Cloud feedback

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What is cloud feedback?

The effect on an externally-forced climate perturbation of the response in cloud properties, especially:

– cloud fraction
– liquid/ice water path
– and their vertical distribution

Main practical interest is GHG-induced global warming:

feedback on global temperature T_s via Δ(TOA radiation) [surface temperature and rainfall patterns]

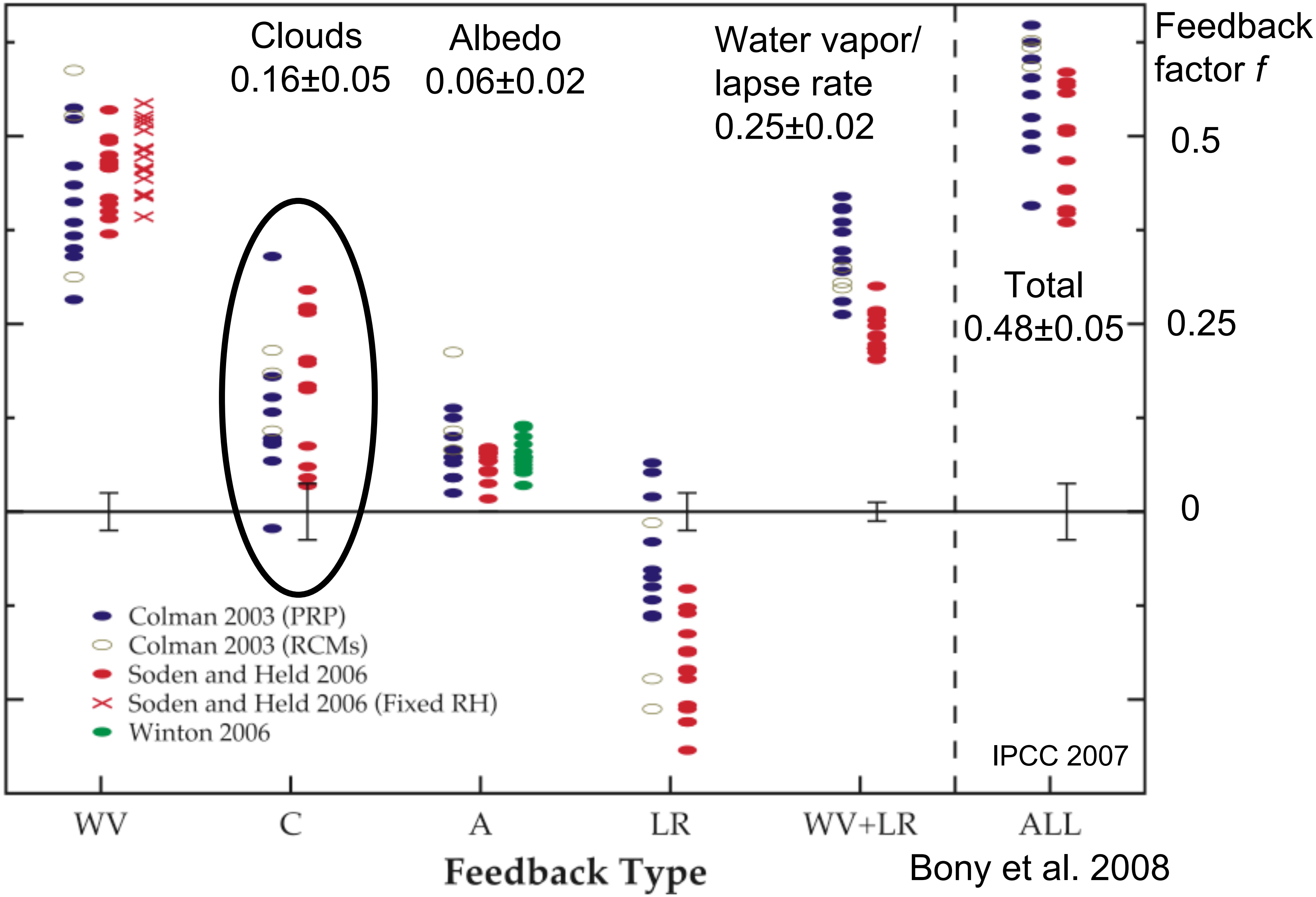
Combination of

- fast 'semidirect' cloud response to GHG radiative changes
- 'temperature-mediated' cloud response to warming T_s

Outline

- GCM cloud feedback is positive, though ΔCRF isn't. Why?
- Subtropical low cloud feedback: compensating processes make models diverge and assessment difficult.
- Observing cloud feedbacks relevant to global warming -as unsolved problem.

Cloud feedback in GCMs is positive but uncertain



Bony et al. 2008

Clouds are hard to simulate with climate models

Clouds challenge both the grid resolution and physical parameterizations of climate models

- Often thin, short-lived
- Often produced by small-scale turbulence (e. g. cumuli)
- Complex interactions of water and ice particles
- Cloud radiative effects can have either sign
  - High, thin clouds warm (greenhouse effect dominates)
  - Low clouds cool (shading effect dominates)

Hence the spread in GCM-simulated cloud feedbacks is not surprising.

Identifying physical mechanisms can help organize model analysis and observational strategies.

Low clouds are particularly difficult due to their strong radiative feedbacks with turbulence.

Current cloud feedback methodologies

- **Analysis of GCM spread (coupled,+2K, step 4xCO_2)**
- Process models and mechanisms.
- Observed cloud and radiation trends and variability.

AR4-mean ΔCRF ≈ 0 for CO_2 doubling.

CRF = TOA cloud radiative forcing = net downward $F_{rad} - F_{rad}^{clr}$

- Tropical ΔSWCRF drives spread but > 0 in most models (less low cld)
- Tropical ΔLWCRF < 0 in most models (less high cld).
- How can cloud feedback be positive even if ΔCRF ≈ 0 ?

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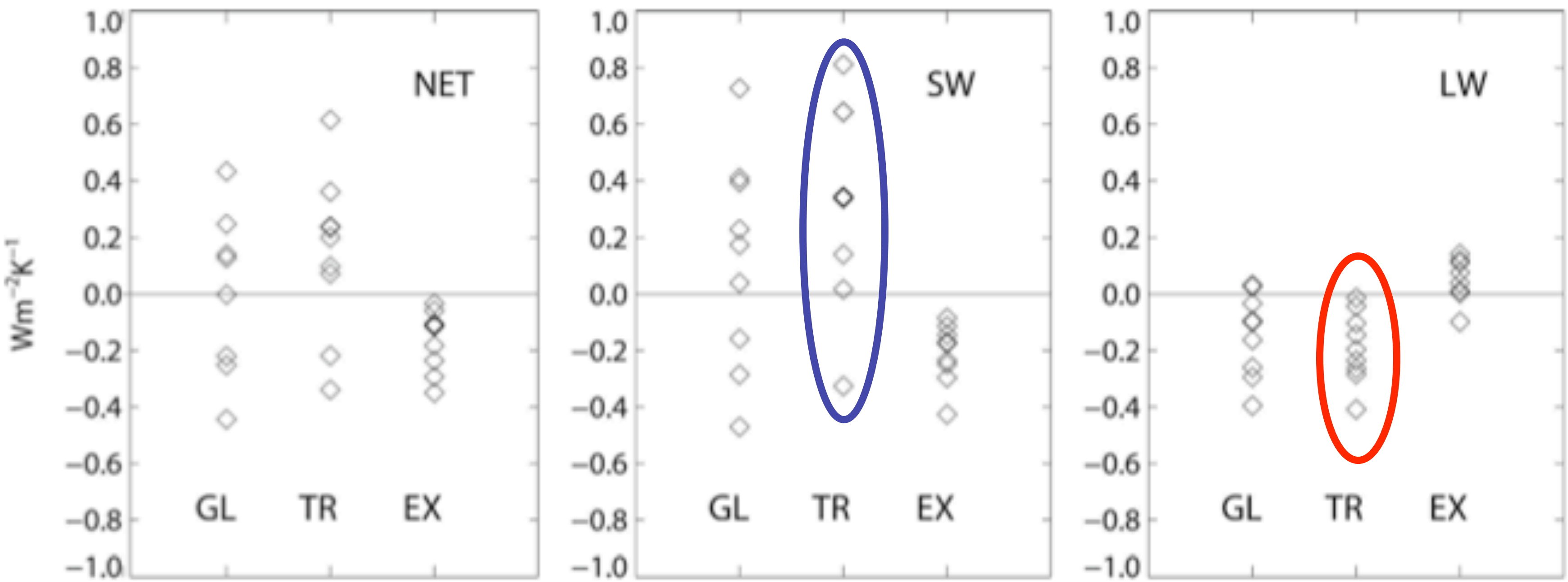
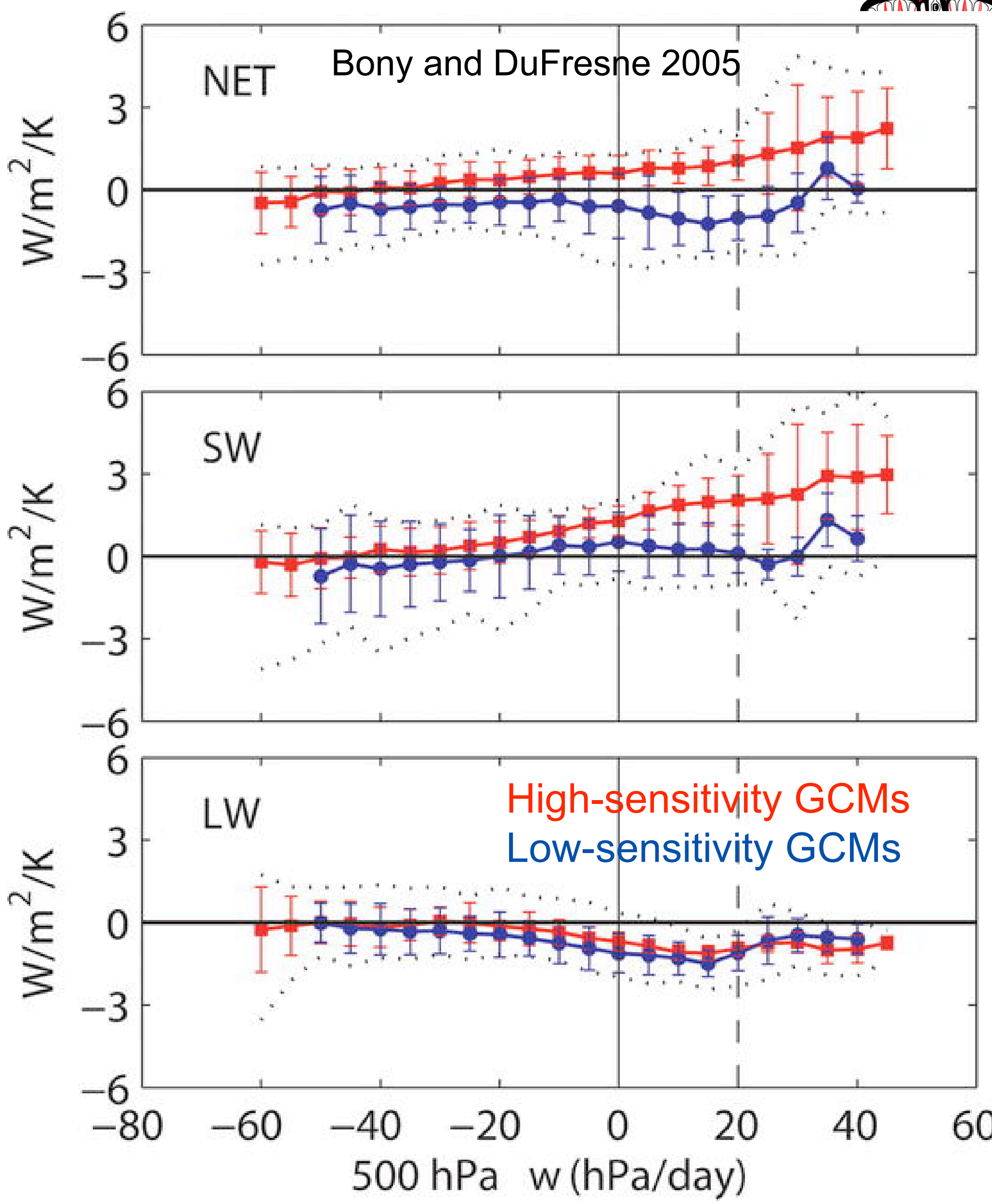


