Entrainment and Detrainment in trade cumulus clouds

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Small clouds feed big clouds

Outline

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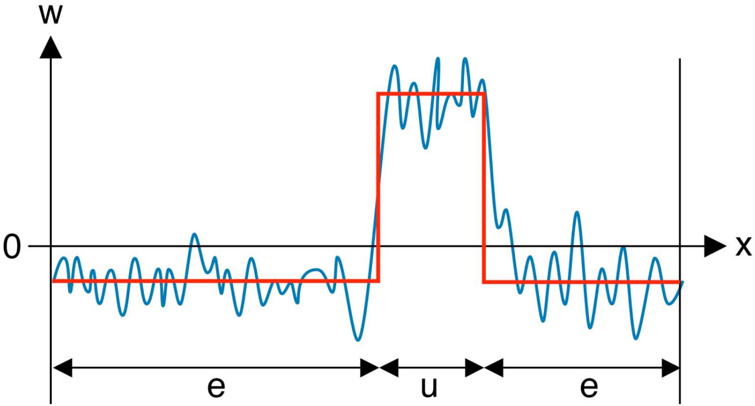
   - Introduce a commonly used cloud model (mass flux/entraining plume)
   - Discuss use of 3-d large eddy simulations to estimate model parameters
   - Examine role of critical mixing fraction χ_c (de Rooy and Siebesma, 2008) and environmental stability (Wu, Stevens and Arakawa, 2009) in determining mass flux profile

Why a mass flux model? Clouds have boundaries



courtesy: Martin Köhler

Cloud-environment averaging (following Siebesma, 1998)

Define an averaging operator:

$$\overline{\phi(z)} = \frac{1}{A}\int_0^{L_x}\int_0^{L_y}\phi(x,y,z)dxdy \tag{1}$$

where $A = L_x L_y$

Separate the domain into environment and cloud:

$$\begin{aligned}
\overline{\phi_c} &= \phi_c = \frac{1}{A_c}\int\int_{\text{cloud}}\phi(x,y,z)dxdy \\
\overline{\phi_e} &= \phi_e = \frac{1}{A_e}\int\int_{\text{env}}\phi(x,y,z)dxdy \\
a_c &= A_c/A \text{ (fractional cloud cover)} \\
\overline{\phi} &= a_c\phi_c + (1-a_c)\phi_e
\end{aligned} \tag{2}$$

$\overline{w'\phi'}$ in terms of the cloud mass flux $M = a_c w_c$

Cloud and environment contribuitons to the turbulent flux:

$$\begin{aligned} \overline{w'\phi'} &= \overline{w\phi} - \overline{w}\overline{\phi} \\ \overline{w'\phi'}^c &= \overline{w\phi}^c - w_c\phi_c \\ \overline{w'\phi'}^e &= \overline{w\phi}^e - w_e\phi_e \end{aligned} \tag{3}$$

Make some approximations:
Assume $\overline{w'\phi'}^c$, $\overline{w'\phi'}^e$, a_c, $\overline{w}$ are all small. Then

$$\overline{w'\phi'} = a_c\overline{w'\phi'}^c + (1 - a_c)\overline{w'\phi'}^e + a_c(w_c - \overline{w})(\phi_c - \phi_e)$$

becomes

$$\overline{w'\phi'} \approx a_c w_c(\phi_c - \phi_e) = M(\phi_c - \phi_e) \tag{4}$$

Where $M = a_c w_c$ is the cloud mass flux.

Solving for M, ϕ_c, ϕ_e

Integrating the continuity equation over the cloud area A_c gives:

$$\frac{\partial a_c}{\partial t} + \frac{1}{A}\oint \hat{\mathbf{n}} \cdot (\mathbf{u} - \mathbf{u_i}) dl + \frac{\partial a_c w_c}{\partial z} = 0 \tag{5}$$

and for the tracer with sources and sinks F:

$$\frac{\partial a_c \phi_c}{\partial t} + \frac{1}{A}\oint \hat{\mathbf{n}} \cdot (\mathbf{u} - \mathbf{u_i}) \phi dl + \frac{\partial a_c \overline{w\phi^c}}{\partial z} = a_c F_c \tag{6}$$

$$\frac{\partial (1 - a_c)\phi_e}{\partial t} + \frac{1}{A}\oint \hat{\mathbf{n}} \cdot (\mathbf{u} - \mathbf{u_i}) \phi dl + \frac{\partial (1 - a_c)\overline{w\phi^e}}{\partial z} = (1 - a_c) F_e \tag{7}$$

