Insights into low-latitude cloud feedbacks from high-resolution models

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CFMIP

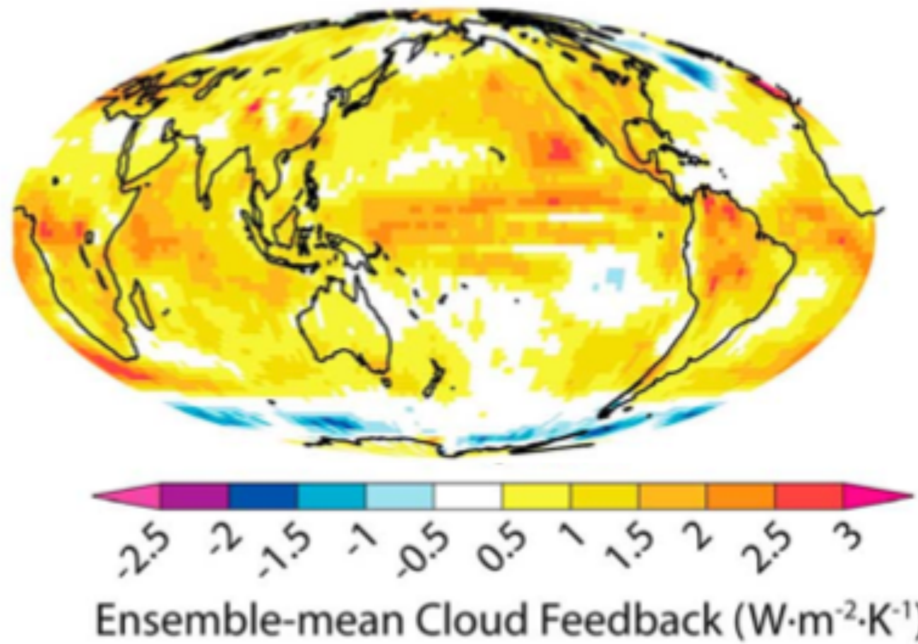
GASS GEWEX WCRP Global Atmospheric System Studies

Atmospheric Sciences University of Washington

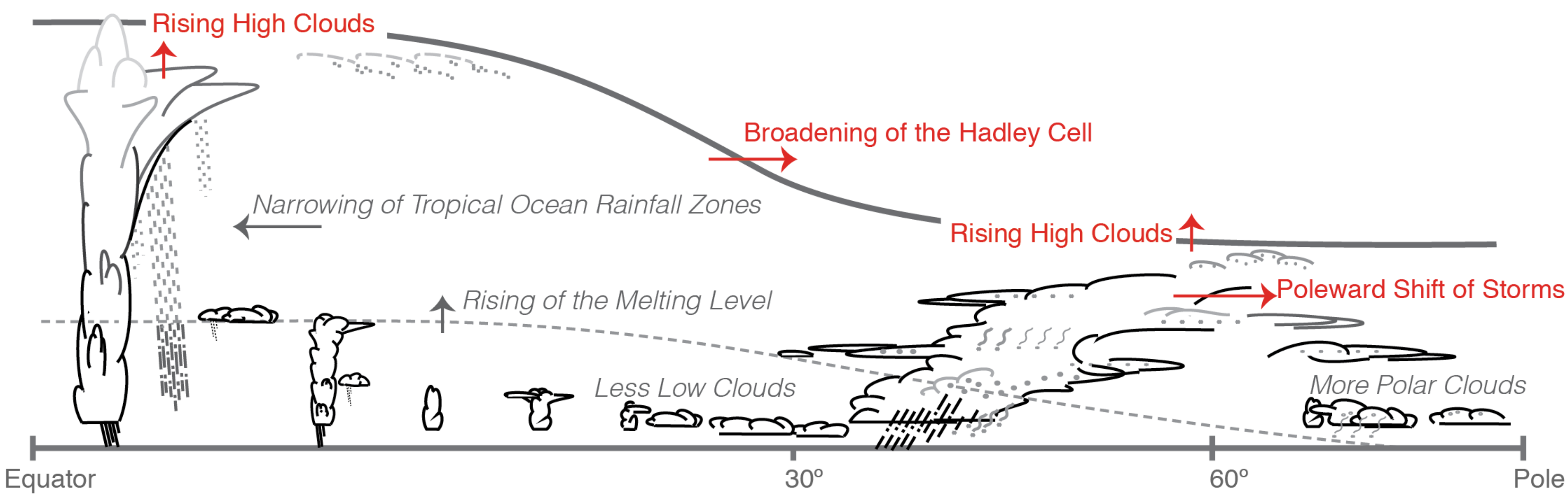
Global cloud feedbacks

IPCC AR5 SPM: 'The net radiative feedback due to all cloud types combined is *likely* positive.'

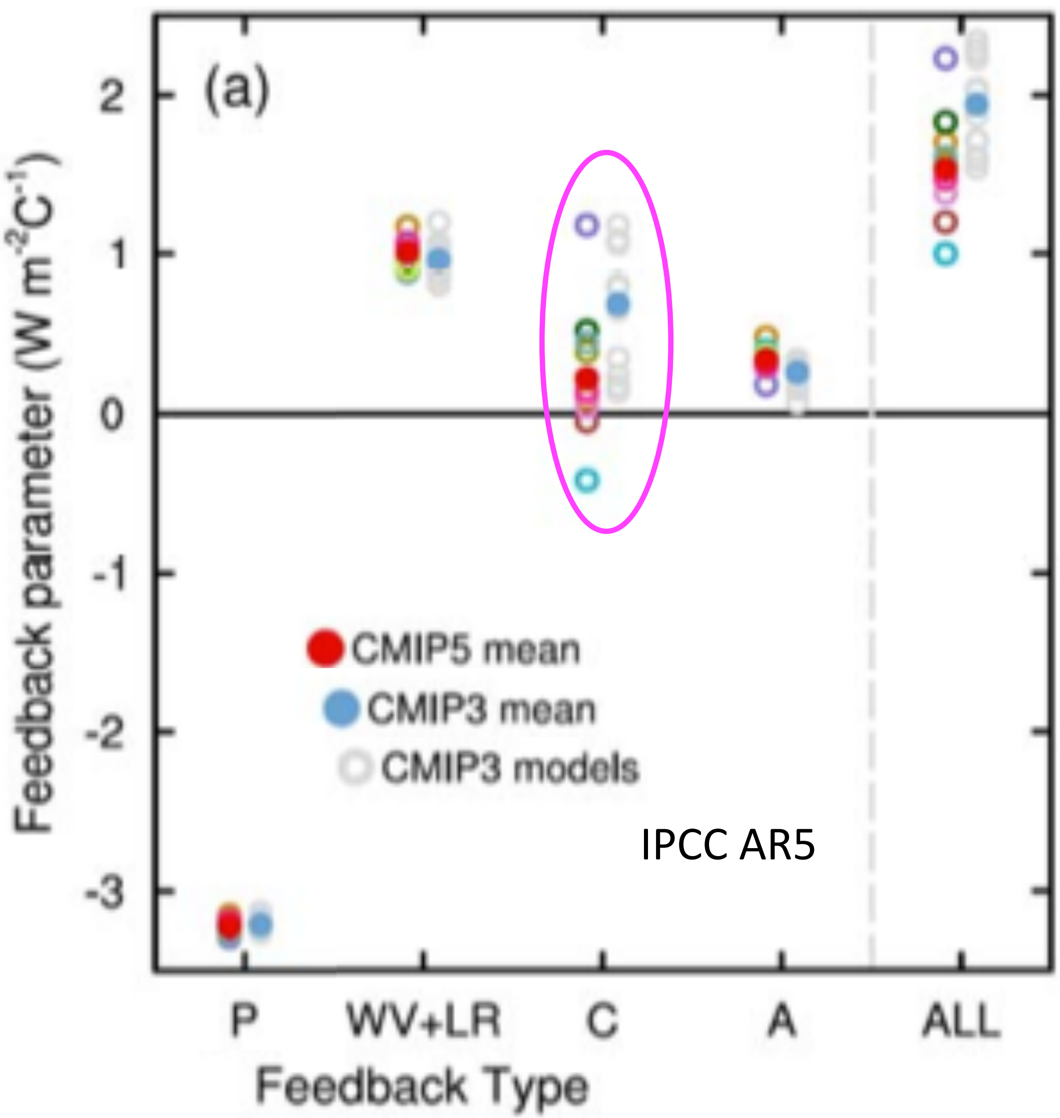
- CMIP GCMs
- 'Robust' cloud feedbacks
- Process understanding



Soden and Vecchi 2011, based on CMIP3



IPCC AR5 SPM: ‘Uncertainty in the sign and magnitude of the cloud feedback is due primarily to continuing uncertainty in the impact of warming on low clouds.’



