Implementation and validation of a three dimensional PBL parameterization for simulation of the flow over complex terrain

NCAR

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Forecast Improvement in Complex Terrain near the Columbia River Gorge

- High spatial resolution is being used for a number of NWP applications including wind forecasting, urban flows, dispersion, etc.
- High spatial resolution is required to achieve more accurate simulations 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 a three-dimensional planetary boundary layer scheme

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 diffusion is parameterized using 2D Smagorinsky type 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.

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

Conservation equation for the zonal wind:

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

- 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.

WRF Development

First phase

- Diagnose the turbulent fluxes in the MYNN PBL parameterization (LEVEL 2.5).
- Add a new diffusion option that uses the turbulent fluxes diagnosed in the PBL.
- The resulting turbulent mixing is three-dimensional.
- Makes use of the PBL approximation to compute the fluxes.

Second phase (In progress)

- Implement a full 3D PBL parameterization in order to…
- Recover the neglected terms by the PBL approximation
- Validate the new 3D PBL parameterization using observations

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

$$\frac{Dq^2}{Dt} - \frac{\partial}{\partial z}\left[lqS_q \frac{\partial}{\partial}\left(\frac{q^2}{2}\right)\right] = P_S + P_B - \varepsilon$$

$$\langle u^2\rangle = \frac{q^2}{3} + \frac{l_1}{q}\left[-4\langle uw\rangle\frac{\partial U}{\partial z} + 2\langle vw\rangle\frac{\partial V}{\partial z} - 2P_B\right]$$

$$\langle v^2\rangle = \frac{q^2}{3} + \frac{l_1}{q}\left[2\langle uw\rangle\frac{\partial U}{\partial z} - 4\langle vw\rangle\frac{\partial V}{\partial z} - 2P_B\right]$$

$$\langle w^2\rangle = \frac{q^2}{3} + \frac{l_1}{q}\left[2\langle uw\rangle\frac{\partial U}{\partial z} + 2\langle vw\rangle\frac{\partial V}{\partial z} + 4P_B\right]$$

$$\langle uv\rangle = \frac{3l_1}{q}\left[-\langle uw\rangle\frac{\partial U}{\partial z} - \langle vw\rangle\frac{\partial V}{\partial z}\right]$$

$$\langle uw\rangle = \frac{3l_1}{q}\left[-(\langle w^2\rangle - C_1q^2)\frac{\partial U}{\partial z} - \beta g\langle u\theta_v\rangle\right]$$

$$\langle vw\rangle = \frac{3l_1}{q}\left[-(\langle w^2\rangle - C_1q^2)\frac{\partial V}{\partial z} - \beta g\langle v\theta_v\rangle\right]$$

LEVEL 2.5 scheme:

Only one prognostic equation

- A linear system must be solved for variances and covariances.
- The PBL approximation neglects horizontal derivatives and vertical derivatives in the vertical velocity.

Stresses (and heat fluxes are diagnosed quantities)

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

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

$$A\,x = B$$

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

Stresses (and heat fluxes are diagnosed quantities)

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A x = B

$$X = \begin{bmatrix} \langle u^2 \rangle \\ \langle v^2 \rangle \\ \langle w^2 \rangle \\ \langle uv \rangle \\ \langle uw \rangle \\ \langle vw \rangle \\ \langle u\theta \rangle \\ \langle v\theta \rangle \\ \langle w\theta \rangle \\ \langle \theta^2 \rangle \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{q^2}{3} + 6l_1 C_1 q \frac{\partial U}{\partial x} \\ \frac{q^2}{3} + 6l_1 C_1 q \frac{\partial V}{\partial y} \\ \frac{q^2}{3} + 6l_1 C_1 q \frac{\partial W}{\partial z} \\ 6l_1 C_1 q \left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y} \right) \\ 6l_1 C_1 q \left(\frac{\partial W}{\partial x} + \frac{\partial U}{\partial z} \right) \\ 6l_1 C_1 q \left(\frac{\partial W}{\partial y} + \frac{\partial V}{\partial z} \right) \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Stresses (and heat fluxes are diagnosed quantities)

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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 mode where TKE and a length scale are diagnosed (Mellor and Yamada 1974, 1982; Yamada and Mellor 1975).

A x = B

A =

$$
\begin{pmatrix}
\left(1+\frac{4l_1}{q}\frac{\partial U}{\partial x}\right) & -\frac{2l_1}{q}\frac{\partial V}{\partial y} & -\frac{2l_1}{q}\frac{\partial W}{\partial z} & \frac{2l_1}{q}\left(2\frac{\partial U}{\partial y}-\frac{\partial V}{\partial x}\right) & \frac{2l_1}{q}\left(2\frac{\partial U}{\partial z}-\frac{\partial W}{\partial x}\right) & -\frac{2l_1}{q}\left(\frac{\partial V}{\partial z}+\frac{\partial W}{\partial y}\right) & 0 & 0 & \frac{2l_1}{q}g\beta & 0 \\
\left(1+\frac{4l_1}{q}\frac{\partial U}{\partial x}\right) & -\frac{2l_1}{q}\frac{\partial V}{\partial y} & -\frac{2l_1}{q}\frac{\partial W}{\partial z} & \frac{2l_1}{q}\left(2\frac{\partial U}{\partial y}-\frac{\partial V}{\partial x}\right) & \frac{2l_1}{q}\left(2\frac{\partial U}{\partial z}-\frac{\partial W}{\partial x}\right) & -\frac{2l_1}{q}\left(\frac{\partial V}{\partial z}+\frac{\partial W}{\partial y}\right) & 0 & 0 & \frac{2l_1}{q}g\beta & 0 \\
-\frac{2l_1}{q}\frac{\partial U}{\partial x} & -\frac{2l_1}{q}\frac{\partial V}{\partial y} & \left(1+\frac{4l_1}{q}\frac{\partial W}{\partial z}\right) & \frac{2l_1}{q}\left(\frac{\partial U}{\partial y}+\frac{\partial V}{\partial x}\right) & \frac{2l_1}{q}\left(2\frac{\partial W}{\partial x}-\frac{\partial U}{\partial z}\right) & \frac{2l_1}{1}\left(2\frac{\partial W}{\partial y}-\frac{\partial V}{\partial z}\right) & 0 & 0 & \frac{4l_1}{q}g\beta & 0 \\
\frac{3l_1}{q}\frac{\partial V}{\partial x} & \frac{3l_1}{q}\frac{\partial U}{\partial y} & 0 & \left[1+\frac{3l_1}{q}\left(\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}\right)\right] & \frac{3l_1}{q}\frac{\partial V}{\partial z} & \frac{3l_1}{q}\frac{\partial U}{\partial z} & 0 & 0 & 0 & 0 \\
\frac{3l_1}{q}\frac{\partial W}{\partial x} & 0 & \frac{3l_1}{q}\frac{\partial U}{\partial z} & \frac{3l_1}{q}\frac{\partial W}{\partial y} & \left[1+\frac{3l_1}{q}\left(\frac{\partial W}{\partial z}+\frac{\partial U}{\partial x}\right)\right] & \frac{3l_1}{q}\frac{\partial U}{\partial y} & \frac{3l_1}{q}\beta g & 0 & 0 & 0 \\
0 & \frac{3l_1}{q}\frac{\partial W}{\partial y} & \frac{3l_1}{q}\frac{\partial V}{\partial z} & \frac{3l_1}{q}\frac{\partial W}{\partial x} & \frac{3l_1}{q}\frac{\partial V}{\partial x} & \left[1+\frac{3l_1}{q}\left(\frac{\partial W}{\partial z}+\frac{\partial V}{\partial y}\right)\right] & 0 & \beta g\frac{3l_1}{q} & 0 & 0 \\
\frac{3l_2}{q}\frac{\partial \Theta}{\partial x} & 0 & 0 & \frac{3l_2}{q}\frac{\partial \Theta}{\partial y} & \frac{3l_2}{q}\frac{\partial \Theta}{\partial z} & 0 & \left(1+\frac{3l_2}{q}\frac{\partial U}{\partial x}\right) & \frac{3l_2}{q}\frac{\partial U}{\partial y} & \frac{3l_2}{q}\frac{\partial U}{\partial z} & 0 \\
0 & \frac{3l_2}{q}\frac{\partial \Theta}{\partial y} & 0 & \frac{3l_2}{q}\frac{\partial \Theta}{\partial x} & 0 & \frac{3l_2}{q}\frac{\partial \Theta}{\partial z} & \frac{3l_2}{q}\frac{\partial V}{\partial x} & \left(1+\frac{3l_2}{q}\frac{\partial V}{\partial y}\right) & \frac{3l_2}{q}\frac{\partial V}{\partial z} & 0 \\
0 & 0 & \frac{3l_2}{q}\frac{\partial \Theta}{\partial z} & 0 & \frac{3l_2}{q}\frac{\partial \Theta}{\partial x} & \frac{3l_2}{q}\frac{\partial \Theta}{\partial y} & \frac{3l_2}{q}\frac{\partial W}{\partial x} & \frac{3l_2}{q}\frac{\partial W}{\partial y} & \left(1+\frac{3l_2}{q}\frac{\partial W}{\partial z}\right) & \beta g\frac{3l_2}{q} \\
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{pmatrix}
$$

Stresses (and heat fluxes are diagnosed quantities)

Validation of Multi-Scale Simulations of the Flow over Big Southern Butte Using WRF Model

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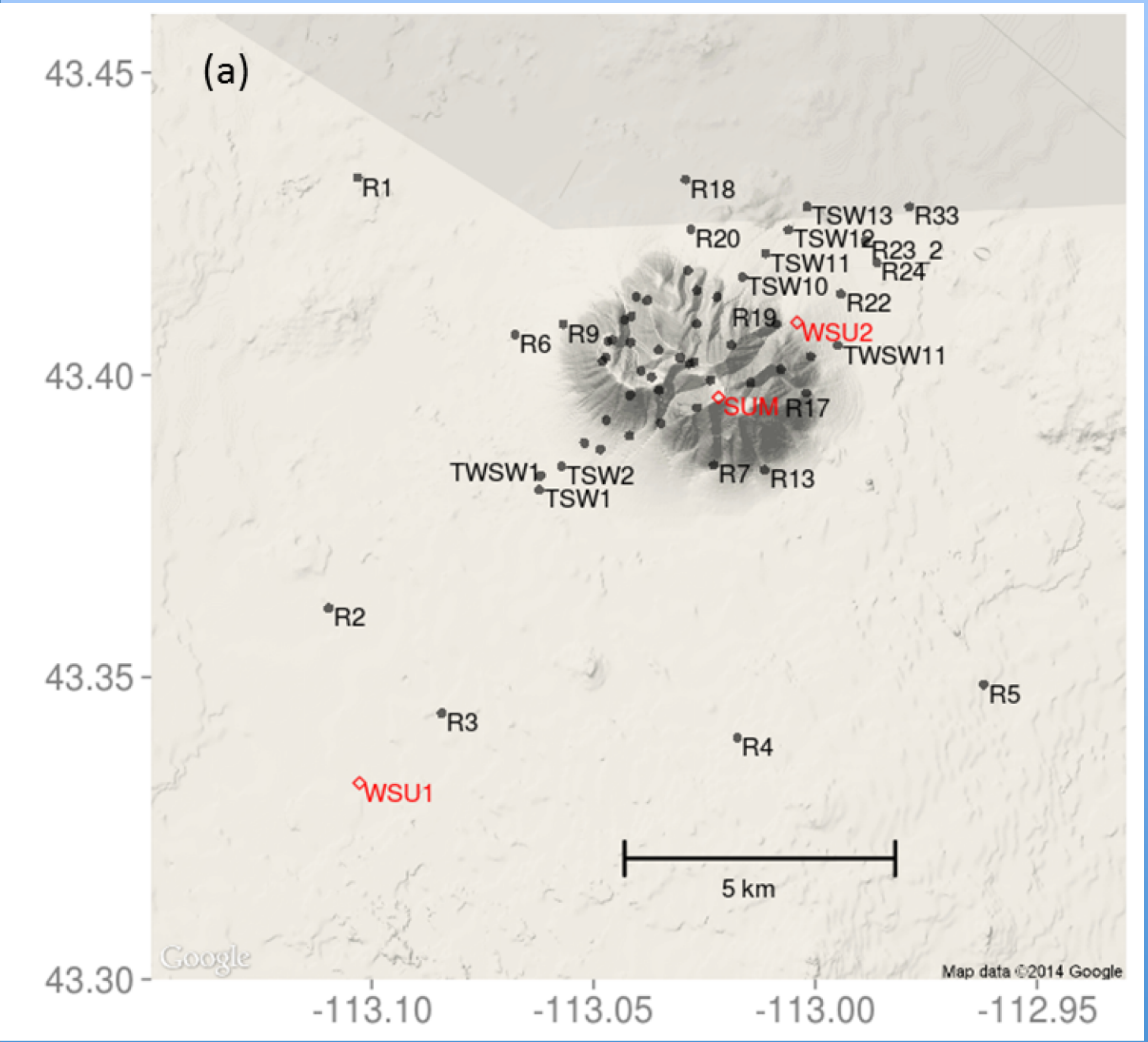
Observations: Big Southern Butte



Butler et. al. ACP (2015)

Date field campaign:
June 10, 2010 – September 9, 2010

Observations: Surface winds at 3 m.

