Nested high-resolution large-eddy simulations in WRF

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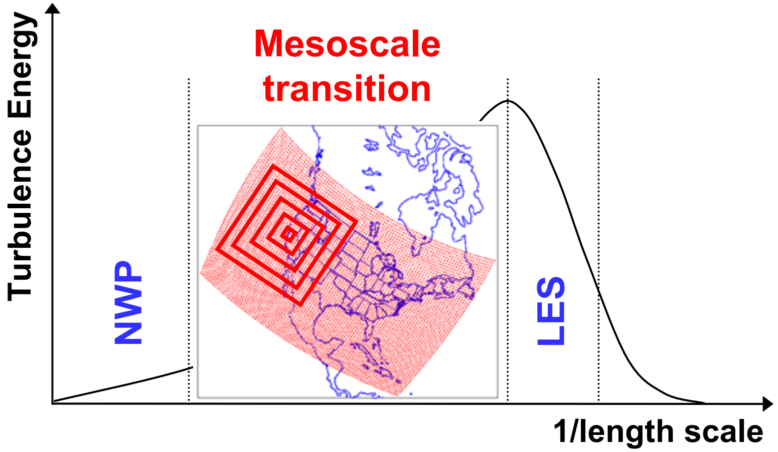
Nesting potentially provides a framework for simulations of flow across multiple spatiotemporal scales

Motivation:

- Nesting can potentially bridge the mesoscale-turbulence gap
- Multiple nests provide successive refinement of flow, inflow
- Large-eddy simulation (LES) can be conducted on innermost nest(s)



Many Challenges:

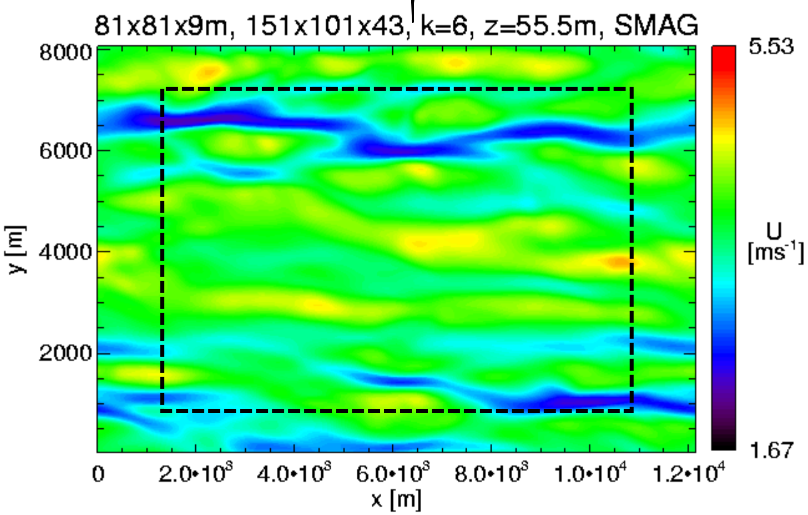
Fundamental: How to parameterize subfilter turbulence when $\Delta x_{NWP} < \Delta x_{mesh} < \Delta x_{LES}$

Technical: Issues that must be addressed to enable a multi-scale simulation capability

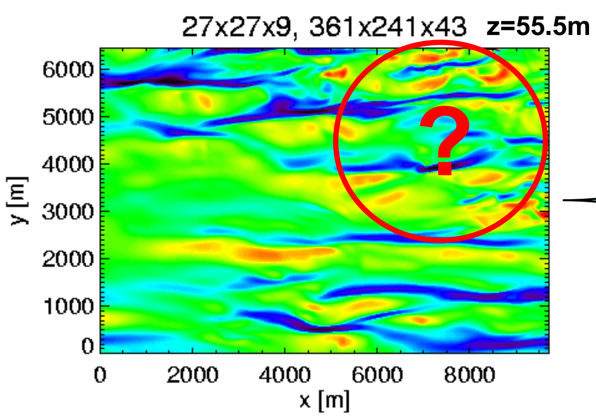
- Optimal Number of nests, Size of nests, mesh ratio (Δx_parent /Δz_child), Aspect ratio (Δx/Δz), Numerical considerations, smoothing, ramps, etc.

