Ongoing improvements to surface-layer turbulence modeling in the Weather Research and Forecasting model

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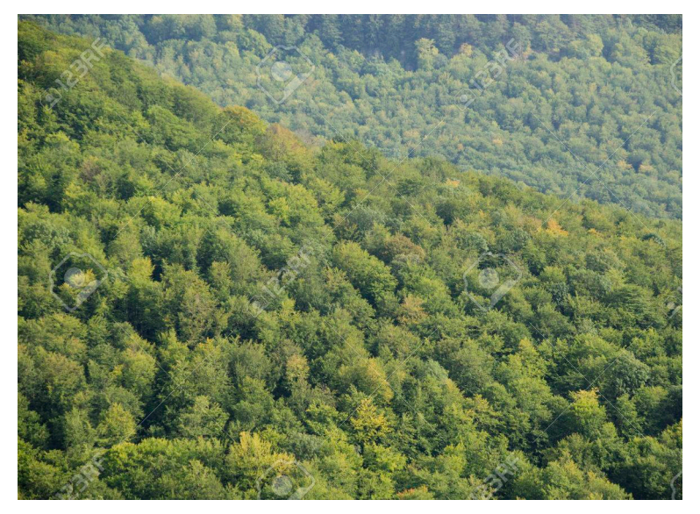
Motivation

The multiscale framework of the Weather Research and Forecasting (WRF) model provides an opportunity to perform large-eddy simulations (LES) of the atmospheric boundary layer with realistic forcing that is downscaled from larger-scale, coarser domains. However, WRF-LES performance is limited in the presence of complex terrain and heterogeneous surface cover:

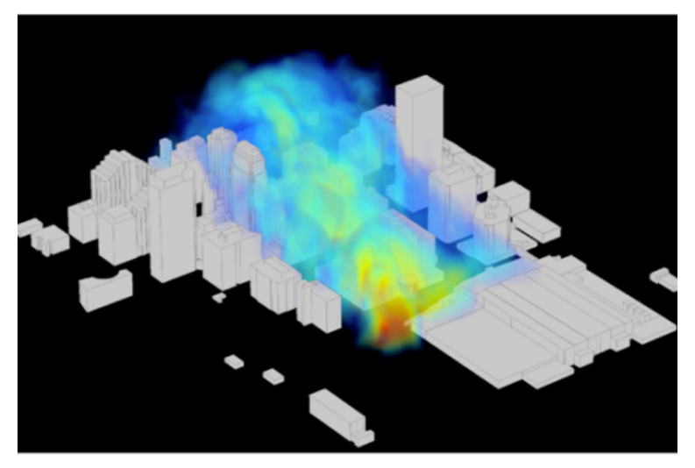

Urban Areas


Mountainous Terrain


Forest Cover

This limited performance stems primarily from two issues: numerical errors related to grid skewness in the presence of steep terrain slopes and inadequate treatment of near-surface turbulence. By addressing these issues, we can better predict flows in complex environments for applications such as:


Wind Energy


Transport and Dispersion


Wildfires

Goals

We are exploring the use of two techniques to improve WRF-LES performance in these complex environments. See the panels to the right for discussions of each.

The first is the immersed boundary method (IBM), which reduces terrain slope-related errors and allows simulations to be run over complex terrain. IBMs have been tested in WRF at high-resolution (roughly 5 m or less), but their performance at the coarser resolutions typical of many LES studies (10s of meters) is not well understood.

① Evaluate different implementations of the immersed boundary method (IBM) in WRF at resolutions coarser than 5 m. Compare to native WRF results and observations.

The second is a canopy model framework that better accounts for turbulence in the presence of resolved surface roughness elements such as trees or other vegetation. As part of this effort, we also developed a "pseudo-canopy" model to account for unresolved surface roughness.

② Apply a canopy model framework to improve WRF-LES performance in the presence of both resolved and unresolved surface roughness.

