Organization development in shallow precipitating cumulus convection

Oumaima Lamaakel & Georgios "George" Matheou
Department of Mechanical Engineering, University of Connecticut

oumaima.lamaakel@uconn.edu • matheou@uconn.edu

@me3250
cfd.engr.uconn.edu

Improvement and calibration of clouds in models
Météo-France, Centre International de Conférences, Toulouse, France

April 12, 2021

Acknowledgments

- Funding support
  - National Science Foundation (NSF) Climate Process Team (CPT): "From boundary layer to deep convection: The multi-plume eddy-diffusivity/mass-flux (EDMF) fully unified parameterization"
    - Lead PI: J. Teixeira, JPL/UCLA
    - Grant NSF-AGS-1916619
  - Many thanks to all CPT members for numerous fruitful and stimulating discussions

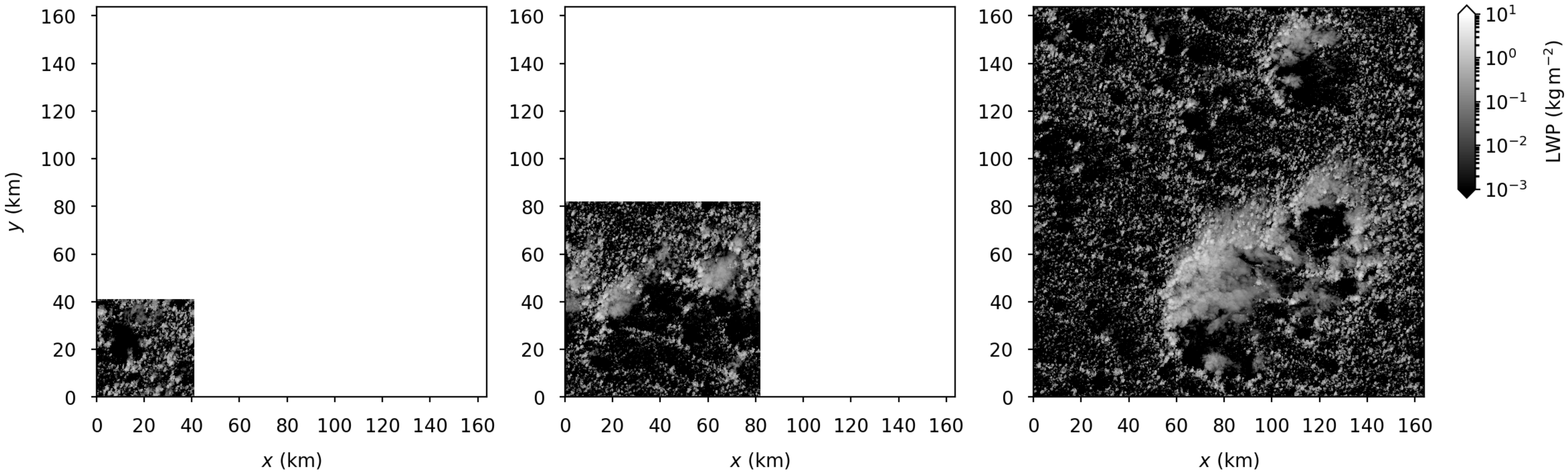
- Computational resources
  - University of Connecticut High Performance Computing (HPC) facility

Motivation – Objectives

- Trade wind cumulus-topped boundary layers play a key role in the global circulation and the Earth's atmospheric energy balance
- Organization, or mesoscale variability, in boundary layers is an important mechanism in the interaction/response of the boundary layer with the large-scale conditions
  - Several previous studies, e.g., Seifert & Heus 2013, Vogel et al. 2016, Bretherton & Blossey 2017, Zuidema et al. 2017, and many others…
- The main question of this study is:
  - What is the time-scale (or growth rate) of development of convective organization in the boundary layer?
- Methodology
  - Trade wind precipitating shallow cumulus case: Rain in (shallow) Cumulus over the Ocean (RICO, Rauber et al. 2007, van Zanten et al. 2011)
  - Large-eddy Simulation (LES) experiments
    - Simulations using three domains sizes: 40, 80, and 160 km in the horizontal
    - 40 m grid spacing (in all directions): largest domain is 2 billion grid cells ($4096^2 \times 125$)
    - Utilize model to get three-dimensional time-resolved data
  - UConn LES model
    - Agreement with observations and grid convergence established in Matheou & Chung (2014)
    - Warm rain microphysics, two-moment bulk scheme of Seifert & Beheng (2001)

