Entrainment-liquid flux adjustment: a thermodynamic mechanism for decreasing subtropical low cloud in a warmer climate

Chris Bretherton and Peter Blossey
University of Washington

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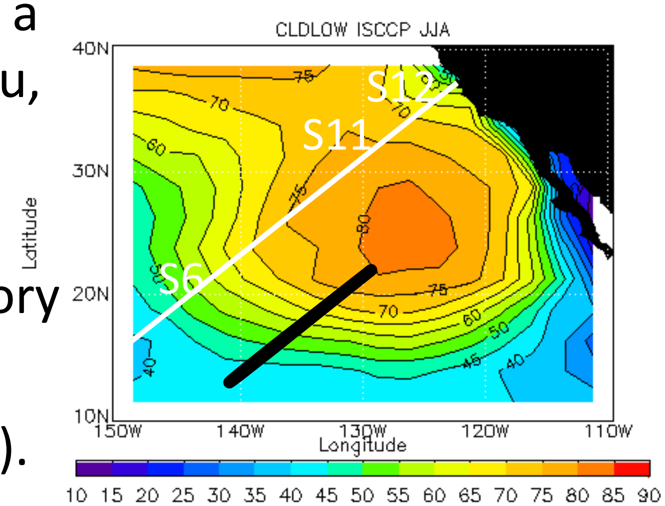
See Wed. night poster if this goes by too fast

Bretherton and Blossey 2013, JAMES, submitted:

ftp://eos.atmos.washington.edu/pub/breth/papers/in-review/Lagr-cldfeed.pdf

Review: A Lagrangian View of Cloud Evolution and Feedbacks

- GASS stratocumulus to trade cumulus transition: a composite case from the Northeast Pacific (Sandu, Stevens & Pincus, 2010; Sandu & Stevens, 2011); summertime conditions (JJA2006-7).
- Simulation follows composite Lagrangian trajectory over warmer SSTs with fixed subsidence.
- Finish after 3 days (before breakup of capping Sc).



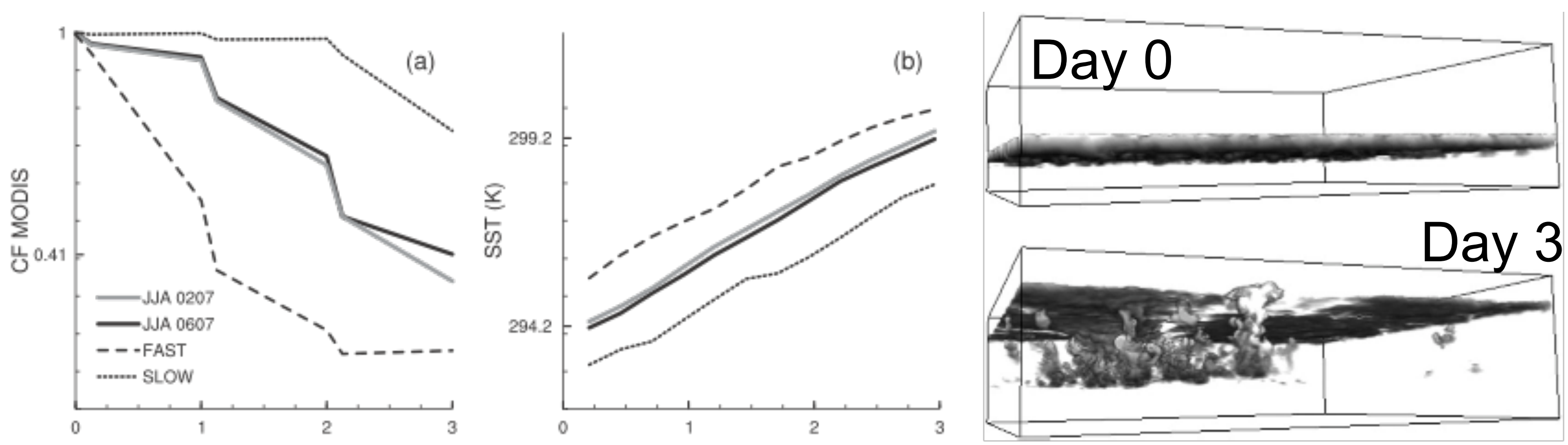
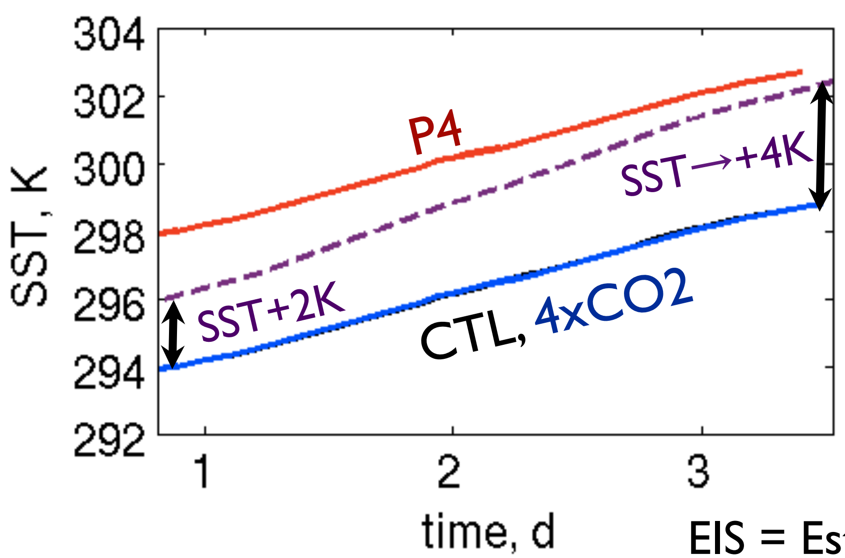
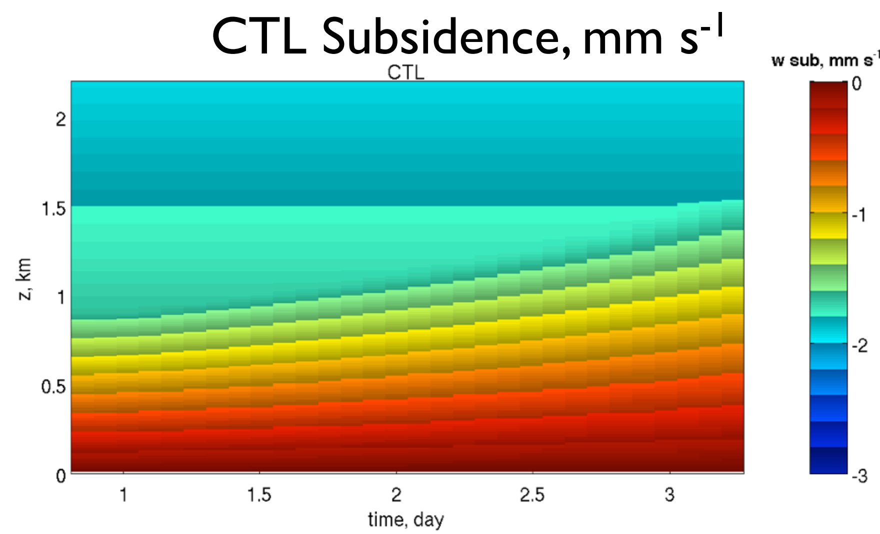


