Cloud Response to Climate Change in SP-CAM

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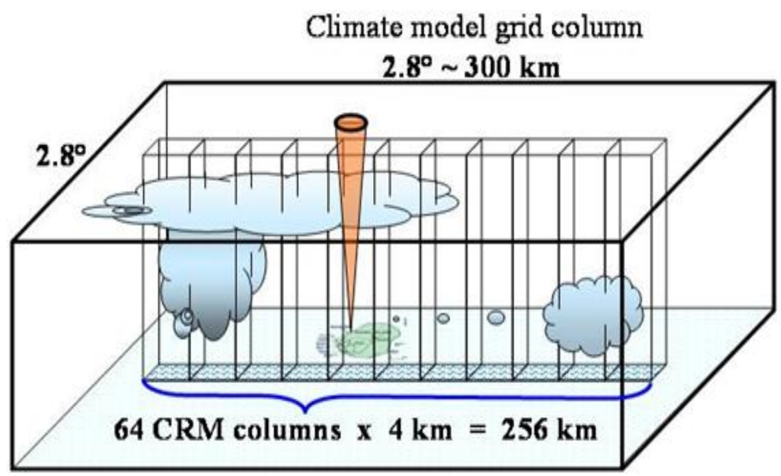
Photo courtesy Rob Wood

SP-CAM cloud response studies

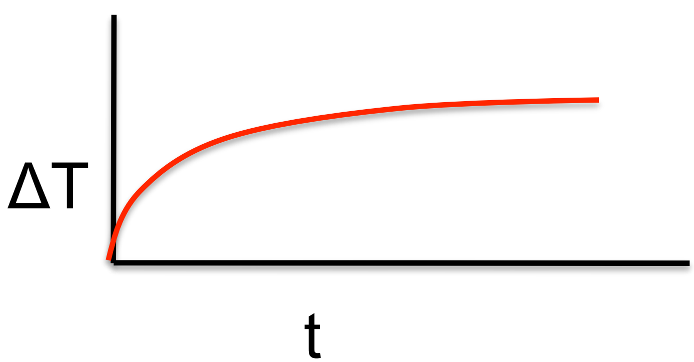
Dauntingly expensive to run fully coupled SP-CAM realistically forced by time-varying anthropogenic greenhouse gases and aerosol emissions.

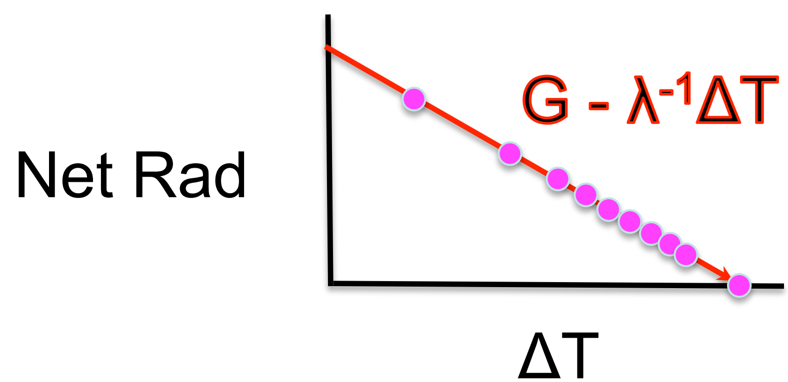
Wang et al. 2011 (aerosol effects in PNNL-MMF) and Cristiana's new 4xCO_2 study are good first cut toward this.



Traditional AGCM feedback assessment

1. Run AGCM to equilibrium over climatological SSTs
2. Calculate implied net energy flux (Qflux) into the ocean
3. Construct a slab ocean model with this Qflux and climatological ocean mixed layer depth
4. Suddenly double CO_2 (radiative forcing G) and run AGCM+SOM to equilibrium (20-50 yrs). Mean surface air temperature increase ΔT_{eq} is the climate sensitivity
5. Feedback analysis used to understand ΔT_{eq} in terms of radiative effects of changes in T, q, snow, clds…





Some wrinkles

- 10-20 year run needed (longish for SP-CAM)
- Notion of ‘cloud feedback’ problematic

