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Designing Simulations to Overcome the Surface Layer Overshoot of Mean Shear in Large-Eddy Simulation of the Neutral Atmospheric Boundary Layer

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Designing High Accuracy Simulation

Primary issues:

- "Frictional" content of the model for sub-filter scale stress.
- Resolution in the vertical direction.
- Mesh aspect ratio.
- Numerical algorithm, dealiasing.

Secondary issues:

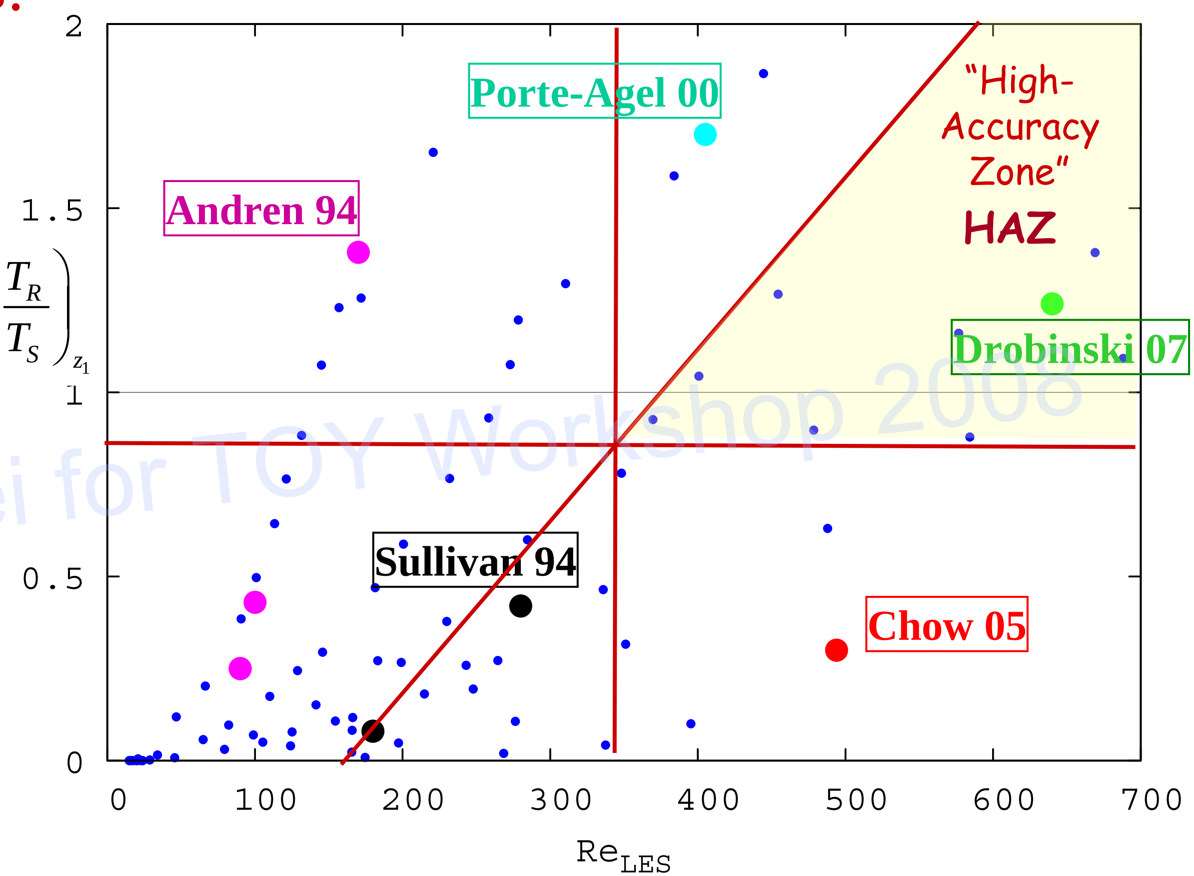
- Lower wall boundary conditions
- Other details of SFS closure
- Other algorithmic issues

Different Studies with different SFS Models

- Previous efforts have focused on the model for SFS stress.

- Eddy viscosity models
  - Smagorinsky model
  - Moeng 1984, 1-eq model
  - Dynamic eddy viscosity model
- Non-eddy viscosity models
  - Similarity model
  - Reconstruction model
  - Resolvable sub-filter scale model (RSFS)

$$\Re = \left(\frac{T_R}{T_S}\right)_{z_1}$$



for Smag:

