Turbulence structure in marine stratocumulus-topped boundary layers: Perspectives from large-eddy simulation

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Where to find more details

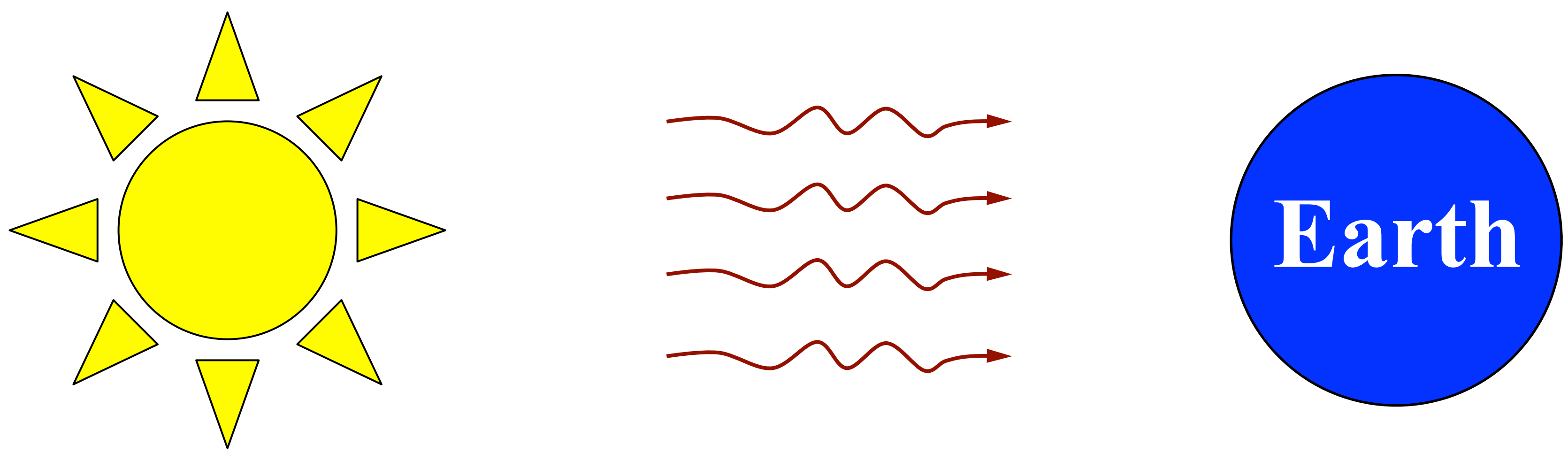
- Matheou, G., A. B. Davis, and J. Teixeira, 2020: The spiderweb structure of stratocumulus clouds, *Atmosphere*, 11(7), 730

- Matheou, G. and J. Teixeira, 2019: Sensitivity to physical and numerical aspects of large-eddy simulation of stratocumulus, *Monthly Weather Review*, 47, 2621–2639

- Matheou, G., 2018: Turbulence structure in a stratocumulus cloud, *Atmosphere*, 9, 392

Earth's mean equilibrium temperature

- Radiative equilibrium: Energy input = energy output



$$f \pi R^2 (1 - \alpha) = 4 \pi R^2 \sigma T^4$$

Energy from sun
≈ 1400 W m^{-2}

Earth's albedo ≈ 0.31

Earth's radius

Stefan–Boltzmann constant
≈ 5.67 × 10^{-8} W m^{-2} K^{-4}

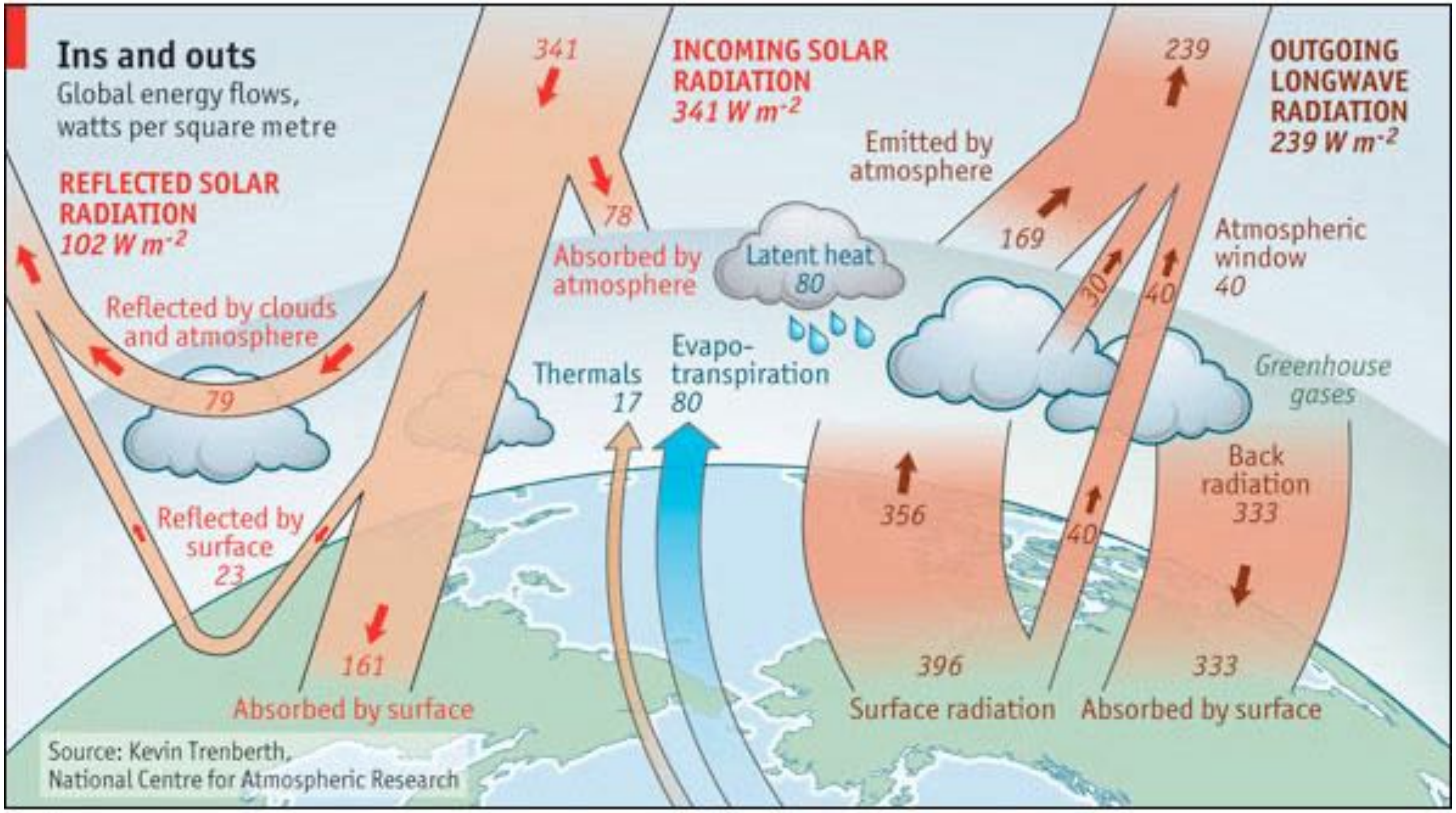
Mean surface temperature

$$T = \left(\frac{(1 - \alpha) f}{4 \sigma} \right)^{1/4} = -18^\circ \mathrm{C}$$

Too cold!!!

The "greenhouse" effect

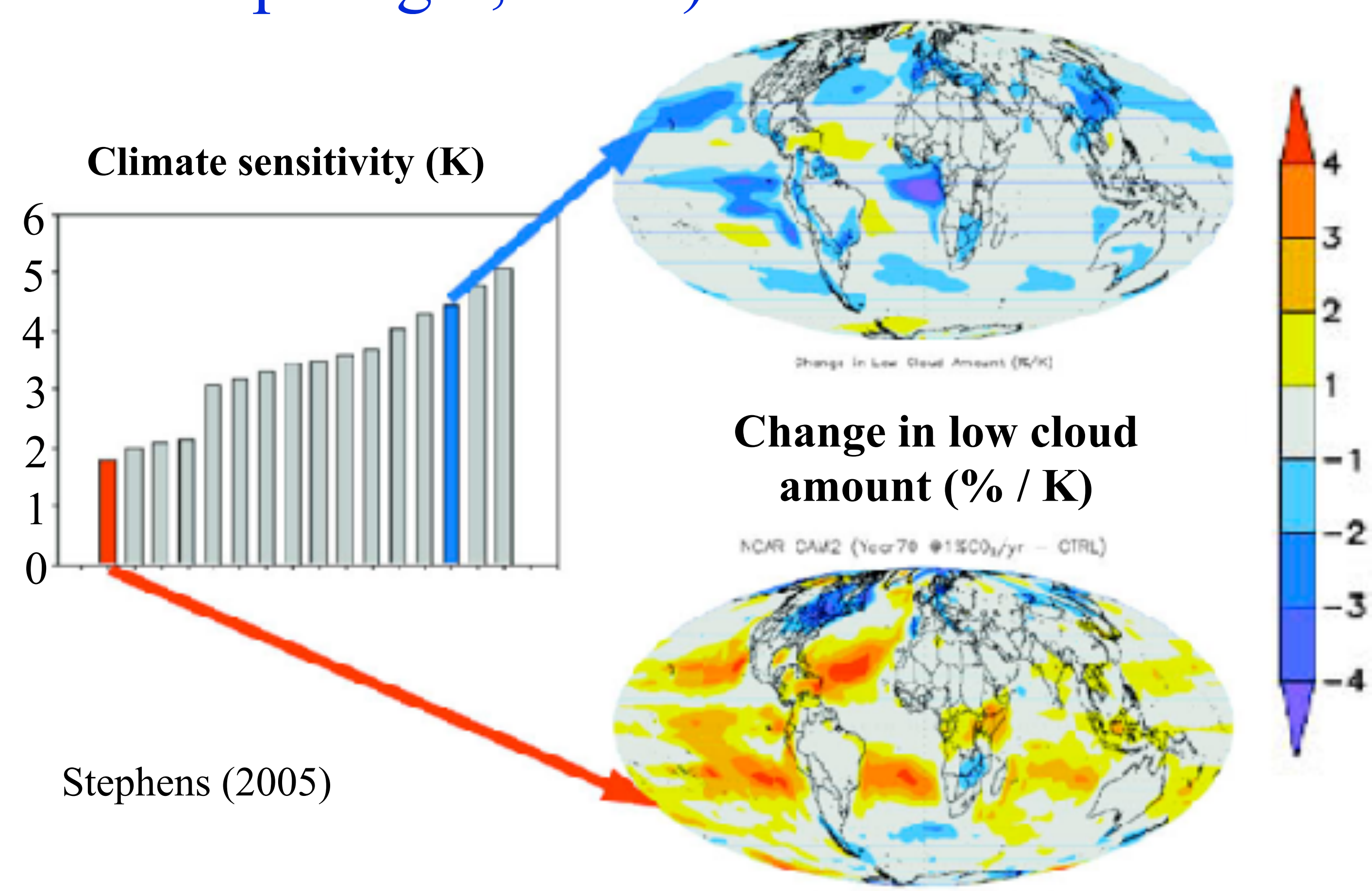
- The atmosphere is a processor of energy
- Water droplets (i.e., clouds) are very efficient absorbers and emitters of radiation
- Currently, there is an imbalance of ~ 0.5 W m^{-2}
  - Solar radiation on a clear day around noon in Warsaw is about 1000 W m^{-2}



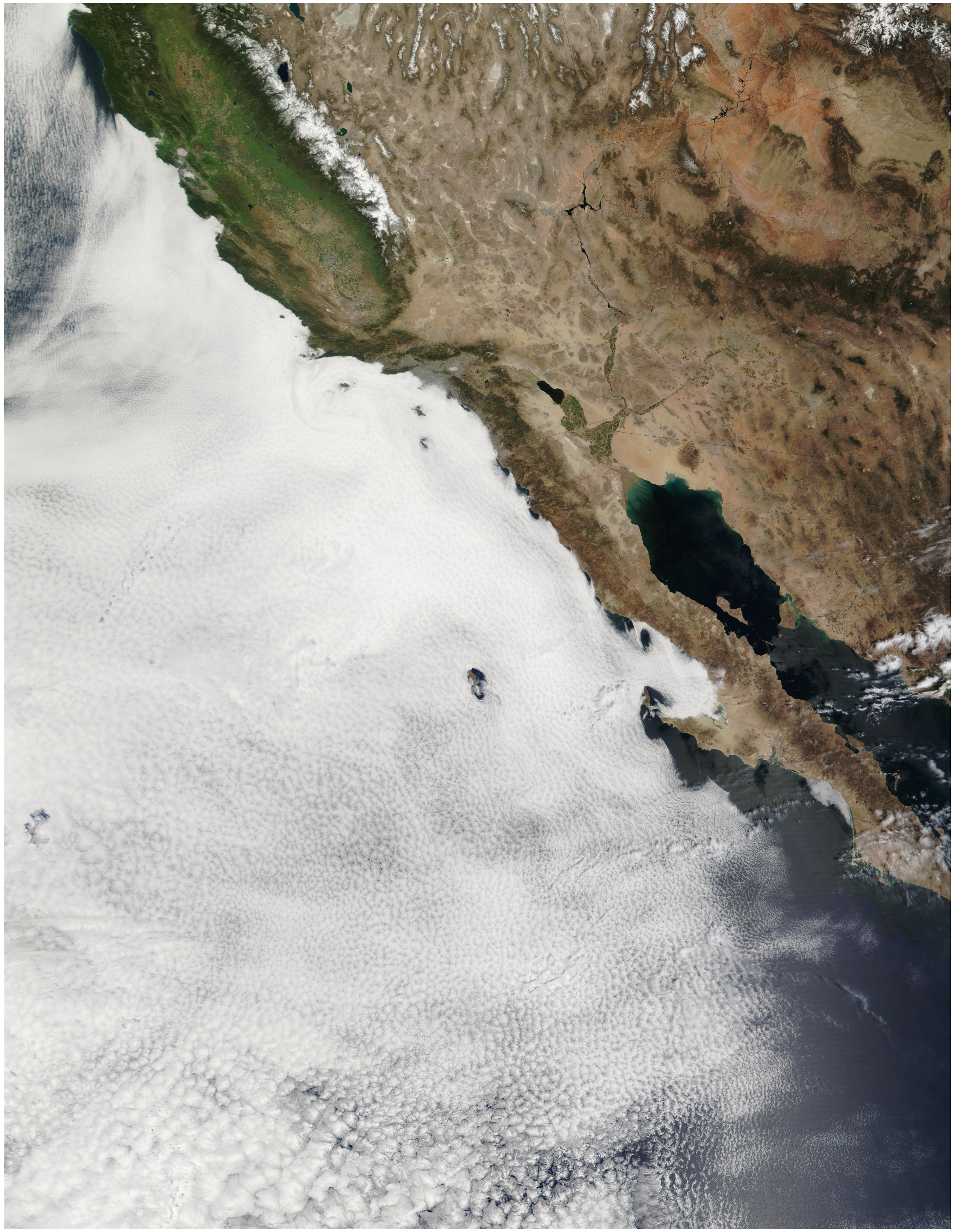
Graphic: The Economist, "The clouds of unknowing," March 18th, 2010
Data/analysis: Trenberth, Fasullo & Kiehl (2009)

Climate forcing and feedbacks

- Increase in greenhouse gases because of human activity has let to an increase in radiative forcing
  - CO_2 +48% and CH_4 +148% since pre-industrial levels (1750)
- Water vapor is the most dominant greenhouse gas
  - ...but we cannot control the amount of water in the atmosphere (thermodynamics, circulation, ocean, etc.) → **feedback**
- Clouds have both warming and cooling effects depending on their characteristics (cloud thickness, cloud top height, etc…)
- Boundary layer clouds have a strong cooling effect
- Intergovernmental Panel on Climate Change (IPCC) 2007: "Cloud feedbacks (particularly from low clouds) remain the largest source of uncertainty [in climate models]."