How does flow entering the a nest equilibrate to the finer-resolution mesh?

Nested simulations



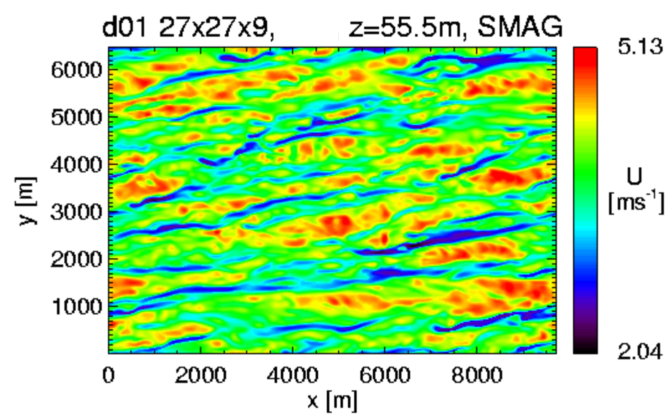
Domain 1



Domain 2 (nest)

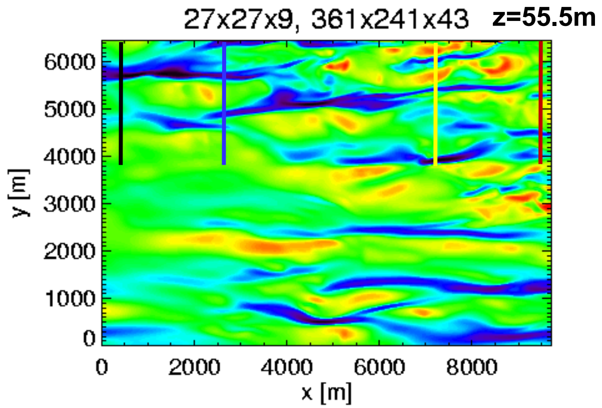
- Flat terrain, z0=0.1,
- surface stresses from log law via drag coefficient
- geostrophic forcing, $[u_g, v_g]=[5,0]$ m/s
- Neutral flow
- no feedback

Stand-alone simulations



"truth" for the nested domain

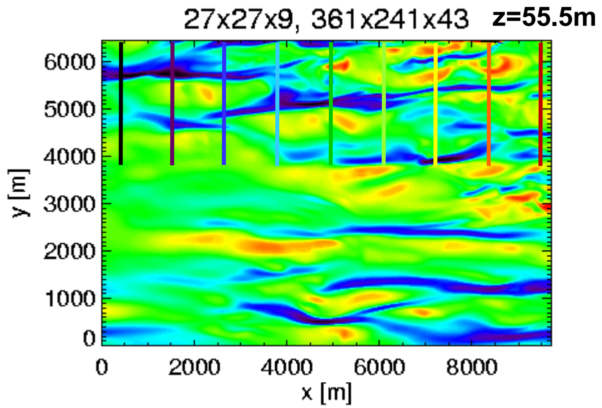
Spectra indicate the proportions of different length scales within a flow