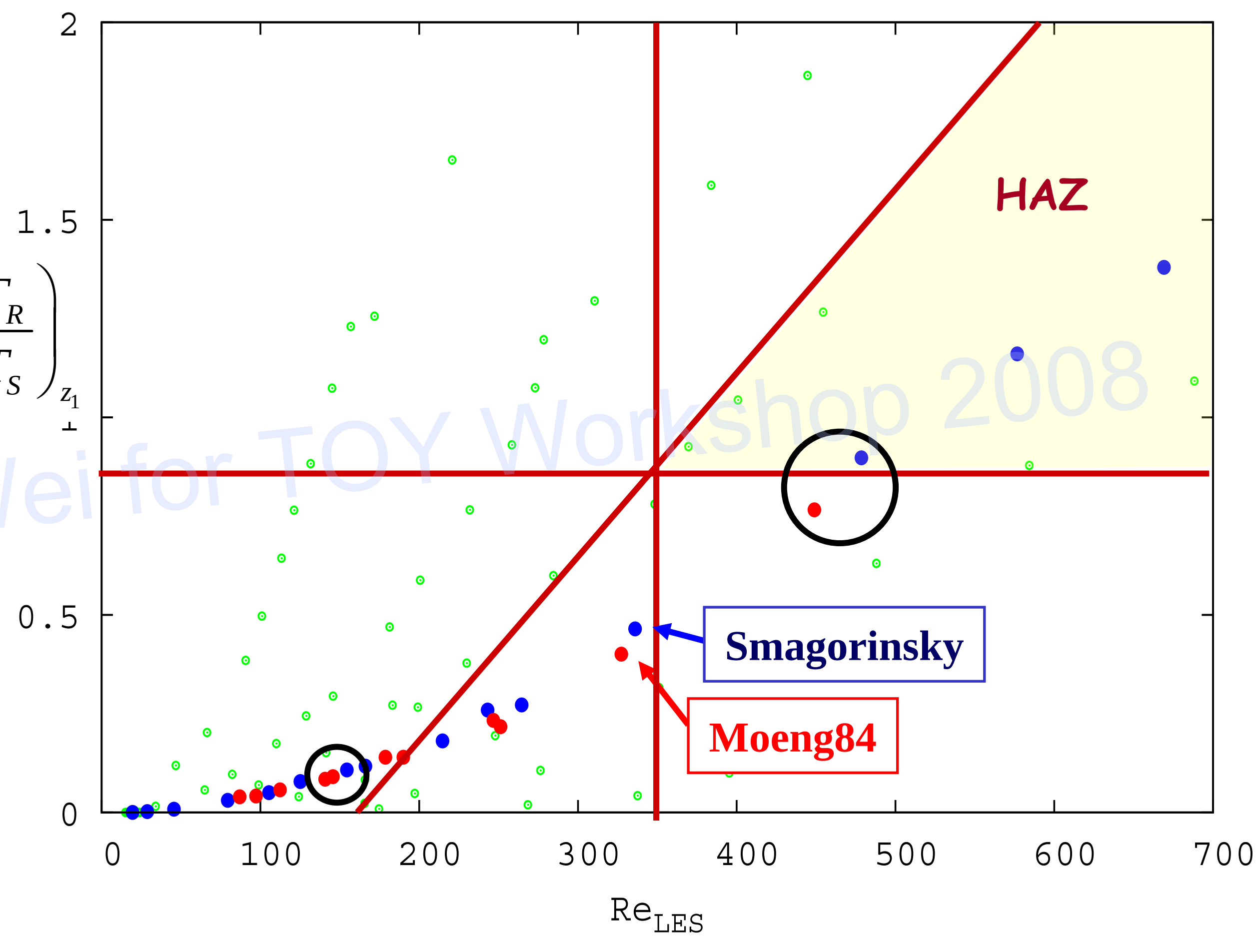
$$\Re \approx \frac{\sqrt{2}\xi\ \tilde{\kappa}_1^2}{C_S^2(AR)^{4/3}} - 1$$

$$Re_{LES} \approx \frac{\sqrt{2}\ \tilde{\kappa}_1 N_\delta}{C_S^2(AR)^{4/3}}$$

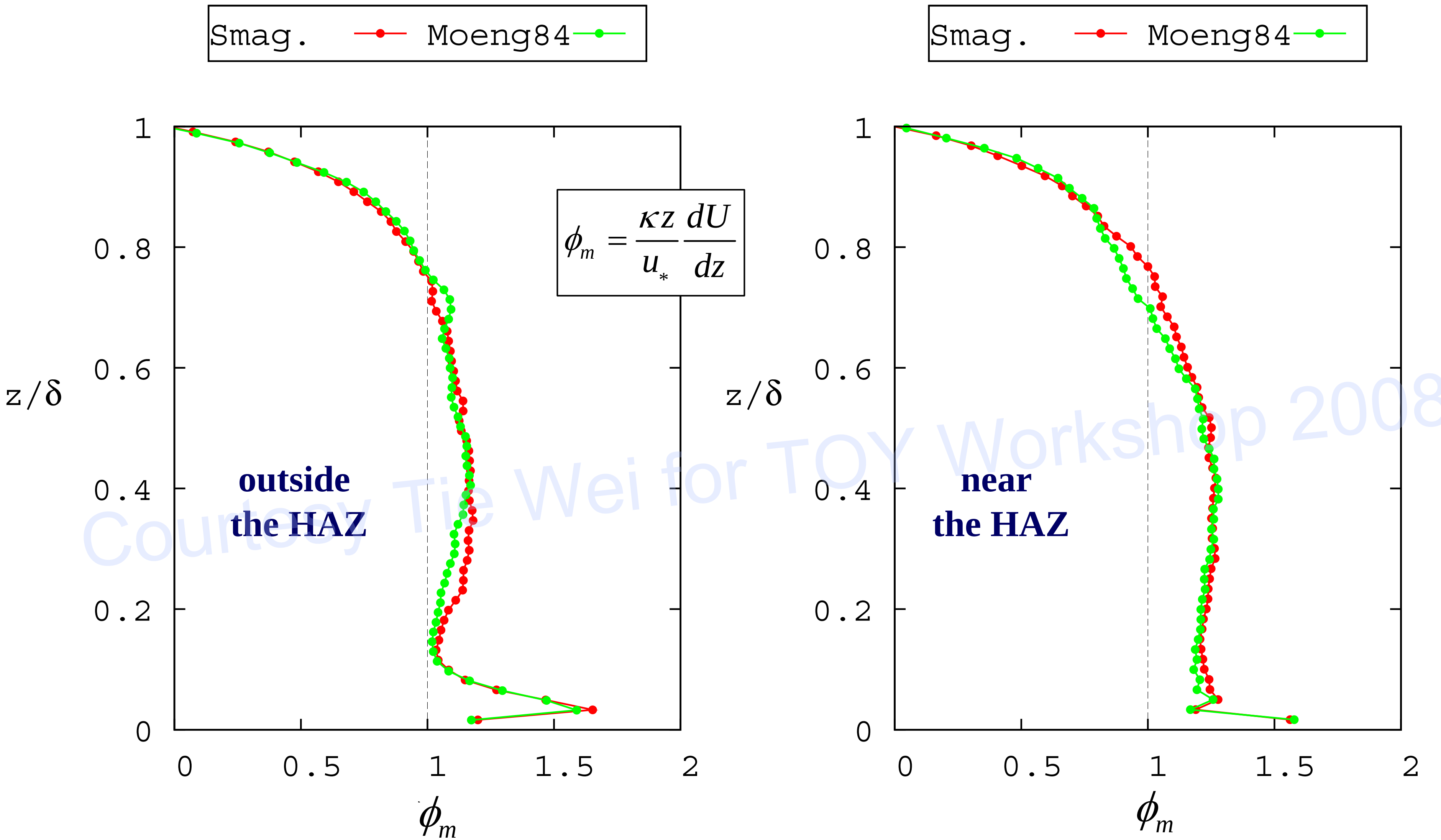
Comparing Eddy Viscosity Models: Smagorinsky vs. Moeng 84