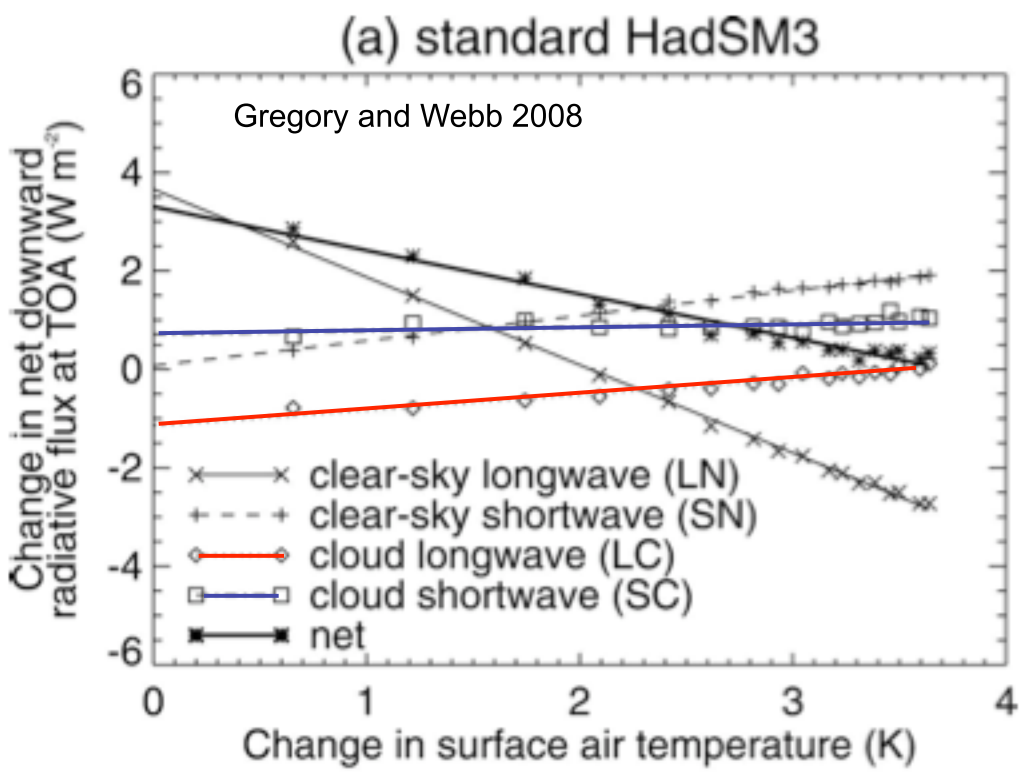
Climate feedbacks usually understood as being on global mean surface temperature $\langle T_s \rangle$

Clouds can respond to a CO_2 change even $\langle T_s \rangle$ does not change through radiative and circulation changes.

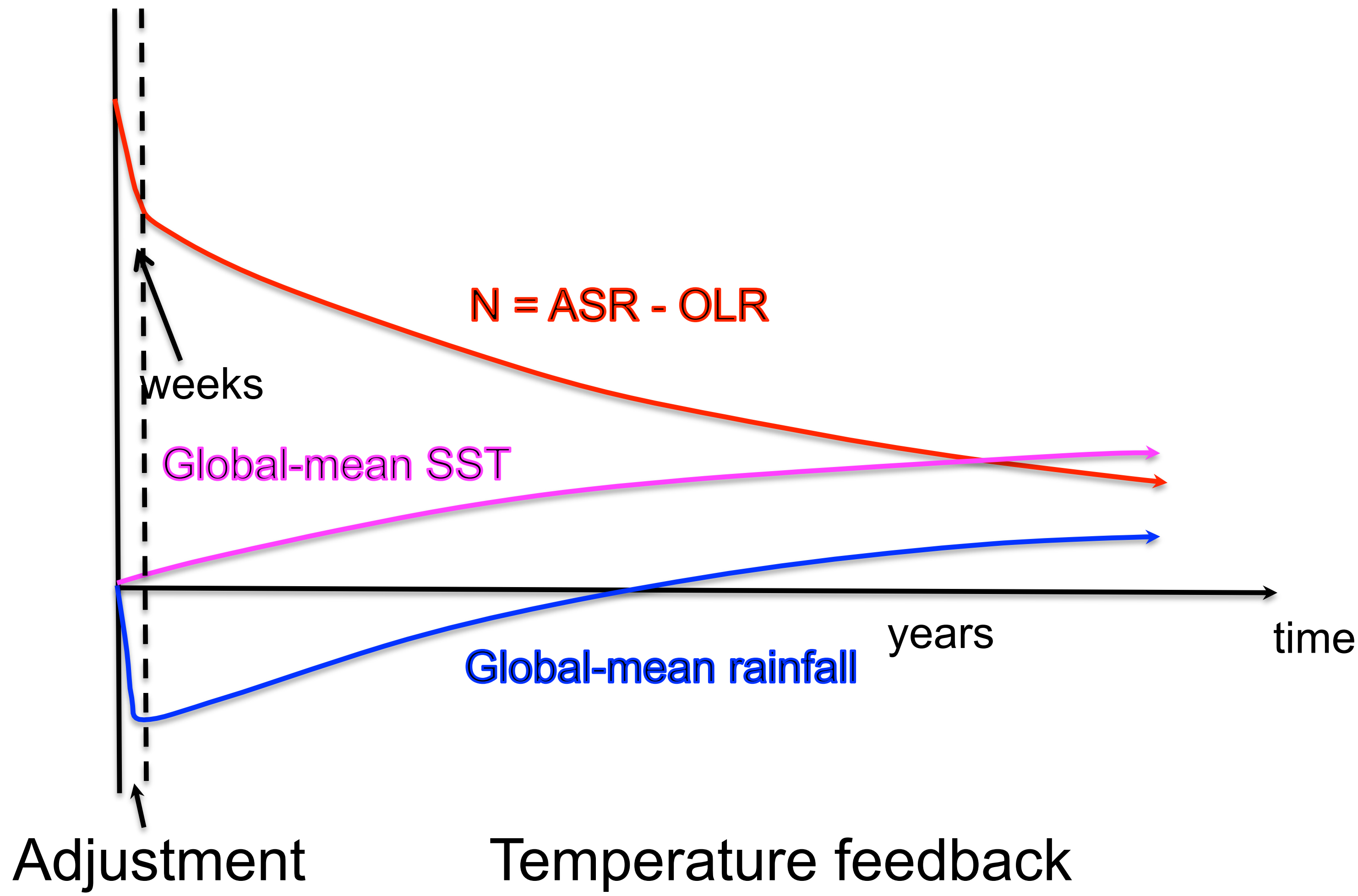
Thus cloud response to a step CO_2 change combines a ‘fast’ adjustment and a slow ‘T-mediated’ adjustment which had different physical mechanisms (Gregory and Webb 2008).

