Large-eddy simulation of the atmospheric boundary layer

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Planetary Boundary Layers in Atmospheres, Oceans, and Ice on Earth and Moons

Kavli Institute of Theoretical Physics

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  - JPL Supercomputing and Visualization Facility

Where to find more details...

- Chung, D. and G. Matheou, 2012: Direct numerical simulation of stationary homogeneous stratified sheared turbulence, *J. Fluid Mech.*, 696, 434–467.
- Matheou, G., and D. Chung, 2012: Direct numerical simulation of stratified turbulence, *Phys. Fluids*, 24, 091106.
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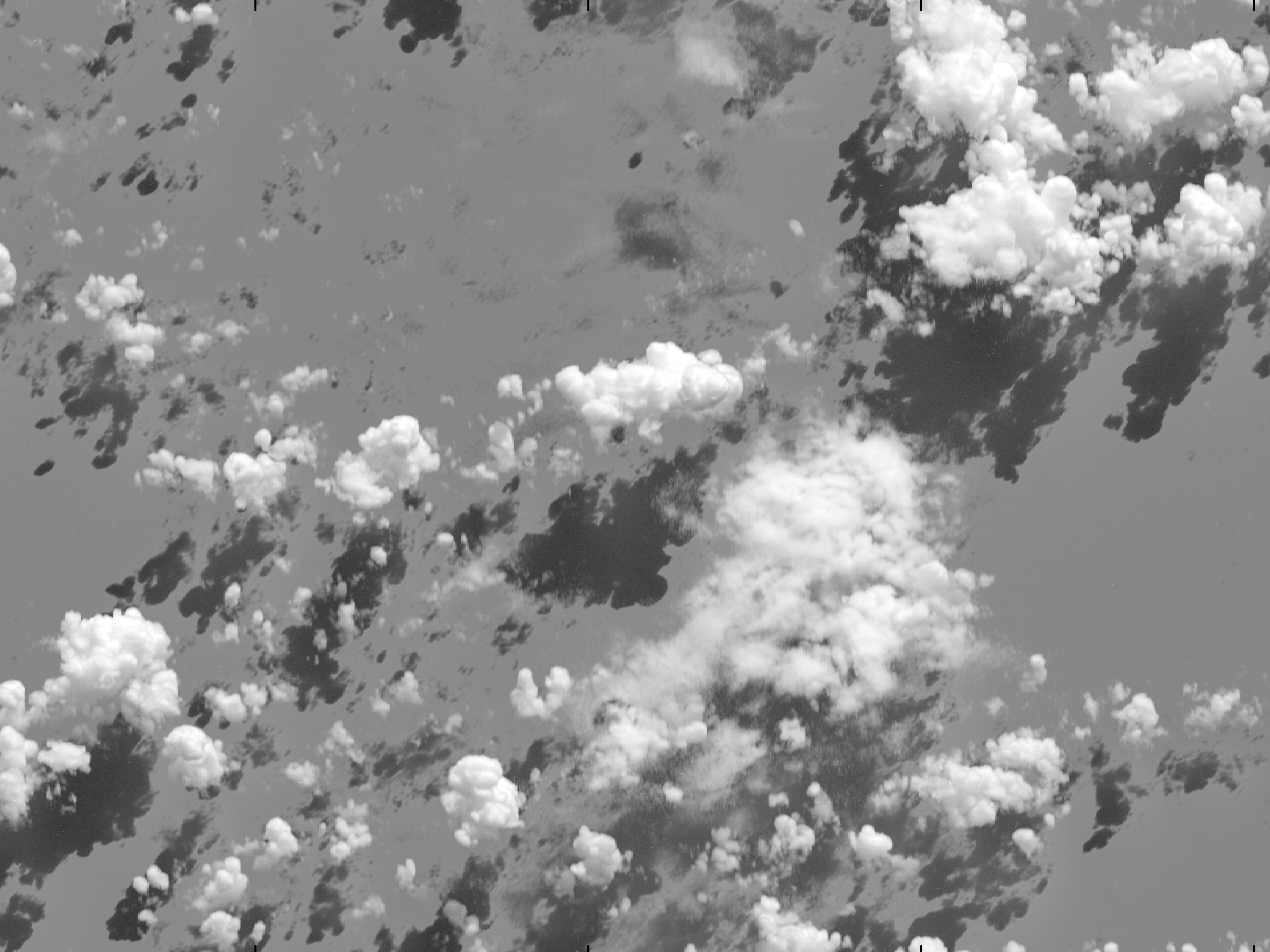
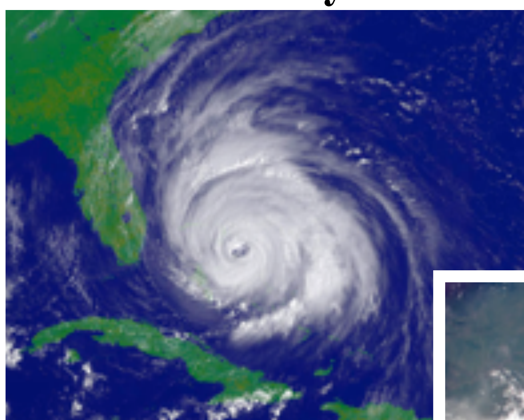


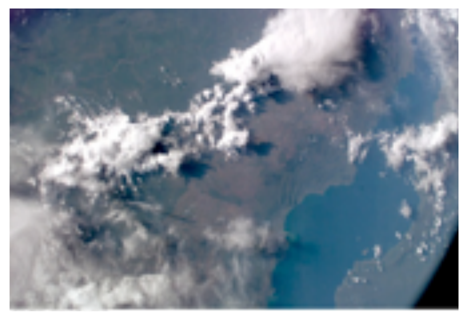
Scales of atmospheric motions and models

Global circulation

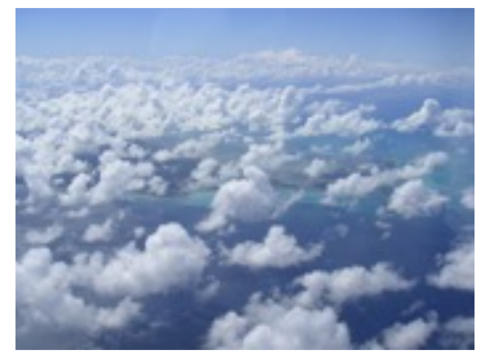
Mesoscale organization
Weather/storm systems



Convection Organization – Thunderstorms

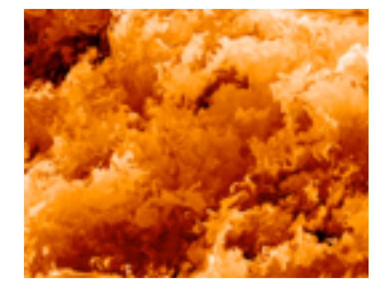


Individual Clouds



Cloud–Environment interactions

Small-scale turbulence



10 000 km — 1000 km — 10 km — 1 km — 100 m — 1 mm

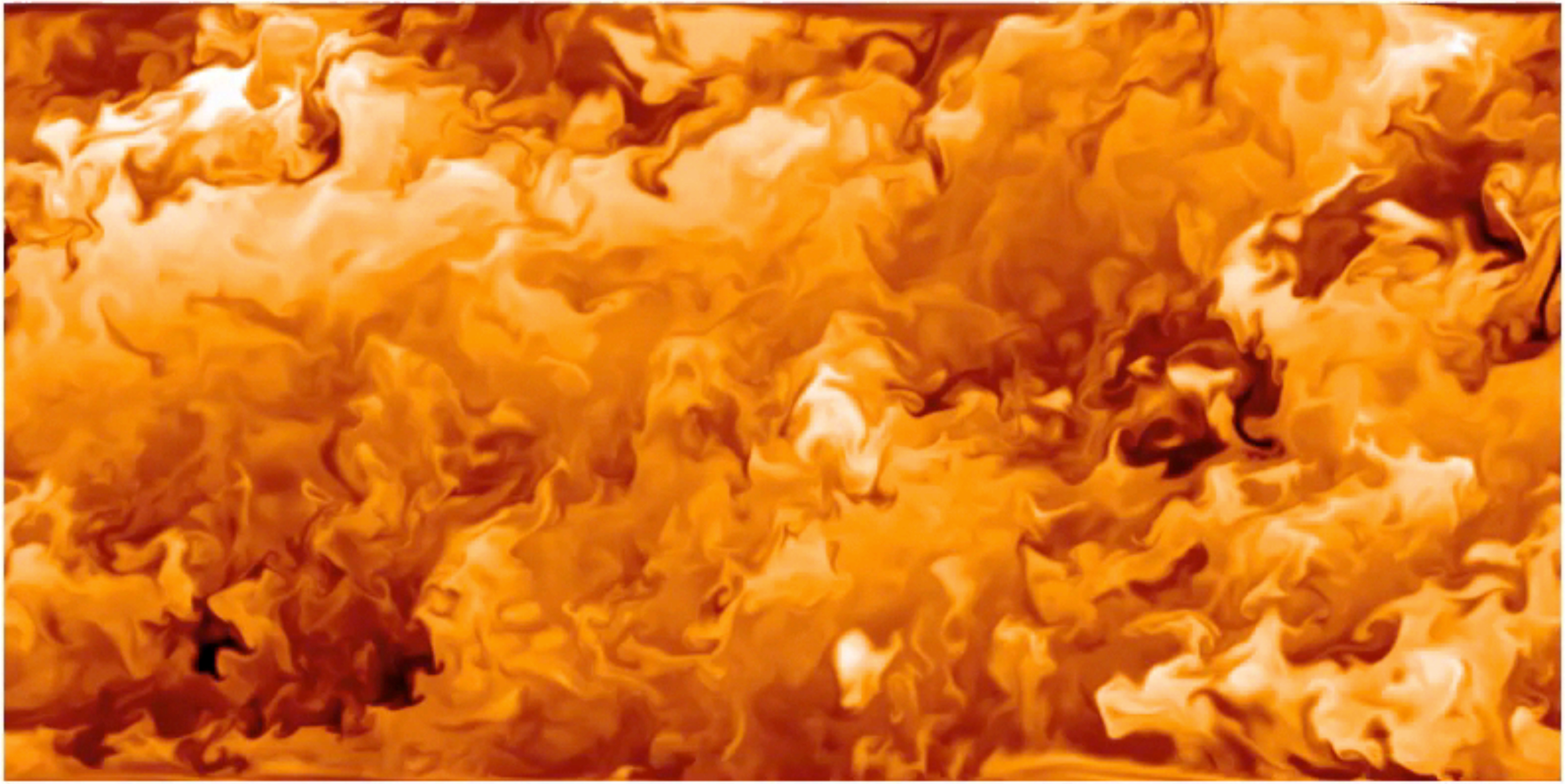
$L/\Delta x \approx 10^{8}$

Model			
Global circulation model (GCM)	Resolved	Parameterized	
Large-eddy simulation (LES)	Input from large scales	Resolved	Parameterized
Direct numerical simulation (DNS)	Forcing / Turbulence production / Large scales		

Computational cost increases ~ $(L/\Delta x)^4$

Images: NASA, B. Stevens, Chung & Matheou

$Re_b \equiv \varepsilon/\nu N^2 = 10^4 \qquad Re_\lambda = 350$



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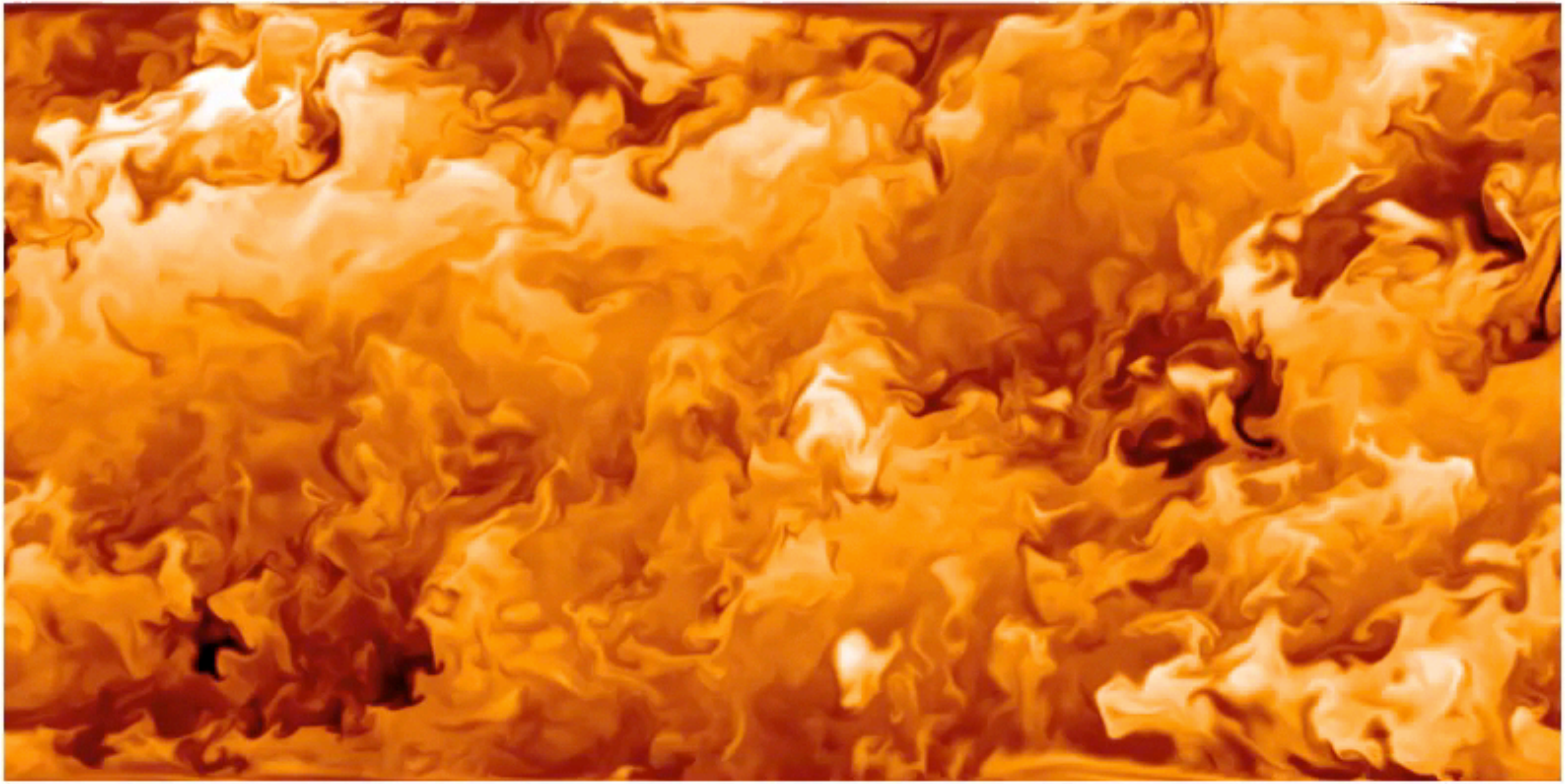

