Hybrid front racking for Stratocumulus clouds considering unsteady entrainment

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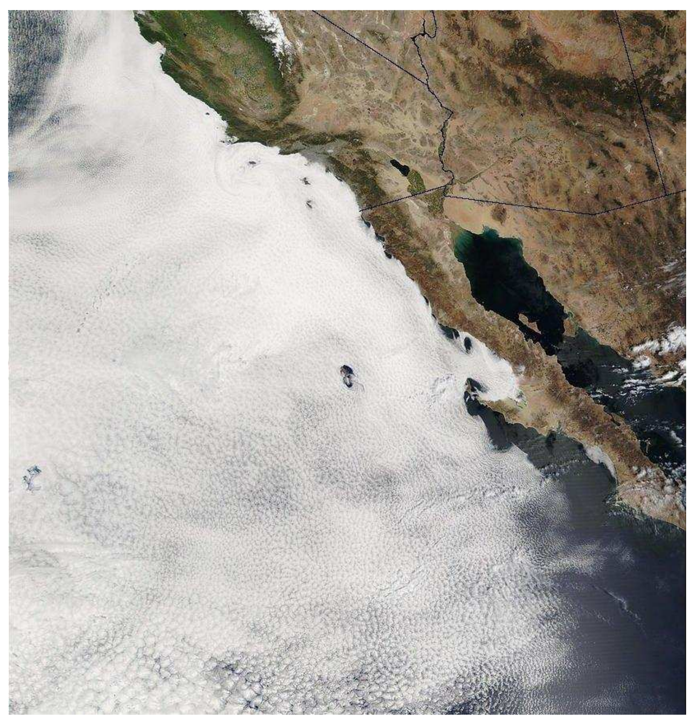
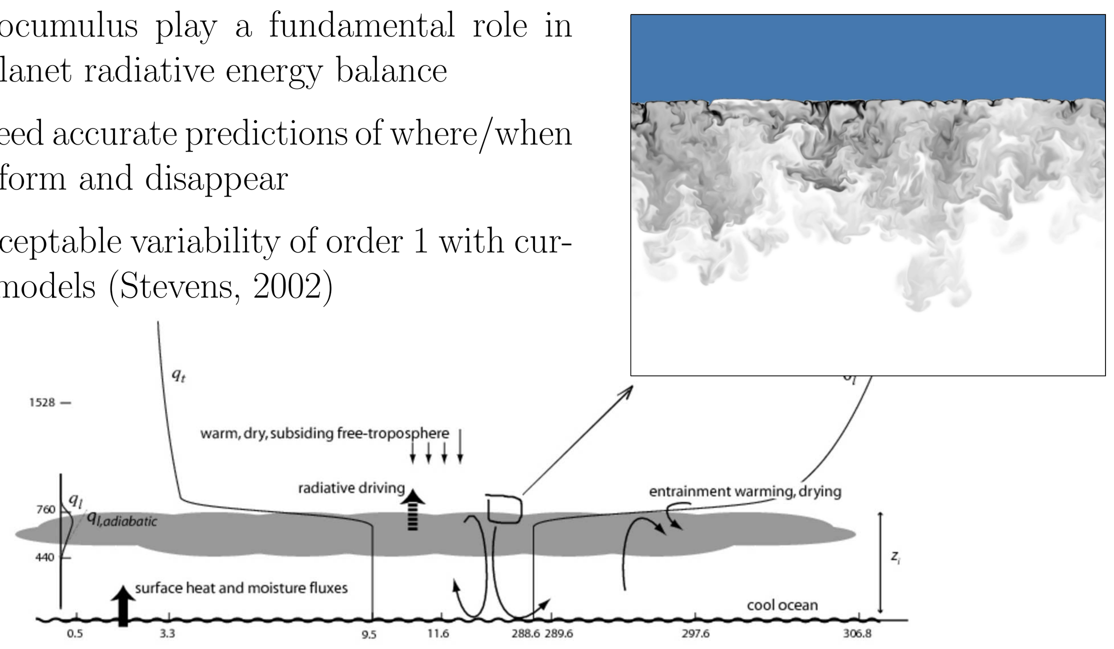


Why ?

