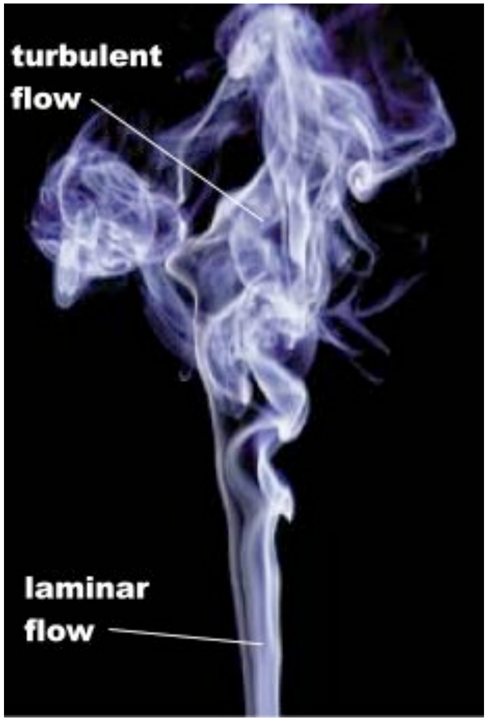
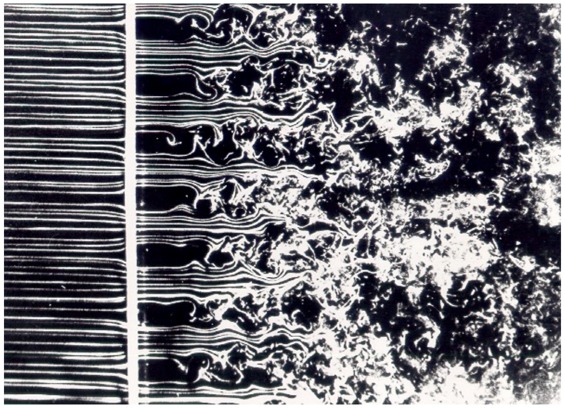
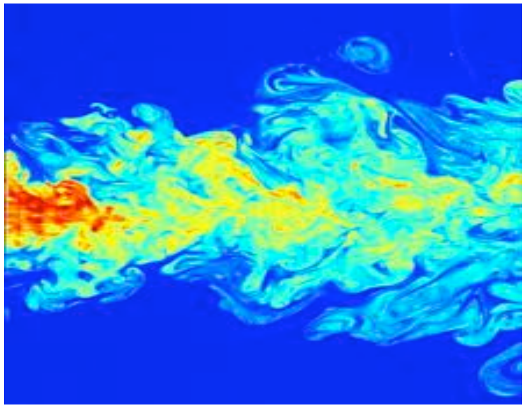
Large-Eddy Simulation of Turbulence in the PBL





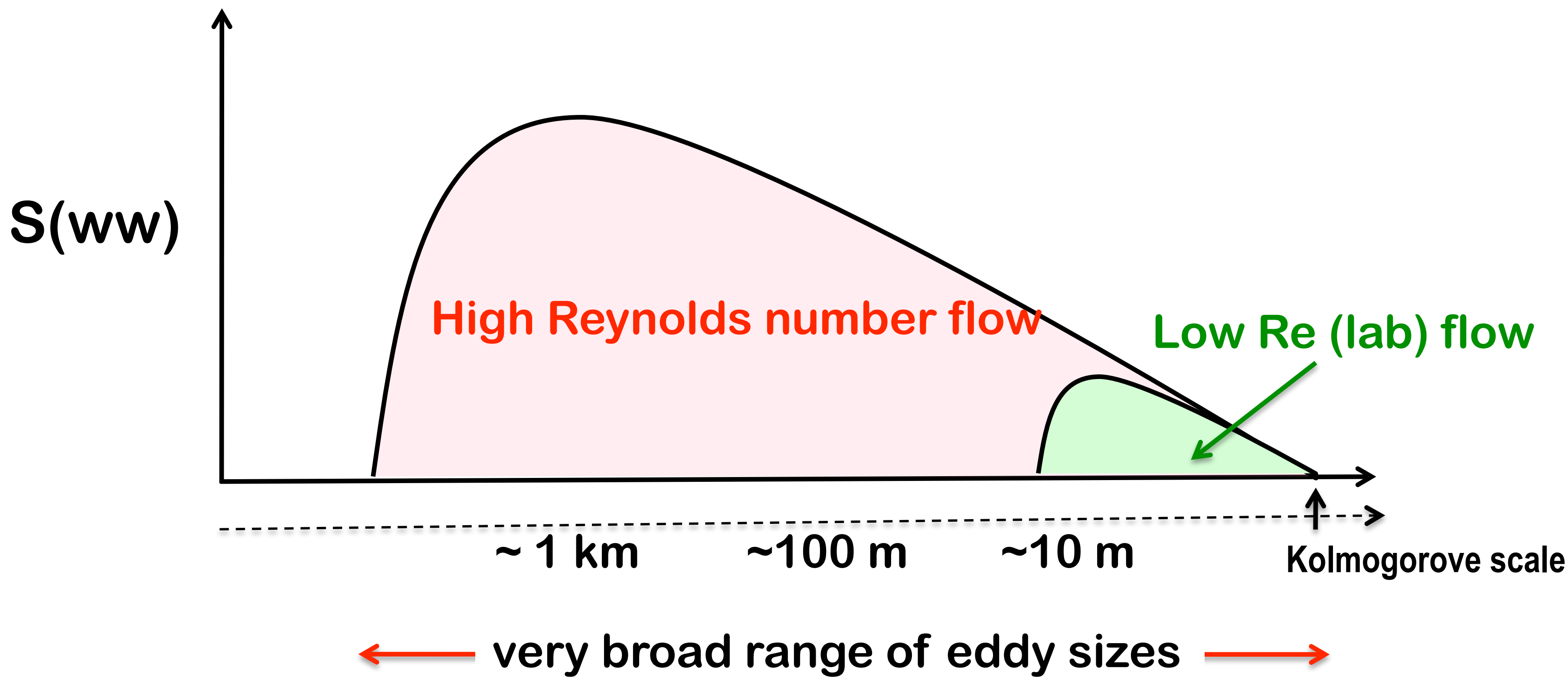


Chin-Hoh Moeng
MMM/NCAR

Few words about turbulence…

- Chaotic motion
- Known governing equation (Navier-Stokes)
- Nonlinear term >> dissipation term
- No analytical solution
- Sources of TKE: wind shear and/or buoyancy
- Highly dissipative
- Highly diffusive, very effective transport
- Smallest eddies ~ mm (Kolmogorov length scale)
- Largest eddies ~ depend on Reynolds number

Power spectrum of turbulent flow



What is Large Eddy Simulation ?

