Simple Solutions to Equilibrium Cumulus Regimes in the Convective Boundary Layer

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Introduction

While our understanding of many detailed cloud processes has significantly increased over the past decades, the interplay between the cumulus-capped boundary layer and large-scale atmospheric tendencies and surface properties is still poorly understood. This work attempts a very simple modeling approach with the aim to set up a framework for studying the response of cumuliform clouds to these forcings.

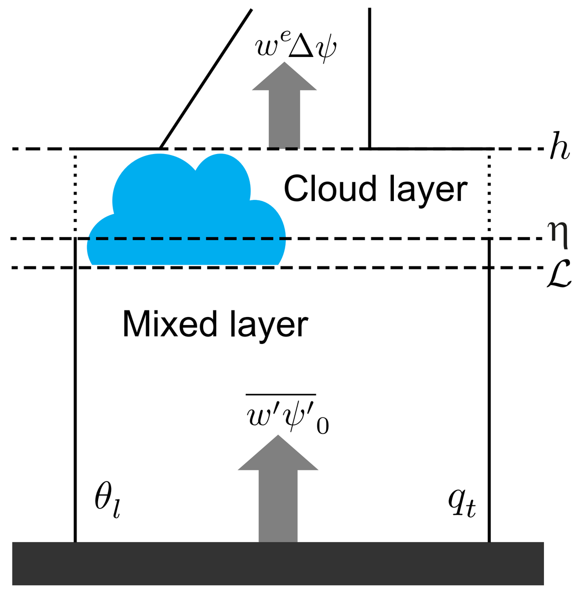
Model

In equilibrium, the standard mixed-layer equations can be shown to be valid also in the case of cumulus convection:

$$\frac{\partial h}{\partial t} = 0 = w^e - w^s$$

$$\frac{\partial \theta_l}{\partial t} = 0 = \frac{w^e \Delta\theta_l + \overline{w'\theta_l'}_0}{h} + S_{\theta_l}$$

$$\frac{\partial q_t}{\partial t} = 0 = \frac{w^e \Delta q_t + \overline{w'q_t'}_0}{h} + S_q$$



The model is closed by assuming the entire boundary layer in quasy-steady state, such that the entrainment relates to the 'dry' virtual potential temperature flux:

$$w^e = \frac{\overline{w'\theta_{vd}'}_0}{\Delta\theta_{vd}}\left[(1+\kappa)\frac{h}{\eta} - 1\right] \quad \text{for} \quad h \geq \eta$$

Equilibrium solution

The model can readily be solved for the equilibrium values (^), dependent on surface and free atmosphere:

