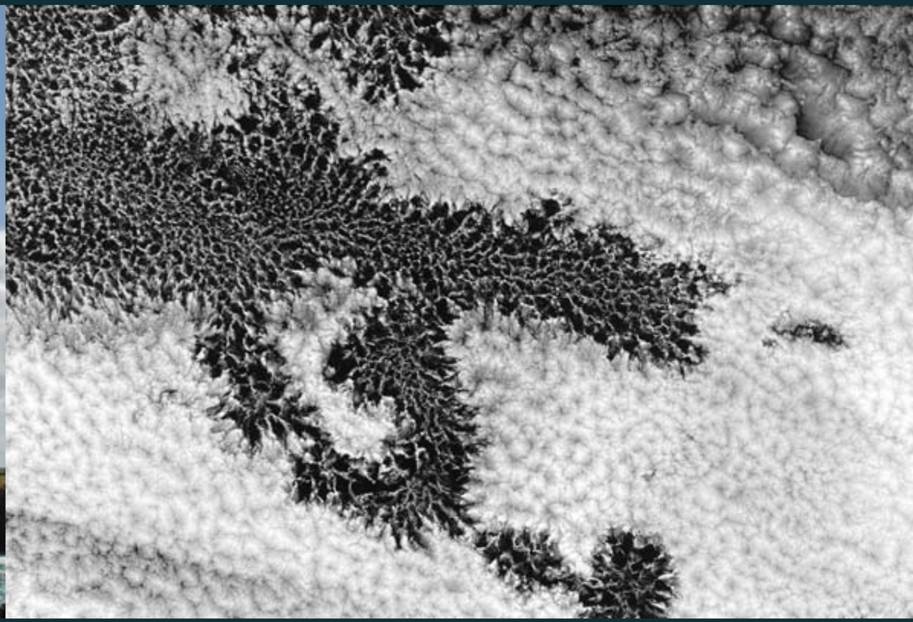


Modeling of clouds in the Earth Atmosphere: Turbulence, Convection & Cold Pools

Exoplanet-bacteria-mars Meeting, 10.7.2020

BETTINA MEYER

With Thanks to: Jan Haerter (NBI)

1. MOTIVATION

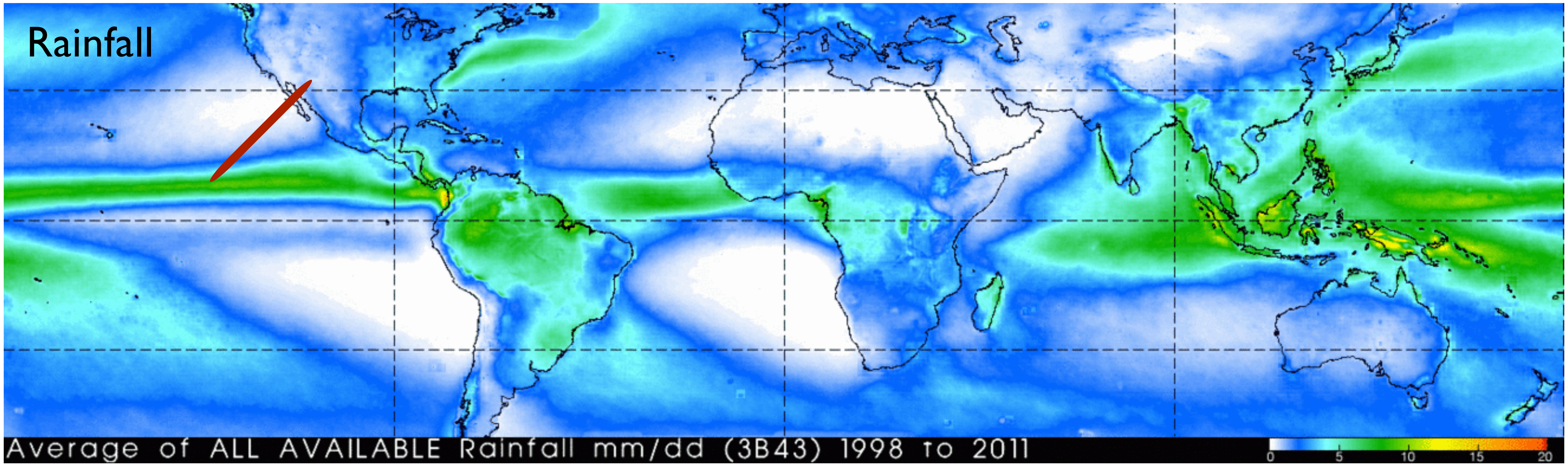


Figure: mean precipitation from TRMM satellite observations (wikipedia.org)

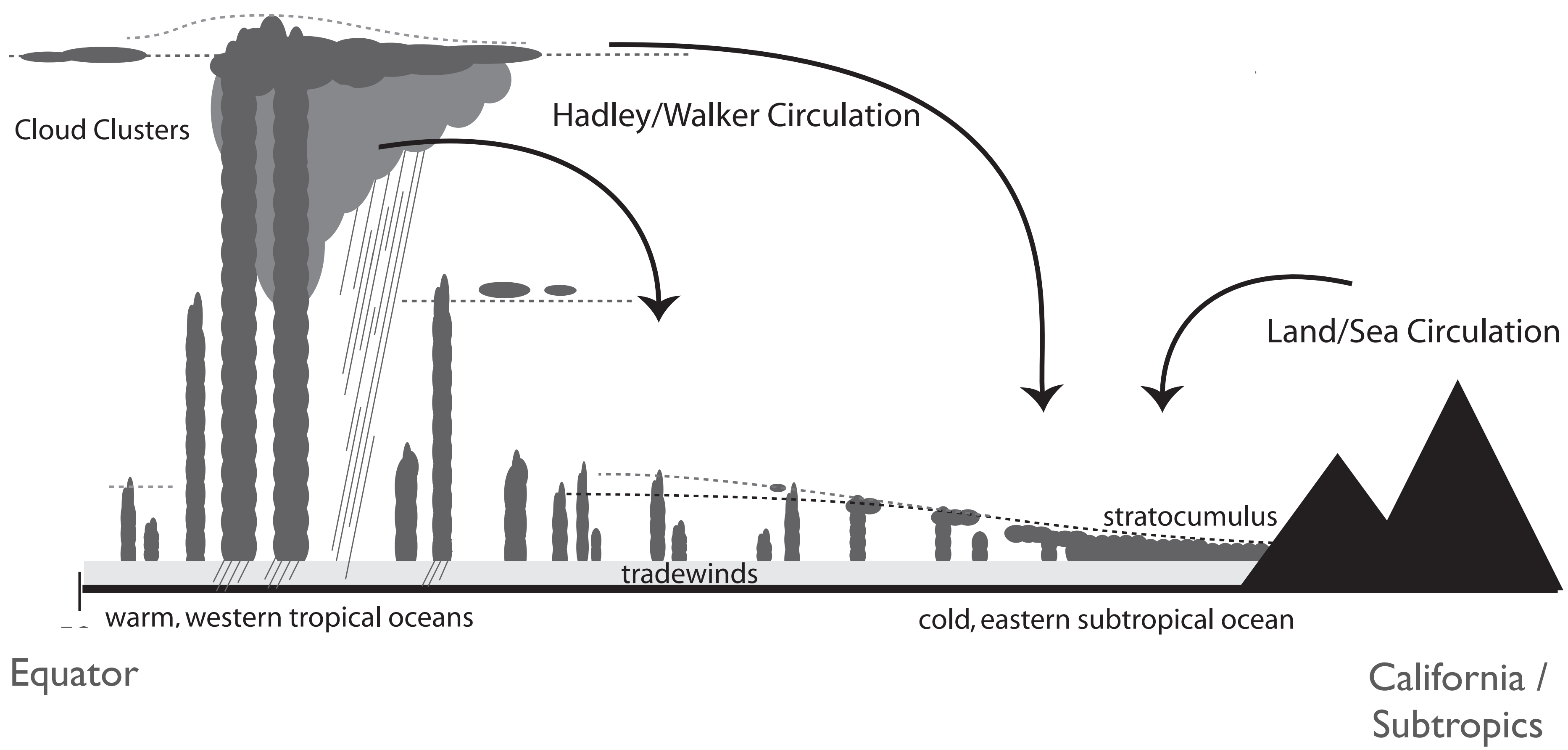
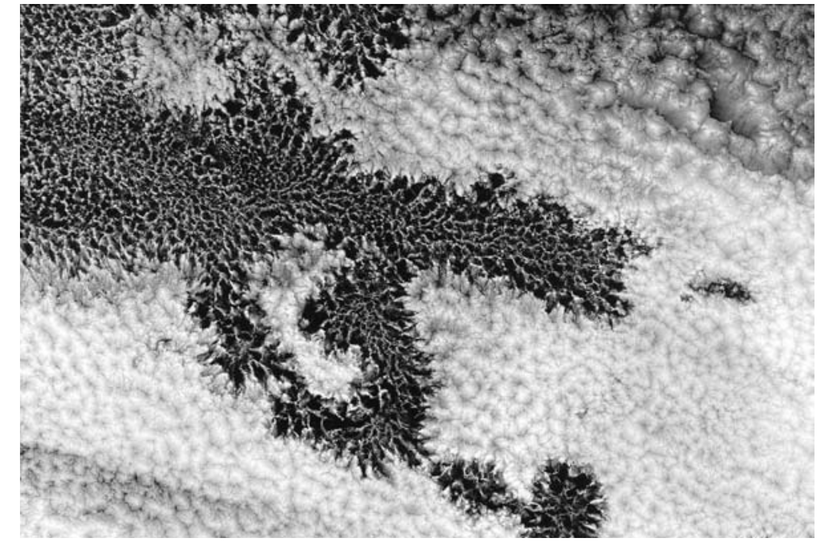


Figure: *Atmospheric Moist Convection*, B. Stevens (2005)

Deep Convection	Shallow Convection	Stratocumulus
		

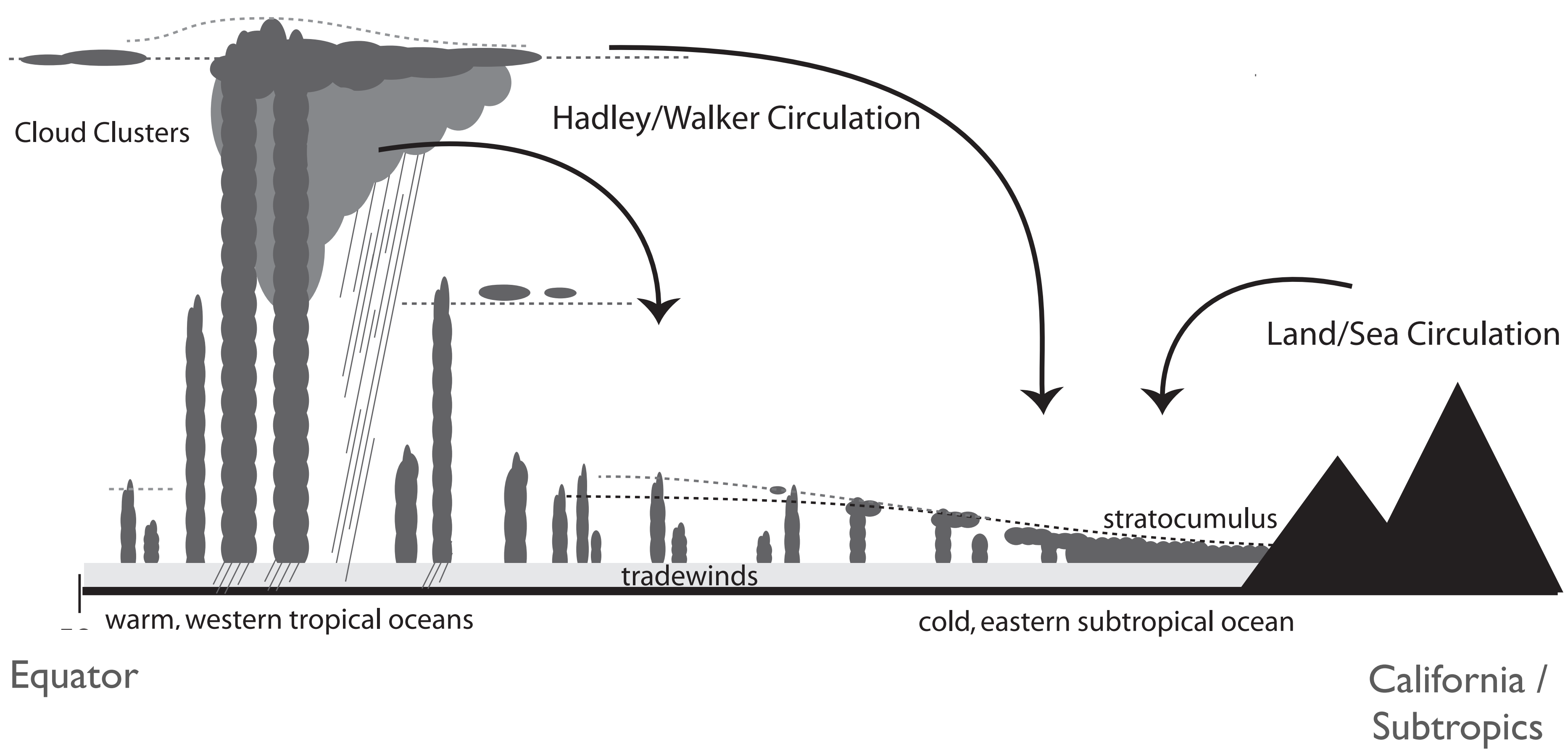


Figure: *Atmospheric Moist Convection*, B. Stevens (2005)

Climate & Weather Models

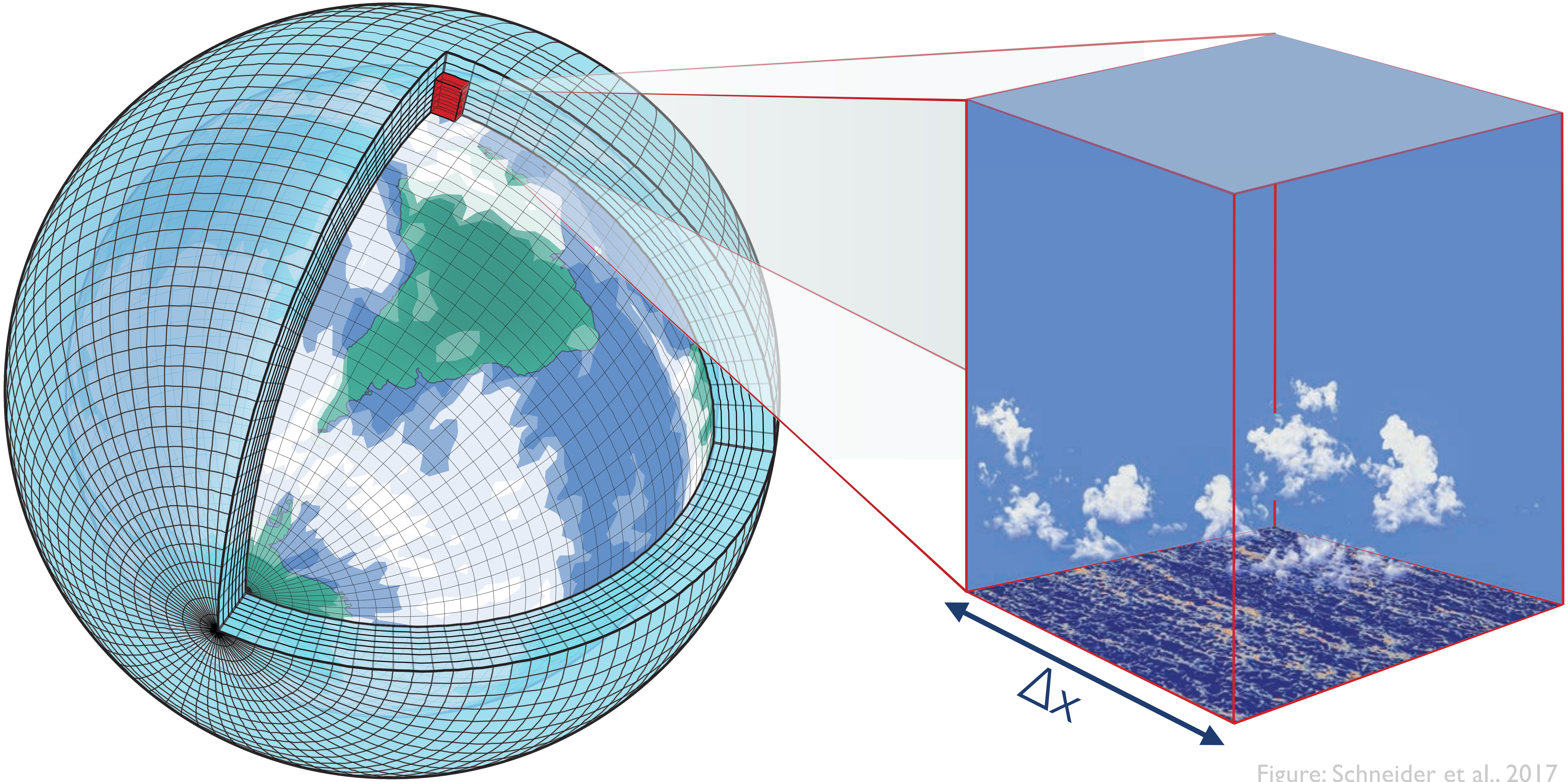


Figure: Schneider et al., 2017

grid resolution weather models:

- global: Δx~O(10km)
- regional: Δx~O(1km)

