

# Subtropical low cloud responses when the energy budget is closed

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# Motivation

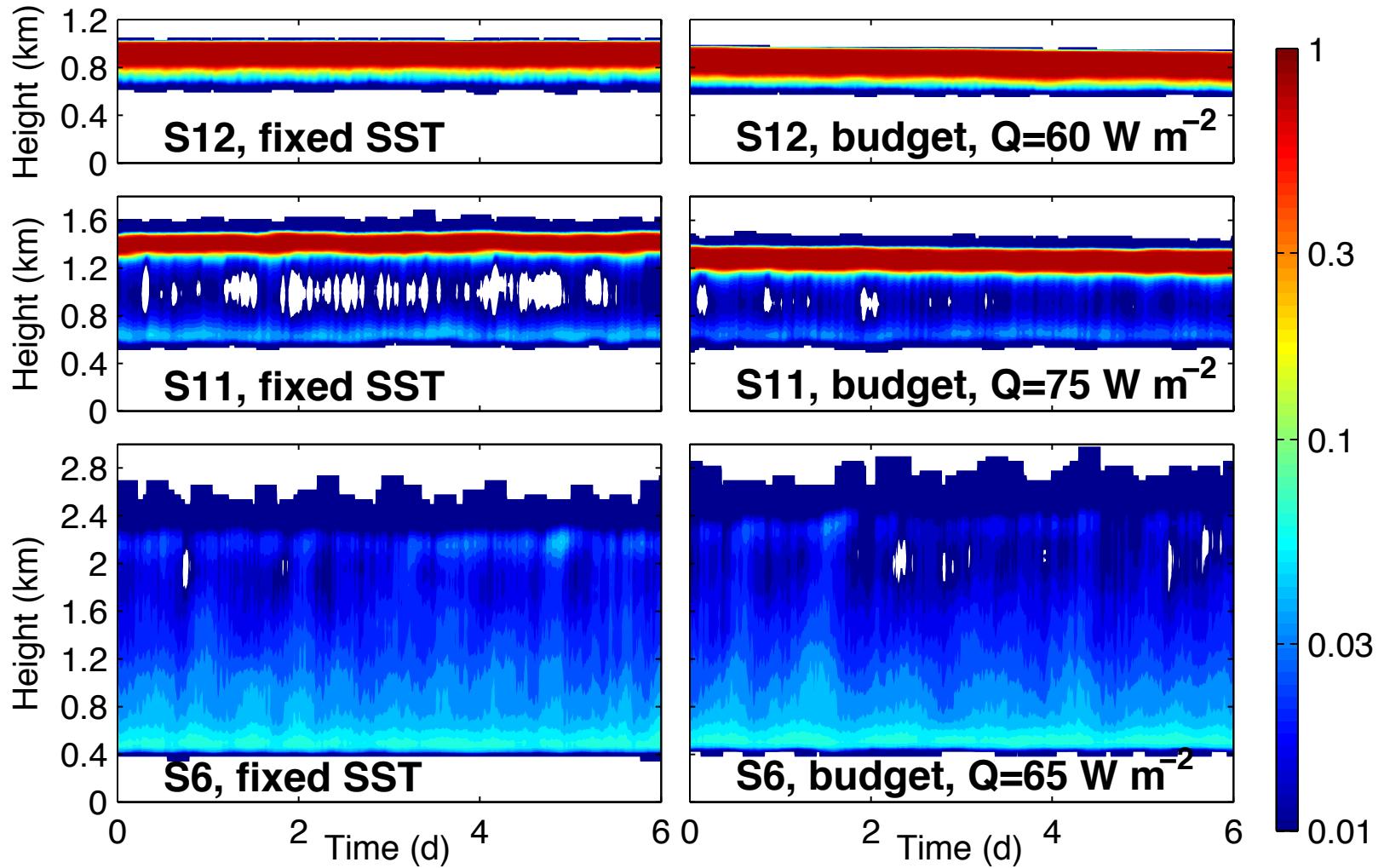
- Surface energy budget constrains global-mean surface latent heat flux (LHF) to increase by  $2\% \text{ K}^{-1}$  under global warming
- CGILS P2S experiments: with prescribed SST, LHF increases by  $4\text{-}5\% \text{ K}^{-1}$  (Blossey et al. 2013)

