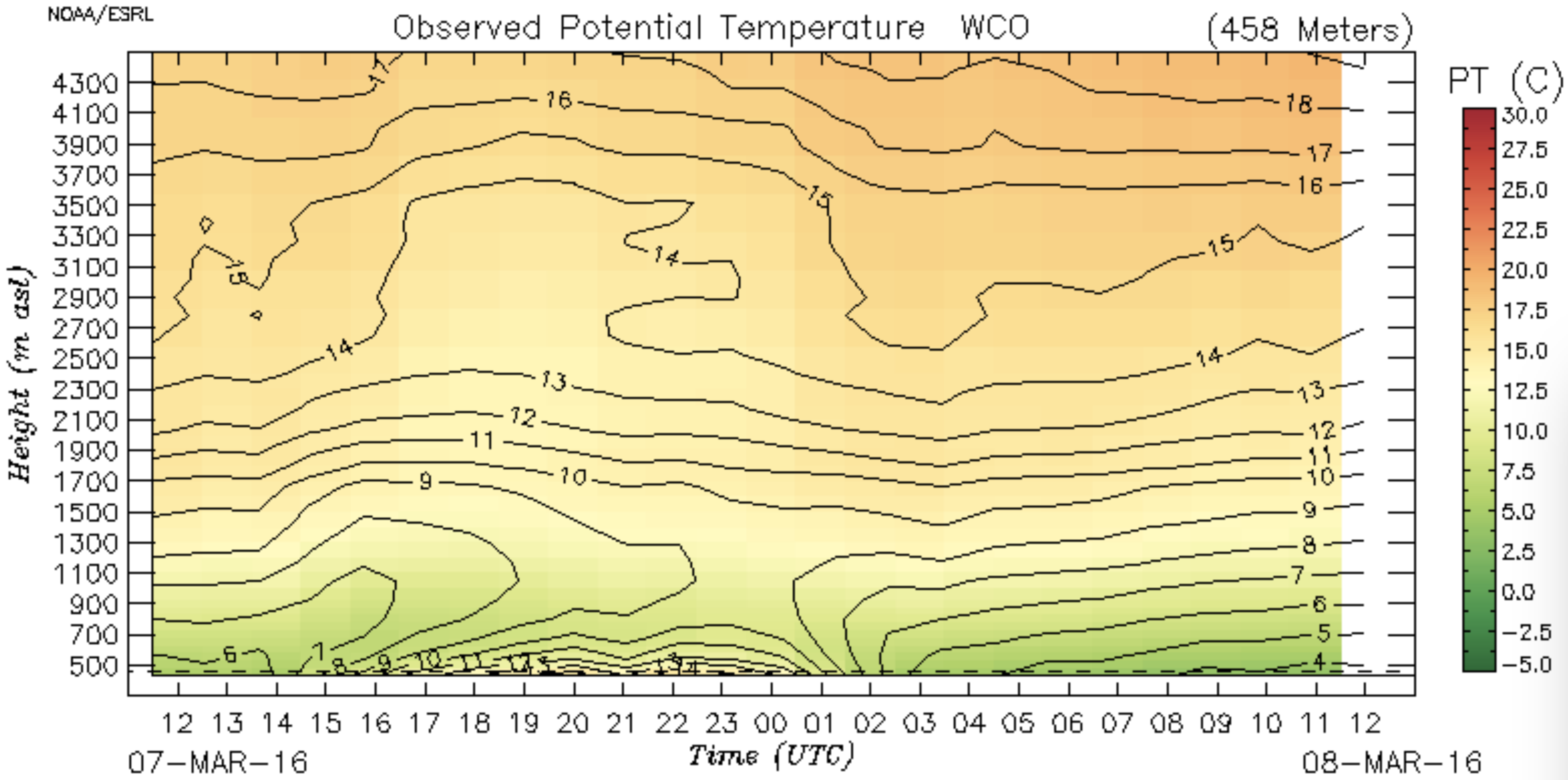
Vertically Profiling Lidar Observations on March 7, 2016



Potential Temperature at Wasco Radiometer Observations



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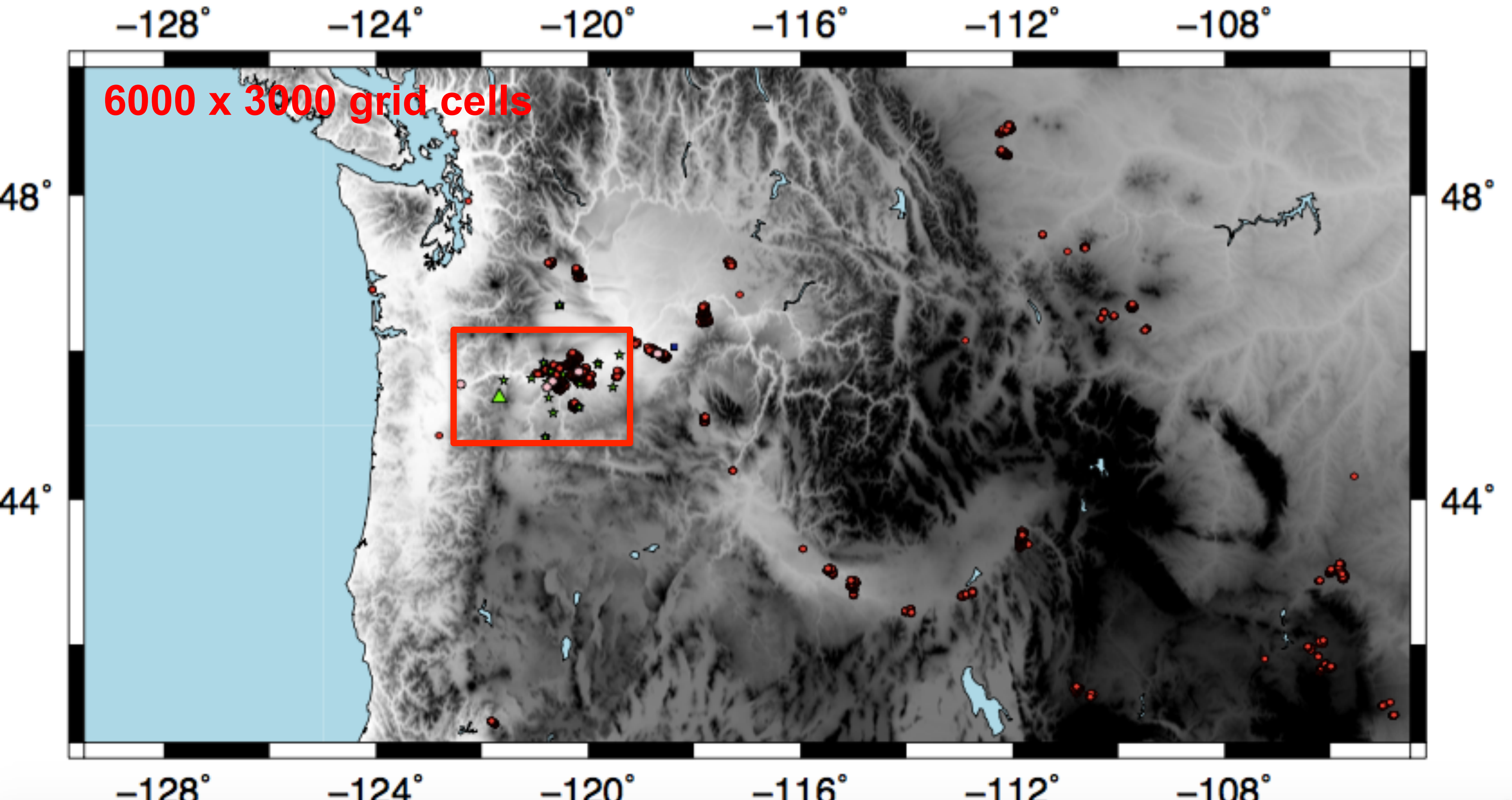
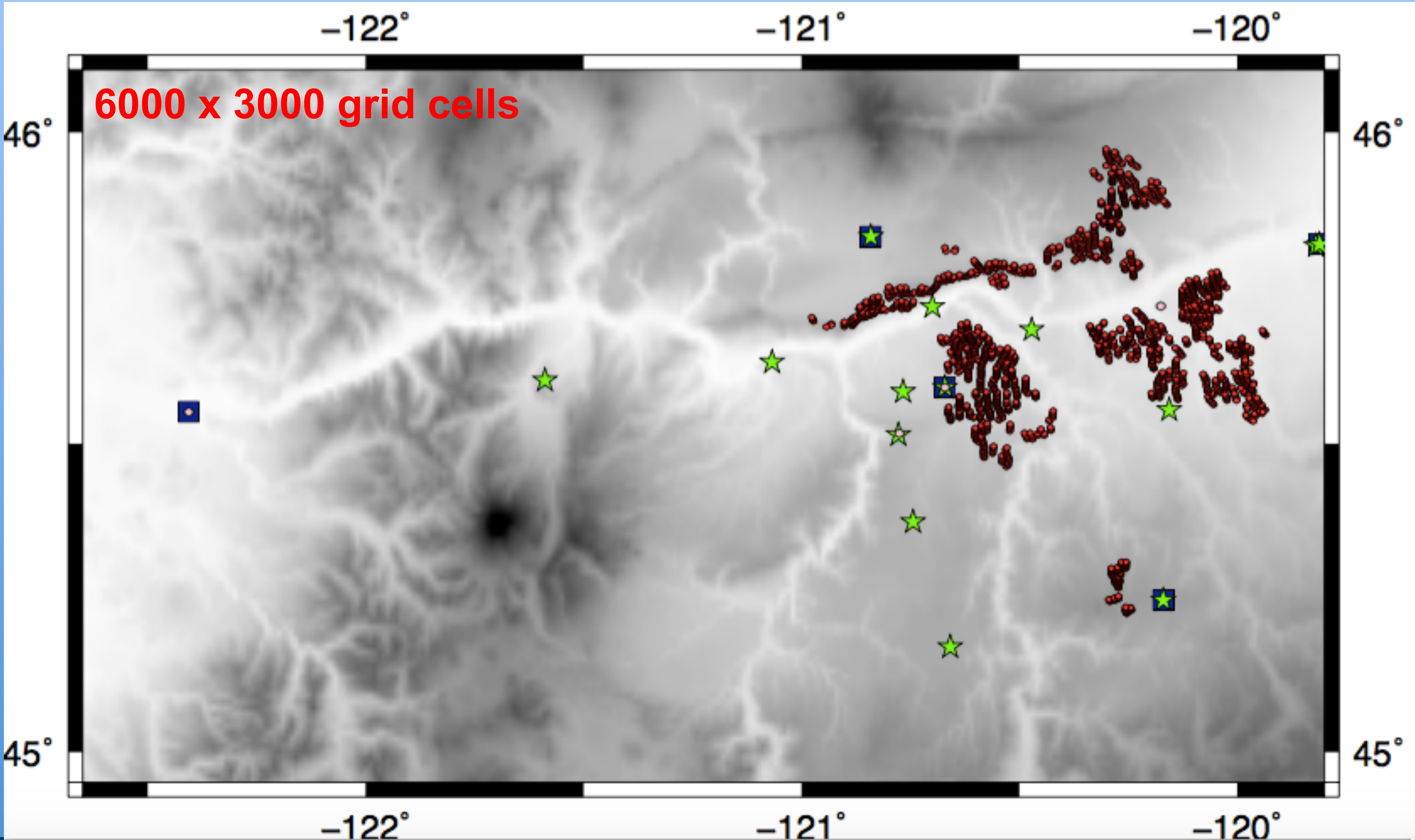
WFIP2 Field Study Area
WRF – Domain 1 - Grid Cell Size 300m