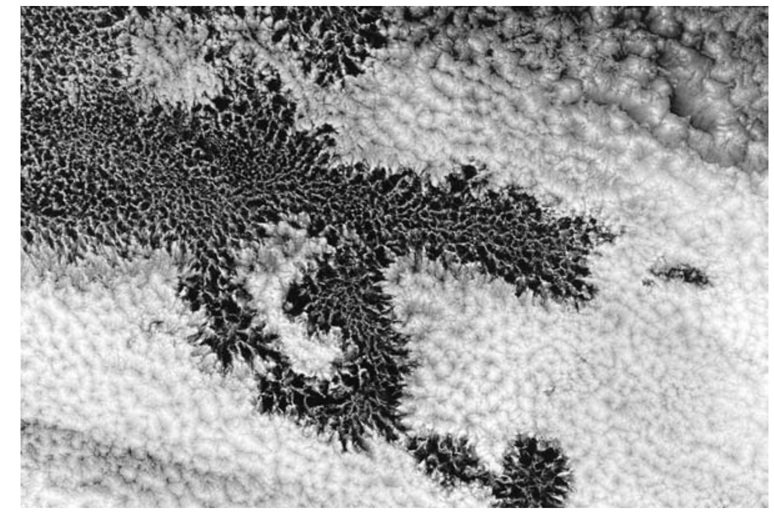
grid resolution climate models: Δx~O(50-100km)

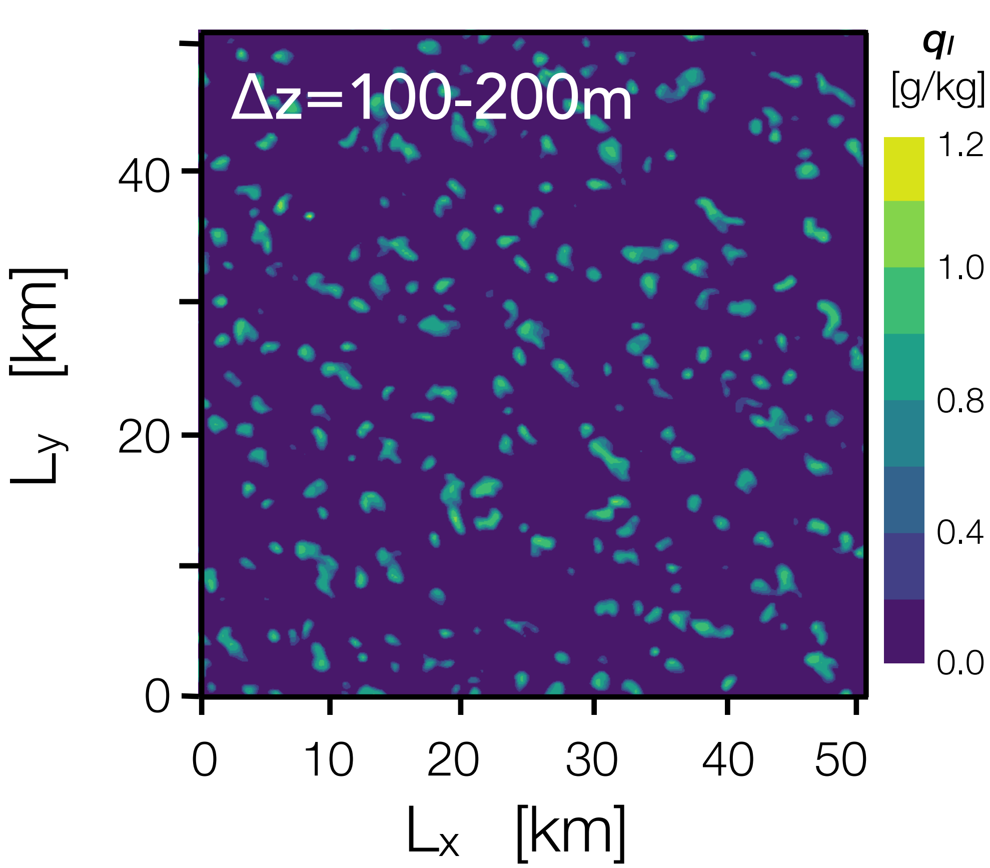
High-Resolution Modeling (Large-Eddy-Simulation)

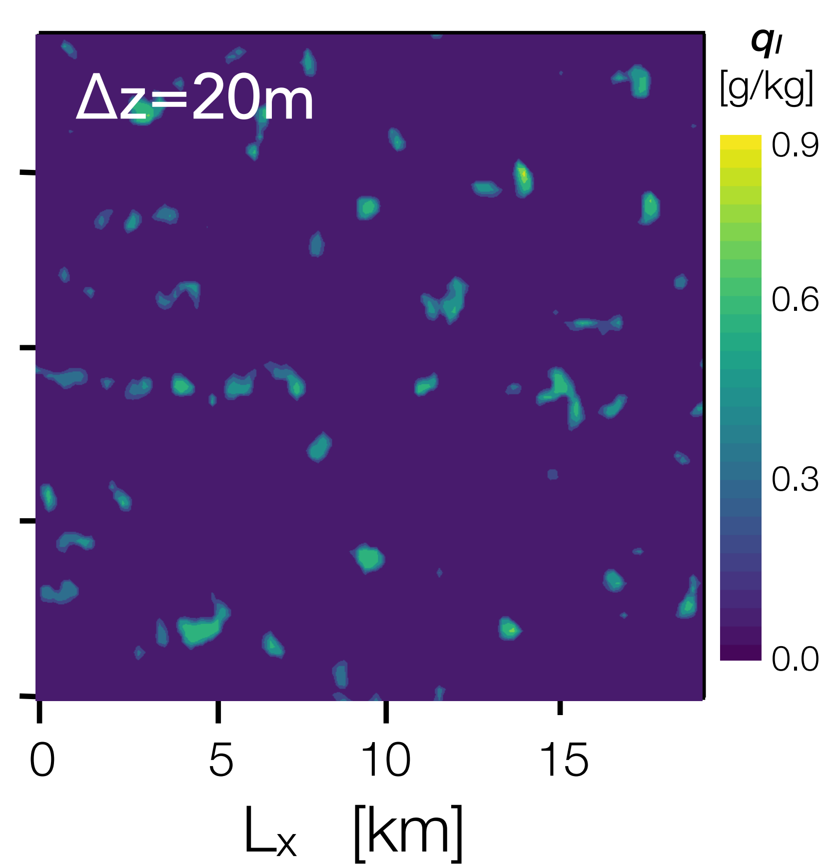
Deep Convection
(TRMM LBA)

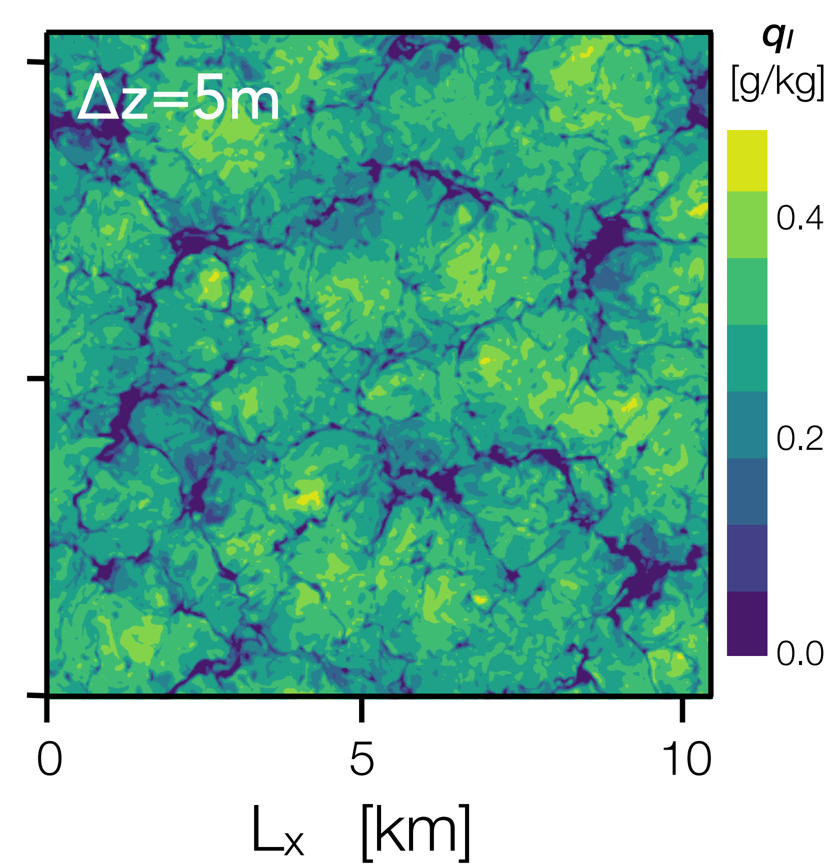
Shallow Convection
(Bomex)

Stratocumulus
(DYCOMS RF01)





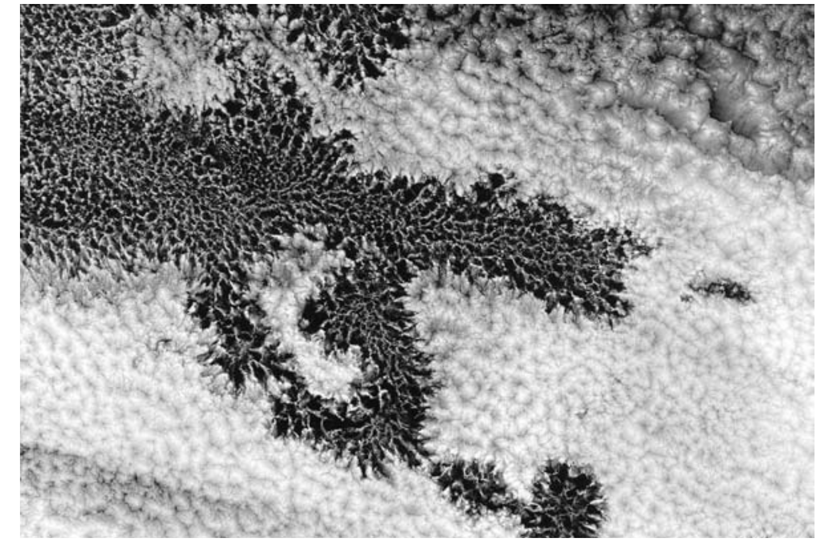




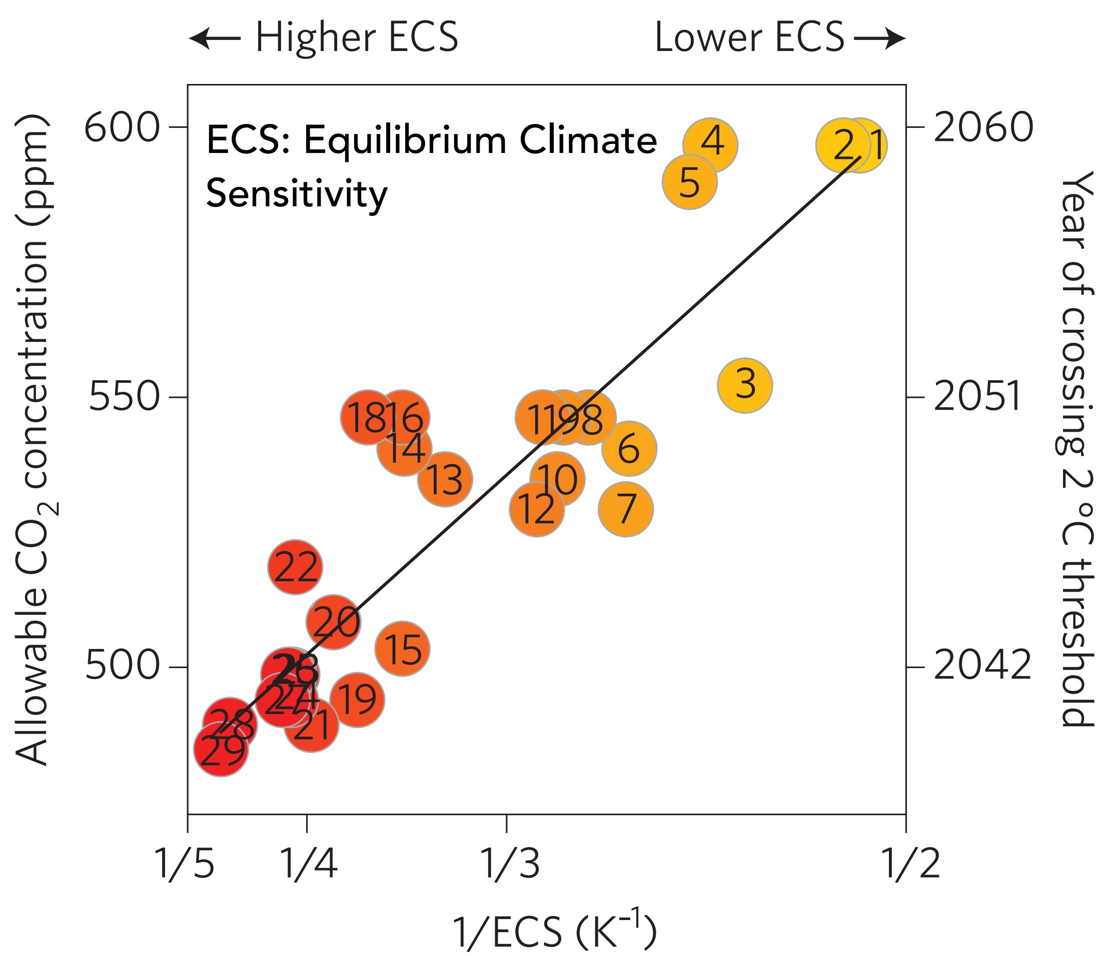
Deep Convection

Shallow Convection

Stratocumulus



How much CO_2 can we emit to stay below the 2°C threshold?

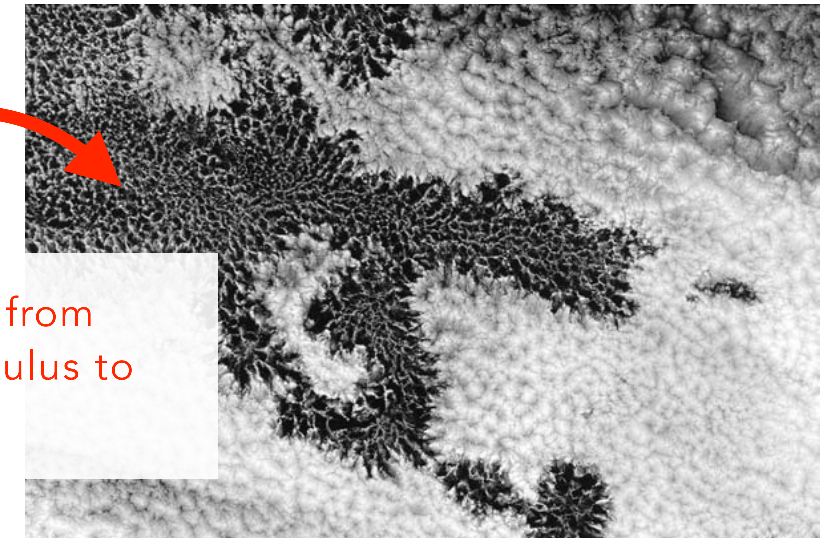


Figures: Cloud Observatory on Barbados, MPI (mpimet.mpg.de), Schneider et al. (2017)