References

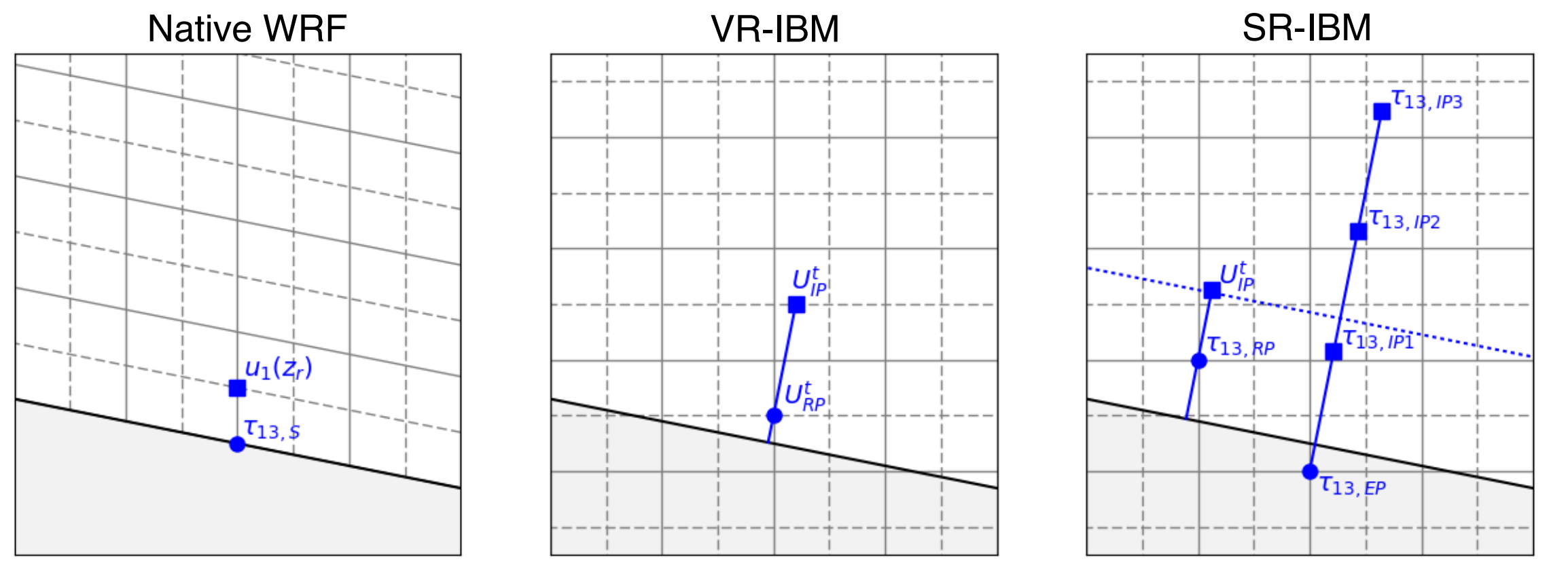
1. **Arthur, R. S.**, Lundquist, K. A., Bao, J., Wiersema, D. J., and Chow, F. K. Evaluating implementations of the immersed boundary method in the Weather Research and Forecasting model. *Monthly Weather Review*, submitted.
2. **Arthur, R. S.**, Mirocha, J. D., Lundquist, K. A., and Street, R. L. (2019) Using a canopy model framework to improve large-eddy simulations of the neutral atmospheric boundary layer in the Weather Research and Forecasting model. *Monthly Weather Review*. 147(1): 31-52.

① Immersed Boundary Method

Methods Comparison

IBMs reduce terrain slope-related errors by using a Cartesian grid and enforcing the bottom boundary condition along an immersed terrain surface. Here, we compare two different IBMs to the native WRF boundary condition.

- Velocity Reconstruction (VR-IBM): The velocity is specified at the first grid point above the immersed surface using the log law.
- Shear Stress Reconstruction (SR-IBM): The shear stress is specified both above and below the boundary, again using the log law.



$$\tau_{13,S} = -\rho C_D V_{horz}(z_r) u_1(z_r)$$

$$U^t_{RP} = U^t_{IP}\frac{ln(d_{RP}/z_0)}{ln(d_{IP}/z_0)}$$

$$\nu_{t,RP} = \nu_{t,IP}\frac{d_{RP}}{d_{IP}}$$

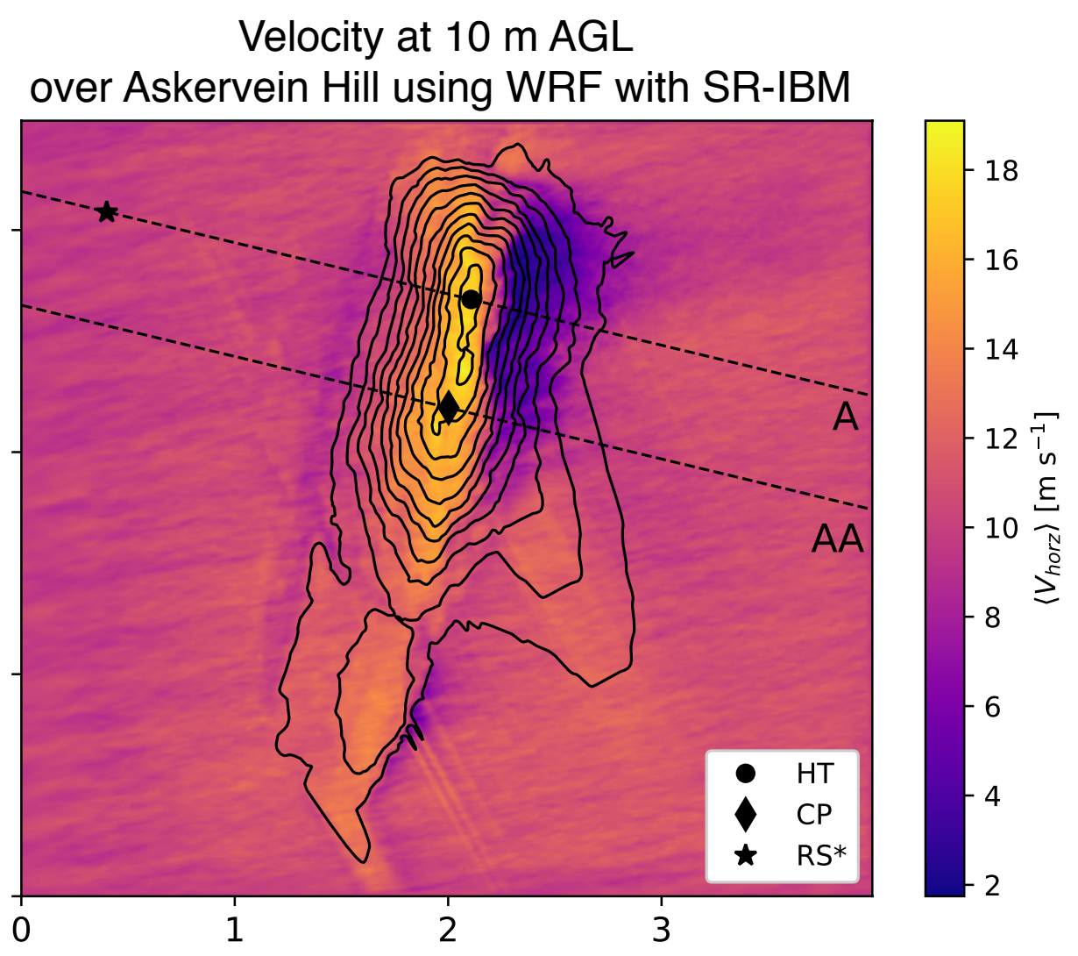
$$\tau^t_S = -\left[\frac{\kappa U^t_{IP}}{ln(d_r/z_0)}\right]$$