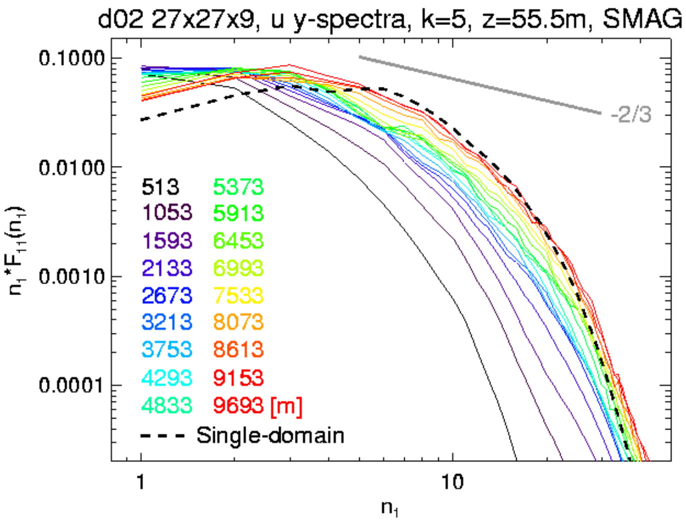


y-spectra

- **computed over 96 gridpoints in y-direction,**
- **Computed at each x-gridpoint across the domain**
- **Hanning-windowed**
- **Time averaged from 1-minute output for 240 minutes**

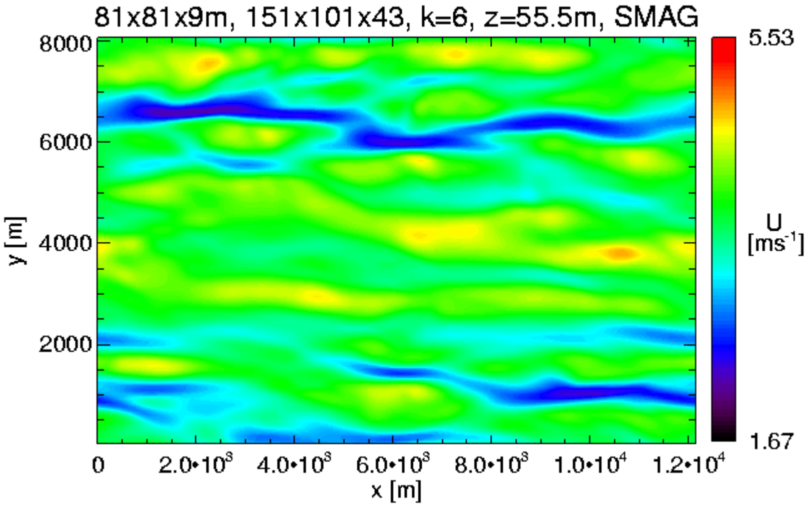
Equilibration rates for the flow can be deduced by examining how the spectra evolve as the flow crosses the nest