WFIP2 Field Study Area
WRF – Domain 2 - Grid Cell Size 30m



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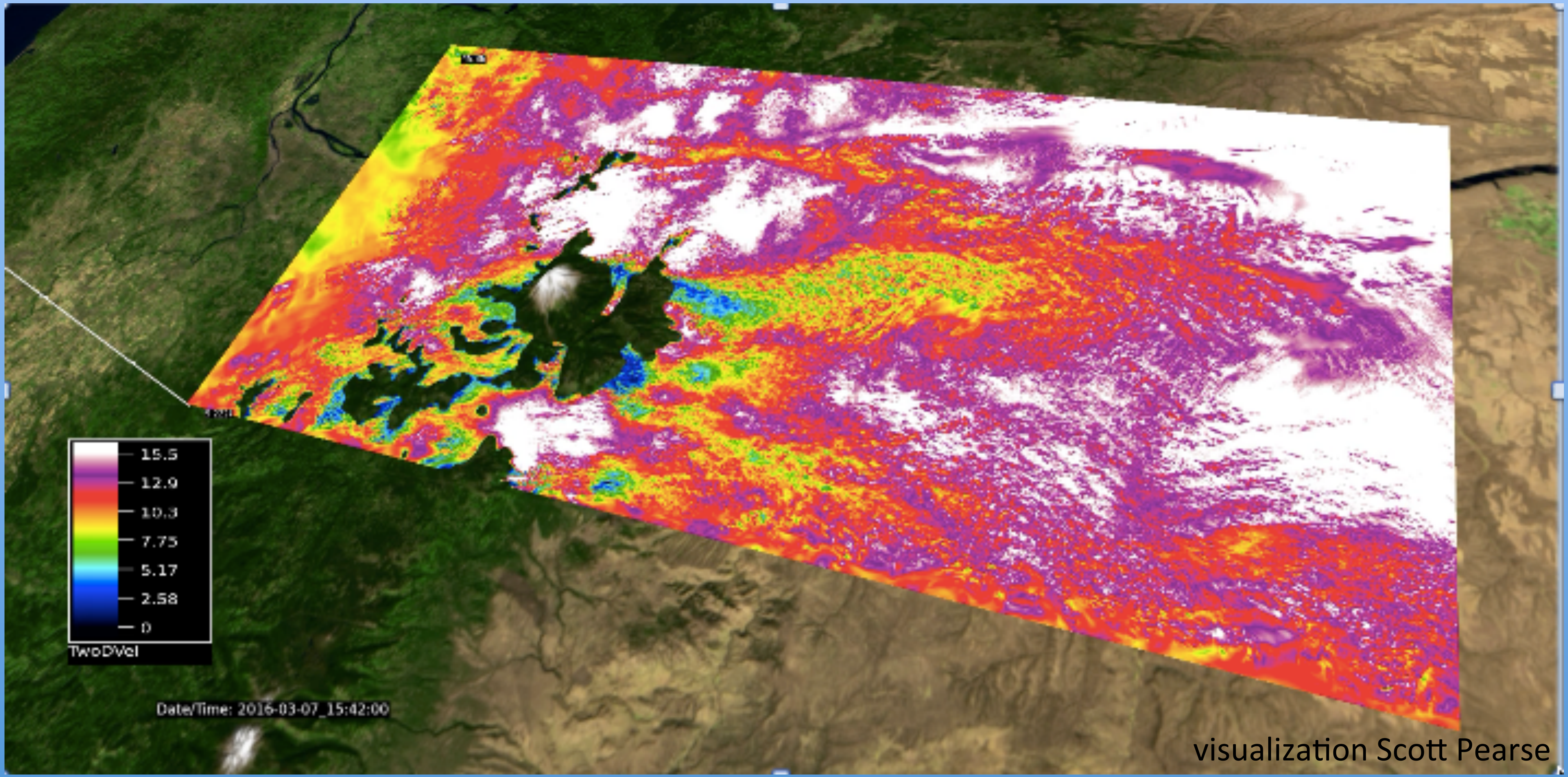
WFIP2 - Topographic Wake
Horizontal Velocity



Topographic wake and gap flow observed on March 07 – 08, 2016

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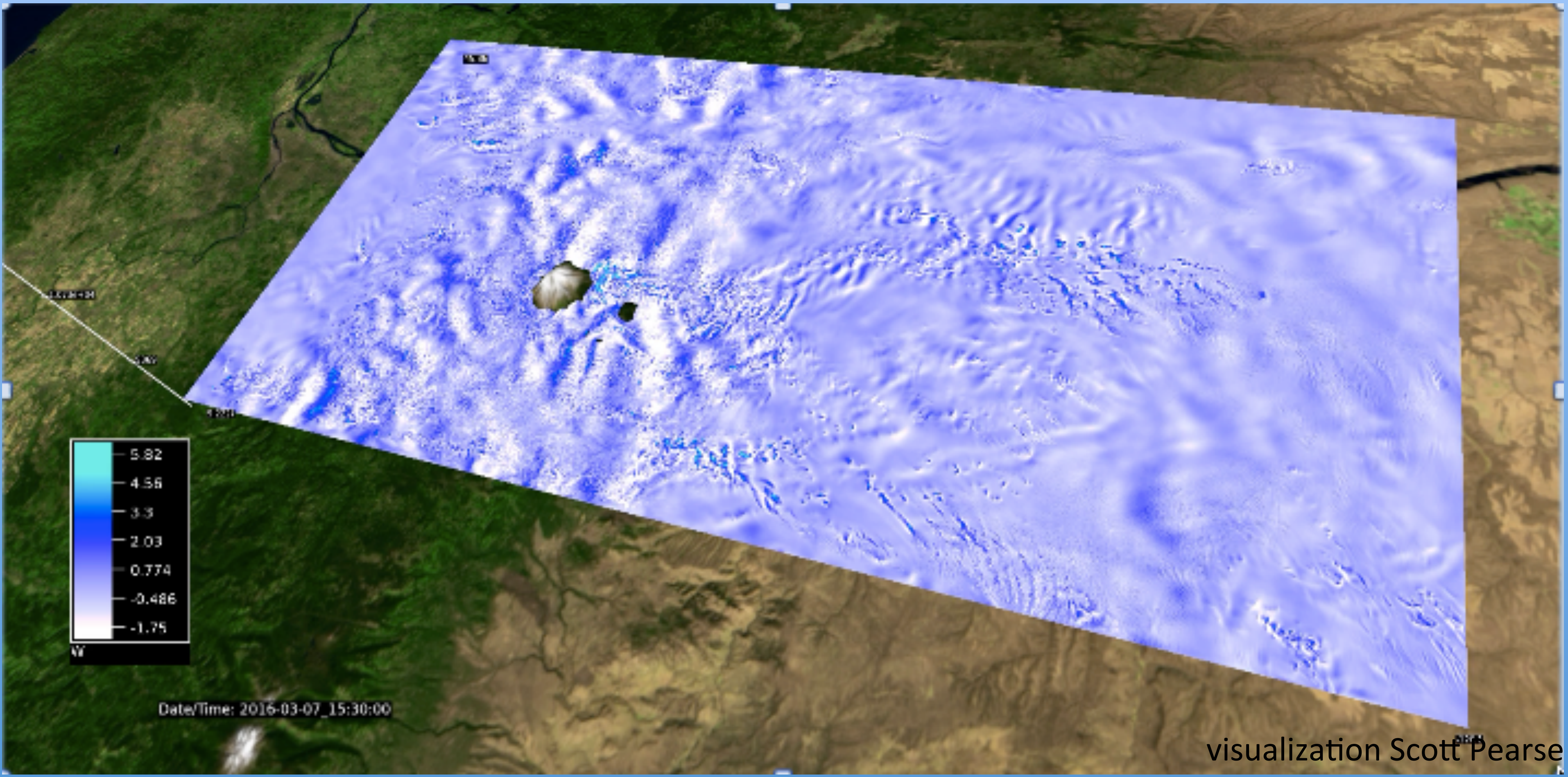
WFIP2 - Topographic Wake Horizontal Velocity

