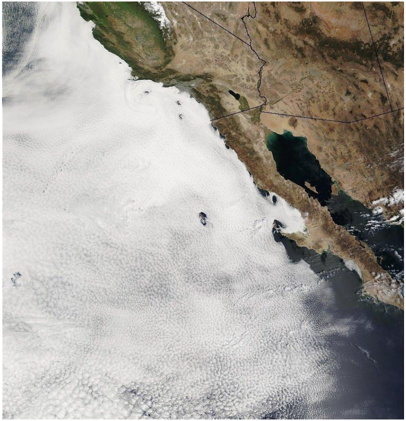
New Results about the Cloud-Top Entrainment Instability



Juan Pedro Mellado, Bjorn Stevens

Max Planck Institute Meteorology, Hamburg

Heiko Schmidt

Brandenburg University of Technology, Cottbus

Norbert Peters

RWTH Aachen University

International MetStröm Conference, FU Berlin

6-10 June 2011

MetStröm

DFG programme 1276

Max-Planck-Institut für Meteorologie

Brandenburgische Technische Universität Cottbus

RWTH AACHEN UNIVERSITY

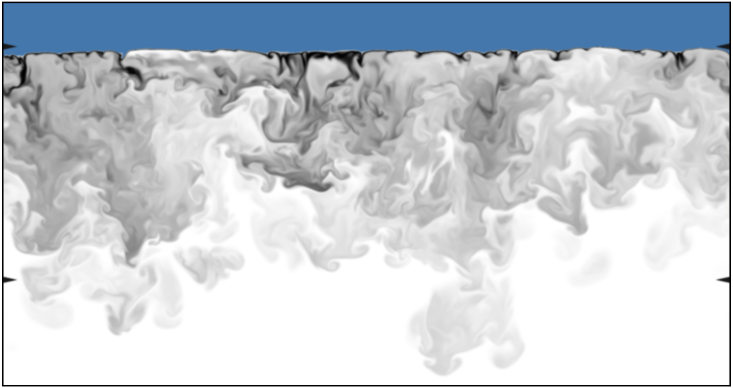
Outline

The Cloud-Top Entrainment Instability

New Results from Direct Numerical Simulations

Evaporative Cooling and Clouds

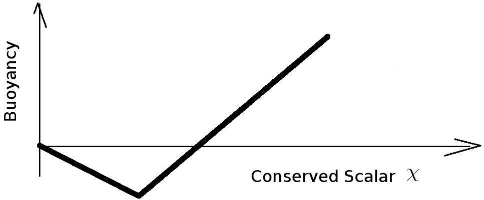
Evaporation at cloud/free-atmosphere interface → cooling → convection:



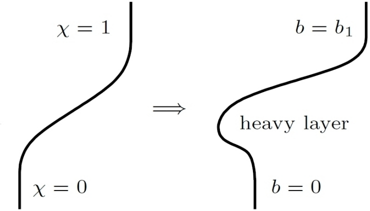
Buoyancy Reversal

The buoyancy may not follow a linear relation wrt conserved scalars:

sign change $\Rightarrow$ buoyancy reversal

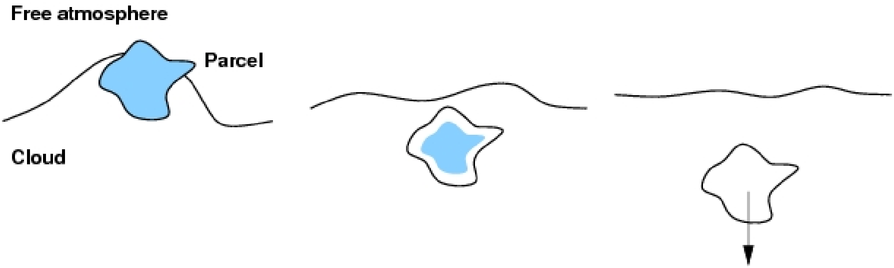


D = min(b) / max(b)