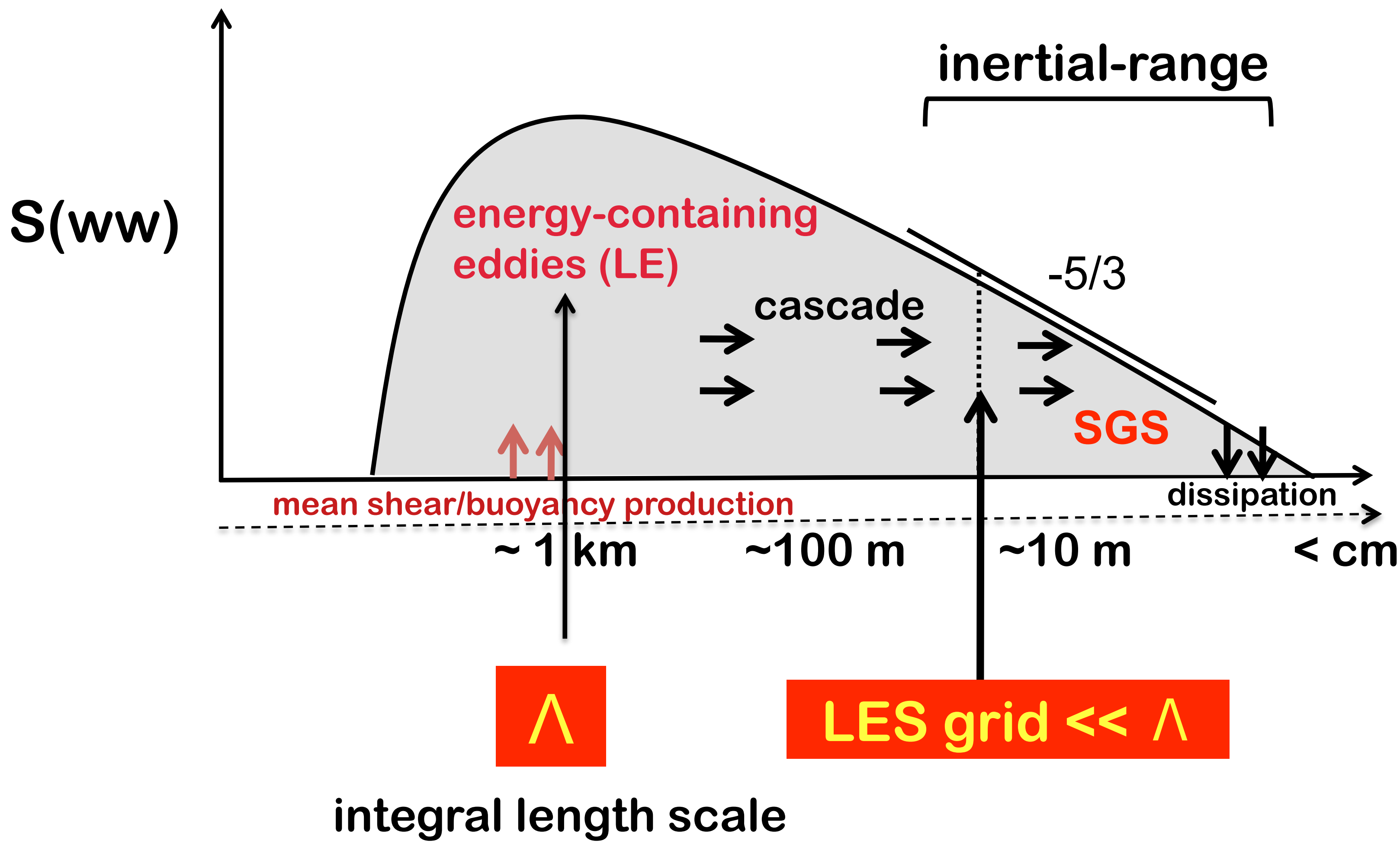
Turbulent flow field

large eddies (LE); resolved

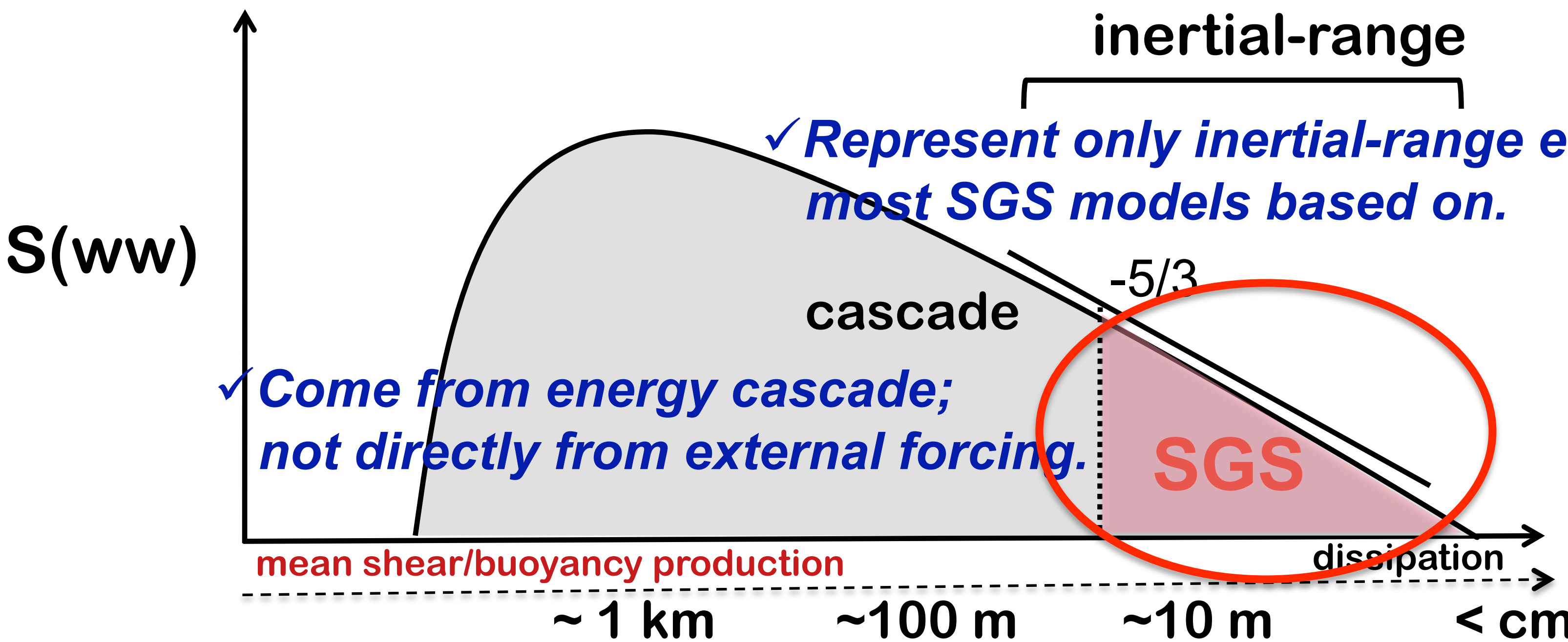
small eddies; modeled

To split the flow, apply a low-pass filter (or average over grid volume) to governing equations.