- SFS eddy viscosity models:
  - Smagorinsky
  - Moeng 84 one-eq model
- Keep N_z=128
- Change aspect ratio by changing horizontal mesh size, Nx and Ny.
- The simulations with the Smag. and Moeng 84 SFS models follow the same curve in the $\Re - \mathrm{Re}_{LES}$ parameter-space.

$$\Re = \left(\frac{T_R}{T_S} \right)_{z_1}$$



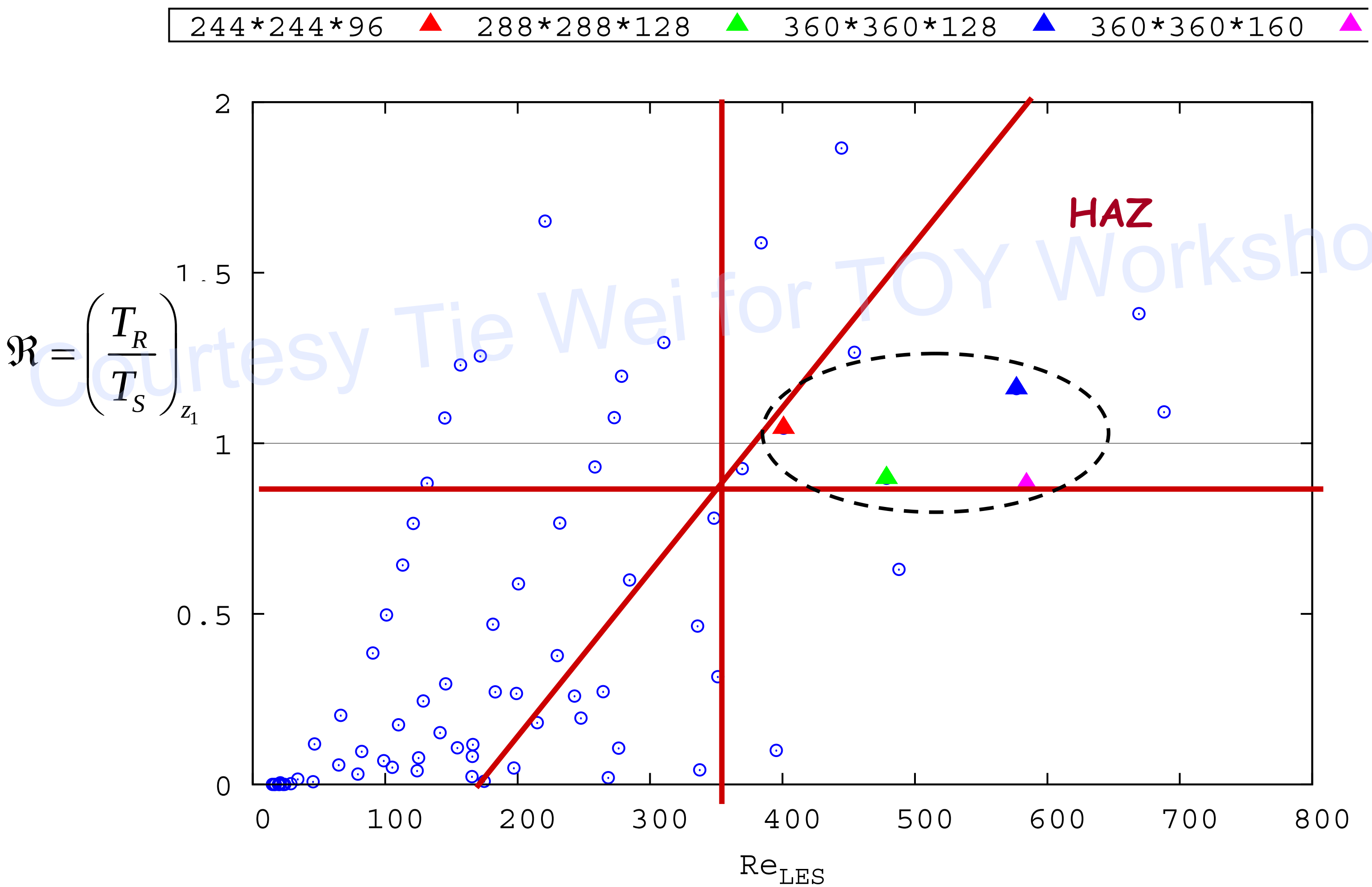
Comparing Smagorinsky vs. Moeng 84 Eddy Viscosity Models



The placement and predicted mean shear are independent of the SFS model.