Define E and D

$$
\begin{aligned}
E_\phi \phi_e &\approx -\frac{1}{A} \oint_{\hat{\mathbf{n}}\cdot(\mathbf{u}-\mathbf{u_i})<0} \hat{\mathbf{n}} \cdot (\mathbf{u} - \mathbf{u_i}) \phi dl \\
D_\phi \phi_e &\approx -\frac{1}{A} \oint_{\hat{\mathbf{n}}\cdot(\mathbf{u}-\mathbf{u_i})>0} \hat{\mathbf{n}} \cdot (\mathbf{u} - \mathbf{u_i}) \phi dl
\end{aligned}
\tag{8}
$$

$$
\frac{\partial a_c \phi_c}{\partial t} = E\phi_e - D\phi_c - \frac{\partial a_c \overline{w\phi^c}}{\partial z} + a_c F_c \tag{9}
$$

$$
\begin{aligned}
\frac{\partial (1 - a_c)\phi_e}{\partial t} = -E\phi_e + D\phi_c - \frac{\partial (1 - a_c)\overline{w\phi^e}}{\partial z} \\
+ (1 - a_c) F_e
\end{aligned}
\tag{10}
$$

Solving for M, E, D (Siebesma and Cuijpers, 1995)

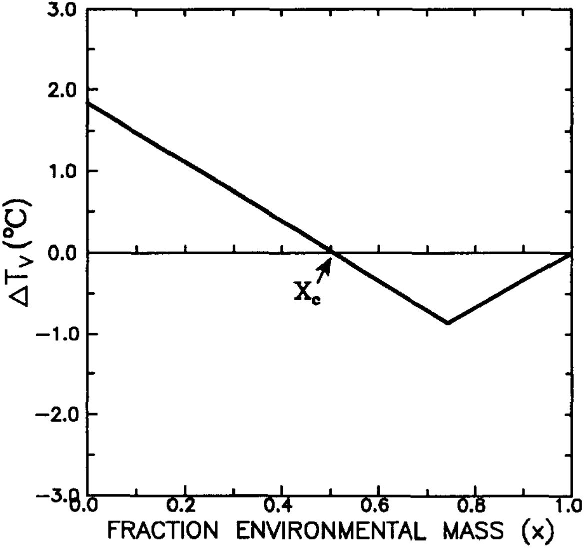
$$\frac{\partial a_c}{\partial t} = E - D - \frac{\partial M}{\partial z} \tag{11}$$

Siebesma and Cuijpers used an LES of a stationary marine boundary layer (BOMEX), to find $\overline{w\phi^e}$, $\overline{w\phi^c}$, M, a_c and get vertical profiles of

$$\begin{aligned} \epsilon(z) &= E/M \\ \delta(z) &= D/M \end{aligned} \tag{12}$$

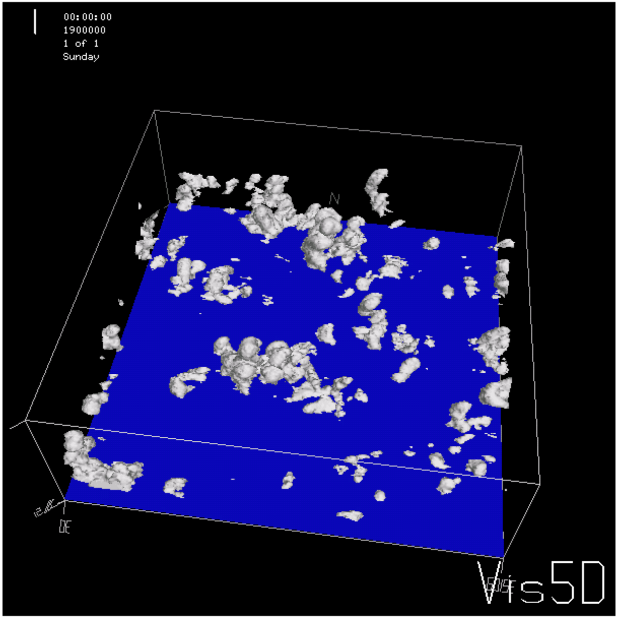
Expect $\epsilon \sim 1/z$ by dimensional arguments (and LES results). But evaporative cooling (aka "buoyancy reversal") makes it likely that M, E, D will be sensitive to environmental humidity.