Topographic wake and gap flow observed on March 07 – 08, 2016

WFIP2 – Topographic Wake Vertical Velocity



Topographic wake and mountain waves observed on March 07 – 08, 2016

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WFIP2 – Topographic Wake
Vertical Velocity

visualization Scott Pearse

Topographic wake and mountain waves observed on March 07 – 08, 2016

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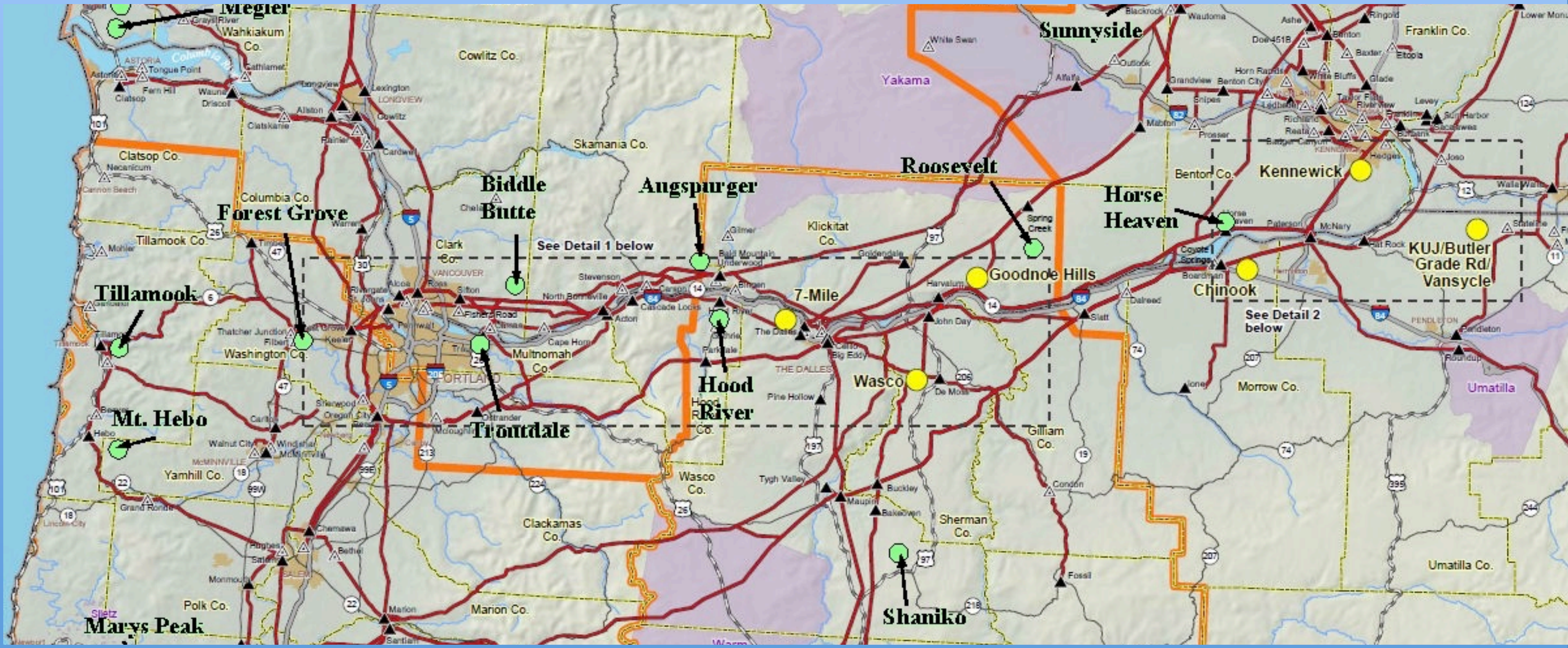
Bonneville Power Administration Meteorological Towers



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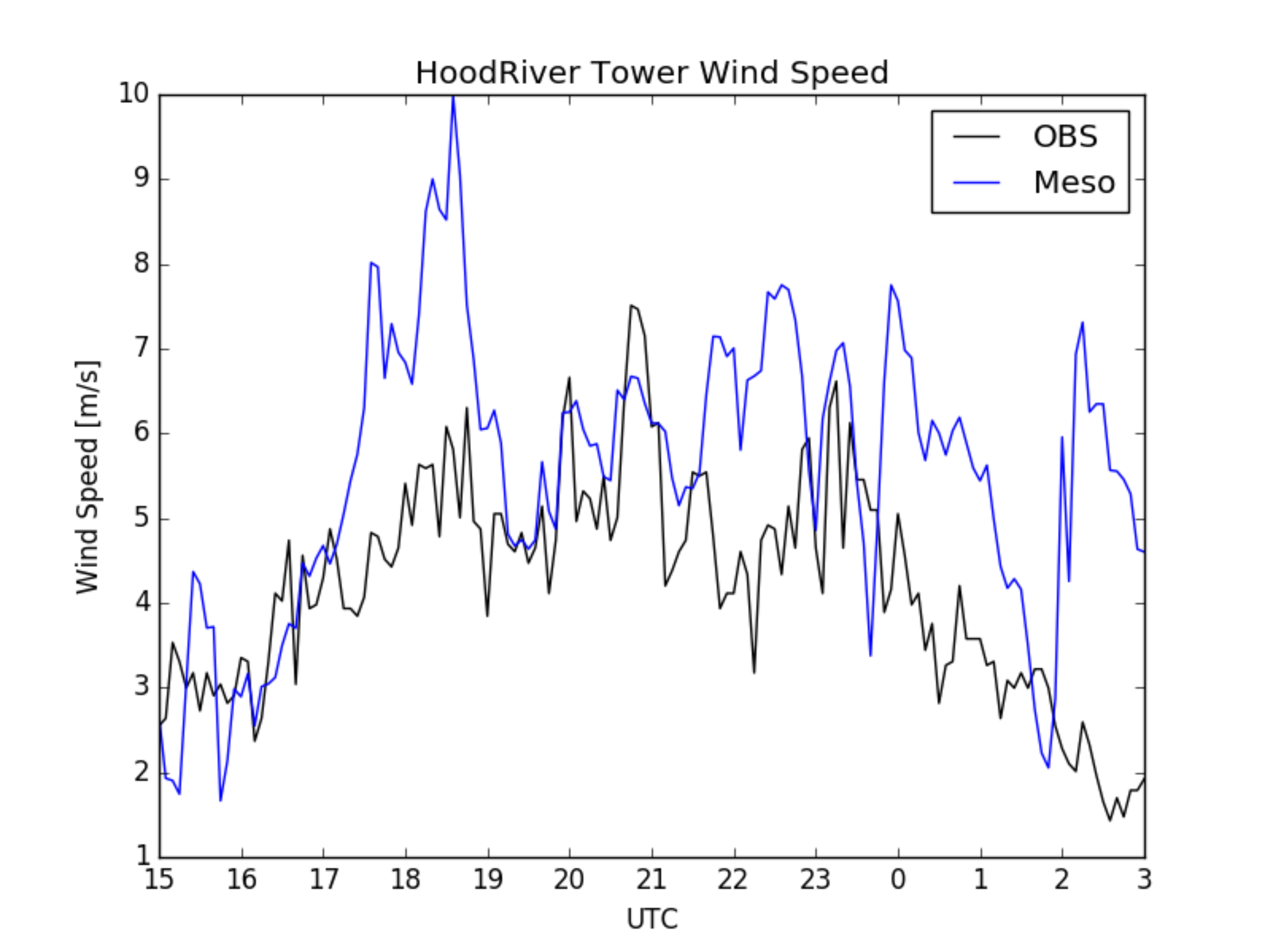
Hood River Tower



