# Demonstration of an Improved Subfilter Stress Closure for WRF

J. D. Mirocha[1]
J. K. Lundquist[1]
F. K. Chow[2]
K. A. Lundquist[2]

[1]Lawrence Livermore National Laboratory
[2]University of California at Berkeley

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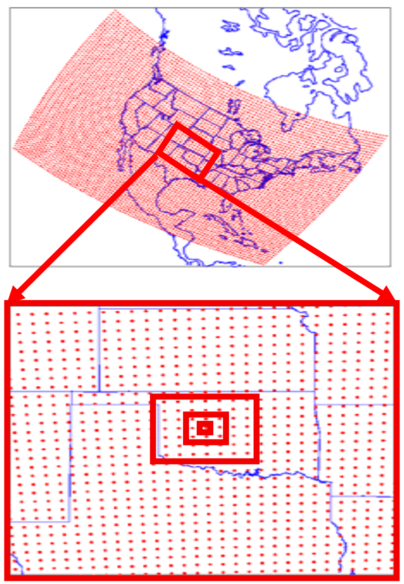
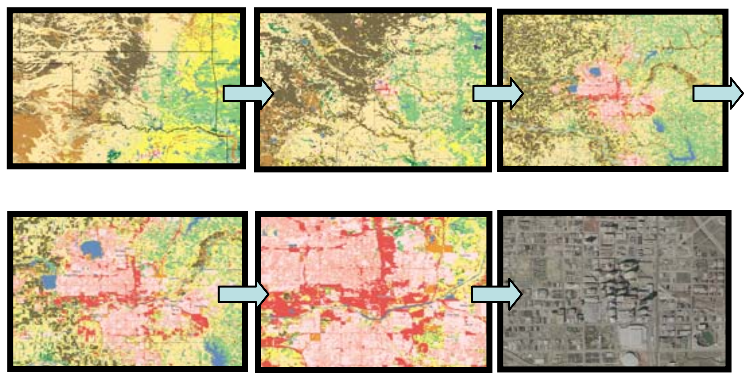
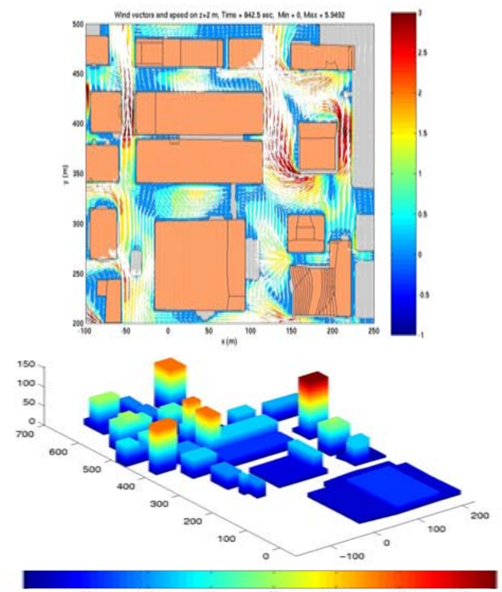
# We are developing of a framework for studying atmospheric dispersion problems involving multiple scales and complex terrain, e.g. urban environments

WRF THE WEATHER RESEARCH & FORECASTING MODEL







**Nesting WRF down to LES scales to provide boundary conditions for CFD models (or resolve urban areas directly) requires improved complex terrain and turbulence modeling capabilities.**

LLNL's CFD model, FEM3MP

**LLNL and UCBerkeley are implementing a new complex terrain approach and several new turbulence subfilter stress models for improved large eddy simulation (LES) capability**

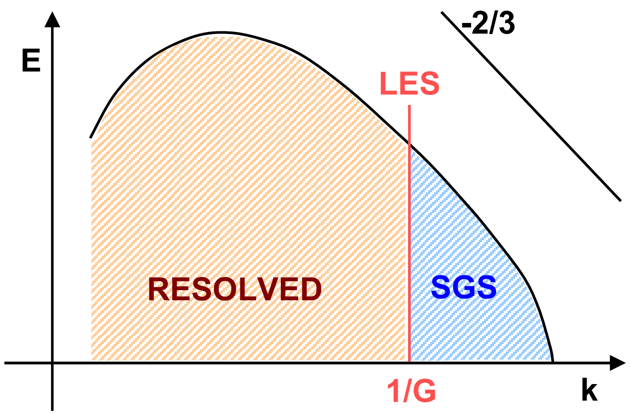
# LES requires modeling of the subfilter-scale (SFS) stresses

$$\partial_t \overline{u}_i + \partial_j(\overline{u}_i \overline{u}_j) = -\partial_i \overline{p} - \partial_j \tau_{ij} + \cdots$$

$$\overline{u}_i(x) = \int G(x-y) u_i(y) dy$$

$$\tau_{ij} \equiv \overline{u_i u_j} - \overline{u}_i \overline{u}_j$$

**Spectral LES requires a model for the subgrid-scale (SGS) stresses.**




**Spectral LES can fully resolve all scales up to the filter cutoff.**

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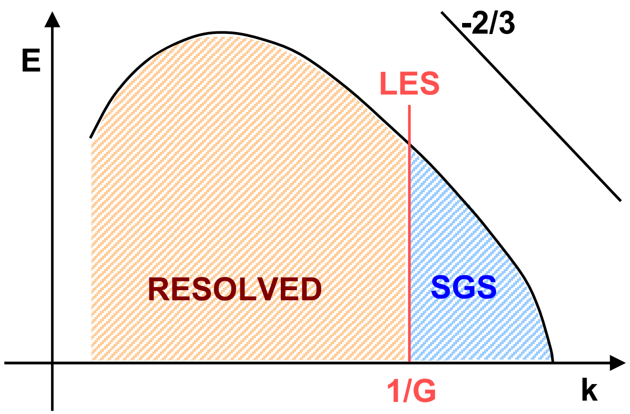