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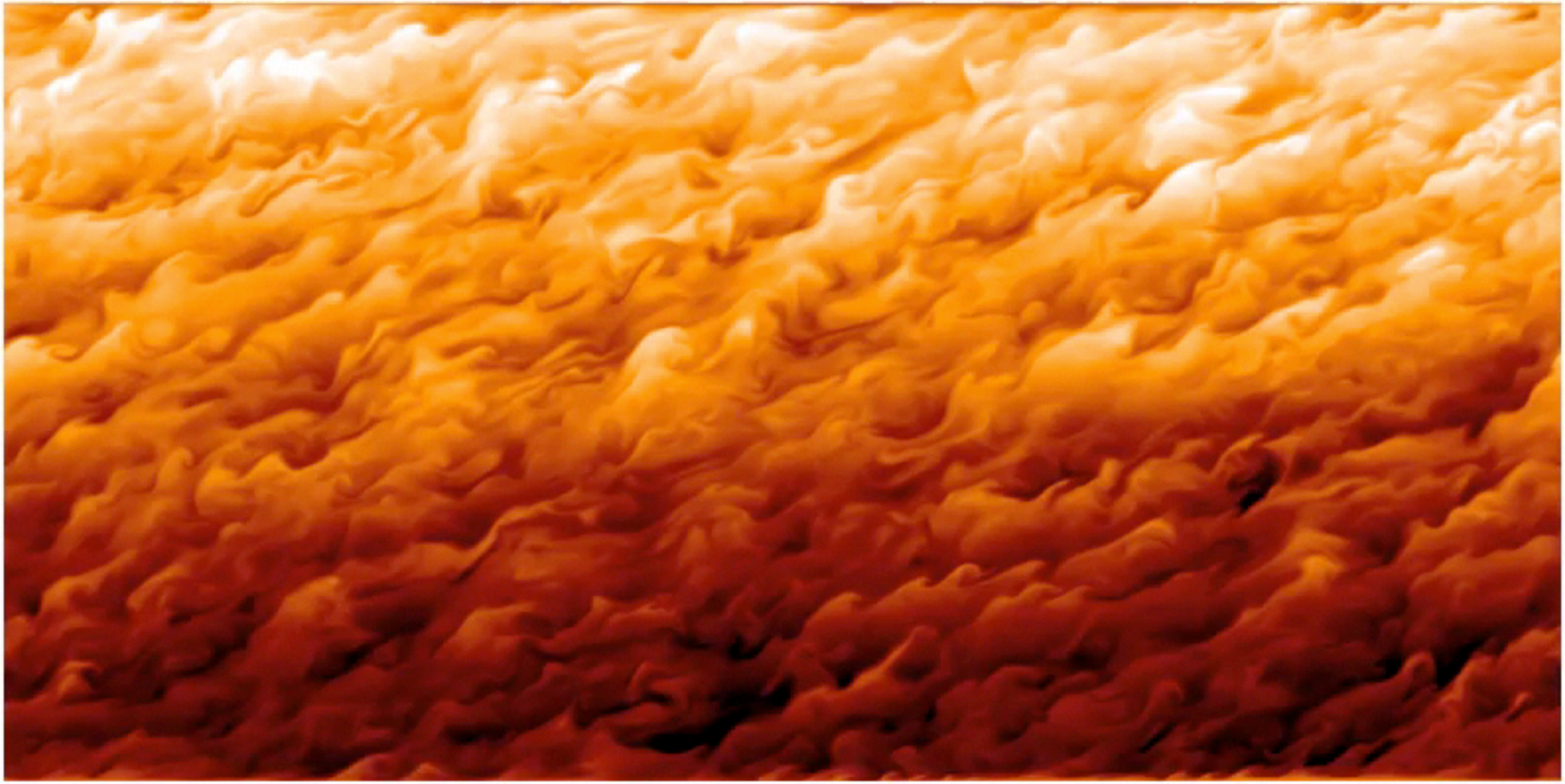
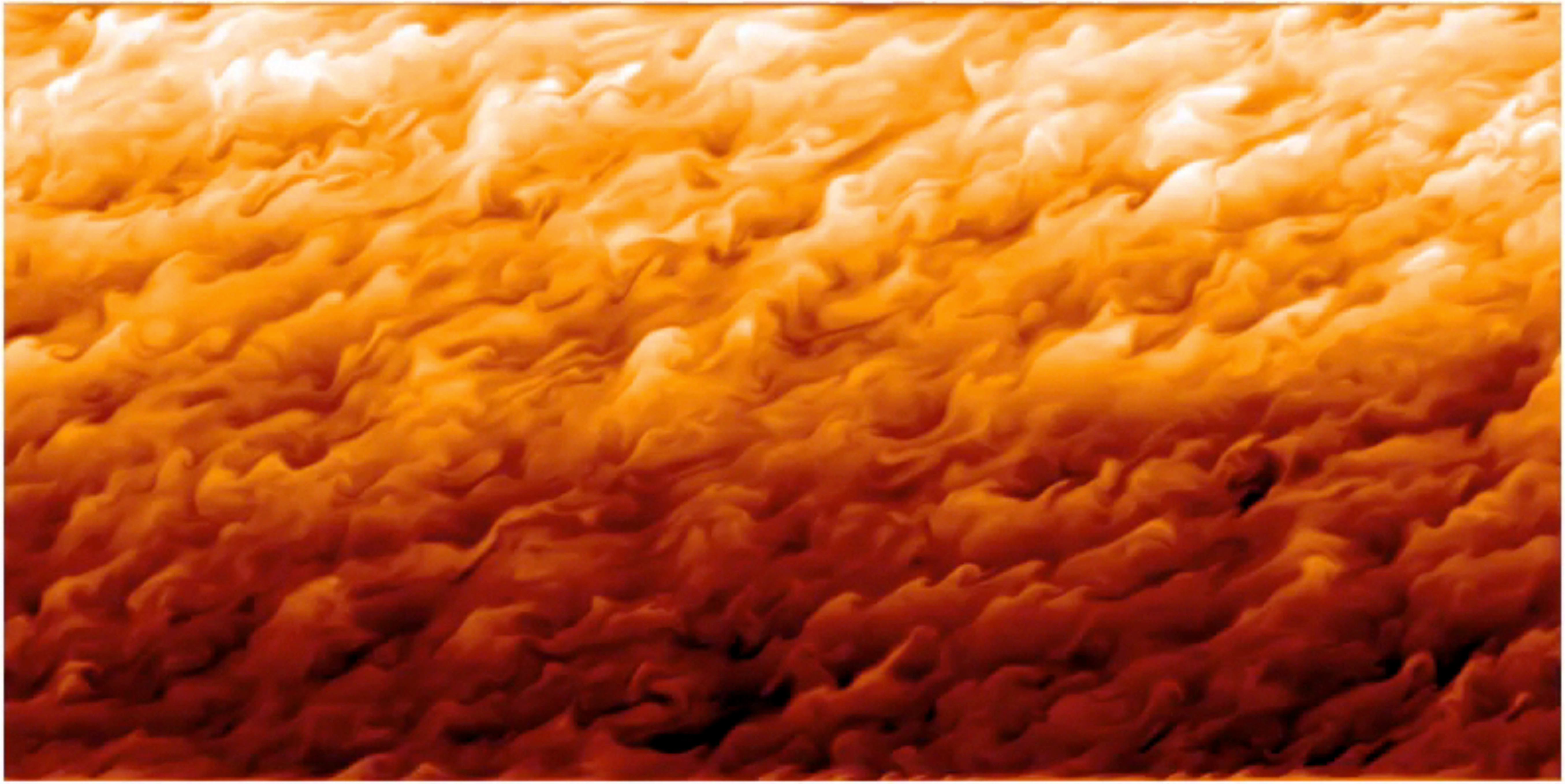
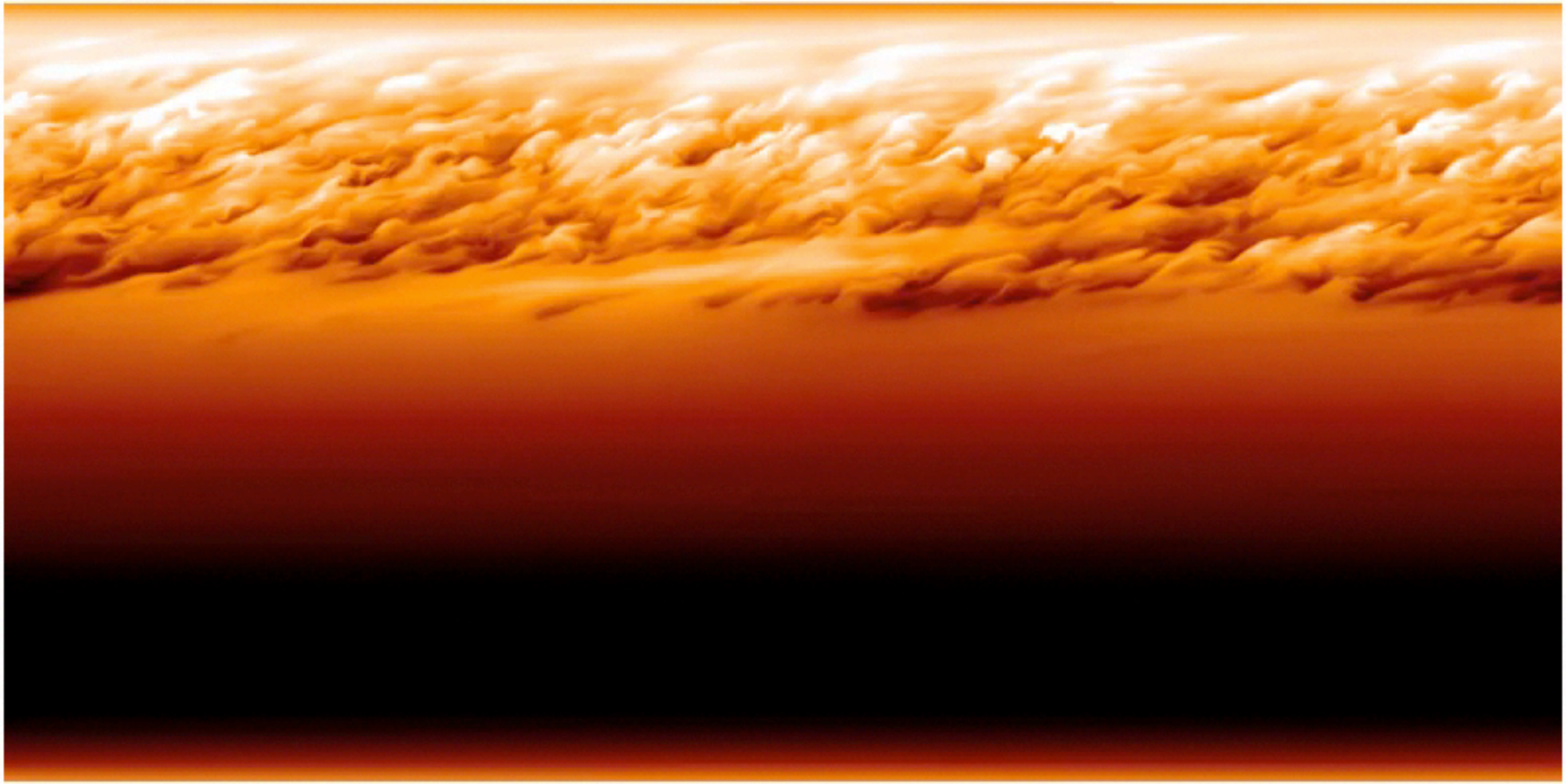


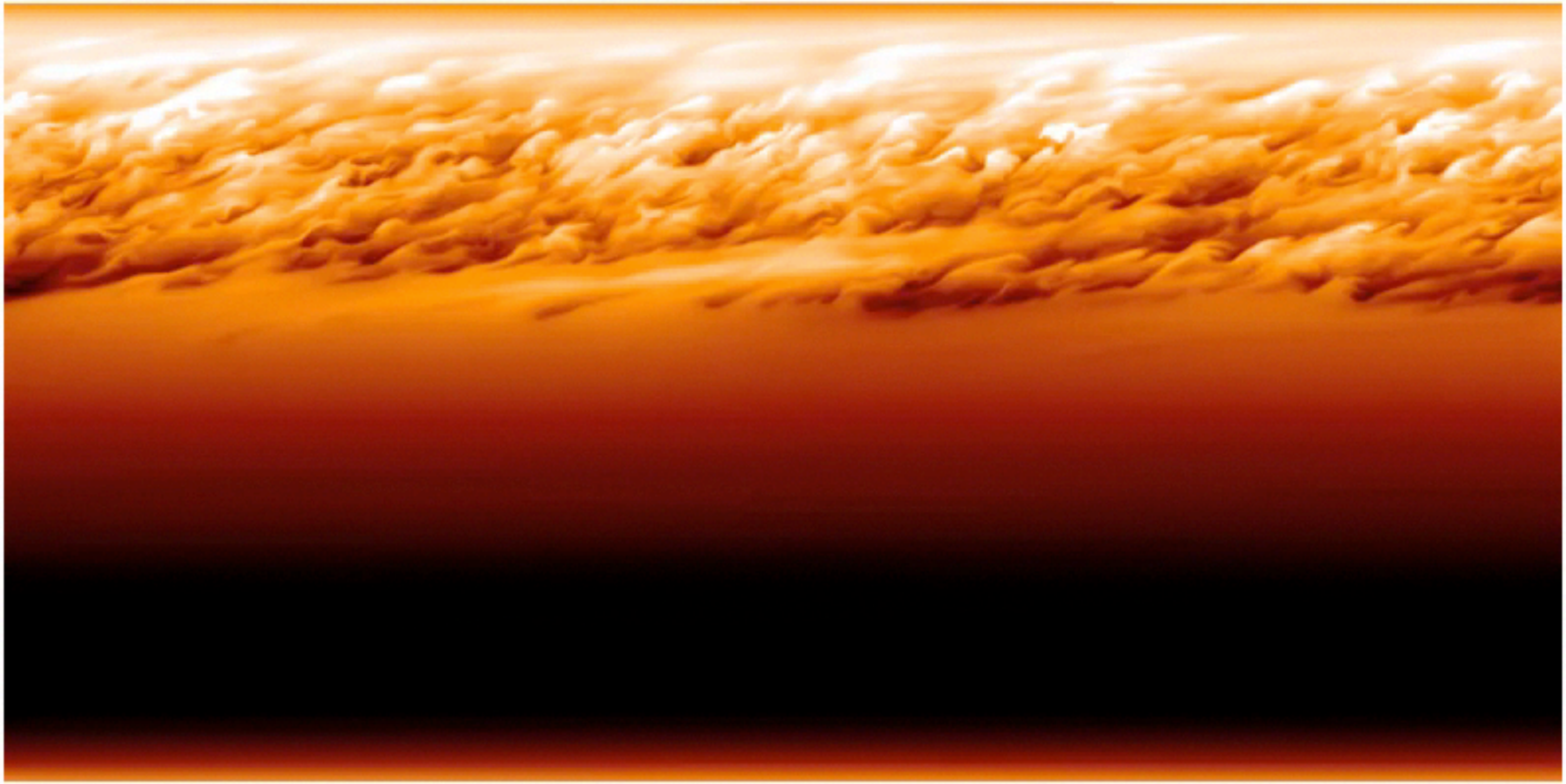
$Re_b \equiv \varepsilon / \nu N^2 = 10^2$