Stratocumulus play a fundamental role in the planet radiative energy balance

We need accurate predictions of where/when they form and disappear

Unacceptable variability of order 1 with current models (Stevens, 2002)



The cloud-top mixing layer

Idealized two-layer configuration defined to investigate in detail small scale dynamics of the cloud top

Small scale means domain sizes in the range 1-10 m, i.e. subfilter scales from the point of view of large eddy simulation

The goal is to perform direct numerical simulations to resolve down to the diffusion scales (Moin et al., 1998)

Evaporative cooling turbulent convection has been studied. Next step is locar shear effects

Modelling

Separation of numerical and physical issues by using a level set based ansatz.

The level set is tracking the inversion layer and is coupled to a LES for the large scales.

The local inversion layer is moved due to entrainment which has to be provided by detailed small scale analysis.

DNS and the one dimensional turbulence (ODT) model are used for this detailed study.

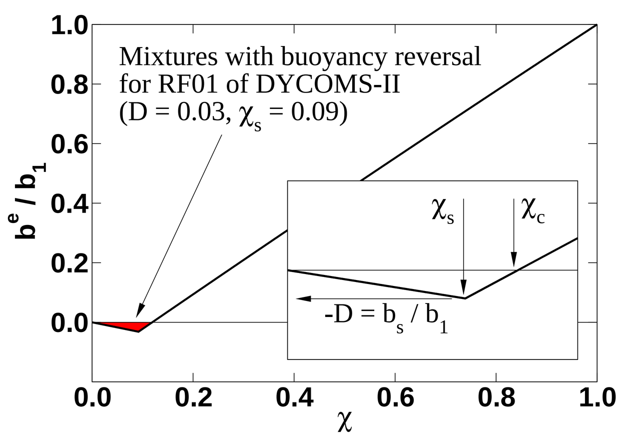
The focus of the poster is on small scale buoyancy reversal and interfacial convection.

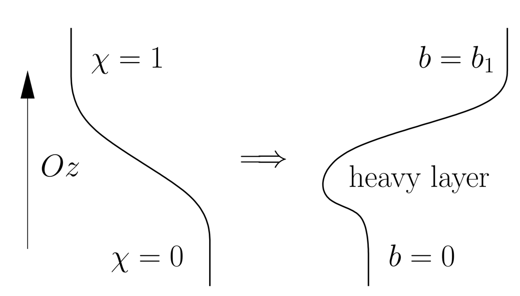
Evaporative cooling convection

Problem definition

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

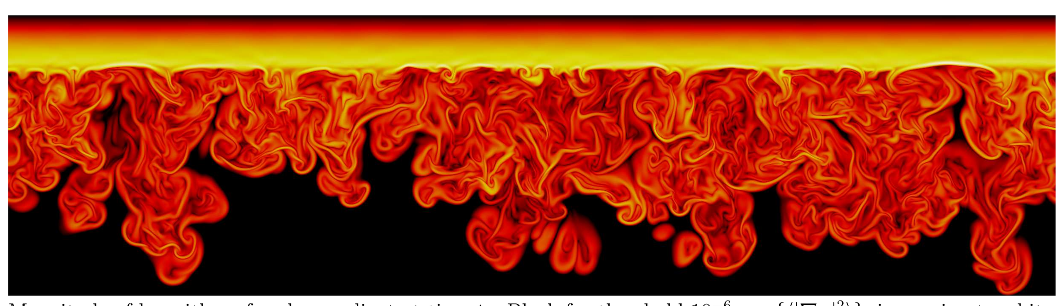
Parameters $\{L_0, \kappa, \nu, b_1, b_s, \chi_s\}$