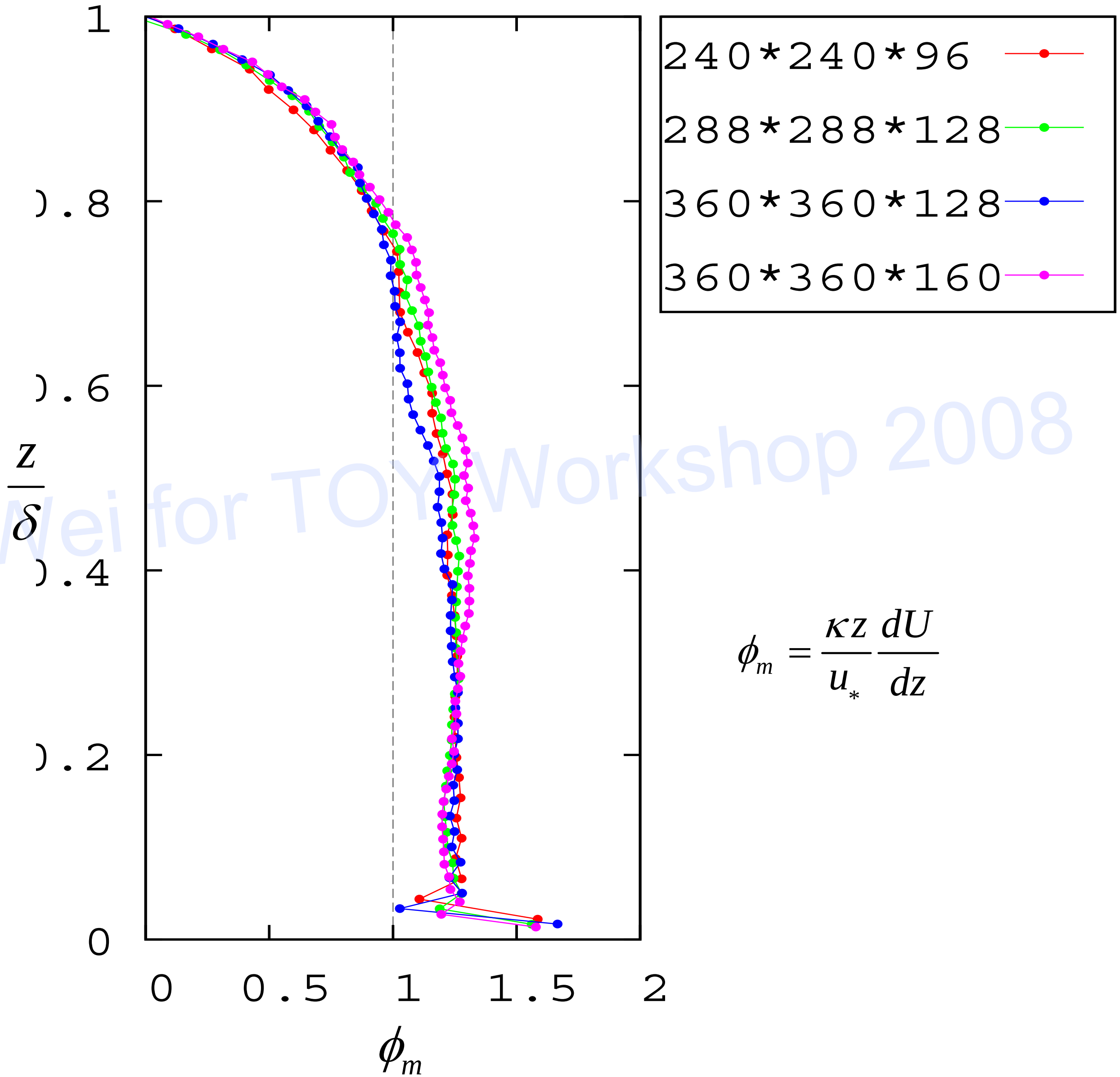
Simulations with High Accuracy

- N_z from 96 to 160
- Smagorinsky model with $C_s = 0.10$
- Aspect ratio 1.6 to 2.0