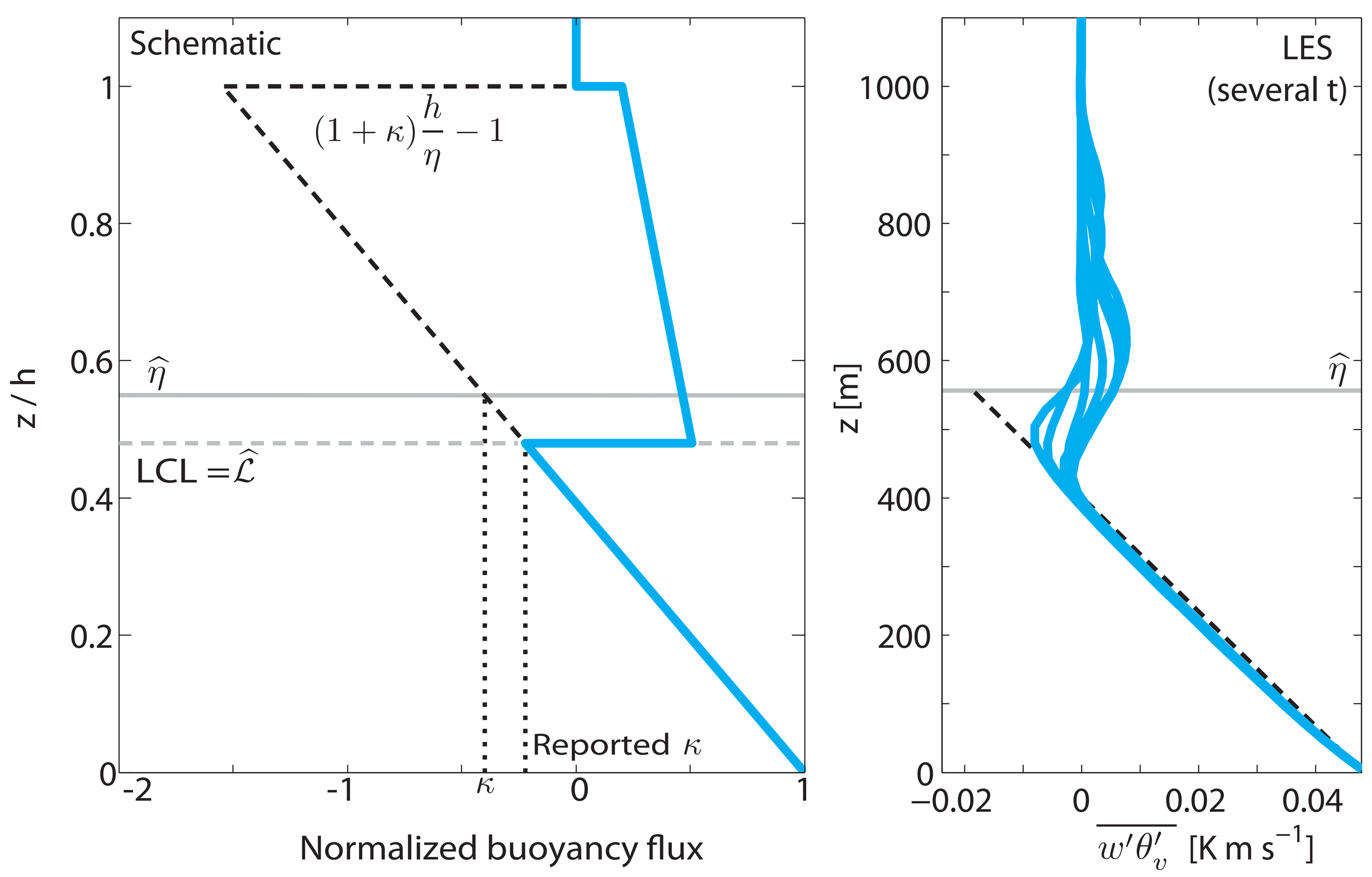
$$\hat{\theta}_l = \theta_l^{f0} + \frac{\overline{w'\theta_l'}_0}{w^s}$$

$$\hat{q}_t = q_t^{f0} + \frac{\overline{w'q_t'}_0}{w^s}$$

However, the third equations predicts an equilibrium 'mixed layer height' $\hat\eta$ which is in general not equal to the lifting condensation level $\hat{\mathcal{L}}$ following from the above equilibrium values:

$$\hat\eta = -\frac{\overline{w'\theta_{vd}'}_0(1+\kappa)}{S_{\theta_{vd}}} \qquad \hat{\mathcal{L}} = f(q_{sat}(\hat\theta_l, p_s), \hat q_t)$$

LES evidence (figure below) suggests that the slope of the buoyancy flux is *dynamically* set through $\hat\eta$, whereas the actual cloud base height is *thermodynamically* set through $\hat{\mathcal{L}}$.

