Numerical studies of cloud turbulence – from mesoscale moist convection to cloud microphysics

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Outline

- Motivation
- Characteristic scales of cloud dynamics
- Direct numerical simulation studies

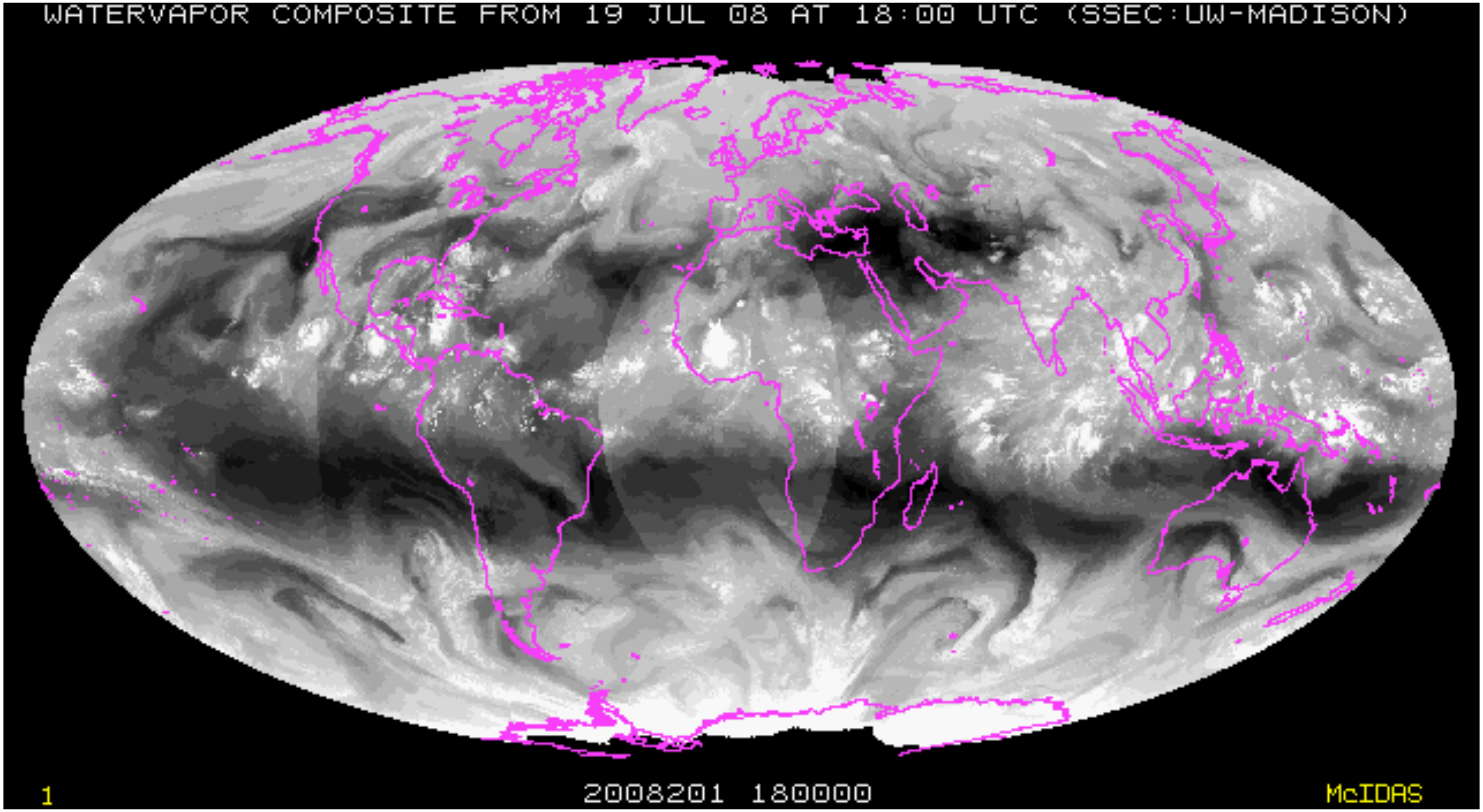
  $\longrightarrow$ Mesoscale: cloud patterns in moist Boussinesq convection

  $\longrightarrow$ Microscale: turbulent entrainment and droplet microphysics
- Outlook

Joint work with:

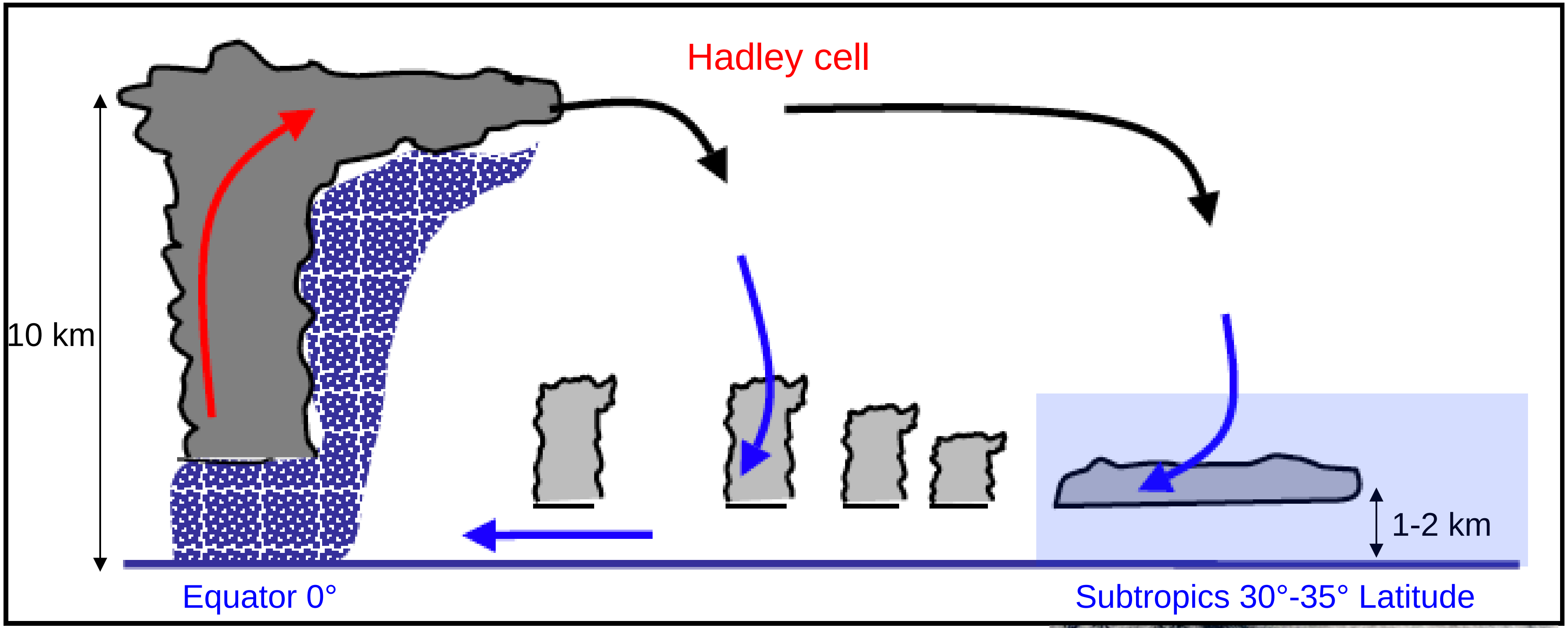
Paul Götzfried (TU Ilmenau)
Bipin Kumar (Indian Institute of Tropical Meteorology Pune)
Olivier Pauluis (New York University)
Raymond A. Shaw (Michigan Technological University Houghton)
Thomas Weidauer (Friedrich Schiller University Jena)

Atmospheric convection



Formation of clouds in the atmosphere

Deep and shallow convection

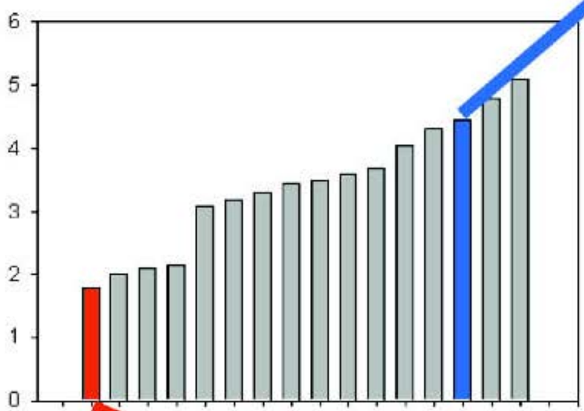


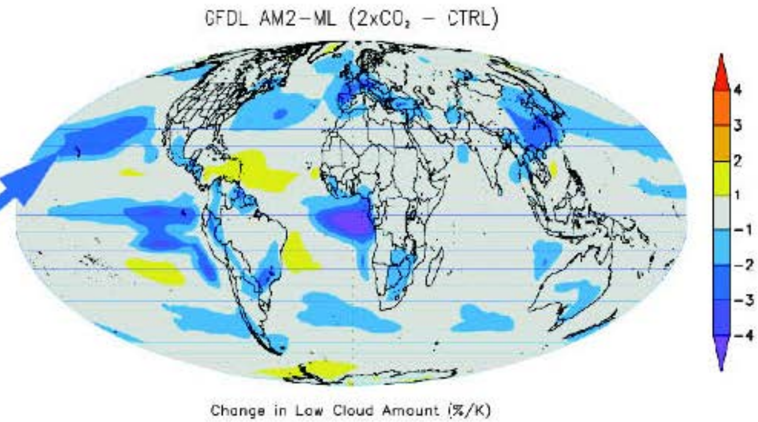
Low cloud parametrization in climate models

Stephens, J. Climate 2005

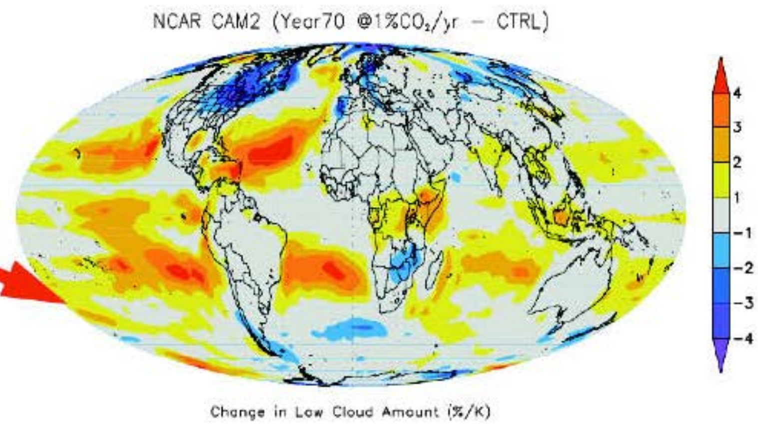
Which feedback results from a fixed 1% per year increase of CO_2 concentration?

Predicted warming from 16 GCMs in K



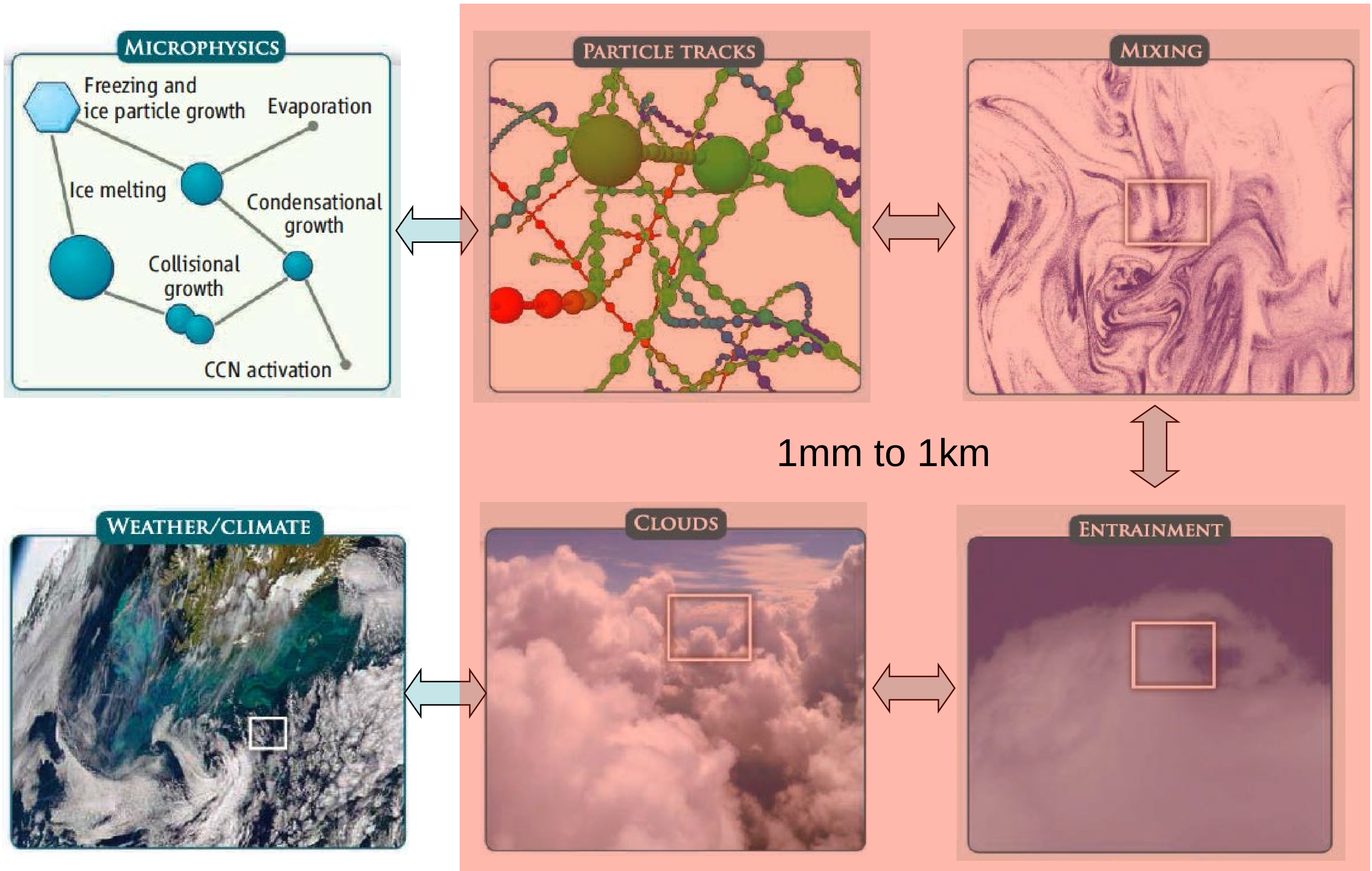


20 year average of change of low cloud amount (in % per K)