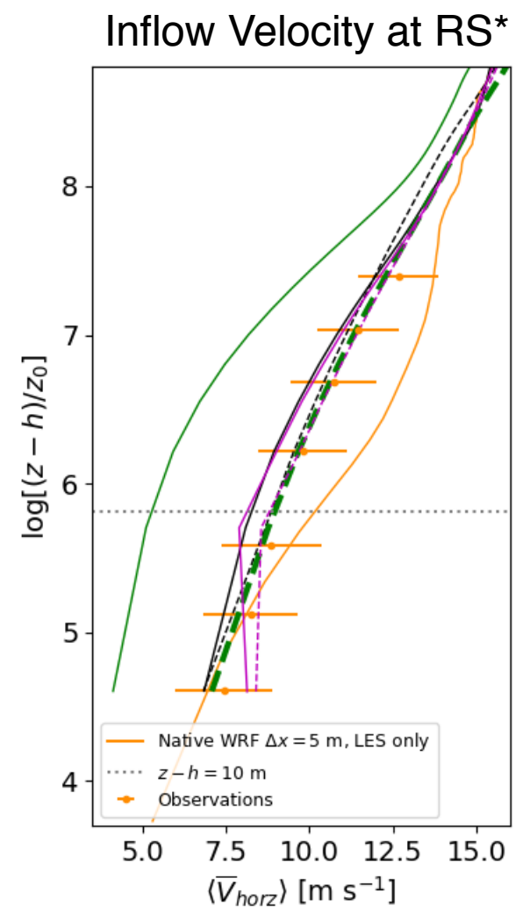
$$\tau_{13,RP} = rot(\tau^t_S)$$

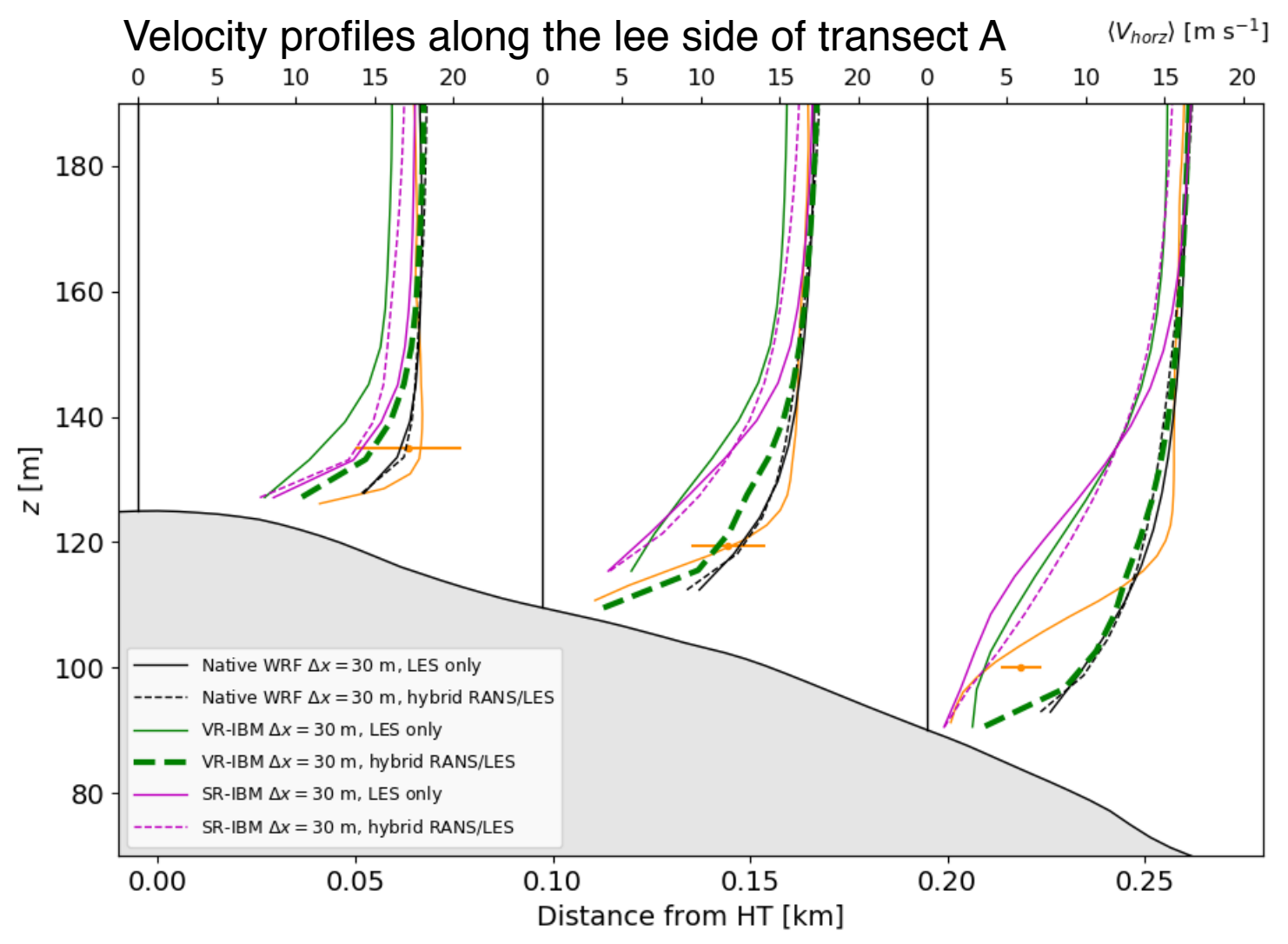
$$\tau_{13,EP} = 3\tau_{13,IP1} - 3\tau_{13,IP2} + \tau_{13,IP3}$$