Fast response of clouds to radiative changes

- Transient behavior of coupled GCM runs in which CO_2 is suddenly doubled shows a quick response of the clouds *before* the climate warms which explains some of the ultimate $2xCO_2$ cloud feedback.
- Quick increase in SWCF (less cloud) after $2xCO_2$.



Adjustment cartoon



Cloud adjustment to step 2xCO_2 is significant

Table 1. Semi-Direct Forcing Components Induced by 2 × CO_2 for Various Slab Ocean GCMs[a] in units of Wm^{-2}

	Clear-Sky LW (F_{LN})	Clear-Sky SW (F_{SN})	Cloud LW (F_{LC})	Cloud SW (F_{SC})	Net (F)
CCSM3.0	−0.28 ± 0.15	0.02 ± 0.28	−0.39 ± 0.12	−0.13 ± 0.14	−0.78 ± 0.34
CGCM3.1(T47)	0.45 ± 0.23	−0.17 ± 0.33	−0.16 ± 0.14	0.86 ± 0.19	0.98 ± 0.54
CGCM3.1(T63)	0.46 ± 0.23	0.02 ± 0.25	−0.22 ± 0.16	1.04 ± 0.43	1.30 ± 0.66
GISS-ER	–	–	–	–	0.01 ± 0.42
MIROC3.2(medres)	−0.57 ± 0.27	0.13 ± 0.24	−0.11 ± 0.09	1.02 ± 0.41	0.47 ± 0.69
MRI-CGCM2.3.2	−0.15 ± 0.36	−0.42 ± 0.25	−0.26 ± 0.17	0.54 ± 0.32	−0.29 ± 0.55
UKMO-HadGEM1	−0.62 ± 0.34	−0.39 ± 0.32	−0.24 ± 0.19	0.57 ± 0.30	−0.67 ± 0.69
Ensemble	−0.12 ± 0.48	−0.14 ± 0.23	−0.23 ± 0.10	0.65 ± 0.44	0.15 ± 0.80

(Andrews and Forster 2008)

Suggests quick decrease in both low and (to lesser extent) high cloud. Fast adjustments are about 20% of equilibrated cloud response to 2xCO_2.

