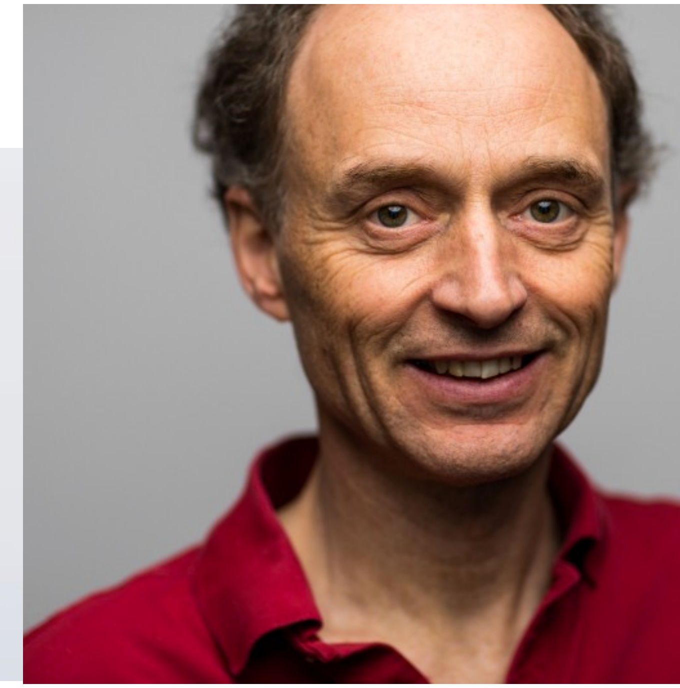
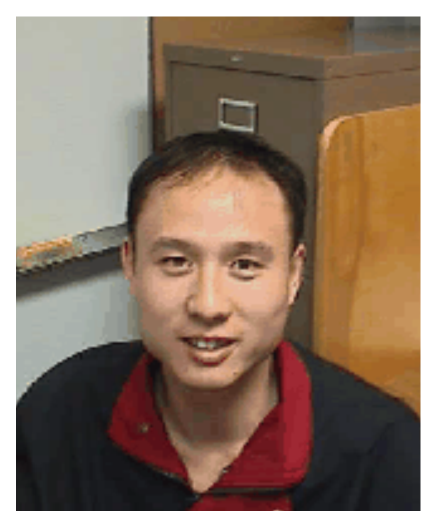
# Clouds and Climate Group in CMMAP





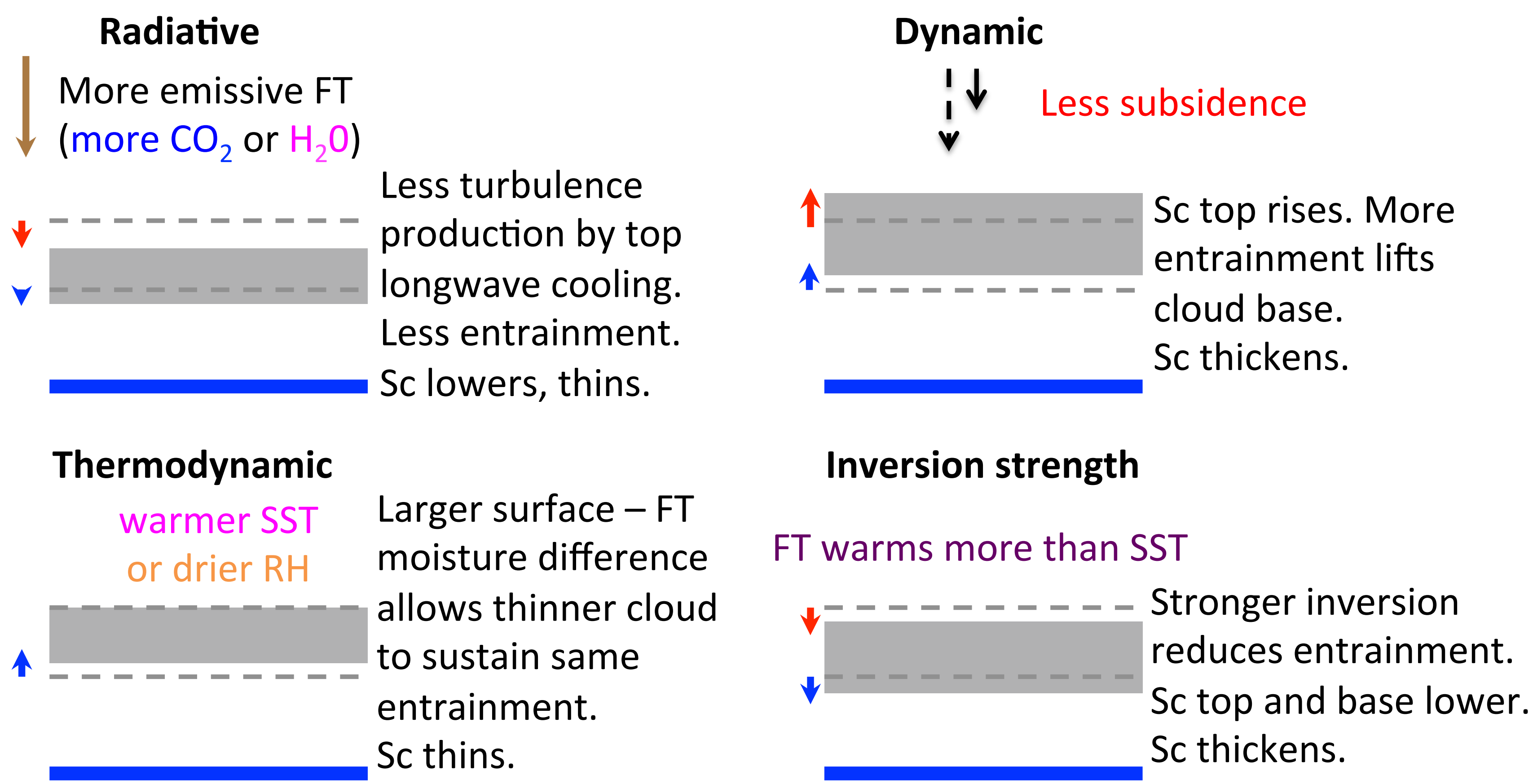
and more …

# Clouds and Climate Group in CMMAP

- Many names:
  - Low Cloud Feedbacks
  - Cloud-Climate Interactions
  - Clouds and Climate
  - Clouds & Climate Modeling (after our merger with the Coupled Modeling group)

# Highlights

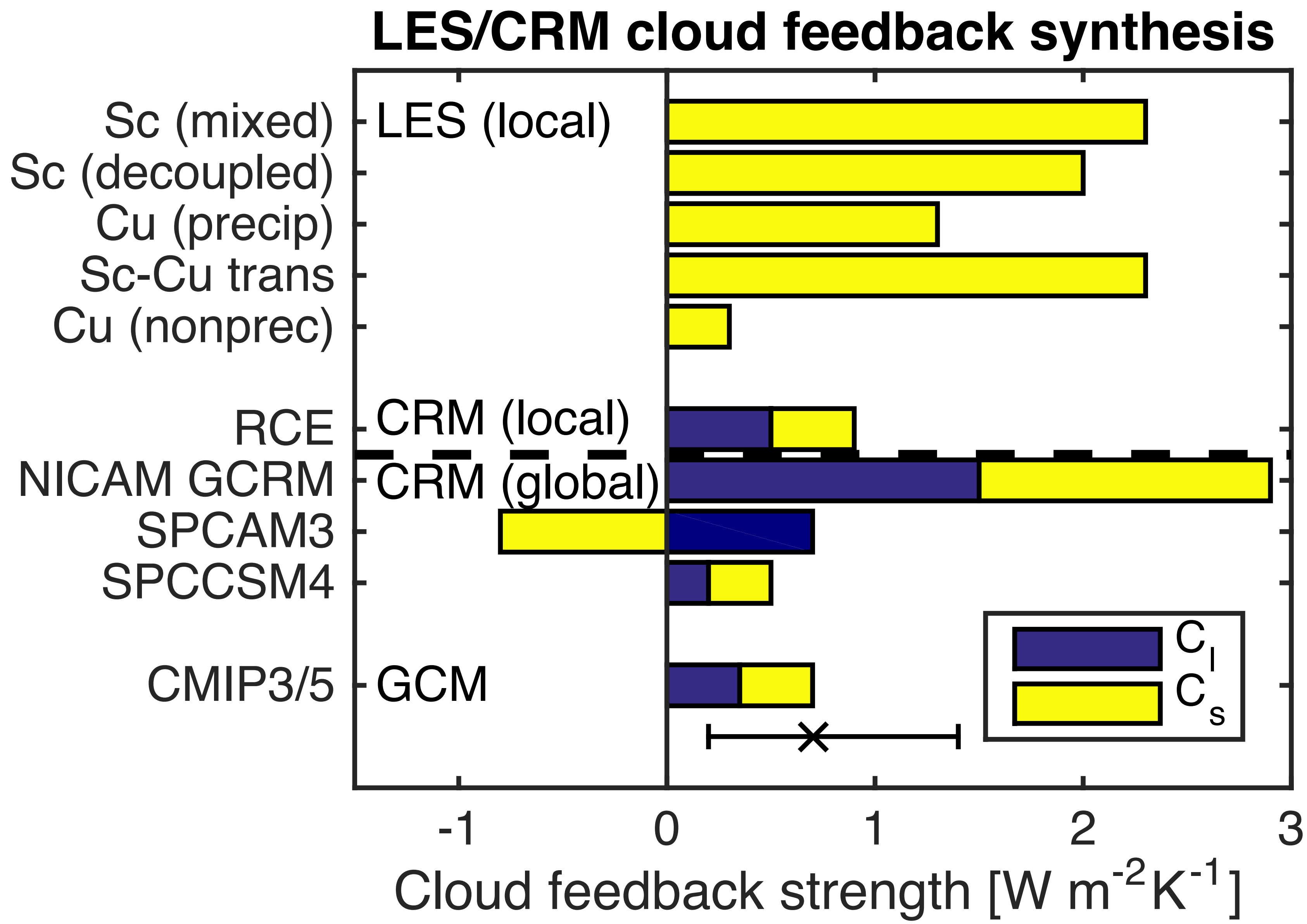
- Analyzed Cloud Response to Climate Change in superparameterized GCMs (SP-CAM, SP-CCSM, SP-CAM-IPHOC).
- Developed idealized frameworks for modeling cloud feedbacks (Aquaplanets, column modeling → CGILS)
- Proposed physical mechanisms underlying subtropical low cloud feedbacks.




