Stratocumulus radiative effect and multiple equilibria of the boundary layer

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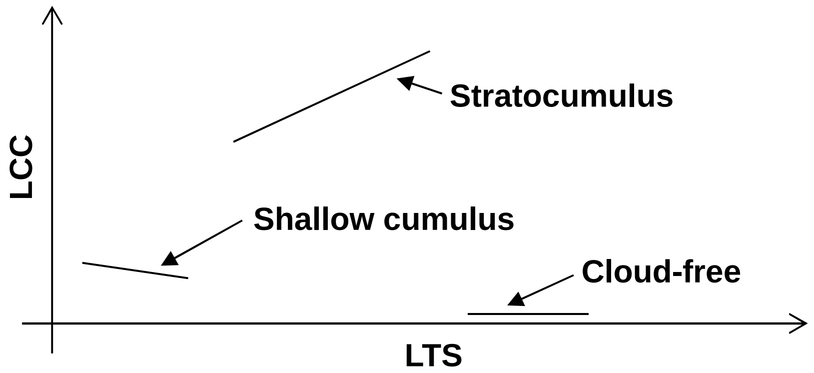
Thanks to: Olivier Geoffroy, Bjorn Stevens (+ Aneto)

Introduction

- ✓ **Low clouds: who here needs convincing?**

- ✓ **Original motivations:**

  - ➢ **explore with a LES the dependency of the equilibrium low cloud cover and thickness to large-scale conditions;**



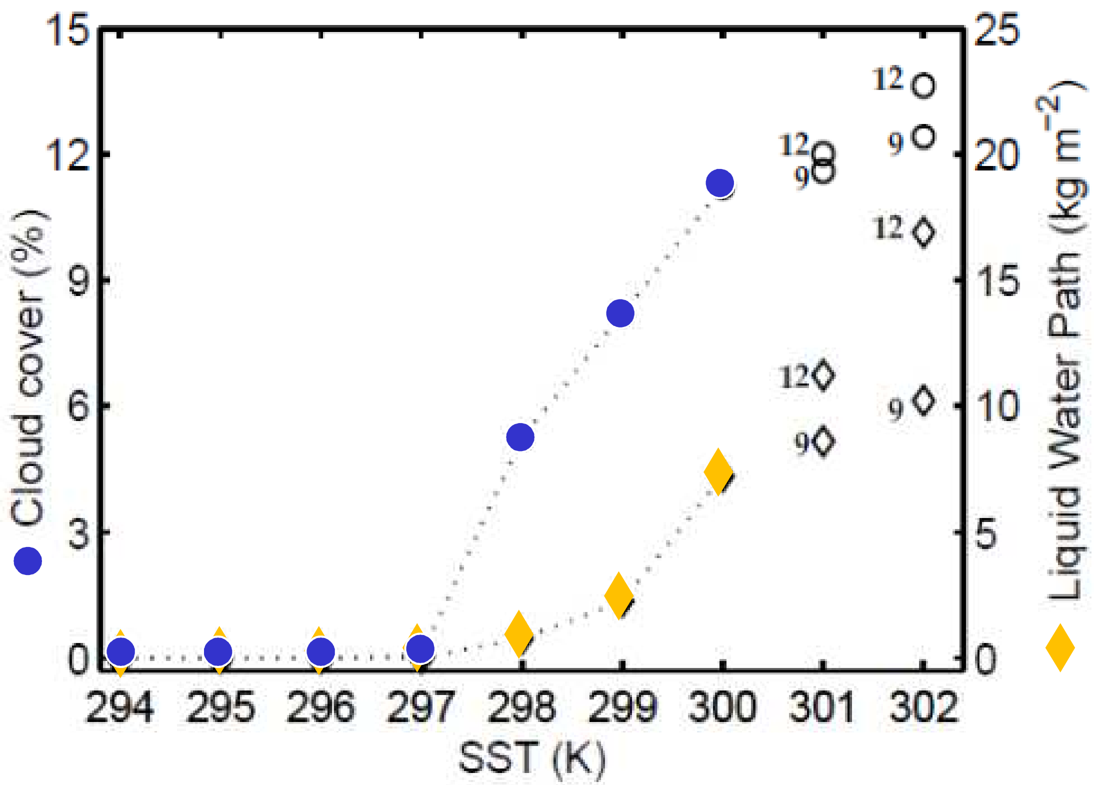
  - ➢ **try to constrain parameterizations, and ultimately cloud feedbacks in climate projections.**

- ✓ **Subsequent motivation:**

  - ➢ **try to understand the local role of cloud radiative effect (CRE) in the boundary layer.**

The sensitivity to SST exhibits a transition from cloud-free to shallow-convective ABL

- ✓ **UCLA/MPI LES (non-precipitating),**
  resolution 50mx50mx10m, domain 6.4kmx6.4km(x0.5-4km)
- ✓ **Run to equilibrium (2 weeks if necessary)**
- ✓ **Fixed radiation: sensitivity of cloud cover / LWP to SST:**



How come there is no stratocumulus regime?

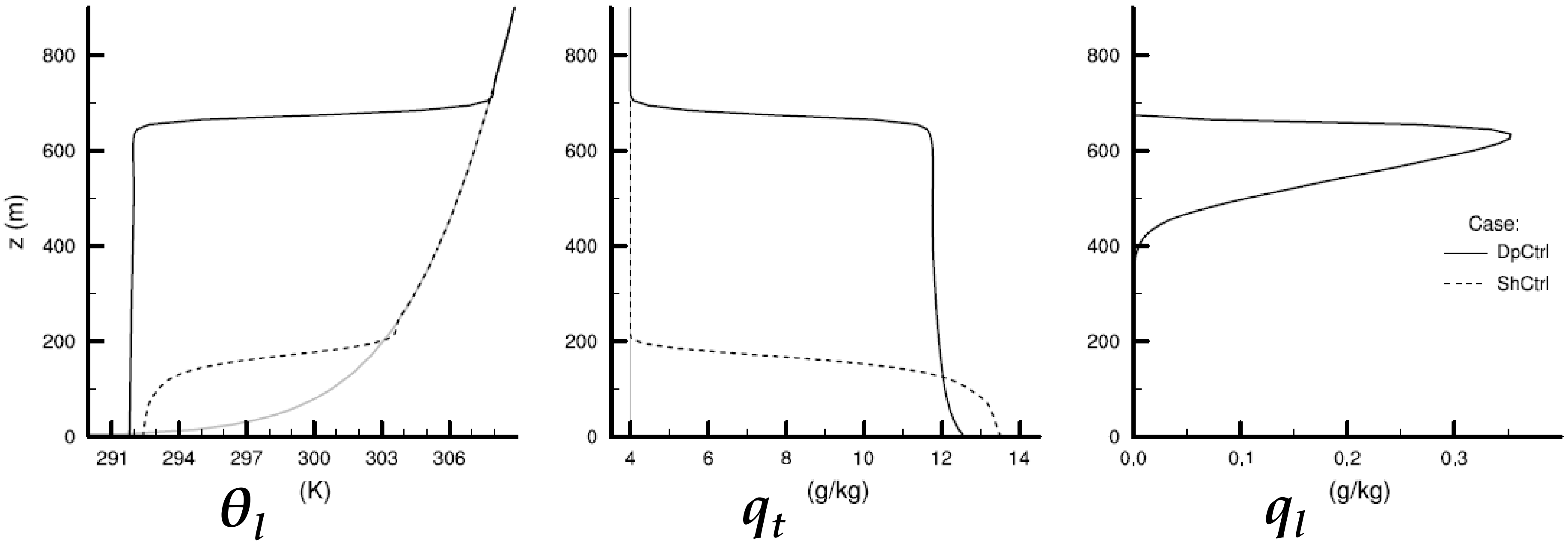
Interactive radiation yields multiple equilibria