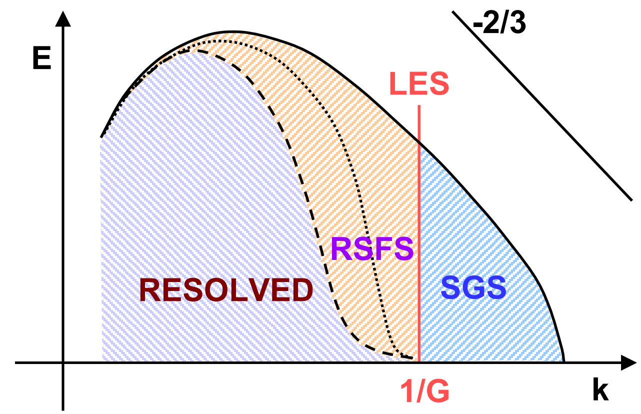

**Spectral LES can fully resolve all scales up to the filter cutoff.**

$$\partial_t \tilde{\bar{u}}_i + \partial_j(\tilde{\bar{u}}_i \tilde{\bar{u}}_j) = -\partial_i \tilde{\bar{p}} - \partial_j \tilde{\tau}_{ij} + \cdots$$

$$\tilde{\bar{u}}_i = D(\bar{u}_i)$$

$$\tau_{ij} \equiv \overline{u_i u_j} - \tilde{\bar{u}}_i \tilde{\bar{u}}_j$$

**Discrete LES (WRF) requires an additional model for the Resolvable Subfilter-Scale (RSFS) Stresses**




**Discretization effects attenuate the energy of resolved flow structures**

# Modeling the Resolvable Subfilter-Scale Stresses

*Subfilter-scale Stresses*

$$\tau_{ij} = (\overline{u_i u_j} - \overline{\tilde{\bar{u}}_i \tilde{\bar{u}}_j}) + (\overline{\tilde{\bar{u}}_i \tilde{\bar{u}}_j} - \tilde{\bar{u}}_i \tilde{\bar{u}}_j)$$

SGS RSFS

$$\partial_t \tilde{\bar{u}}_i + \partial_j (\tilde{\bar{u}}_i \tilde{\bar{u}}_j) = -\partial_i \tilde{\bar{p}} - \partial_j \tilde{\tau}_{ij} + \cdots$$

$$\tilde{\bar{u}}_i = D(\bar{u}_i)$$

$$\tau_{ij} \equiv \overline{u_i u_j} - \tilde{\bar{u}}_i \tilde{\bar{u}}_j$$

**Reconstruction**

**Approximate Deconvolution Model**
**Unfiltered velocities are reconstructed (approximately) by successive applications of an explicit filter, G (tophat)**

$$\tilde{u}_i = \tilde{\bar{u}}_i + (I - G)\tilde{\bar{u}}_i + (I - G)[(I - G)\tilde{\bar{u}}_i] + \ldots$$

NE: Numerical Errors limit reconstruction

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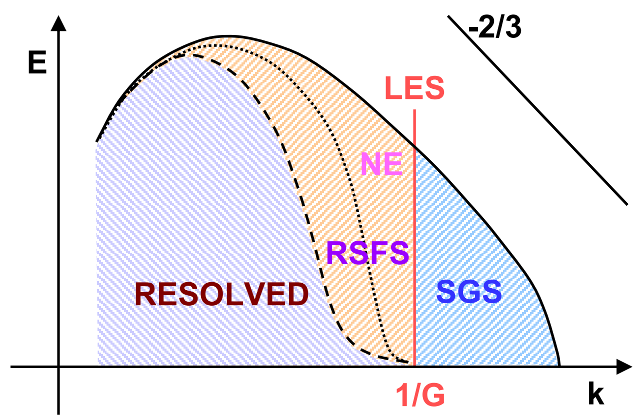



**Discretization effects attenuate the energy of resolved flow structures**

# Subgrid-scale stresses

**Any SGS model can be used for the 'SGS' part of the SFS stresses:**

**WRF utilizes either a Static Smagorinsky or a TKE-based SGS model**

- **Do not permit backscatter**
- **Assume local balance between TKE production and dissipation**
- **Contribute significant errors**

**We have implemented the Dynamic SGS Model of Wong and Lilly**

- **Formulates SGS stresses based on smallest well-resolved stresses**
- **Permits backscatter**
- **Does not assume local balance between TKE production and dissipation**

**Near-wall stress model (Brown et al. 2001):** $\tau_{i,\text{wall}} = -\int C_c a(z) \tilde{\overline{u}}_i \, | \tilde{\overline{u}}_i | \, dz$