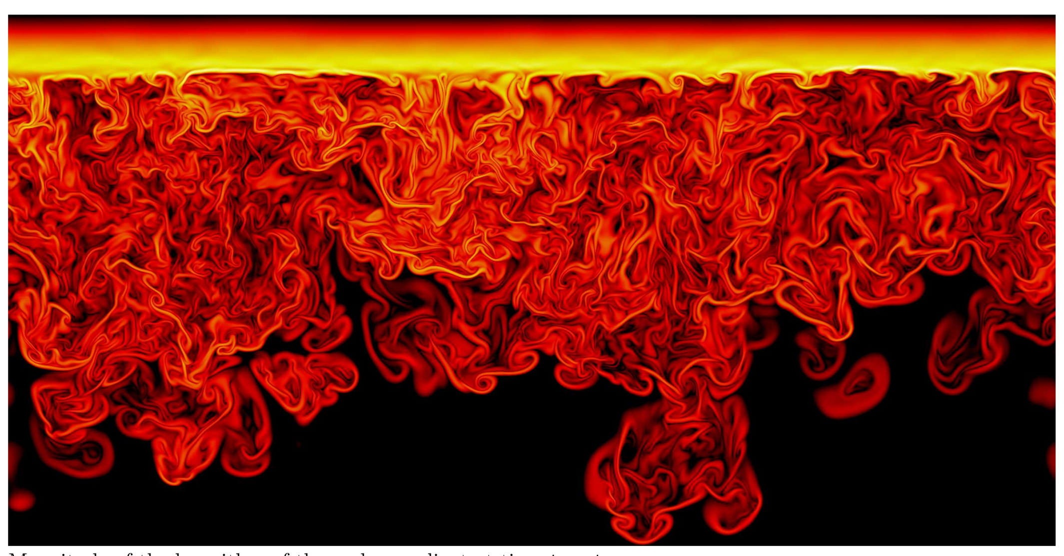


Horizontal dimension $L_0 = 7.7$ m

Vertical structure



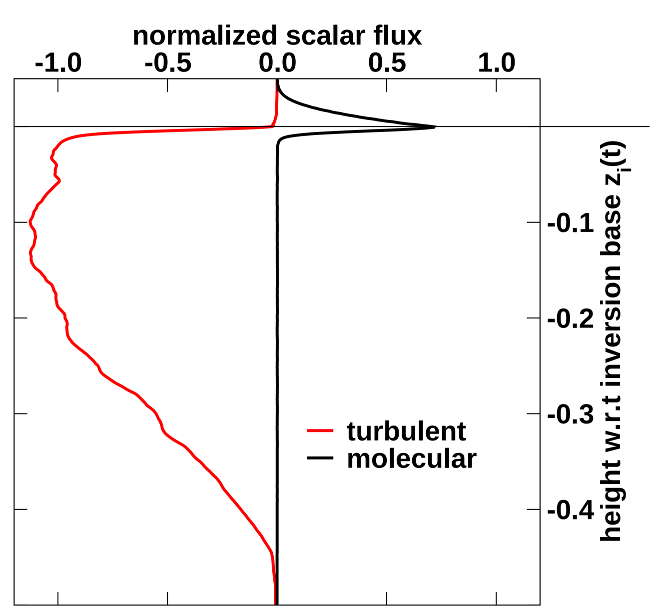
Magnitude of logarithm of scalar gradient at time t_1. Black for threshold $10^{-6}\max\{\langle|\nabla\chi|^2\rangle\}$, increasing to white



Magnitude of the logarithm of the scalar gradient at time $t_2 > t_1$

Evolution of the mixture fraction χ:

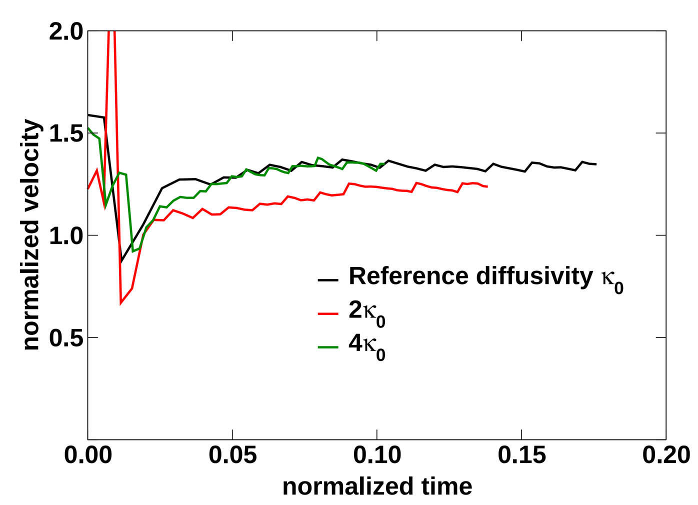
$$\frac{\partial\langle\chi\rangle}{\partial t} = \frac{\partial}{\partial z}\left(\kappa\frac{\partial\langle\chi\rangle}{\partial z} - \langle w'\chi'\rangle\right)$$



Observations

1. Layered structure with **inversion layer** on top, dominated by molecular transport, and **convection layer** below, dominated by turbulent transport.
2. Convection layer thickens in time downwards engulfing cloud fluid into the turbulent region. Velocity fluctuation $\simeq 4$ cm s^{-1}.
3. Inversion is **not broken** by the turbulent motion below and has a constant thickness. It moves upwards with a **mean entrainment velocity** $w_e = dz_i/dt$ relatively small $\simeq 0.2$ mm s^{-1}.
4. w_e constant $\Rightarrow$ independent of length L_0 $\Rightarrow$ scales with scalar **molecular diffusivity** κ

$$\frac{w_e}{(\kappa b)^{1/3}} = f(D, \chi_s)$$



free convection below a cold surface !

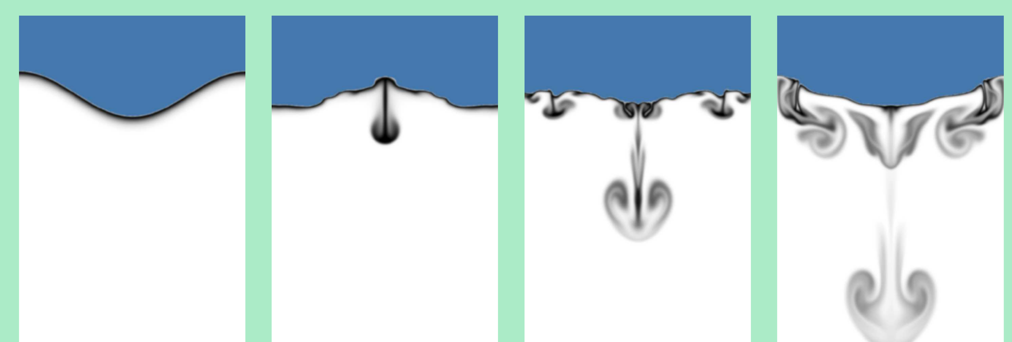
Buoyancy Reversal Instability

Atmospheric conditions for which the saturation buoyancy b_s is negative are unstable and a turbulent motion can develop (Randall, 1980; Deardorff, 1980)

One way of understanding it is by realizing that the two-layer structure in terms of the conserved scalar χ leads to a three-layer structure in terms of the density (buoyancy), as shown to the left of this block.

$$\sigma_s^2 \sim -kb_1/2$$
$$\sigma_u^2 \sim \quad kb_1 D(1 - e^{-2kh})/2$$

k = wavenumber
h = thickness of reversing layer



Linear stability analysis of a three-layer ideal-fluid system with a stepwise vertical density profile leads to the dispersion relation $\sigma(k)$ shown above in the Boussinesq limit with small D. It shows that:

1. There are two modes. One of them corresponds to interfacial gravity waves; the second one is unstable if $D > 0$ (nondimensional Randall-Deardorff criterion).
2. Parameter $\sqrt{D}$ is the ratio of the time scales associated with each mode. Small values of D means that the restoring force is relatively fast w.r.t. falling downdraft $\Rightarrow$ hole formation is unlikely.