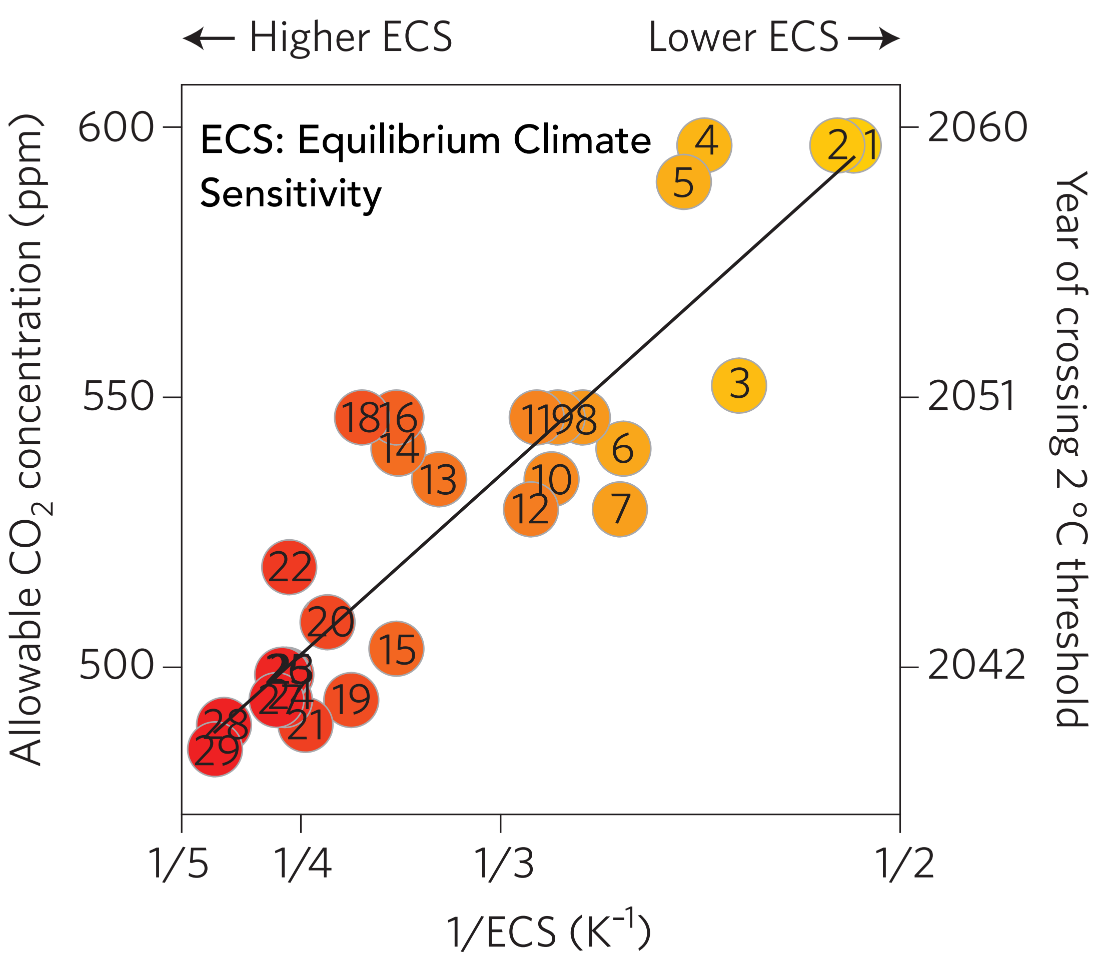
Deep Convection

Shallow Convection

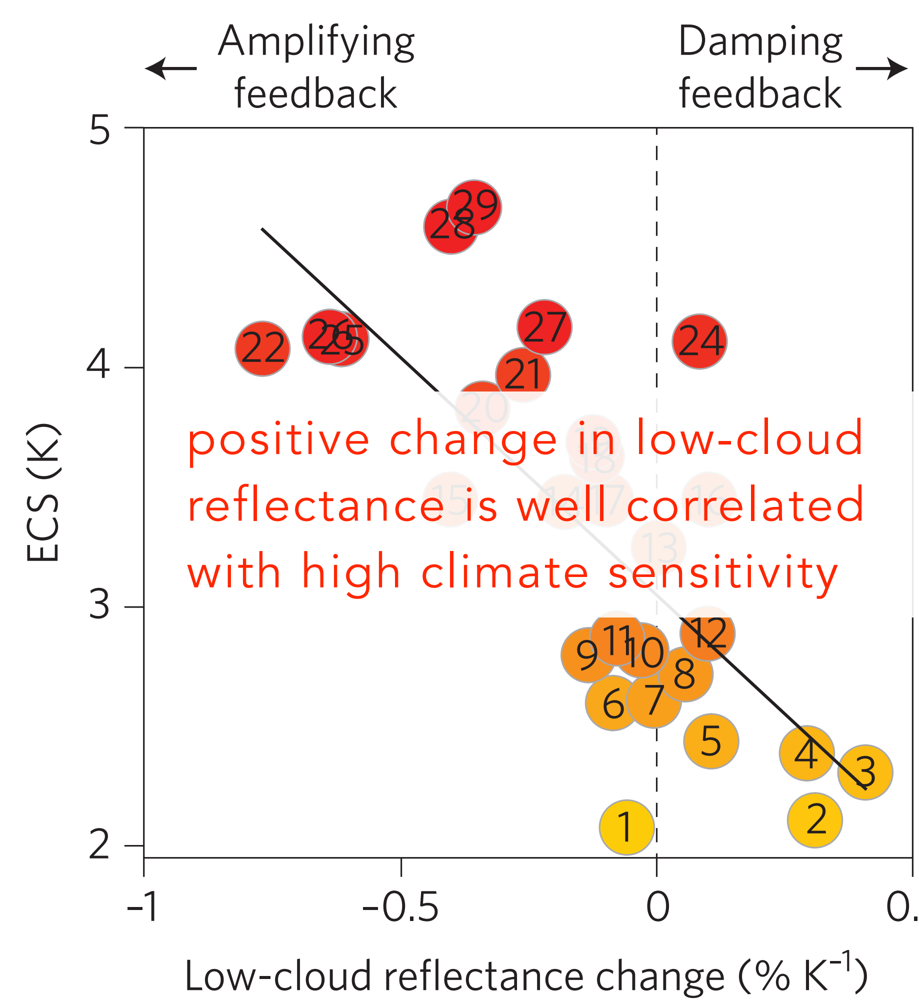
Stratocumulus



transition from
stratocumulus to
cumulus



Radiative Cloud Feedback



positive change in low-cloud reflectance is well correlated with high climate sensitivity

Figures: Cloud Observatory on Barbados, MPI (mpimet.mpg.de), Schneider et al. (2017)

2. BACKGROUND & CLIMATE MODELS

Equations of Motion (Navier-Stokes Equations)

Mass Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0.$$

$\mathbf{v}$: velocity vector
ρ: density

If density is constant this reduces to $\nabla \cdot \boldsymbol{v} = 0$.

Momentum Equation

$$\frac{\mathrm{D}\boldsymbol{v}}{\mathrm{D}t} = -\frac{\nabla p}{\rho} + \nu \nabla^2 \boldsymbol{v} + \boldsymbol{F},$$

p: pressure, density
$\mathbf{F}$: body forces (e.g., gravity)
ν: viscosity

If density is constant, or pressure is given as a function of density alone (e.g., $p = C\rho^{\gamma}$), then (EOM.1) and (EOM.2) form a complete system.

Irreversible sink / source terms

Thermodynamic Equation

$$\frac{\mathrm{D}I}{\mathrm{D}t} + \frac{p}{\rho}\nabla \cdot \boldsymbol{v} = \dot{Q}, \qquad \text{or} \qquad \frac{\mathrm{D}\theta}{\mathrm{D}t} = \frac{1}{c_p}\left(\frac{\theta}{T}\right)\dot{Q},$$

I: internal energy
θ: potential temperature
$\dot{Q}$: diabatic sources (heating, diffusion)
p, ρ: pressure, density

condensational heating: $$Q_{cond} = -L_c \frac{\mathrm{D}w_s}{\mathrm{D}t},$$

w_s: liquid water content, snow, ice (condensed phases)

radiation: $$Q_{rad} = Q^{LW} + Q^{SW}$$

$Q_{rad} = f(\rho(z))$, where ρ strongly depends on atmospheric composition and aerosols

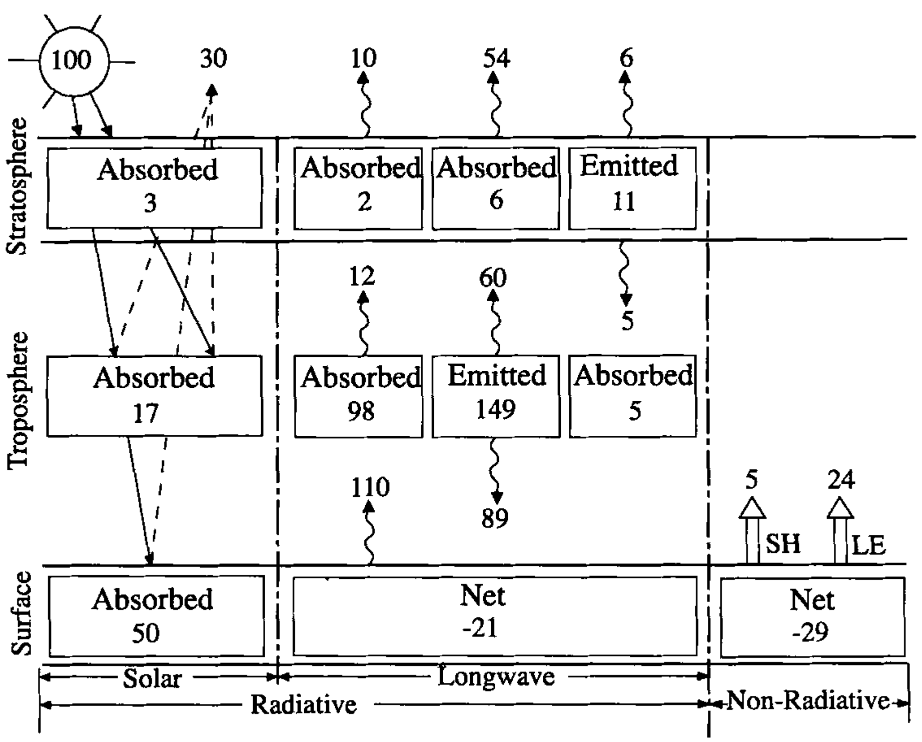
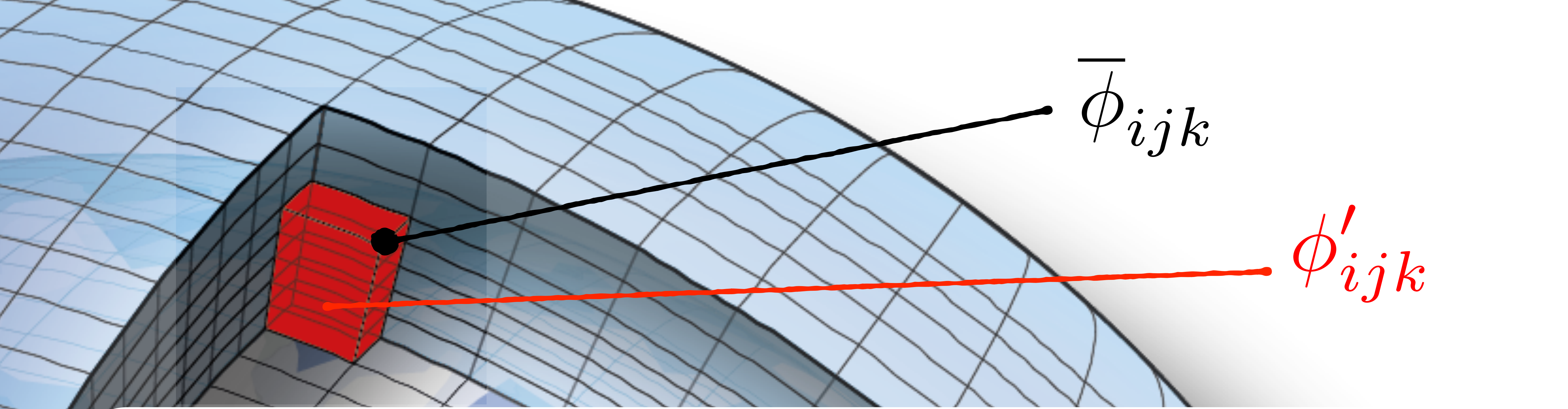


Fig. 2.4 Radiative and nonradiative energy flow diagram for Earth and its atmosphere. Units are percentages of the global-mean insolation (100 units = 342 W m^{-2}).

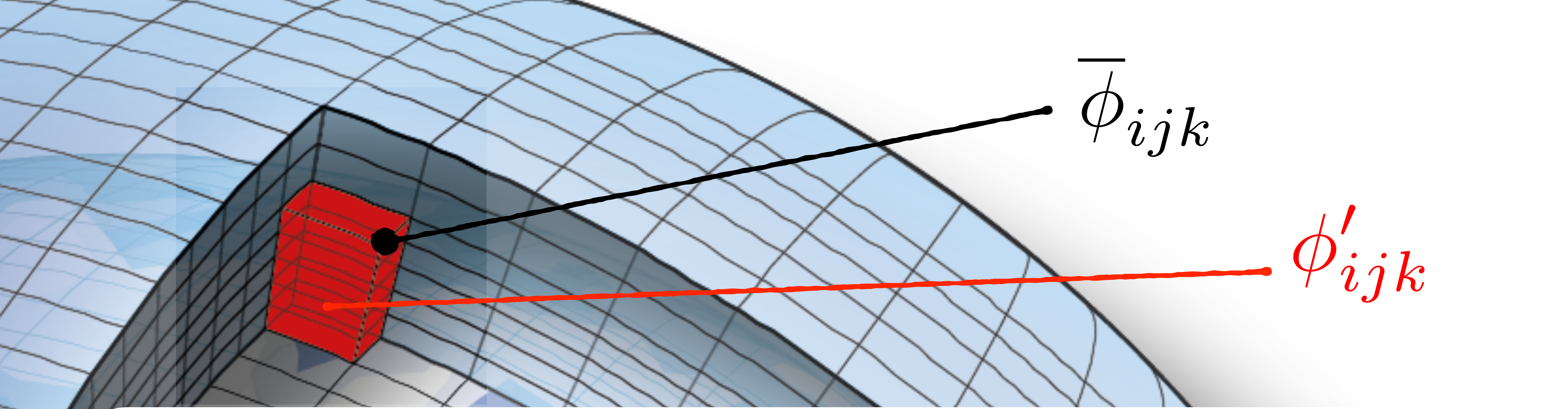


$$\phi = \overline{\phi} + \phi', \qquad \phi \in \{u, v, w, \theta, q_t\}$$

$$\overline{(\cdot)} := \int_{x_0}^{x_0+\Delta x} \int_{y_0}^{y_0+\Delta y} \mathrm{d}x\, \mathrm{d}y\, (\cdot)\,.$$

total field: $\partial_t \phi = -(\vec{v} \cdot \nabla)\phi + F_\phi$

Figure: Schneider et al., 2017



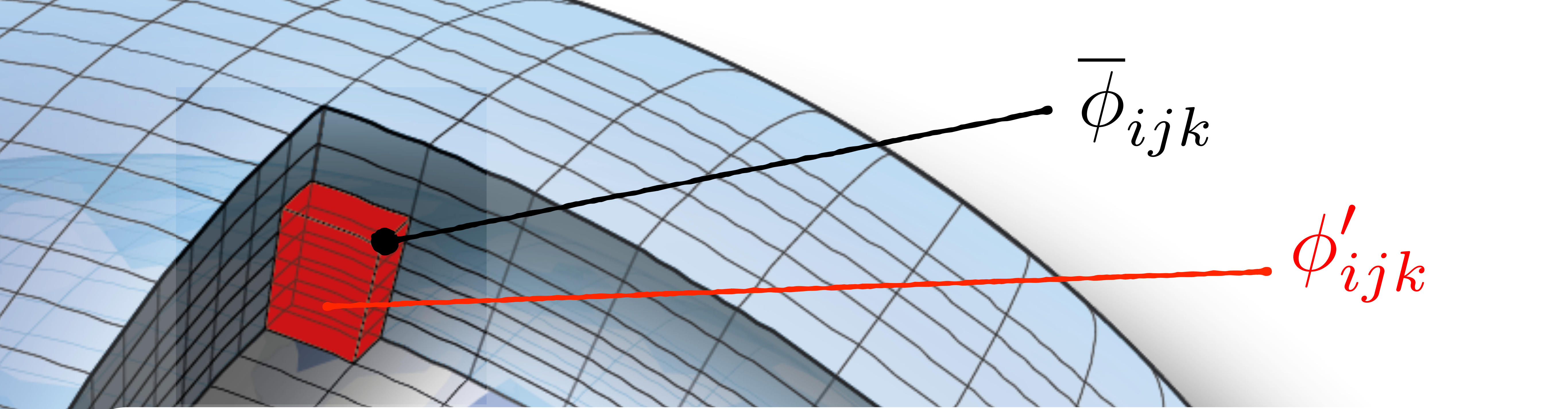
$$\phi = \overline{\phi} + \phi', \qquad \phi \in \{u, v, w, \theta, q_t\}$$

$$\overline{(\cdot)} := \int_{x_0}^{x_0+\Delta x} \int_{y_0}^{y_0+\Delta y} \mathrm{d}x \, \mathrm{d}y \, (\cdot) \, .$$

total field: $\partial_t \phi = -(\vec{v} \cdot \nabla)\phi + F_\phi$

$$= -\left[(\overline{\vec{v}} \cdot \nabla)\overline{\phi} + (\overline{\vec{v}} \cdot \nabla)\phi' + (\vec{v}' \cdot \nabla)\overline{\phi} + (\vec{v}' \cdot \nabla)\phi' \right] + F_\phi$$

Figure: Schneider et al. 2017

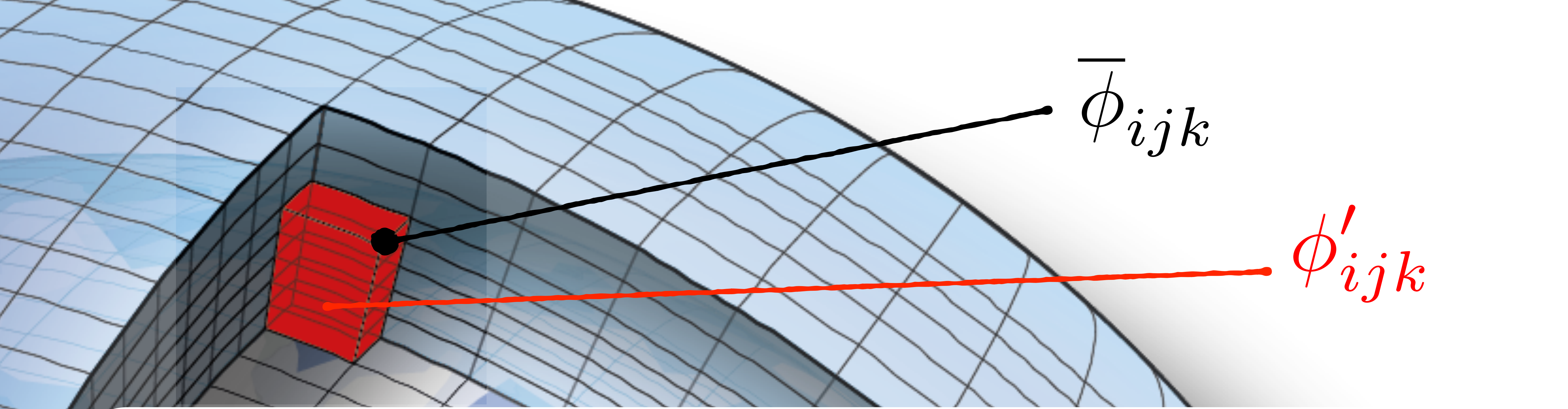


$$\phi = \overline{\phi} + \phi', \qquad \phi \in \{u, v, w, \theta, q_t\}$$

$$\overline{(\cdot)} := \int_{x_0}^{x_0+\Delta x} \int_{y_0}^{y_0+\Delta y} \mathrm{d}x \, \mathrm{d}y \, (\cdot) \, .$$

$$\begin{aligned} \text{total field:} \quad \partial_t \phi &= -(\vec{v} \cdot \nabla)\phi + F_\phi \\ &= -\left[(\overline{\vec{v}} \cdot \nabla)\overline{\phi} + (\overline{\vec{v}} \cdot \nabla)\phi' + (\vec{v}' \cdot \nabla)\overline{\phi} + (\vec{v}' \cdot \nabla)\phi'\right] + F_\phi \\ \text{resolved field:} \quad \partial_t \overline{\phi} &= -(\overline{\vec{v}} \cdot \nabla)\overline{\phi} - \overline{(\vec{v}' \cdot \nabla)\phi'} + \overline{F}_\phi \end{aligned}$$