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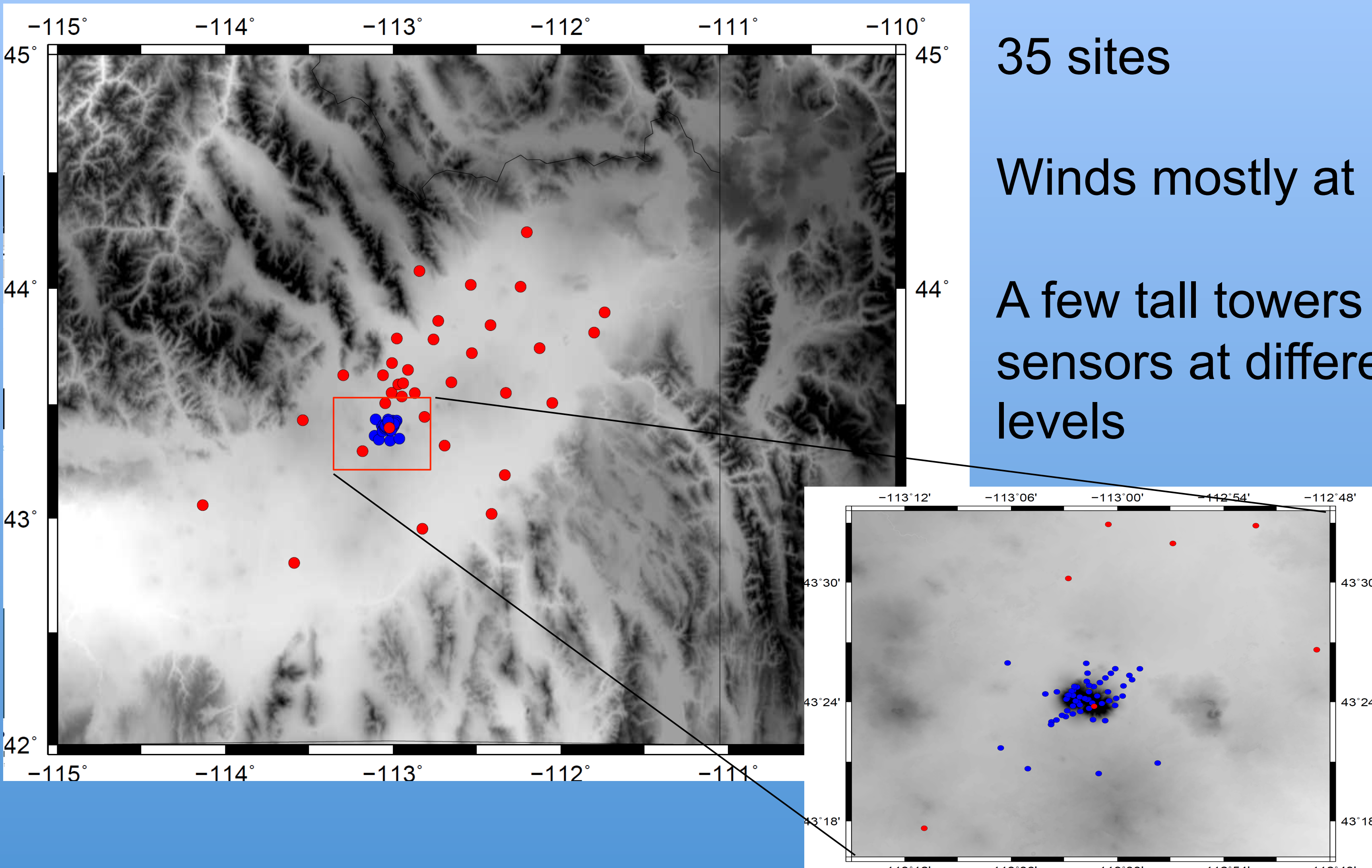
Observations: NOAA Field Research Division



35 sites

Winds mostly at 15 m

A few tall towers with sensors at different levels

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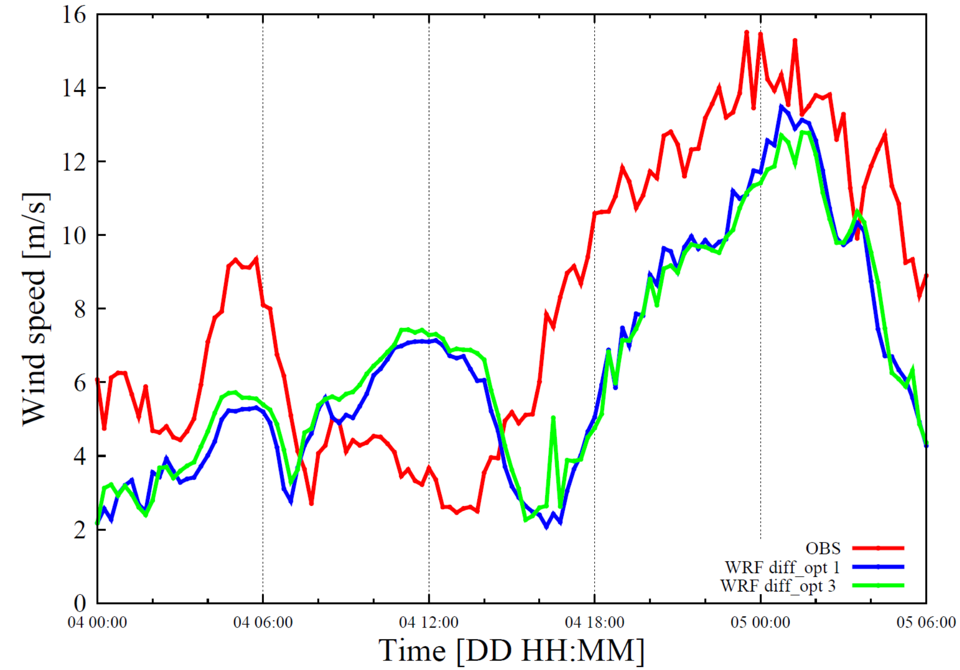
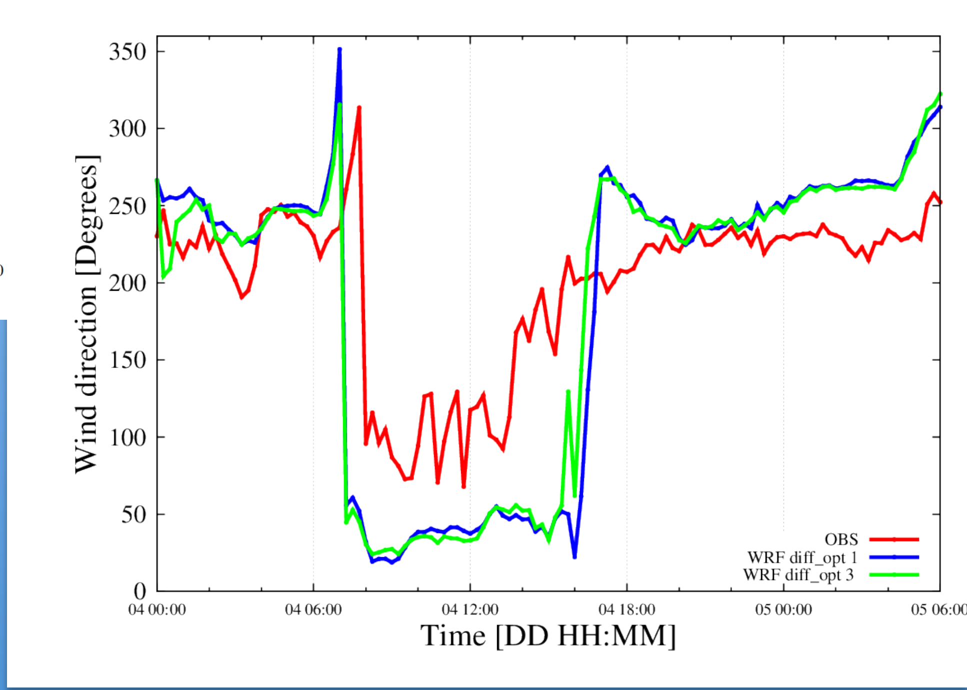
Differences in mean wind speed from WRF mesoscale simulations with 1D and 3D PBL schemes are small



Regional wind at 3 m calculated with the wind observations over the SBS In July 2010 and co-located winds from WRF.



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We Have Started Testing 3D PBL Parameterization Using Data from WFIP2

- We are testing the model on Wind Forecast Improvement Project 2 (WFIP2) domain data.
- We have selected March 7 and 8 as the days to carry out the first validation of the new 3D PBL scheme.
- HRRR results indicated presence of mountain wakes.
- Initial and boundary conditions from HRRR (3km grid cell size)
- Downscaling HRRR to 1 km grid cell size and then 110 m grid cell size.

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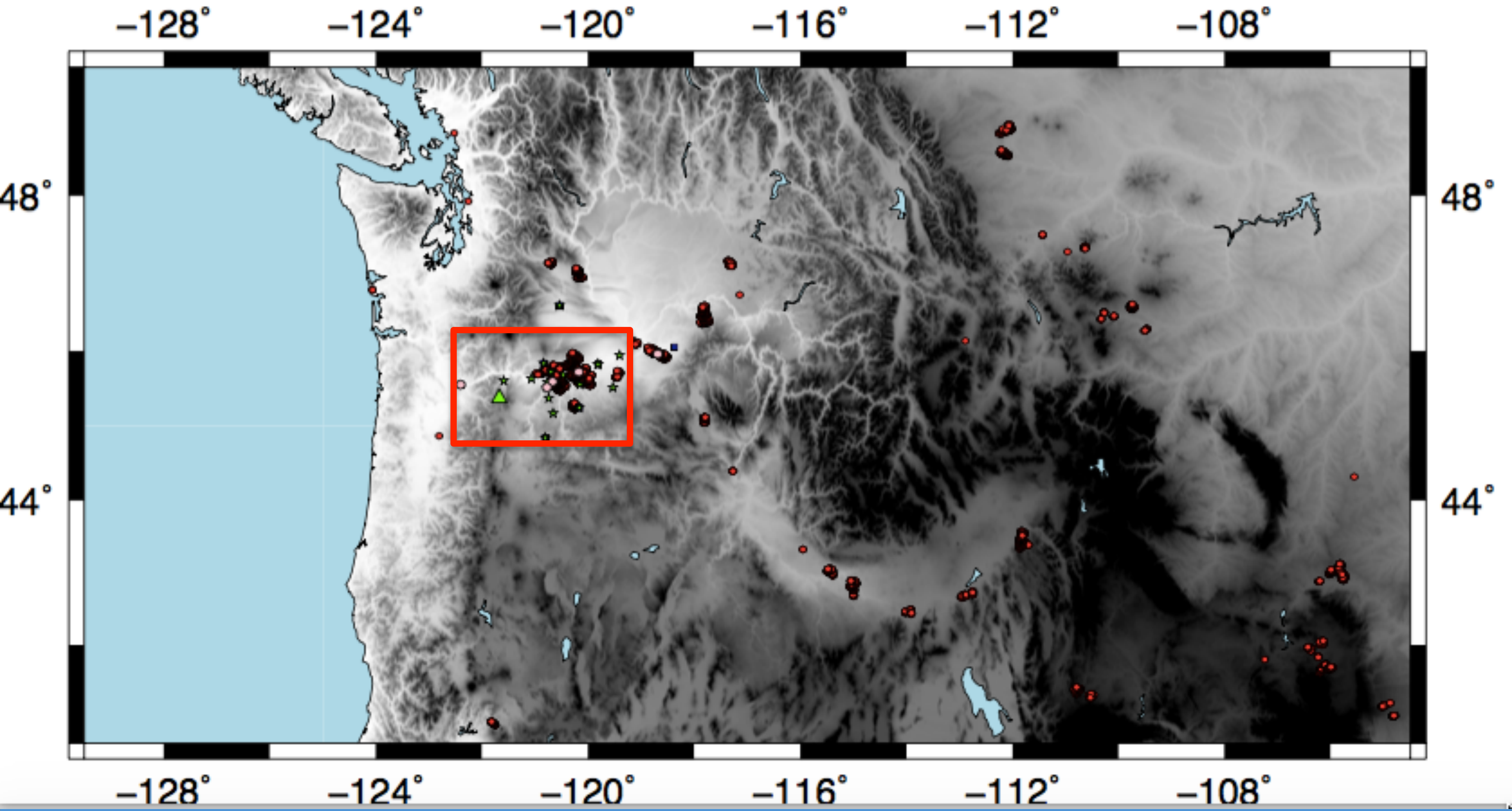
WFIP2 WRF – Domain 1