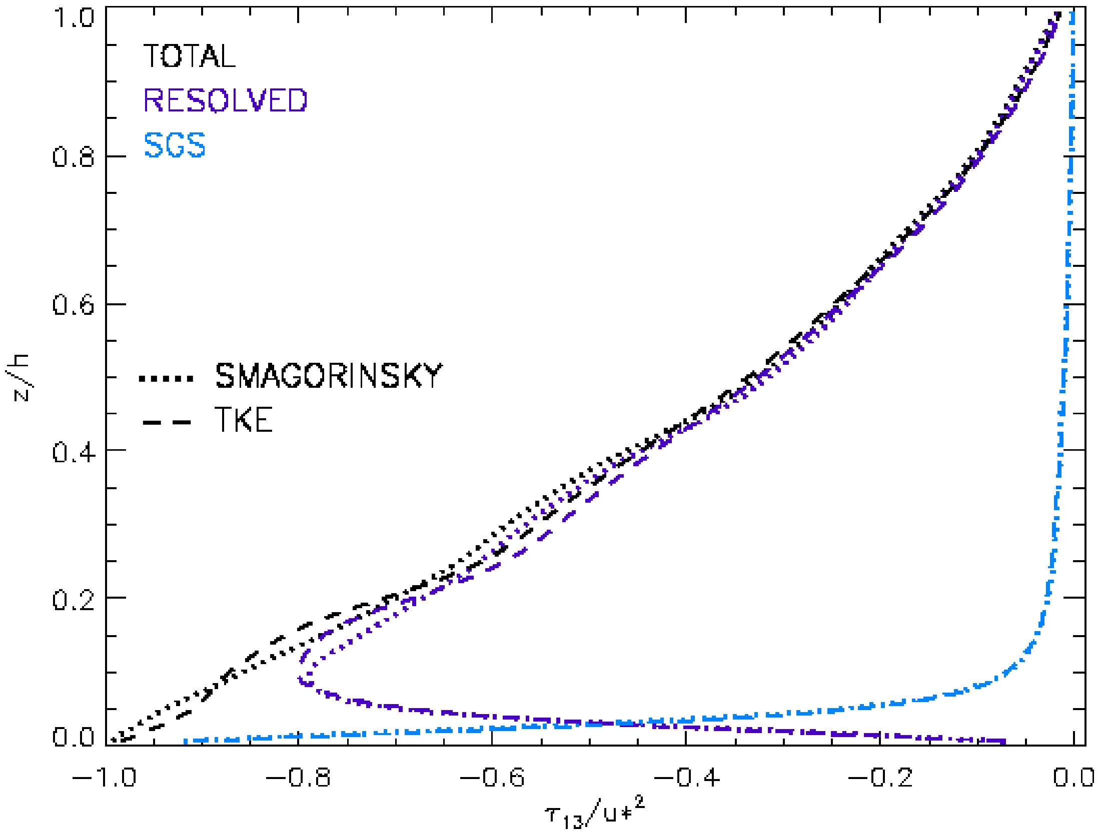
$$a(z) = \cos(z / H)^2$$

**Total DRM SFS stress model:**

$\tau_{ij}$ = **RSFS** + **SGS** + **WALL**

# Results for neutral, geostrophic flow over a flat, rough plate

**$u_g$=10.0, $v_g$ = 0, $z_0$=0.1, $42^3$ nodes, ~1500$m^3$ domain, $\Delta x$=$\Delta y$=32m, $\Delta z$ stretched, lowest = 10m**