$Re_b \equiv \varepsilon / \nu N^2 = 10$



$Re_b \equiv \varepsilon/\nu N^2 = 10$



DNS of homogeneous stratified sheared turbulence

$Re_\lambda \approx 400$

$S^* = S\frac{\overline{u_i u_i}^2}{\epsilon} = 4-12$

$Sc = 0.7$

$k_{\max}\eta = 1.2$

$Re_b \equiv \frac{\epsilon}{\nu N^2} \sim \left(\frac{l_O}{\eta}\right)^{4/3}$

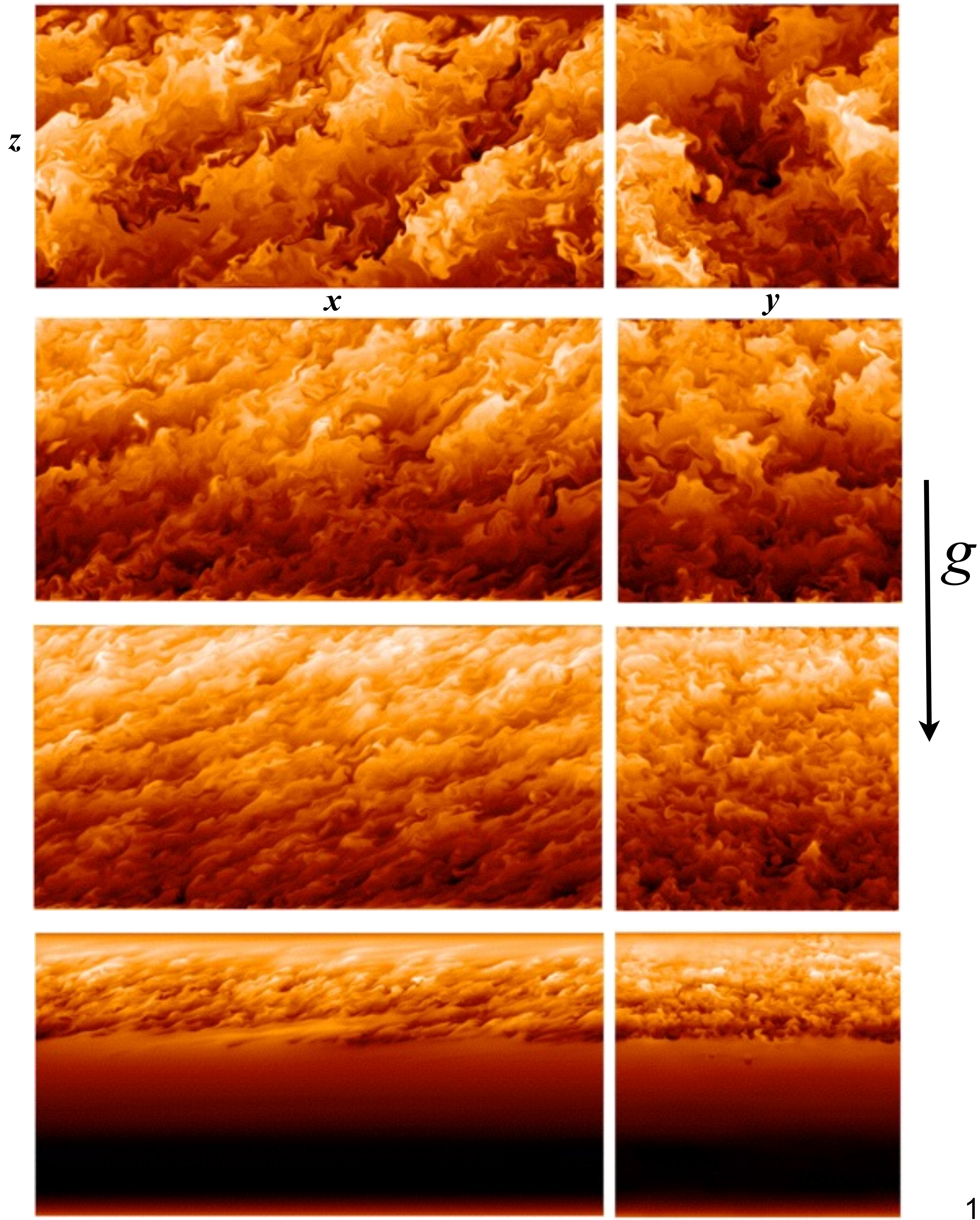
$L_* \equiv \frac{Lu_*}{\nu}$

$Ri = 0.026$
$Rf = 0.026$
$Re_b = 10^4$
$L_* = 10^4$

$Ri = 0.053$
$Rf = 0.062$
$Re_b = 10^3$
$L_* = 1500$

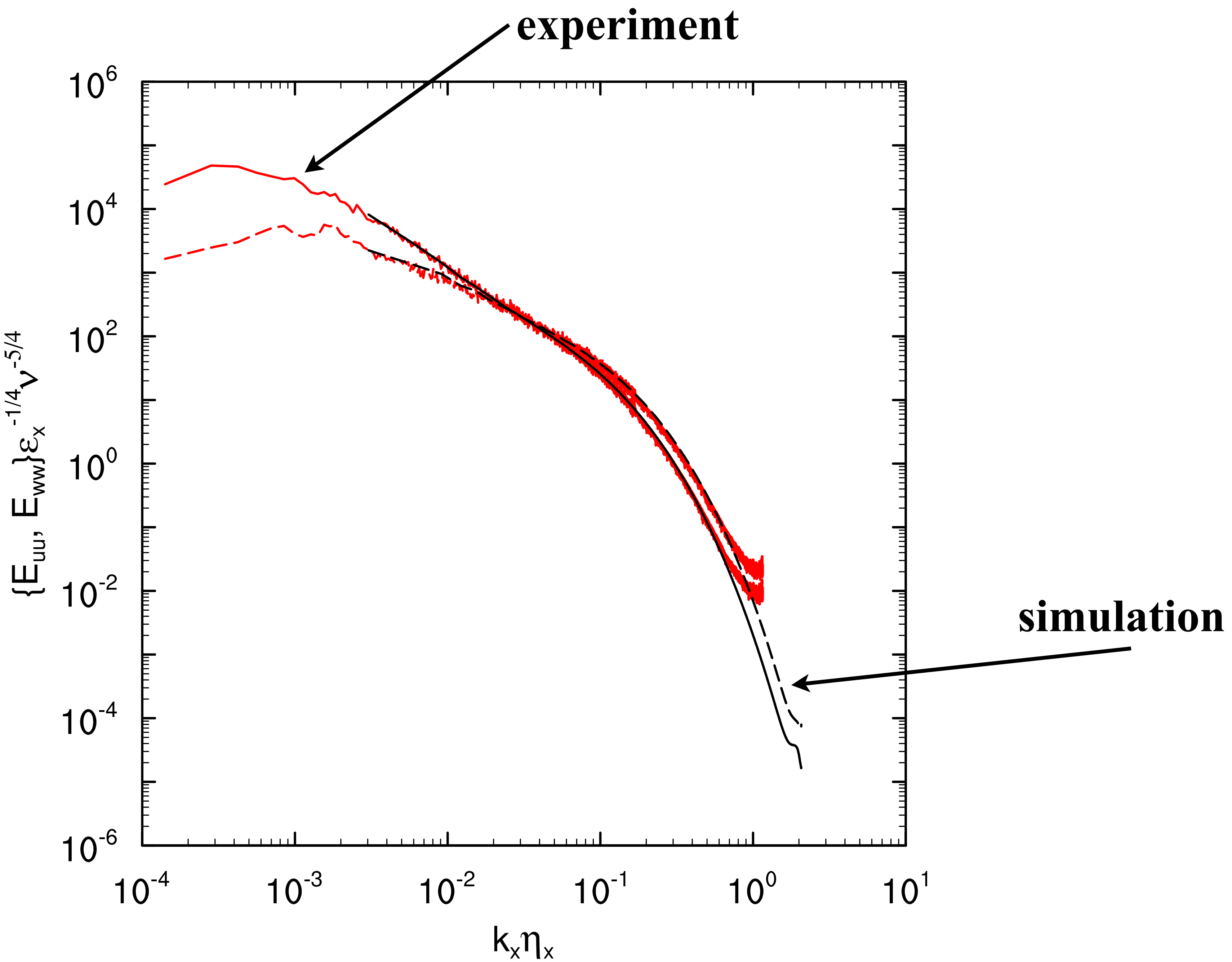
$Ri = 0.125$
$Rf = 0.134$
$Re_b = 10^2$
$L_* = 200$

$Ri = 0.157$
$Rf = 0.161$
$Re_b = 10$
$L_* = 30$



Validation

- Experiments of shear neutrally stratified turbulence by Isaza, Warhaft & Collins (2009)
  - $Re_\lambda = 450$, active grid
- Measurements in high-*Re* stratified flows under well-controlled conditions are not presently available



Monin–Obukhov theory interpretation of DNS results

- The simulation domain imposes a length scale to a flow that does not have an outer scale
- The group $\frac{L_z}{u_*}\frac{\partial \overline{u}}{\partial z}$ is a universal constant
- Use $\frac{\kappa z}{u_*}\frac{\partial \overline{u}}{\partial z} \equiv 1$ to define a confinement scale z

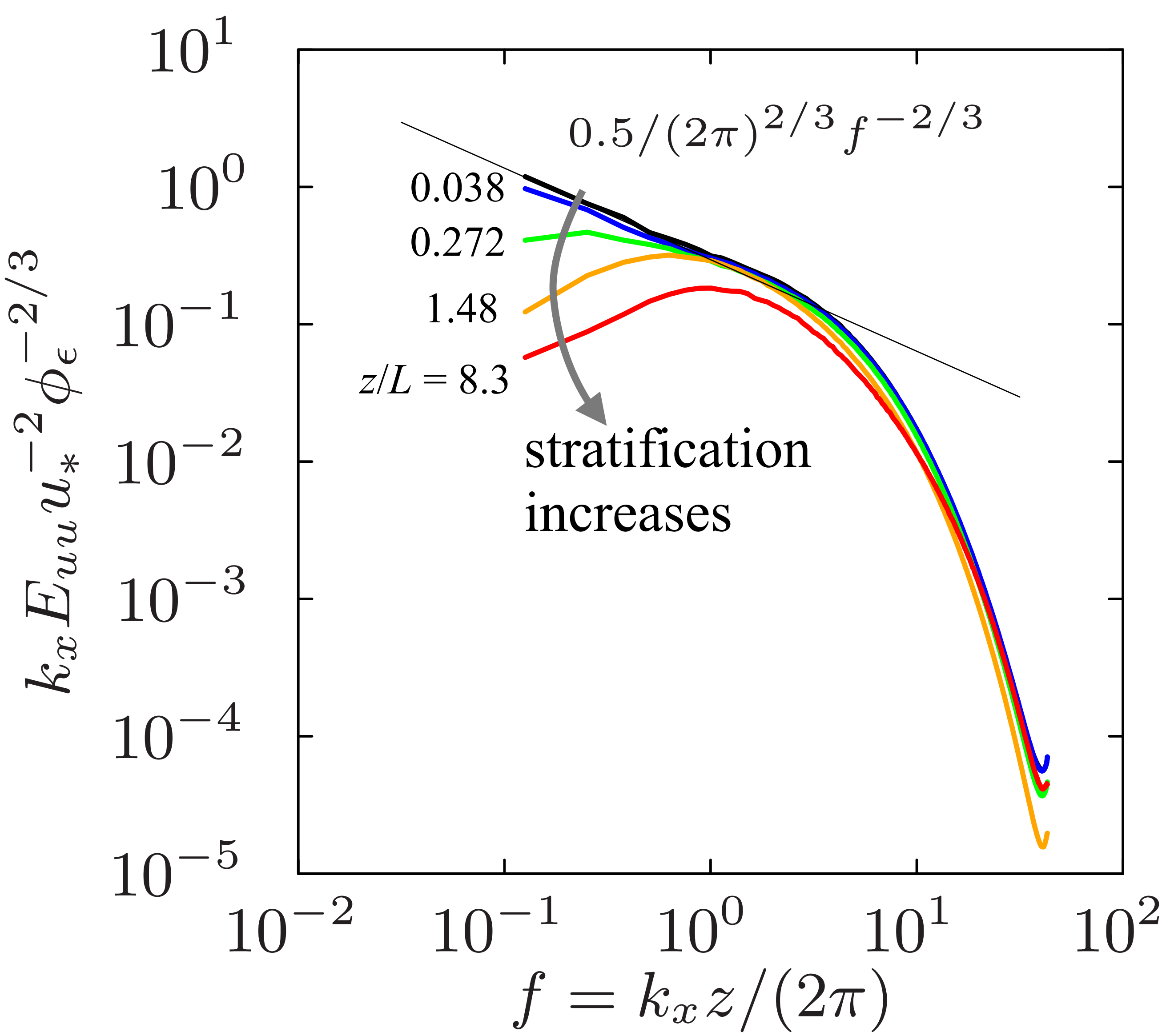
  in a similar way that the height z is a confinement scale for turbulent eddies in the atmospheric surface layer
  - Calculate confinement scale, z, from neutral stratification and use for all stratifications
- Assumption: $z_* \equiv \frac{z u_*}{\nu} \gg 1$ (current DNS: $z_* = 735$)
- Non-dimensional form of streamwise spectra

$$E_{uu}(k_x) = \alpha_1 \epsilon^{2/3} k_x^{-5/3} \longrightarrow \frac{k_x E_{uu}(k_x)}{u_*^2} = \frac{\alpha_1}{(2\pi\kappa)^{2/3}} \phi_\epsilon^{2/3} \left(\frac{k_x z}{2\pi}\right)^{-2/3} \qquad \phi_\epsilon \equiv \frac{\epsilon \kappa z}{u_*^3}$$

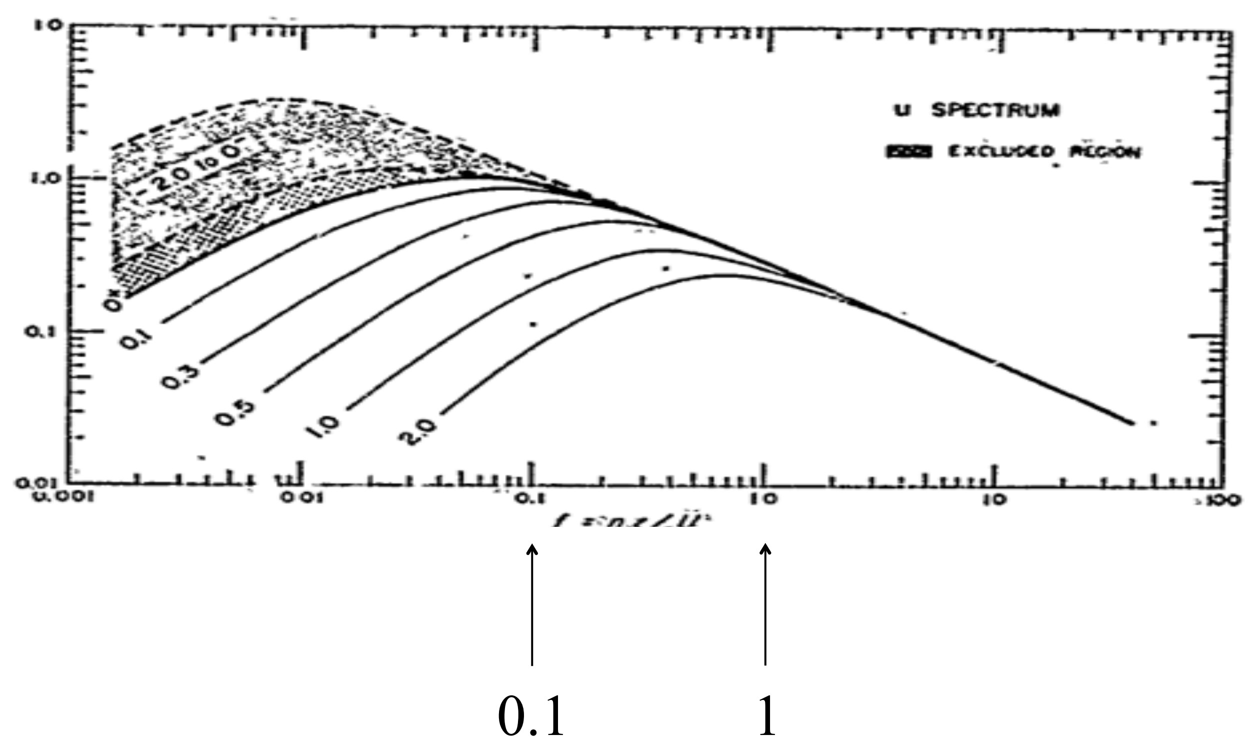
$$E_{bb}(k_x) = \beta_1 \epsilon^{-1/3} \chi\, k_x^{-5/3} \longrightarrow \frac{k_x E_{bb}(k_x)}{b_*^2} = \frac{\beta_1}{(2\pi\kappa)^{2/3}} \phi_\epsilon^{-1/3} \phi_\chi \left(\frac{k_x z}{2\pi}\right)^{-2/3} \qquad \phi_\chi \equiv \frac{\chi \kappa z}{u_* b_*^2}$$

Kaimal et al. (1972) scaling – Streamwise velocity

Stationary homogeneous stratified shear turbulence



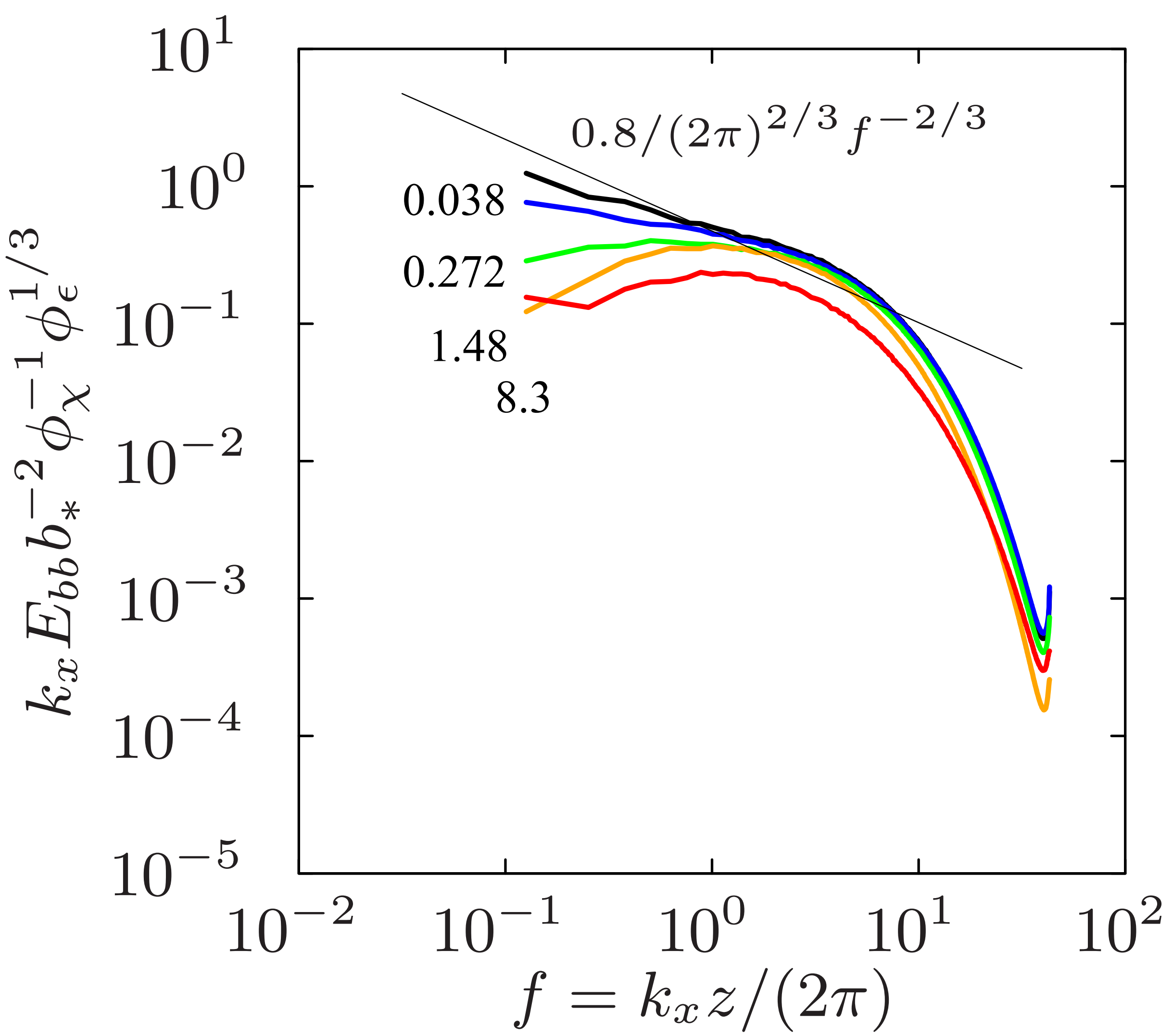
Atmospheric surface layer measurements



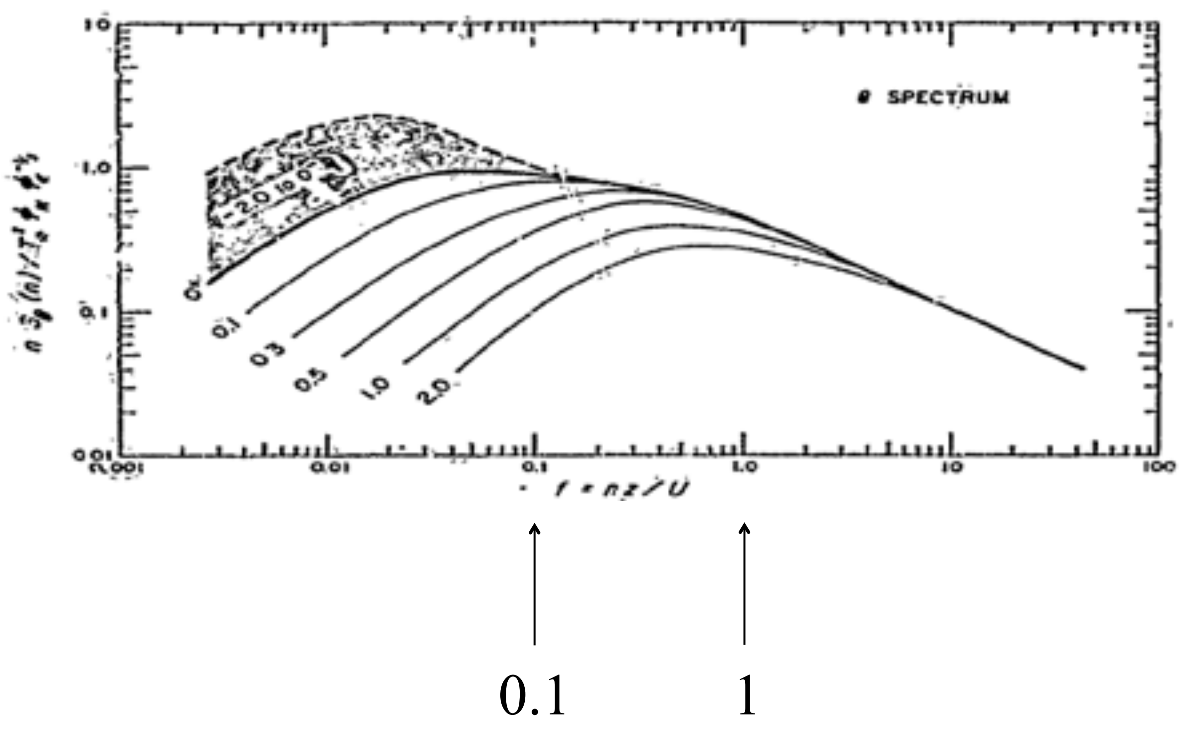
J. C. Kaimal, J. C. Wyngaard, Y. Izumi & O. R. Coté: 1972 Spectral characteristics of surface-layer turbulence, *Quart. J. R. Met. Soc.*, 98, 563–589.