Stratocumulus Top

In addition, inversion at the cloud boundary:



adapted from D. Randall, *J. Atmos. Sci.*, 1980

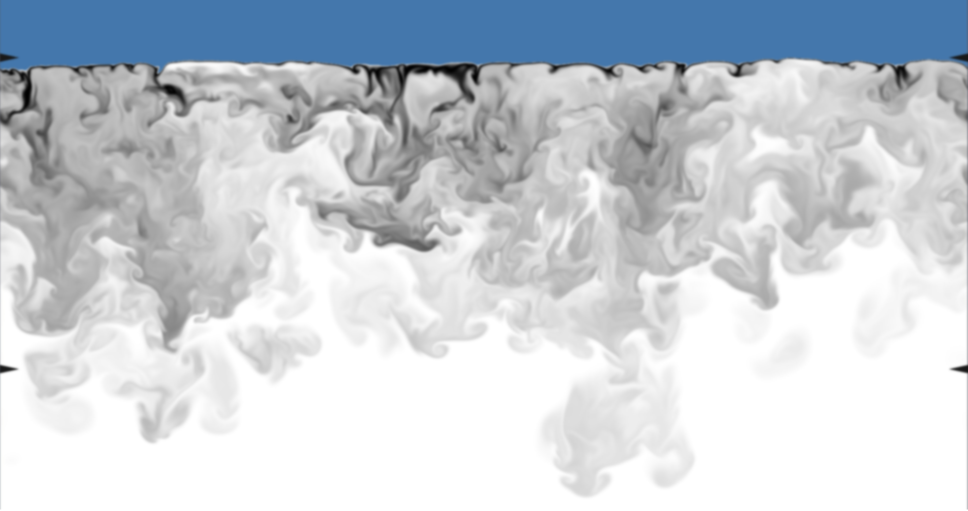
Cloud-Top Entrainment Instability

(Randall, 1980; Deardorff, 1980)

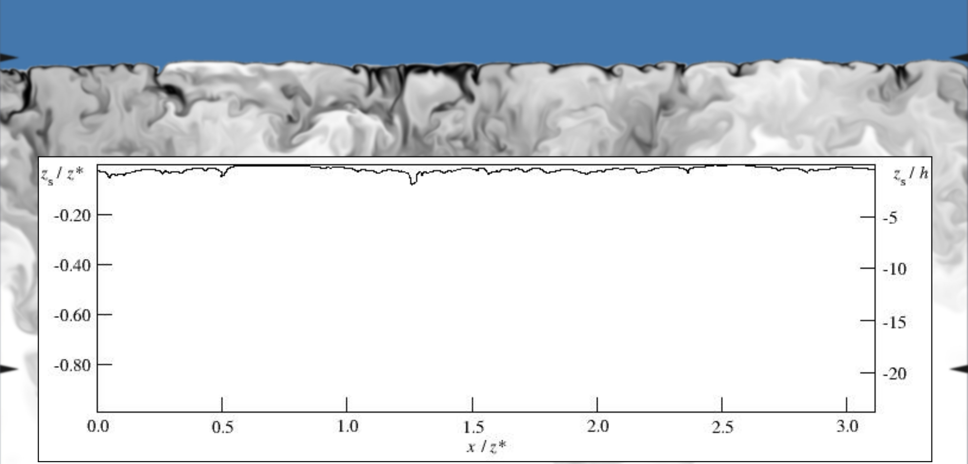
Outline

The Cloud-Top Entrainment Instability

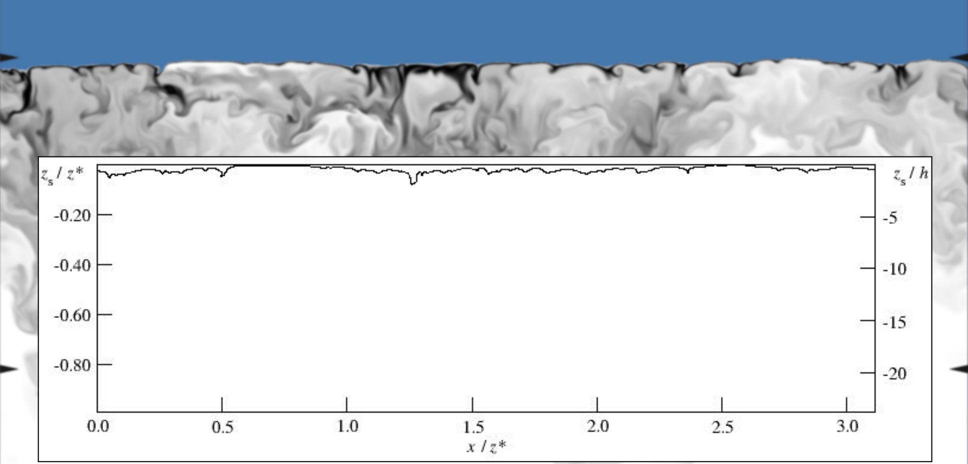
New Results from Direct Numerical Simulations