*CGILS + surface energy budget constraint?*

# Experiment set-up

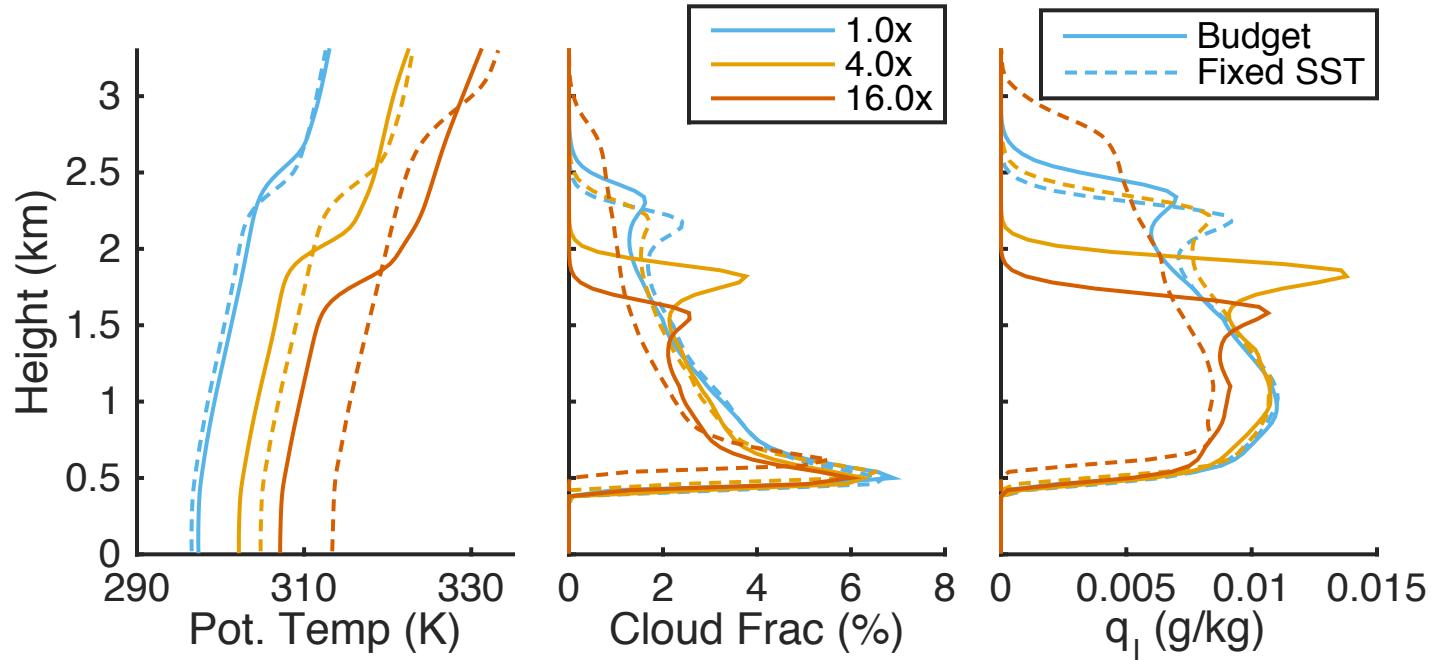
- Warming is driven by increased CO<sub>2</sub>
  - Upper-tropospheric temperature shifts with tropical climate sensitivity of +4 K/(2xCO<sub>2</sub>).
- Slab ocean surface, with SST evolving according to surface energy budget
  - Surface heat uptake fixed under warming.
- Large-scale forcing and radiation scheme similar to CGILS.
  - Cumulus case (S6), with Grabowski (1998) single-moment warm-rain scheme.