FIG. 3. An image of the cloud field simulated in the REF case, at (top) the beginning and (bottom) the end of the simulation.

Lagrangian cloud response to climate perturbations

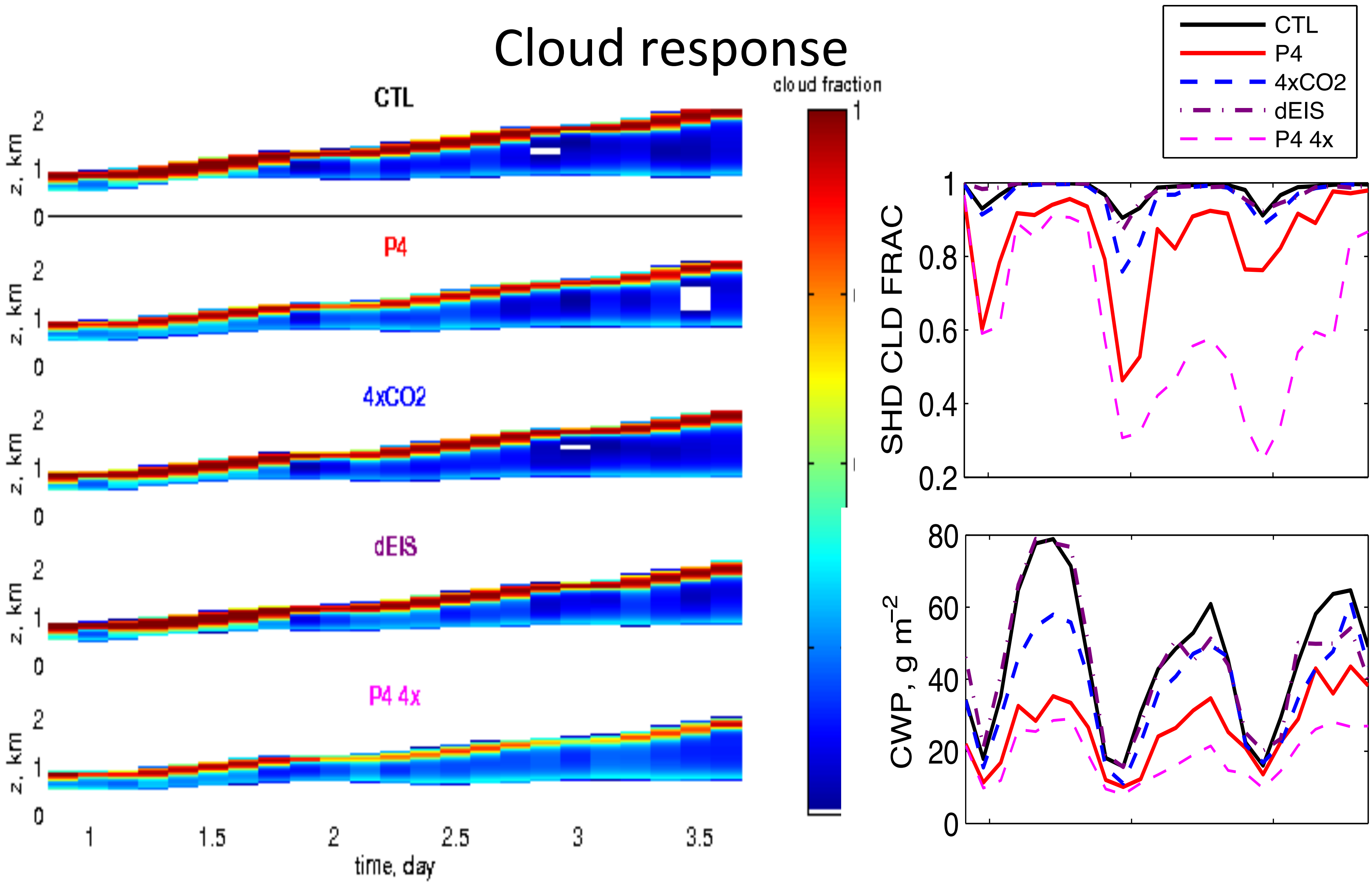
- Modified GASS Lagrangian transition case.
- Four climate perturbations (no changes to wind speed, FT RH):
  - P4 (warming): SST+4K, moist adiabatic warming aloft,
  - dEIS (stability↑): SST+2K locally, SST+4K in deep tropics.
  - $4xCO_2$,
  - P4 4x (combined warming and $4xCO_2$).
- Adapt (weak) subsidence profile so free tropospheric energy budget is in approximate balance (P4 subsidence ~ 0.9 CTL subsidence).