GCM=Global Circulation Model

Turbulence in clouds



Typical scales in a cloud

- Cloud droplet radius $r = 10^{-5} m$

- Largest scale of turbulence $L \sim 10^3 m$
  Smallest scale of turbulence $\eta_K \sim 10^{-3} m$
  Characteristic velocity $U \sim 1\, m/s$

  $$Re = \frac{UL}{\nu} \sim 10^8 \Rightarrow Re_\lambda \sim 10^4$$

- Lifetime of cloud $T_L \sim 10^3 s$
  Shortest time scale $\tau_\eta \sim 50\, ms$

- Particle inertia effects $St = \frac{\tau_p}{\tau_\eta} = \frac{2\rho_l r^2}{9\rho_v \eta_K^2} \sim 2 \times 10^{-2}$

- Gravitational settling $Sv = \frac{\tau_p g}{v_\eta} = \frac{2\rho_l r^2 g \tau_\eta}{9\rho_v \nu \eta_K} \sim 10^{-1}$

- Droplet Evaporation

  $$Da_\eta = \frac{\tau_\eta}{\tau_{phase}} \sim 10^{-2}$$

  $$Da_L = \frac{T_L}{\tau_{phase}} \sim 100$$

Turbulent mixing in clouds = multiscale + multiphysics

Homogeneous vs. inhomogeneous mixing

Burnet & Brenguier, J. Atmos. Sci. 2007; Lehmann, Siebert & Shaw, J. Atmos. Sci. 2009

Homogeneous mixing

$Da \ll 1$

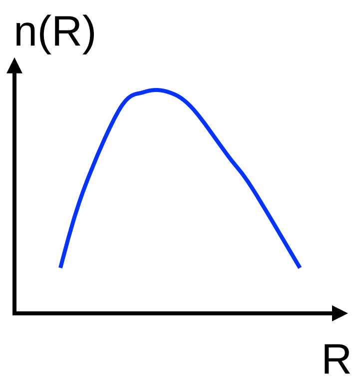
Inhomogeneous mixing

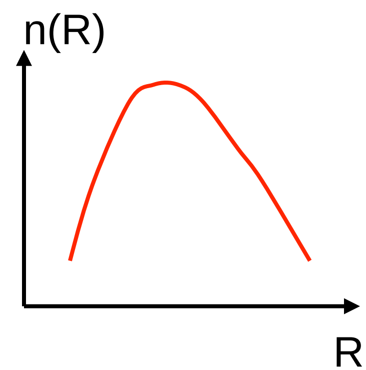
$Da \gg 1$

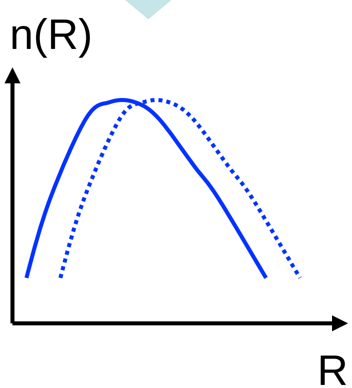
$$Da = \frac{\tau_{fluid}}{\tau_{phase}}$$

Damköhler number

Turbulence = Continuum of τ_{fluid}

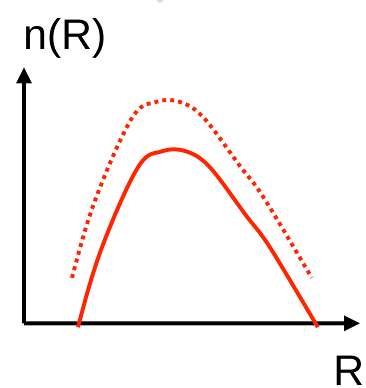






All droplets shrink slowly in well-mixed environment

Droplets at the edge evaporate completely while those inside cloud remain unchanged



Both regimes are relevant !

Part 1

Moist Rayleigh-Bénard convection simulations at cloud mesoscale

Boussinesq equations for moist convection

Bannon, J. Atmos. Sci. 2001

Mass balance

$$\nabla \cdot \vec{u} = 0$$

Momentum balance

$$\partial_t \vec{u} + (\vec{u} \cdot \nabla)\vec{u} = -\frac{1}{\rho_0}\nabla p + \nu \nabla^2 \vec{u} + \vec{f}$$

Energy balance

$$\partial_t T + (\vec{u} \cdot \nabla) T = \kappa \nabla^2 T + \frac{L}{c_p} C_d$$

Vapor mixing ratio

$$\partial_t q_v + (\vec{u} \cdot \nabla) q_v = \kappa_v \nabla^2 q_v - C_d$$

Liquid water mixing ratio

$$\partial_t q_l + (\vec{u} \cdot \nabla) q_l = C_d$$

$$\vec{f} = g \left[\frac{T - T_0}{T_0} + \left(\frac{R_v}{R_d} - 1 \right) (q_v - q_{v0}) - q_l \right] \vec{e}_z$$

plus b.c. & model to determine condensation rate C_d

Additional space- and time-dependent latent heat release or evaporative cooling

Boussinesq equations for shallow clouds

Bannon, J. Atmos. Sci. 2001

No fallout of rain

Ice-free clouds

Compressibility effects are negligible due to low heights

Mass balance
$$\nabla \cdot \vec{u} = 0$$

Momentum balance
$$\partial_t \vec{u} + (\vec{u} \cdot \nabla)\vec{u} = -\frac{1}{\rho_0}\nabla p + \nu \nabla^2 \vec{u} + \vec{f}$$

Energy balance
$$\partial_t T + (\vec{u} \cdot \nabla)T = \kappa \nabla^2 T + \frac{L}{c_p} C_d + Q_{rad}$$

Total water mixing ratio
$$\partial_t q_T + (\vec{u} \cdot \nabla) q_T \simeq \kappa_v \nabla^2 q_T$$

$$\vec{f} = \vec{f}(T, q_T, z)$$

plus b.c. & model to determine condensation rate C_d

Simple thermodynamics of phase changes

Bretherton, J. Atmos. Sci. 1987, 1988; Pauluis & JS, Comm. Math. Sci. 2010

What is the least set of moist convection equations to describe cloud formation processes?

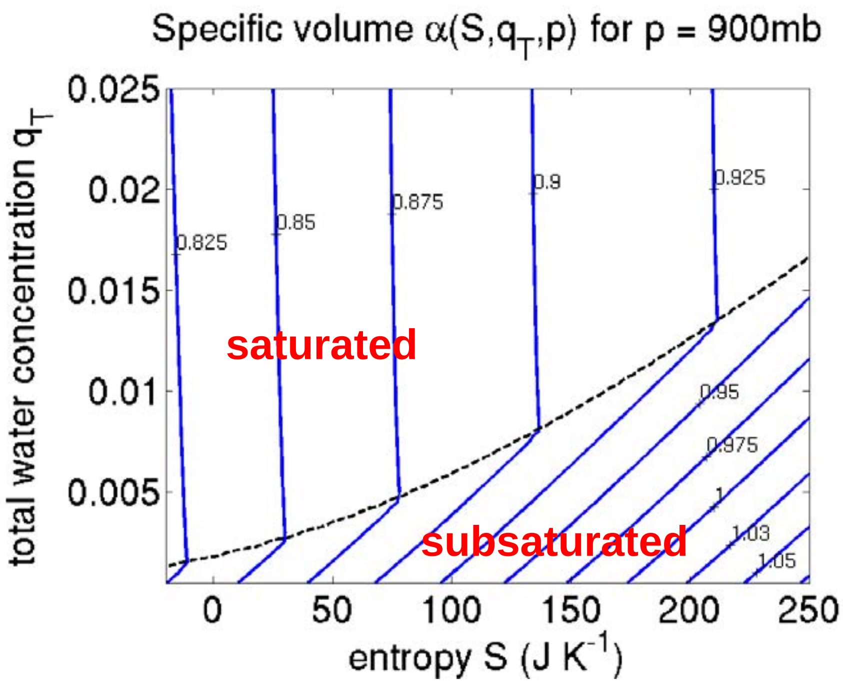
- Nearly adiabatic motion $T \rightarrow S$
- Total water content

$$q_T = q_l + q_v$$

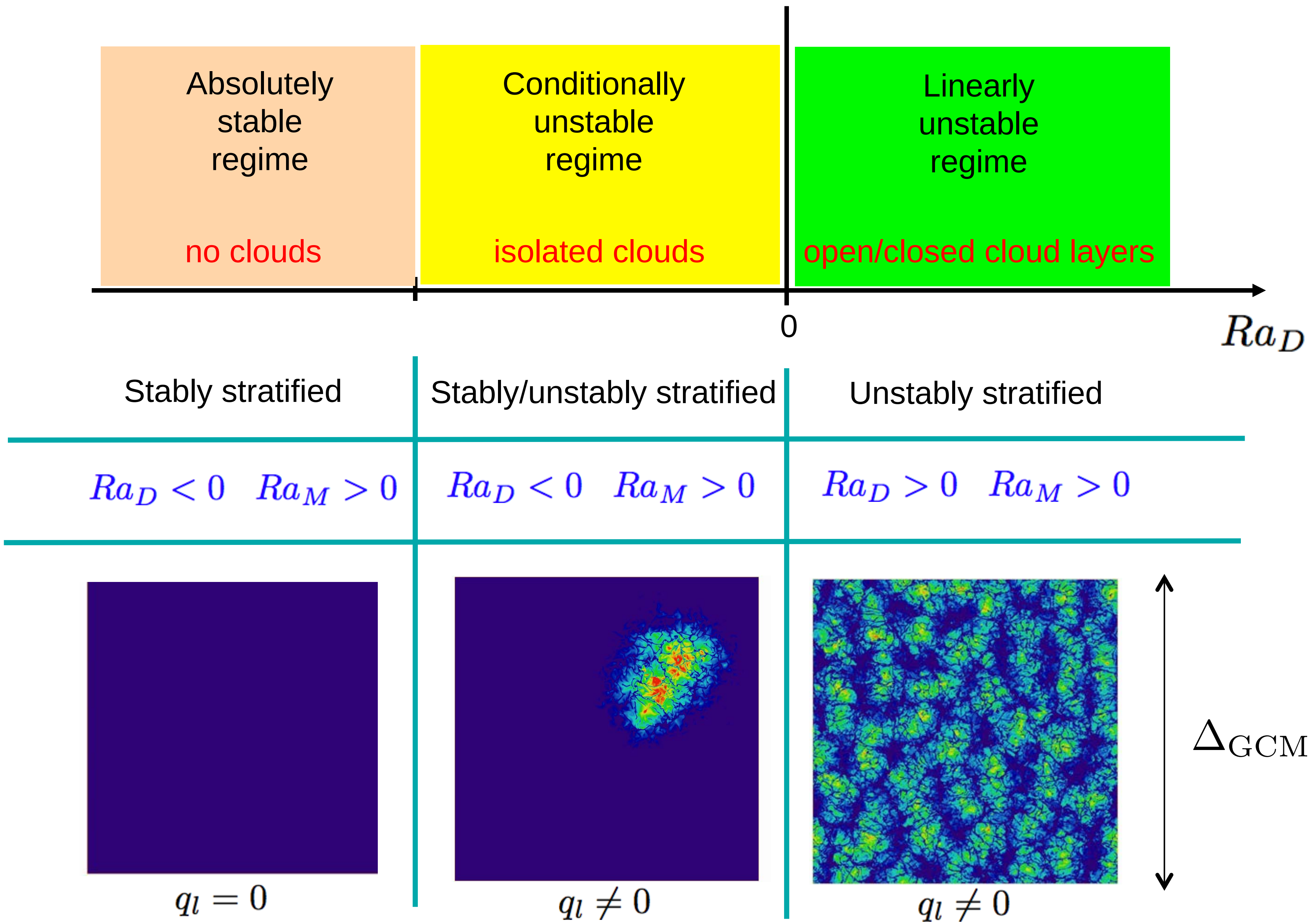
- Piecewise linear equation of state

$$(S, q_T, p) \rightarrow (D, M)$$

- Simple saturation condition without supersaturation
- DNS in a large-aspect ratio layer
  Two buoyancy fields D and M with Ra_D and Ra_M