Bretherton (2015), adapted from Bretherton et al (2013)

# Review Article

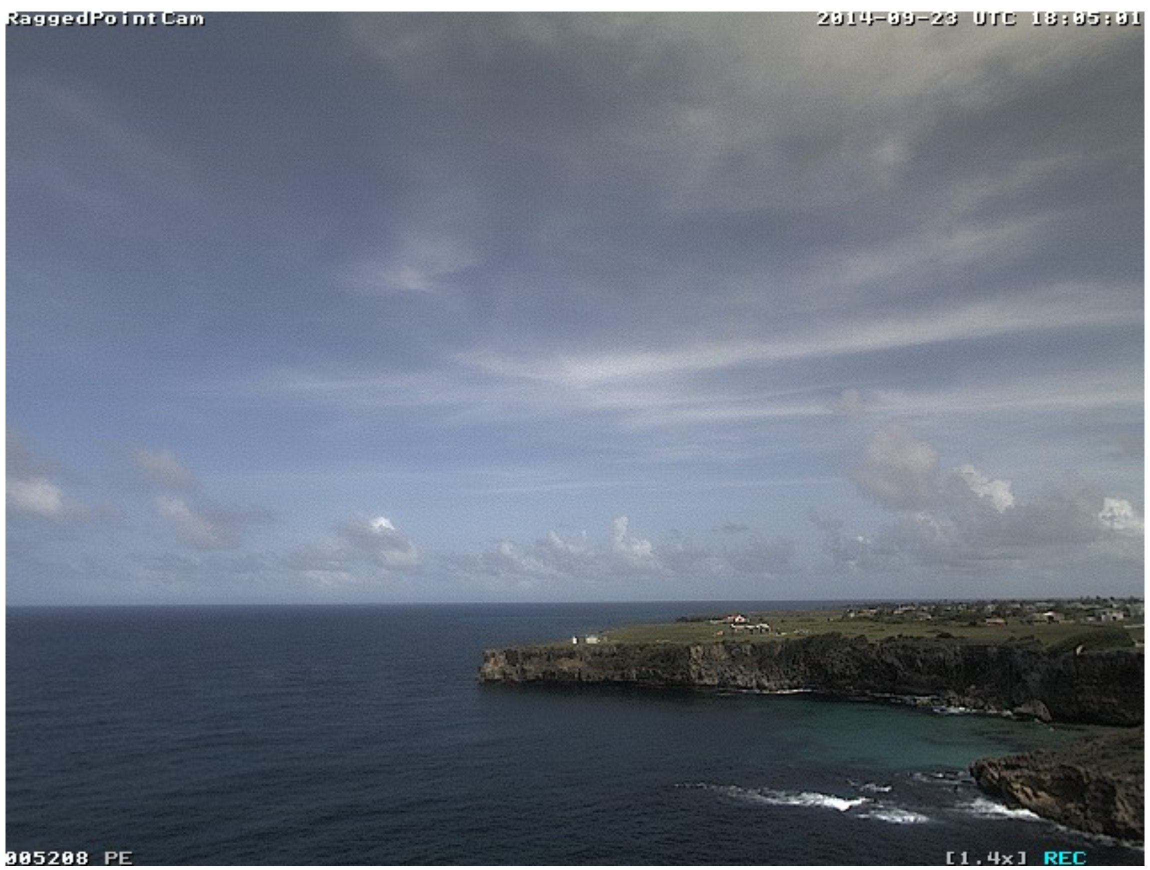
- Bretherton, C. S., 2015: Insights into low-latitude cloud feedbacks from high-resolution models. *Phil. Trans. Roy. Soc. A*, submitted 3/2015.



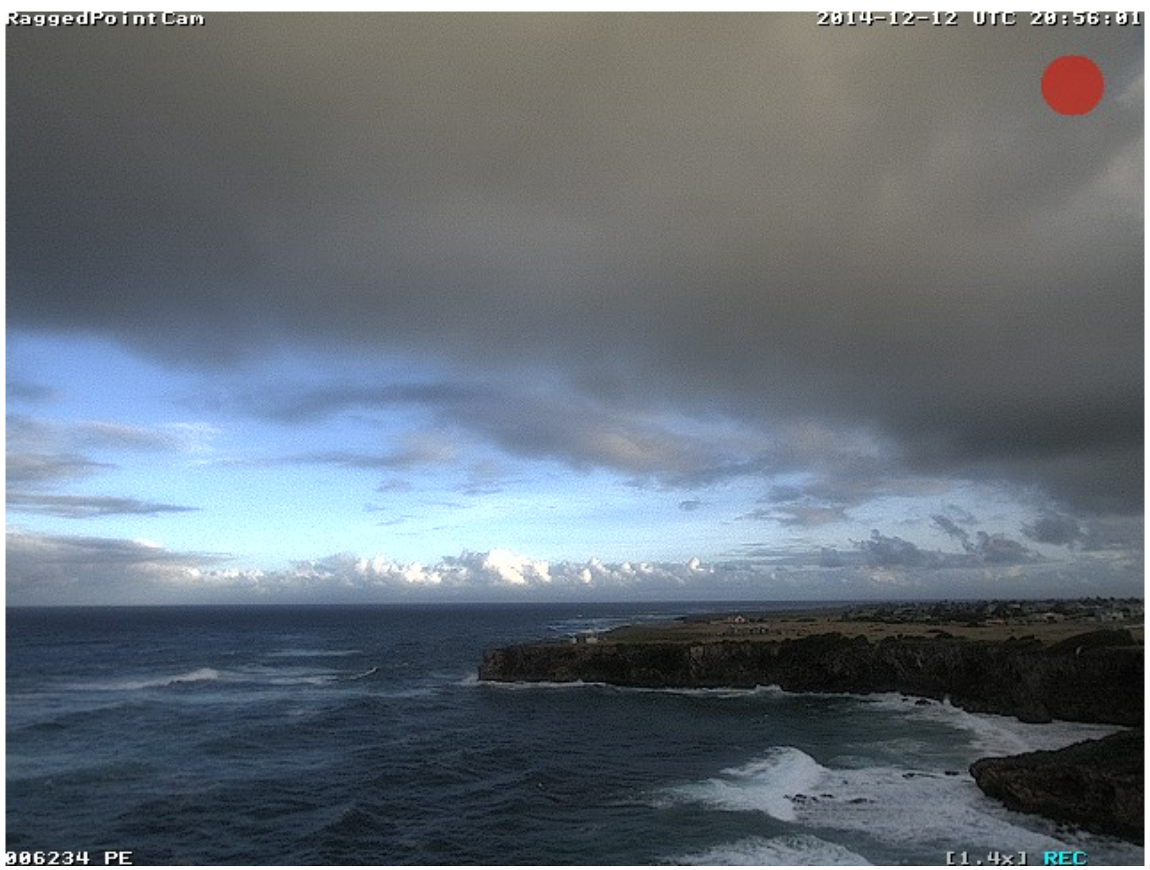

Bretherton (2015)

# Exploring Cloud Feedbacks in Shallow Cumulus Clouds

Peter Blossey and Chris Bretherton
University of Washington




Barbados Cloud Observatory (MPI)




Barbados Cloud Observatory (MPI)

Thanks to NSF and CMMAP for support and to Marat for sharing SAM. Thanks also to Louise Nuijens and her colleagues at MPI, Barbados and elsewhere for their observations that helped inspire this work.