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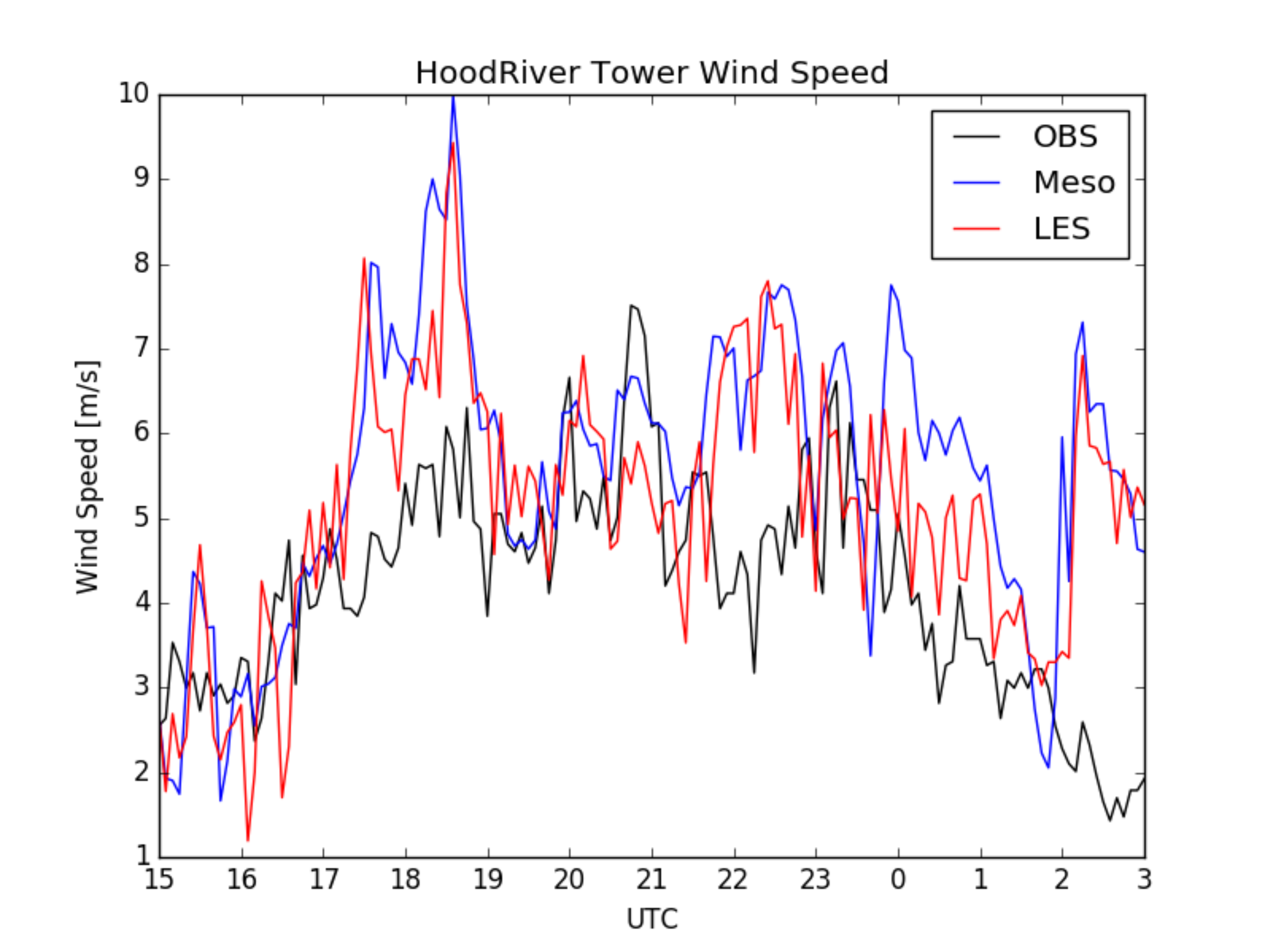
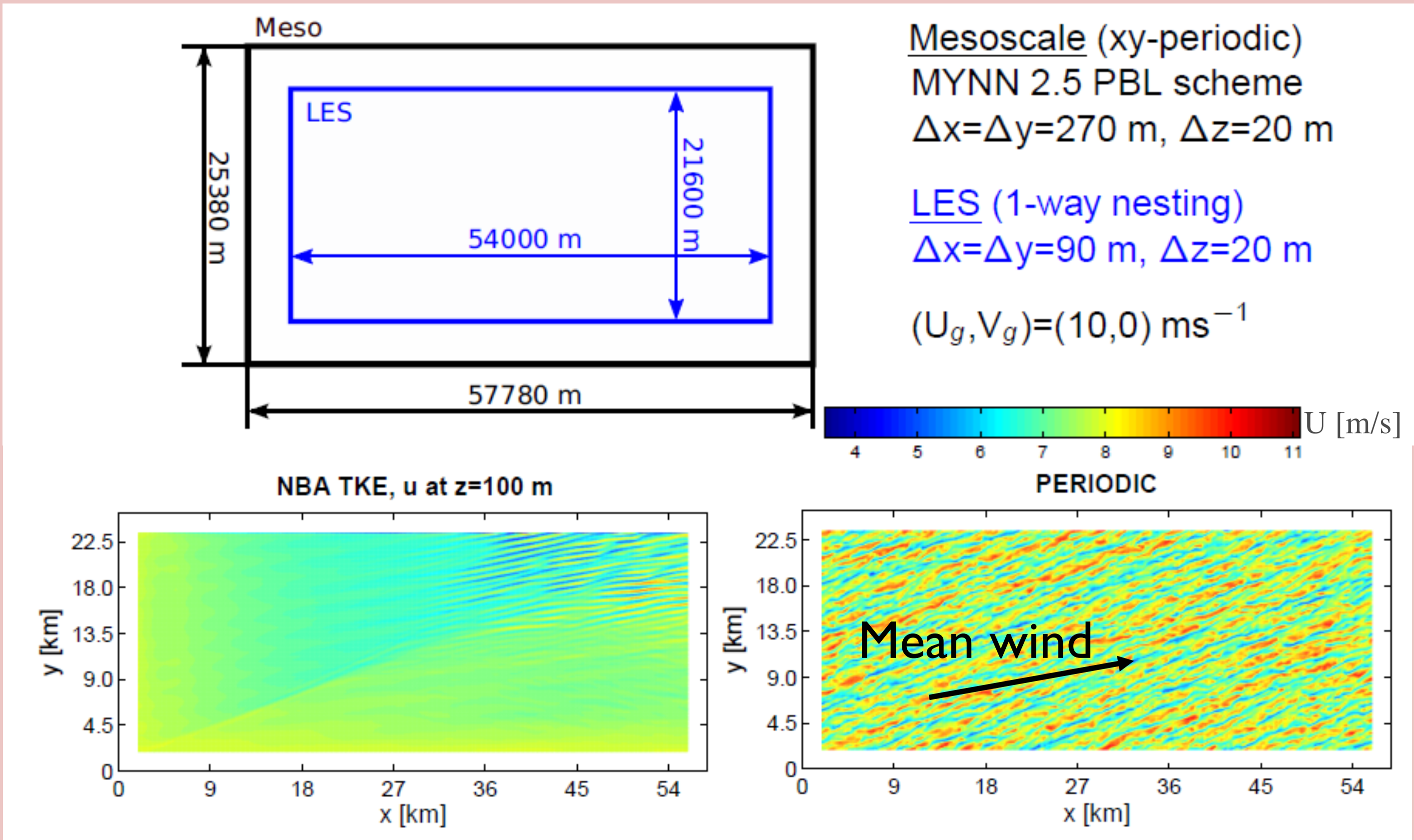
Hood River Tower



Nested LES forced with mesoscale inflow slow to produce resolved turbulence

Mesoscale-Microscale simulations in WRF; LES nested (one way) within Mesoscale simulation



Munoz-Esparza et al. 2014, 2015, 2016

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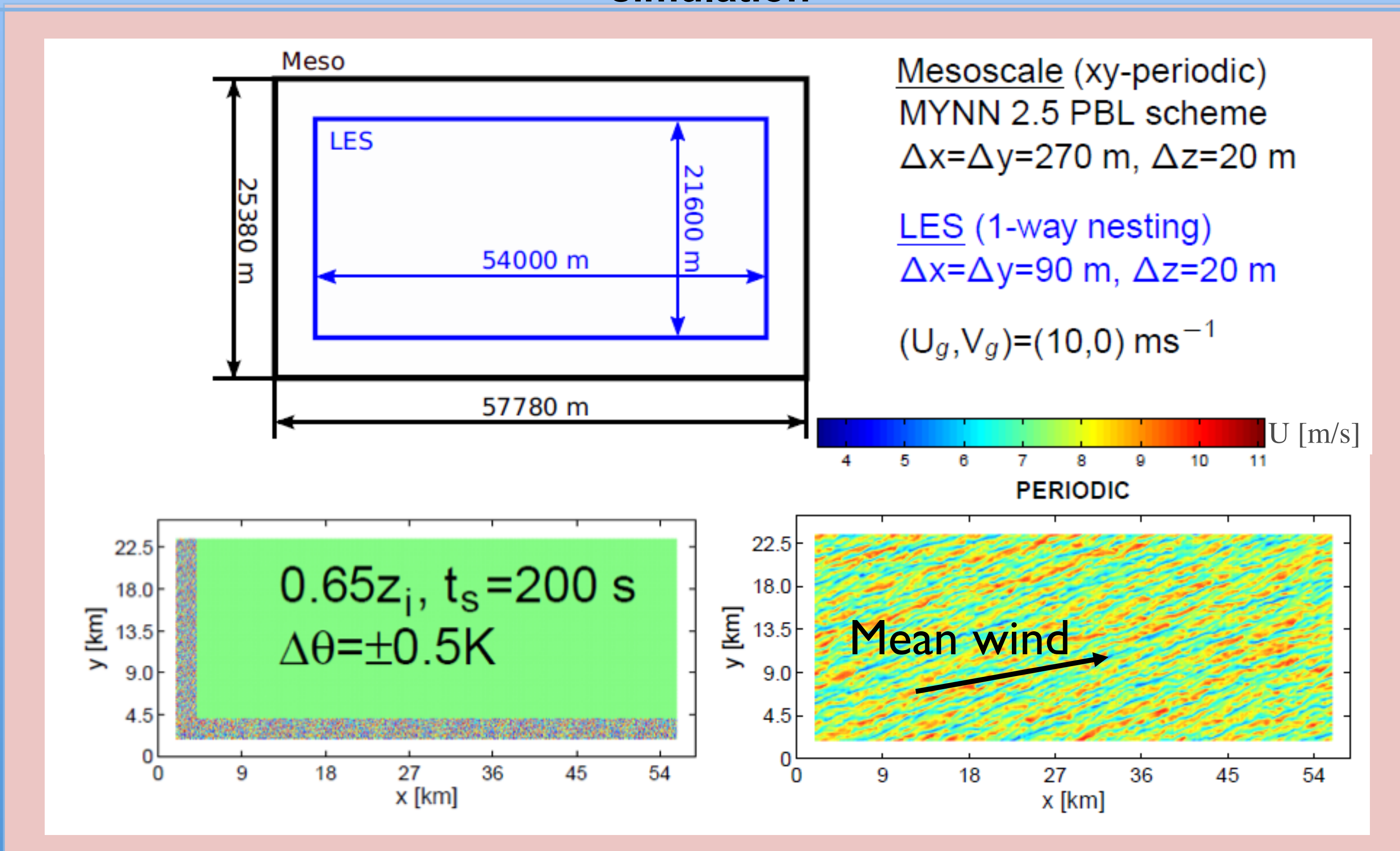