Figure: Schneider et al. 2017



$$\phi = \overline{\phi} + \phi', \qquad \phi \in \{u, v, w, \theta, q_t\}$$

$$\overline{(\cdot)} := \int_{x_0}^{x_0+\Delta x} \int_{y_0}^{y_0+\Delta y} \mathrm{d}x\, \mathrm{d}y\, (\cdot)\,.$$

total field: $\partial_t \phi = -(\vec{v} \cdot \nabla)\phi + F_\phi$

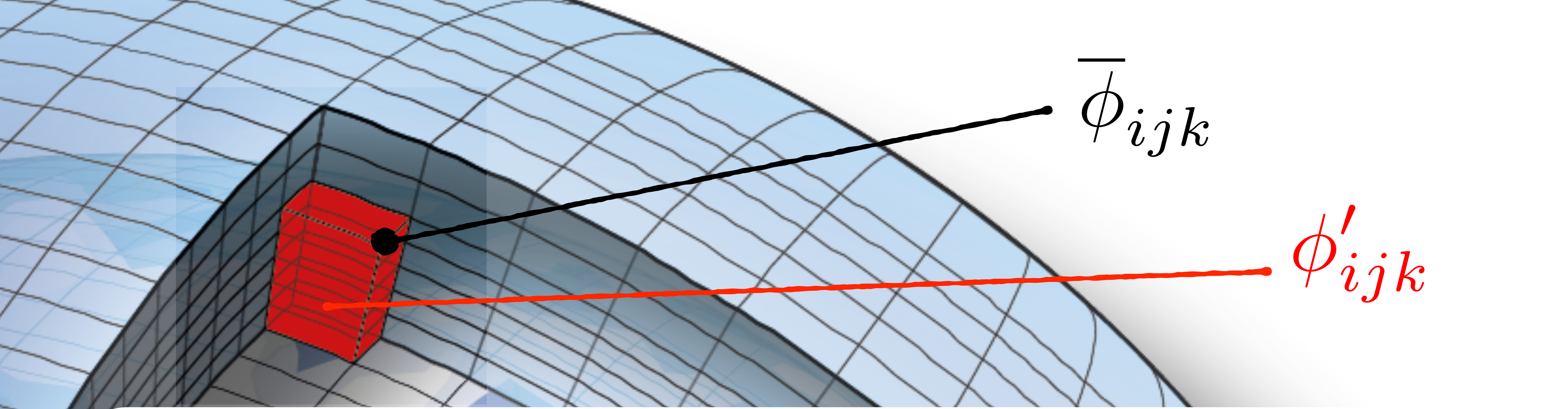
$$= -\left[(\overline{\vec{v}} \cdot \nabla)\overline{\phi} + (\overline{\vec{v}} \cdot \nabla)\phi' + (\vec{v}' \cdot \nabla)\overline{\phi} + (\vec{v}' \cdot \nabla)\phi'\right] + F_\phi$$

Reynolds Stress

resolved field: $\partial_t \overline{\phi} = -(\overline{\vec{v}} \cdot \nabla)\overline{\phi} - \overline{(\vec{v}' \cdot \nabla)\phi'} + \overline{F}_\phi$

sub-grid scale field: $\partial_t \phi' + (\overline{\vec{v}} \cdot \nabla)\phi' + (\vec{v}' \cdot \nabla) + \left[(\vec{v}' \cdot \nabla)\phi' - \overline{(\vec{v}' \cdot \nabla)\phi'}\right] = F'_\phi$

Figure: Schneider et al., 2017



$$\phi = \overline{\phi} + \phi', \qquad \phi \in \{u, v, w, \theta, q_t\}$$

$$\overline{(\cdot)} := \int_{x_0}^{x_0+\Delta x} \int_{y_0}^{y_0+\Delta y} \mathrm{d}x \, \mathrm{d}y \, (\cdot) \, .$$

total field: $\partial_t \phi = -(\vec{v} \cdot \nabla)\phi + F_\phi$

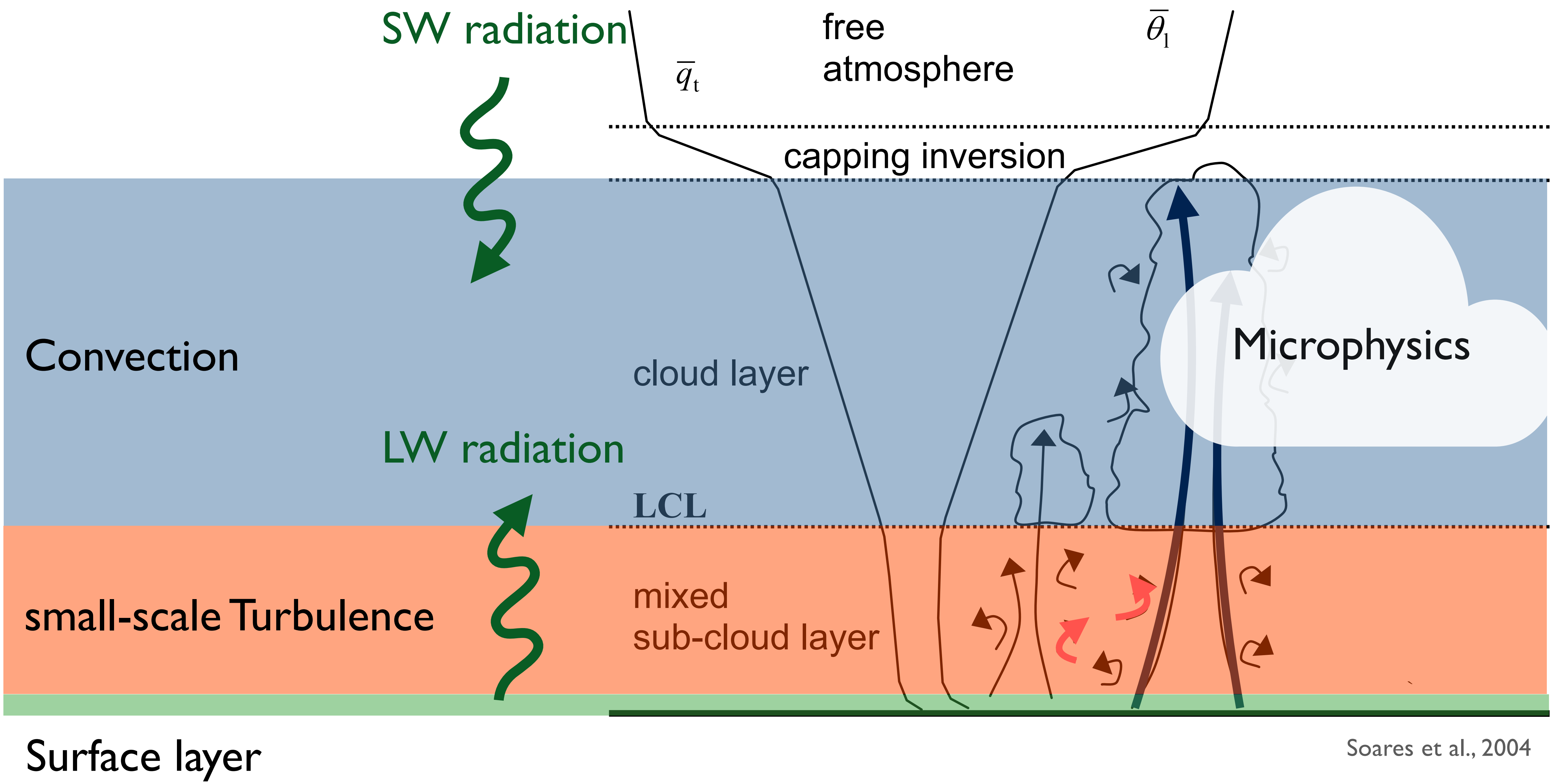
$$= -\left[(\overline{\vec{v}} \cdot \nabla)\overline{\phi} + (\overline{\vec{v}} \cdot \nabla)\phi' + (\vec{v}' \cdot \nabla)\overline{\phi} + (\vec{v}' \cdot \nabla)\phi'\right] + F_\phi$$

resolved field: $\partial_t \overline{\phi} = -(\overline{\vec{v}} \cdot \nabla)\overline{\phi} - \overline{(\vec{v}' \cdot \nabla)\phi'} + \overline{F}_\phi$ Reynolds Stress

sub-grid scale field: $\partial_t \phi' + (\overline{\vec{v}} \cdot \nabla)\phi' + (\vec{v}' \cdot \nabla) + \left[(\vec{v}' \cdot \nabla)\phi' - \overline{(\vec{v}' \cdot \nabla)\phi'}\right] = F'_\phi$

Figure: Schneider et al., 2017

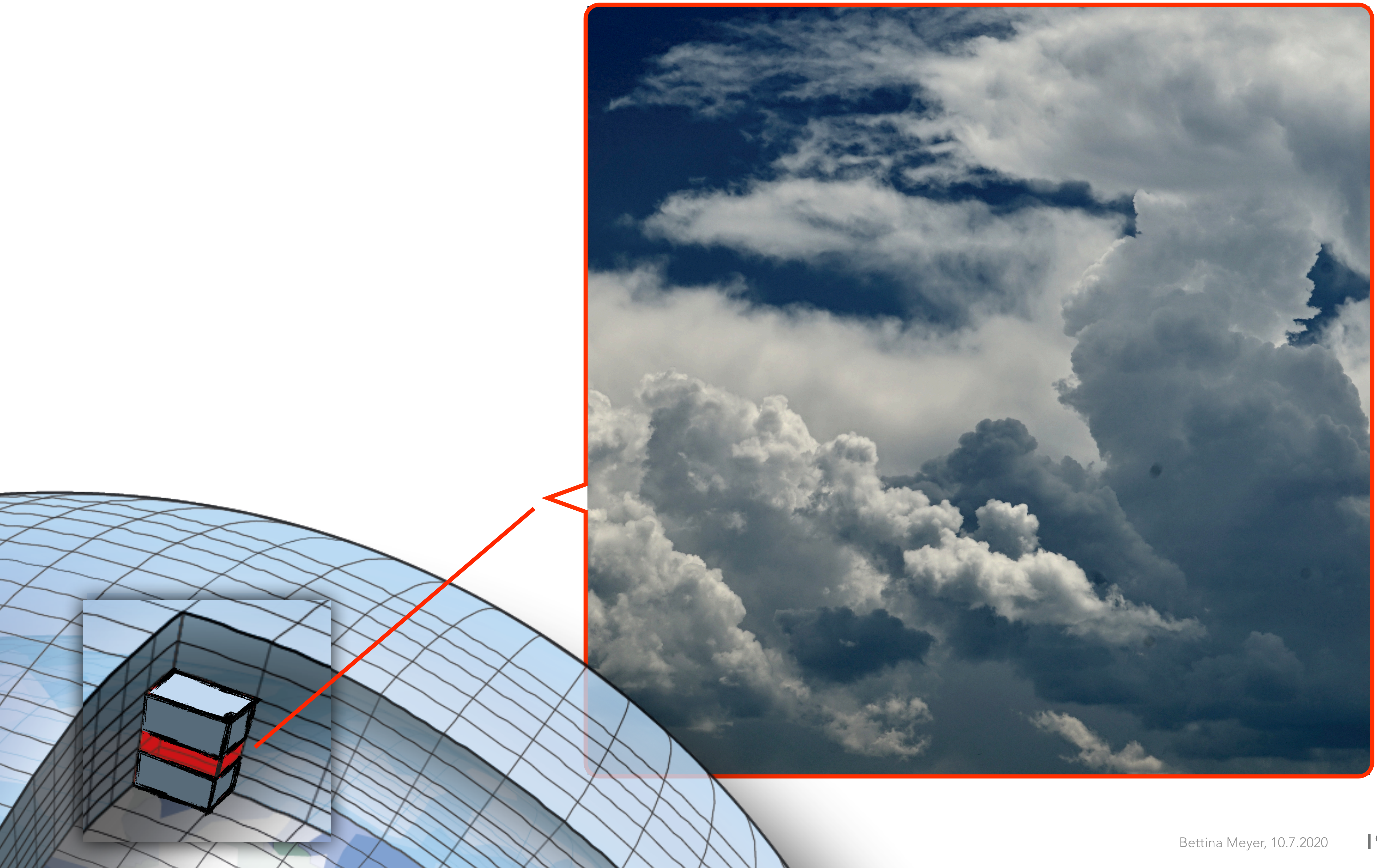
Sub-Grid Scale Parameterisations



Soares et al., 2004

3. CLOUD MICROPHYSICS

Cloud Schemes



Irreversible sink / source terms

Thermodynamic Equation

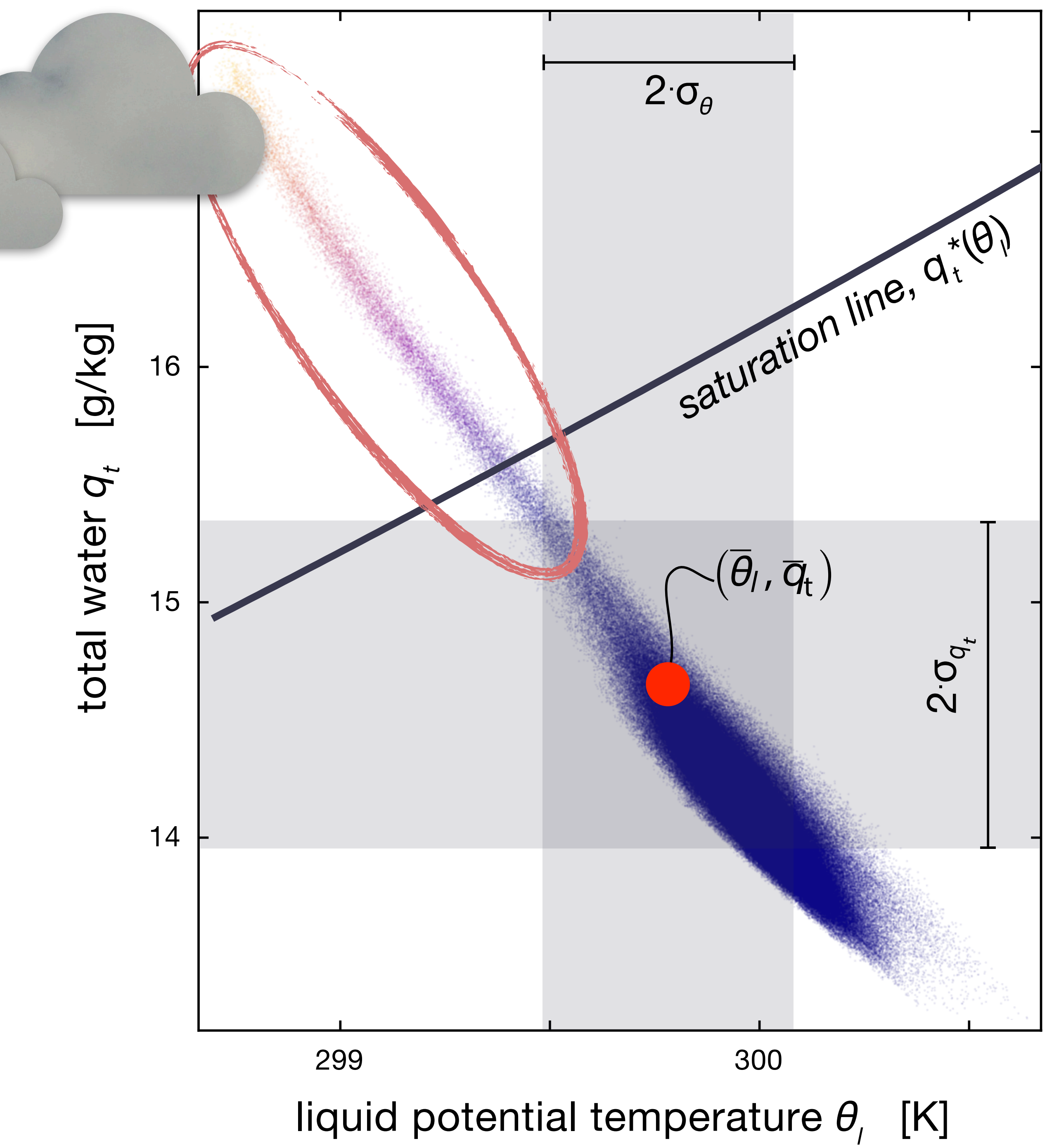
$$\frac{\mathrm{D}I}{\mathrm{D}t} + \frac{p}{\rho}\nabla \cdot \boldsymbol{v} = \dot{Q}, \qquad \text{or} \qquad \frac{\mathrm{D}\theta}{\mathrm{D}t} = \frac{1}{c_p}\left(\frac{\theta}{T}\right)\dot{Q},$$

I: internal energy
θ: potential temperature
$\dot{Q}$: diabatic sources (heating, diffusion)
p, ρ: pressure, density

condensational heating: $Q_{cond} = -L_c \frac{\mathrm{D}w_s}{\mathrm{D}t},$

w_s: liquid water, snow and ice content (condensed phases)