Performance Evaluation

We evaluate the performance of the IBMs relative to native WRF and observations for the common Askervein Hill case. Running WRF with different surface boundary conditions produces different flow solutions, especially in the lee of the hill, where flow separation may occur. This is true regardless of grid resolution, but is exacerbated at coarser resolutions. Here, we focus on results for a Δx = 30 m case.


Velocity at 10 m AGL over Askervein Hill using WRF with SR-IBM

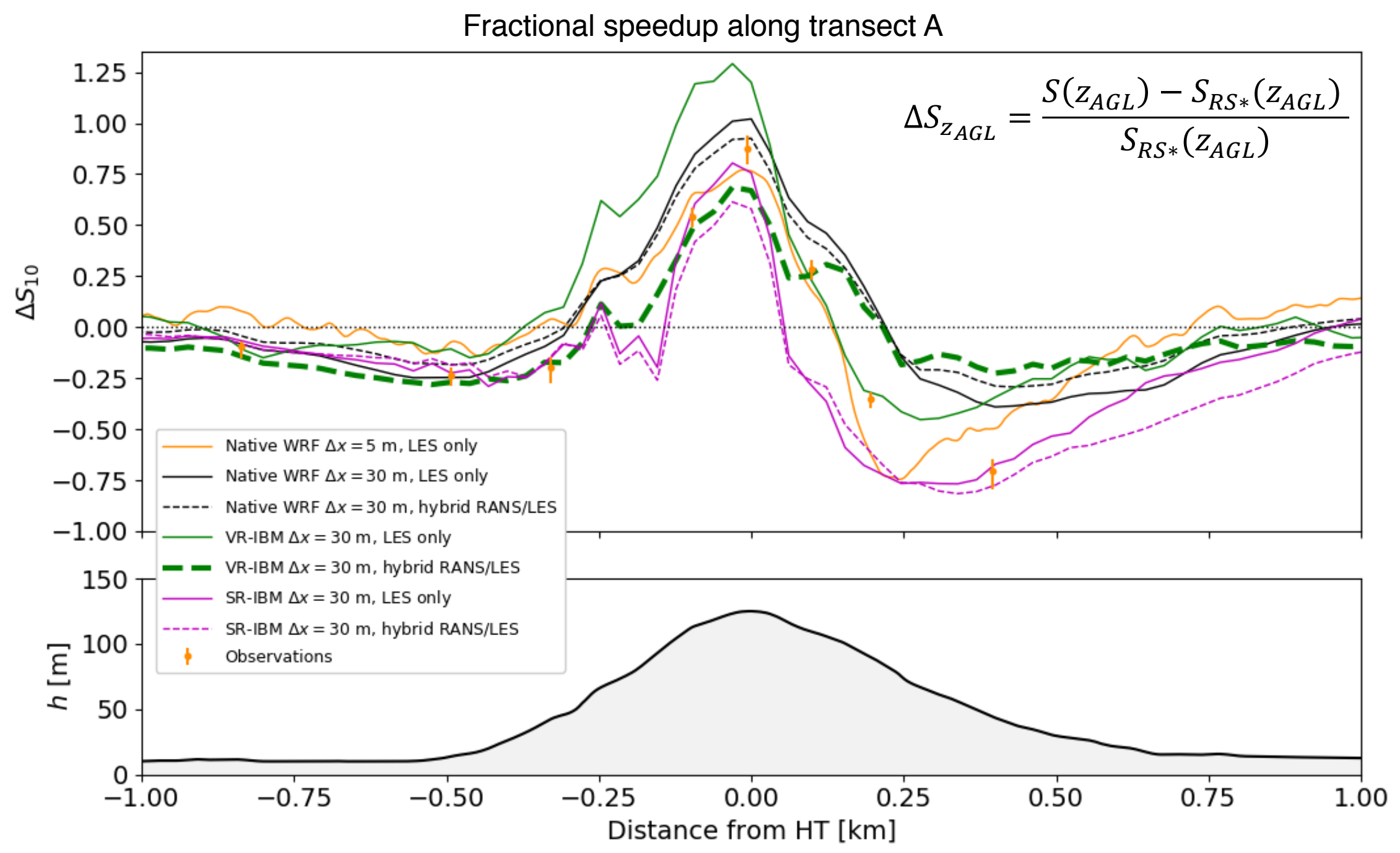

Inflow Velocity at RS*


Velocity profiles along the lee side of transect A

In addition to the velocity profiles shown above, the fractional speedup ΔS, shown below, quantifies the flow over the hill relative to the "inflow" at the reference site RS*. A summary of the performance of each method relative to observations is shown in the table. The best performing IBM cases are shown in bold.