IPCC AR5

Do high-resolution (CRM and LES) limited-area and global models add insight into cloud feedbacks:

- In given regimes?
- Globally?

Use of high-resolution models to study cloud feedbacks

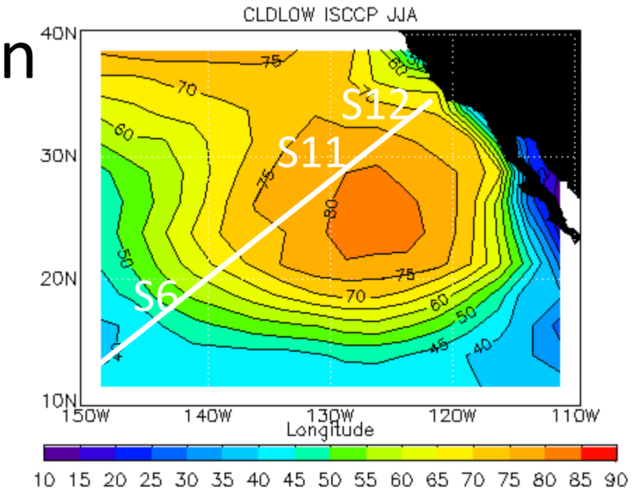
- High-resolution = cloud-resolving (CRM) or large-eddy simulation
- Simulate cloud-turbulence-convection-precipitation interactions with less subjective subgrid parameterizations than GCMs.
- Easier to compare with small-scale cloud observations
- Help identify cloud response mechanisms to climate change,
- Help test plausibility of possible emergent constraints.
- But simulation of full global to turbulence range of scales over climate timescales is computationally infeasible.
- This talk looks at:
  - LES of subtropical low cloud responses to idealized imposed climate change
  - Local and global cloud-resolving simulations of deep convective response

Large-eddy simulation of low cloud climate-change response

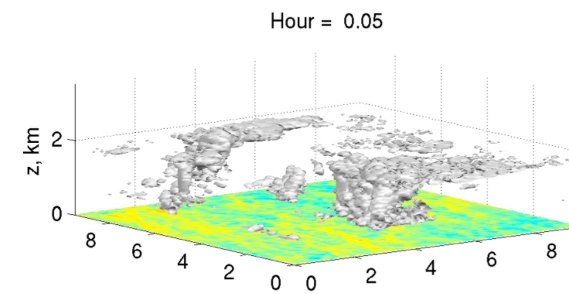
- LES with sufficiently fine grids simulate cloud-topped boundary layers more accurately and robustly than GCM parameterizations
- LES domain is a few km on a side; large-scale drives the LES
- Hence, use LES to explore cloud response to prescribed large-scale changes expected from GCMs, and compare with available observations and the GCMs themselves.
- Do LES support the GCM consensus of less subtropical marine low cloud in a greenhouse-warmed climate?
- If so, do they provide a physical explanation for this?

CGILS LES cloud feedback intercomparison

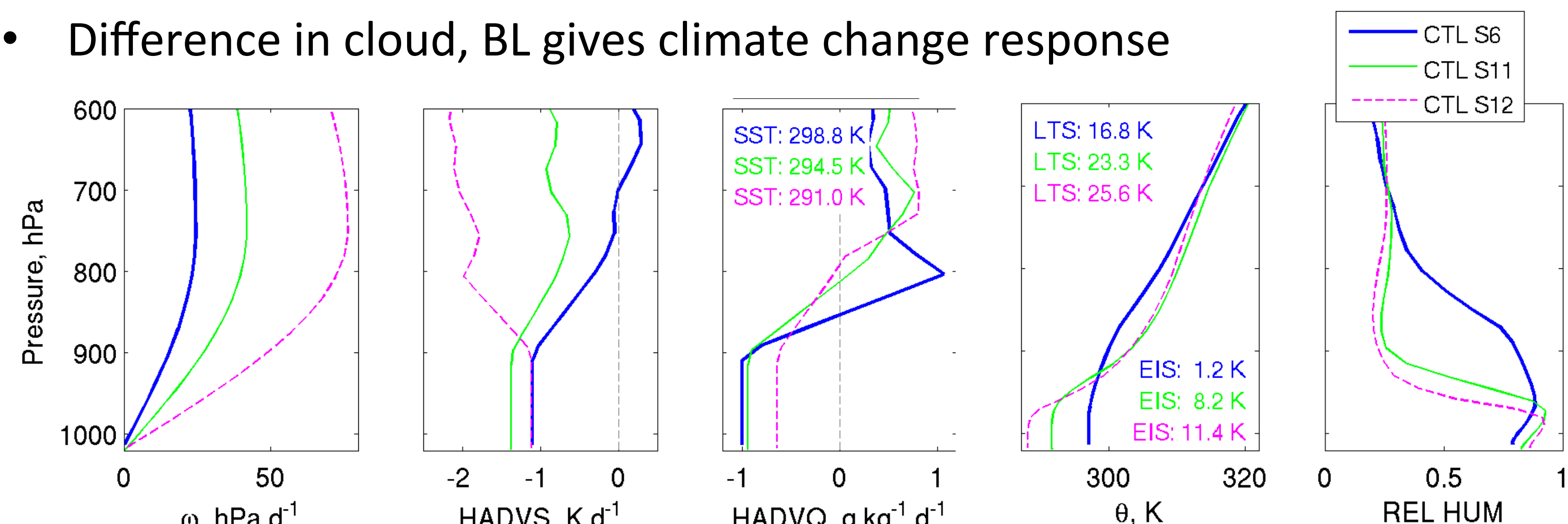
(Blossey et al. 2013)



- Mean summertime forcing at 3 NE Pacific locations:
  - S12: Shallow coastal stratocumulus (Sc)
  - S11: 'Decoupled' Cu rising into Sc
  - S6: Shallow Cu

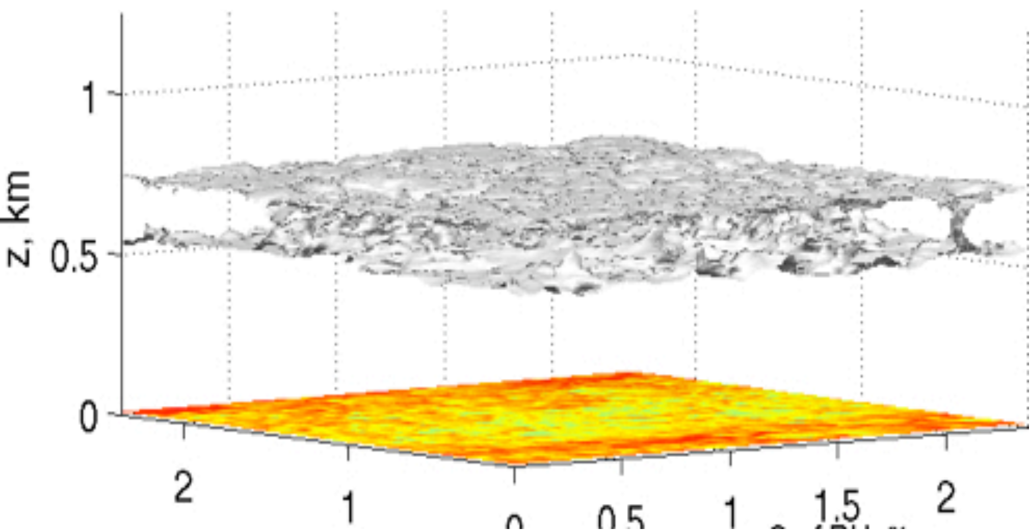


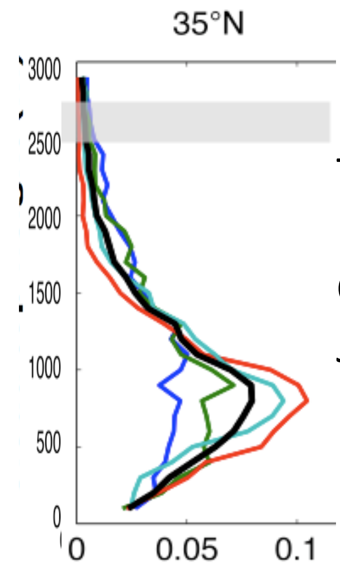
- LES 'control' run 10 d to near steady-state with diurnal-mean insolation, 100 cm^{-3} cloud droplet conc.
- LES rerun to steady state with climate perturbations added to forcing (temperature, subsidence, CO_2 etc.)
- Difference in cloud, BL gives climate change response