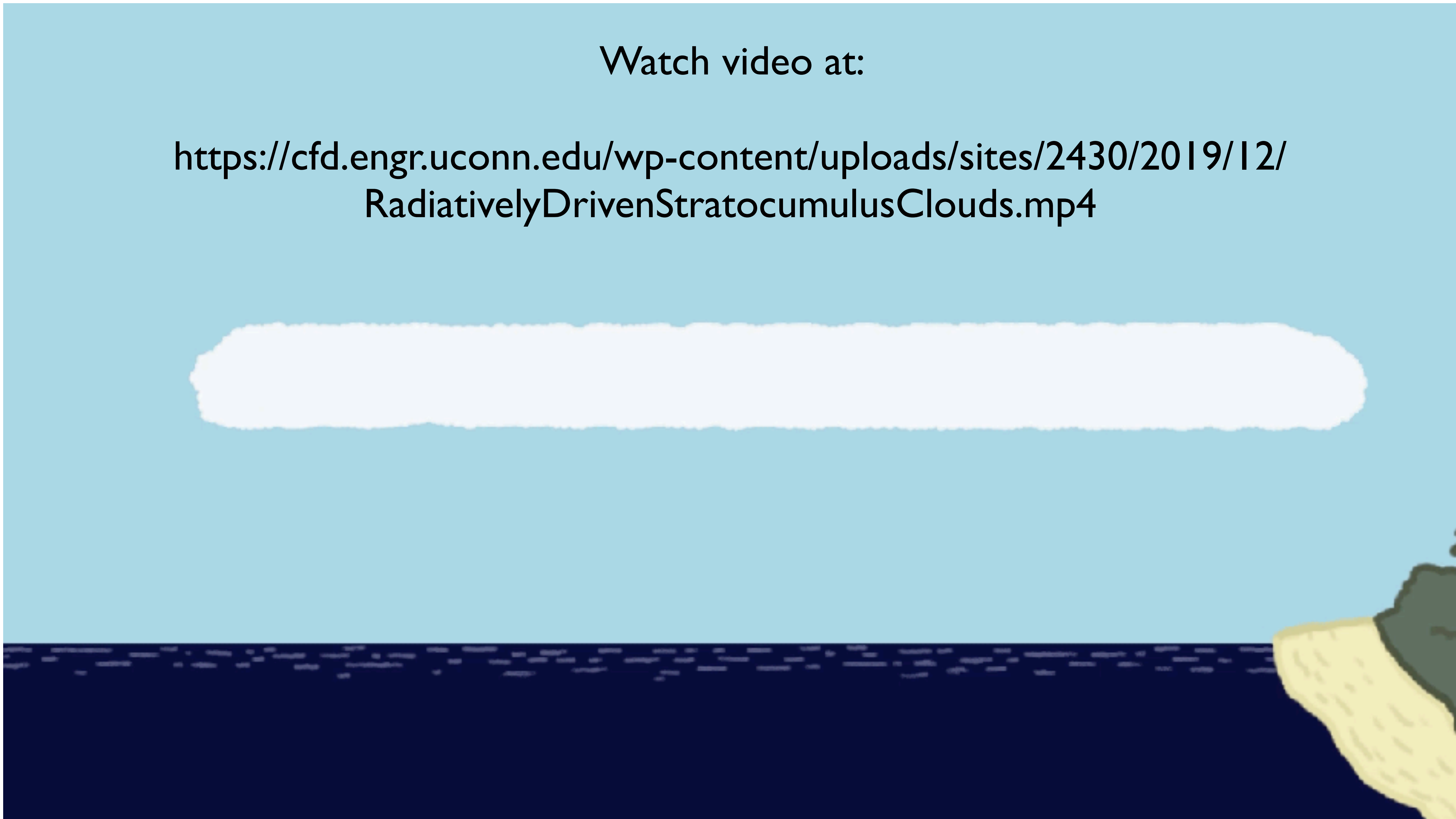


Stratocumulus clouds



- Stratocumulus (Sc) clouds form near the surface, covering 25% 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

Stratocumulus clouds



Scales of atmospheric motions and models

Mesoscale organization
Weather/storm systems

Global circulation

Convection Organization – Thunderstorms

Individual Clouds

Cloud–Environment interactions

Small-scale turbulence

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

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

Reynolds Averaged Navier–Stokes (RANS)

Global circulation model (GCM): Resolved | Parameterized

LES Subgrid-Scale model (LES-SGS)

Large-eddy simulation (LES): Input from large scales | Resolved | Parameterized

Direct numerical simulation (DNS): Forcing / Turbulence production / Large scales

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

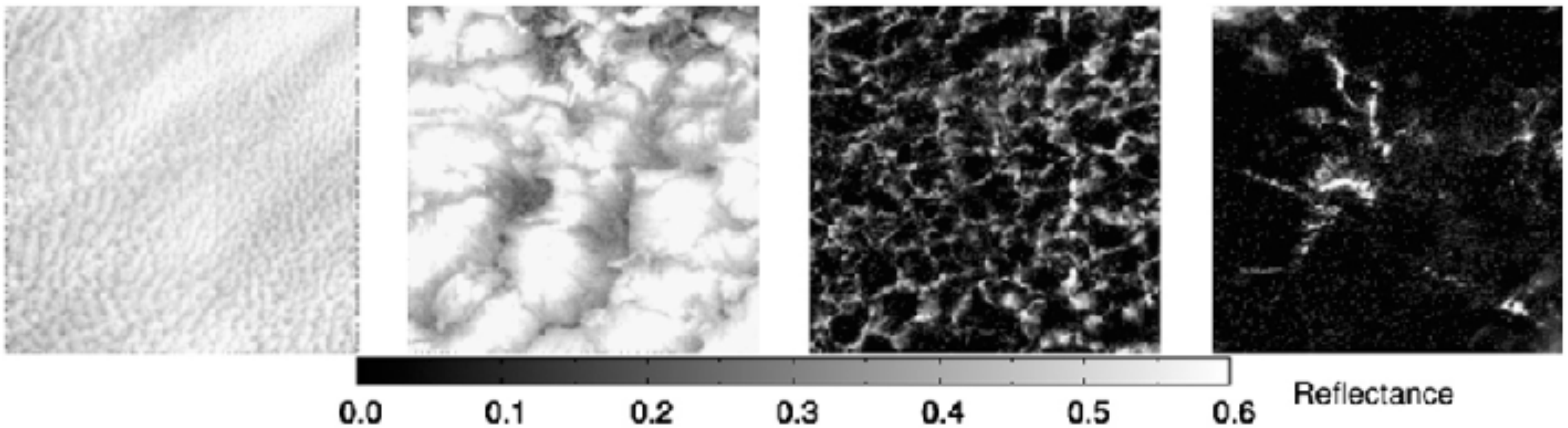
Images: NASA, B. Stevens, Chung & Matheou

Large-Eddy Simulation (LES) of Stratocumulus

- Challenging determination of cloud properties given large-scale spatially-averaged conditions
  - Parameterization problem for climate and numerical weather prediction (NWP) models
  - Resolution ~100 km
- High-resolution models are expected to perform better
  - Large-eddy simulations (LES) with resolution ~ 10 m
  - Turbulence parameterization is more reliable (compared to NWP)
- Challenges persist in LES of stratocumulus
  - Agreement with observations is poor
  - No grid convergence of flow statistics
- Main question is why performance of LES of stratocumulus is poor?
  (compared to other boundary layer regimes)

Boundary-layer cloud regimes

Figure from Kawai & Teixeira (2010) – 200 × 200 km regions – space-borne observations



Large-Eddy Simulation model

- LES model of Matheou & Chung (2014)
- Anelastic approximation of the Favre-filtered equations of motion on an *f*-plane
- Periodic boundary conditions in the horizontal directions
- Prescribed surface fluxes based on observations

$$\frac{\partial \bar{\rho}_0 \tilde{u}_i}{\partial x_i} = 0$$

$$\frac{\partial \bar{\rho}_0 \tilde{u}_i}{\partial t} + \frac{\partial (\bar{\rho}_0 \tilde{u}_i \tilde{u}_j)}{\partial x_j} = -\theta_0 \bar{\rho}_0 \frac{\partial \bar{\pi}_2}{\partial x_i} + \delta_{i3} g \bar{\rho}_0 \frac{\tilde{\theta}_v - \langle \tilde{\theta}_v \rangle}{\theta_0} - \epsilon_{ijk} \bar{\rho}_0 f_j (\tilde{u}_k - u_{g,k}) - \frac{\partial \tau_{ij}}{\partial x_j}$$

$$\frac{\partial \bar{\rho}_0 \tilde{\theta}_l}{\partial t} + \frac{\partial \bar{\rho}_0 \tilde{\theta}_l \tilde{u}_j}{\partial x_j} - D x_3 \frac{\partial \bar{\rho}_0 \tilde{\theta}_l}{\partial x_3} = -\frac{1}{\pi c_p} \frac{\partial F_{\mathrm{rad}}}{\partial x_3} - \frac{\partial \sigma_{\theta,j}}{\partial x_j}$$

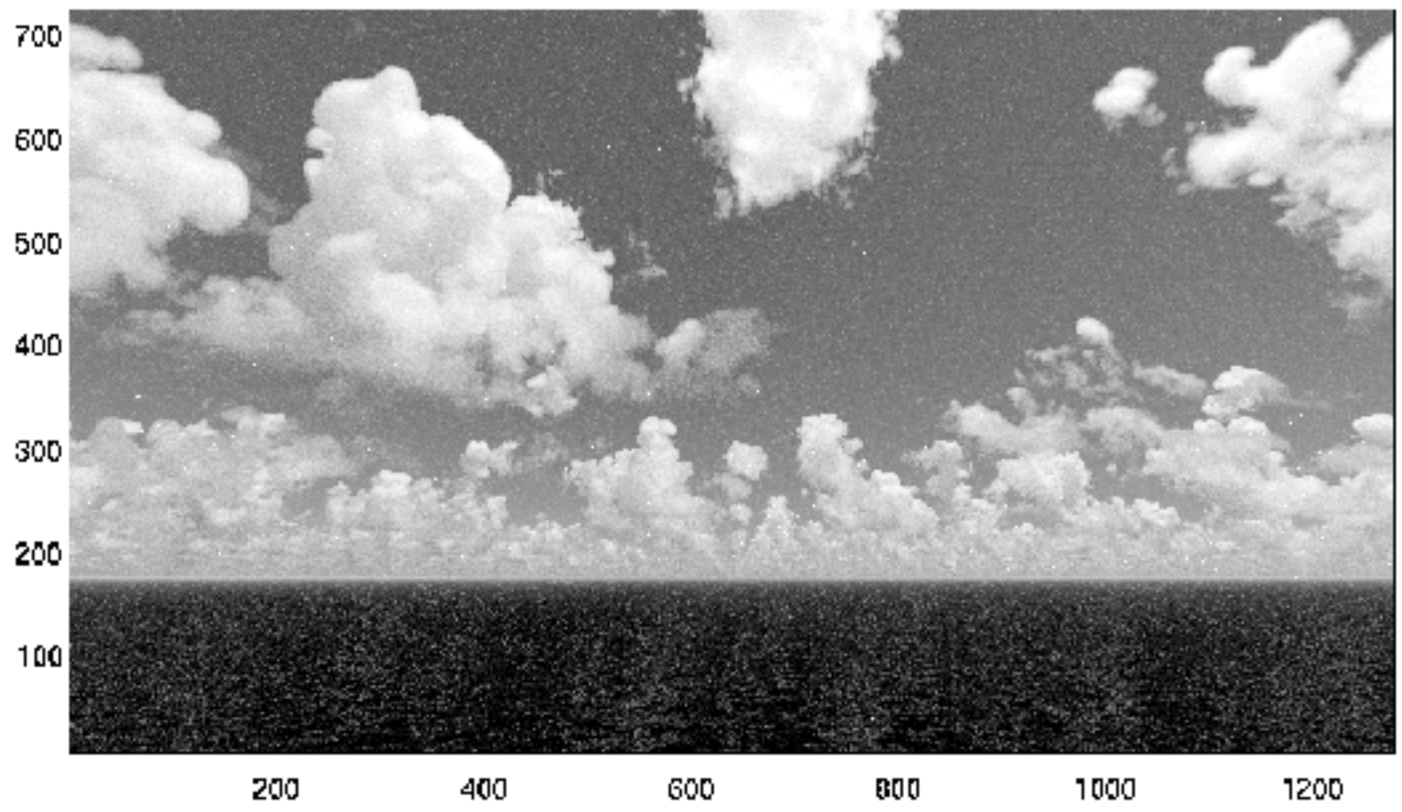
$$\frac{\partial \bar{\rho}_0 \tilde{q}_t}{\partial t} + \frac{\partial \bar{\rho}_0 \tilde{q}_t \tilde{u}_j}{\partial x_j} - D x_3 \frac{\partial \bar{\rho}_0 \tilde{q}_t}{\partial x_3} = -\frac{\partial \sigma_{q,j}}{\partial x_j}$$

- Liquid is diagnosed from mean state in each grid cell
  - no microphysics, cloud liquid assumed suspended
- Radiative flux parameterization (Stevens et al. 2005):

$$F_{\mathrm{rad}}(t,x,y,z) = F_0 e^{-Q(z,\infty)} + F_1 e^{-Q(0,z)} + \rho(z_i) c_p D \alpha_z [(z - z_i)^{4/3}/4 + z_i (z - z_i)^{1/3}]$$

$$Q(z_1, z_2) = \kappa \int_{z_1}^{z_2} \rho \, r_l(t,x,y,z) \, \mathrm{d}z$$

Large-Eddy Simulation model: basic formulation

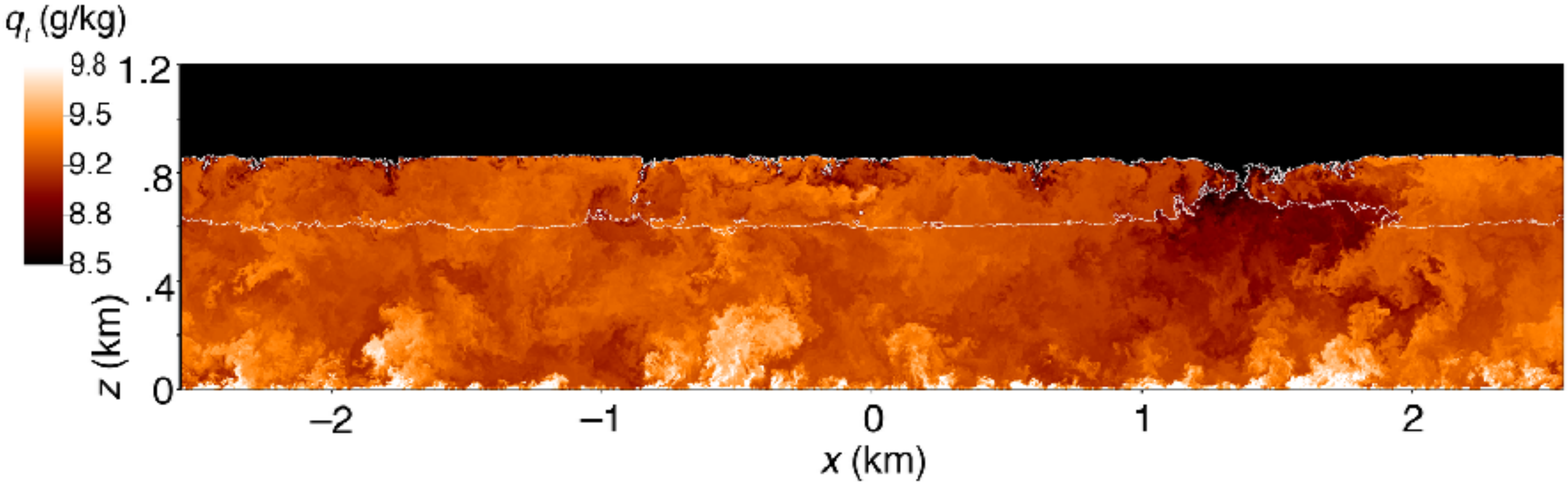


- Cloud field from LES of the BOMEX case (Siebesma et al. 2003)
  - Trade-wind shallow Cu
- LES output rendered with High-Tune: RenDeRer radiative transfer model (Villefranque et al. 2019)
- Image shows radiance field at 700 nm plotted at logarithmic intervals

- Finite differences discretization
  - 2nd to 6th order, centered (non-dissipative), fully conservative for momentum and scalar (Morinishi et al. 1998)
  - QUICK (linear upwinding, dissipative, *not* monotone) for scalars (Leonard 1979)
  - Flux limited, monotone scheme (usually used for microphysics transport)
- Buoyancy adjusted stretched vortex subgrid-scale model (Chung & Matheou 2014)
  - Structural closure (Smagorinsky and TKE-based are functional closures)
  - Fully anisotropic closure, does not assume isotropy of SGS fields
  - No flow adjustable parameters: same formulation for any atmospheric conditions