Dynamics of turbulence in the PBL



Sub-Grid Scale (SGS) in LES



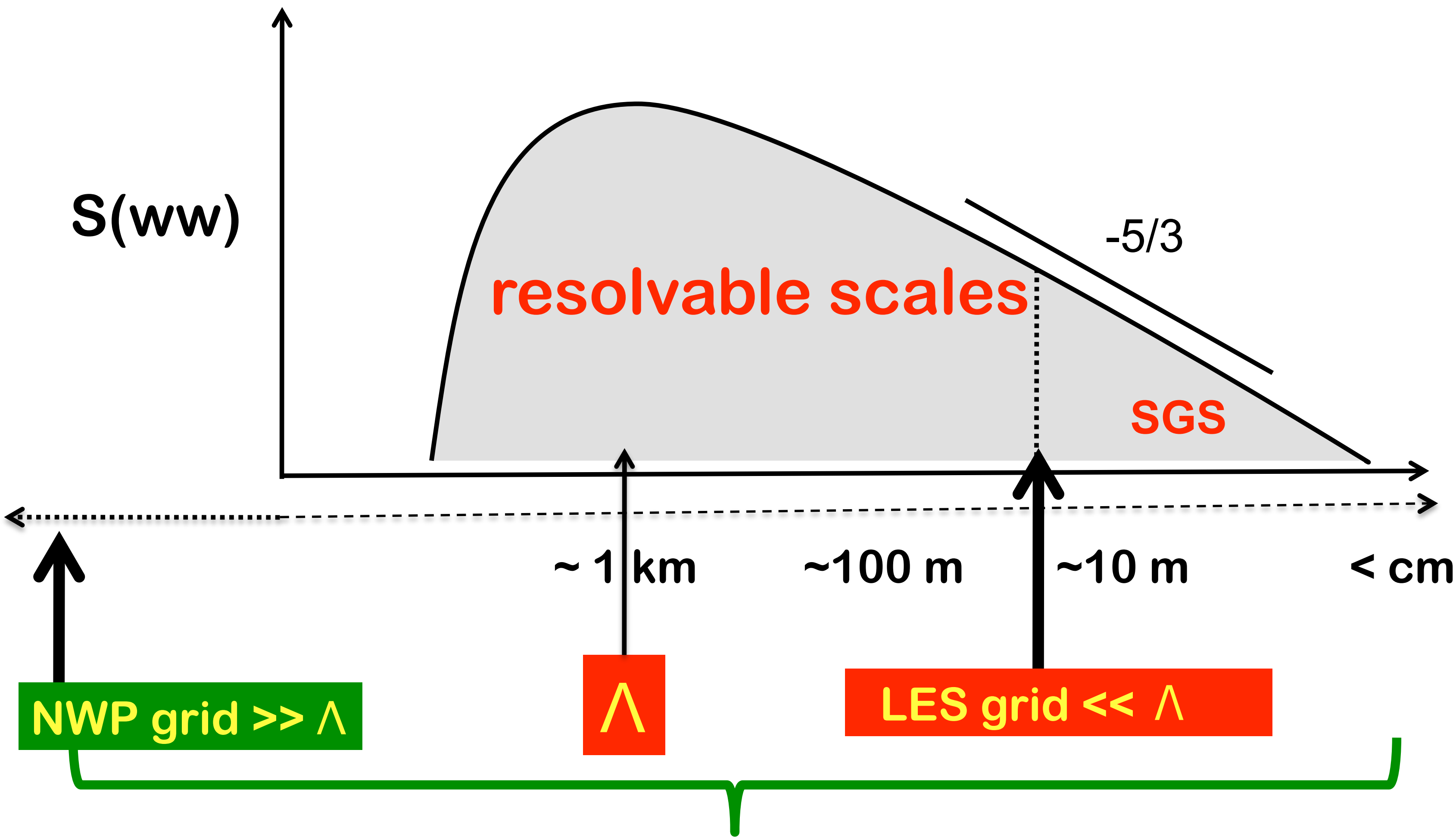
✓*Represent only inertial-range eddies; most SGS models based on.*

✓*Come from energy cascade; not directly from external forcing.*

✓*Contain little amount of TKE and fluxes.*

✓***Don't (usually) affect LES solutions.***

Ensemble statistics model vs. LES

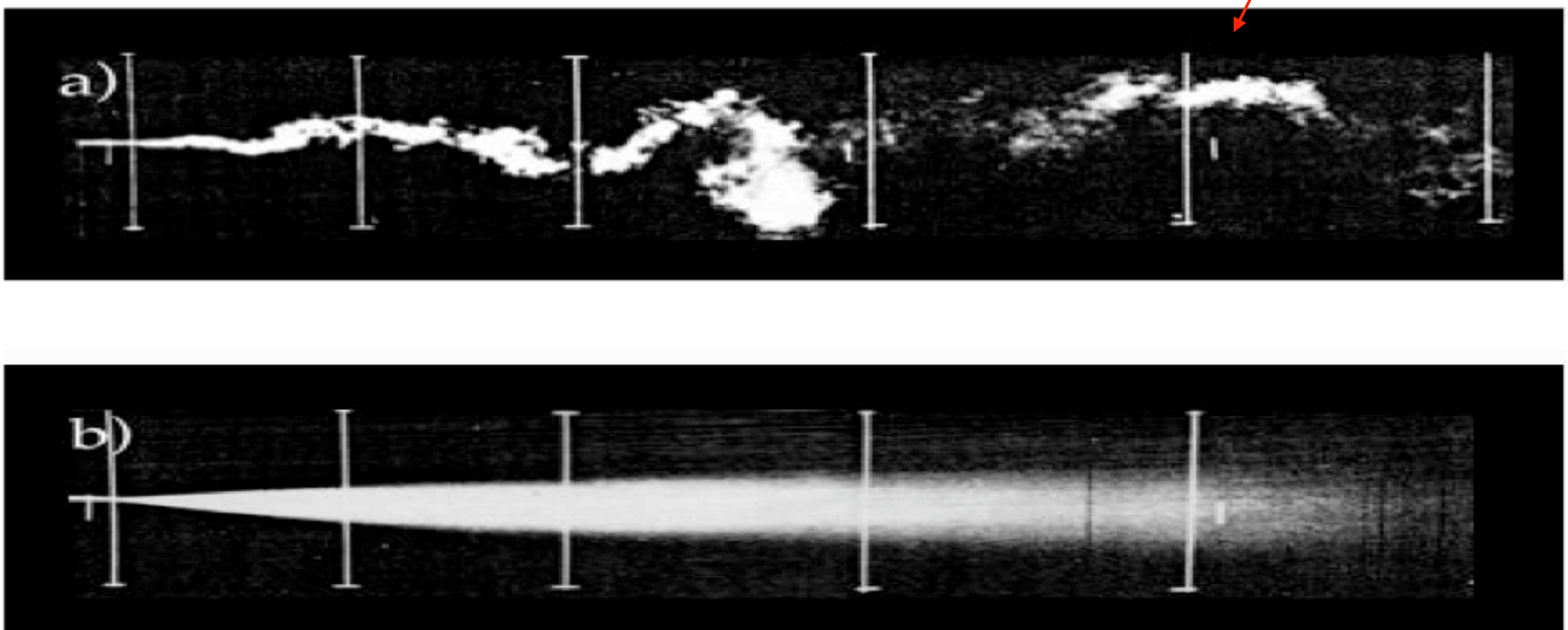


SGS: All turbulent motions are parameterized by an <u>ensemble statistical model</u> (e.g., YSU or MYJ PBL scheme).