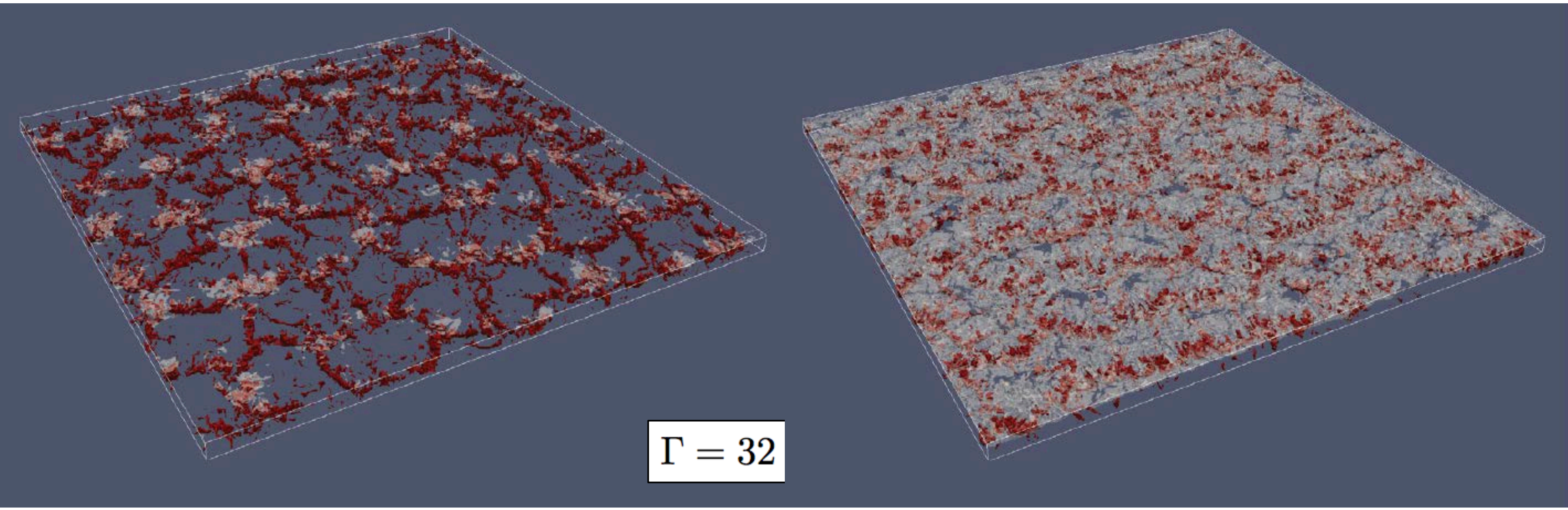
Three regimes of moist RB convection

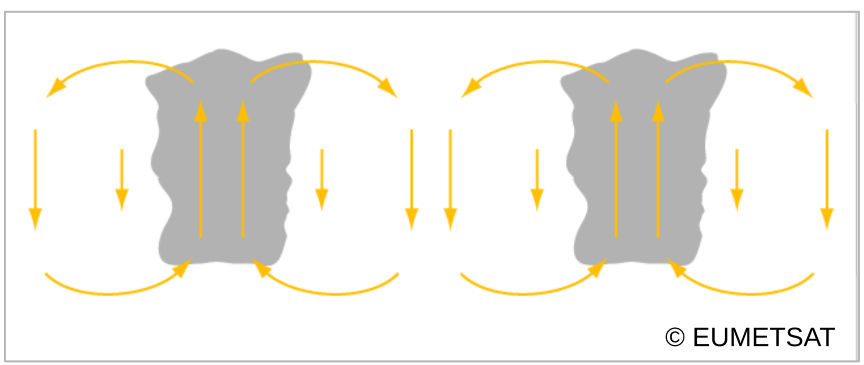


Linearly unstable regime

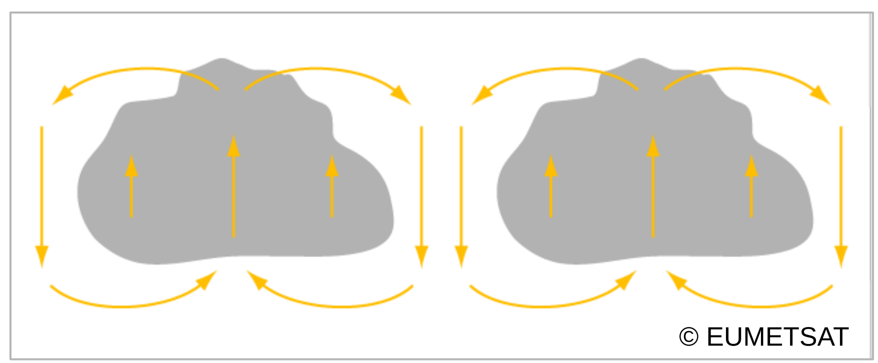
Weidauer, Pauluis & JS, New J. Phys. 2010

Cloud cover determined by the cloud water deficit at the top boundary





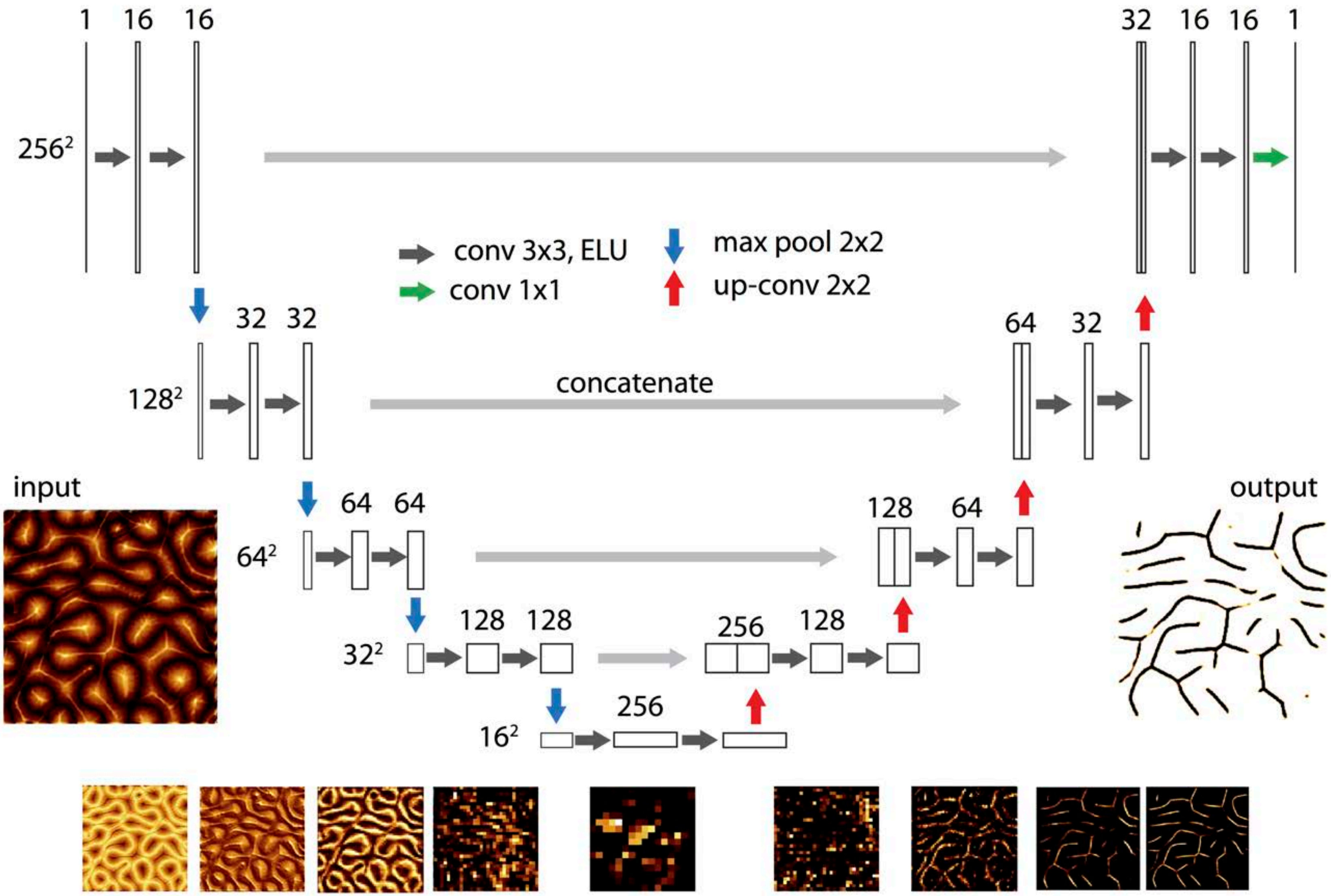
Open Cell Convection



Closed Cell Convection

Turbulent transport networks in dry convection

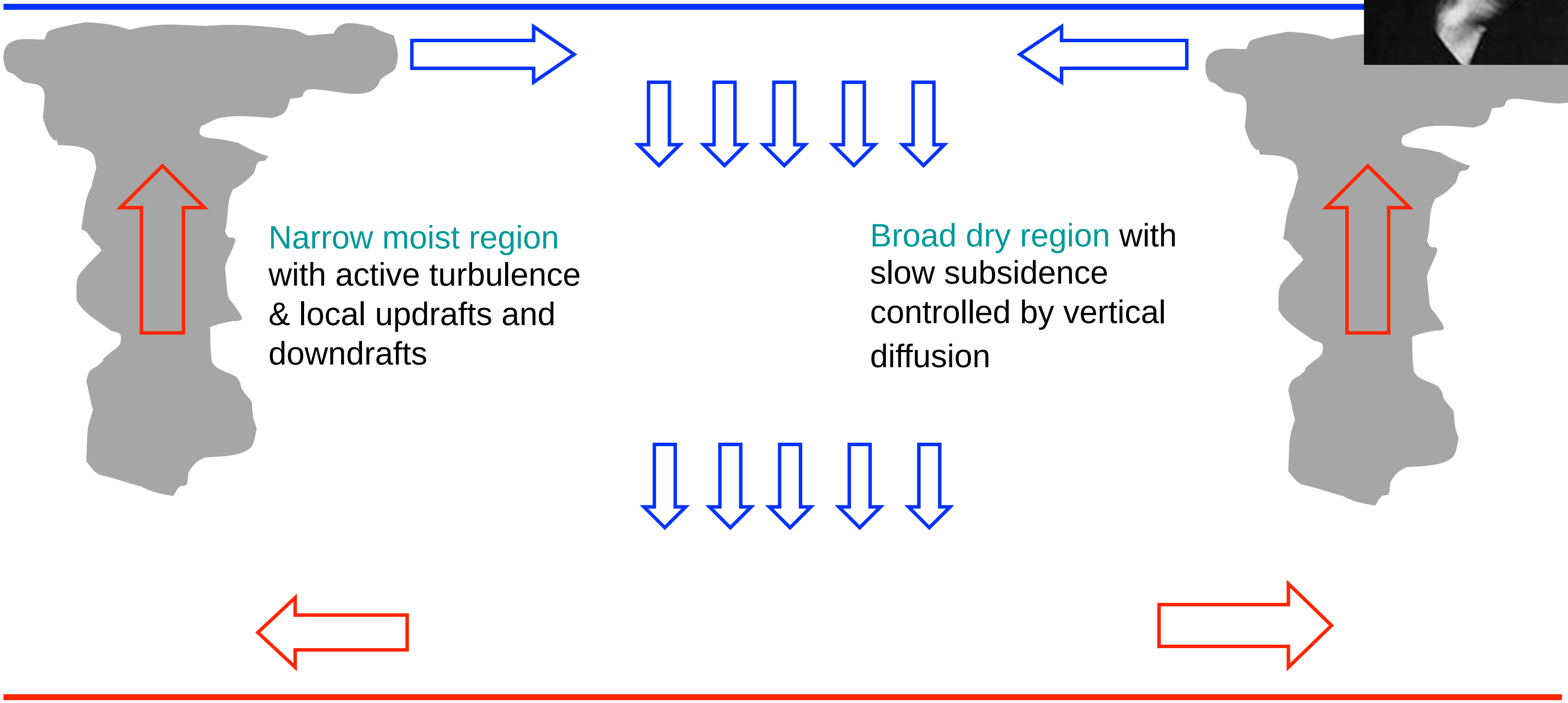
Pandey, Scheel & JS, Nat. Commun. 2018



Ronneberger et al.,LNCS, 2015

Conditionally unstable regime

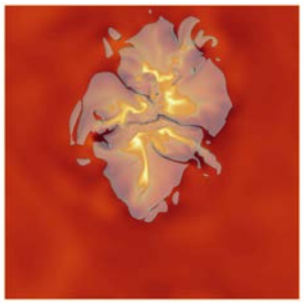
Bjerknes, Quat. J. Royal Meteor. Soc. 1938



