Direct Numerical Simulation of Climate Relevant Cloud Mixing Processes

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Motivation & Goal

Cloud feedbacks remain a major source of uncertainty in climate models.

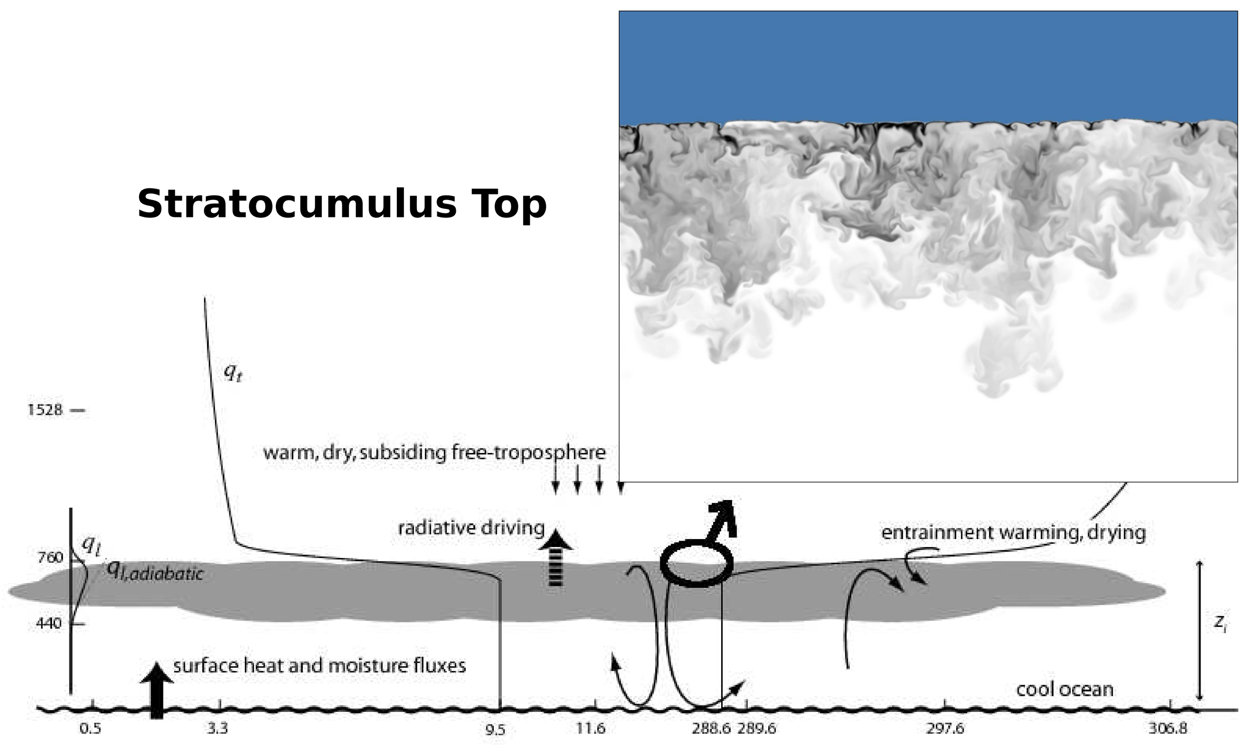
We investigate the role of buoyancy reversal by **evaporative cooling** at the cloud boundary due to turbulent isobaric mixing in the small scales (meters, tens of meters).

We study the Stratocumulus Top, a horizontal cloud boundary, and the Cumulus Subsiding Shell, a vertical configuration.

Direct numerical simulation (DNS) is used to resolve down to the diffusion scales.

