Recent advances in three-dimensional turbulent mixing parameterization in the WRF model

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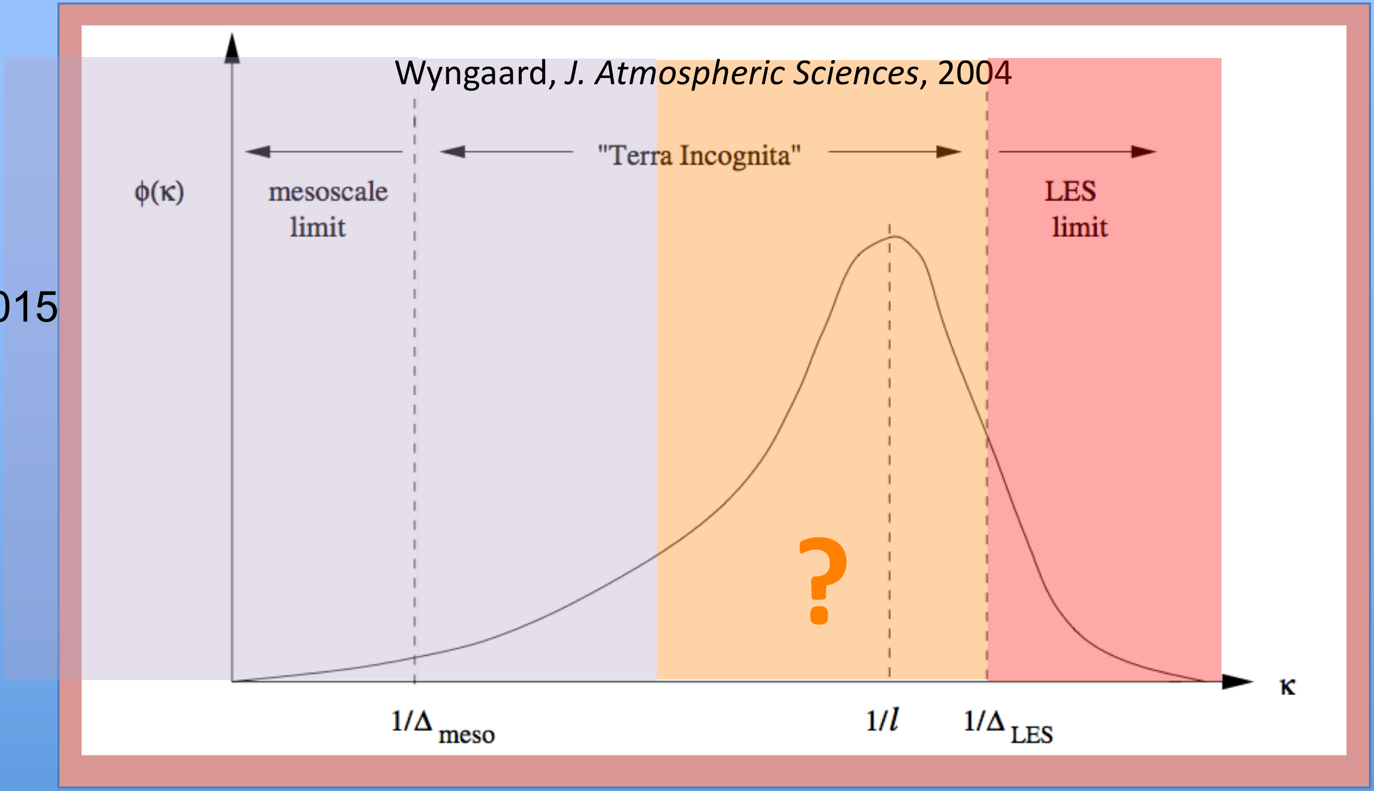
Improving forecast in complex terrain focusing on the Columbia River Gorge

- 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

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.



Hommert and Masson 2014 indicate that horizontal motions must be represented at
dx = 0.5 times the PBL height in free convection and
dx = 3 times the PBL height in forced convection
under a cloud free boundary layer

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Adapted from Mirocha (LLNL)

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.

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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.

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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Heterogeneous convective ABL

Sensible heat flux set to:

1) 160 W / m2 for I <= 20

2) 320 W / m2 for I > 20

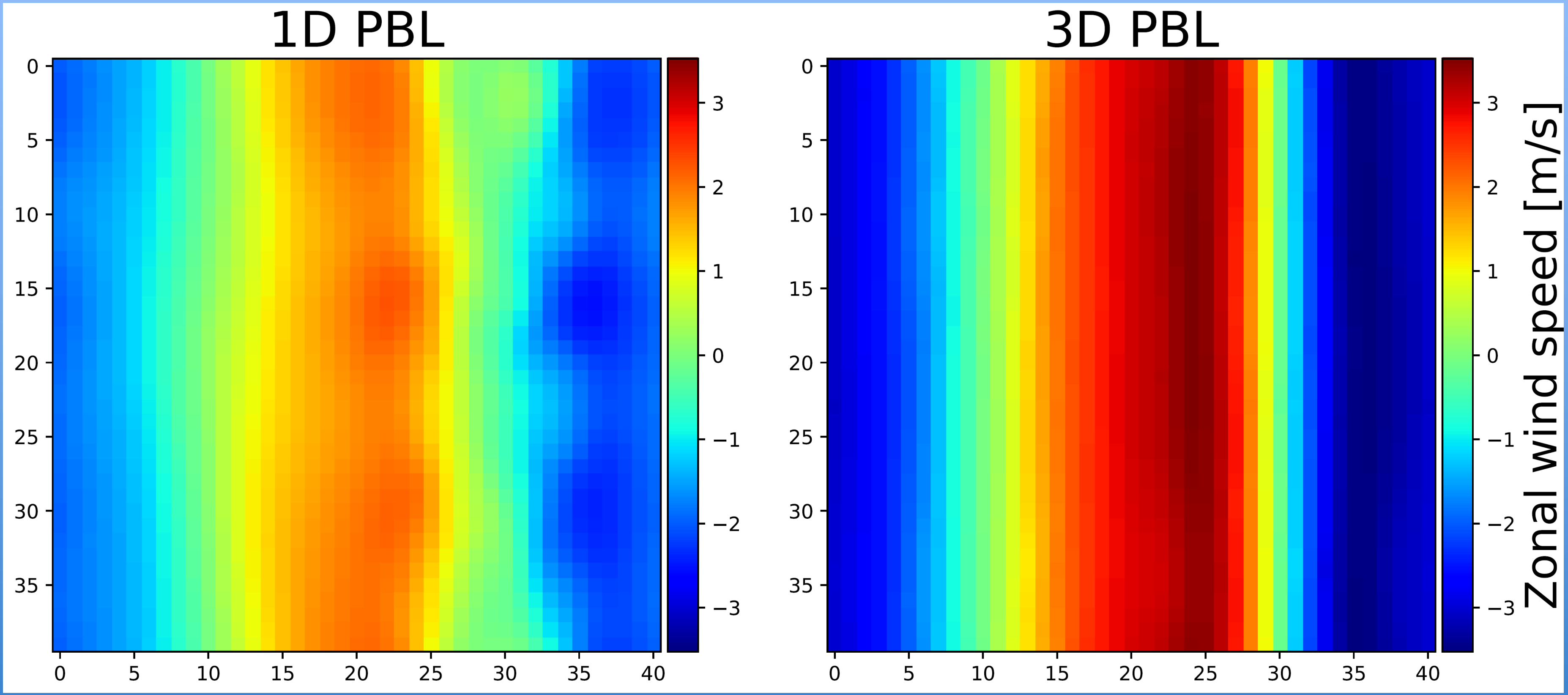
dx = 200 m

Initial wind speed set to:

u = 0 m/s

v = 2 m /s

Horizontal cross section at ~ 250 m at t = 1h



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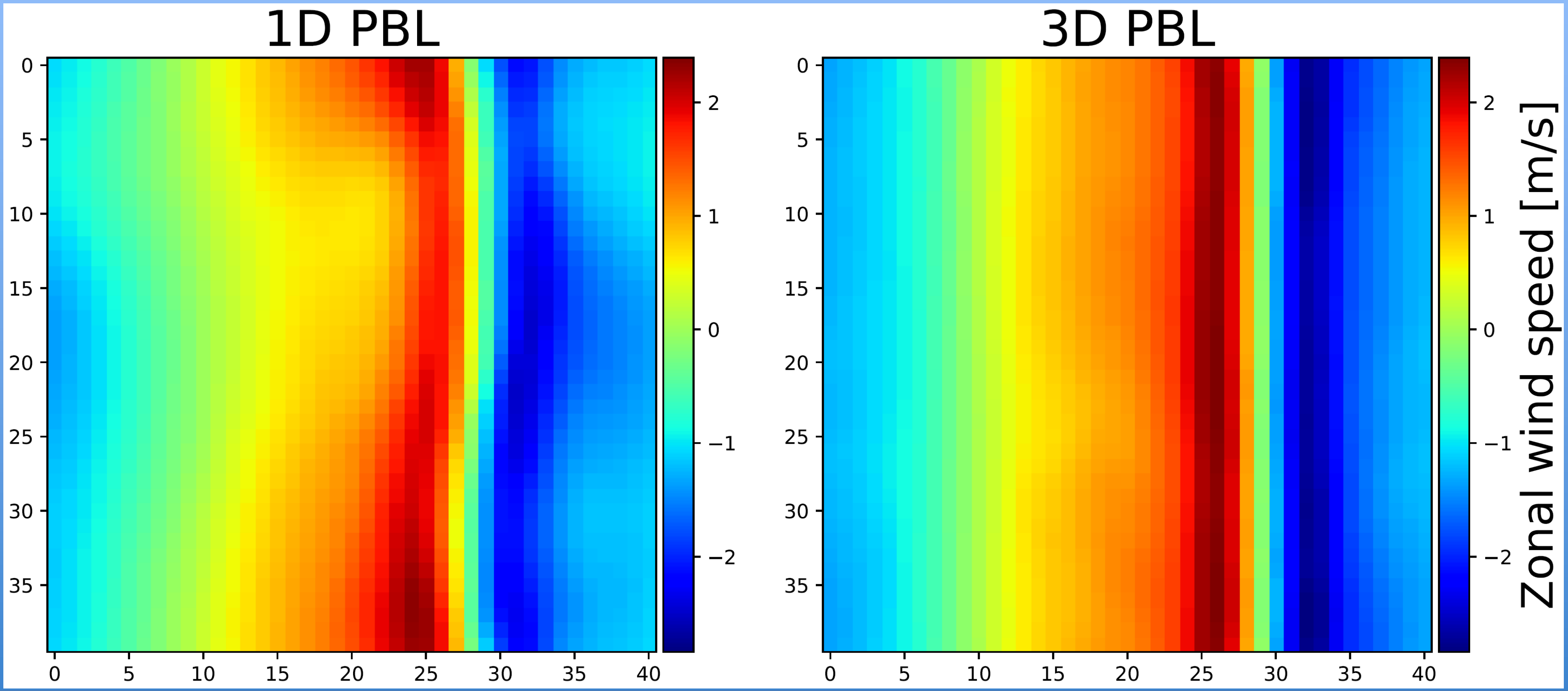