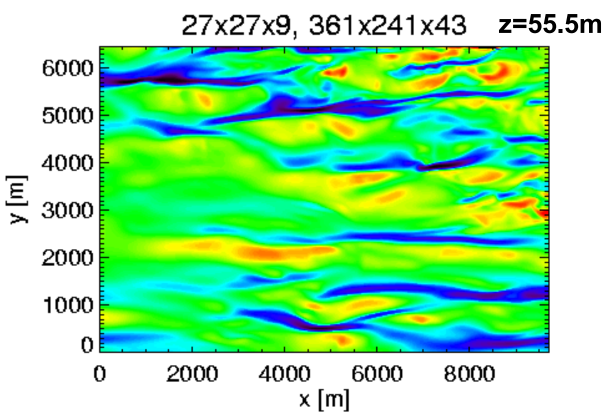




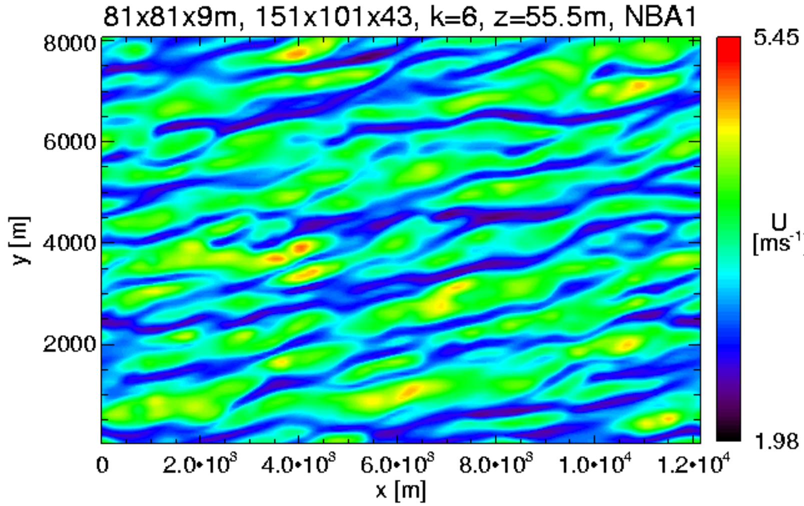
SFS turbulence model makes a significant difference in the characteristics of the resolved turbulence, especially near the surface

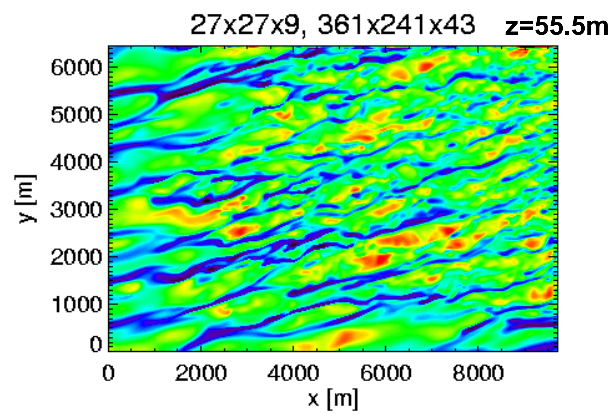
Smagorinsky



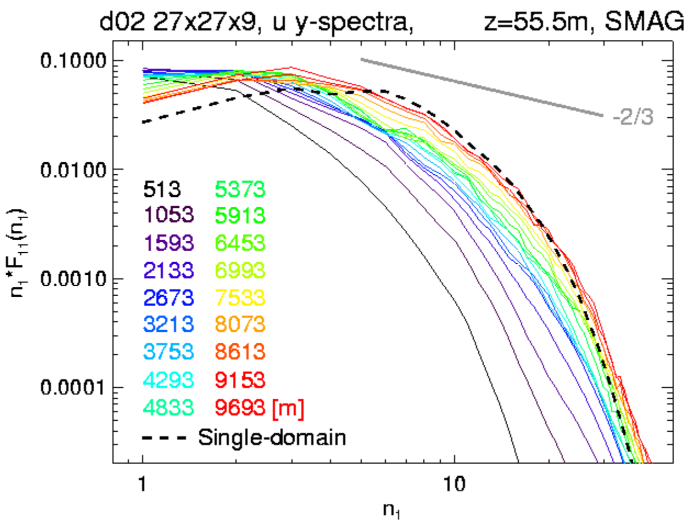


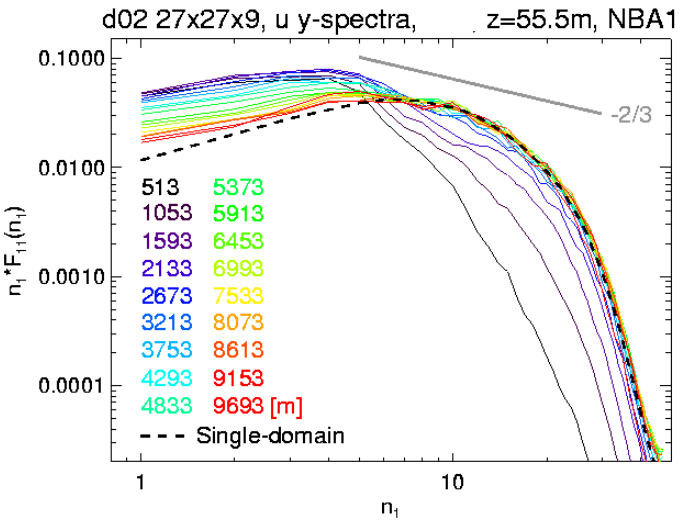
Nonlinear Backscatter and Anistropy (NBA) model (Kosović, 1997)