CGILS forcings:Zhang et al. 2012

S12 Cloud Response

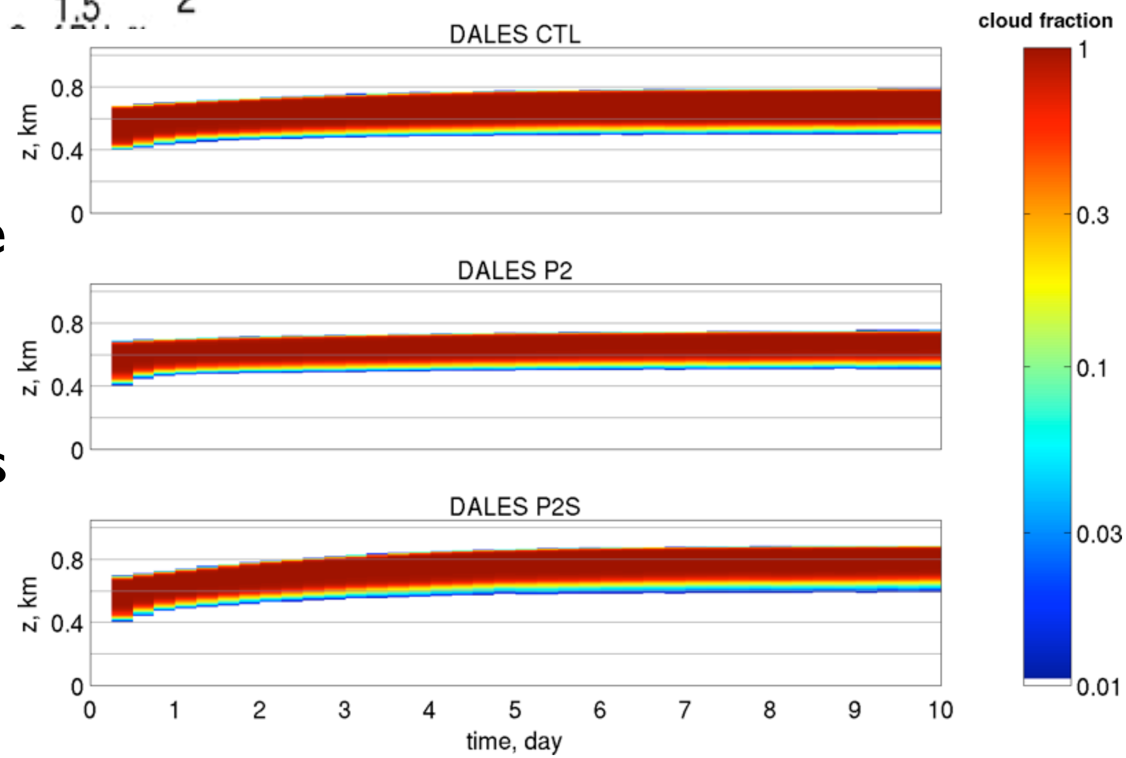




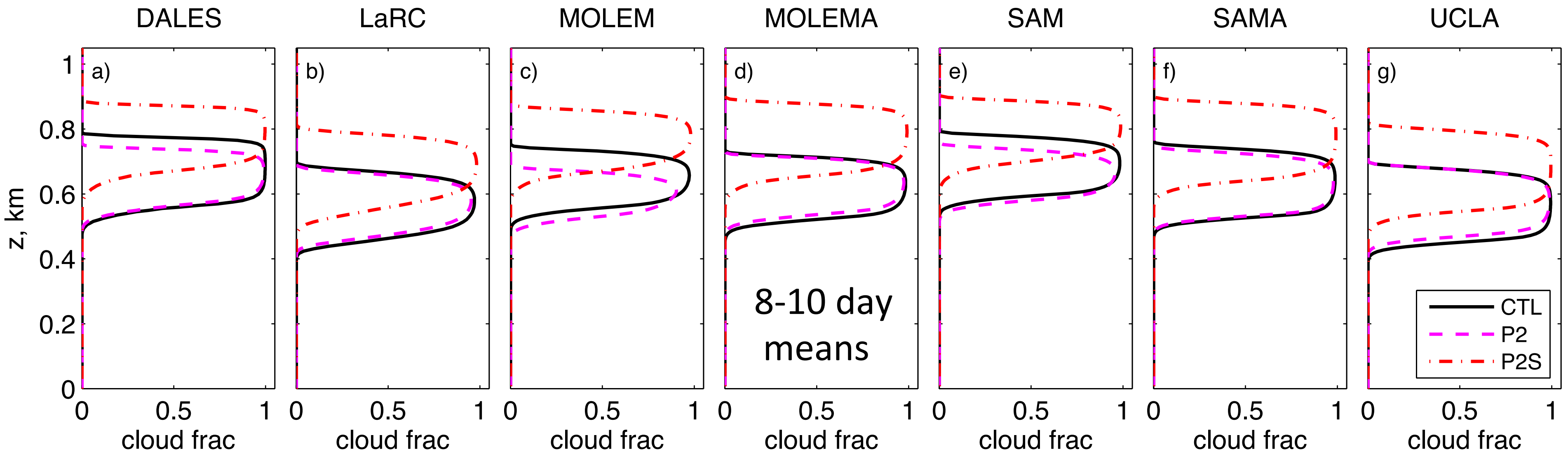
MISR Cloud Top Height PDF Courtesy of J. Karlsson.

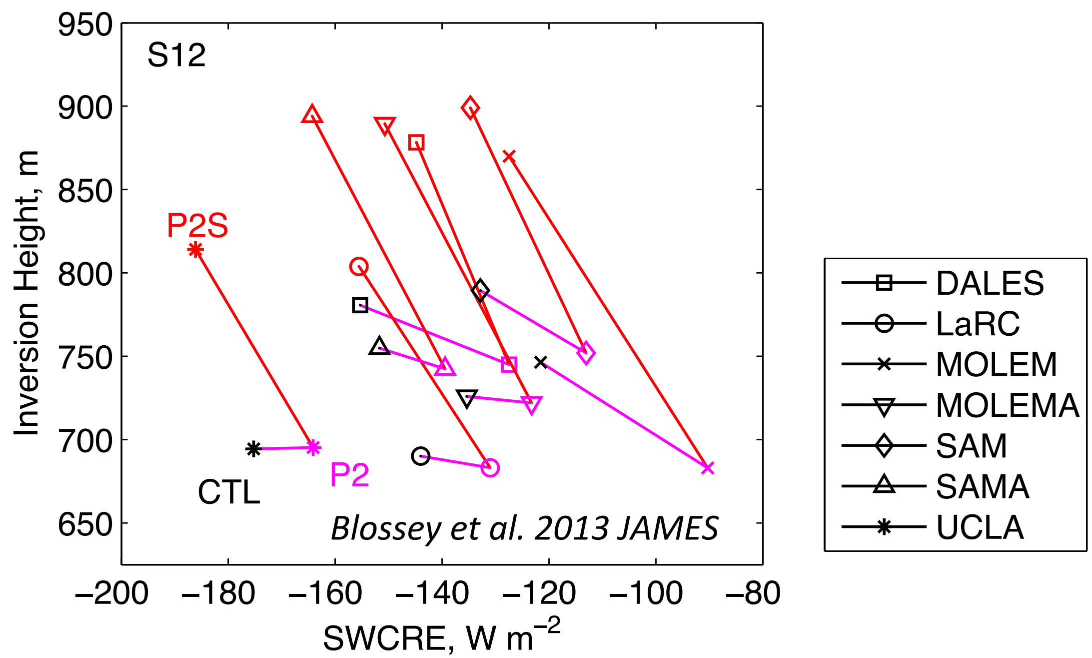
Δx = Δy = 25 m, Δz = 5 m at inv.