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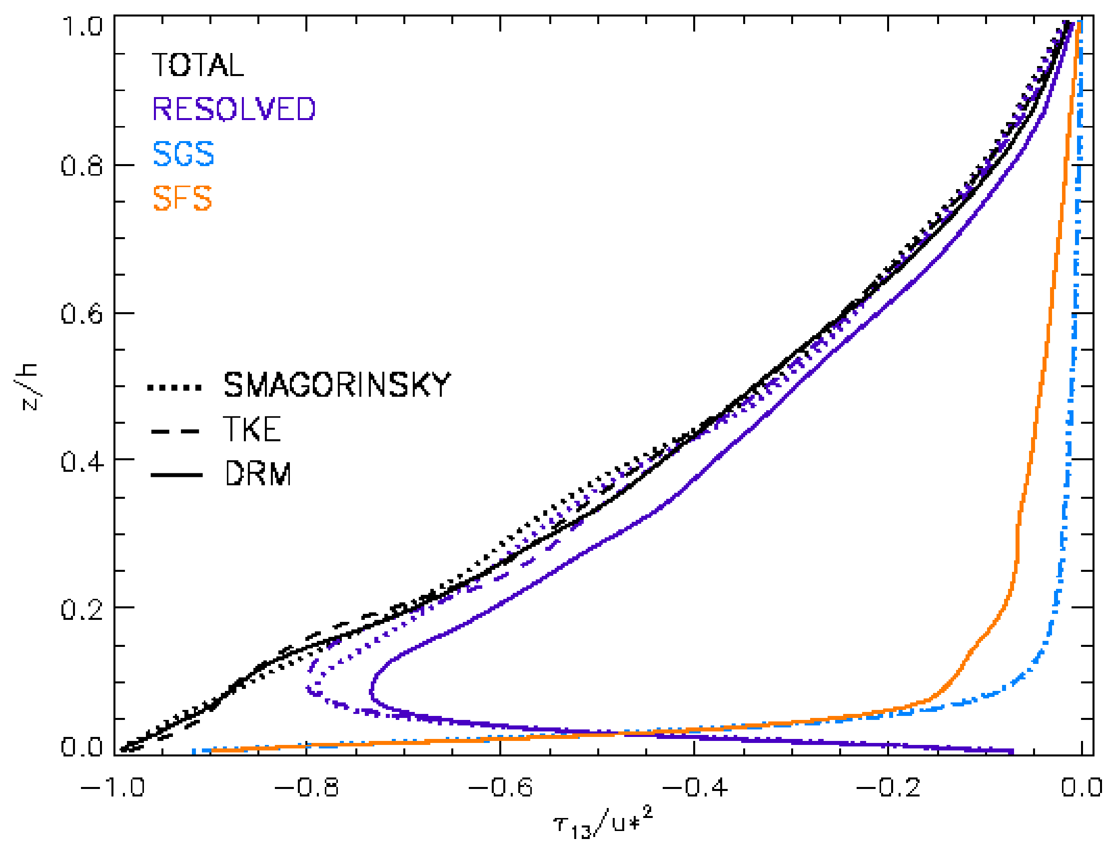