- ✓ **Simplified cloud radiative effect (CRE) following GCSS:**

$$F_R = F_0 \exp(-\kappa LWP^+) + F_1 \exp(-\kappa LWP^-)$$

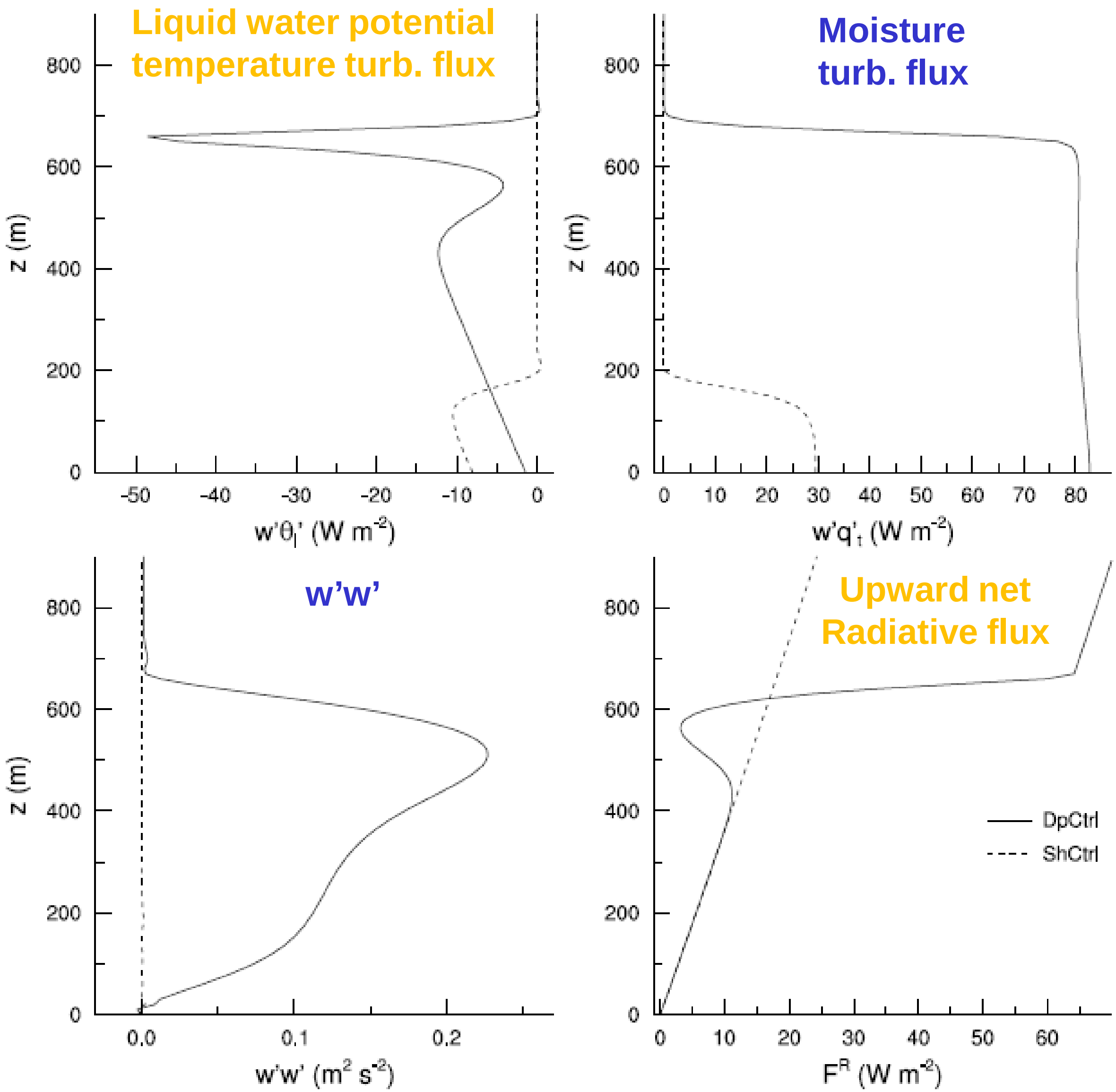
with $LWP^-(z) = \int_0^z q_l \rho dz$ **and** $LWP^+ + LWP^- = LWP$

