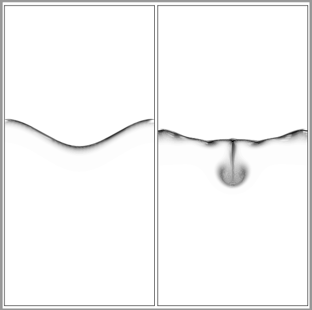
LES vs. DNS of a two-dimensional evaporatively driven cloud-top mixing layer



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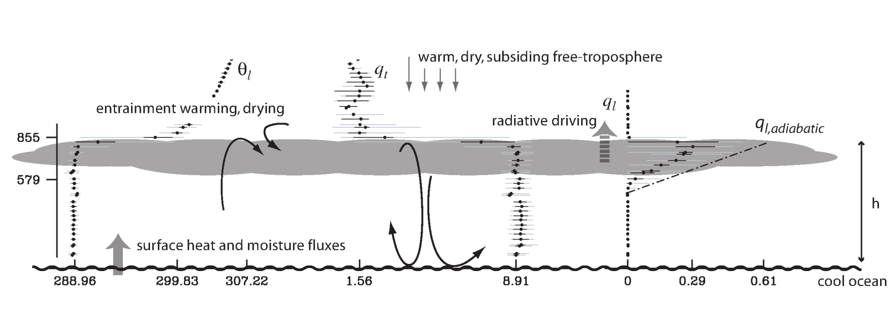
Outline

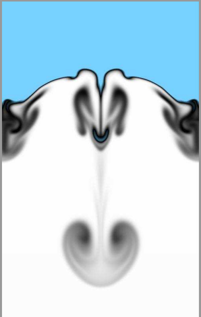
Marine stratocumulus

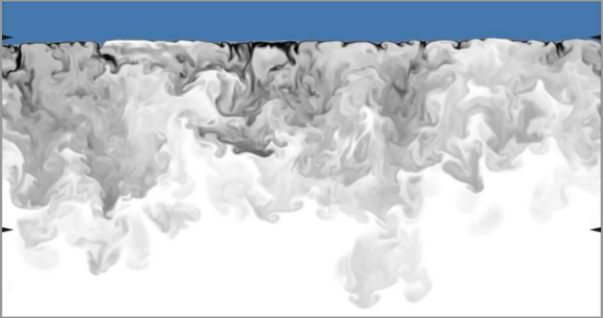


Important at the cloud top:

- Separate *numerical* and *physical effects*.
- Get interaction between *large* and *small scales* right.

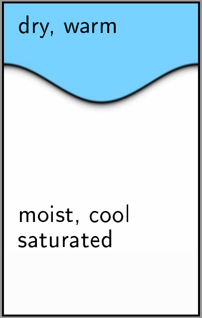
2D/3D DNS reference data





→ driven by evaportive cooling

Objectives



Benchmark case: 2D evaporatively driven cloud-top mixing layer[a]

- well defined, intermediate complexity: stable oscillation, diffusion, thermodynamics
- accurate DNS solution available for verification

Objectives:

→ Verify the LES for the DNS case

→ Quantify sensitivity of solution to numerical errors

[a] J. P. Mellado, B. Stevens, H. Schmidt, and N. Peters. Buoyancy reversal in cloud-top mixing layers. *Quarterly Journal of the Royal Meteorological Society*, 135:963–978, 2009.

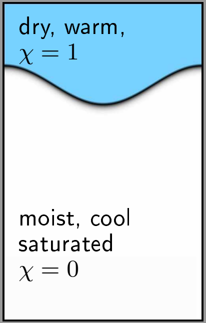
Formulation

Simplifying assumptions[a]

- two-fluid formulation
- thermodynamic equilibrium

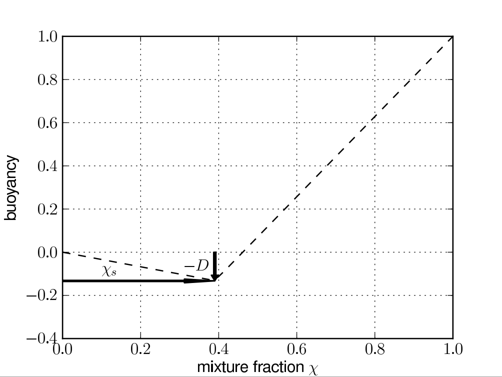
→ Mixture fraction[b] χ completely defines the thermodynamic state.