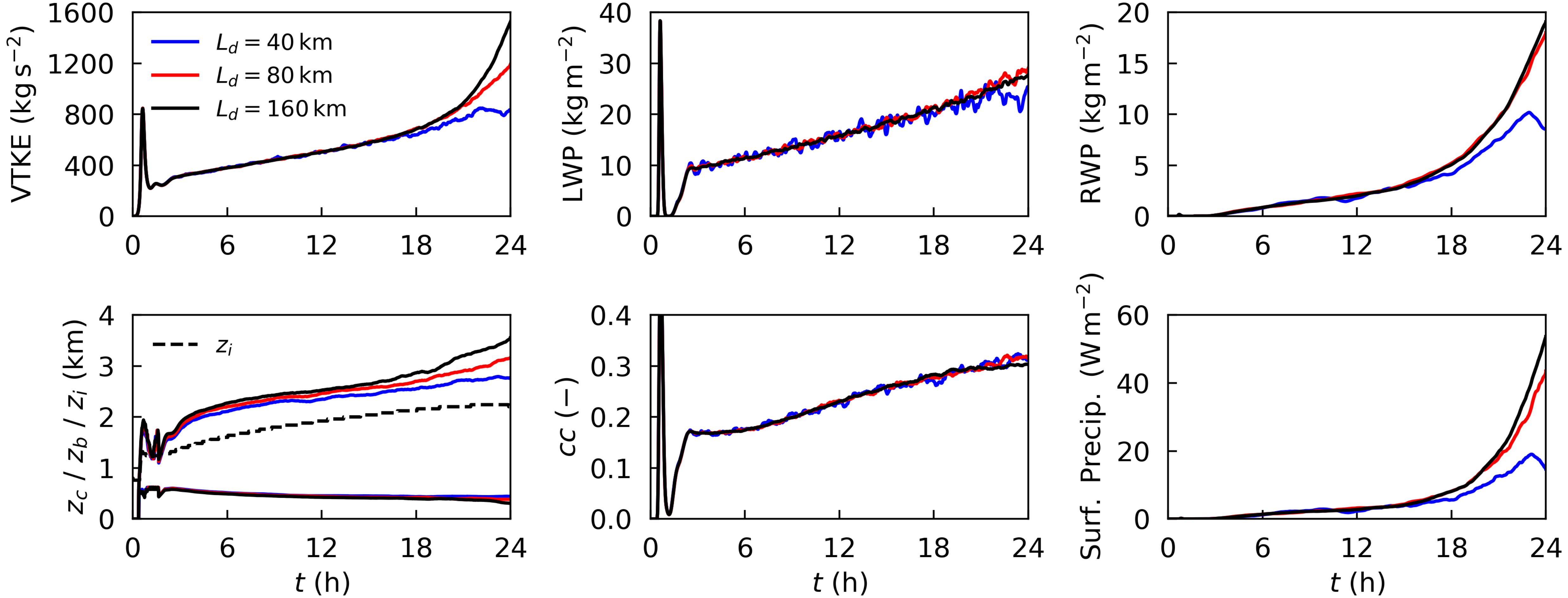
LES domain size effects: LWP

- Liquid water path at $t = 24$ h
  - All three domains are periodic in the horizontal
- Large horizontal structures (cloud arcs, cold pools)
- Only largest domain (160 km) contains several cold pools (at distance from one another)
- Boundary layers are not always boring…
  - Not everything is a "popcorn cloud"