- ✓ **Multiple equilibria (DpCtrl and ShCtrl):**



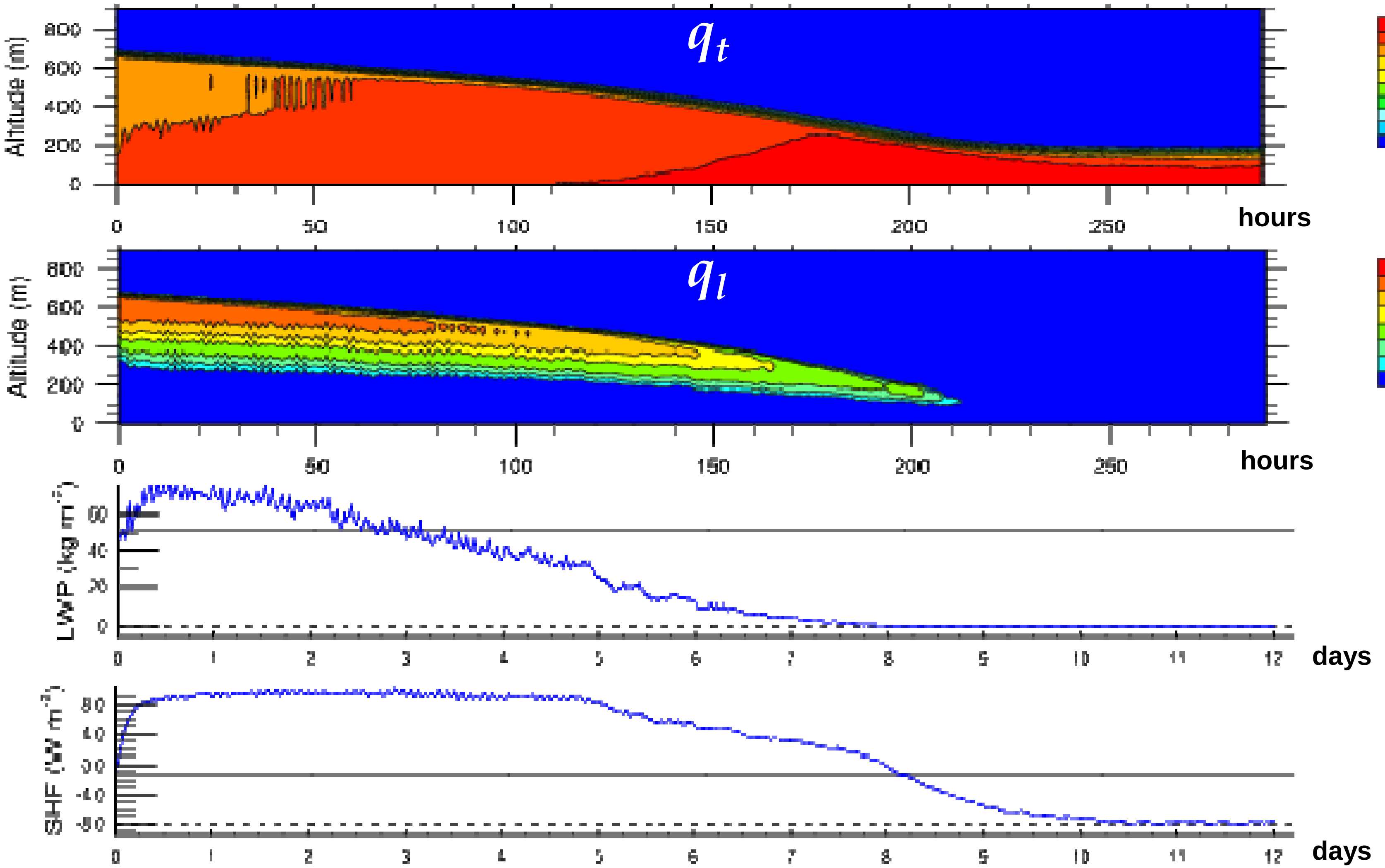
Interactive radiation yields multiple equilibria

- ✓ **Flux profiles :**



The vertical profile of CRE matters

If the CRE is vertically homogeneized in the boundary layer:



the stratocumulus equilibrium is destabilized

Simplifying profiles of CRE

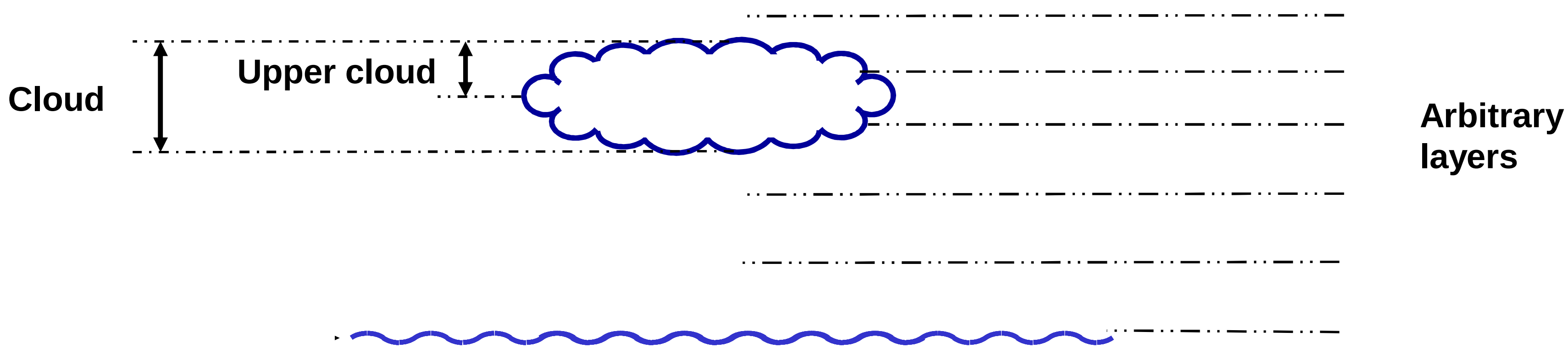
What is crucial to the simulation of stratocumulus in the vertical profile of CRE?

Three ways to explore that:

A. Simplify using physically-based layers (cloud, cloud top, etc.);

B. Simplify using arbitrary layers (as in larger-scale models);

C. A hybrid of A and B



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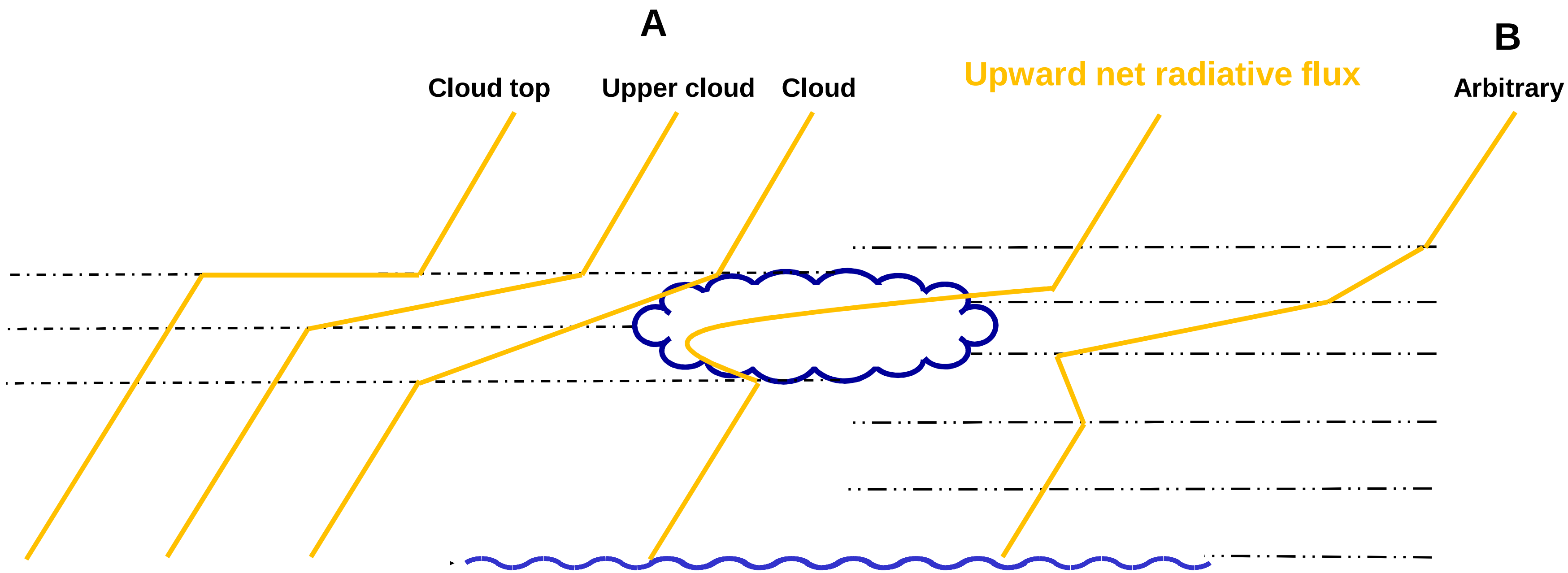
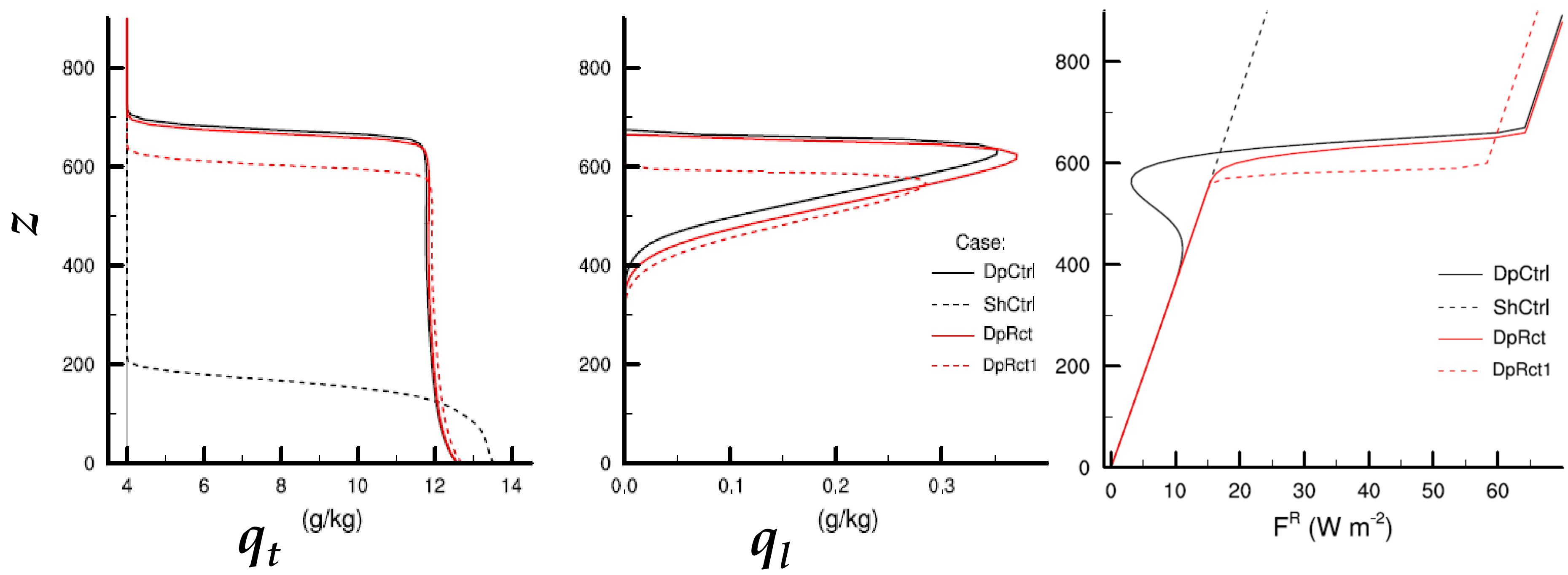


A. Simplifying profiles of CRE using physically-based layers

If the CRE is vertically homogeneized

- ✓ **in the cloud:** **the stratocumulus equilibrium is destabilized;**
- ✓ **in the upper cloud (DpRct):** **the stratocumulus equilibrium is stable:**

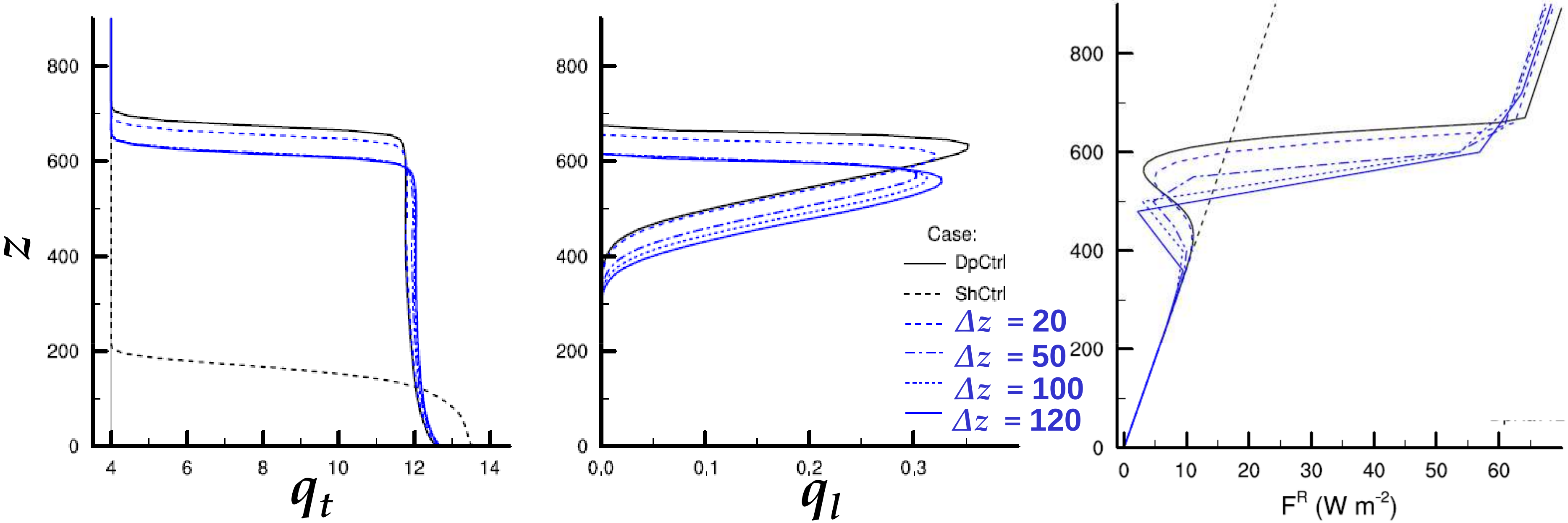
If the CRE is concentrated in a single LES layer at cloud top (DpRct1):
the stratocumulus equilibrium is stable, but thinner:



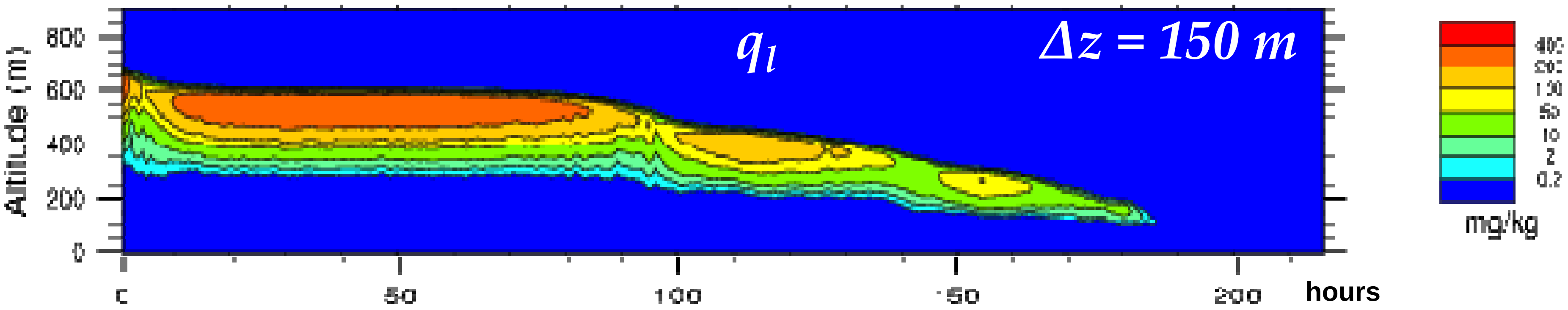
B. Simplifying profiles of CRE using arbitrary layers

If the CRE is vertically homogeneized over layers of $\Delta z = N$ * 10 meters:

For $\Delta z \leq 120$ m, the cloud top is anchored at a multiple of Δz

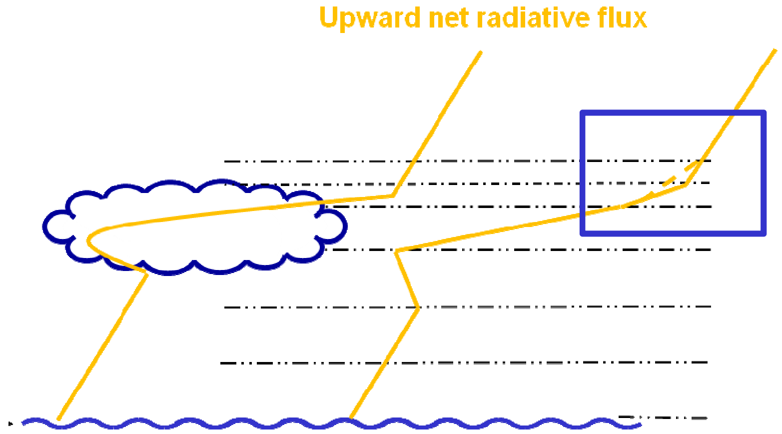


For $\Delta z > 120$ m, the stratocumulus equilibrium is destabilized for $\Delta z > 120$ m

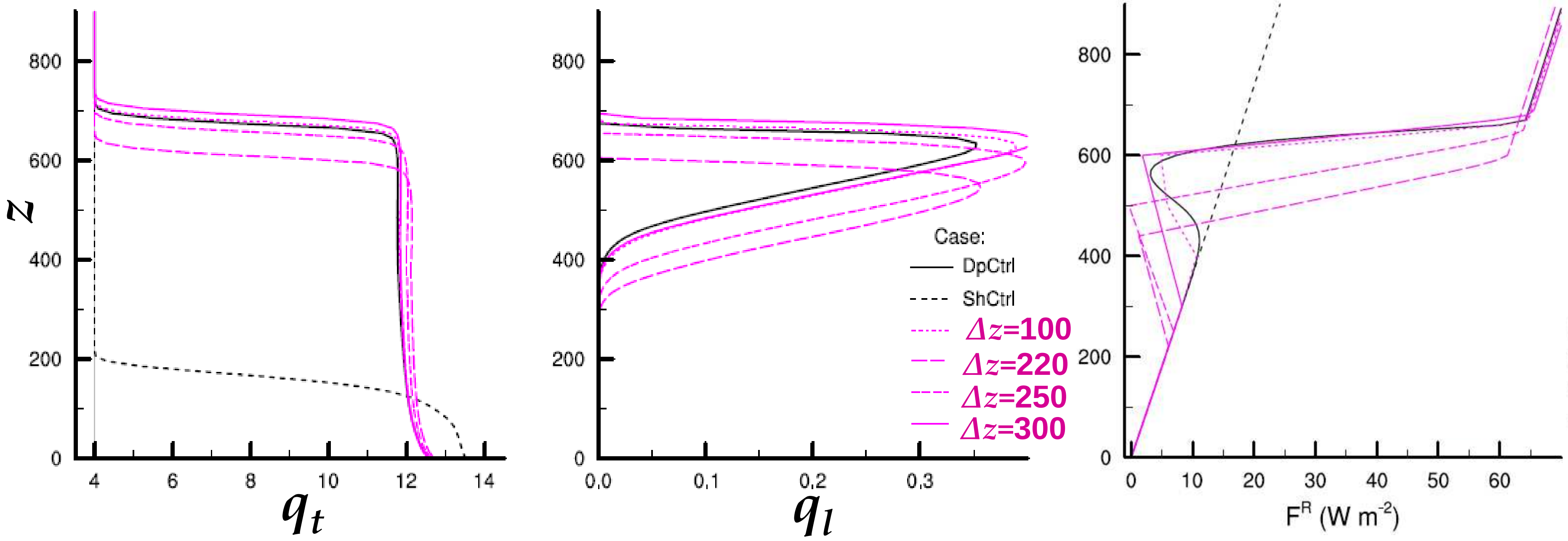


C. Simplified profiles of CRE using arbitrary layers plus cloud top

If the CRE is vertically homogeneized over layers of $\Delta z = N$ * 10 meters, except around cloud top where the layer is split in two:



the stratocumulus equilibrium is stable, but the cloud-top altitude is sensitive to Δz



