Slow Manifolds and Multiple Equilibria in Cloud-Topped Boundary Layers

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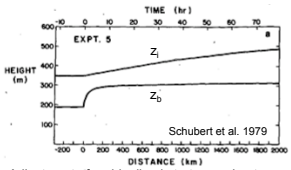
- Subtropical cloud-topped boundary layers (CTBLs) typically have a thermodynamic adjustment timescale of less than a day, but a multiday inversion adjustment timescale.
- Analysis of a mixed-layer model and LES of a steadily-forced idealized Sc layer imply that on this longer timescale, the CTBL structure collapses onto one or more slow manifolds which may evolve toward steady equilibria.
- Slow manifold behavior may also be approximated in realistic CTBLs subject to synoptically varying forcings and is relevant to POC dynamics.

Adjustment timescales in a Sc mixed layer

Thermodynamic $t_{fast} = z_i/(w_s+w_e) \sim 0.5$ d

Inversion $t_{inv} = D^{-1} \sim 3$ d



z_i: inversion height
z_b: cloud base
w_s: surface exchange velocity
w_e: entrainment rate
D: large-scale divergence

Adjustment of an idealized stratocumulus-topped mixed layer to a sudden 2 K SST increase at t = 0. Note fast 'thermodynamic' adjustment of cloud base but slow adjustment of inversion z_i

The slow manifold concept

After thermodynamic adjustment ($t >> t_{fast}$) the entire CTBL structure and entrainment rate are slaved to the slowly-evolving $z_i(t)$ and the boundary conditions. This functional dependence is a *slow manifold* (Leith 1980).

An idealized test case for MLM and LES

GCSS DYCOMS-II RF01 case (Stevens et al. 2005 MWR)
- Nonprecipitating well-mixed nocturnal Sc
- Entrainment rate, liquid water path, turbulence well-observed.
- Initialized with cloud-topped mixed layer, z_i = 840 m, N = 150 cm^{-3}.
- Linear θ, moisture profiles above cloud layer, initial Δθ = 9 K.
- D = 3.75x10^{-6} s^{-1}, SST = 292.5 K
- Simplified dependence of radiative cooling on cloud structure

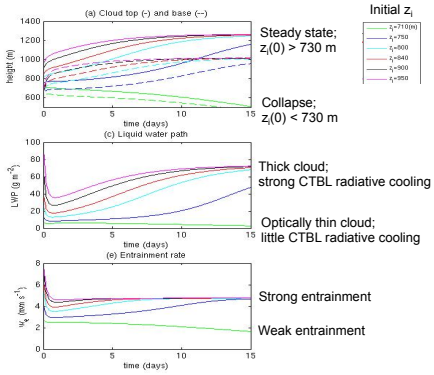
MLM: Caldwell et al. (2009) with LES-tuned entrainment and drizzle

LES: SAM6.7, Δx = Δy = 25 m, Δz = 5 m up to 1500 m, $L_x = L_y$ = 2.4 km, periodic BCs (More details: Uchida et al. 2010, ACP).

New twists

- Compare different initial $z_i(t = 0)$ but with the same mixed layer θ and humidity.
- Run MLM and LES 15 days; look for slow evolution and steady states.
- Use only MLM runs with BIR < 0 at all times. These runs have ~ no cloud base drizzle.
- Calibrate MLM entrainment closure to LES (more efficient entrainment than observed).

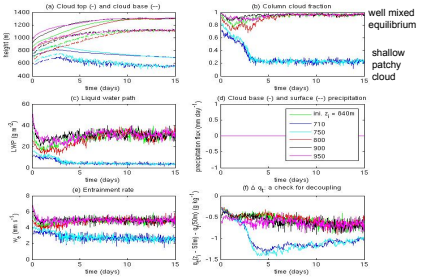
MLM time series show two evolution paths



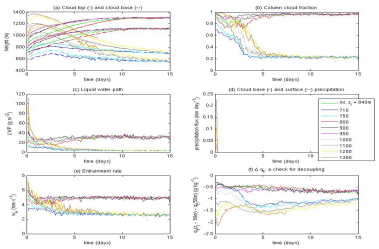
LES time series

Like MLM, LES has two possible evolutions depending on $z_i(0)$. A first demonstration of multiple equilibria in LES of CTBL.

Plot 1: Same range of $z_i(0)$ as MLM.
770 m< $z_i(0)$ < 970 m: thicken to steady Sc
$z_i(0)$ < 770 m: collapse to partly-cloudy steady state



Plot 2: $z_i(0)$ > 970 m: Decouple, collapse to partly-cloudy steady state

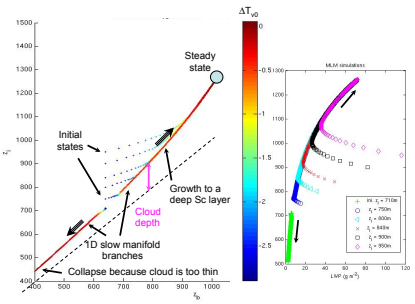


Slow manifolds and pockets of open cells

Across a POC edge, two cloud regimes (slow manifolds?) interact as shown at right. The broken cloud regime entrains less than the solid cloud regime, but compensating vertical motions keep the strong inversion flat and lock the inversion heights in the two regimes together (Berner et al. 2011 ACP).

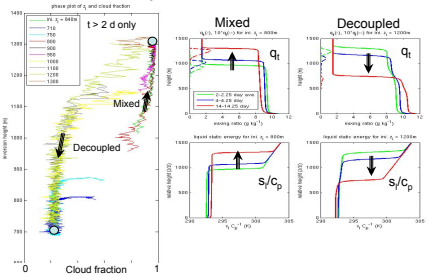
That is… two branches of a slow manifold

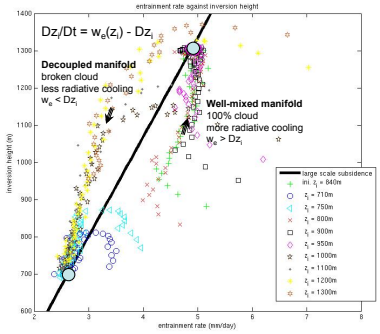
- Visualize by plotting variables vs. z_i hourly

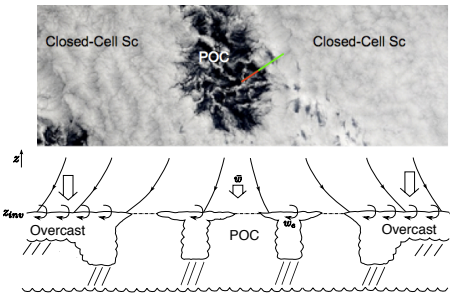


LES slow manifold description

- Two manifolds, one well-mixed/solid and one decoupled/partly cloudy, each evolving toward a steady state.







Conclusions

- Fast thermodynamic adjustment slaves CTBL evolution to the slowly-evolving inversion height and boundary/forcing conditions.
- A MLM and LES both show slow manifold behavior with collapse of initially optically thin cloud layers while deeper cloud layers thicken into a deep steady state.
- The LES shows separate mixed and decoupled slow manifolds, each evolving toward its own steady state.

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To learn more, see:

Bretherton et al., 2010: *JAMES*, **2**, Art. #14