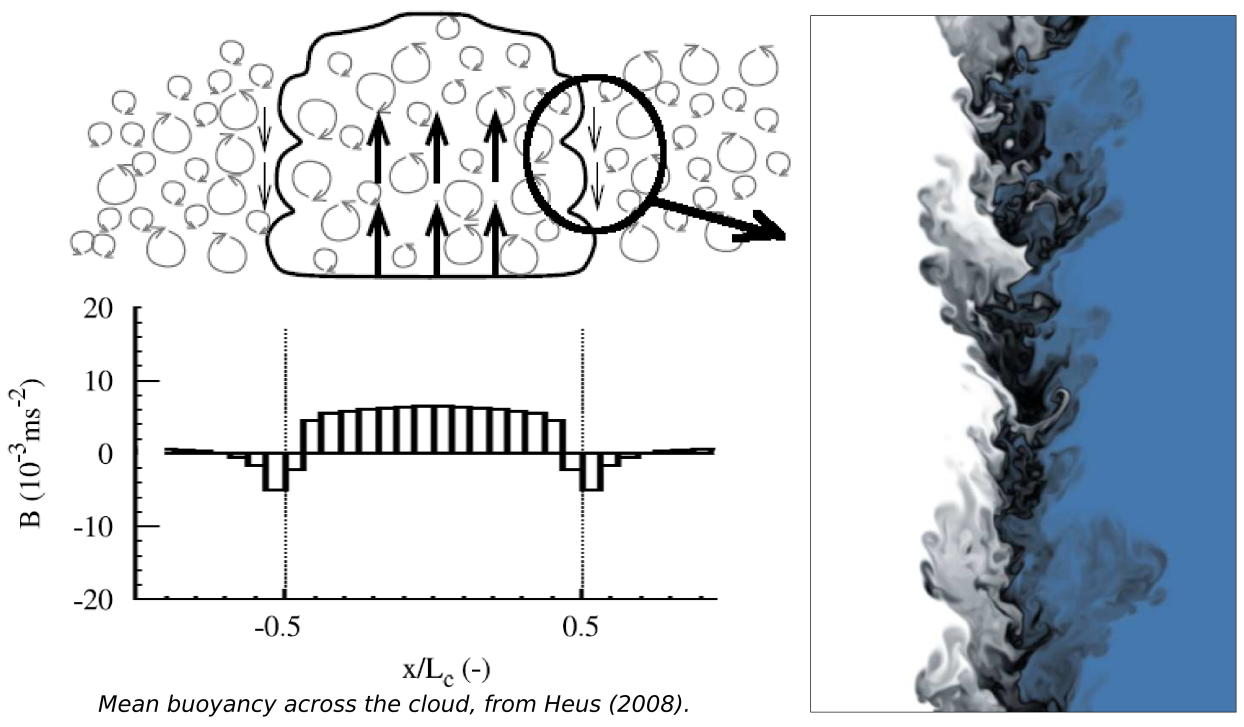
Structure, transfer rates, time scales and reference data for single column models and large-eddy simulations are provided.

Stratocumulus Top



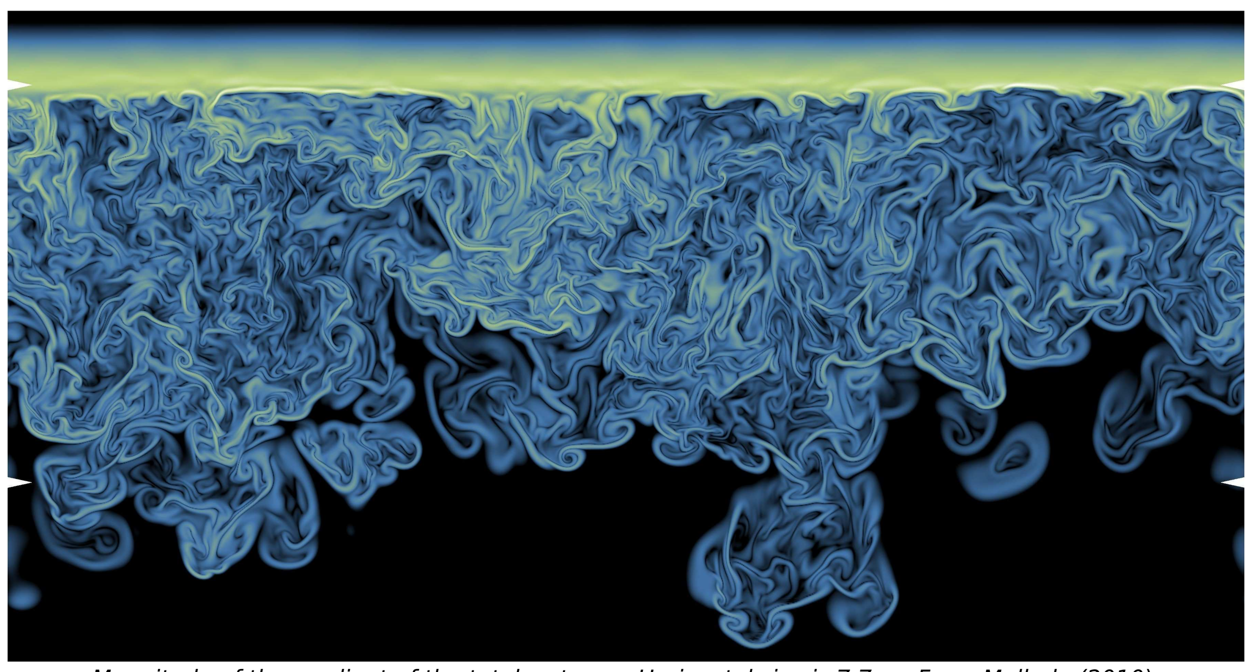
Stratocumulus-topped boundary layer, from Stevens (2005). We focus on the cloud top (circle).