# How do we expect clouds to change with climate in the trades?

**Bony et al (2015, Nature Geoscience):**

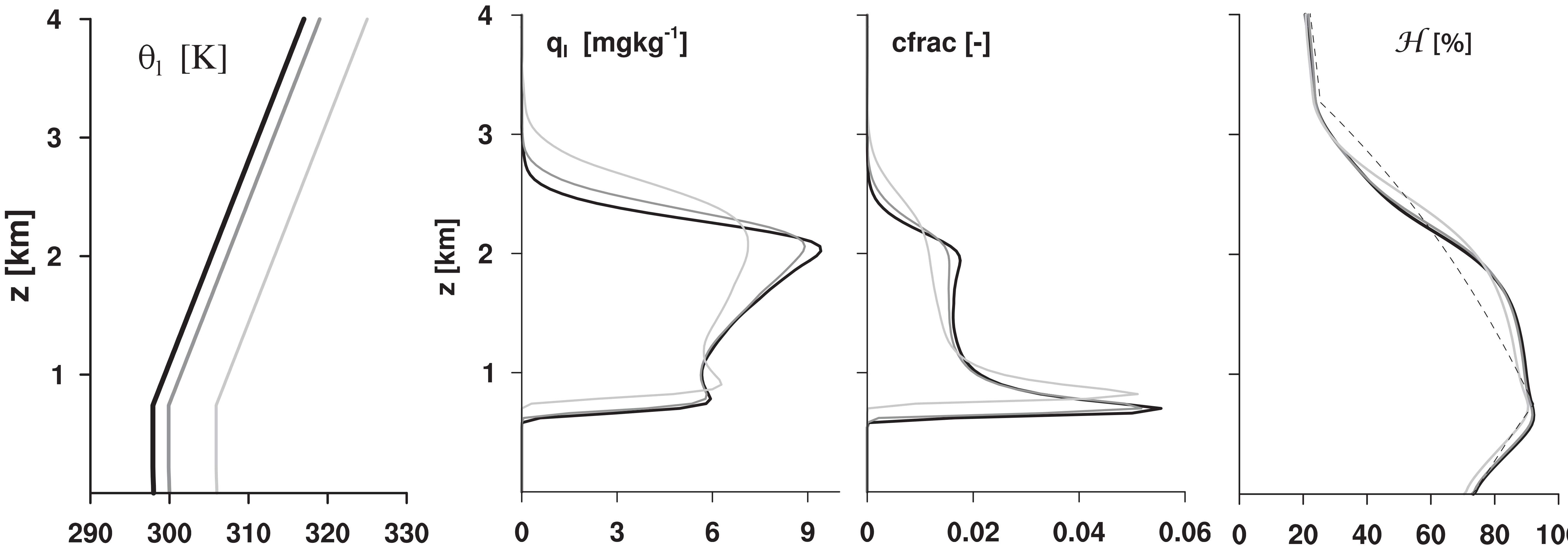
"Feedbacks from clouds in the planetary boundary layer over oceans (Fig. 1), which make one of the largest contributions to inter-model spread in climate sensitivity, seem to be driven largely by mixing of the lower troposphere by shallow convection [Refs];

in a warmer climate, these processes are expected to dry the marine boundary layer over the vast expanse of the tropical oceans, reducing the low-cloud amount and the Earth's albedo in a way that amplifies warming."

# Rieck, Nuijens & Stevens (2012)

| Case | Cloud Cover |
|---|---|
| CTL | 12.2 |
| +2K | 11.2 |
| +8K | 10.5 |

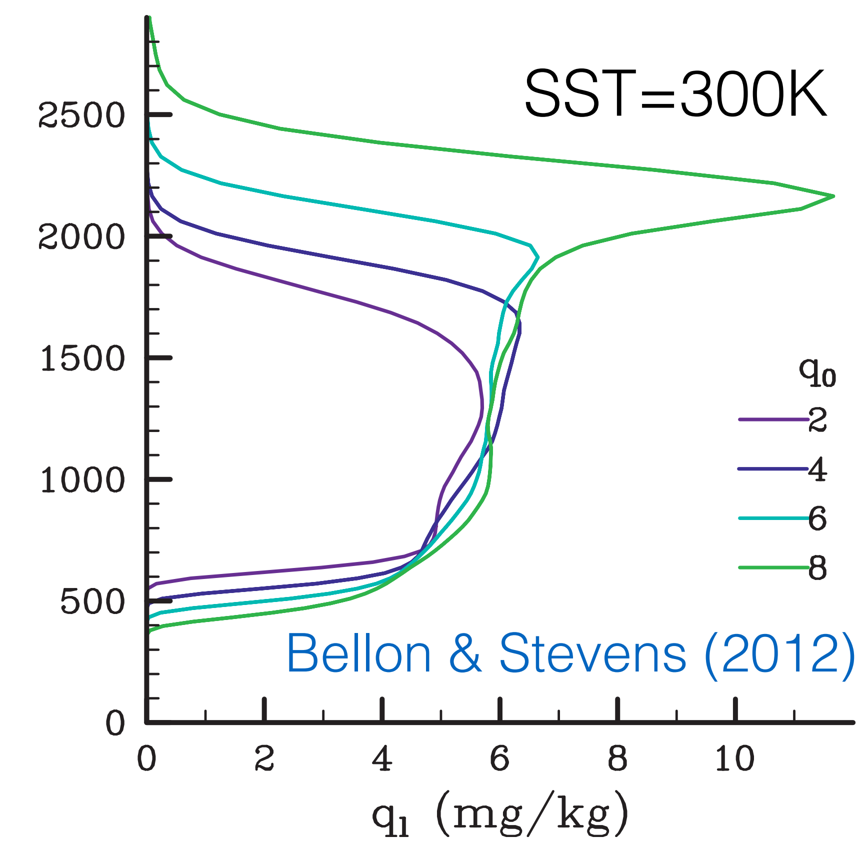
- One-day simulations of RICO inter comparison case, along with uniform warming of SST/theta by 2K and 8K.
- Warmer runs are deeper, drier and less cloudy.
- Changes attributed to:
  - **More energetic convection due to increased surface fluxes,**
  - stability changes driven by increased Δq across inversion.

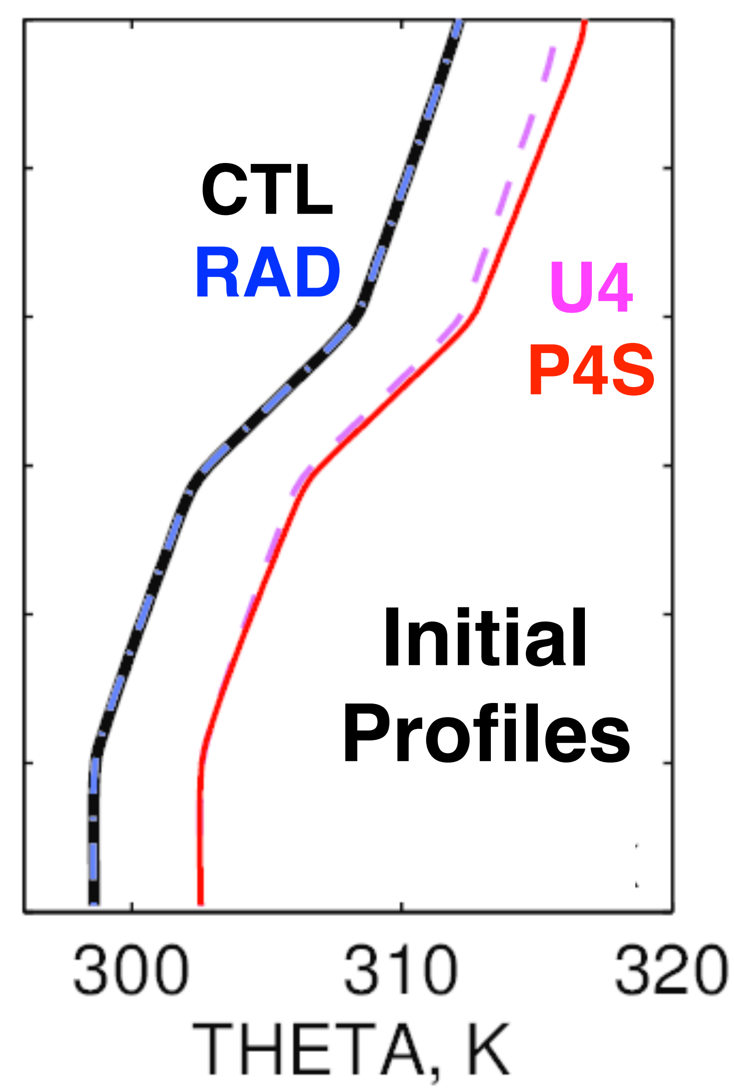



- **Note:** While a uniform warming of theta is a reasonable first-order assumption and keeps the forcings in balance, it implies a decrease in EIS.

