# Multi-scale modelling of stratocumulus clouds

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## Motivation

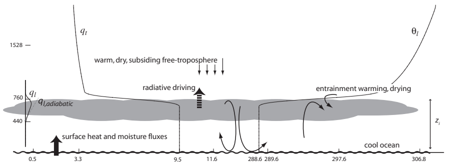
- Low clouds are increasingly recognized as the main source of divergence in model based estimates of climate change.
- One common tool for understanding clouds and microphysical interactions is LES, but fundamental issues emerge in precisely those quantities of interest (e.g. Albedo)
- Culmination of more than 10 years of work shows limitations of LES to be fundamental!

## Problem

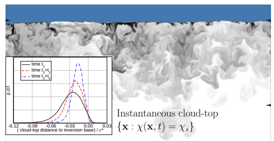
1. **Numerical vs. Physical**
   - Current LES cannot resolve the interface physics due to insufficient resolution.
   - Elaborate physically based subgrid models are numerically smeared out.
   - Distinction between numerical and physical effects is impossible.
2. **Small vs. Large Scale**
   - Interface motion is driven by large scales.
   - But mixing across the interface is a small scale phenomenon.
   - The coupling between both is not trivial.

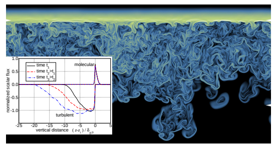
## Key Ideas

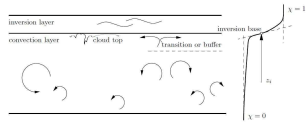
1. **Separation of Numerical and Physical Issues**
   - Interface method to avoid numerical smearing
   - Consistent embedding of entrainment physics
2. **Separate Treatment of Small and Large Scales**
   - UCLA-LES + front tracking for large scales
   - DNS, one dimensional turbulence (ODT), and lower order models for small scale
   - Modular coupling procedure which has been developed for combustion and two phase flow problems, helps to combine both scales in a consistent manner.




## DNS and ODT




- Maximum stratification height $z_i$ separates:
  1. Inversion layer on top; molecular transport
  2. Convection layer below; turbulent transport
- Const. entrainment velocity $w_e = dz_i/dt \ll w_{rms}$
- Convection scales based on ref. buoyancy flux

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

**The key idea of the ODT model:**

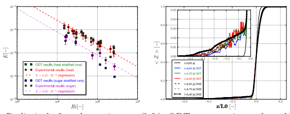
- ODT is a 1D DNS with a stochastic model for turbulent advection (implemented via maps). Time, location, and length of those are sampled from a probability distribution based on the local energetic of the turbulent field. The time scale can be interpreted as the turn over time of an eddy of size $l$.
- Resolves all the fine scale processes while keeping acceptable run times.

**Results and work in progress:**

- ODT reproduces experimentally observed molecular effects on entrainment in radiatively forced convection experiments (see figure).
- Comparisons with DNS on buoyancy reversal and shear results as a validation of the modeling strategy (see figure).

**Future work for DNS/ODT:**

- Does ODT see any additional parameter dependences (e.g. Pr effects)?
- Do these results change when we extend the scales beyond DNS limits (future work)?
- Following future DNS (shear and finite rate effects)



Radiatively forced entrainment (left): ODT vs. experimental results; Buoyancy reversal study (right): ODT vs. DNS results

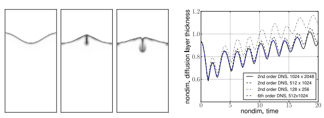
## Towards a coupled level set/LES

### DNS of 2d buoyancy reversal using UCLA-LES

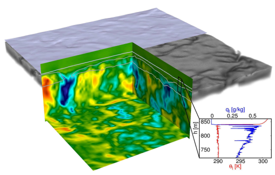
Here the UCLA-LES model is used with constant molecular viscosity as SGS model to essentially run a (2nd-order) DNS. The lower-order DNS solution

⇒ converges to Mellado's (2009) solution at double resolution, validating UCAL-LES code for this configuration, and

⇒ is much more diffusive, yielding an order 1 increase in growth rate of diffusion layer at 1/4 of ref resolution.




### Level Set Methodology



Schematic: Stratocumulus-topped atmospheric boundary layer. Grey fog indicates liquid water; blue sheet indicates layer of strongest stratification; colors indicate vertical velocity.

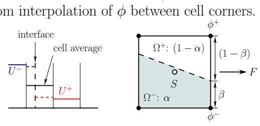
- Interface $\partial\Omega$ implicitly defined as $\partial\Omega = \{\boldsymbol{x} \mid \phi(\boldsymbol{x}) = 0\}$
- Evolution of the level set function $\phi$:
$$\frac{\partial \phi}{\partial t} + (\boldsymbol{v} + E\boldsymbol{n}) \cdot \nabla\phi = 0 \qquad (1)$$
- Entrainment $E$ has to be provided by a model. ODT is a very promising candidate.
- To avoid very steep $\nabla\phi$, $\phi$ is initialized as a *signed distance function* of the interface ($|\nabla\phi| \equiv 1$).
- $\phi$ will generally not retain this desirable property, esp. close to $\partial\Omega$ were only $\phi$ has a physical meaning.

→ Frequent reinitialization of $\phi$ into signed distance

- One efficient technique is to iterate through a reinitialization equation of the form
$$\frac{\partial \phi}{\partial \tau} + \text{sign}(\tilde{\phi})(|\nabla\phi| - 1) = 0 \qquad (2)$$
in artificial time $\tau$, where sign($\tilde{\phi}$) is the sign function of the original level set.
- It is crucial to maintain the position of $\partial\Omega$ during reinitialization to high accuracy, which is not trivial in multi-D.

### Modification of the FV Method

- In a cell cut by the interface, volume fraction $\alpha$ of a cell and surface fraction $\beta$ of cell faces result from interpolation of $\phi$ between cell corners.

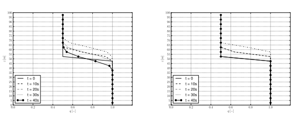



- Net fluxes $F$ and source terms $S$ result from the superimposition
$$F = \beta F^- + (1-\beta) F^+ \qquad (3)$$
$$S = \alpha S^- + (1-\alpha) S^+ \qquad (4)$$
- To get $F^\pm$ and $S^\pm$ right, prognostic quantities have to be reconstructed (In-cell reconstruction) on both sides of $\partial\Omega$ from their cell average $U$.

▶ This idea has been successfully used in combustion modelling and might be applied to many geophysical flows.

### 1D advection of a scalar

- Prescribed velocity $w(t) = w_0 \cdot \sin(2\pi f \cdot t)$
- Amplitude $w_0 = 1\,m/s, \quad 1/f = 40s$
- Vertical resolution $\Delta z = 5\,m$



Evolution of a moisture profile under an uniform oscillating vertical velocity field. Standard UCLA-LES (left), Coupled level set/UCAL-LES (right).

- As opposed to the unmodified LES (left) the coupled level set/UCLA-LES is preserving the discontinuity during one oscillation period.

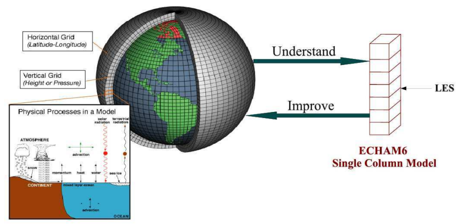
### Work done

- FD solver for advection of *phi* on staggered grid
- Extraction of geometric information from $\phi(\boldsymbol{x})$ needed to couple Level Set ($\alpha, \beta, \boldsymbol{n}$, etc.)
- Coupling of advective scalar fluxes

### Work in progress

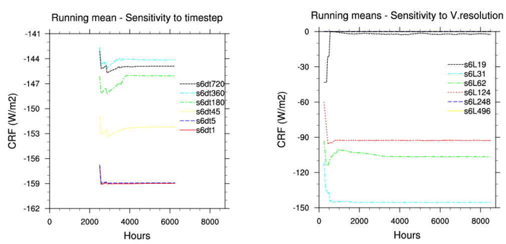
- Efficient Reinitialization for $\phi$
- Coupling to further terms (momentum transport, source terms, etc.)
- Inclusion of ODT as entrainment model

## Numerical uncertainties in a climate model

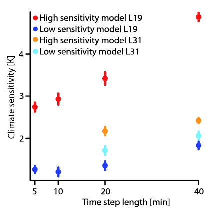



$$\frac{\partial \overline{\Theta}}{\partial t} \;=\; -\overline{u}.\nabla\overline{\Theta} \;+\; S\left[_{Unresolved\ Proceses\,/\,Parametrizations}\right]$$

- Single column model (SCM) is a column of a climate model with all the physical parameterizations for unresolved scales and is prescribed with large scale flow. In this study it is used as a fundamental tool to understand and improve representation of stratocumulus clouds.




- Simulations of realistic low cloud test cases using the single column model reveal how simulation of these clouds depends on the timestep size and vertical resolution, indicating interplay between physical and numerical effects.
- The net impact of these effects due to numerical formulation has a potential to explain some key uncertainties in climate projections.




- **Tasks acomplished**
  - Development of ECHAM6 single column model
  - Extablishing how simulations of low clouds in depend on numerical formulation.
  - Extablishing how the such effects have a potential to reduce uncertainty in climate projections.
- **Ongoing work**
  - Understanding and fixing sensitivities to $\Delta t$
  - Implementing level set method to reduce errors related to vertical resolution
  - Final goal is to make the model a physical based one rather than based on numerical effects