FIG. 10. Global change in the (left) NET, (middle) SW, and (right) LW CRF normalized by the change in global mean surface air temperature predicted by AR4 mixed layer ocean atmosphere models in $2xCO_2$ equilibrium experiments. For each panel, results (in W m^{-2} K^{-1}) are shown for global (GL), tropical (TR, 30°S–30°N) and extratropical (EX) areas. The intermodel spread of the global CRF response to climate warming primarily arises from different model predictions of the change in tropical SW CRF. (Adapted from WEBB.)

Bony et al. 2006

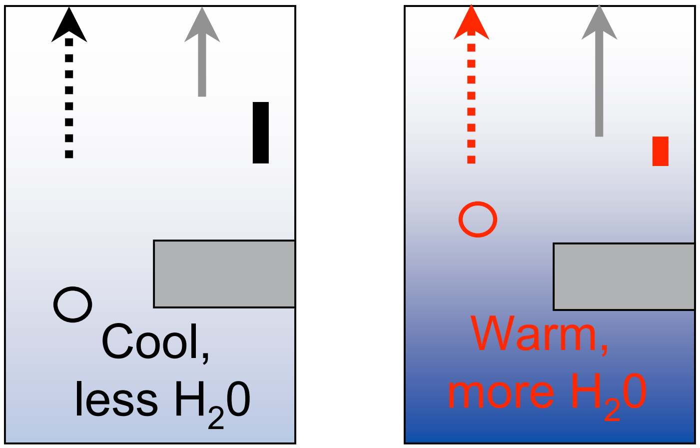
Partitioning of AR4 tropical $\Delta CRF/\Delta T_s$ vs. dynamical regime

- Median model shows little shortwave or longwave $\Delta CRF/\Delta T_s$ in deep convective regimes ($\omega_{500} < 0$)
- Model spread comes from subsiding regimes (boundary-layer clouds)

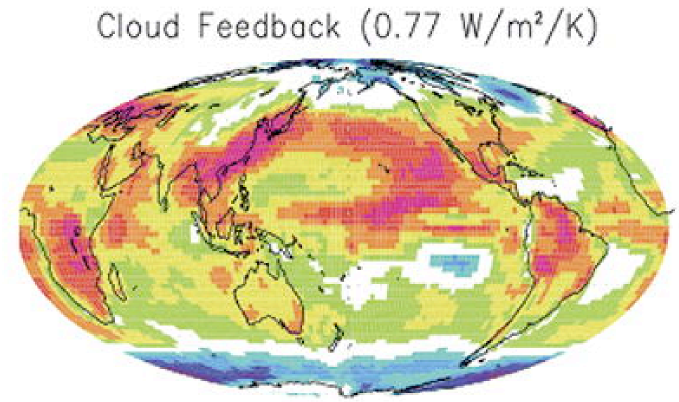


Soden et al (2004): ΔCRF $\neq$ cloud feedback

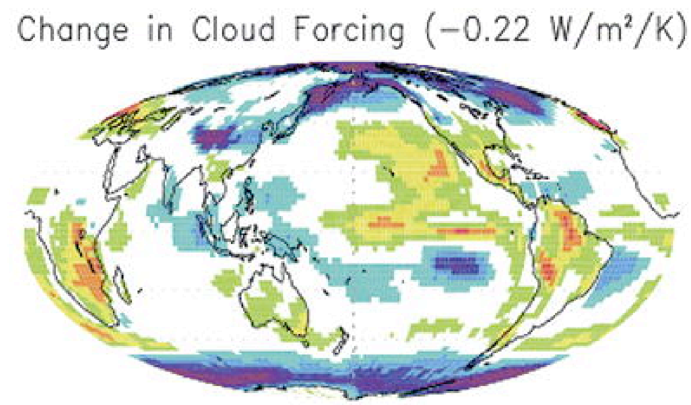
... though they are well correlated.

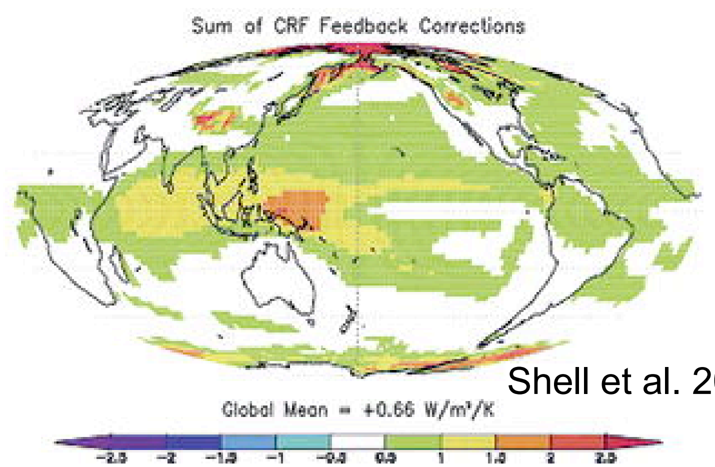


Tropical mechanism: In a warmer, moister climate, the same cloud at the same level has less additional greenhouse effect. Hence, with no cloud feedback, $\Delta CRF \approx \Delta LWCRF < 0$.



Soden et al. 2008





Shell et al. 2008

FAT and positive high cloud feedback

- Fixed Anvil Temperature (FAT) hypothesis (Hartmann and Larson 2002): Tropical ice clouds move upward in a warmer climate following isotherms, at least in models.

- This is a major contributor to positive cloud feedback.

Fixed Anvil Temperature (FAT) hypothesis

- Substantial clear-sky radiative cooling requires water vapor
- Upper tropospheric water vapor is temperature-limited.
- Clear-sky radiative cooling is weak for T < 200 K.

⇒ Convective anvil tops will occur near T = 200 K, regardless of surface temperature.

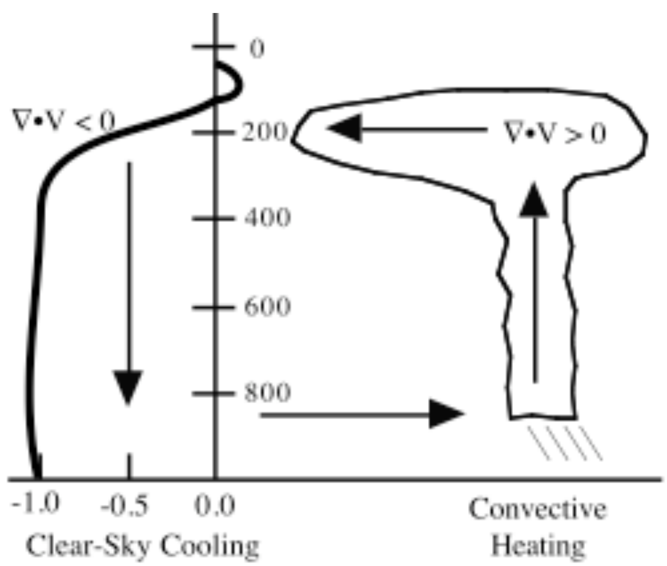
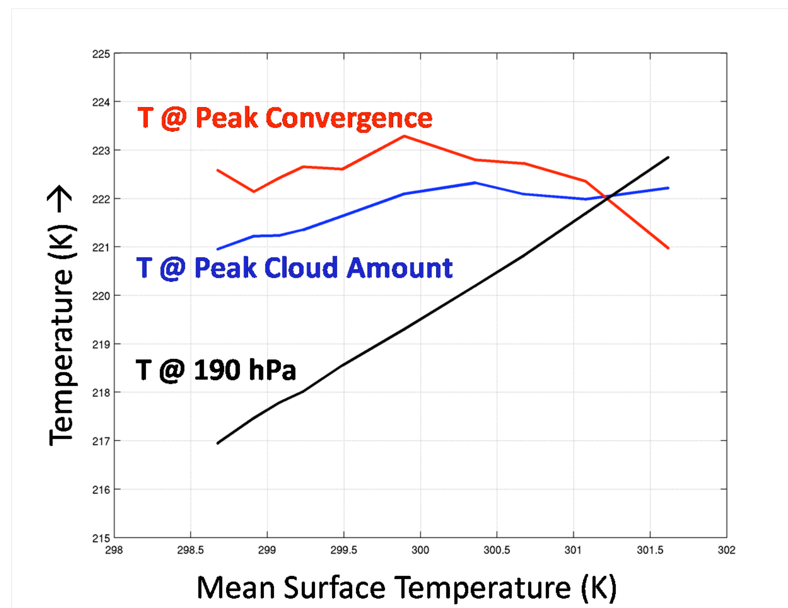


Figure 1. Schematic showing relation of clear sky radiative cooling to upper level divergence (∇oV) and convective anvil outflow.