Critical mixing fraction: χ_c



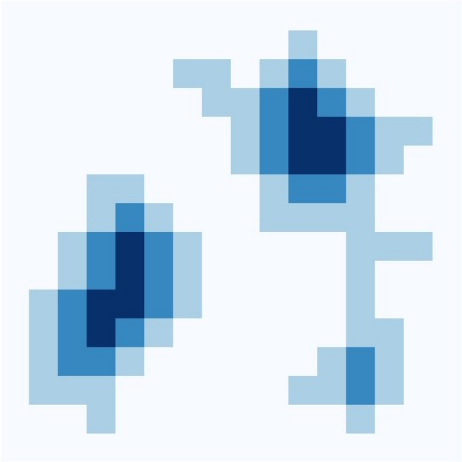
Kain and Fritsch, 1990

Examples using the SAM LES



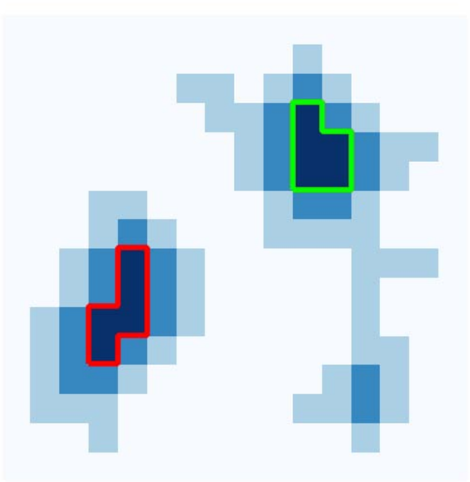
cloud tracking

Identify “cloudlets”



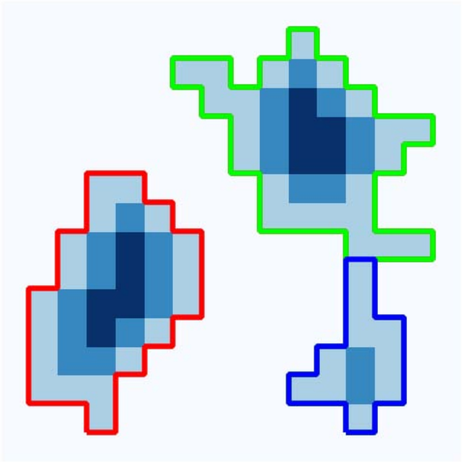
cloud tracking

Move outward, labeling connected cells by distance from central cell



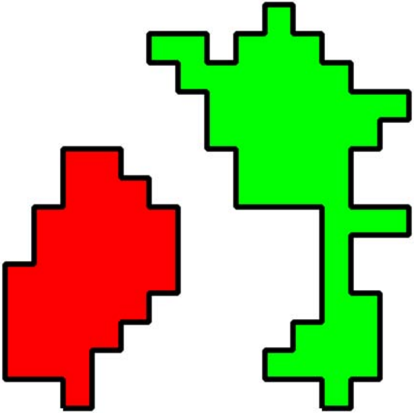
cloud tracking

Stop at the cloud boundaries and ...