# Cloud fraction in control climate



\* 6-hourly mean cloud fraction in steady state

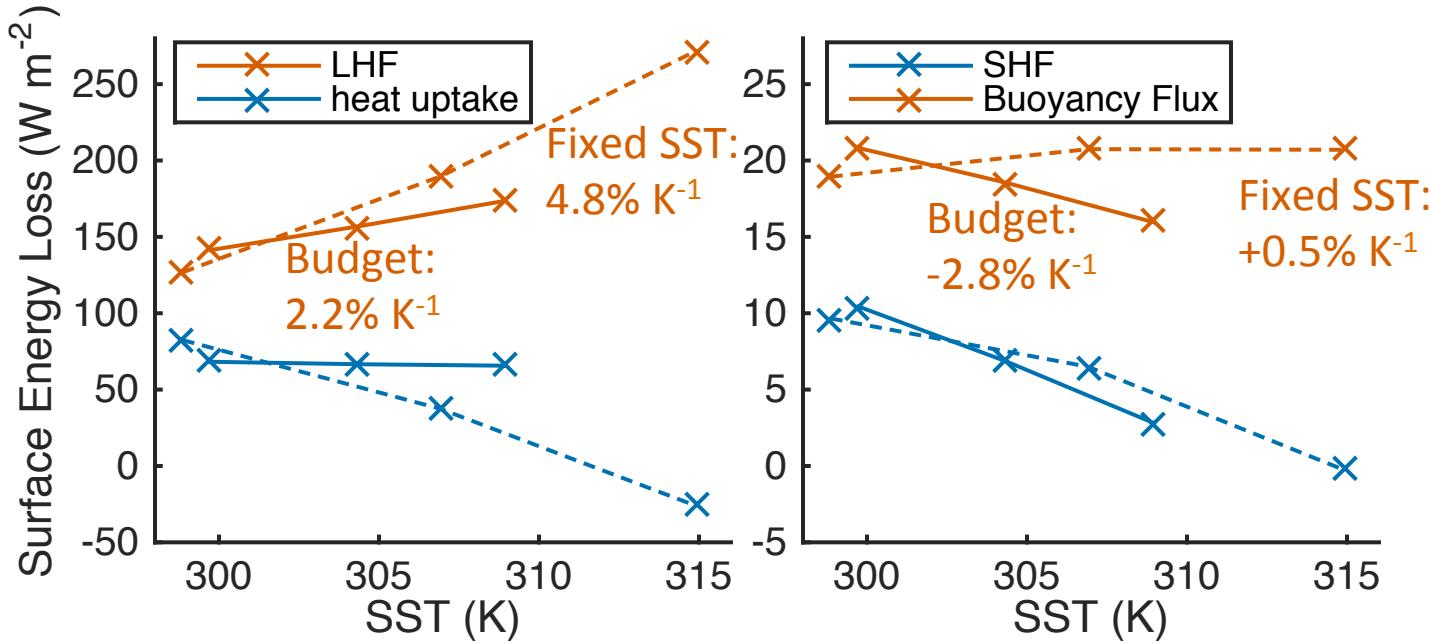
# Cumulus (S6) under warming



With surface energy budget:

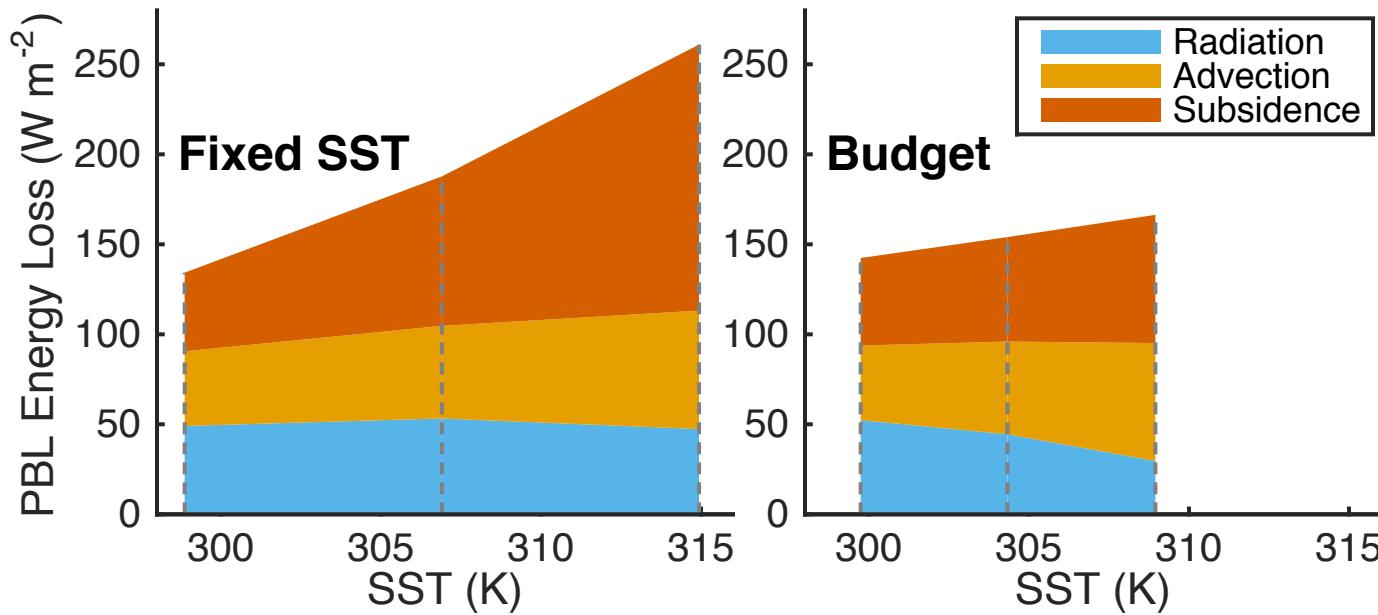
- SST increase is weaker ( $2.5\text{K}/2\text{xCO}_2$ ) than fixed SST;
- Inversion height decreases with warming.