- **P2:** Cloud thins with little change in inversion height or entrainment.
- **P2S:** Cloud layer thickens as inversion deepens in response to weakened subsidence.



Different LES give similar cloud responses

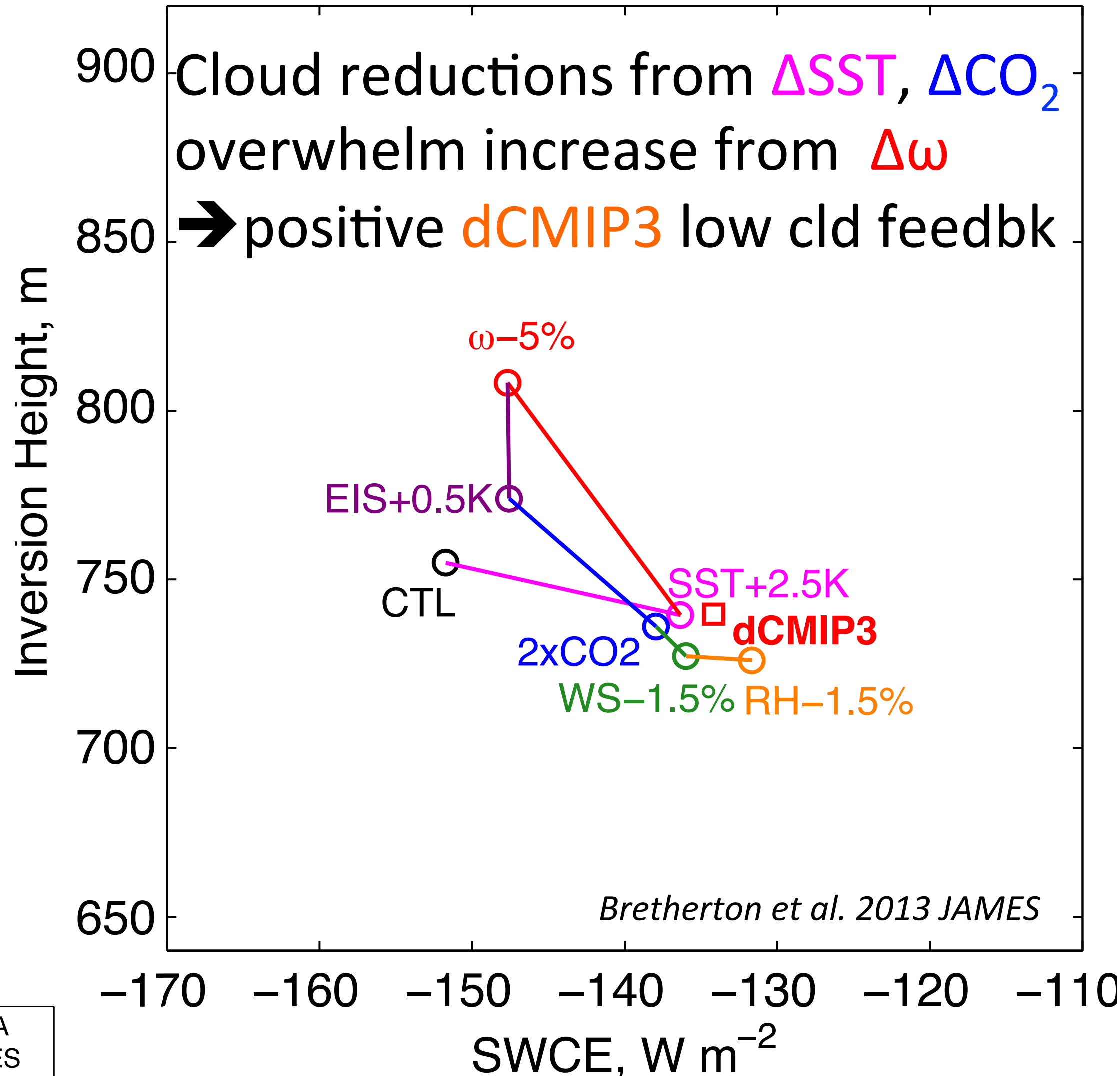


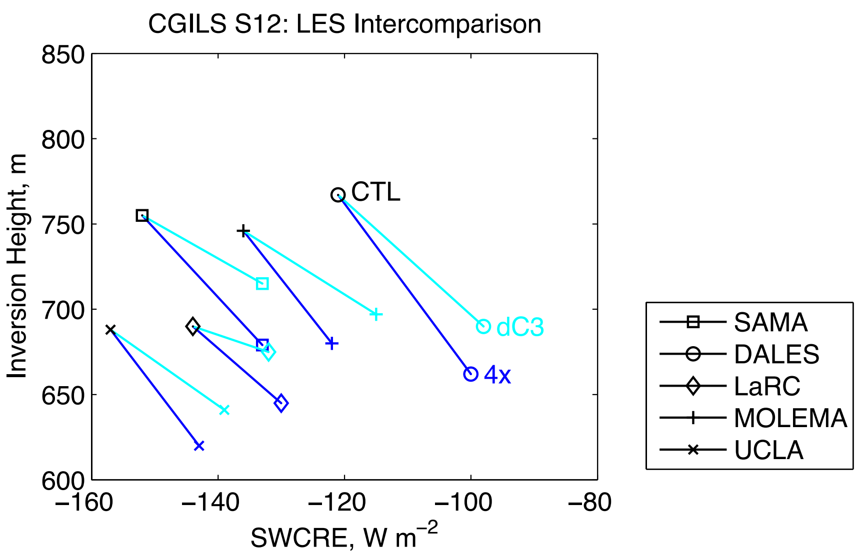


dCMIP3 forcing changes

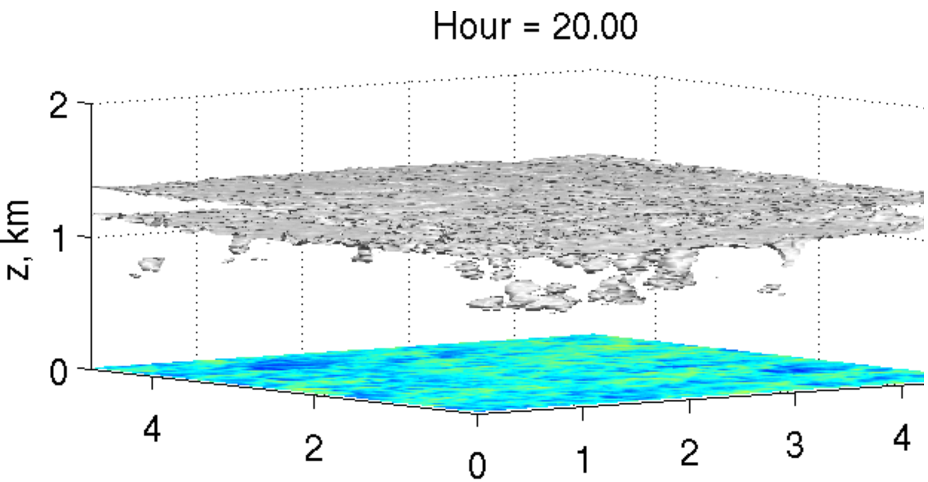
S12

Perturbation	dCMIP3
δSST	2.5 ± 0.5 K
δω(500 hPa)	-5 ± 3 %
δEIS	0.6 ± 0.2 K
δRH	-1.5 ± 1 %
δ(wind speed)	-1.5 ± 1.5 %