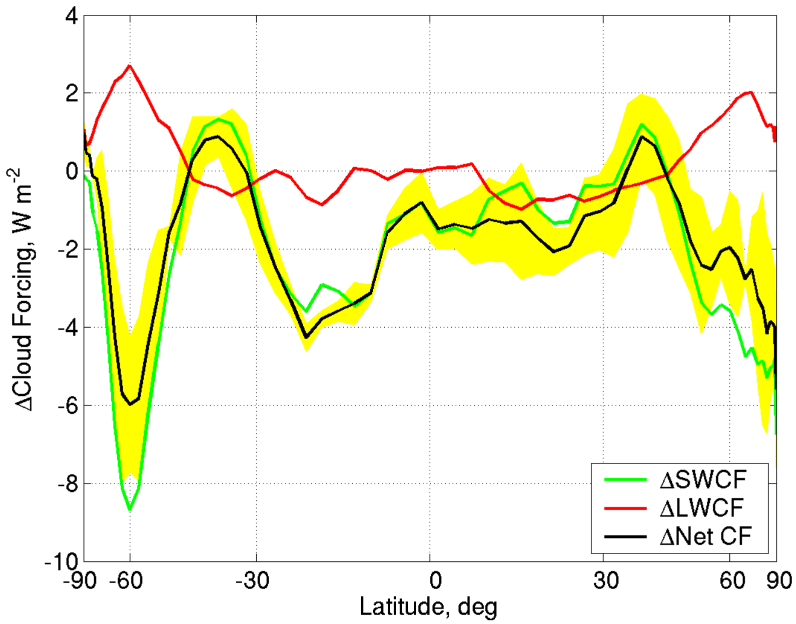
Geographical pattern of fast cloud adjustment is fairly complex and model-dependent, like for T-mediated cloud change.

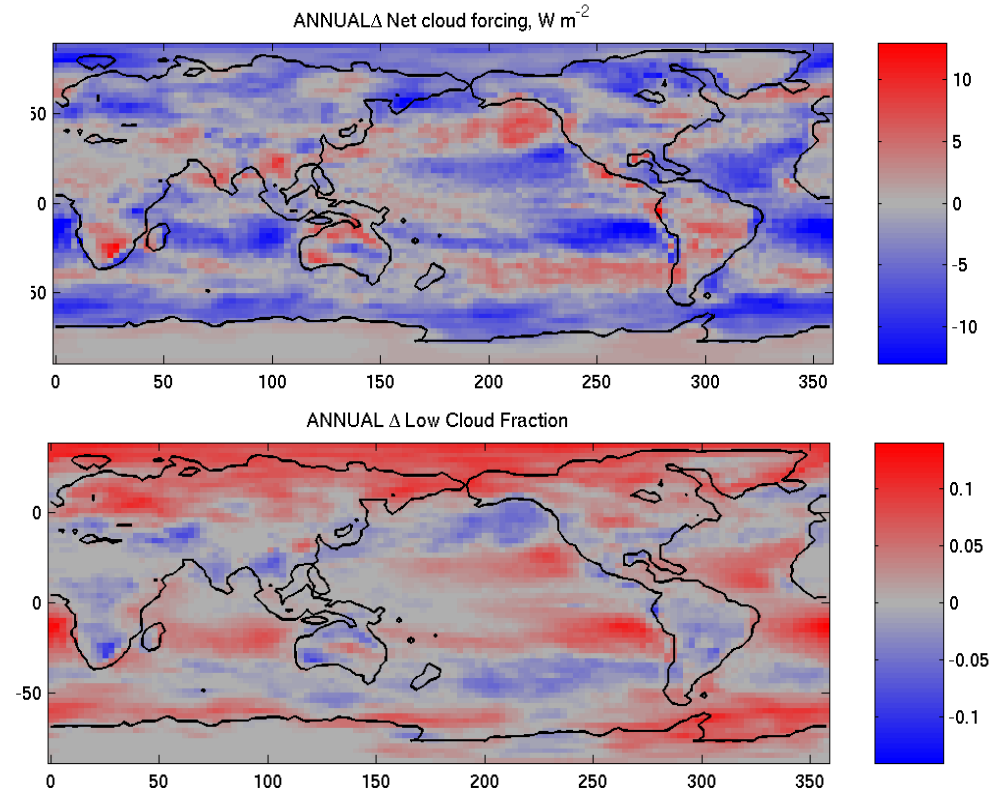
Cloud response work at UW

We have separately analyzed SP-CAM fast and T-mediated adjustment in shorter model runs of a few years. For comparison with Cristiana's work, I summarize this work:

- T-mediated cloud response
  - Uniform +2K SST increase (Wyant et al. 2006, 2009)
  - 0.5 yr spinup + 3 yr analysis period
- Fast cloud response
  - $4xCO_2$ with specified SST (Wyant et al. 2012)
  - 0.5 yr spinup + 2 yr analysis period
- CGILS column-cloud change cases with SP–SAM (new)