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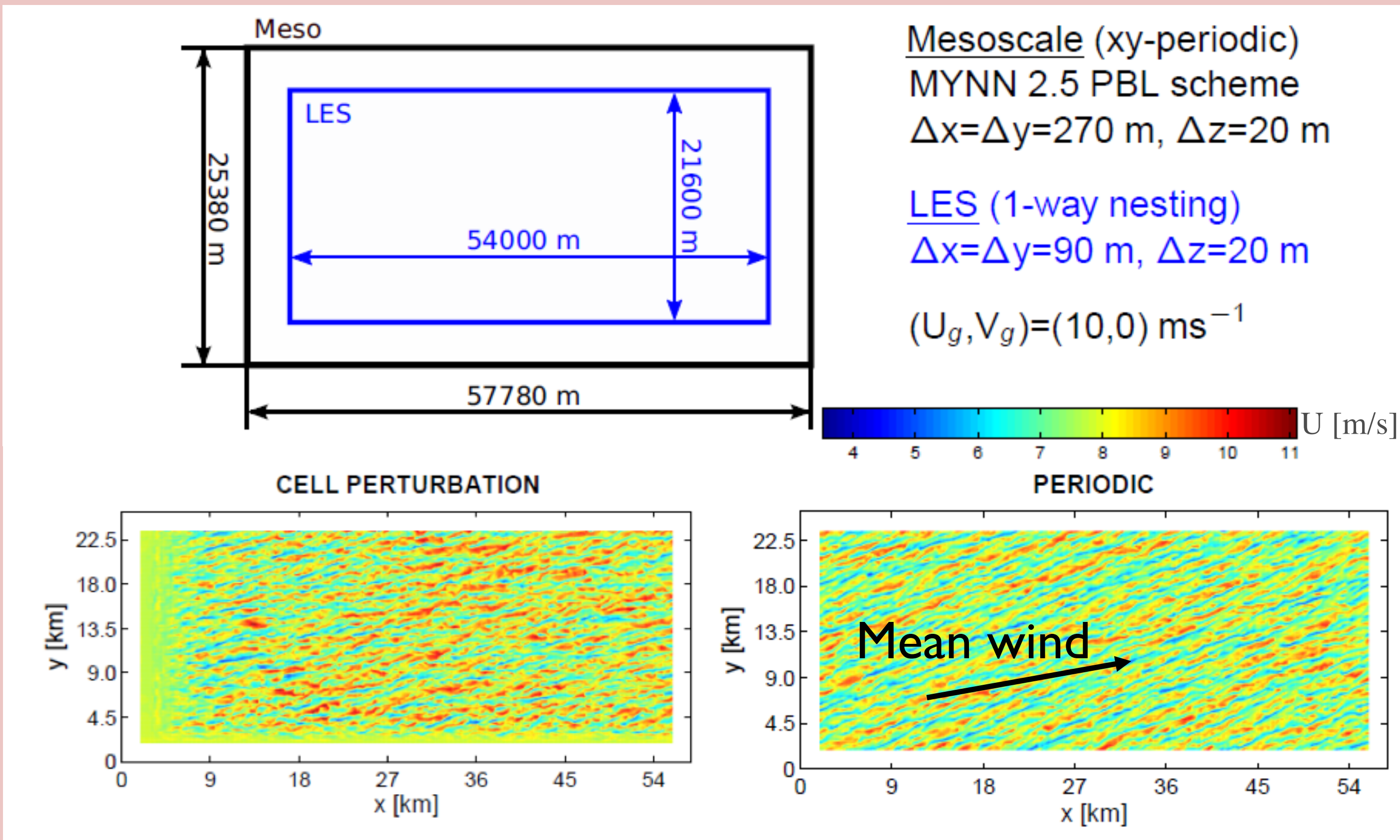
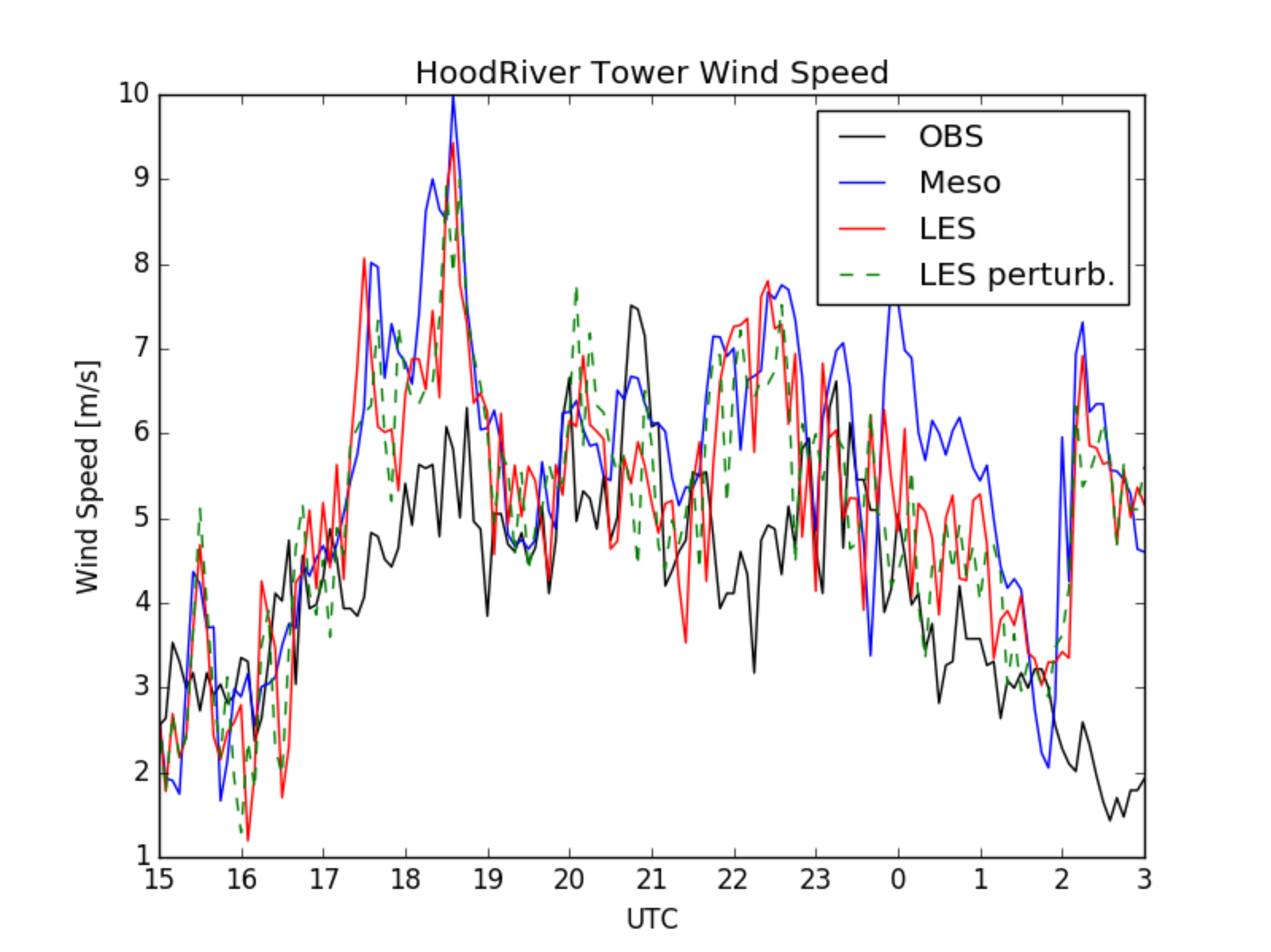


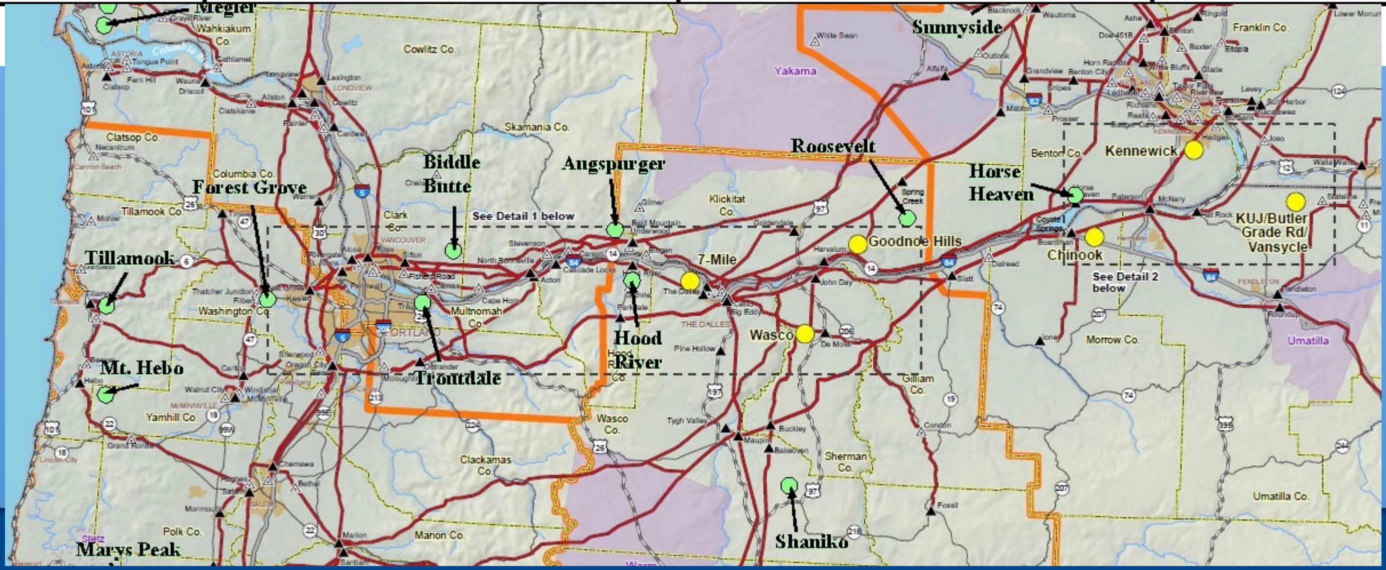
Munoz-Esparza et al. 2014, 2015, 2016

Hood River Tower



Mean Absolut Error – 5-minute Averages

Mean Absolute Error [m/s]			
BPA Tower	Mesoscale	LES	LES w. cell perturbation
Augspurger	4.73	3.99	3.91
Biddle Butte	2.71	2.39	2.43
Goodnoe Hills	1.53	1.16	1.18
Hood River	1.59	1.39	1.30
Roosevelt	1.81	2.02	2.03
Seven Mile Hill	1.74	1.82	1.79
Wasco	2.53	2.44	2.52



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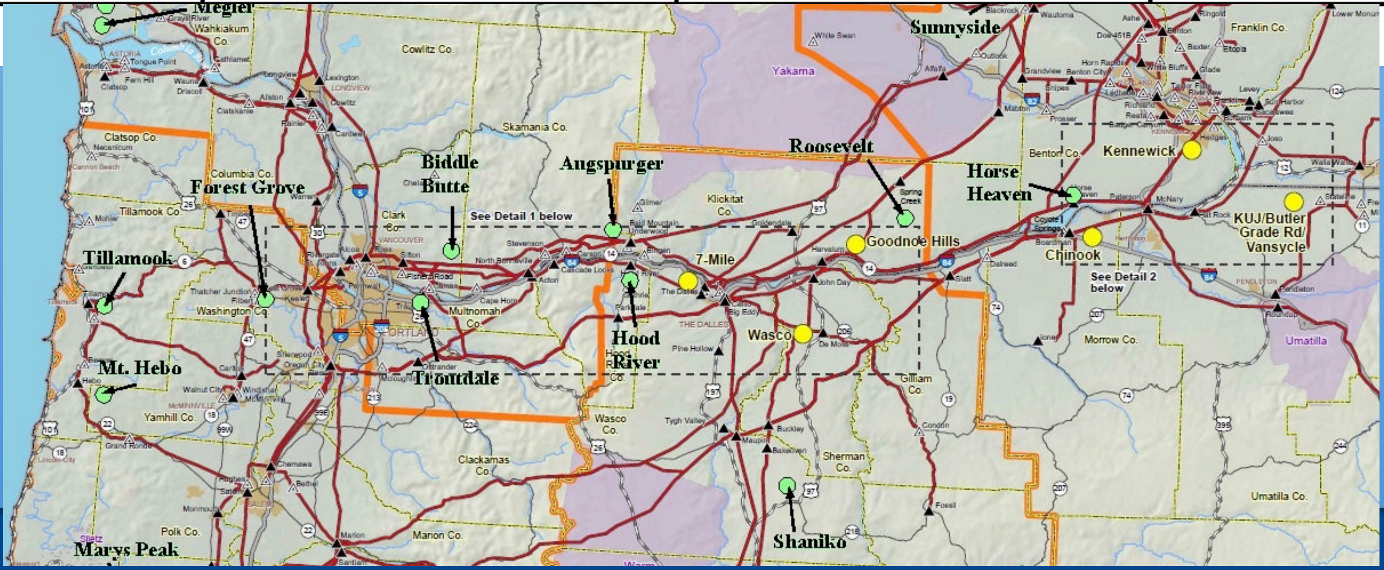
Root Mean Square Error – 5-minute Averages

Root Mean Square Error [m/s]			
BPA Tower	Mesoscale	LES	LES w. cell perturbation
Augspurger	5.11	4.42	4.35
Biddle Butte	3.48	3.12	3.09
Goodnoe Hills	1.94	1.46	1.51
Hood River	2.04	1.76	1.68
Roosevelt	2.13	2.36	2.40
Seven Mile Hill	2.14	2.21	2.18
Wasco	3.25	3.18	3.22



Thank you!