Kaimal et al. (1972) scaling – buoyancy

Stationary homogeneous stratified shear turbulence



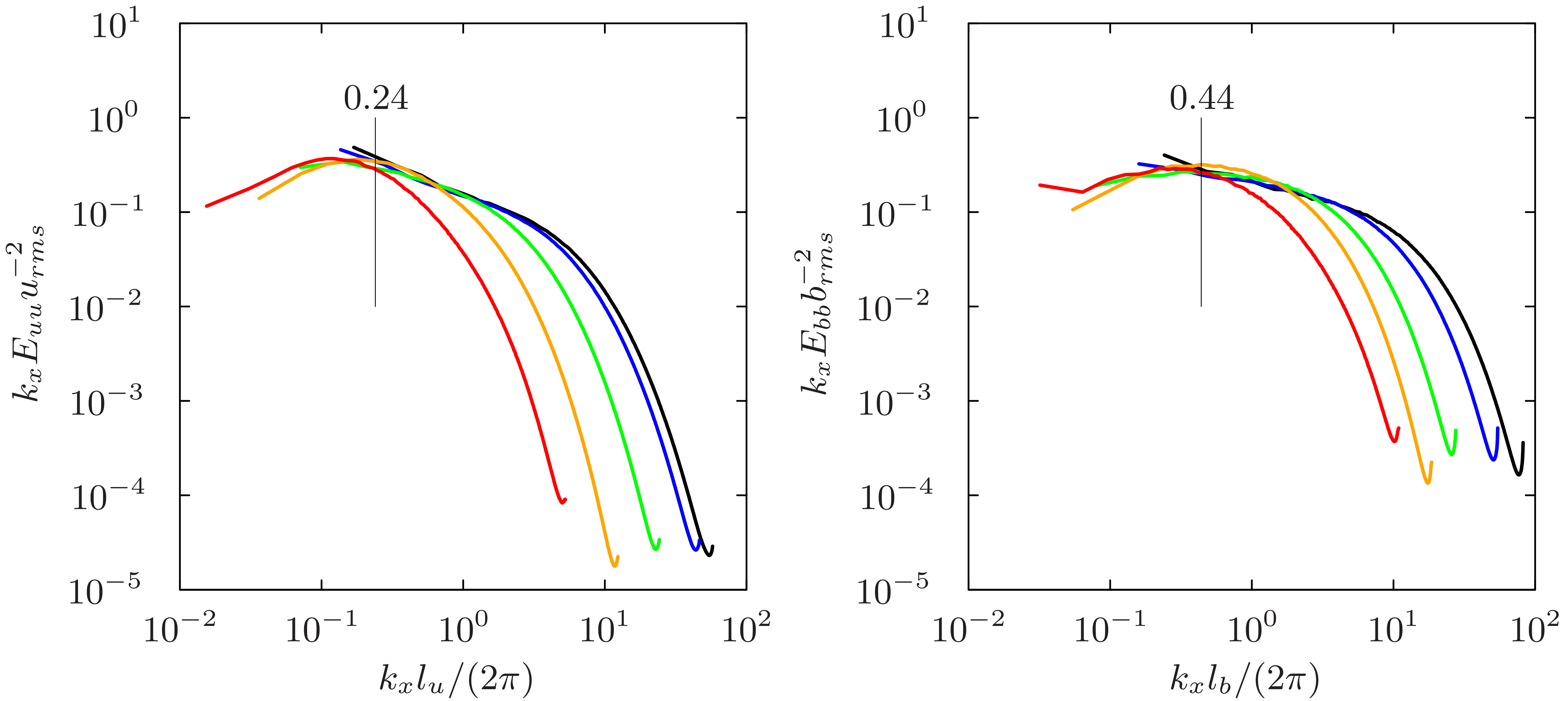
Atmospheric surface layer measurements



Scaling of the energy peaks

- Peak energy of premultiplied spectra scale with
- Similar to measurements of Kaimal et al. (1972)

$$l_u \equiv \frac{u_{rms}^3}{\epsilon} \qquad l_b \equiv \frac{b_{rms}^3 \epsilon^{1/2}}{\chi^{3/2}}$$



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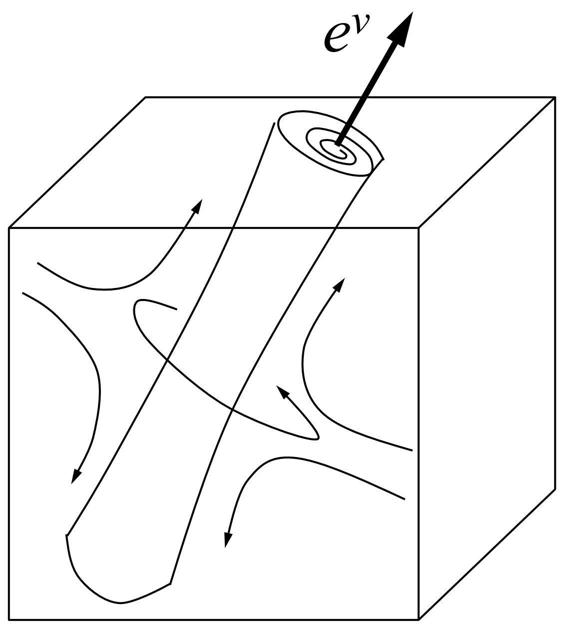
Images: NASA, B. Stevens, Chung & Matheou

Stretched vortex LES–SGS model

- Stretched-vortex LES–SGS model (Misra & Pullin 1997; Pullin 2000)
  - Structural LES–SGS closure
  - Good past performance for neutral and unstably stratified flows
    - Voelkl et al. 2000; Kosovic et al. 2002; Hill et al. 2006; Pantano et al. 2008; Chung & Pullin 2009; Matheou et al. 2010; Inoue et al. 2012
  - Excellent SGS anisotropic properties

- Develop a "stability correction" to capture stably and unstably stratified turbulence
- Aim is to capture two main effects
  - Decrease of TKE as stratification increases
  - Increase of anisotropy
    - Reduction of vertical length scales as stratification increases
- Retain the physics-based character of the closure

Stretched-vortex SGS model – neutral conditions



- The closure is based on two main assumptions
  - Representation of the subgrid motions including scalar fields
  - Estimate of the local subgrid kinetic energy
- Subgrid motion is represented by an ensemble of nearly axisymmetric vortical structures (Pullin & Saffman 1994)
- Assume a single vortex with orientation e^v: $\tau_{ij} = \rho K(\delta_{ij} - e_i^v e_j^v)$
- e^v is the largest extensional eigenvector of the rate of strain tensor
- K is the subgrid kinetic energy per unit mass: $K = \int_{\pi/\Delta}^{\infty} E(k)\mathrm{d}k$
- Subgrid scalar flux: $\sigma_i = -\rho \frac{\Delta}{2} K^{1/2} (\delta_{ij} - e_i^v e_j^v) \frac{\partial \tilde{\theta}}{\partial x_j}$
- Lundgren (1982) stretched-spiral vortex: $E(k) = K_0 \epsilon^{2/3} k^{-5/3} \exp[-2k^2 \nu / 3(|\tilde{\alpha}|)]$
- Estimate product of Kolmogorov prefactor and dissipation: $K_0 \epsilon^{2/3} = \frac{\tilde{F}_2}{A_s \Delta^{2/3}}$
  - Second-order velocity structure function: F_2

Adjustment for stably stratified turbulence

- Modify SGS TKE and length scale (but assume same tensorial form)

$$K_s = f_K K \qquad \Delta_s = f_\Delta \Delta$$

where f_k and f_Δ are functions that depend on stability

- Stationary and homogeneous SGS TKE equation

$$0 = \overline{\theta u_3} - \epsilon_{sgs} - \tau_{ij} \frac{\partial \tilde{u}_i}{\partial x_j}$$

- Substitute buoyancy flux and SGS tensor expressions

$$0 = -\frac{\Delta_s}{2} K_s^{1/2} (\delta_{3j} - e_3^v e_j^v) \frac{\partial \tilde{\theta}}{\partial x_j} - \epsilon_{sgs} - K_s (\delta_{ij} - e_i^v e_j^v) \frac{\partial \tilde{u}_i}{\partial x_j}$$

$$0 = -\frac{\Delta_s}{2} K_s^{1/2} N_v^2 - \epsilon_{sgs} - K_s S_v$$

- Define SGS vortex gradient Richardson number

$$Ri_v = \frac{N_v^2}{S_v^2}$$

  – *Ri_v depends on vortex orientation*

SGS TKE–length scale relation

- Dissipation as a function of 'large-scale' variables (Taylor 1935)

$$\epsilon_{sgs} = \frac{K_s^{3/2}}{\kappa_v \Delta_s}$$

- Determine κ_v by matching to neutral stratification (κ_v is a generalized von Karman constant)

$$\frac{\kappa_v \Delta}{K^{1/2}} S_v = 1$$

- Define an Obukhov length

$$L_v \equiv \frac{K_s^{3/2}}{-\kappa_v \overline{\theta u_3}} = \frac{K_s}{\kappa_v (\Delta_s / 2) N_v^2}$$

  - L_v depends on the orientation of the vortex
  - $\Delta_s^{1/2} L_v^{1/2} \sim K_s^{1/2} / N_v$ where $K_s^{1/2} / N_v$ is the vortex-based buoyancy scale
  - consistent with $l_m^{1/2} L^{1/2} \sim l_b$

- Relation between SGS TKE and length scale

$$\left(\frac{K}{K_s}\right)^{1/2} = \frac{\kappa_v \Delta}{K_s^{1/2}} S_v = \frac{\Delta}{L_v} + \frac{\Delta}{\Delta_s}$$

- Unstable stratification: $\Delta_s = \Delta$ and $f_\Delta = 1$, i.e. the largest scale is confined by Δ

$$K_s = f_K K = \frac{1}{(1+\zeta_v)^2} K \qquad \zeta_v \equiv \Delta / L_v \longleftarrow \textbf{stability parameter}$$

Stability correction functions for stable stratification

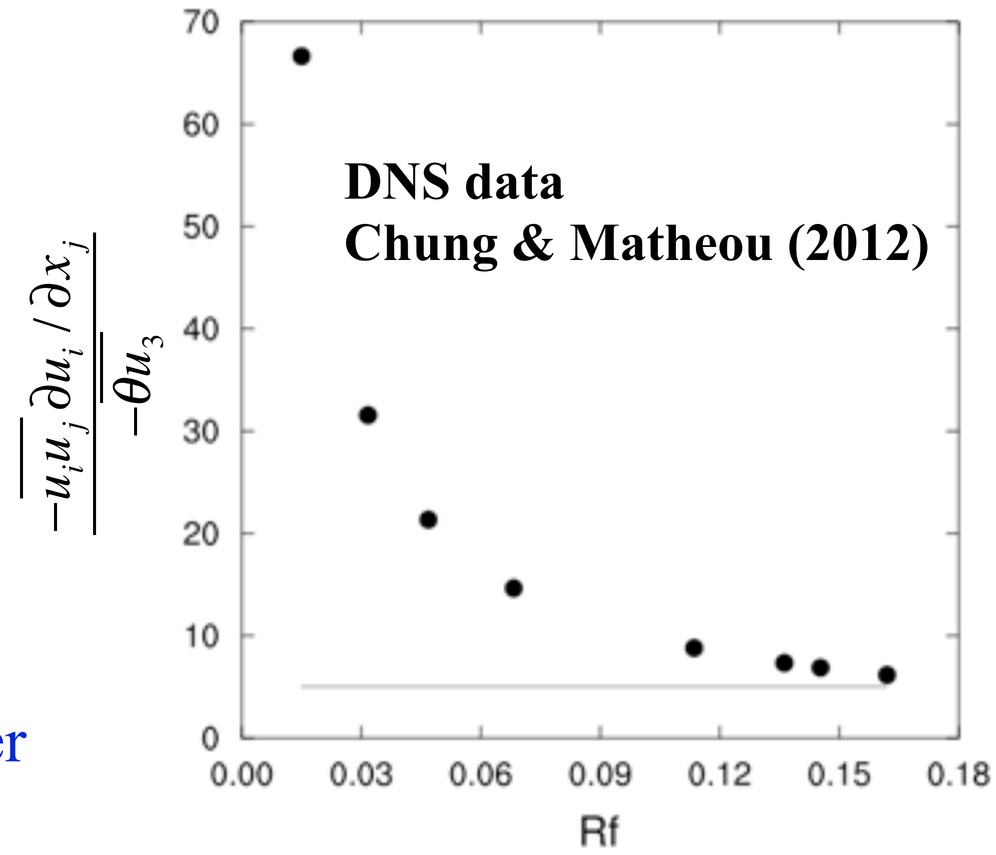
- Main model assumption:

$$\frac{1}{\Delta_s} = \frac{1}{\Delta} + (\alpha - 1)\frac{1}{L_v} \qquad \Delta_s = f_\Delta(\zeta_v)\Delta = \frac{1}{1+(\alpha-1)\zeta_v}\Delta$$

- The model constant α only affects the strongly stratified regime
  – How fast overturning motions are damped as $\zeta_v \to \infty$, that is:

$$\alpha \sim \frac{\kappa_v}{K_s^{1/2} S_v L_v} \sim \frac{K_s S_v}{-\overline{\theta u_3}} \sim \frac{-\overline{u_i u_j}\,\partial u_i / \partial x_j}{-\overline{\theta u_3}}$$

  – DNS implies a value $\alpha \approx 5$



- Stability correction for TKE:

$$K_s = f_K(\zeta_v)K = \frac{1}{(1+\alpha\zeta_v)^2}K$$

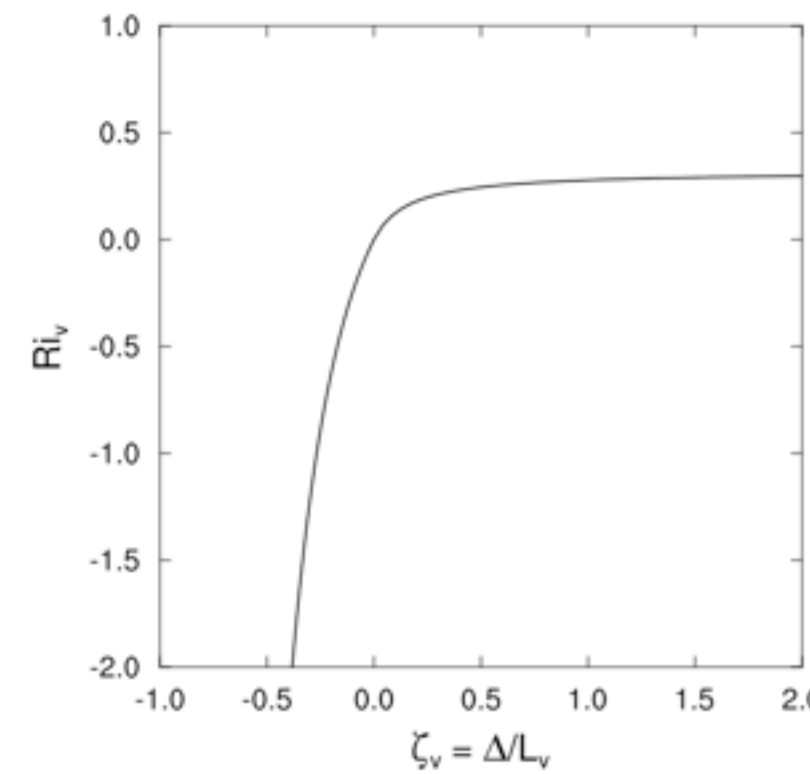
- ζ_v is a function of the SGS vortex Richardson number