DNS, grid size $2048 \times 2048 \times 1536$ (JPM, 2010; JPM et al., 2010)



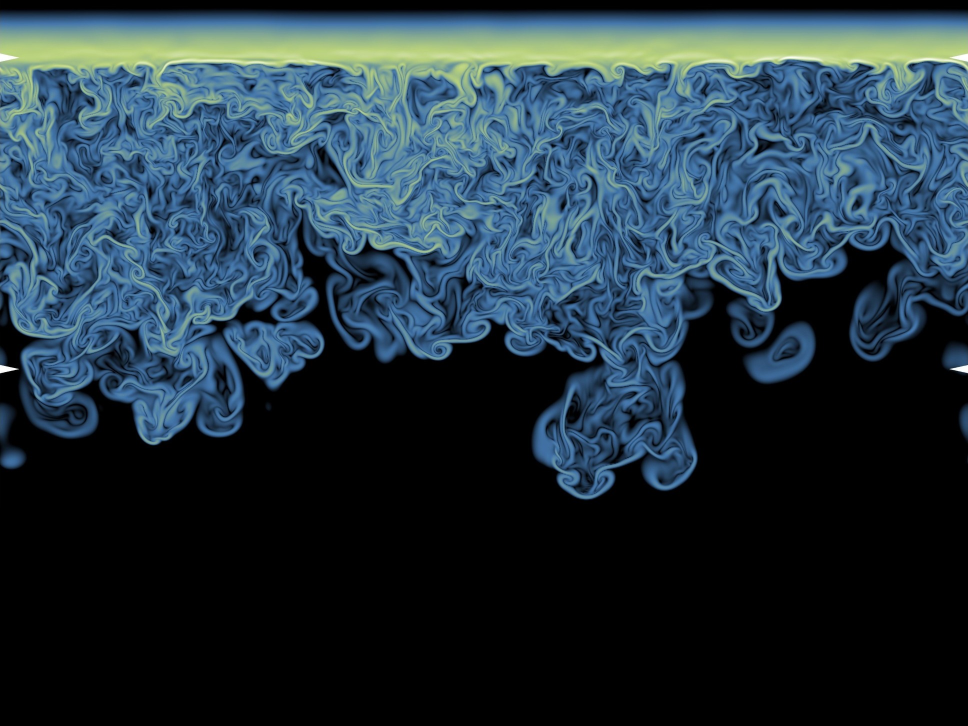
Instantaneous cloud-top $\{\mathbf{x} : \chi(\mathbf{x}, t) = \chi_s\}$



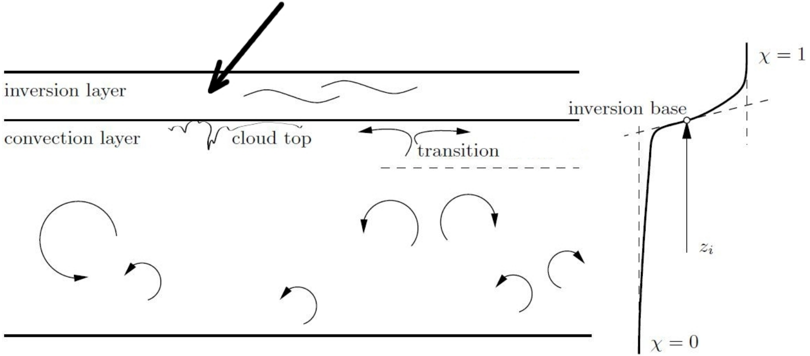
Instantaneous cloud-top $\{\mathbf{x} : \chi(\mathbf{x}, t) = \chi_s\}$

Cloud-top not broken and flat:

Two time scales associated w/ buoyancies b_1, $|b_s|$:$D = |b_s|/b_1 \ll 1$.