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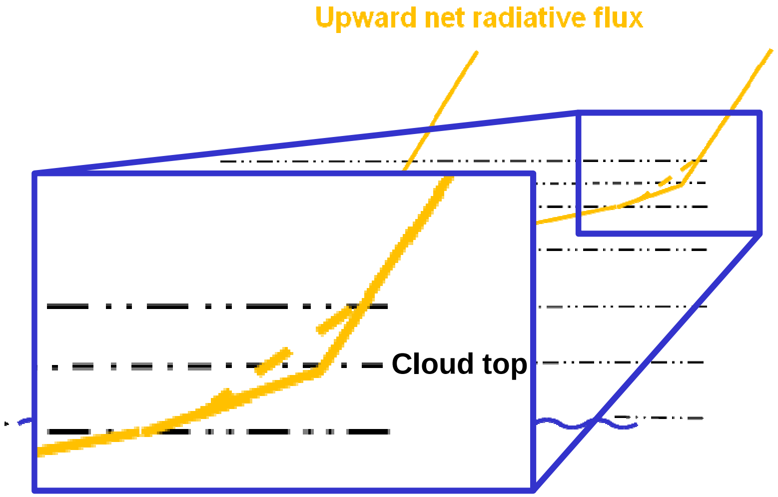

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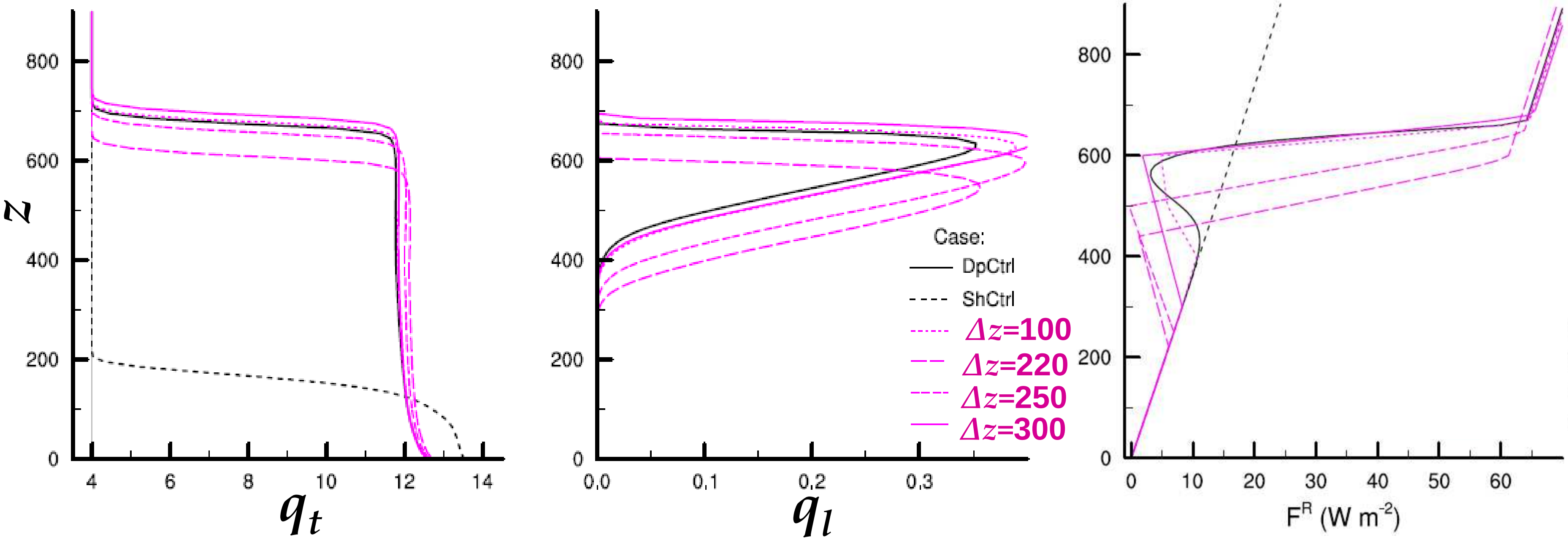

A few conclusions

- ✓ **What features of the SCu cloud radiative effect do we need?**
  - ➢ **Enough cloud-radiative cooling in the upper part of the cloud;**
  - ➢ **None above.**
- ✓ **Does it mean anything for parameterizations in larger-scale models?**
  - ➢ **The turbulence scheme has to feel a fairly detailed CRE profile at cloud top;**
  - ➢ **Explicitly: particular treatment of the model layer containing the cloud top;**
  - ➢ **Implicitly (e.g., via entrainment closure).**
  - ➢ **Projection of variables on empirical profiles in the boundary layer scheme;**
- ✓ **Unadddressed issues:**

  Horizontal averaging, time stepping.