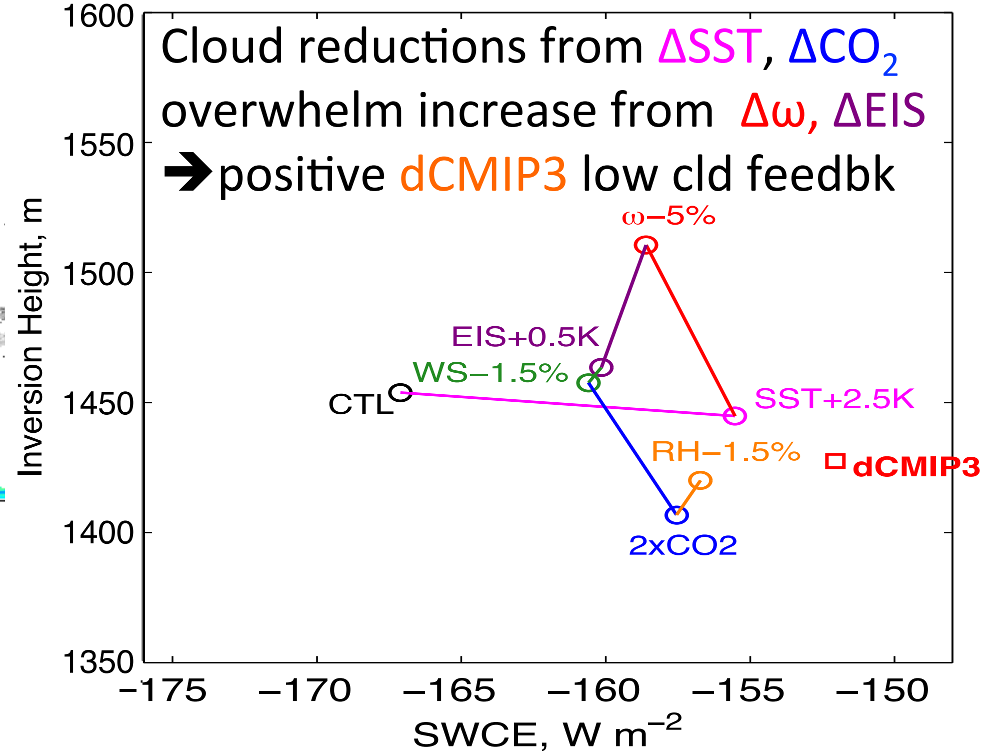




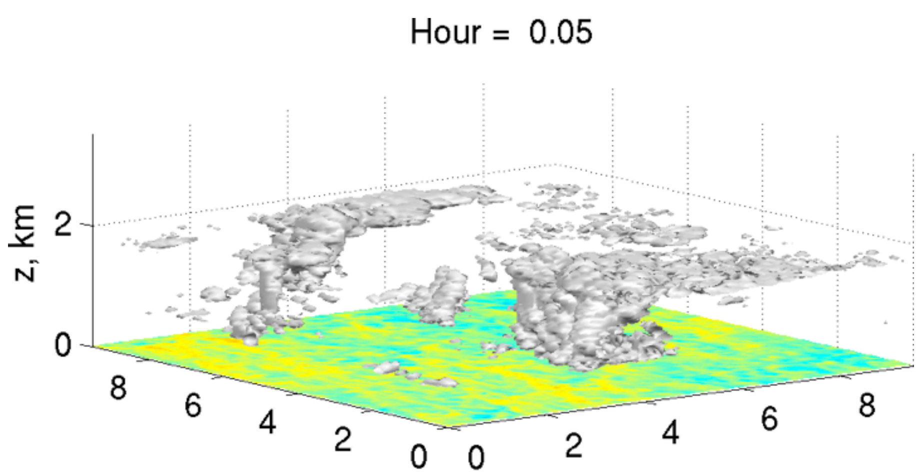
S11: Decoupled Cu under Sc



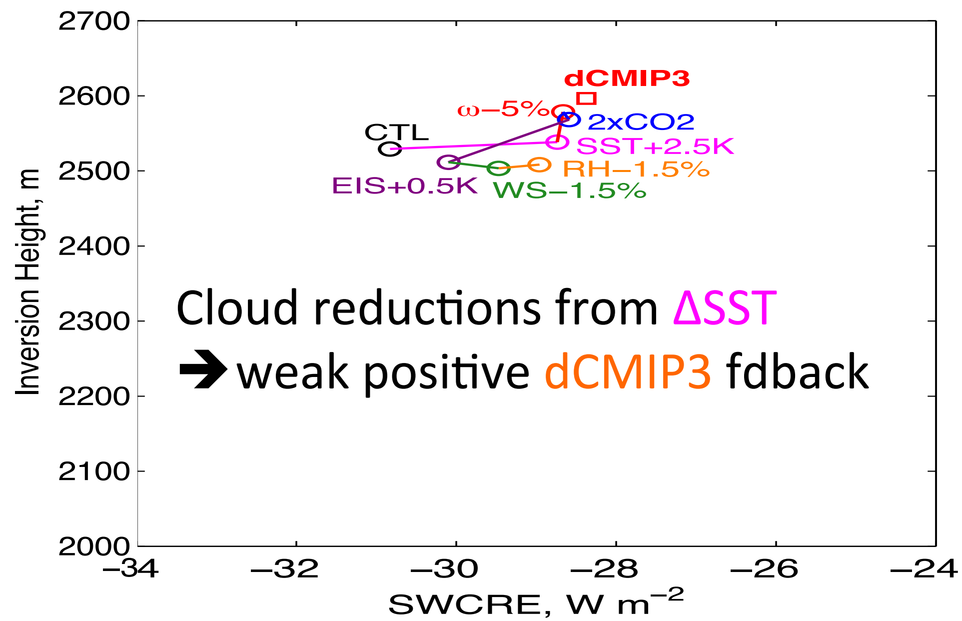
$\Delta x = \Delta y = 50$ m, $\Delta z = 5$ m at inv.



S6: Cu



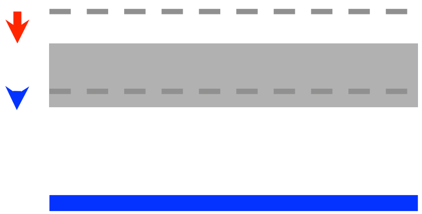
$\Delta x = \Delta y = 100$ m, $\Delta z = 40$ m at inv.



Mechanisms of Sc Cloud Response

Radiative

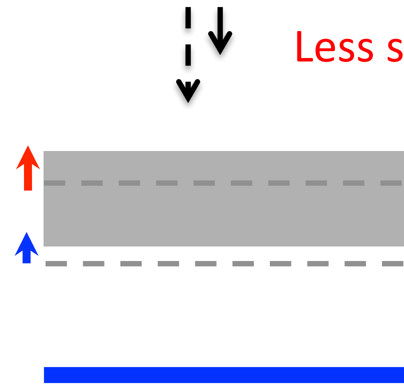
More emissive FT
(more CO_2 or H_20)



Less turbulence production by top longwave cooling.
Less entrainment.
Sc lowers, thins.

Dynamic

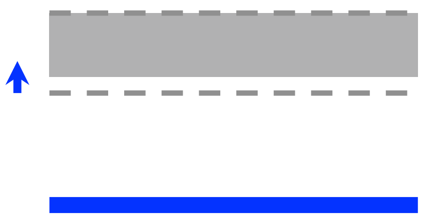
Less subsidence



Sc top rises. More entrainment lifts cloud base.
Sc thickens.

Thermodynamic

warmer SST
or drier RH



Larger surface – FT moisture difference allows thinner cloud to sustain same entrainment.
Sc thins.

Inversion strength

FT warms more than SST

Stronger inversion reduces entrainment.
Sc top and base lower.
Sc thickens.

Bretherton et al. 2013 *JAMES*

Observational support:

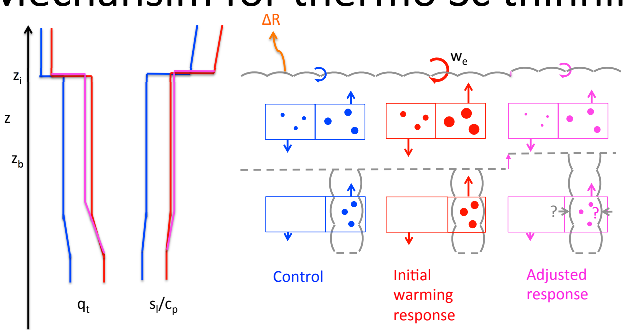
Thermodynamic: Qu et al. 2013, *Clim Dyn*
Radiative: Christensen et al. 2013, *JAS*
Dynamic: Myers and Norris 2013, *J Clim*
Inversion strength: Klein and Hartmann 1993, *J Clim*