# Our Simulations

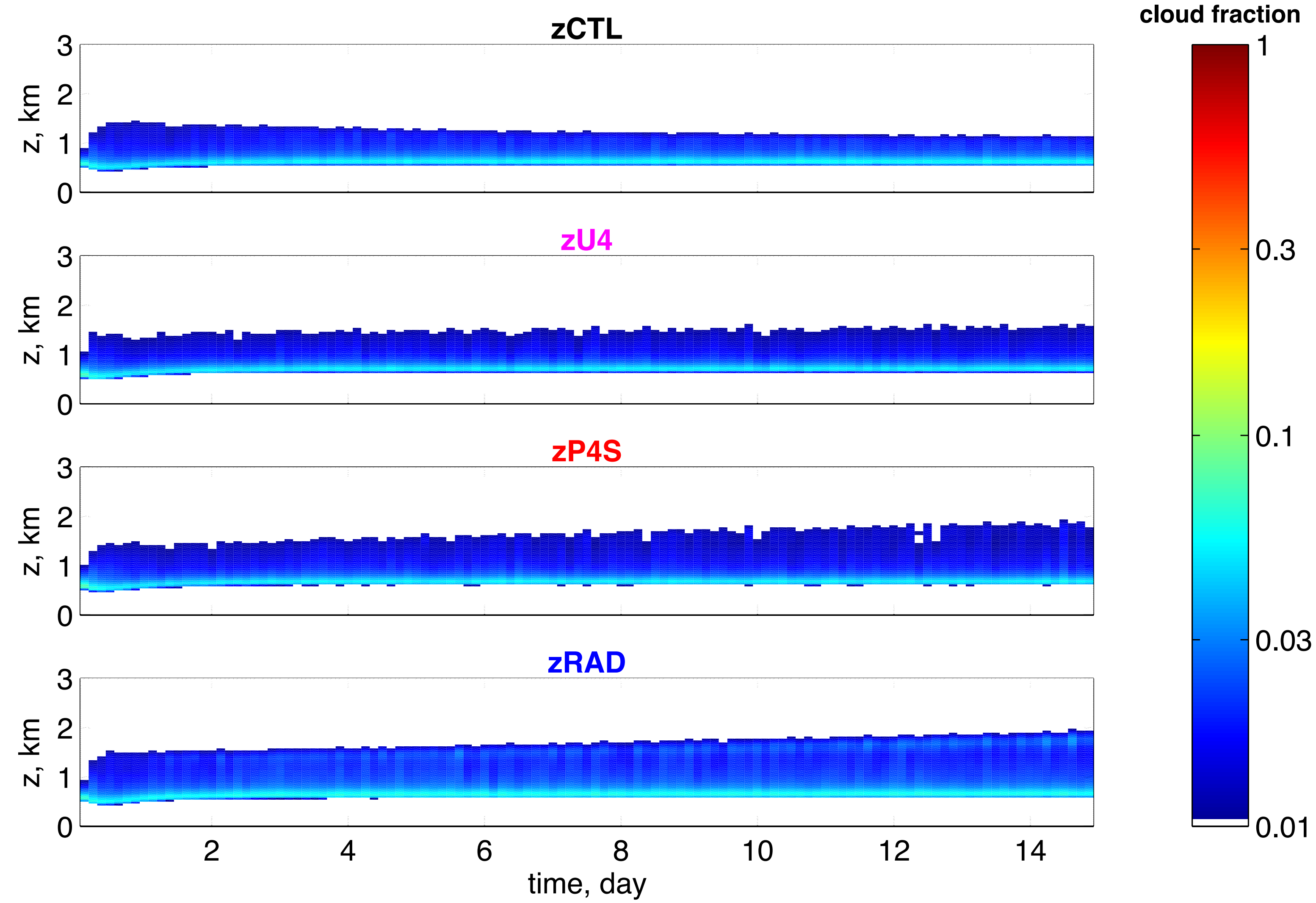
- Based on a BOMEX-like case developed by Bellon & Stevens (2012), who used 10-day runs:
  - Exponentially increasing subsidence w/height,
  - Uniform “radiative” cooling of 2 K/day.
  - No cloud-radiation interactions.
  - No horizontal moisture advection.
- We reformulated the case in terms of height and dry static energy (rather than θ) to be consistent w/SAM.
- Our simulated BL height tends to be shallower and to take longer to reach equilibrium than Bellon & Stevens (2012).
- Four simulation setups (all use same RH profile):
  - **CTL**: SST=300K, LTS=14.4K, EIS=-1.2K.
  - **U4**: Uniform warming (+4K) in dry static energy.
  - **P4S**: Moist adiabatic warming (SST+4K), reduced subsidence aloft balances heat budget.
  - **RAD**: 20% stronger “radiative” cooling.
- All use warm rain Morrison microphysics w/$N_d$=100 $cm^{-3}$.