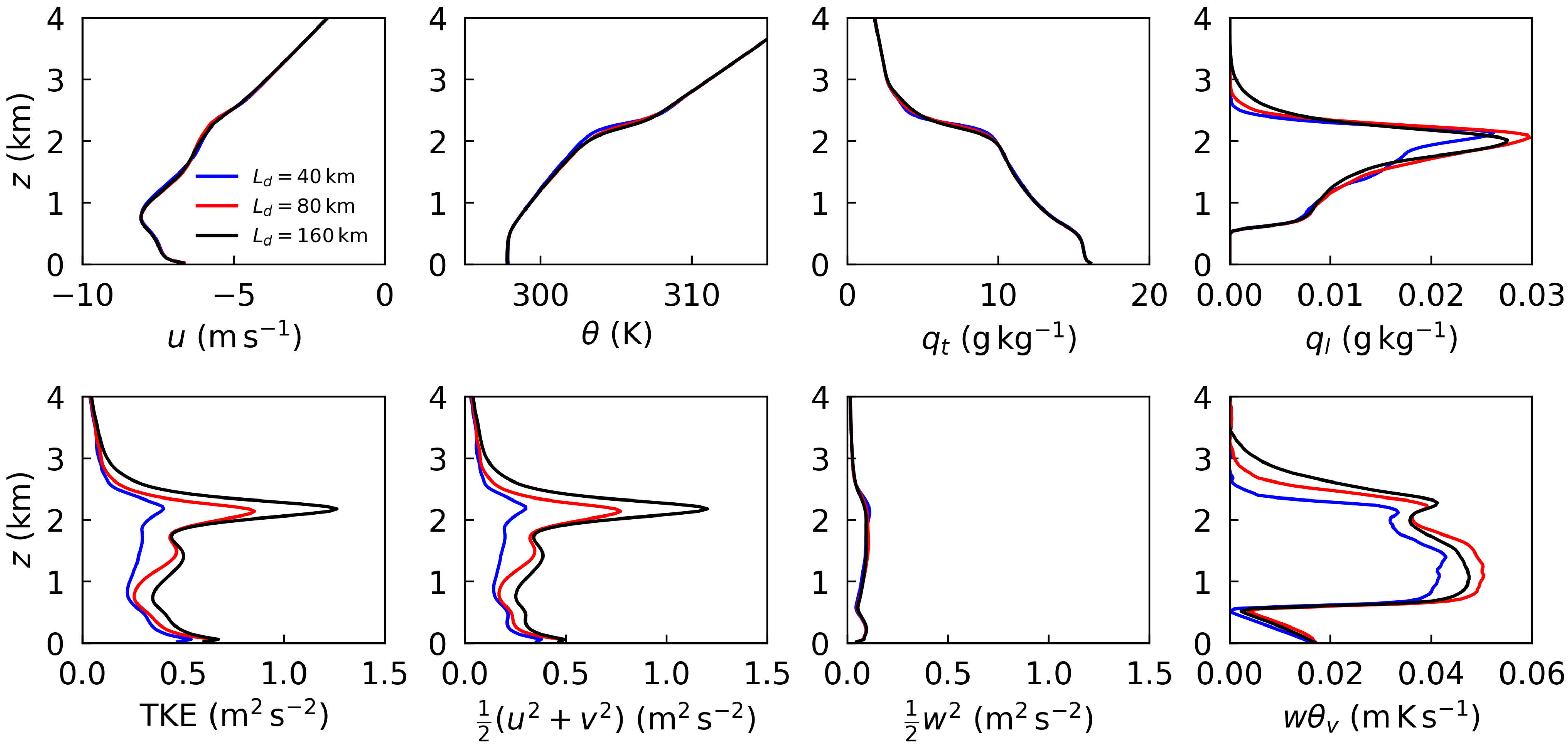
LES domain size effects: time traces

- Identical mean surface heat flux for all domains
  - Same forcing and boundary conditions
- Same inversion height z_i for all domains
  - z_i is the height of maximum gradient of potential temperature
- Traces in small domain “saturate” at about $t = 22$ h
  - We will run all domains for longer



