Stratocumulus Cloud Thinning

Influence of Inversion Stability

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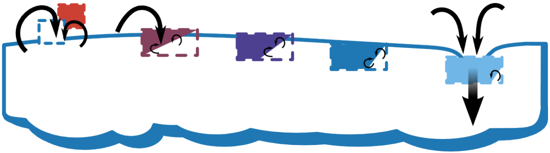
Introduction

What mechanism causes SCu to thin and break up?

Theory

Candidate: Cloud Top Entrainment Instability (CTEI)



- Free atmospheric air is more buoyant than boundary layer air
- Mixing cloudy with entrained air $\rightarrow$ positively buoyant parcel

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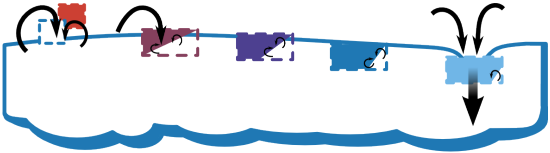
Theory

Candidate: Cloud Top Entrainment Instability (CTEI)



- Free atmospheric air is more buoyant than boundary layer air
- Mixing cloudy with entrained air $\rightarrow$ positively buoyant parcel
- Parcel could start sinking due to evaporative cooling
- Sinking promotes additional entrainment

Theory
CTEI criterion

Deardorff (1980) and Randall (1980) derived that CTEI should occur when

$$\kappa > \kappa_{\mathrm{RD}} \approx 0.23$$

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CTEI criterion

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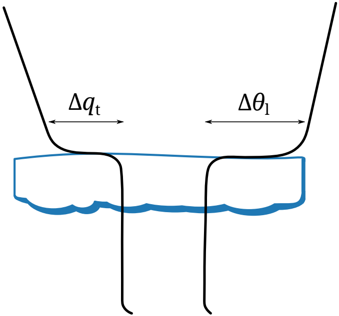
$$\kappa > \kappa_{\mathrm{RD}} \approx 0.23$$

κ is in **inversion stability parameter**†

$$\kappa \equiv 1 + \frac{c_p}{L_\mathrm{v}} \frac{\Delta\theta_\mathrm{l}}{\Delta q_\mathrm{t}}$$



Siems et al. (1990) *Buoyancy reversal and cloud-top entrainment instability*

Theory

Many such criteria have been proposed

TABLE 2. List of proposed CTEI criteria.

Criteria	Formula	References	Comment
RD	$\Delta_{RD} < 0$	Randall (1976, 1980); Deardorff (1980)	This criterion is derived with the assumption that mixed air is saturated.
KS	$\kappa > 0.23$	Kuo and Schubert (1988)	This is equivalent to the RD criterion.
SB	$D > 1.3$	Siems et al. (1990); Shy and Breidenthal 1990)	SB considered the ratio of the strongest possible negative buoyancy to the inversion strength. $D = 0$ for $\Delta_{RD} = 0$.
MM	$\kappa > 0.7$	MacVean and Mason (1990)	This criterion is derived through an analysis of a potential-to-kinetic energy conversion between clear and cloudy layers.
DK	$\Delta_a < 0$	Duynkerke (1993)	This criterion is derived by consideration of the total buoyancy of a parcel per unit mass of entrained air. It reduces to the RD criterion with large liquid water content.
LL	$\frac{-L\Delta r}{c_p\Delta\theta_l} > \kappa_L$	Lilly (2002)	This criterion is derived from the dependency of the buoyancy flux on the entrainment rate in Lilly's (2002) new entrainment rate parameterization. The value of κ_L decreases with lower cloud base height and larger cloud-top wetness. In a limit, it reduces to the RD criterion.

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Yamaguchi and Randall (2008) *Large-eddy simulation of evaporatively driven entrainment in cloud-topped mixed layers*

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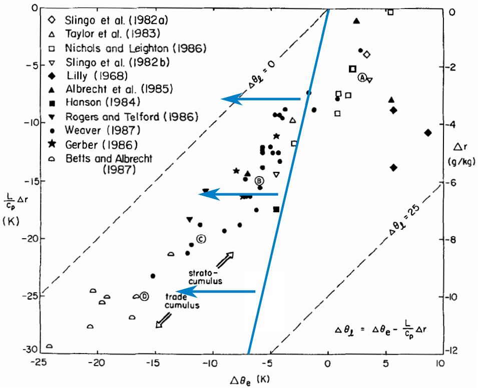
Does CTEI cause SCu breakup?