Ensemble-mean statistics

Smoke visualization downstream of a point source in a wind tunnel

Instantaneous plume
(short time exposure)



Ensemble average plume
(long time exposure)

An example of PBL schemes:

A theory to estimate the ensemble-mean q-flux:

$$\overline{wq} = -K\left(\frac{\partial \overline{q}}{\partial z} - \gamma\right)$$

Also need closure assumptions for K and γ

LES is based on Navier-Stokes eq:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = \frac{g_i}{T_0}\theta - \frac{1}{\rho}\frac{\partial p}{\partial x_i} + \upsilon \frac{\partial^2 u_i}{\partial x_j^{\ 2}}$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = \frac{g_i}{T_0}\tilde{\theta} - \frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i} - \frac{\partial(\widetilde{u_i u_j} - \tilde{u}_i\tilde{u}_j)}{\partial x_j} + \upsilon \frac{\partial^2 \tilde{u}_i}{\partial x_j^{\ 2}}$$

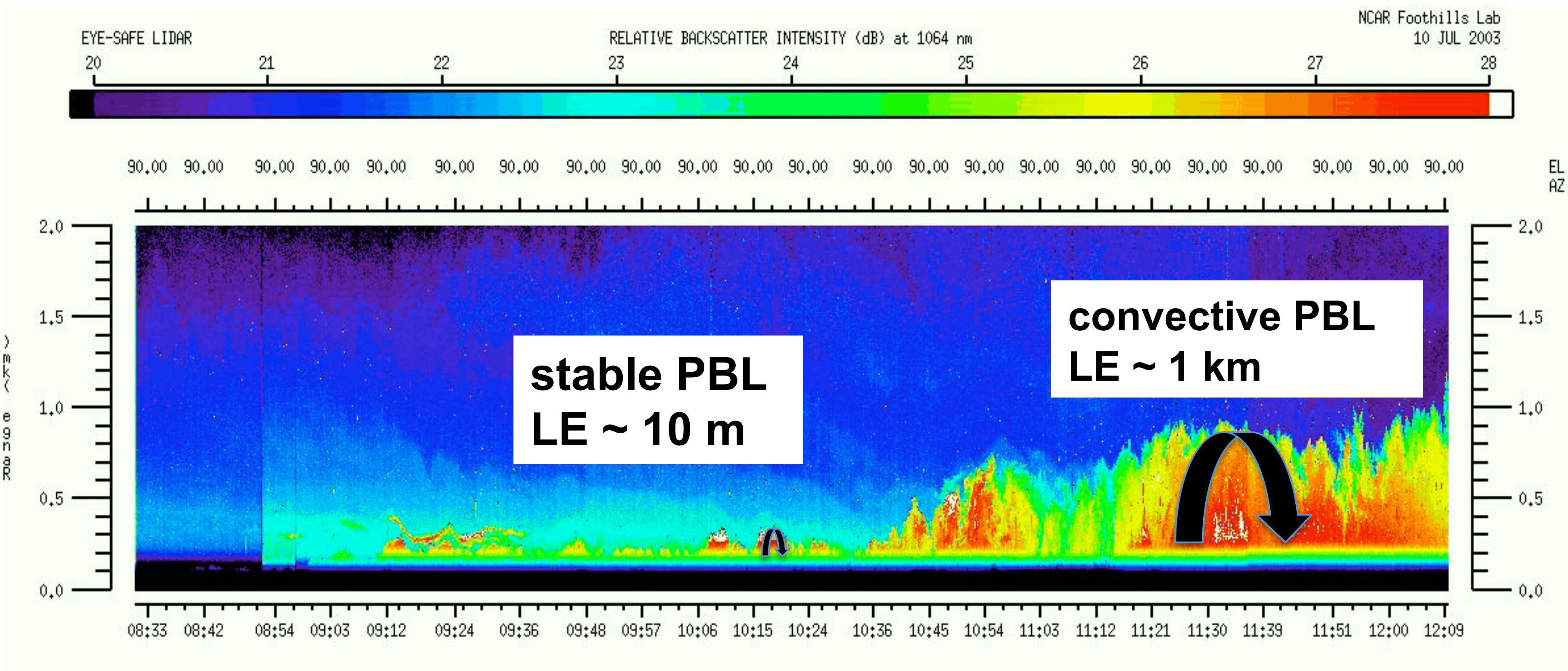
$\tilde{u}_i$: velocity averaged over LES grid volume

SGS (need closure)

$\overline{wq}$ **= resolvable flux + SGS flux**

What's the proper grid spacing for LES?

➢ It depends on the sizes of "LE".



(Lidar obs. from Shane Major)

The premise of LES:

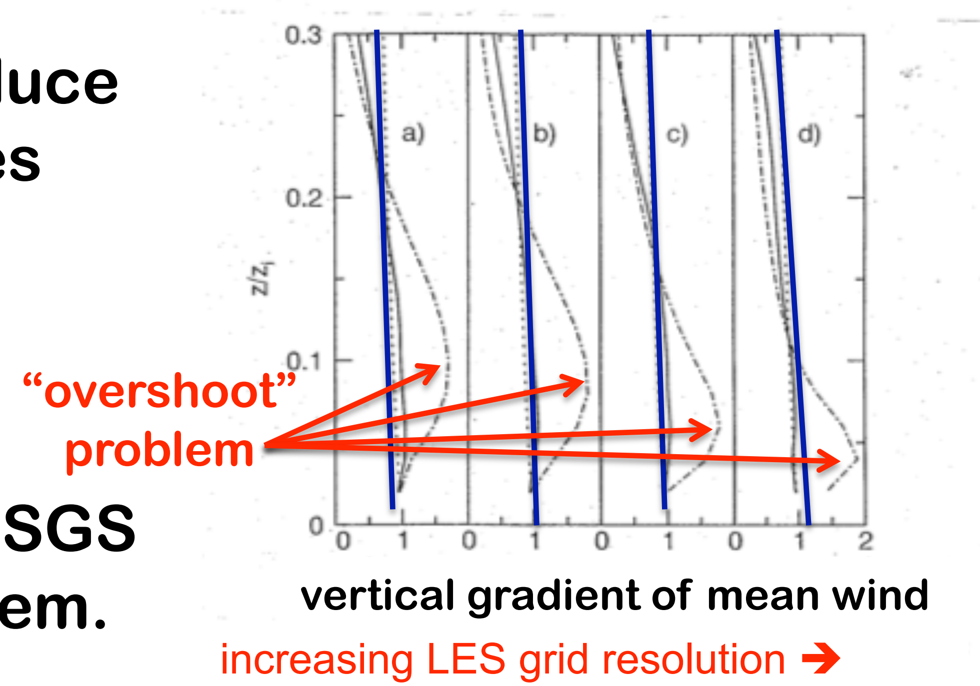
- Large eddies, with most energy and fluxes, are explicitly calculated.
- Small eddies, consisting of little energy and fluxes, are parameterized based on inertial-range theory.

➡ LES is ideal for problems that are insensitive to small eddies.