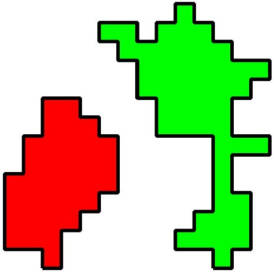
cloud tracking

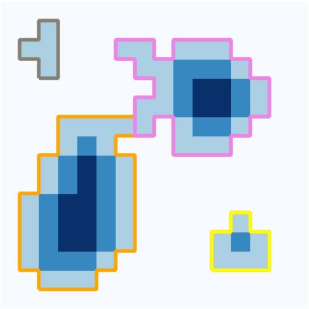
form clusters



cloud tracking

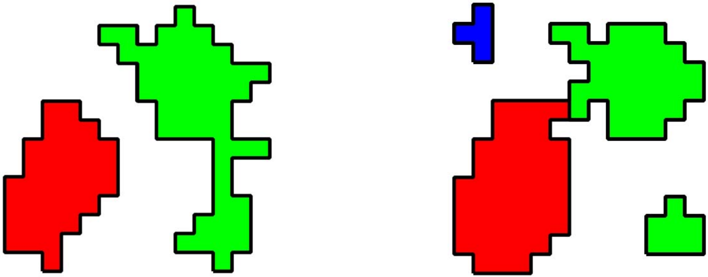
Use overlap to label clusters at next time step



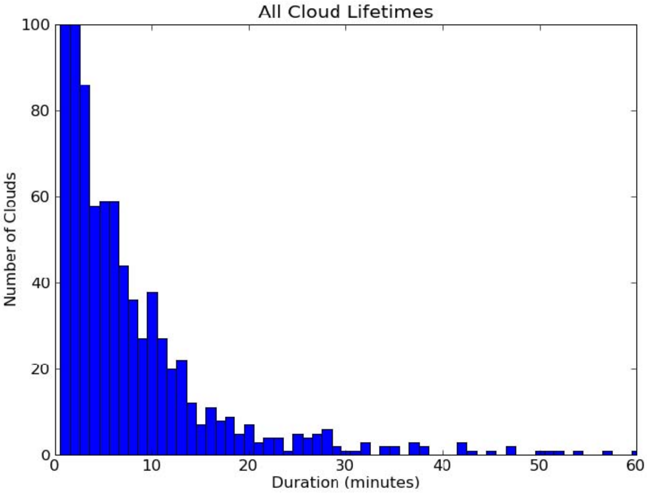


cloud tracking

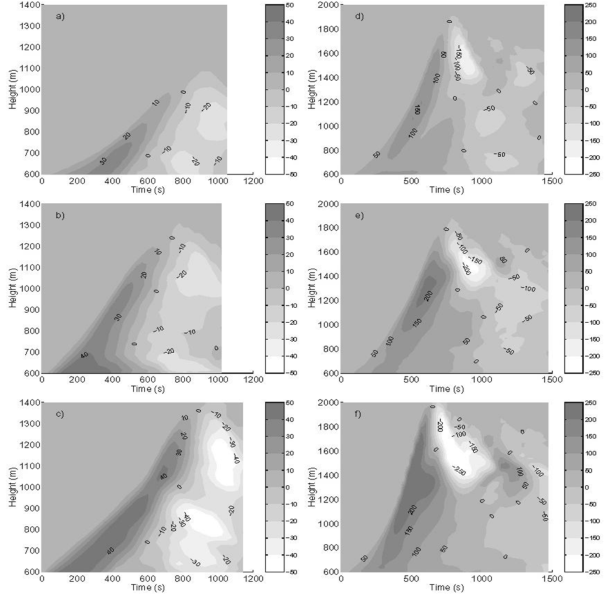
can gather statistics on lifetimes, mergers, splits



1580 cloud histories

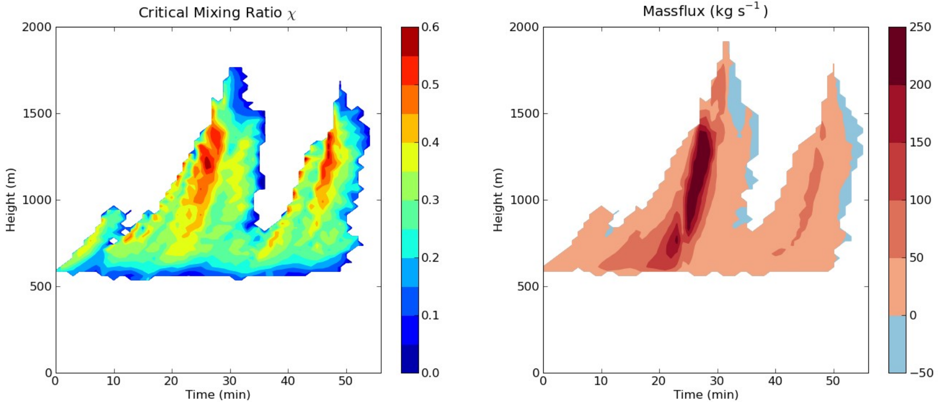


Massflux evolution: six clouds

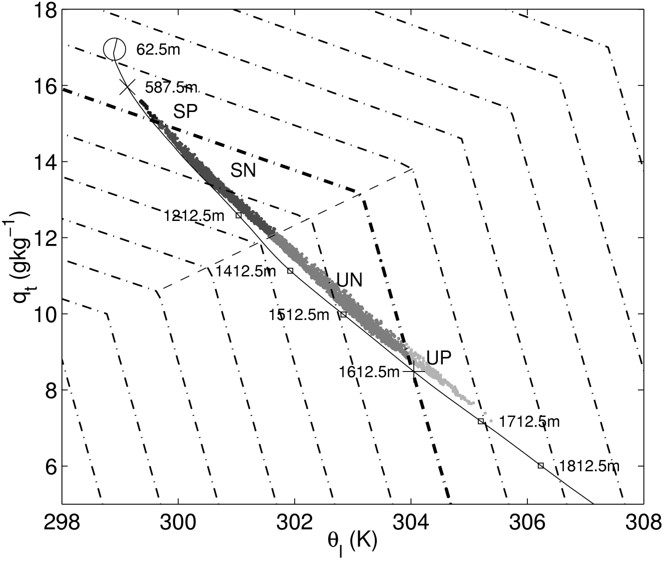


Zhao and Austin, 2005

χ_c vs. mass flux

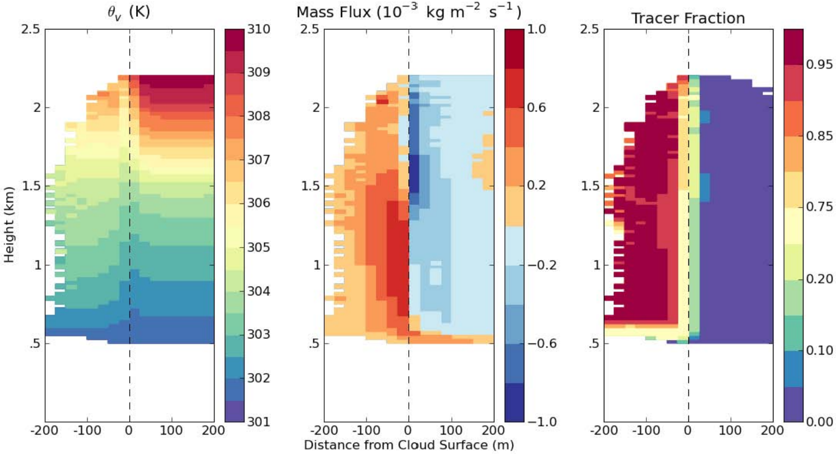