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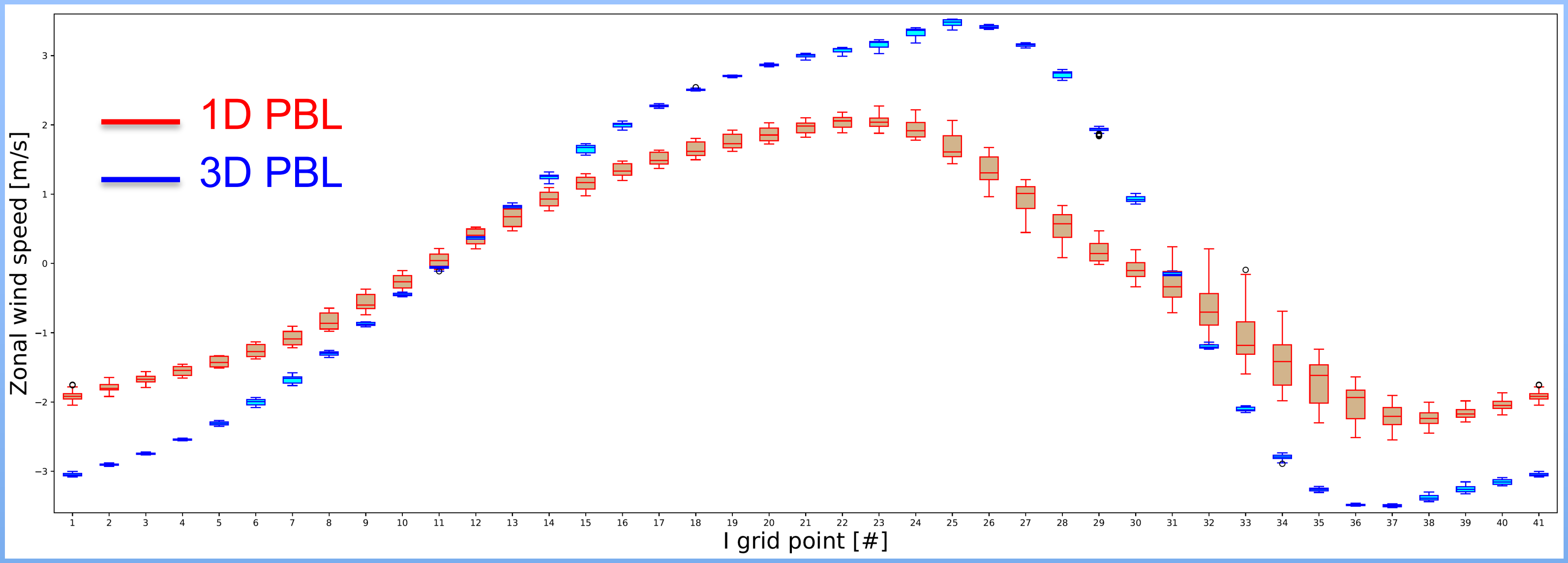