A long-standing problem with LES:

✓ **Near surface, eddies are small, under-resolved in LESs.**

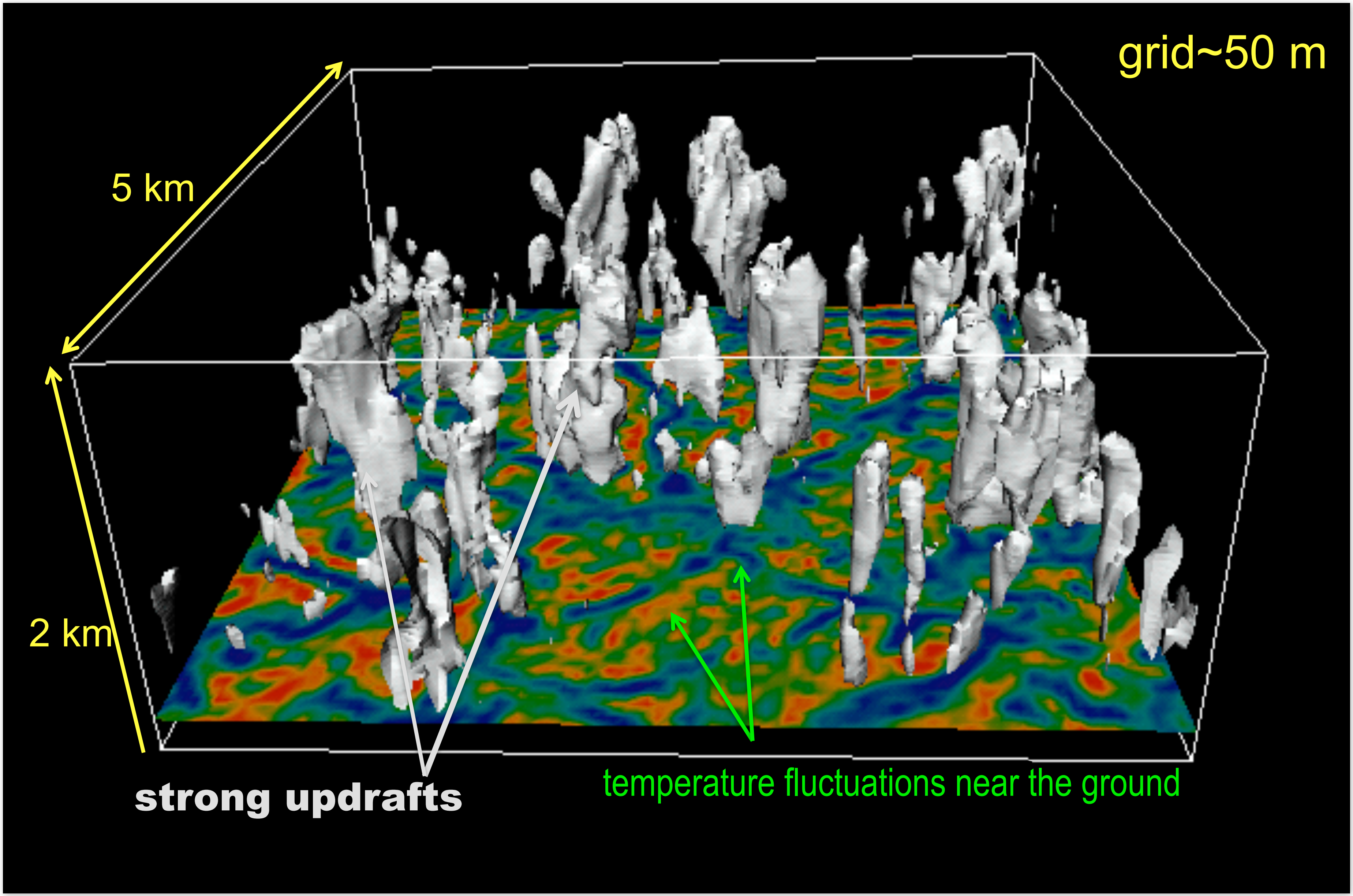
✓ **Most LESs cannot reproduce the law-of-the-wall profiles (for neutral/stable PBLs).**



(from Sullivan et al 1994)

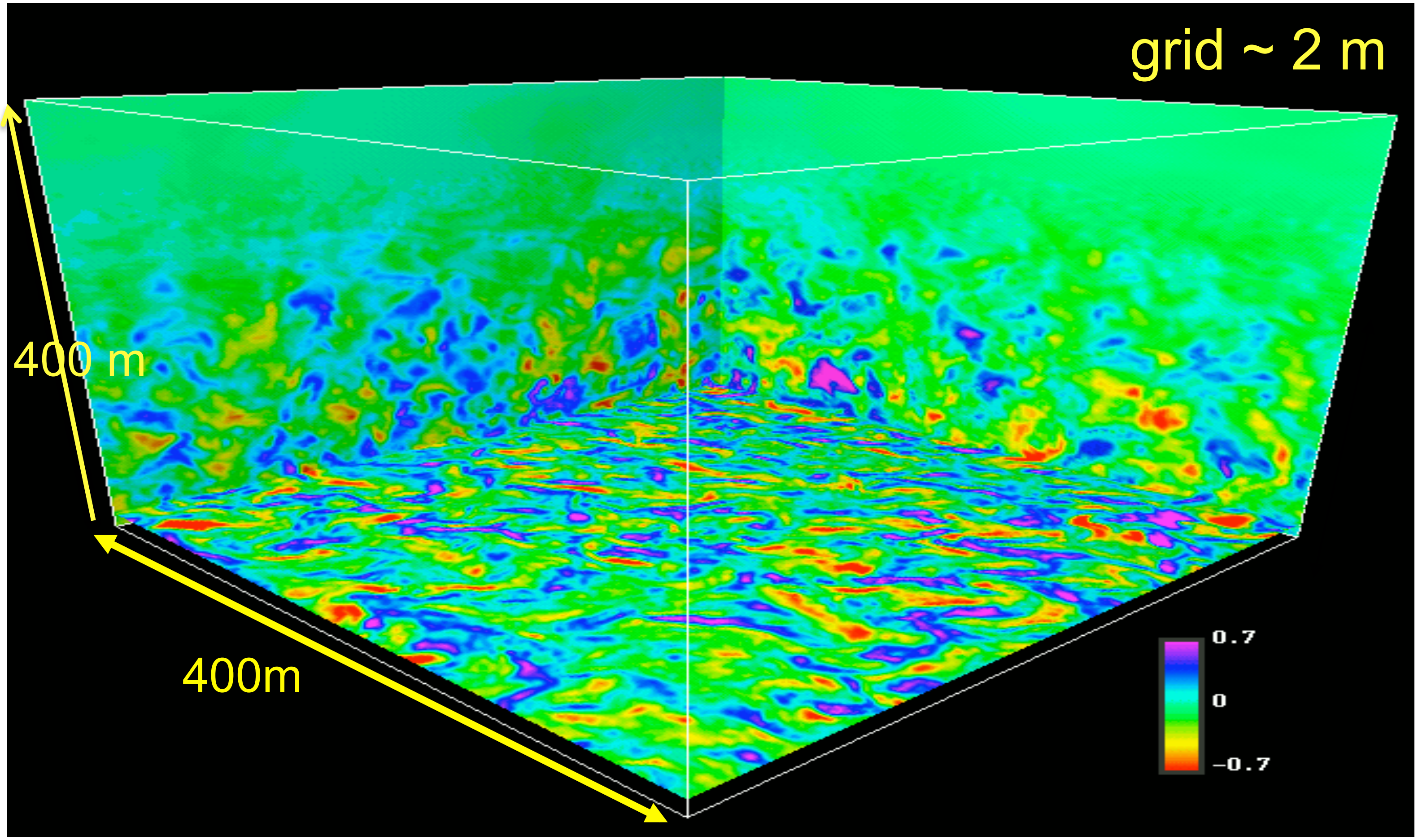
✓ **Many studies to improve SGS models to ease the problem.**

LES Solution of a Convective Boundary Layer (CBL)