Negatively buoyant mixtures at: 1600 m



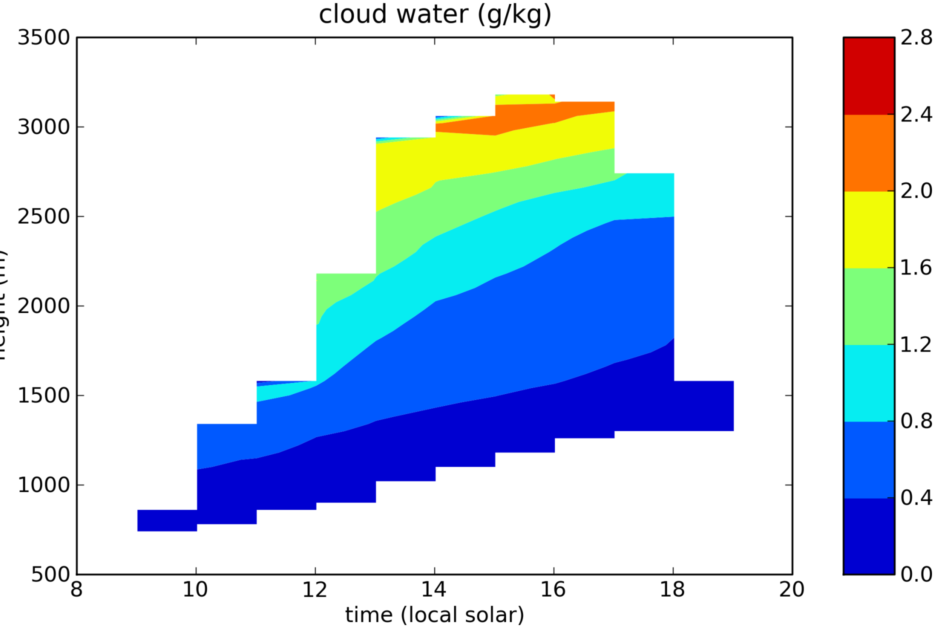
Zhao and Austin, 2005

Negatively buoyant mixtures descend in thin shell

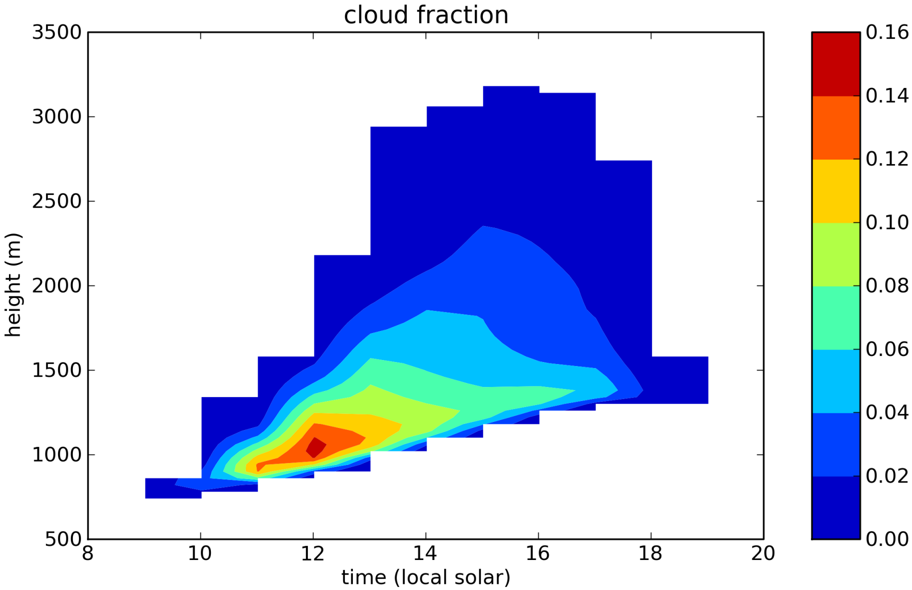


(see also Heus and Jonker, 2008)