# Surface energy budget analysis



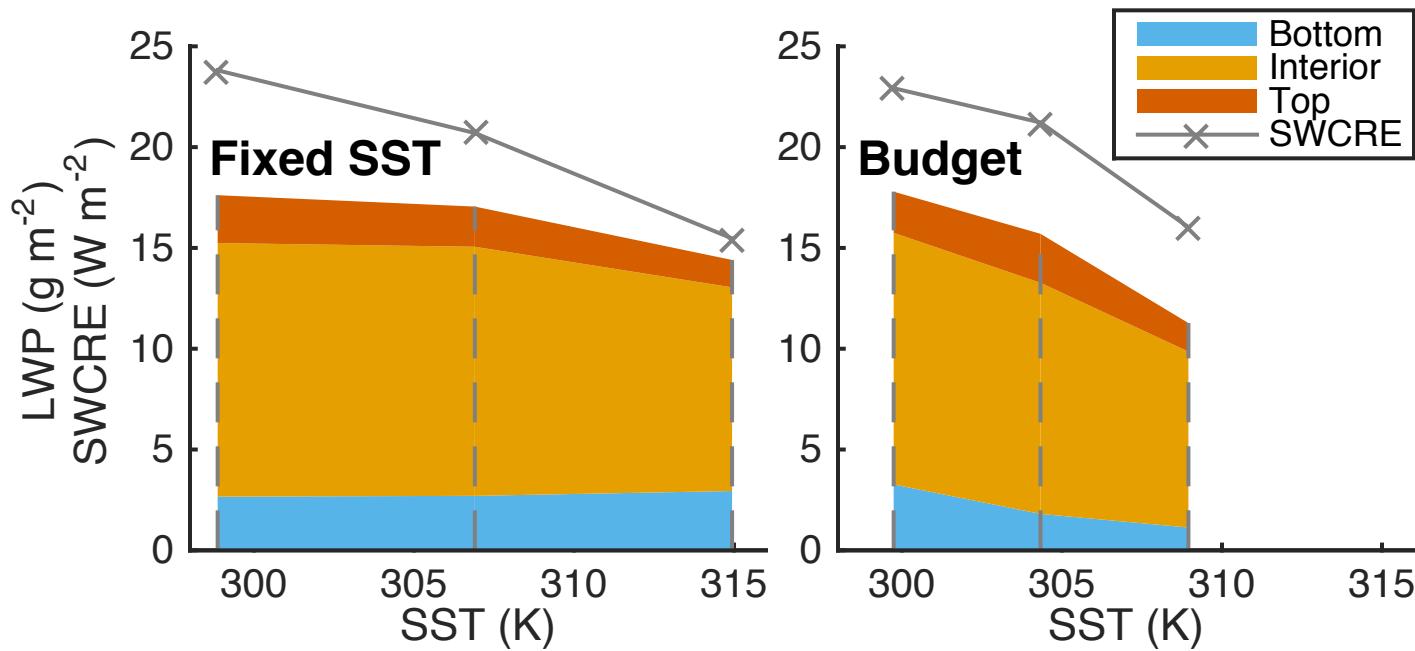
- Fixed SST: C-C increase of LHF (balanced by ocean heat uptake); slight increase of buoyancy flux.
- Energy budget: much weaker increase of LHF; significant decrease of buoyancy flux.