LES of a Stable Boundary Layer

vertical velocity fluctuations

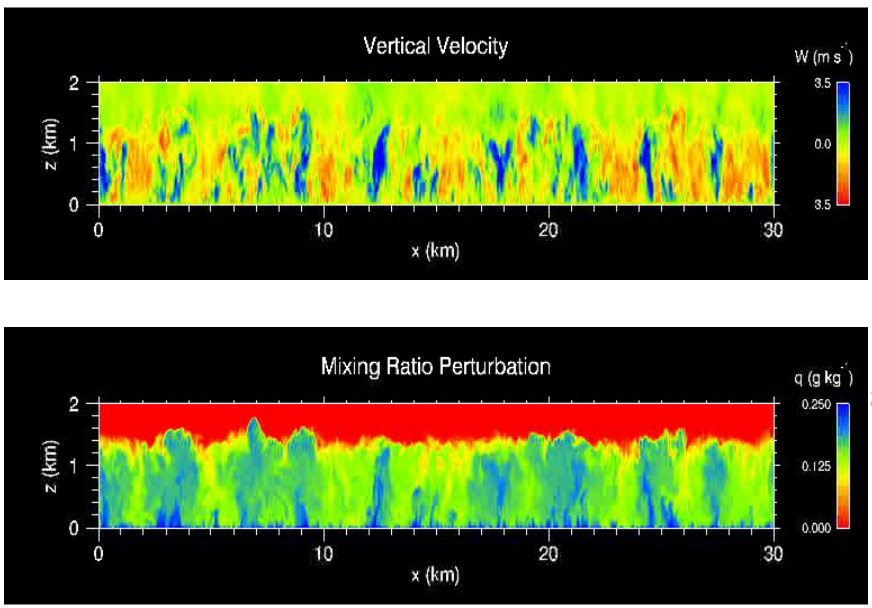


- **The PBL is shallow.**
- **Turbulence is weak and localized.**

Courtesy Peter Sullivan

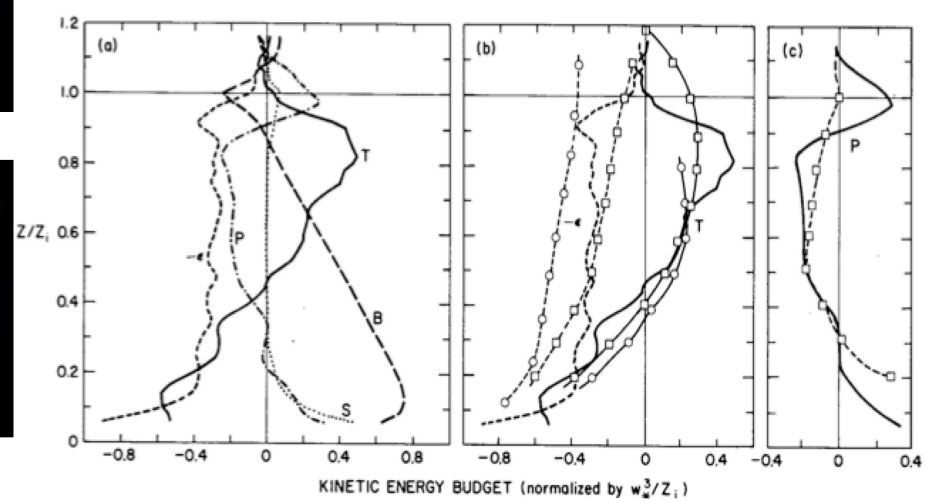
LES-generated flow fields:

- LES solutions are chaotic, random motions. Individual events have no physical meaning.



Courtesy Ned Patton

- Only statistics matter. Compute statistics.



TKE budget (compared to obs./lab.)

Why and when to do LES?

- **To understand turbulence structure.**
- **To acquire more accurate estimates of turbulence statistics.**
- **To serve as a surrogate to develop/calibrate PBL schemes---for conditions where conventional PBL schemes don't apply.**

Though LES has become a useful tool for PBL research…

So far it has been mostly applied to idealized PBLs: flat or periodic surfaces.

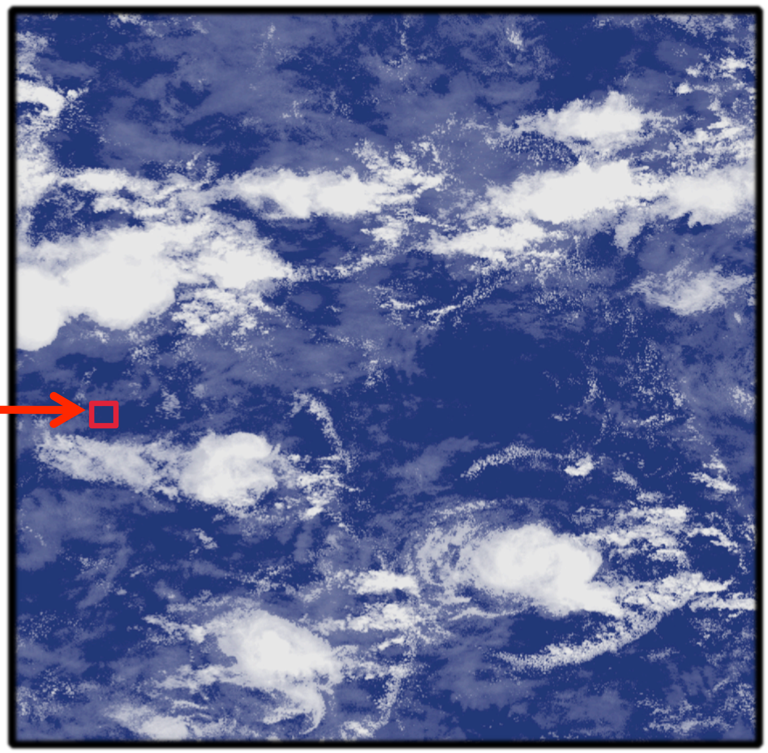
Real-world PBLs are complicated…




Challenges ahead: Applications of LES towards “real-world” problems.

Approach 1 to include mesoscale & turb.:
greatly extend the LES domain

typical LES domain!



204.8 km

(~ a GCM grid cell)

Example:

Giga-LES of a tropical deep convection system

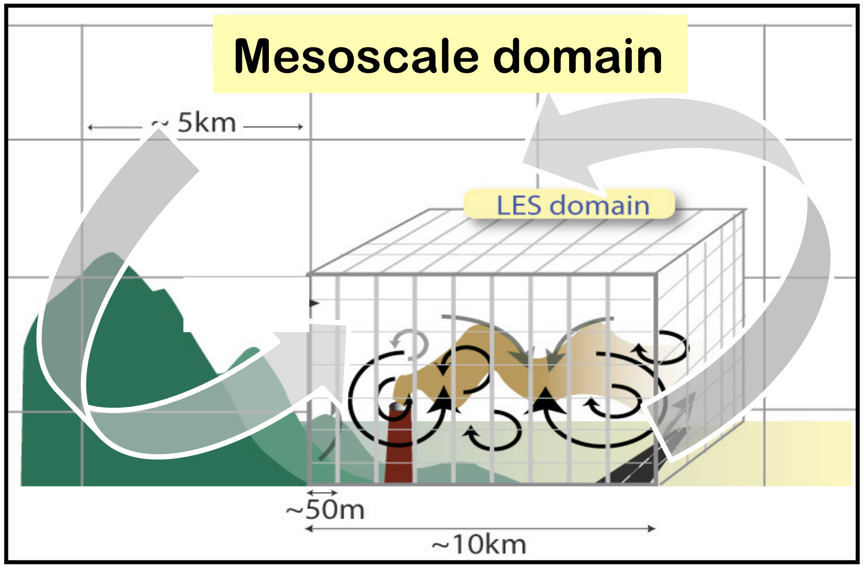
horizontal grid: 100 m

(2048 x 2048 x 256 grid points)