Hartmann and Larson 2002



AR4 models, A1B scenario
(Zelinka and Hartmann 2009)

Vertical cloud profile changes with ΔT_s

Kuang and Hartmann 2007: Radiative-convective equilibrium over fixed SST in a cloud-resolving model (CRM).

KUANG AND HARTMANN

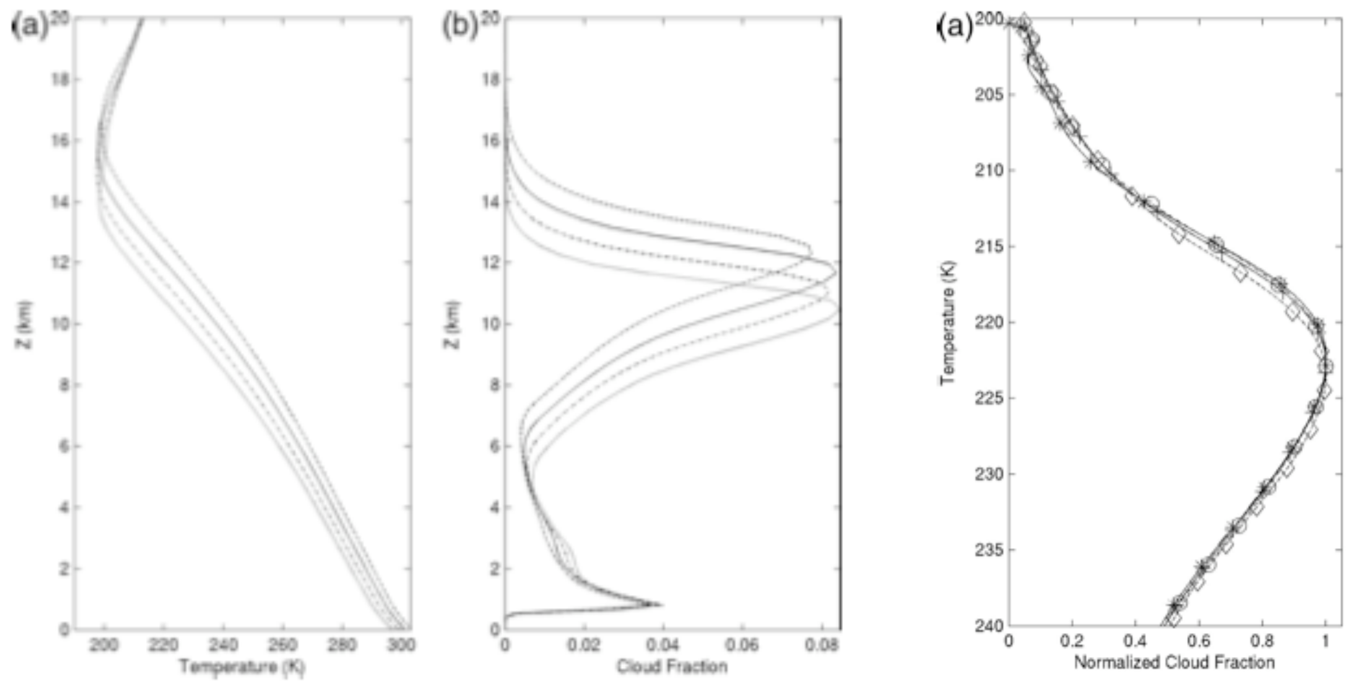


FIG. 1. RCE profiles of (a) temperature and (b) cloud fraction for SSTs of 32.5° (dashed), 30.5° (solid), 28.5° (dashed–dotted), and 26.5°C (dotted).

- Entire cloud profile above the freezing level collapses when plotted vs. T, while it rises 350 m/K_{SST} when plotted vs. z. GCMs do similarly.
- FAT control anchors anvil tops, freezing level anchors bases, T-dependence of ice microphysics may help.

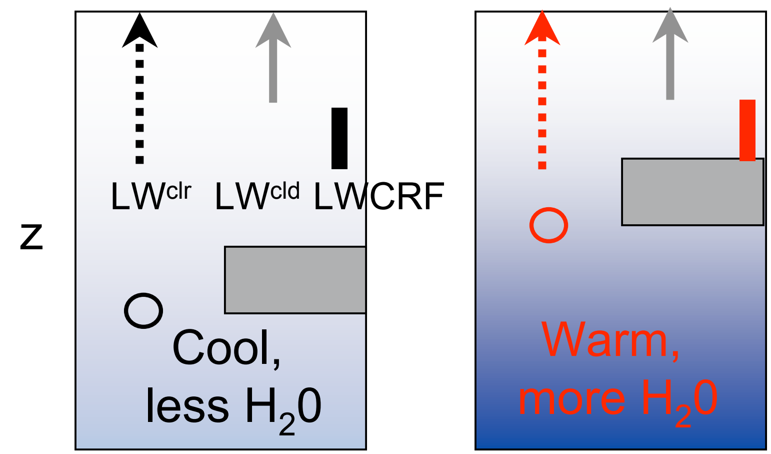
Summary of GCM cloud feedbacks

- Upward migration of tropical ice cloud and RH profiles produce strong high cloud feedback despite ΔLWCF ≈0.

$$\Delta LW_{FAT} = -\sigma\left[T_A^4 - \left(T_A + \Delta T(z_A)\right)^4\right] f_{hi}$$

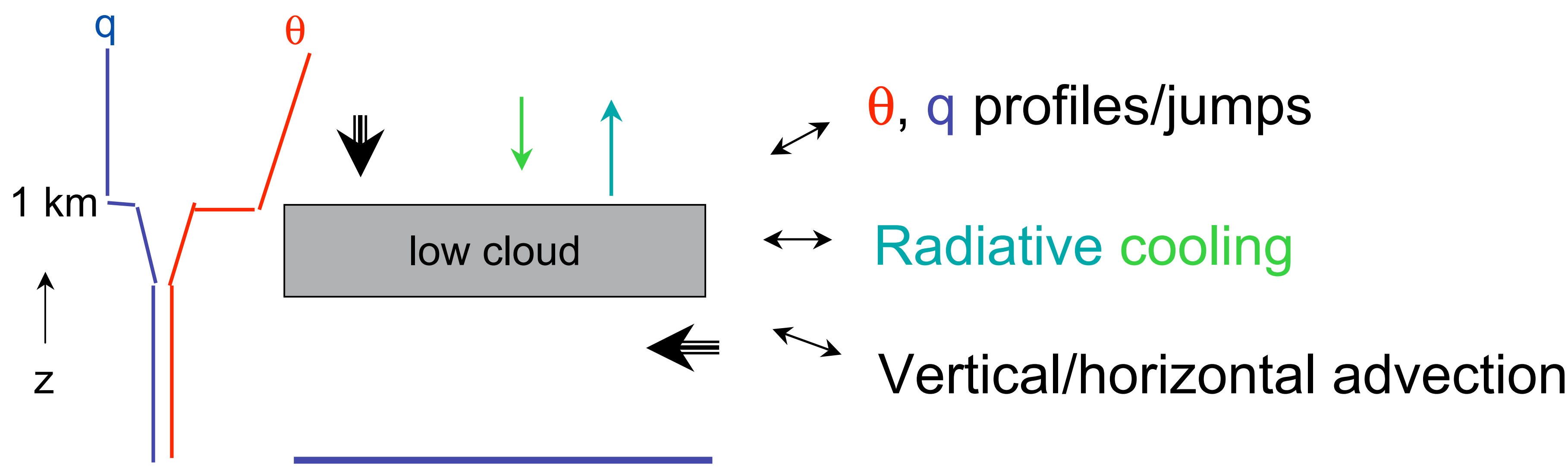
$$= -\underbrace{4\sigma T_A^3}_{2.5\,\mathrm{Wm^{-2}K^{-1}}} \underbrace{\left(\Delta T(z_A)/\Delta T_s\right)}_{2} \underbrace{f_{hi}}_{0.2}$$

$$\approx 1\,\mathrm{Wm^{-2}K^{-1}}$$



- Enhanced in many models by positive subtropical low cloud feedback.
- In midlatitudes, rising freezing level induces a deeper layer of optically thick water cloud below (negative SW feedback) ; Senior and Mitchell (1993)

Subtropical marine low cloud dynamics



Clouds are turbulently maintained by radiative cooling and surface moistening/heating.
Turbulence drives entrainment through capping inversion, which counteracts mean subsidence.
Shallow PBL is well mixed with Sc, deep PBL is ‘Cu-coupled’

Subtropical low cloud feedback mechanisms

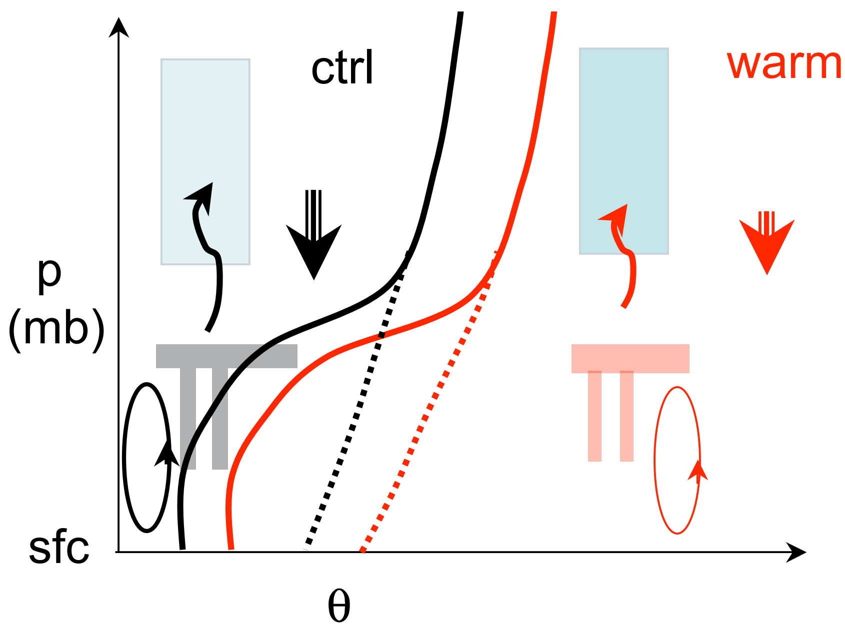
Due mainly to changes in stratification and free-trop emissivity