# Boundary layer budget analysis



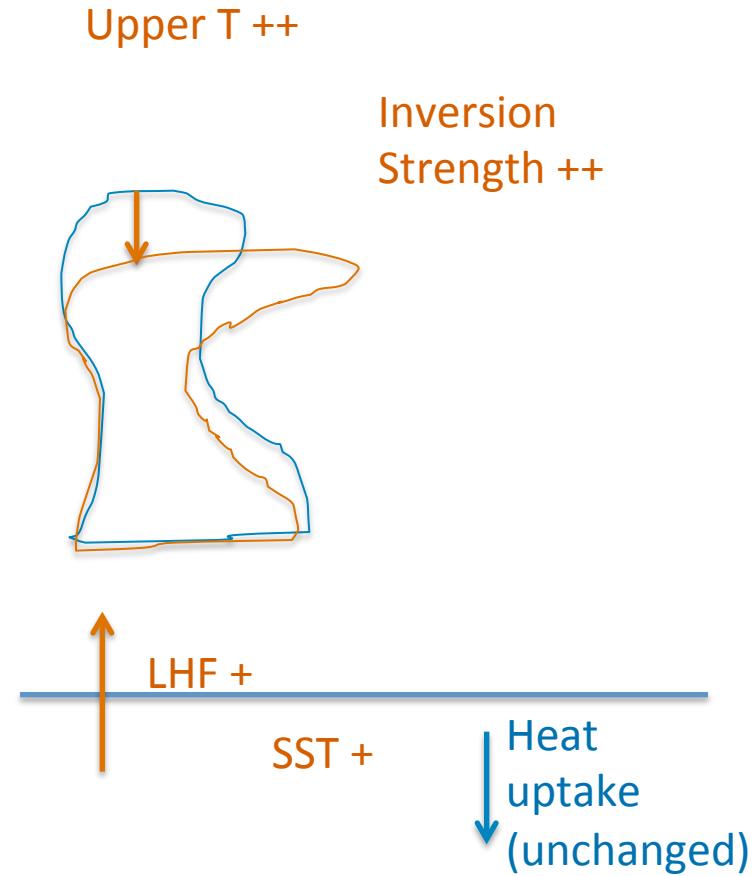
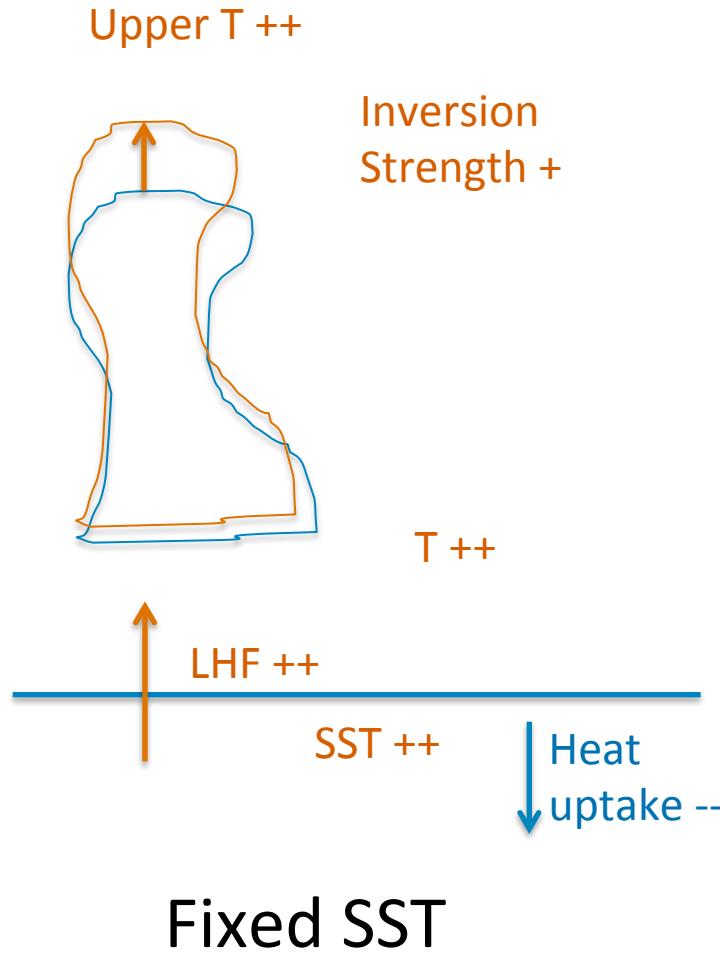
- Fixed SST: C-C increase of surface LHF is balanced by C-C increase of subsidence drying.
- Energy budget: subsidence drying increases weakly, consistent with lower inversion height.