Methodology – Grid resolution study

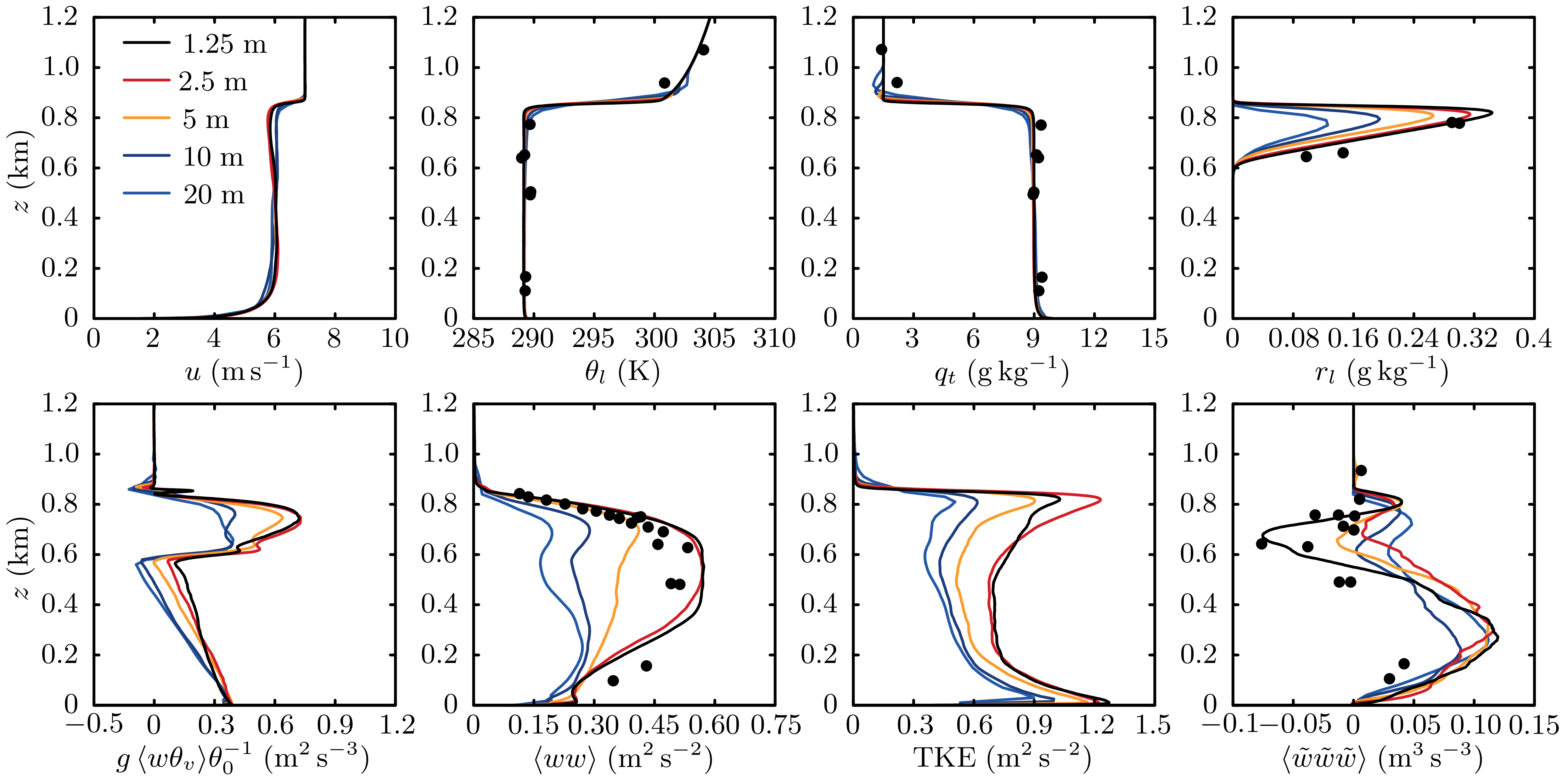
- LES of the nocturnal Sc case of DYCOMS II RF01 (Stevens et al. 2005)
  - No precipitation, no drizzle
- Fourth-order fully conservative scheme for momentum advection (Morinishi et al. 1998)
- QUICK scheme for water and temperature advection (Leonard 1979)
- Computational domain is 5 × 5 × 1.5 km
  - Boundary layer depth is ~ 0.8 km
- Grid resolutions at **Δx = 20**, **10**, **5**, **2.5**, and **1.25 m**
  - All grids are uniform and isotropic, i.e., $\Delta x = \Delta y = \Delta z$
- Highest resolution runs are the largest LES to date
  - 4096 × 4096 × 1200 = 20 billion grid cells



LES cloud, Δx = 5 m at t = 4 h

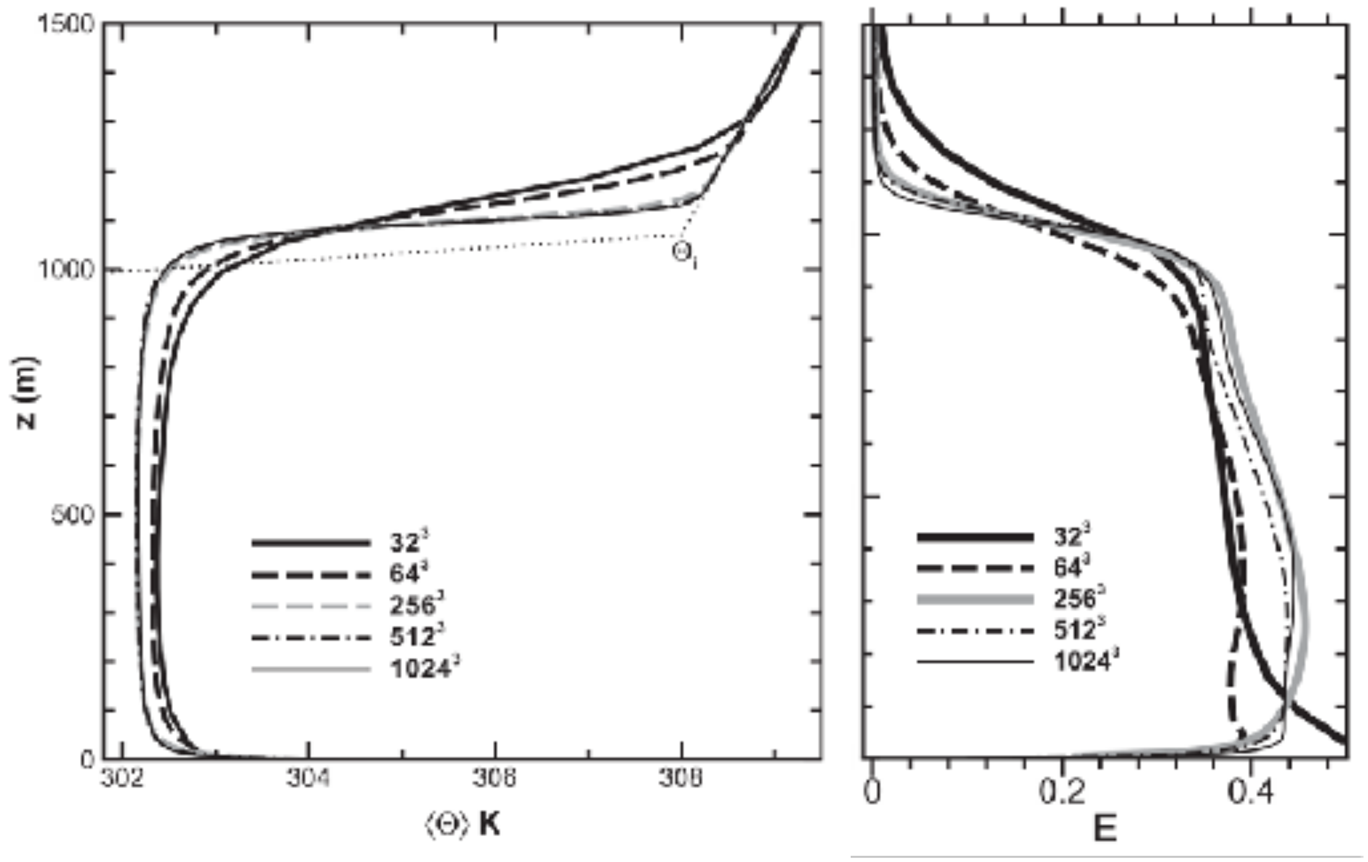
LES with radiation

- Grid convergence and comparison with observations (shown using circles)
- Boundary layer profiles at $t = 2$ h
- No grid resolution dependence for vector of state mean fields
- Liquid water and turbulence statistics show large variability w.r.t. Δx



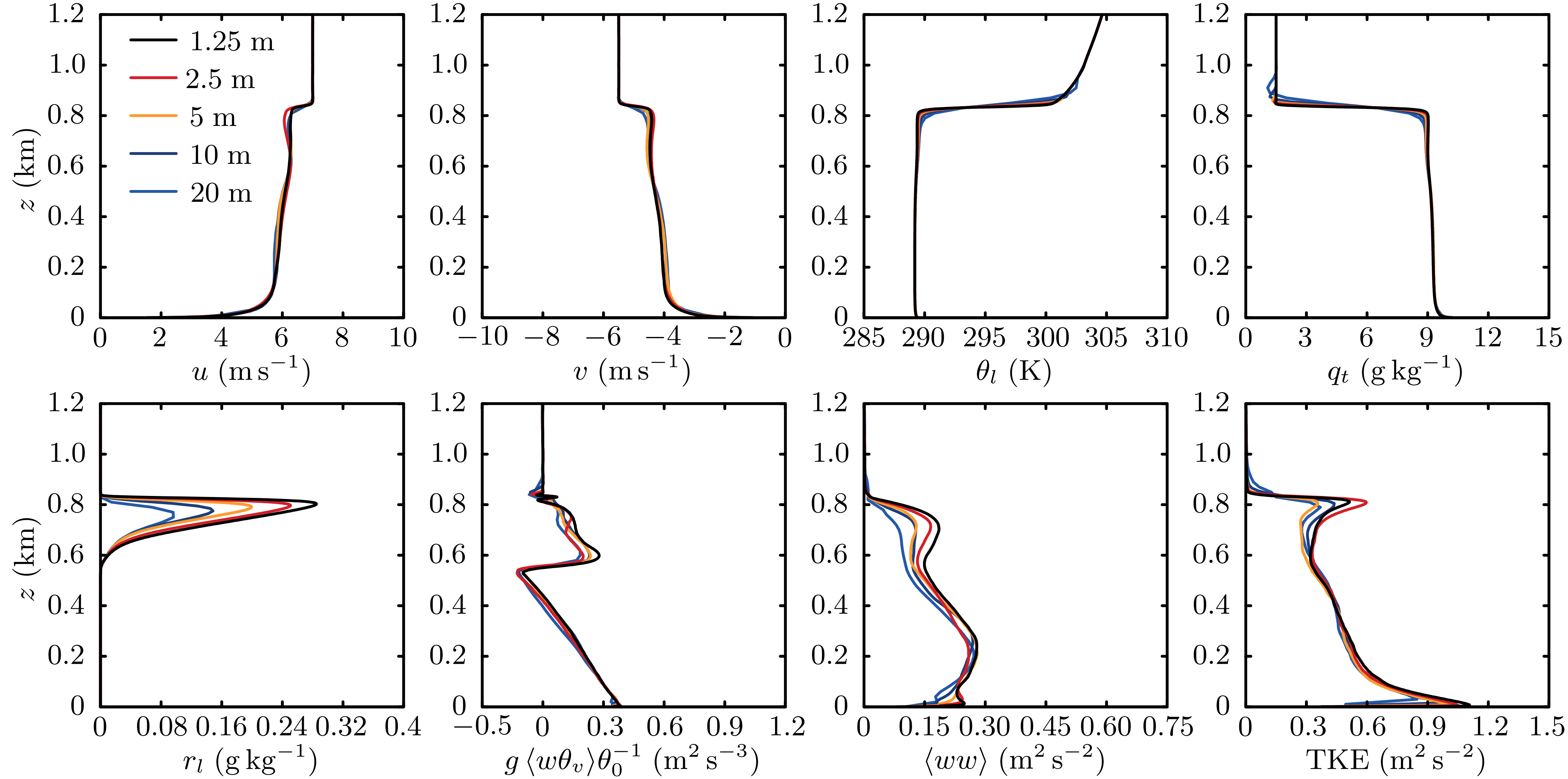
Why is grid convergence challenging?

- Present stratocumulus grid convergence results are consistent with several past studies
- Why is grid convergence challenging?
  - Inversion strength hypothesis?
    - Strongly stratified turbulence creates very small vertical scales
    - Numerical model cannot resolve overturning motions near the inversion leading to incorrect entrainment (Stevens and Bretherton 1999, Pressel et al. 2017)
  - Is the challenge particular to stratocumulus cloud physics?
- Dry convection case of Sullivan & Patton (2012)
  - Inversion $\Delta\theta = 6$ K, convergence for $\Delta x \leq 15$ m



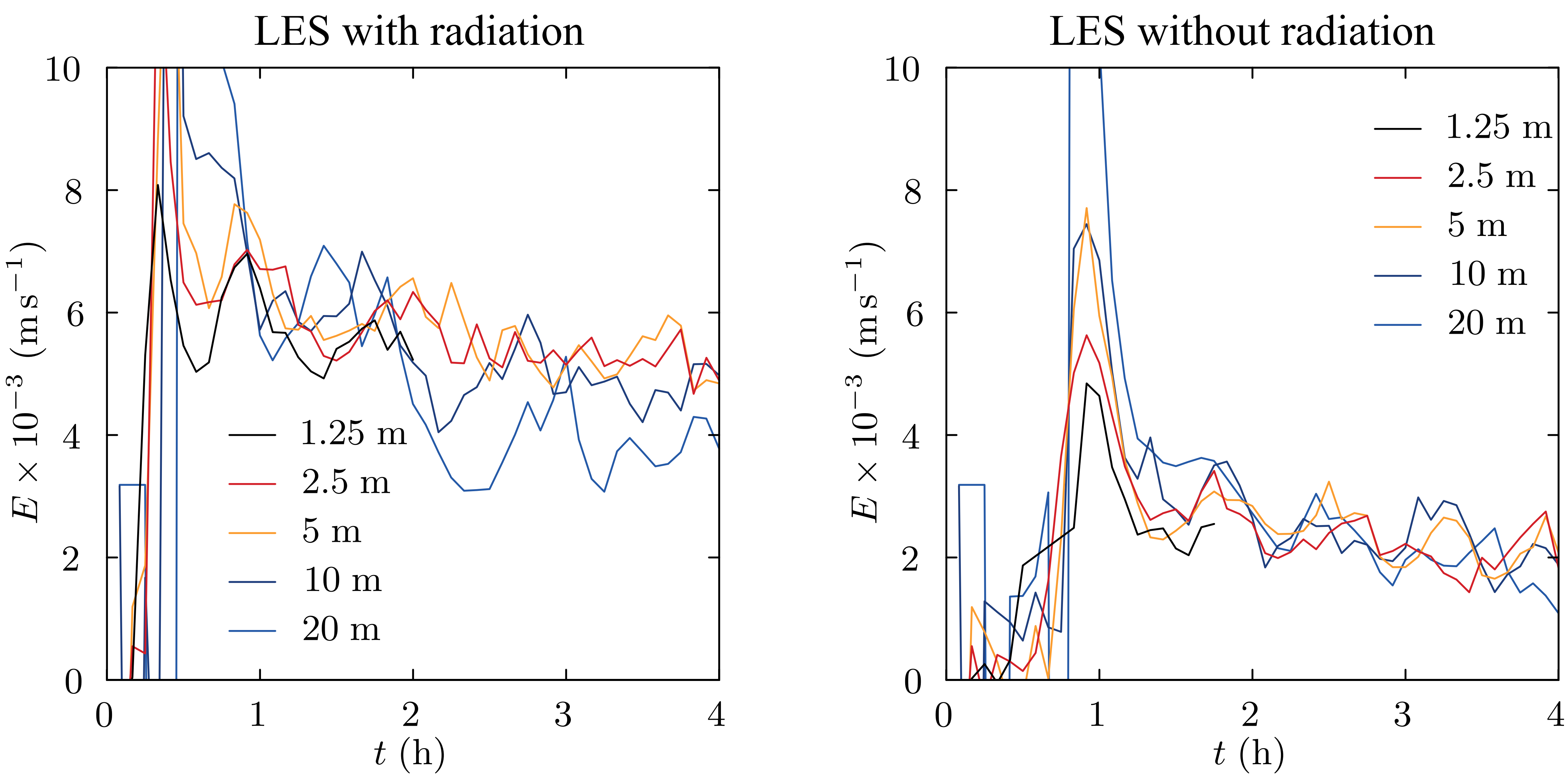
LES without radiation

- No grid resolution dependence for:
  - Vector of state mean fields
  - Turbulence statistics
- Sensitivity of liquid water to grid resolution remains



Entrainment rate

- Entrainment rate is not sensitive to grid resolution
  - Consequently entrainment is not sensitive to the amount of cloud liquid
  - This result is likely model dependent and other SGS models might have different trends
- What about entrainment efficiency? $A_e = w_e \, \Delta b \, z_i \, \overline{ww}^{-3/2}$