Khairoutdinov et al (2009; JAMES)

- Computationally costly
- Periodic BC in x-y

Approach 2 to include mesoscale:
Nest LES inside a weather model



- *replace periodic B.C.*
- *include effects from weather/complex terrain*

But there are issues:

1. **Spin-up of turbulence at inflow boundaries**
2. **Different SGS physics between domains**

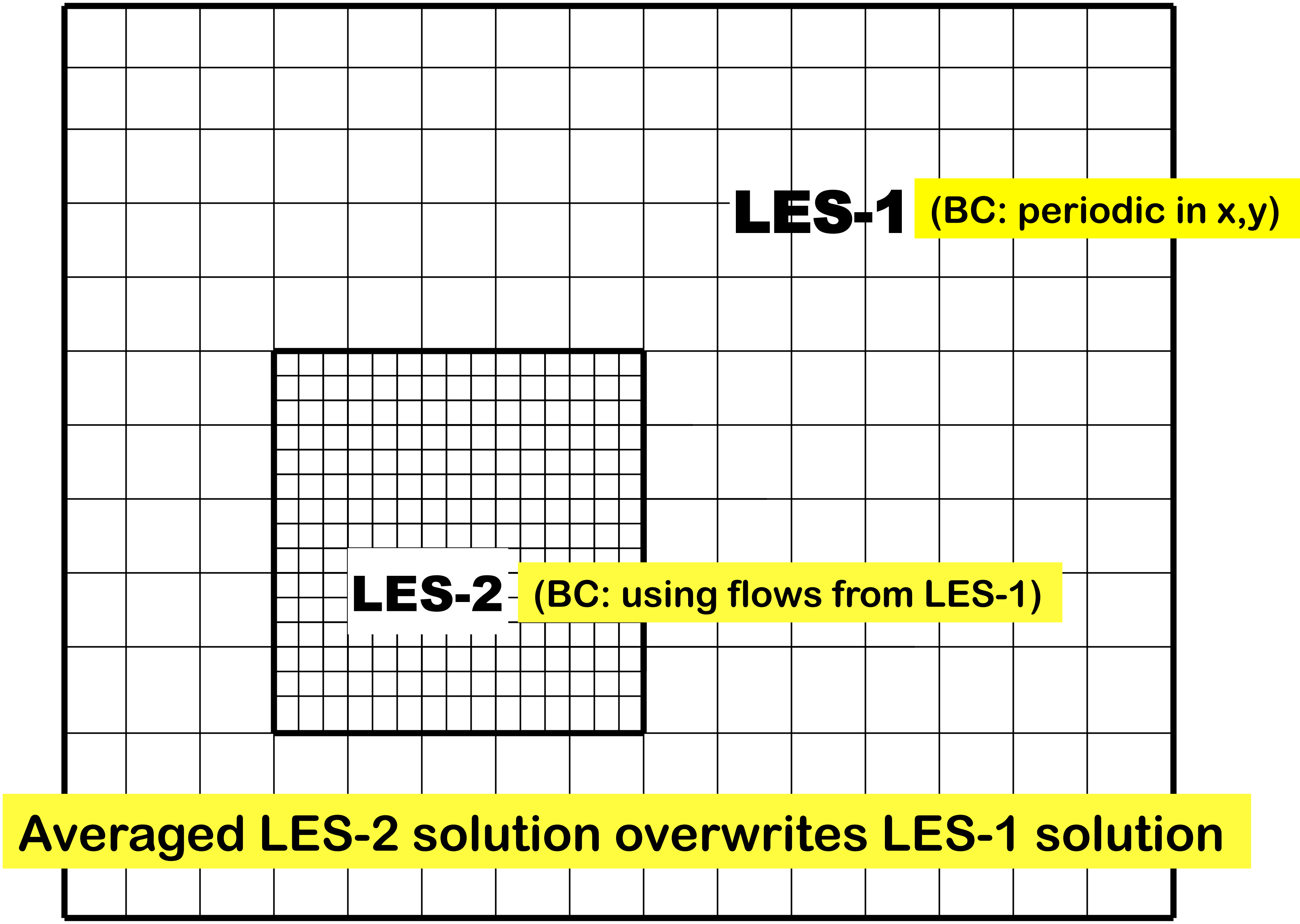
Simple experiment using WRF-LES

(Moeng et al. 2007, MWR)

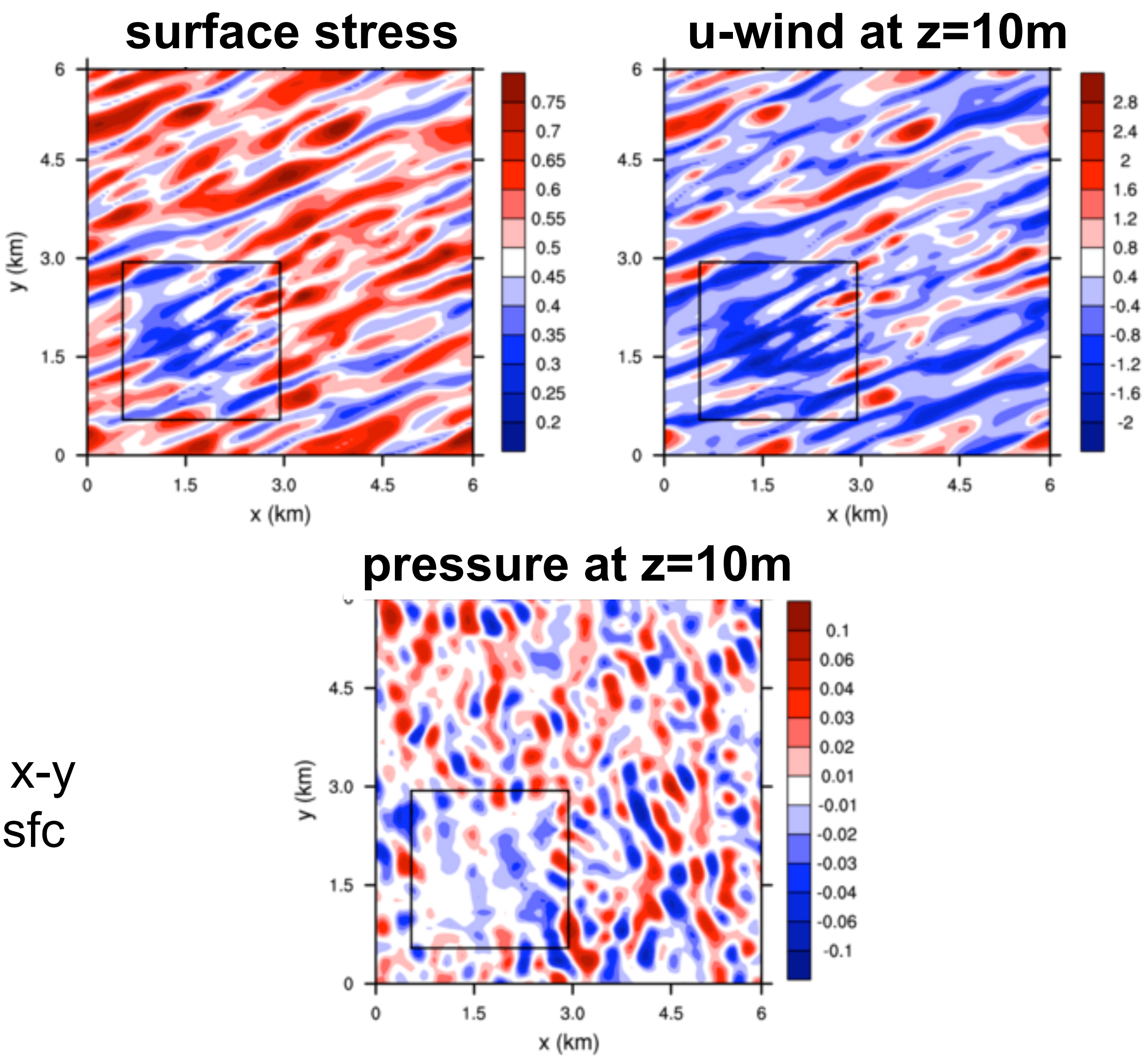
- ❑ Outer domain: coarse-grid LES-1
- ❑ Inner domain : fine-grid LES-2
- ❑ Same forcing and environment
- ❑ Well-studied, idealized PBL cases