Tabulated differences along transect A

Method	Δx	Surface scheme	RMSE RS* V_{horz} [m/s]	RMSE A V_{horz} [m/s]	RMSE A ΔS
WRF	5	LES only	1.33	2.24	0.18
WRF	5	RANS/LES	0.79	2.10	0.17
VR-IBM	**5**	**LES only**	**0.63**	**2.74**	**0.21**
VR-IBM	5	RANS/LES	1.57	3.96	0.29
SR-IBM	5	LES only	0.87	3.57	0.38
SR-IBM	**5**	**RANS/LES**	**0.74**	**1.56**	**0.15**
WRF	30	LES only	0.79	1.75	0.25
WRF	30	RANS/LES	0.54	2.12	0.25
VR-IBM	30	LES only	3.52	3.37	0.30
VR-IBM	**30**	**RANS/LES**	**0.34**	**2.21**	**0.24**
SR-IBM	30	LES only	0.65	2.63	0.24
SR-IBM	30	RANS/LES	0.41	2.40	0.25


Fractional speedup along transect A

$$\Delta S_{z_{AGL}} = \frac{S(z_{AGL}) - S_{RS*}(z_{AGL})}{S_{RS*}(z_{AGL})}$$

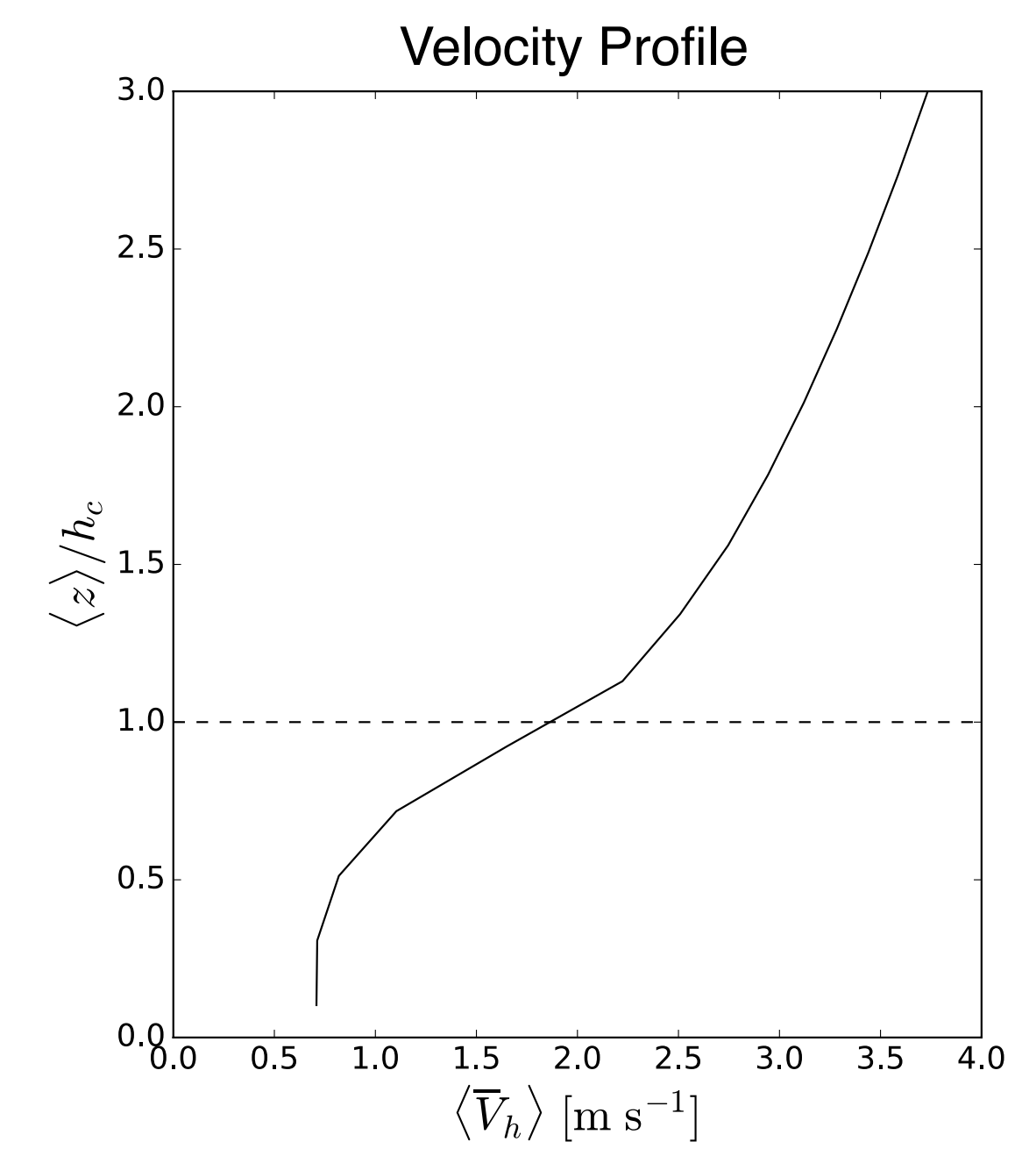