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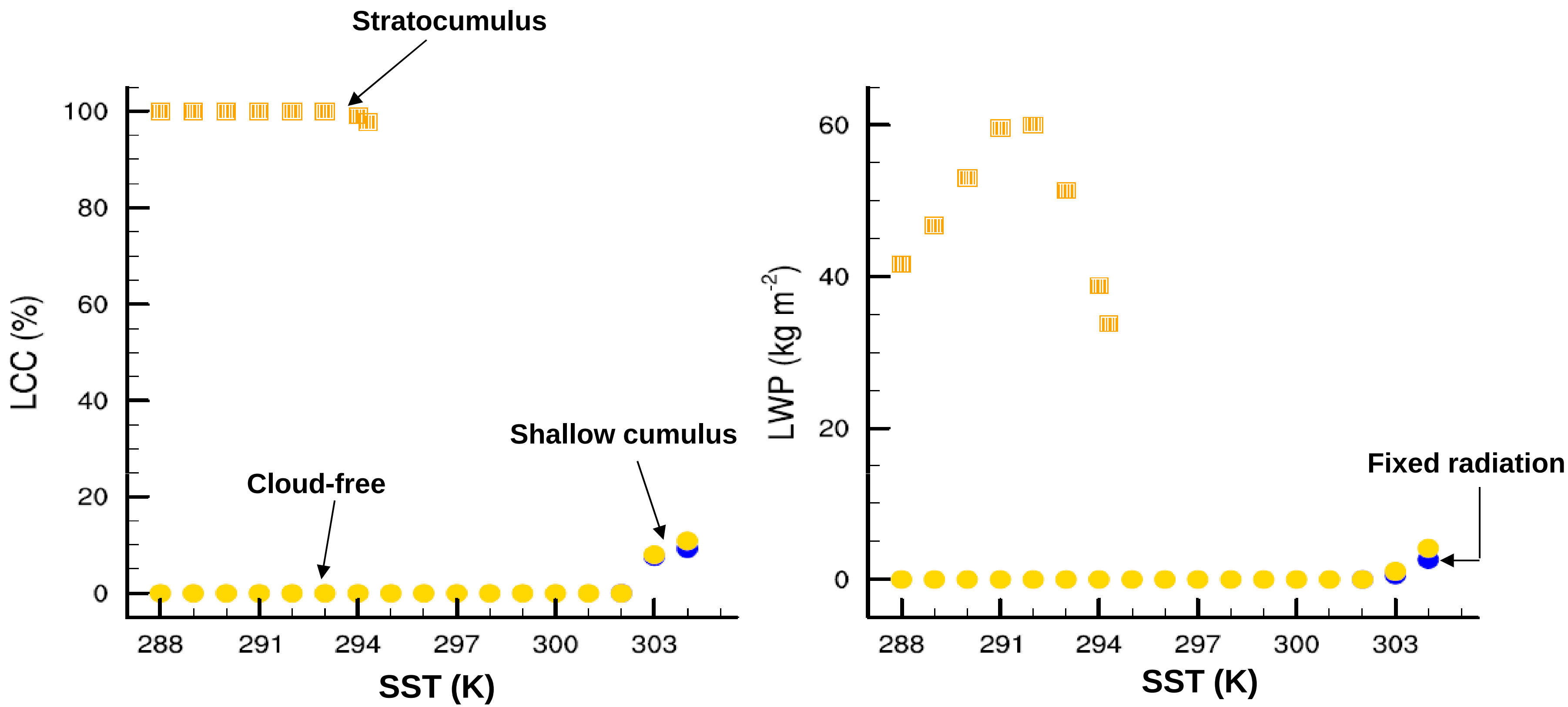
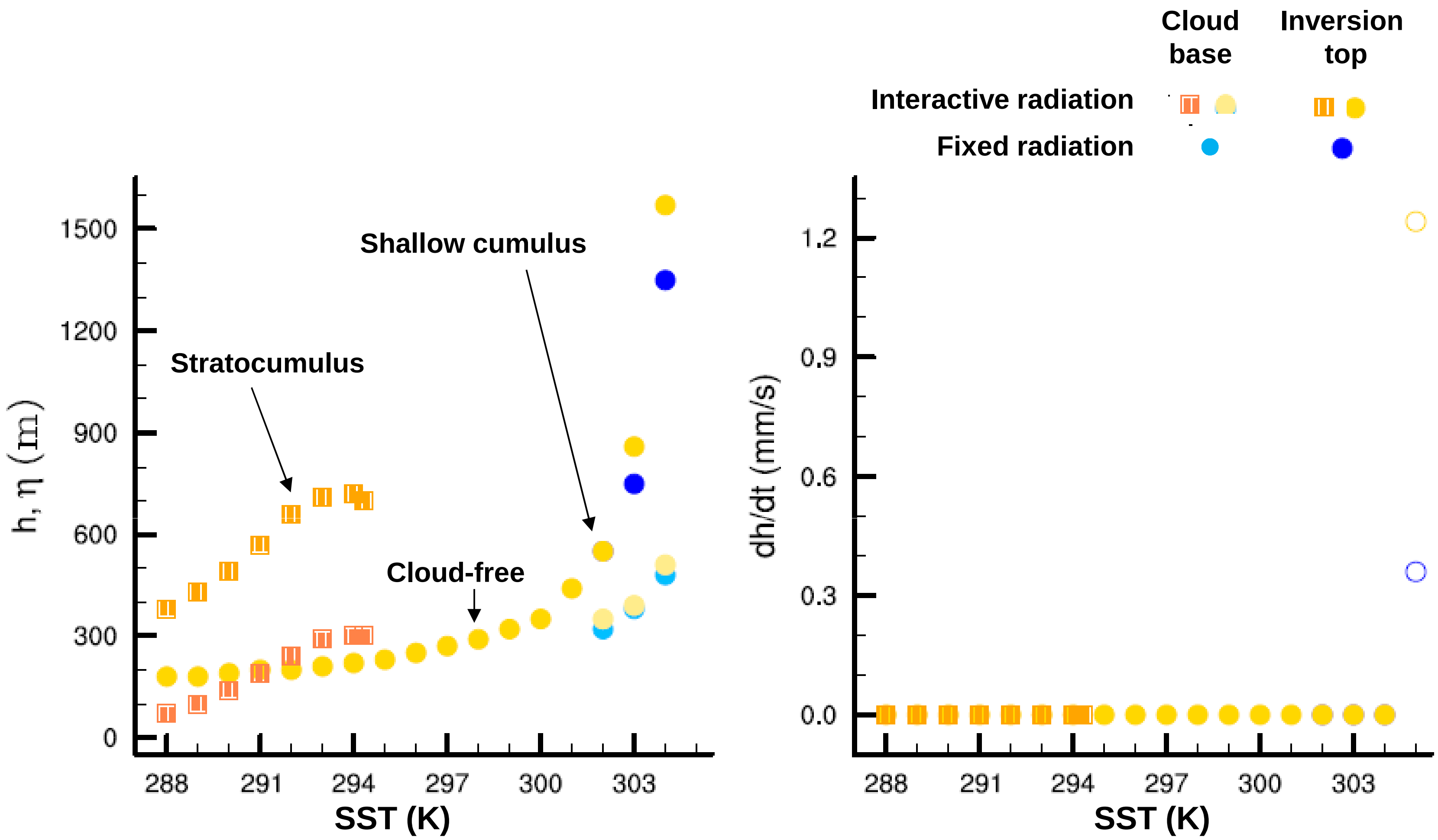
What happens to the sensitivity to SST?



- ✓ **The stratocumulus equilibrium is destabilized when the SST is increased;**
- ✓ **The shallow, cloud-free boundary-layer turns into a shallow-convective equilibrium;**
- ✓ **Interactive radiation increases the shallow-cumulus cloud cover.**

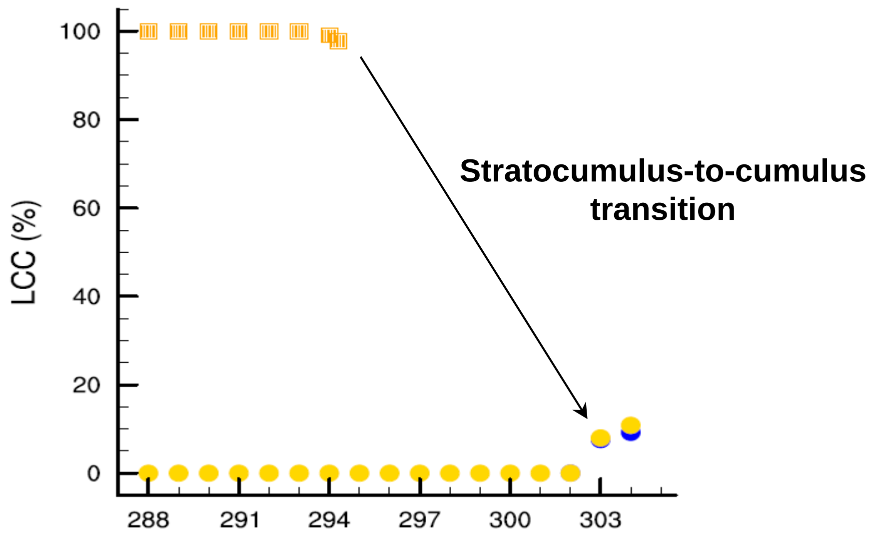
What happens to the sensitivity to SST?