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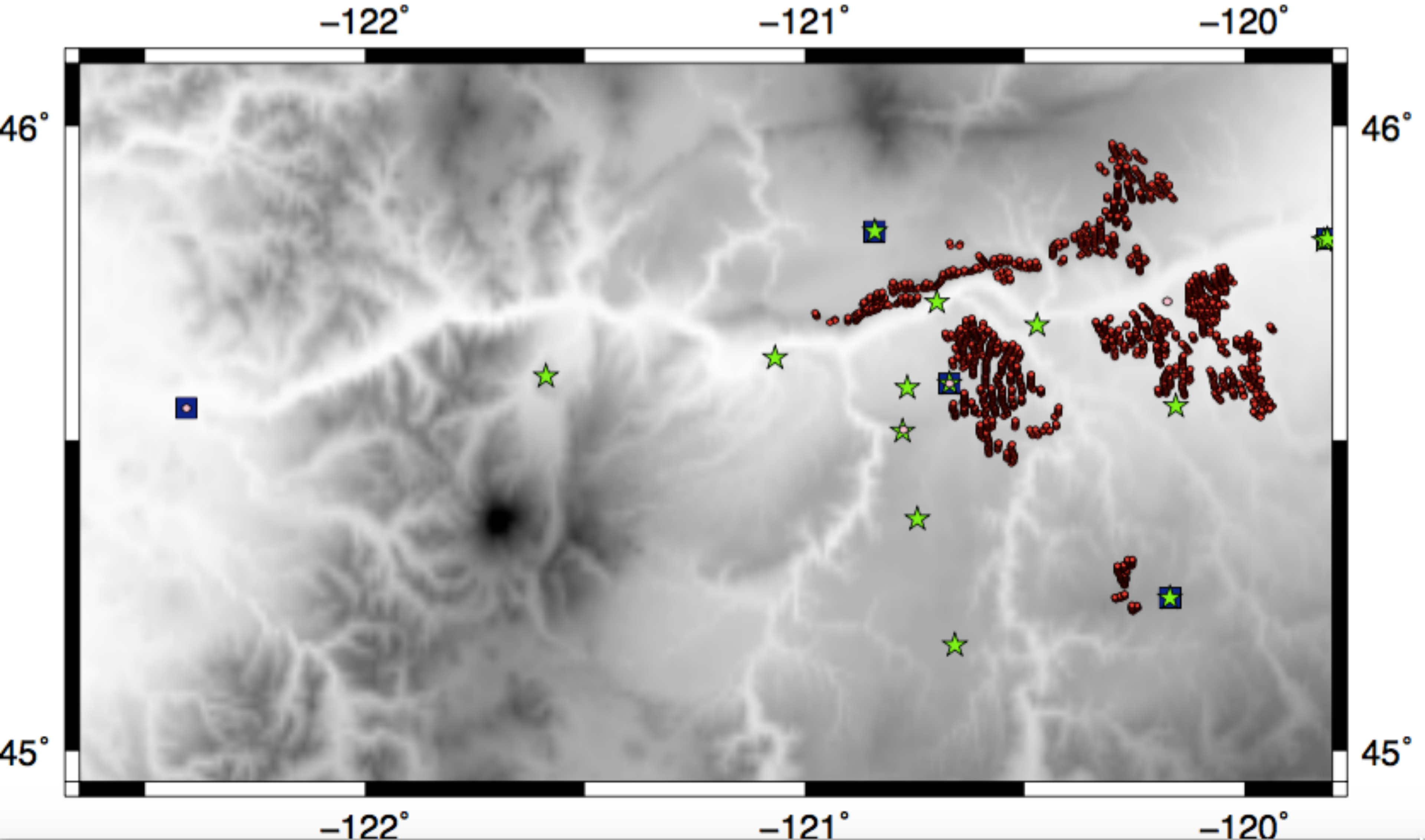
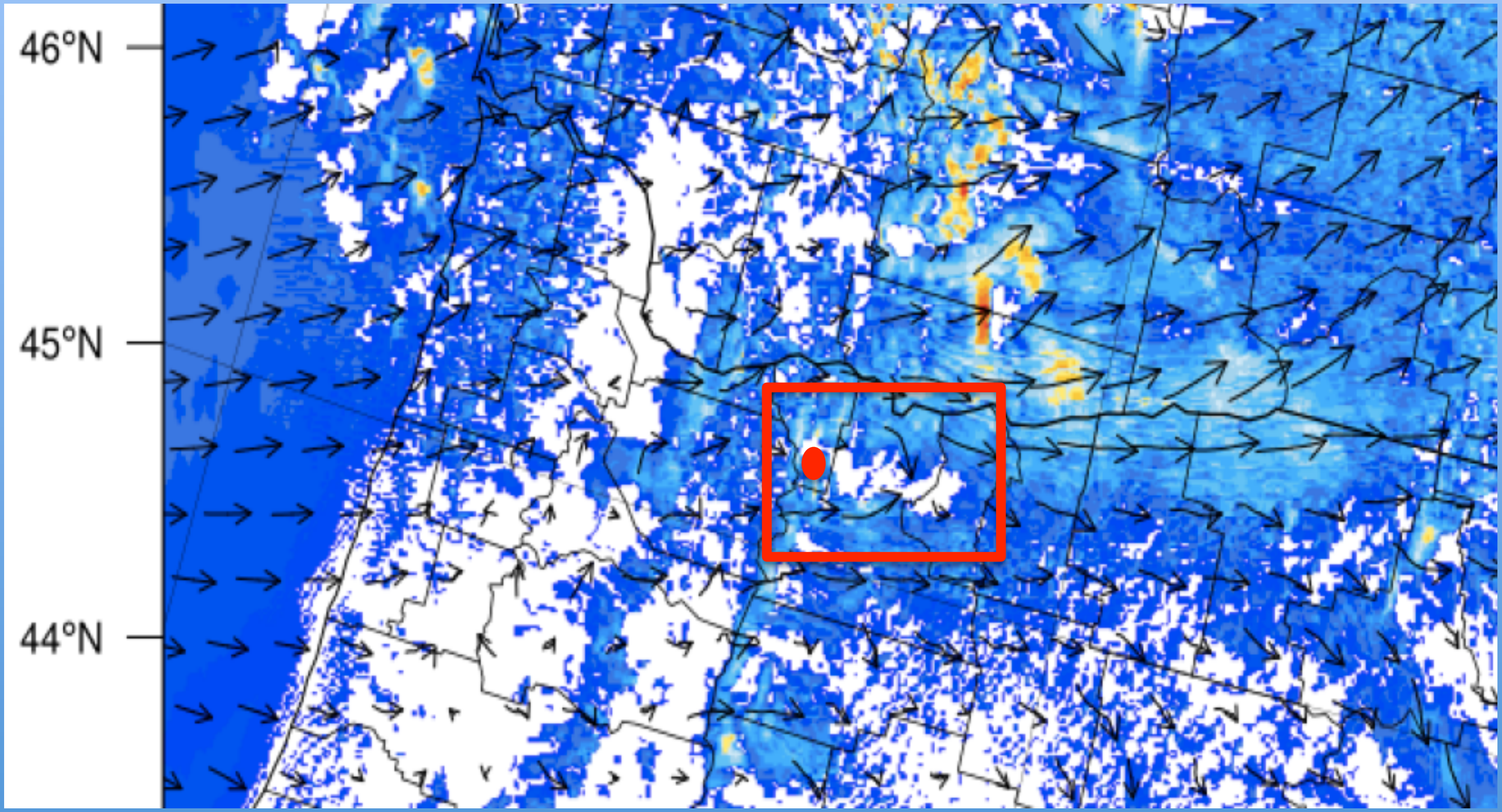
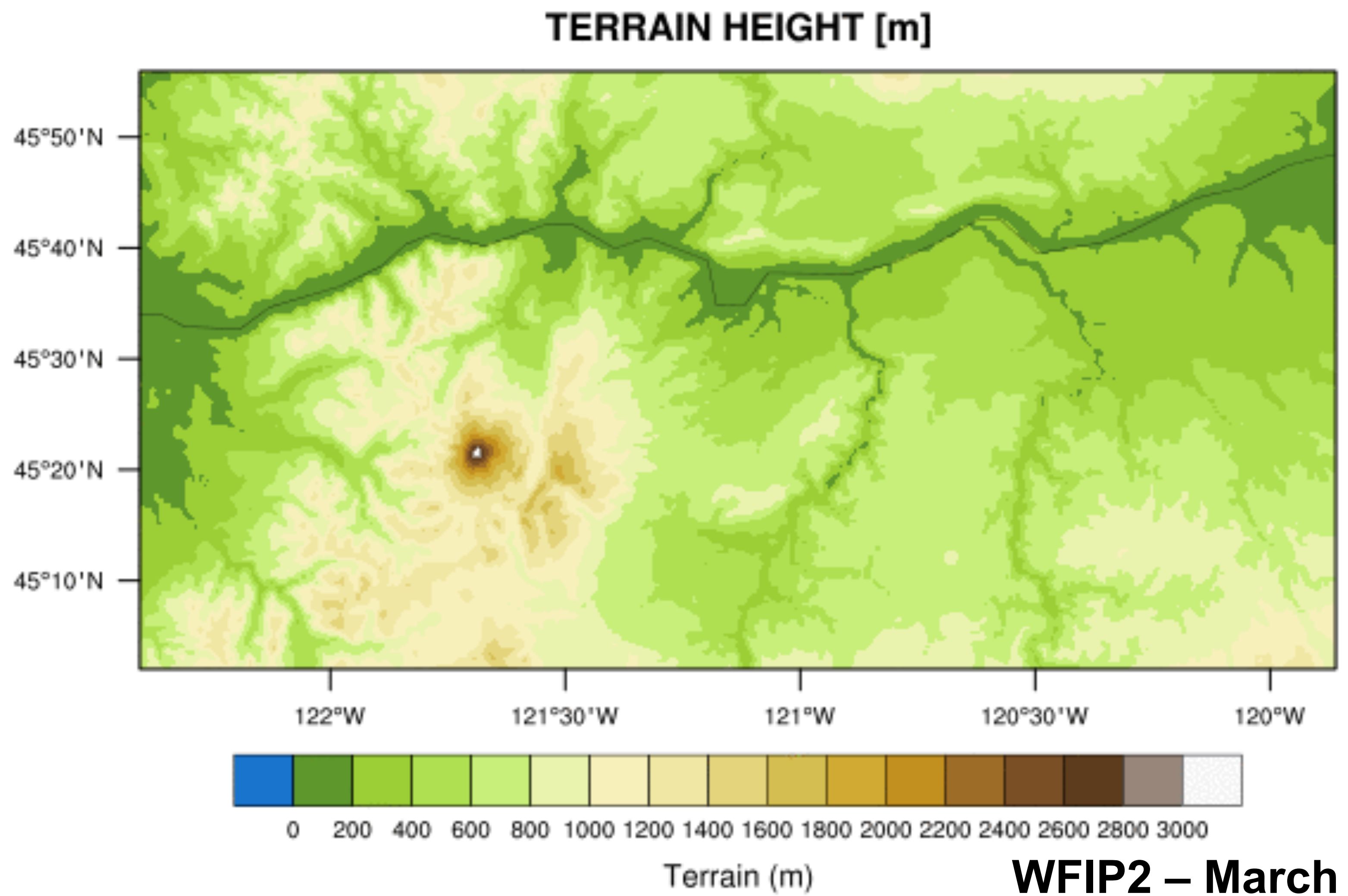
WFIP2 WRF – Domain 2



Mountain Hood Wake on March 7, 2016
HRRR



Water Vapor Mixing Ratio – as a Tracer Used to Visualize the Gap Flow



WFIP2 – March 7, 2016

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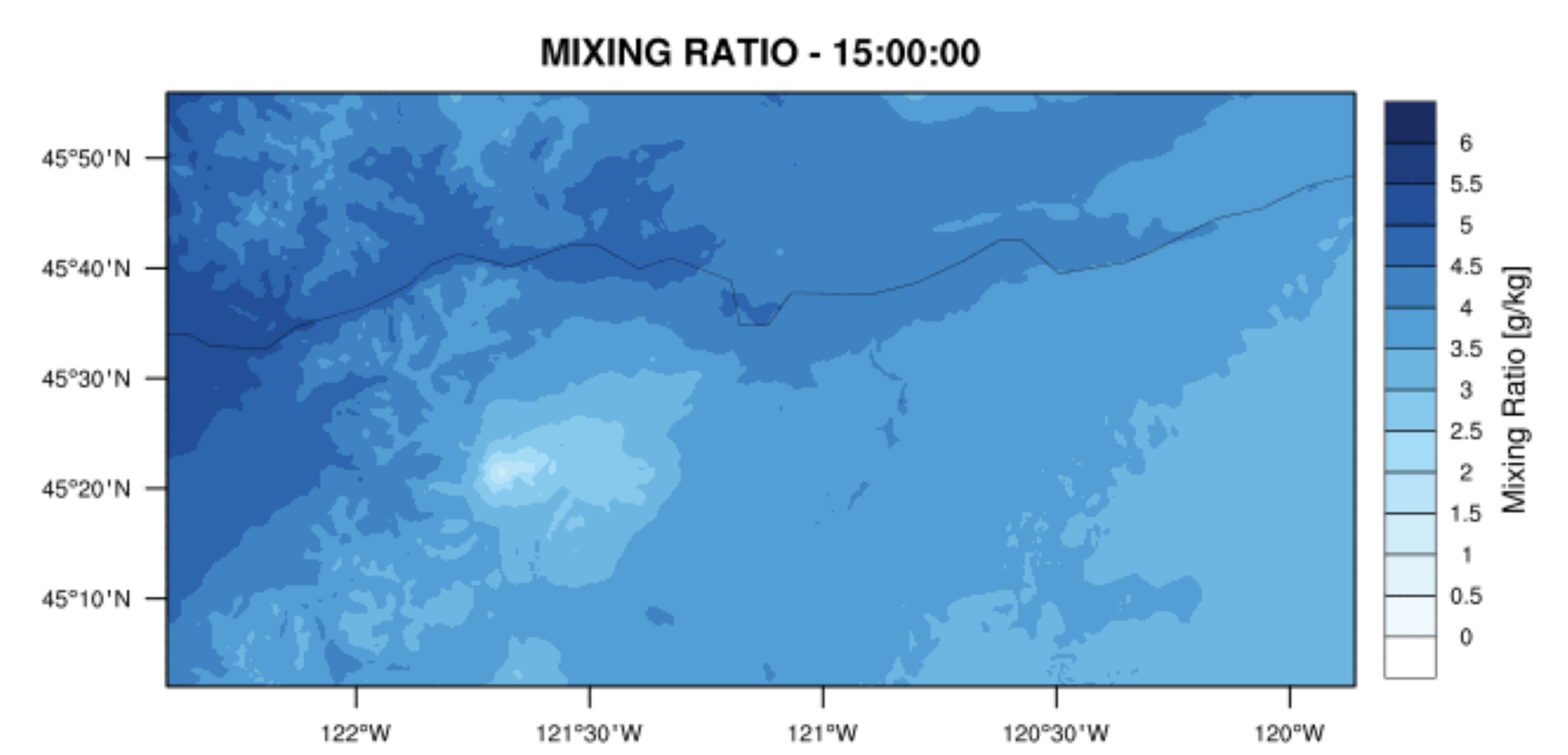
Water Vapor Mixing Ratio - as a Tracer Used to Visualize the Mountain Wake