Takeaway Points

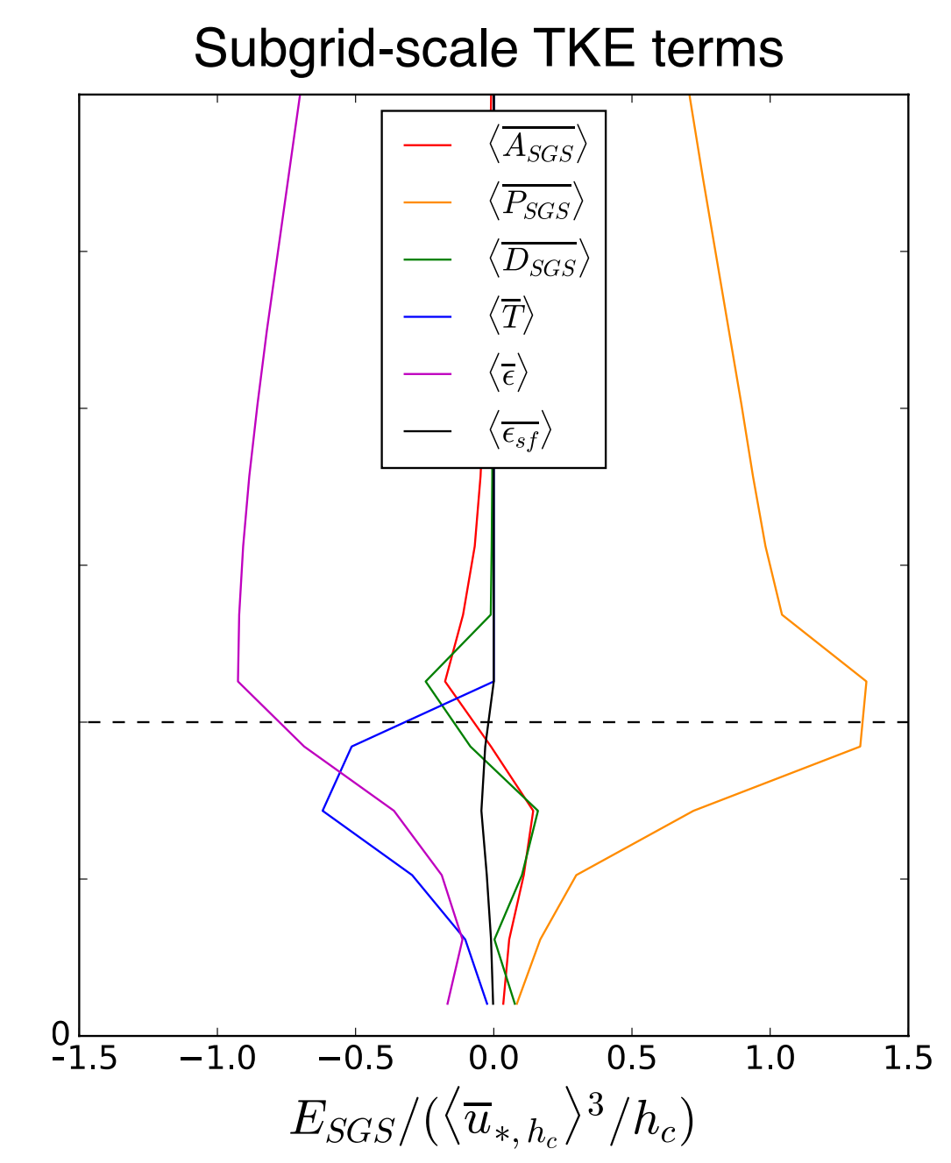
- In some cases, a hybrid RANS/LES surface scheme (Senocak *et al.*, *BLM*, 2007; DeLeon *et al.*, *BLM*, 2018) can improve IBM performance by encouraging attached flow in the lee of the hill.
- The velocity reconstruction method (VR-IBM) is sensitive to algorithmic details but shows relatively consistent performance as long as the optimal setup is used for the given resolution.
- The shear stress reconstruction method (SR-IBM) consistently underestimates the velocity in the lee of the hill and can perform poorly at the first grid point above the surface.
- Future work will explore IBM performance at coarser LES resolution (roughly 100 m).