No



"Two thirds of the stratocumulus observations [...] are at odds with the predictions of the thermodynamic theory of CTEI."

Kuo and Schubert (1988) *Stability of Cloud-topped Boundary Layers*

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Does CTEI cause SCu breakup?
No

"this phenomenon does not appear to occur in the range of hydrodynamic parameters characteristic of mixing at the inversion capping a subtropical stratocumulus cloud layer. Thus it appears unlikely that CEI triggers stratocumulus breakup."

Siems et al. (1990)
Buoyancy reversal and cloud-top entrainment instability

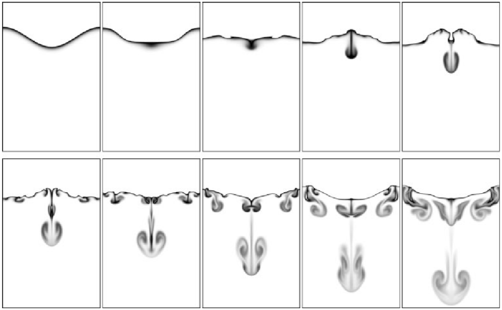
"Since the positive feedback of CTEI is weak, cloud breakup is not expected when the clouds are strongly maintained by other processes."

Yamaguchi and Randall (2008)
Large-Eddy Simulation of Evaporatively Driven Entrainment in Cloud-Topped Mixed Layers

Does CTEI cause SCu breakup?

No

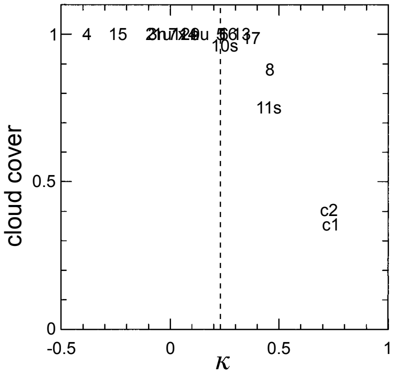
“These simulations [...] show that convoluted flow patterns can be generated by the evaporative cooling even for the low levels of buoyancy reversal found in stratocumulus clouds. They also show that there is no enhancement of turbulent entrainment of upper-layer fluid [...]”



Mellado et al. (2009) *Buoyancy reversal in cloud-top mixing layers*

Does CTEI cause SCu breakup?

... or yes?



"For cloud fraction and LWP, buoyancy reversal measured by the CTEI parameter κ [...] is found to be the most controlling mechanism when the Randall–Deardorff CTEI criterion is satisfied."

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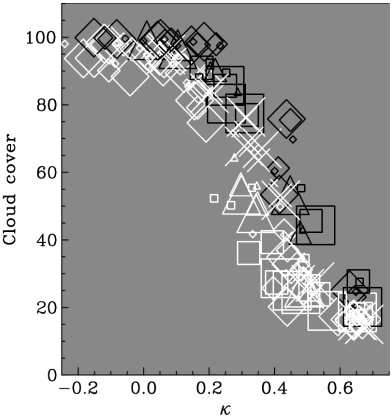
Moeng (2000) *Entrainment rate, cloud fraction, and liquid water path of PBL stratocumulus clouds*

Does CTEI cause SCu breakup?

... or yes?



- Lock (2009) peformed many LESs varying Δq_t and $\Delta\theta_\mathrm{l}$
- Different symbols denote LES sensitivity experiments
- Symbol size increases with time

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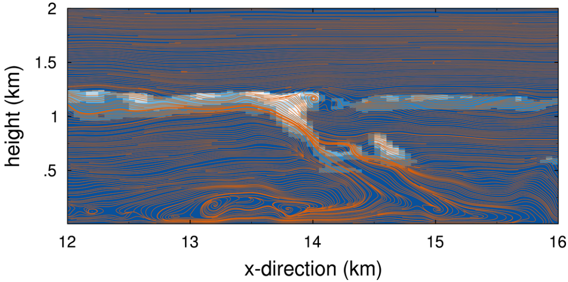
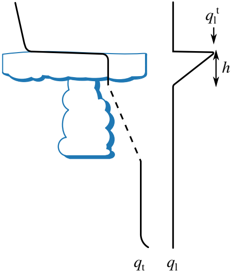
Lock (2009) *Factors Influencing Cloud Area at the Capping Inversion for Shallow Cumulus Clouds*