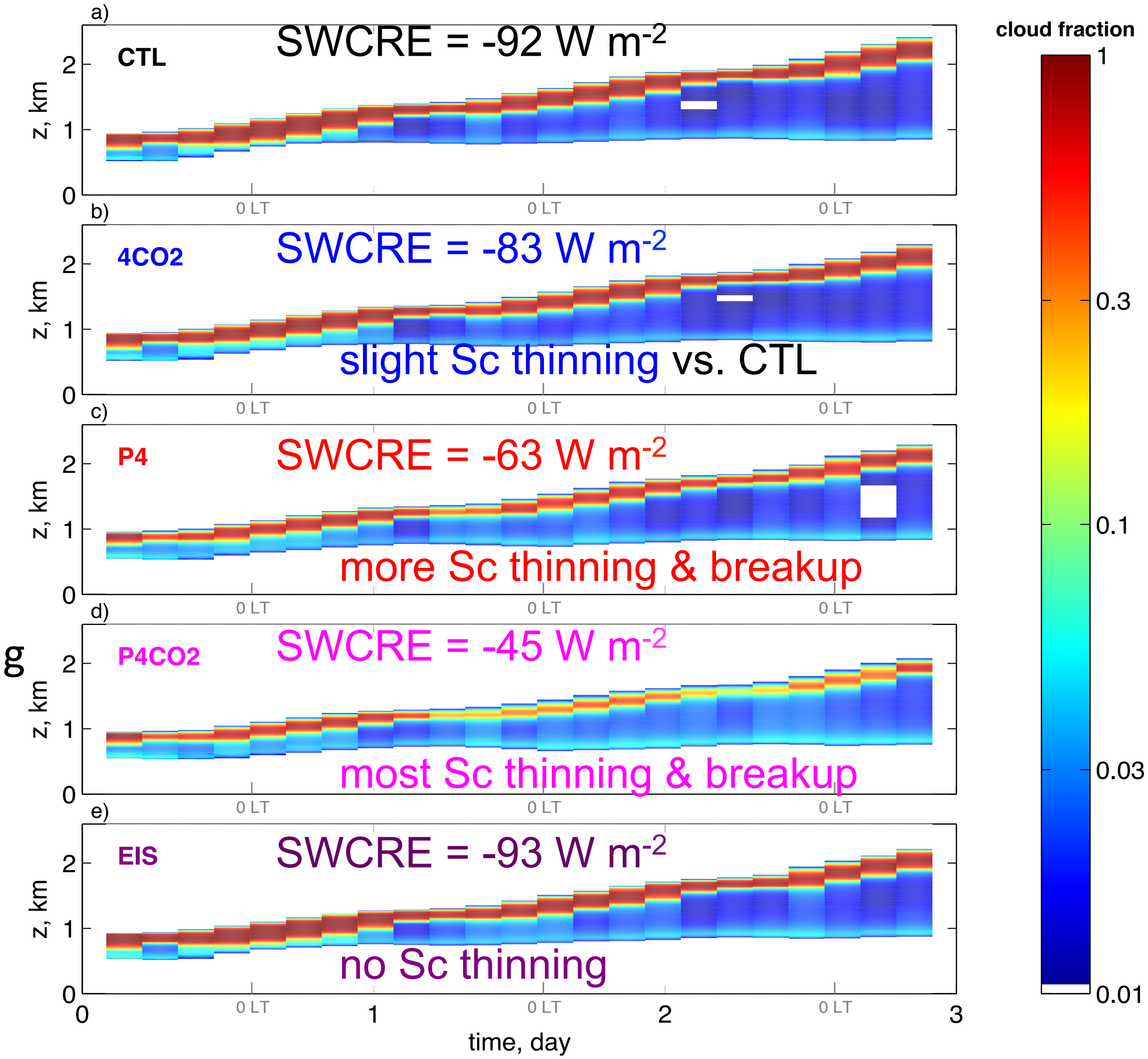
GASS Lagrangian case

(Bretherton and Blossey 2014)

$\Delta x = \Delta y$ = 35 m, Δz = 5 m,
4.5x4.5 km doubly-periodic
diurnal insolation
N_d = 100 cm^{-3}

Entrainment liquid flux feedback
Mechansim for thermo Sc thinning



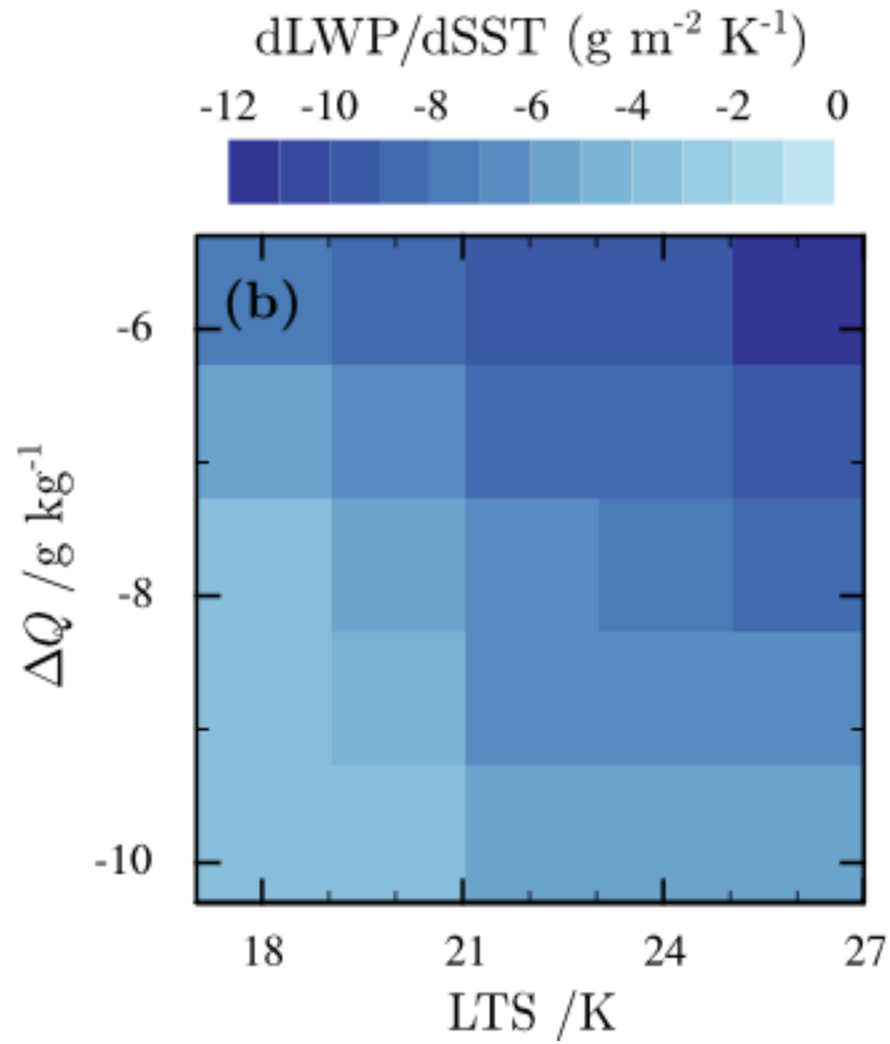


- Like CGILS, Sc cloud thins in 4CO2, more in P4, most in P4 4x.
- dEIS simulation recovers CTL cloud due to stronger inversion.

dSc/dSST across inversion jump phase space

Dussen et al. 2015 JAMES

- Idealized steady Sc BLs with different inversion jumps.
- Apply 2 K ΔSST w fixed RH+
- All cases show Sc thinning, consistent with CGILS thermodynamic mechanism



Rieck et al. (2012 JAS)

- Idealized nonprecipitating BOMEX trade Cu.
- Slight cloud cover decrease with warming; more pen. entrainment