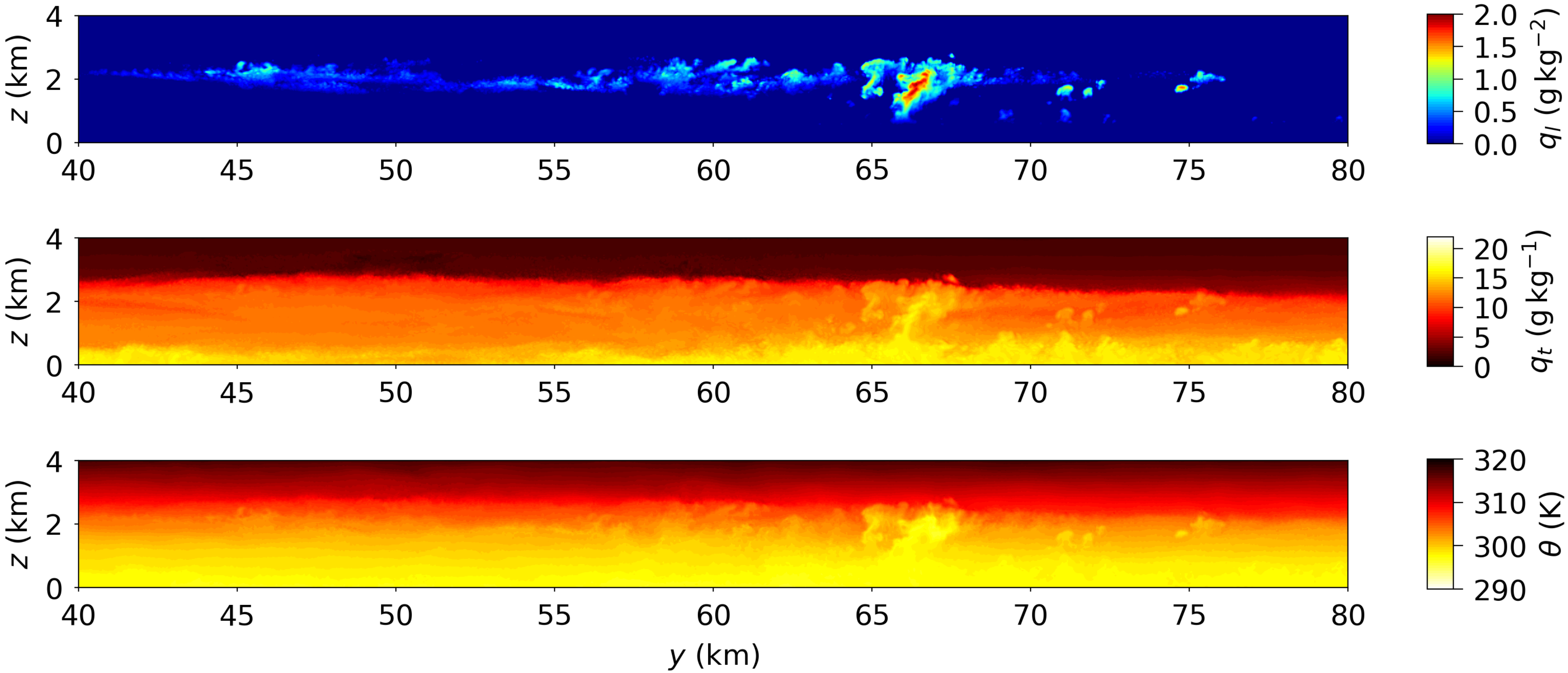
LES domain size effects: Profiles at t = 24 h

- Same mean profiles for all domains (wind and thermodynamic variables)
  - Mean cloud liquid shows clouds penetrating higher as domain size increases
- Buoyancy flux shows deeper updrafts in larger domains
- Large differences in turbulent kinetic energy is solely because of the horizontal components
  - Same vertical velocity variance