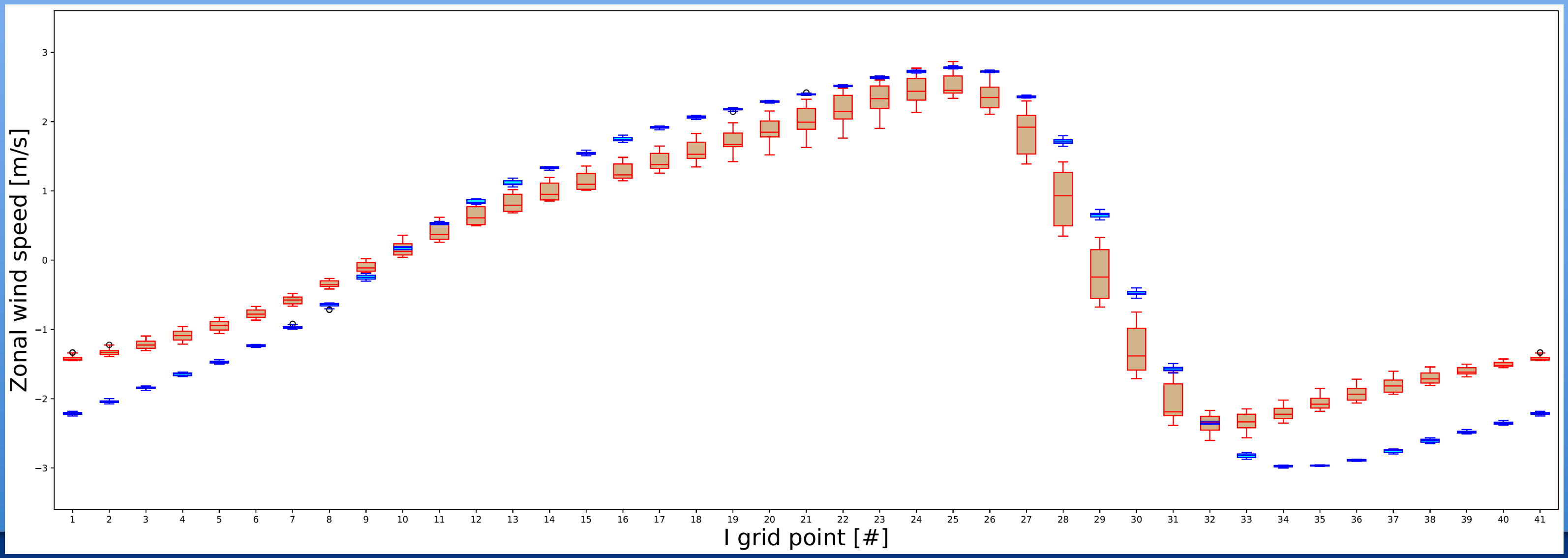

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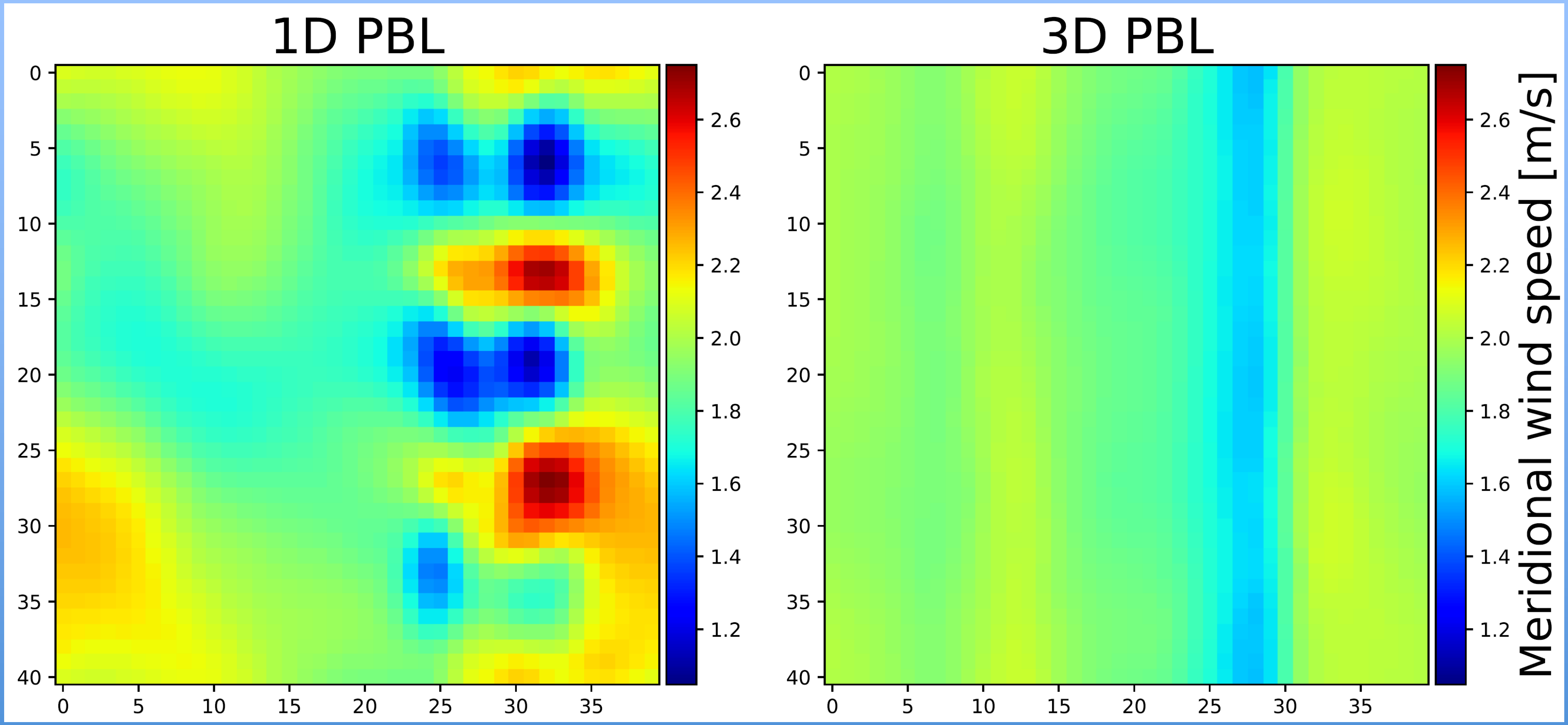

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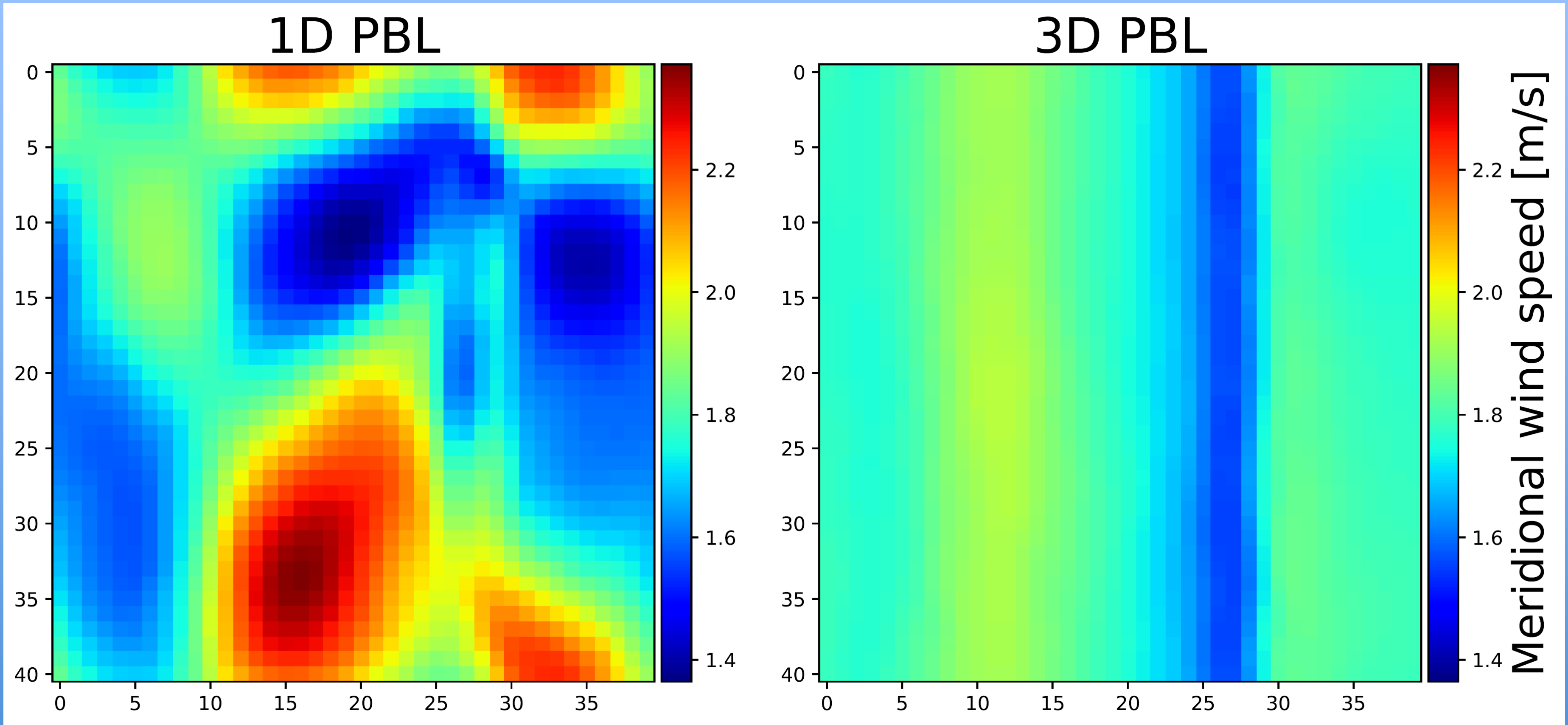

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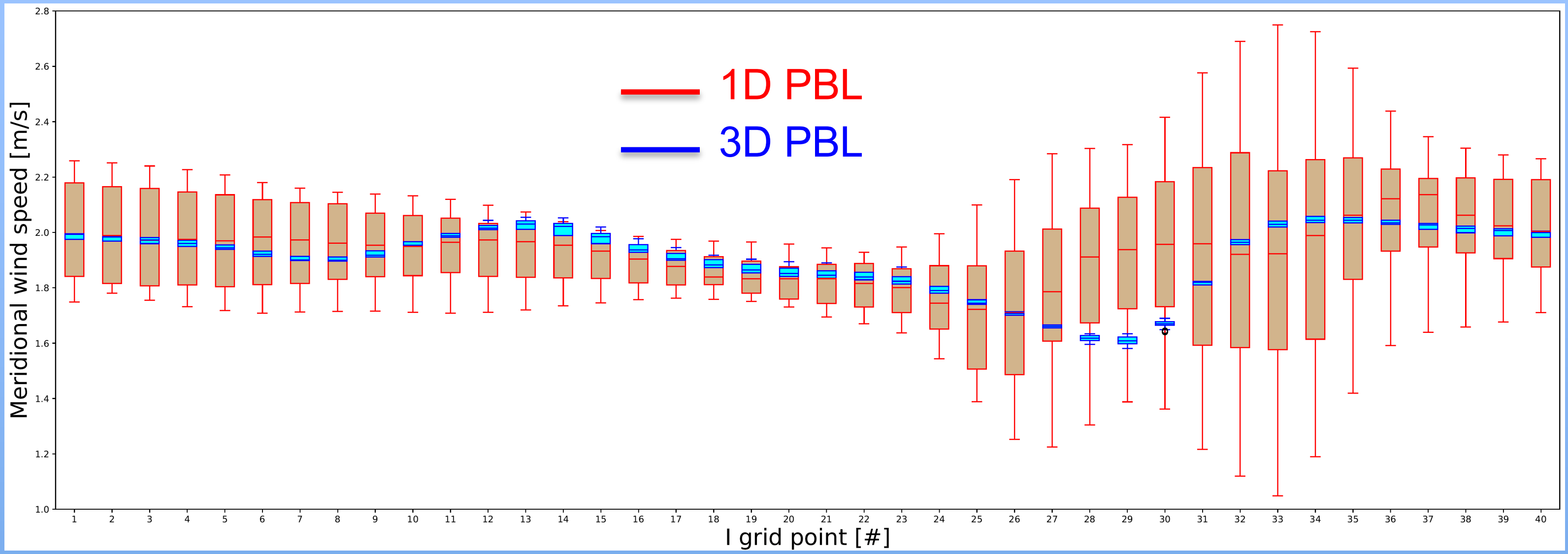