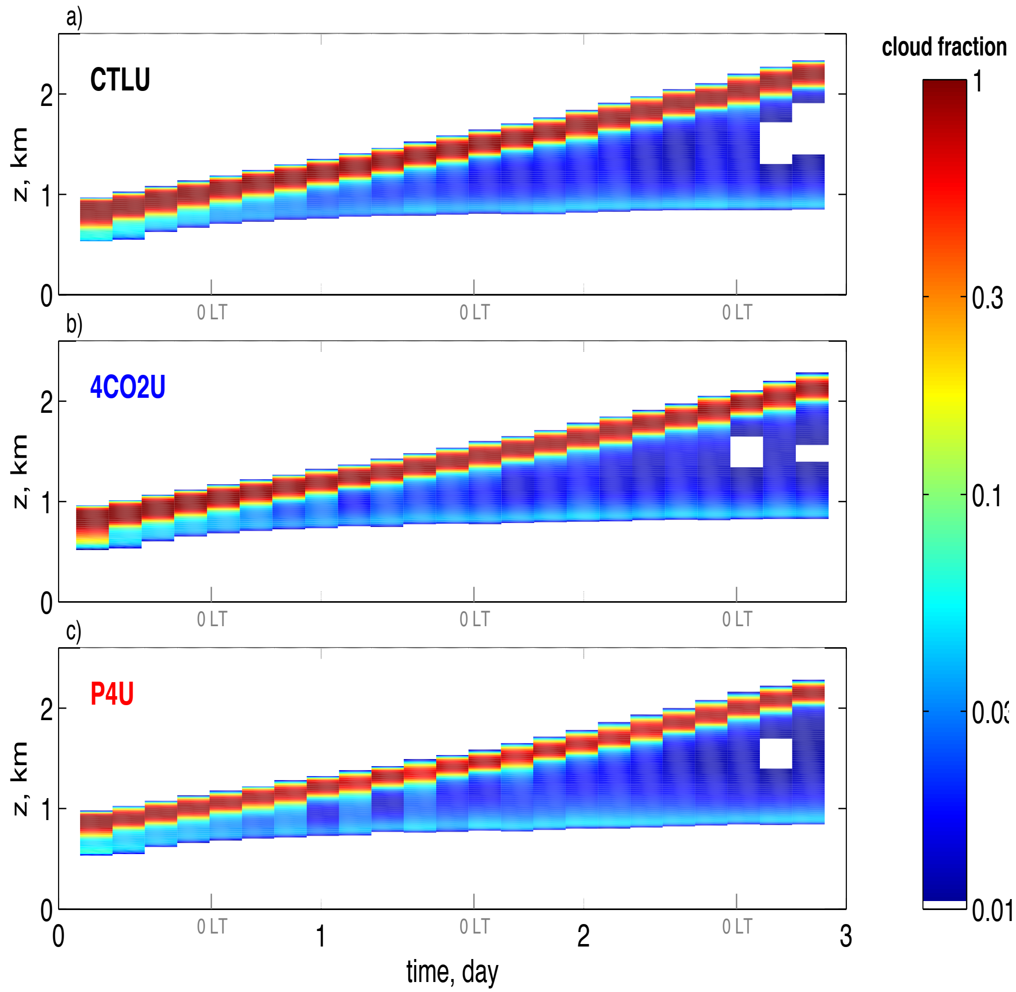
EIS = Estimated Inversion Strength (Wood & Breth, 2006)