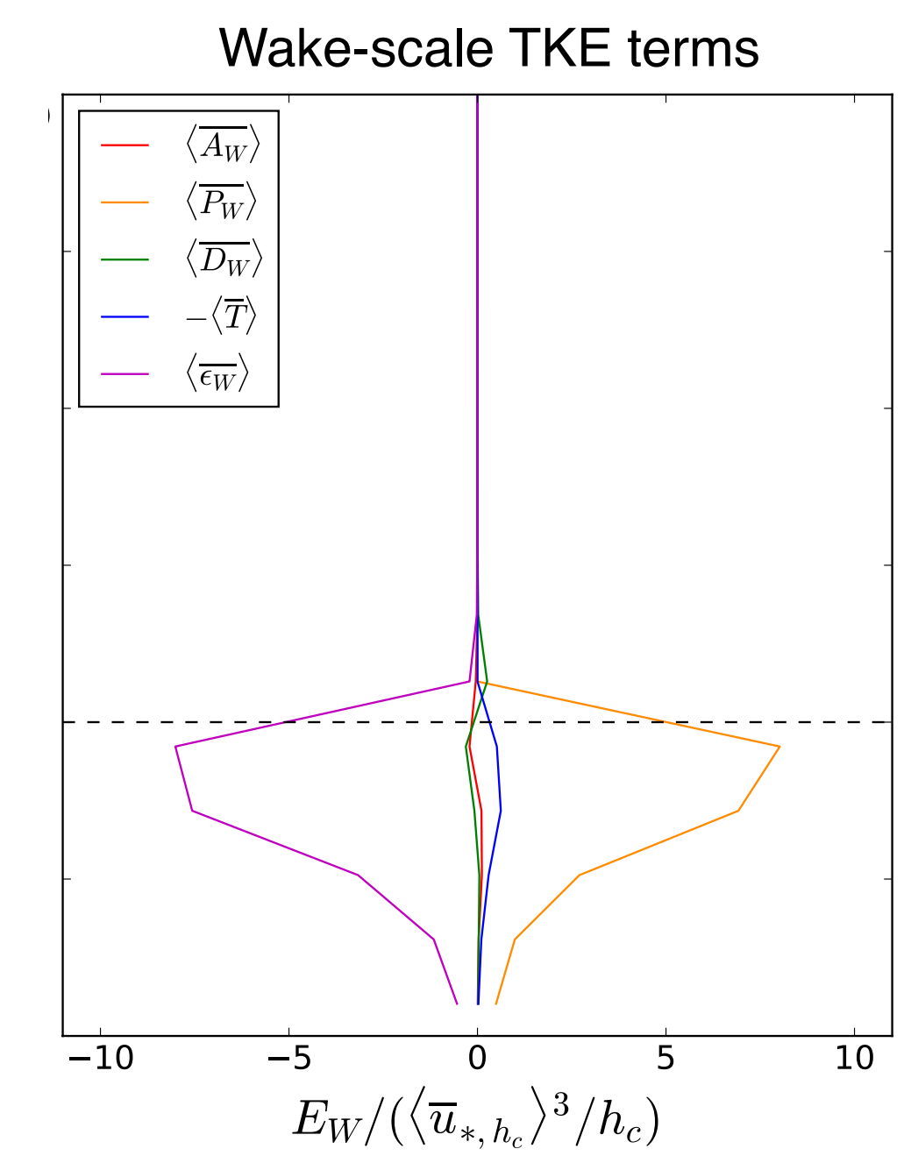
② Canopy Model Framework

Resolved Canopy Model

A traditional bottom boundary condition based on Monin-Obukhov Similarity Theory (MOST) does not predict the correct flow profile in the presence of roughness elements that are larger in vertical scale than the vertical grid spacing of the model. In this case, the addition of a canopy drag term and a canopy LES model can improve the prediction. Here, we implement the canopy model of Shaw & Patton (*Agric. For. Meteor.*, 2003) into WRF and demonstrate its performance:


Velocity Profile

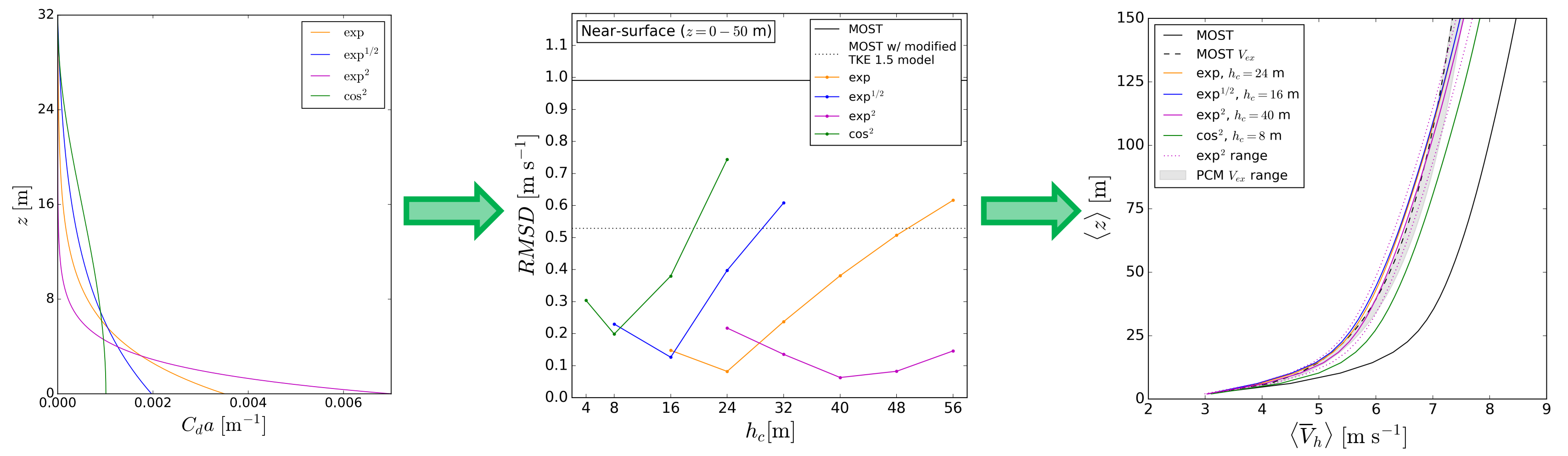

Subgrid-scale TKE terms


Wake-scale TKE terms

The canopy LES model is an adaptation of the common TKE-based closure scheme. It includes an additional evolution equation for wake-scale TKE and a transfer term between wake-scale and subgrid-scale TKE.