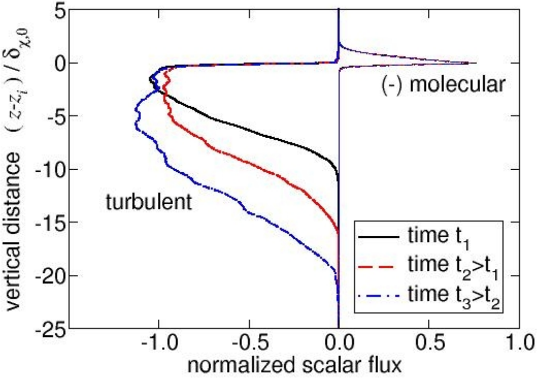
Inversion Layer



Molecular transport controls the system

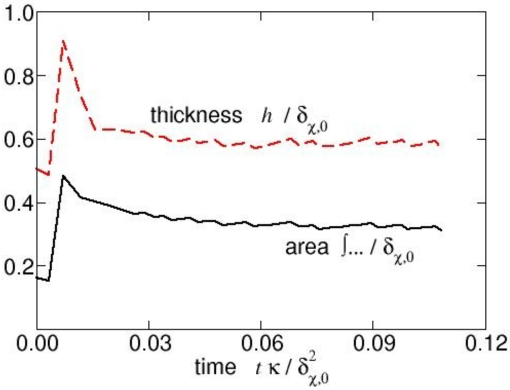
Inversion Layer

$$\frac{d}{dt}\left[\int_{z_i}^{\infty}(1-\langle\chi\rangle)\,dz\right]+\langle w'\chi'\rangle(z_i,t)=\kappa\frac{\partial\langle\chi\rangle}{\partial z}(z_i,t)-(1-\chi_i)\frac{dz_i}{dt}$$



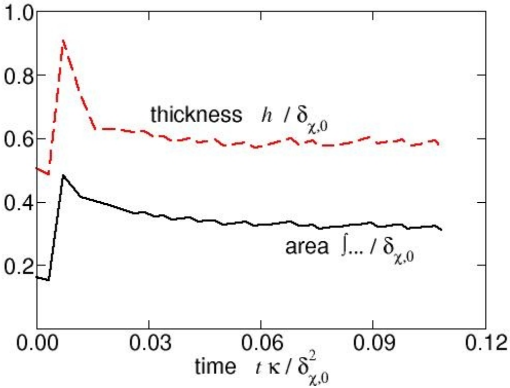
Inversion Layer

$$\frac{d}{dt}\left[\int_{z_i}^{\infty}(1-\langle\chi\rangle)\,dz\right] + \cancel{\langle w'\chi'\rangle(z_i,t)} = \kappa\frac{\partial\langle\chi\rangle}{\partial z}(z_i,t) - (1-\chi_i)\frac{dz_i}{dt}$$



Inversion Layer

$$\cancel{\frac{d}{dt}\left[\int_{z_i}^{\infty}(1-\langle\chi\rangle)\,dz\right]} + \cancel{\langle w'\chi'\rangle(z_i,t)} = \kappa\frac{\partial\langle\chi\rangle}{\partial z}(z_i,t) - (1-\chi_i)\frac{dz_i}{dt}$$



Dominant balance

$$w_e = \frac{dz_i}{dt} \simeq \frac{\kappa}{h}$$

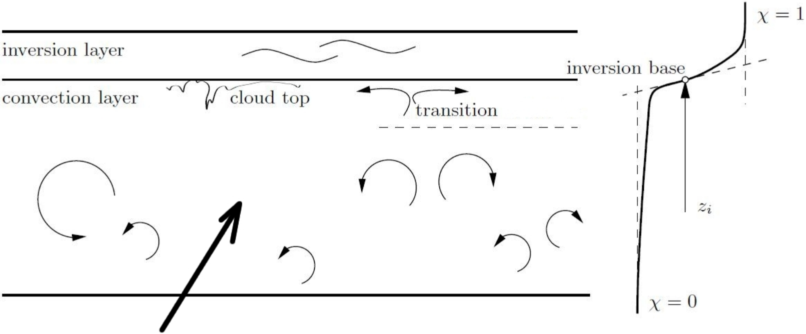
Constant thickness

$$h = \frac{1-\chi_i}{\frac{\partial\langle\chi\rangle}{\partial z}(z_i,t)}$$

$$\Downarrow$$

Constant entrainment rate

Convection Layer



Convection Layer

$$\frac{d}{dt}\int_{-\infty}^{z_i}\langle\chi\rangle dz = \kappa\frac{\partial\langle\chi\rangle}{\partial z}(z_i,t) - \langle w'\chi'\rangle(z_i,t) + \chi_i w_e \simeq w_e$$

Then, w_e determines also scaling inside the turbulent zone.

