Stratocumulus Cloud Thinning

Influence of Inversion Stability

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Evaporative cooling can cause entrained parcels to become negatively buoyant.

Theory: buoyancy reversal leads to runaway entrainment → rapid breakup of cloud layer.
Occurrence of CTEI described using inversion properties $\Delta q_T$ and $\Delta \theta_L$:

$$\kappa = 1 + \frac{c_p}{L_v} \frac{\Delta \theta_L}{\Delta q_T} > 0.23.$$  

Criterion derived by Randall (1980) and Deardorff (1980).
“Two thirds of the stratocumulus observations lie to the left of the critical curve and hence are at odds with the predictions of the thermodynamic theory of cloud top entrainment instability.”

“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 CTEI 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*
Introduction
Nevertheless strong relation between $\kappa$ and cloud cover

- Different symbols denote LES sensitivity experiments
- Symbol size increases with time
- Many simulations with different $\Delta q_T$ and $\Delta \theta_L$

Note: transition is smooth rather than abrupt

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

See also SCM results presented at EUCLIPSE meeting in Paris by Roel Neggers
Theory
Budget for stratocumulus LWP

- Assume well-mixed, adiabatic stratocumulus layer
- Include
  - entrainment
  - cloud base fluxes
  - precipitation
  - radiation
  - large scale subsidence

Wood and Bretherton (2004)
*Boundary Layer Depth, Entrainment, and Decoupling in the Cloud-Capped Subtropical and Tropical Marine Boundary Layer*
Theory
Contributions to LWP budget

\[
\frac{\partial \text{LWP}}{\partial t} = \text{Ent} + \text{Base} + \text{Rad} + \text{Prec} + \text{Subs}
\]

Van der Dussen, de Roode and Siebesma (2013)
Factors controlling rapid stratocumulus cloud thinning
(under review)
Theory
Contributions to LWP budget

\[ \frac{\partial \text{LWP}}{\partial t} = \text{Ent} + \text{Base} + \text{Rad} + \text{Prec} + \text{Subs} \]

\begin{align*}
\text{Ent} &= \rho w_e (\eta \Delta q_T - \Pi \gamma \eta \Delta \theta_L - h_c \Gamma q_L) \\
\text{Base} &= \rho \eta \left( \frac{w' q'_T}{b} - \Pi \gamma w' \theta'_L \right) \\
\text{Rad} &= \rho \eta \gamma \delta \hat{F}_r \\
\text{Prec} &= -\rho \delta \hat{F}_p \\
\text{Subs} &= -\rho h_c \Gamma q_L \bar{w}(z_i)
\end{align*}

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Results

LWP tendency due to entrainment

\[ \text{Ent} = \rho w_e (\eta \Delta q_T - \Pi \gamma \eta \Delta \theta_L - h_c \Gamma q_L) \]

Substitute definition \( \kappa \):

\[ \left. \frac{\partial \text{LWP}}{\partial t} \right|_{\text{Ent}} = \rho \eta w_e \left( \frac{c_p}{L_v} \frac{\Delta \theta_L}{\kappa - 1} - \Pi \gamma \Delta \theta_L - \frac{h_c \Gamma q_L}{\eta} \right) \]

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Results
LWP tendency due to entrainment

Substitute simple entrainment relation*:

\[ w_e = A \frac{\delta \hat{F}_r}{\Delta \theta_L} \]

- \( A \) assumed constant 1.3
- no dependency on \( \Delta q_T \)

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

What about the other processes?

Find zeros of LWP tendency equation:

\[
\frac{\partial \text{LWP}}{\partial t} = 0 = \text{Ent} + \text{Base} + \text{Rad} + \text{Prec} + \text{Subs}
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What about the other processes?

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Equations define equilibrium set of inversion jumps ($\Delta q_T^*, \Delta \theta_L^*$)

$$\Delta q_T^* = f \left( \Delta \theta_L^*, w' q_T^b, A, \ldots \right)$$
Results

What about the other processes?

$\kappa = 0.23$

DYCOMS-II

Stratocumulus Cloud Thinning
Results
Equilibrium value of $\kappa$

$$\kappa = 1 + \frac{c_p}{L_v} \frac{\Delta \theta_L}{\Delta q_T}$$

is used to substitute out $\Delta q_T$

$\kappa^*$ is not a constant, but depends on many parameters (mainly $w'q_T^b$)
Discussion
Qualitative agreement with LES results of transition cases

ASTEX
surface lhf ~ 60 W/m²

Composites
surface lhf ~ 150 W/m²

Δκ*

ASTEX
surface lhf ~ 60 W/m²

Composites
surface lhf ~ 150 W/m²

Stratocumulus Cloud Thinning
Discussion
Effect of decoupling

Reduced moisture flux from surface to cloud layer lowers $\kappa^*$

Xiao et al. (2010)
Buoyancy Reversal, Decoupling and the Transition from Stratocumulus to Shallow Cumulus Topped Marine Boundary Layers
Thanks for your attention!

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