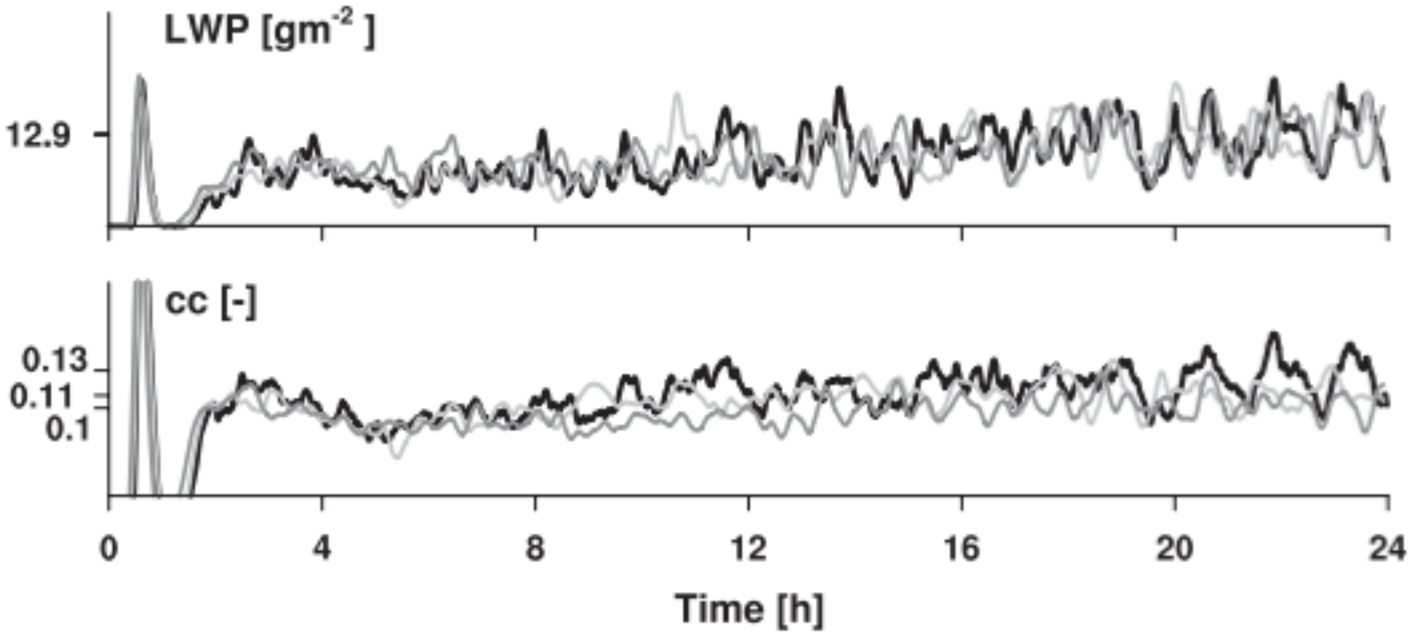


FIG. 5. Temporal evolution of the (top) liquid water path and (bottom) cloud cover for the control (black), $^{+}$2 K (dark gray), and $^{+}$8 K (light gray) simulations. The ordinate displays an average value for the final 4 h of each simulation.

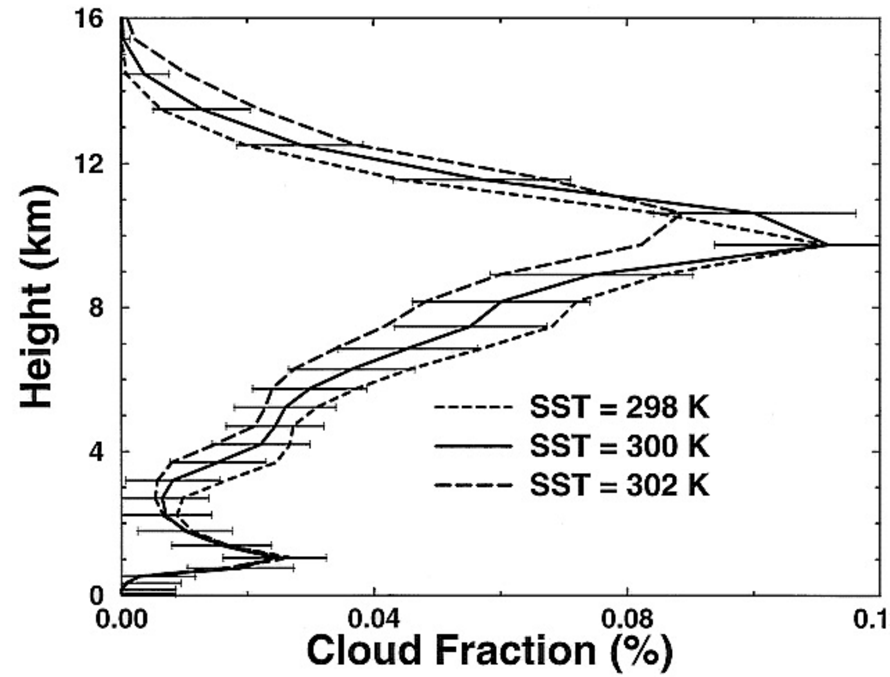
How about deep convective response to ΔSST in CRMs?

Limited-area simulations of radiative-convective equilibrium (Tompkins and Craig 1999 *JClim*)

RCE for SST = 298, 300, 302 K; 45 days, 60 x 60 km x 21 km, Δx = 2 km, L35.

Clouds rise following isotherms in a warmer climate with very slight reduction in horizontal extent.

Kuang and Hartmann (2007, *J Clim*) found similar results (FAT ➔ positive cloud height feedback)



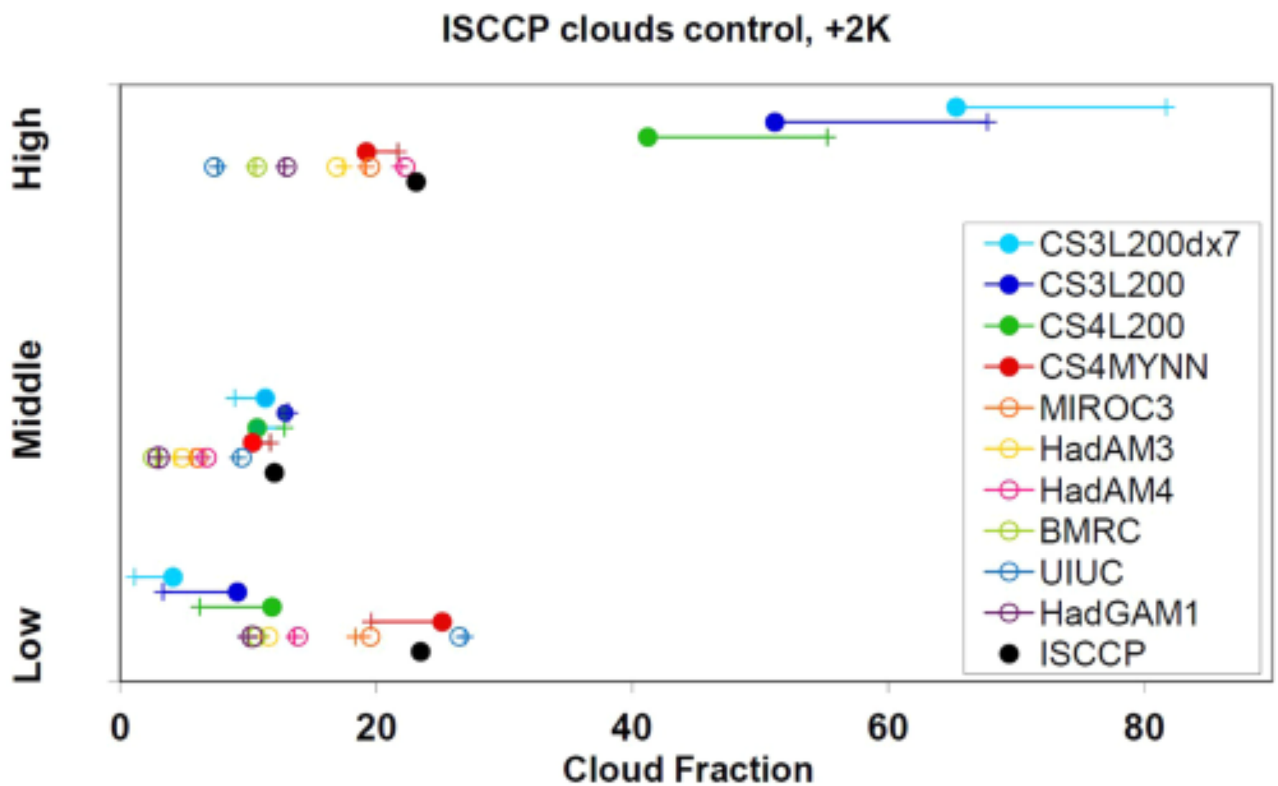
The main conclusion of the paper is that, despite significant temperature sensitivities in many of the conversion terms between bulk water categories, convection is very insensitive to changing SST in the absence of large-scale flow. This is a result of the moist adiabatic temperature profile that the tropical atmosphere is constrained to take. A parcel of air rising through a deep convective cloud experiences approximately the same range of temperatures but at higher altitudes as SST increases. Thus the vertical profiles of cloud fraction and other cloud-related statistics are simply shifted in height, but not changed in overall magnitude.