- $q_t = (1-\chi)\, q_{t,0} + \chi\, q_{t,1}$
- $h = (1-\chi)\, h_0 + \chi\, h_1$
- solve transport equation for χ instead



[a] Mellado, et al., 2010
[b] Albrecht, 1987

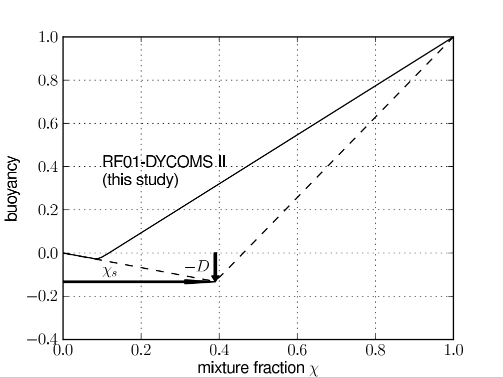
Formulation – buoyancy mixing function



$\rightarrow$ buoyancy reversal parameter

$$D = -b_{max}/b_{min} = 0.031$$

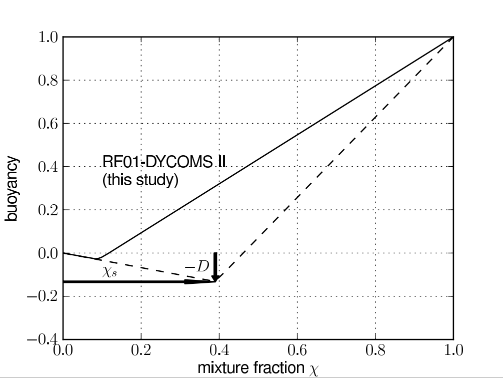
Formulation – buoyancy mixing function

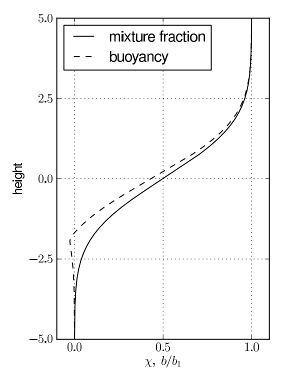


→ buoyancy reversal parameter

$$D = -b_{max}/b_{min} = 0.031$$

Formulation – buoyancy mixing function



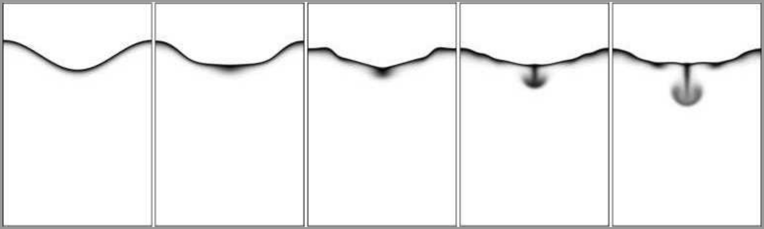


→ buoyancy reversal parameter

$$D = -b_{max}/b_{min} = 0.031$$

→ stably stratified except for thin unstable sheet

Evolution of the flow



The UCLA-LES

- Boussinesq equations

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial \pi}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j^2} + b(\chi)\delta_{i3} + \text{SGS}$$

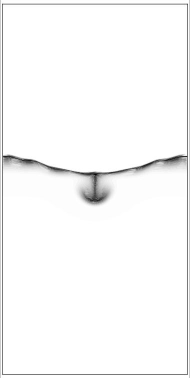
$$\frac{\partial \chi}{\partial t} + u_j \frac{\partial \chi}{\partial x_j} = \nu \frac{\partial^2 \chi}{\partial x_j^2} + \text{SGS}$$

$$\frac{\partial u_i}{\partial x_i} = 0$$

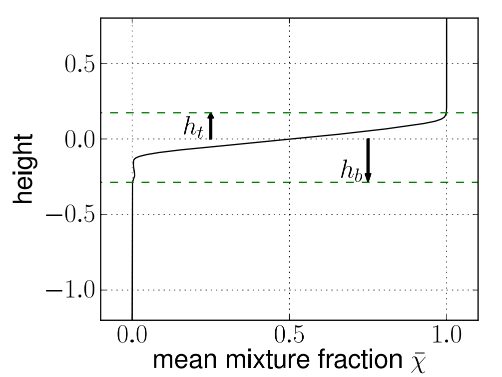
- SGS model replaced by constant moleular diffusivity ν
- 2nd-order flux-limited FV discretization on Arakawa-C grid
- 3rd-order Runge-Kutta time integration scheme
- Tridiagonal Poisson solver for dynamic pressure perturbation π