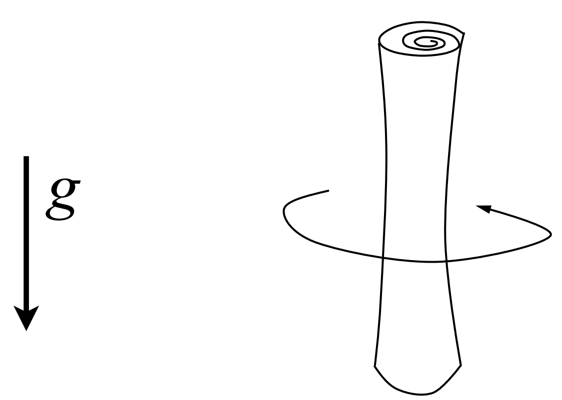
$$\frac{Ri_v}{\kappa_v} = \frac{2\zeta_v[1+(\alpha-1)\zeta_v]}{[1+\alpha\zeta_v]^2} \qquad \text{for } \zeta_v > 0$$

Physical interpretation – anisotropy of SGS motions

- Ri_v depends on vortex orientation

$$Ri_v = \frac{N_v^2}{S_v^2} = \frac{(\delta_{3j} - e_3^v e_j^v)\dfrac{\partial \tilde{\theta}}{\partial x_j}}{\left[(\delta_{ij} - e_i^v e_j^v)\dfrac{\partial \tilde{u}_i}{\partial x_j}\right]^2}$$

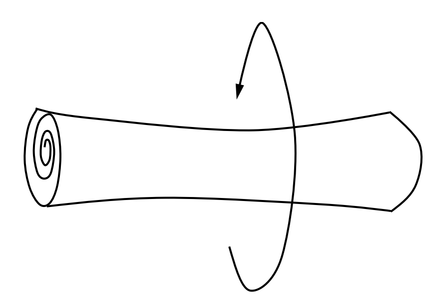




$N_v = 0$

$Ri_v = 0$

pancake eddies



$N_v = \max$

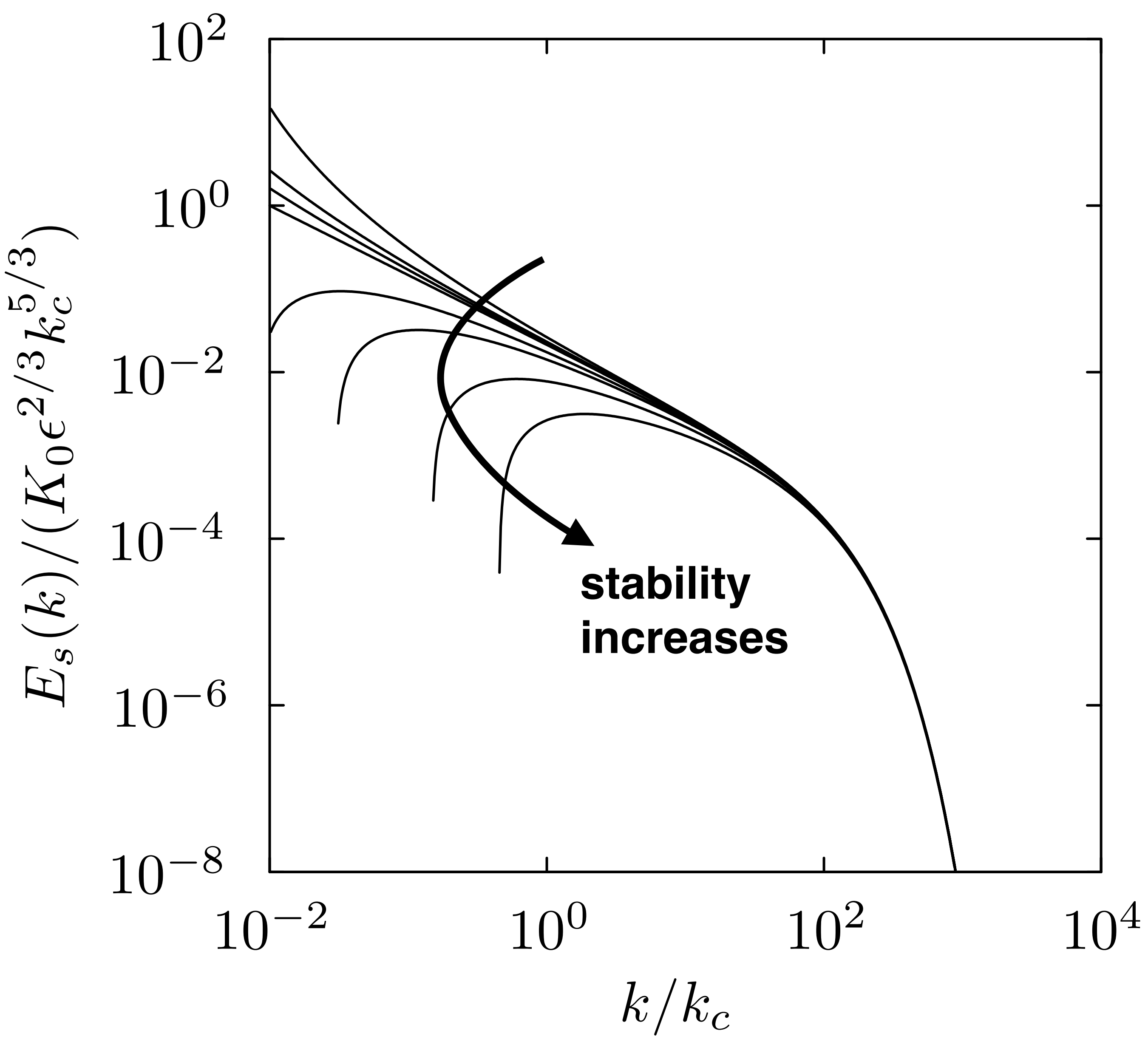
$Ri_v = \max$

SGS motions must work against stratification

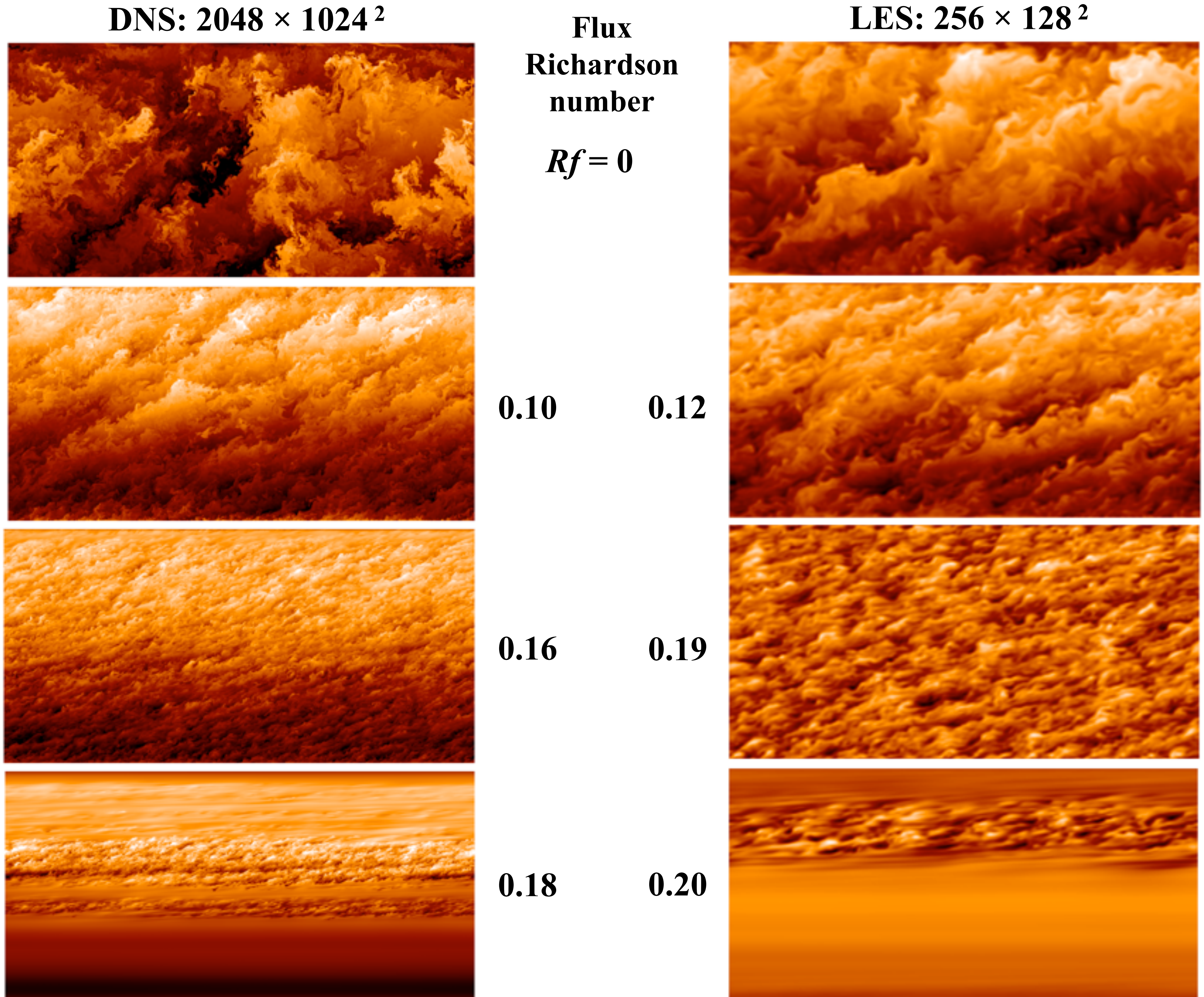
- SGS closure remains local and dynamic
- No adjustable parameters

Modification to the SGS spectrum

- Buoyancy affects low wavenumbers in stratified flows
- The Lundgren energy spectrum must be modified to correspond to the adjusted SGS TKE



Homogeneous stratified sheared turbulence



LES of atmospheric boundary layers

- Consider variable atmospheric conditions
- Use identical model setup
- Compare against theory, observations, previous model results
- Look for grid convergence
  - Grid aspect ratio = 1, i.e., $\Delta x = \Delta y = \Delta z$

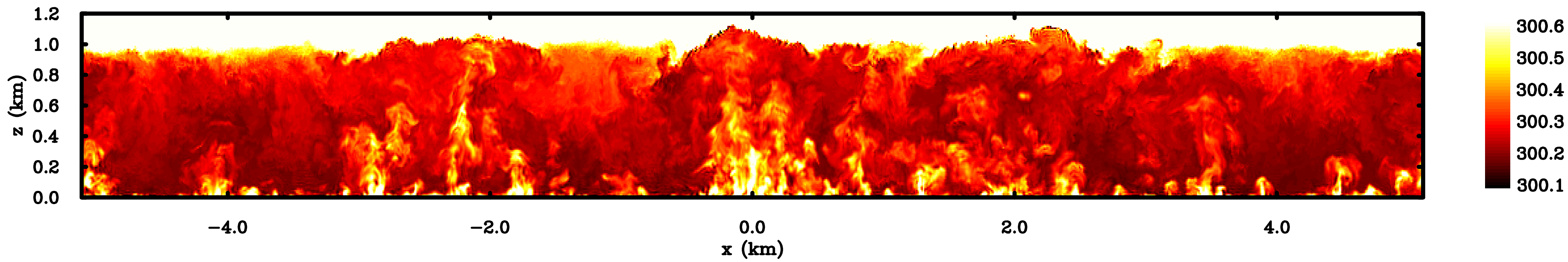
Numerical approximation of PBL LES

- Computational domain is a box, e.g. 20 × 20 × 4 km^3 (zonal × meridional × height)
  - Periodic horizontal directions
  - Impermeable top and bottom planes
  - Sponge region near the top to minimize gravity wave reflection
- Staggered "Arakawa C" grid
- Fourth-order fully-conservative finite difference scheme of Morinishi et al. (1998) adapted for the anelastic approximation
  - Non-dissipative
  - Conserves kinetic energy and variance for scalars
- An MC flux-limited scheme is used for rain advection to preserve conservation of water (Van Leer 1977)
- QUICK advection (Leonard 1979) for scalars in stratocumulus
- Exact Poisson solver using discrete Fourier transforms (Schumann 1985)
- Third-order Runge–Kutta of Spalart et al. (1991) for time marching

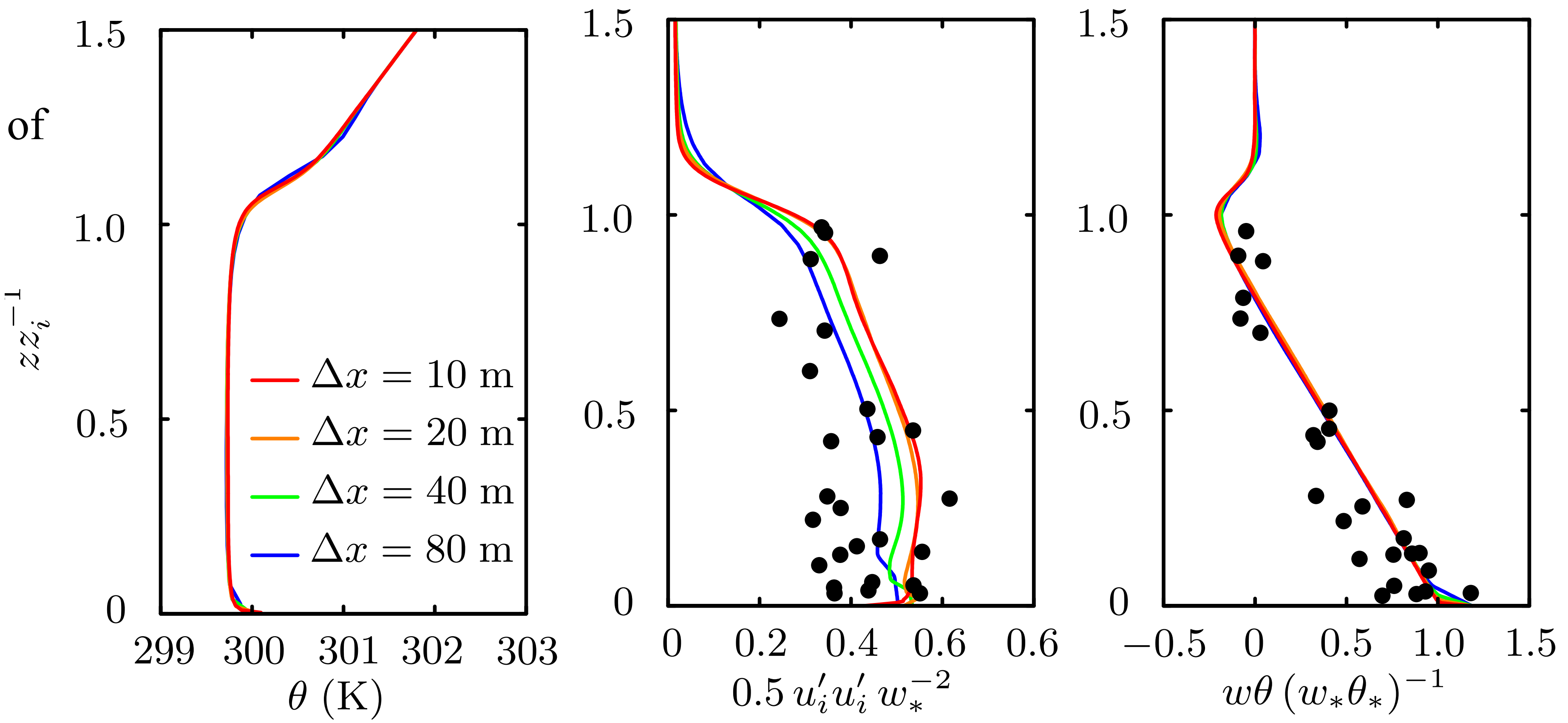
Convective boundary layer

- 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

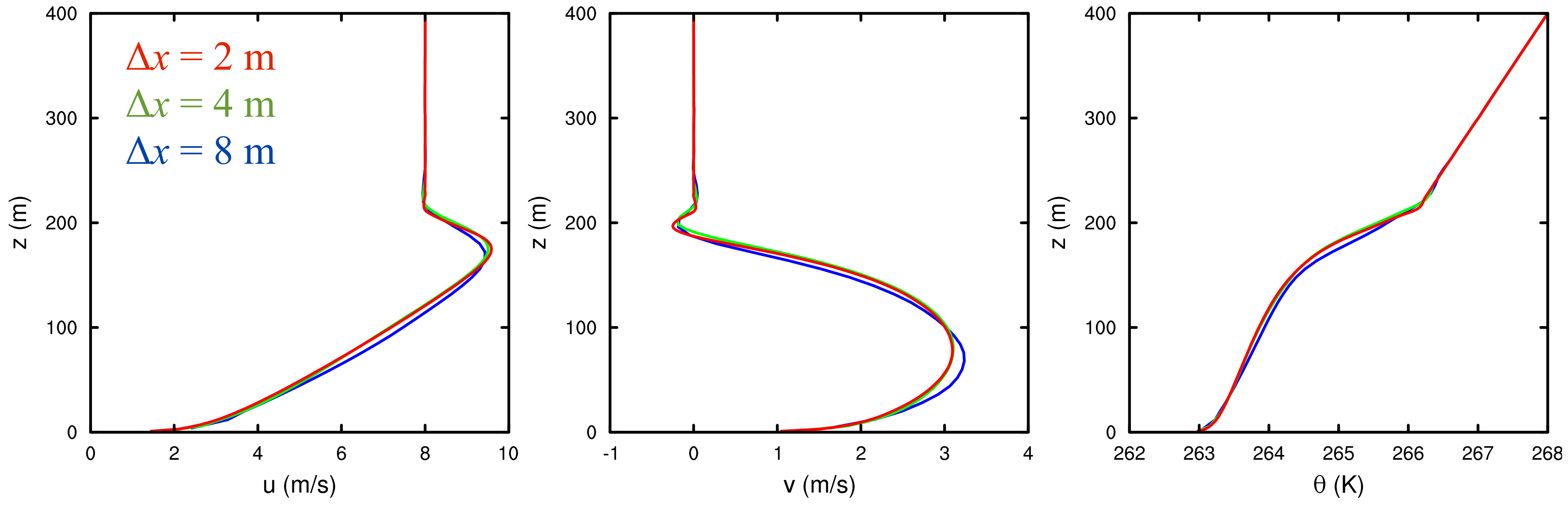


Circles: Measurements of Lenschow et al. (1980)