The small changes in cloud properties that do occur lead to a small reduction in cloud fraction as SST increases (Tompkins and Craig 1999)

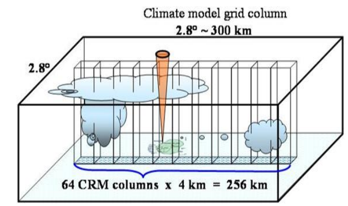
NICAM global cloud-resolving model

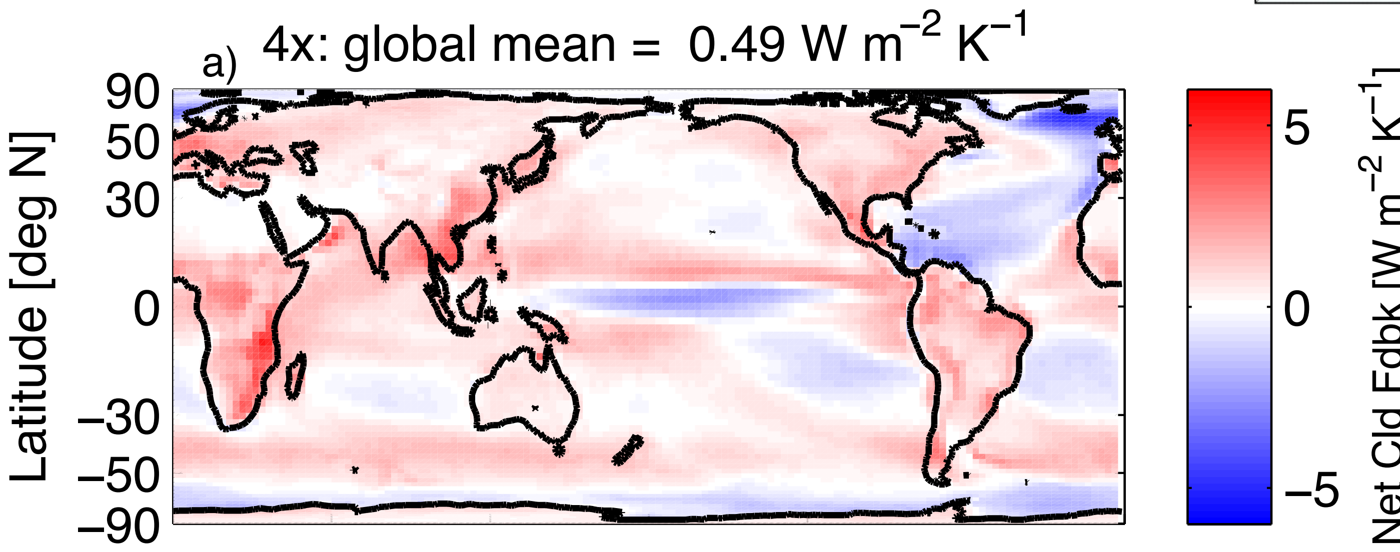
(Tsushima et al. 2014 *JAMES*)

- Δx = 14 km for 90 days/Δx = 7 km for 30 days; 40 vertical levels.
- With specified SST increase, large tropical cirrus increase
  ➔ strong positive longwave cloud feedback,
- Results are sensitive to subgrid turbulence parameterization (MYNN), snow fall speed, Δx ➔ uncertainties in GCRM, too!



SP-CCSM4 superparameterized climate model

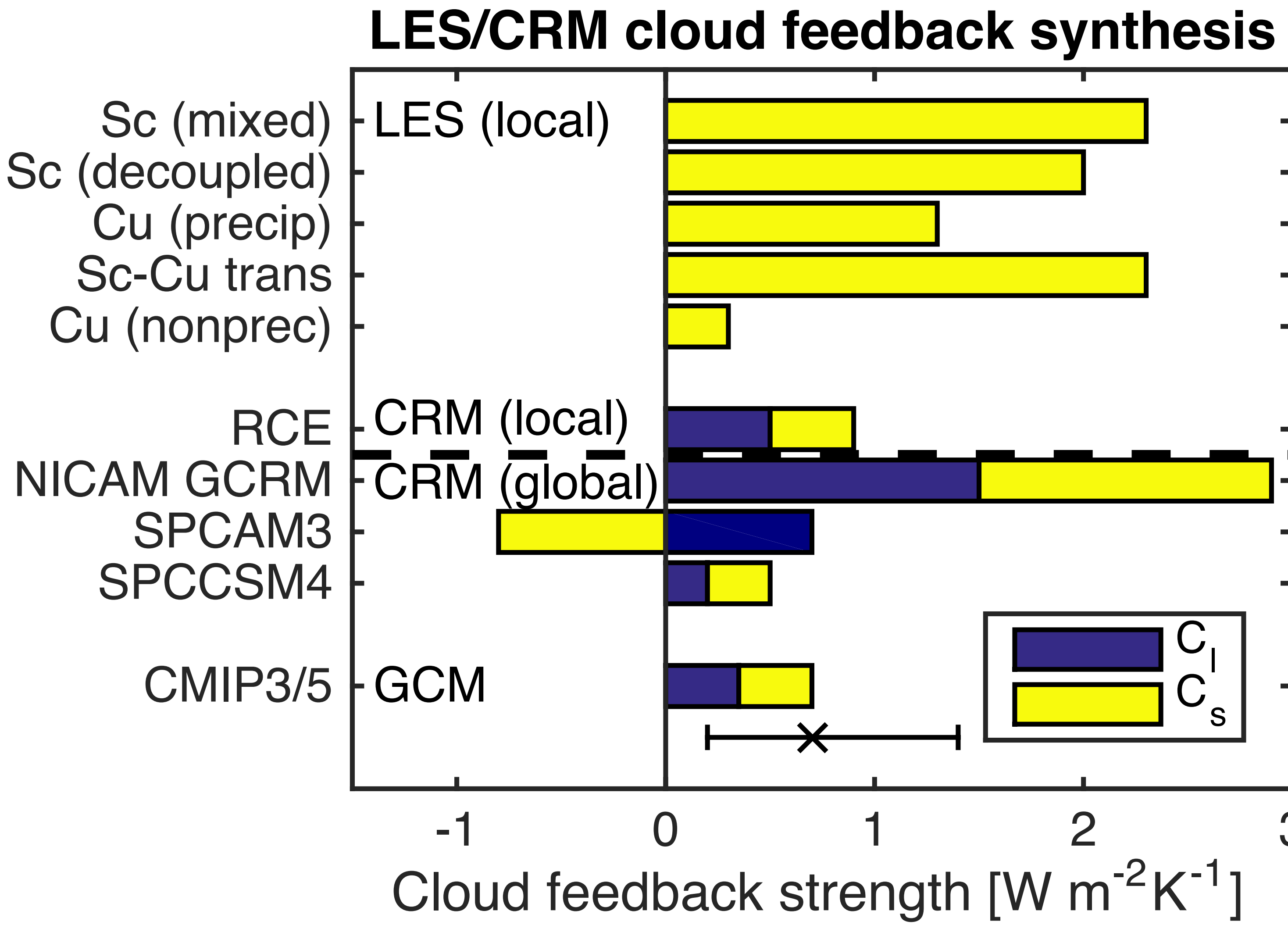




- Abrupt 4xCO_2: ECS of 2.8 K and global cld feedback in CMIP5 range
- Positive SW feedback mainly due to low cloud decrease over land
- Low-lat marine subtropical Sc feedback slightly negative (opposite of LES! – under-resolution?)

Bretherton et al. 2014 *JAMES*

Comparison of GCM and hi-res cloud feedbacks



Synthesis: LES and CRM of cloud response to climate change

- Do LES support the GCM consensus of less subtropical marine low cloud in a greenhouse-warmed climate? Yes
- Do they provide a physical explanation for this? Yes (thermodynamic and radiative mechanisms, but competing with ΔEIS, Δw)
- Limited-area and global CRMs suggest that deep convection has a positive cloud height feedback, show no evidence for an iris effect, and show insensitivity of associated shallow Cu to SST.
- These results support the GCM consensus of positive low-latitude cloud feedbacks on climate change.
- However, high-resolution models have not yet constrained the CMIP5 GCM-simulated range of global cloud feedbacks.