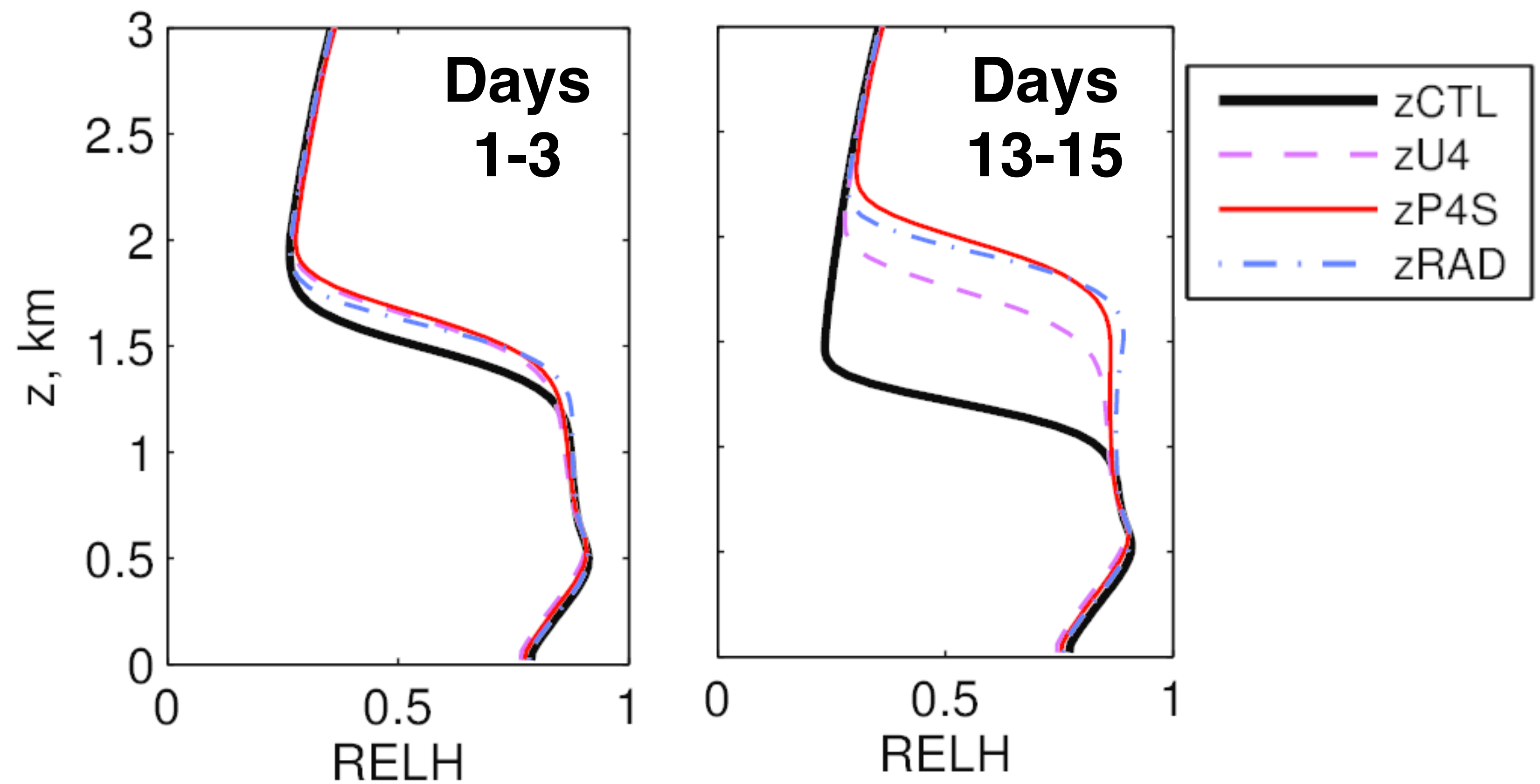


# Results

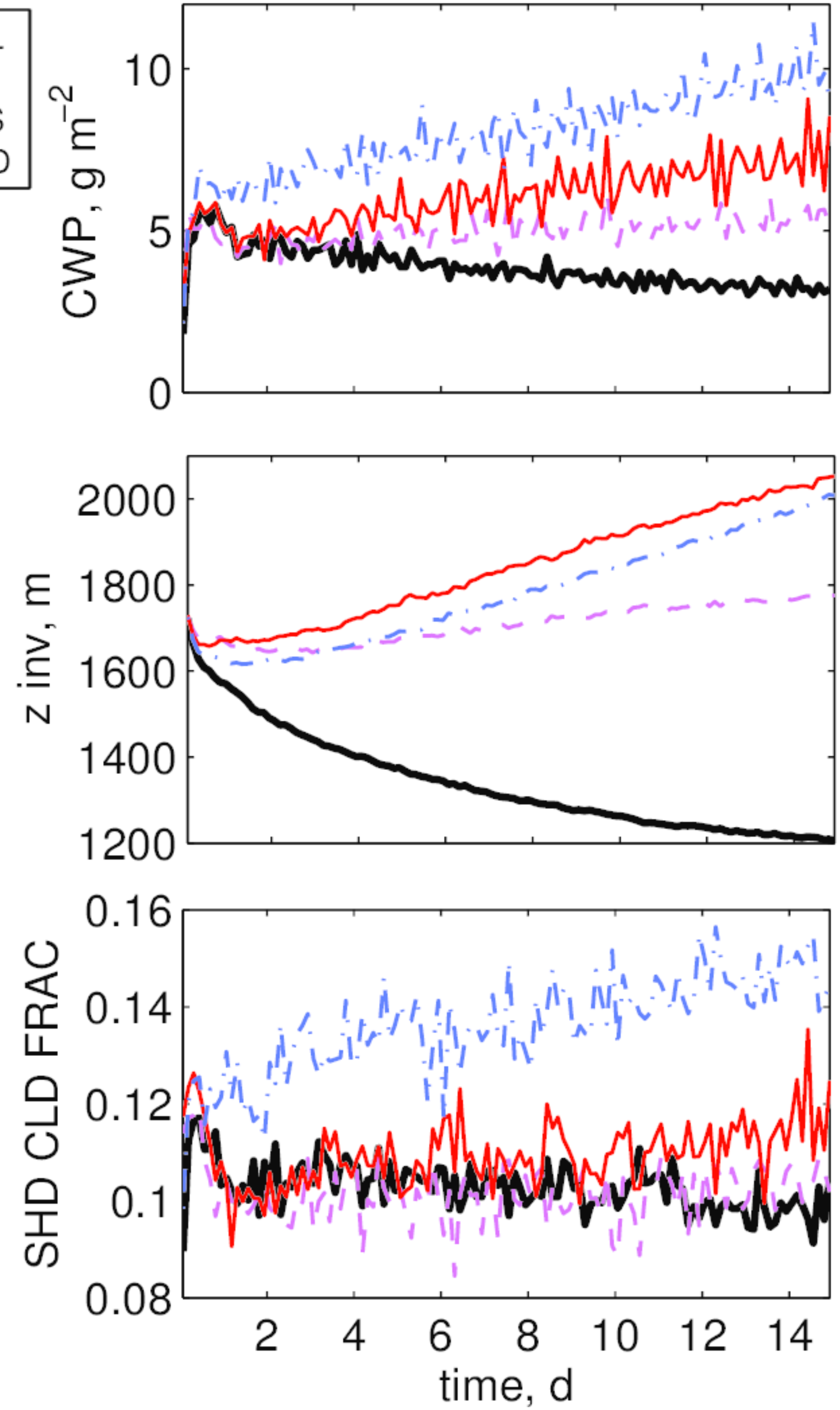
- BL deepens in warmer simulations.
- Cloud-layer RH is almost unchanged in warmed runs.
- Cloud base rises in warmer runs, as in Rieck et al (2012).



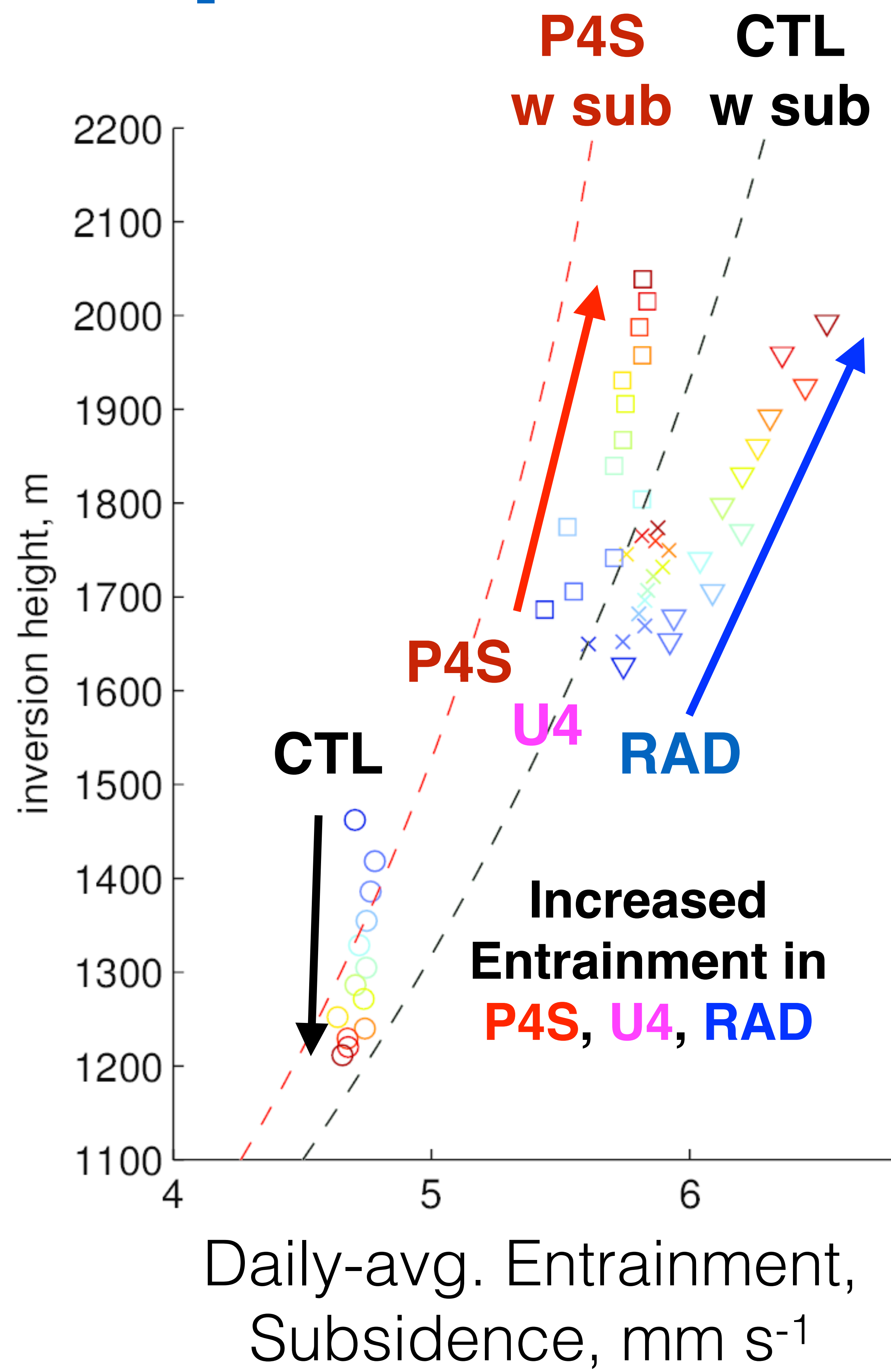
# More Results

- BL deepens in warmer runs and with increased BL cooling.
- Cloud liquid water path (LWP) scales with BL height, largest in **RAD** simulation.
- Cloud cover changes weak except for **RAD** decreases initially but then increases with further deepening.
- CTL simulation becomes shallow.
- Long time to reach equilibrium (>10 days). A bit longer than Bellon & Stevens (2012).