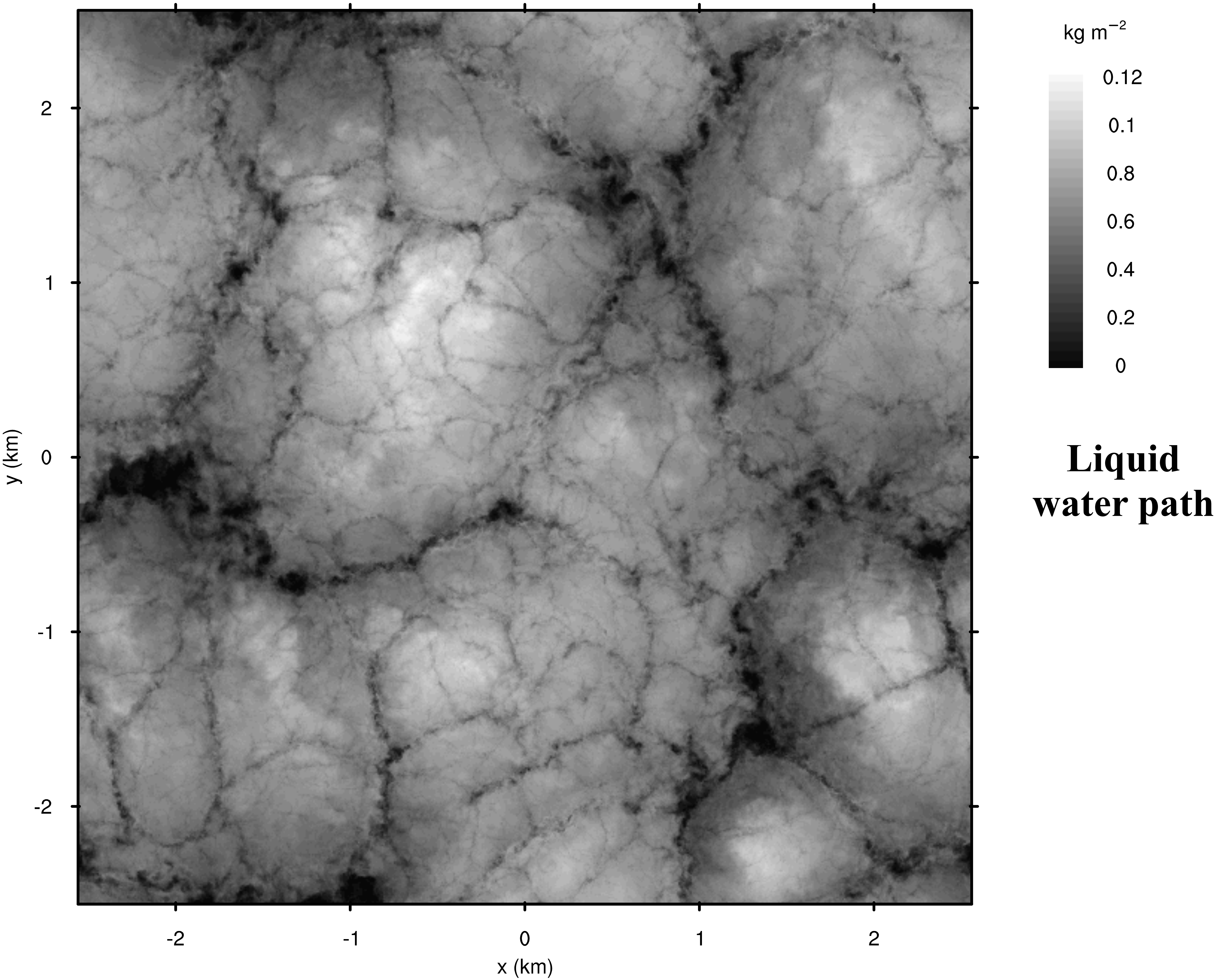


Radiation–buoyancy–turbulence feedback

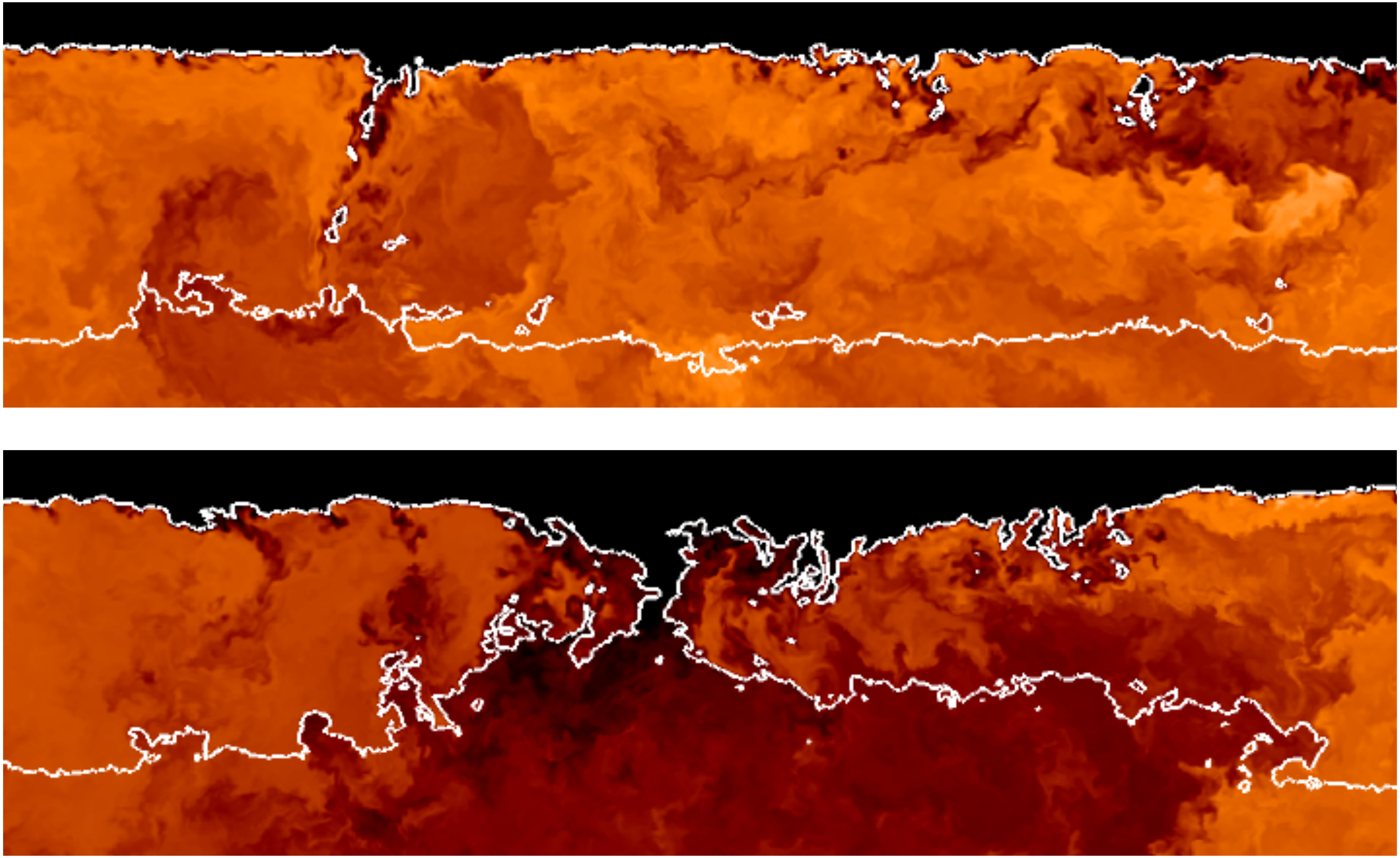
- LES implementation integrates conserved variables
  - Statistics of mean fields are accurate even for very coarse grid resolutions
  - Entrainment rate is not found to depend on resolution
- Small errors ($< 5\%$) in temperature and humidity result in larger errors in liquid water (> 50 % changes in liquid water path)
- Cloud top radiative cooling depends exponentially on liquid water
- Radiative cooling is a strong source of buoyancy near the boundary layer top
- Δx ▼ → Liquid ▲ → Buoyancy forcing ▲ → Turbulence ▲
- Very small errors in a small region near the cloud top are amplified to produce large buoyancy forcing and large vertical turbulence transport altering the dynamics of the entire boundary layer
  - Change from a decoupled to a coupled boundary layer structure
- Performance of SGS model is not as poor as previous studies suggest
  - Are errors of < 1 % possible for present SGS models at reasonable resolutions?

Stratocumulus cloud turbulence

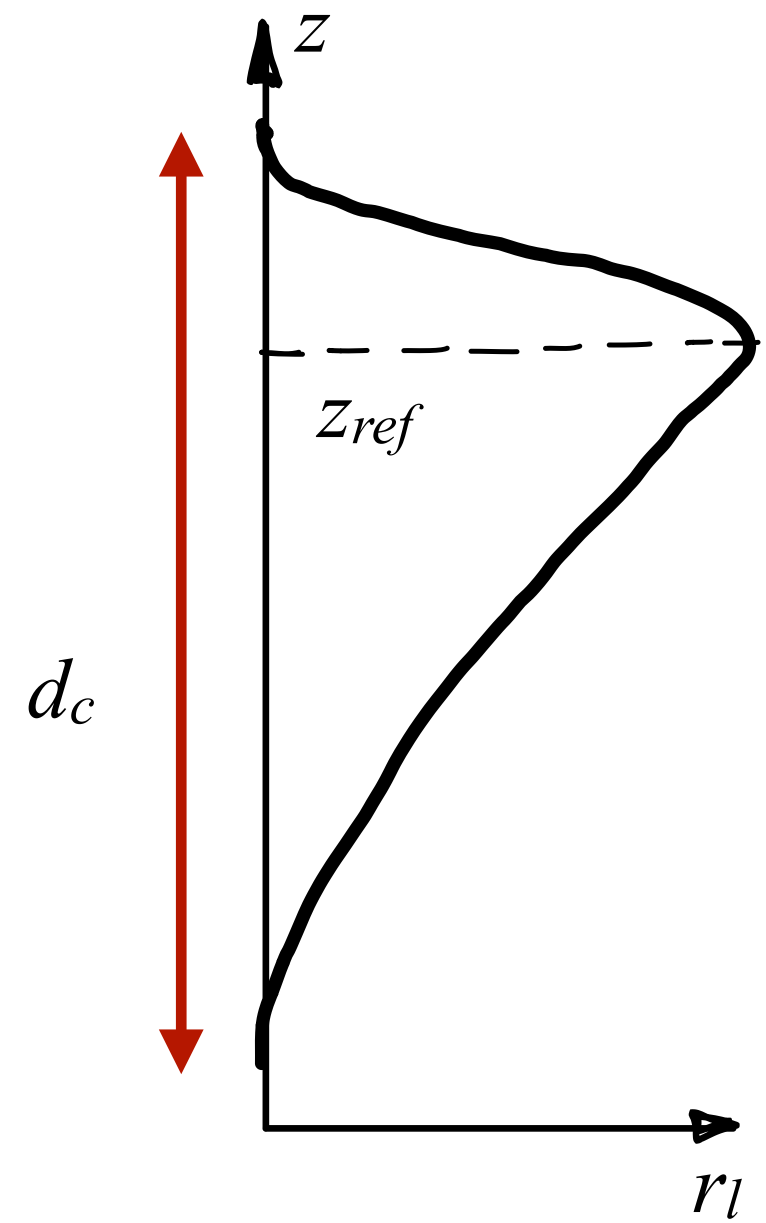
- Goal is to explore turbulence in the cloud
- Use high resolution LES at $t = 2$ h
- Computational domain is $5 \times 5 \times 1.5$ km
  - Boundary layer depth is ~ 0.8 km
- Grid resolution is $\Delta x = 1.25$ m
  - Grid is uniform and isotropic, i.e., $\Delta x = \Delta y = \Delta z$
  - $4096 \times 4096 \times 1200 = 20$ billion grid cells

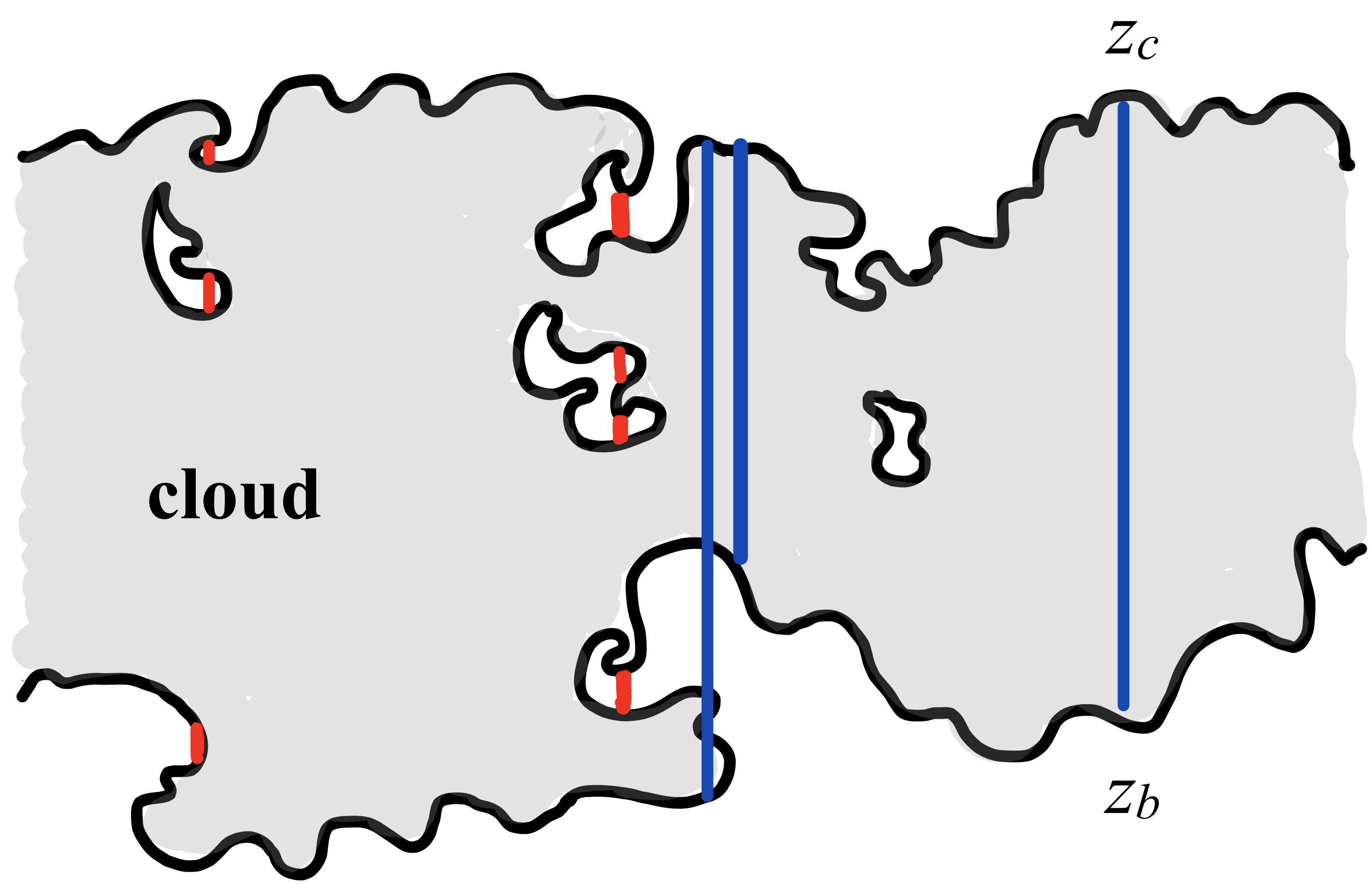

kg m⁻²
0.12
0.1
0.8
0.6
0.4
0.2
0
Liquid water path
y (km)
2
1
0
-1
-2
x (km)
-2
-1
0
1
2