Pseudo-canopy Model

When roughness elements are unresolved by the model grid, the canopy drag framework can still be used to improve flow predictions. We created a pseudo-canopy model that distributes the stress that would be applied at the surface using a traditional MOST boundary condition over a pseudo-canopy. The model works as follows:



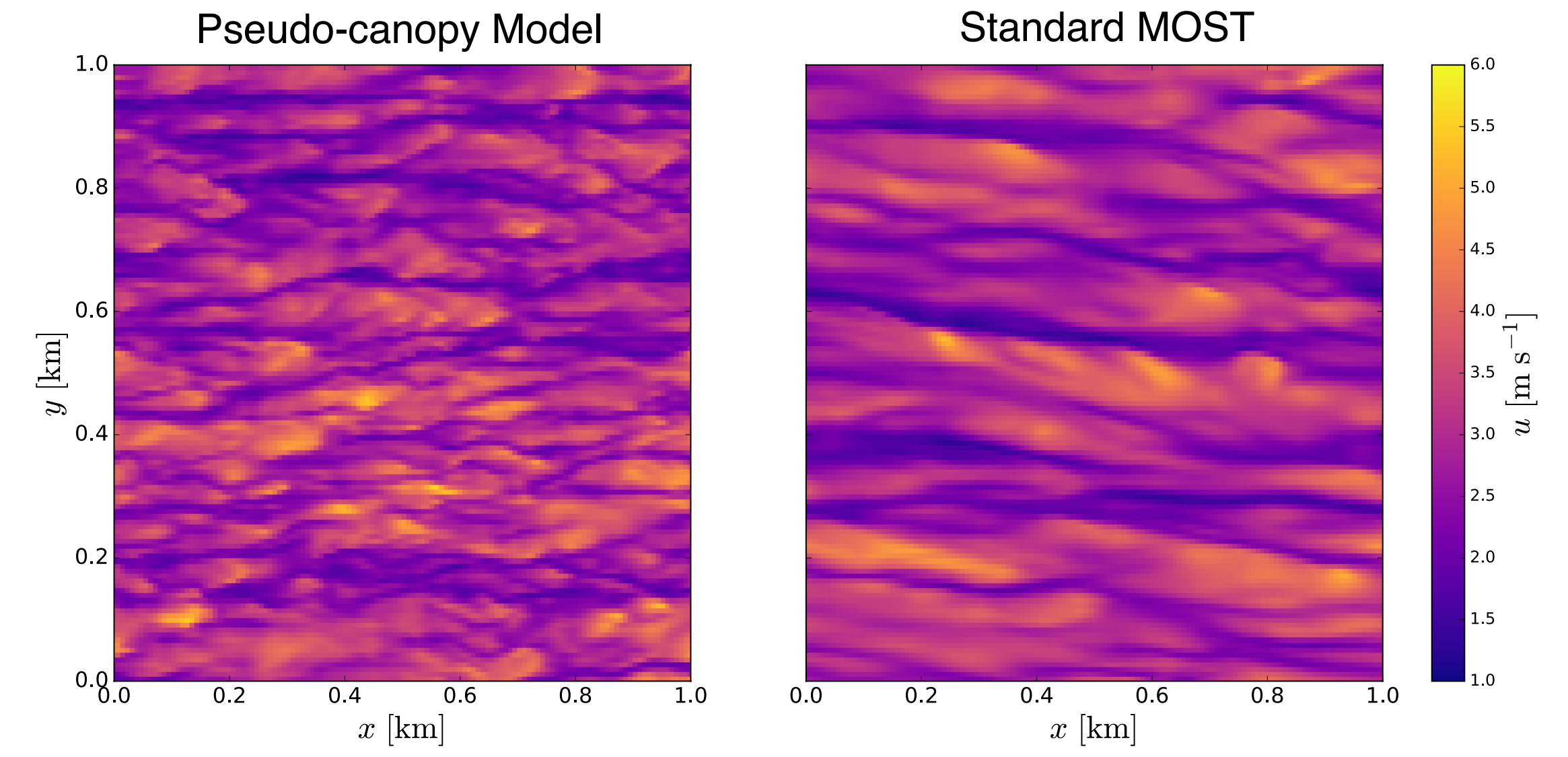
1. Choose a pseudo-canopy drag shape function, height h_c, and roughness scale z_0.

2. Choose the optimal pseudo-canopy height based on the root mean square difference (RMSD) with a log-law profile.

3. Compare results to theory and native WRF with MOST.

Takeaway Points

- The pseudo-canopy model allows WRF to resolve more fine-scale turbulence structures, and thus more realistic vertical momentum transport, near the surface. When MOST is used, these structures are damped out and the model depends more on the LES closure scheme for vertical momentum transport, leading to errors.
- See our paper in *Monthly Weather Review* for additional testing with various surface roughness values and grid aspect ratios.
- In future work, we are planning to test the pseudo-canopy model in non-neutral stability conditions.



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