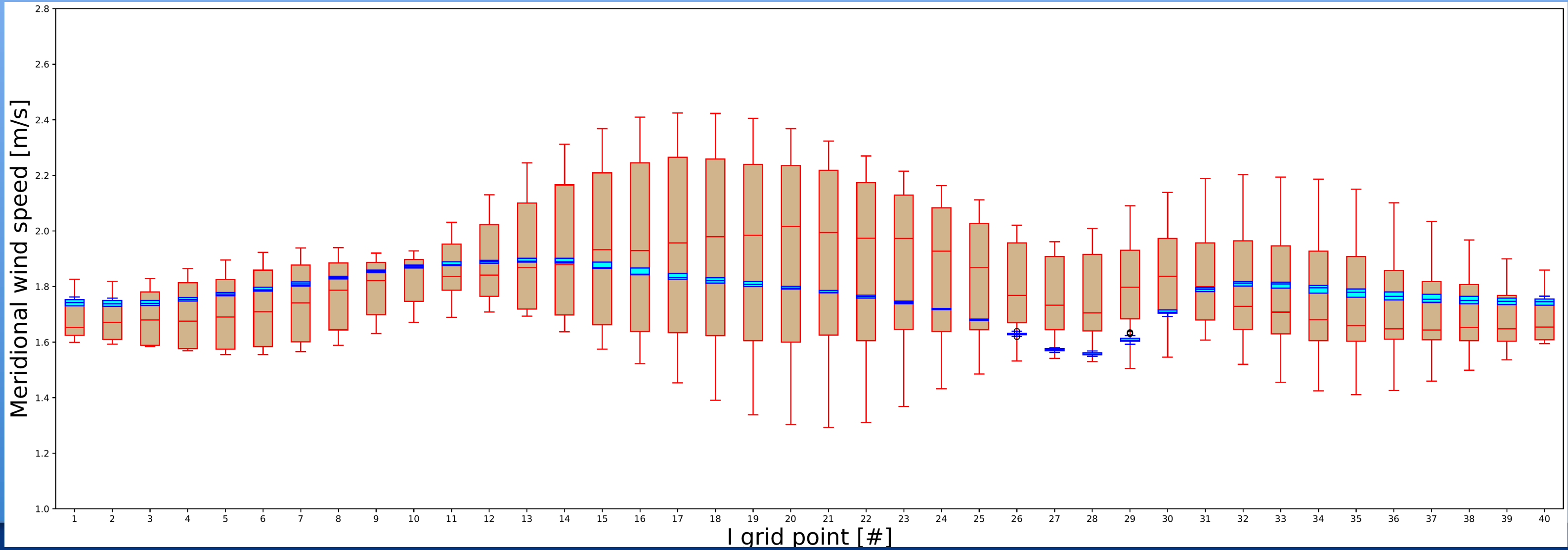

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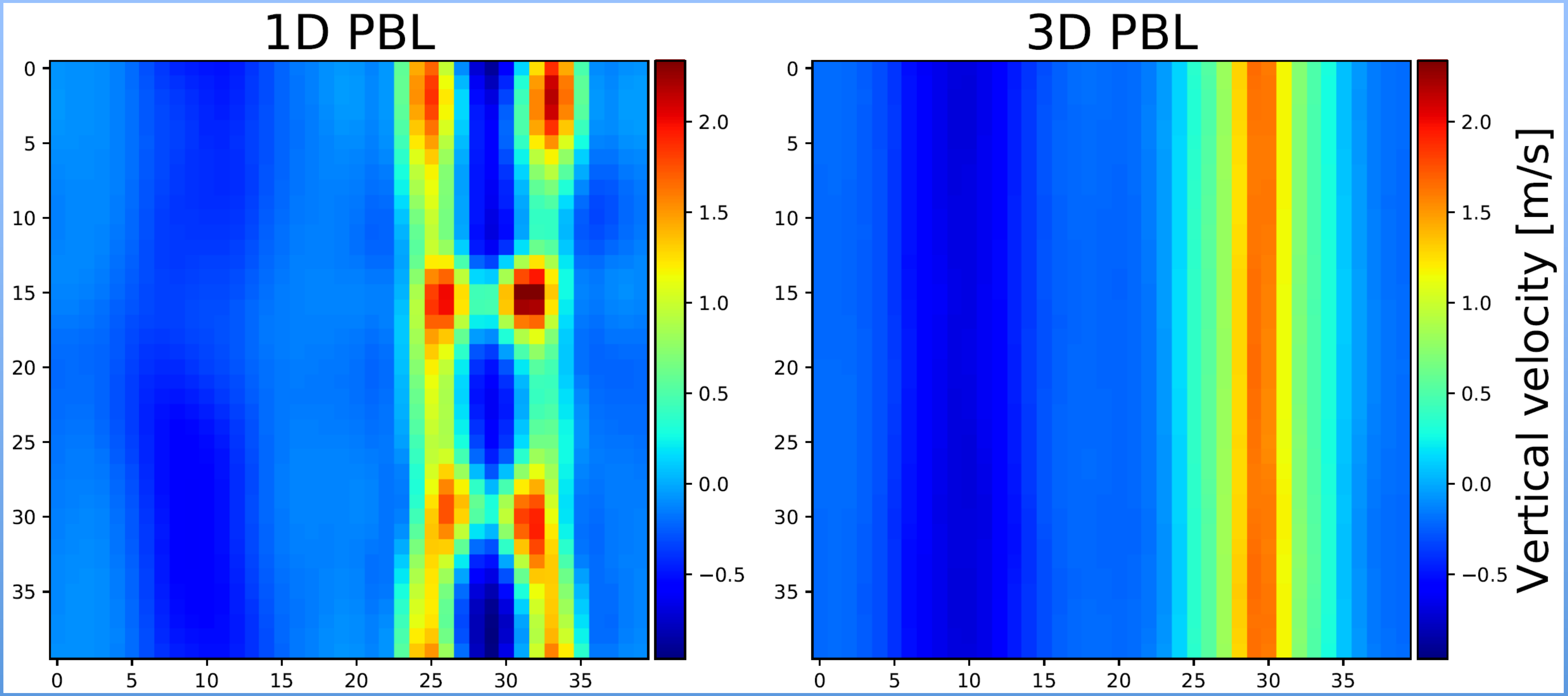