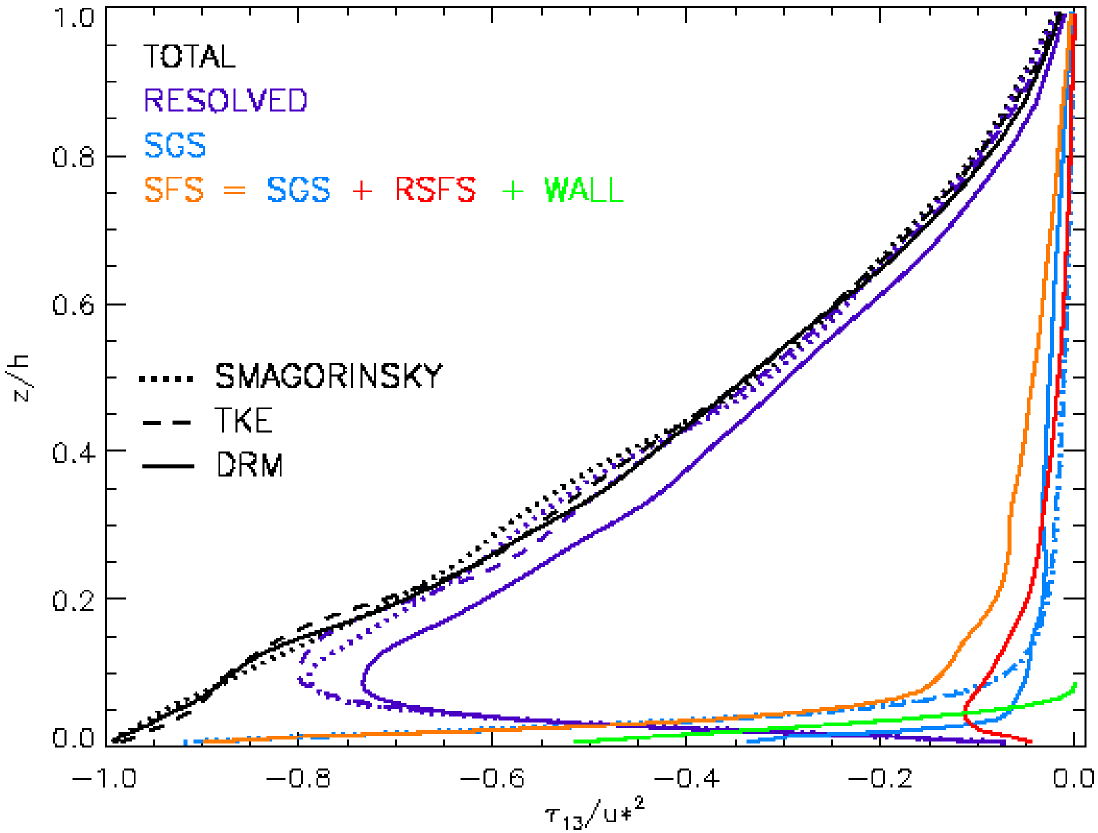
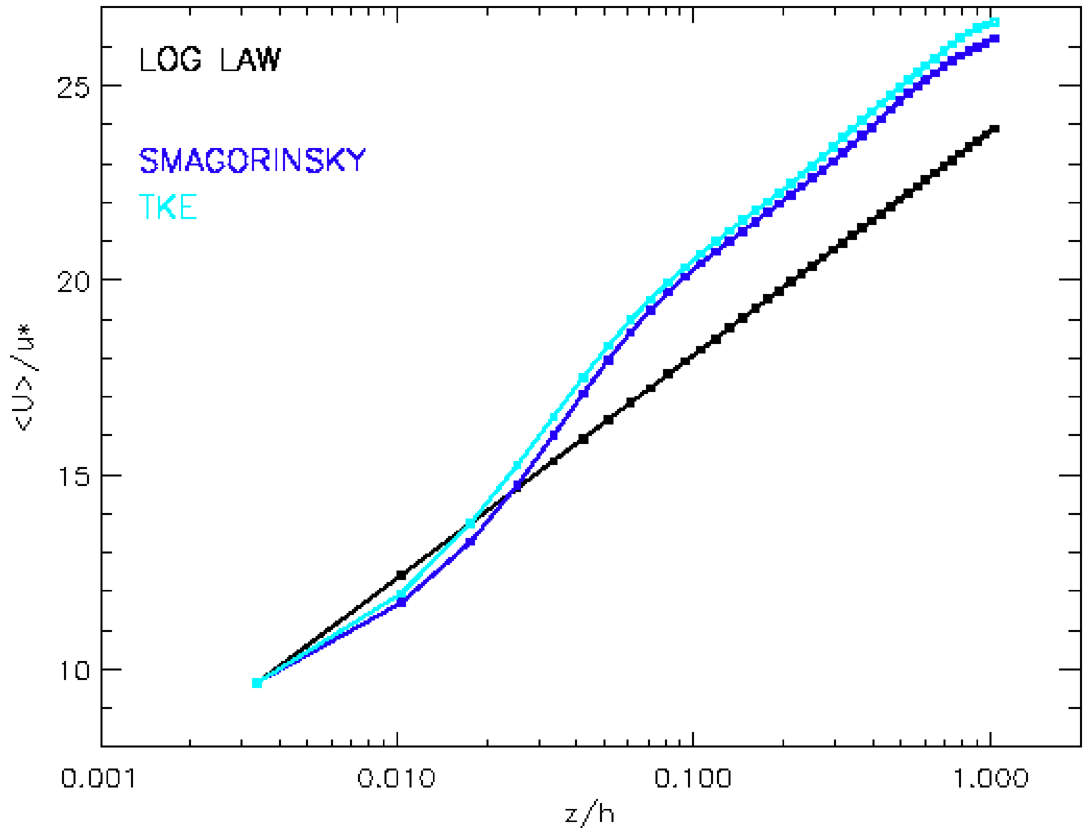