WFIP2 – March 7, 2016

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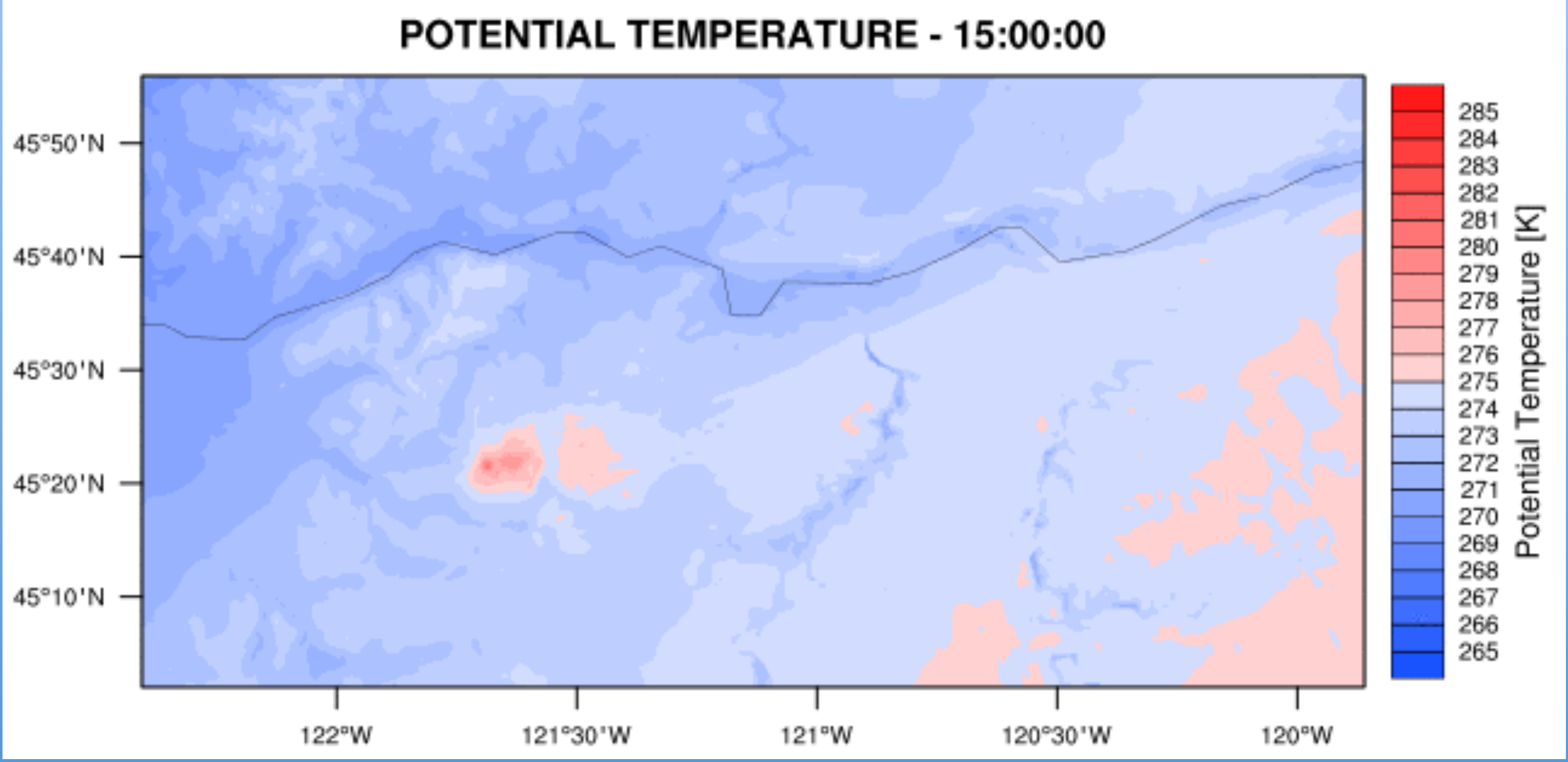
Potential Temperature Shows the Effect of Complex Terrain on Entrainment



WFIP2 – March 7, 2016

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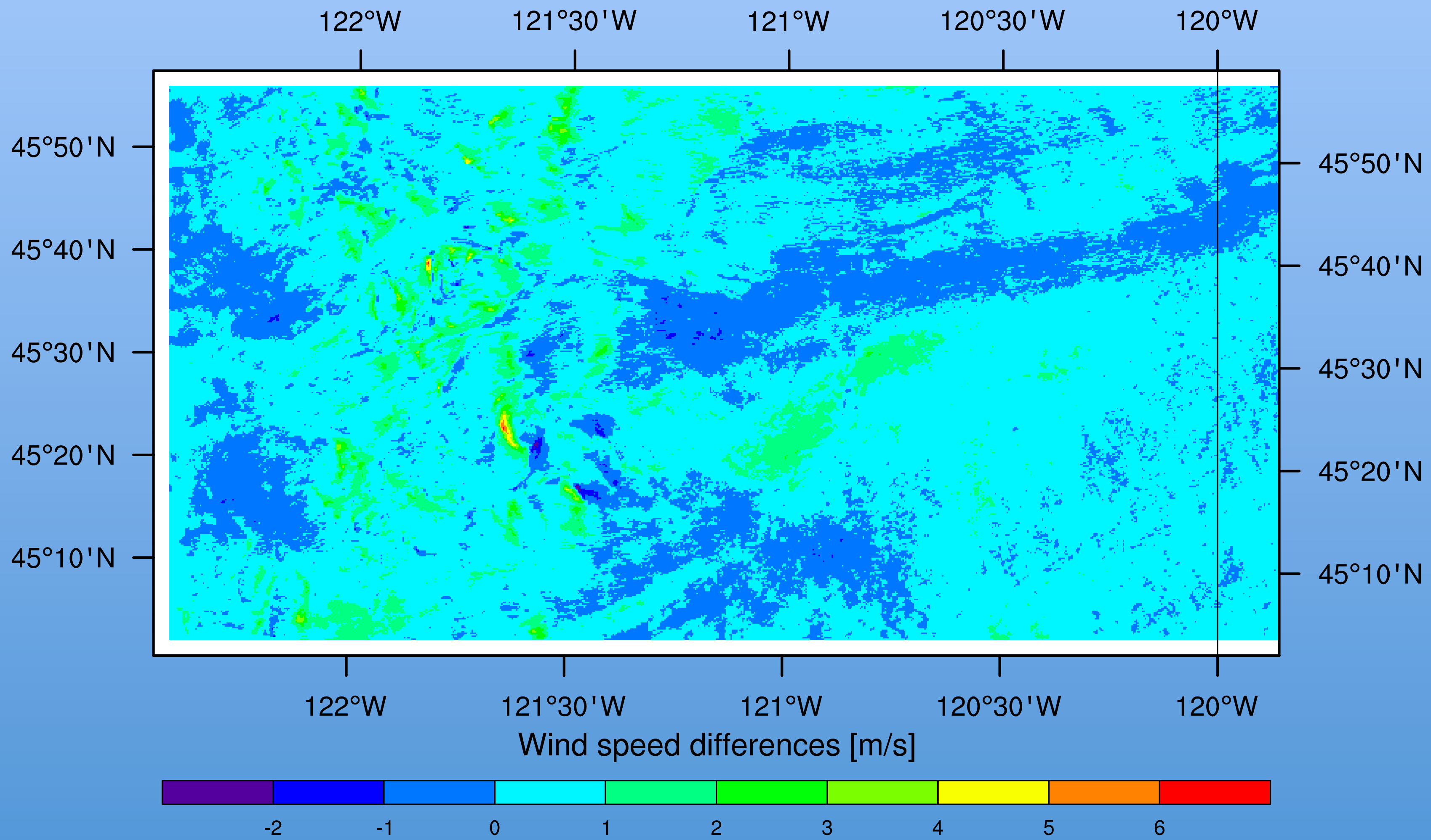
Wind Speed Difference Between 1D PBL and 3D PBL



WFIP2 – March 7

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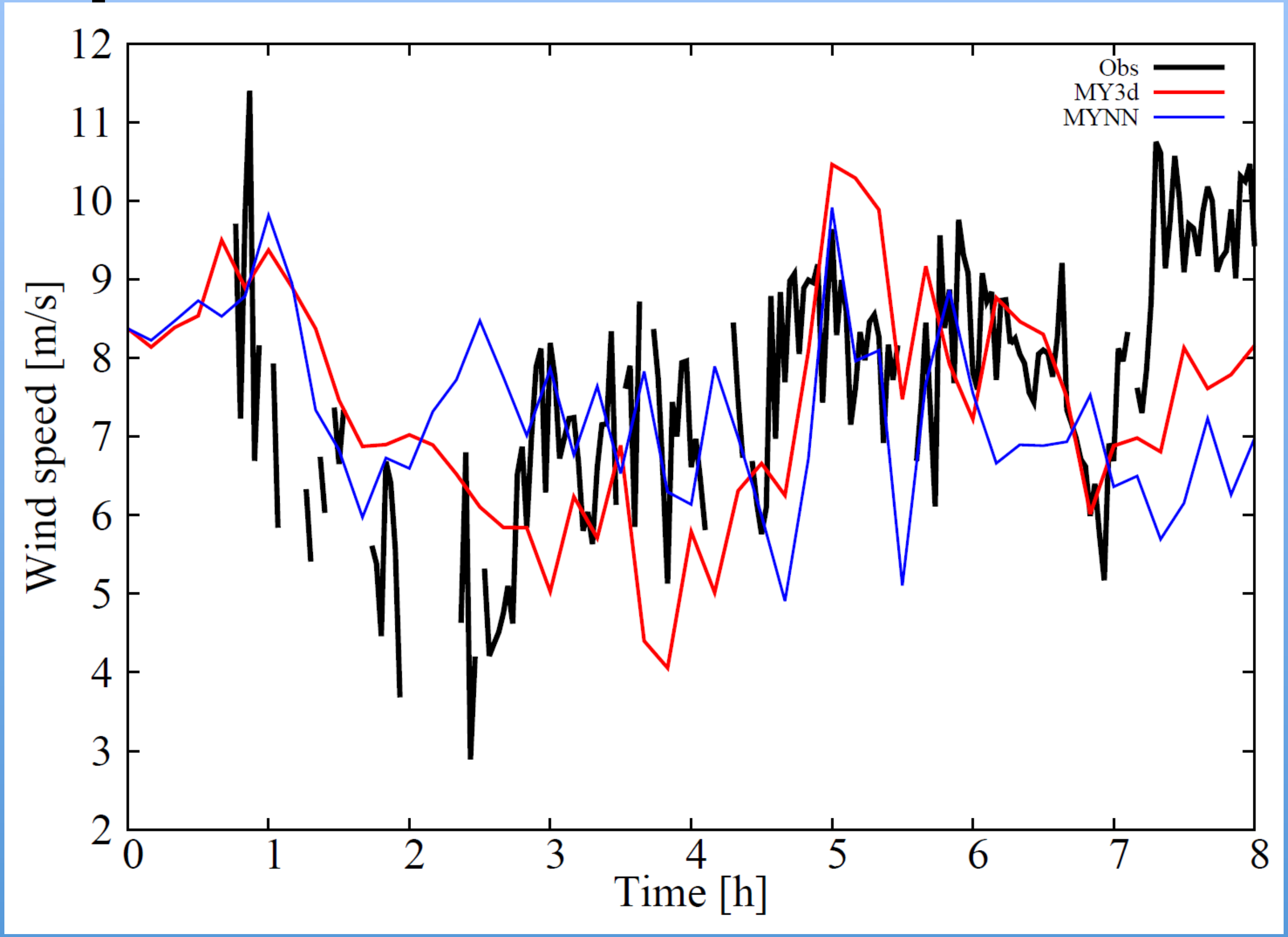
Simulated Hub-height Wind Speeds are Compared to Observations at Wasco



Observations from CU LIDAR at Wasco

WFIP2 – March 7, 2016

Next Steps

- Implement solution of the full set of algebraic equations for turbulent stresses and fluxes.
- Carry out high-resolution simulation of the selected period 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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Thank you!

Questions?

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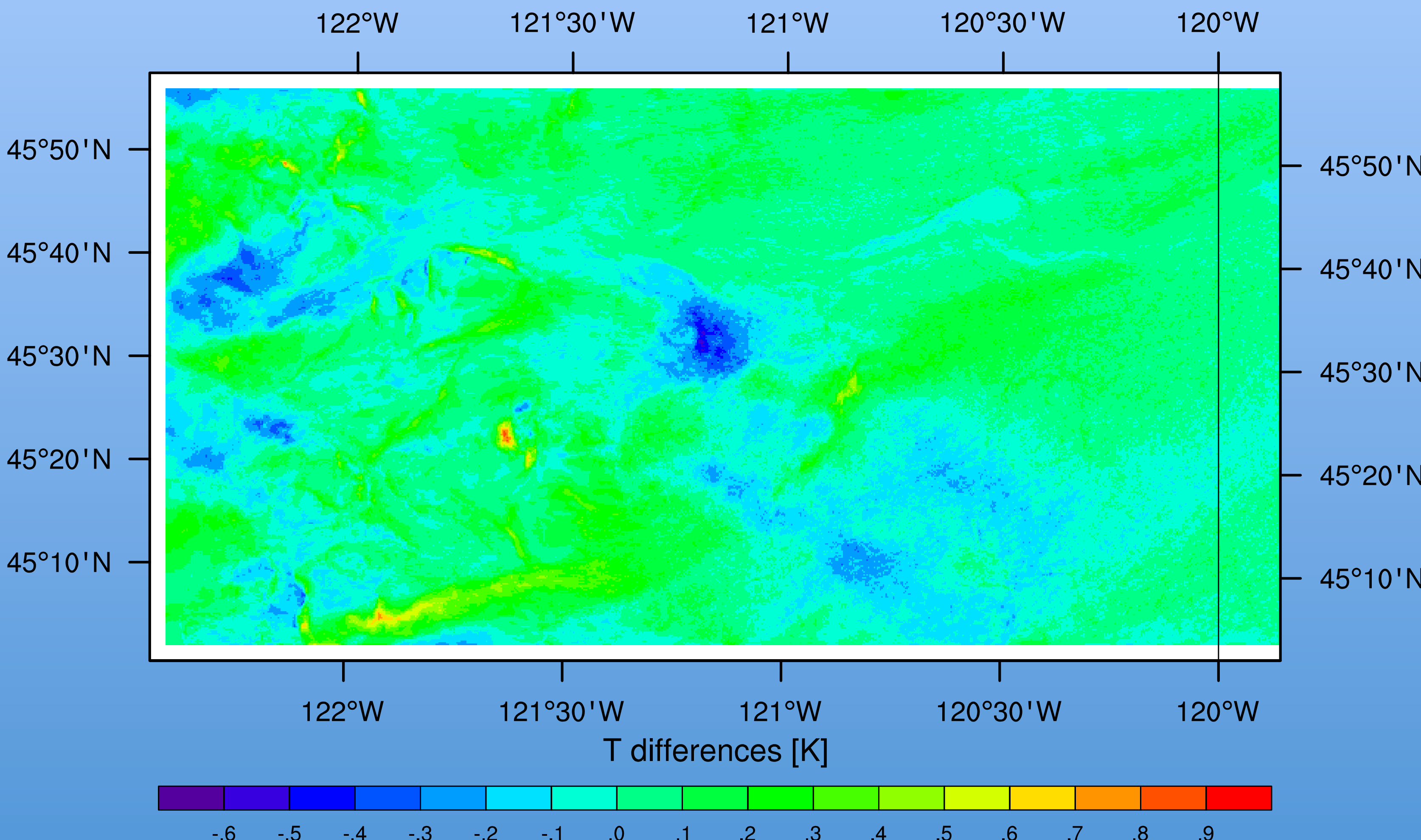
Potential Temperature Difference Between 1D PBL and 3D PBL



WFIP2 – March 7, 2016

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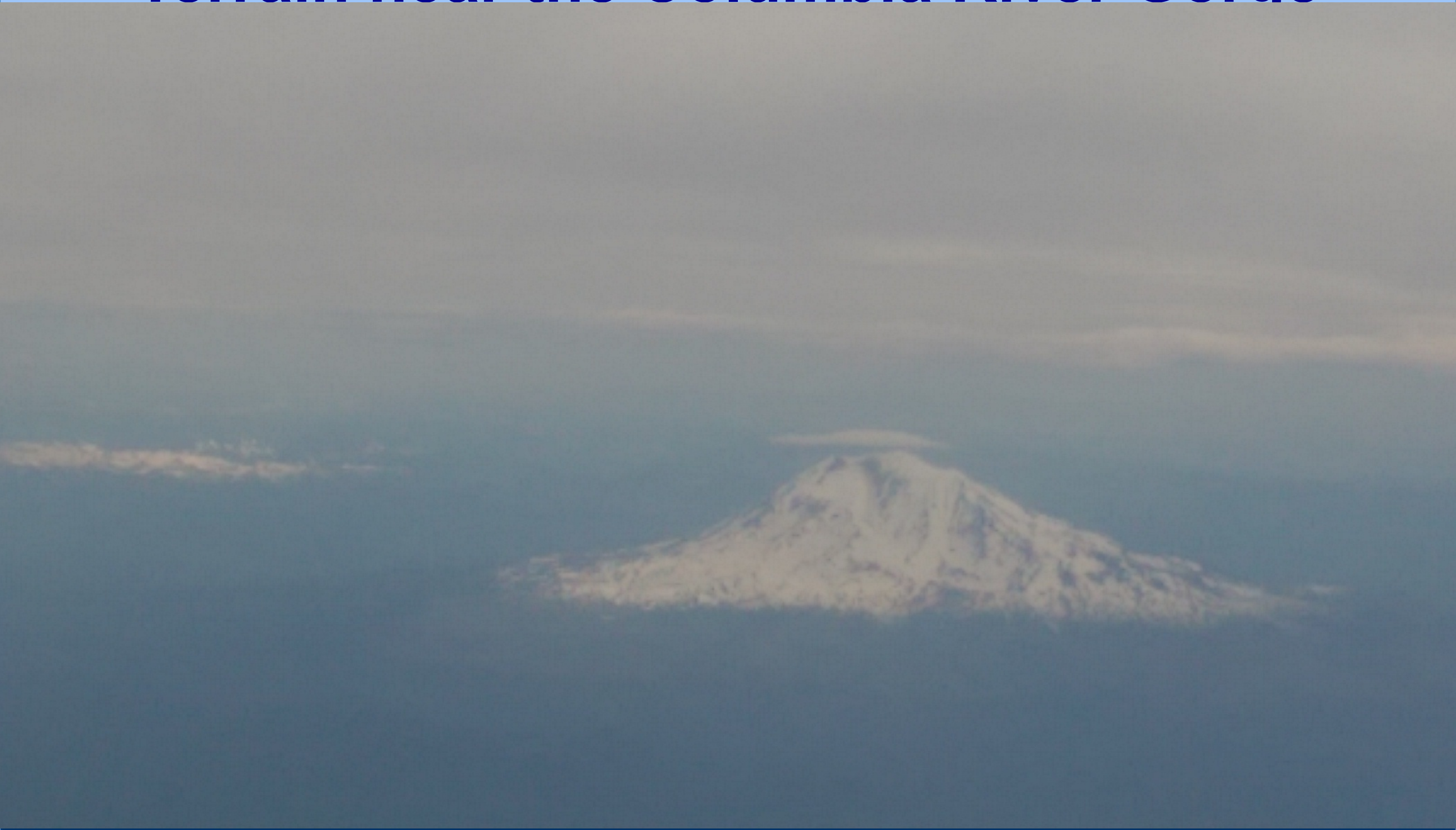
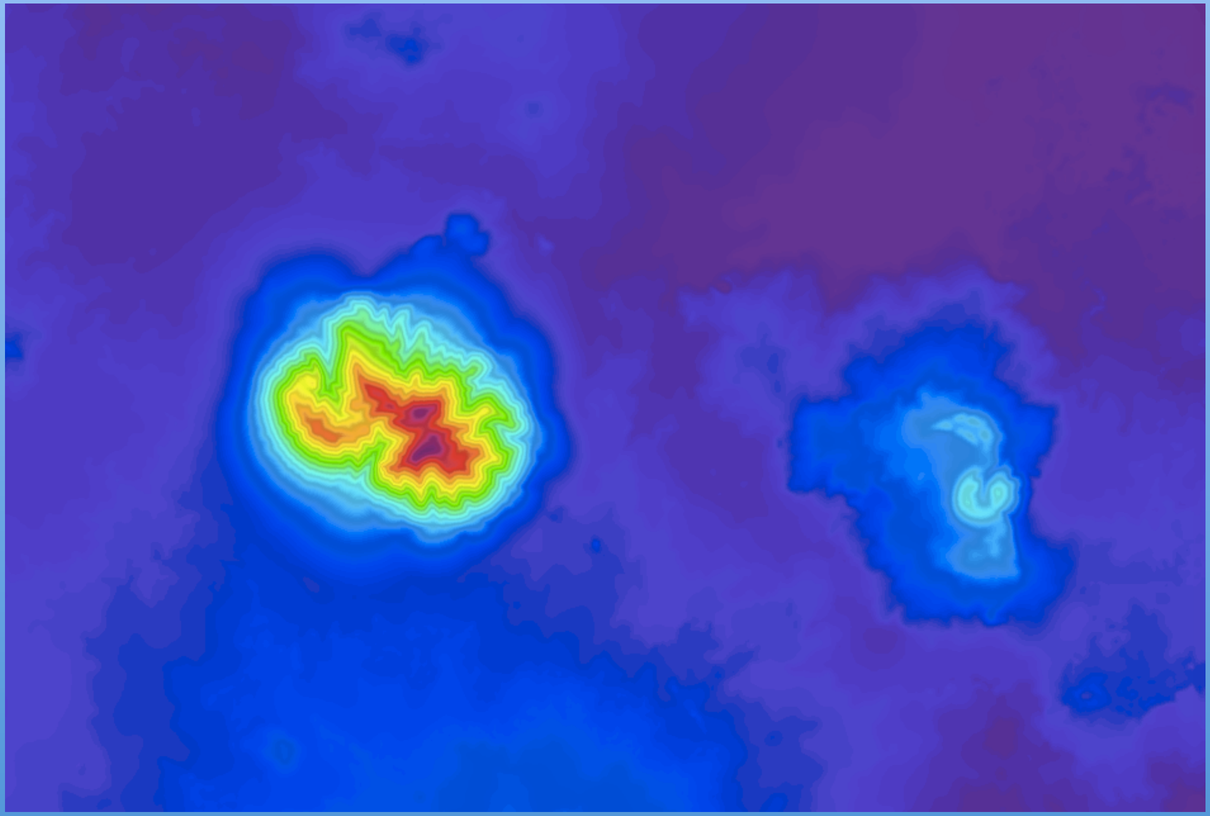
Forecast Improvement in Complex Terrain near the Columbia River Gorge

Forecast Improvement in Complex Terrain near the Columbia River Gorge



We Used 6 WRF Domains with Grid Cell Sizes from 27km to 111m

Six domains one way nested to reach a horizontal resolution of 111 m over Big Southern Butte



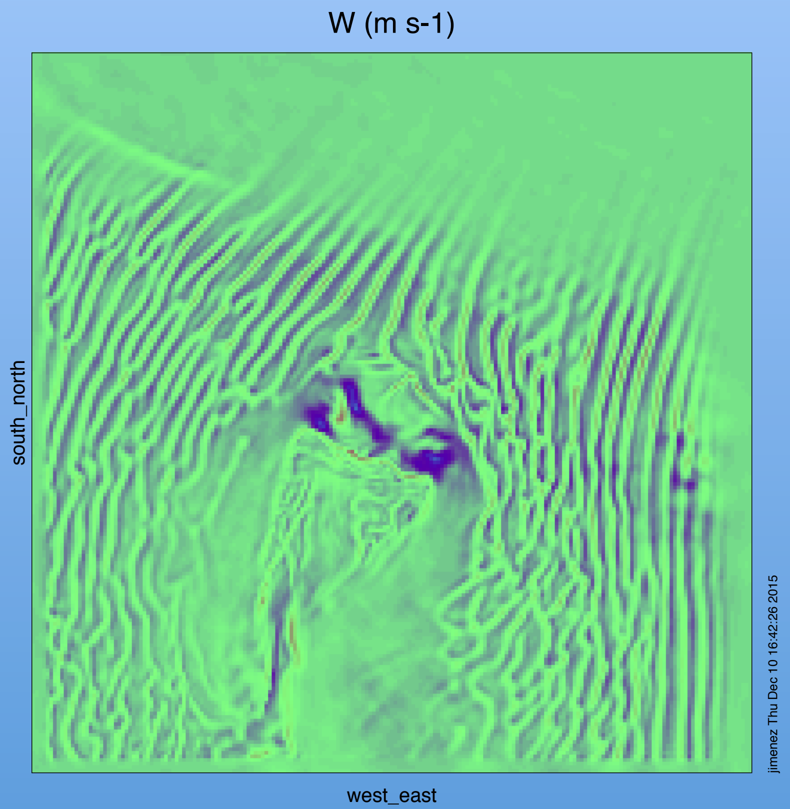
WRF developments:

Implemented a 10 m elevation data set covering the BSB

Diagnose the winds at 3 m

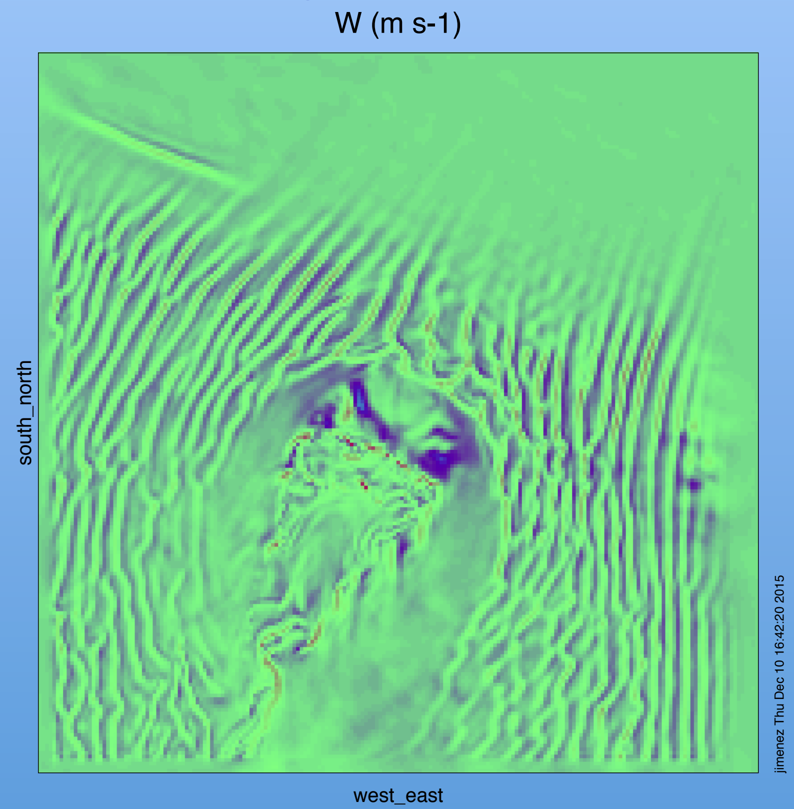
Instantaneous vertical velocities using 1D and 3D PBL show differences in heterogeneous terrain