$\Delta\theta$ Warmer $\Rightarrow$ stronger inversion $\Rightarrow$ more cloud (-)

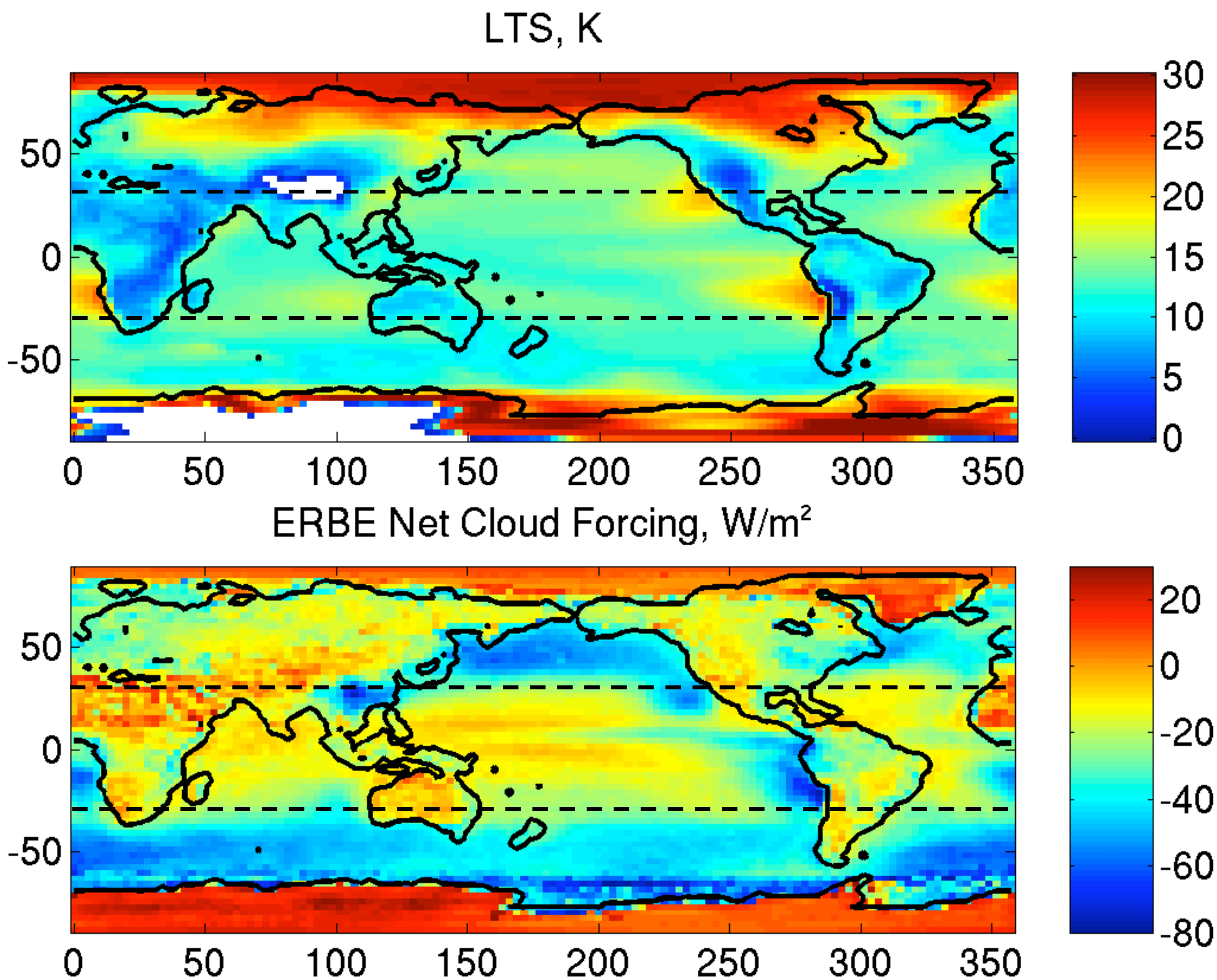
ΔCO_2 More CO_2 $\Rightarrow$ Less PBL rad cooling $\Rightarrow$ less cloud (+)

Δw Warmer $\Rightarrow$ less subsidence $\Rightarrow$
deeper, more cumuliform PBL $\Rightarrow$ less cloud (+)
[but w is driven by radiative + eddy cooling]

ΔRH Drier free-trop $\Rightarrow$ More PBL rad cool $\Rightarrow$ more cloud (-)



Lower tropospheric stability LTS = θ_{700} - θ_{1000}



Correlated with subtropical marine low cloud cover in current climate (Klein & Hartmann)

+1 K ΔLTS
$\leftrightarrow$ +6% Δlow cld
$\leftrightarrow$ -6 W m^{-2}ΔCRF

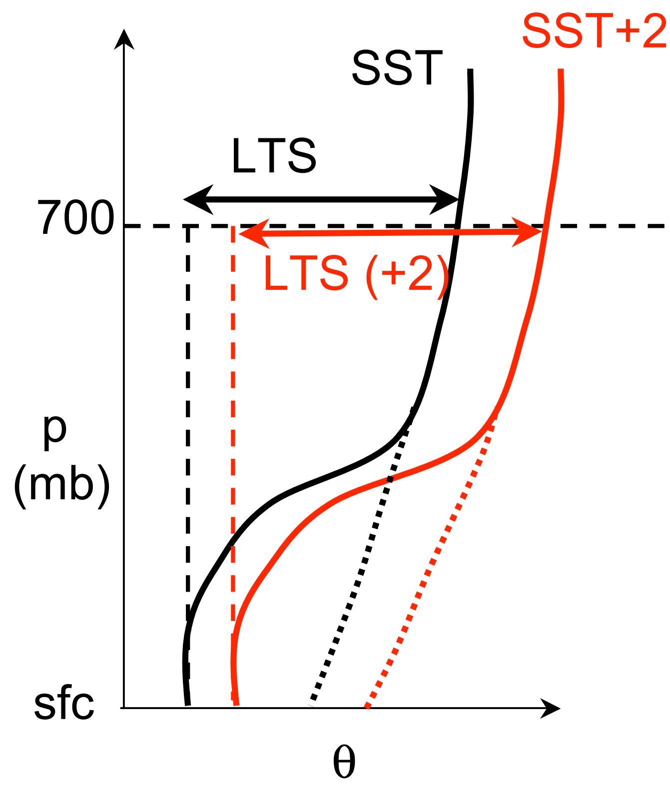
Less skillful in mid-latitudes. (EIS better)

LTS-predicted cloud feedback

- In a warmer climate, the low-latitude free troposphere has larger $d\theta/dz$.
- For spatially uniform SST increase,

  $$\Delta LTS \approx 0.5 \Delta SST$$

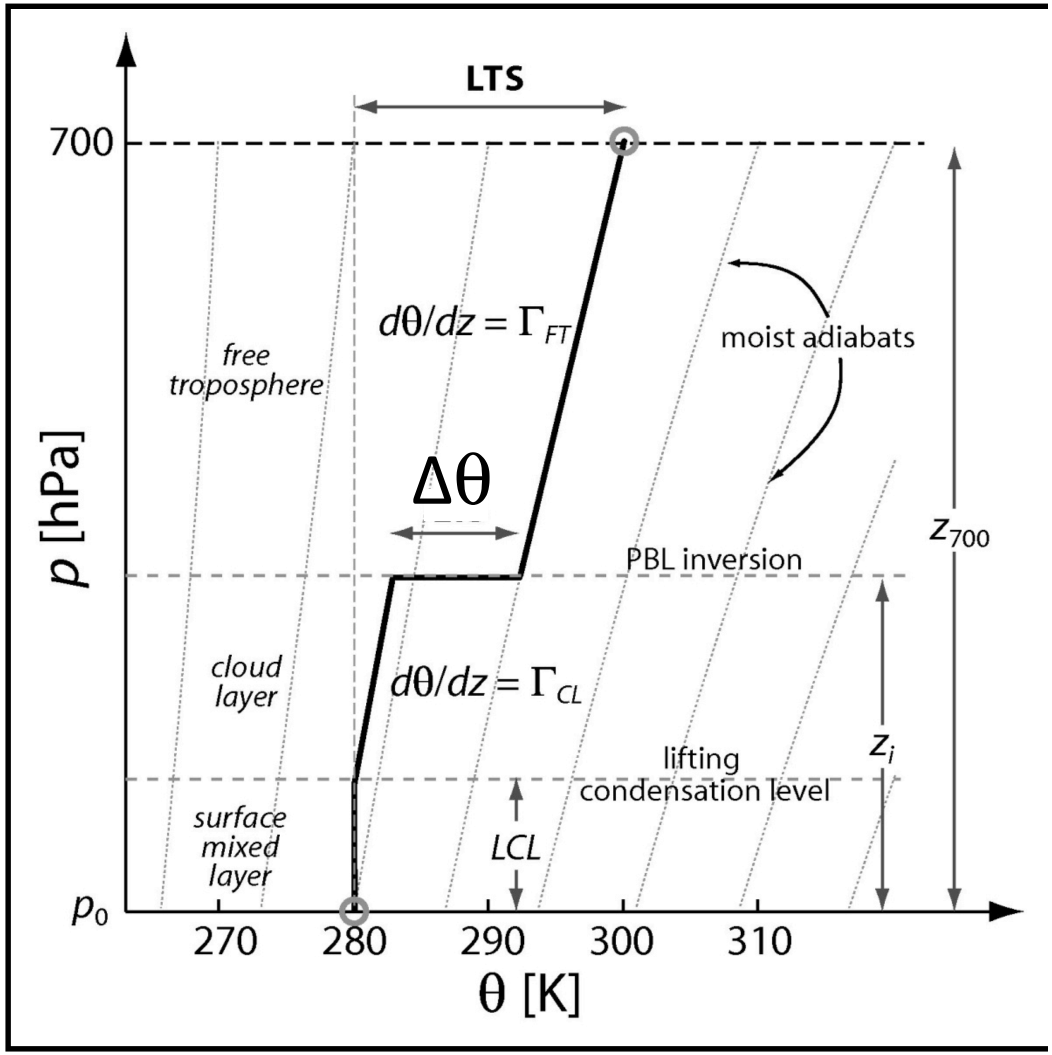
- Klein-Hartmann regression predicts 3%/K SST increase (Miller 1997), creating a strong negative low cloud feedback on climate change.
- However, 'Klein line' not predictive of GCM 2xCO_2 low cloud change Meideros et al. 2008) - may not be climate-invariant.