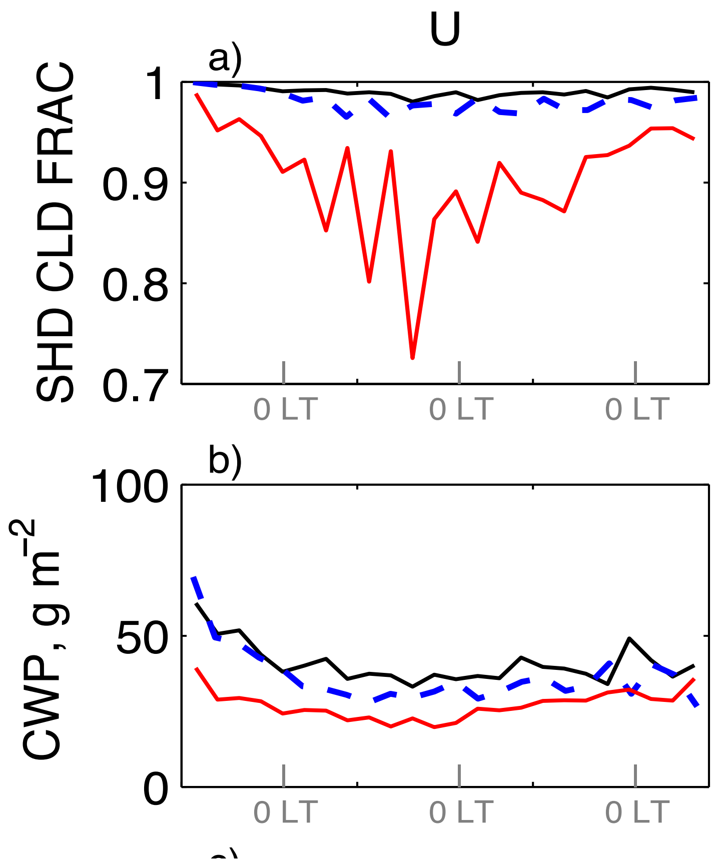
Cloud response



- Cloud thins in P4 simulation relative to CTL. Yet more thinning in P4 4x.
- 4xCO2 also thins, but not as much as P4
- dEIS very similar to CTL.

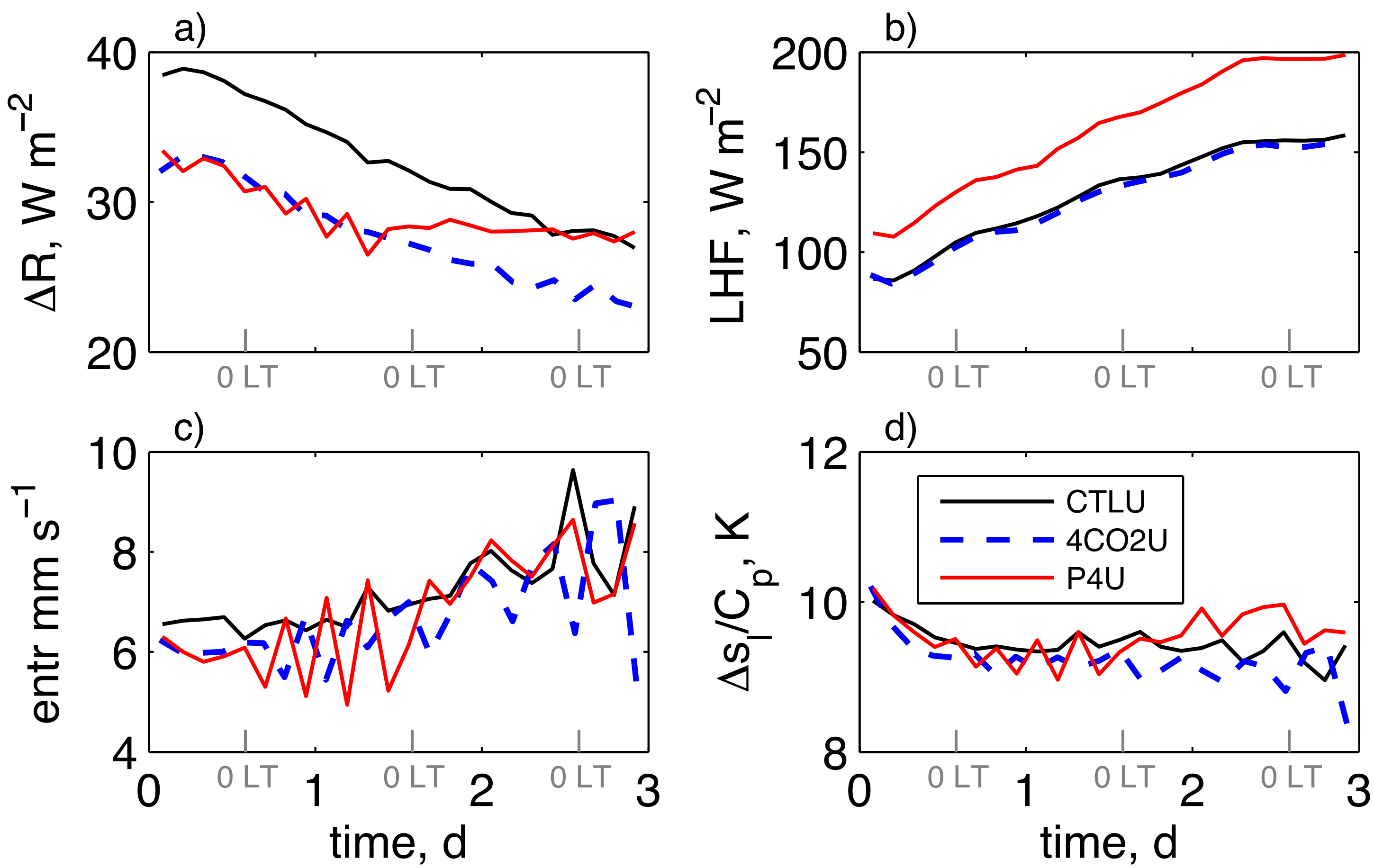
Cloud Response – Diurnal-Mean Insolation





- Cloud thins in P4 simulation relative to CTL. Yet more thinning in P4 4x.
- P4, 4xCO2 runs more decoupled on first night than CTL, dEIS.