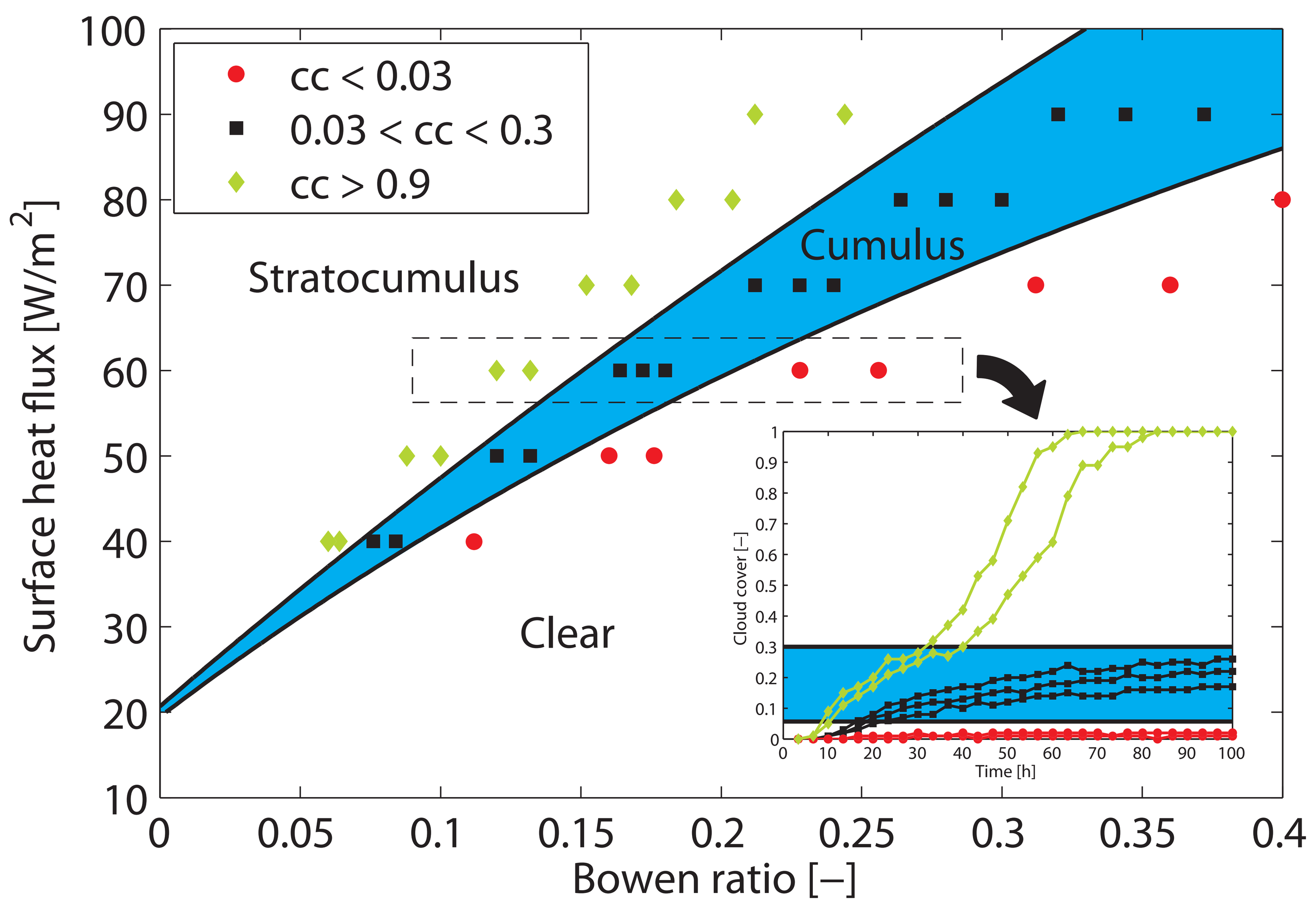


Cloud regimes

The key idea is that $\hat\eta$ and $\hat{\mathcal{L}}$ are independent, and together 'draw' the buoyancy flux profile. This allows for the identification of different regimes, depending on the expected minimum in buoyancy flux.

$$\begin{array}{llll} \hat{\mathcal{L}} \geq \hat\eta & : & & \textit{clear} \\ \hat{\mathcal{L}} < \hat\eta < (1+\kappa)\hat{\mathcal{L}} & : & \overline{w'\theta_v'}^{min} < 0 & \textit{decoupled} \\ \hat\eta \geq (1+\kappa)\hat{\mathcal{L}} & : & \overline{w'\theta_v'}^{min} \geq 0 & \textit{coupled} \end{array}$$

These distinctions allow for an immediate identification of equilibrium 'cloud regimes' *à priori*.
LES results (points) show a striking resemblance to the analytical solutions (shaded areas).



Conclusions

The presence of cumulus cloud inhomogeneity in itself does not invalidate the mixed-layer approach. By comparing the thermodynamical and dynamical tendencies set by external forcings, an estimate can be made of the equilibrium cloud state of the boundary layer, which is successfully reproduced by LES.

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