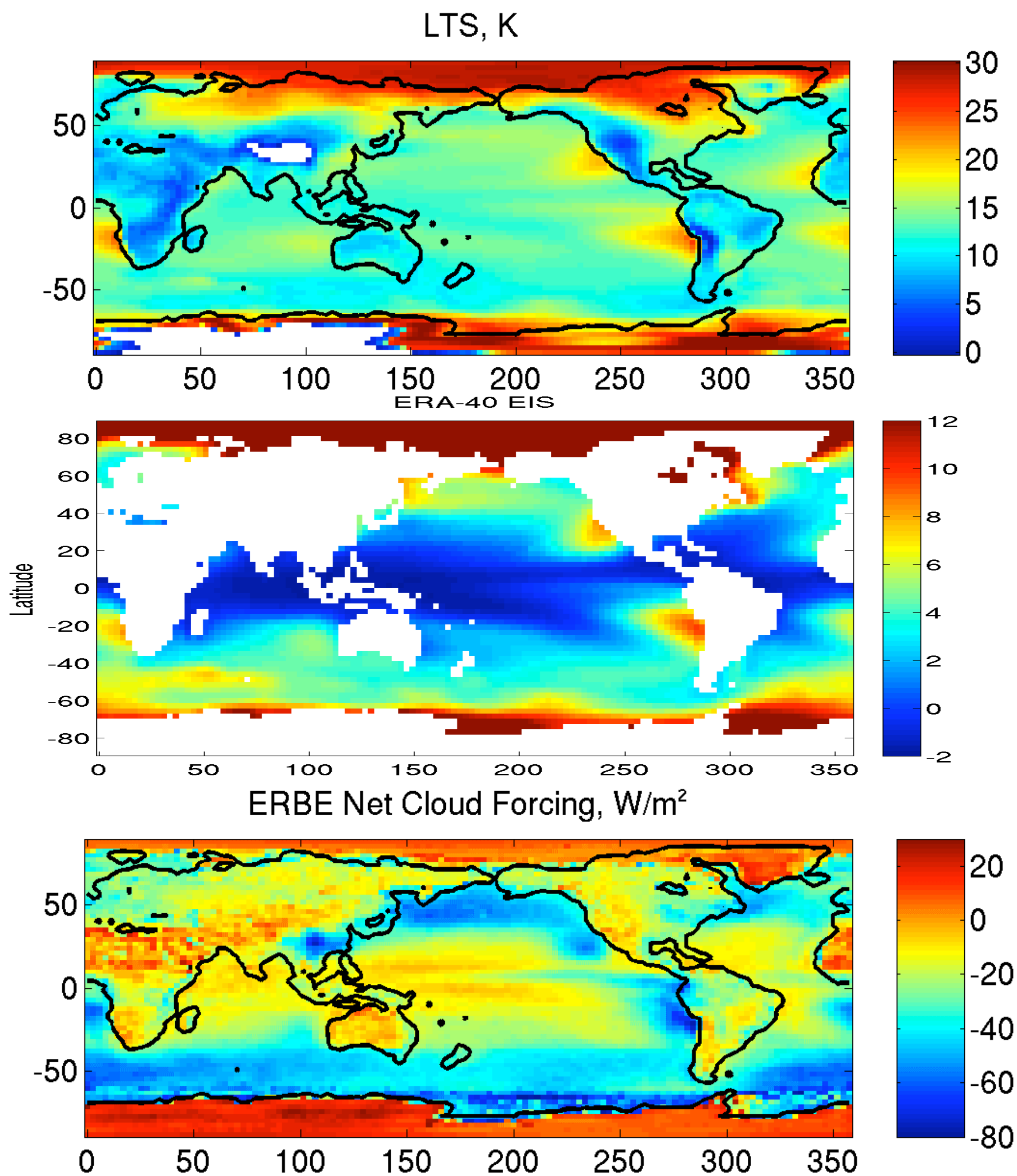
Estimated Inversion Strength

Wood and Bretherton (2006)

- In the free-troposphere, $d\theta/dz= \Gamma_{FT}$ follows a moist adiabat from 700 hPa to the MBL top.
- Well mixed surface layer below the LCL, i.e. $d\theta/dz=0$
- In the cloud layer, $d\theta/dz=\Gamma_{CL}$ follows a moist adiabat from the top of the LCL to the MBL top.