# LWP analysis

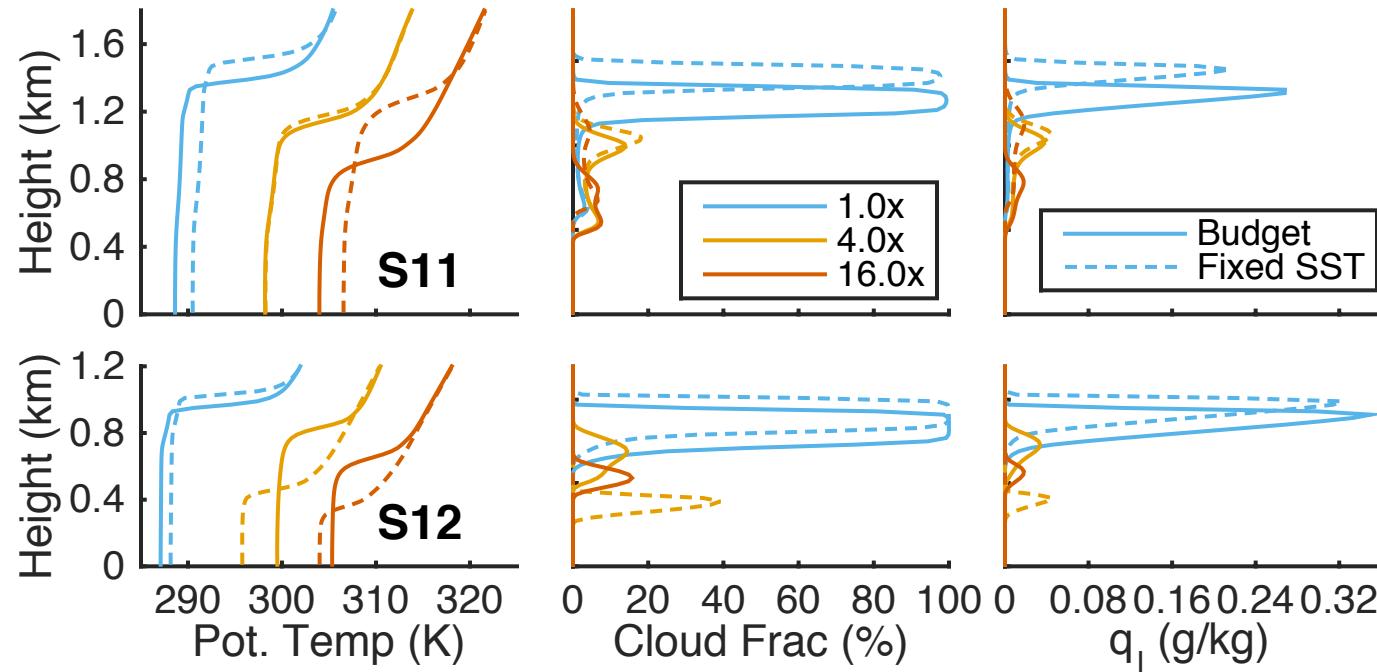


- As Cu-layer shallows under surface energy constraint, LWP decreases more strongly than with fixed SST.
- Cu-depth effect on SWCRE is partly offset by the anvil effect related to the intensified inversion.

# Schematics for mechanisms



# Decoupled (S11) and well-mixed (S12) stratocumulus cases



- Stratocumulus breaks up in all warming cases.  
(minimal +8K and 4x $\text{CO}_2$  with same subsidence)
- Cloud SW feedback enhances the 4.0x  $\text{CO}_2$  warming with surface budget.

