University of Connecticut LES
(some) GABLS4 results and
perspectives on modeling of stable boundary layers

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GABLS4 Workshop

September 13, 2018

Introduction

- Stable boundary layers (SBL) are ubiquitous
  - Typically forming at night and in polar regions throughout the day
- The dynamics of the SBL are poorly understood, with implications for night forecasts, e.g., of temperature and fog, and pollution dispersion
- LES remains challenging
  - Stable stratification leads to reduction of the energetic scales and large anisotropy

image by R. Beare from Fernando & Weil (2010)

- LES modeling challenges are often attributed to inadequacies of subgrid-scale (SGS) models
  - Most LES investigations employ sophisticated SGS models
  - Simple SGS models, e.g., the constant coefficient Smagorinsky–Lilly, are not typically used (in contrast to convective flows)
- Hypothesis: numerical model error is key for accurate predictions
  - Strong integration between the discrete approximation (order of accuracy or resolving power, grid spacing) and the physical model (turbulence closure)

Problem description

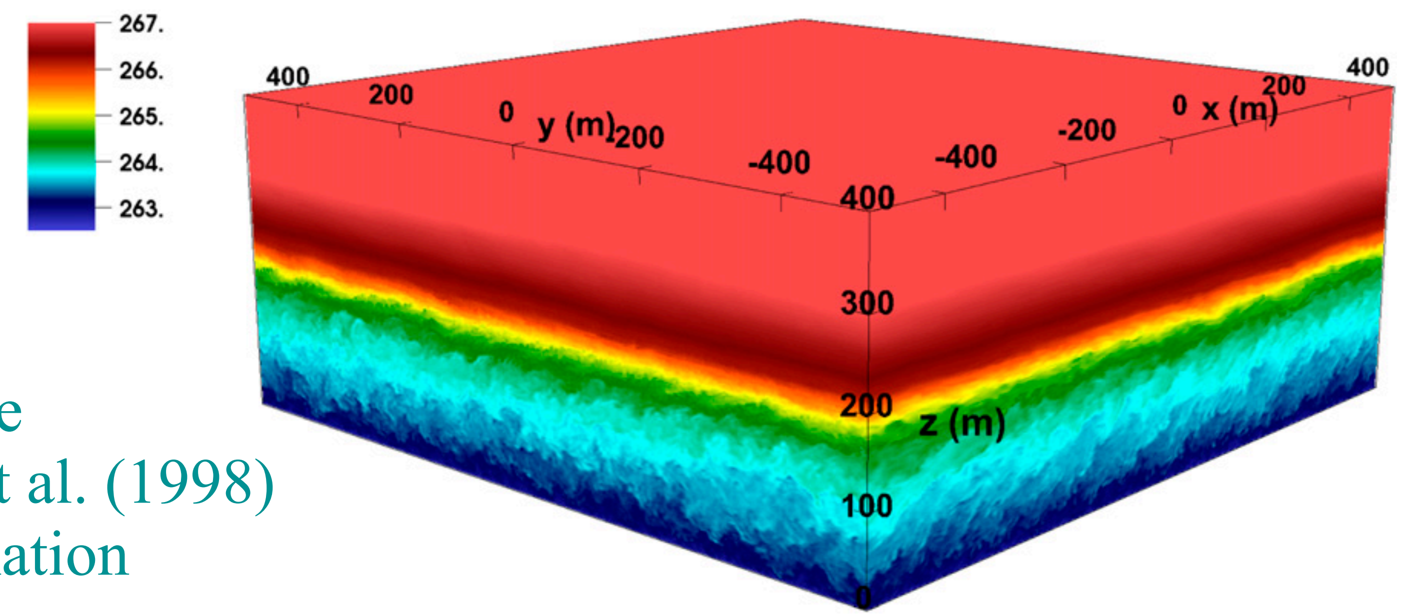
- Moderately stable atmospheric boundary layer case of Beare et al. (2004)
- Governing equations (anelastic approximation)
  - Mass: $$\frac{\partial \bar{\rho}_0 \tilde{u}_i}{\partial x_i} = 0$$
  - Momentum: $$\frac{\partial \bar{\rho}_0 \tilde{u}_i}{\partial t} + \frac{\partial (\bar{\rho}_0 \tilde{u}_i \tilde{u}_j)}{\partial x_j} = -\theta_0 \bar{\rho}_0 \frac{\partial \bar{\pi}_2}{\partial x_i} + \delta_{i3} g \frac{\bar{\rho}_0 (\tilde{\theta} - \langle \tilde{\theta} \rangle_x)}{\theta_0} - \epsilon_{ijk} \bar{\rho}_0 f_j (\tilde{u}_k - u_{g,k}) - \frac{\partial \tau_{ij}}{\partial x_j}$$
  - Potential temperature: $$\frac{\partial \bar{\rho}_0 \tilde{\theta}}{\partial t} + \frac{\partial \bar{\rho}_0 \tilde{\theta} \tilde{u}_j}{\partial x_j} = -\frac{\partial \sigma_j}{\partial x_j}$$
- Subgrid scale models
  - Smagorinsky–Lilly $$\tau_{ij} = -2 \bar{\rho}_0 \nu_t \tilde{D}_{ij} \qquad \sigma_j = -\bar{\rho}_0 \frac{\nu_t}{\mathrm{Pr}_t}$$

    eddy diffusivity: $\nu_t = \Delta^2 |\tilde{D}| f_m(\mathrm{Ri})$, where $\Delta = C_s \Delta x$ is the SGS eddy scale
  - Buoyancy adjusted stretched vortex model (Chung & Matheou 2014) is used as reference
- Surface cooling rate of 0.25 K/h
  - Surface fluxes computed dynamically using Monin–Obukhov similarity theory (MOST)
- Periodic boundary conditions in the horizontal and sponge layer at domain top
- Flow attains a stationary state after 8 hours

Parametric study

- Smagorinsky model constant
  - $C_s = 0.10 - 0.24$, with 0.01 increments
  - Theoretical value $C_s \approx 0.18$
- Advection scheme
  - Fully conservative non-dissipative family of schemes of Morinishi et al. (1998) adapted to the anelastic approximation
  - Second-, fourth- and sixth-order approximations
- Grid resolution
  - $\Delta x = 4 - 8$ m, with 1 m increments (5 values)
  - All runs have 128×128 grid points in the horizontal and 400 m vertical domains

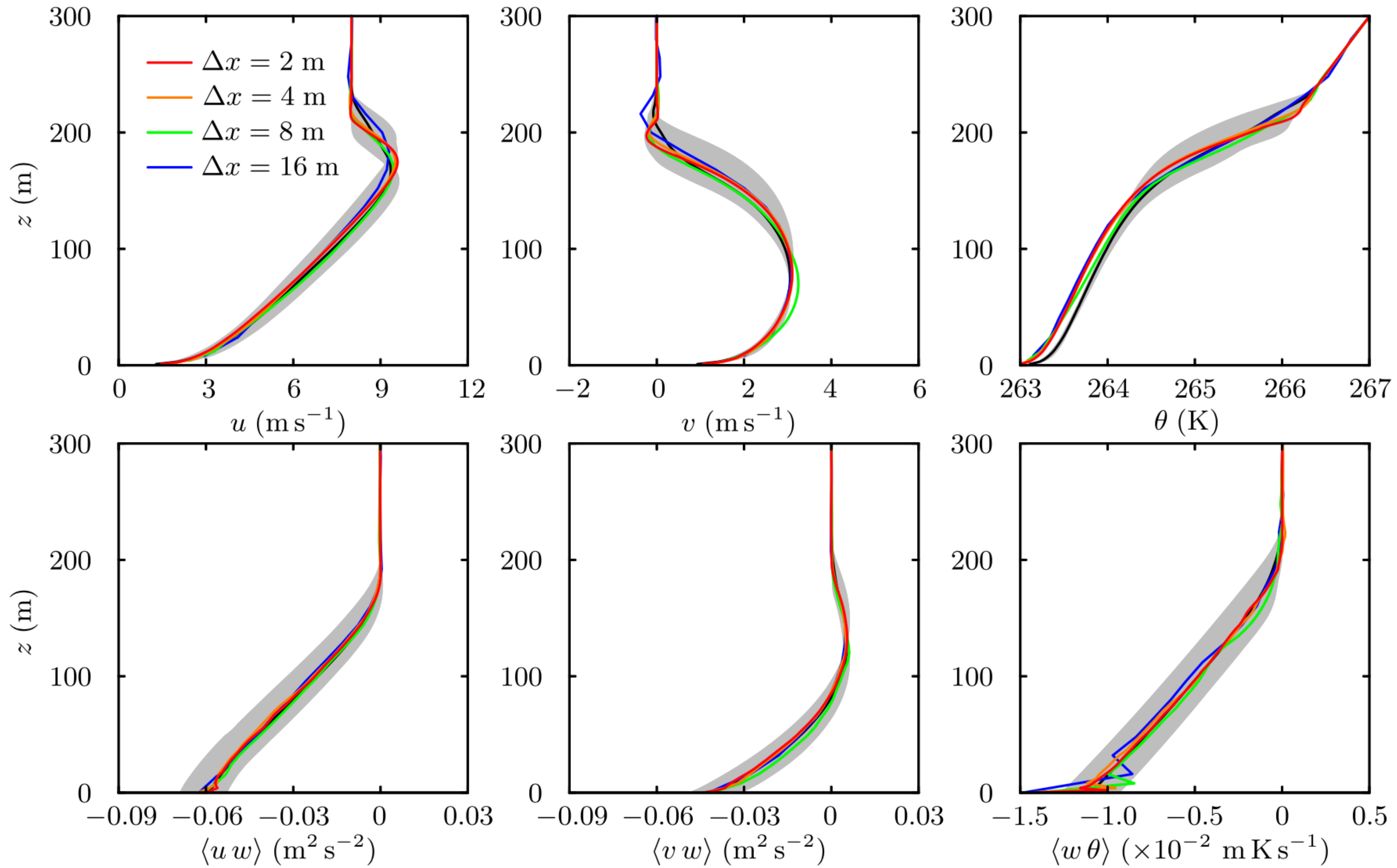
Potential temperature



- Reference run: $\Delta x = 2$ m, sixth-order advection, buoyancy adjusted stretched vortex model
  - Grid resolution independent results
- Total of 485 LES runs