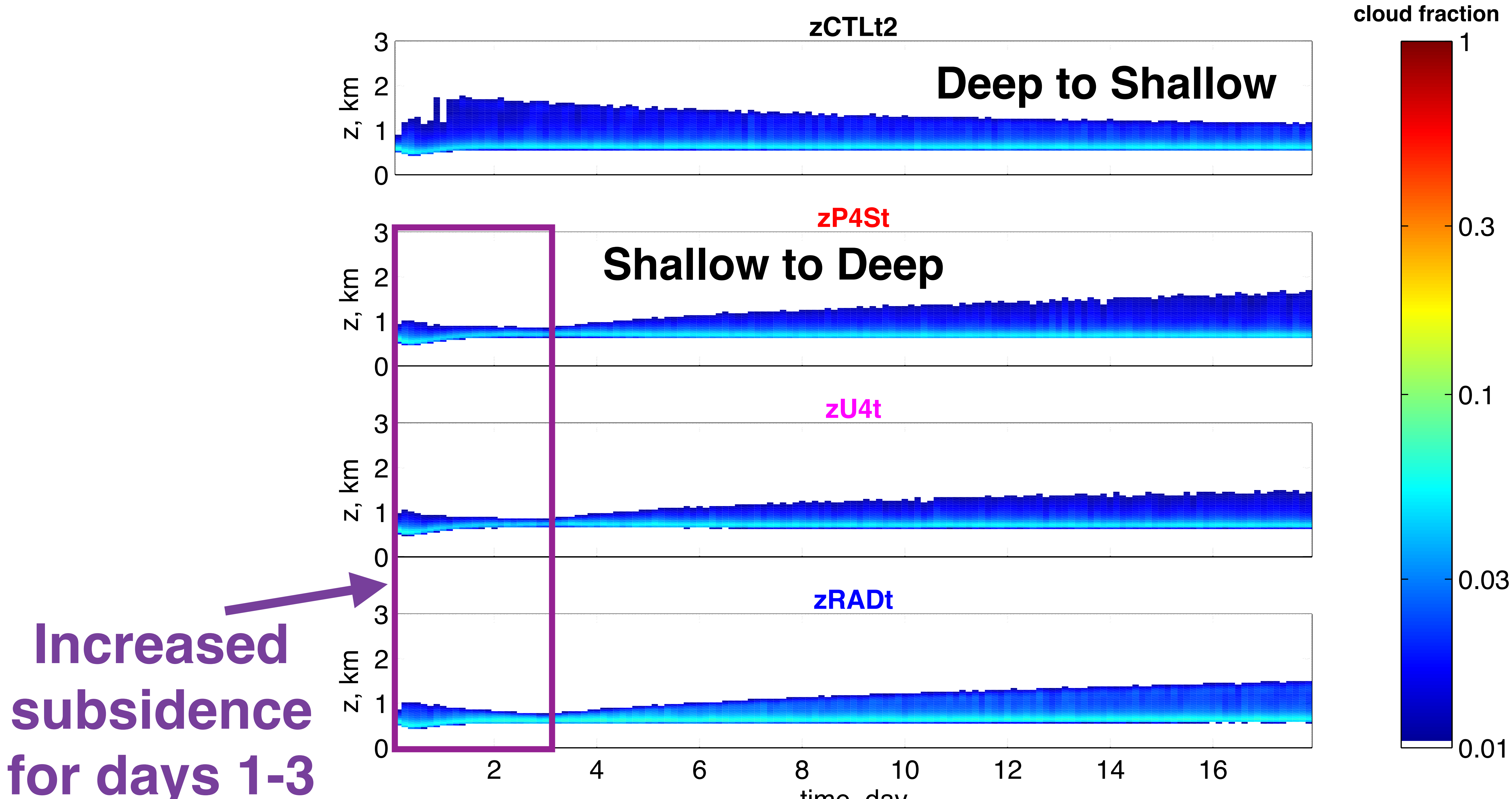
# Slow Manifold Interpretation

- These runs took a long time to reach equilibrium.
- Clouds in the actual subtropics don't have that long to reach their equilibrium depth, perhaps only a few days.
- However, the internal adjustment of the boundary layer (in terms of cloud base height, surface fluxes, etc.) is much quicker, so let's compare the responses as a function of inversion height.
- This is the slow manifold approach of Bretherton et al (2010).



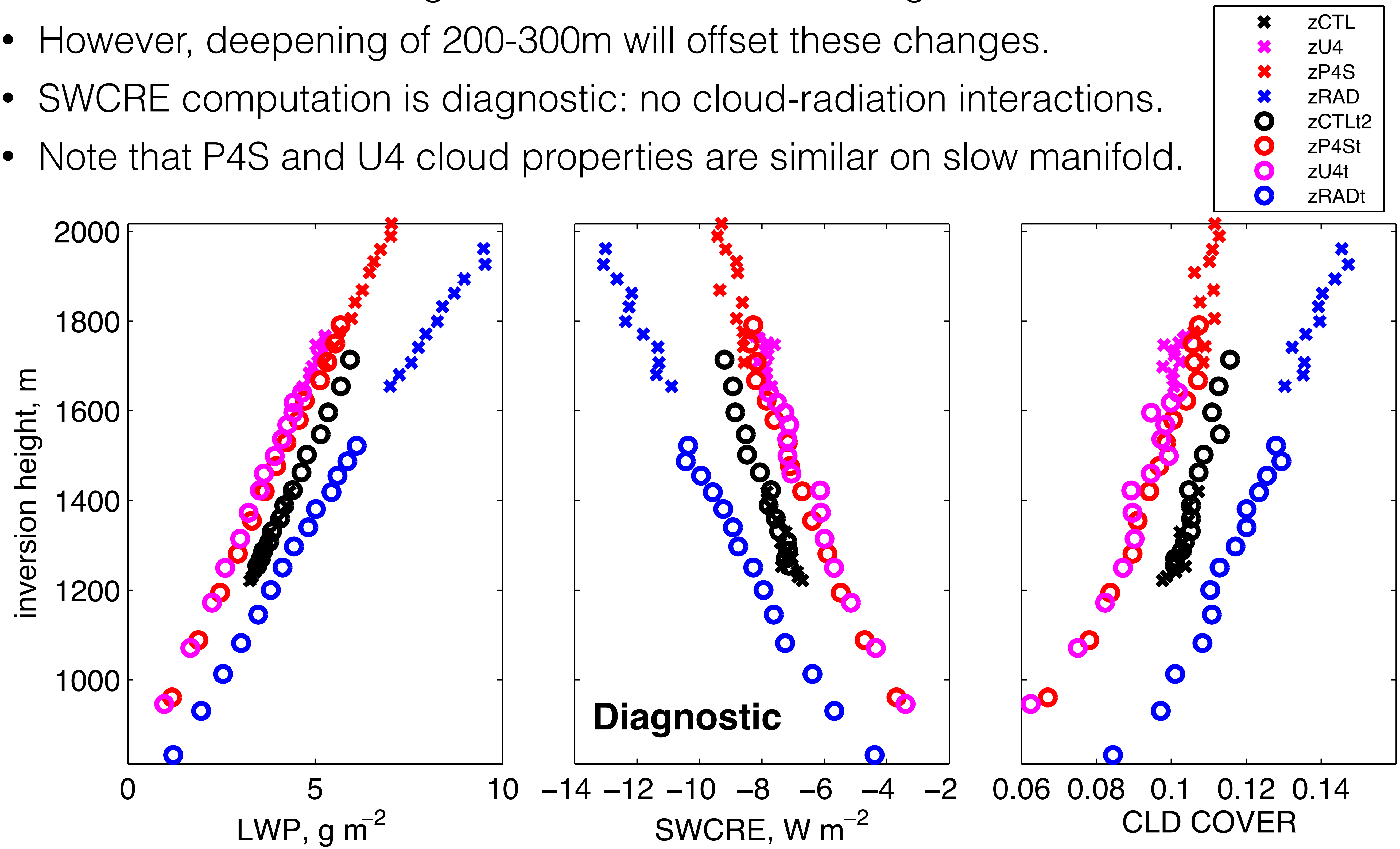
# Cloud Feedbacks on the Slow Manifold

- Make long runs that traverse a good range of BL heights.
- Compare cloud and BL properties as a function of $z_{inv}$.