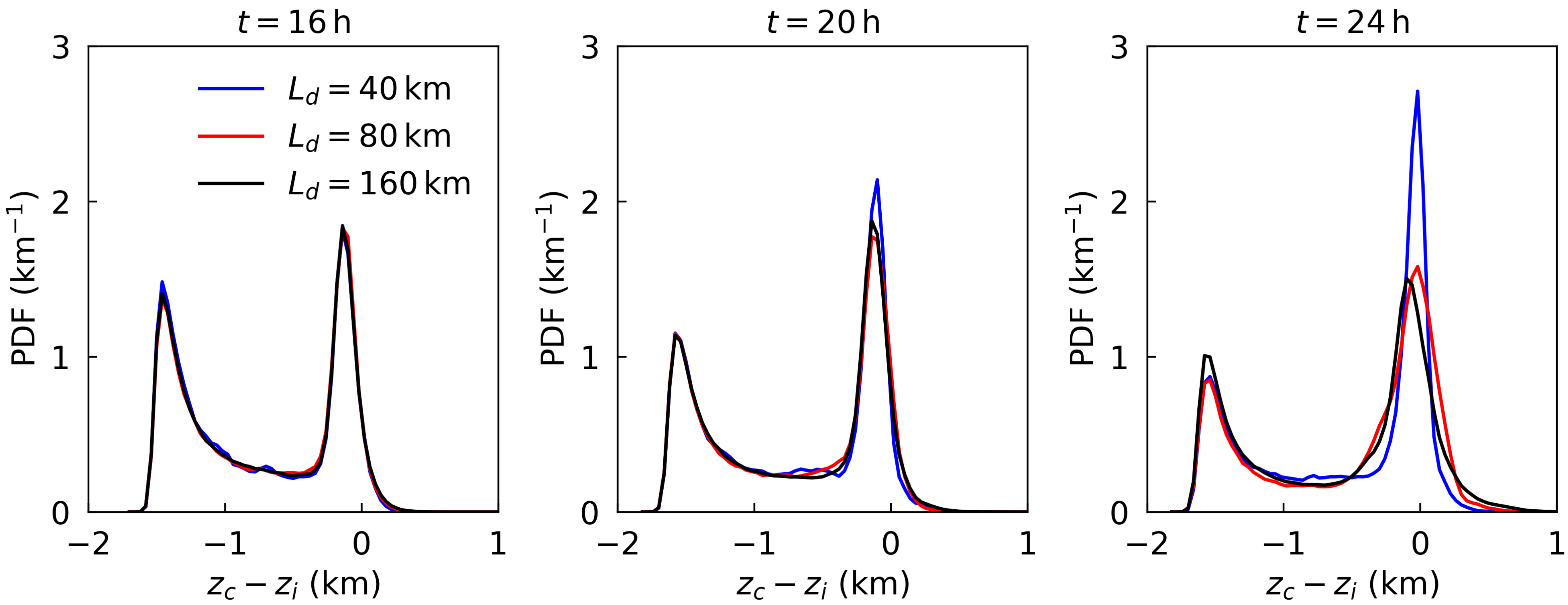
Fields on vertical planes

- Large cloud-top height variability
  - Cumulus towers penetrating > 0.5 km above the inversion
  - Challenging to graphically represent the three-dimensional cloud structure
- Most stratiform cloud is at the inversion height ($z_i = 2.2$ km)
- LES domain height is 5 km (only up to 4 km shown here)