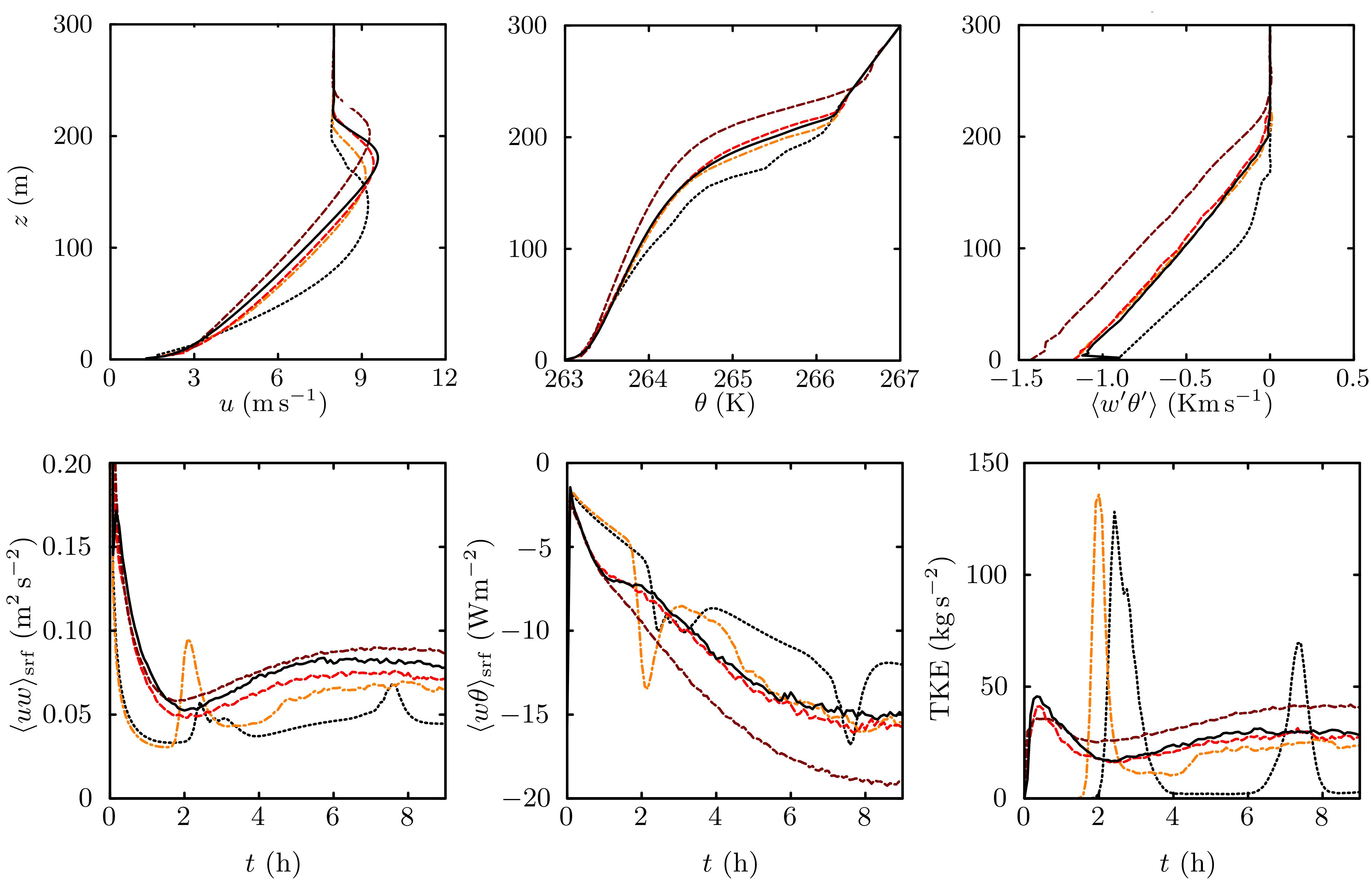
Reference model grid convergence

- Buoyancy adjusted stretched vortex SGS model (figure from Matheou & Chung 2014)



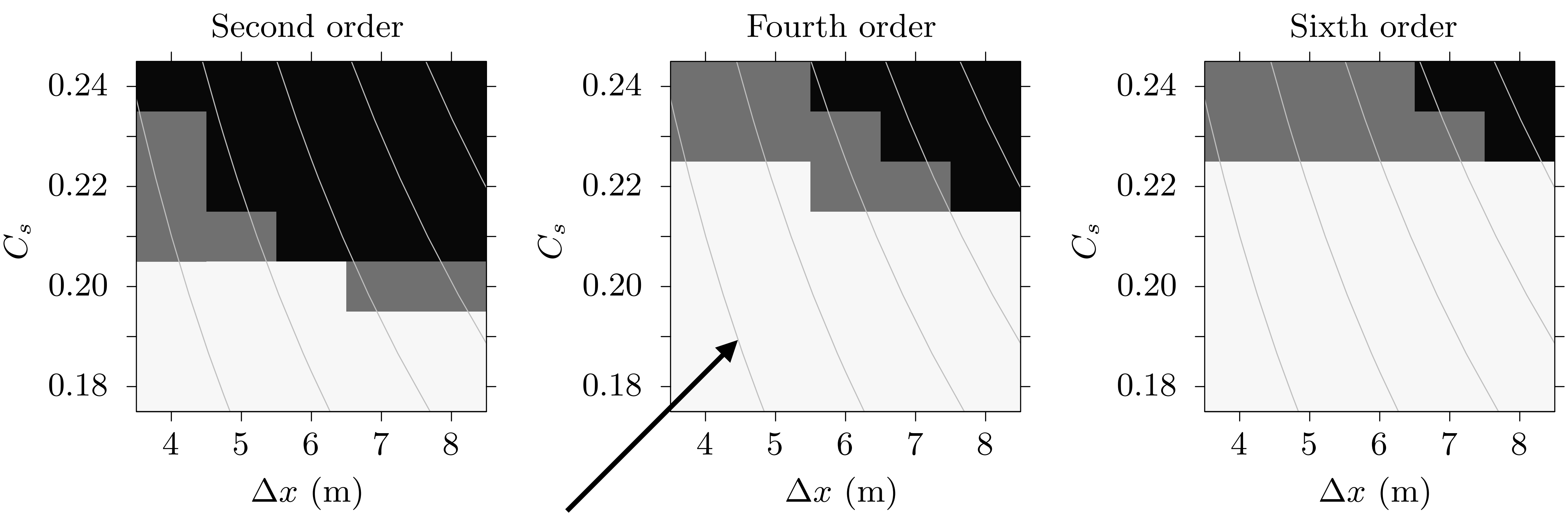
Smagorinsky results – Overview

- Range of LES results is large
- Spurious turbulence collapse observed in some runs