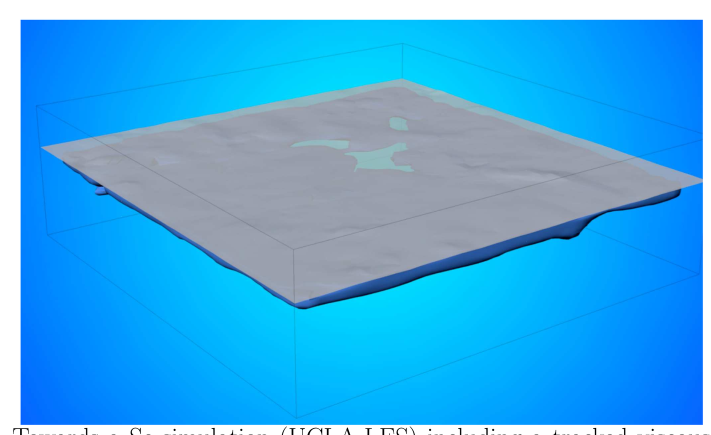
The non-linear evolution of a monocromatic perturbation is illustrated by the sequence above.

from Mellado, Stevens, Schmidt and Peters, Q. J. R. Meteorol. Soc, **135**:963-978 (2009)

Modelling

Large Scales

- We are implementing a Heterogeneous Multiscale Model into the anelastic UCLA-LES solver. Comparison with DYCOMSII is far goal.
- Evolution of the Interface using a level set: $\frac{\partial}{\partial t}\Phi + (\mathbf{v} + E\mathbf{n})\cdot\nabla\Phi = \mathrm{sign}(\Phi)\,(1 - |\nabla\Phi|)\frac{|\Phi|}{\zeta}$
- Entrainment E has to be provided locally via parameterizations



Towards a Sc simulation (UCLA-LES) including a tracked viscous super-layer: Isosurface of liquid water (blue) and zero levelset (gray)

Subgrid Scale Entrainment Modeling

- Extension of a One Dimensional Turbulence Model (Kerstein1999) to assist DNS investigations
- Further goals are parametric studies and an qualitative/quantitative understanding of the interplay of different physical mechanisms relevant in Sc clouds

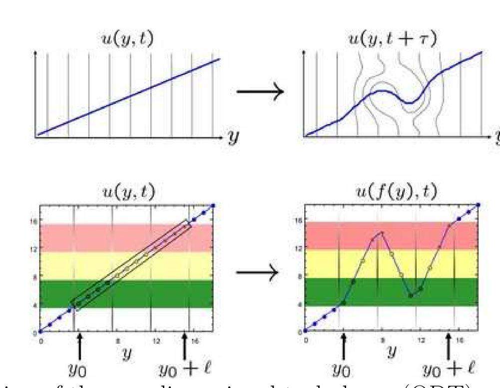


Illustration of the one dimensional turbulence (ODT) ansatz

The mixture fraction

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

These major assumptions lead to PDEs similar to those describing the evolution of multi-component reacting gas mixtures.

Small velocities and small dimensions allow an incompressible approach, and total specific enthalpy h and total water content q_t, conserved quantities, follow the same advection-diffusion equation.

A two-layer system, say region 0 below region 1, allows the normalization

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

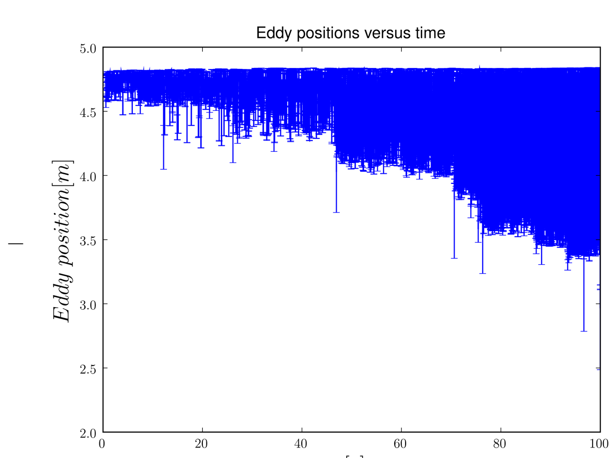
The mixture fraction χ so defined indicates the relative amount of matter of the fluid particle that proceeds from the upper layer.