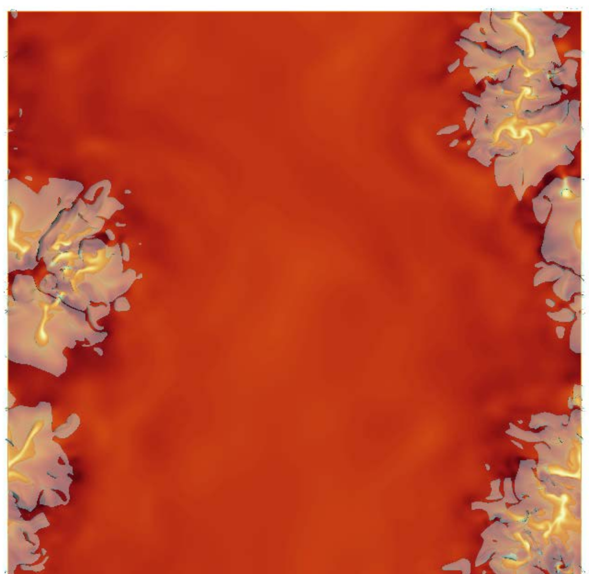
$$6\,\mathrm{K\,km}^{-1} \sim \Gamma_m < \Gamma = \left|\frac{d\overline{T}}{dz}\right| < \Gamma_d = 10\,\mathrm{K\,km}^{-1}$$

Cloud aggregation

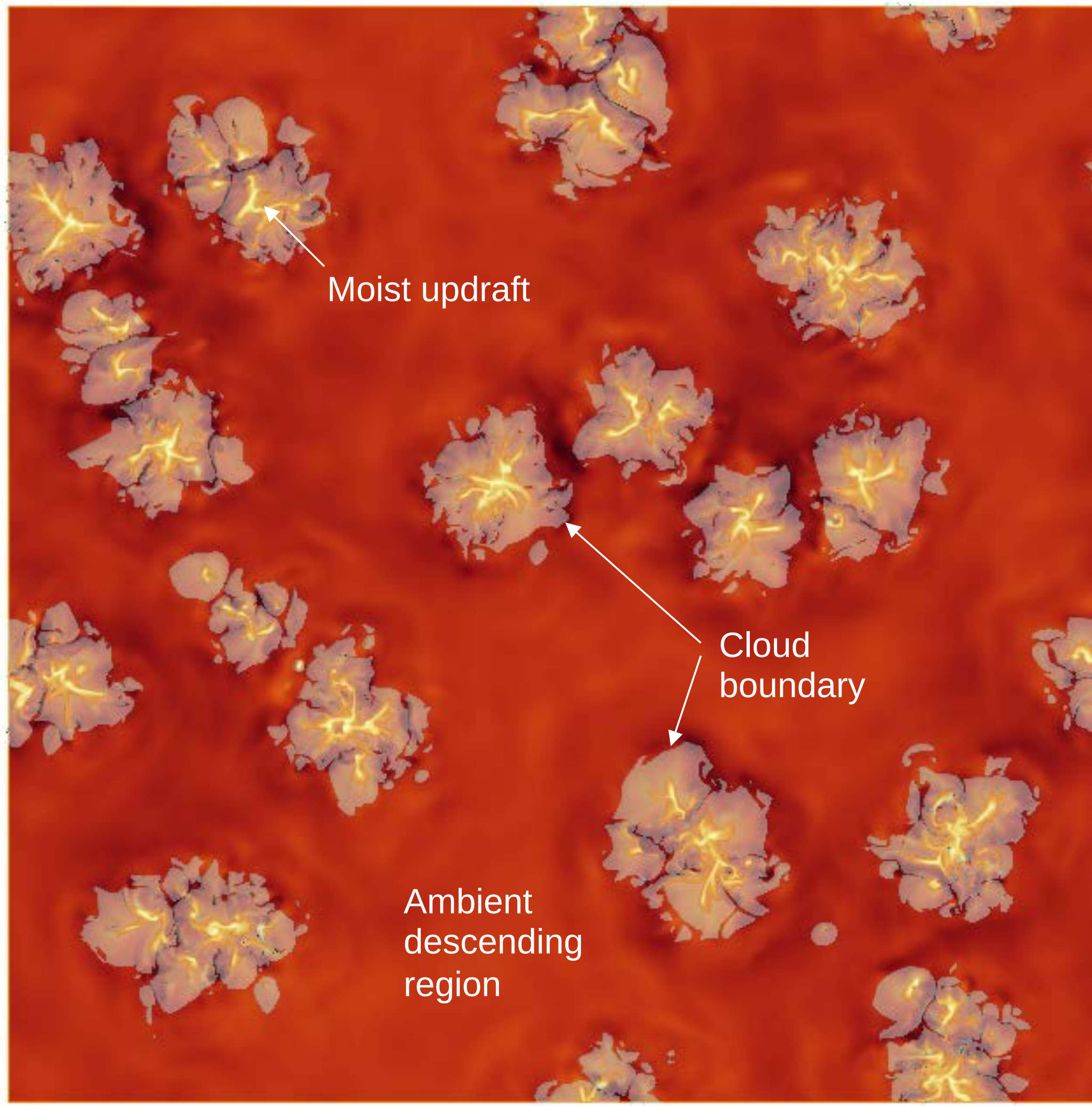
Pauluis & JS, PNAS 2011



$\Gamma = 16$



$\Gamma = 32$



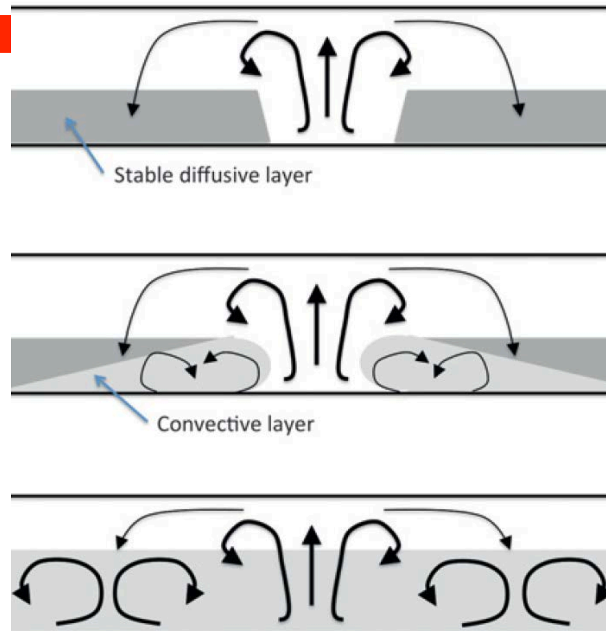
$\Gamma = 64$

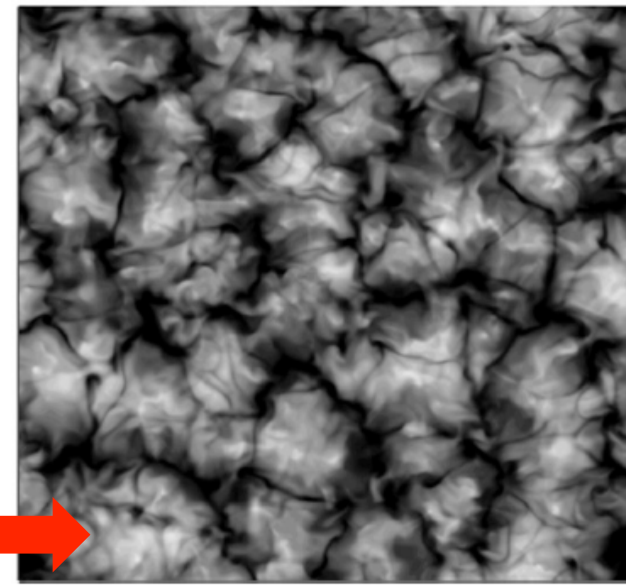
Additional radiative cooling

Pauluis & JS, J. Atmos. Sci. 2013

$$\mathrm{LWP} = \int_0^H q_l \, dz$$

No cooling





Strong cooling

Additional radiative cooling destabilizes lower diffusion layer and enhances heat transfer and cloud formation

- Simplest extension of Rayleigh-Bénard convection to moist convection with phase changes
- Study of cloud turbulence in cumulus or stratocumulus-type regimes
- Analysis of pattern formation and related variability of moist buoyancy fluxes at mesoscale

O. Pauluis and JS, Comm. Math. Sci. 8, 295 (2010).

JS and O. Pauluis, J. Fluid Mech. 648, 509 (2010).

T. Weidauer, O. Pauluis, and JS, New J. Phys. 12, 105002 (2010).

O. Pauluis and JS, PNAS 108, 12623 (2011).

T. Weidauer, O. Pauluis, and JS, Phys. Rev. E 84, 046303 (2011).

T. Weidauer and JS, Phys. Fluids 24, 076604 (2012).

O. Pauluis and JS, J. Atmos. Sci. 70, 1187 (2013).

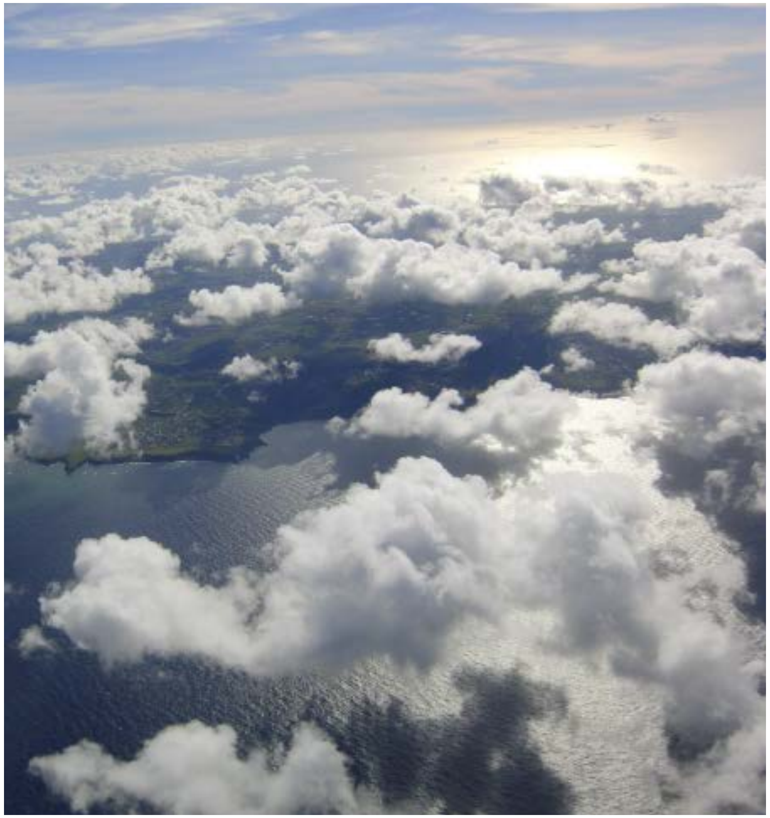
T. Weidauer and JS, New J. Phys. 15, 125025 (2013).

Part 2

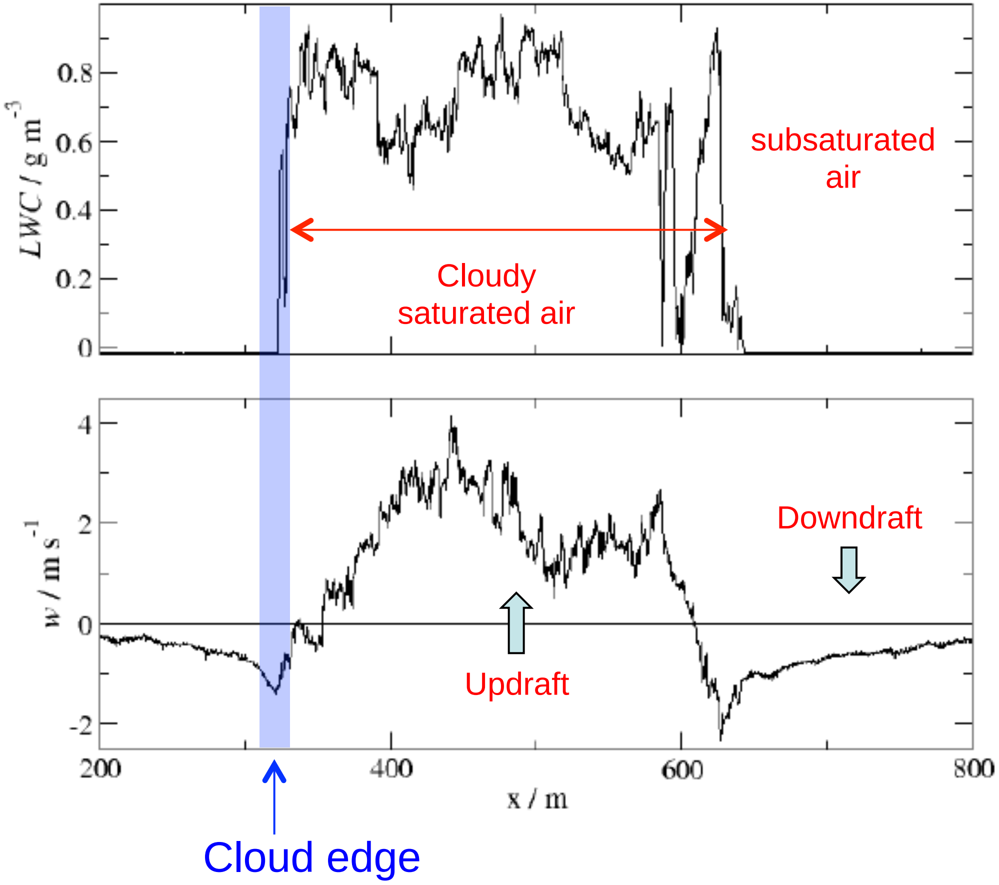
Euler-Lagrangian simulations at cloud microscale