Cumulus Subsiding Shell

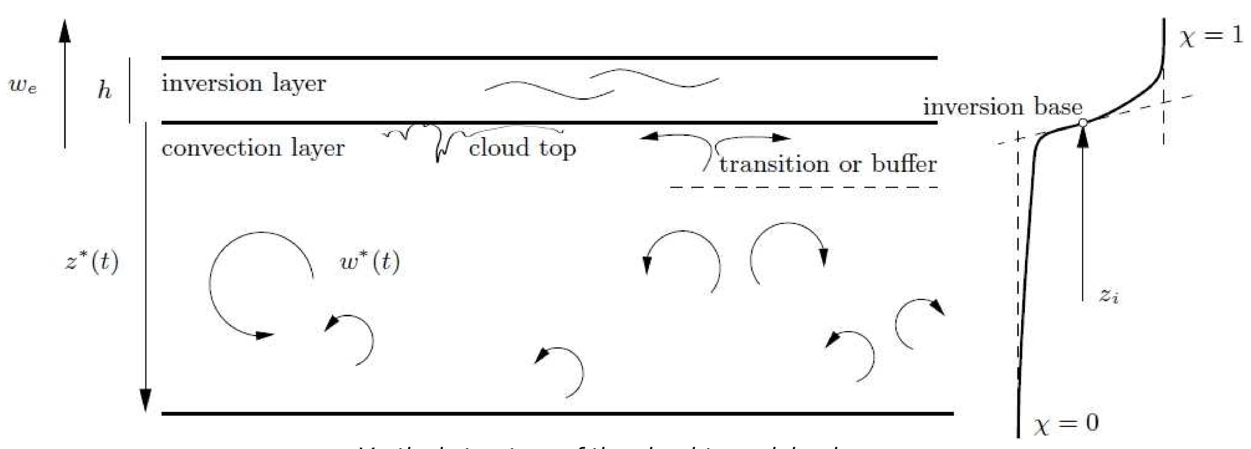


Mean buoyancy across the cloud, from Heus (2008).

Stratocumulus Top

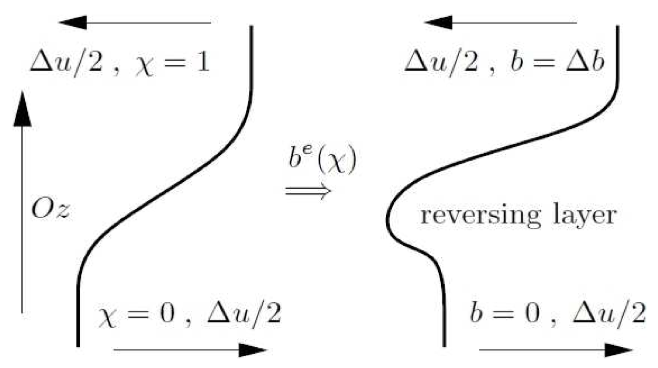


Magnitude of the gradient of the total water q_t. Horizontal size is 7.7 m. From Mellado (2010).



Vertical structure of the cloud-top mixing layer.

The buoyancy difference Δb quantifies the strength of the inversion at the cloud top. The evaporative cooling, measured by the saturation buoyancy b_s, leads to turbulent convection inside the cloud.



Case 1. Shear-free case ($\Delta u = 0$)

Turbulence does not break the cloud top (large Richardson number), but enhances mixing up to a constant entrainment rate

$$w_e \propto (\kappa |b_s|)^{1/3}$$

controlled by molecular properties (diffusivity κ). The constant of proportionality is obtained from the DNS.

Cloud top remains flat ⇒Buoyancy flux $B_s = w_e |b_s| / \chi_s$ determines the turbulent length scale

$$z^* \propto (B_s t^3)^{1/2}$$

and velocity scale $w^* = (B_s z^*)^{1/3}$ inside the cloud.