Spurious turbulence collapse

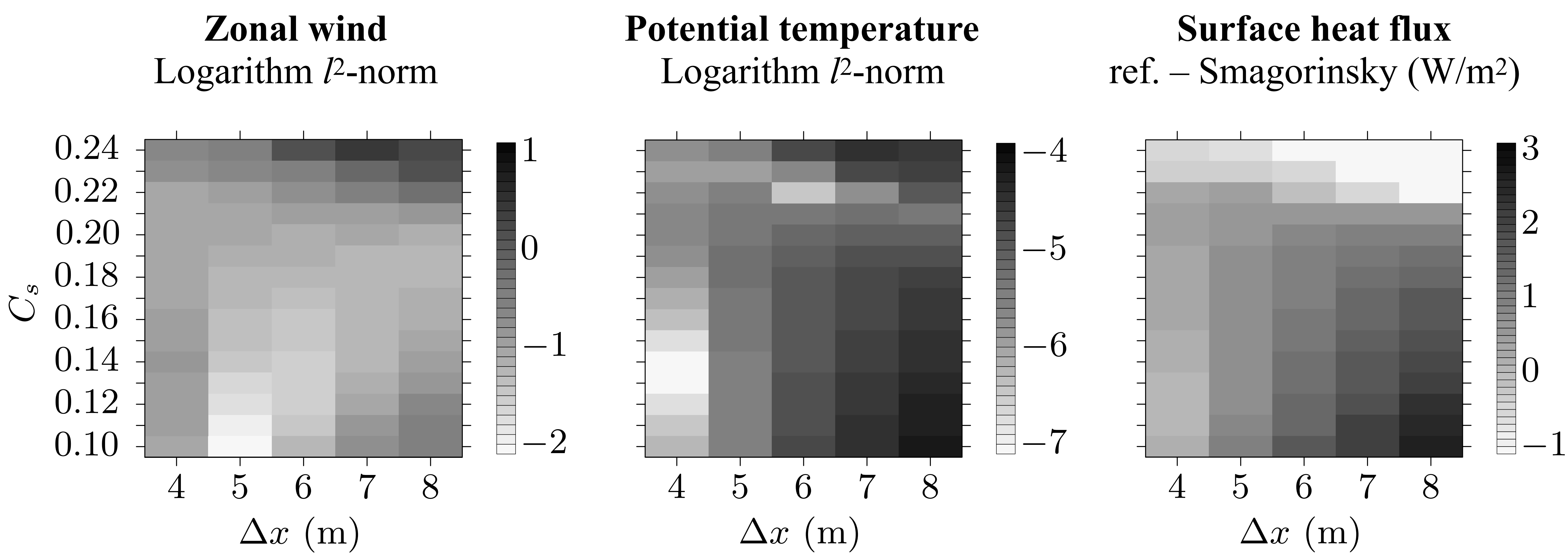
- Turbulence collapse flags
  - Global collapse, entire boundary layer laminarization (black rectangles)
  - Collapse during model spin-up: negligible TKE in $0 < t < 0.5$ h, and subsequent recovery (gray rectangles)
- Spurious turbulence collapse depends on advection scheme order



$\Delta = C_s \Delta x = \text{constant}$

“Error” norms with respect to reference LES

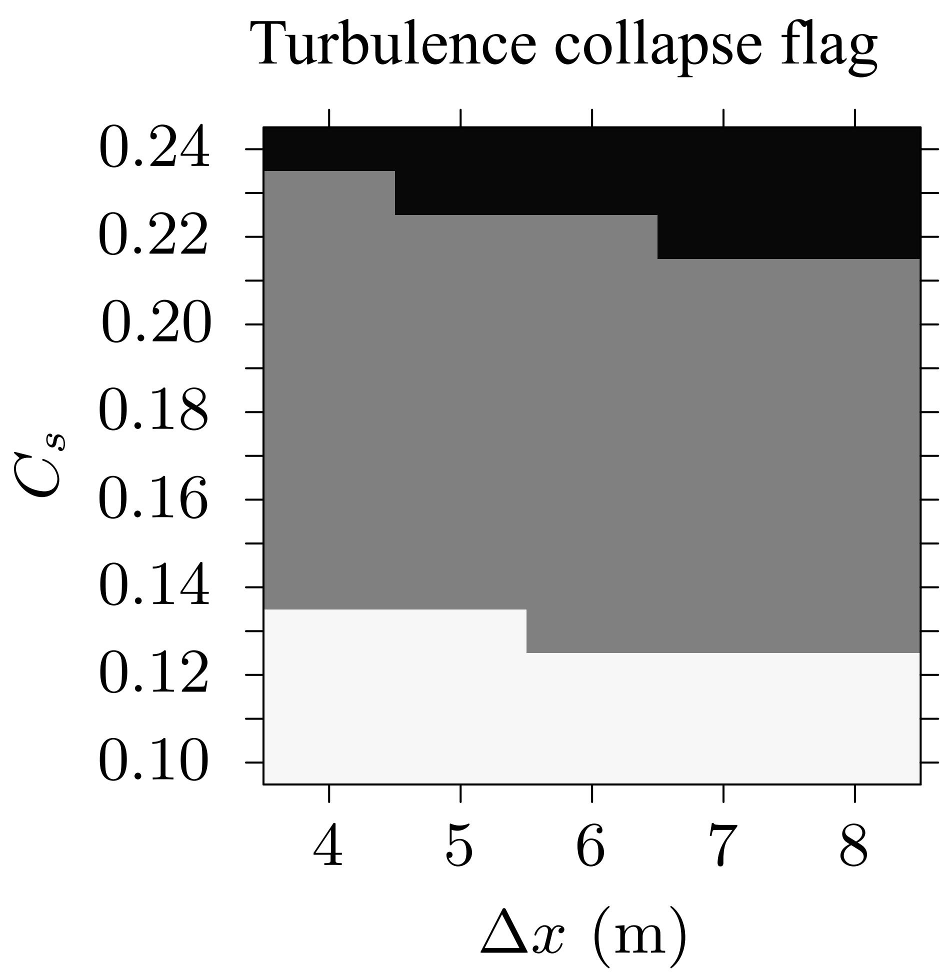
- Define error (or distance) between parametric study runs and reference LES
  - l^2-norm for mean profiles (i.e., wind and temperature)
  - Difference of time-mean values for surface fluxes
- Error does not converge
- Large differences in surface heat flux (~ 20% difference)



only fourth-order advection shown

Prescribed heat flux simulations

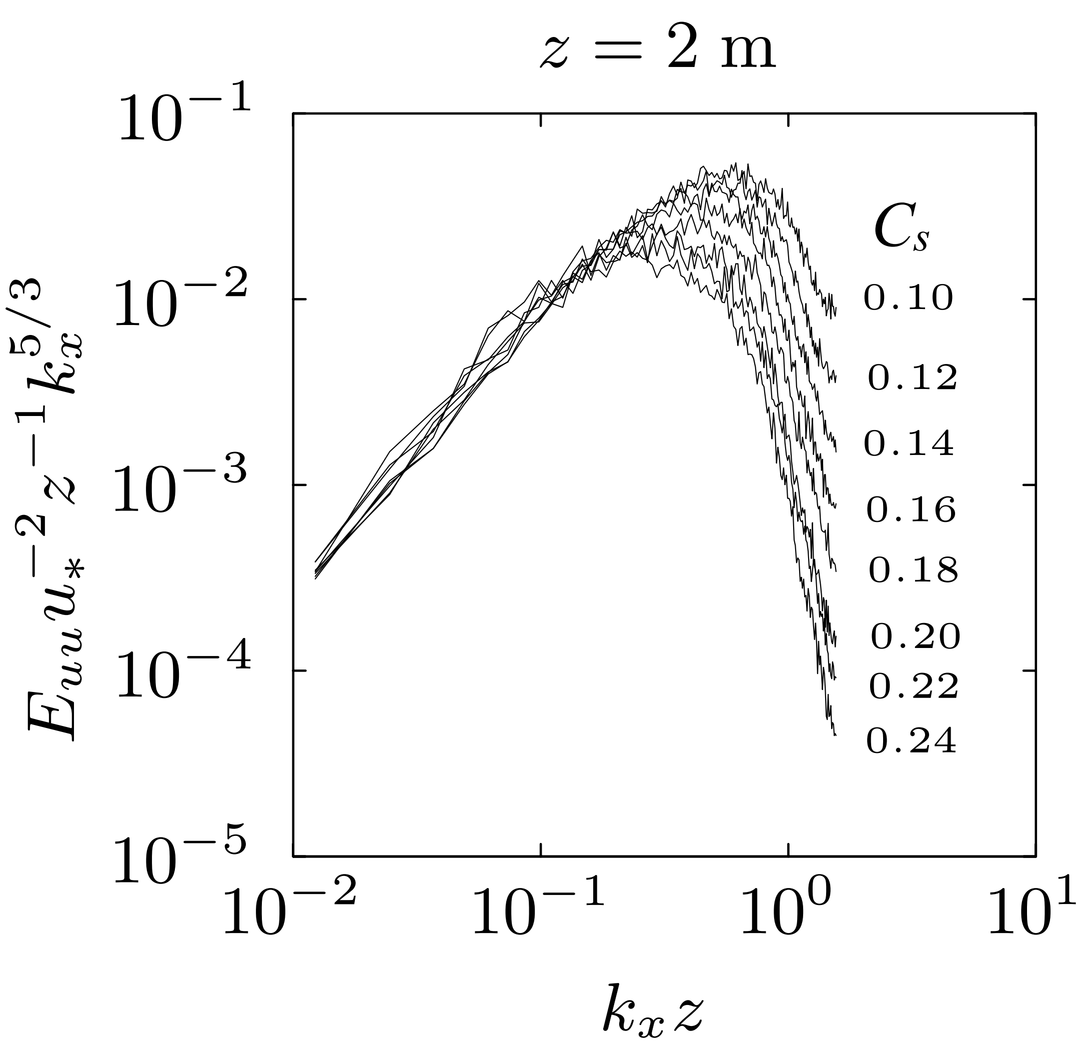
- The time-dependent heat flux from the reference run is used uniformly in all surface grid cells of the Smagorinsky runs
- The momentum flux is computed dynamically using MOST
- Spurious turbulence collapse regime expands
- Error increases when heat flux is not dynamically computed