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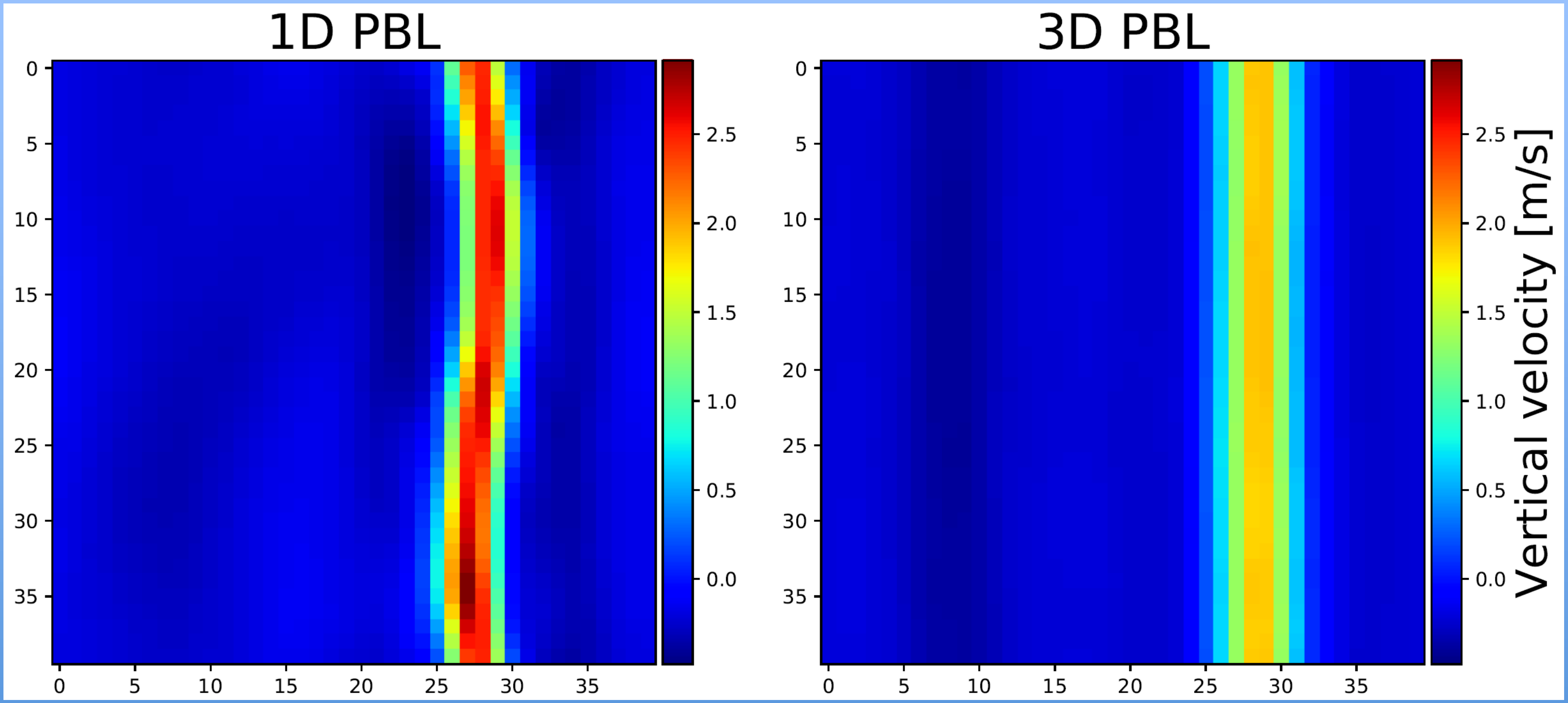