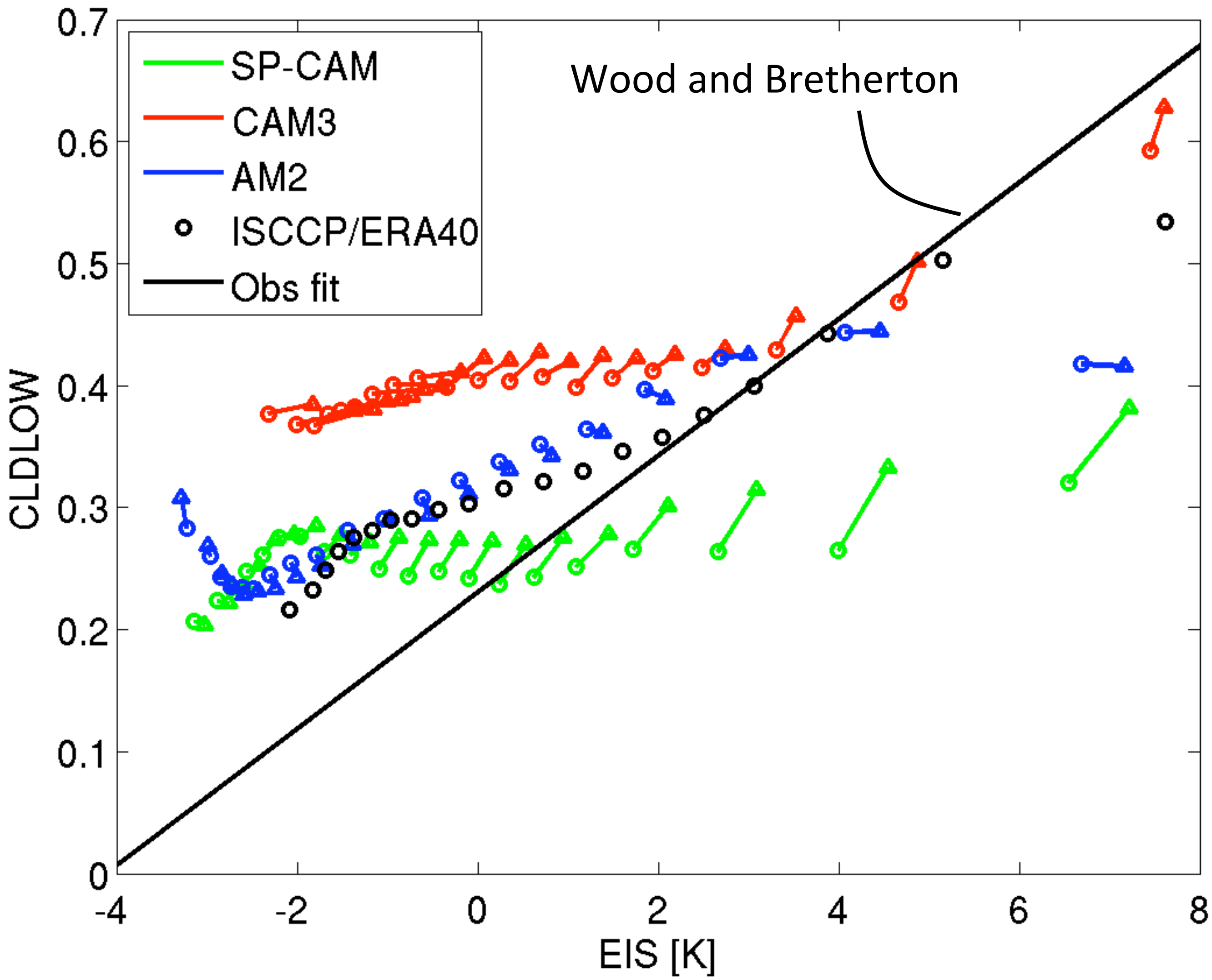
EIS vs. LTS

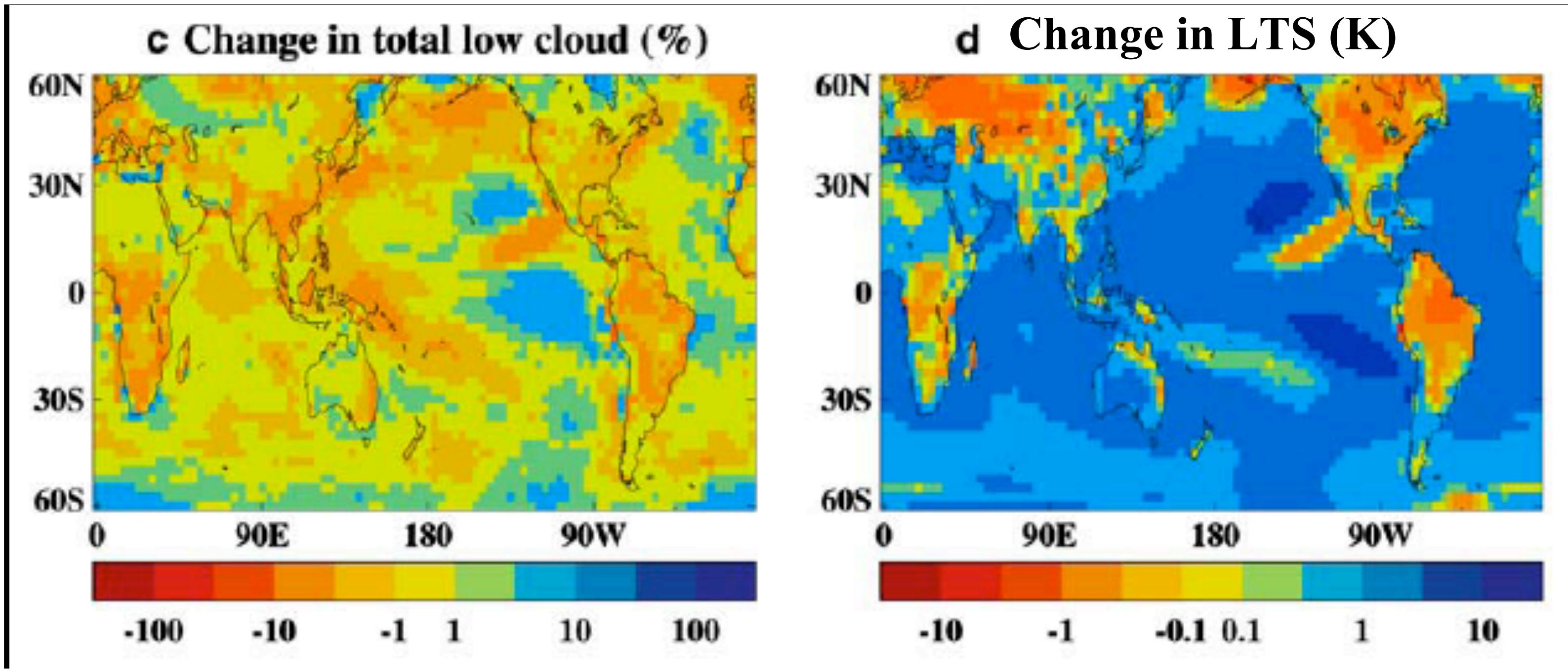


EIS much better correlated than LTS with low cloud over the midlatitude oceans (where the summertime free troposphere is also close to moist-adiabatic but not as warm as in tropics)

EIS more climate-invariant?

Cloud amount vs EIS (SST+2K)



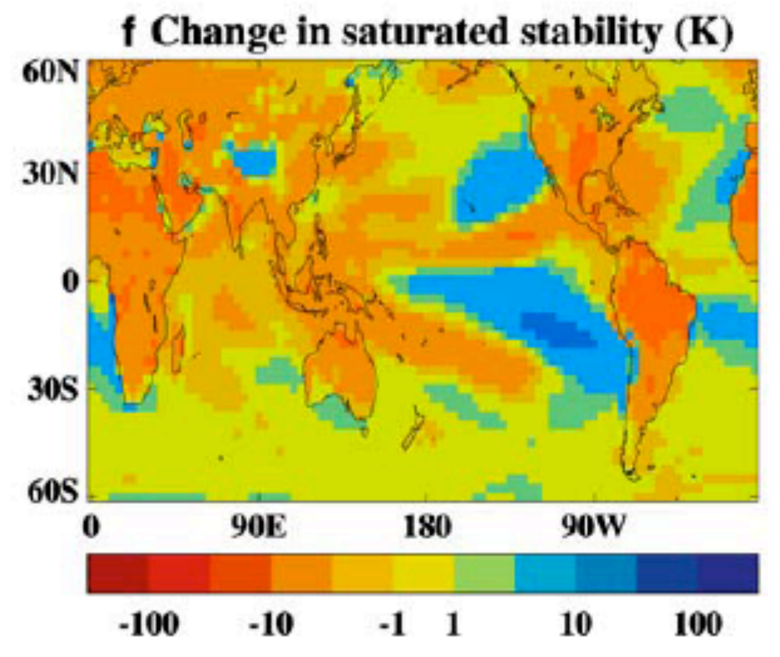


Low cloud change in an ensemble of $2xCO_2$-control GCM simulations is poorly estimated using ΔLTS.

Much better agreement with change in saturated stability (related to ΔEIS).

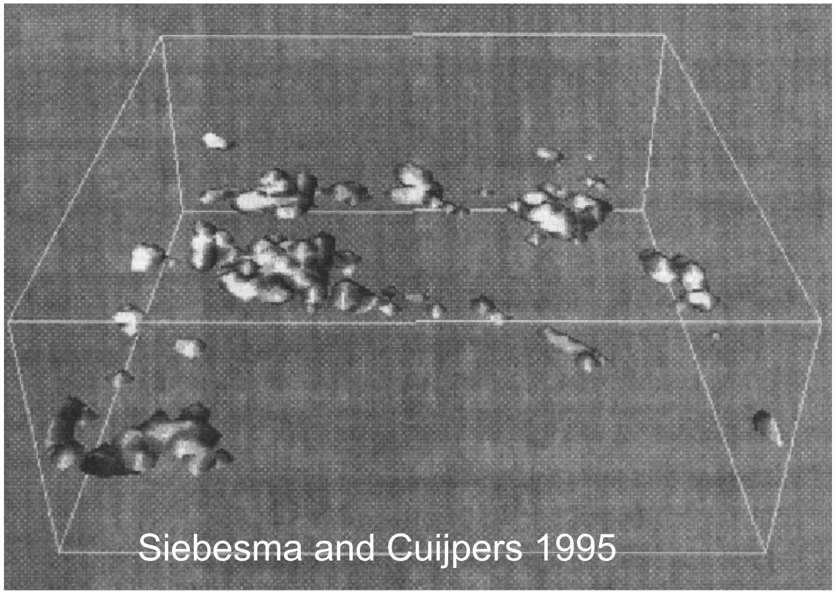
Models with ΔEIS >0 over subtropics tend to have Δlowcld>0.

$L\delta q/c_p\delta\theta$ also relevant? (Lock 2009)



Williams et al. (2006)

A new path forward: Cloud-resolving models



- CRMs can simulate PBL clouds more realistically, given adequate grid resolution and ‘large-scale advective forcings’ of temperature, humidity.
- To apply CRMs to cloud feedback problem, must either:

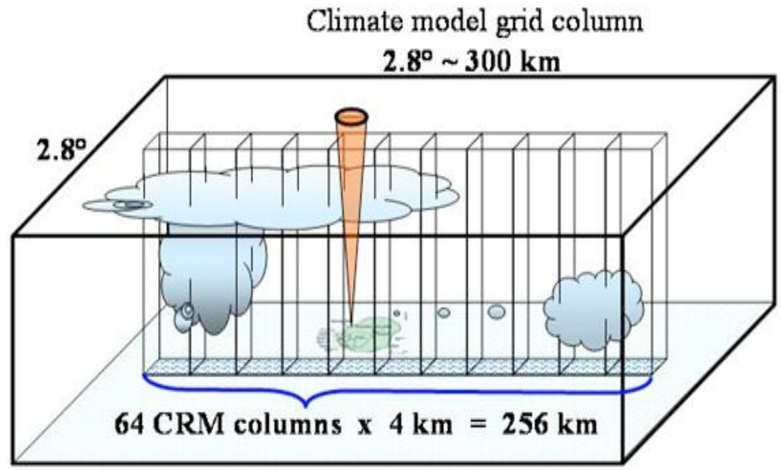
    run on a global scale (computationally intense)

or run in limited domain, specify large-scale context

Focus: subtropical trades - important, well represented by CRMs with $\Delta z < 100$ m, $\Delta x < 250$ m.

Cloud feedbacks in a superparameterized GCM

- Superparameterization - a climate model with a small CRM running in place of the normal physical parameterizations in every grid column.
- Computationally expensive, but may simulate turbulent clouds (especially deep convection) more realistically.



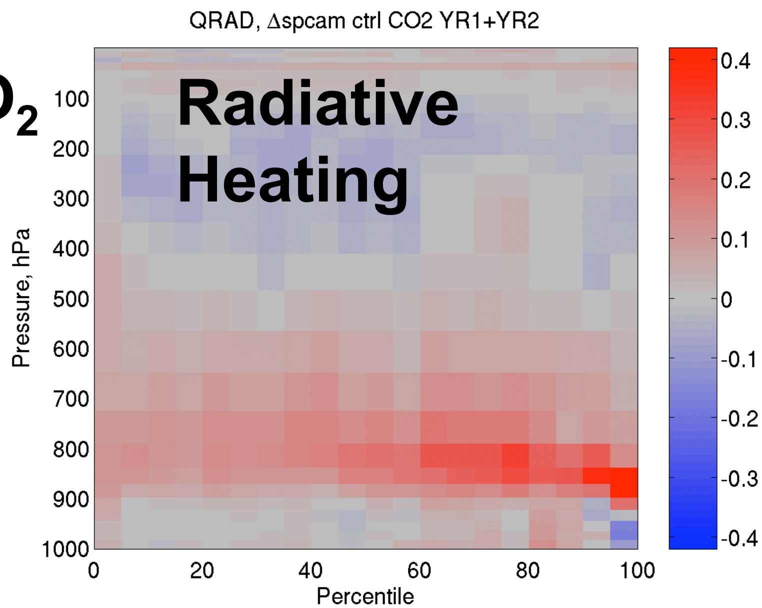
- SP-CAM (Khairoutdinov and Randall 2005) uses 2D CRMs with 32x30 gridpoints, Δx = 4 km and Δz ~ 200 m in PBL - underresolves boundary-layer Cu and Sc.
- Has strong negative subtropical +2K low cloud feedbacks with ΔEIS > 0 and increased boundary-layer radiative cooling (Wyant et al. 2009)
- Investigate low cloud response to instantaneous 4x CO_2 increase with fixed SST.