Radiation and Entrainment

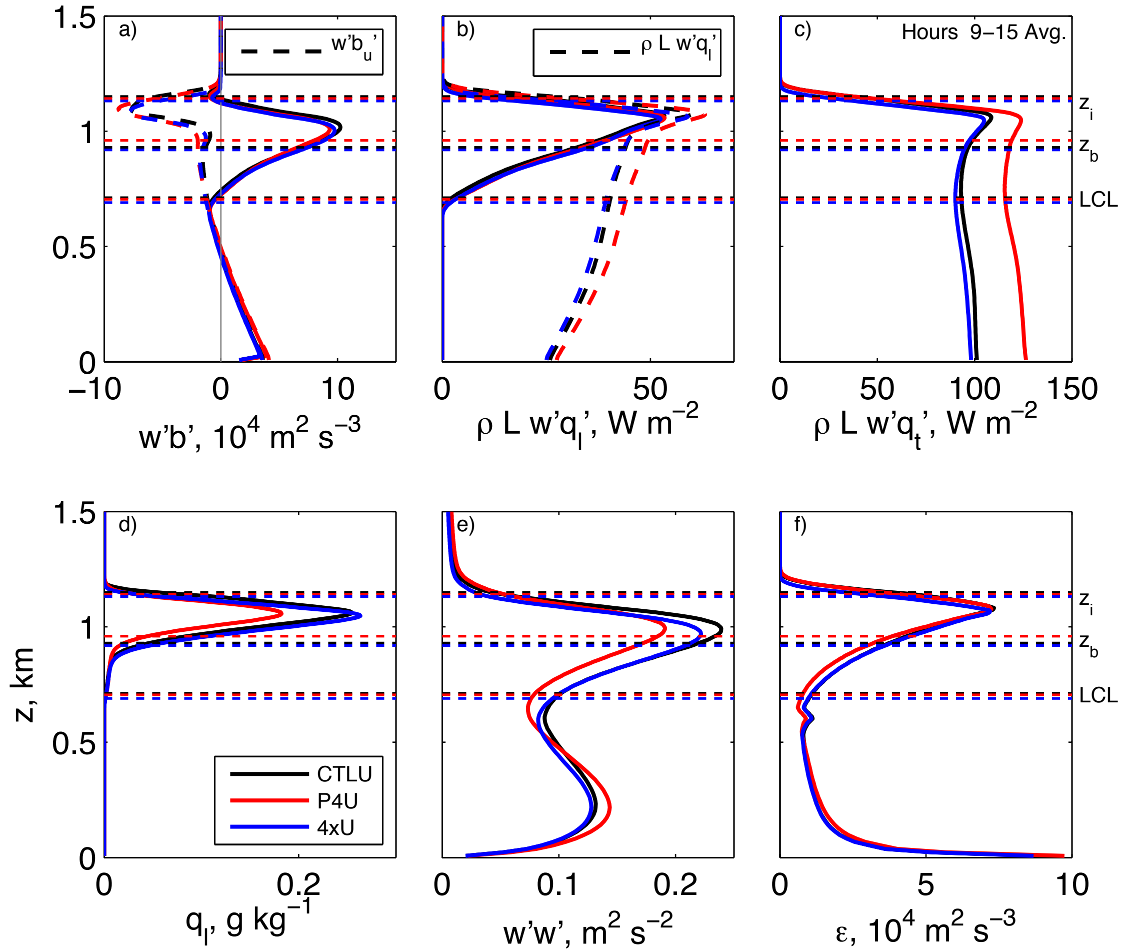


In the first half of the simulation, 4CO2U and P4U have approximately the same:

- Boundary-layer radiative cooling ΔR
- Entrainment rate (and inversion height evolution and cloud-top turbulence levels)
- Inversion strength $\Delta s_l/c_p$

How does P4U maintain the same entrainment rate across the same inversion strength with the same radiative driving, but with less cloud than in 4CO2U?