Evaporative cooling effects are small. For the DYCOMS-II case, $w_e \simeq 0.16$ mm/s; $h \simeq 0.1$ m; $B_s \simeq 10^{-5}$ m^2/s^3. DNS run up to $z^* \simeq 2.5$ m, $w^* \simeq 30$ mm/s. From growth laws, 100 m are reached in about 45 min, $w^* \simeq 0.1$ m/s.

Conclusion: buoyancy reversal is too slow and too weak to control the cloud-top dynamics.

Case 2. Mean shear effects ($\Delta u \neq 0$)

A new dynamical balance is established, with an inversion thickness of the order of $(\Delta u)^2/(\Delta b)$ determined by a critical Richardson number (Mellado et al.).

There is a transition from the molecularly dominated regime towards an inviscid scaling precisely in the range of velocity differences across the inversion between 0.1 and 1 m/s. DNS reaches up to 0.5 m/s.

The inversion still remains thin, less than 1 m.

Formulation

1. Boussinesq limit.
2. Disperse liquid-phase is considered as a continuum.
3. Local thermodynamic equilibrium.
4. Liquid-phase diffusivity equal to that of vapor and dry air.

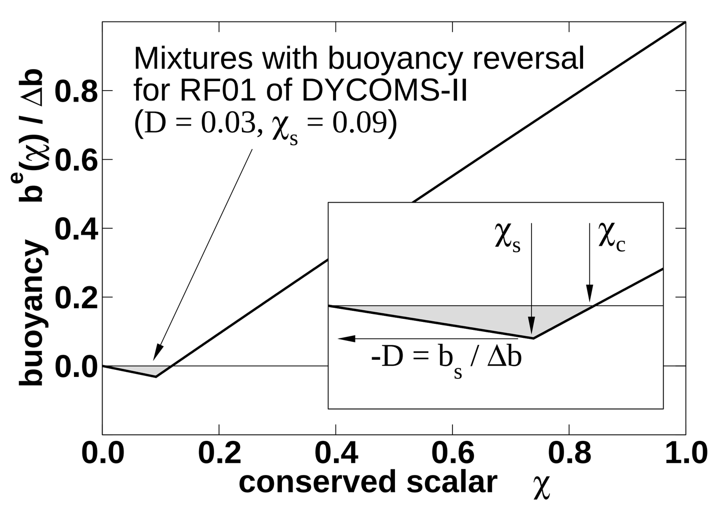
Total enthalpy h and total water q_t obey the same advection-diffusion equation. Thus, for a two-layer system,

$$\chi = \frac{q_t - q_{t,0}}{q_{t,1} - q_{t,0}} = \frac{h - h_0}{h_1 - h_0}\,.$$

The mixture fraction χ indicates the relative amount of matter of the fluid particle that proceeds from layer 1.

$$\frac{\partial \chi}{\partial t} + \nabla\cdot(\mathbf{v}\chi) = \kappa \nabla^2 \chi$$

$$\frac{\partial \mathbf{v}}{\partial t} + \nabla\cdot(\mathbf{v}\mathbf{v}) = -\nabla\pi + \nu\nabla^2\mathbf{v} + b\mathbf{k}\,, \qquad \nabla\cdot\mathbf{v} = 0\,, \qquad b = b^e(\chi)$$