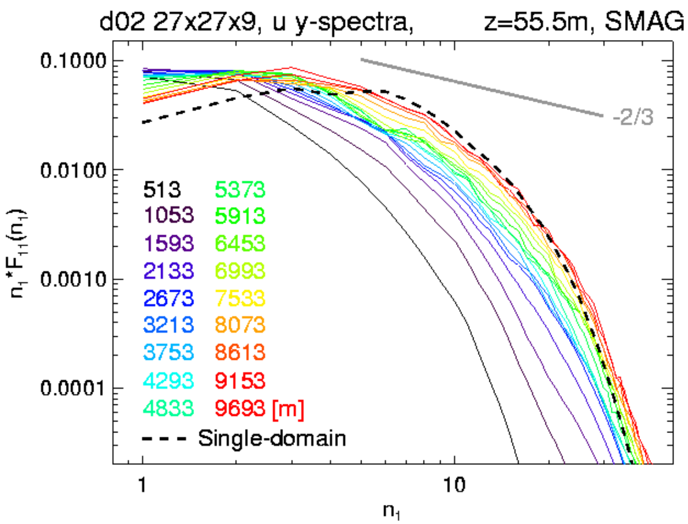


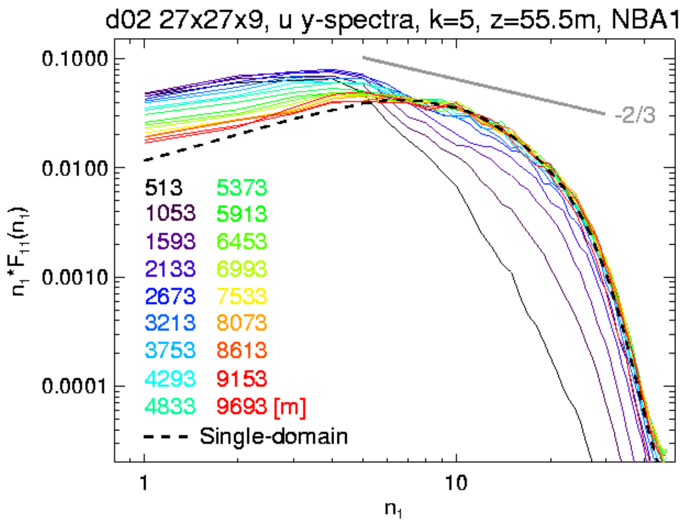
Different SFS turbulence produce significantly different spectral characteristics and equilibration behavior