Questions?

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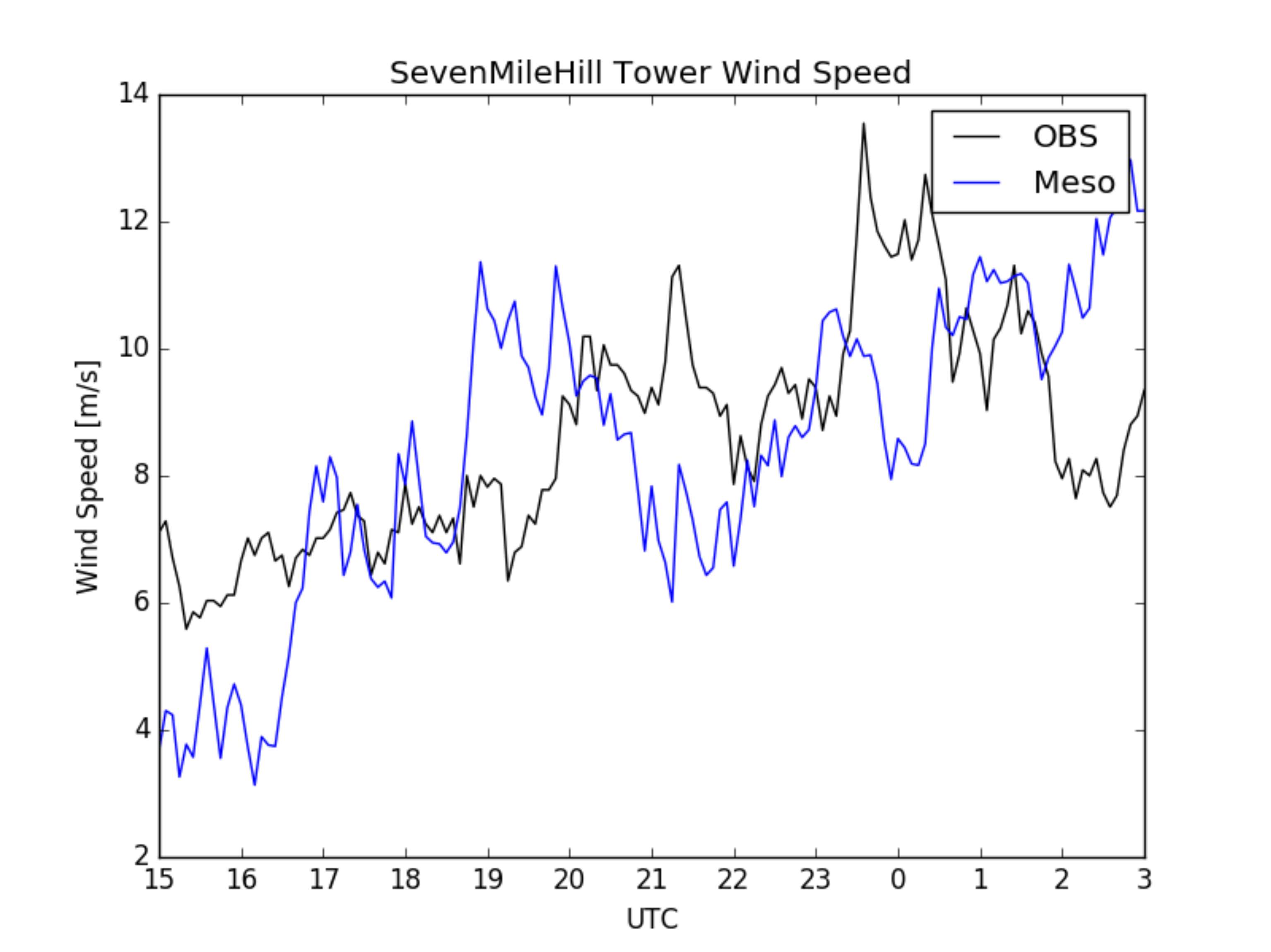
Seven Mile Hill Tower



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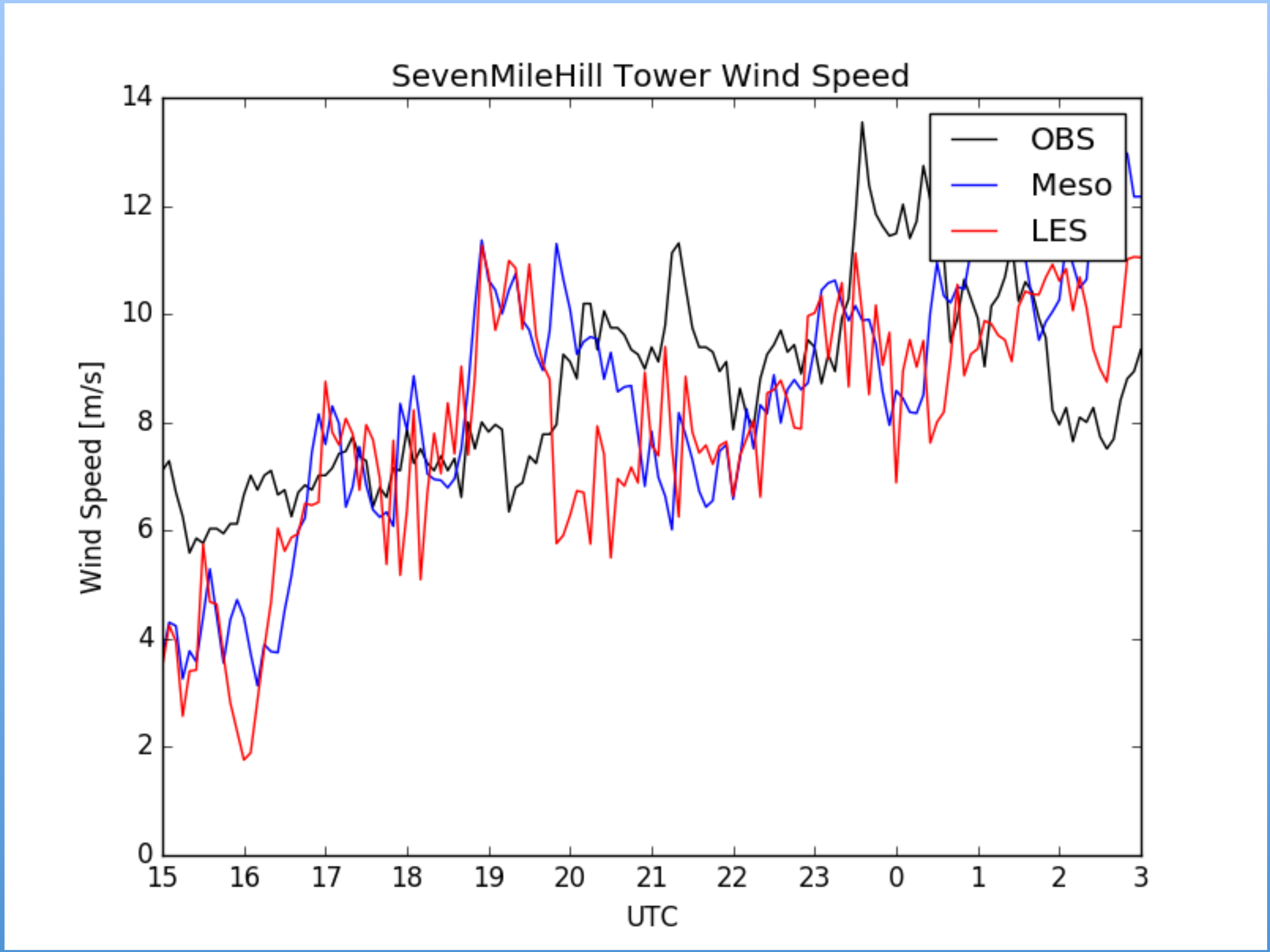
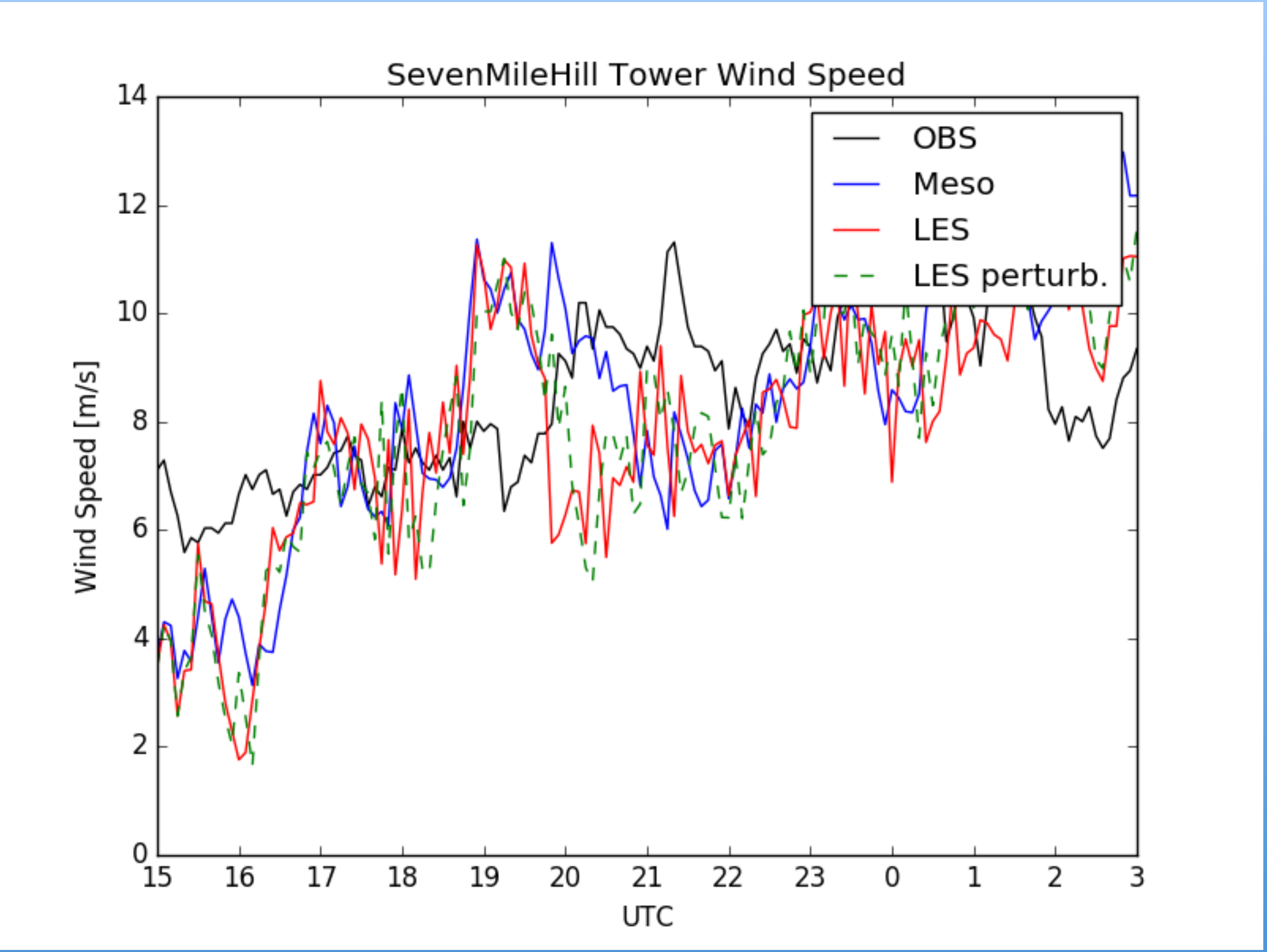
Seven Mile Hill Tower