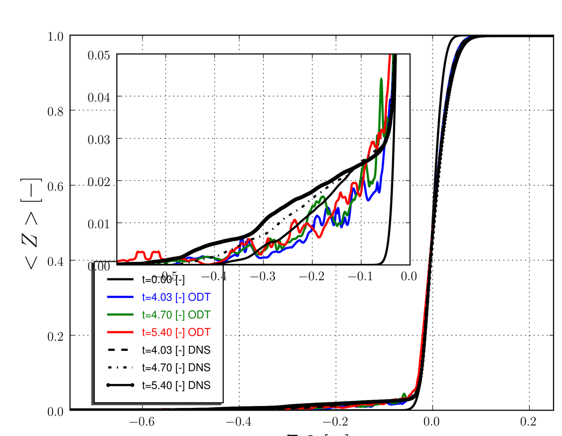
Introduced by Albrecht et al. (1985) and Bretherton (1987). Very often used in nonpremixed turbulent combustion, where it has allowed a strong development in the field during the last decades (Peters, 2000).

from Mellado, Stevens, Schmidt and Peters, submitted to Theor. Comput. Fluid Dyn., (2009)

Results for evaporative cooling

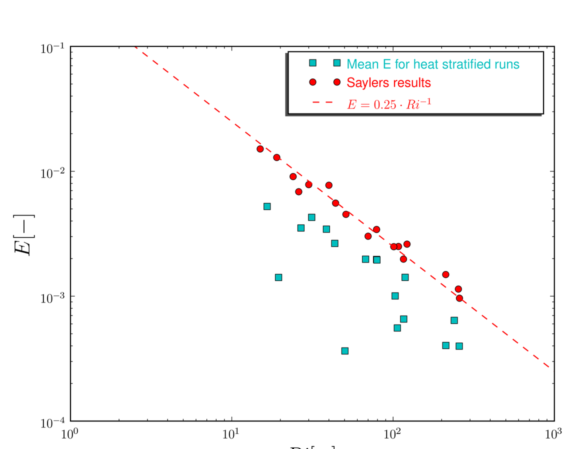
- Same equation system (including mixture fraction Z) as for the DNS case is solved
- Advection is done via triplet maps
- Buoyancy influences eddy probabilities

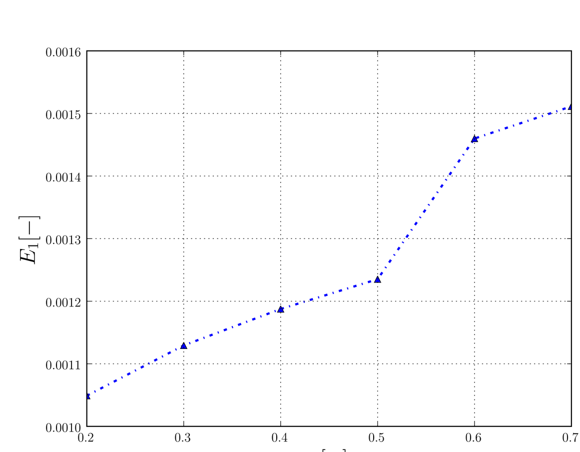




Results for radiative cooling (heating)

- A temperature equation including radiative source terms is added to the ODT model
- Radiatively induced convection is investigated. ODT results are compared to tank experiments.
- Results show the importance of the resolution of the diffusive layers to get correct entrainment rates
- Results will be used for a DNS setup





Experimental vs ODT results for E (left), E influenced by location of first absorption $Z_e = 1/(1 + \tau)$