Helicopter-based field measurements

Siebert et al., Atmos. Chem. Phys. 2013

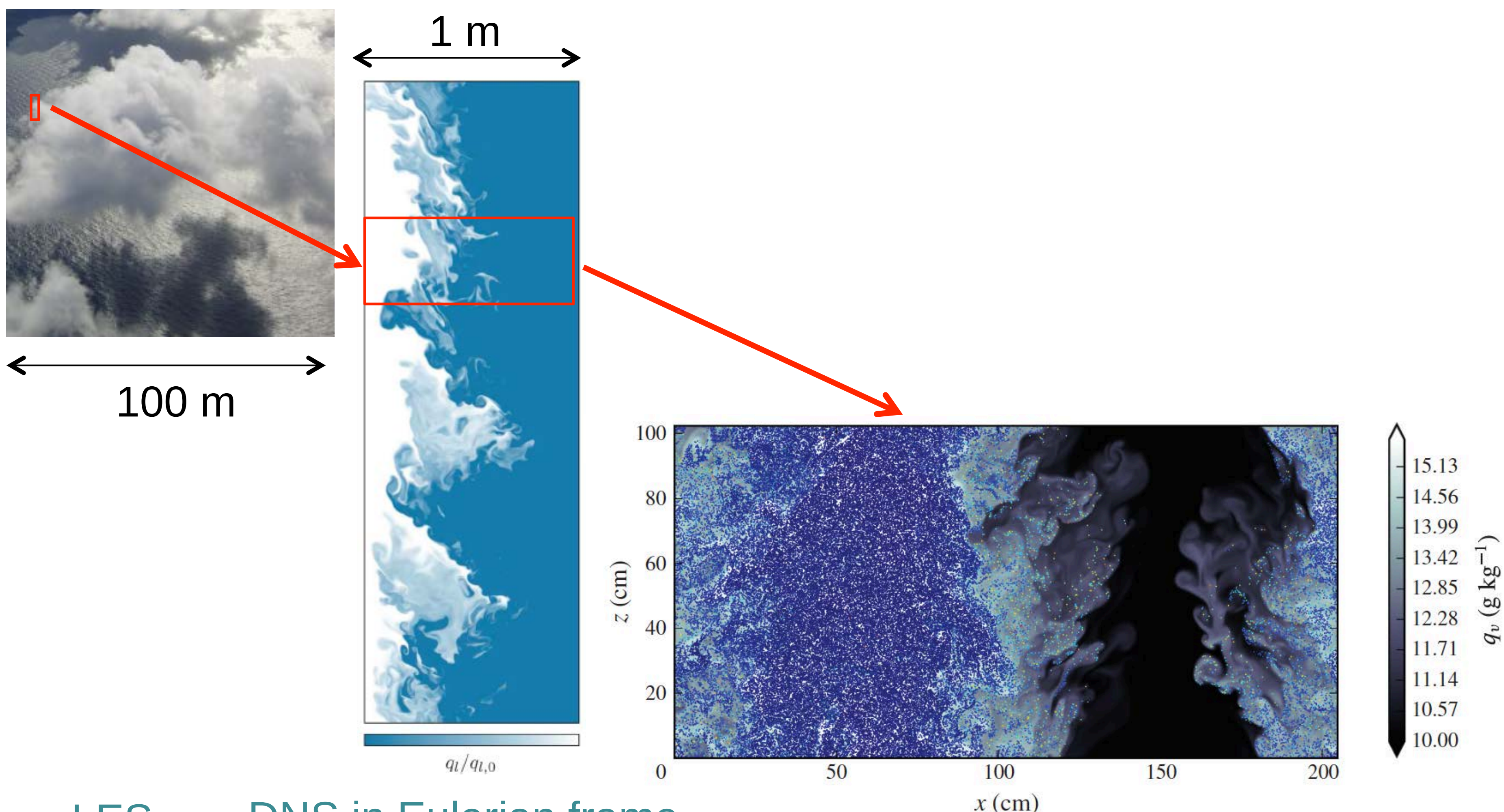


Trade wind cumuli over Barbados



How does the droplet size distribution at the edge of the cloud respond to the turbulent entrainment and subsequent mixing?

DNS at the cloud interface



LES

Sardina et al.
J. Atmos. Sci.. 2018

DNS in Eulerian frame

Abma et al.
J. Atmos. Sci.. 2013

Euler-Lagrangian DNS
with phase changes

Coupled Euler-Lagrange model

$$\begin{aligned}
\nabla \cdot \vec{u} &= 0 \\
\partial_t \vec{u} + (\vec{u} \cdot \nabla)\vec{u} &= -\frac{1}{\rho_0}\nabla p + \nu \nabla^2 \vec{u} + \vec{f} \\
\partial_t T + (\vec{u} \cdot \nabla) T &= \kappa \nabla^2 T + \frac{L}{c_p} C_d \\
\partial_t q_v + (\vec{u} \cdot \nabla) q_v &= \kappa_q \nabla^2 q_v - C_d \\
\vec{f} &= g \left[\frac{T - T_0}{T_0} + \epsilon (q_v - q_{v0}) - q_l \right] \vec{e}_z
\end{aligned}$$

Velocity

Temperature

Water Vapor Content

$$S(T) = \frac{q_v}{q_{vs}(T)} - 1$$

$$q_{vs}(T) = A \exp(-B/T)$$

$$C_d(\vec{x}, t) = \frac{1}{\rho_0 a^3} \sum_{\beta=1}^{\triangle} \frac{\mathrm{d}m_l(\vec{X}_\beta, t)}{\mathrm{d}t}$$

$$\begin{aligned}
\frac{\mathrm{d}\vec{X}}{\mathrm{d}t} &= \vec{V}(\vec{X}, t) \\
\frac{\mathrm{d}\vec{V}}{\mathrm{d}t} &= \frac{1}{\tau_p} \left[\vec{u}(\vec{X}, t) - \vec{V} \right] + \vec{g} \\
r(\vec{X}, t) \frac{\mathrm{d}r(\vec{X}, t)}{\mathrm{d}t} &= K S(\vec{X}, t)
\end{aligned}$$

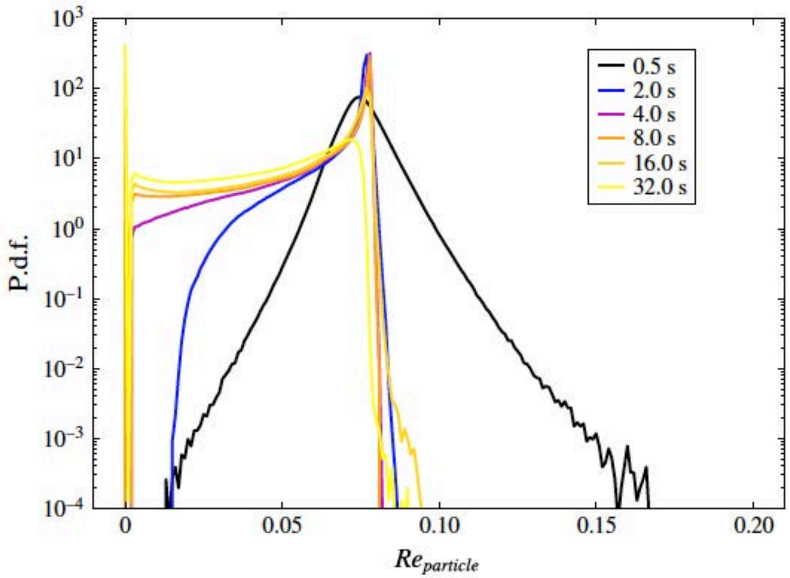
Droplet Dynamics

Diffusional Growth

Water vapor saturation mixing ratio q_{vs} via Clausius-Clapeyron equation is now a function of T

Simplifications

- Stokes drag term only, no history effects (particle Reynolds number <0.1)



$$Re_{particle} = \frac{|u_i(X_j, t) - V_i(X_j, t)|d}{\nu}$$

- Droplet collisions are neglected (collision time is for present conditions ~ 1 h)

$$\tau_{1,2} \sim (n\pi(d_1 + d_2)^2 |v_{t,1} - v_{t,2}| \epsilon_{1,2})^{-1}$$

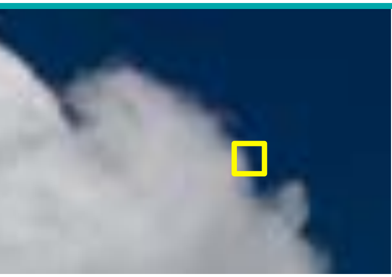
Devenish et al. QJRMS 2012; Onishi et al., J. Atmos. Sci. 2015; Saito & Gotoh, New J. Phys. 2018

- No two-way coupling (small droplet number density ~ 100 cm^{-3})

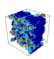
- Initially monodisperse droplet ensemble *Yang et al. ACP 2018*

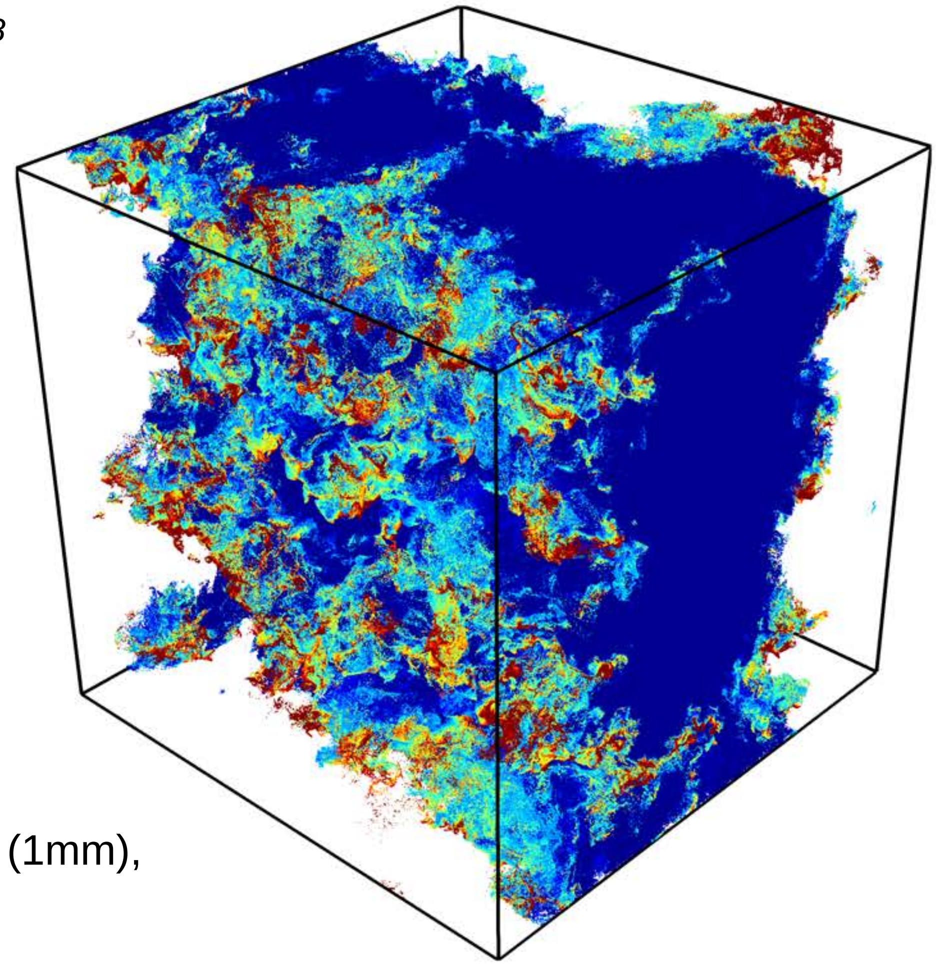
- Constant material parameters (viscosity, conductivity,..) since T difference is a few degrees only