Seven Mile Hill Tower



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Mesoscale Simulation
Mean Absolut Error & Root Mean Square Error
5-minute Averages

	Mesoscale	
BPA Tower	MEA [m/s]	RMSE [m/s]
Butler Grade	2.14	2.58
Forest Grove	1.45	1.81
Horse Heaven	1.15	1.42
Kennewick	4.78	5.39
Mary's Peak	3.56	4.20
Megler	2.67	3.45
Mt Hebo	1.63	1.98
Naselle	1.97	2.53
Shaniko	3.00	3.71
Tillamook	1.44	2.07
Troutdale	1.93	2.36

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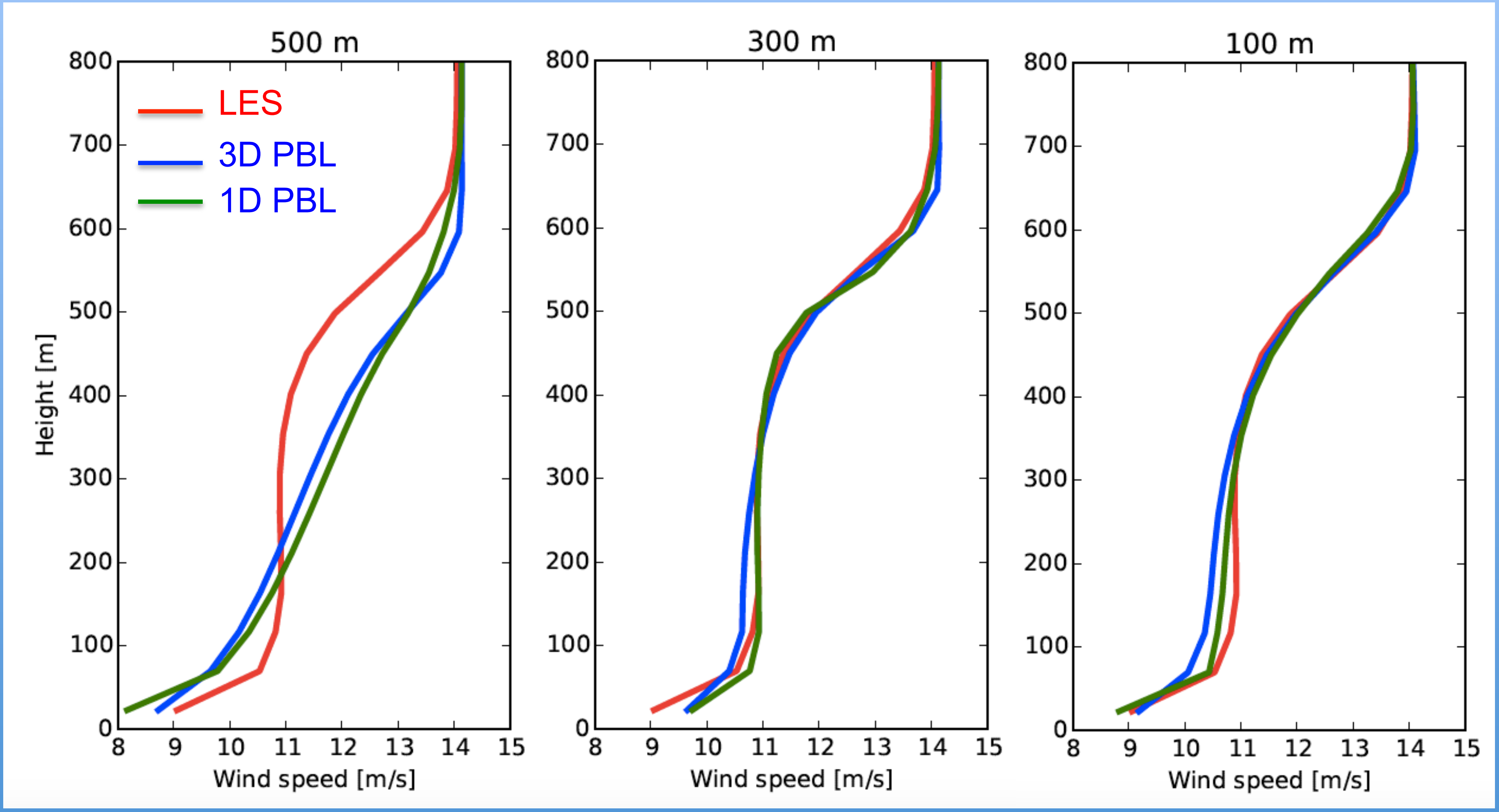
Convective ABL - comparison of wind speed profiles from 3D PBL and LES



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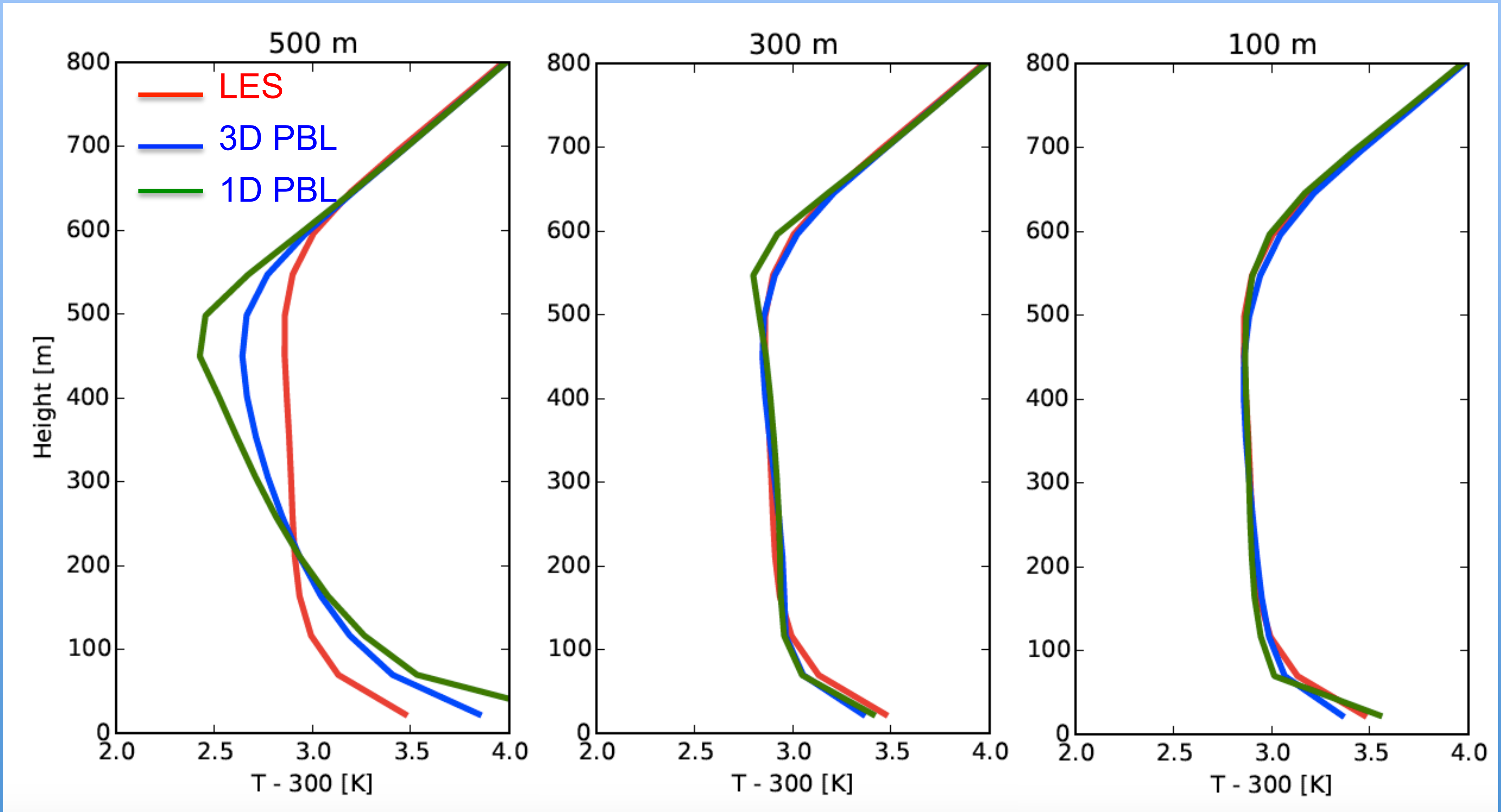
Convective ABL - comparison of potential temperature profiles from 3D PBL and LES