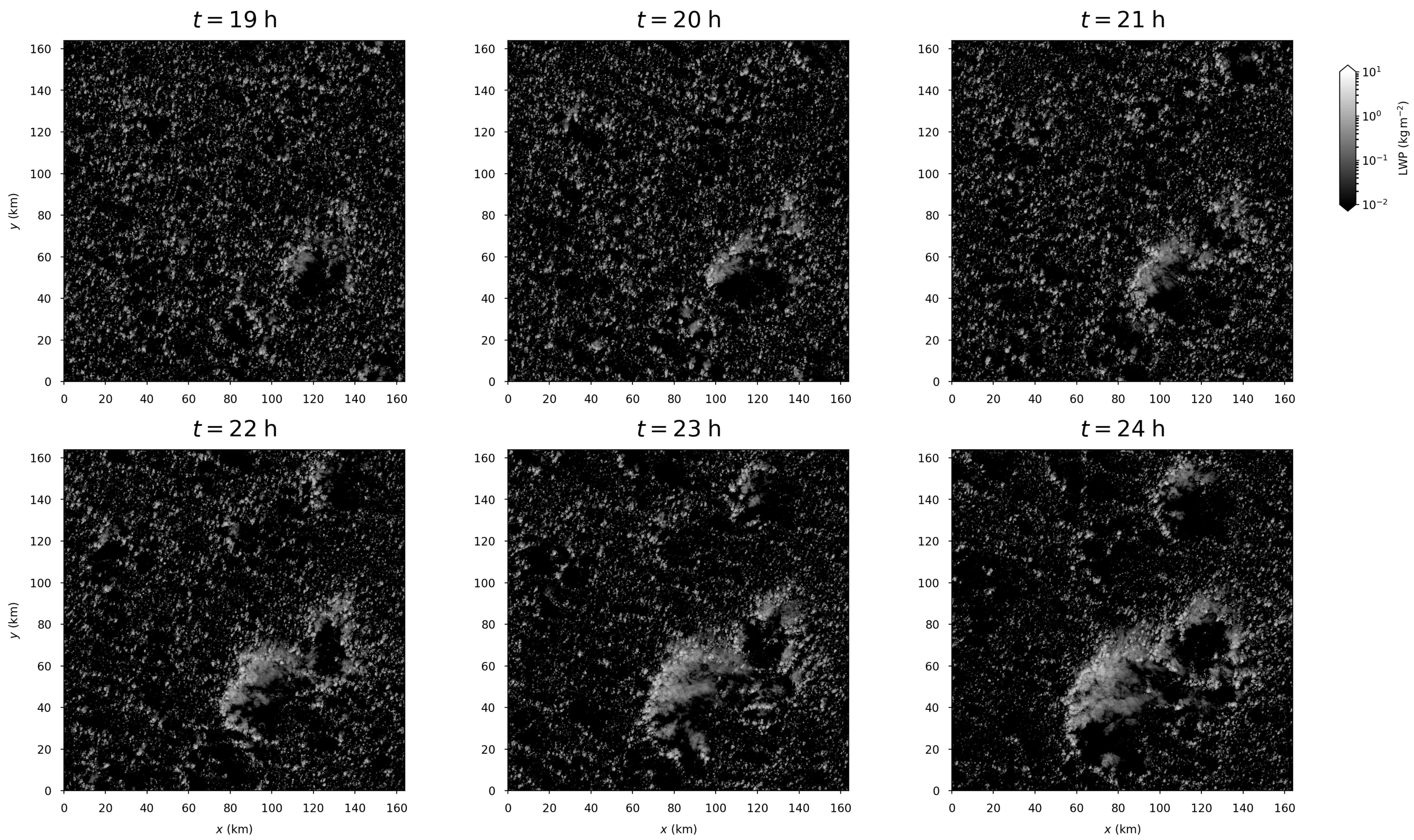
Cloud-top height distribution

- Most stratiform anvils are below the inversion height z_i
- Organization in larger domains allows cloud tops to reach $> z_i + 0.5$ km
- 40 km domain is too small for $t > 20$ h



LWP *vs* time: largest domain, 160 × 160 km

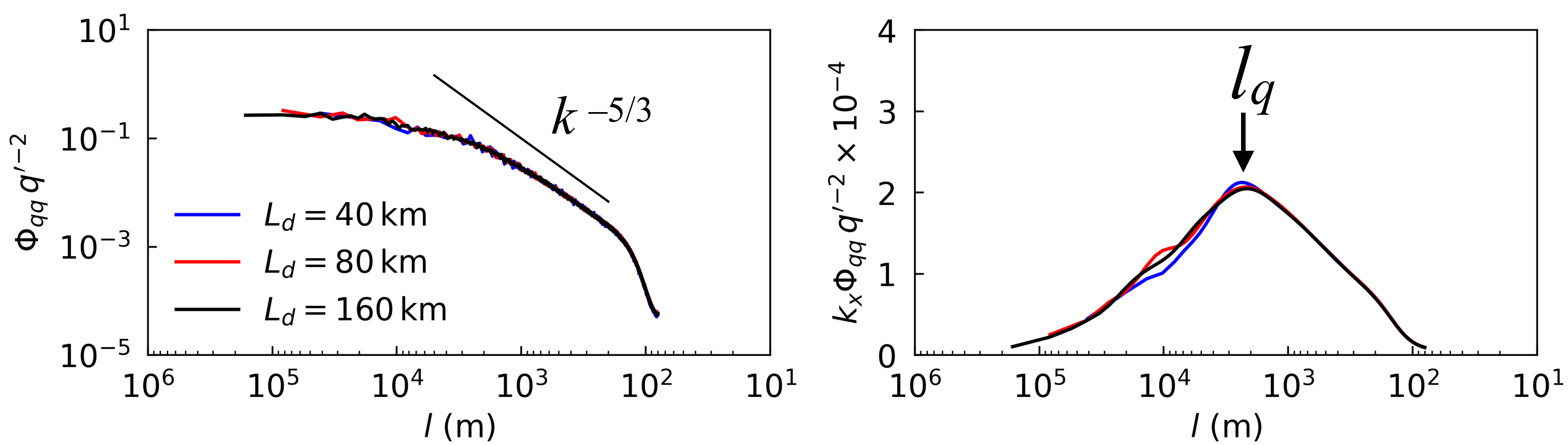
- Large-scale organization develops at about $t = 18$ h
- Multiple “cold pools” develop and grow
  - First generation of cold pools developing in a spatially homogeneous shallow Cu field