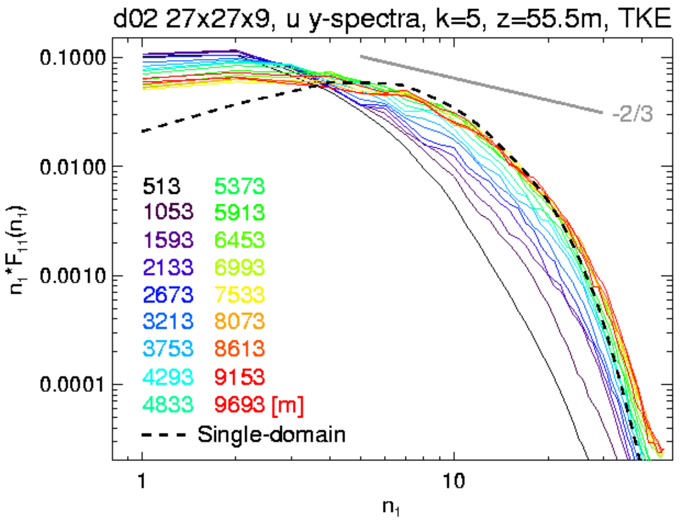




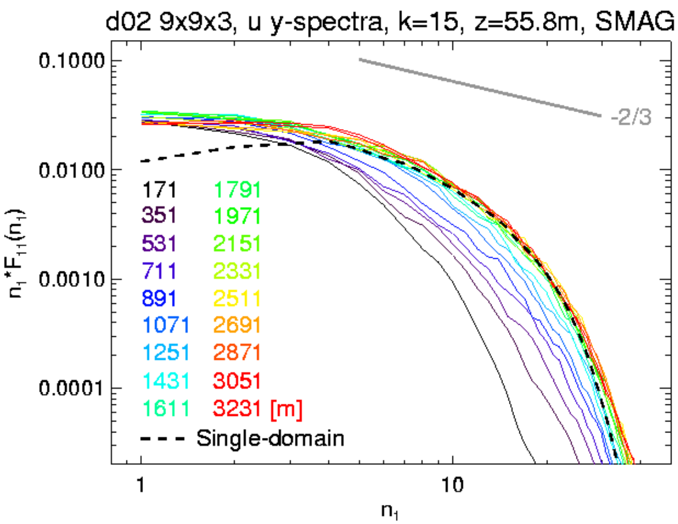
Results similar to SMAG are obtained using TKE SFS model