+2K cloud/CRF changes



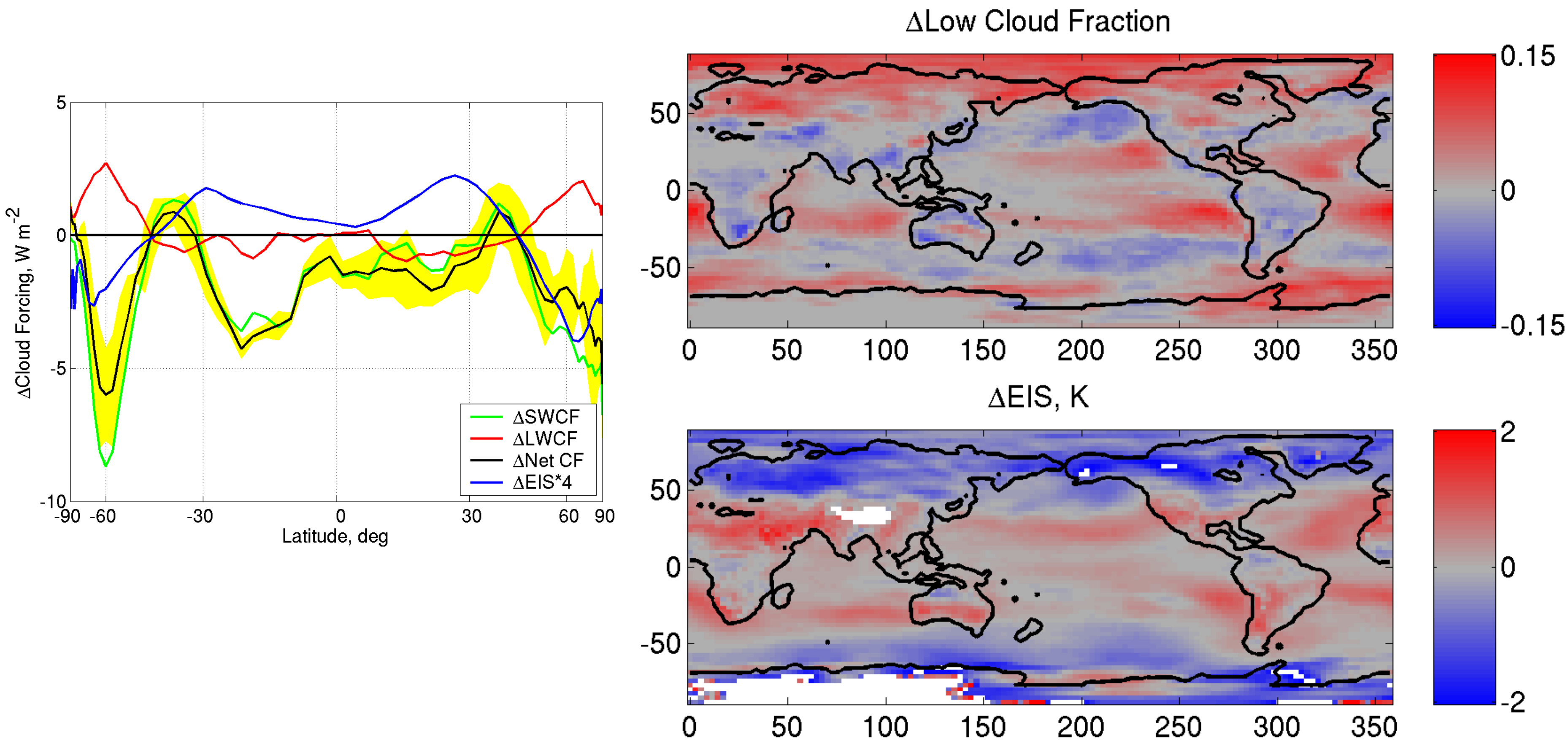


- SWCF trends dominate net ⇒ low cloud response.
- Low cloud increases: subtropics, summer polar.
- ΔSWCF = -1.0 [-0.1] W m^{-2} K^{-1} [ ] = masking correction

  ΔLWCF = 0.1 [+0.45] W m^{-2} K^{-1} (Soden et al. 2004)

  Net cloud radiative feedback = -0.55 W m^{-2} K^{-1} (negative!)

