Sensitivity of low cloud transitions to greenhouse warming

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Based on GASS composite transition case (Sandu and Stevens 2011)

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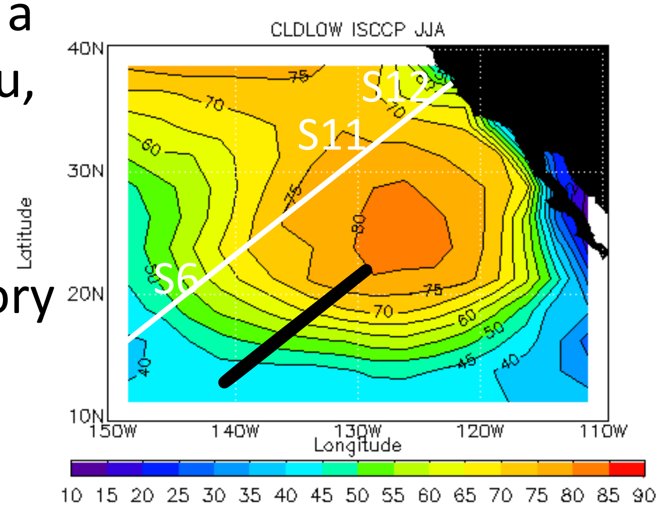
A Lagrangian View of Cloud Evolution and Feedbacks

- 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.



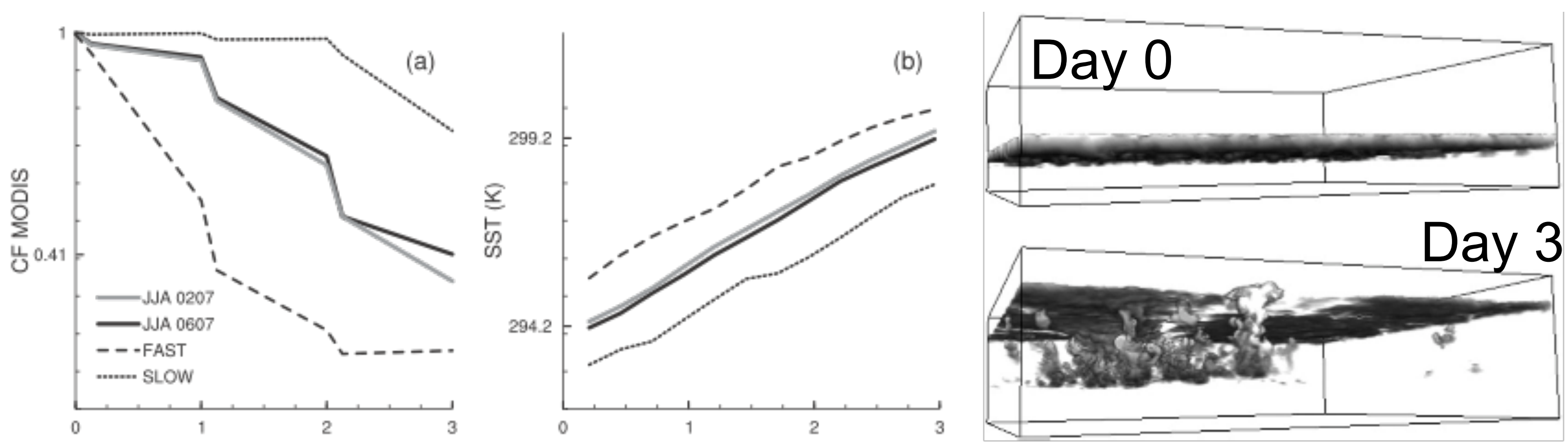
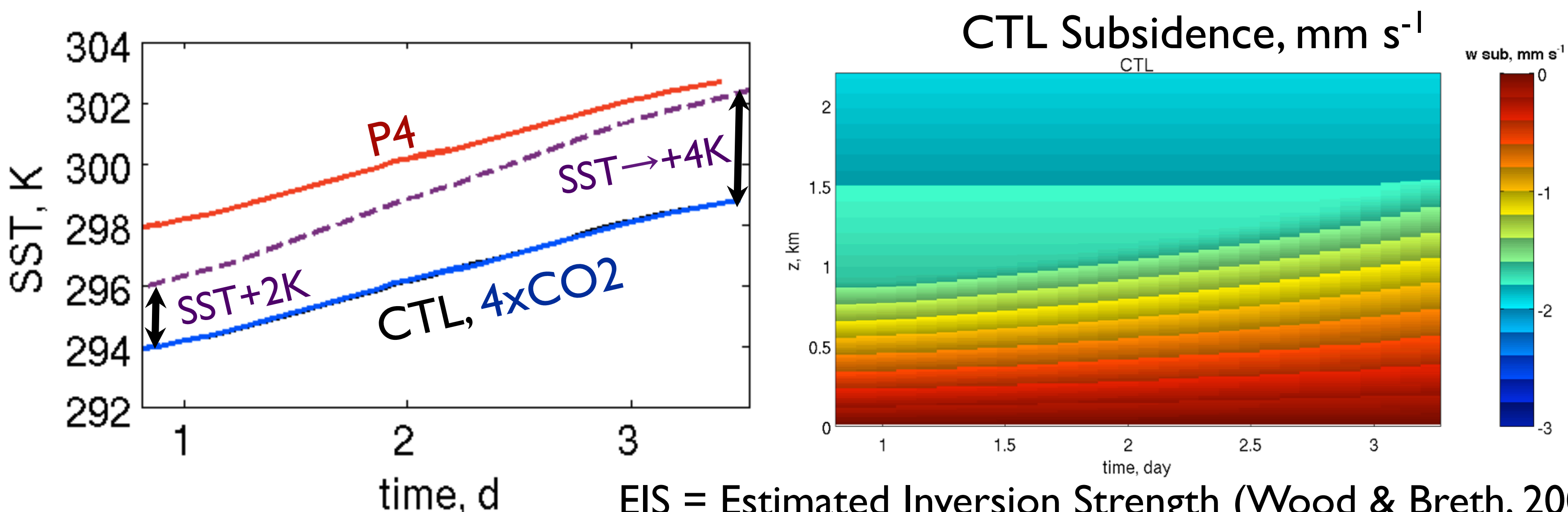


FIG. 3. An image of the cloud field simulated in the REF case, at (top) the beginning and (bottom) the end of the simulation.

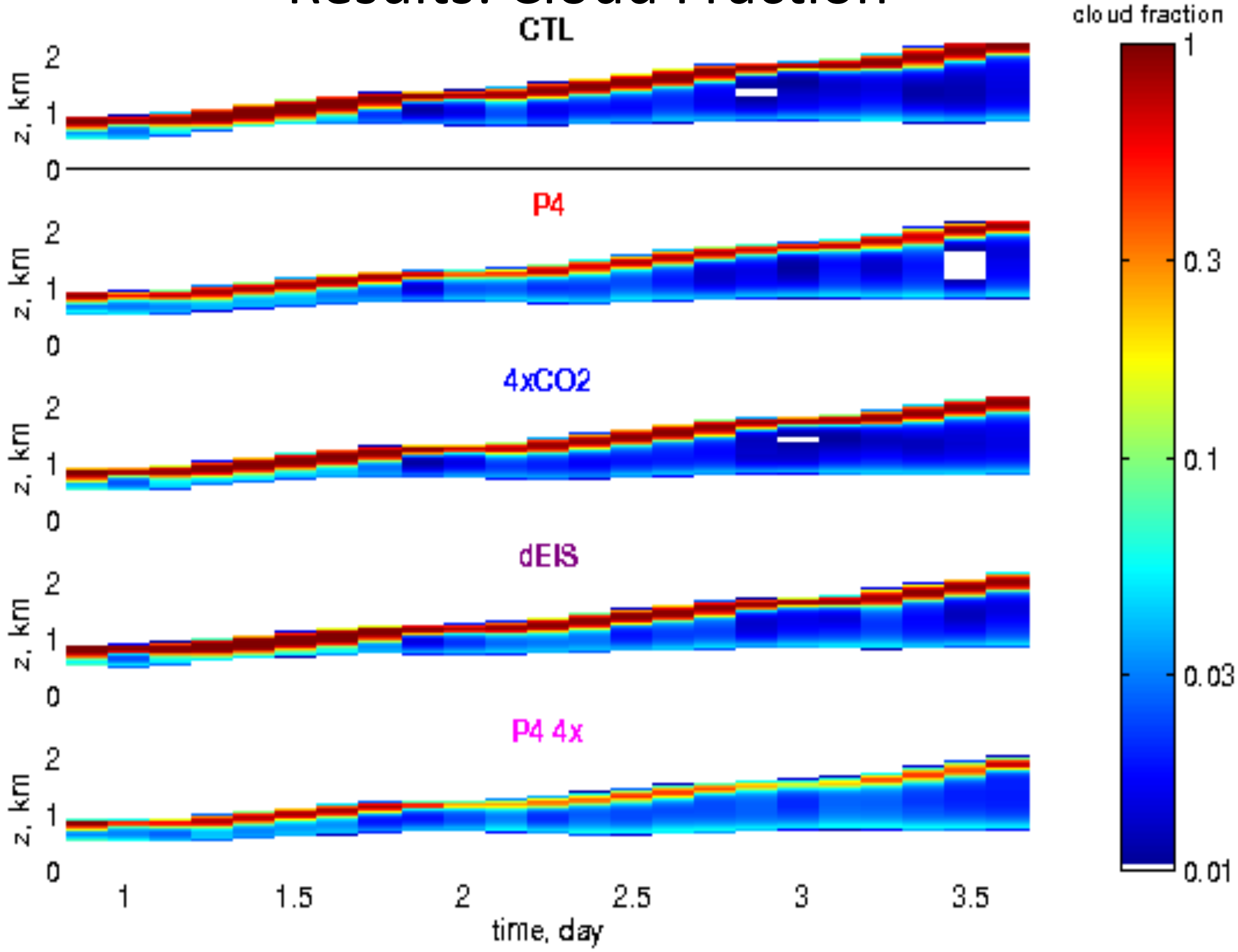
Lagrangian cloud response to climate perturbations

- 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. Causes EIS increase of 3K at start vs. CTL, P4. Stronger than expected changes based on CMIP3 models (ΔEIS<~1K),
  - $4xCO_2$,
  - P4 4x (combined warming and $4xCO_2$).
- Adapt (weak) subsidence aloft in each case so that free tropospheric energy budget is in approximate balance (P4 subsidence ~ 0.9 CTL subsidence).



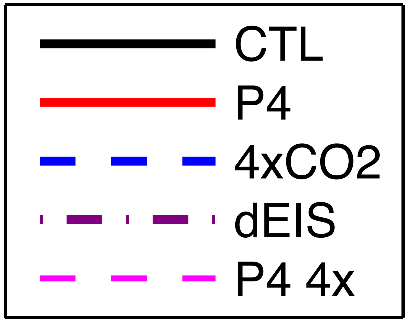
EIS = Estimated Inversion Strength (Wood & Breth, 2006)

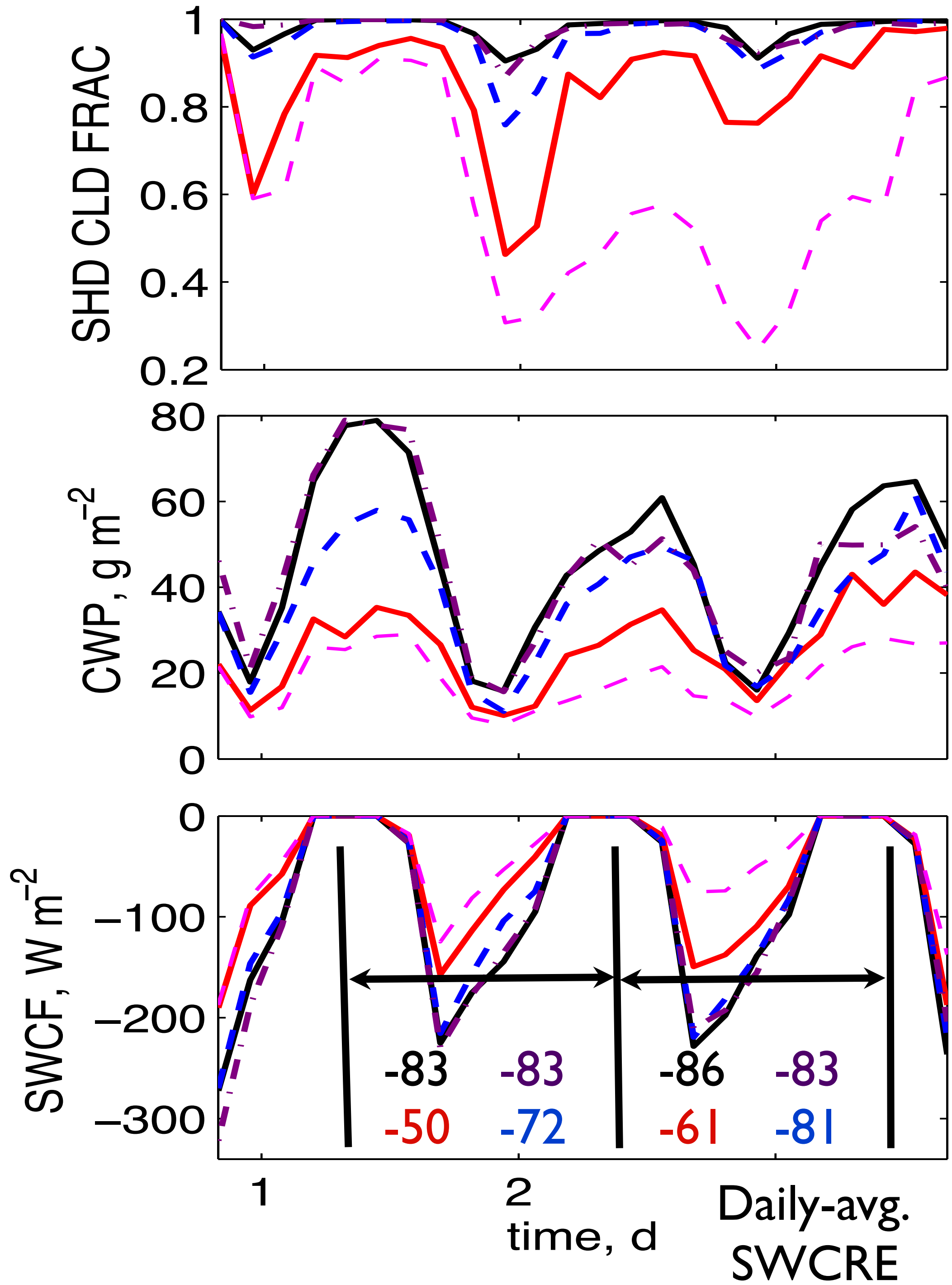
Results: Cloud Fraction



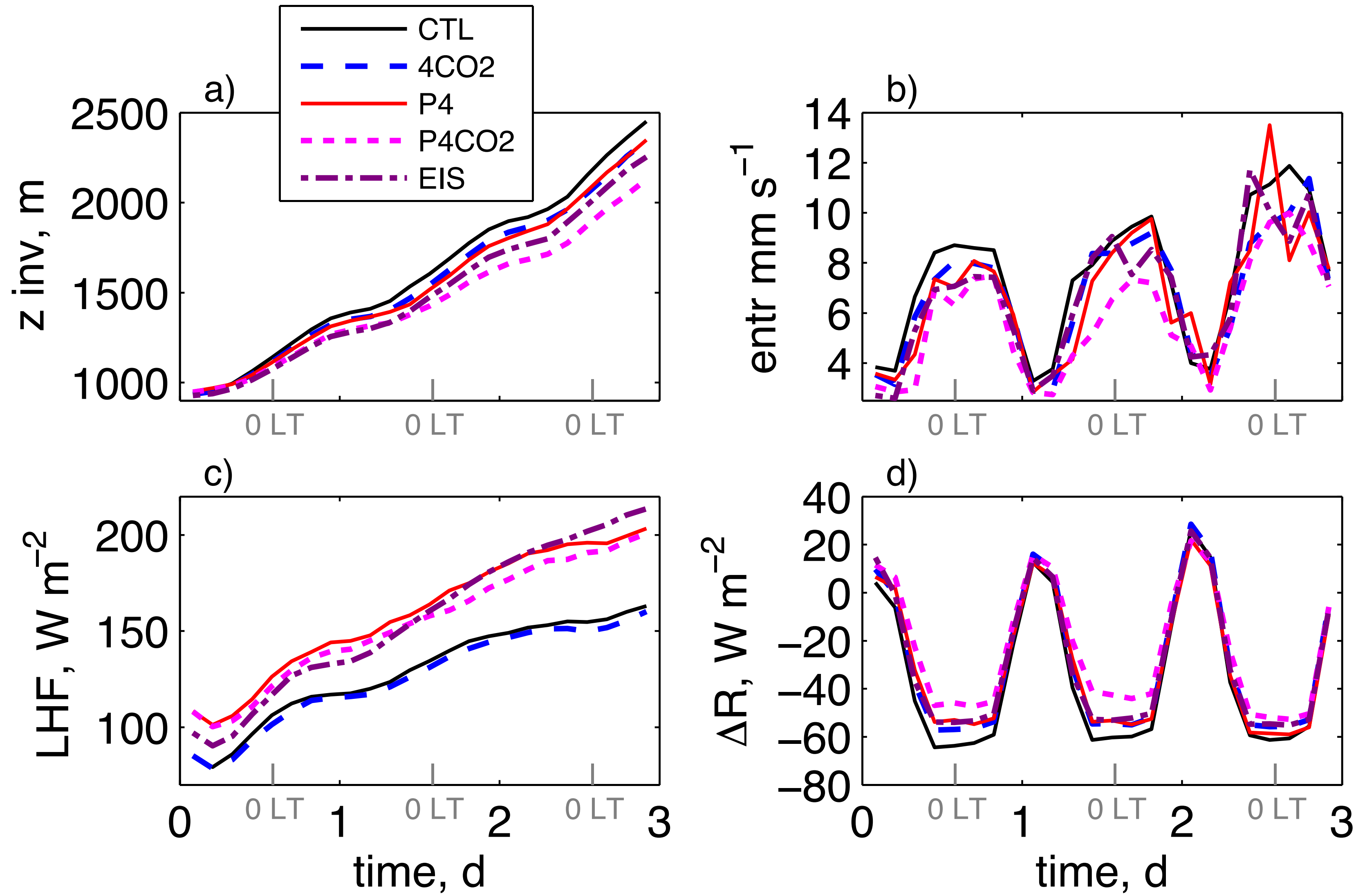
- Cloud thins in P4 simulation relative to CTL. Yet more thinning in P4 4x.
- P4, 4xCO2 runs more decoupled on first night than CTL, dEIS.

Time series



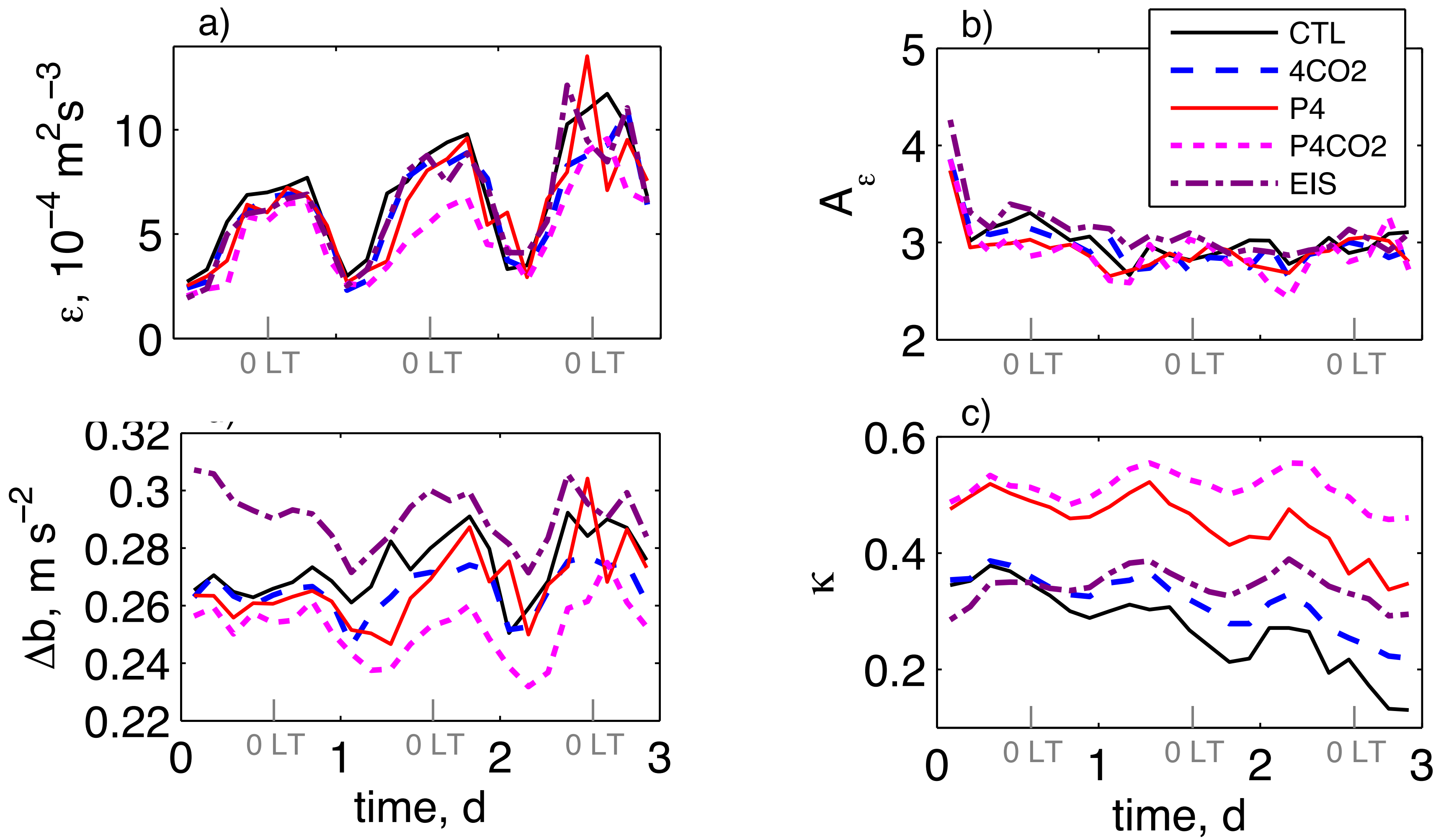


- Warming (P4) leads to thinner more broken cloud.
- Large ΔSWCRE (CTL→ P4) due in part to partial cloud cover (~80-85%), stronger decoupling.
- With 4xCO_2, cloud thinner on first full day but mostly recovers on second.
- Increase stability offsets warming in dEIS simulation.
- More thinning in combined P4 4x run than in other runs.



- Entrainment (and cloudiness) increases with MBL radiative flux divergence ΔR (inversion strength Δb also important, but varies less between runs)
- However, P4 and 4CO2 have similar ΔR and Δb, but P4 is less cloudy
- ➔ radiative and thermodynamic mechanisms, as in CGILS (Breth. et al. 2013).

Entrainment efficiency



- Higher $\kappa = 1 + \Delta s_l / L \Delta q_t$ and less cloud in warmer cases
- However, entrainment efficiency $A_\varepsilon = w_e \Delta b / \varepsilon$ does not increase
- Warmer: less cloud ➔ same turb ➔ same entrainment.

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

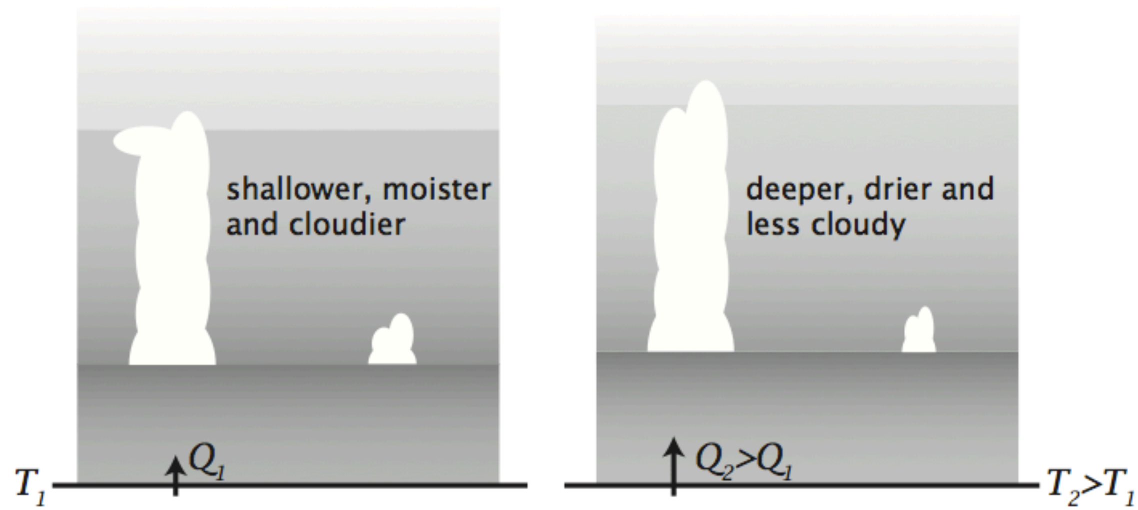


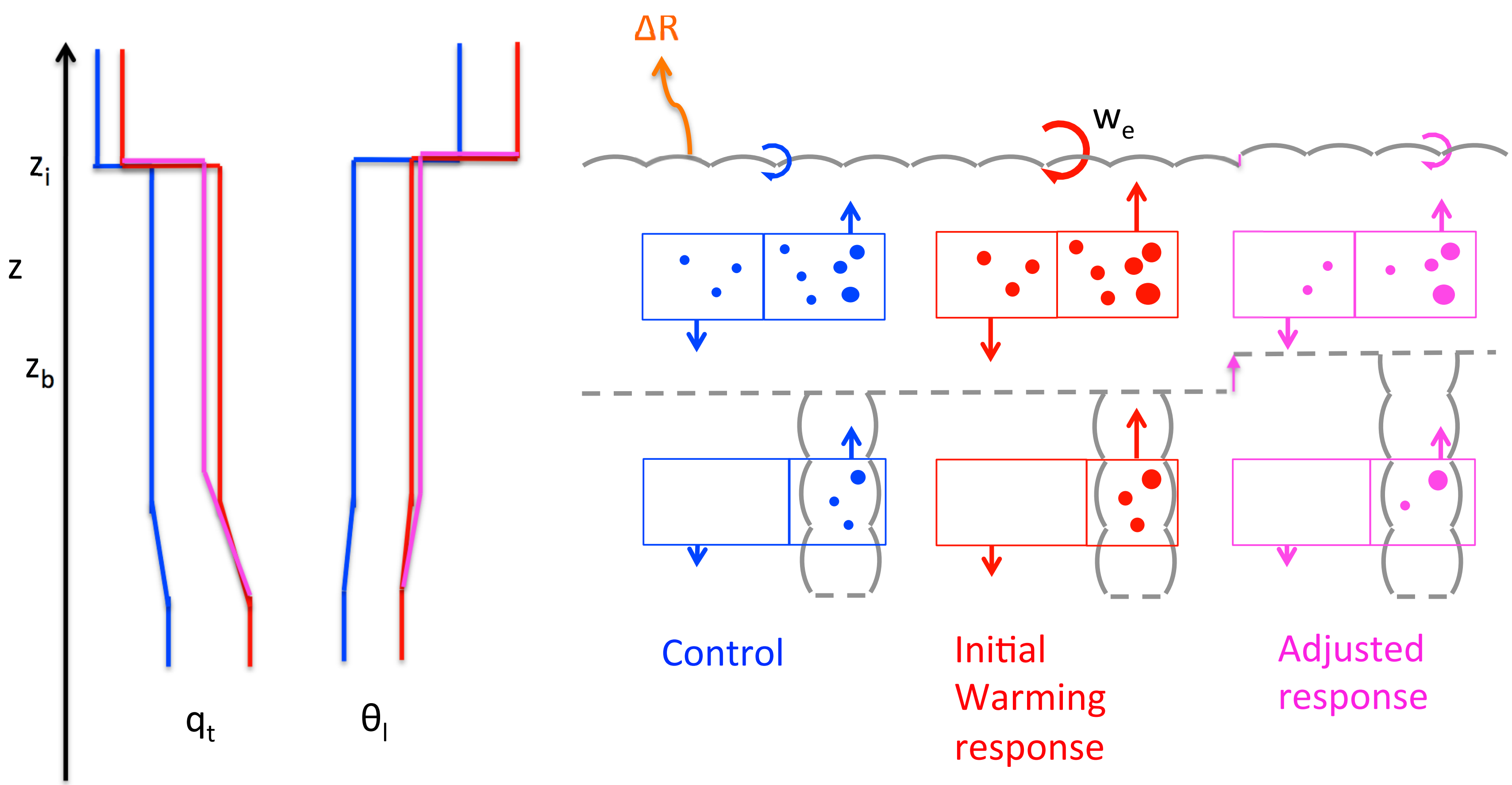
FIG. 11. Schematic diagram showing the main response of the cloud-topped boundary layer to a change in temperature, assuming large-scale processes act to keep the humidity constant.

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.

Warming-induced cloud thinning mechanism

- 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, $\Delta\theta_l$.
- In our LES runs, this cloud thinning adjustment takes only 2-4 hours.



Simple model of this process

- $q_l = \beta \max(RH-1, 0)$, $\delta\beta/\delta T = 2\text{-}3\%\ K^{-1}$
- Horizontal RH variability Gaussian with std dev σ_R.
- Vertical RH lapse rate Γ_R (negligible dependence on δT)
- Radiative cooling ⇔ entrainment warming ⇔ buoy flux

$$\Delta R \propto w_e \Delta b \propto \frac{1}{l_{turb}} \int_{z_{LCL}}^{z_i} \overline{w'b'}\, dz$$

$$b' = b_u' + cgq_l' \quad \Rightarrow \quad \int_{z_{LCL}}^{z_i} \overline{w'b'}\, dz \approx \int_{z_{LCL}}^{z_i} \overline{w'b_u'}\, dz + cg \int_0^{z_i} \overline{w'q_l'}\, dz$$

$$\text{and } w' \sim b' \sim q_l' \quad \Rightarrow \quad \int_0^{z_i} \overline{w'q_l'}\, dz = a \int_0^{z_i} \overline{q_l'q_l'}\, dz$$

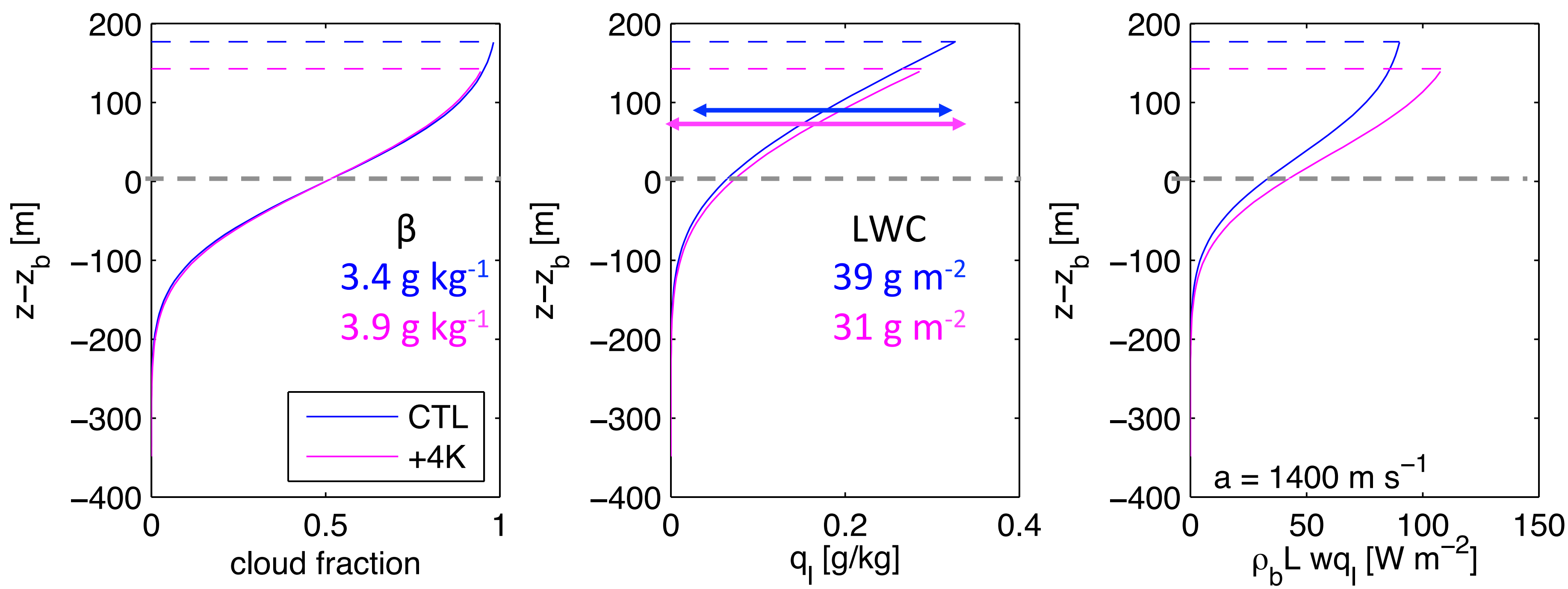
$$\Rightarrow F = \int_0^{z_i} \overline{q_l'q_l'}\, dz \propto l_{turb} \Delta R$$

→ Adjust cloud thickness in warmer climate to keep F = constant in the presence of larger horizontal moisture variability.

Results for Day 1 average parameters

$F = 3.5\ (\text{g kg}^{-1})^2\ \text{m}$
$\sigma_R = 4.5\%$
$a = 1400\ \text{m s}^{-1}$

$T_{cb} = 282$ K
$p_{cb} = 900$ hPa
$\Gamma_R = 0.53\ \text{km}^{-1}$



- This simple model will always predict a warming-induced cloud fraction and LWP reduction, regardless of the chosen F and σ_R.
- Decreased ΔR lowers F in the warmer climate, accentuating cloud reduction.

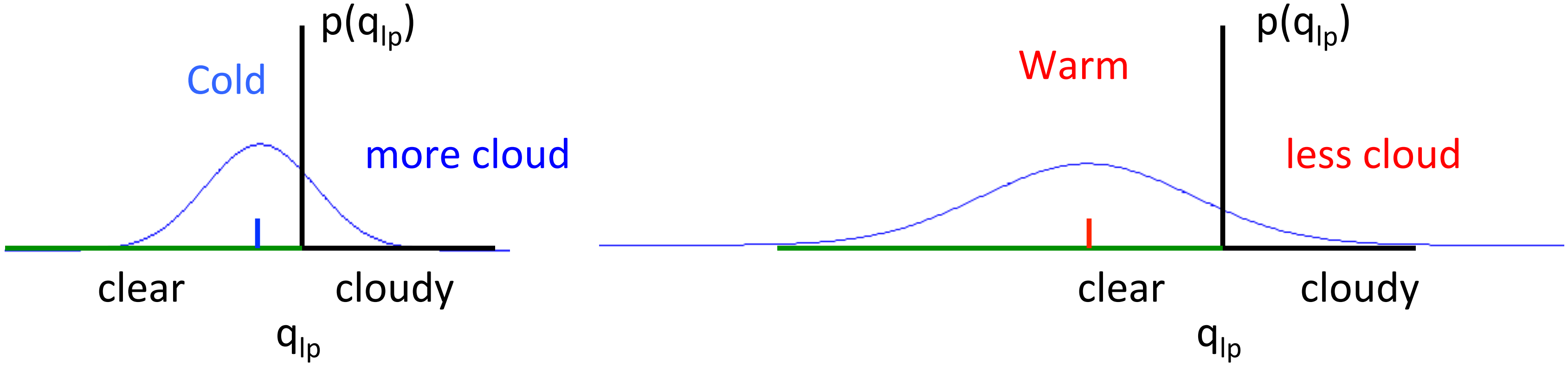
Shallow Cu example (vertically uniform RH in cloud layer)

Fixed F, σ_R. Let R = mean RH in a layer of thickness z_{Cu}.

Define 'potential liquid water' $q_{lp} = \beta(RH-1)$. Its distribution broadens in warmer climate with larger β.

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 $\overline{q_l' q_l'}$



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.