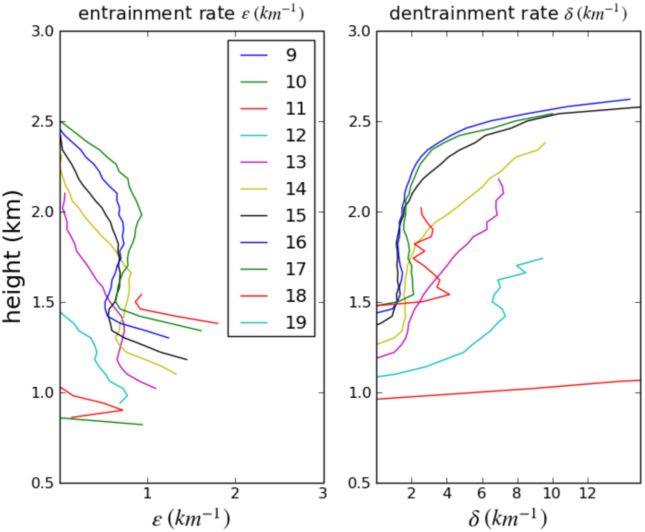
E, D, M and χ_c: ARM diurnal case



ARM diurnal case: Cloud fraction

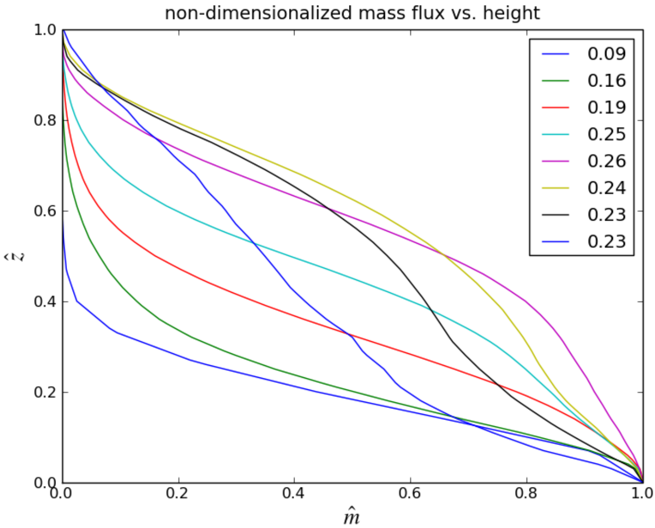


ϵ, δ for 10 hours

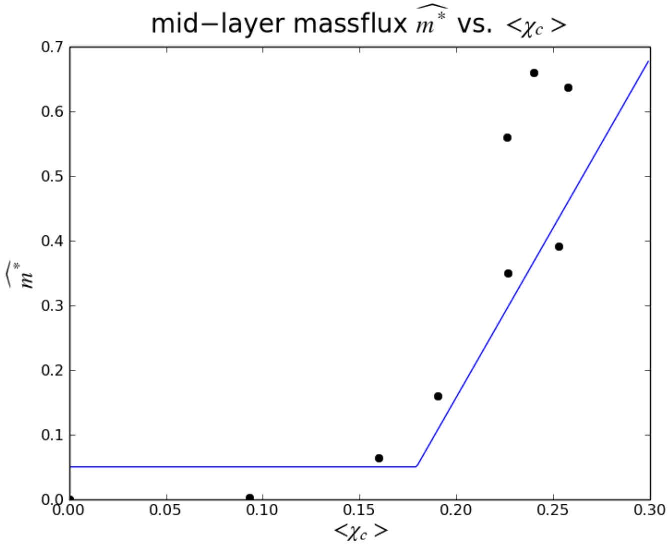


following de Rooy and Siebesma, 2008

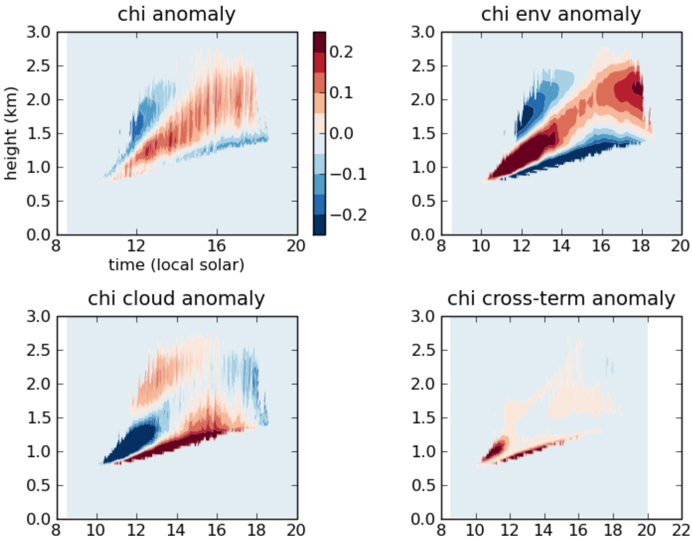
Non-dimensional mass flux profiles: 10 χ_c values