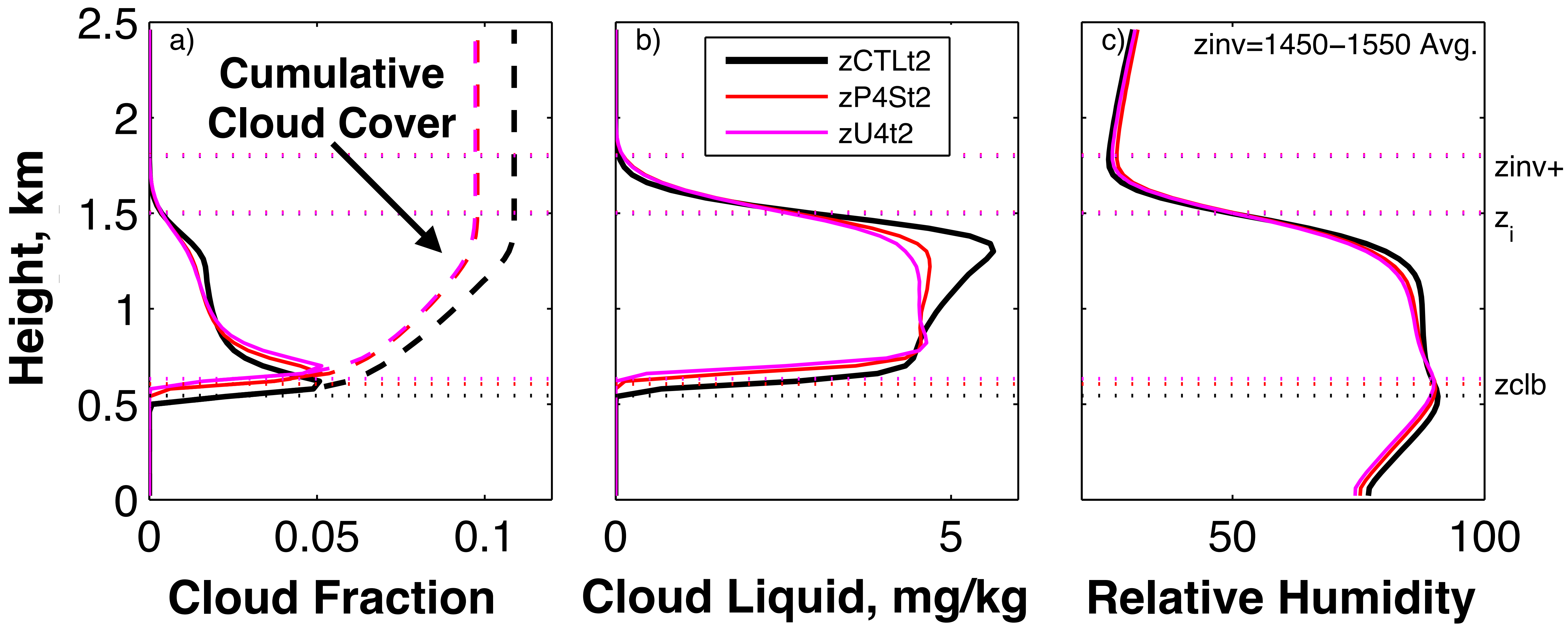
# Cloud Feedbacks on the Slow Manifold

- Daily-averages from day 4 onward collapse onto slow manifolds.
- At a fixed inversion height, cloud amount and LWP go down.
- However, deepening of 200-300m will offset these changes.
- SWCRE computation is diagnostic: no cloud-radiation interactions.
- Note that P4S and U4 cloud properties are similar on slow manifold.



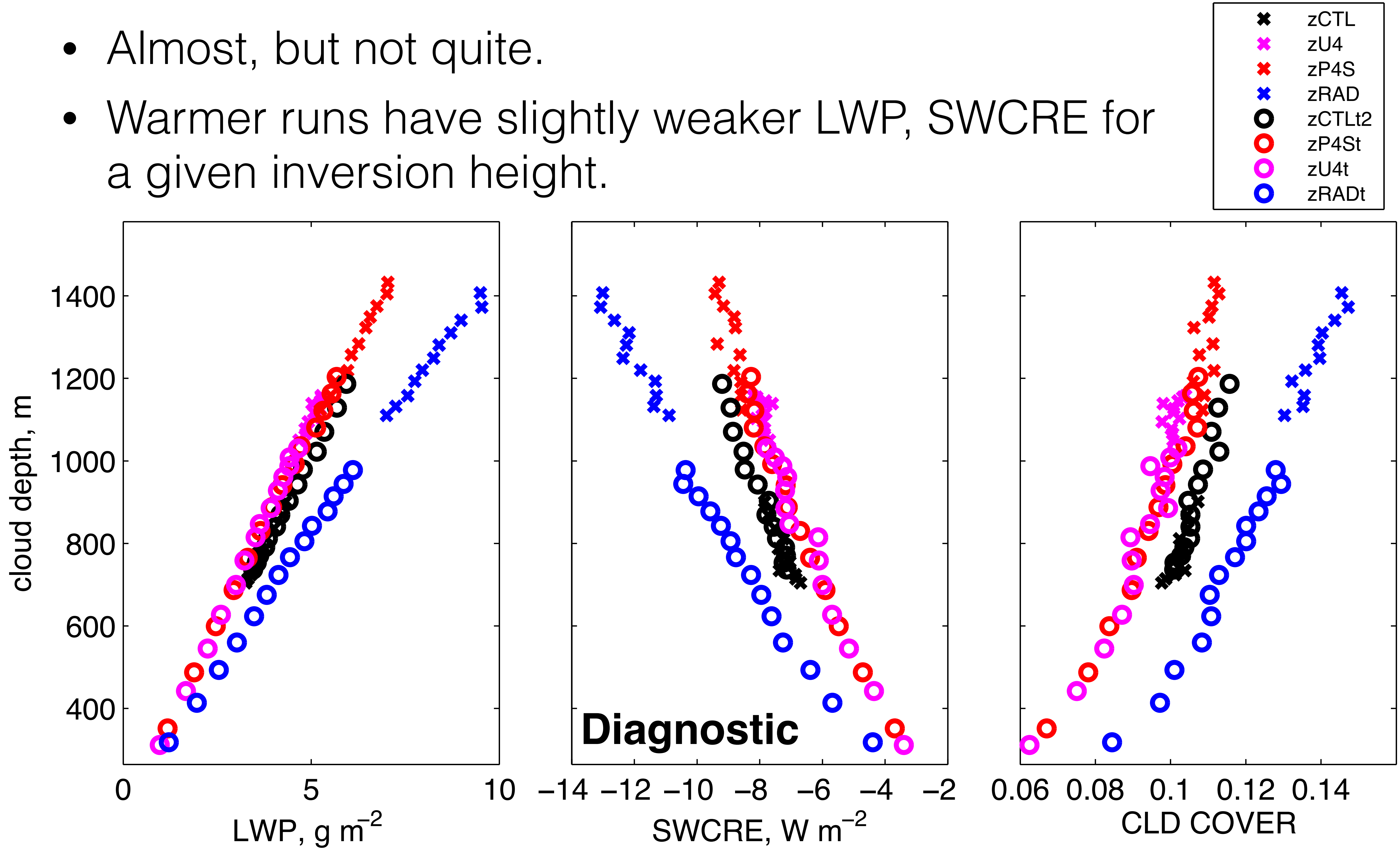
# What Controls Changes in LWP and SWCRE with warming?

- Cloud layer is slightly drier and has less liquid water near the inversion.
- For a fixed inversion height, cloud base rises systematically, so that cloud depth decreases.