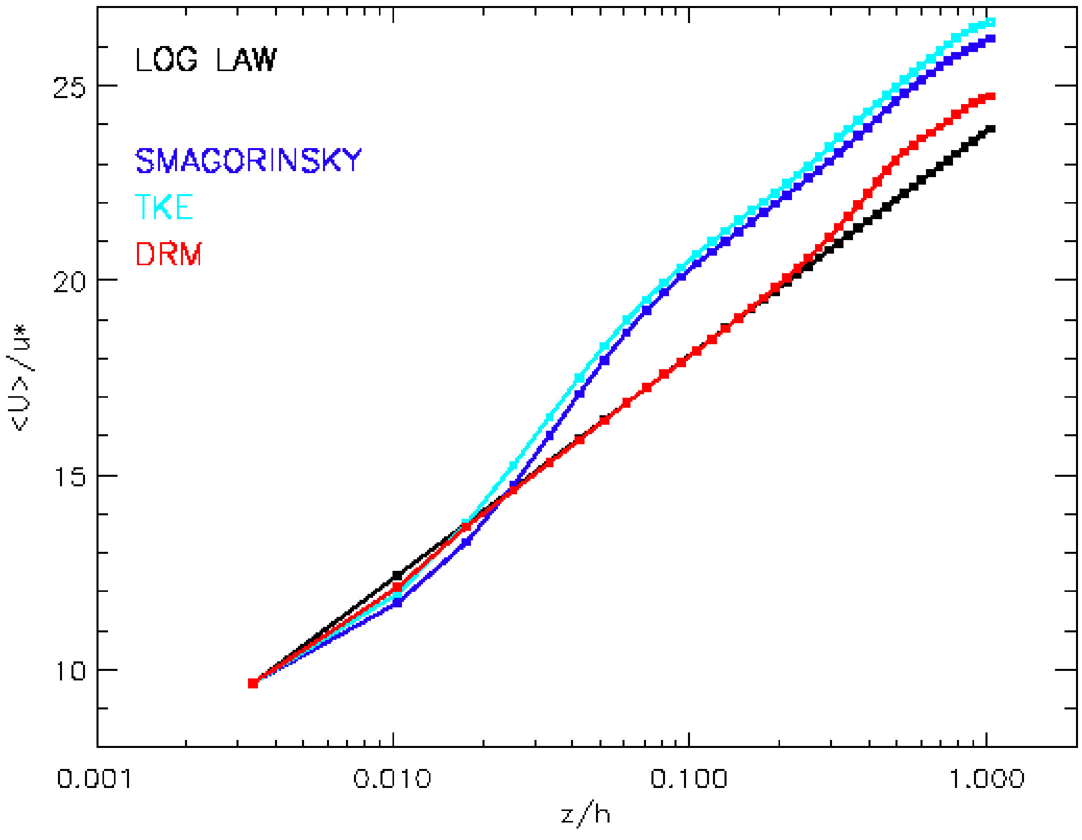
# Partitioning of DRM SFS stresses



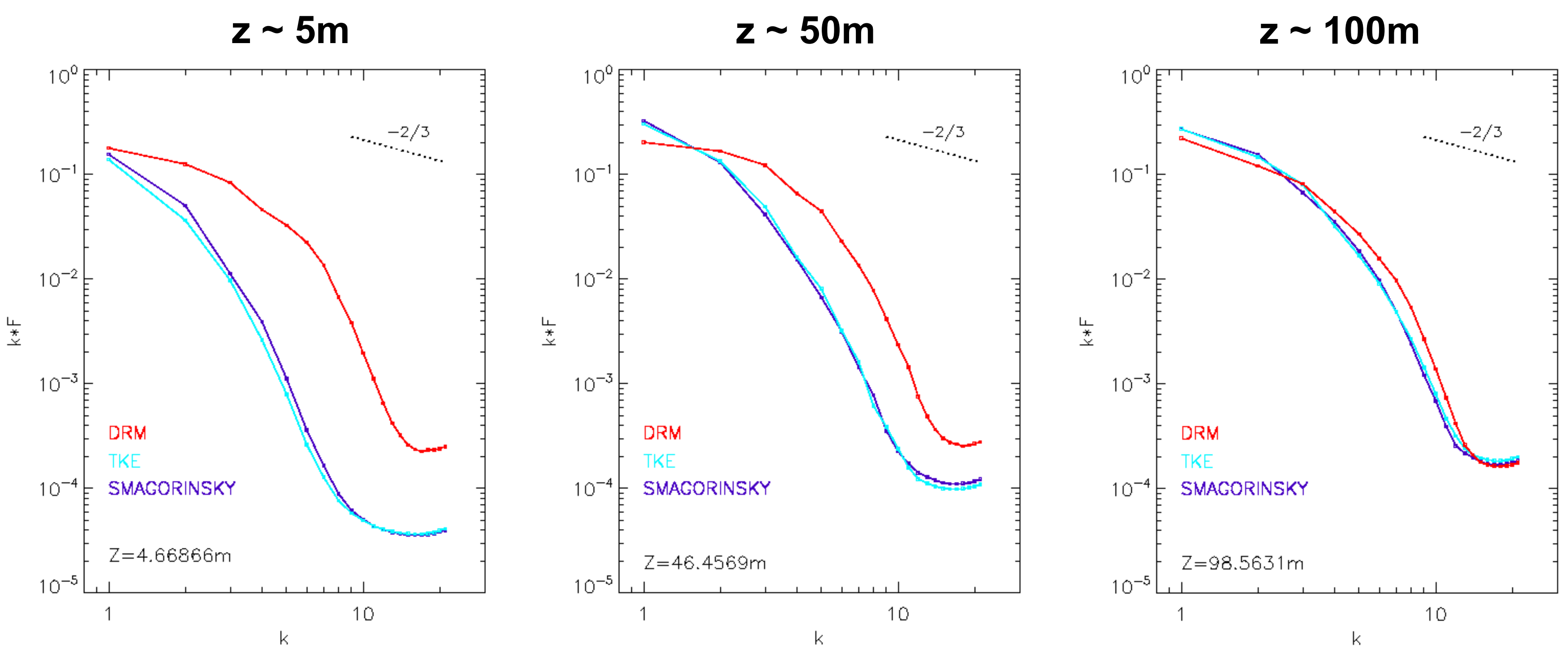
# WRF SGS models deviate from the Log Law