Stable atmospheric boundary layer

- A moderately stable arctic boundary layer, 1st GABLS (Beare et al. 2006)
  - Surface cooling, shear, stratification and planetary rotation (73˚ N)



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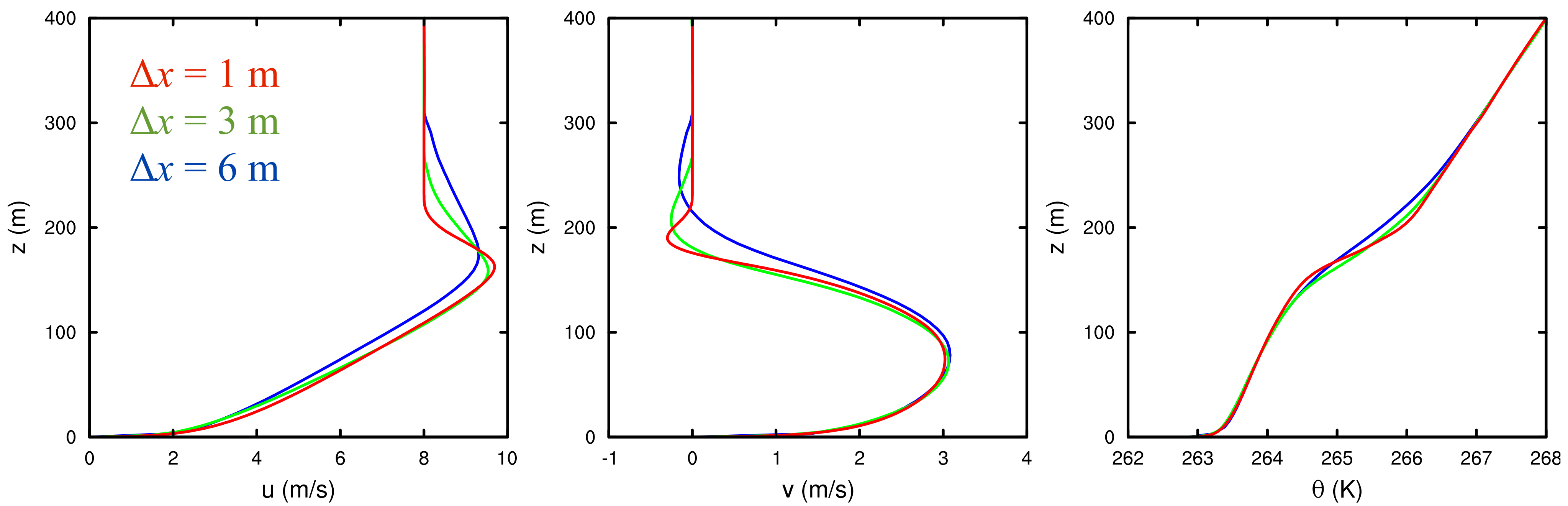
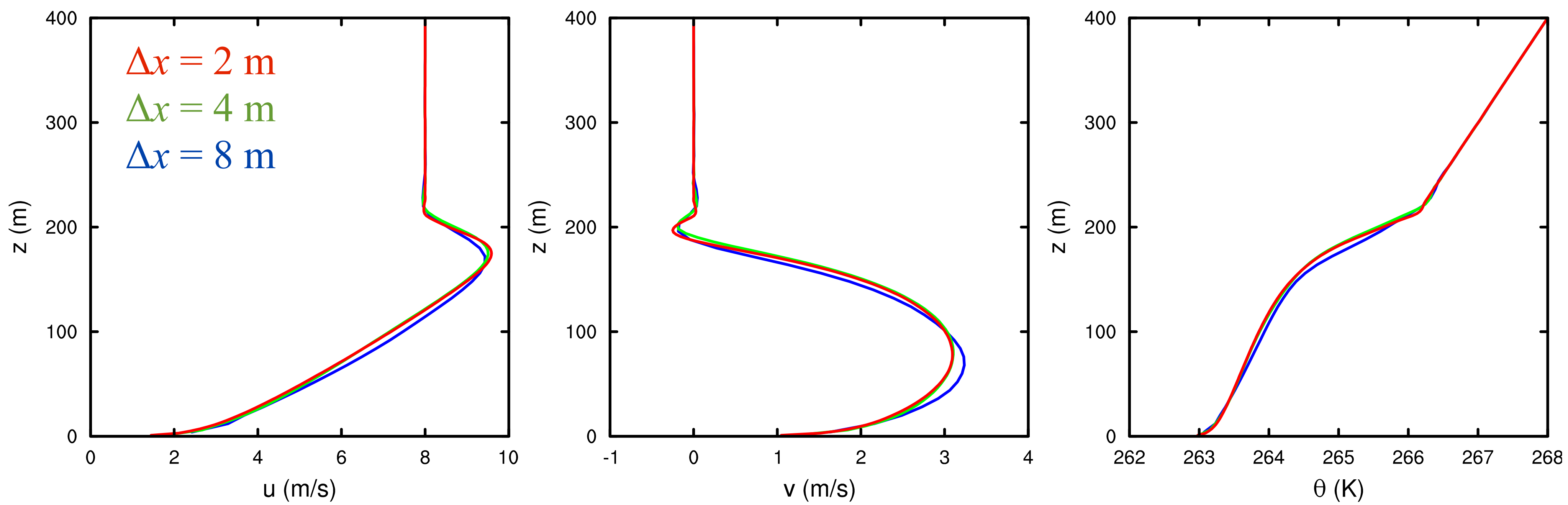
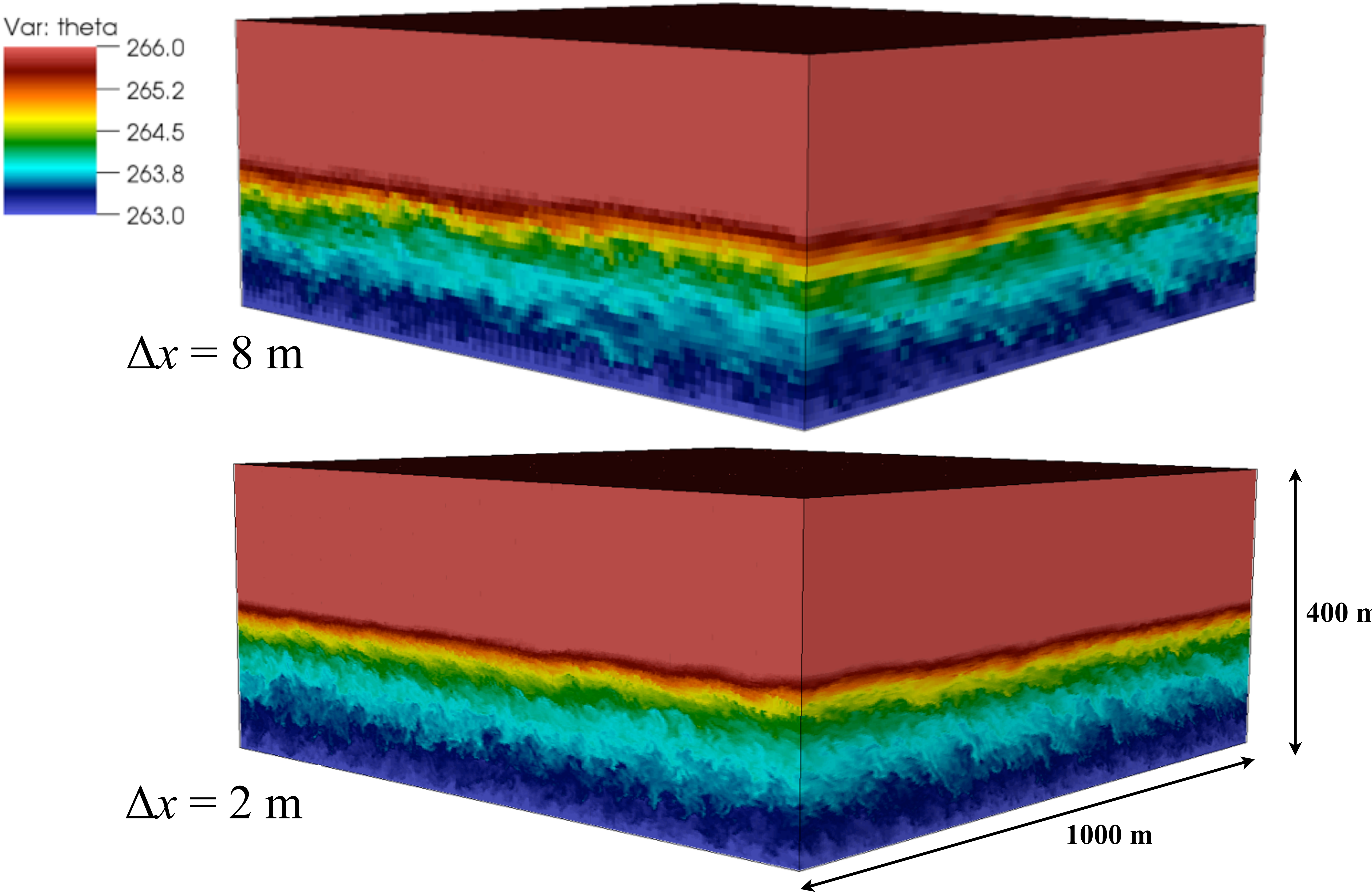
a model in Beare et al. (2006)