Cloud Schemes



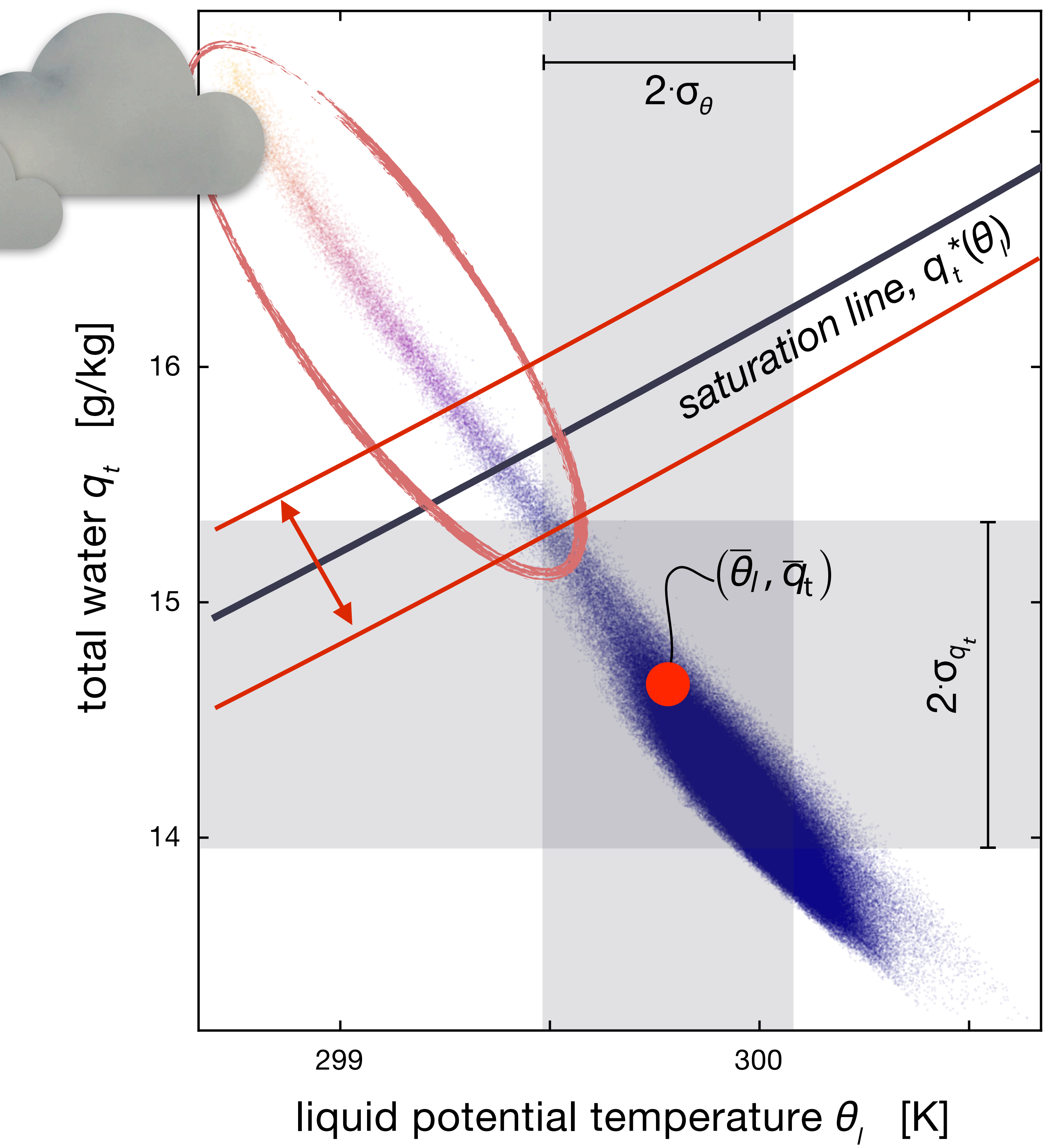
Data, sampled from a large-eddy simulation of a shallow convection (BOMEX) cloud layer (z = 800m), accumulated over one hour.

The colouring indicates the liquid water content.

liquid potential temperature:

$$\bar{\theta}_l \approx \theta \left(1 - \frac{r_l}{\epsilon + r_t} \right)$$

Cloud Schemes



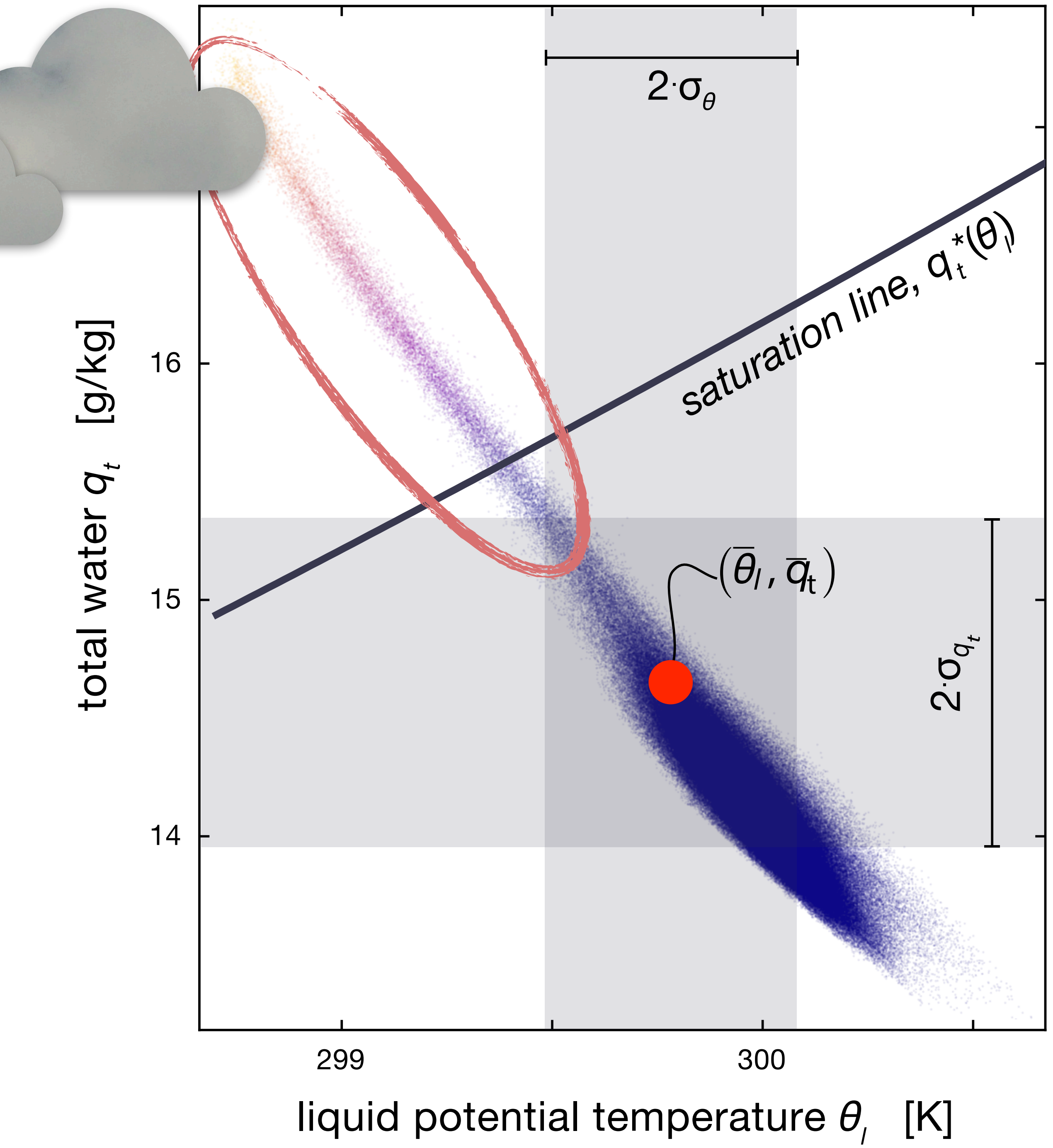
shallow convection (BOMEX) cloud layer (z = 800m); colouring indicates liquid water content.

Saturation Line:

- equilibrium vs. non-equilibrium phase partitioning
  - **equilibrium:** either sub-saturated or at saturation
  - **non-equilibrium:** supersaturation, supercooled liquid

- **nucleation:** *homogeneous nucleation* (formation of a drop of pure water from vapour) vs. *heterogeneous nucleation* (collection of molecules onto a foreign substance).
  >> aerosols (condensation nucleation)

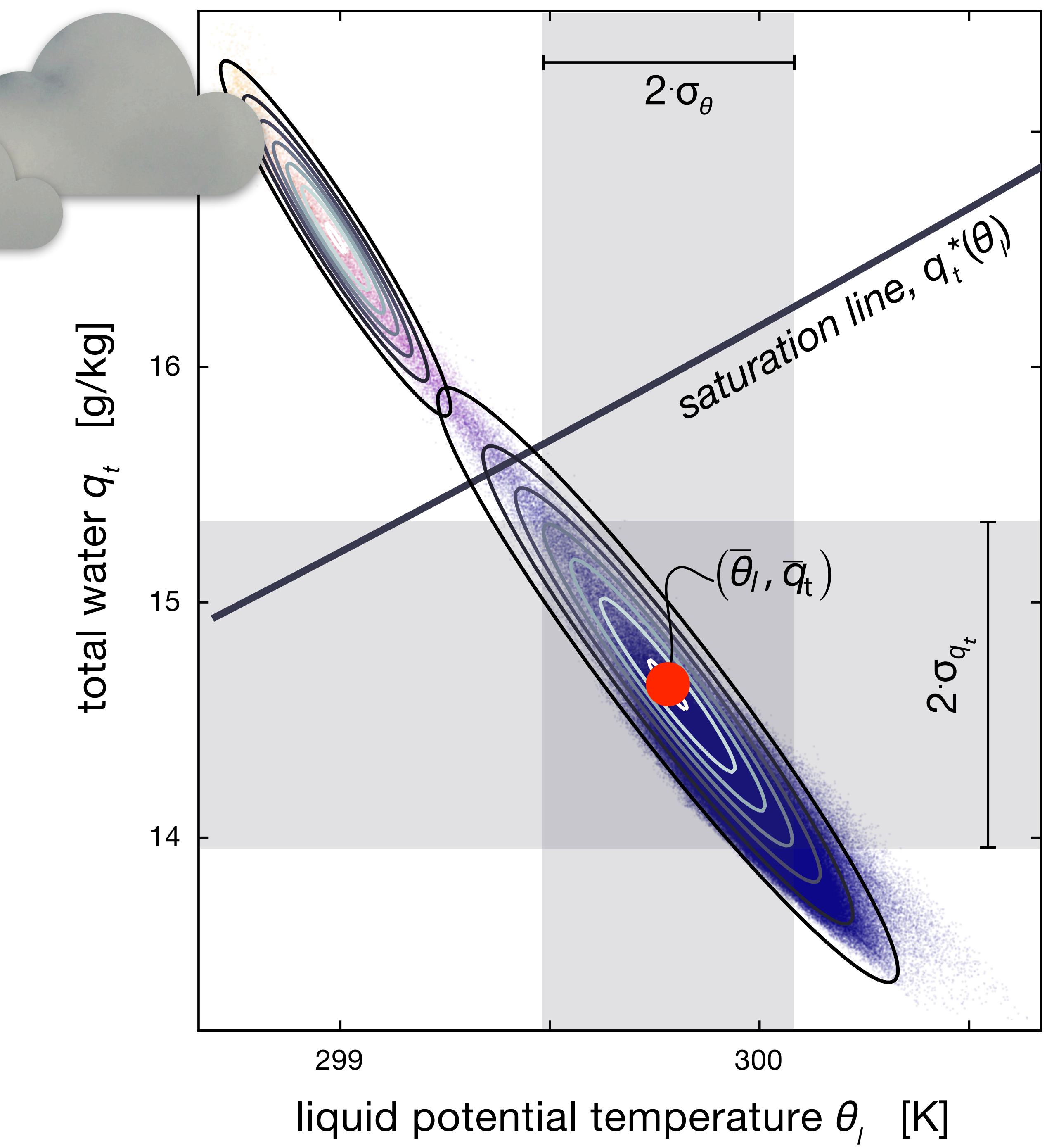
Cloud Schemes



shallow convection (BOMEX) cloud layer (z = 800m); colouring indicates liquid water content.

- **warm clouds:** only liquid phase
- **mixed phase cloud:** liquid and ice phase (snow, graupel, ice)

Cloud Schemes



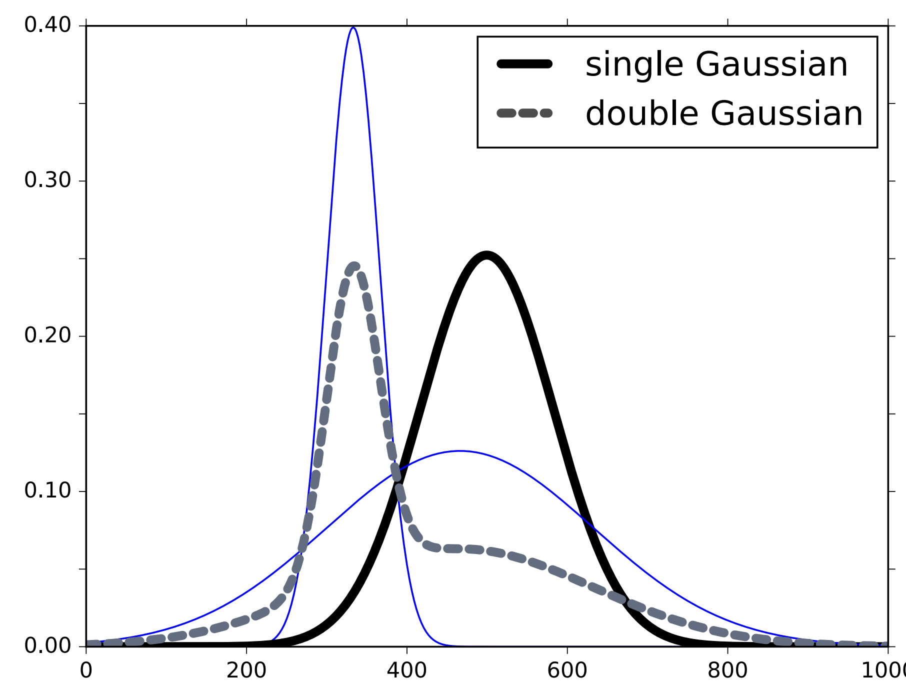
shallow convection (BOMEX) cloud layer (z = 800m); colouring indicates liquid water content.

Cloud Fraction:

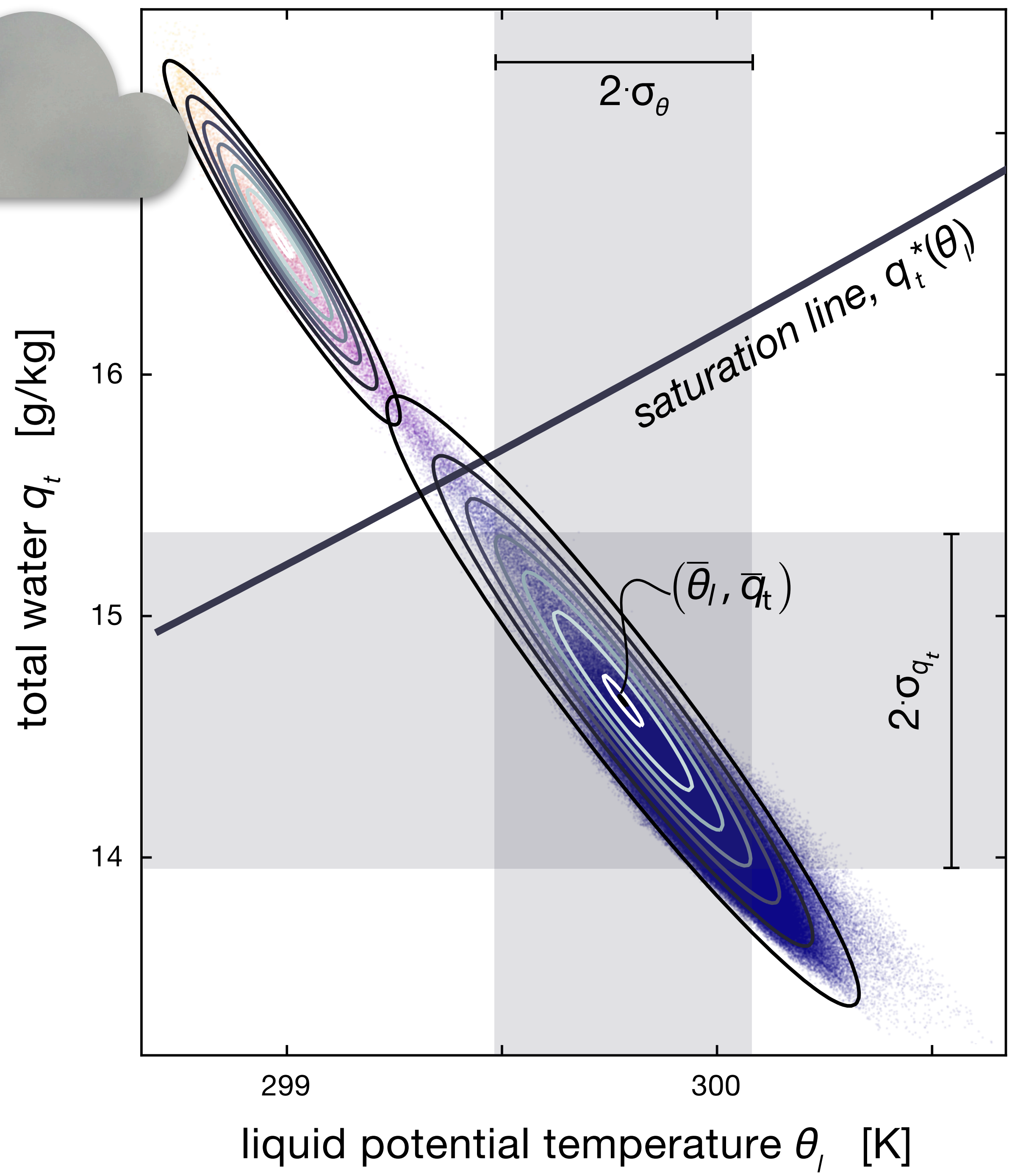
$$CF = \int_{-\infty}^{\infty} \int_{q_{l,s}}^{\infty} G(\theta_l, q_t)\, dq_t\, d\theta_l$$