# Does cloud depth control LWP and SWCRE?

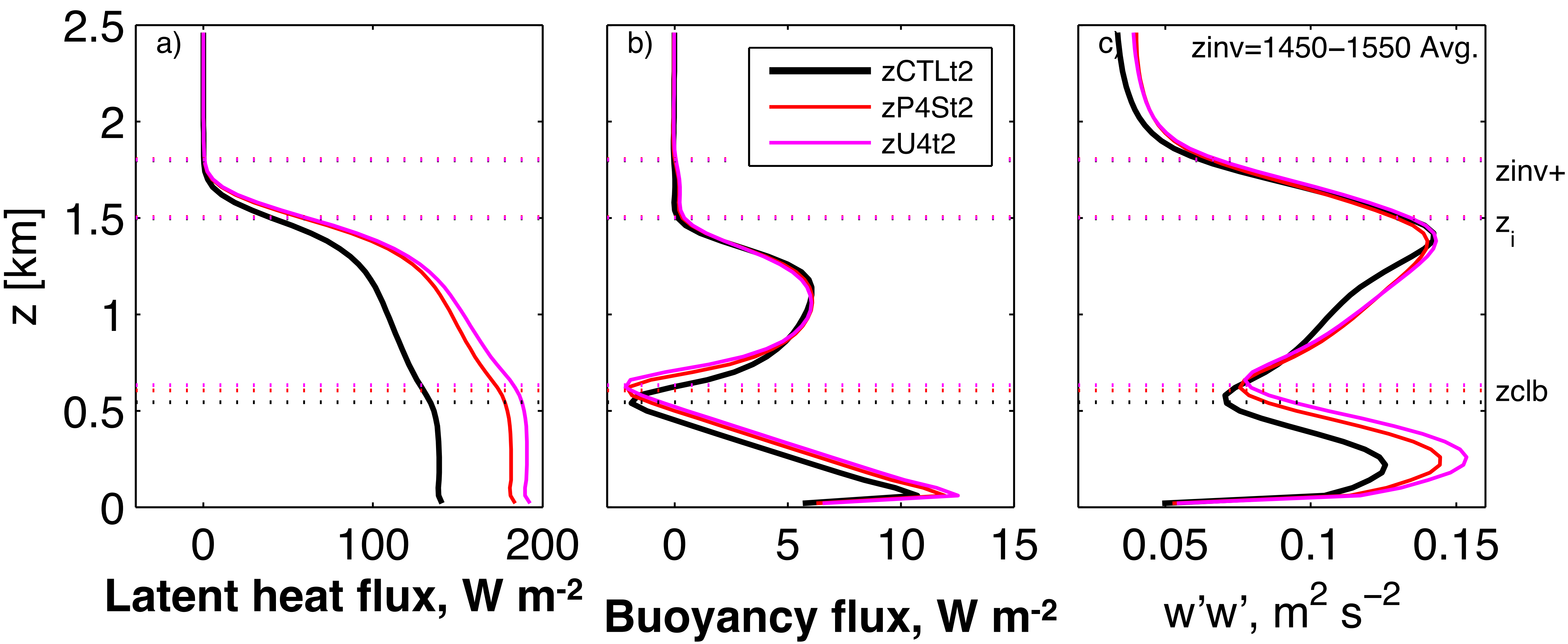
- Almost, but not quite.
- Warmer runs have slightly weaker LWP, SWCRE for a given inversion height.



# Preliminary Conclusion

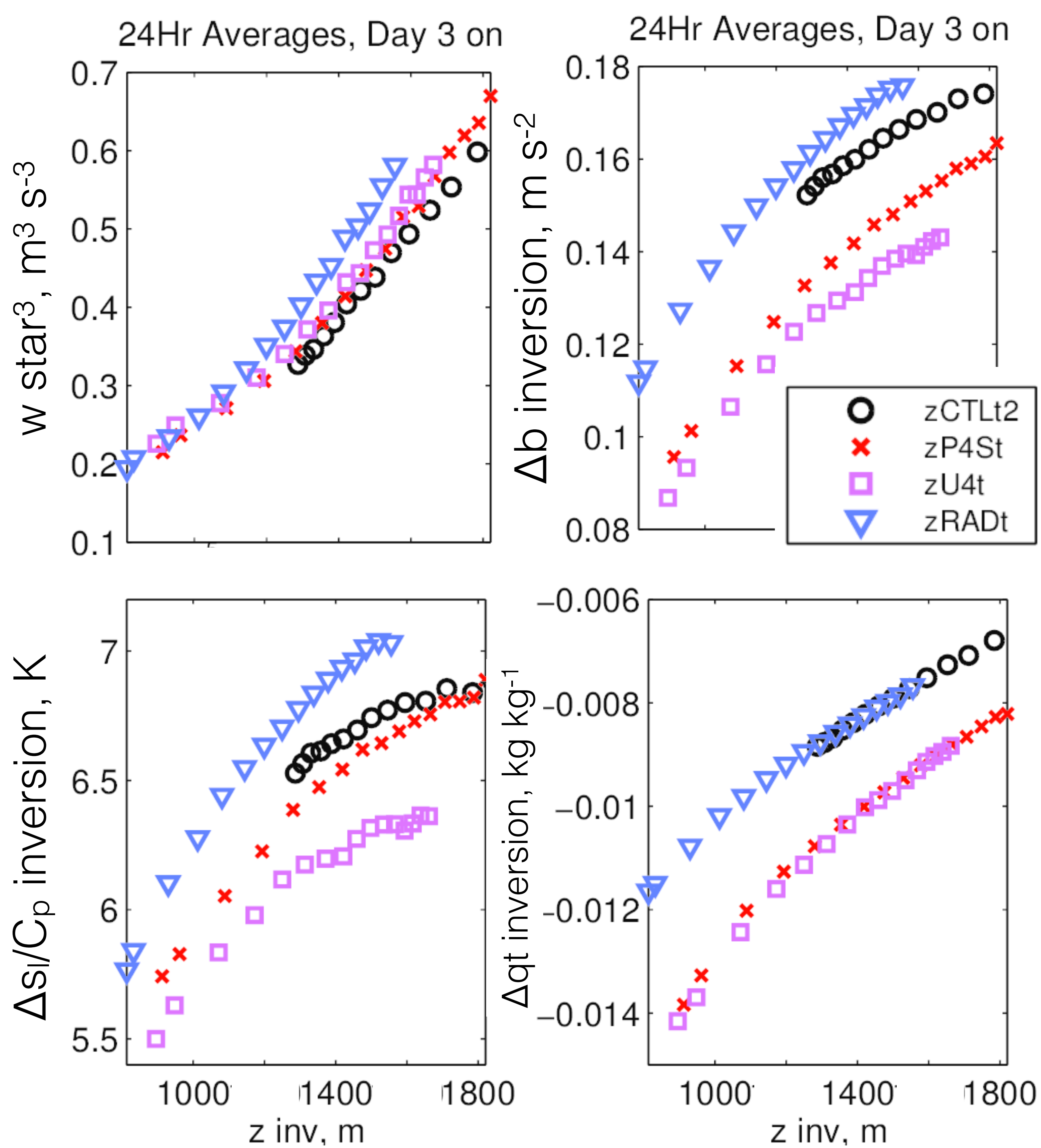
- SWCRE primarily controlled by cloud layer depth, with small weakening due to warming.
- Note that changes in cloud layer depth are caused by interplay of entrainment, forcing and transient evolution.
- … would need a GCM to understand how BL depth will change in a perturbed climate.
- **Next:** Rieck et al suggests that BL deepening in a warmer climate is mainly induced by increased surface fluxes driving stronger entrainment, with a small contribution from a decreased buoyancy jump.
- Let's look at this in our simulations.

# Despite much larger latent heat fluxes through the BL, the buoyancy flux and turbulence near the inversion are almost unchanged…



# Why do warmer runs entrain more strongly?

- Changes in buoyancy flux occur mostly in subcloud layer.
- Weaker buoyancy jump induces stronger entrainment.
- Buoyancy jump weakens due to more negative Δq/Δz across inversion.
- In these simulations, efficiency of entrainment does not increase in a warmer climate.



# Conclusions

- Our basic results agree with Rieck et al (2012):
  - inversion moves higher with warming, and
  - cloud layer is drier when compared at a fixed inversion height.
- We find:
  - weak positive feedbacks for a fixed inversion height, mainly due to the increased cloud base height, and
  - increasing cloud as the BL deepens suggest that $\Delta z_{inv}$~250m offsets cloud reduction due to warming.
- Increased entrainment in warmer climate is mainly driven by a reduced buoyancy jump across the inversion.

# Complications

1. Our domain is relatively small, with $L_x = L_y = 6.4$ km.
2. Cloud-radiation interactions could play a role in feedbacks.
3. Climate-mediated changes in other quantities (radiation, wind speed, stability,…) could have a bigger impact on cloud than warming itself.
4. At Barbados, cloud cover variations are dominated by deeper cloud, rather than the relatively shallow cumulus clouds studied here (Nuijens et al, 2014). Cloud feedbacks might well be dominated by that type of cloud as well.
5. GCMs don't typically show inversion height increases in the trades with warming. Why? Possibilities: precipitation, poor representation of shallow cumulus (Nuijens et al, 2015), …