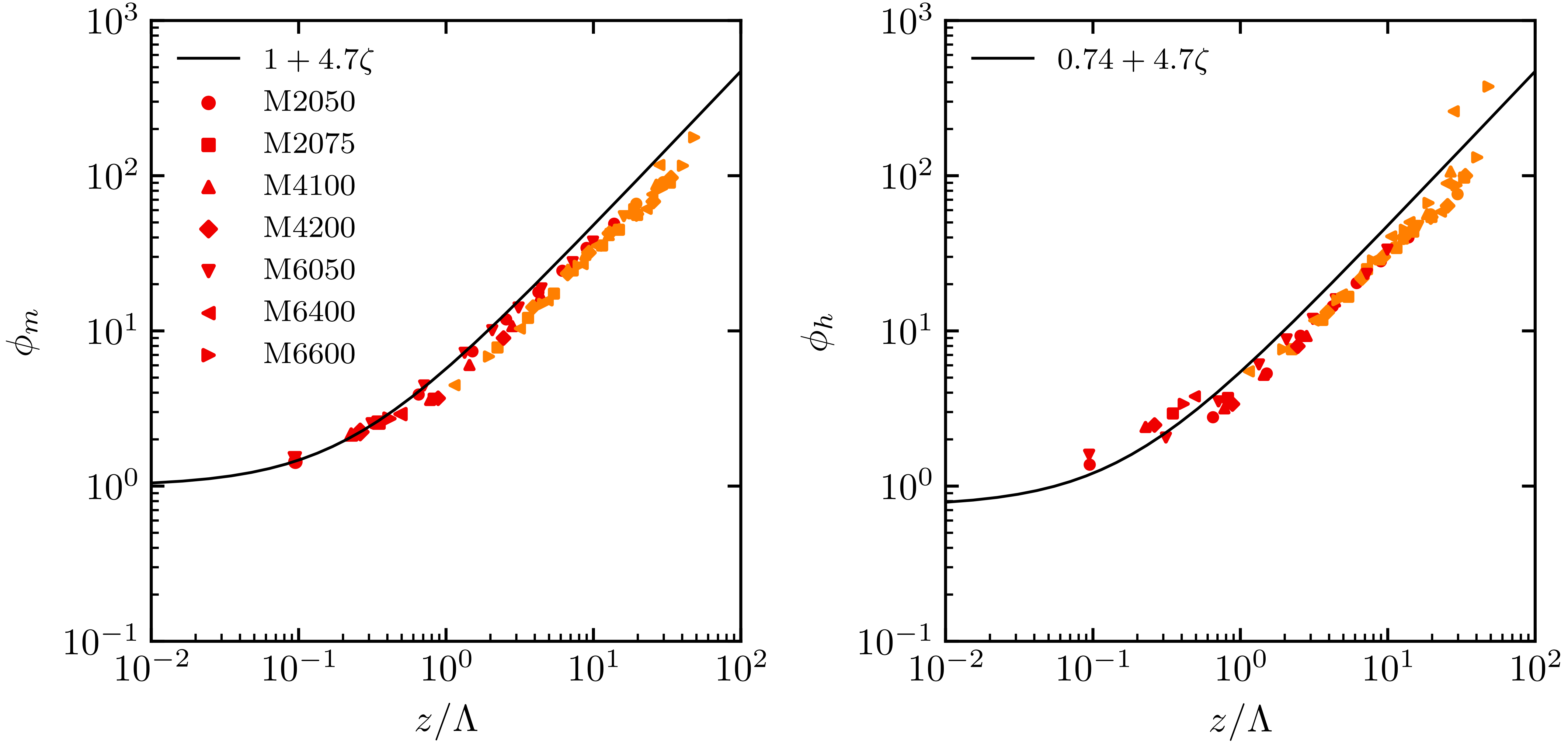
Present LES



Potential temperature field at two grid resolutions

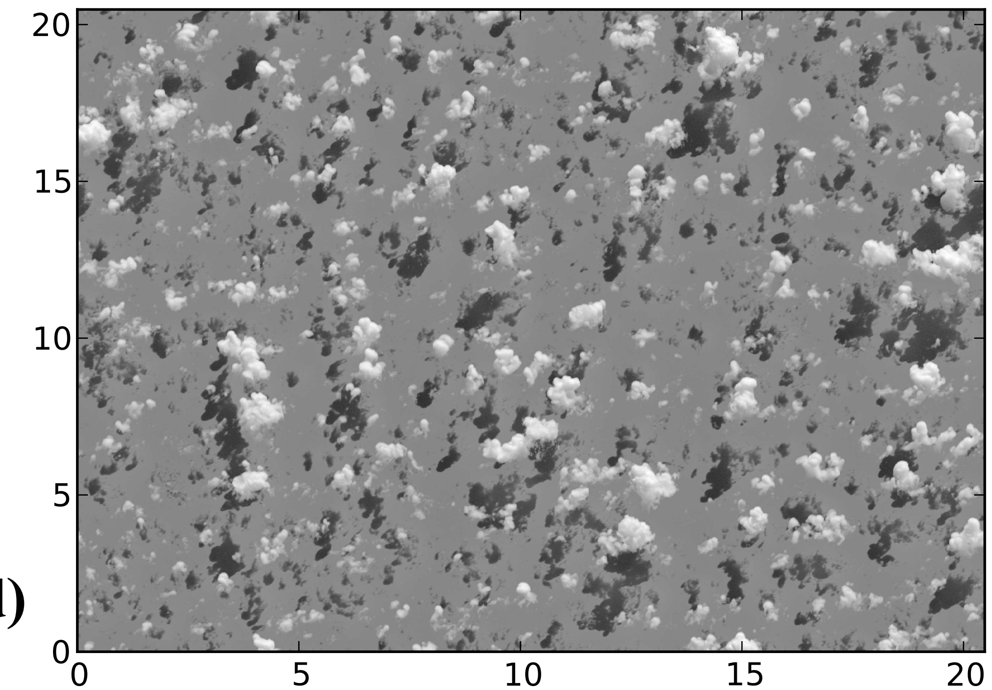


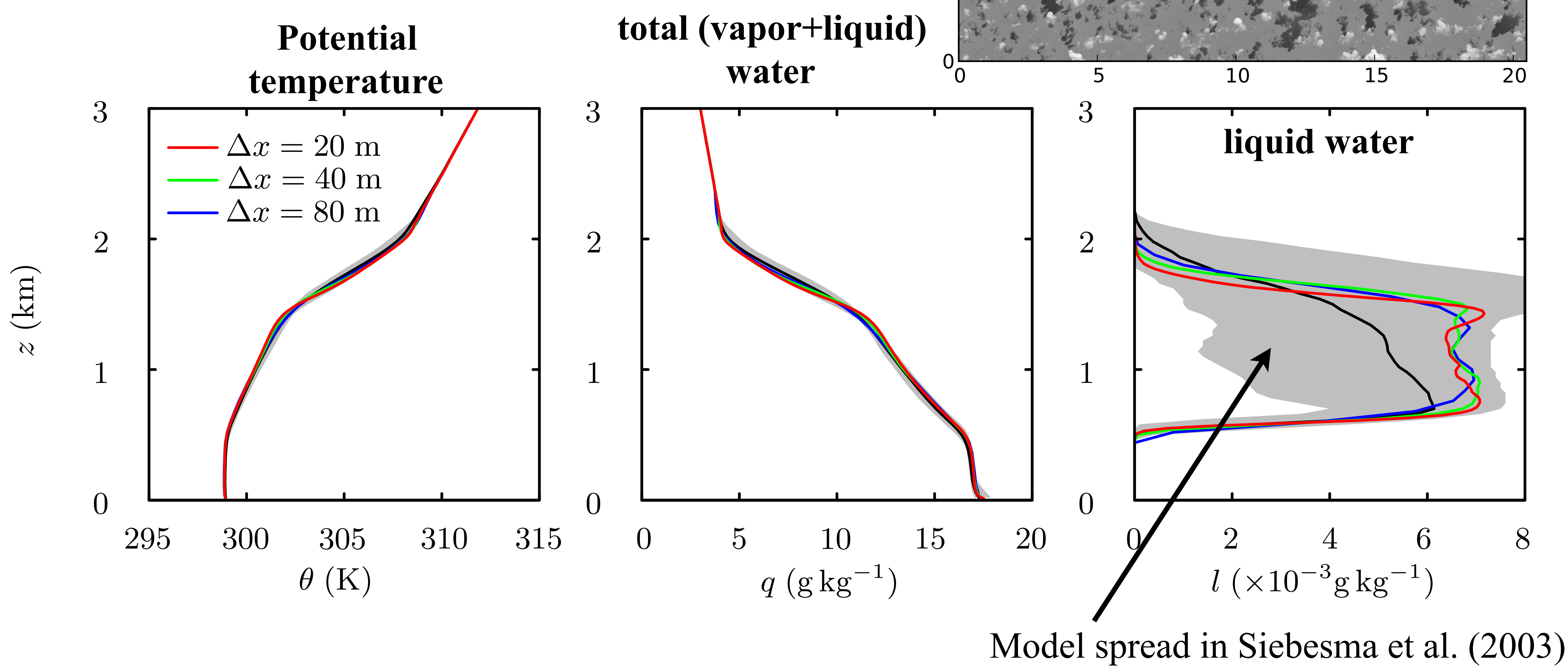
Monin-Obukhov local scaling



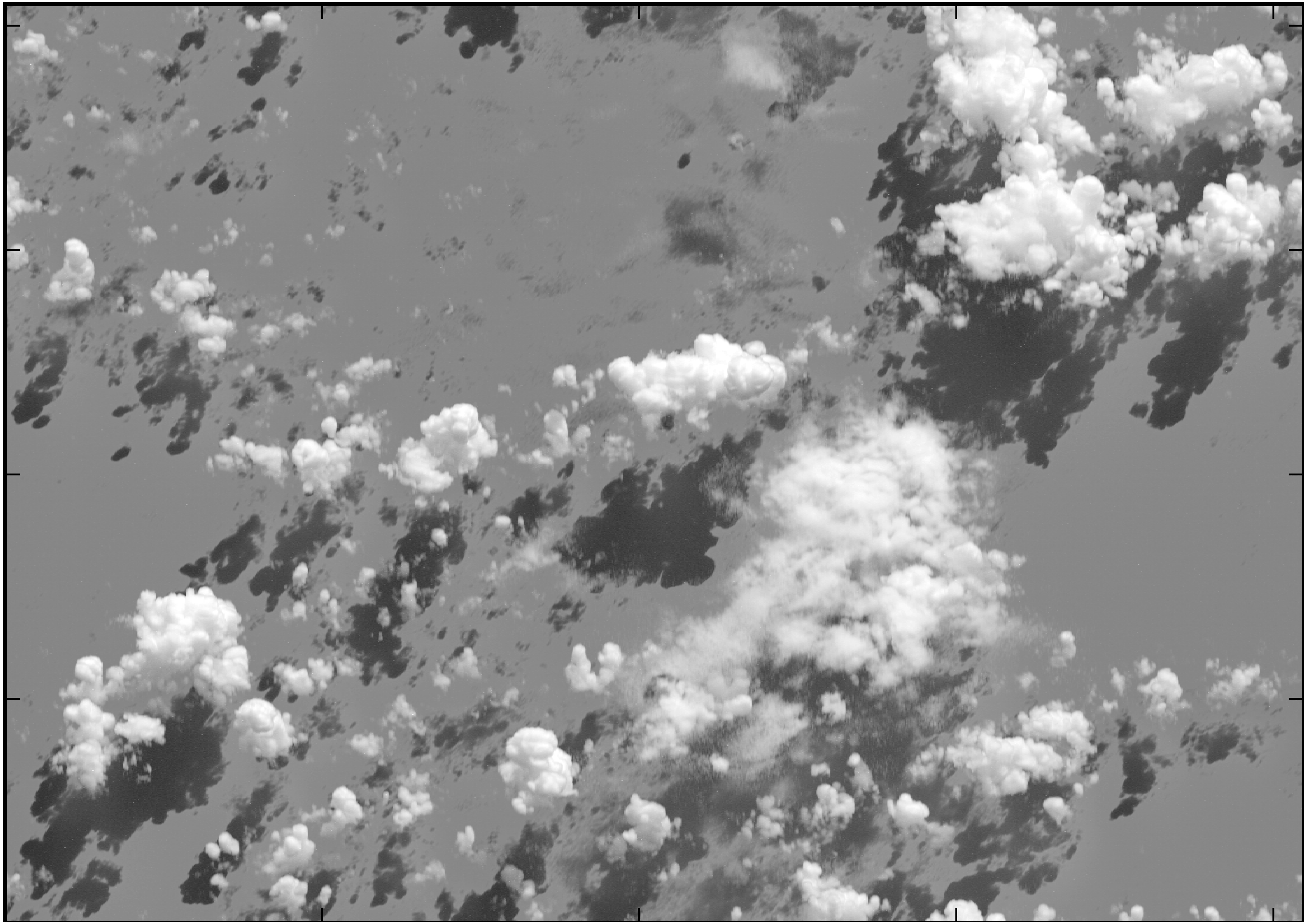
Shallow cumulus: conditionally unstable boundary layer

- Trade wind boundary layer
  - Shallow cumulus (non-precipitating)
  - BOMEX model inter-comparison study (Siebesma et al. 2003)