Mean Liquid Water:

$$\overline{q}_l = \int_{-\infty}^{\infty} \int_{q_t^*}^{\infty} G(\theta_l, q_t)\, q_l(\theta_l, q_t)\, dq_t\, d\theta_l$$



Cloud Schemes



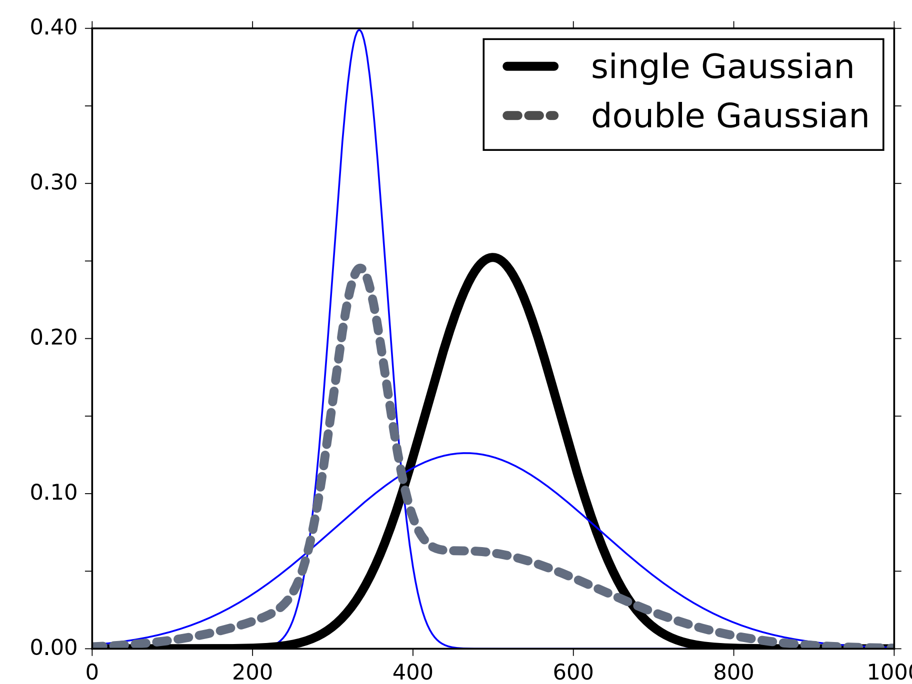
Data, sampled from a shallow convection (BOMEX) cloud layer (z = 800m) and the coloring indicates the liquid water content.

Cloud Fraction:

$$CF = \int_{-\infty}^{\infty} \int_{q_{l,s}}^{\infty} G(\theta_l, q_t)\, dq_t\, d\theta_l$$

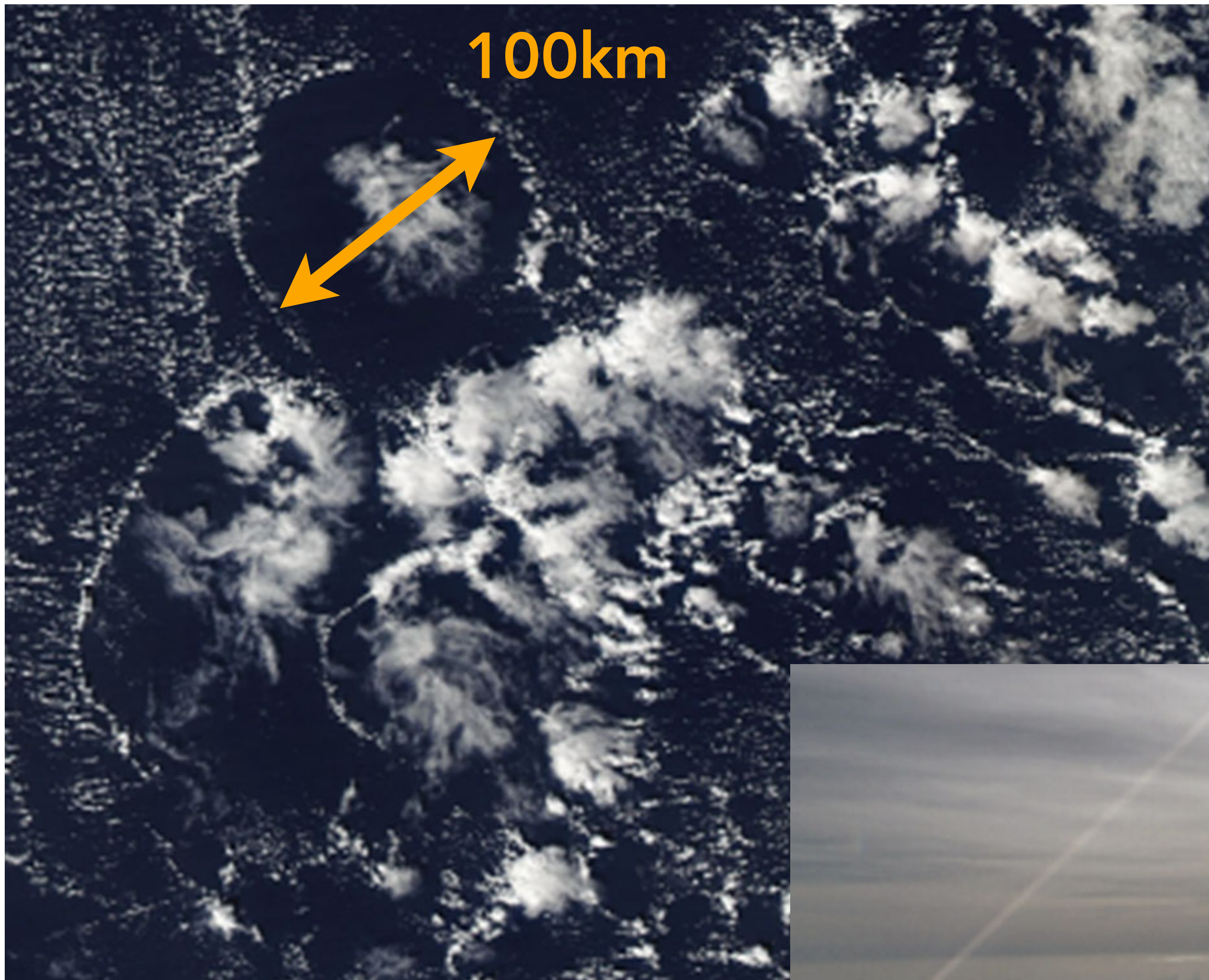
Mean Liquid Water:

$$\overline{q}_l = \int_{-\infty}^{\infty} \int_{q_t^*}^{\infty} G(\theta_l, q_t)\, q_l(\theta_l, q_t)\, dq_t\, d\theta_l$$



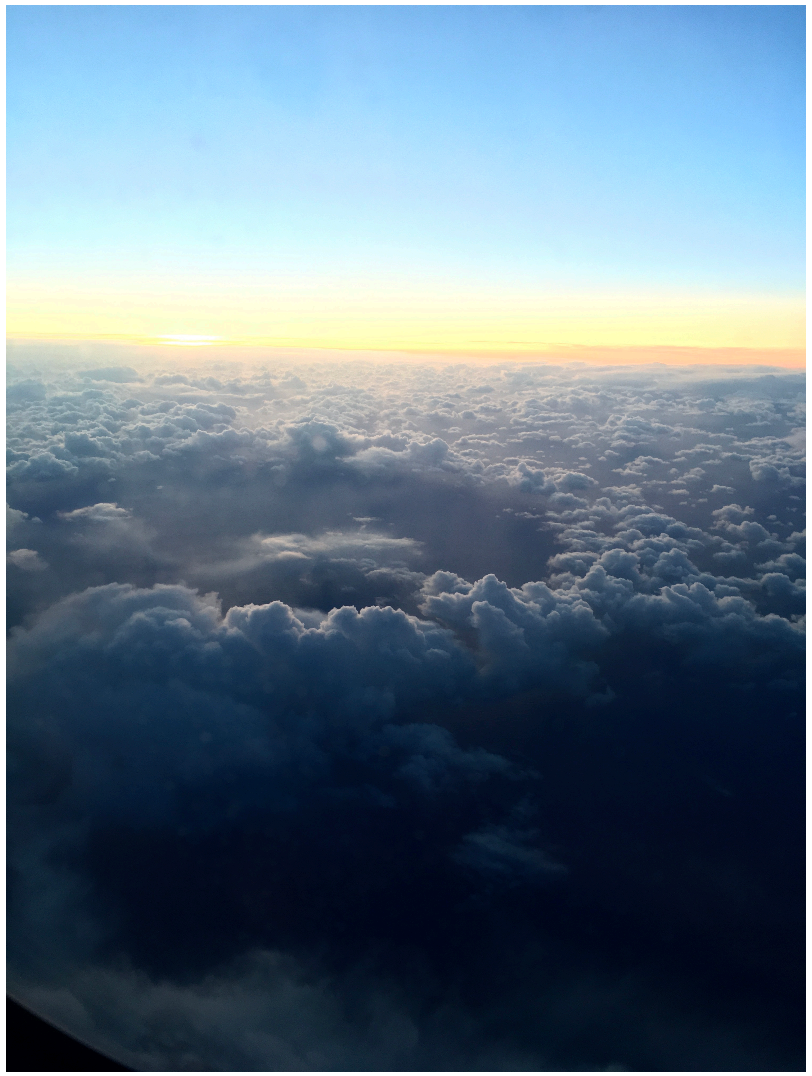
4. COLD POOLS

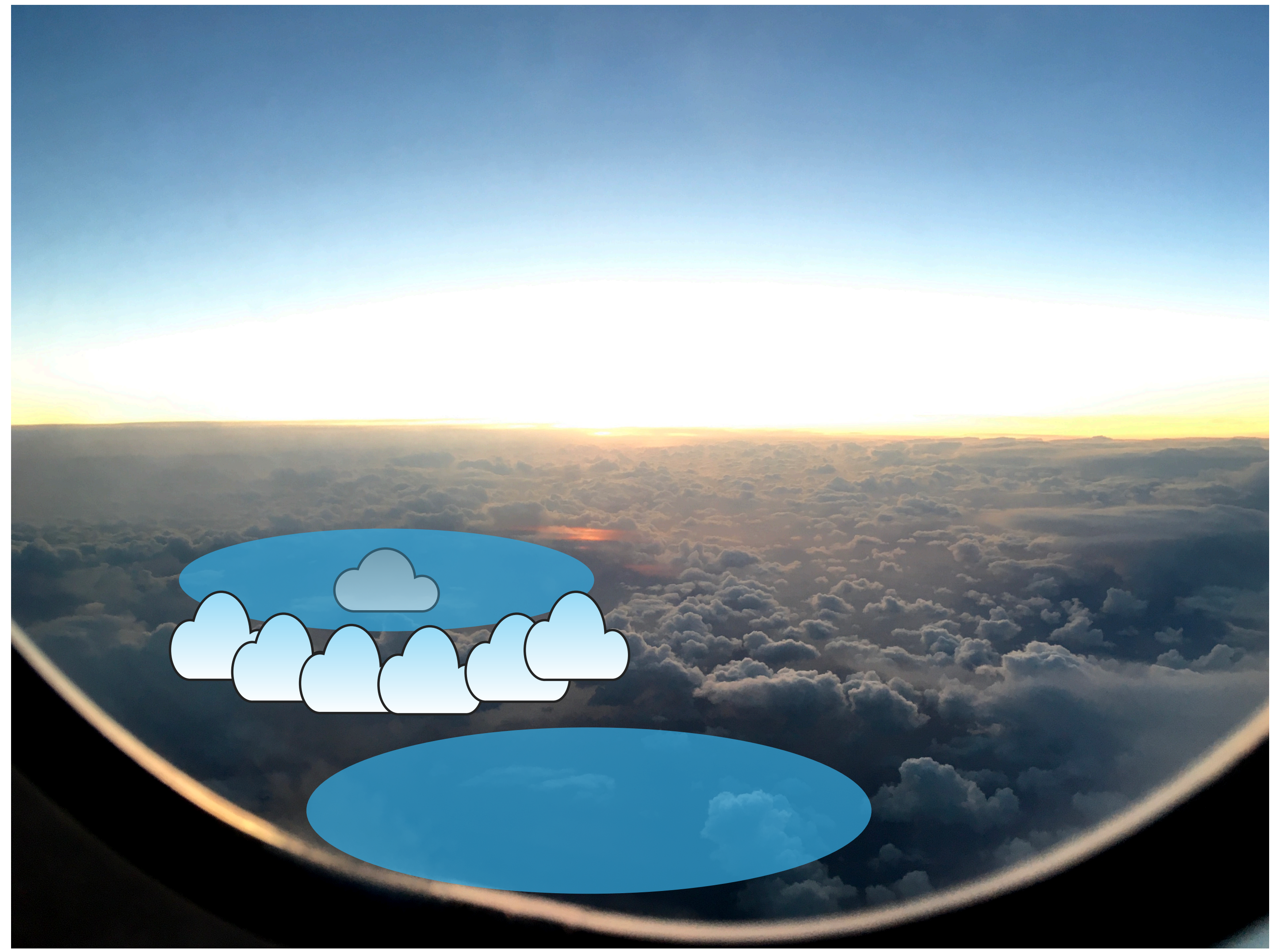
Cold Pools



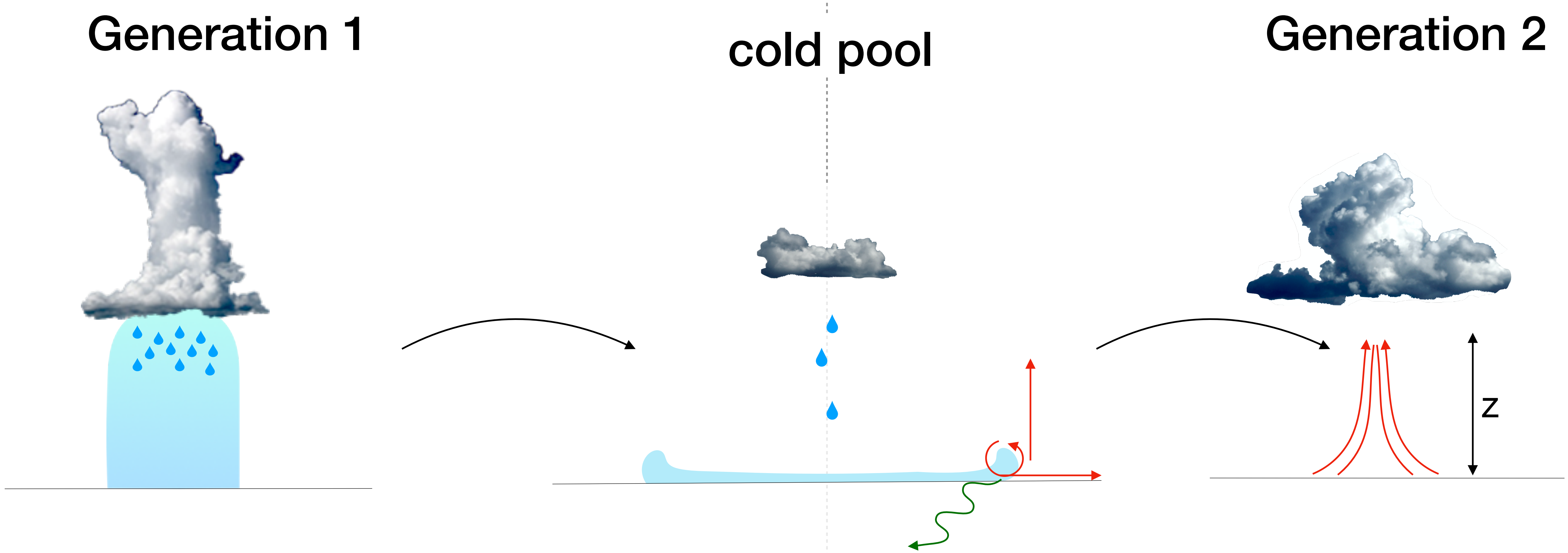
Figures:
Zuidema et al., Surv Geophys (2017)
NASA / JPL-Caltech, S. Böing (2016)