From functional dependence between b and χ, **reference buoyancy flux**

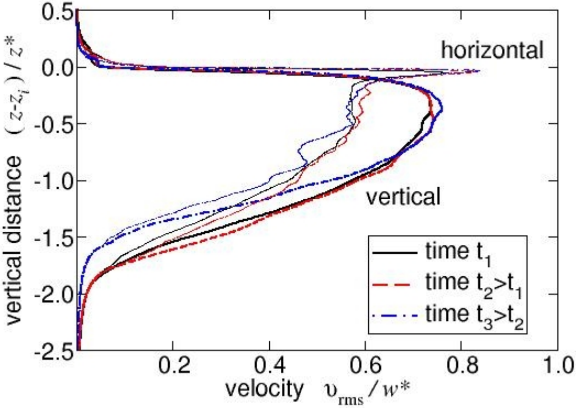
$$B_s = w_e|b_s|/\chi_s = (0.1 f_1 \chi_c^{2/3}/\chi_s)(\kappa b_s^4)^{1/3}$$

and then **convection scales**

$$z^* = (1/B_s)\int B dz \qquad , \qquad w^* = (z^* B_s)^{1/3}$$

characterize (some statistics of) the turbulent region (Deardorff, 1980)

Turbulent Velocity Fluctuations



- Self-preservation.
- Anisotropy.
- Inhomogeneity.

Temporal Evolution of Convection Scales

Integrating transport equation for $q^2/2$,

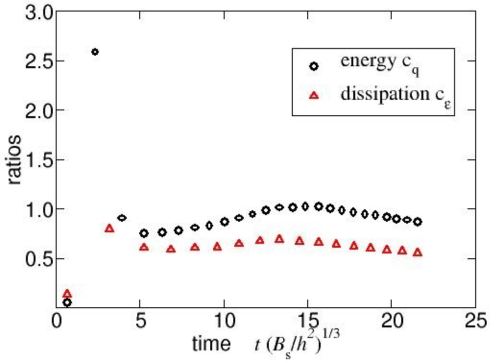
$$\frac{\partial q^2/2}{\partial t} = -\frac{\partial T}{\partial z} + B - \varepsilon \ ,$$

Temporal Evolution of Convection Scales

Integrating transport equation for $q^2/2$,

$$\frac{d}{dt}(c_q z^* w^{*2}) = 2(1 - c_\varepsilon)w^{*3}$$

$$c_\varepsilon = \frac{1}{w^{*3}} \int \varepsilon \, dz \; , \qquad c_q = \frac{1}{w^{*2} z^*} \int q^2 \, dz$$



Constant $c_q(D, \chi_s)$

Constant $c_\varepsilon(D, \chi_s)$

With def. $w^{*3} = B_s z^*$, closed system for $w^*(t)$ and $z^*(t)$

Temporal Evolution of Convection Scales

Solution:

$$z^*(t) = z^*(t_1)\left[1 + (2f_2/3)\frac{t - t_1}{[z^*(t_1)^2/B_s]^{1/3}}\right]^{3/2}$$

$$w^*(t) = (1/f_2)\, dz^*/dt\ ,\ \ f_2 \simeq 0.5$$

Scalings:

$$z^* \propto t^{3/2} \qquad w^* \propto t^{1/2} \qquad b^* \propto t^{-1/2}$$

Time scale:

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

Stratocumulus

Turbulence does not break the cloud top, but enhance mixing up to a linear entrainment rate.

Some numbers:

$w_e \simeq$ 0.16 mm/s; $h \simeq$ 0.1 m; $B_s \simeq 10^{-5}$ m^2/s^3; $z^* \simeq$ 2.5 m; $w^* \simeq$ 30 mm/s.

From previous growth rates, 100 m reached in about 45 min. Then, $w^* \simeq$ 0.1 m/s; still $\ll$ measurements of 1 m/s (radiative forcing).

Structure:

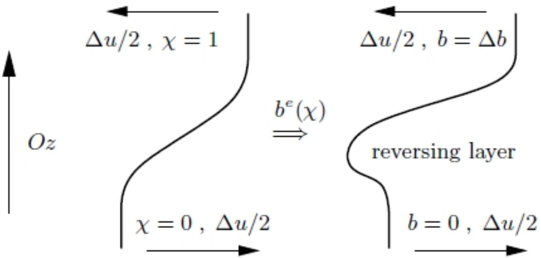
Vertical interface displacement $\delta = w^{*2}/b_1$ small and $Ri^* = z^*/\delta \propto t^{1/2}$. Internal Richardson number $Ri_{(I)} = h/\delta \propto t^{-1}$ decreases, but order 1 only after $z^* = 300$ m.