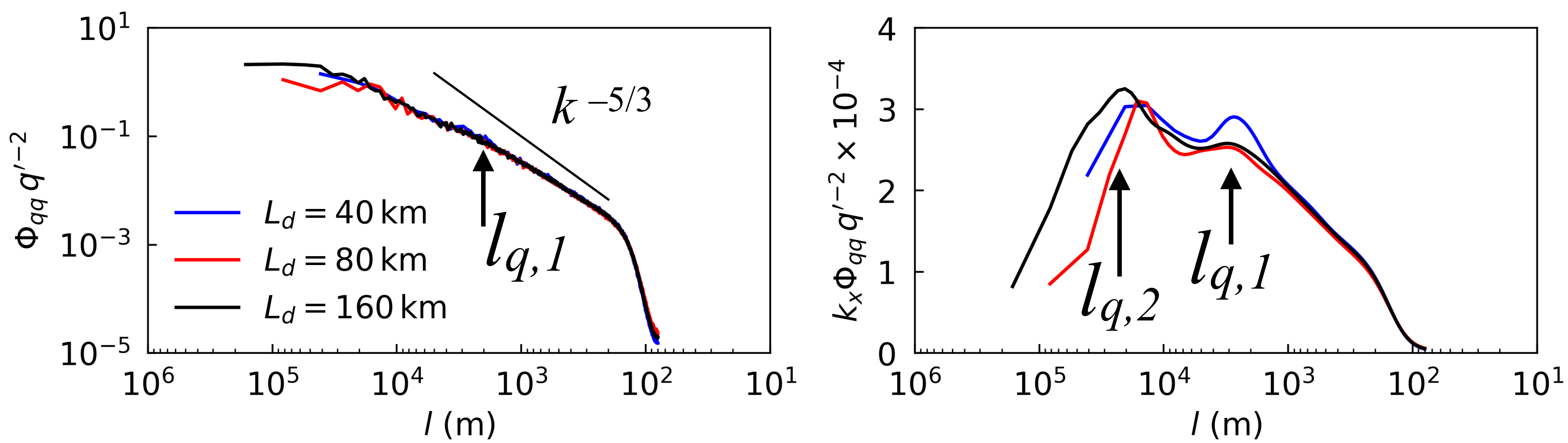
Spectra

- For $t < 16$ h spectra from all domains are very similar
  - Power-law scaling for scales smaller than premultiplied spectra peak ($l = 2$ km)
  - Premultiplied spectra have a single maximum
- For $t > 16$ h spectra are different at the large scales
  - Premultiplied spectra have multiple peaks, and peaks vary with time (except w)
  - Power-law scaling extends to large scales (and inconspicuous spectral bumps)
- Spectra of total water mixing ratio at $z = 340$ m (flow is continuously turbulent) are shown