Cold Pools





Cold Pools - Linking Clouds over Time and Space



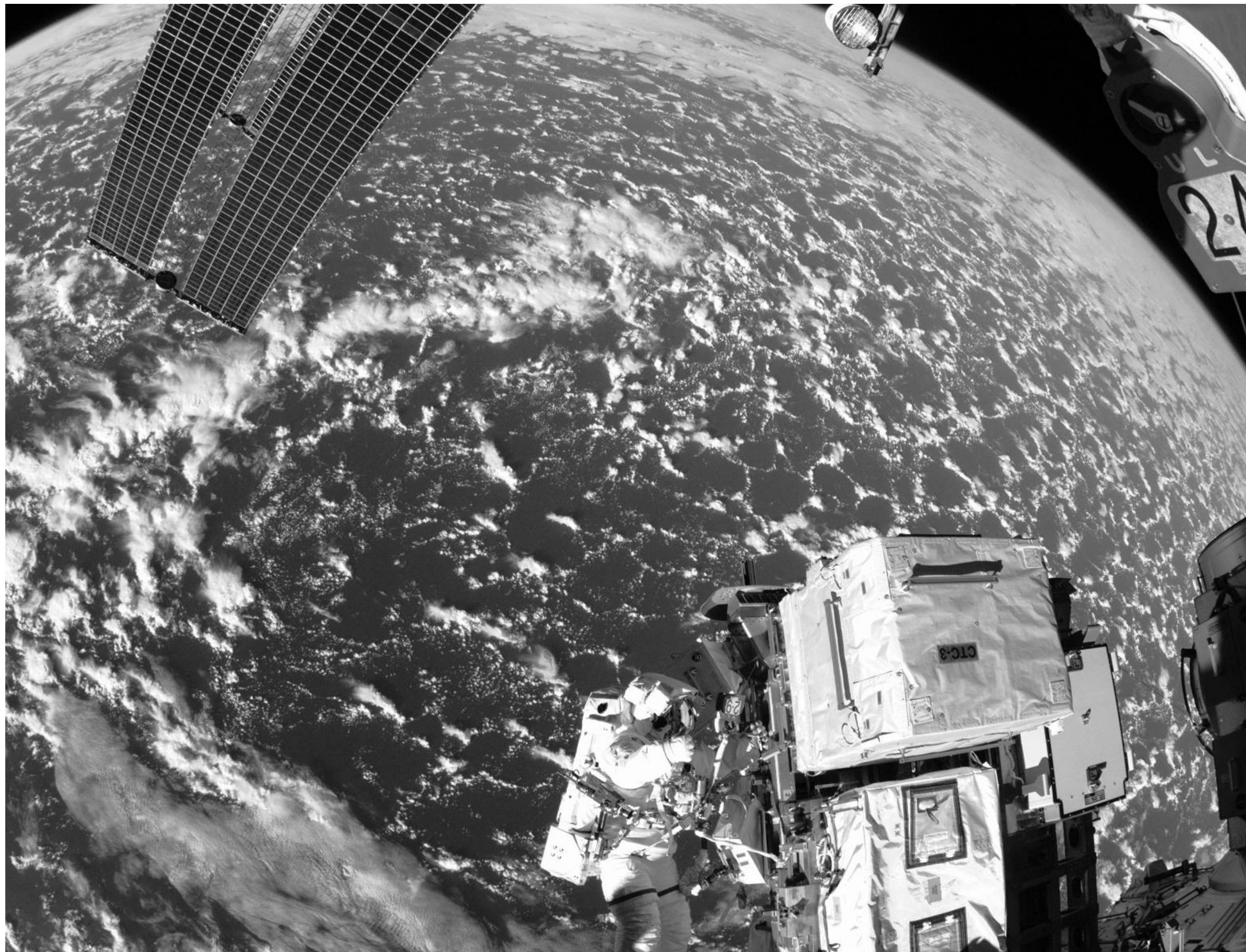
Potential Energy
from evaporative cooling

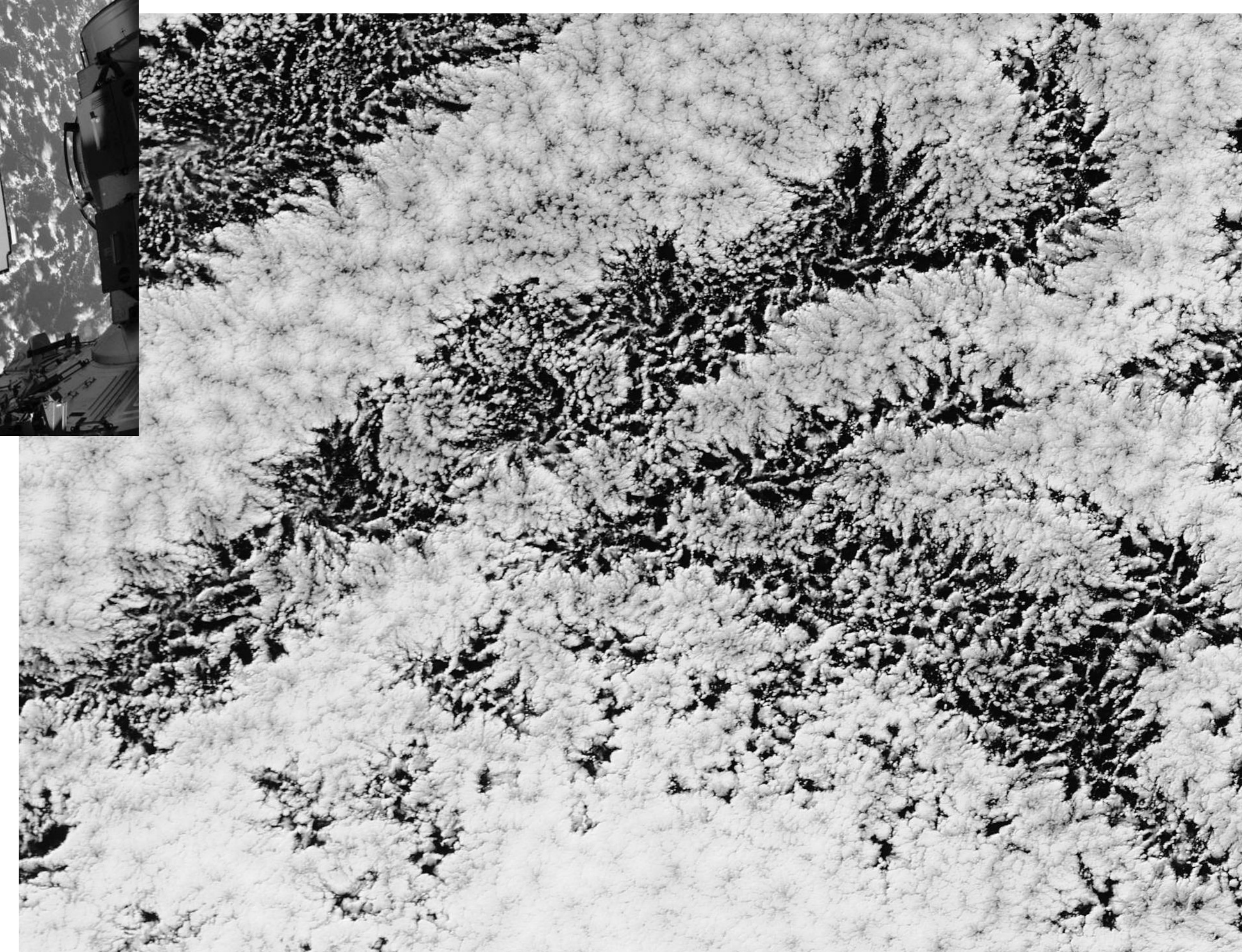
Kinetic Energy:
CP rotation and spreading,
ambient motion

Energy Dissipation:
Friction, surface fluxes, mixing

Potential Energy
to overcome CAPE, transport of sensible and latent heat

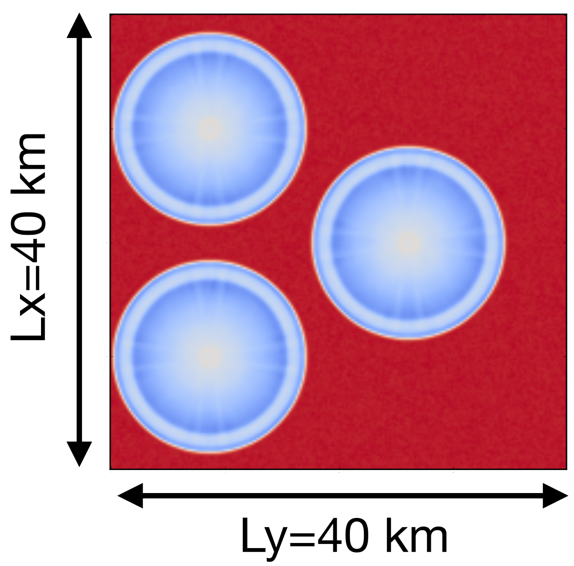
Cold Pools - Organisation of the Cloud Field



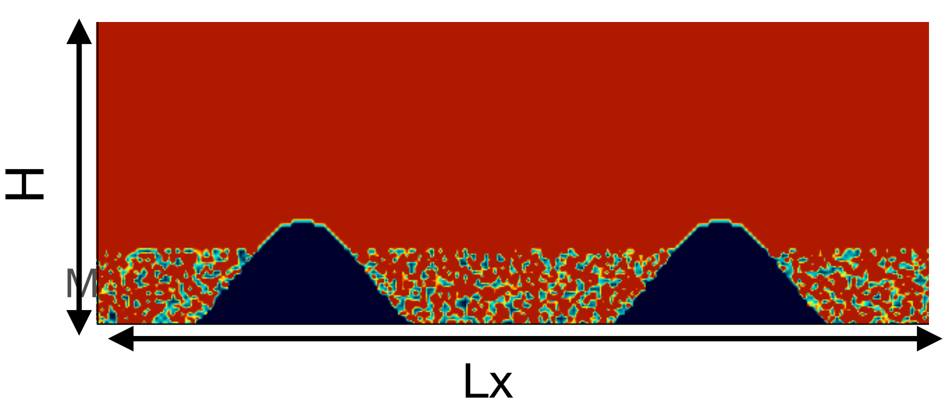


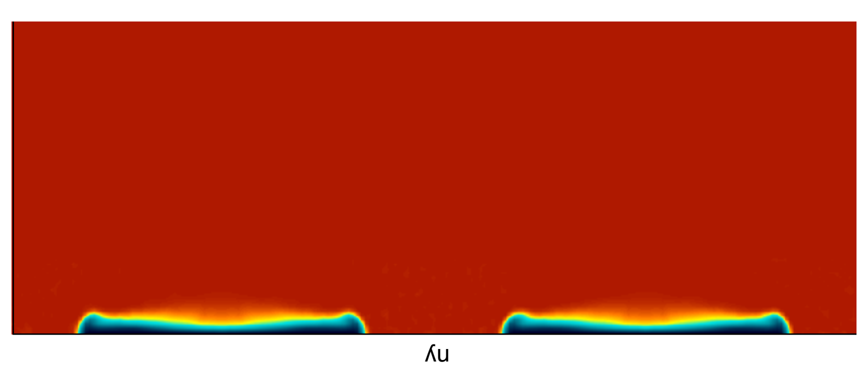
Figures:
Zuidema et al., Surv Geophys (2017)
NASA / JPL-Caltech, S. Böing (2016)

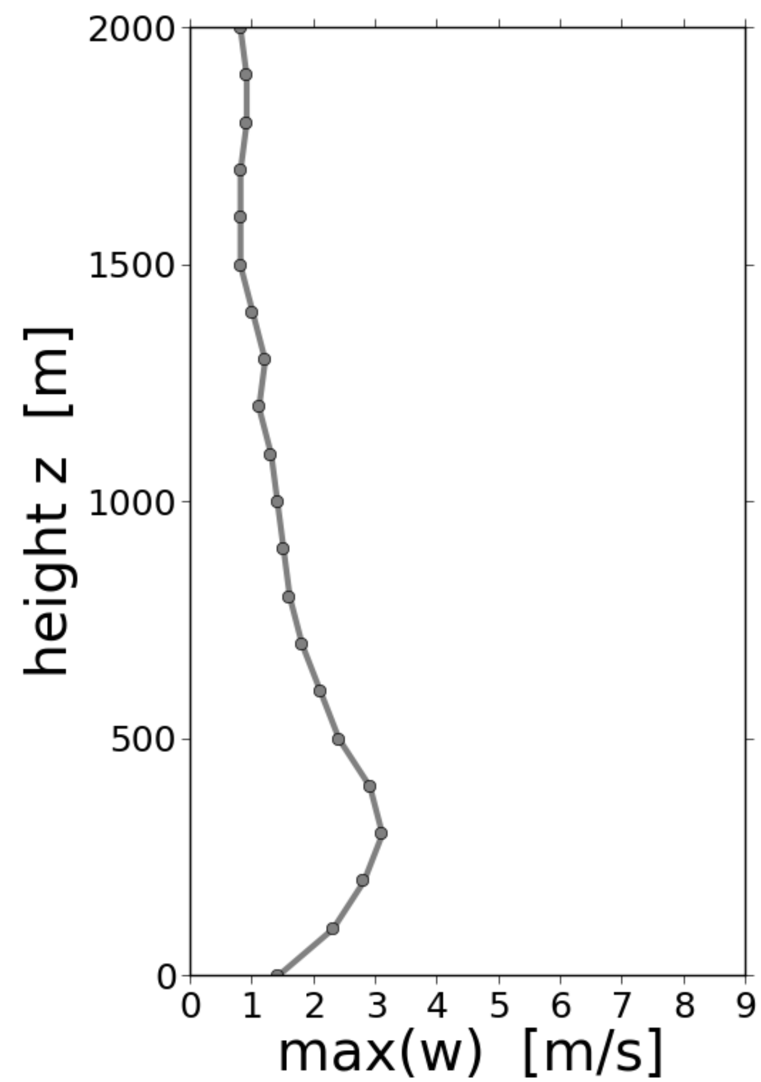
Vertical velocity - triple collision



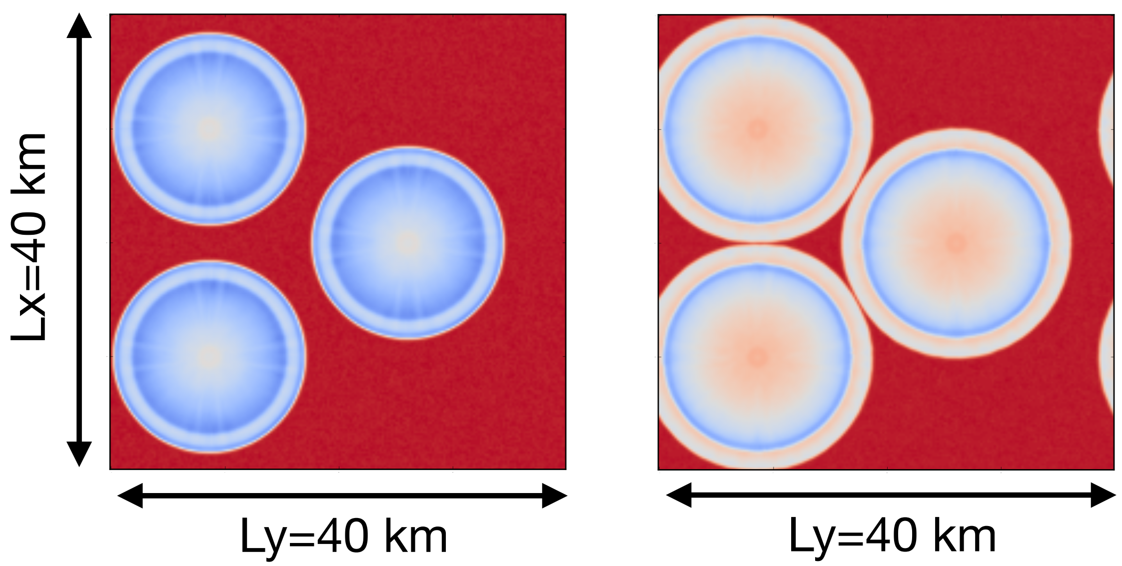
— single CP (undisturbed front)