Cloud structure: q_t contours & cloud boundary



Definitions





$d_t\,(x,y) = z_c - z_b =$ **total cloud depth**

$d_v\,(x,y) =$ **total cloud void depth**

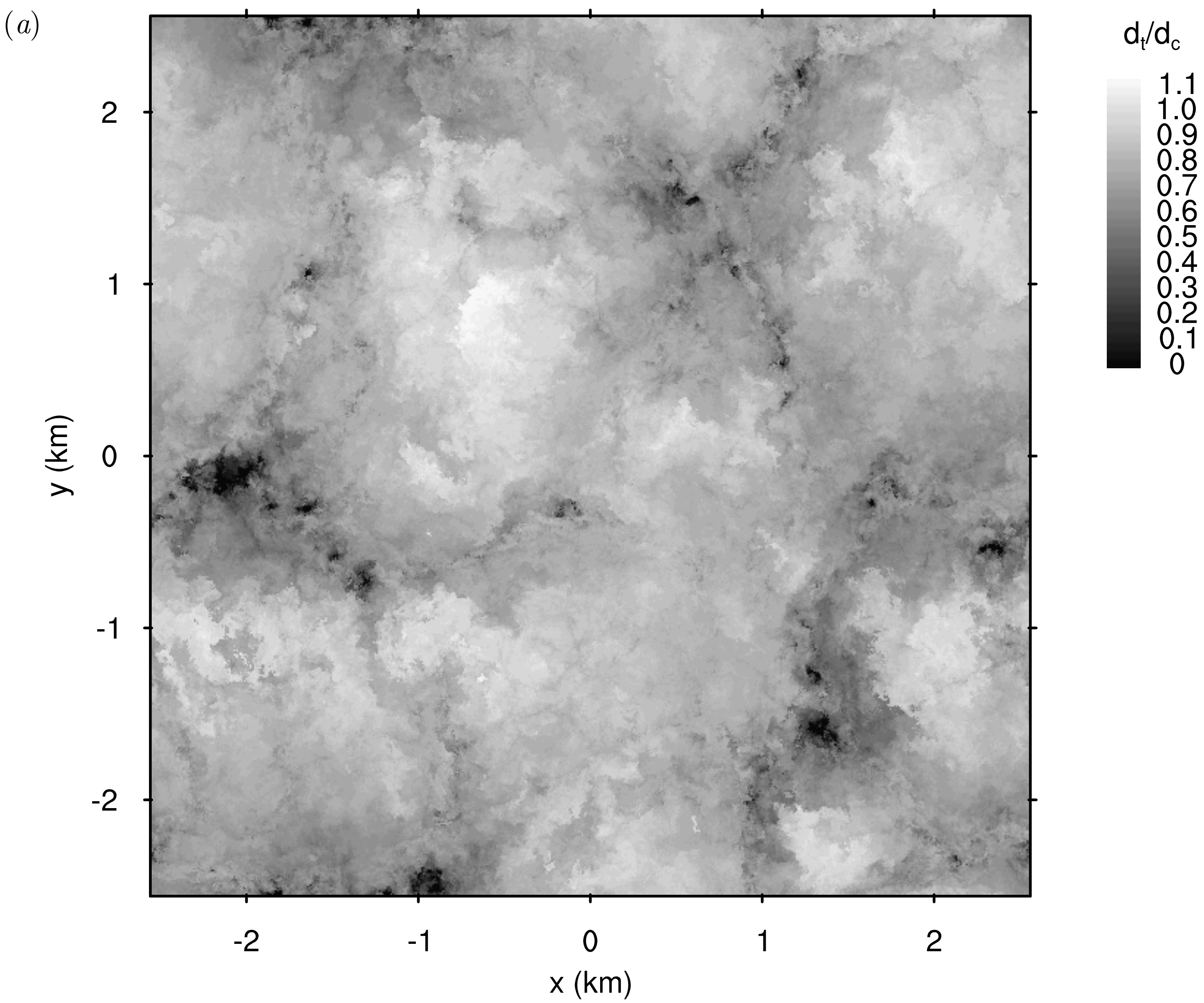
$d_c =$ **mean cloud depth**

$z_{ref} =$ **reference height** (z at maximum of r_l)

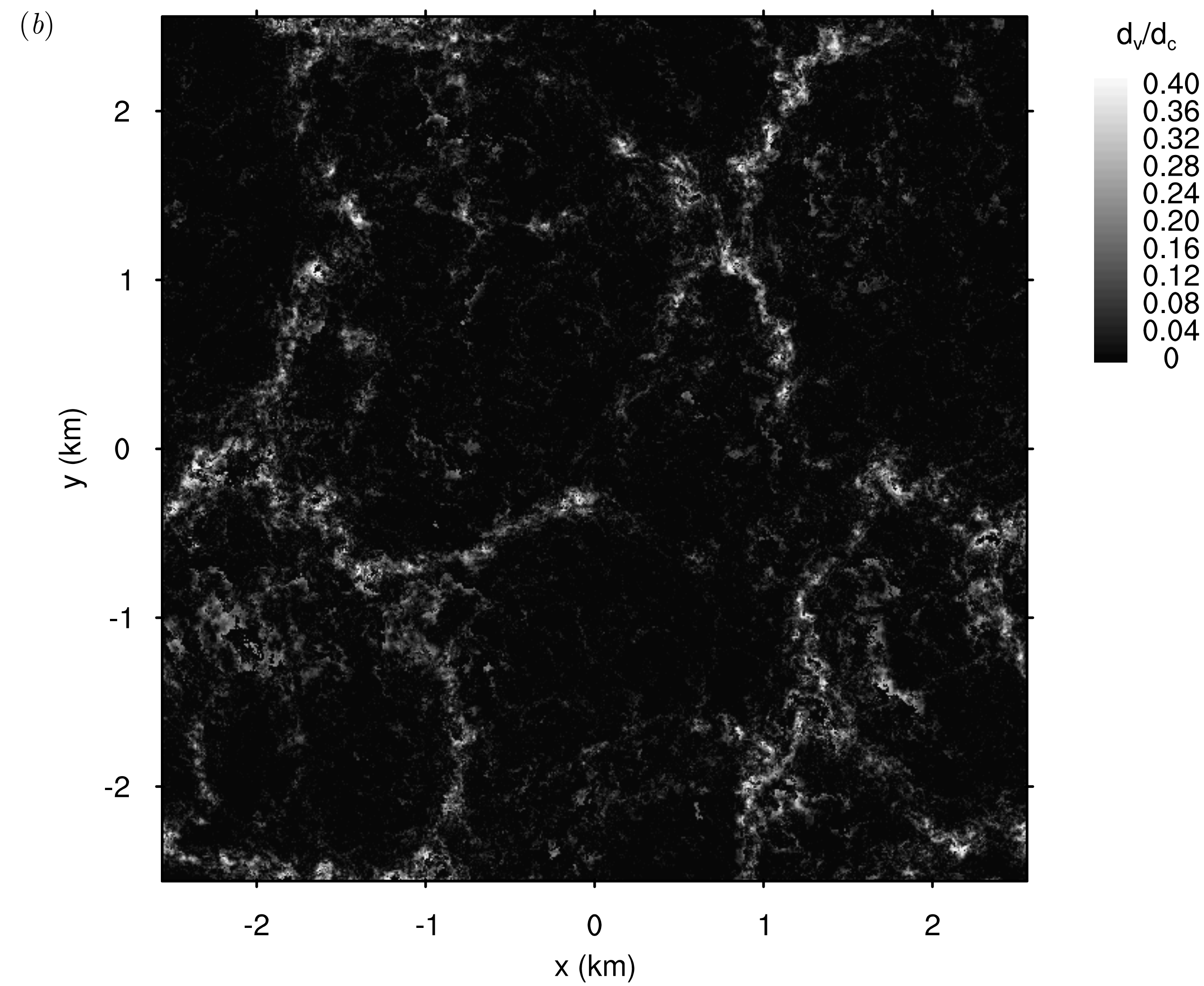
Cloud depth and cloud voids

- Cloud voids correspond to entrainment events?