Effect of domain size



Kumar et al., submitted, 2018





Cubic box with statistically stationary turbulence

Box size varies from 0.128 to 2.048 m

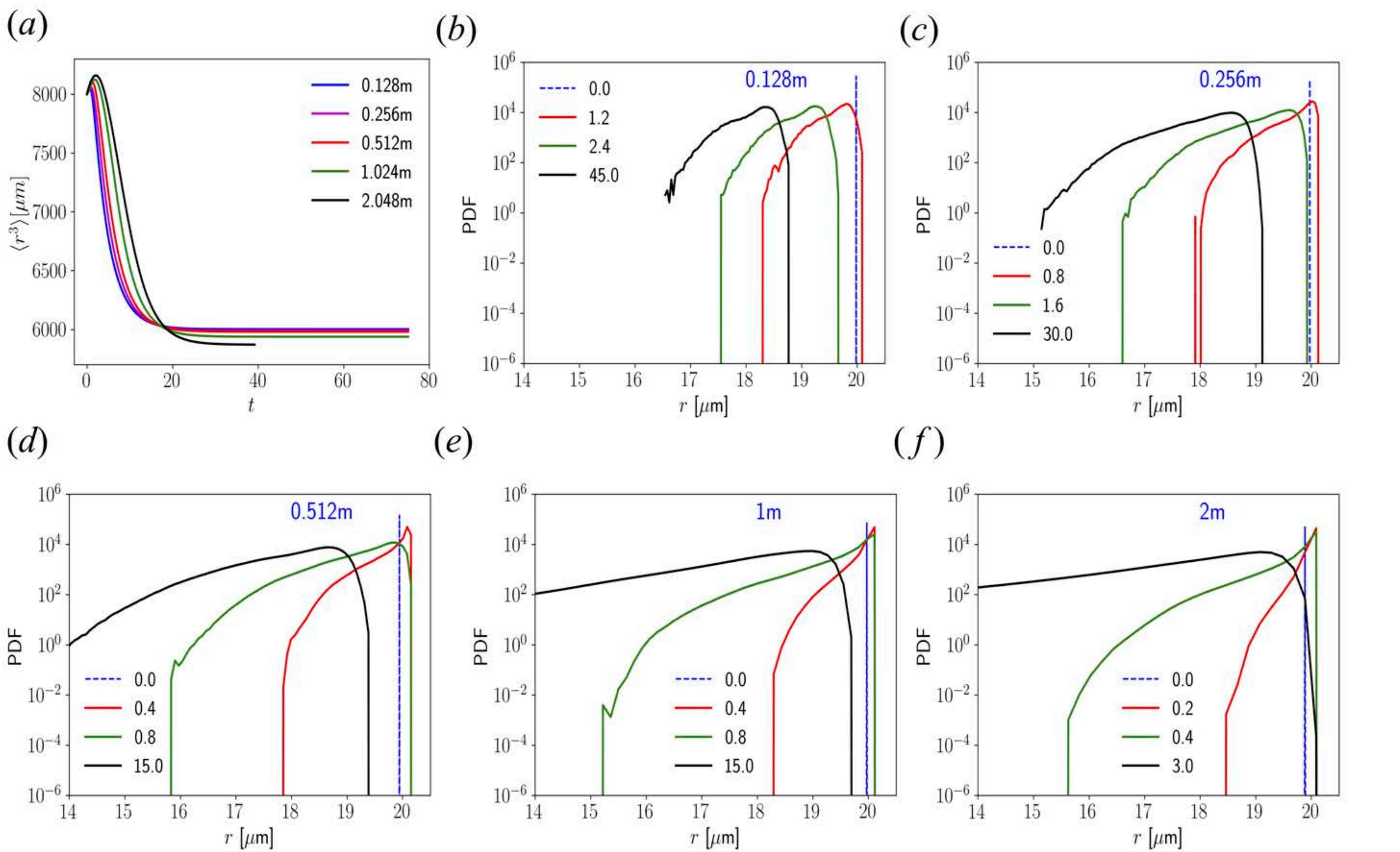
Droplet number varies 1.05×10^5 to 4.33×10^8

Same mean dissipation rate, Kolmogorov length (1mm), liquid water content & total water content

Same slab-like initial condition and grid resolution (periodic b.c.)

Entrainment and mixing evolution for a minute or more

Liquid water content and size distributions



complete evaporation of some droplets

Mixing diagrams

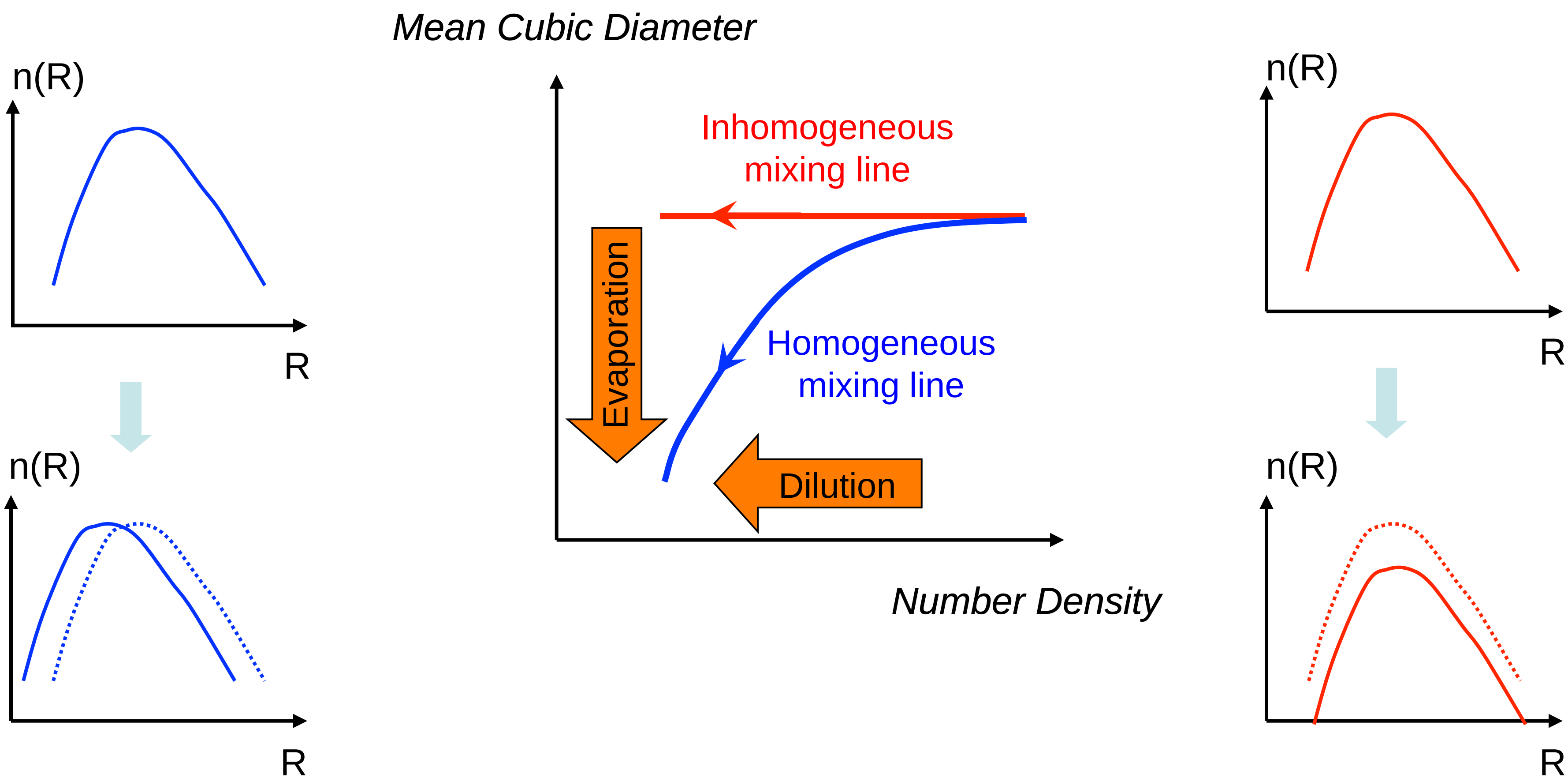
Burnet & Brenguier, J. Atmos. Sci. 2007; Lehmann, Siebert & Shaw, J. Atmos. Sci. 2009