LWP budget

Equation for LWP tendency of SCu

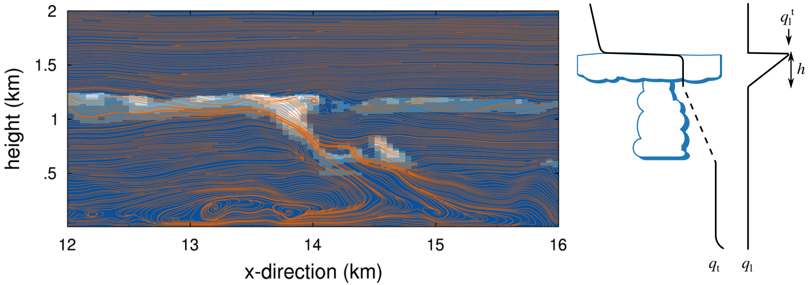




Wood and Bretherton (2004) *Boundary layer depth, entrainment, and decoupling in the cloud-capped subtropical and tropical marine boundary layer*

LWP budget

Equation for LWP tendency of SCu



$$\frac{\partial \mathrm{LWP}}{\partial t} = \mathrm{Ent} + \mathrm{Base} + \mathrm{Rad} + \mathrm{Prec} + \mathrm{Subs}$$

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Van der Dussen, de Roode and Siebesma (2013)
Factors controlling rapid stratocumulus cloud thinning

LWP tendency due to entrainment

$$\left.\frac{\partial \mathrm{LWP}}{\partial t}\right|_{\mathrm{Ent}} = \rho \eta w_{\mathrm{e}} \left(\Delta q_{\mathrm{t}} - \Pi \gamma \Delta \theta_{\mathrm{l}} - \frac{h \Gamma_{q_{\mathrm{l}}}}{\eta} \right)$$

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LWP tendency due to entrainment

Substitute out Δq_t using definition κ

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$$\Downarrow \qquad \kappa \equiv 1 + \frac{c_p}{L_\mathrm{v}} \frac{\Delta \theta_\mathrm{l}}{\Delta q_\mathrm{t}}$$

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$$\Downarrow \qquad \kappa \equiv 1 + \frac{c_p}{L_v} \frac{\Delta \theta_l}{\Delta q_t}$$

$$\left.\frac{\partial \mathrm{LWP}}{\partial t}\right|_{\mathrm{Ent}} = \rho \eta w_e \left(\frac{c_p}{L_v} \frac{\Delta \theta_l}{\kappa - 1} - \Pi \gamma \Delta \theta_l - \frac{h \Gamma_{q_l}}{\eta} \right)$$

Results

Assume simple entrainment relation

$$w_\mathrm{e} = A\frac{\delta F_\mathrm{rad}}{\Delta\theta_\mathrm{l}}$$

- no dependence Δq_t
- constant entrainment efficiency A

Stevens et al. (2005) Evaluation of Large-Eddy Simulations via Observations of Nocturnal Marine Stratocumulus

Results

Assume simple entrainment relation

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- no dependence Δq_{t}
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$$\left.\frac{\partial \mathrm{LWP}}{\partial t}\right|_{\mathrm{Ent}} = \rho\eta A\delta F_{\mathrm{rad}}\left(\frac{c_p}{L_{\mathrm{v}}}\frac{1}{\kappa - 1} - \Pi\gamma - \frac{h\Gamma_{q_{\mathrm{l}}}}{\eta\Delta\theta_{\mathrm{l}}}\right)$$

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Results

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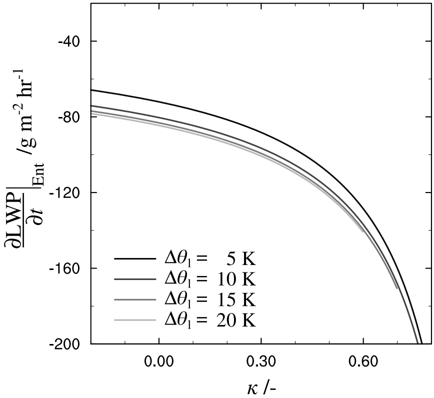

- no dependence Δq_t
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$$\left.\frac{\partial \mathrm{LWP}}{\partial t}\right|_\mathrm{Ent} = \rho\eta A\delta F_\mathrm{rad}\left(\frac{c_p}{L_\mathrm{v}}\frac{1}{\kappa-1} - \Pi\gamma - \frac{h\Gamma_{q_\mathrm{l}}}{\eta\Delta\theta_\mathrm{l}}\right)$$

Results

What about other processes?