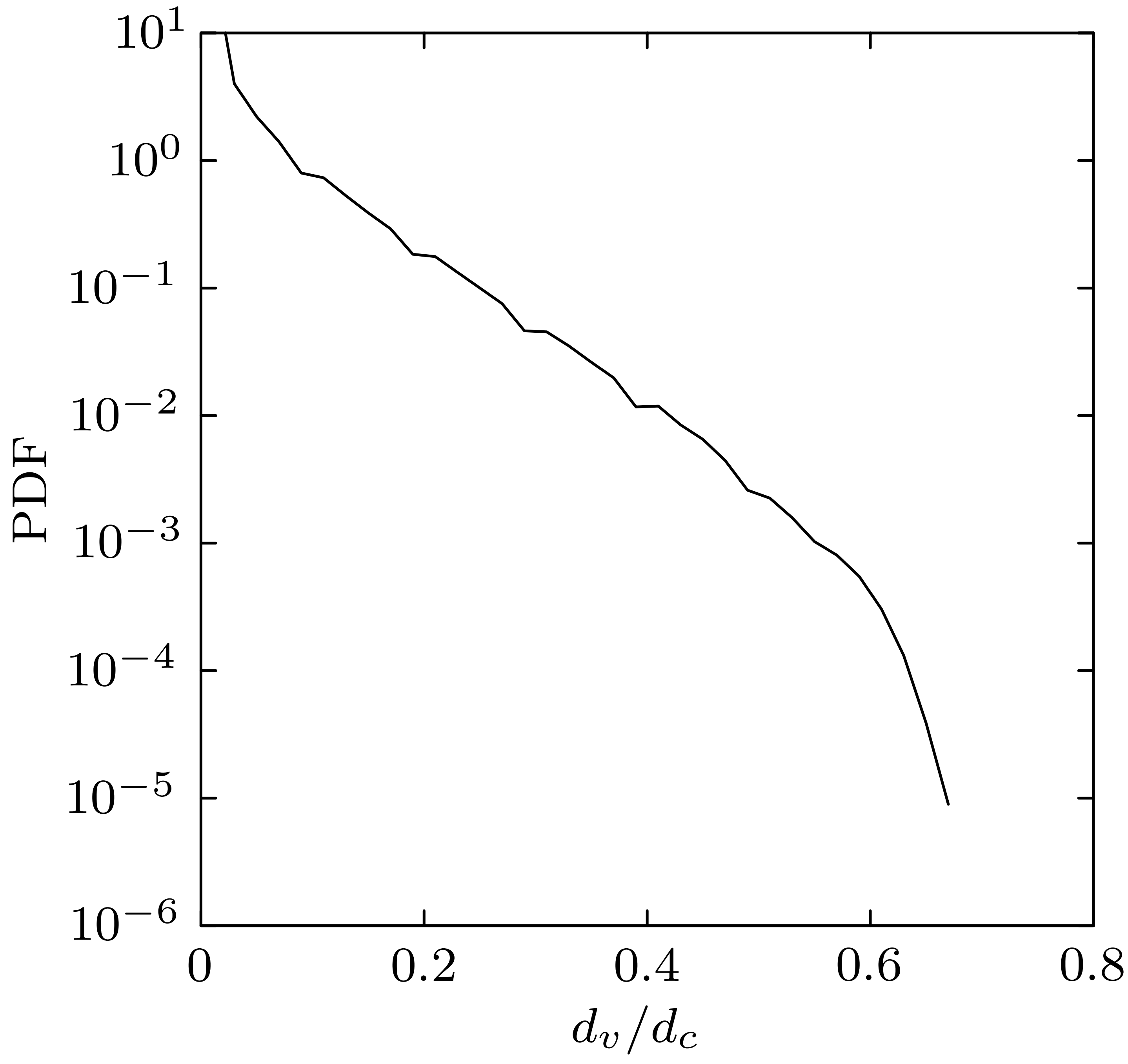
total cloud depth



total cloud void depth

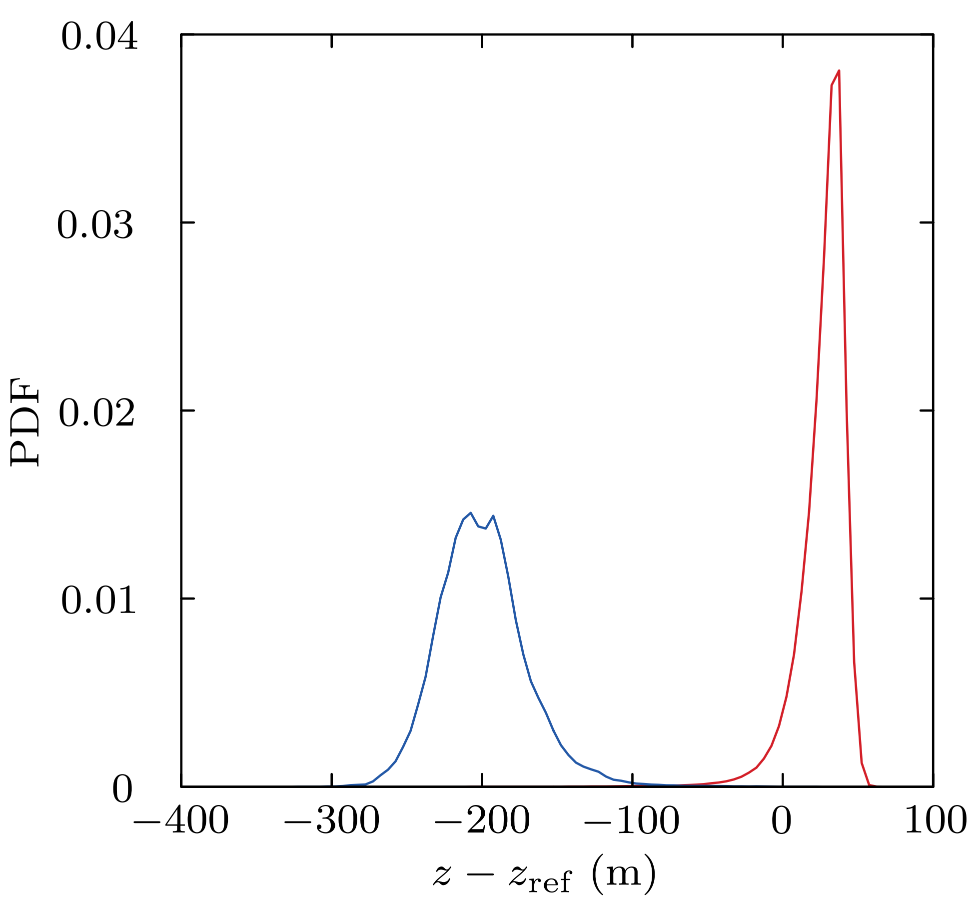


Distribution of cloud voids

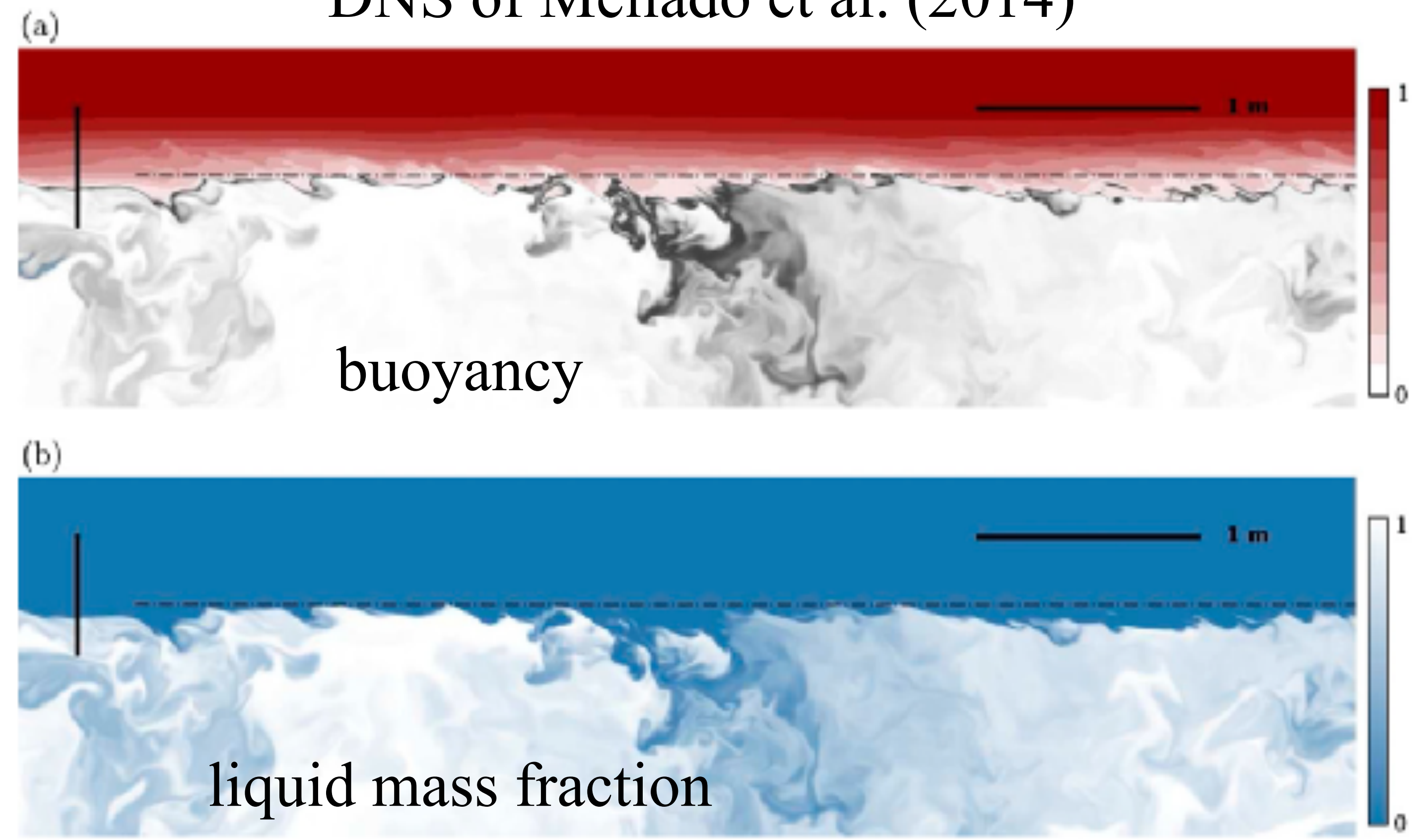


Cloud boundary statistics

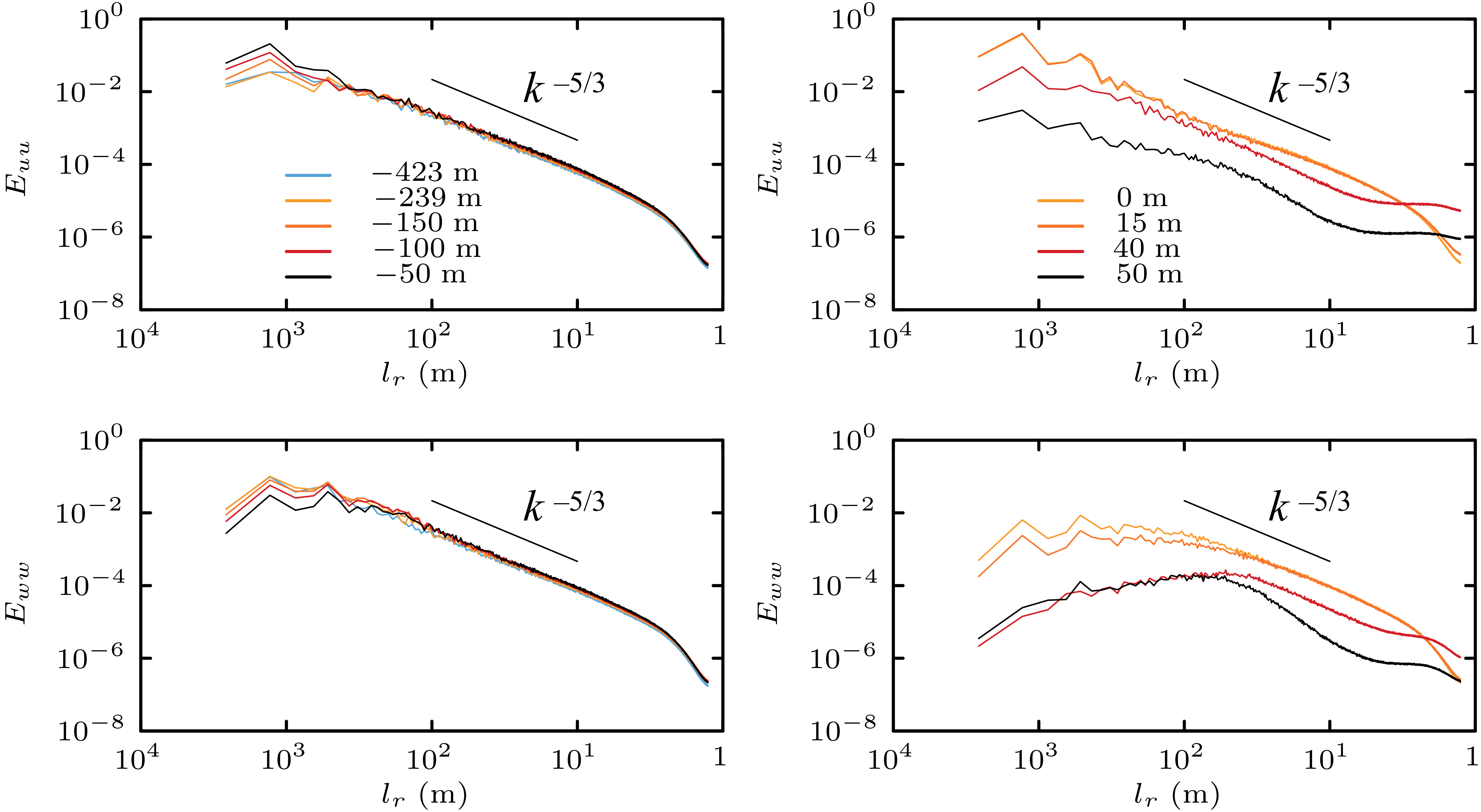
- Length scales at the cloud-top interface are large
- What are the implications for Direct Numerical Simulation (DNS) where these ~50 m length scales are not captured?
  - Also, currently no updrafts in the DNS



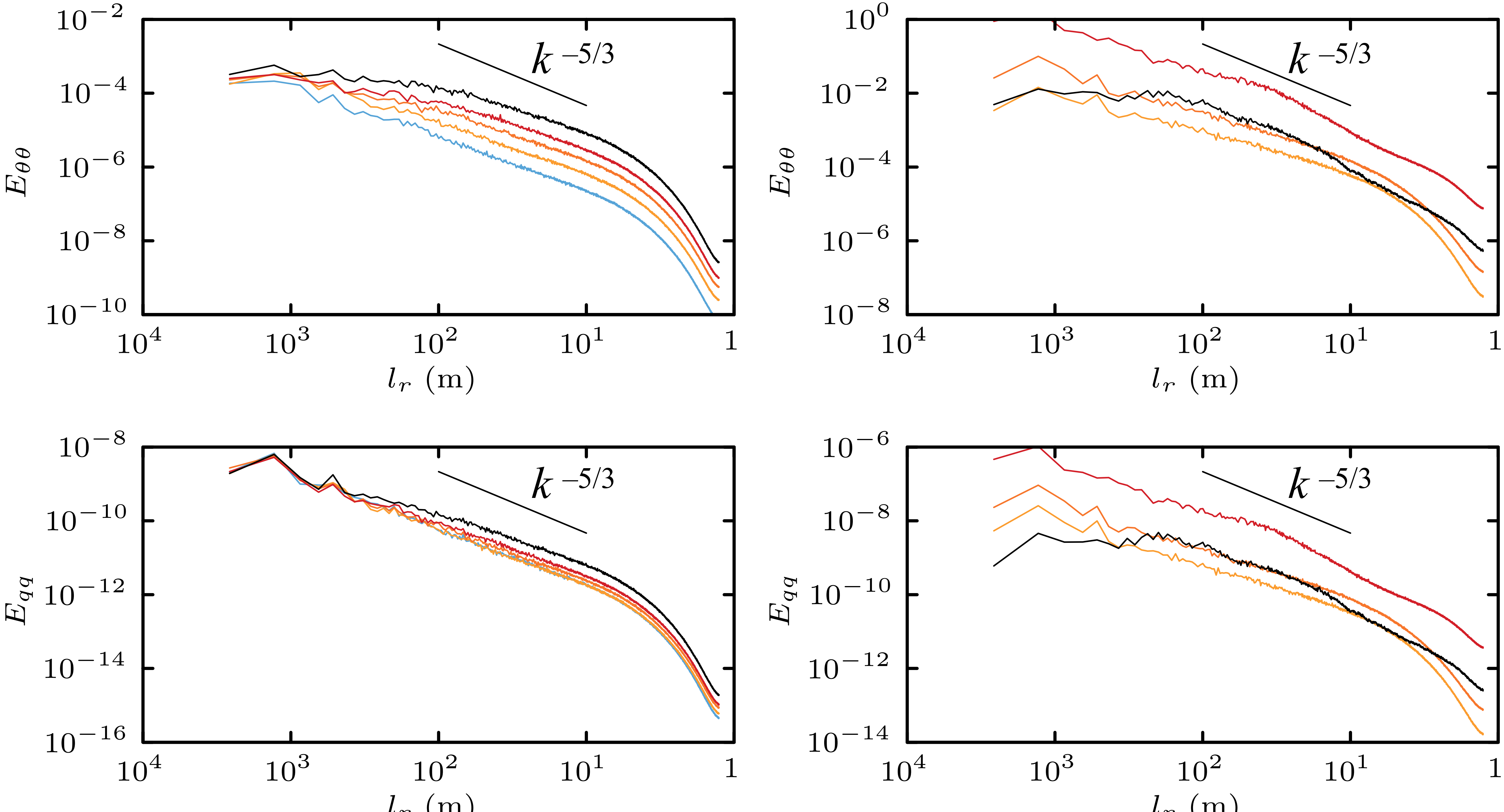
DNS of Mellado et al. (2014)



Spectra: *u* & *w*

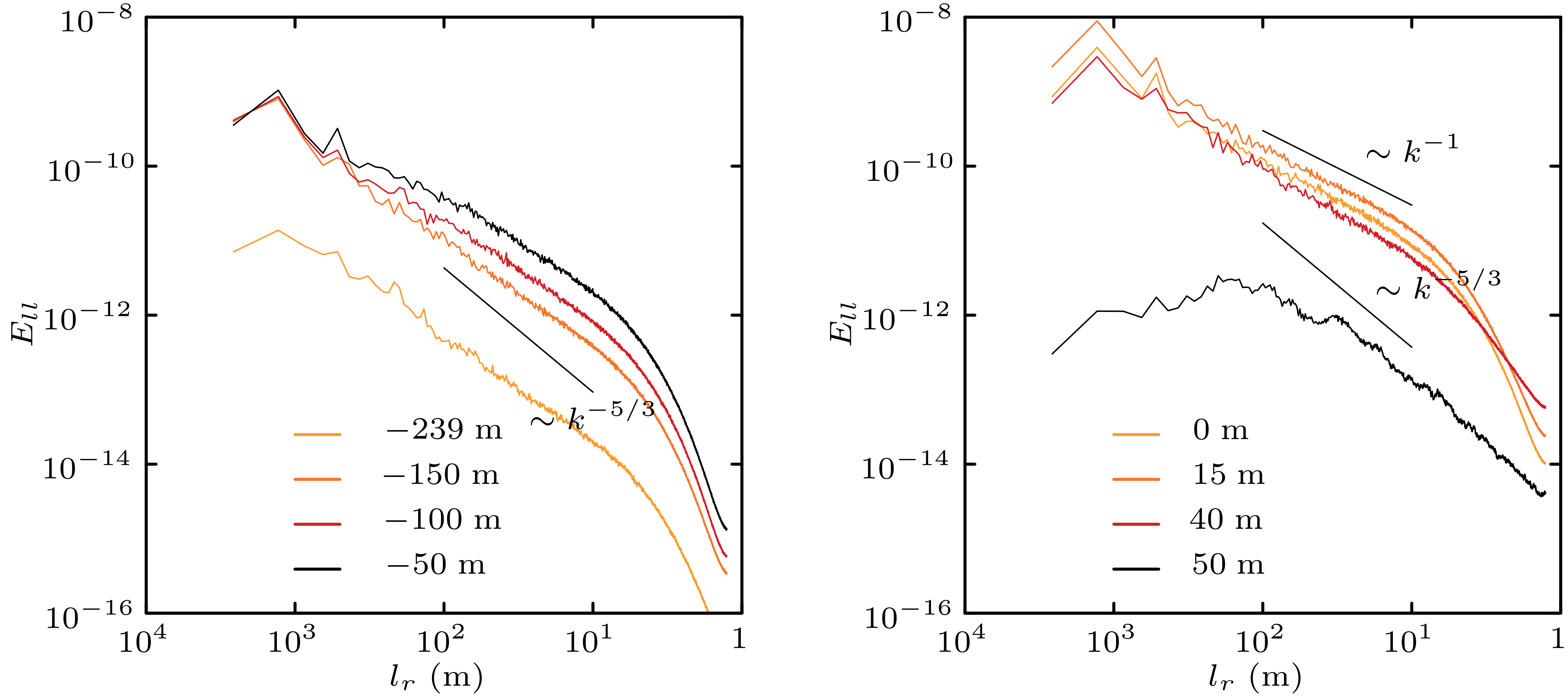


Spectra: q_t & θ_l



Spectra: liquid

- Observations (e.g., Davis et al. 1999) show $\sim k^{-5/3}$ scaling for scales larger than 2–5 m, and a transition to a shallower scaling at smaller scales.
- Presently, the scaling exponent depends on height, increasing from –5/3 near the cloud base to –1 near cloud top



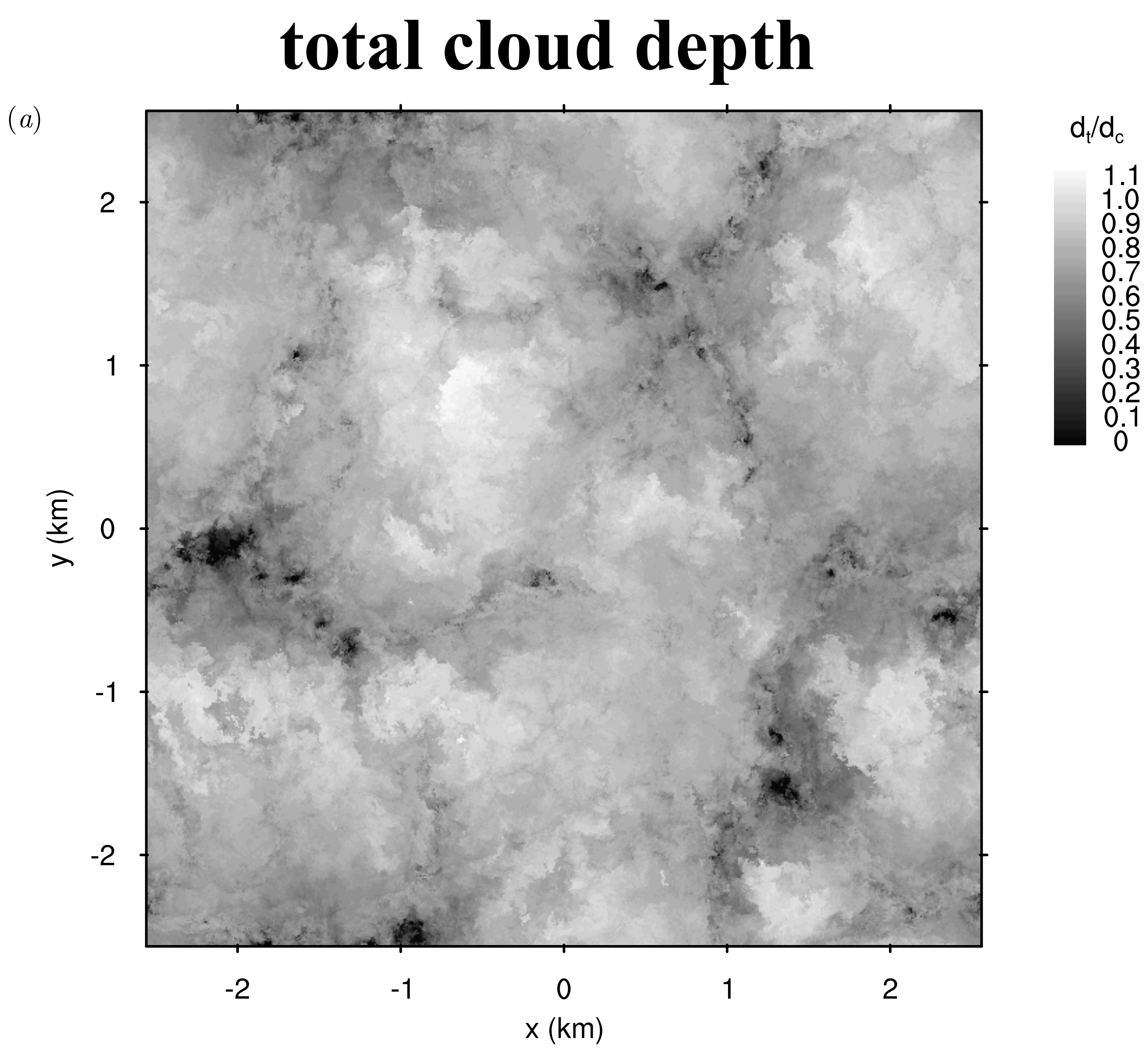
Sc liquid water path spatial structure

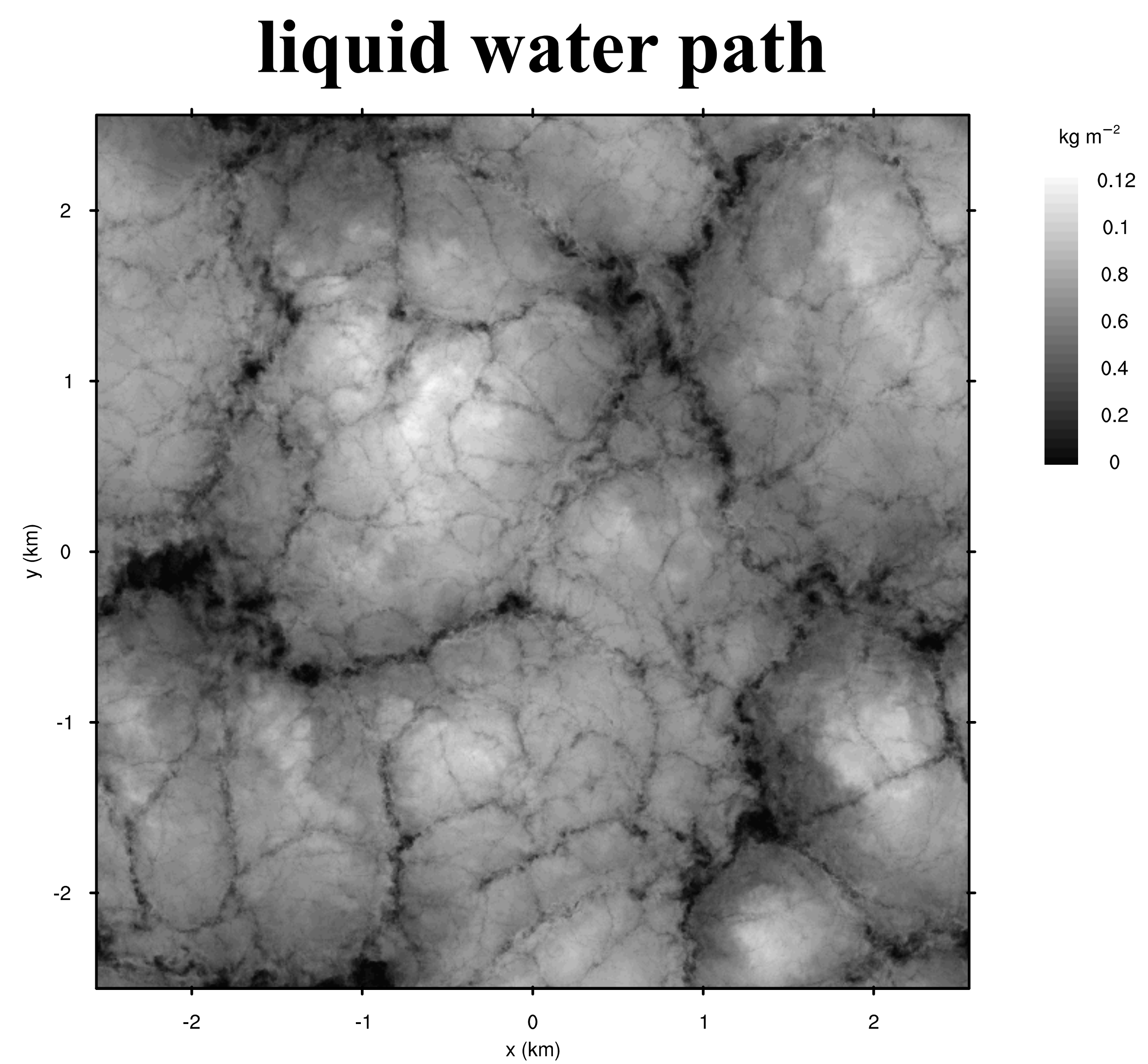
- The objective is to understand the physical processes that modulate the Sc liquid water spatial structure