Homogeneous mixing

$Da \ll 1$

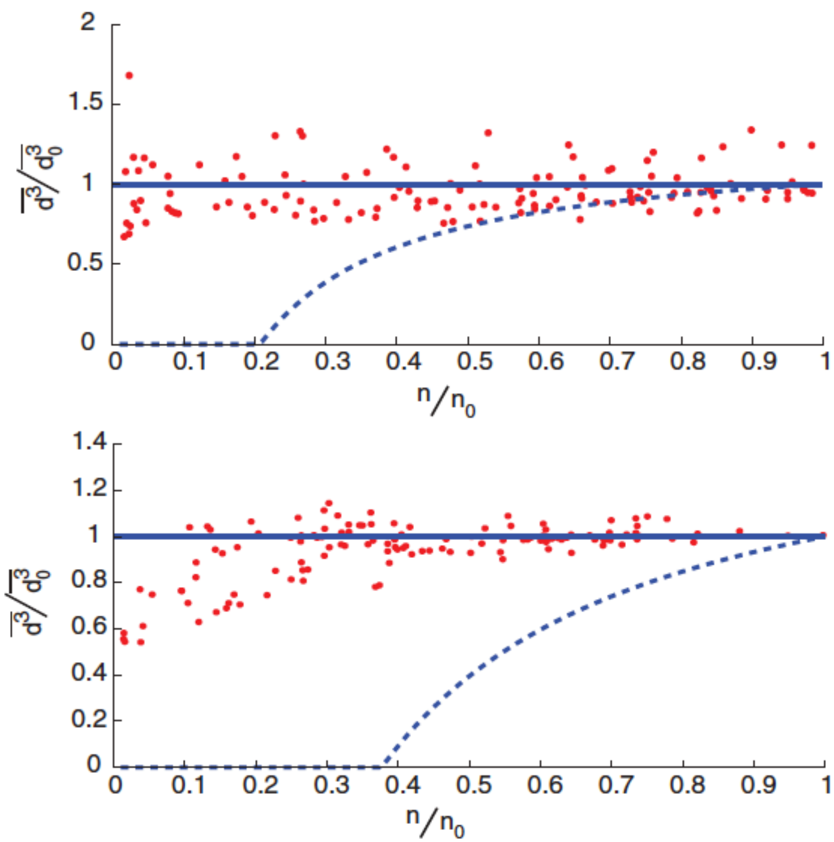
Inhomogeneous mixing

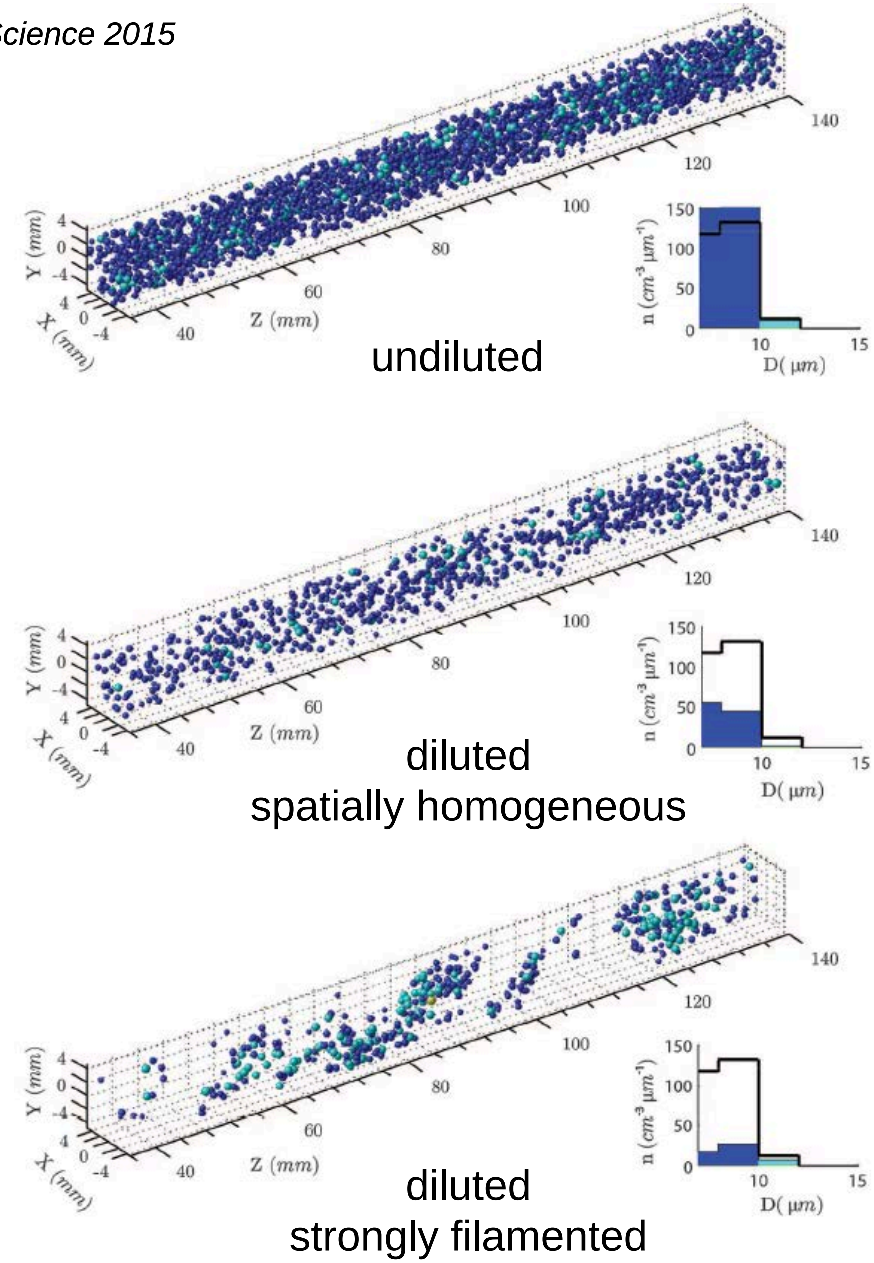
$Da \gg 1$



Holographic airborne measurements

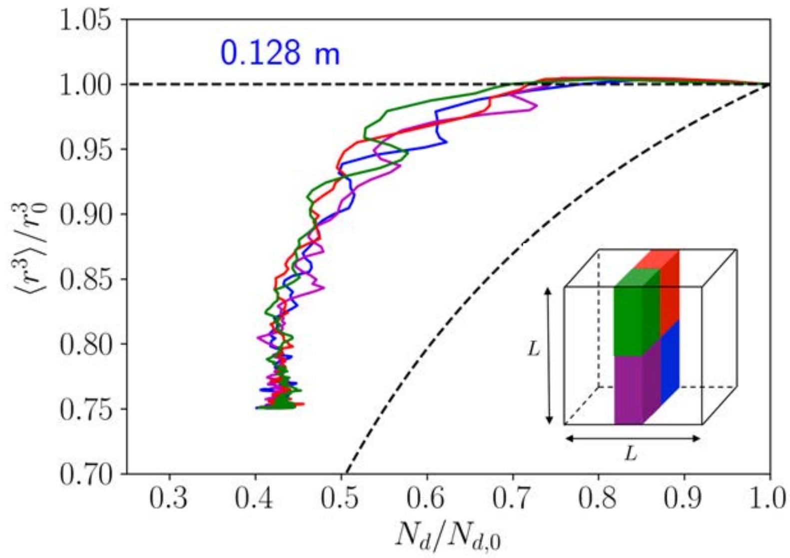
Beals et al., Science 2015

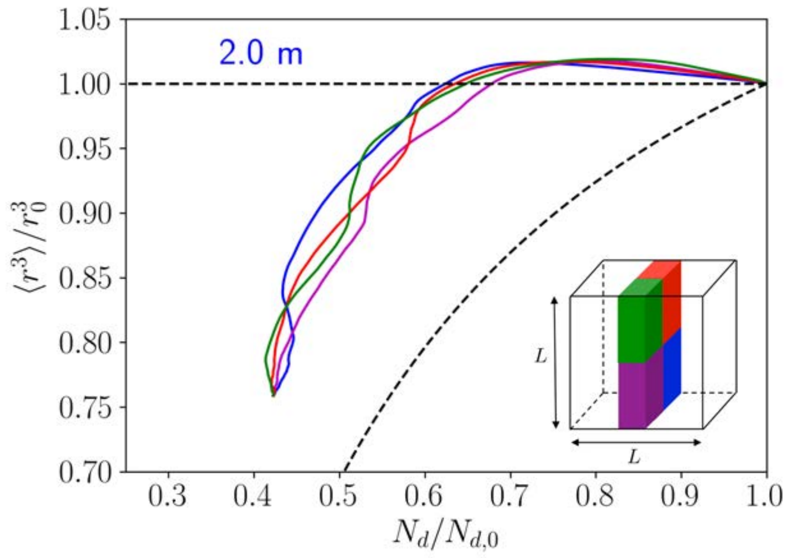


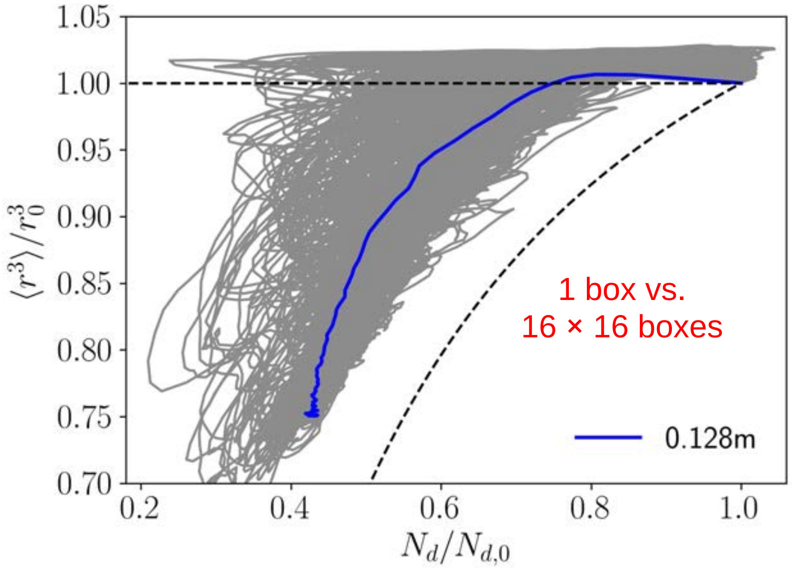


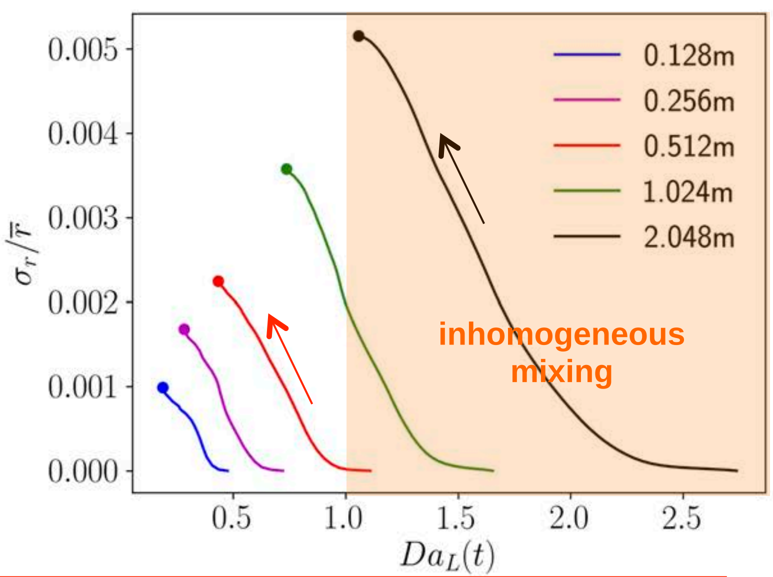
Confirmation of strong inhomogeneous mixing at cloud edge

Mixing diagrams







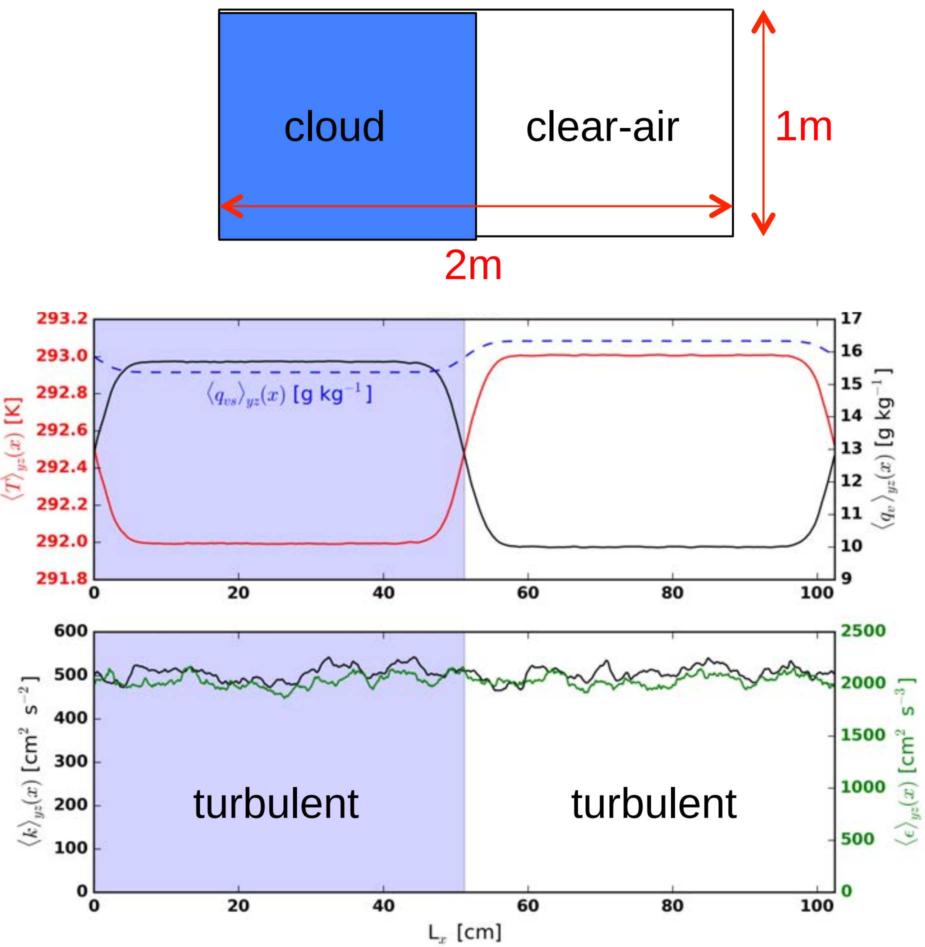


Inhomogeneous mixing effects increase with domain size

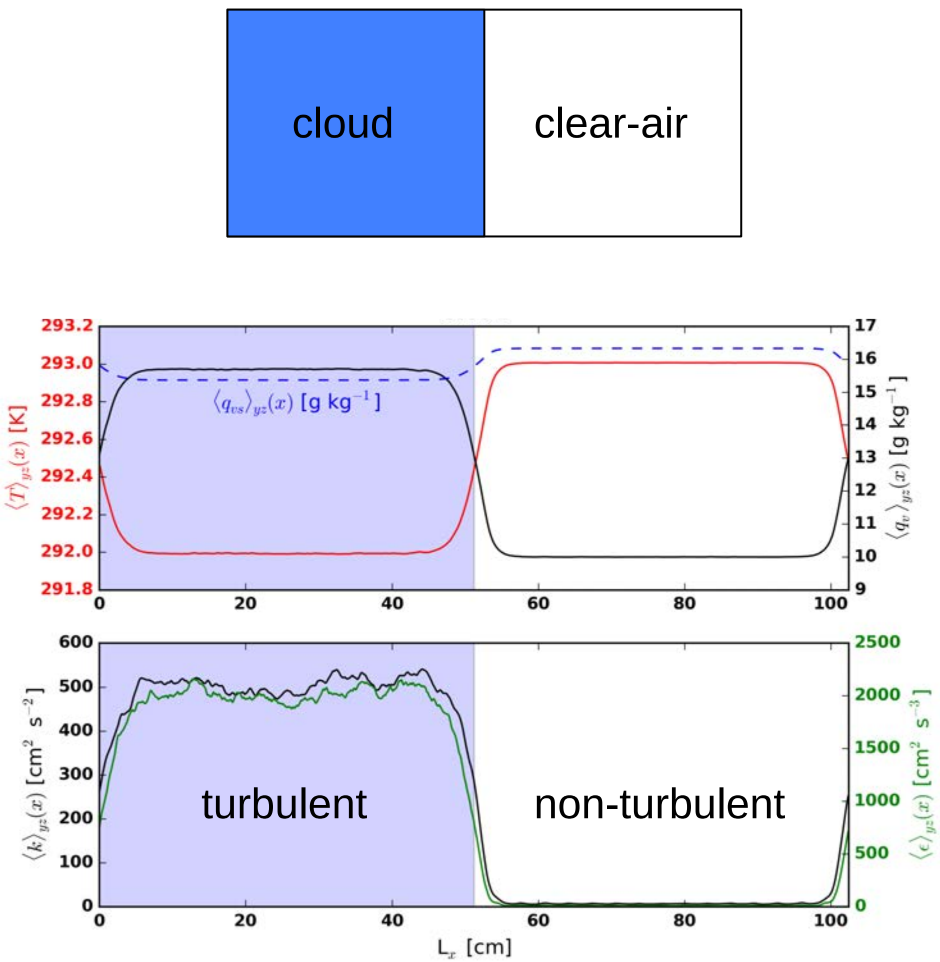
Shear-free mixing layer with phase changes