1D PBL



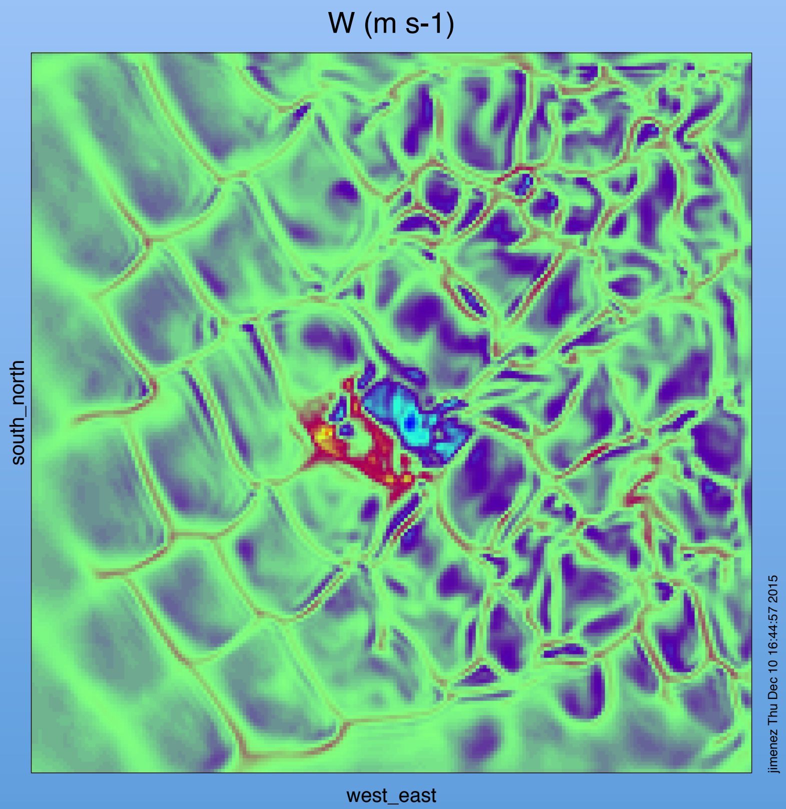
Range of W: -6 to 7 m s-1
Range of west_east: 0 to 200
Range of south_north: 0 to 200
Current Time: 10
Current bottom_top_stag: 3
Frame 11 in File wrfout_d06_2010-07-04_12:00:00

3D PBL

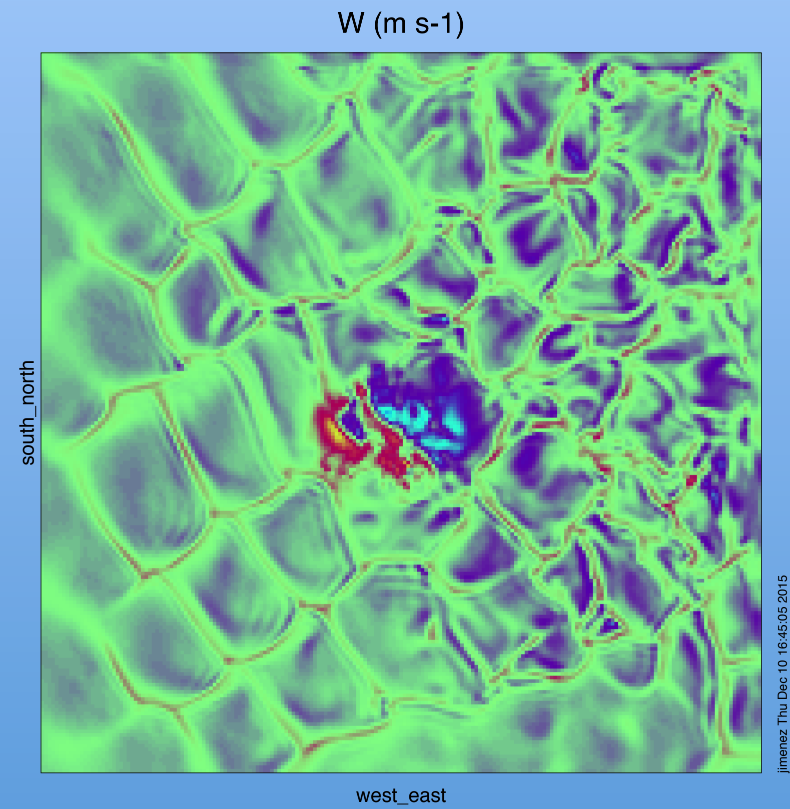


Range of W: -6 to 7 m s-1
Range of west_east: 0 to 200
Range of south_north: 0 to 200
Current Time: 10
Current bottom_top_stag: 3
Frame 11 in File wrfout_d06_2010-07-04_12:00:00

Instantaneous vertical velocities using 1D and 3D PBL show differences in heterogeneous terrain



Range of W: -6 to 7 m s-1
Range of west_east: 0 to 200
Range of south_north: 0 to 200
Current Time: 31
Current bottom_top_stag: 3
Frame 32 in File wrfout_d06_2010-07-04_12:00:00



Range of W: -6 to 7 m s-1
Range of west_east: 0 to 200
Range of south_north: 0 to 200
Current Time: 31
Current bottom_top_stag: 3
Frame 32 in File wrfout_d06_2010-07-04_12:00:00

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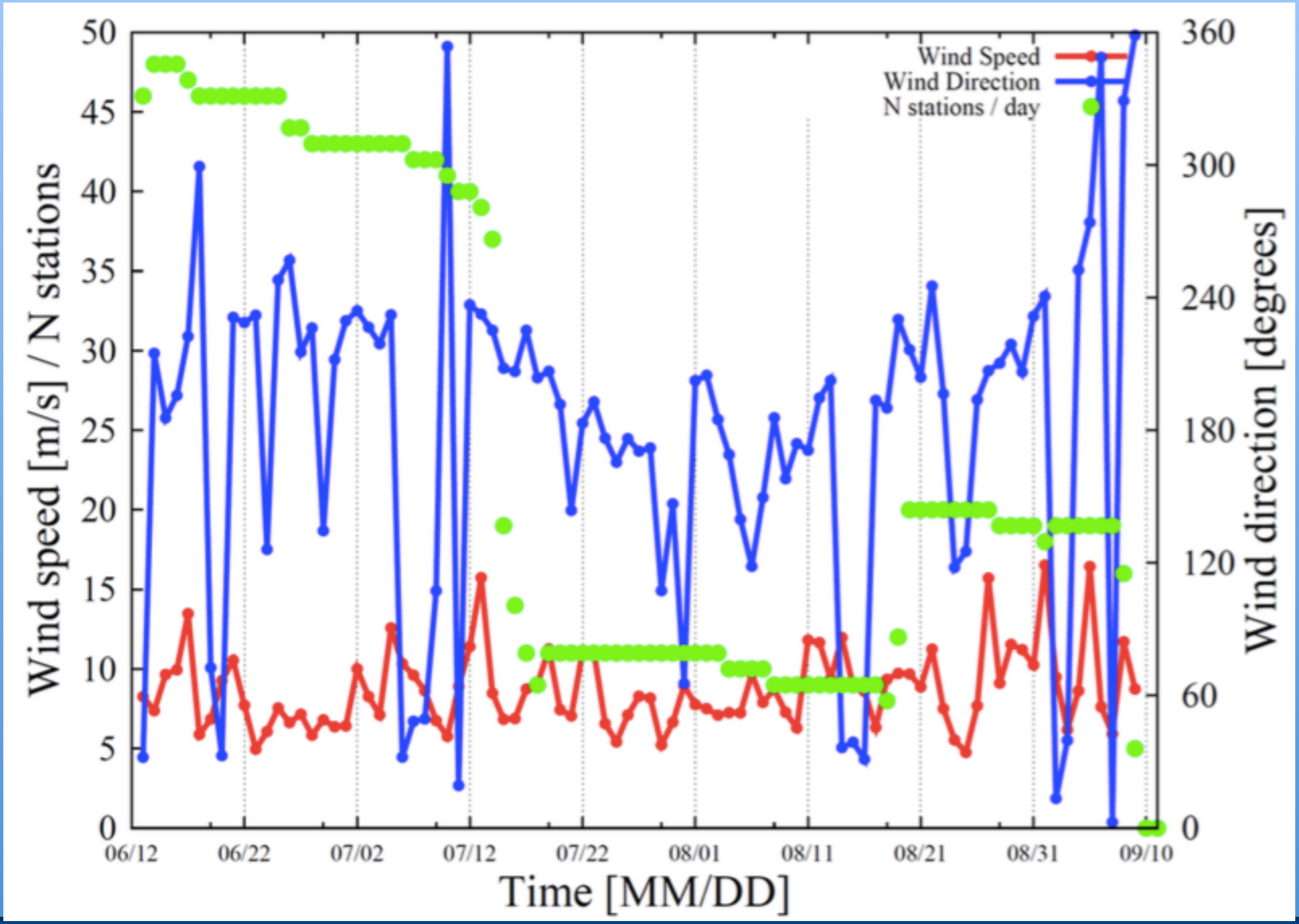
Case Study Was Selected Base on the Availability and Quality of Data



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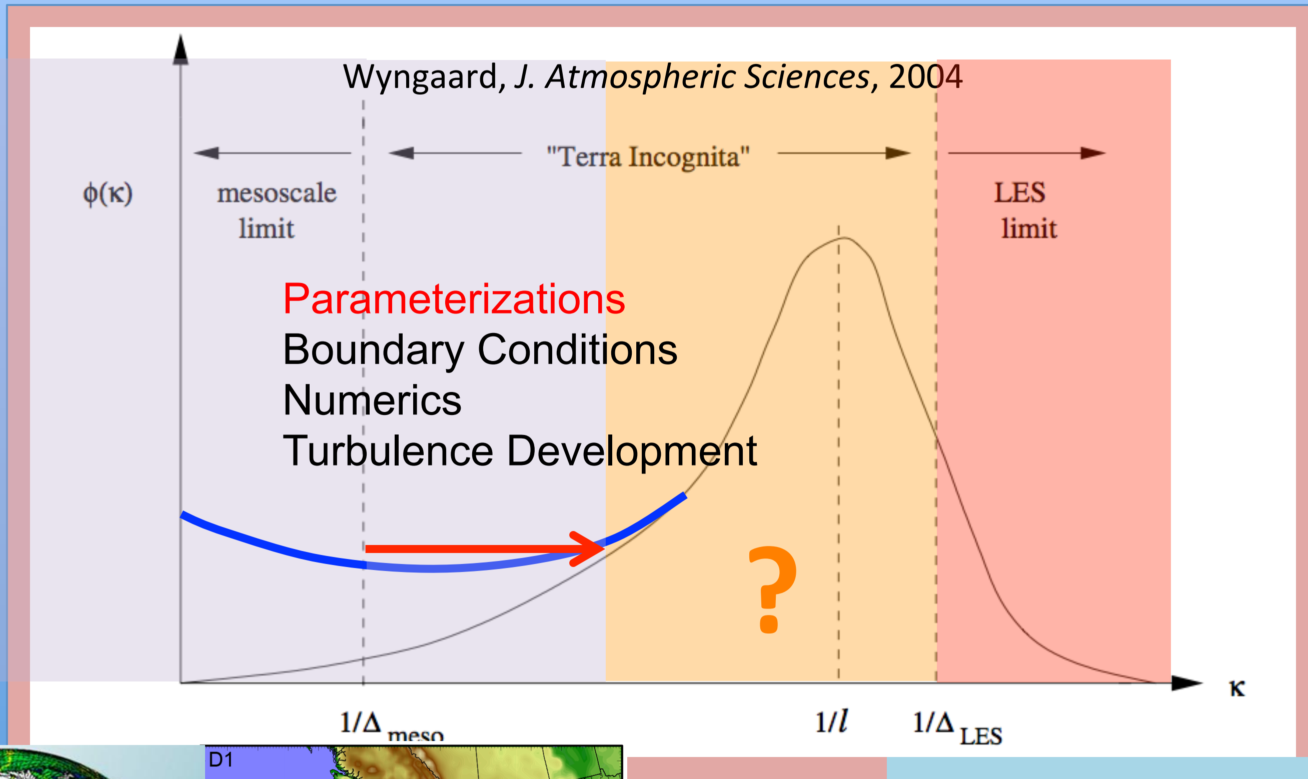
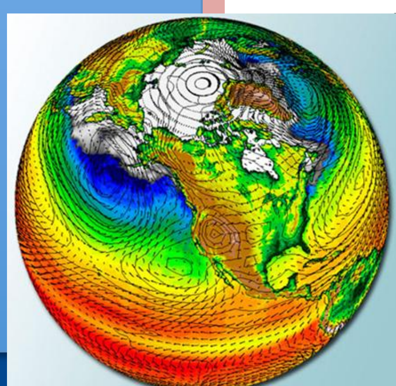
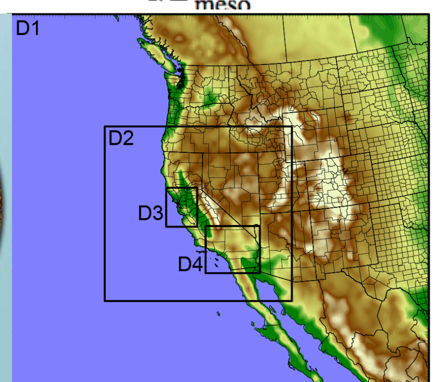
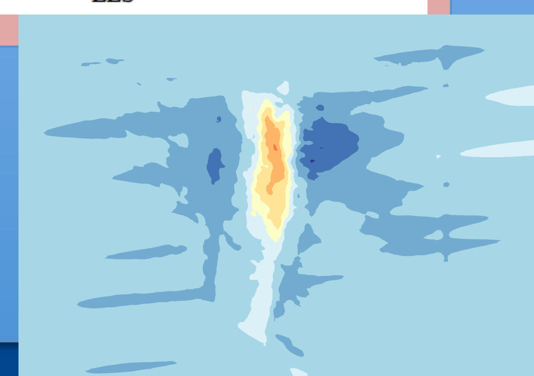
What is the Effective Approach to Simulating Mesoscale-Microscale Interactions?