- The present study aspires to create direct links between the atmospheric boundary layer dynamics and cloud radiative properties by linking the effects of individual physical processes to the cloud liquid structure

Cloud depth and LWP

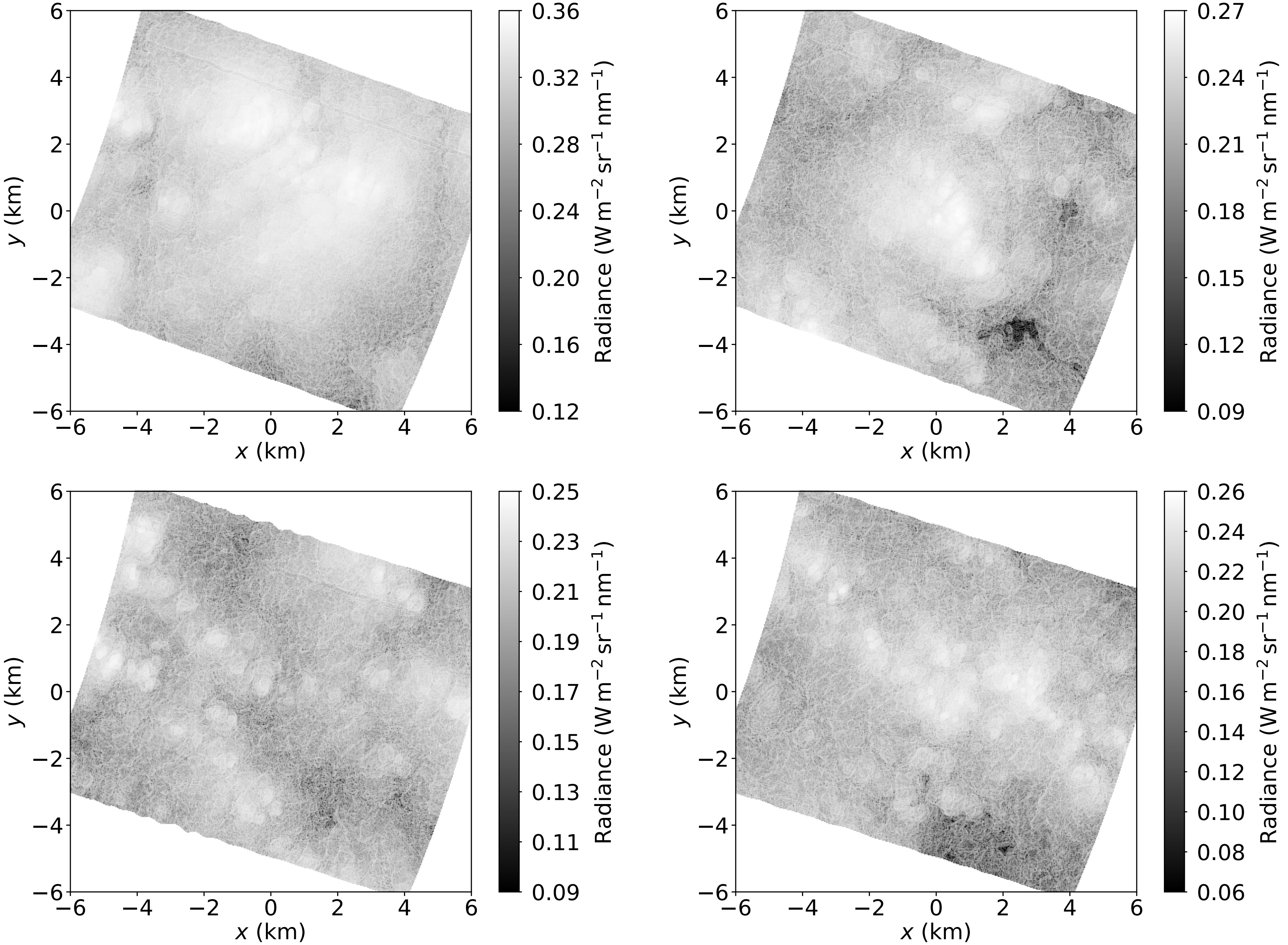
- Regions of cloud with low LWP and large cloud depth





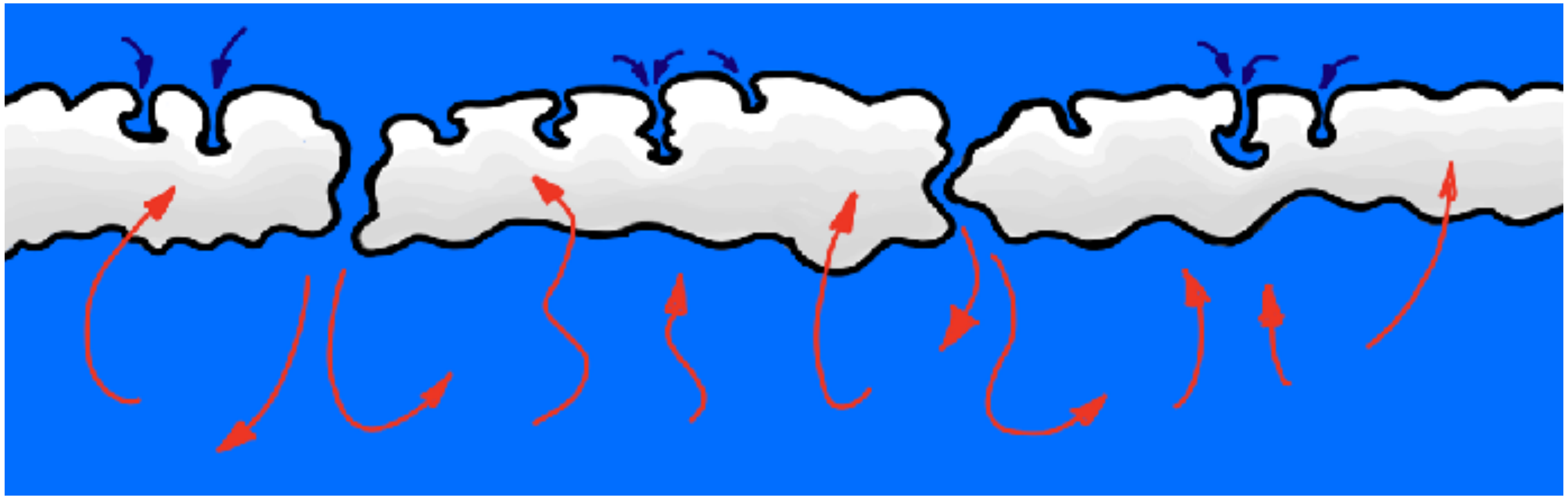
Observations

- Airborne Multiangle SpectroPolarimetric Imager (AirMSPI) observations
- ORACLES campaign, 22 September 2016, off coast of Namibia
- Nadir views of 450 nm band
- 10-m pixels



Hypothesis

- Two main mechanisms control the spatial cloud liquid structure
  - Boundary-layer-deep convective motions, which create the cloud lumpy cellular structure
  - Evaporative cooling near the cloud top, which creates the spiderweb structure
- Implications of the working hypothesis
  - Self-similarity of cloud liquid spatial structure may not hold across all scales because two different processes with different length and time scales modulate the cloud liquid distribution (Davis et al. 1999, Ma et al. 2017)
  - Correct attribution of cloud liquid structure to different physical processes:
    - Decompose the effects of cloud-top radiative and evaporative cooling
    - In the past, rather general terms such as “entrainment,” “radiative cooling,” and “cloud holes” have been used with somewhat indefinite meanings and interchangeably



Model setup

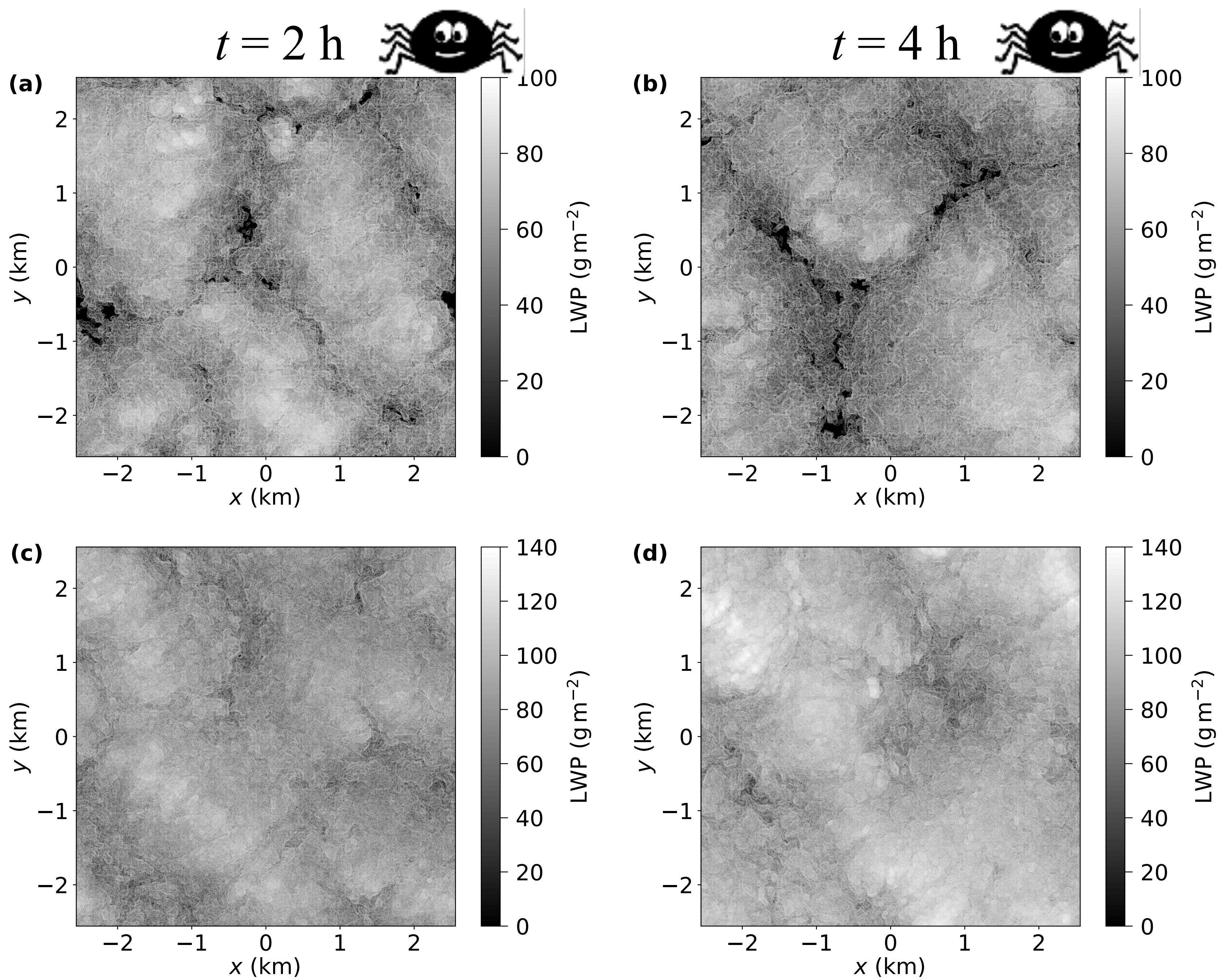
- Buoyancy in LES: $b' = g\bar{\rho}_0 \dfrac{\tilde{\theta}_v - \langle \tilde{\theta}_v \rangle}{\theta_0}$
- Virtual potential temperature: $\theta_v = \theta \left(1 + \left(\dfrac{R_m}{R} - 1 \right) r - r_l \right)$
- Modified virtual potential temperature: $\theta_{v,\mathrm{mod}} = \theta_l \left(1 + \left(\dfrac{R_m}{R} - 1 \right) q_t \right)$
  - Modified virtual potential temperature equivalent to atmosphere without condensate
  - Condensate (suspended liquid) is present in the model and used in radiation calculations

Effects of evaporative cooling in “full physics” LES

- DYCOMS-II RF01 setup
  - LES with and without evaporative cooling (i.e., use of modified buoyancy)