Convergence of LES Over the Entire ABL

The simulations converge well over the entire ABL

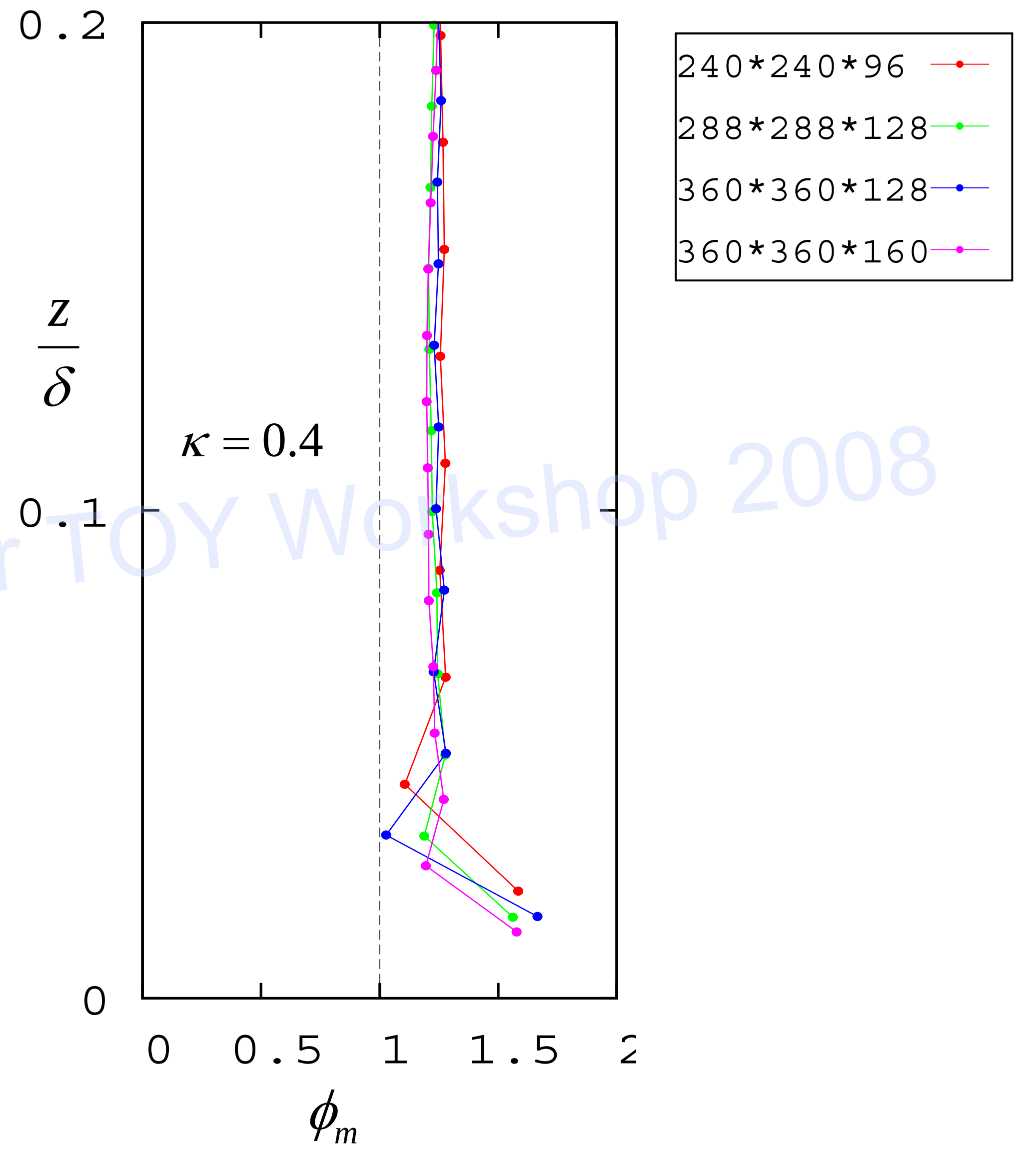


$$\phi_m = \frac{\kappa z}{u_*}\frac{dU}{dz}$$

The Surface Layer

- Predicted non-dimensional mean shear converges well in the inertial region.

- However, $\phi_m \approx 1.2$ when κ is assumed to be 0.4



Predicted von Karman Constant

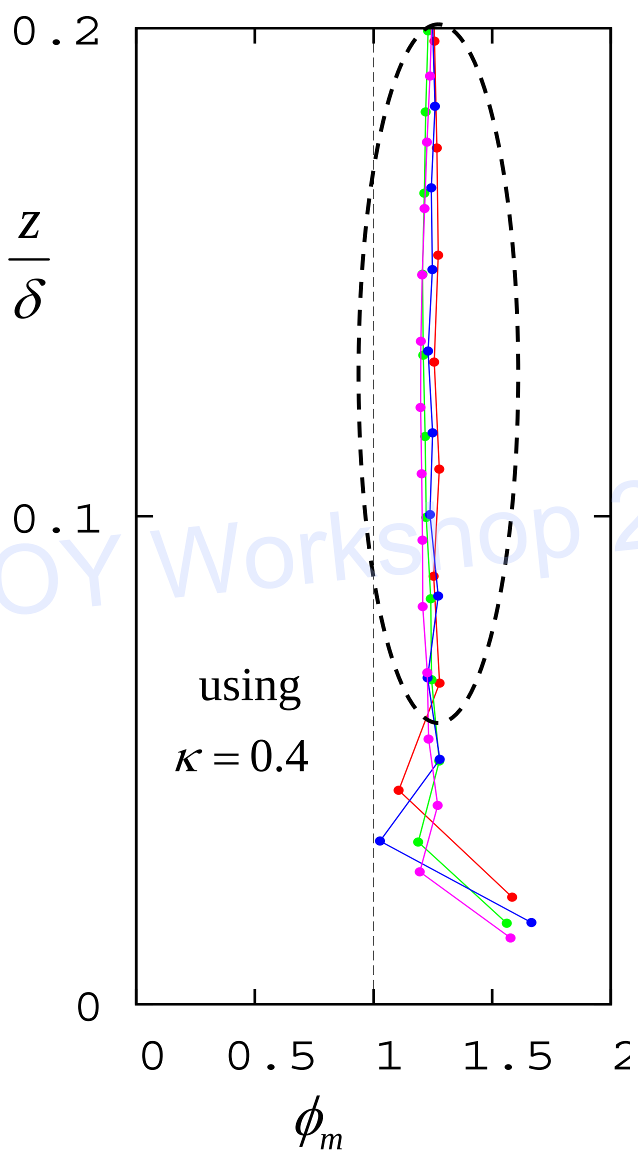
- **For each simulation, we average the predicted ϕ_m in the lower 20% of the boundary layer to obtain the predicted $\tilde{\kappa}$ so that**