➡ ***Would both LESs yield the same (known) statistics (resolved + SGS) ?***

LES-in-LES experiment (WRF two-way nesting)

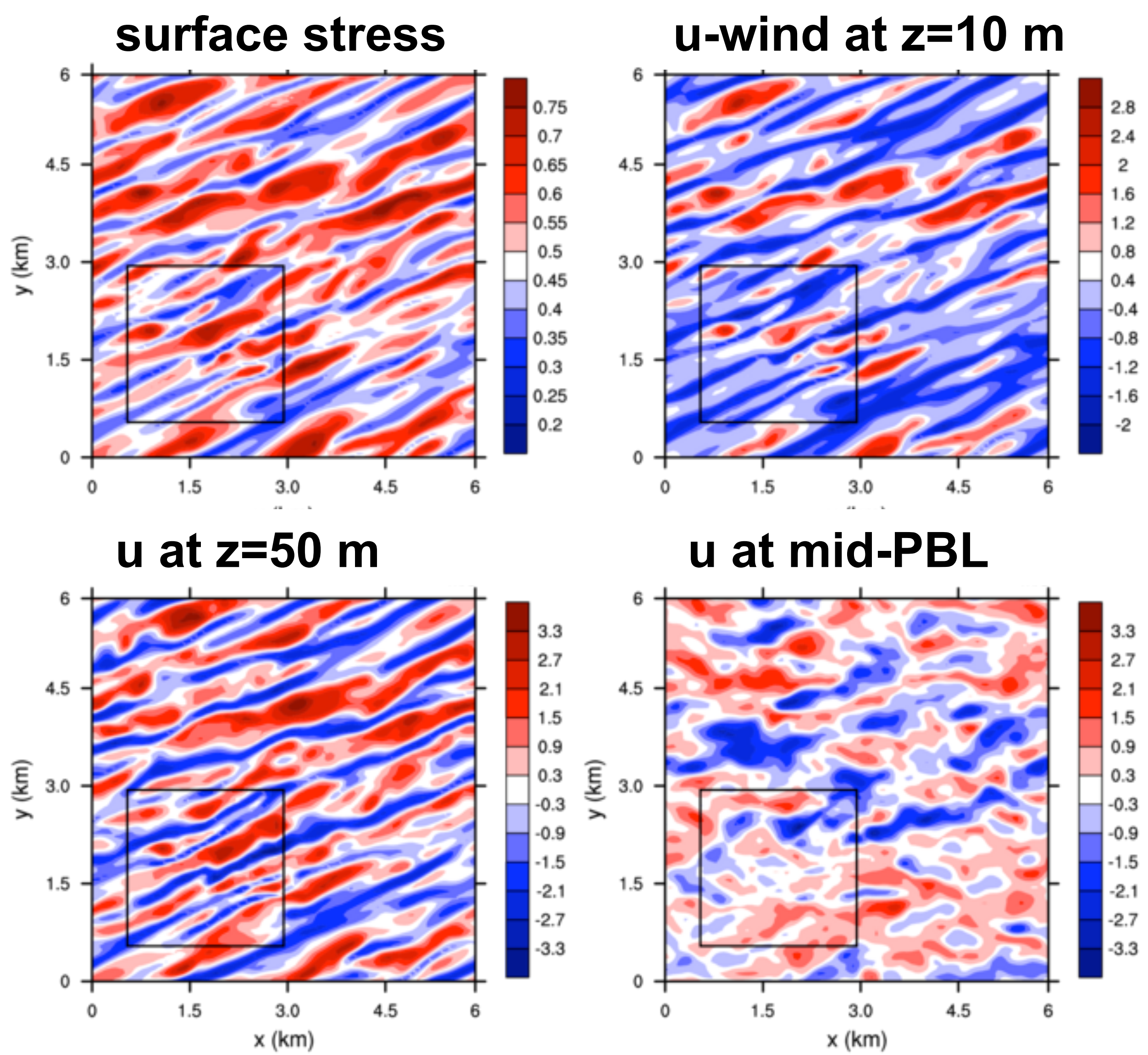


Smagorinsky-Deardorff SGS model: Bias in surface stress and near-surface wind



contours in x-y plane near sfc

A two-part (hybrid) SGS model: Near-wall bias reduced or disappeared



LES-in-LES experiments show:

Turbulent motions flow smoothly across the nest boundaries.

Statistics of both LES domains behave similarly and reasonably.

Need a proper SGS model to obtain consistent flows across domains.

Challenge: LES-in-Mesoscale domains, blend in a PBL scheme with LES turb. (e.g., Zhu et al. 2010 JGR) summary 1

- **Most existing LES codes use periodic lateral BCs, thus may not be applicable to complex PBLs.**

- **WRF-LES: a good candidate for real-world PBL applications:**
  - ***available input data*:**
    -terrain, land properties, meteorol. conditions
  - ***two-way, multiple-layer horizontal nesting capability***

summary 2

Few words about using WRF-LES…

1. Must be 3D.
2. Grid spacing must be << energy-containing eddies (to resolve “large eddies”).
3. Set domain to be ~ 5 times of PBL height zi and vertical domain ~ 2 zi.
4. Turn off PBL schemes; use 3D diffusion (the TKE diffusion scheme).
5. Test a well-documented PBL case first.
6. For statistical analysis, need to define averaging & fluctuations are along z (not p).
7. If do nesting, be careful about spin-up process.

SUMMARY

- **WRF-LES a potentially useful tool for studying real-world PBLs:**
  - urban air pollution
  - local wind fluctuations at wind farms
  - frost formation (agriculture; military)
  - effect of local land use

- **Nest LES inside WRF mesoscale domain remains a challenge.**
  - issues: spin-up at inflow bndy & SGS physics

- **Only <u>statistics</u> matter with LES solutions.**