Patterns of CAM-SP +2K Δlowcld ∝ ΔEIS over oceans



- Cloud increase in subtropical margins due to broadening of warm tropical belt aloft (opposite response to most GCMs)
- Reduced low cloud over low-latitude land

SP-CAM 4xCO_2 but fixed SST

Table 1: Tropical means for the control simulation and changes due to the 4xCO_2 perturbation. (*Note: for ω_{500}, the percentage change is normalized with the tropical-mean absolute value of the control ω_{500}.)

	Control			Δ_{4xCO_2}			
	Ocean	Land	Total	Ocean	Land	Total	Total %
ω_{500}	0.93	-1.98	0.20	0.71	-2.98	-0.22	* -0.8
Low Cloud Fraction	0.303	0.154	0.265	-0.0011	0.0056	0.0006	0.2
Middle Cloud Fraction	0.060	0.095	0.069	-0.0032	0.0057	-0.0010	-1.4
High Cloud Fraction	0.173	0.168	0.172	-0.0042	0.0203	0.0020	1.2
Total Cloud Fraction	0.433	0.310	0.402	-0.0038	0.0184	0.0018	0.4
LWP (g m^{-2})	82.3	64.3	77.8	-2.9	3.9	-1.2	-1.6
IWP (g m^{-2})	24.7	25.5	24.9	-0.8	3.1	0.1	0.6
Rainfall (mm day^{-1})	3.61	2.39	3.30	-0.25	0.25	-0.13	-3.8
LH Flux (W m^{-2})	135.1	46.1	112.7	-5.8	1.5	-3.9	-3.5
SH Flux (W m^{-2})	13.9	58.8	25.2	-1.0	0.0	-0.7	-3.0
SWCF (W m^{-2})	-63.9	-44.3	-59.0	1.3	-2.5	0.3	0.6 (0.4)
LWCF (W m^{-2})	30.8	28.1	30.1	-2.2	1.5	-1.2	-4.1 (-0.5)
Net LW up TOA (W m^{-2})	253.6	257.4	254.6	-7.0	-10.9	-8.0	-3.1
Net LW up Surf.(W m^{-2})	53.5	81.8	60.6	-2.7	-5.3	-3.3	-5.5

Over land: More rain, clouds, ascent

Over ocean: Less rain, clouds, ascent

Over full tropics: Less atmos. radiative cooling, less cld, no net cloud feedback.