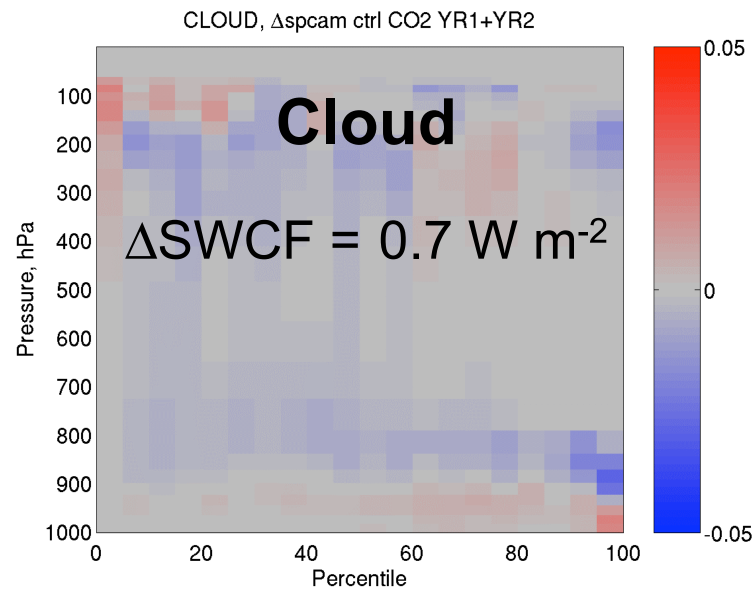
4xCO_2 experiment with SP-CAM

- 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 $\Rightarrow$ More downwelling LW $\Rightarrow$ Less PBL radiative cooling

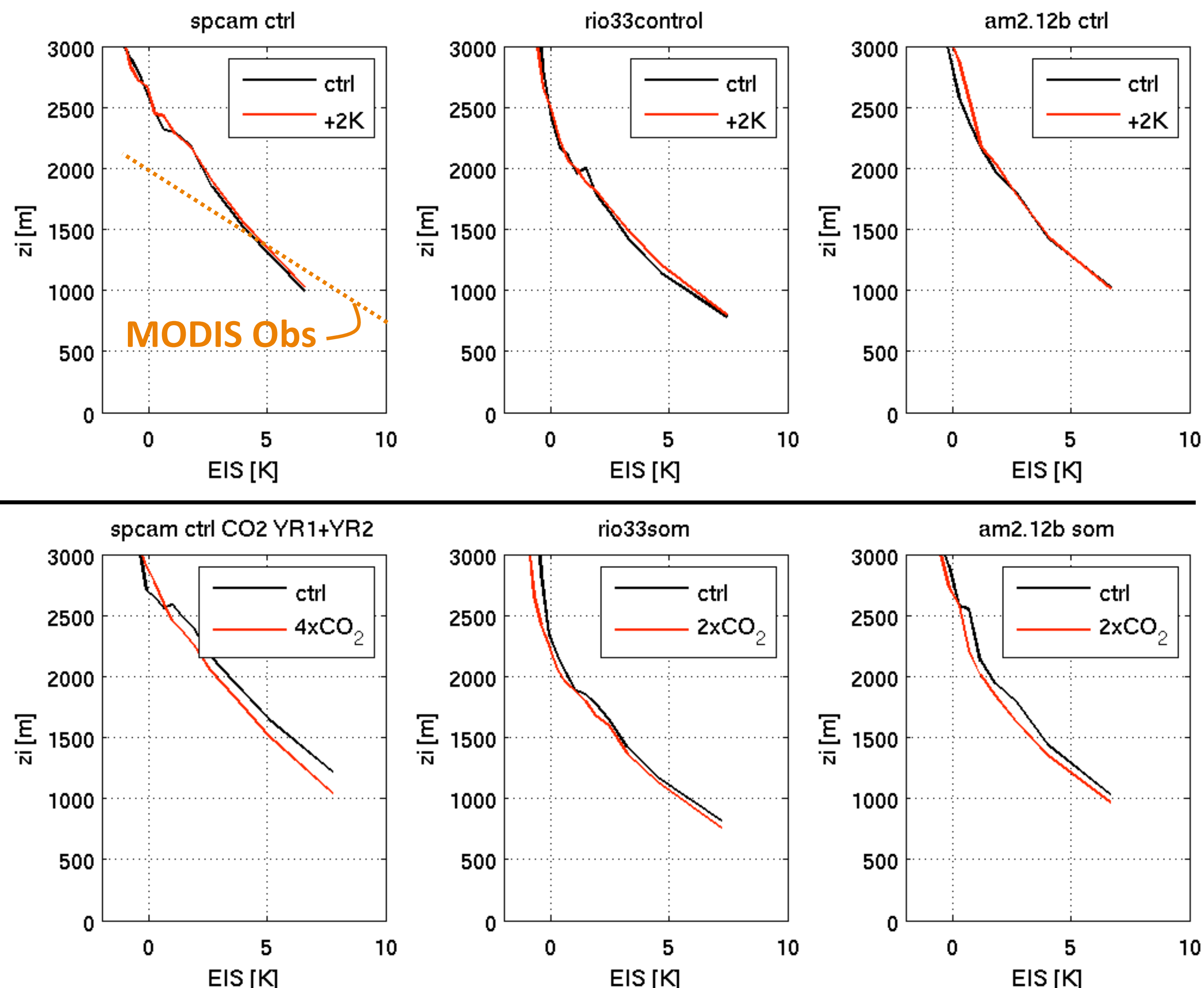
Δ4xCO_2





MBL depth for control and perturbed runs

SST+2K

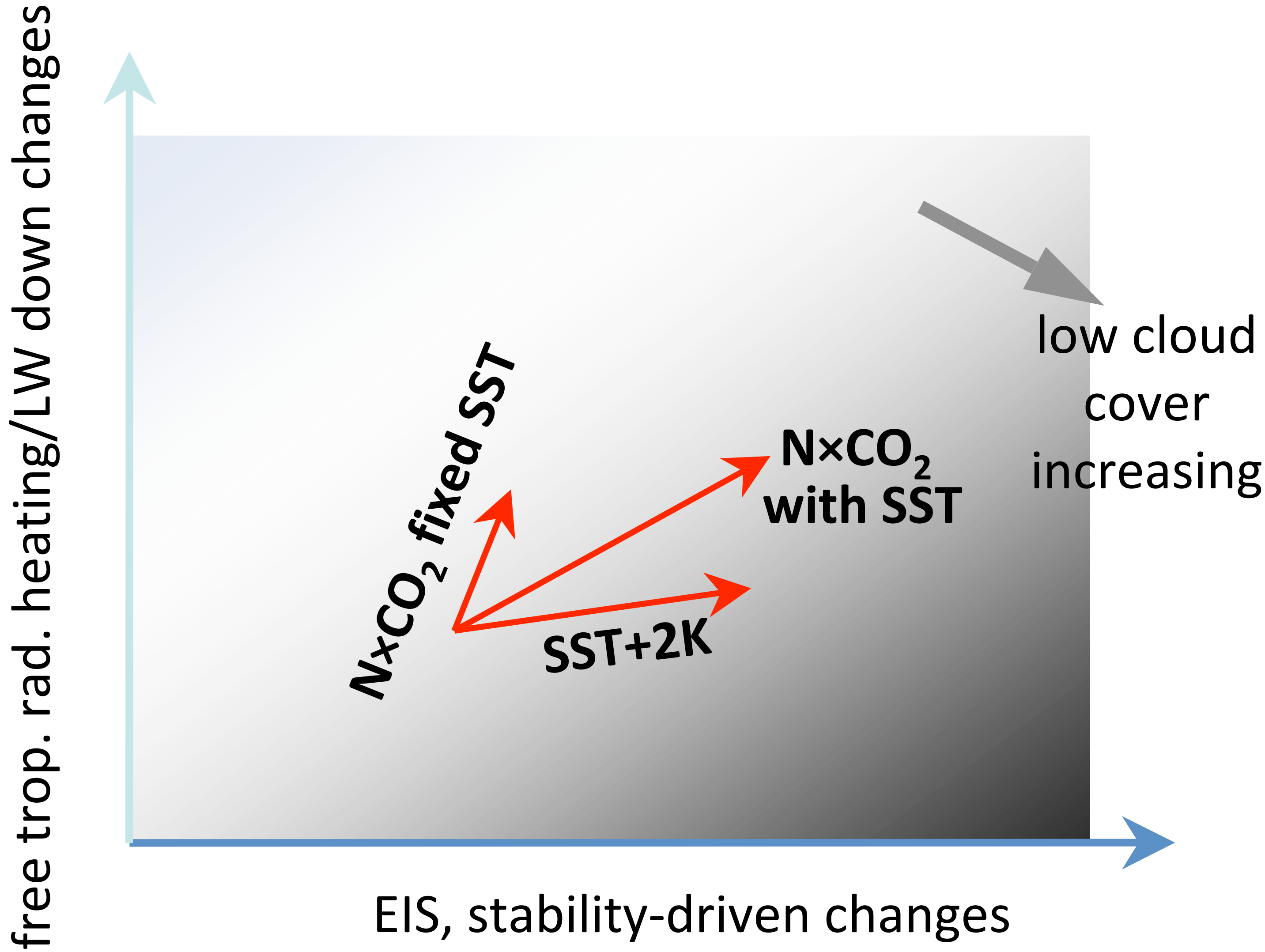


N×CO_2

MBL depth decreases despite reduced subsidence from CO_2 FT warming $\Rightarrow$ MBL turbulence weakens