Tordella & Iovieno, J. Fluid Mech. 2006

TTI



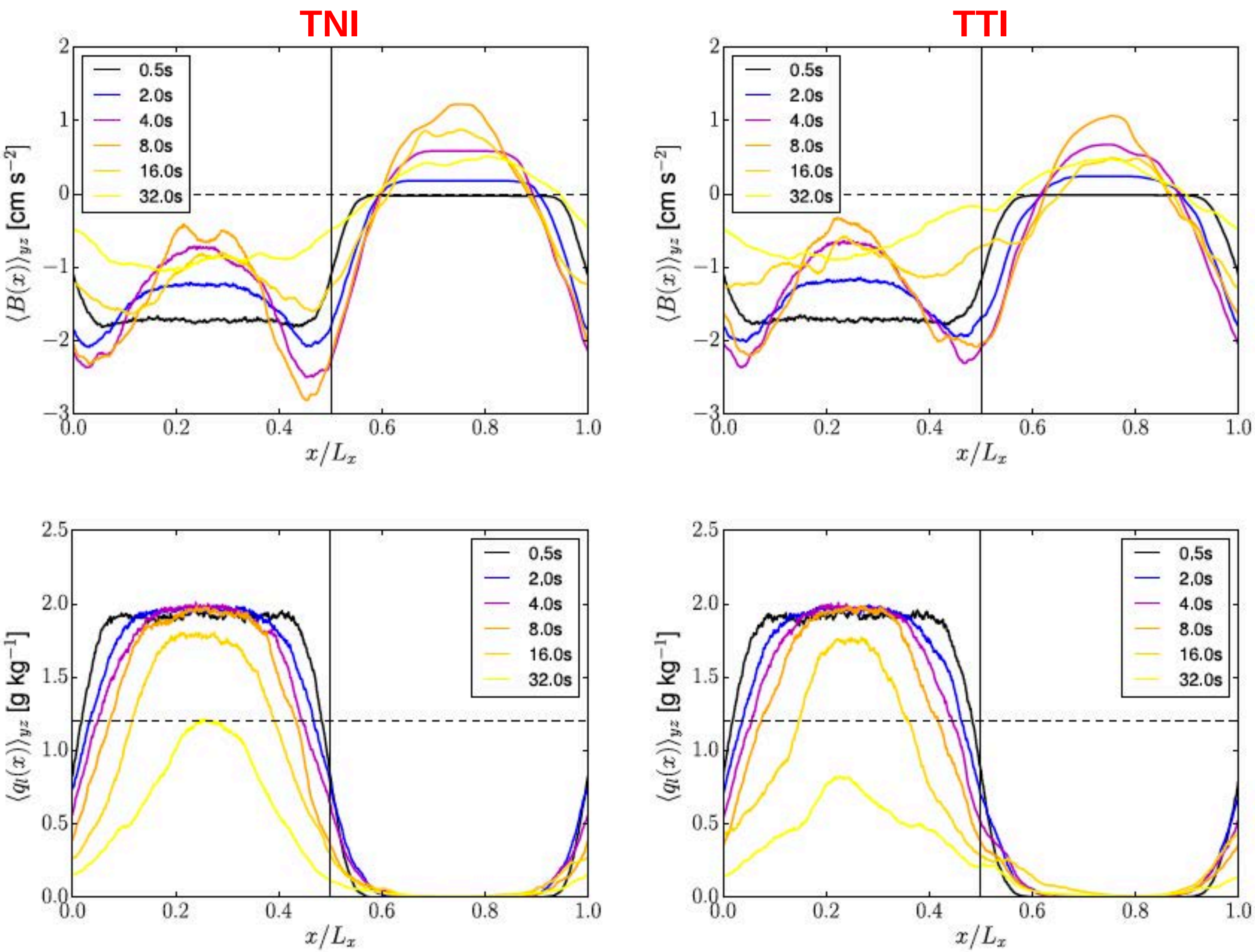
TNI



Freely decaying turbulence = dissolving cloud

Entrainment process

Götzfried et al., J. Fluid Mech. 2017

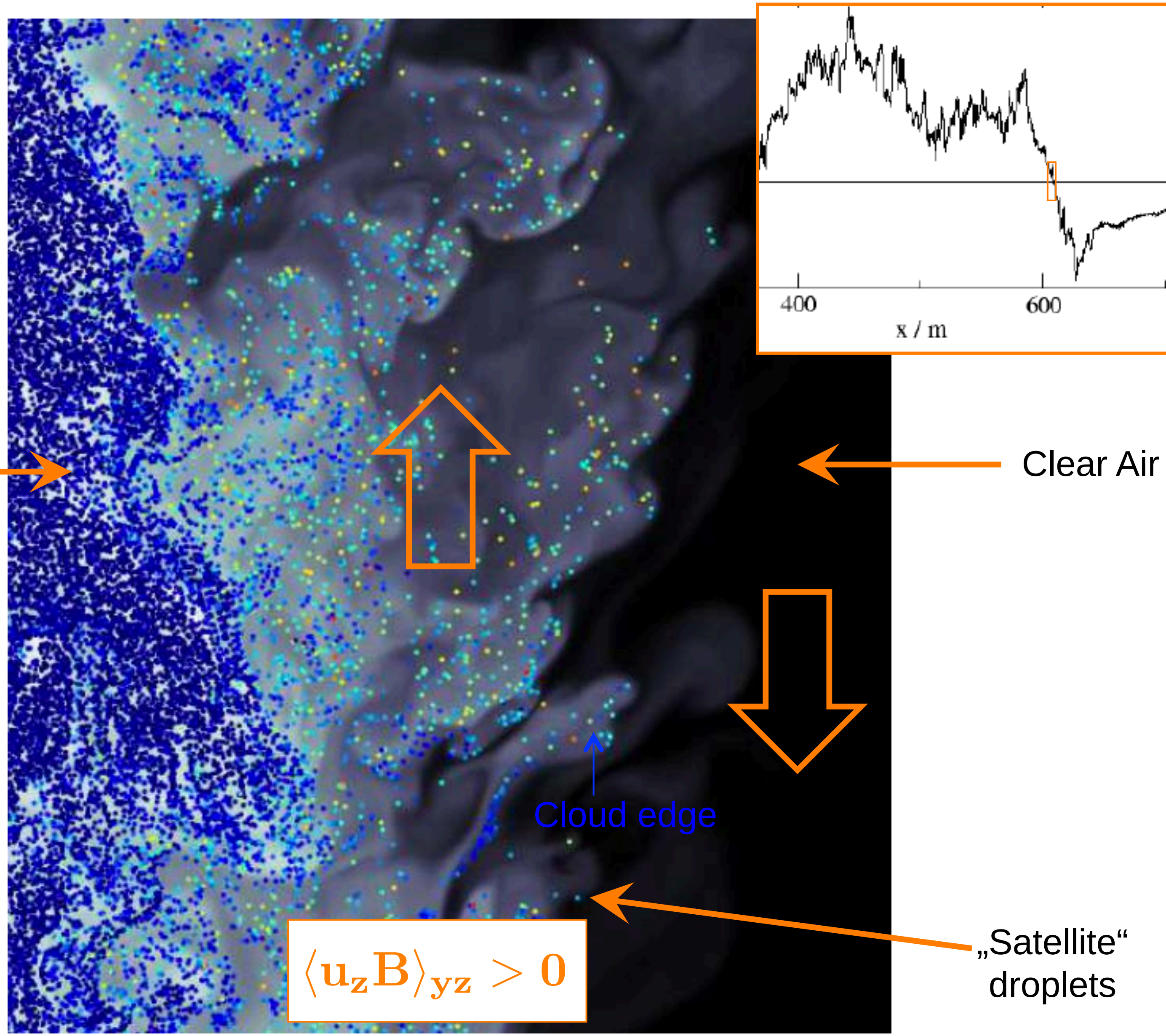


Different initial flow conditions affect large scale turbulence only slightly

Evaporative cooling induces shear layer

Cloud Core

Droplets almost unaffected

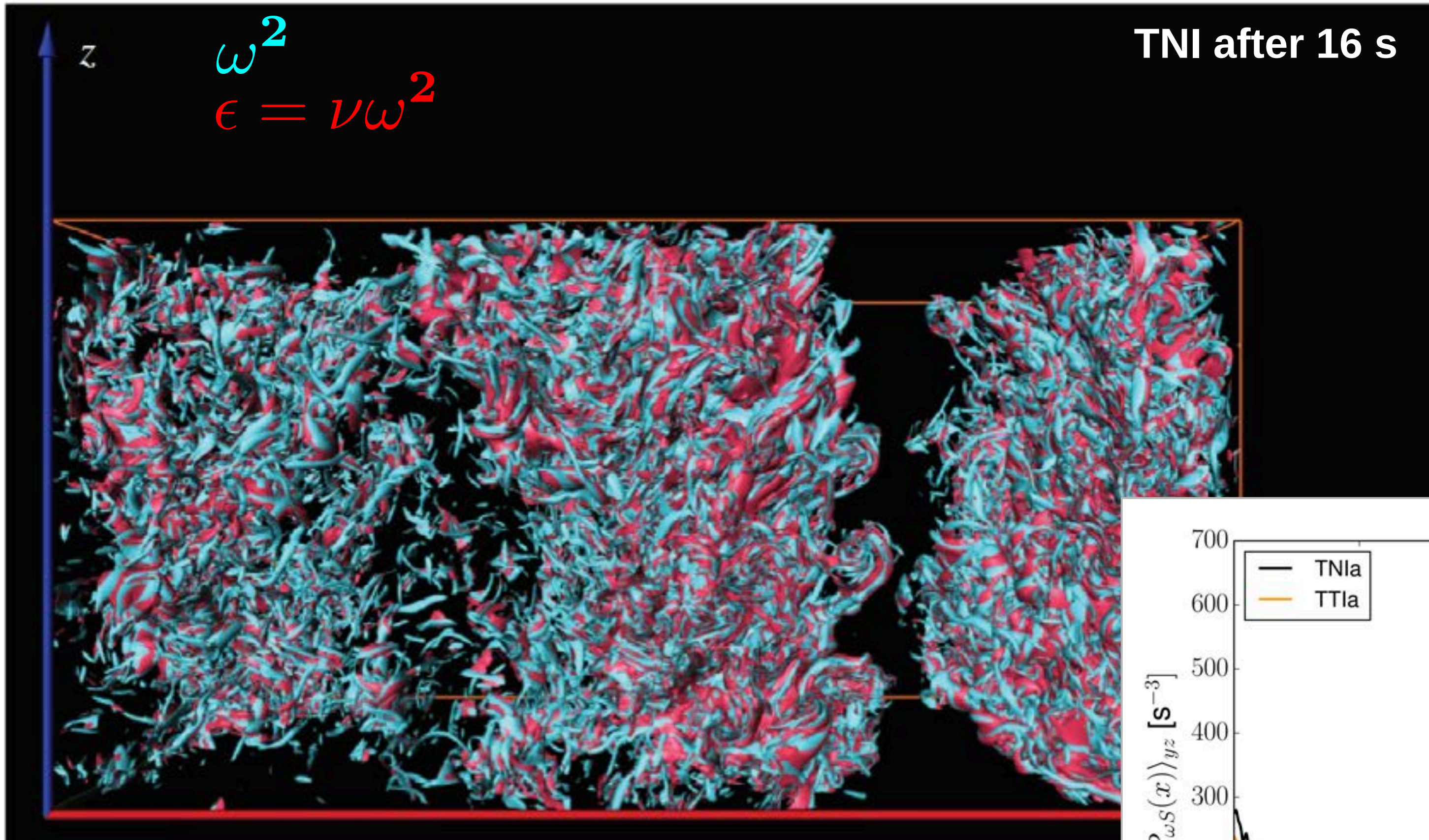


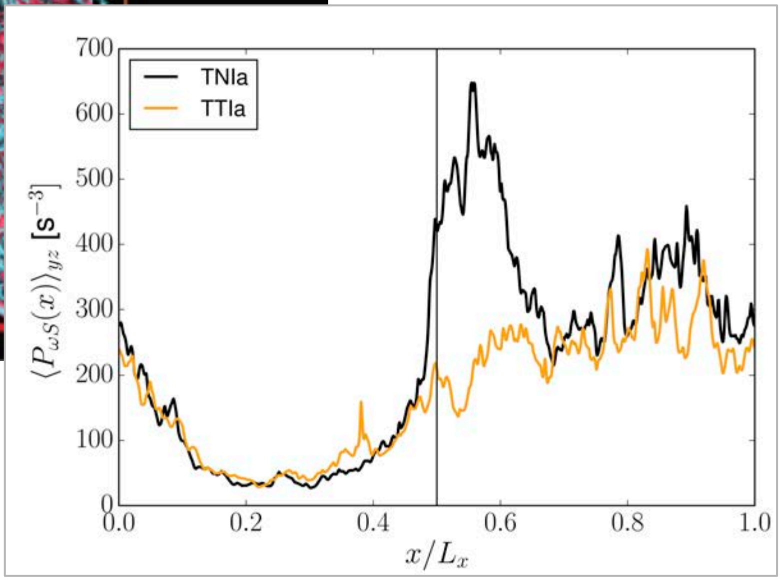
Clear Air

„Satellite" droplets

Enstrophy production

Götzfried et al., J. Fluid Mech. 2017





Different initial turbulent flow fields affect small-scale mixing significantly

- Coupled Euler-Lagrangian model to study interplay between turbulence and droplet dynamics at cloud interface
- Effect of different turbulence levels on mixing process remains small
- Increasing box size leads to increase of inhomogeneous mixing and droplet size dispersion
- Evaporative cooling causes downdraught at interface

B. Kumar, F. Janetzko, JS, and R. A. Shaw, New J. Phys. 14, 115020 (2012)

B. Kumar, JS, and R. A. Shaw, Theor. Comput. Fluid Dyn. 27, 361 (2013).

B. Kumar, JS and R. A. Shaw, J. Atmos Sci. 71, 2564 (2014); 74, 1681 (2017).

P. Götzfried, B. Kumar, R. A. Shaw and JS, J. Fluid Mech. 814, 452 (2017).

B. Kumar, P. Götzfried, N. Suresh, JS and R. A. Shaw, submitted (2018).

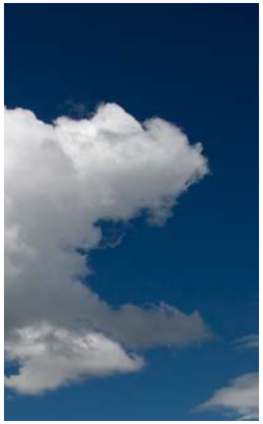
Outlook

Mesoscale

- Extensions of moist Boussinesq models
  - large-scale flow forcing
  - rotation
  - radiative forcing
- Effective parametrization in larger-scale models

Microscale

- Activation of cloud condensation nuclei in an environment with highly fluctuating supersaturation
- Radiative cooling and collision impact on droplet growth



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