$t = 16$ h

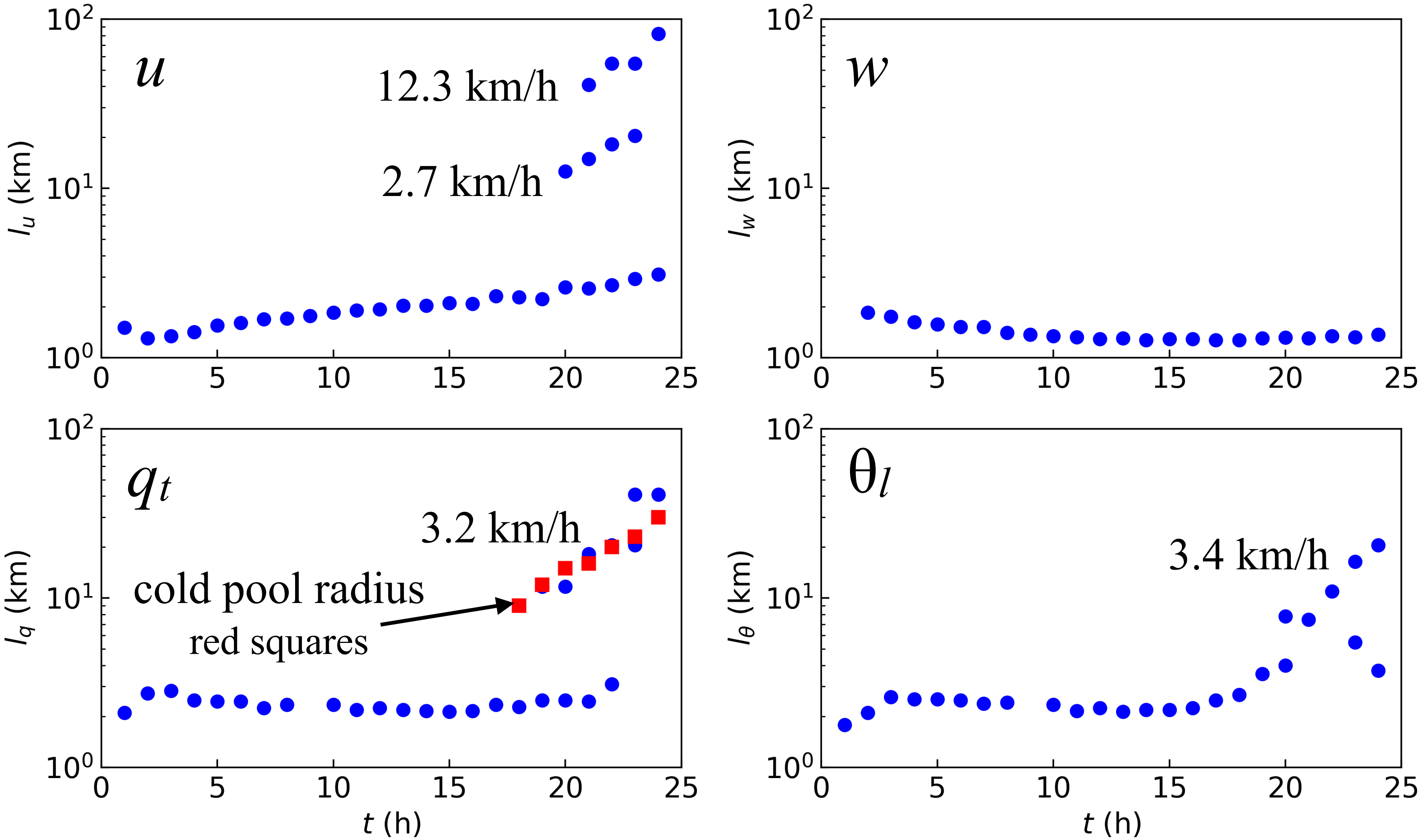


$t = 22$ h



Length scales

- Length scale of the premultiplied spectra peaks and size of cold pool (red symbols)
- Generation of cold pools results in additional, fast-growing length scales for horizontal wind and thermodynamic variables
- No change in vertical velocity length scale
  - Expected? Same size updrafts but organized?
  - Corroborated by insensitivity of vertical velocity variance with respect to domain size?



Summary, Conclusions (and a few more questions…)

- Studied time evolution of organization in shallow precipitating convection
  - LES of RICO case for domains up to 160 km in the horizontal directions
- Key limitation: uniform large scale (geostrophic wind, subsidence, SST, etc.)
- Strong domain-size sensitivity for some flow statistics
  - Sensitivity results from the generation of horizontal inhomogeneity
  - Large length scales are generated after $t = 20$ h
    - Two-point correlation functions (not discussed in this presentation) show large correlations even at 160 km (the largest domain size)
- Organization results in deeper clouds (> 0.5 km higher tops than inversion)
- Development of organization (and domain size) have no impact on vertical velocity second-order statistics and length scale
  - Good news for convective parameterizations?
- Growth rate of thermodynamic large scale is about 3 km/h (0.83 m/s)
  - Horizontal velocity has an additional adjustment large scale growing at about 12 km/h
  - Is this a "typical" case of trade wind precipitating cumulus? Are these results general?
- Key question for parameterization development:
  - Which of the present results a successful parameterization needs to capture?