$$\frac{\tilde{\kappa} z}{u_*}\frac{\partial U}{\partial z} = 1$$

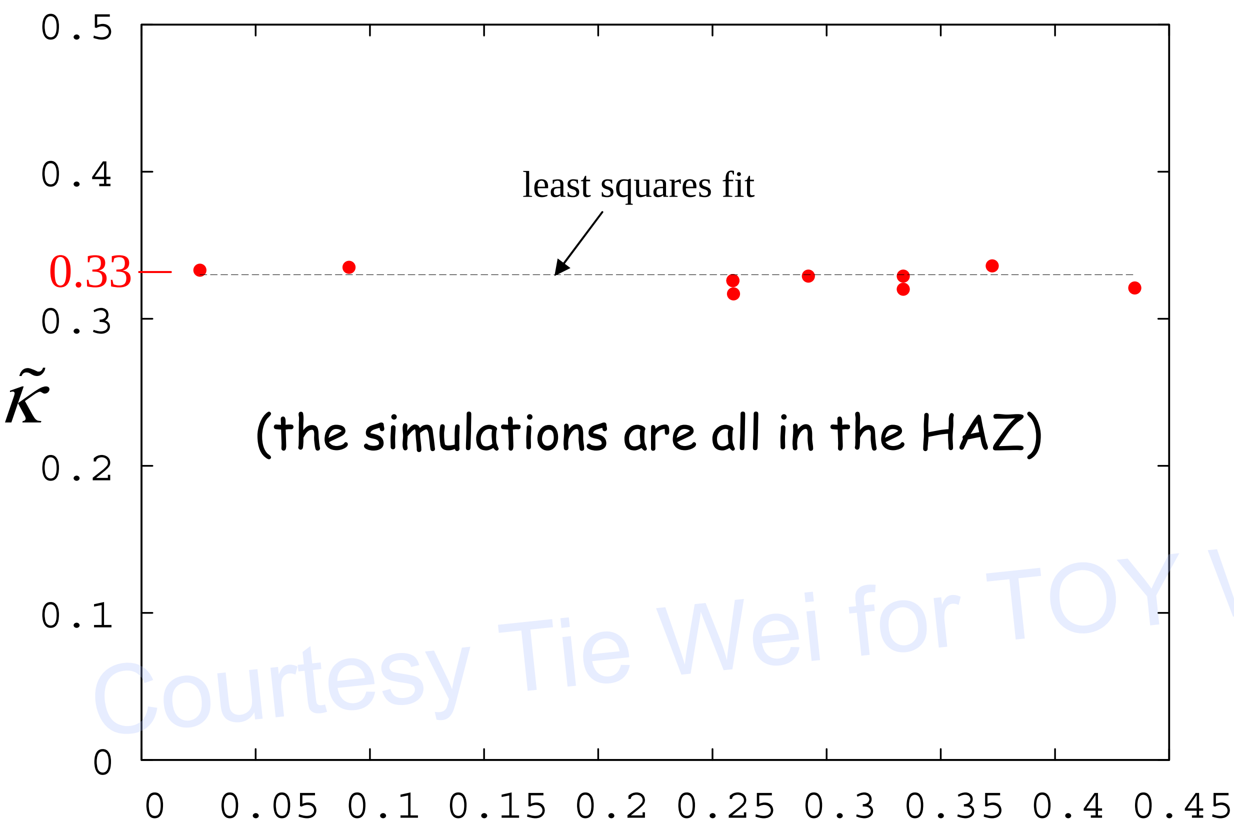
- **Vary the input roughness parameter z_0 in the code:**

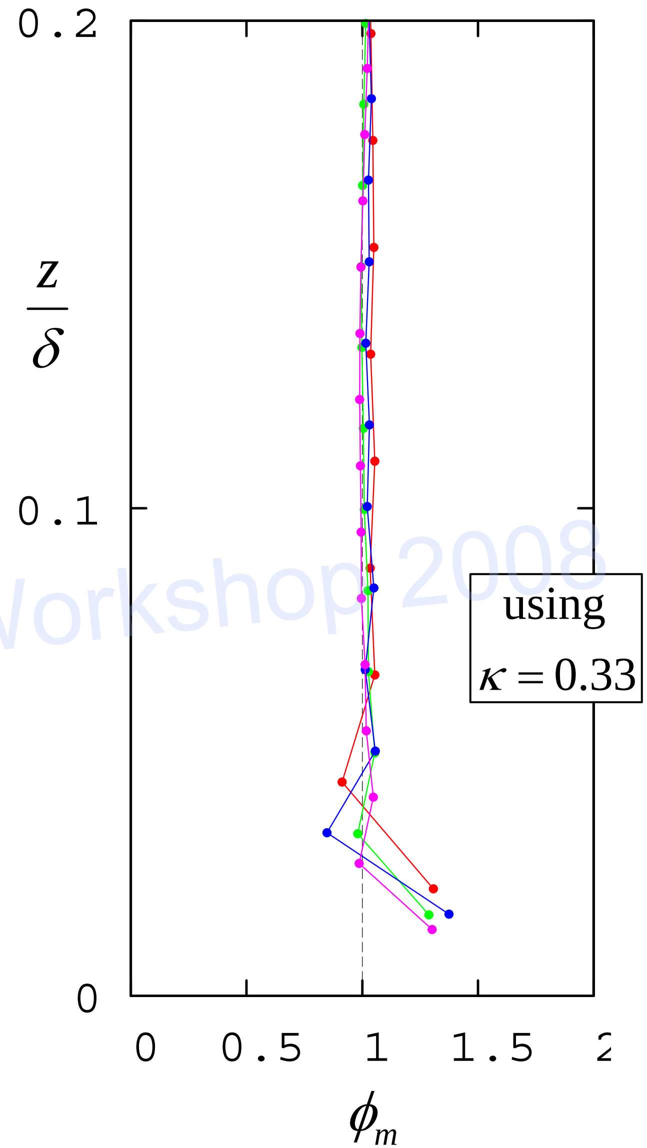
$$\frac{U}{u_*} = \frac{1}{\tilde{\kappa}} \log \frac{z}{z_0}$$

- **z_0 = 1 cm, 5 cm, 16 cm, 30 cm**



Predicted von Karman Constant





roughness LES Reynolds number $\mathrm{Re}_{\hat{z}_0} = \dfrac{\hat{z}_0 u_*}{\nu_{LES}}$ $\mathrm{Re}_{LES} = \dfrac{\delta u_*}{\nu_{LES}}$