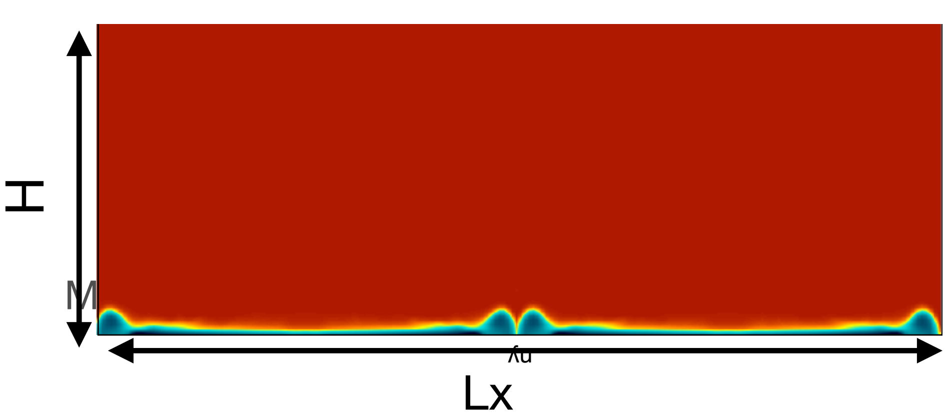


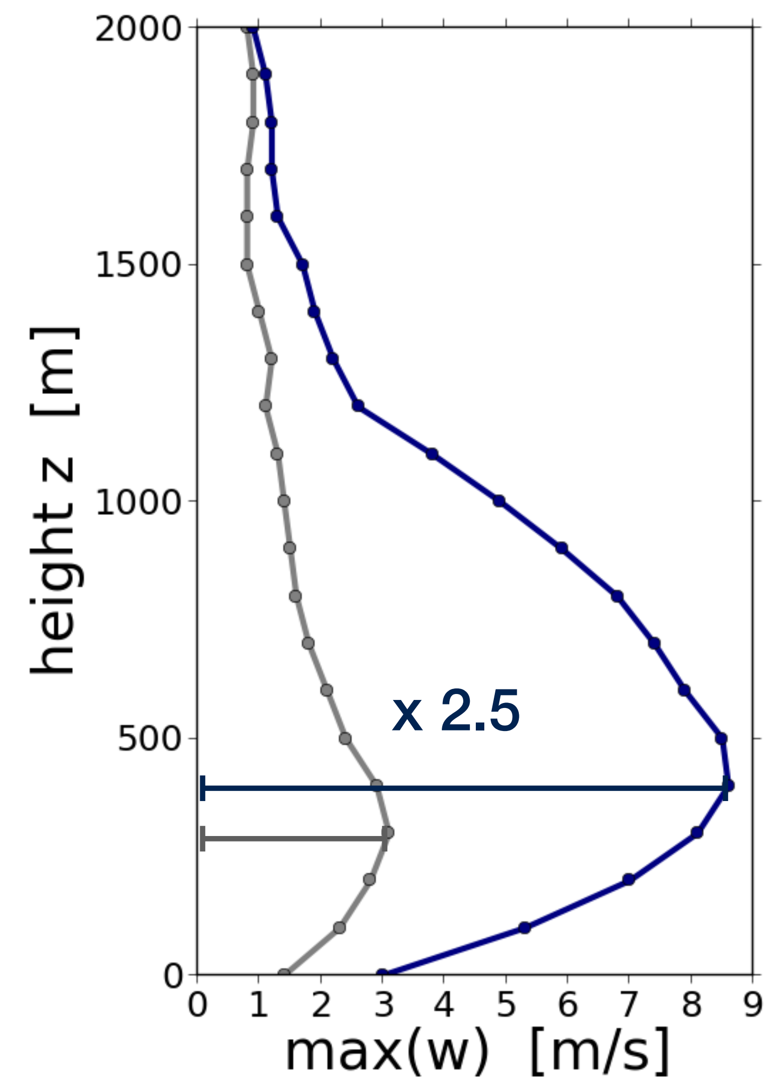


Vertical velocity - triple collision

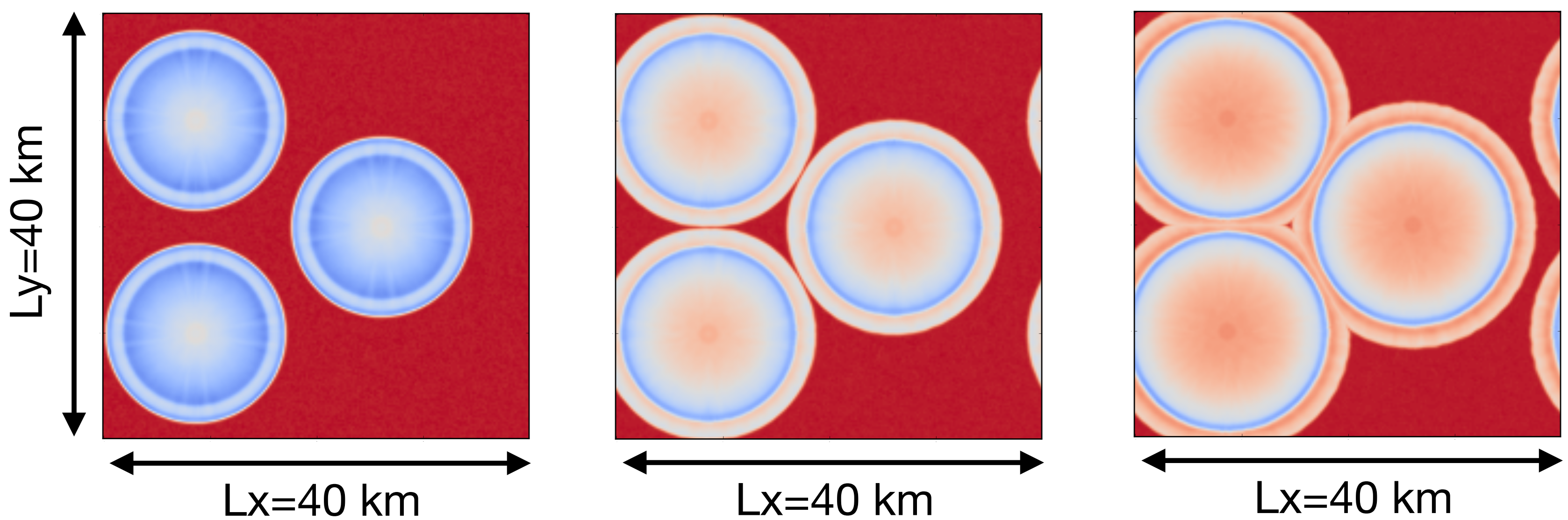


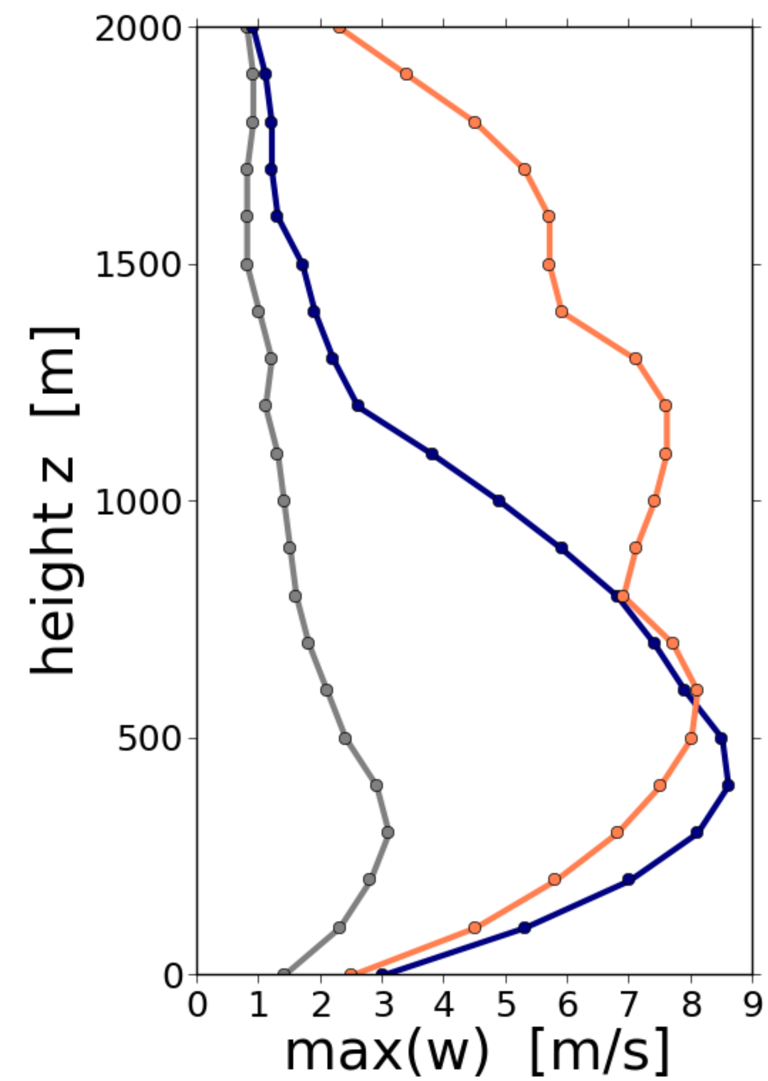
— single CP (undisturbed front)
— 2-CP collision



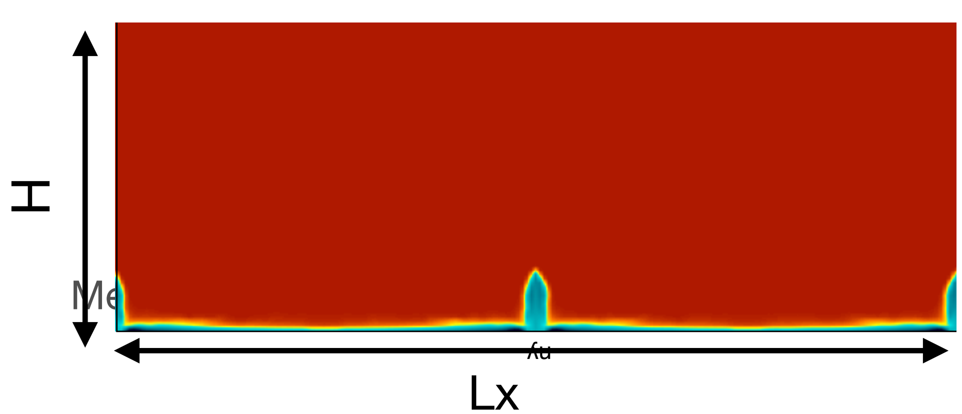


Vertical velocity - triple collision

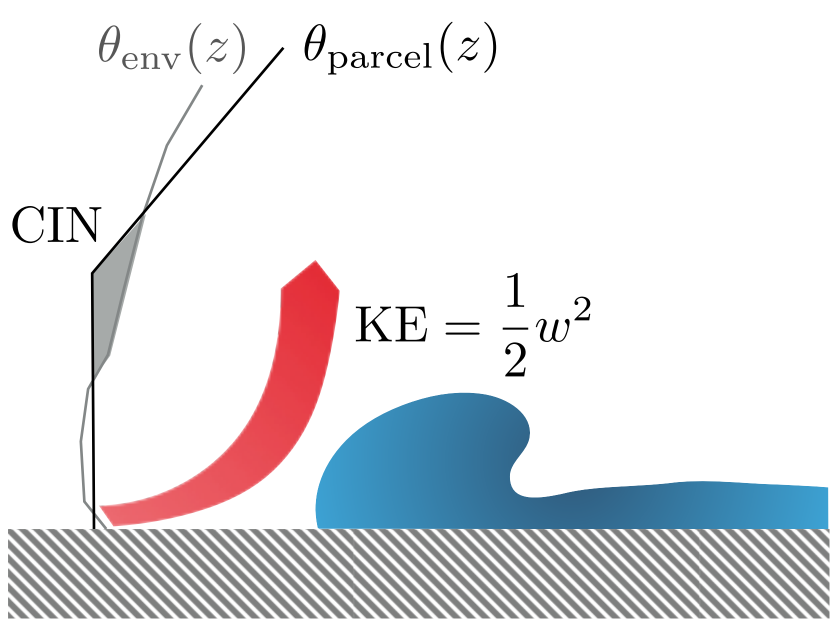


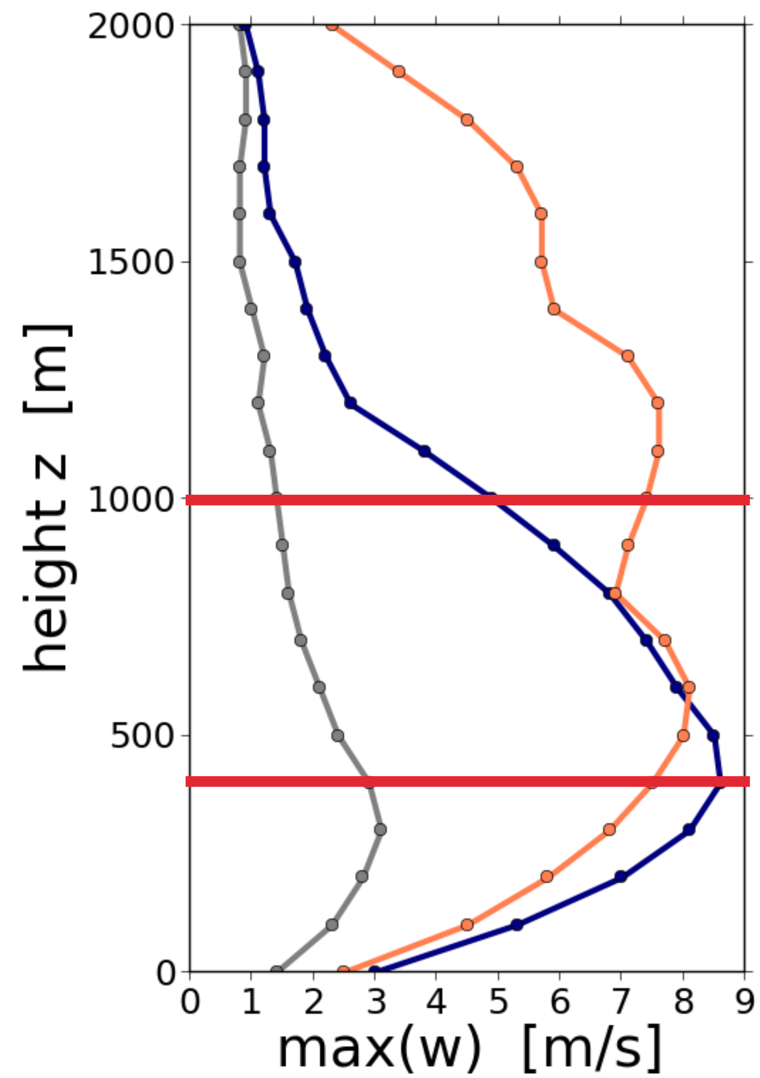


single CP (undisturbed front)
2-CP collision
3-CP collision



Convection triggering



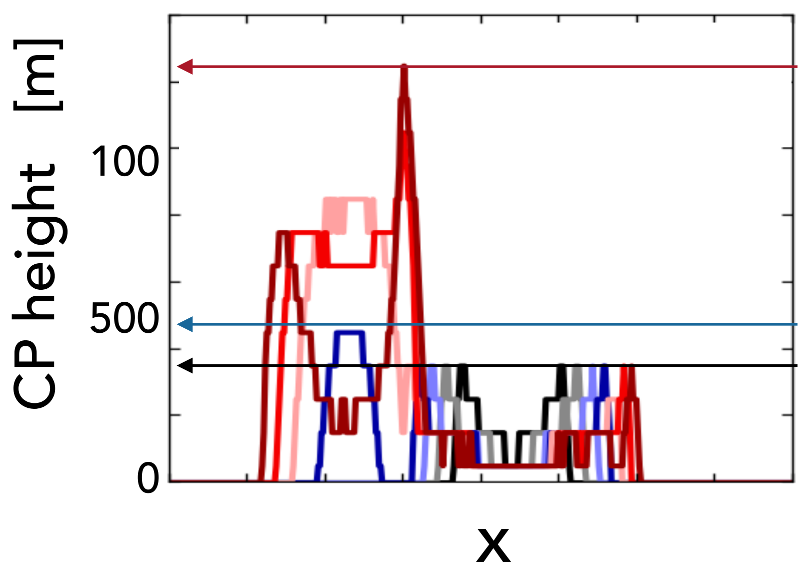


Triggering condition: $\text{KE} = \frac{1}{2}w^2 > |CIN|$

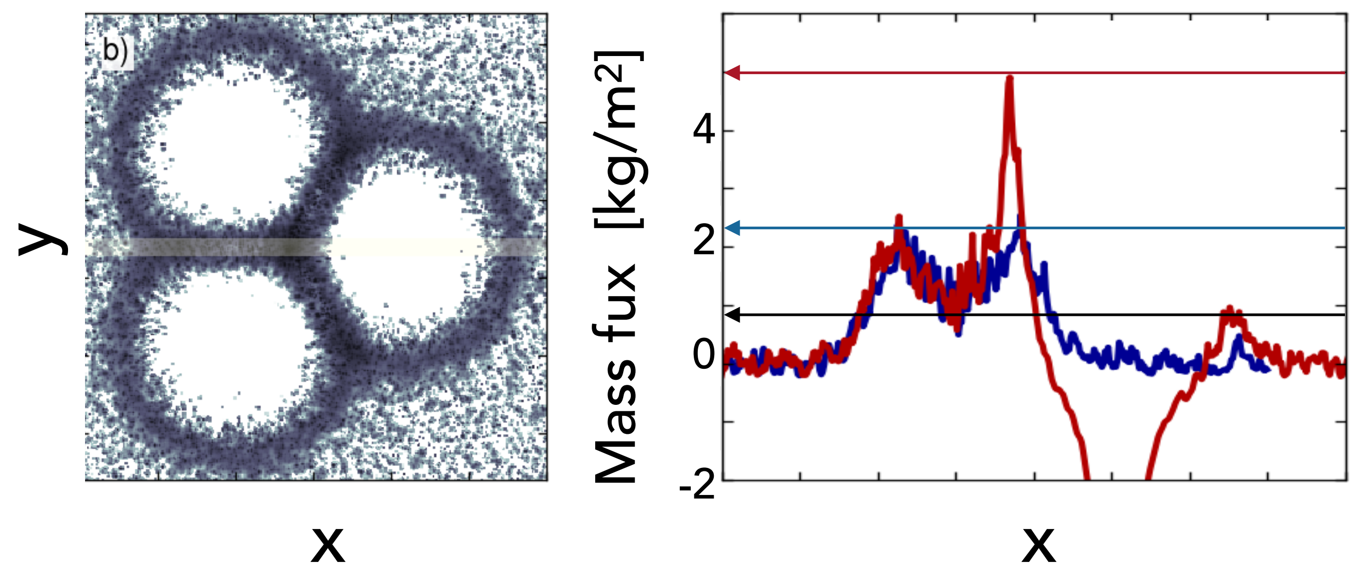
Meyer and Haerter, 2002 (in prep.)

Vertical mass (moisture) flux & cold pool height

Cold pool height



Vertical mass flux

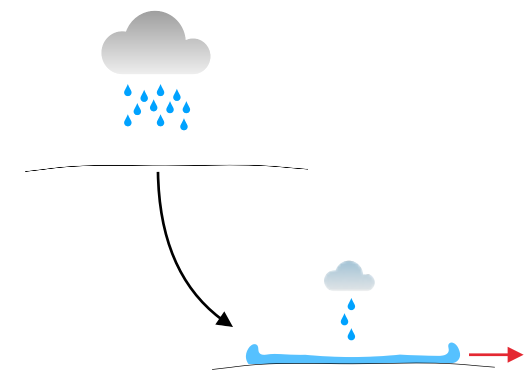


single CP
2-CP collision
3-CP collision

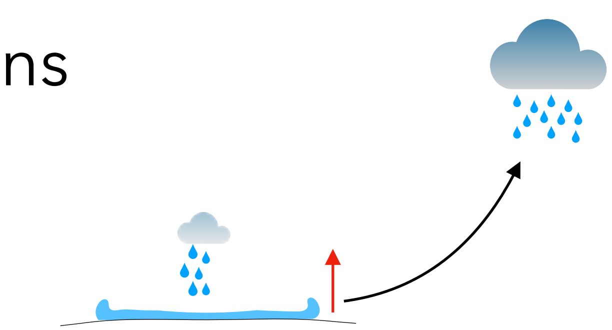
Meyer and Haerter, 2002 (in prep.)

Conclusions

- **Convection triggering:**
  - Stronger updrafts in 2-CP collisions
    > *strongly stratified / inhibited environments*
  - Deeper updrafts & highest mass flux in 3-CP collisions
    > *pre-moistening in (deep) convection*



- **Climate Models:** need representation of cold pool collisions
  > organisation of the cloud field
  > precipitation intensity



Thank you for your input: bettina.meyer@nbi.ku.dk