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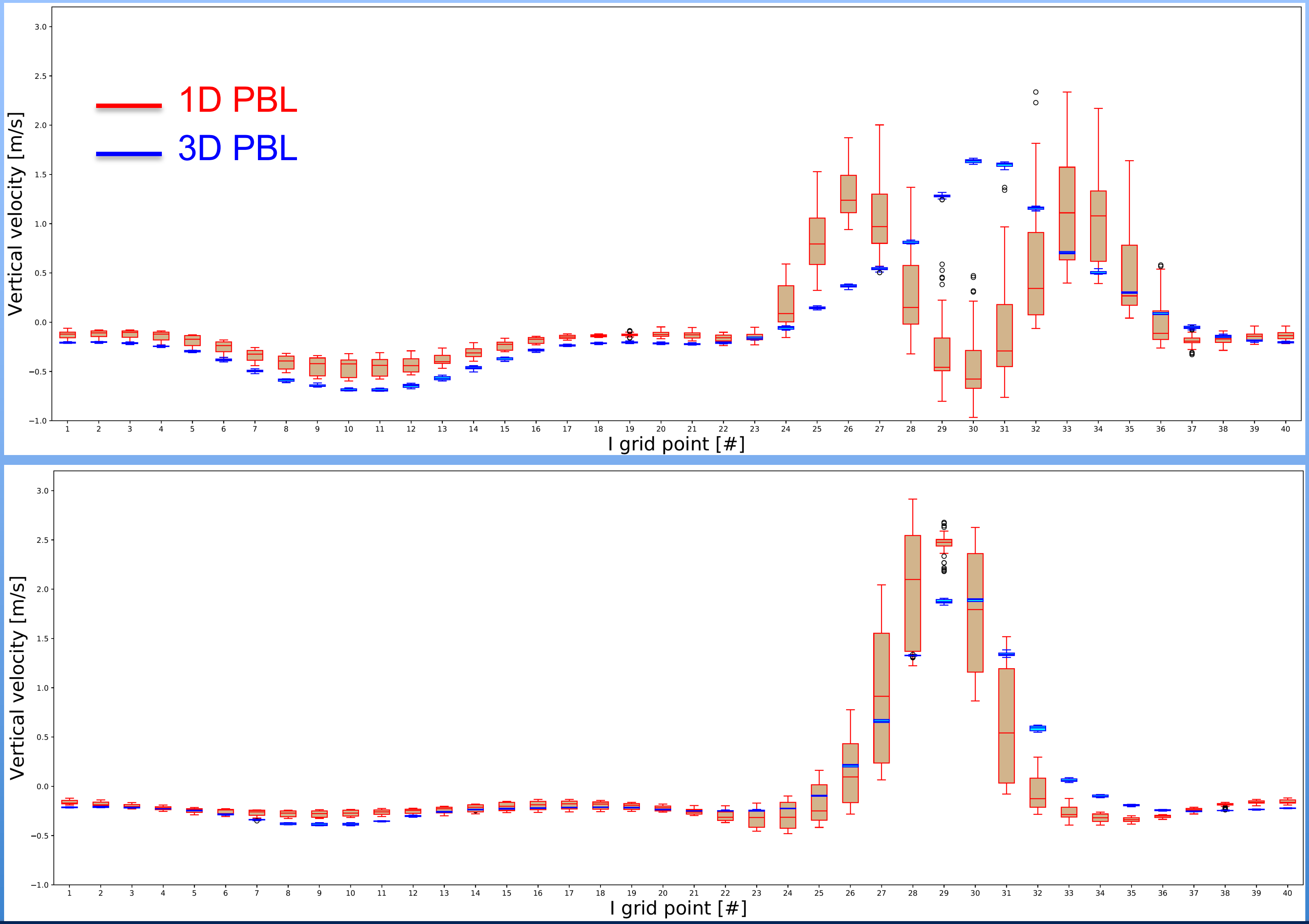
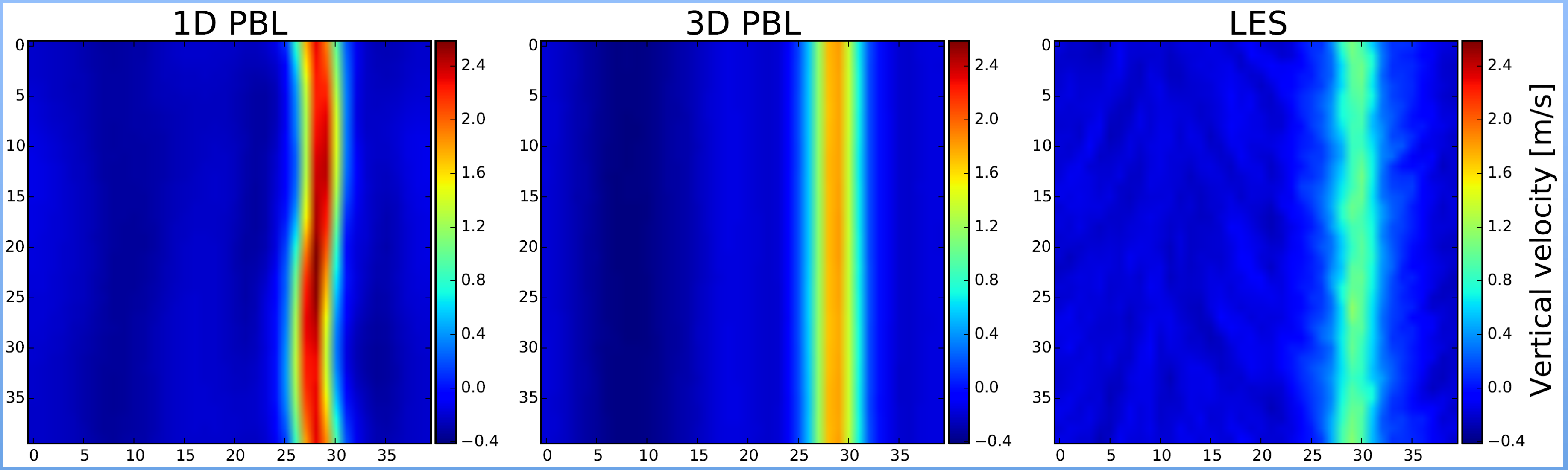


Heterogeneous convective ABL



Summary and next steps

- We have implemented a 3D PBL parameterization in the WRF model based on the MY model.
- Accounting for the horizontal turbulent fluxes in the 3D PBL parameterization is necessary to ensure the homogeneous North-to-South solution in a heterogeneous ABL experiment.
- Future steps include 1) the comparison of 1D and 3D-PBL results with LES for the heterogeneous case and 2) simulate real cases to validate the new 3D PBL scheme and compare results to 1D PBL scheme

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