- ✓ **Interactive radiation deepens the shallow-convective boundary layer and hastens its instability;**
- ✓ **The non-linear sensitivity of LWP is related to a lifting of the cloud layer.**

More conclusions

- ✓ **The stratocumulus-to-cumulus transition is a change of basin of attractions, far from equilibria:**



- ✓ **CRE**
  - ✓ **is crucial to the existence of equilibrium stratocumulus;**
  - ✓ **can account for up to 15-20% of the depth of the equilibrium shallow-convective boundary layer;**
  - ✓ **can account for a large part (70-80%) of the boundary layer growth in unstable (non-precipitating) cases.**


Thank you

Describing large-scale with as few parameters as possible

✓ **Idealized forcing/boundary conditions :**

$$w(z) = -w_0 \left(1 - e^{-\frac{z}{z_w}}\right),$$

$$q_{ft}(z) = q_0,$$

$$\partial_z \theta_{ft} = \frac{R}{w_0\left(1-e^{-\frac{z}{z_w}}\right)},$$

$$\theta_{ft}(z) = \frac{R}{w_0} z_w ln\left(e^{\frac{z}{z_w}} - 1\right) + \theta_0;$$

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SST

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SST

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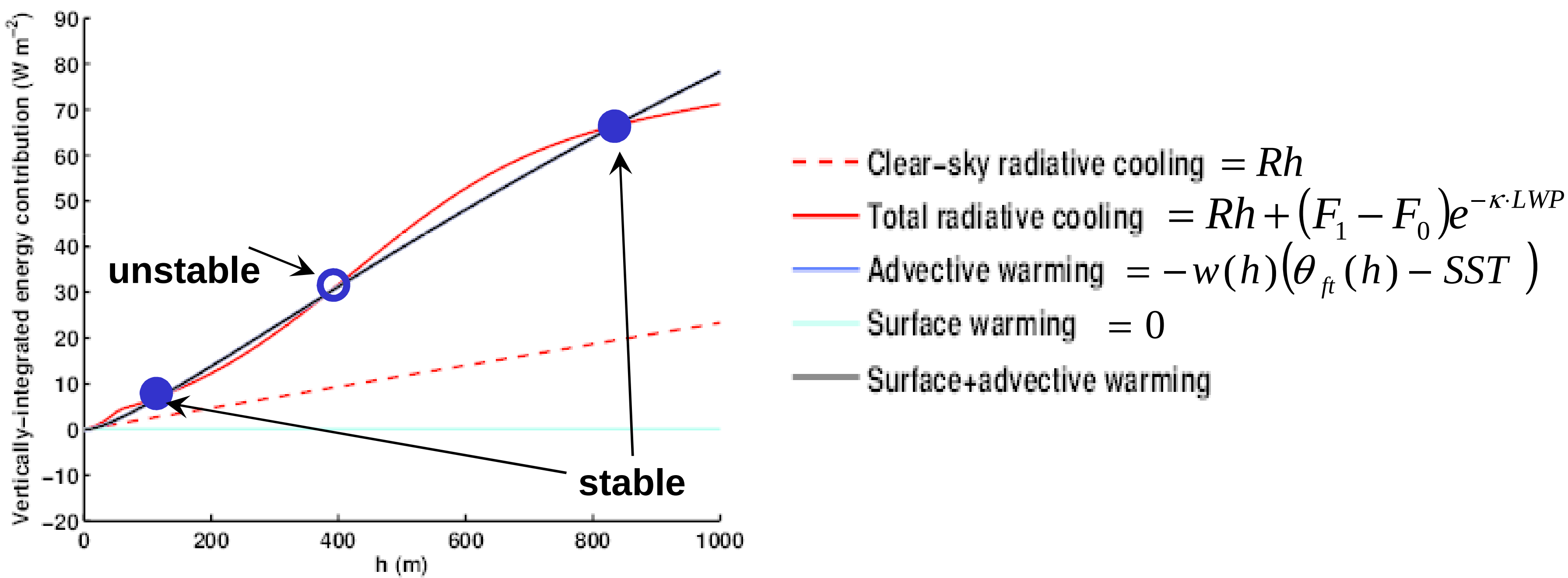
✓ **Run to equilibrium (2 weeks if necessary)**

Multiple equilibria from an energetics point of view

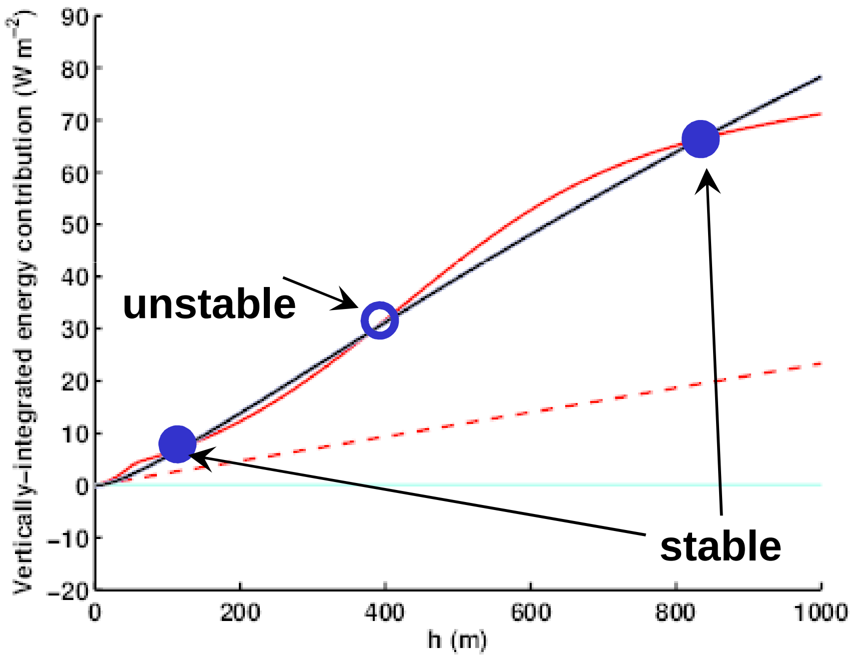
✓ **A simple interpretation as a well-mixed layer:**
More radiative cooling, evolving non-linearly with height, allows the emergence of multiple equilibria.



Predicts multiple equilibria, but too shallow and too deep, and both cloudy

Multiple equilibria from an energetics point of view

✓ **Only a change in turbulence can explain the LES behavior:**



Ad-hoc relationship for the mixed-layer temperature $\theta_M = f(SST)$: