Boundary-Layer Cloud Feedbacks on Climate - An MMF Perspective

Matthew E. Wyant
Peter N. Blossey
Christopher S. Bretherton
University of Washington

Marat Khairoutdinov
Minghua Zhang
Stony Brook University

Photo courtesy Rob Wood

Superparameterization and cloud feedbacks

- Cloud feedbacks and cloud-aerosol interaction remain key uncertainties for climate change.
- A major cause is low-latitude marine boundary layer cloud, because it has large TOA radiative effects and involves multiple processes unresolved by GCMs.
- Cloud-resolving models simulate these interacting processes better and with less parameterization assumptions than GCM column models, given adequate grid resolution.

⇒ An MMF-type model could improve prediction of boundary-layer cloud feedbacks and cloud-aerosol interaction.

⇒ High-resolution CRMs run with large-scale forcings that respond appropriately to climate perturbations may also shed light on cloud feedbacks.

Outline

- Cloud feedback mechanisms in the proto-MMF
- Column-modeling framework for low cloud feedbacks.
- The CFMIP-GCSS SCM/CRM intercomparison study.

Cloud feedbacks in SP-CAM

SP-CAM:

- T42, 2D CRMs, 28 levels, Δx = 4 km
- Under-resolves boundary-layer Cu & Sc, but still useful?
- Physical mechanism of SP-CAM low cloud response?

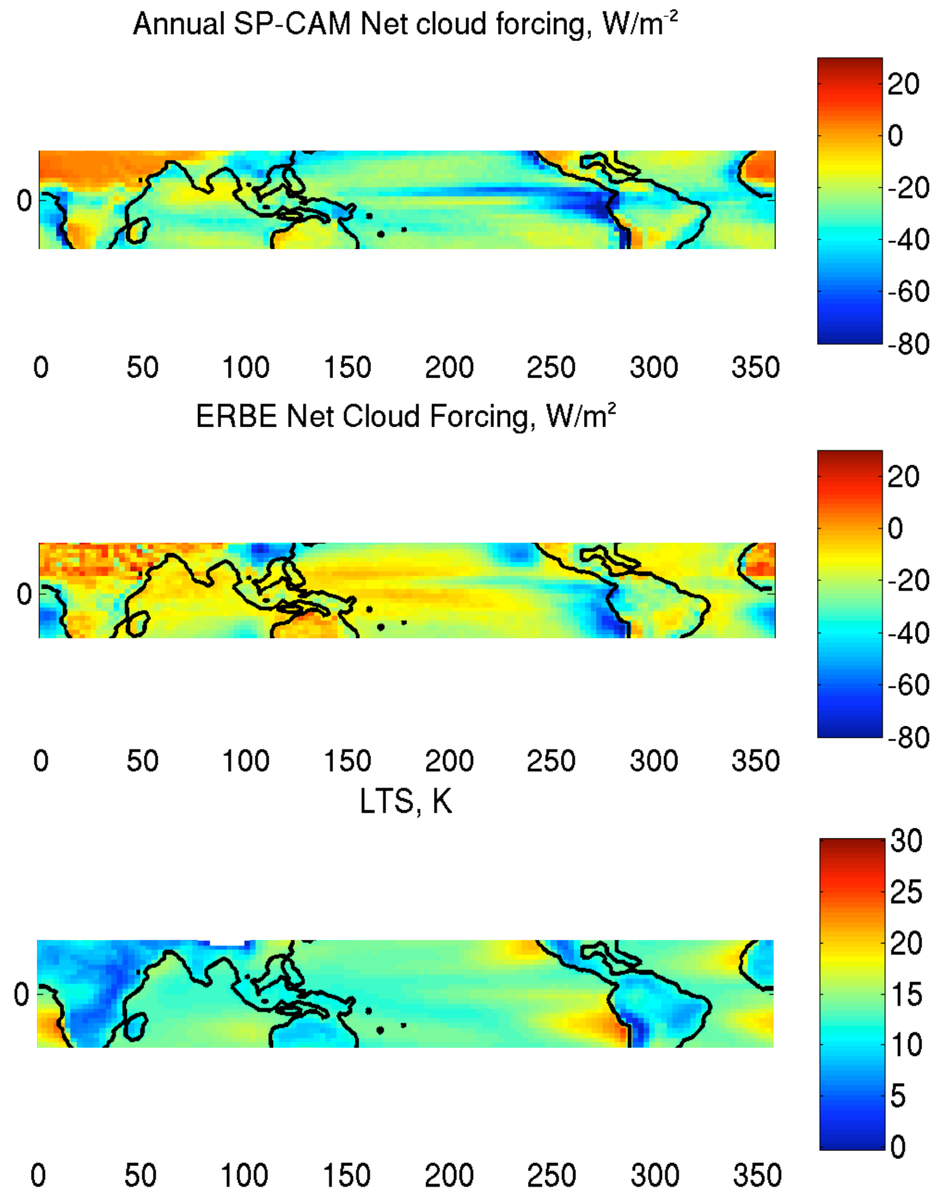
- Wyant et al. (2006, 2009) compared SP-CAM cloud response to +2K SST change using 3.5-year simulations.
- We have also looked at 4xCO_2 response with fixed SST.

SPCAM has reasonable net CRF and low clouds

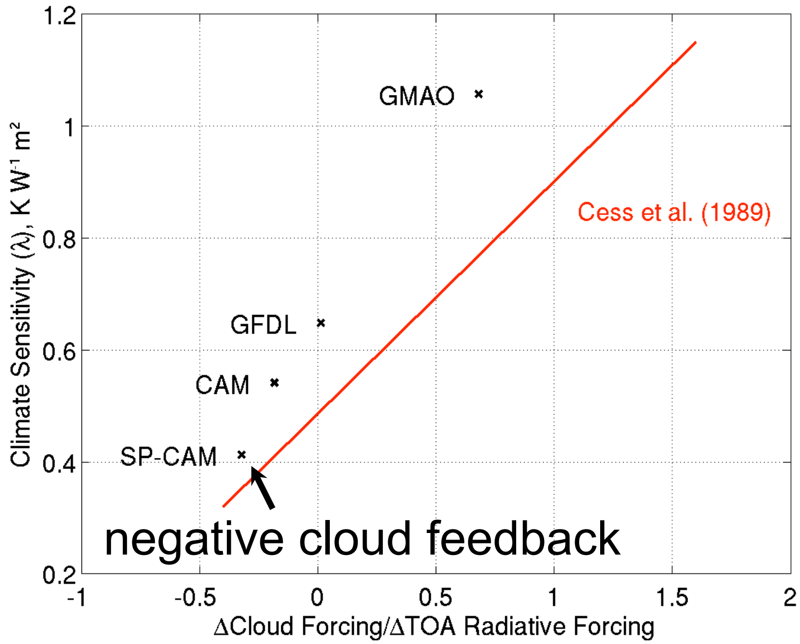
- Patterns good; not enough offshore stratocumulus; ‘bright’ trades/ITCZ.

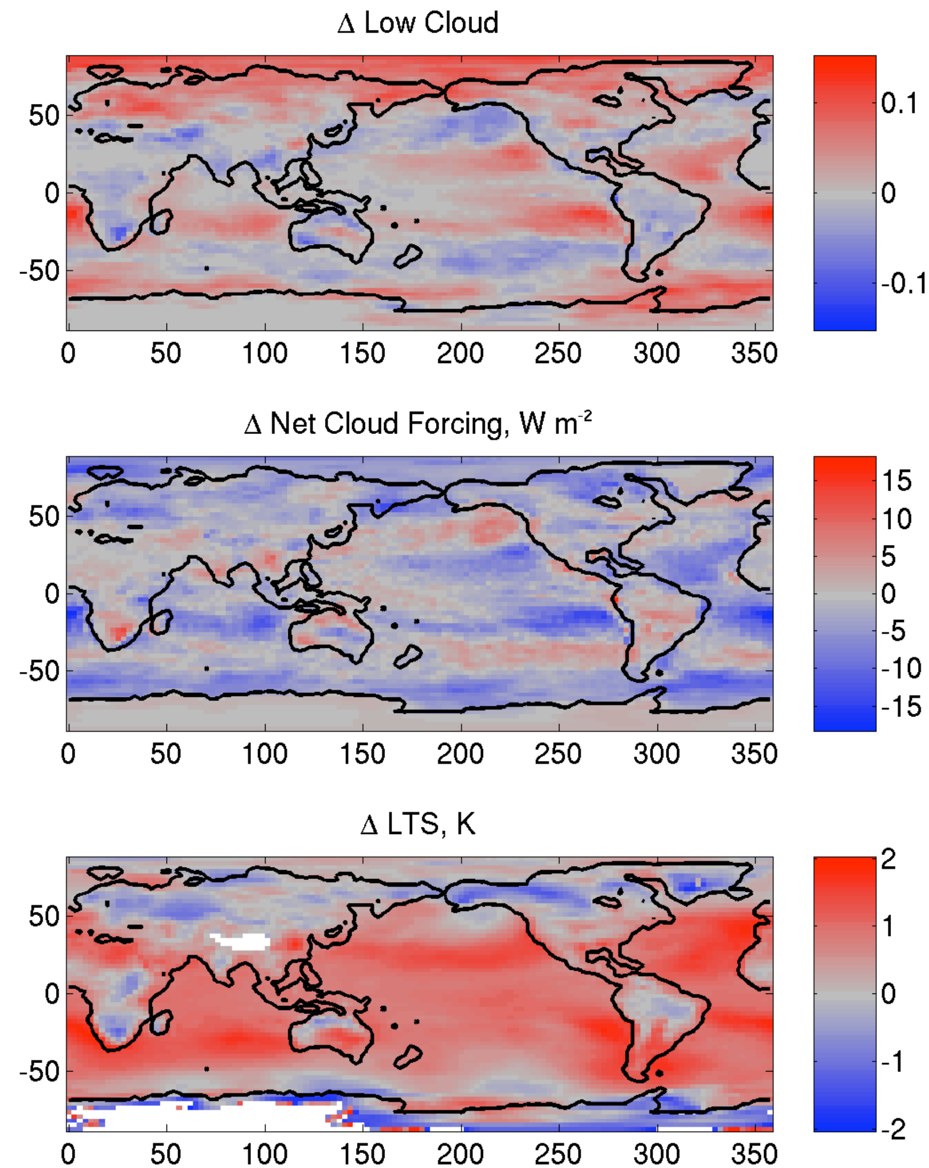
LTS = $\theta_{700} - \theta_{1000}$
- correlated to net CRF over subtropical oceans.
- Natural separator between subtropical cloud regimes.
- warm SST ⇔ low LTS

Use LTS for Bony-type cloud regime sorting’ to analyze subtropical (30S-30N) oceanic low cloud response



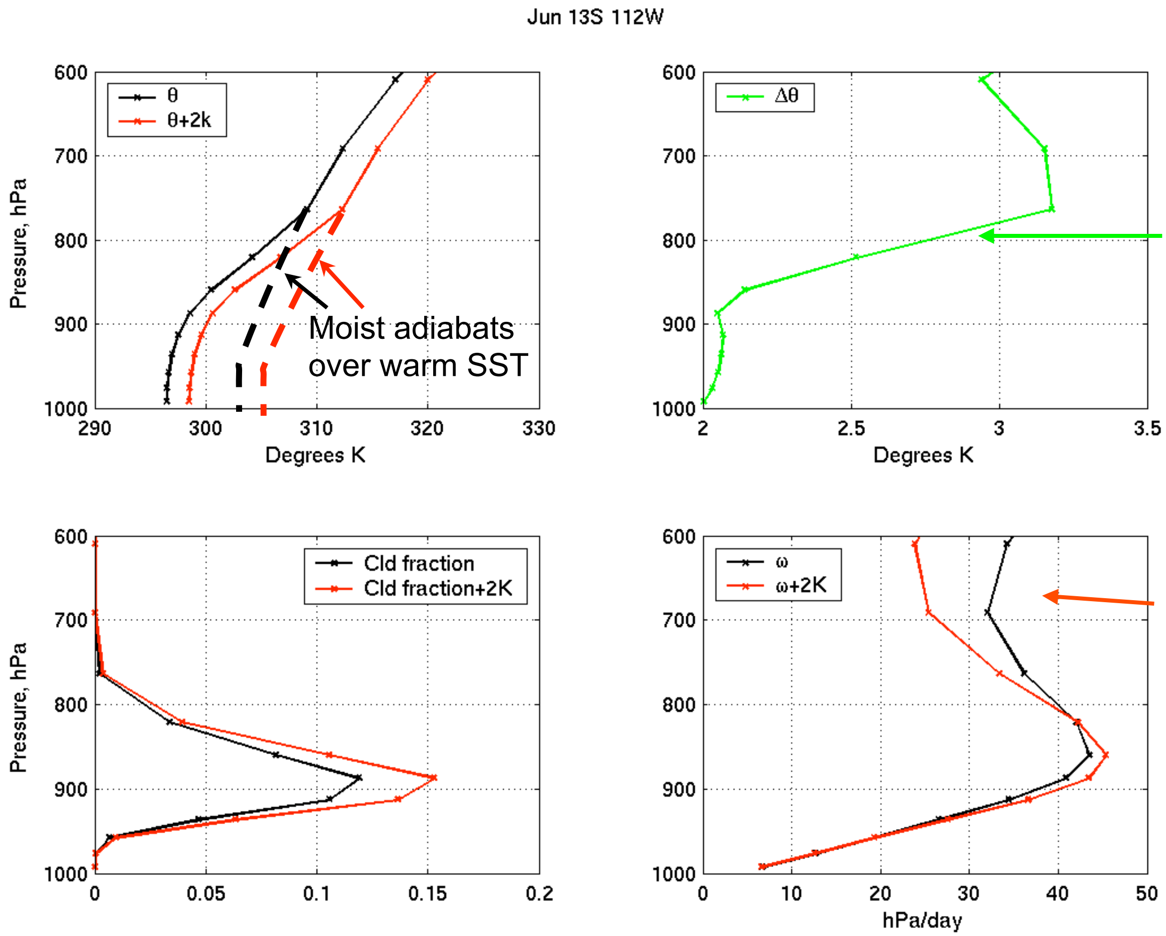
+2K cloud/CRF changes





- Low cloud increases in subtropics, summer hi-lats, making CRF more negative.
- LTS rises ~1K over ocean regions, like other GCMs.

Typical vertical structure in trades (SE Pac)

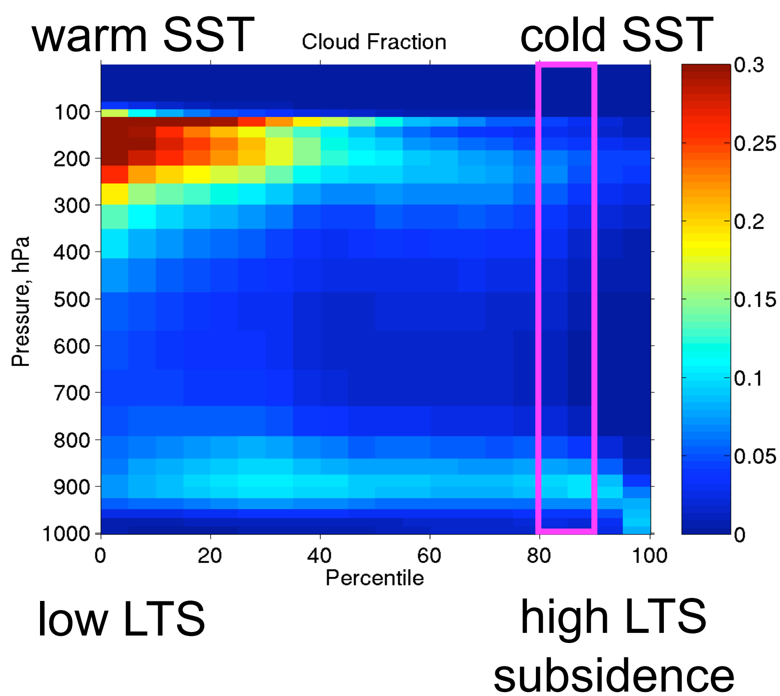


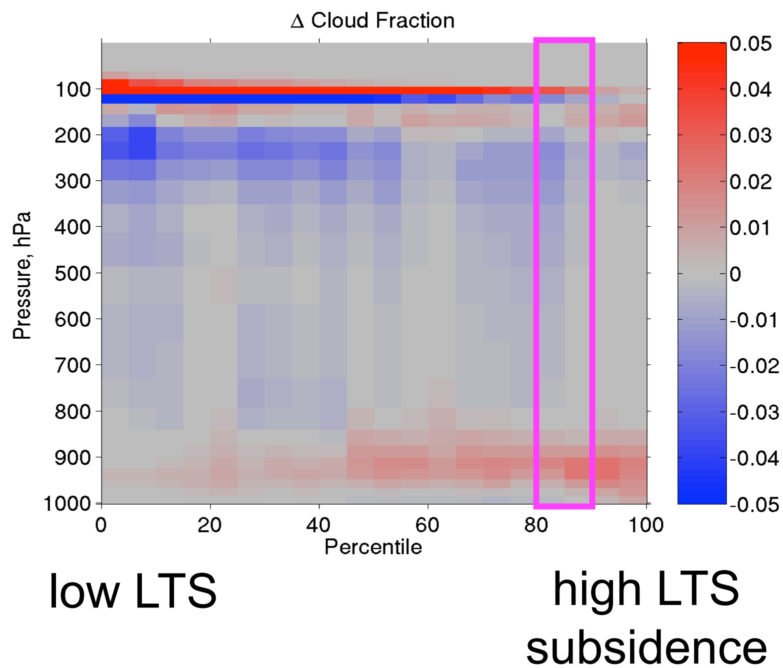
Inversion strengthens and LTS increases because moist-adiabatic dθ/dz increases with SST.

Subsidence changes are location-dependent.

- Cloud fraction and inversion strength increase.
- Net CRF (not shown) proportional to cloud fraction.

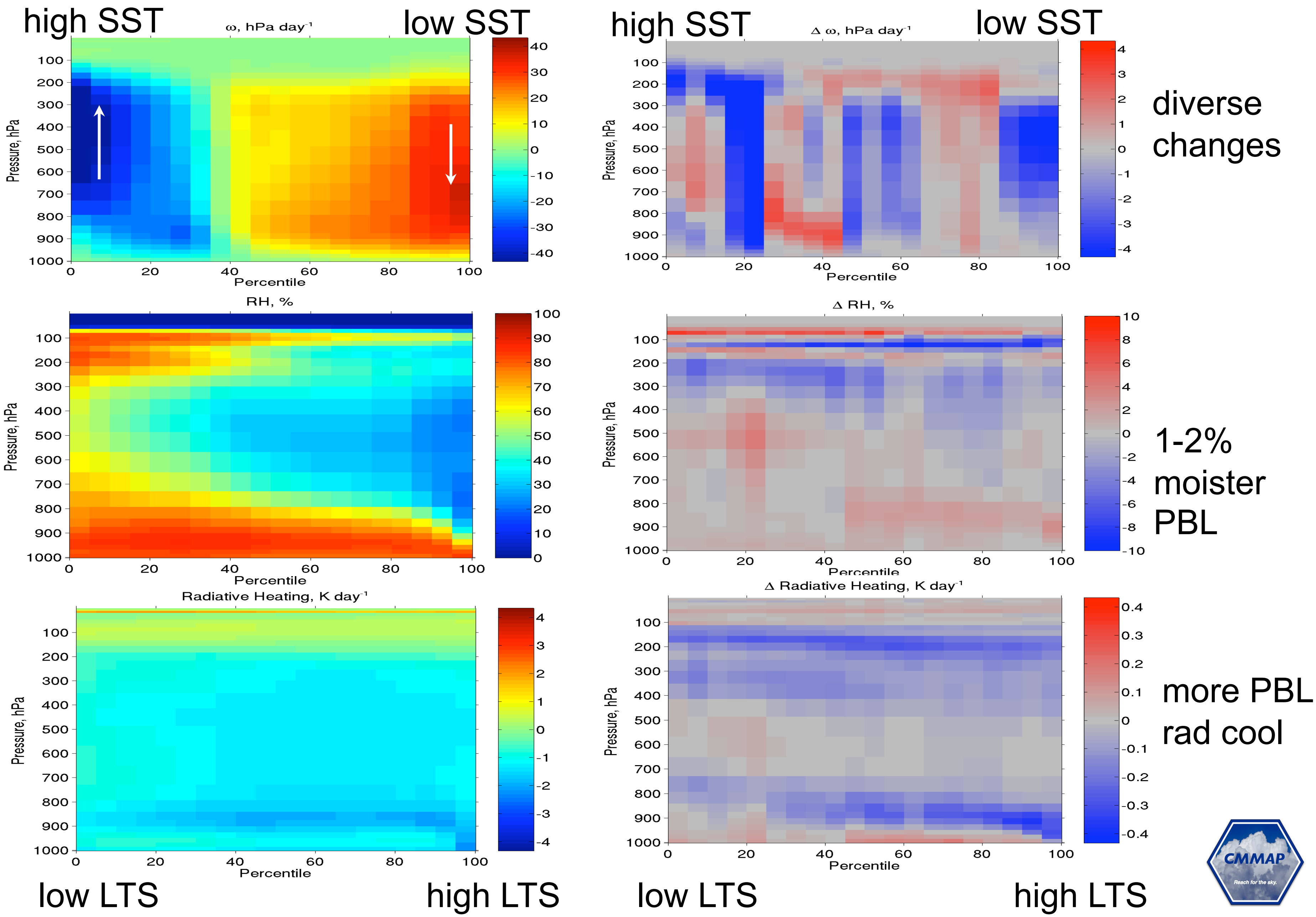
LTS-sorted low-latitude ocean cloud response





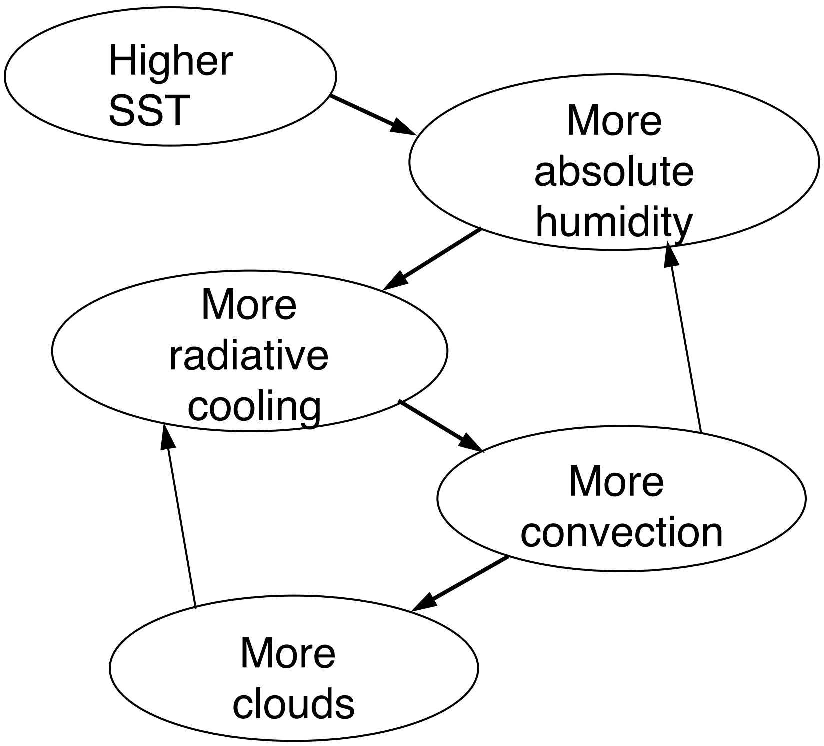
- 10-20% relative increase in low cld fraction/condensate across all high-LTS (cool-SST, subsiding) regimes.

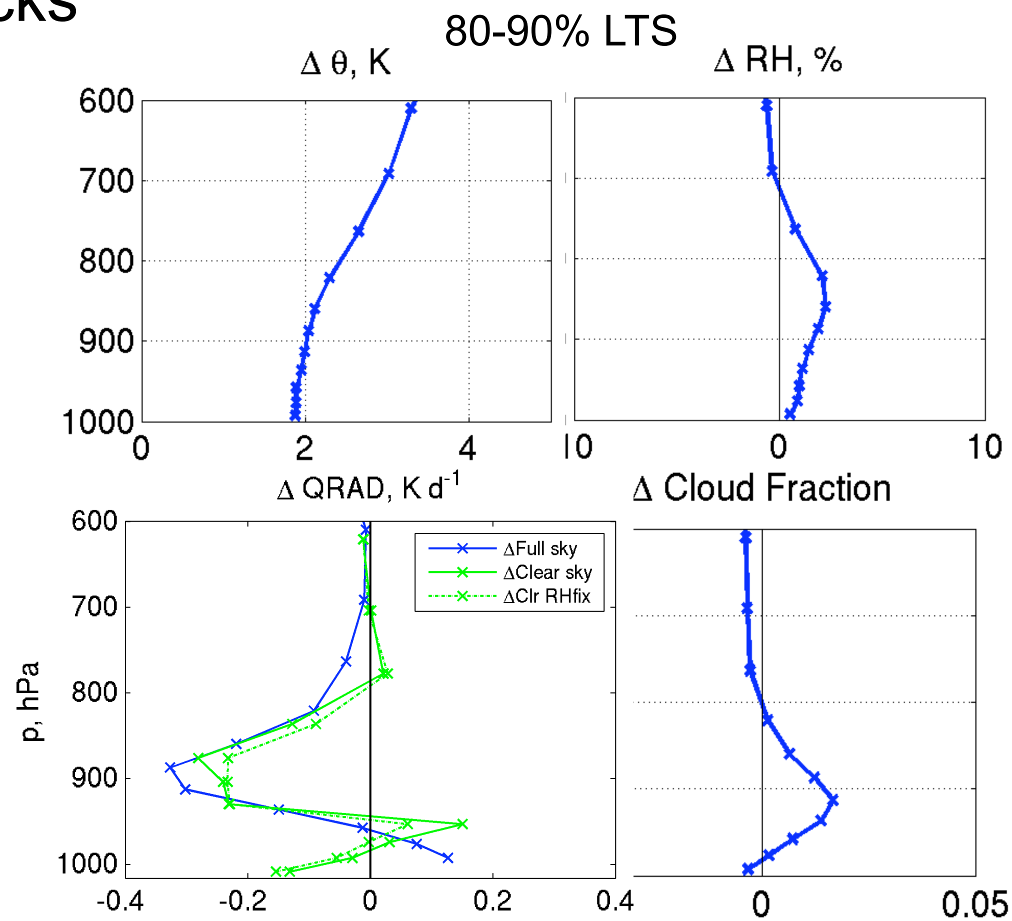
Other LTS-ordered fields



Conceptual model of SP-CAM trade 'Cu' feedbacks

Radiative Mechanism





Wyant et al. 2009 JAMES

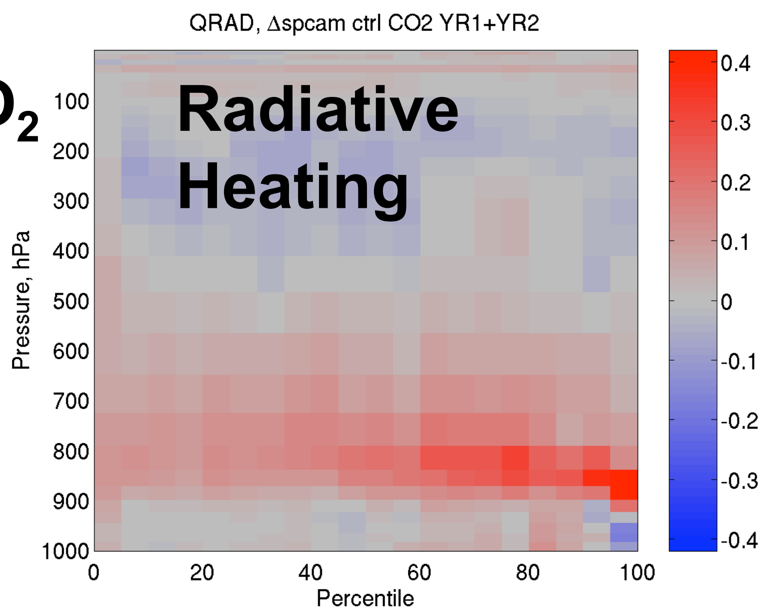
Mechanism could be sensitive to ΔGHG and warming scenario since radiatively-driven. Stronger inversion keeps PBL from deepening in +2K case.

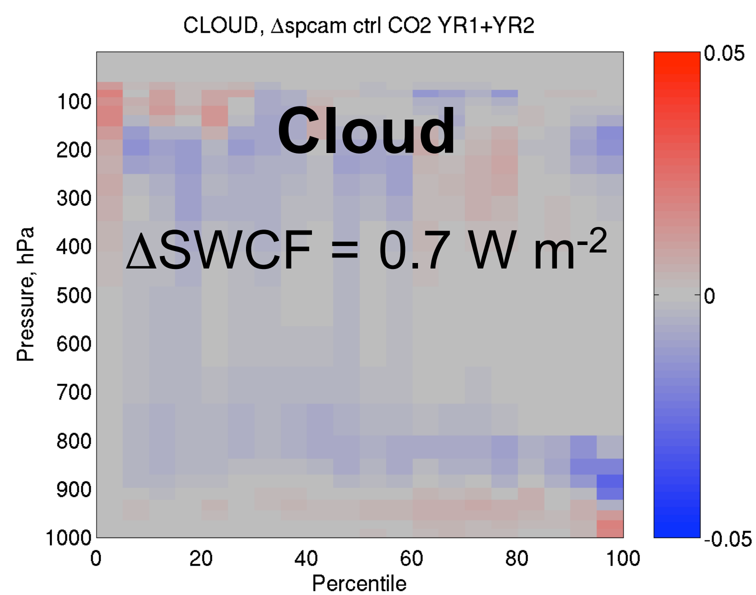
4xCO_2 experiment (run by Marat)

- Increase CO_2 while keeping SST constant (Gregory and Webb 2008) .
- Complements +2K SST experiment by focusing on direct effects of CO_2-induced radiative changes on clouds .
- 2½ year integrations are used with the first ½ year discarded...short, but results hold in each of the 2 years.

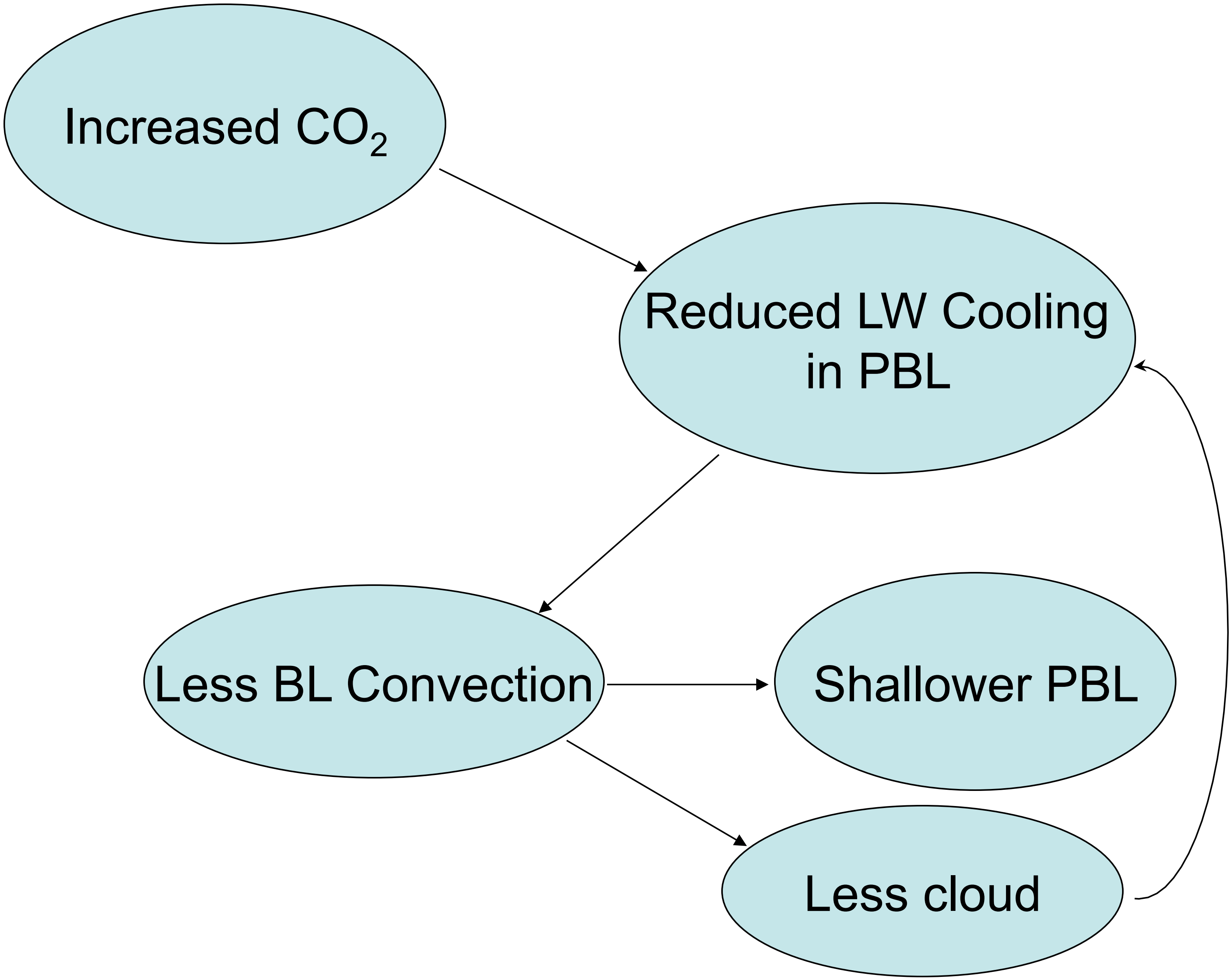
Concept: More CO_2 ⇒ More downwelling LW ⇒ Less PBL radiative cooling

Δ4xCO_2





Radiatively driven cloud response to CO_2 increase



Column-modeling framework for low cloud feedbacks

Vision: Study boundary-layer cloud feedbacks in a chosen dynamical regime (e.g. trade Cu or Sc) using a single CRM/SCM with appropriate large-scale forcings.

Goals:

(1) Mimic SP-CAM cloud feedbacks in simpler, controllable setting.

(2) Study their sensitivity to higher CRM grid resolution

(3) Compare cloud feedbacks simulated by different CRMs and SCMs given the same large-scale forcings (GCSS-CFMIP)

Key assumptions: (like Zhang&Breth 08, Caldwell&Breth08)

1. Regime-mean +2K cloud response can be recovered from regime-mean profile/advective tendency changes.
2. In low latitudes, strong nonlocal dynamical feedbacks counteract changes in column temperature profile.

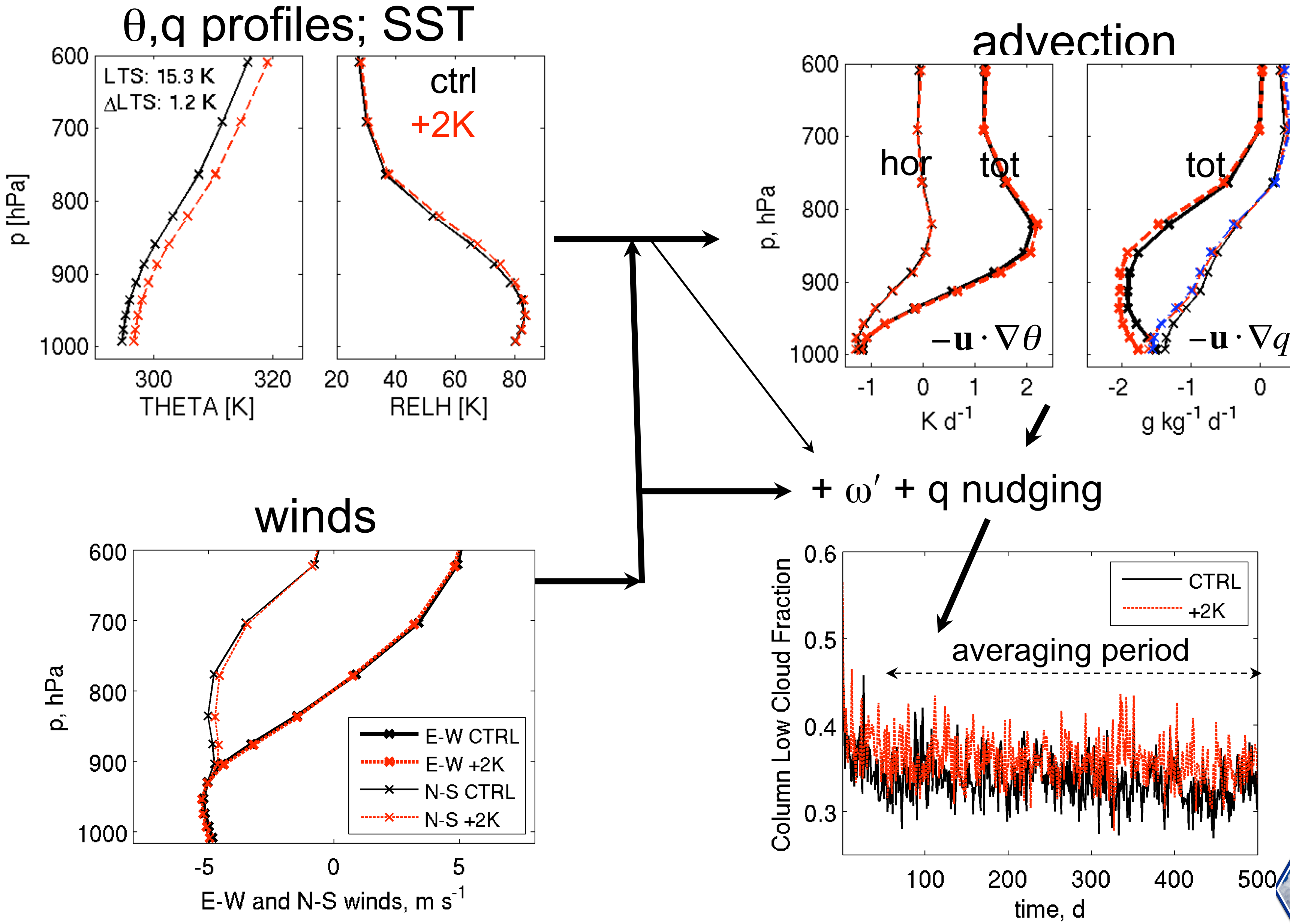
Column analogue to SP-CAM

Method (Blossey et al. 2009 JAMES):

1. Make composite forcings/profiles for a cloud regime defined with 80-90 percentiles of LTS over low-lat ocn column-months, for ctrl and SST+2K SP-CAM runs:
   - SST and surface wind speed
   - profiles and horizontal advective tendencies of T,q
   - vertical p-velocity ω.
2. Configure SAM6.5 CRM to use identical microphysics, radiation, resolution, domain orientation as in SP-CAM.
3. Run CRM to steady-state. A pair of 500 day integrations is used to calculate +2K cloud differences.

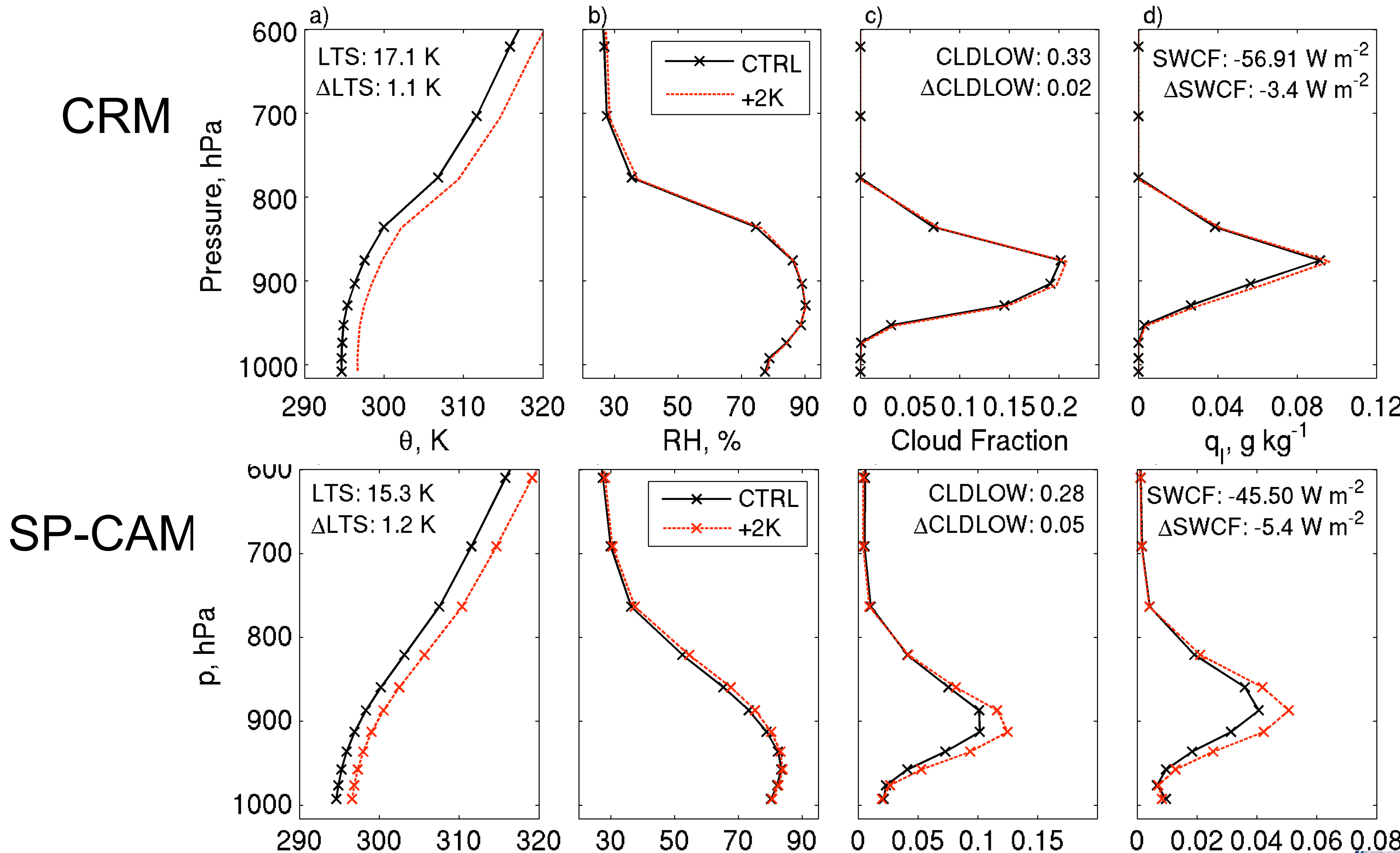
   To prevent slow drift of free-tropospheric CRM T,q profiles, q is slightly nudged above PBL and a WTG feedback is applied to ω. This is vital for obtaining results quantitatively comparable to SP-CAM.

LTS80-90 forcings and profiles



Results

- CRM has deeper moist layer, but similar +2K cloud response.

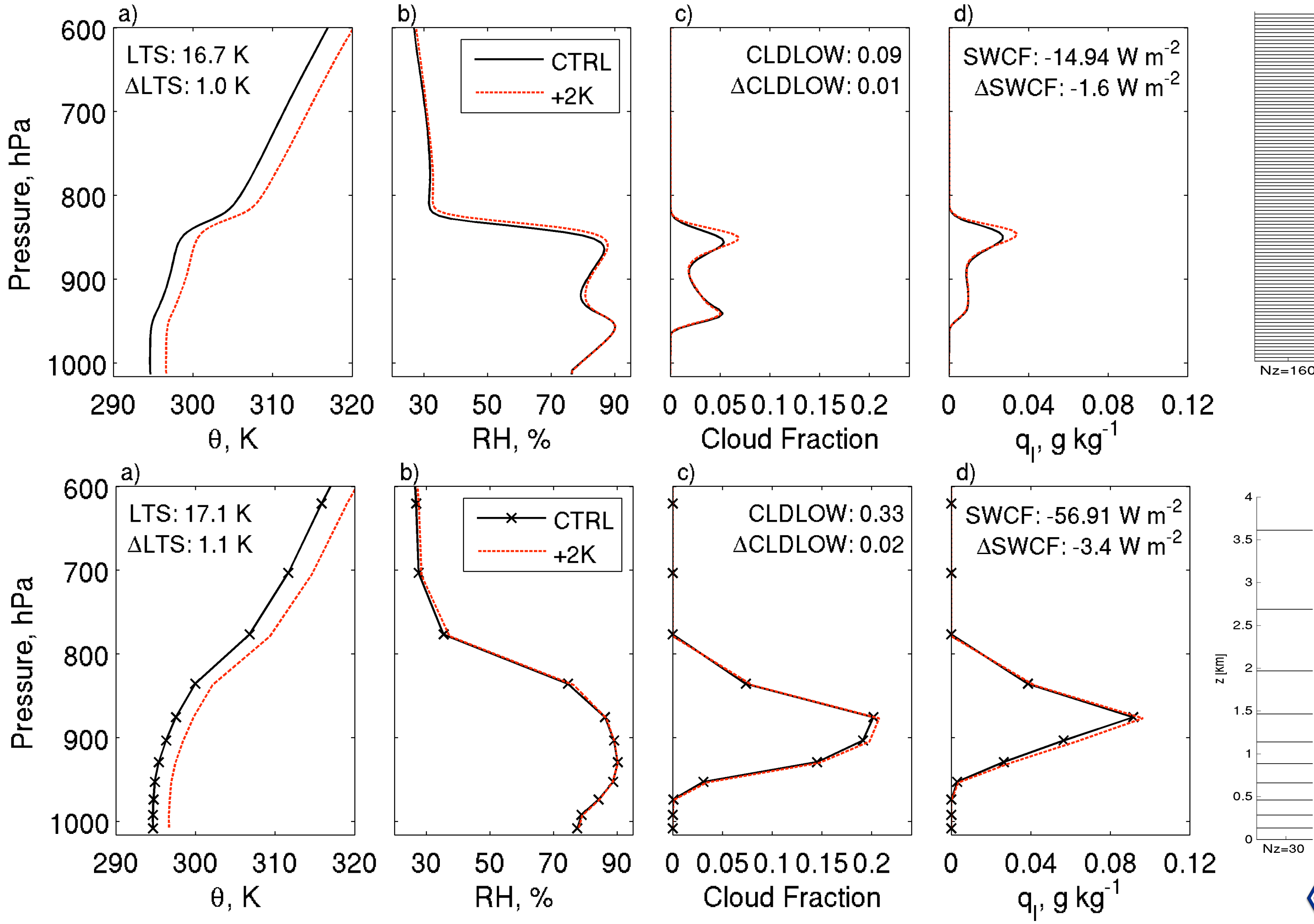


LES resolution (Δx=100 m, Δz=40 m, N_x=512)

- Large reduction in mean and +2K change in low cloud
- 2x or 0.5x LES grid spacing has little impact, but 4x too large.

LES

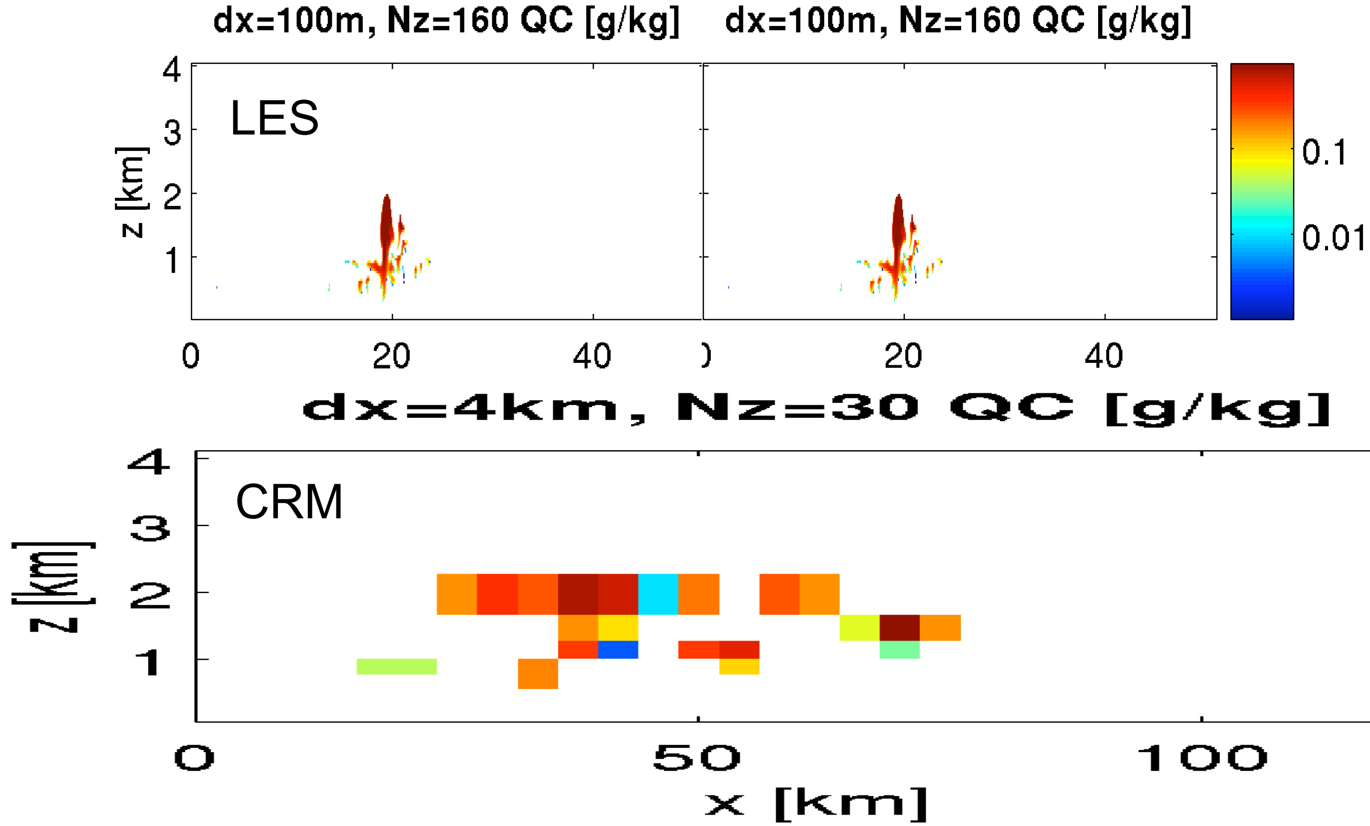
CRM



Interpretation

4 km makes Cu clouds too weak and broad

- Excessive Cu needed to flux water up to inversion.



In LES,+2K cloud increase is due to more inversion cloud (stronger inversion) instead of more Cu.

GCSS-CFMIP intercomparison

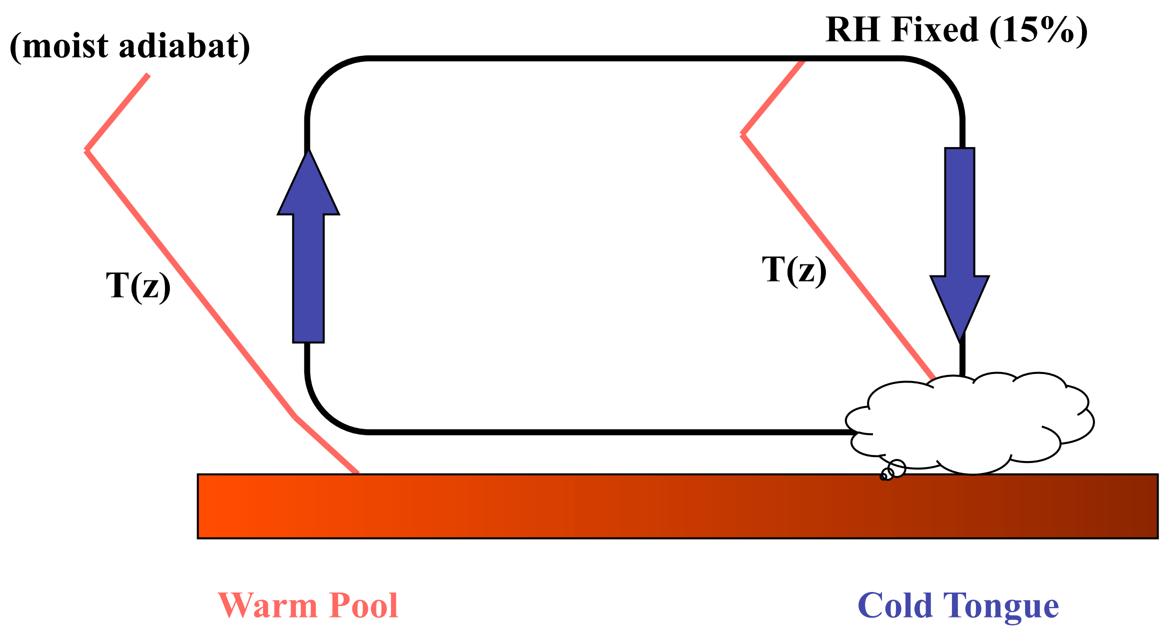
Vision: Use a column framework for intercomparison of SCM and LES cloud feedbacks.

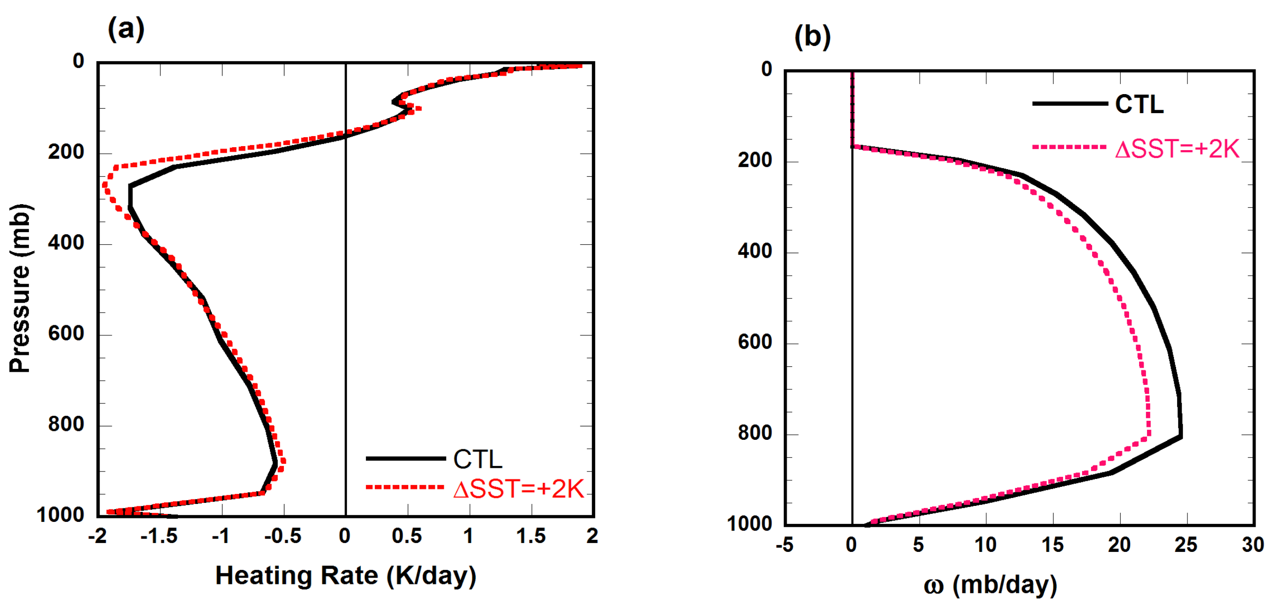
Basis: Zhang and Bretherton (2008), who used an earlier version of the above approach:

For control and +2K cases, specify:

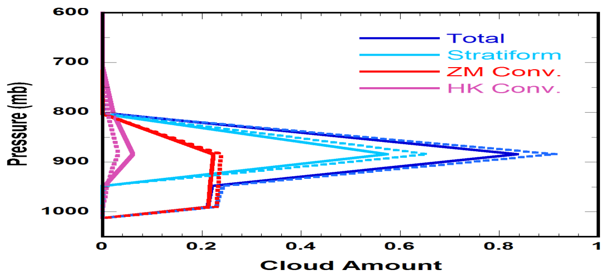
- Moist-adiabatic reference temperature profile
- Idealized reference ω and RH profiles.
- Horizontal advection used to balance reference-state heat, moisture budgets.
- No T,q nudging, so large model-dependent drifts from reference state.

The SCM/CRM community will soon be invited to run a refined version of this setup for discussion at GCSS/CFMIP meeting on June 8-12 2009, Vancouver BC. Minghua Zhang and I are case coordinators. Anning Cheng will present some preliminary results in the low clouds breakout tomorrow.


(moist adiabat)
RH Fixed (15%)
T(z)
T(z)
Warm Pool
Cold Tongue


(a)
Pressure (mb)
Heating Rate (K/day)
CTL
ΔSST=+2K
(b)
ω (mb/day)
CTL
ΔSST=+2K

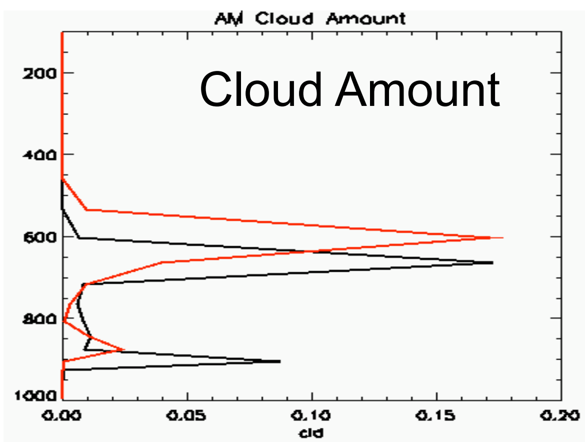
Results for Zhang-Bretherton case

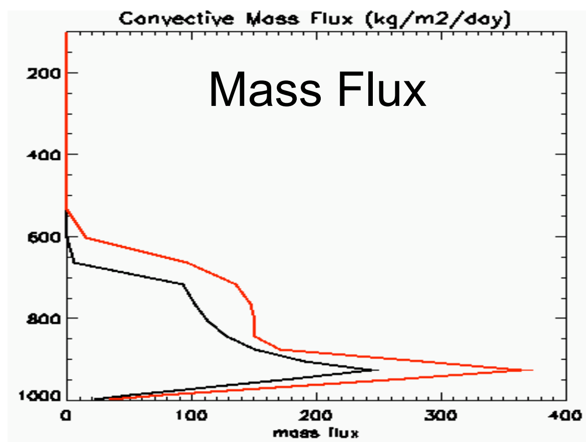


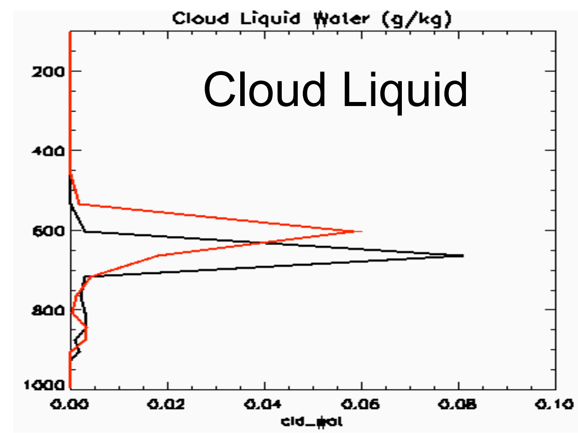
CAM3 - negative cloud feedback

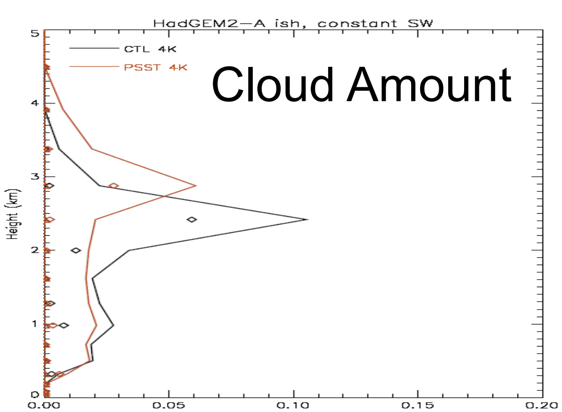
Cloud amount, convective mass flux, cloud liquid all increased for +2K

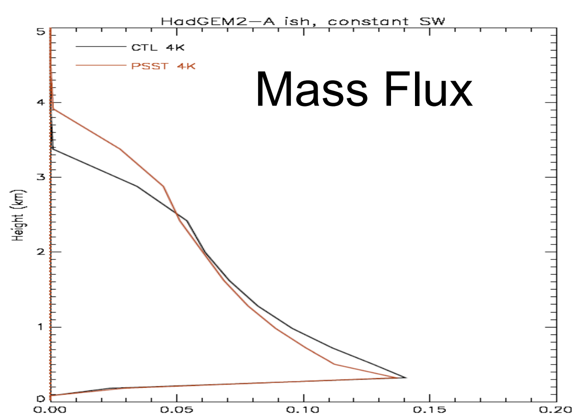
GFDL AM - Cu deepen and thin with +2K⇒ positive feedback





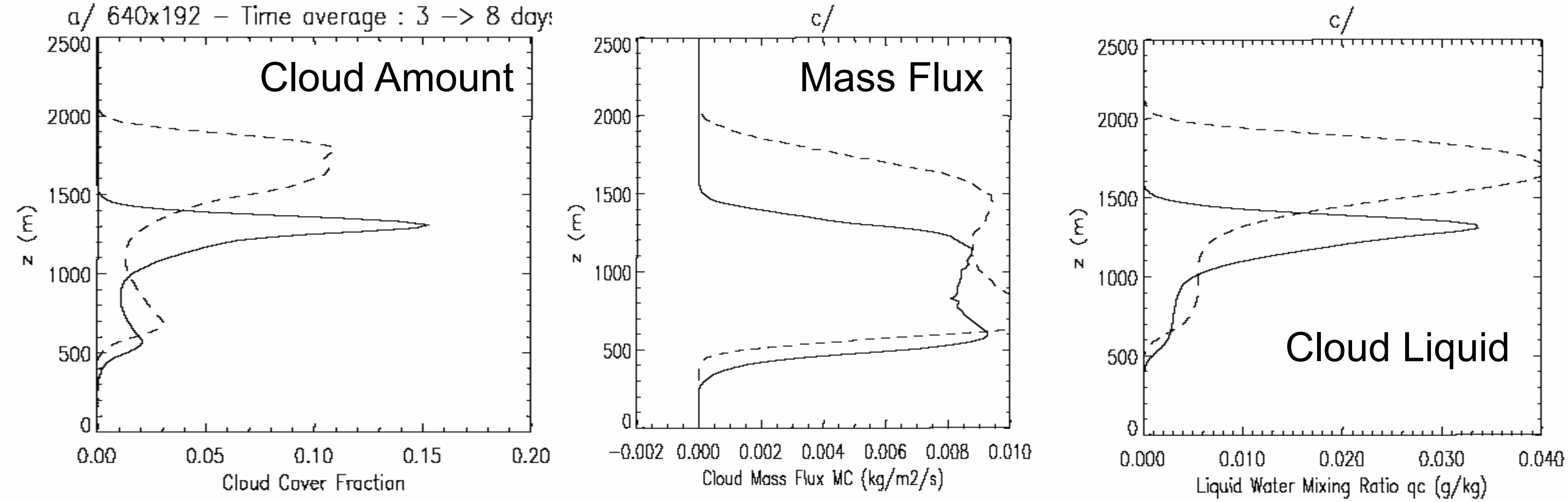


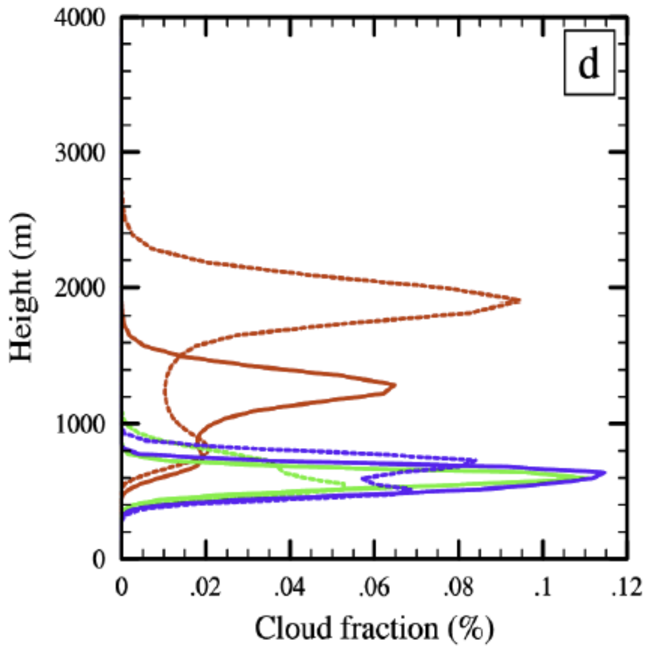




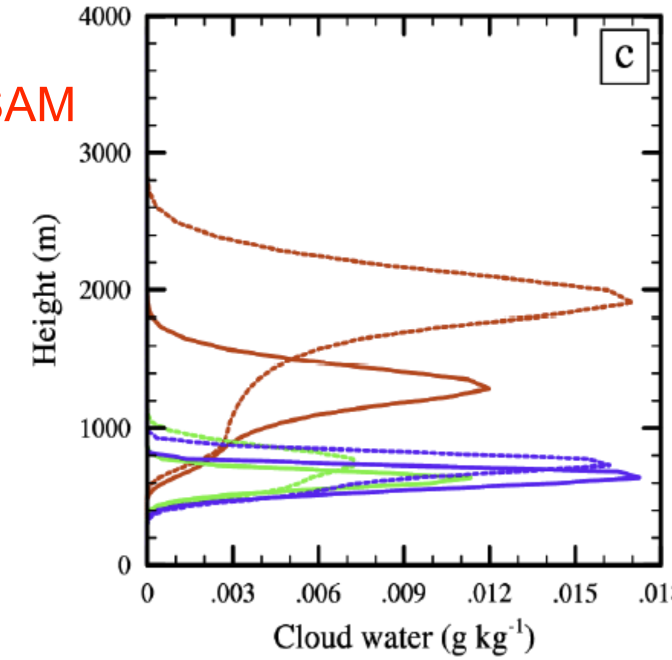
HadGEM2 - similar to AM

SAM LES: +2K cloud deepens but thickens ⇒ negative feedback





UCLA LES: Similar to SAM
Negative Feedback



GCSS/CFMIP preliminary conclusions

- In the intercomparison, each SCMs shows the same feedback sign as its parent GCMs. This supports use of a column framework for understanding low cloud feedbacks.
- The +2K forcing changes are much more similar between GCMs than the low cloud response.
- Both CRMs show negative low cloud feedbacks.
- Feedbacks should be added to the intercomparison setup to prevent excessive PBL deepening and achieve quantitative realism.
- Stay tuned! CRMs and the MMF have much more to contribute to cracking the low cloud feedbacks problem.

It is a challenge to us all to engineer an MMF that is the world's best tool for simulating two key climate projection uncertainties - cloud and cloud/aerosol feedbacks.

Atmospheric Sciences
University of Washington

CMMAP
Reach for the sky.

Large-scale WTG ω feedback

$$\bar{\omega}(p,t) = \omega_0(p) + \omega'(p,t)$$

$$\frac{d^2\omega'}{dp^2} = r\frac{\overline{T_v} - T_{v0}}{p}$$

$r = 3.8\text{x}10^{-6}\ \text{K}^{-1}\ \text{s}^{-1}$

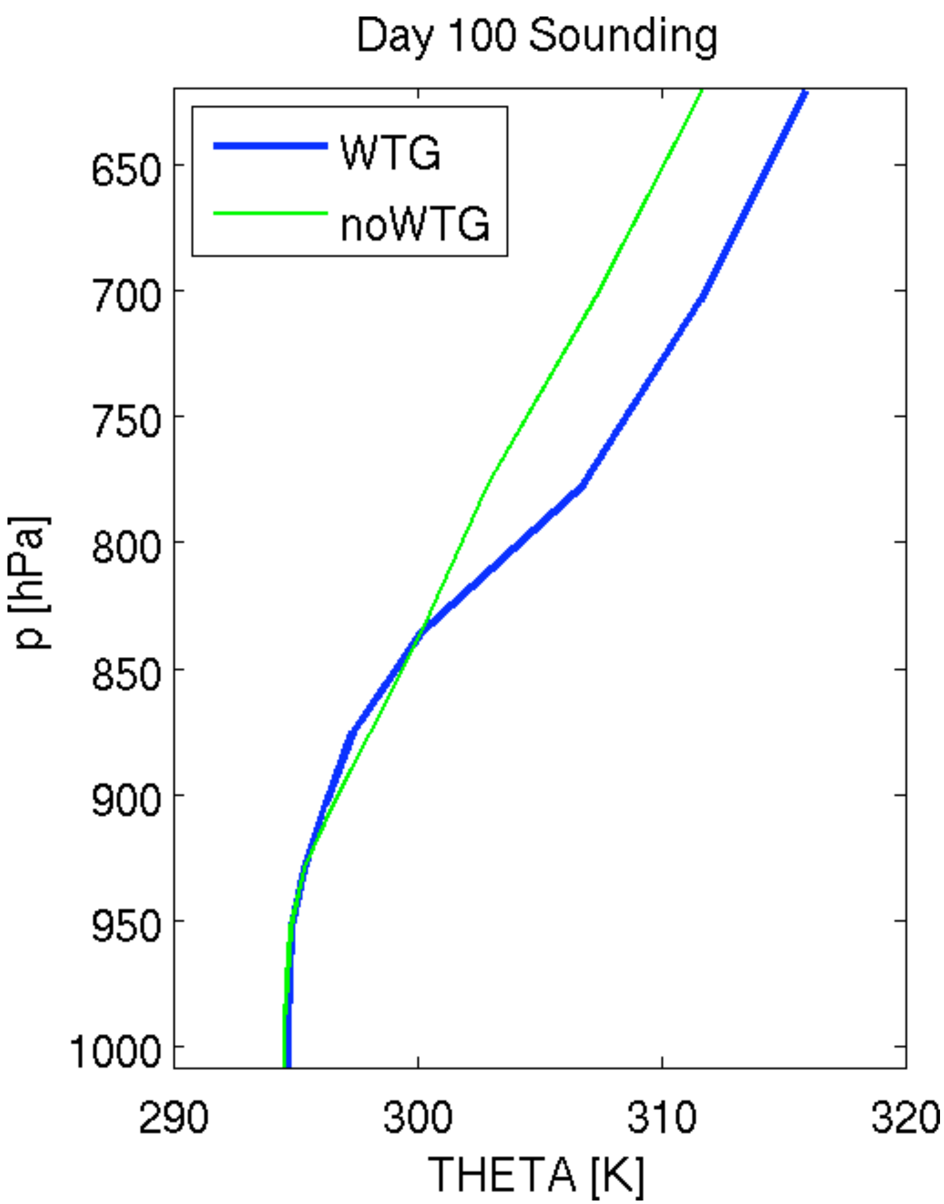
$$\frac{d\bar{\theta}}{dt} = Q_1 - (u \cdot \nabla\theta)_0 - (\omega_0 + \omega')\frac{d\bar{\theta}}{dp}$$

q nudging

$$\frac{d\bar{q}}{dt} = Q_q - (u \cdot \nabla q)_0 - \omega'\frac{d\bar{q}}{dp} + \frac{q_0 - \bar{q}}{\tau_q}$$

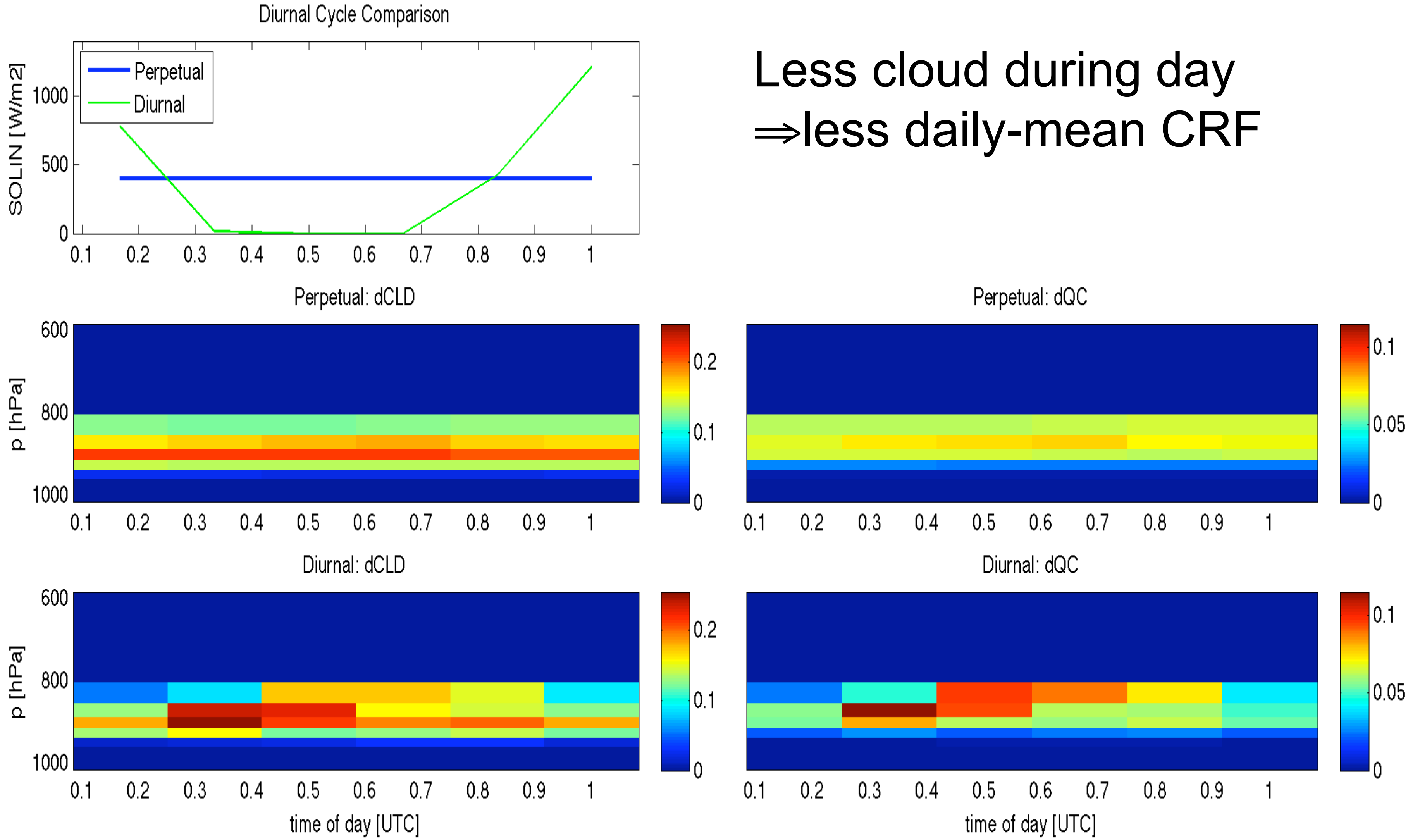
$$\tau_q = \begin{cases} 1\ \text{d}^{-1}, p \le 550\,\text{hPa} \\ 0\ \text{d}^{-1}, p \ge 850\,\text{hPa} \end{cases}$$

T drifts without WTG feedback

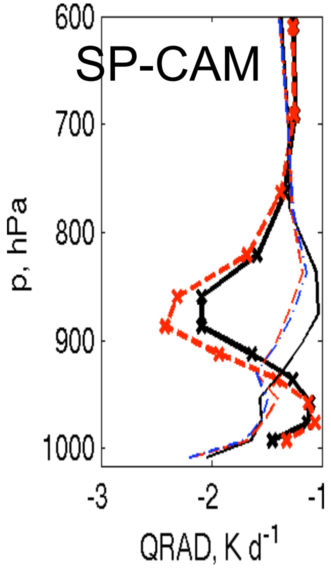


Diurnal cycle added to column model

Less cloud during day
⇒less daily-mean CRF



Cu-layer heat/moisture budgets

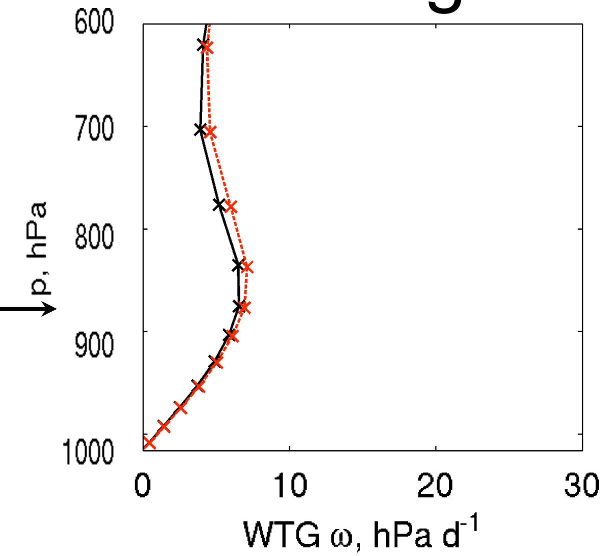


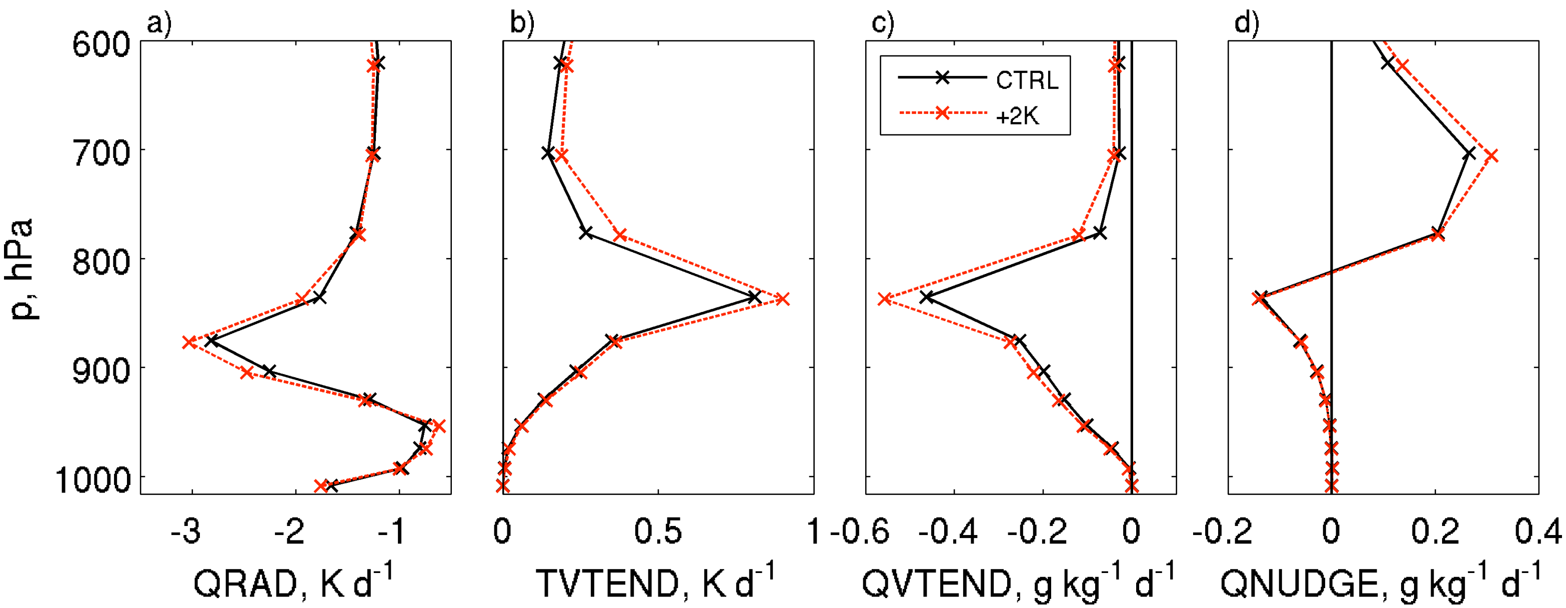
CRM dynamical feedback:

$Q_{dia}' < 0$

$\Rightarrow \omega' > 0$

$\Rightarrow -\omega' d\theta_0/dp > 0$





+2K: CRM has more radiative cooling, forcing more Cu.