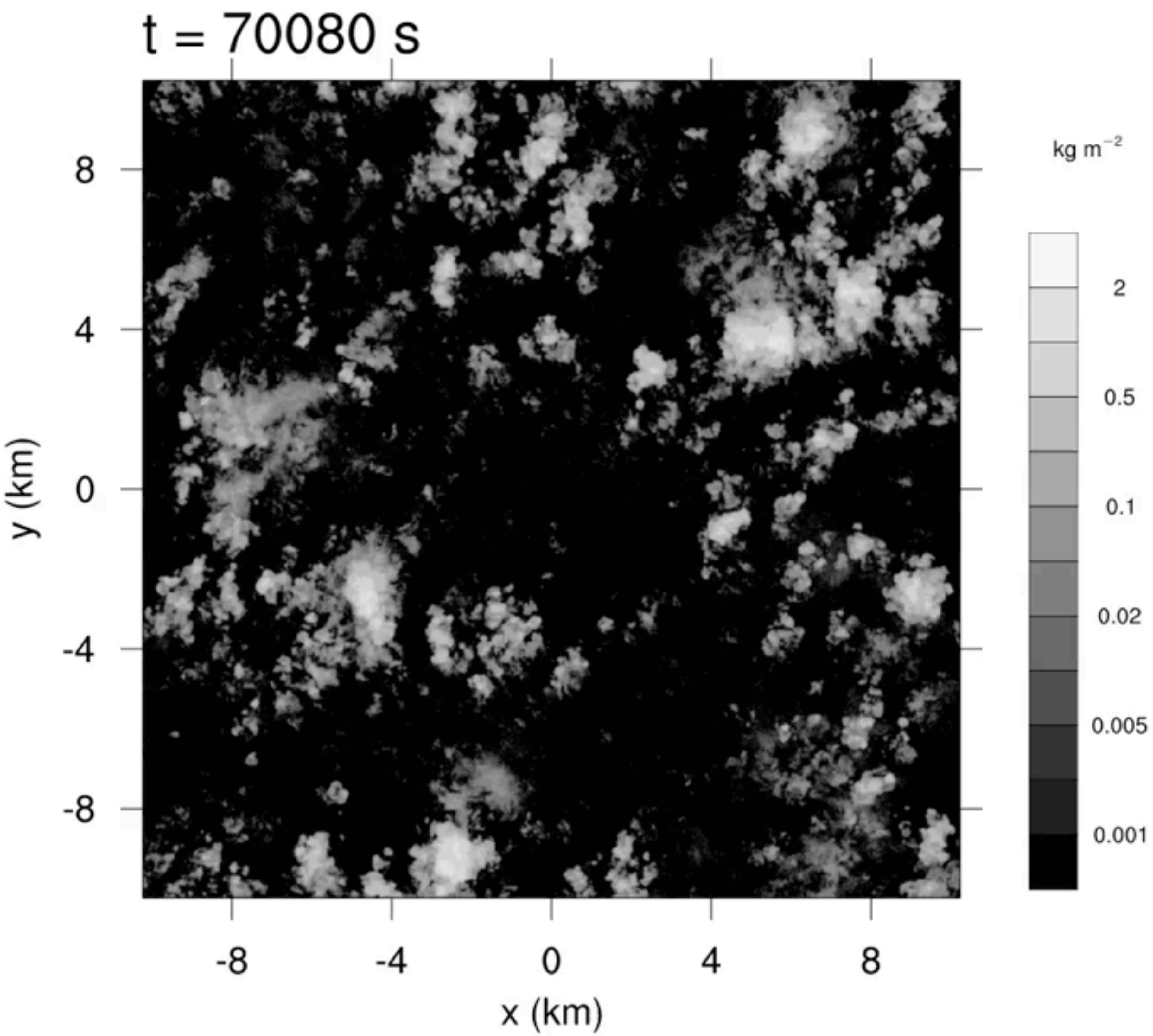




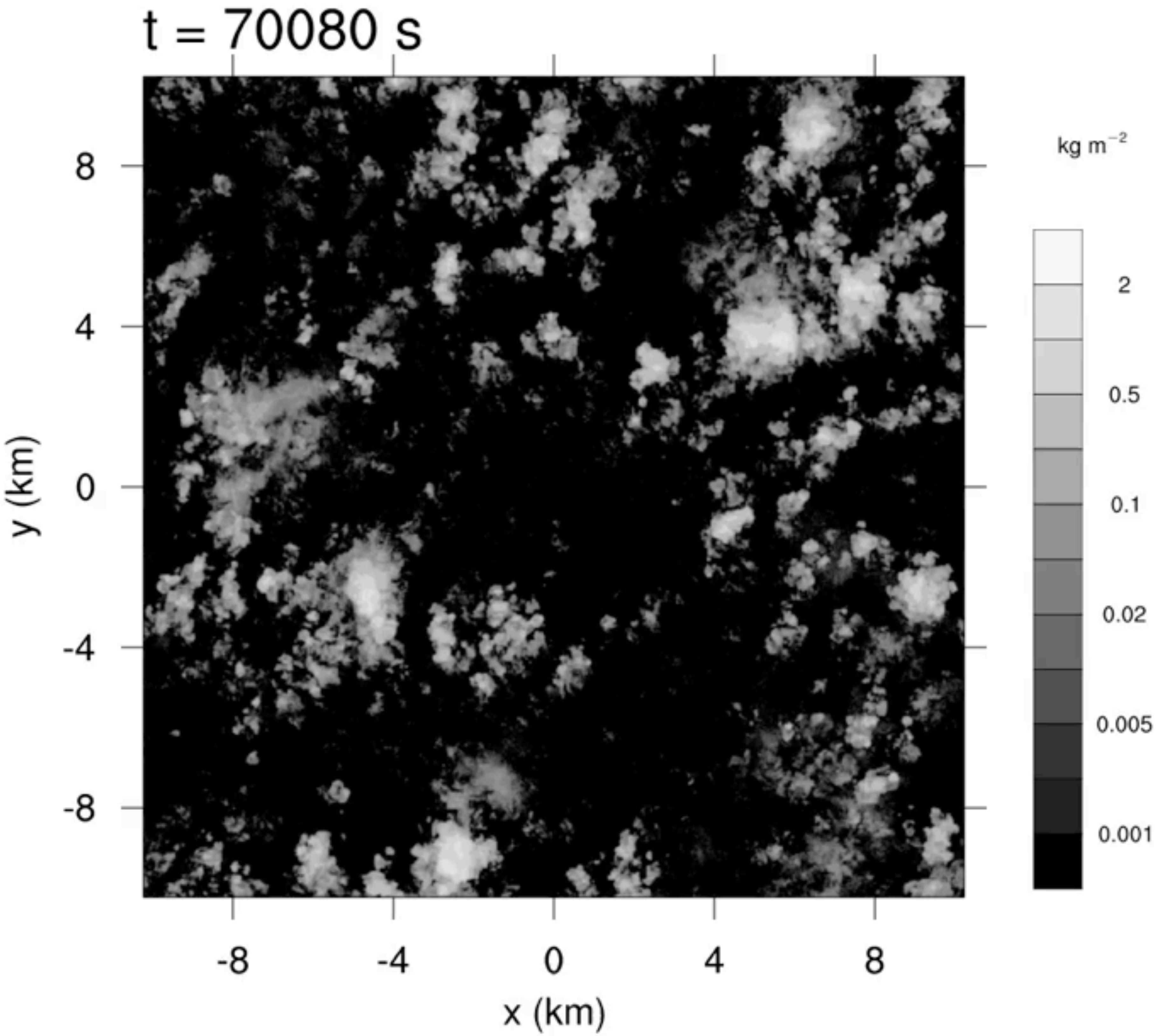
Precipitating shallow cumulus



Evolution of the cloud field



Evolution of the cloud field

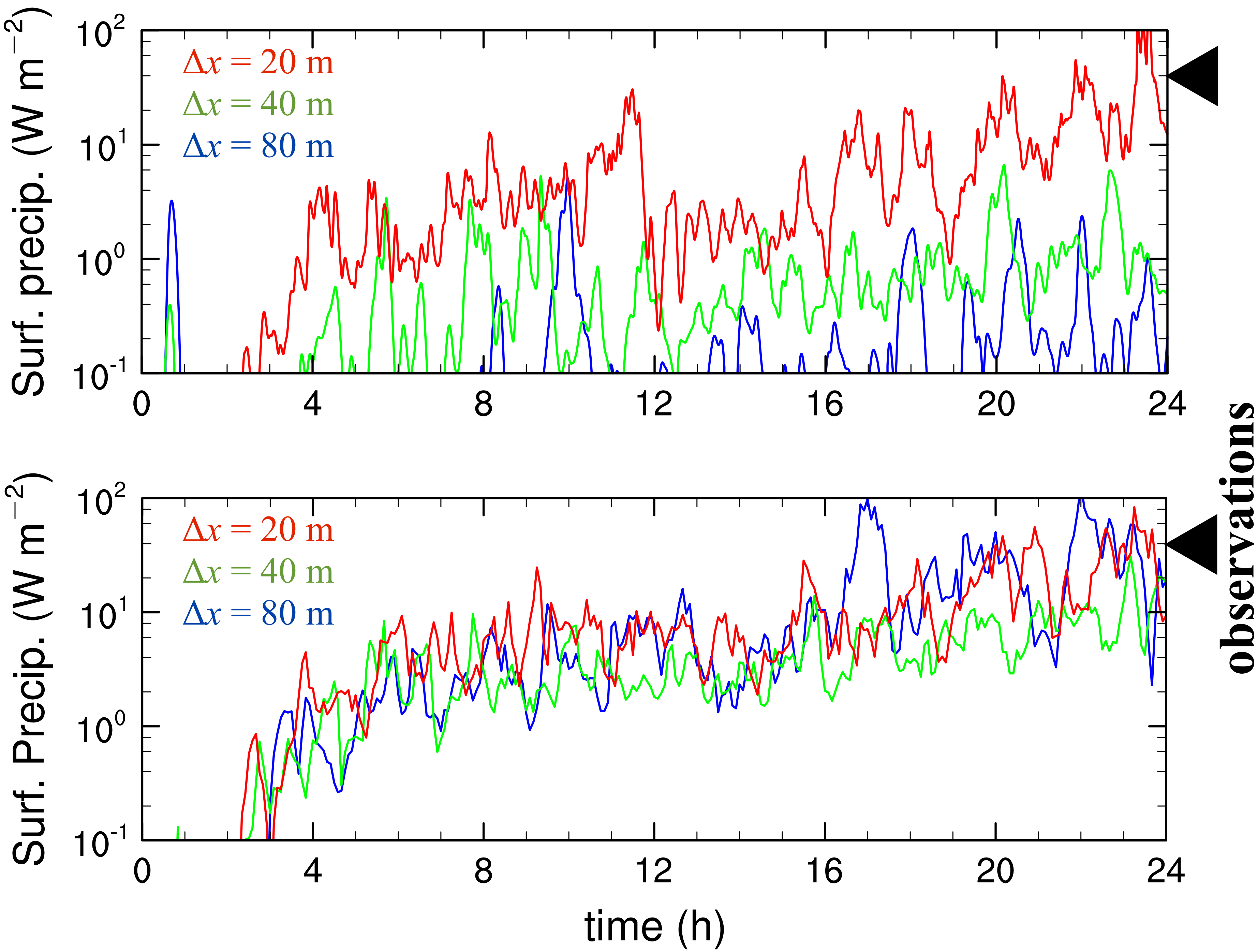


Precipitating shallow cumulus

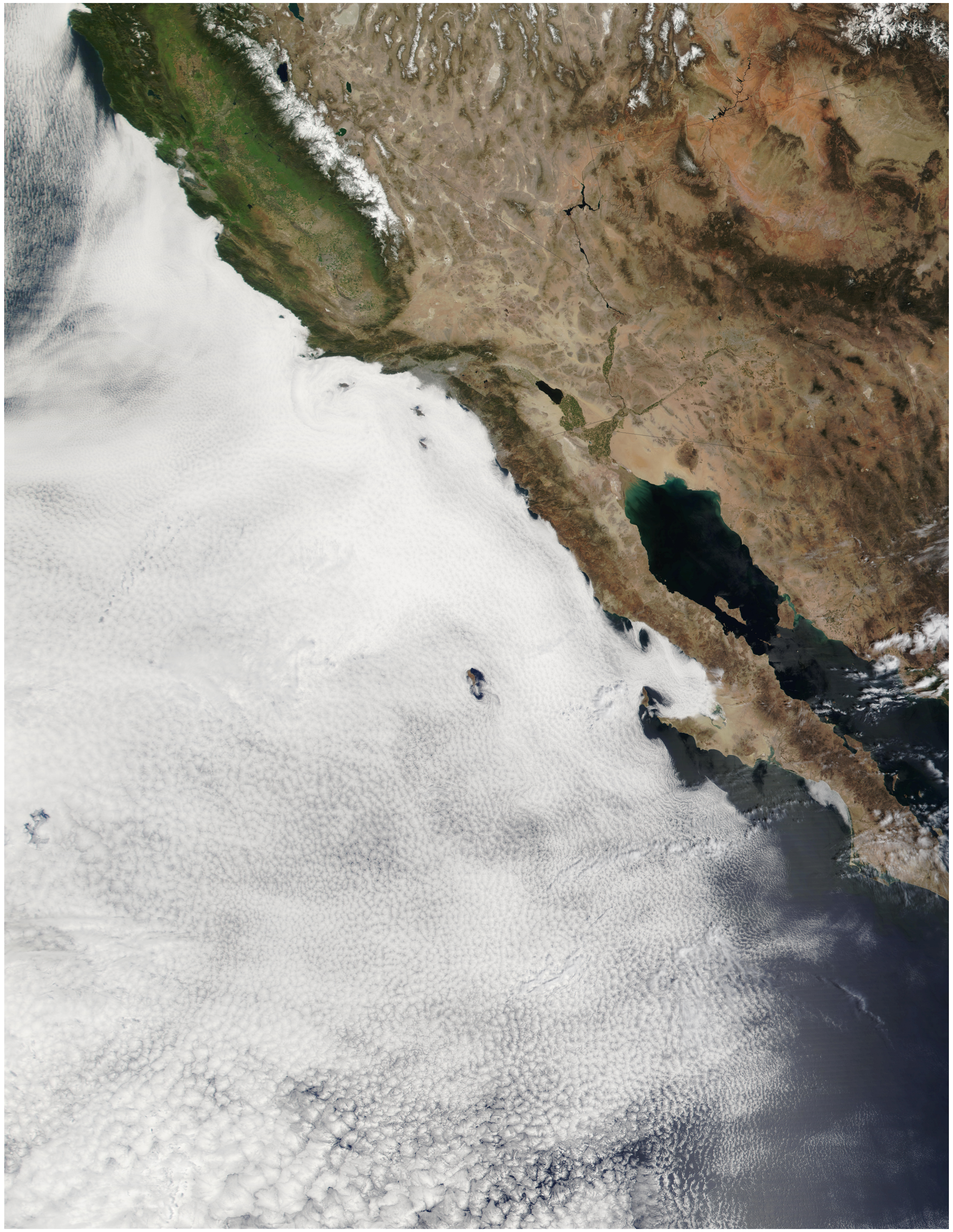
- RICO campaign model inter-comparison study (vanZanten et al. 2011)
- Double-moment bulk microphysical scheme of Seifert & Beheng (2001)

Matheou et al. (2011)
Smagorinsky SGS

Present LES
Stretched-vortex SGS



Stratocumulus clouds



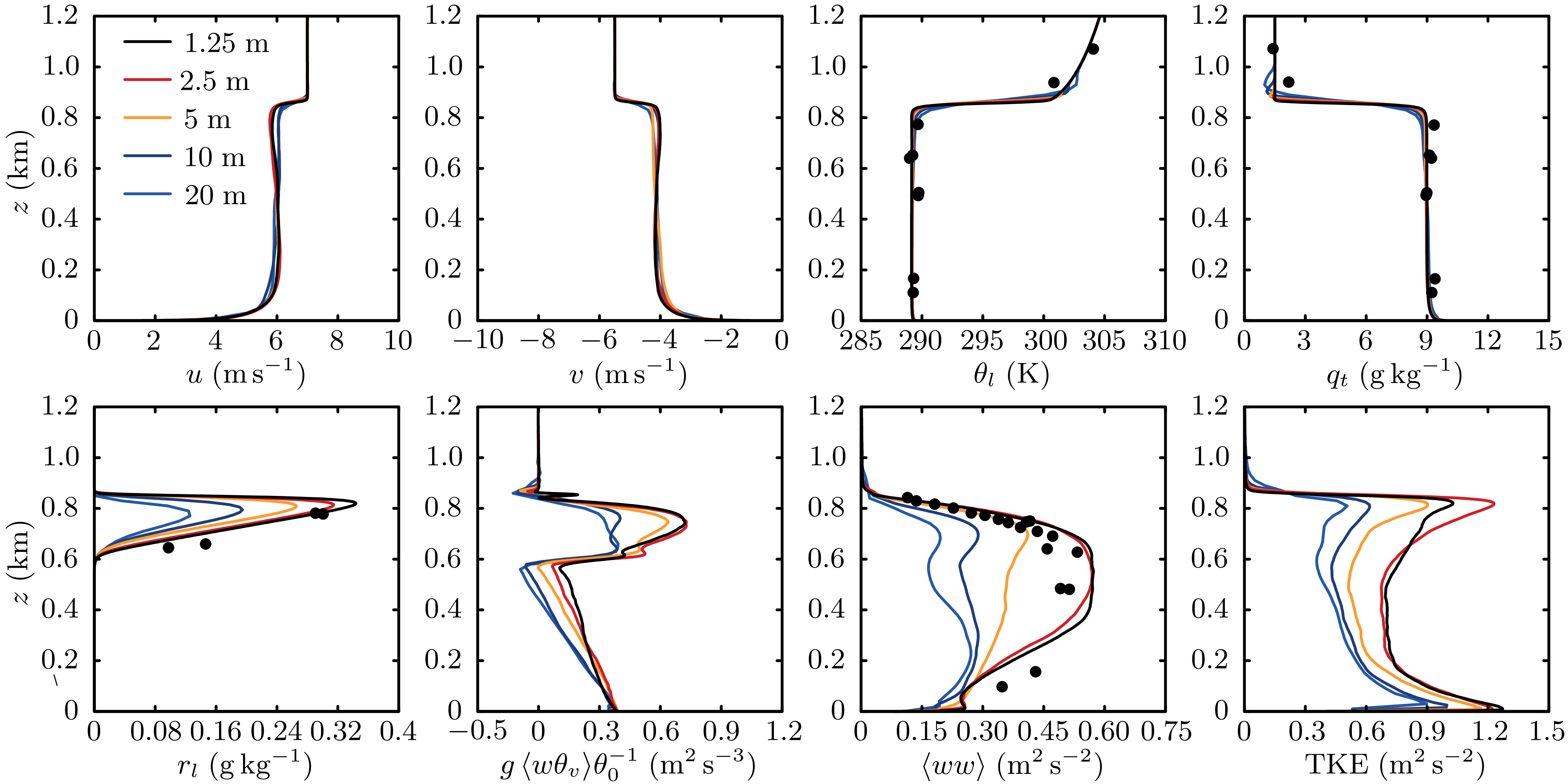
- Stratocumulus (Sc) clouds form near the surface, covering 20% the Earth's surface, and typically appear as a lumpy cloud layer
- Sc have a large effect on the Earth's energy balance because they strongly reflect incoming solar radiation
- Climate projections are sensitive to the amount of cloud cover and small variations in the Sc area coverage can produce energy-balance changes comparable to those due to greenhouse gases

Large-eddy simulation of a stratocumulus cloud

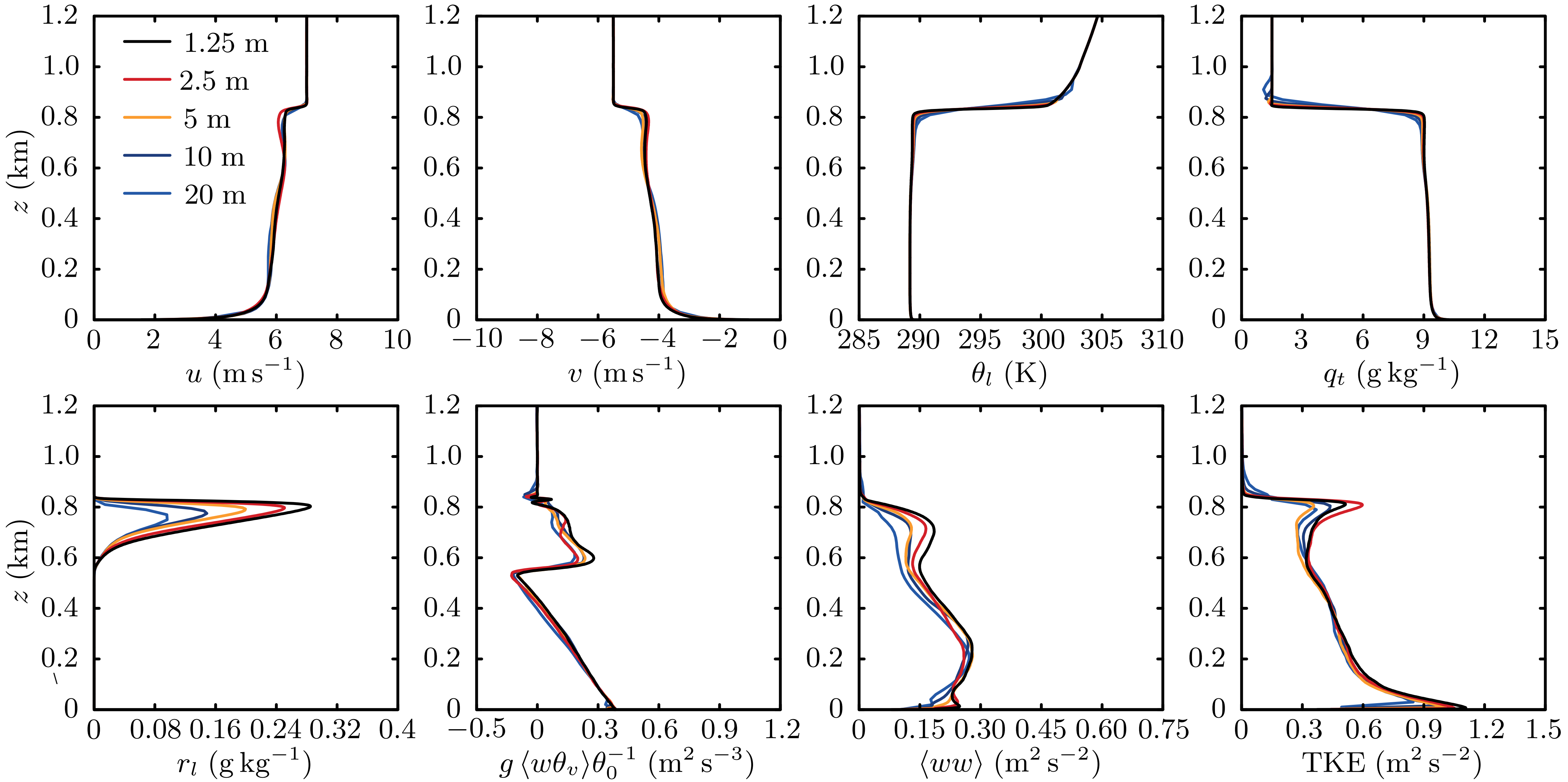
- Nocturnal Sc case of DYCOMS II RF01 (Stevens et al. 2005)
- QUICK scheme for water and temperature advection
  - Fourth-order fully conservative scheme for momentum advection
- Computational domain is 5 × 5 × 1.5 km
  - Boundary layer depth is ~ 0.8 km
- All grids are uniform and isotropic, i.e., $\Delta x = \Delta y = \Delta z$
- Grid resolutions at Δx = 20, 10, 5, 2.5, and 1.25 m
- Highest resolution runs are the largest LES to date
  - 20 billion grid cells
  - 4096 CPU-cores at Pleiades computer at NAS NASA
- Flow visualizations at APS Gallery of Fluid Motion: gfm.aps.org

Grid-convergence: LES with radiation

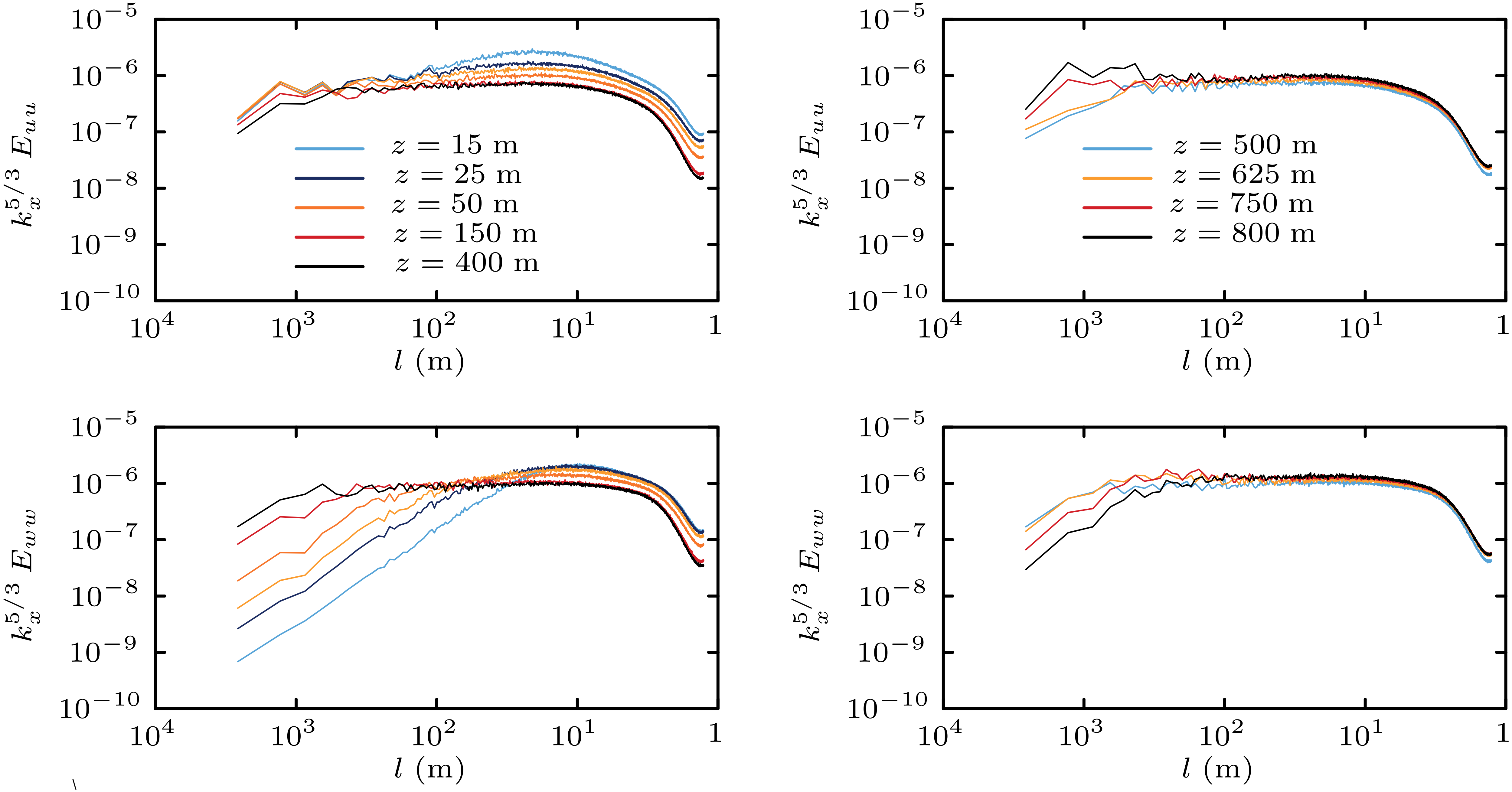
- Feedback between radiative cooling and turbulence leads to poor grid convergence
- Cloud-top radiative cooling depends exponentially on liquid water
- Amount of liquid water is 3% of total (vapor + liquid)



Grid-convergence: LES without radiation



Spectra: velocity



Spectra: temperature and humidity