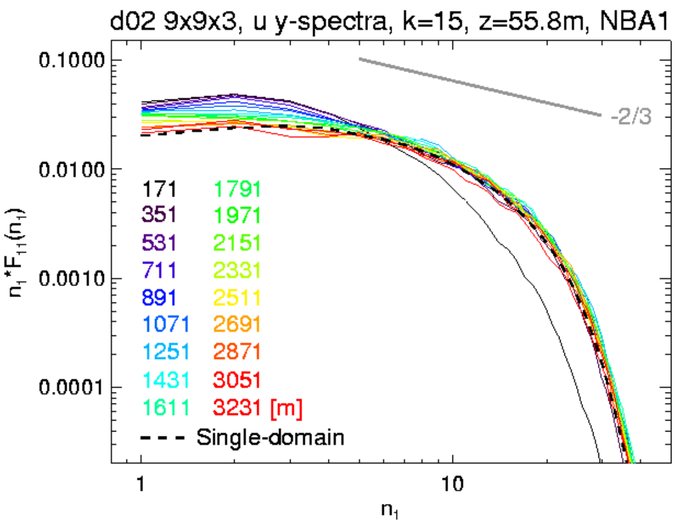






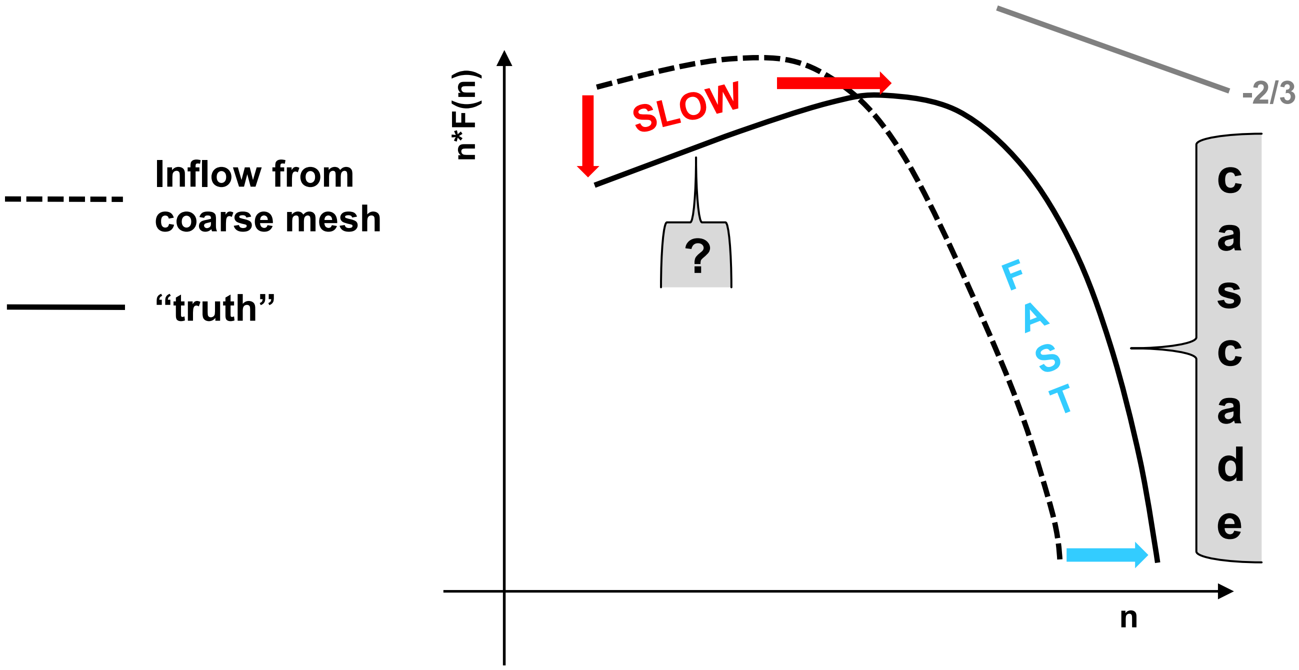
Patterns remain similar when resolution is increased by a factor of 3





Equilibration rates of different scales of flow on the finer mesh depends on spectral characteristics of inflow.

- Formation of smaller scales can be rapid
- Attenuation of larger scales, shift of spectral peak to higher frequencies, are slow
- Strong dependence on SFS model



Attenuation of the erroneously large structures flowing into the nest from the coarser simulation largely controls the equilibration process

Conclusions

- **For well-resolved turbulent inflow, the cascade to smaller-scales is fast, the breakup of larger scales is slow**
  - **Larger scales control the equilibration process**
  - **Larger-scales strongly depend on SFS model**

- **Larger scales are responsible for most of the energetics, fluxes, transport…if these scales are wrong, then what are the impacts of these errors relative to the benefits of resolving the smaller scales better?**

- **Largest-scales flowing into the nest must be correct for the nest solution to be correct**
  - ***Should* be the case for LES within LES, but we see that this is not so**

- **LES requires that the filter be well within the inertial subrange**
  - **Will not be the case for nests intermediate between mesoscale and LES**
  - **Never true near the surface**

- **SFS models require further development to address their near-surface biases**
  - **Separate near-wall stress models could help**

SMAG and NBA SFS models

Smagorinksy model (Smagorinsky, 1963; Lilly, 1967), eddy-viscosity approach:

$$\tau_{ij} = -2\vartheta_T S_{ij}$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$\vartheta_T = (C_S l)^2 \max\left[0, 2(S_{mn}S_{mn} - Pr^{-1}N^2)^{\frac{1}{2}}\right]$$

TKE model: $\vartheta_T = C_e l \sqrt{\mathrm{e}}$

Nonlinear Backscatter and Anisotropy (NBA) model (Kosović, 1997)

$$M_{ij} = -(C_S l)^2 \left\{ \begin{array}{c} 2(2S_{mn}S_{mn})^{\frac{1}{2}} S_{ij} + \\ C_1\left(S_{ik}\,S_{kj} - \frac{1}{3}S_{mn}S_{mn}\,\delta_{ij}\right) + C_2\left(S_{ik}\,R_{kj} - R_{ik}\,S_{kj}\right) \end{array} \right\}$$

$$R_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right)$$

NBA1 is based on strain-rate only, NBA2 uses SFS TKE

Each SFS model has large-scale bias near the surface, SMAG moreso