Conclusions

The cloud-top entrainment instability cannot explain break-up

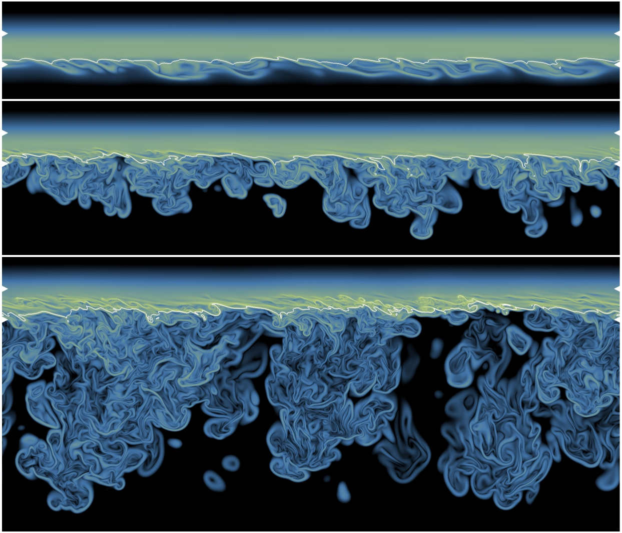
- Evaporative cooling effects are one order of magnitude too small.
- Buoyancy reversal w/o mean shear depends on molecular props.

Mean Vertical Shear

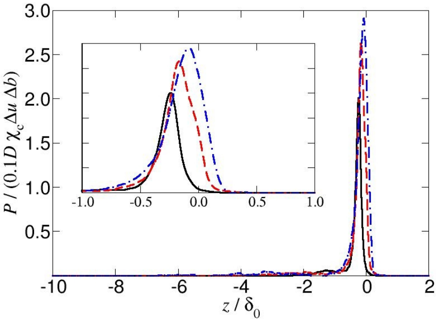


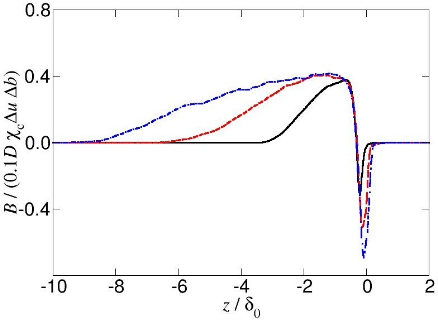
$$\{\nu,\ \kappa,\ \Delta b,\ b_s,\ \chi_s,\ \Delta u\} \quad \Rightarrow \quad \{Pr,\ D = -b_s/\Delta b,\ \chi_s,\ (\Delta u)^3/(\nu \Delta b)\}$$

Turbulent Inversion Layer



Turbulent Inversion Layer

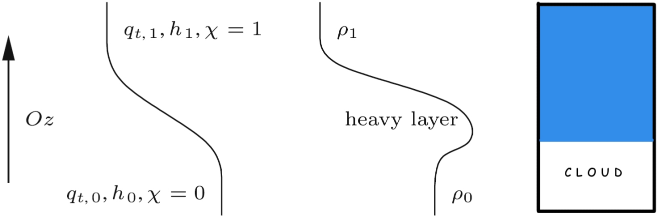




Formulation

Two-fluid formulation ($St \simeq 0.01$, $Sv \simeq 0.3$, $\phi_d \simeq 10^{-6}$)

Mixture fraction χ (*Albrecht et al. 1985; Bretherton 1987; JPM et al. 2010*)

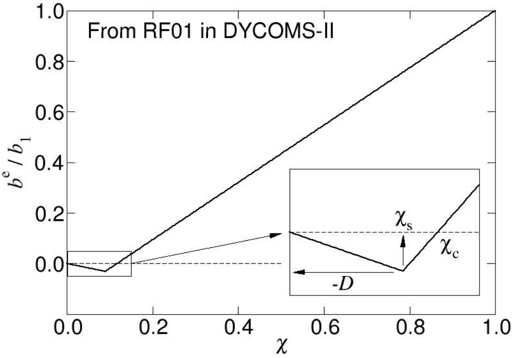


$$\frac{q_t - q_{t,0}}{q_{t,1} - q_{t,0}} - \frac{h - h_0}{h_1 - h_0} \longrightarrow 0 \qquad \frac{\mathbf{q_t - q_{t,0}}}{\mathbf{q_{t,1} - q_{t,0}}} = \frac{\mathbf{h - h_0}}{\mathbf{h_1 - h_0}} = \boldsymbol{\chi}$$