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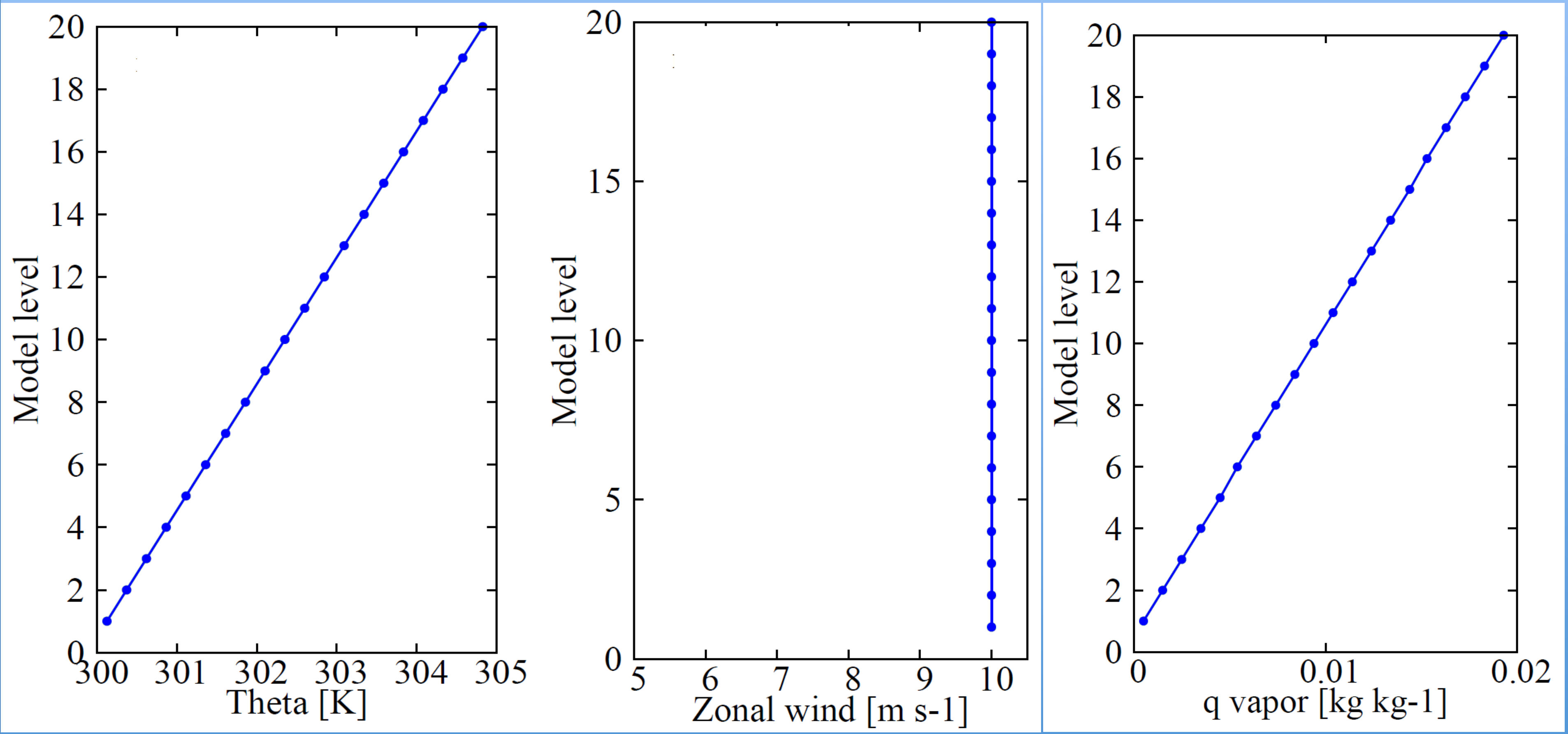
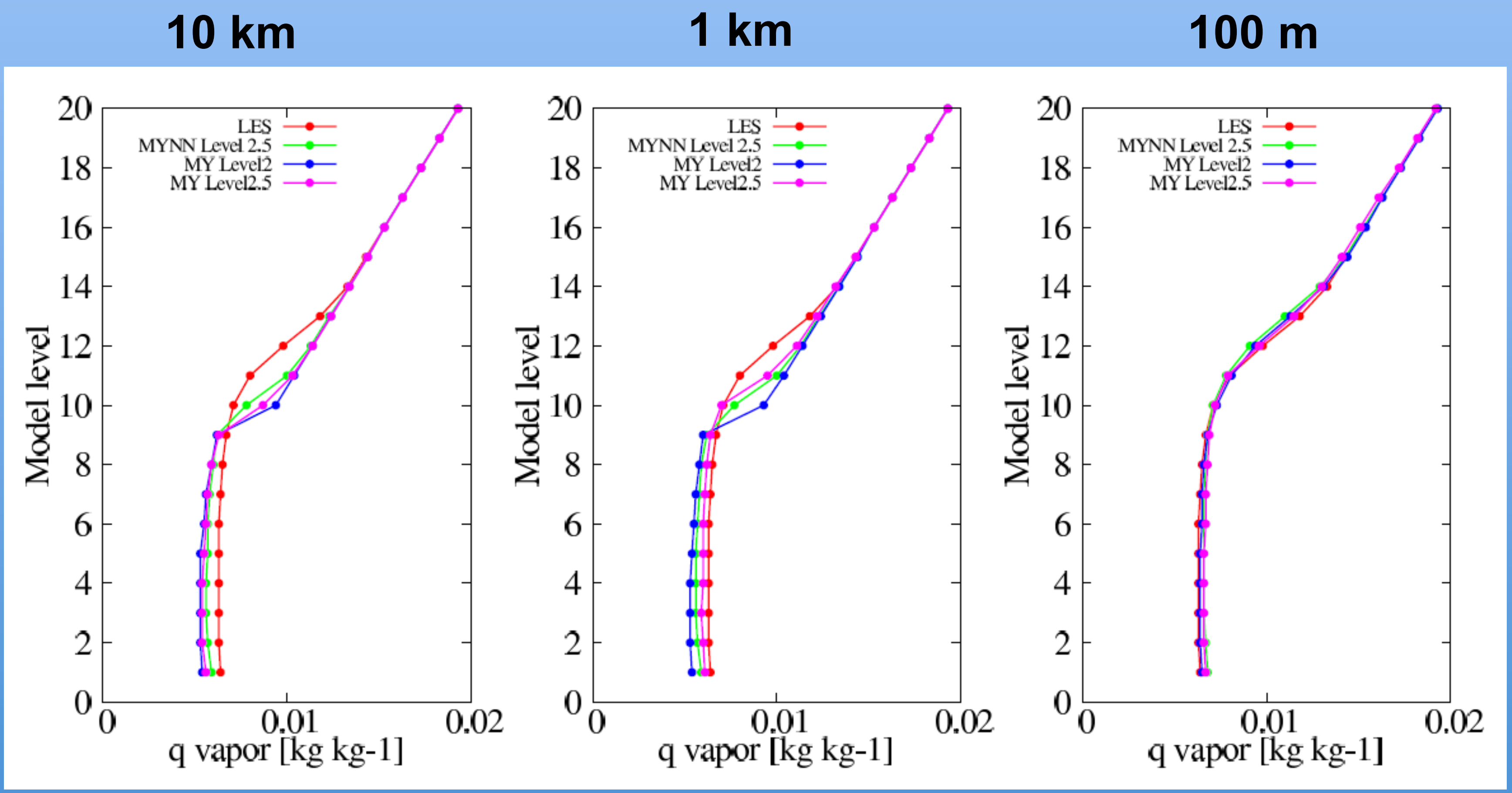
Adapted from Mirocha (LLNL)

Growing PBL: initial conditions



and meridional
wind

Humidity profiles after 1h sim



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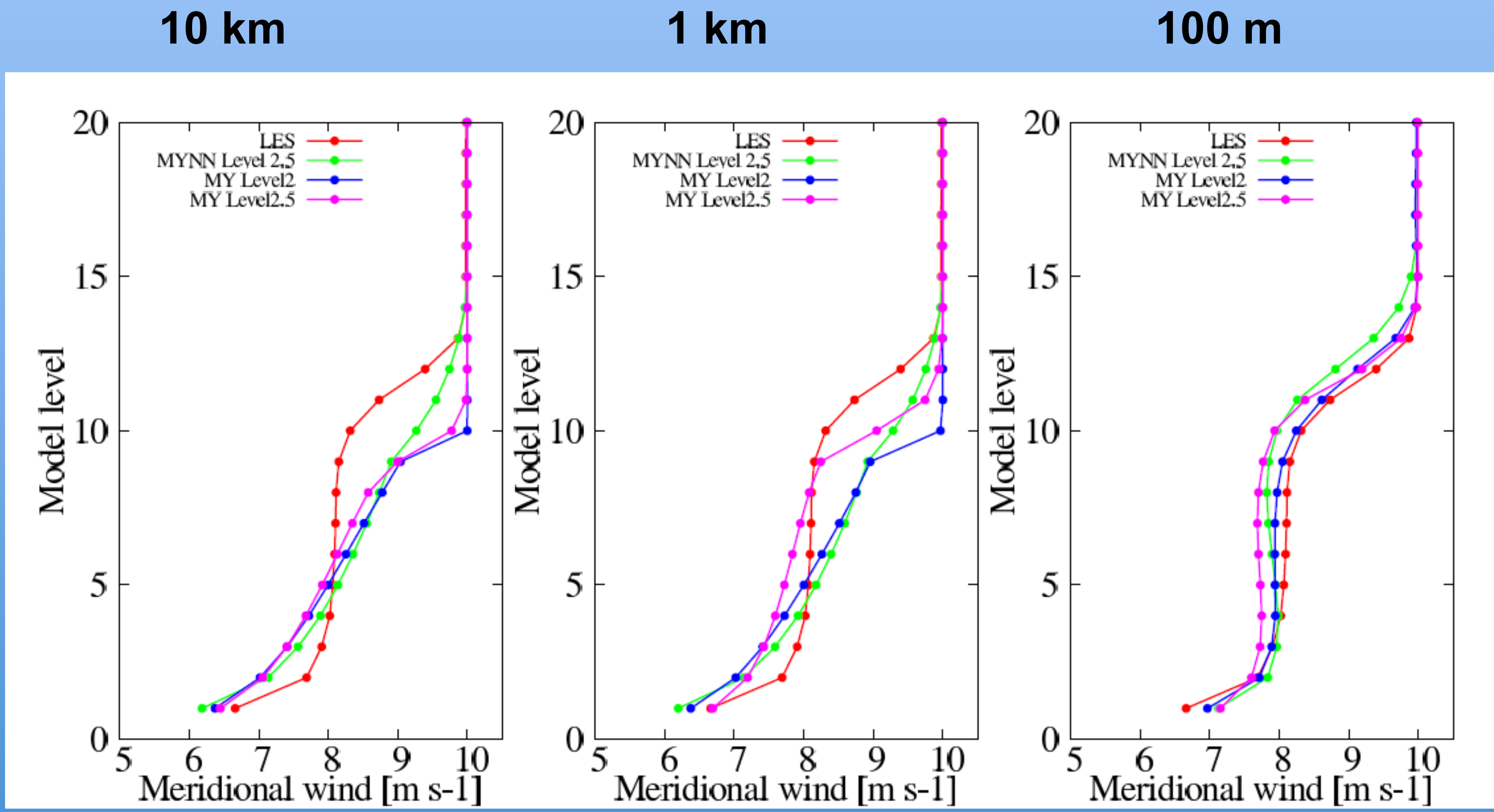
Meridional wind profiles after 1h sim