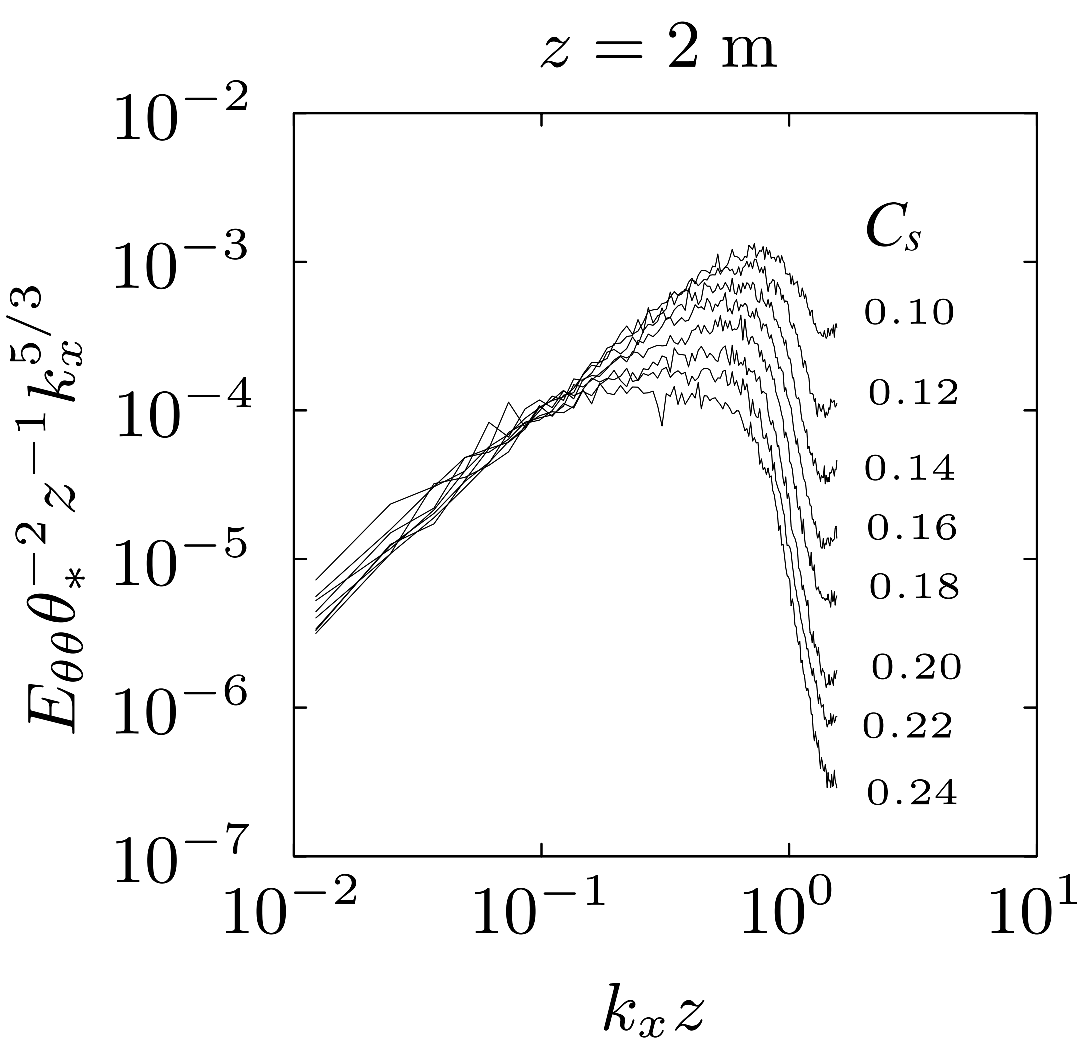


Black: Global collapse
Gray: Collapse during model spin-up

Spectra

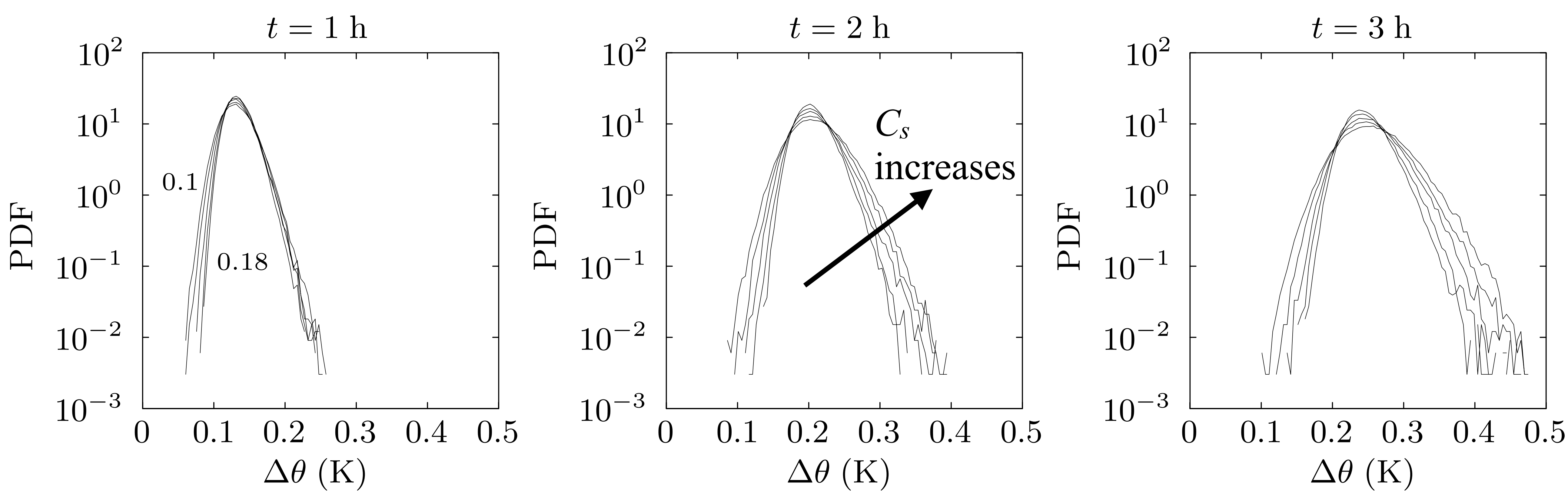
- Energy accumulation at small scales as model constant is reduced
- Runs with Δx = 4 m, sixth-order advection at t = 9 h (end of the run)





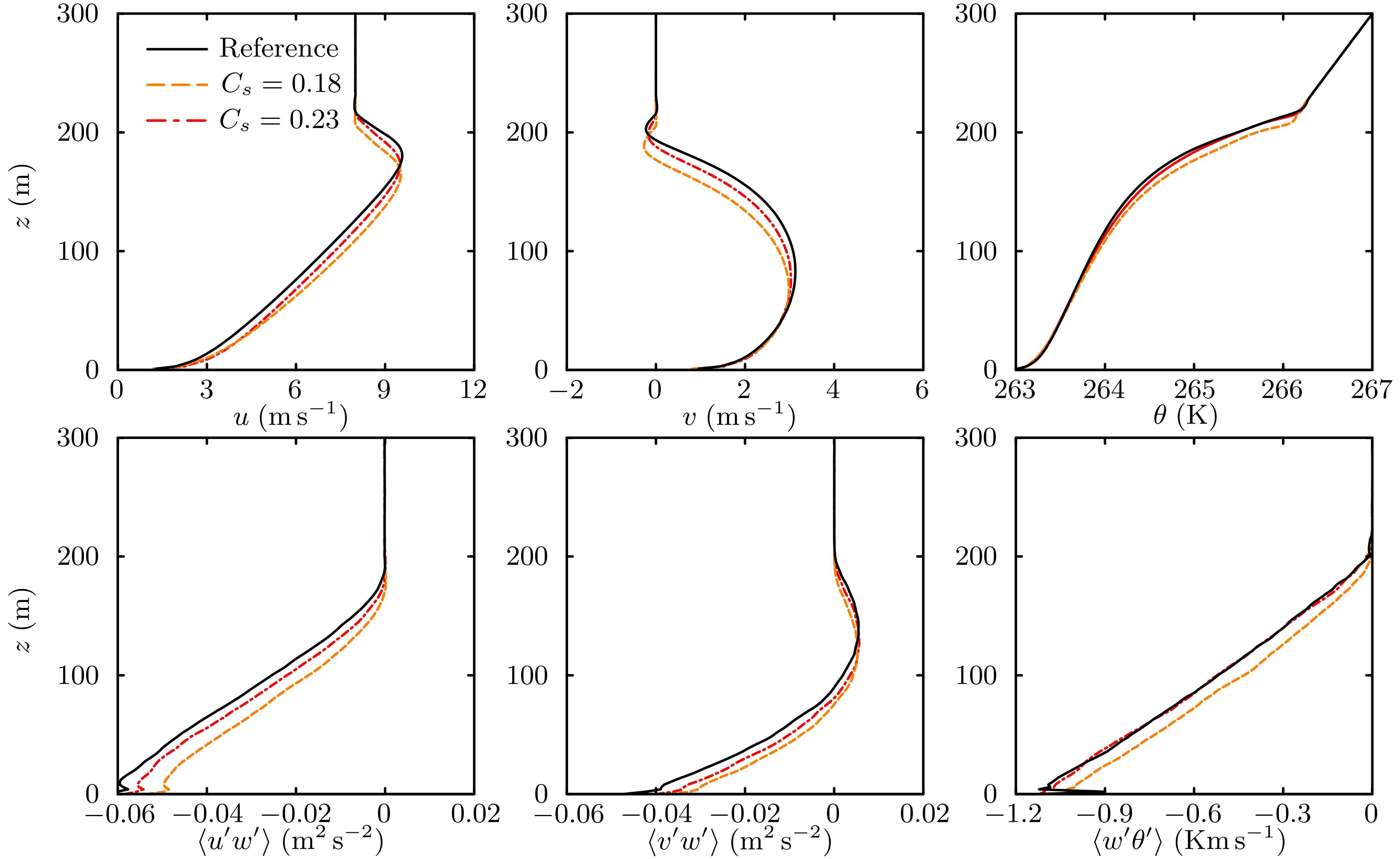
Distributions of near-surface temperature difference

- Probability density functions (PDF) of temperature difference, $\Delta\theta$, between surface and first grid cell
- PDFs become broader as model constant, C_s, decreases
- Surface heat flux depends on $\Delta\theta^3$
- Broader PDFs result in larger in magnitude mean surface fluxes (increased cooling)



A posteriori comparison with reference

- Smagorinsky can accurately capture the boundary layer structure
- …but the value of the constant is not know a priori and may be flow dependent



Part 1: Summary and conclusions

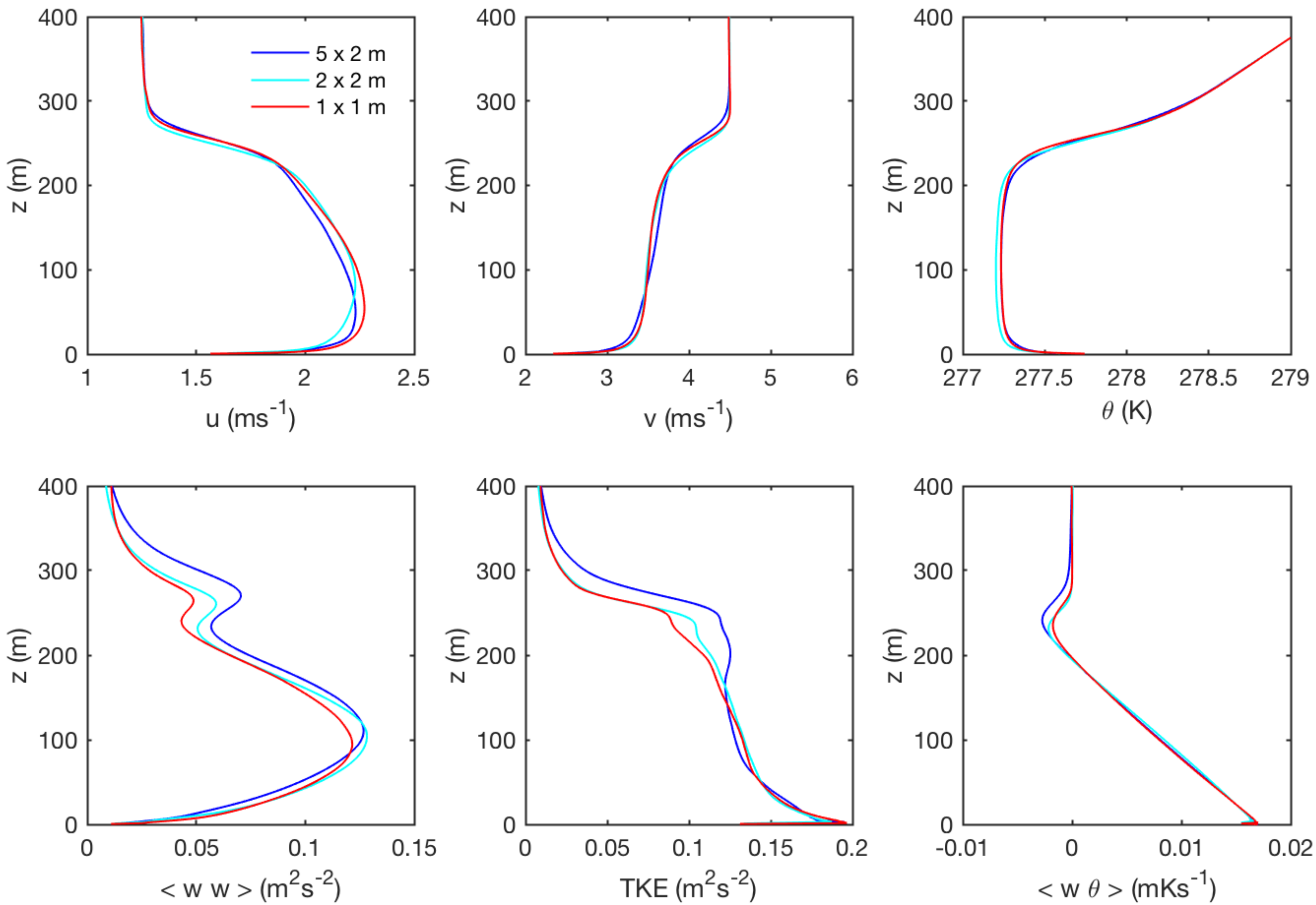
- Aspects of a large-eddy simulation model are studied in simulations of a moderately stable atmospheric boundary layer
- Three model parameters are considered: the grid spacing, the value of the SGS model constant, and the order of accuracy (resolving power) of the advection discretization
- Two main error-producing mechanisms are identified:
  - For high values of the model constant spurious turbulence collapse is observed
  - For low values of the model constant, numerical discretization errors dominate, leading to accumulation of energy at the small scales and over-prediction of the magnitude of the surface heat flux
- The constant coefficient Smagorinsky–Lilly model can accurately capture moderately stable flows, in contrast to the conclusions of previous studies
  - Judicious choice of parameters is necessary (but not known *a priory*)
- Surface fluxes depend on model constant
  - The observed differences are relatively large given that the flow and model configuration is identical
  - The feedback between boundary-layer turbulence and surface flux is important

Part 2: GABLS4 LES results

- LES model of Matheou & Chung (2014)
- Buoyancy adjusted stretched-vortex model (Chung & Matheou 2014)
- Advection scheme
  - Same for momentum and temperature
  - Fully conservative non-dissipative family of schemes of Morinishi et al. (1998) adapted to the anelastic approximation
  - Sixth-order approximation
  - No numerical dissipation

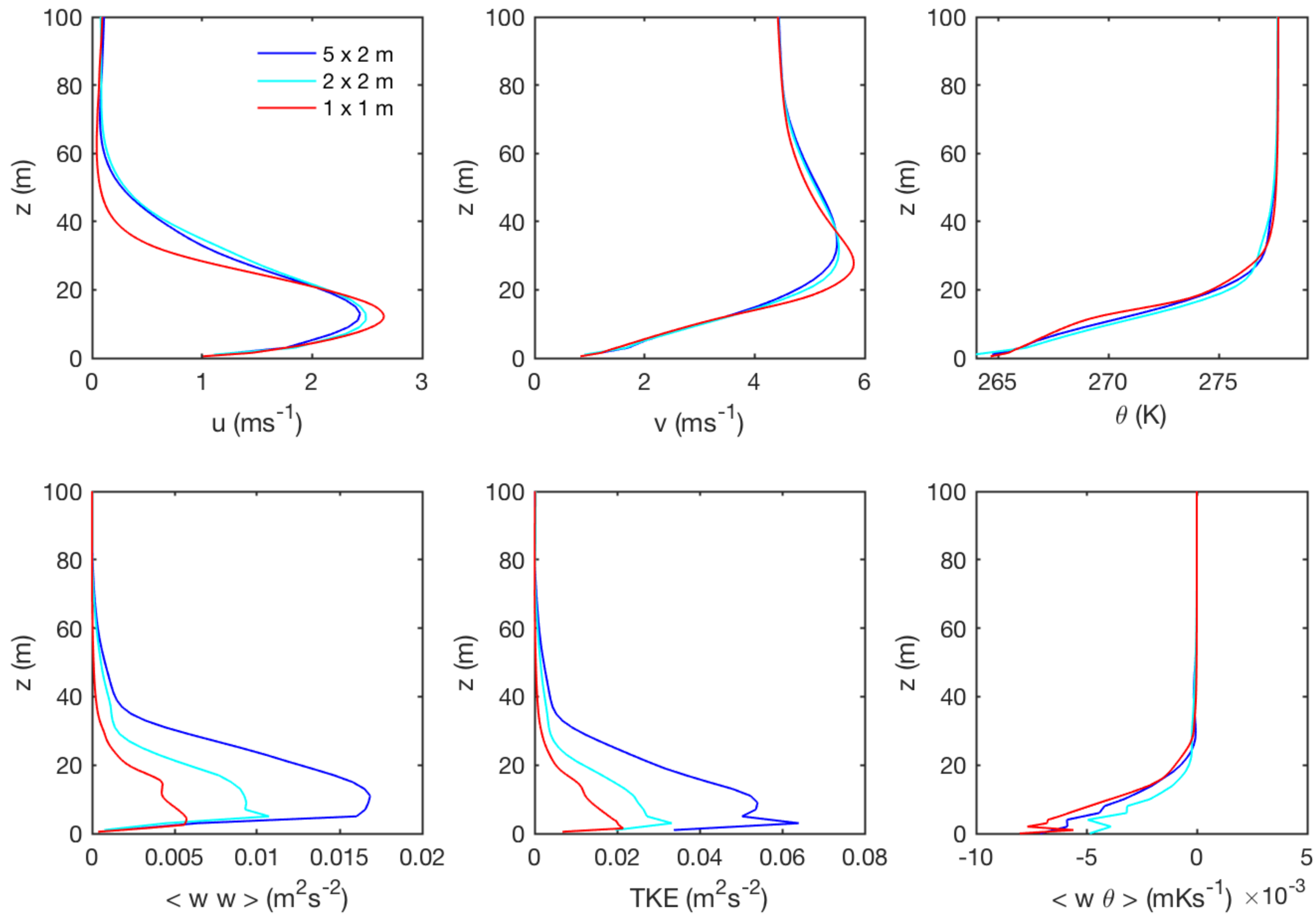
GABLS4: Grid convergence, diurnal LES, daytime $t = 6$ h