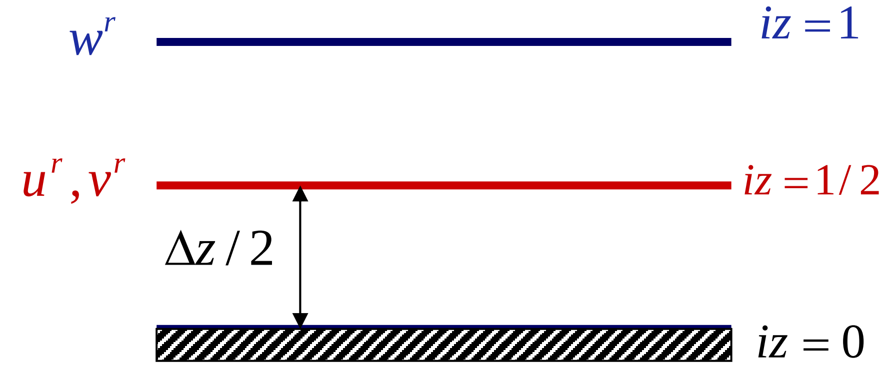
$\Rightarrow$ LES predicts von Karman constant $\kappa \approx 0.33$ (!?)

Surface Stress Boundary Conditions

- Equation at the first (u,v) level

$$\left.\frac{\partial u^r}{\partial t}\right|_{\frac{1}{2}} = \ldots - \left.\frac{\partial\left(u^r w^r + \tau_{uw}^{SFS}\right)}{\partial z}\right|_{\frac{1}{2}}$$

- Finite difference representation:



Staggered mesh in vertical direction

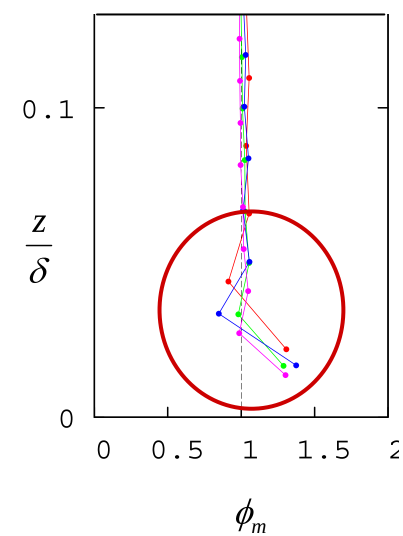
$$\left.\frac{\partial\left(u^r w^r + \tau_{uw}^{SFS}\right)}{\partial z}\right|_{\frac{1}{2}} \approx \frac{\left.\left(u^r w^r + \tau_{uw}^{SFS}\right)\right|_1 - \left.\left(u^r w^r + \tau_{uw}^{SFS}\right)\right|_0}{\Delta z}$$

$\left. T_{uw}^{Tot} \right|_1 \Rightarrow$ Only total shear stress is known at the wall

$$= \frac{\left.\left(u^r w^r + \tau_{uw}^{SFS}\right)\right|_1 - \left. T_{uw}^{Tot}\right|_0}{\Delta z}$$

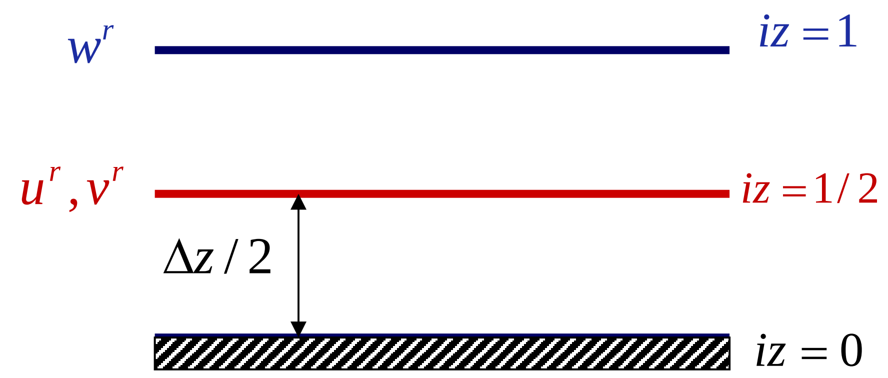
$$= \frac{\left\langle u^r w^r + \tau_{uw}^{SFS}\right\rangle_1 - \left\langle T_{uw}^{Tot}\right\rangle_0}{\Delta z}$$ Mean

$$+ \frac{\left(u^r w^r + \tau_{uw}^{SFS}\right)'_1 - \left. T_{uw}^{Tot}\right|'_0}{\Delta z}$$ Fluctuations



Surface Stress Boundary Condition

specify $T_{uw}^{Tot}(x,y,0)=[u^r w^r + \tau_{uw}^{SFS}]_0$



Staggered mesh in vertical direction

There are two parts to the lower BC:

Part 1: define displacement of surface layer with z_0

$$\frac{u_*}{U(z_1)}=\frac{\kappa}{\ln\left(z/z_0\right)}$$

Part 2: add **fluctuations** to lower wall shear stress

$$T_{uw}^{Tot}(x,y,0)=\left\langle T_{uw}^{Tot}\right\rangle_0+[T_{uw}^{Tot}(x,y,0)]'$$

model

from global force balance

Models for Surface Stress

- Schumann-Grotzbach (SG) model (1975)

$$\tau_{uw}(x,y,0) = -u_*^{\,2}\frac{u^r(x,y,1)}{\langle S(x,y,1)\rangle}$$

- Piomelli et al. (1989) shifted SG model

$$\tau_{uw}(x,y,0) = -u_*^{\,2}\frac{u^r(x+\delta_d,y,1)}{\langle S(x,y,1)\rangle}$$

- Xie *et al.* (2004)

$$\tau_{uw}(x,y,0) = -u_*^{\,2}\frac{\langle u^r(x,y,1)\rangle + \beta\left(u^r(x,y,1)-\langle u^r(x,y,1)\rangle\right)^3/u_*^{\,2}}{\langle S(x,y,1)\rangle}$$