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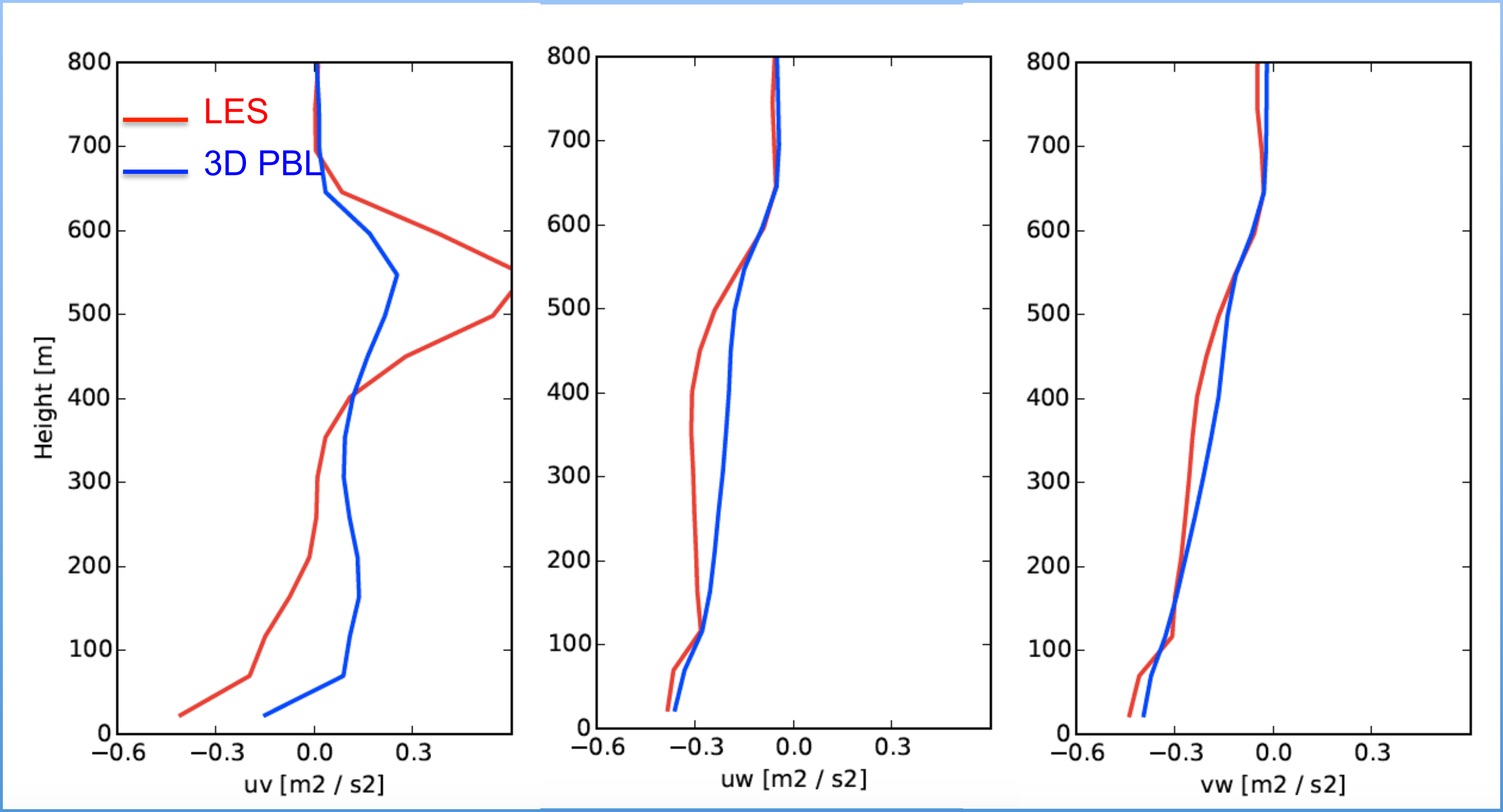
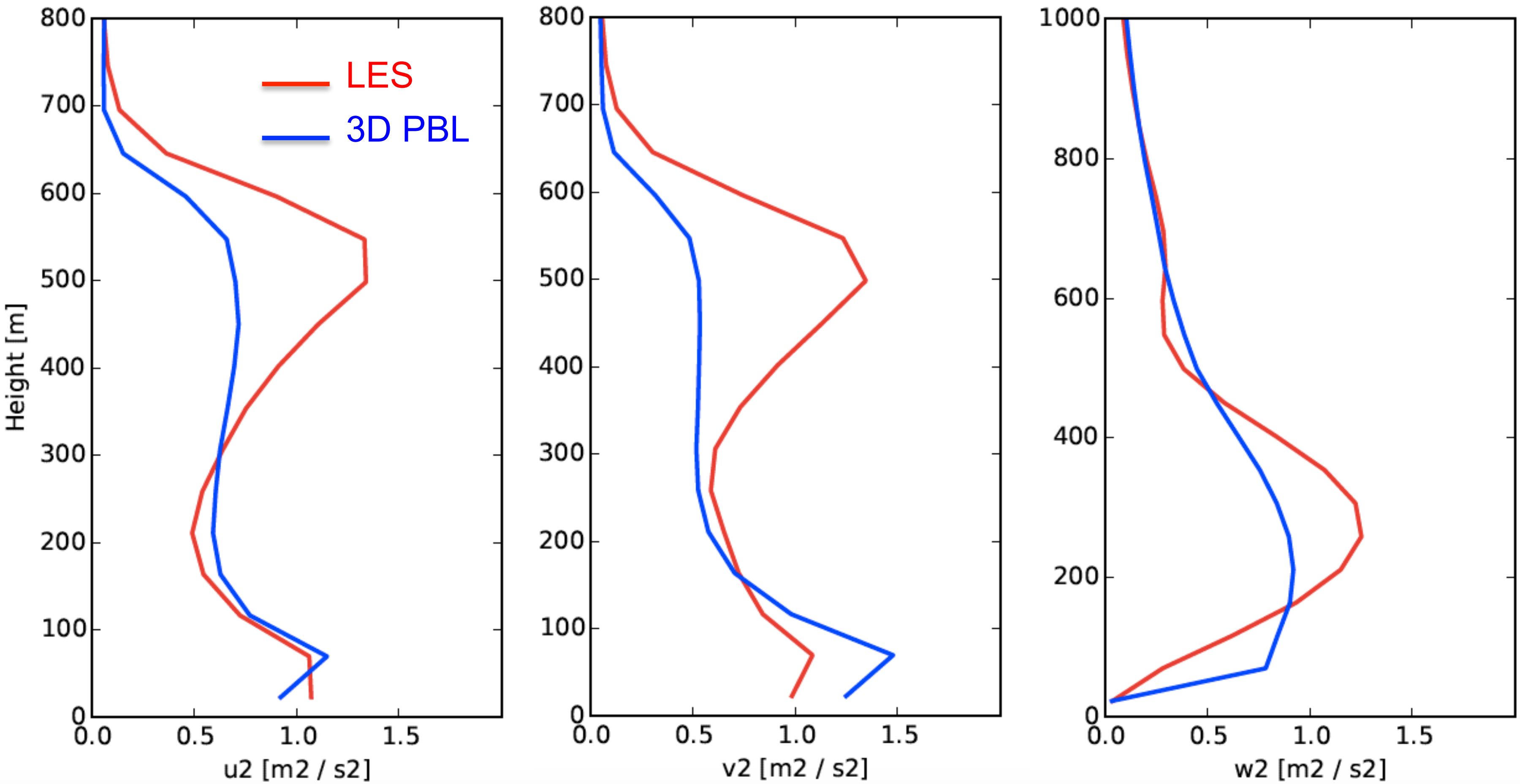
Convective ABL - comparison of shear stresses from 3D PBL and LES



Convective ABL - comparison of normal stresses from 3D PBL and LES



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The goal is to develop a new 3D PBL scheme based on LEVEL 2.5 scheme

Level 2.5 model is an algebraic model with a prognostic equation for TKE and a diagnosed "master' length scale (Mellor and Yamada 1974, 1982; Yamada and Mellor 1975).

$$\frac{\partial q^2}{\partial t} + U\frac{\partial q^2}{\partial x} + V\frac{\partial q^2}{\partial y} + W\frac{\partial q^2}{\partial z} = -\overline{u^2}\frac{\partial U}{\partial x} - \overline{v^2}\frac{\partial V}{\partial x} - \overline{w^2}\frac{\partial W}{\partial x}$$
$$-\overline{uv}\left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right) - \overline{uw}\left(\frac{\partial U}{\partial z} + \frac{\partial W}{\partial x}\right) - \overline{vw}\left(\frac{\partial V}{\partial z} + \frac{\partial W}{\partial y}\right)$$
$$-\beta g\overline{w\theta} - \frac{q^3}{\Lambda_1}$$
$$+\frac{\partial}{\partial x}\left(lqS_q\frac{\partial q^2}{\partial x}\right) + \frac{\partial}{\partial y}\left(lqS_q\frac{\partial q^2}{\partial y}\right) + \frac{\partial}{\partial z}\left(lqS_q\frac{\partial q^2}{\partial z}\right)$$

Stresses (and heat fluxes are diagnosed quantities)

$$A\,x = B$$

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Next Steps

- Carrying out tests of the new 3D PBL parameterization and comparing results to 1D PBL and LES results
- Implement 3D PBL parameterization in NOAA's version of WRF
- Carry out high-resolution simulation of the selected periods from WFIP2
- Validated the new 3D PBL scheme using several selected cases from WFIP2 and compare results to 1D PBL scheme
- Carry out longer-term simulations of the field study domain

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