Definitions

- penetration length h_b
- upper perturbation thickness h_t

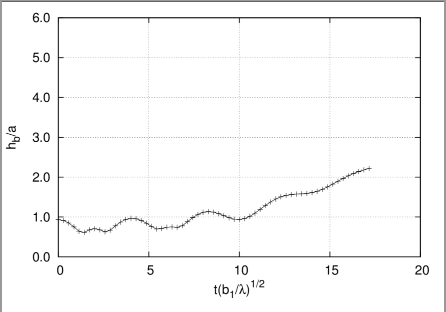


horizontal average $\Longrightarrow$

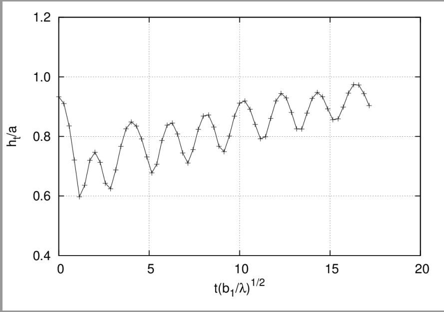


DNS results

penetration length h_b



upper perturbation thickness h_t



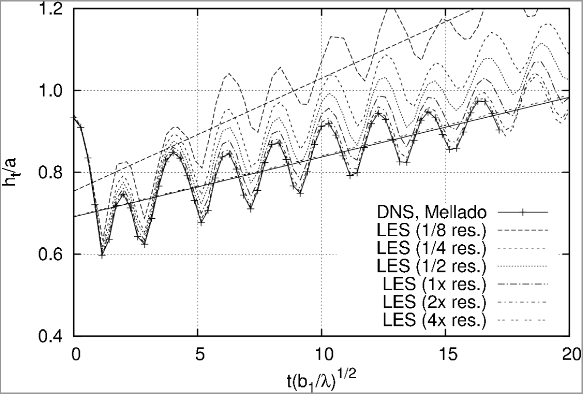
- superimposition of a *stable* and an *unstable mode*
- growth of inversion height due to diffusion and downward transport of dry fluid

LES order of convergence

grid res.	1/8	1/4	1/2	[512x1024]	2x	4x
p $[L_2]$	-	1.9991	1.9975	1.9987	1.9976	-
p $[L_{max}]$	-	1.9948	1.9951	1.9874	1.9508	-

LES results

upper perturbation thickness h_t



h_t growth rate:

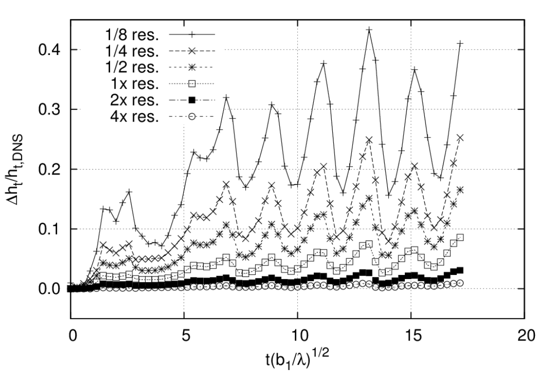
- $89\,\%$ error on coarsest grid ($\Delta z \approx 1\,cm$)

→ coarsest grid still much finer than typical LES grids ($\Delta z > 1\,m$).

- error $< 1.5\%$ on 4x refined grid

Relative errors to DNS

upper perturbation thickness h_t



- coarsest grid: max errors 40%
- reference grid: max errors 9%
- finset grid: max errorrs $< 1\%$

$\rightarrow$ LES converges to DNS solution

Summary

- LES shows the anticipated 2nd order of convergence in this case.
- LES converges to the DNS
- significant errors at 1/8th of the DNS resolution (89% in vertical growth)

→ Spurious mixing in traditional LES due to discretization errors at the cloud-top can be expected to be of leading order, supporting efforts to separate numerical from physical mixing (Level set).

next steps:

- compare computational efficency: 4th order DNS vs. 2nd order LES
- anelastic vs. Boussinesq
- DNS vs. LES comparison for 3D case

Thank you for your attention!