- Small differences with respect to grid resolution, fluxes are converged



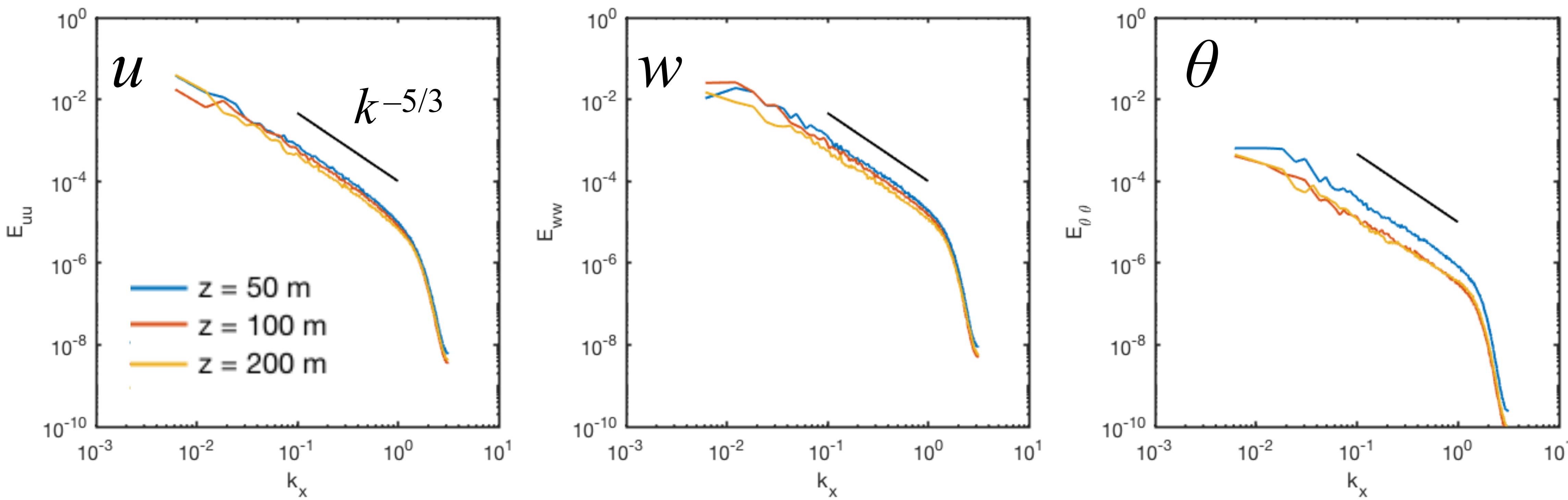
GABLS4: Grid convergence, diurnal LES, “nighttime” t = 16 h

- Mean profiles somewhat change decreasing Δx
- Fluxes exhibit larger differences, model is more energetic at coarse resolution