# DRM improves agreement with the with Log Law



# DRM increases high-frequency power near the surface as seen in velocity spectra




**averaged u-velocity spectra**

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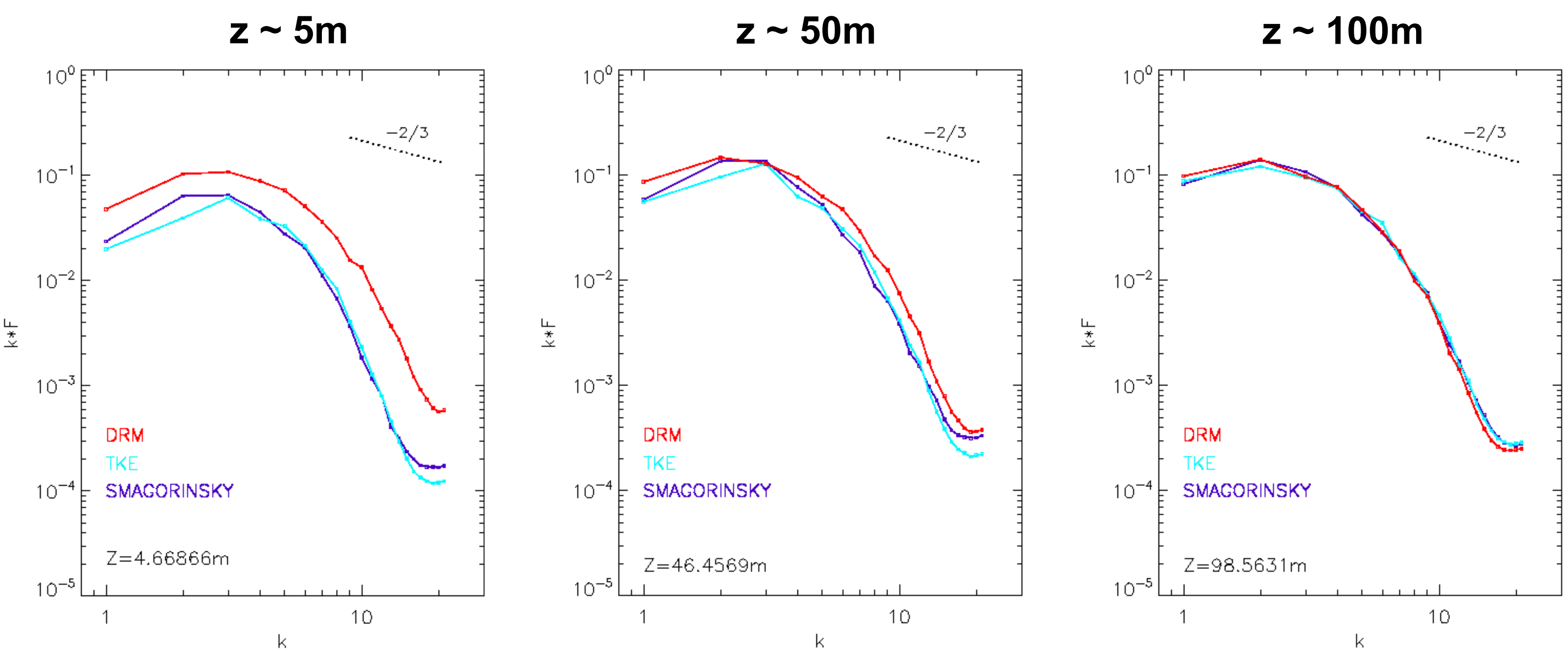
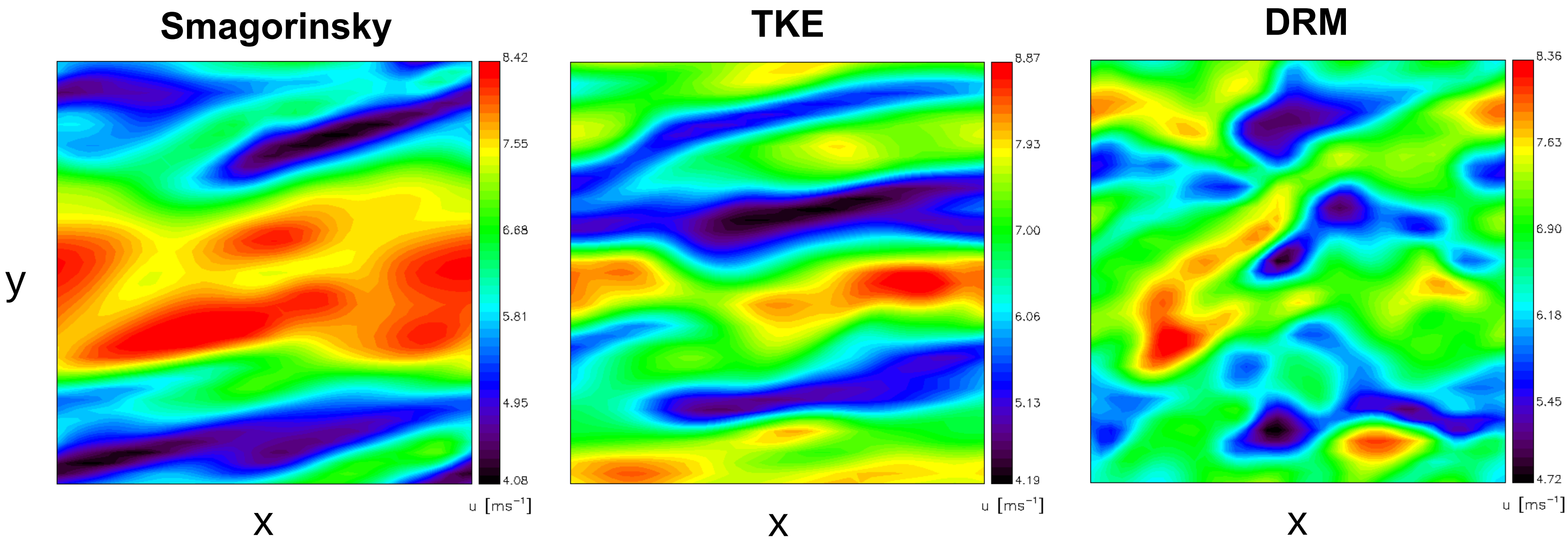


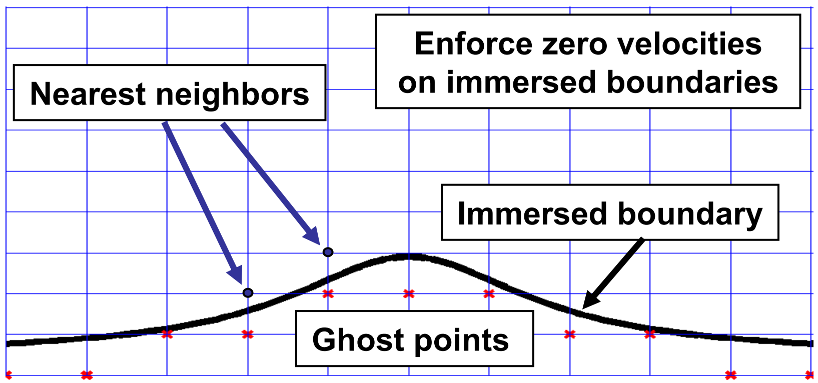

**averaged v-velocity spectra**

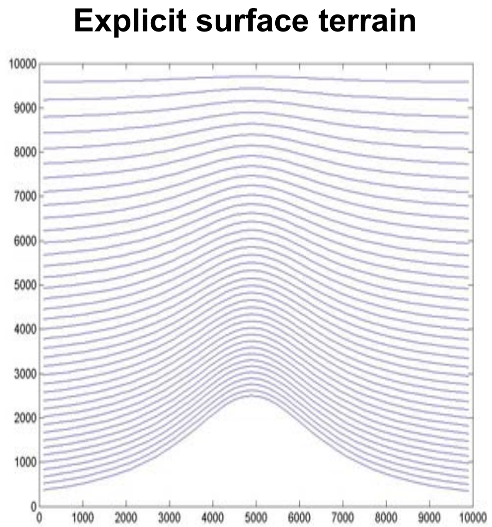
# DRM decreases streamwise streaks in velocity field