χ_c predicts mass flux in middle of cloud layer

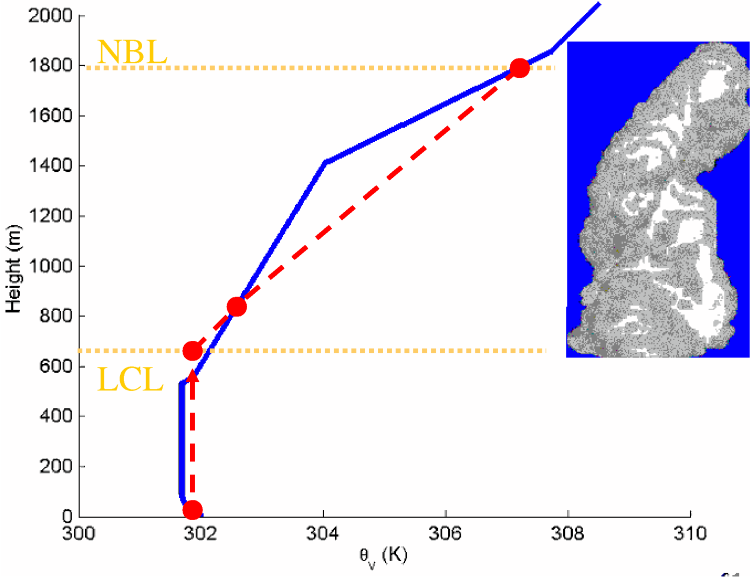


χ_c change is driven by environmental moistening

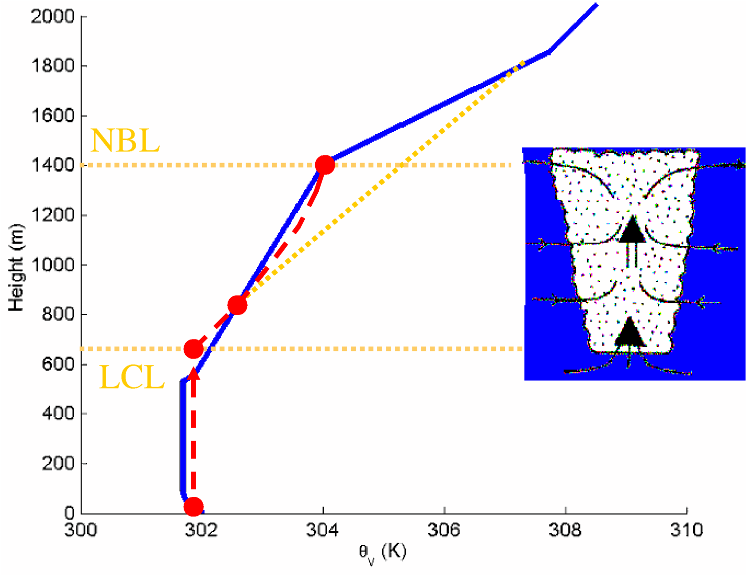


What about environmental stability?

Look at $d\theta_v/dz$ differences for cloud and environment

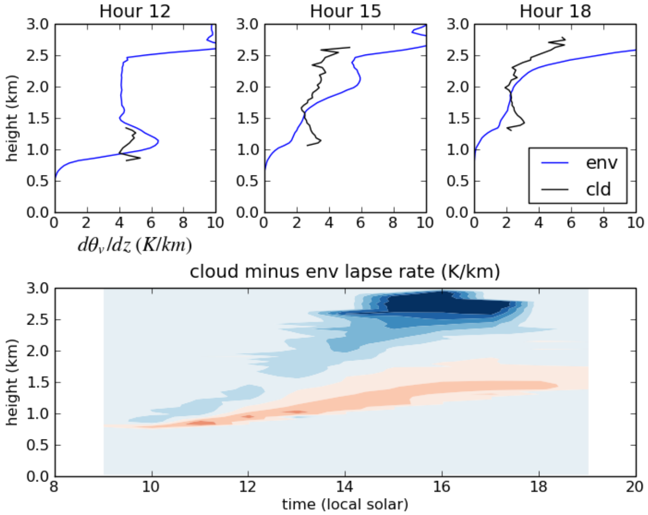


Entrainment can produce a stable lapse rate in the cloud layer



Cloud detrainment modifies environment

On average, clouds are negatively buoyant through most of the simulatio



following Wu, Stevens, Arakawa (2009)

Summary

1. The shallow cumulus cloud life cycle controls the transport of energy and moisture.
2. Large eddy simulations can provide detailed information on convection and mixing. This can be used to inform a simple cloud model that captures both the contributions of positive and negatively buoyant mixtures
3. The critical mixing fraction, χ_c and the cloud-environment stability difference are useful abstractions for parameterizing shallow cloud transport.