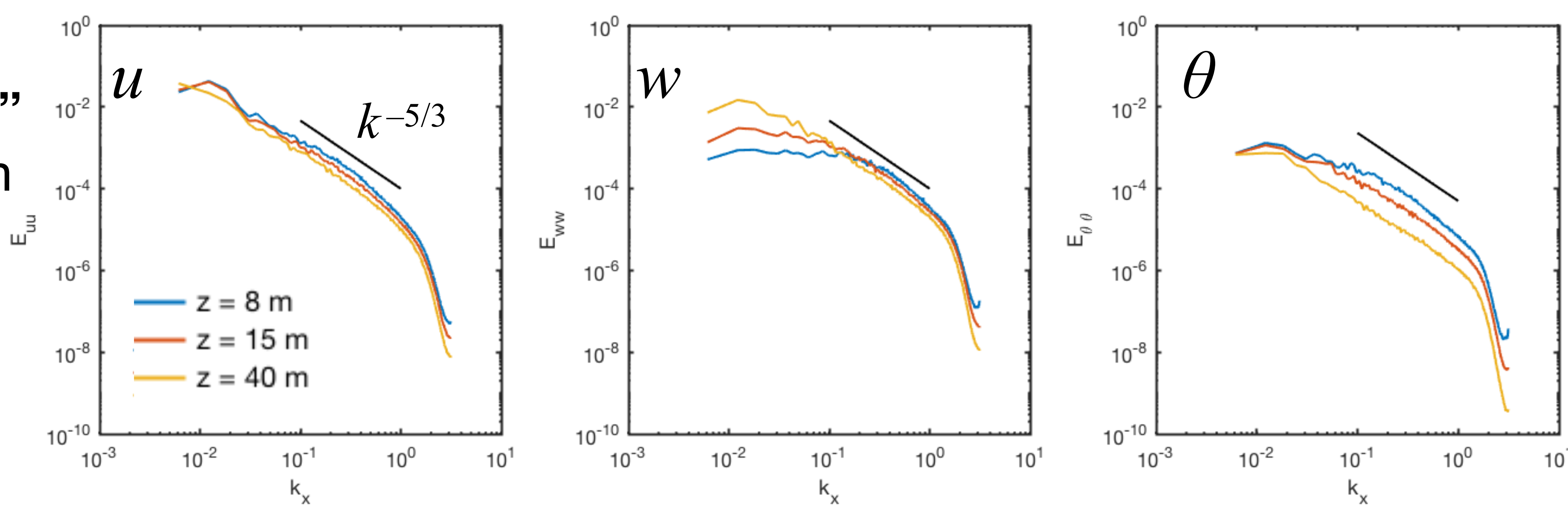


Spectra: convective and stable conditions $\Delta x = 1$ m

Day
t = 6 h

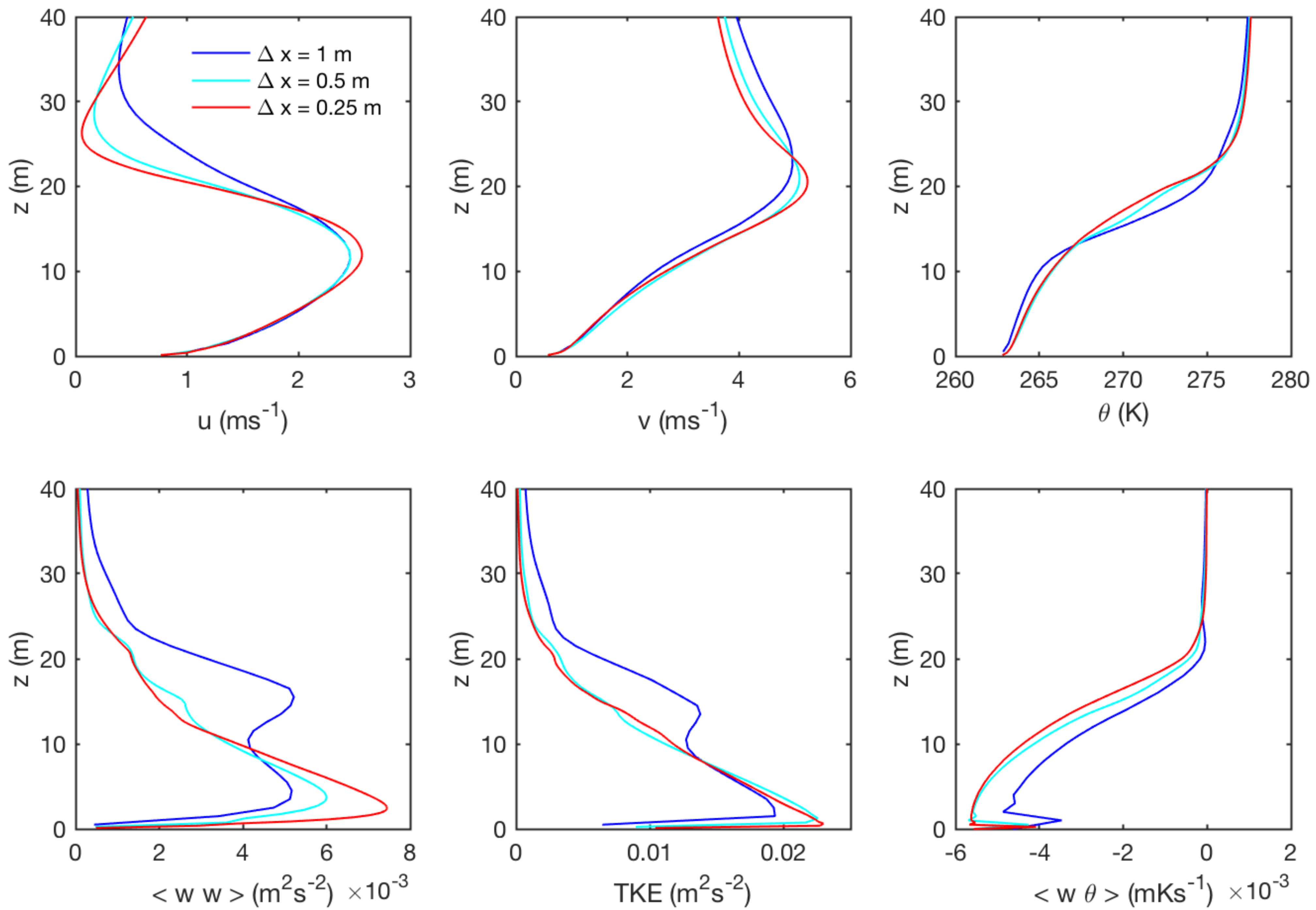


"Night"
t = 16 h



Grid convergence, "nighttime" LES $t = 18$ h

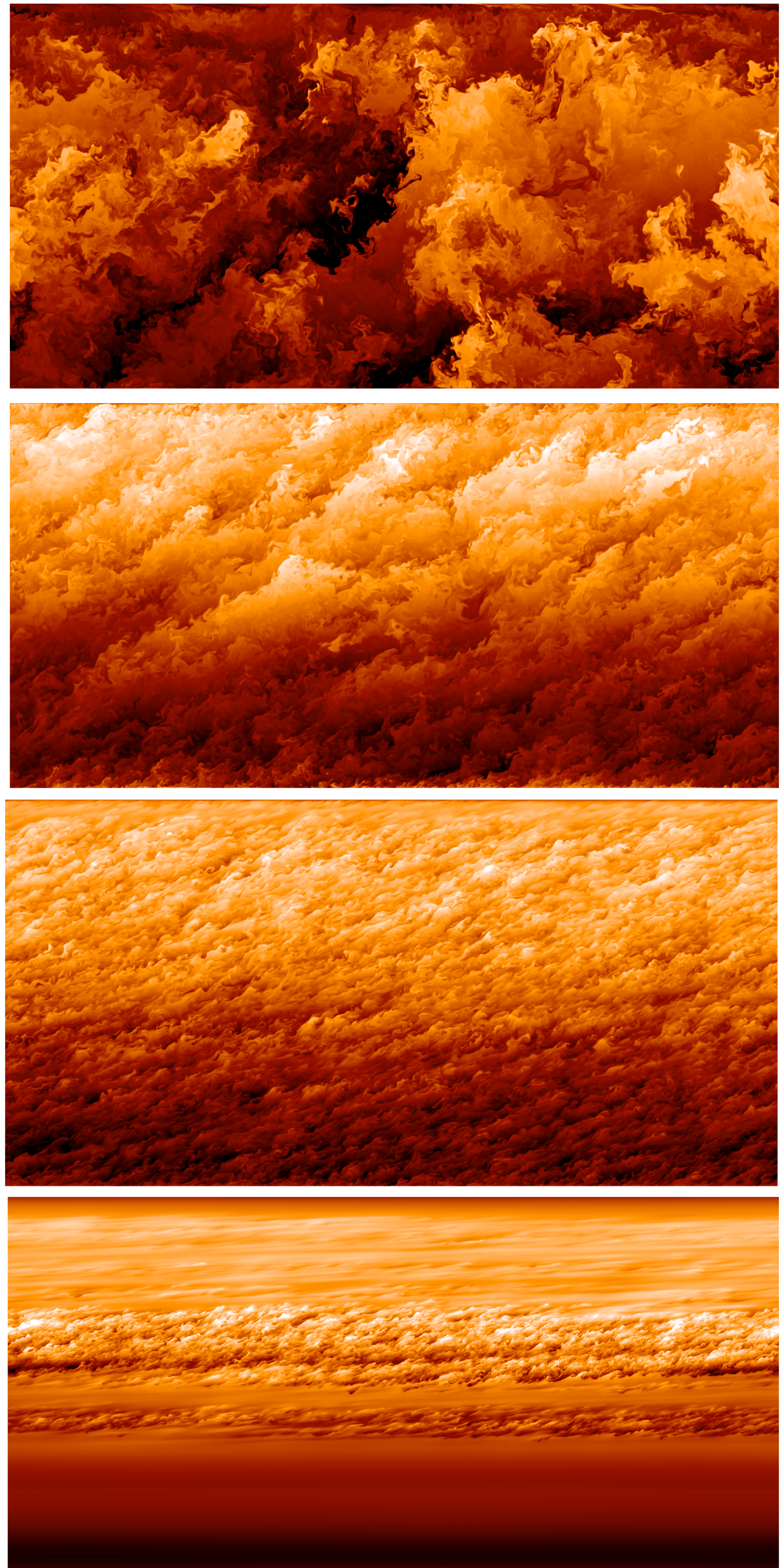
- Grid converged results at $\Delta x = 0.5$ m