Liquid flux and buoyancy production of turbulence



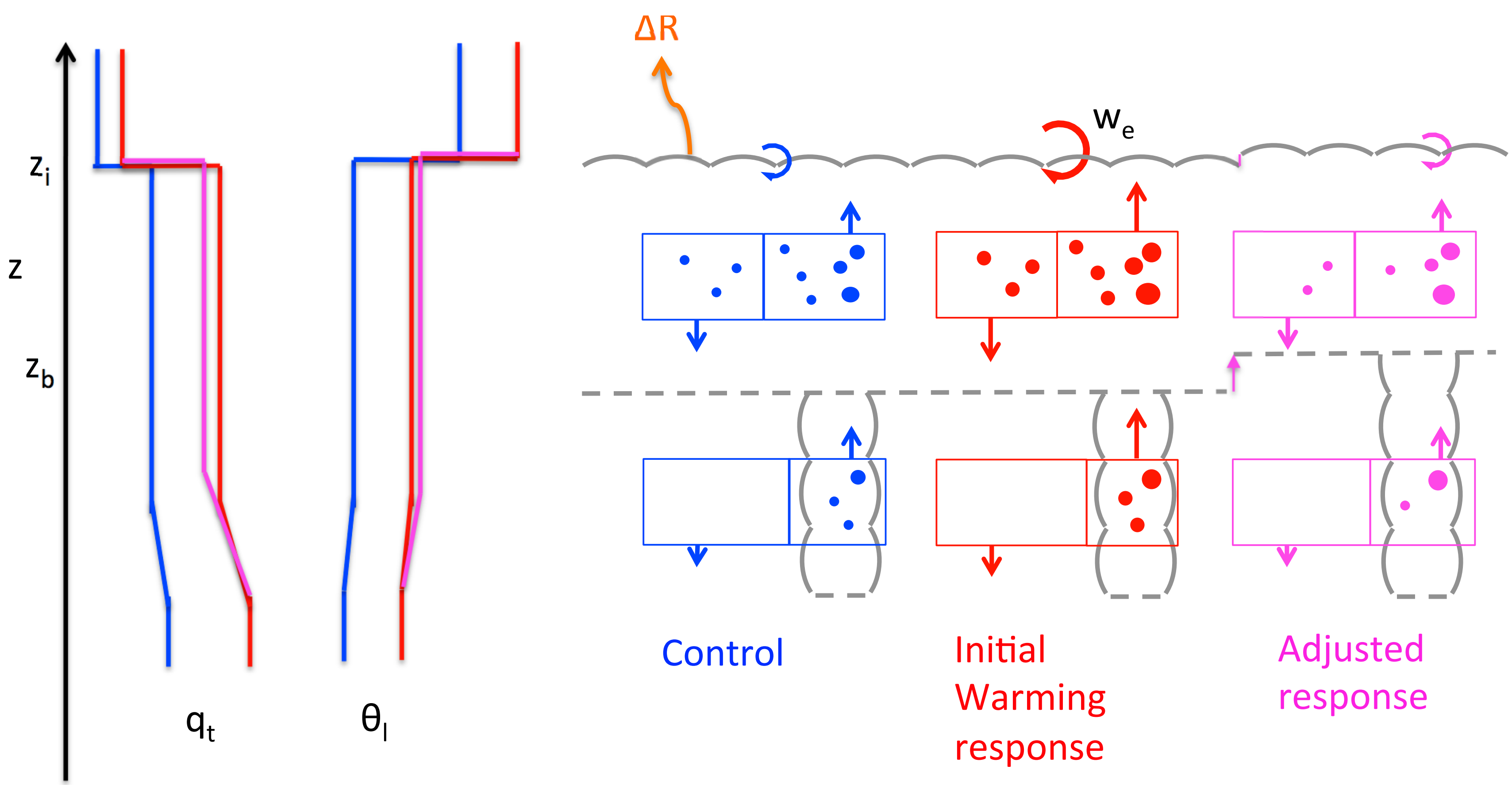
- In the cloud layer, turbulent buoyancy production and its P4 response are tightly controlled by the upward liquid flux, because of latent heat release by condensation of q_l

$$w'b' = \overline{w'b'_u} + c\boxed{\overline{w'q'_l}}$$

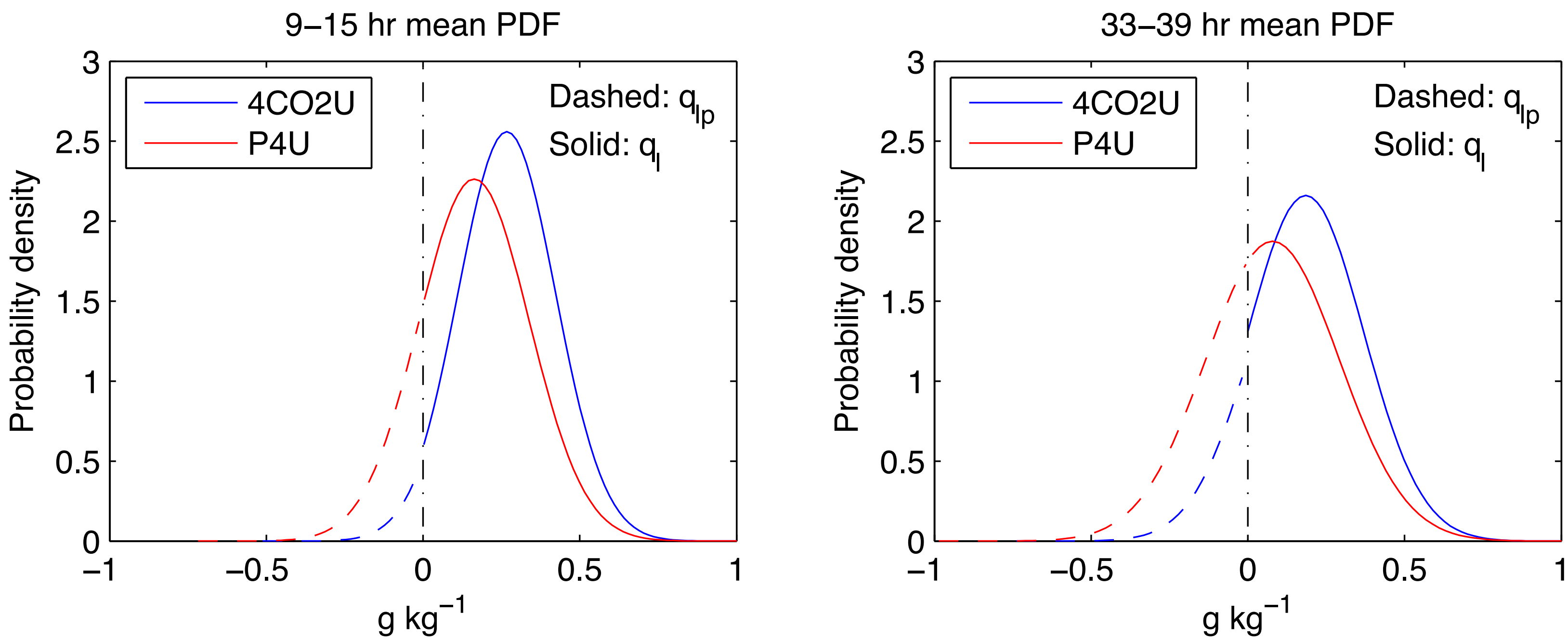
- In a fully saturated layer, C-C implies the liquid flux increases 2.5%/K in warmer climate