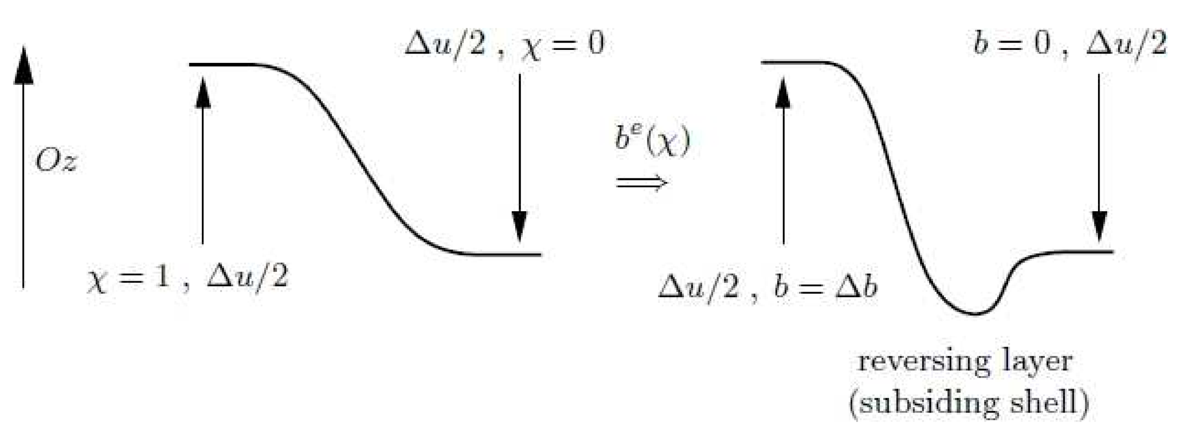


Parameters $\{\nu, \kappa, \Delta b, b_s, \chi_s, \Delta u\} \Rightarrow \{Pr, D, \chi_s, (\Delta u)^3/(\nu \Delta b)\}$

Cumulus Subsiding Shell

The ascending motion of the cloud core due to a buoyancy difference Δb causes a turbulent shear layer at the cloud boundary, a first cause of lateral entrainment.

Evaporative cooling, measured by b_s, causes a descending turbulent jet at the lateral cloud boundary: the subsiding shell. This is a second cause of entrainment.

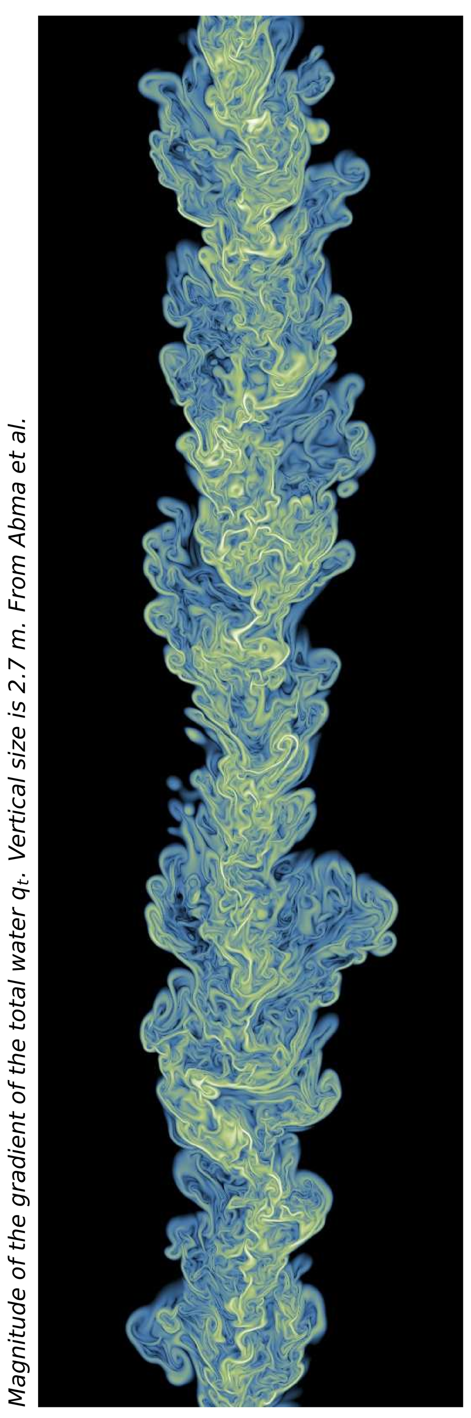


For $\Delta b = \Delta u = 0$, an inviscid self-preserving regime is established in which the only relevant scales are a characteristic buoyancy fluctuation, constant in time and proportional to b_s, and the thickness δ of the turbulent shell, increasing in time.

Dimensional analysis shows that $\delta \propto b_s t^2$, and the mean velocity at the center $w \propto b_s t$ (free fall). Constants of proportionality are obtained from DNS, and are a function of χ_s, the saturation mixture fraction (the thermodynamic state of the system).

For typical values of $b_s \simeq 0.03$ m/s^2, DNS run up to $\delta \simeq 0.40$ m, $w \simeq 0.24$ m/s. From growth laws, 10 m thickness is reached in about 4 min, $w \simeq 1.2$ m/s, in agreement with observations and large-eddy simulations.

Conclusion: the subsiding shell is fast and strong enough to influence lateral entrainment.



Magnitude of the gradient of the total water q_t. Vertical size is 2.7 m. From Abma et al.

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