Governing Equations

Boussinesq + Mixture Fraction χ + Non-Linear Eqn. State

$$
\begin{aligned}
\partial_t u_k &= -\partial_i(u_k u_i) - \partial_k p + \nu \partial_i \partial_i u_k + b\delta_{k3}\,,\ \partial_i u_i = 0 \\
\partial_t \chi &= -\partial_i(\chi u_i) + \kappa \partial_i \partial_i \chi \\
b &= b^e(\chi;\, b_1,\, b_s,\, \chi_s)
\end{aligned}
$$



Parameter space:

$$\{\nu,\, \kappa,\, b_1,\, b_s,\, \chi_s\}$$

$$\downarrow$$

$$\{Pr = 1,\, D = -b_s/b_1,\, \chi_s\}$$

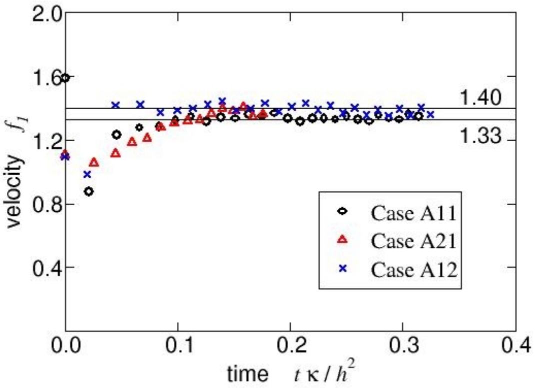
Mean Entrainment Rate

Marginally stable thermal boundary layer $\chi_c h$:

$$\frac{(\chi_c h)/(\kappa/h)}{\nu/(\chi_c h|b_s|)} \simeq 10^3 \qquad \Rightarrow \qquad h \simeq (10/\chi_c^{2/3})(\kappa^2/|b_s|)^{1/3}$$

$$f_1 = \frac{w_e}{(\chi_c^{2/3}/10)(\kappa|b_s|)^{1/3}}$$

$$f_1 = f_1(D, \chi_s)$$



Previous Work

Siems et al. (1990), Shy and Breidenthal (1990), Siems et al. (1992)

- Tank experiments with liquid mixtures. Mechanically driven ICs.
- Definition of the problem in terms of $D = -b_s/b_1$ and χ_s.
- Sims. Almost laminar behavior for $D \simeq 0.04$ (real conditions).
- Small reversal ($D \ll 1$) cannot explain cloud break-up.

Wunsch (2003)

- Stochastic models.
- Confirms previous results.
- Points to possible relevance of diffusion at cloud interface.

What is really going on at the interface?

Further Discussion

	z^*/h	$\eta/\Delta x$	z^*/λ_z	λ_z/η	u'/w^*	w'/w^*	Re_t	Re_λ	Re^*	Ri^*	Ra^*
A11	24	1.2	19	28	0.84	0.74	1800	220	4800	590	0.4×10^9
A21	39	0.9	26	31	0.86	0.78	2400	250	8000	293	1.1×10^9
A12	39	1.2	19	28	0.90	0.76	1600	200	4800	716	0.5×10^9

TABLE 2. Length-scale ratios, turbulence intensities and derived quantities at the final time t_2. Reynolds numbers $Re_t = (q^2/2)^2/(\varepsilon\nu)$, $Re_\lambda = w'\lambda_z/\nu$ and $Re^* = z^* w^*/\nu$; convection Richardson number $Ri^* = b_1 z^*/w^{*2}$; Rayleigh number $Ra^* = z^{*3}|b_s|/(\kappa\nu)$; Nusselt number $Nu^* = w_e z^*/\kappa = z^*/h$. Maximum values are used for the mean turbulent dissipation rate ε and the turbulence intensities.

- Unsteady free convection; $Nu^*(t)/(Ra^*(t))^{1/3} = 0.1 f_1 \chi_c^{2/3}$ const.
- Turbulent mixing across a density interface; $Ri^*(t)$ increasing.
- Stratocumulus.