$$\frac{\partial \mathrm{LWP}}{\partial t} = 0 = \mathrm{Ent} + \mathrm{Base} + \mathrm{Rad} + \mathrm{Prec} + \mathrm{Subs}$$

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Results

What about other processes?

$$\frac{\partial \mathrm{LWP}}{\partial t} = 0 = \mathrm{Ent} + \mathrm{Base} + \mathrm{Rad} + \mathrm{Prec} + \mathrm{Subs}$$

Equations define equilibrium set of inversion jumps $(\Delta q_{\mathrm{t}}^{*},\ \Delta\theta_{\mathrm{l}}^{*})$

$$\Delta q_{\mathrm{t}}^{*} = f\left(\Delta\theta_{\mathrm{l}}^{*}, \overline{w' q_{\mathrm{t}}'}(z_{\mathrm{b}}), A, \ldots\right)$$

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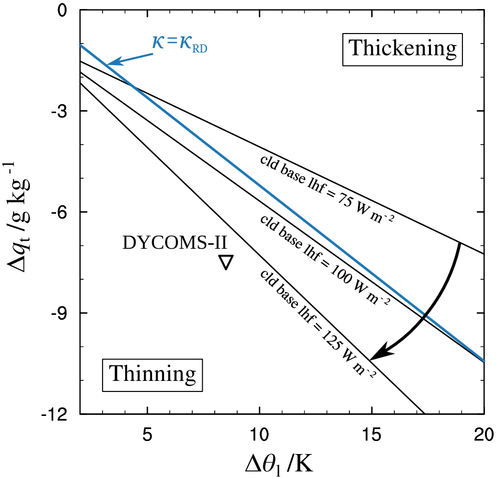
Results

What about the other processes?



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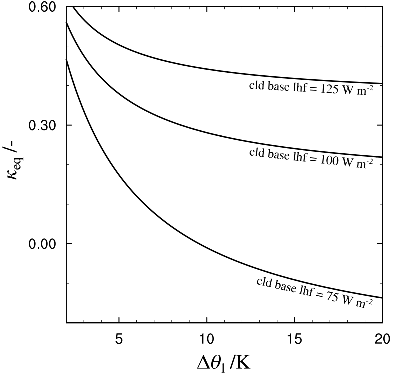
Results

Equilibrium value of κ

$$\kappa = 1 + \frac{c_p}{L_\mathrm{v}} \frac{\Delta\theta_\mathrm{l}}{\Delta q_\mathrm{t}}$$ is used to substitute out Δq_t



κ_eq not constant, but depends mainly on $\overline{w'q'_\mathrm{t}}(z_\mathrm{b})$

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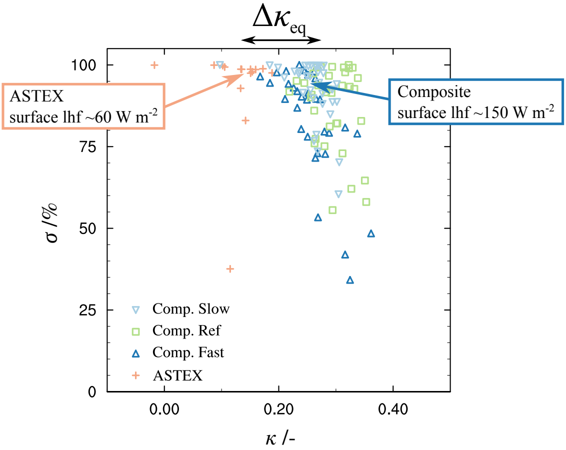
Discussion

Qualitative agreement with LES results of transition cases



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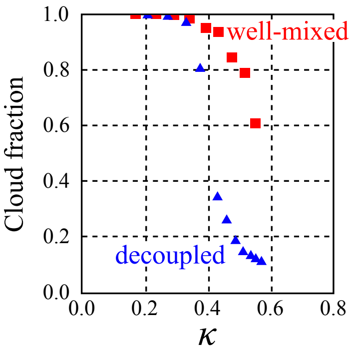
Discussion
Effect of decoupling

Reduced moisture flux from surface to cloud layer lowers κ_{eq}



Xiao et al. (2010) *Buoyancy reversal, decoupling and the transition from stratocumulus to shallow cumulus topped marine boundary layers*

Summary

- Cloud thinning for $\kappa \rightarrow 1$ can be expected on the basis of pure budget arguments

- The κ-value beyond which the cloud layer thins, is not a constant but depends on among others the surface latent heat flux