- Moeng/Wyngaard (1984) - nonlinear

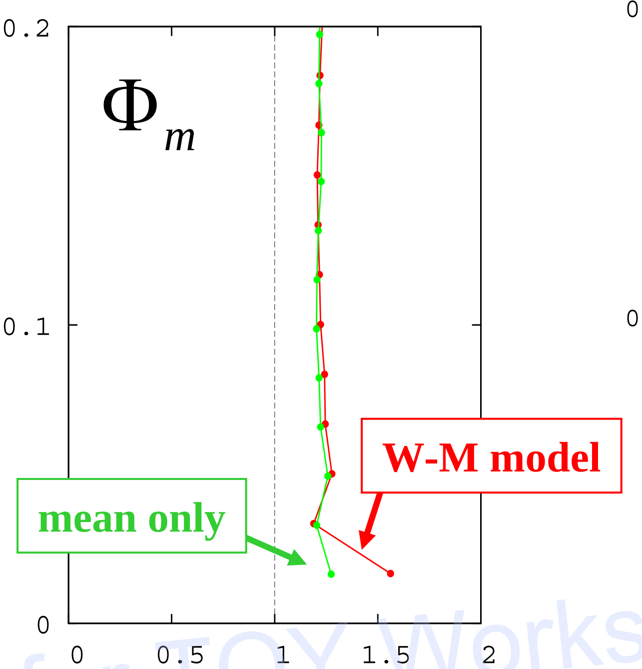
$$\tau_{uw}(x,y,0) = -u_*^{\,2}\frac{\langle S(x,y,1)\rangle\left(u^r(x,y,1)-\langle u^r(x,y,1)\rangle\right)+S(x,y,1)\langle u^r(x,y,1)\rangle}{\langle S(x,y,1)\rangle^2}$$

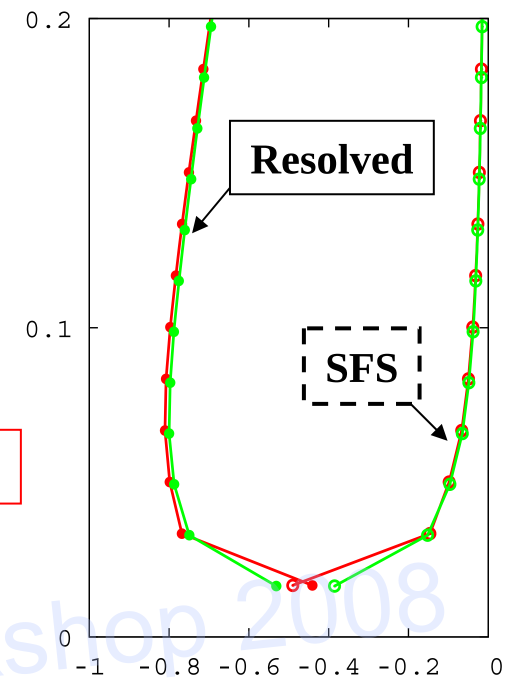
Note: In all models, the fluctuations in wall shear stress are assumed to be correlated with the streamwise velocity fluctuations at first grid level

Effect of Wall Stress Boundary Condition

Lower wall BCs applied:

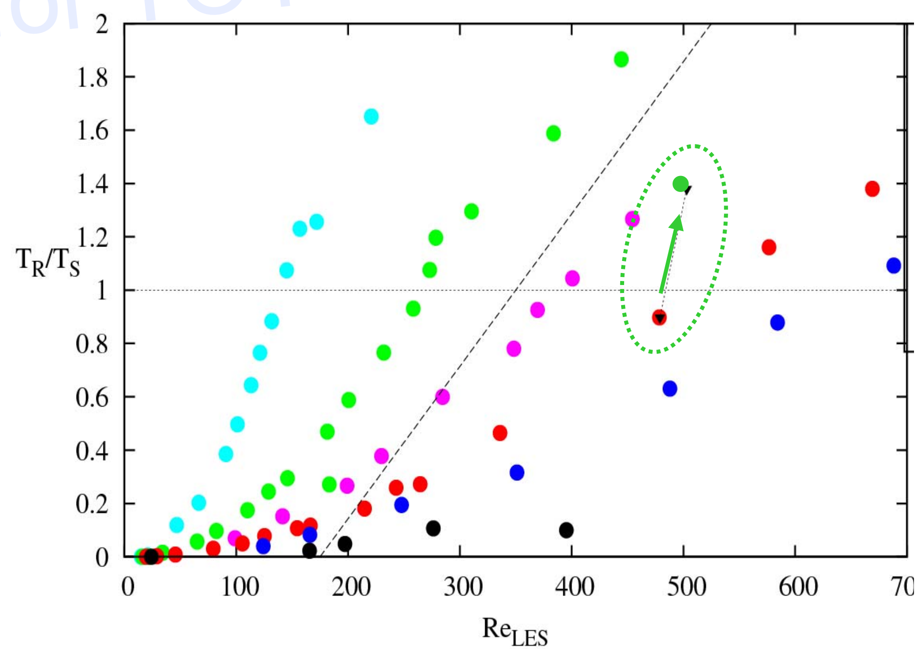
1. Wyngaard-Moeng model
2. Mean stress *only* (no fluctuations)





Removing Fluctuations in Wall Shear Stress:

- Instability is reduced by removing fluctuations in wall shear stress.
- The simulation moves farther into the high-accuracy zone.



Conclusions

- To achieve high accuracy in the near surface region, LES needs to be moved into in the high accuracy zone of the parameter space, *regardless of the SFS model.*
- The von Karman constant predicted by eddy viscosity models in HAZ is about 0.33.
- The lower wall boundary conditions becomes important when the LES is in the HAZ.

- Instability at the first grid level is improved by removing the fluctuations in the lower wall BC.
- We are exploring interaction between fluctuations in the lower boundary conditions and details of different SFS models on the accuracy of LES when in the HAZ.