# Conclusion

- LES with a closed surface energy budget can simulate current subtropical low-cloud regimes.
- Sc layers break up under warming (for fixed SST and closed energy budget).
- Cu response to warming differs whether SST is fixed or energy budget is closed:
  - With closed energy budget, LHF and SST increase less, contributing to a shallower Cu-layer with less LWP.
- Results highlight the importance of closing the surface energy budget and formulating large-scale forcing consistently in LES experiments.
- Next: With Circulation Change. Thank you!



# What if circulation spins down...

- Surface wind weakens:
  - $LHF \sim C_D U^*(1-RH)*q_s(T_s)$  should not change much.
  - $T_s$  may increase more, or RH may decrease.
  - May be closer to the fixed SST results.
- Subsidence weakens:
  - Inversion height may increase.

# Surface Energy Budget in CGILS

- How consistent are the CGILS surface energy budget with ERA Interim reanalysis?

Plot: x-axis: S6, S11, S12; y-axis: SHF, LHF for CGILS LES and reanalysis

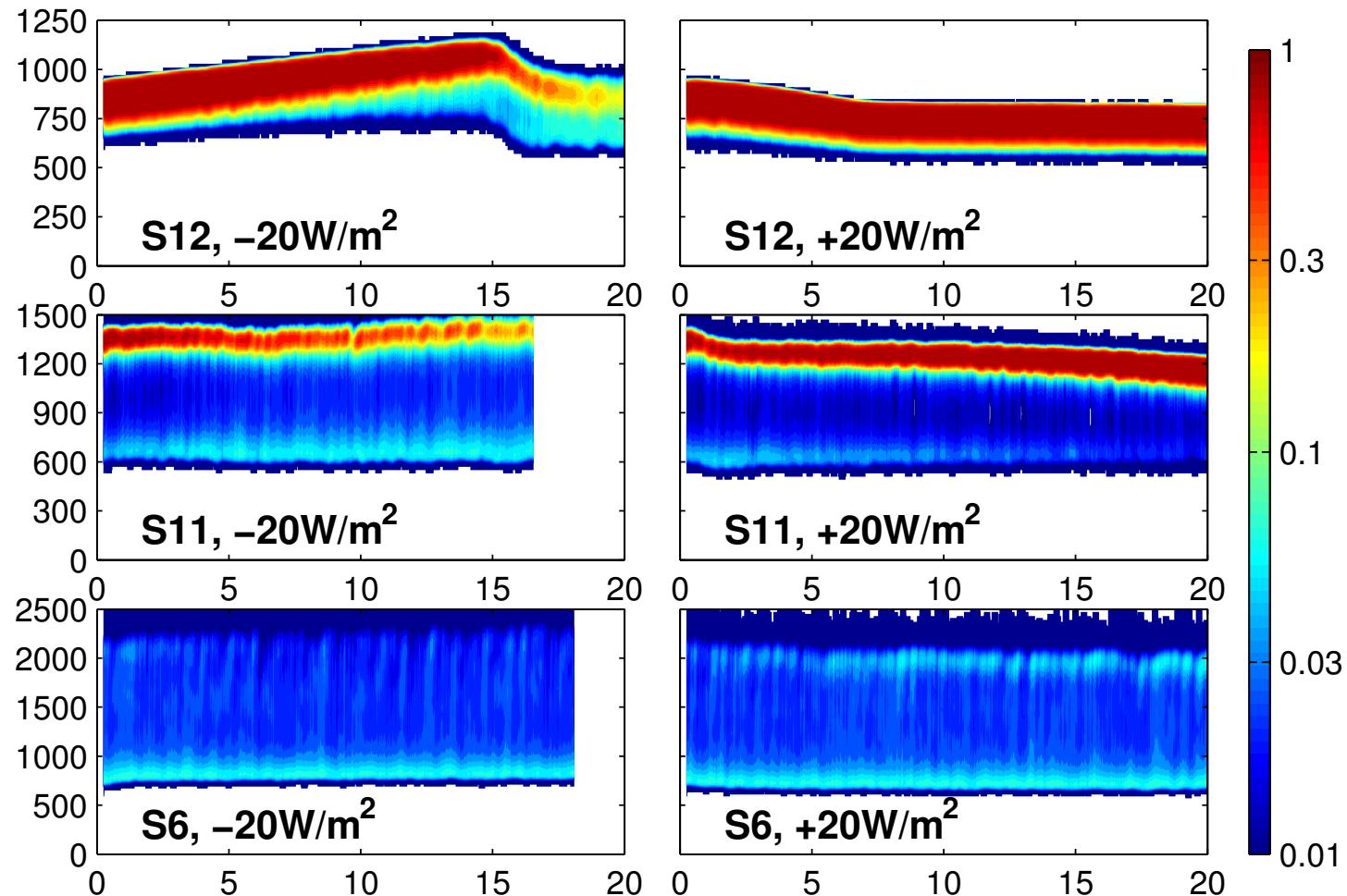
# Overview of this approach

- Goal: study the steady-state cloud response under the surface energy balance constraint.
  - Surface heat uptake is assumed to be constant under climate change; SST can freely evolve.