Full physics →

No evaporative cooling →

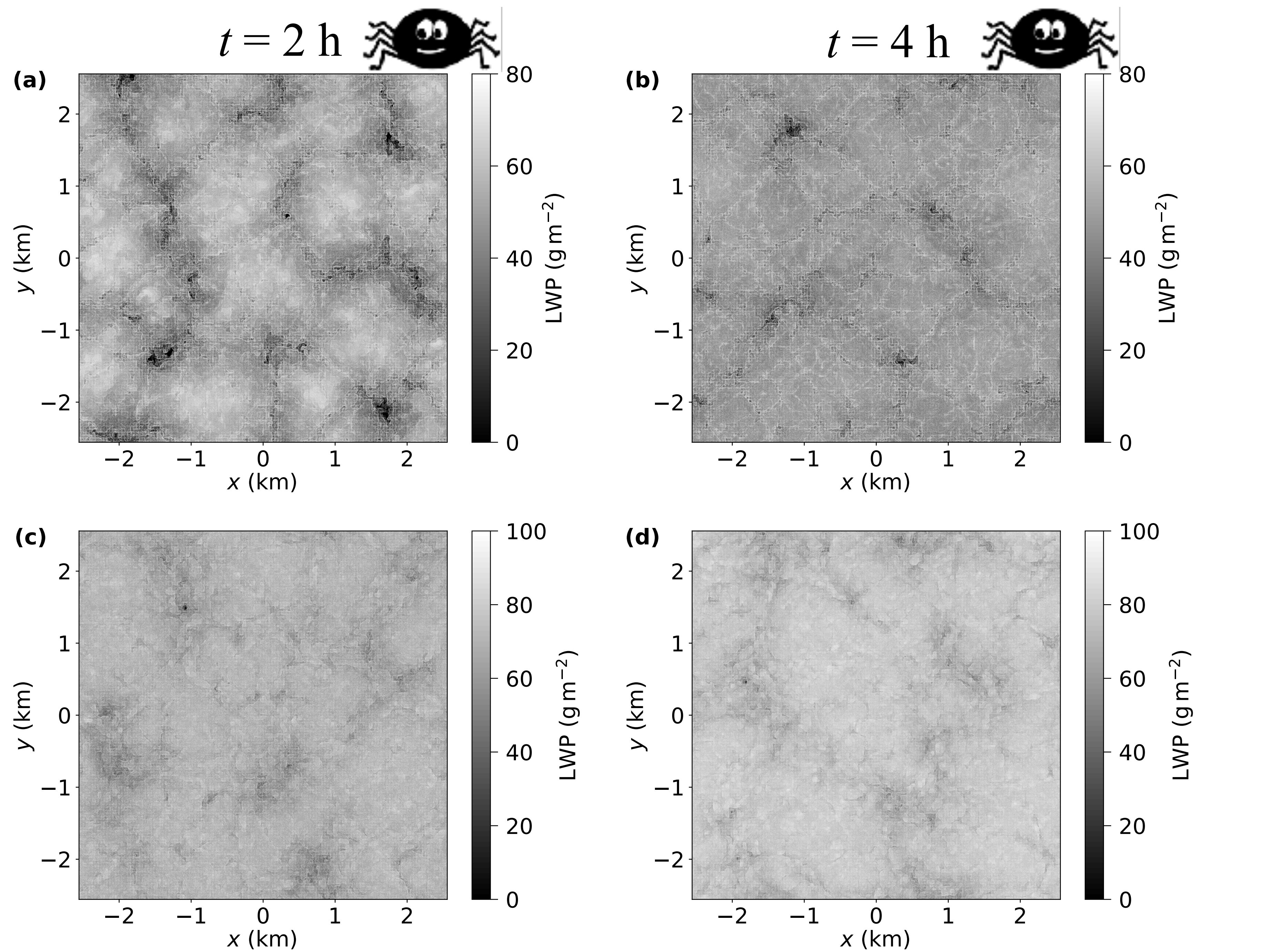


Stratocumulus driven by radiation only

- No surface heat fluxes
- No mean surface shear

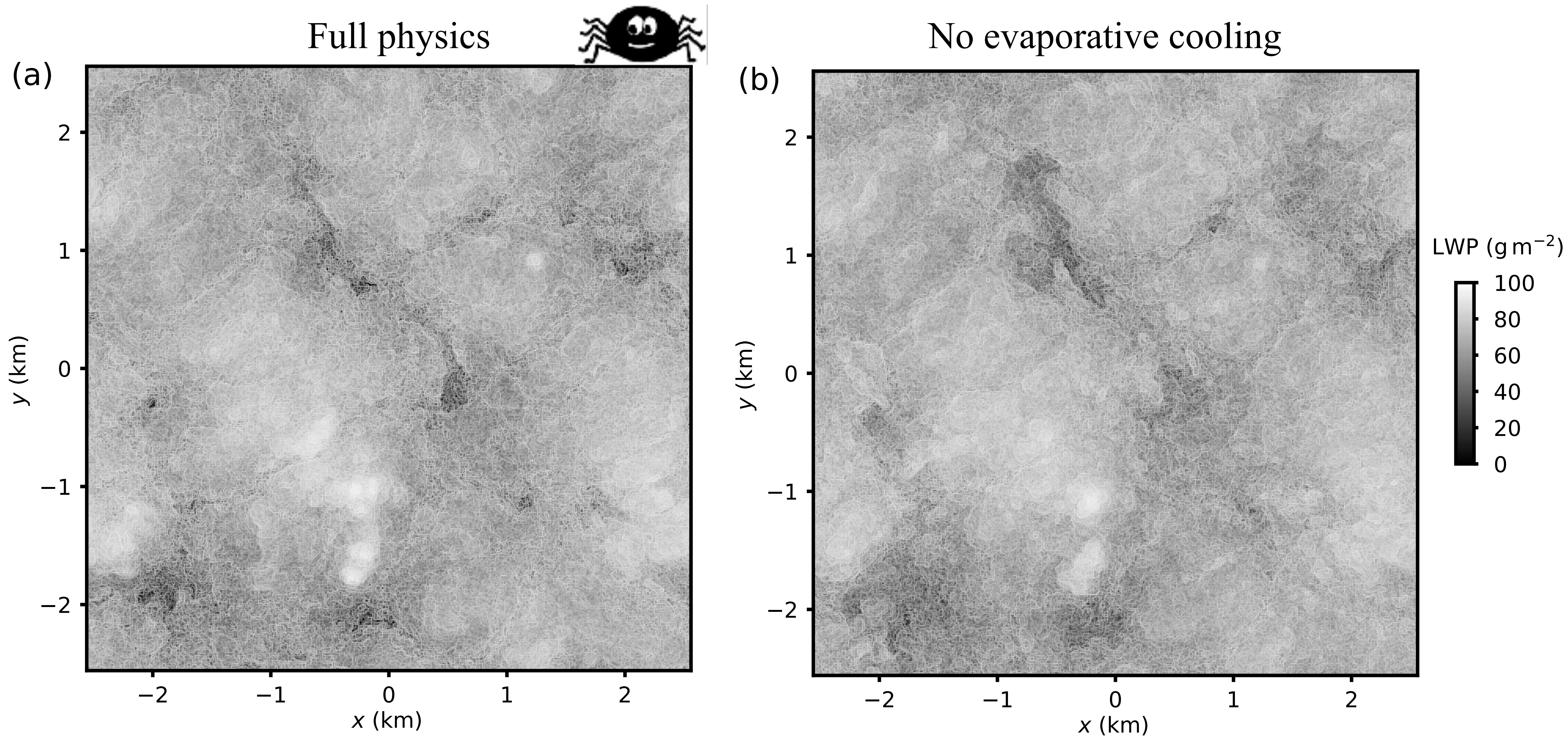
Radiative cooling
+
Evaporative cooling

Radiative cooling only



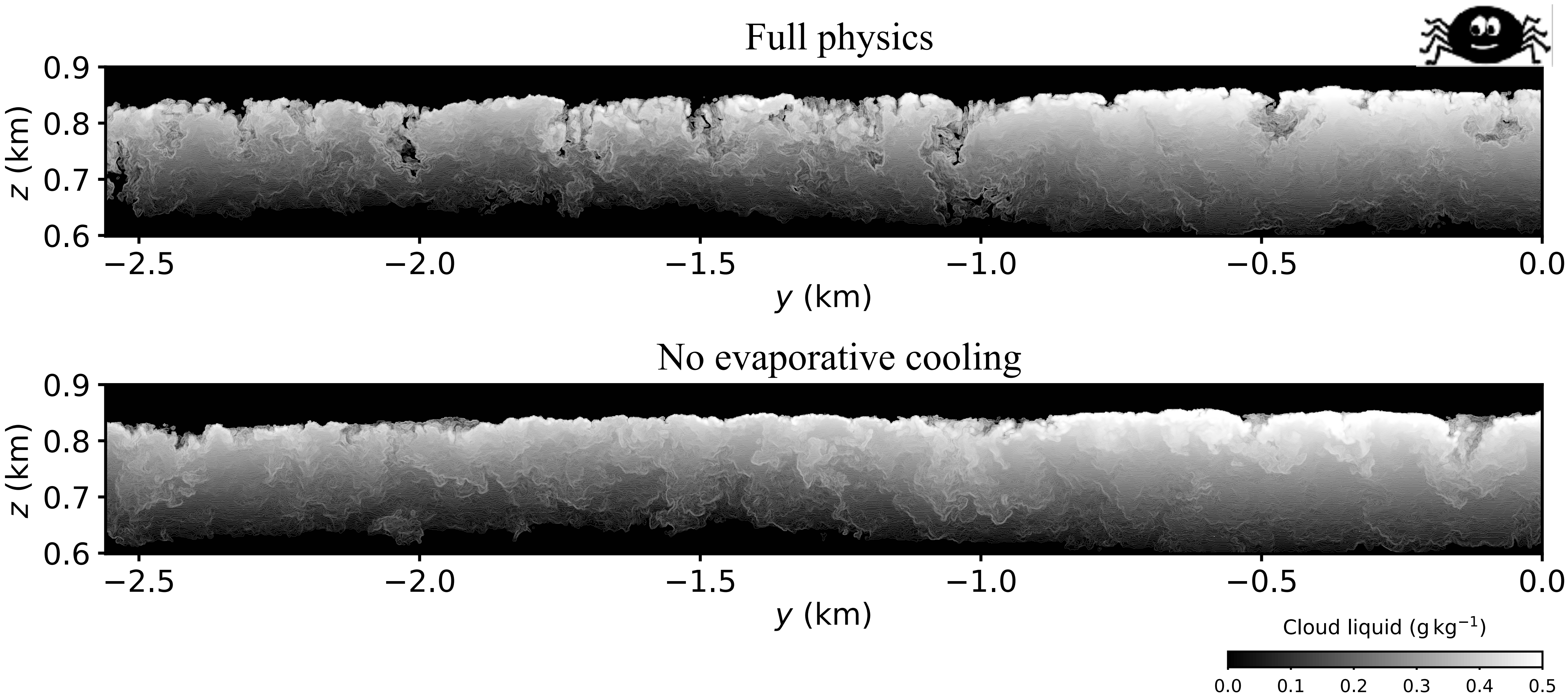
10-minute Sc evolution without evaporative cooling

- Initialize from a "full physics" run at $t = 2$ h
- Run 2 simulations for 10 minutes with and without evaporative cooling
  - 10 minutes is about half the convective time scale
  - Fine grid resolution $\Delta x = 1.25$ m
- Large scale remains correlated but spiderweb dissipates



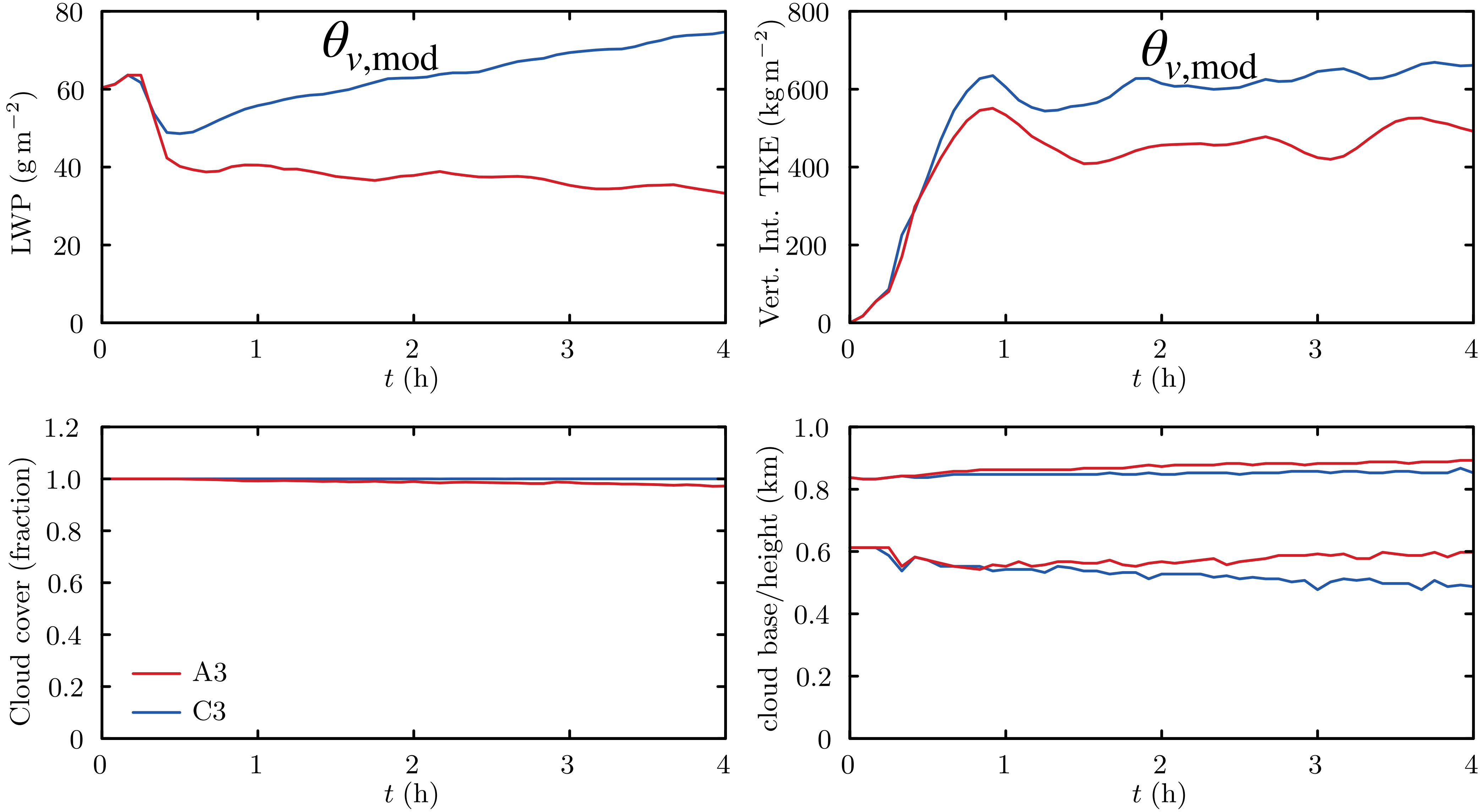
10-minute Sc evolution without evaporative cooling: liquid

- Cloud liquid vertical slices
  - Only half domain shown
- Evaporative cooling near the cloud top creates shallow grooves on the cloud top
- Most of the cloud-liquid mass is near the cloud top, thus even shallow corrugations of the cloud top have a large impact on LWP

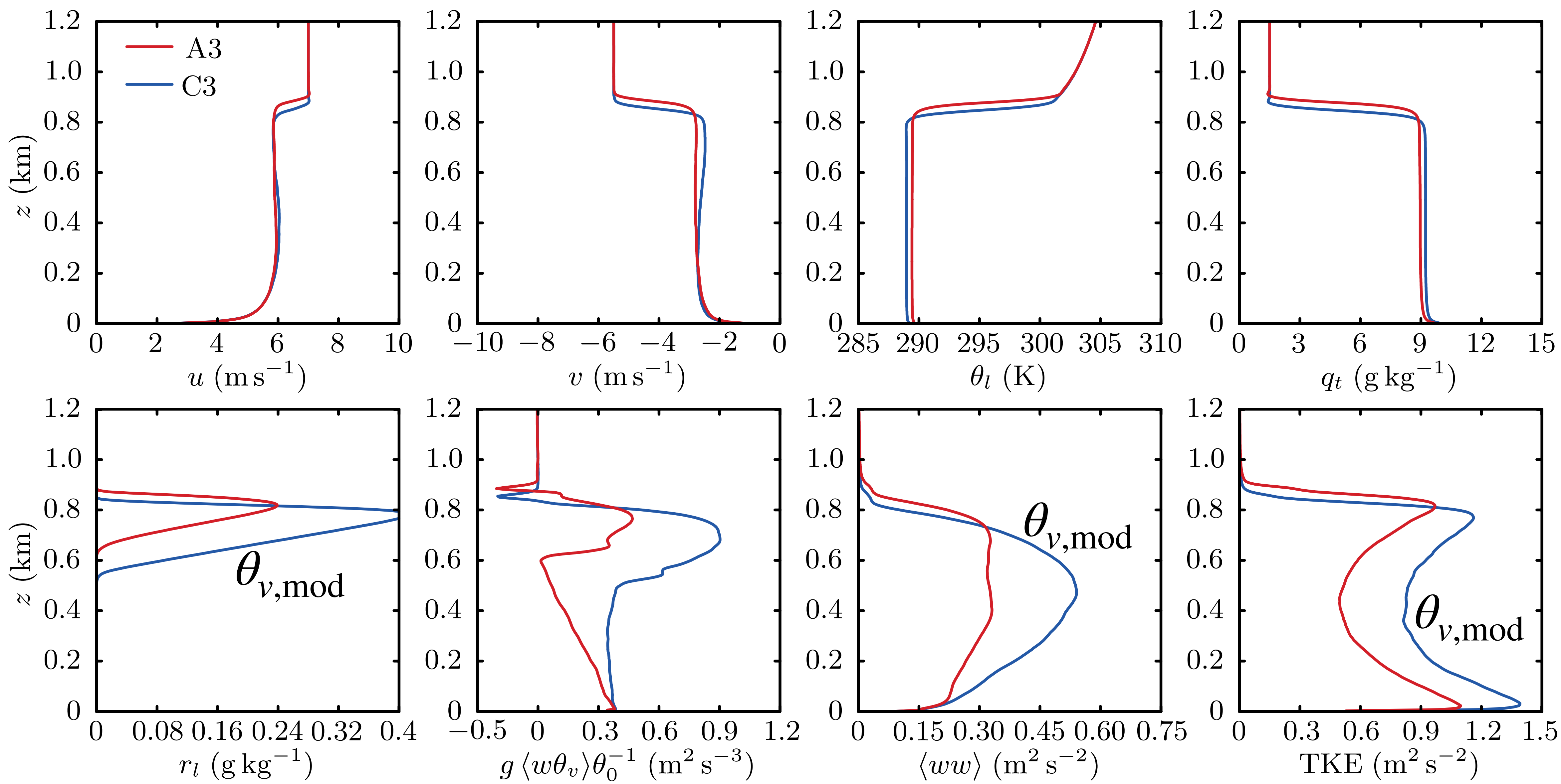


Boundary layer evolution

- LES with modified buoyancy (no latent heat exchange):
  - Less entrainment
  - More cloud liquid
  - Higher TKE (likely because of larger radiative forcing)



Boundary layer profiles at $t = 4$ h



Summary and Conclusions

- Studied LES model performance for a nocturnal stratocumulus case
  - Variable grid resolution $\Delta x = 1.25 - 20$ m (factor of 16 change)
  - Simulations with and without radiation
- LES agrees with observations and exhibits grid convergence
  - No *ad hoc* model choices
- Challenges in accurate LES of stratocumulus are because of the radiation–buoyancy–turbulence feedback
  - Small errors in humidity and temperature result in larger errors in the amount of cloud liquid
  - Radiative cooling depends exponentially on cloud liquid
- Accuracy of the subgrid-scale model is not as poor as previously assumed
- Stratocumulus clouds have a distinctive structure composed of a combination of lumpy cellular structures and thin elongated regions, resembling canyons or slits
  - The spiderweb structure is generated by cloud-top evaporative cooling
  - Cloud-top evaporative cooling generates relatively shallow slits near the cloud top