Backup

Homogeneous stratified sheared turbulence

DNS: 2048×1024^2

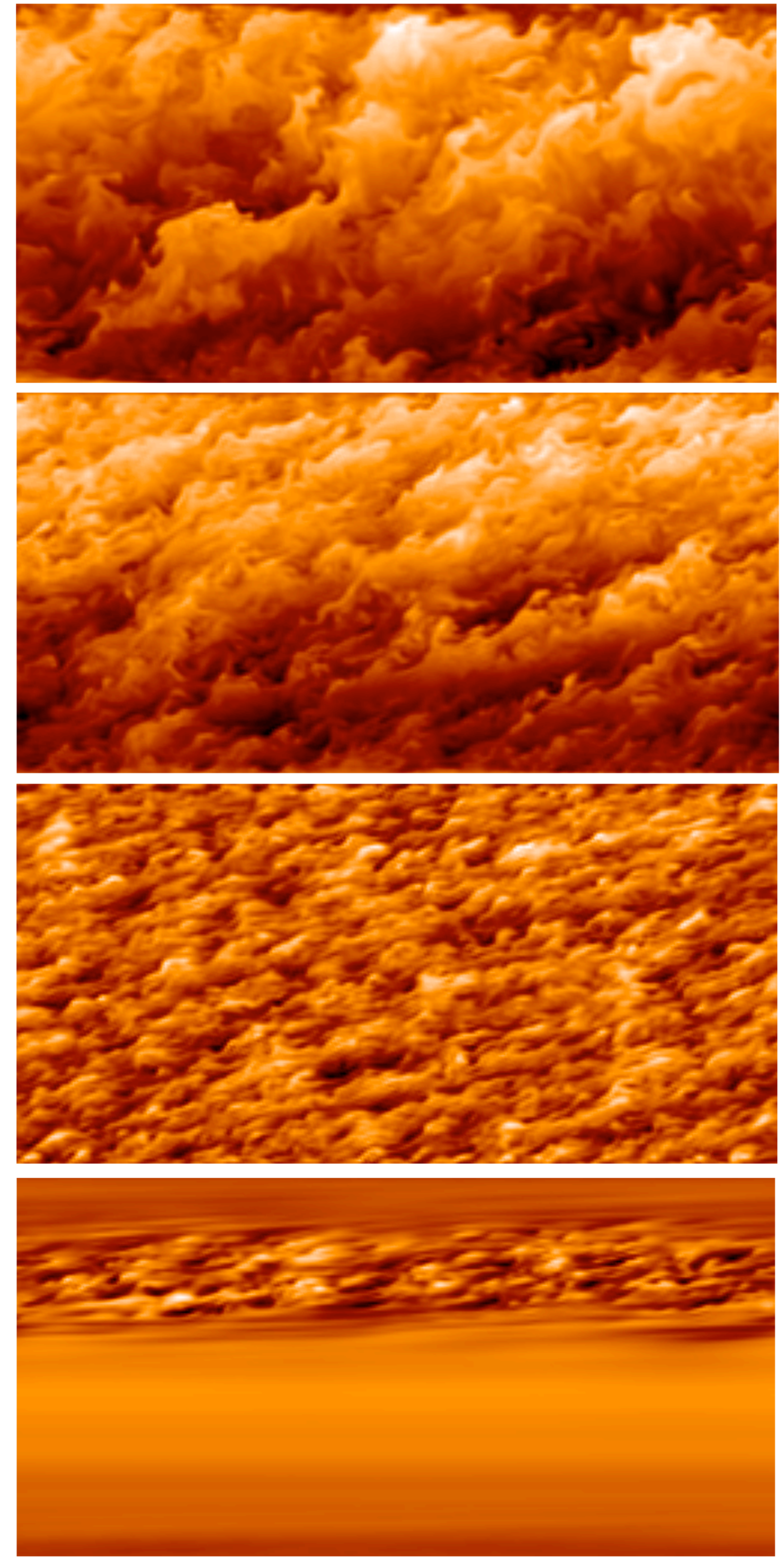


Flux Richardson number

$Rf = 0$

DNS	LES
0.10	**0.12**
0.16	**0.19**
0.18	**0.20**

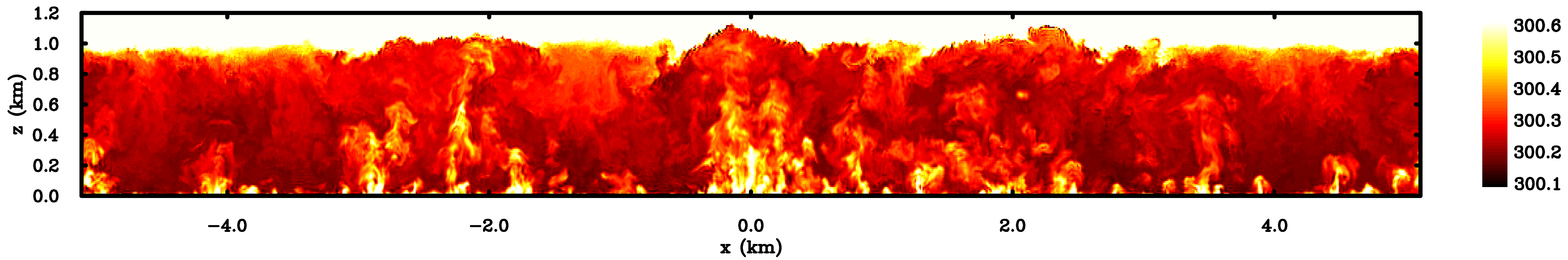
LES: 256×128^2



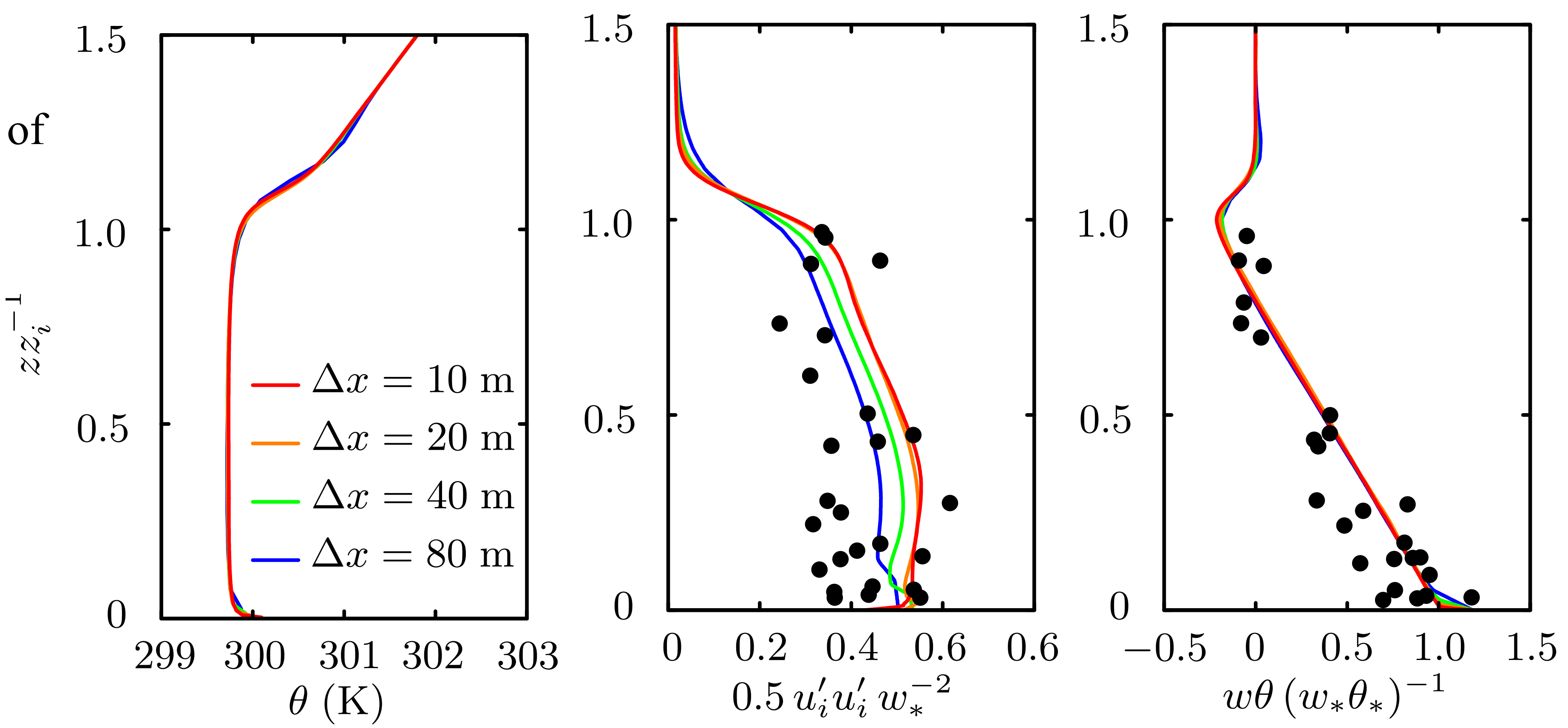
Convective boundary layer

- Quality assessment of LES predictions: comparison to measurements and grid convergence (and theory – not shown here)
- Grid convergence is prerequisite for any predictive model

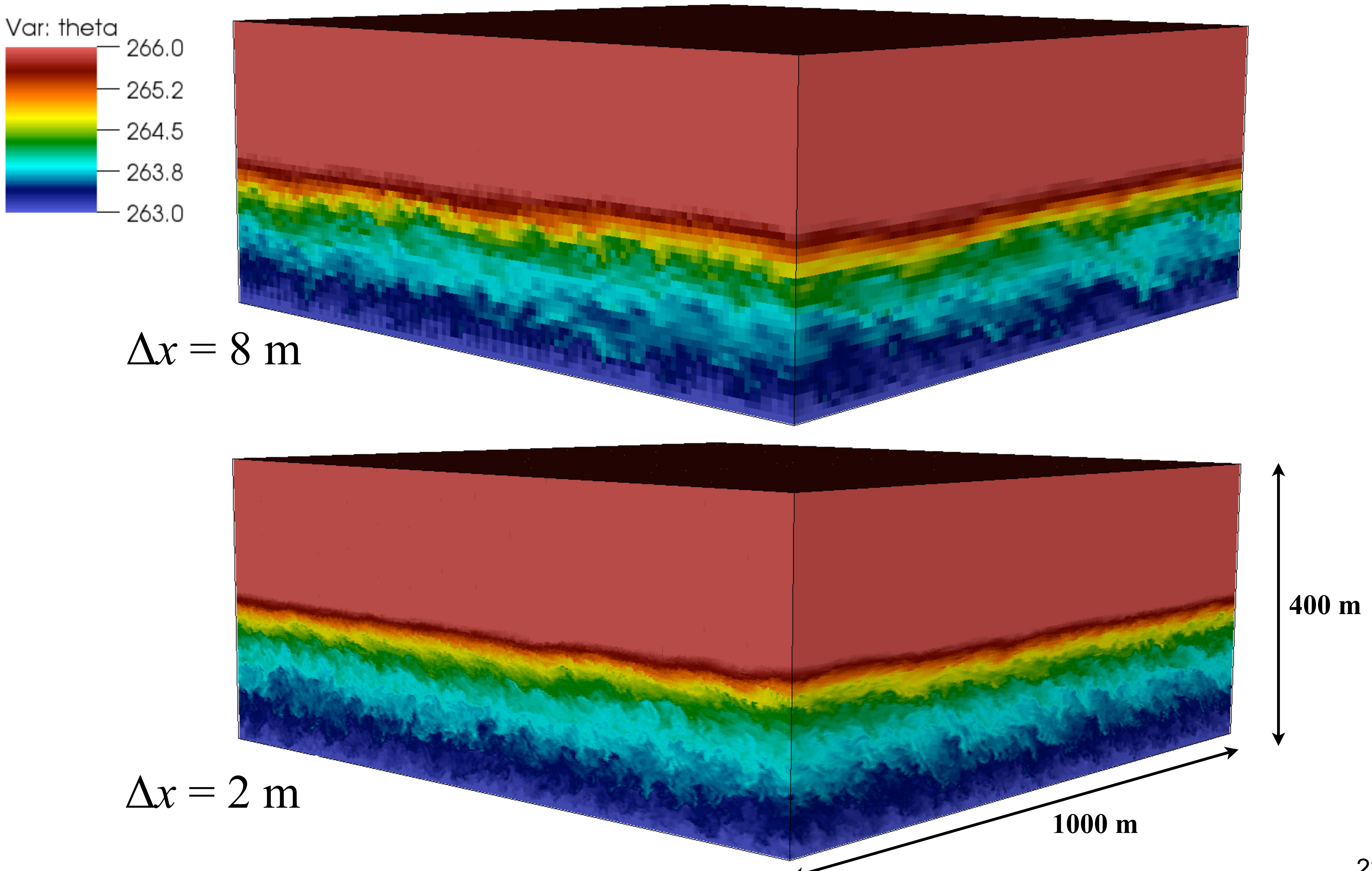
Potential temperature



Circles: Measurements of Lenschow et al. (1980)



Potential temperature field at two grid resolutions



Monin-Obukhov local scaling