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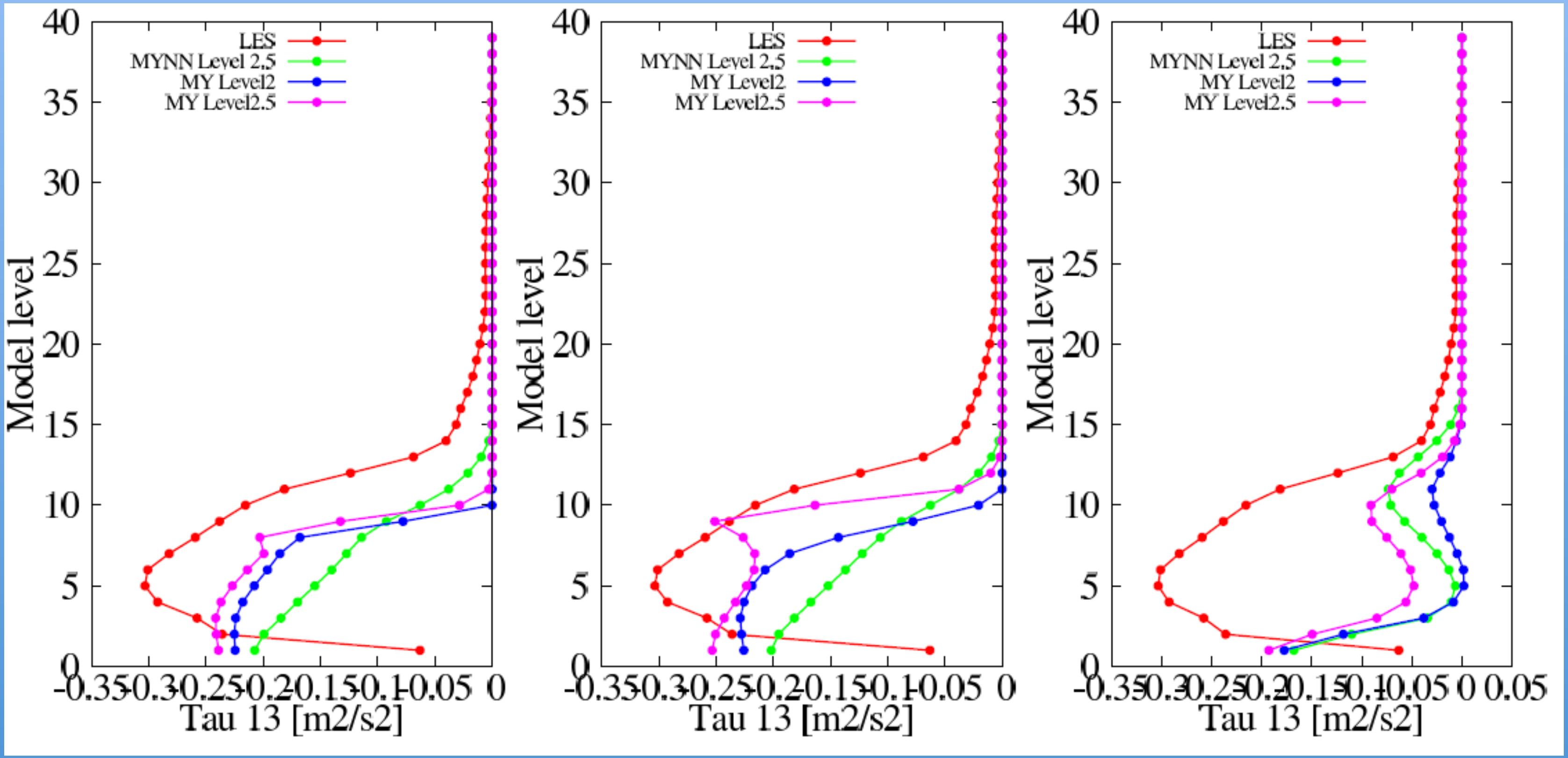
Tau_13 profiles after 1h sim

10 km **1 km** **100 m**



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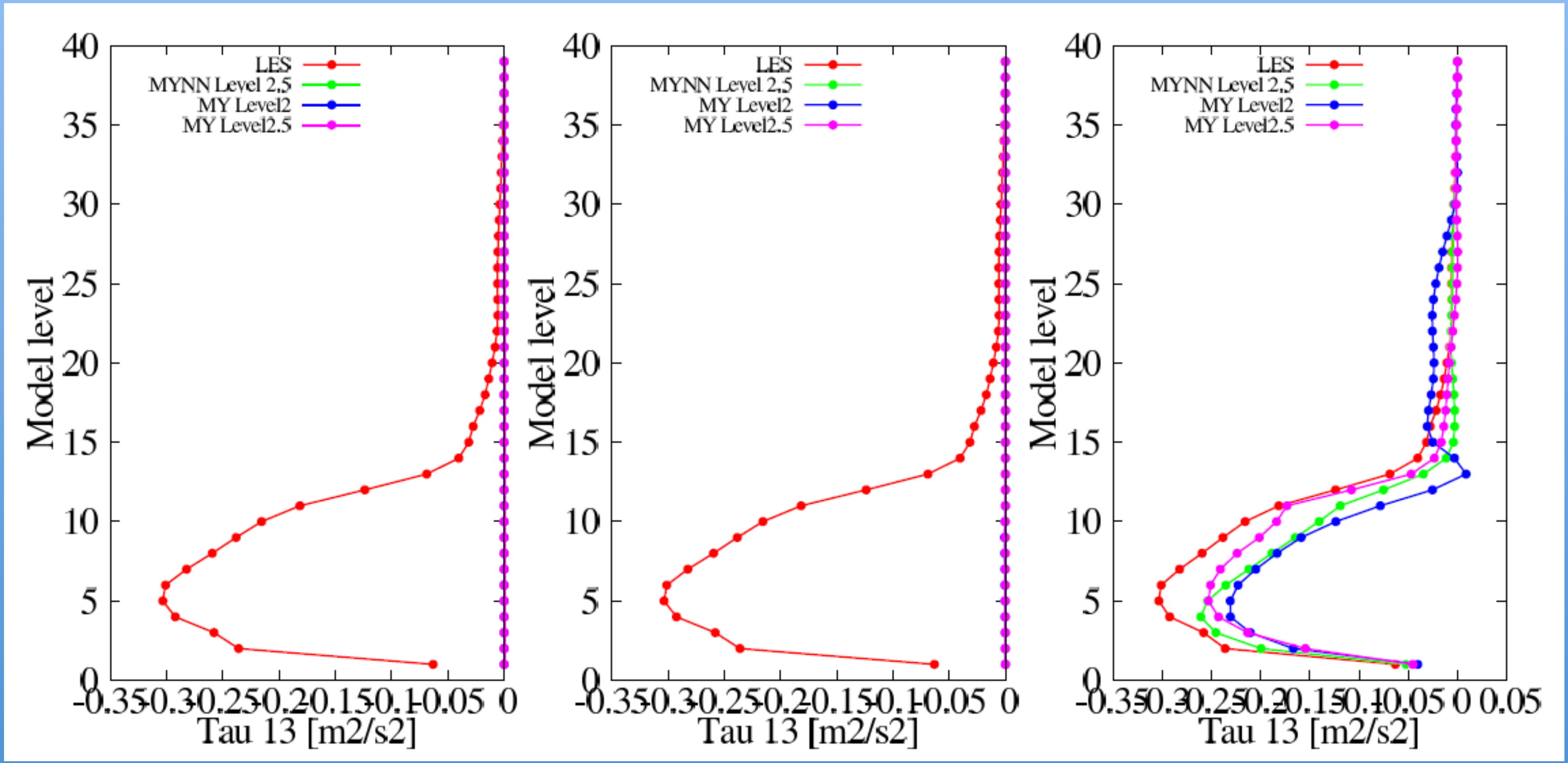
Tau_13 profiles after 1h sim

10 km **1 km** **100 m**



First phase development

Registry

Added the momentum stress to the model state
Add diffusion option 3 (diff_opt = 3)

MYNN PBL parameterization

1. Pass the momentum stress as subroutine arguments
2. Fills in the momentum stress arrays:
   Diagnose them making use of PBL approximation

Module_firts_rk_step_part2.F

If dif_opt = 3 calls horizontal_diffusion_3 in module_diffusion_em.F passing the turbulent fluxes as subroutine arguments

Module_diffusion_em.F

Calculates the spatial derivatives of the turbulent fluxes to calculate the tendencies

Second phase development

Registry

Added the momentum stress to the model state
Add diffusion option 3 (diff_opt = 3)
Add new PBL option module_bl_my3d.F

MY3D PBL parameterization

1. Implemented level 2 and level 2.5 model
2. Fills in the momentum stress arrays:
   Diagnose them making use of PBL approximation

Module_firts_rk_step_part2.F

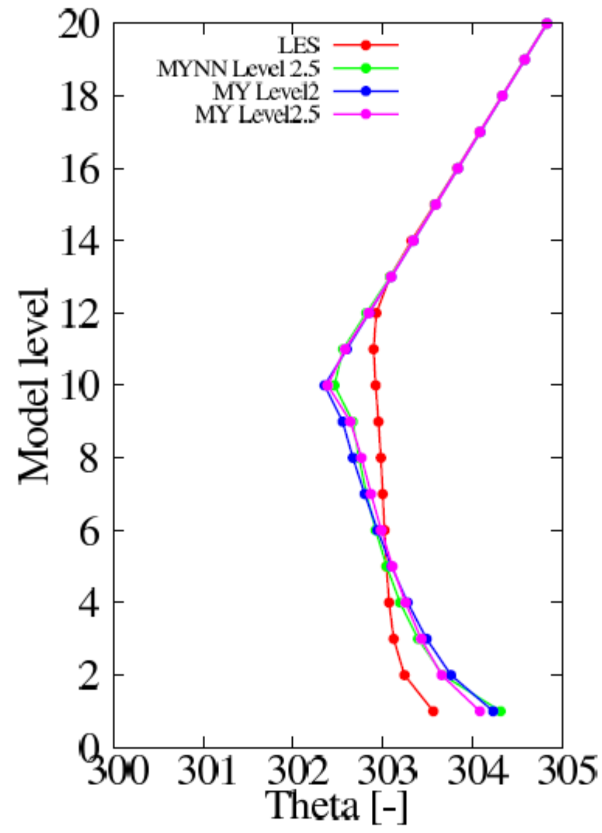
If dif_opt = 3 calls horizontal_diffusion_3 in module_diffusion_em.F passing the turbulent fluxes as subroutine arguments

Module_diffusion_em.F

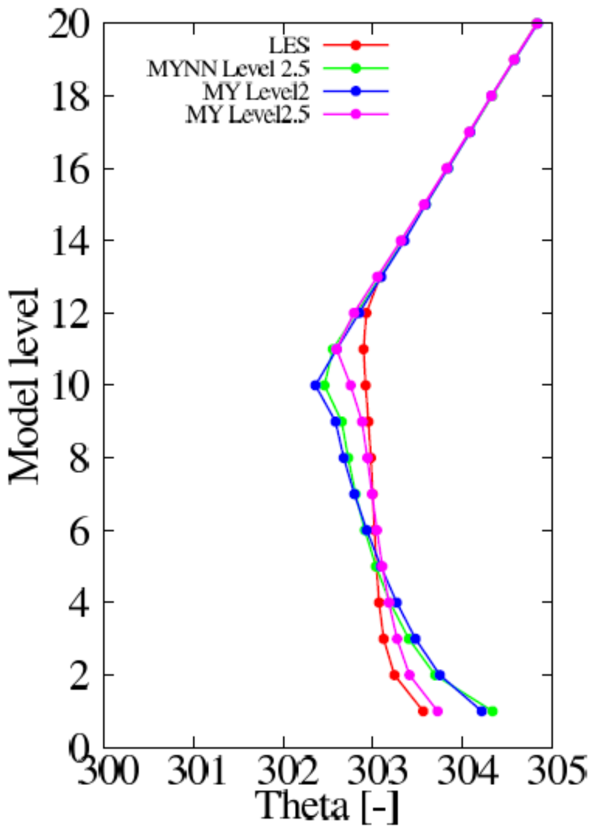
Calculates the spatial derivatives of the turbulent fluxes to calculate the tendencies

Temperature profiles after 1h sim

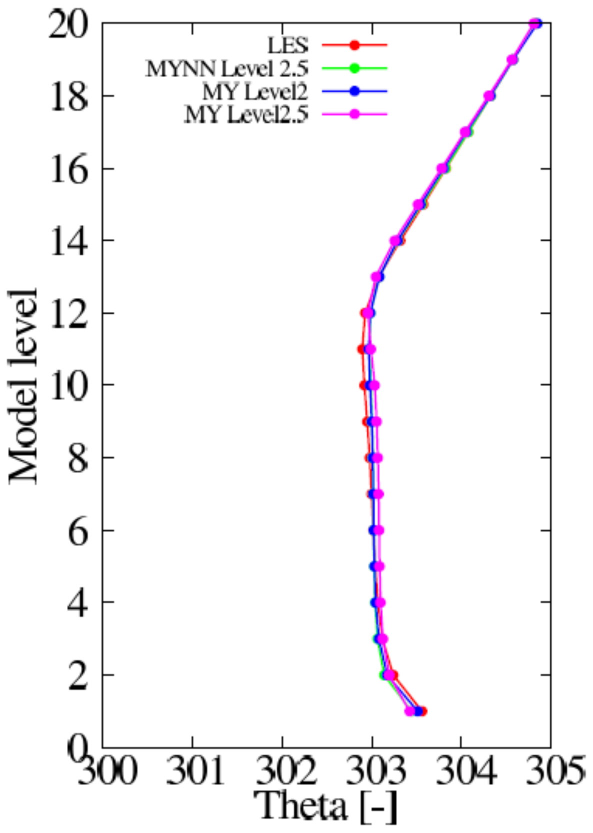
10 km



1 km



100 m



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