Cloud thinning by entrainment liquid flux (ELF) adjustment

- Instantaneously warm T_l of a turbulent CTBL and the overlying free troposphere by δT, keeping RH = $q_t/q_s(z, T_l)$ and radiative flux divergence ΔR constant.
- The initial CTBL response is to increase horizontal q_l and T perturbations, increasing turbulent buoyancy production & entrainment rate w_e (like Rieck et al)
- Entrainment drying thins Sc cloud until w_e readjusts to the pre-existing ΔR, $\Delta\theta_l$.



PDFs of 'potential LWC'

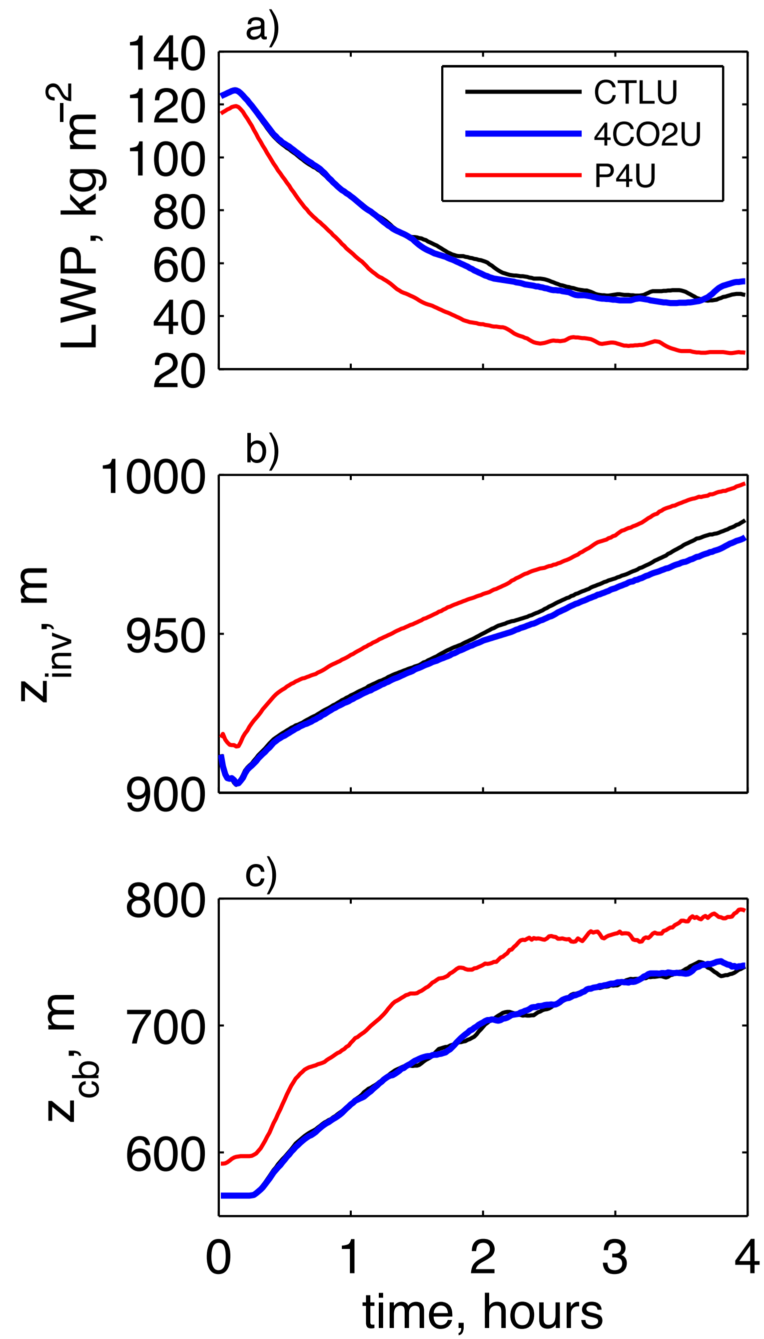


$$q_{lp} = \frac{q_t - q_s(p, T_l)}{1 + \frac{L}{c_p}\frac{\partial q_s}{\partial T}} = a(RH - 1)$$ = q_l when positive

In the warmer P4 climate, the PDF of q_{lp} broadens as expected, forcing the Sc layer to dry to keep the upward liquid water flux, the buoyancy production of turbulence, and entrainment warming in balance with radiative cooling.