Rob Wood

A phase space for subtropical low cloud change



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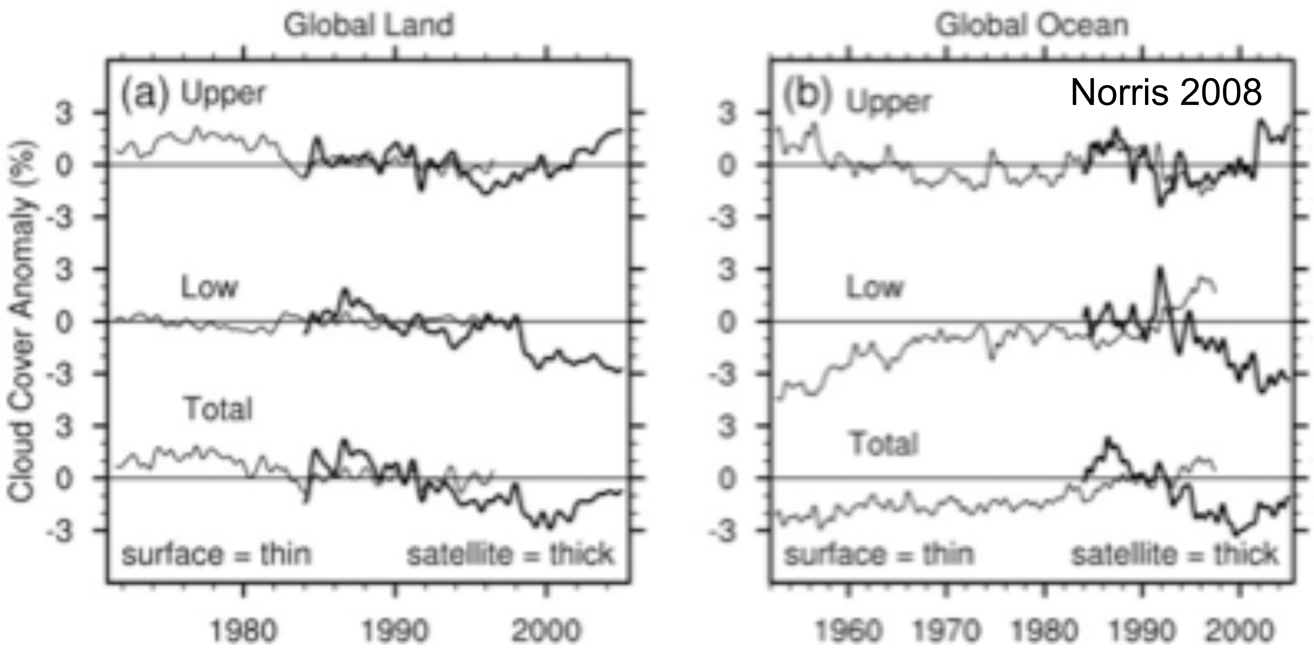
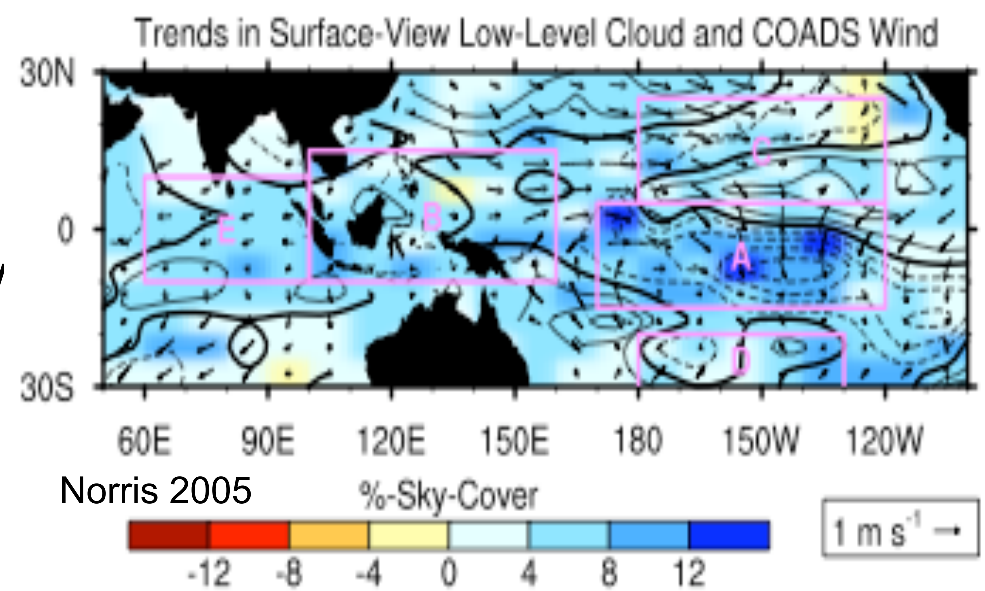
Trends in surface and satellite cloud observations



- Surface ship observations show implausible low cloud cover increase since 1950 (sampling/reporting changes?)
- Satellite observations show low cloud decrease since 1983 (orbital and sensor drift)

⇒ Observations inadequately constrain global cloud feedbacks.



NE Pacific cloud variability: a cloud feedback analogue? (Clement et al. 2009 Science)

- NE Pacific interannual low cloud variability responds to Pacific Decadal Oscillation, increasing when regional SST decreases (noted earlier by Klein&Hartmann, Norris, etc.)
- Clement et al. treat this as evidence of positive cloud response to a warmer climate (warmer SST$\Rightarrow$less clouds).
- This ignores crucial role of free troposphere:

  Global warming: free trop warms more than subtropical SST, increasing LTS.

  NE Pac variability: free trop changes much less than subtropical SST, decreasing LTS.
- One MUST look for observational analogues with vertical stratification changes similar to global warming

  and/or

  convincingly test individual cloud feedback mechanisms (Clement et al. present a flawed approach to this, too)

Conclusions

- GCMs produce positive cloud feedback due to isothermal rise of high clouds and (in most models) subtropical cloud decreases.
- SP-CAM LES-based GCM suggests direct radiative response to more CO_2 is decreased low cloud.
- T-mediated cloud response is a tradeoff between a stronger inversion (more cloud) and deeper, decoupled boundary layer (less cloud) in a warmer climate. Models uncertain due to compensating feedbacks.
- Observations have not yet usefully constrained cloud feedbacks. A major breakthrough in cloud feedbacks would be to *convincingly* bring observations and models together.

Column analogue to SP-CAM

Hypothesis

Low cloud change can be idealized as a steady-state response to large-scale changes in subtropical free-trop temperature, RH, and GHG profiles and horizontal T/q advection.

Method (Blossey et al. 2009 JAMES):

1. For some cloud regime, make composite forcings/profiles for ctrl and SST+2K runs:

   - SST and surface wind speed

   - profiles and advective tendencies of T,q

   - Vertical p-velocity ω

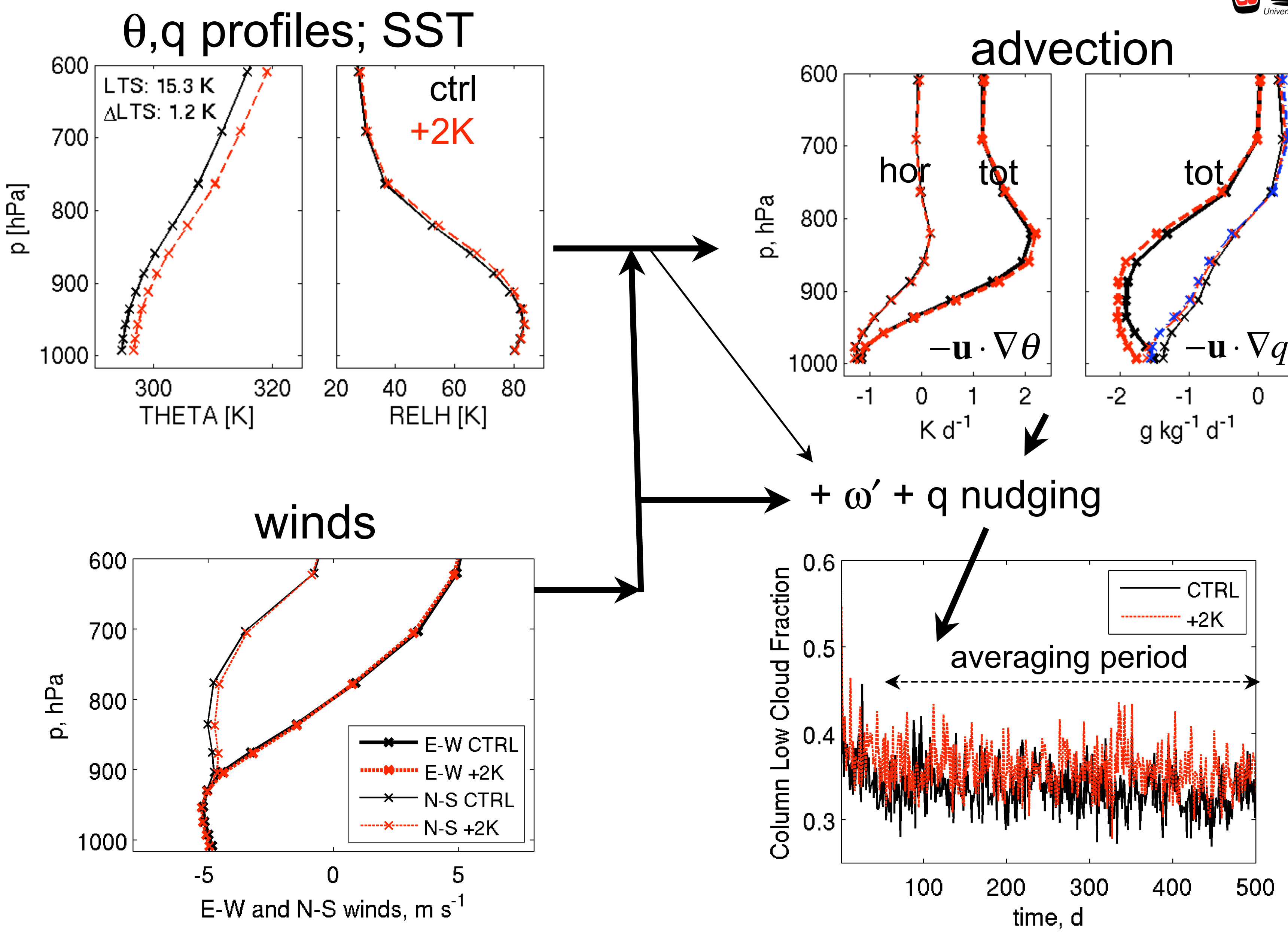
   We defined a Sc-to-Cu transitional regime using 80-90 percentiles of LTS over low-lat ocean column-months, and calculated the forcings from SP-CAM.

   CGILS is using regimes defined along NE Pacific transect.

2. Run CRM to steady-state with both forcings. 500 day integrations are used to calculate +2K cloud differences.

   Compare ‘CRM4km’ configured as in SP-CAM (dx=4km, L30) and high resolution CRM (dx= 100m, dz=40m) to SP-CAM composites.

LTS80-90 forcings and profiles (from SP-CAM)



SP-CAM

CRM4km

(similar to
SP-CAM)

CRM100

Less cld
and Δcld
than 4km