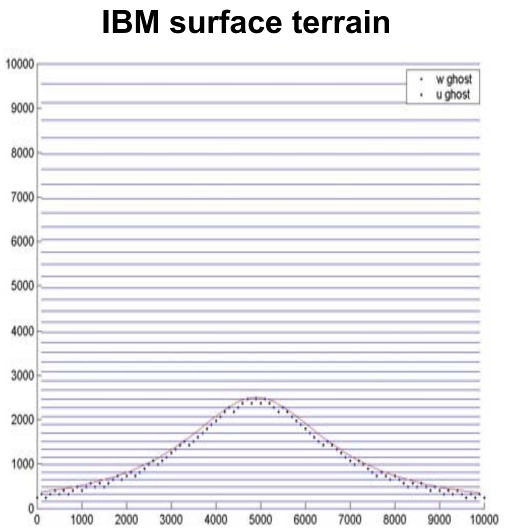



**instantaneous u-velocity contours at ~50 m**

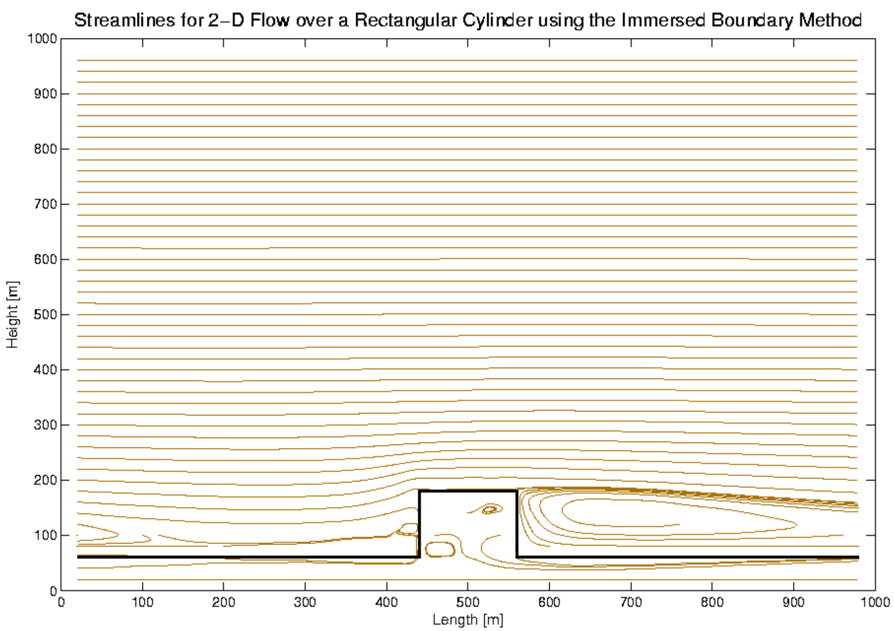
# Immersed Boundary Method (IBM) will provide complex terrain capability using WRF's native grid.

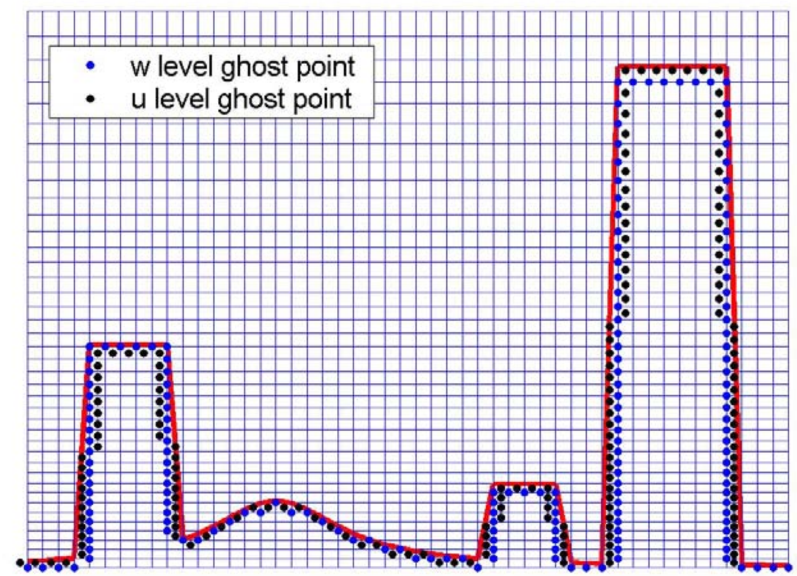


# The Immersed Boundary Method expands WRF applicability to flows over steep terrain



# Conclusions

DRM turbulence model significantly improves LES performance at a reduced cost over increasing resolution throughout the domain.

Immersed boundaries will increase WRF's flexibility for use in environments with complex terrain: urban environments

# Future Work

Further experimentation with model parameters

Implementation of the nonlinear backscatter SGS model of Kosović, 1997

Validation in nonidealized simulations (non neutral, terrain, synoptic forcing, etc.)

Nesting of LES domain, downscaling issues