Fast spinup of ELF cloud thinning response

P4 LWP reduction sets in rapidly with burst of more entrainment in first 2 hrs during spinup, consistent with an entrainment adjustment



Rieck et al. (2012) Cu-entrainment-desiccation mechanism

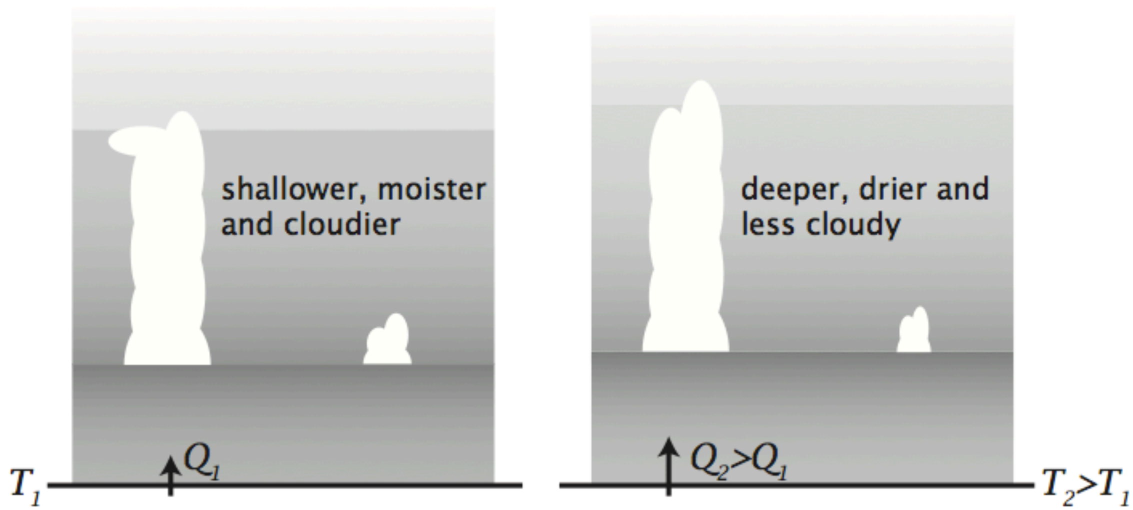


FIG. 11. Schematic diagram showing the main response of the cloud-topped boundary layer to a change in temperature, assuming large-scale processes act to keep the humidity constant.

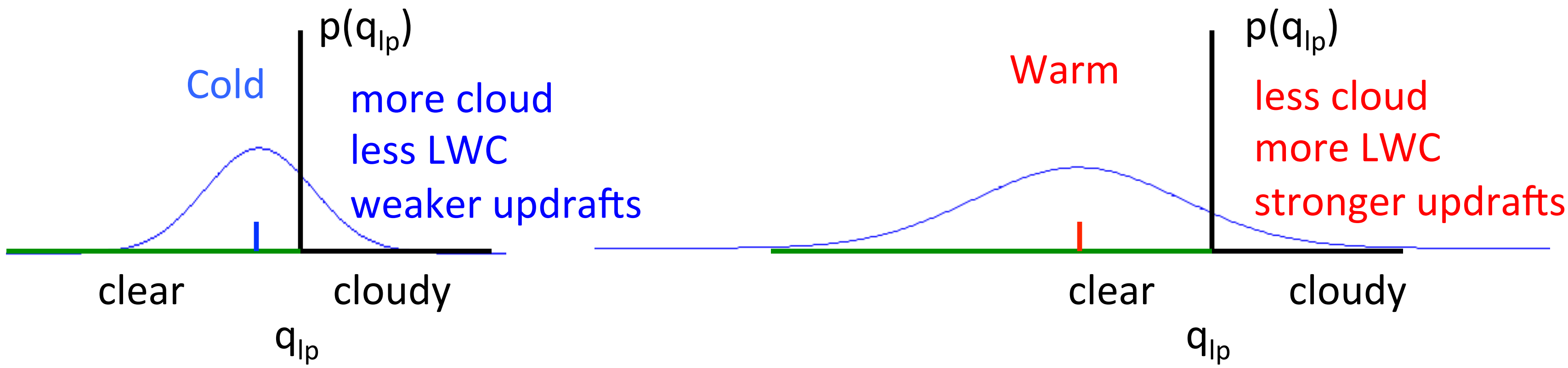
Rieck: In a 'constant RH' atmosphere, stronger LHF ➔ More entrainment
Entrainment drying ➔ higher Cu base
Lower Cu-layer RH ➔ less cloud cover even though in-cloud LWC higher
(positive cloud feedback)

Lagr P4: Stronger LHF
vs. 4CO2 Entrainment and Cu base hardly change due to cloud-radiative control
Still get less cloud, even though Rieck mechanism doesn't apply here.

Shallow Cu example (vertically uniform RH in cloud layer)

Same liquid water variance (and flux) and turbulence production can be maintained with a lower R and less cloud fraction in warmer climate, due to the broader humidity variance.

Same $\overline{w'q_l'}$



Conclusions

- As in CGILS, Lagrangian framework corroborates cloud thinning in a warmer climate, moderated by EIS increases.
- Cloud thinning is due to
  1. reduced radiative destabilization
  2. thermodynamically-driven increase in cloud heterogeneity
- A simple model isolates thermodynamic feedback on cloud.
- In a warmer climate, more moisture variance generates clouds with more heterogeneous liquid water. These generate the same levels of turbulence and entrainment with less cloud fraction and liquid water path.