  - Heating is driven by increased CO<sub>2</sub>, and influenced by upper tropospheric temperature shifts.
- Cases: similar to CGILS.
  - Sc, Sc-over-Cu, Cu cases of NH summer conditions.

# Model Configuration

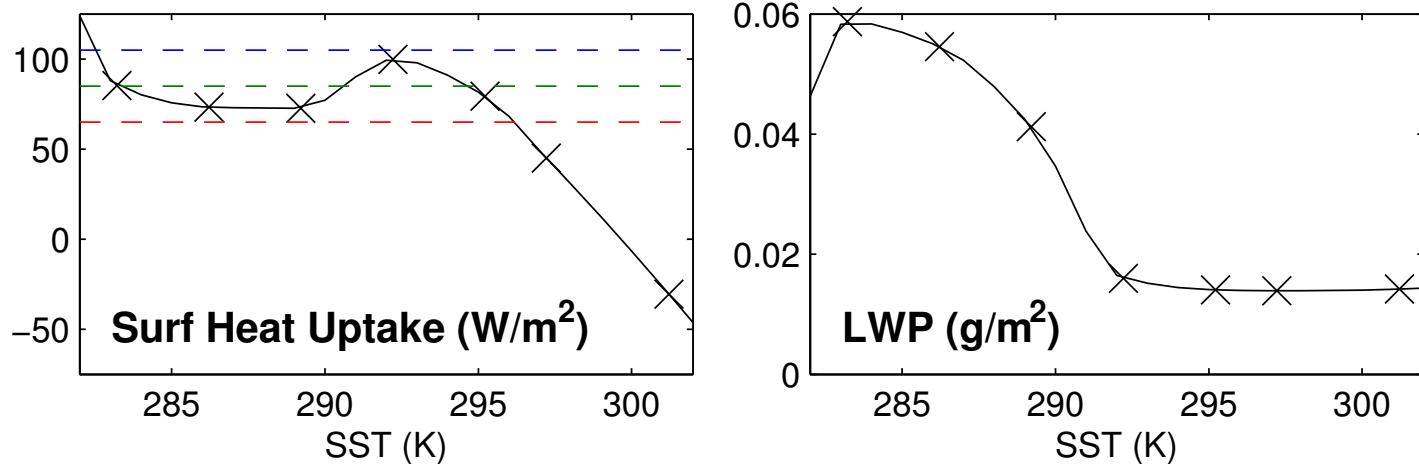
- LES.  
(PyCLES description: highlighting key improvements)
- Large-scale forcing.  
(advection, relaxation, subsidence)
- Radiation: RRTMG scheme
- Microphysics: simple threshold scheme;  
Grabowski; Seifert Beheng.

# Sensitivity on surface heat uptake



# Bifurcation in fixed heat uptake experiments (Case S11)

- For intermediate values of surface heat uptake, two steady states are possible (Sc, shallow Cu)
- Unstable branch corresponds to runaway cloud albedo feedback that warms/cools surface.



# Configuration of climate-change experiments

- Perturbed:
  - CO<sub>2</sub> concentration (4.0x of current).
  - Relaxation profiles (tropical RCE +4K/2xCO<sub>2</sub>).
  - Advective drying (scales with  $q_{sat}$ ).
- Fixed:
  - Subsidence, advective cooling, wind profiles.
  - Surface heat uptake.
- Fixed SST experiments (+4K/2x CO<sub>2</sub>) are also run for comparison.

# Discussion for S11 and S12

- Why clouds break up -> feedback
- Difference between fixed SST and fixed heat uptake?