SST fixed, but land heats up due to enhanced greenhouse effect

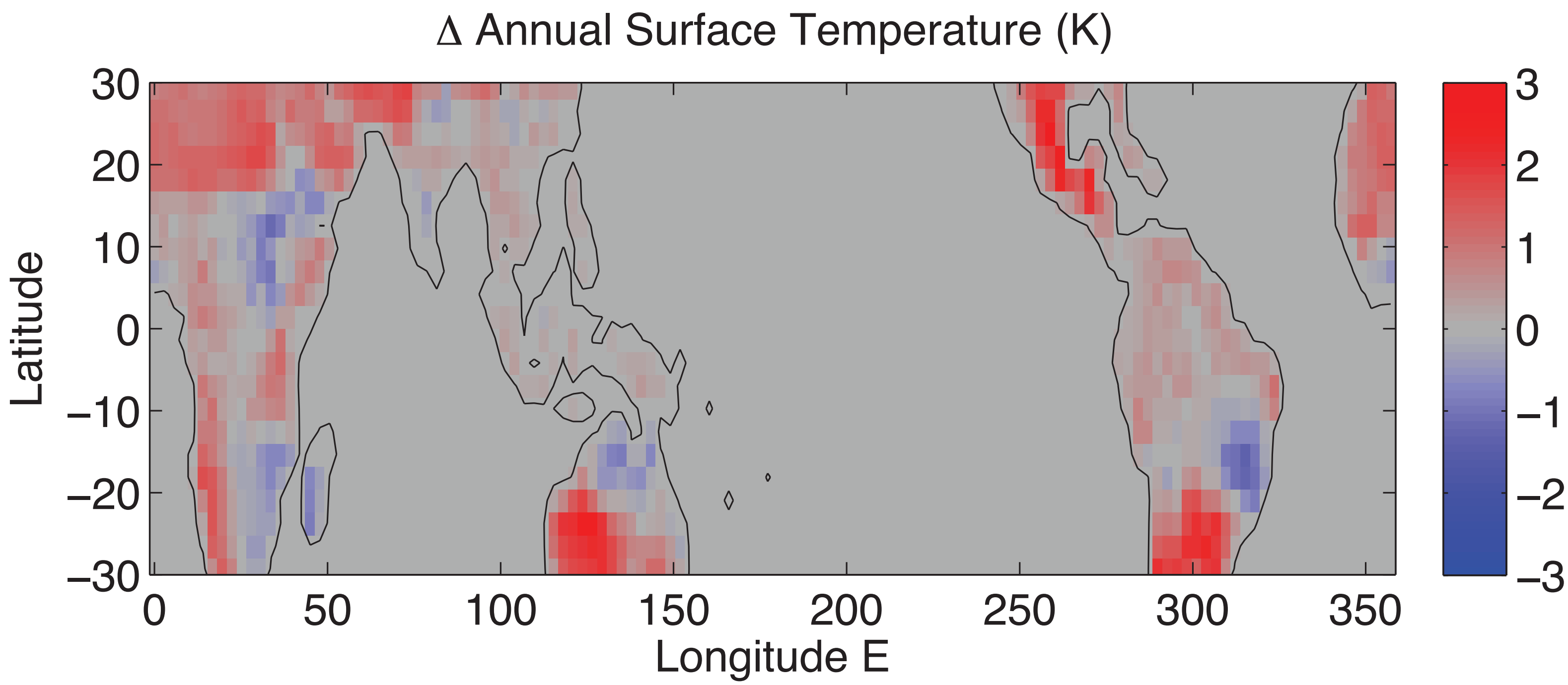
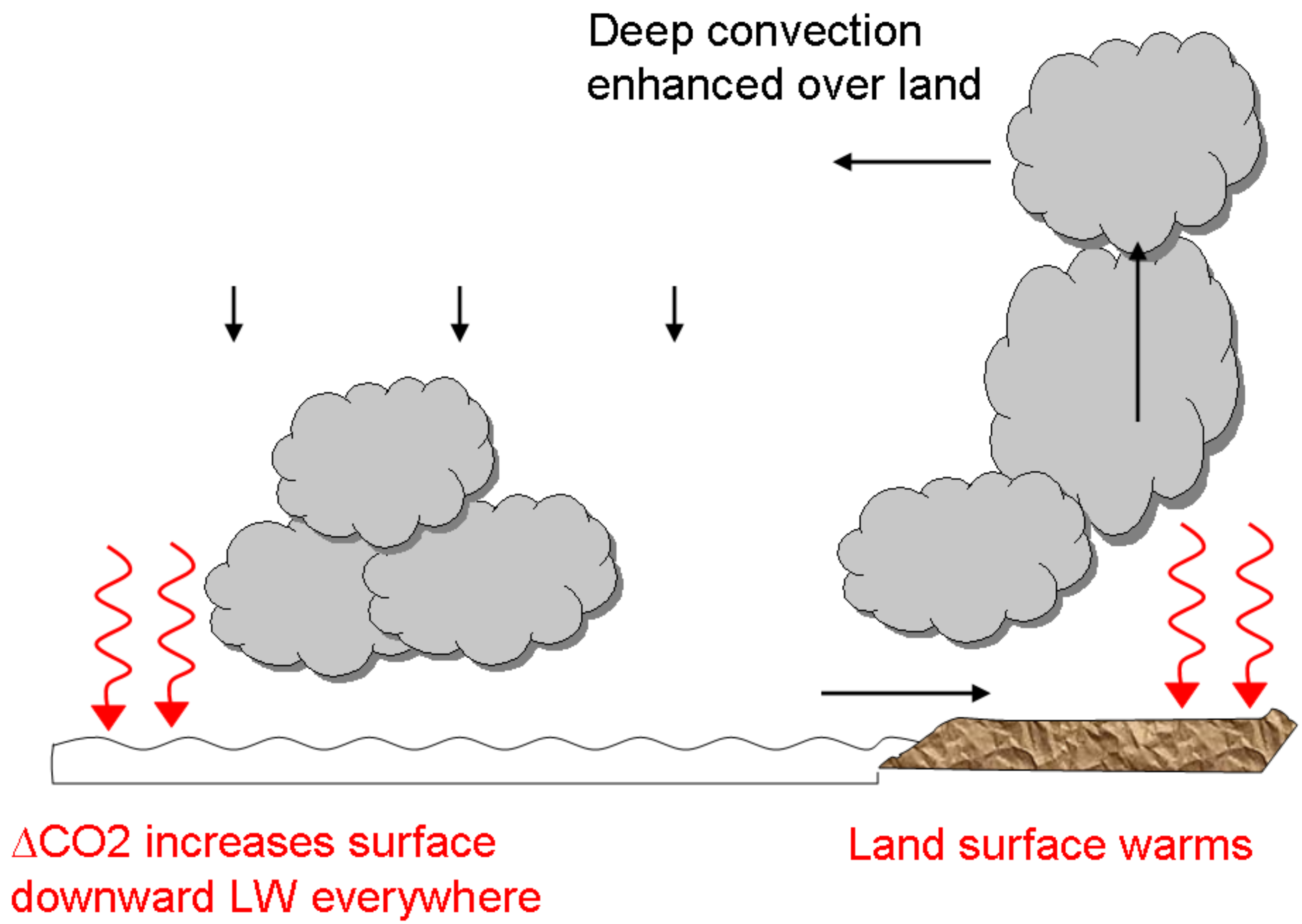
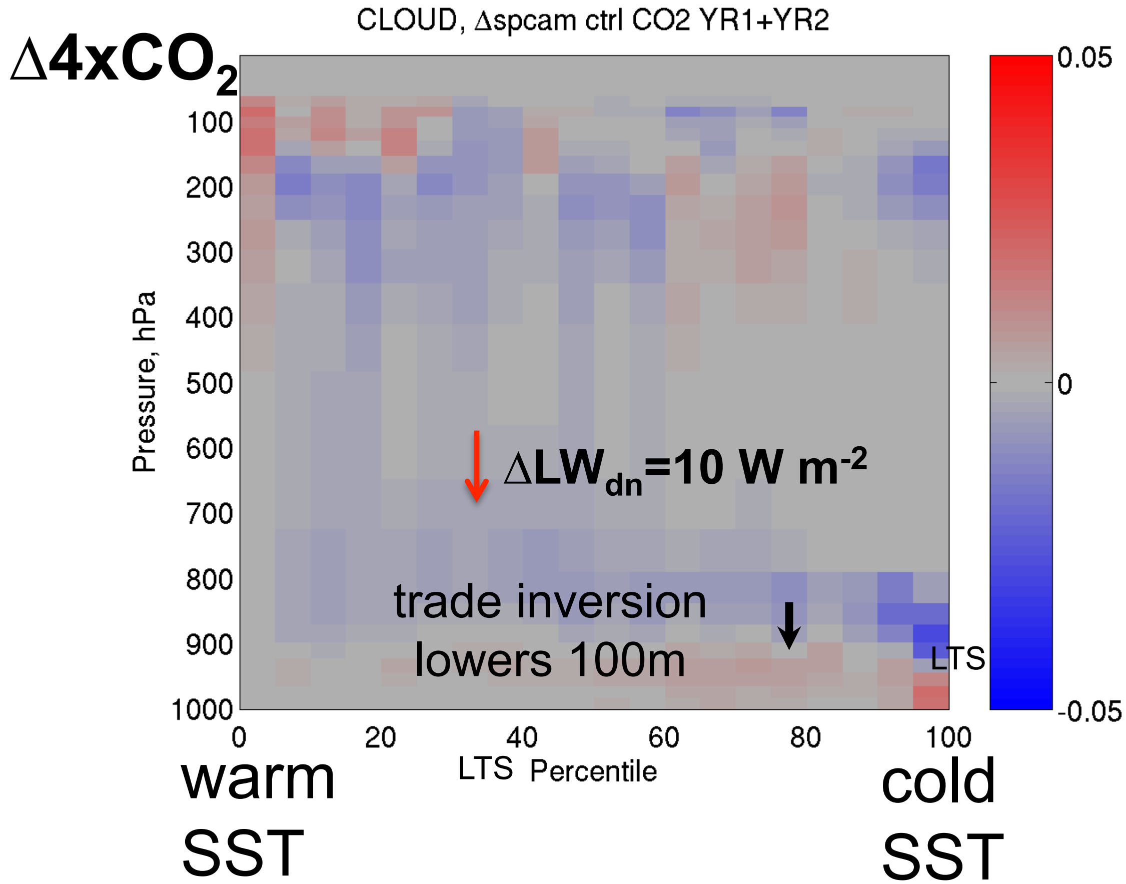


Figure 1: Annual mean change in surface temperature for SP-CAM due to $4xCO_2$.


Deep convection
enhanced over land
ΔCO2 increases surface
downward LW everywhere
Land surface warms

4xCO_2 fixed SST experiment with SP-CAM



4xCO_2 ➔ ~10 W m^{-2} more LW_{dn} at low cloud top.

➔ Less PBL radiative destabilization

➔ Warmer free overlying free troposphere

➔ Less entrainment

➔ Shallower inversion

SP-CAM cloud response synopsis

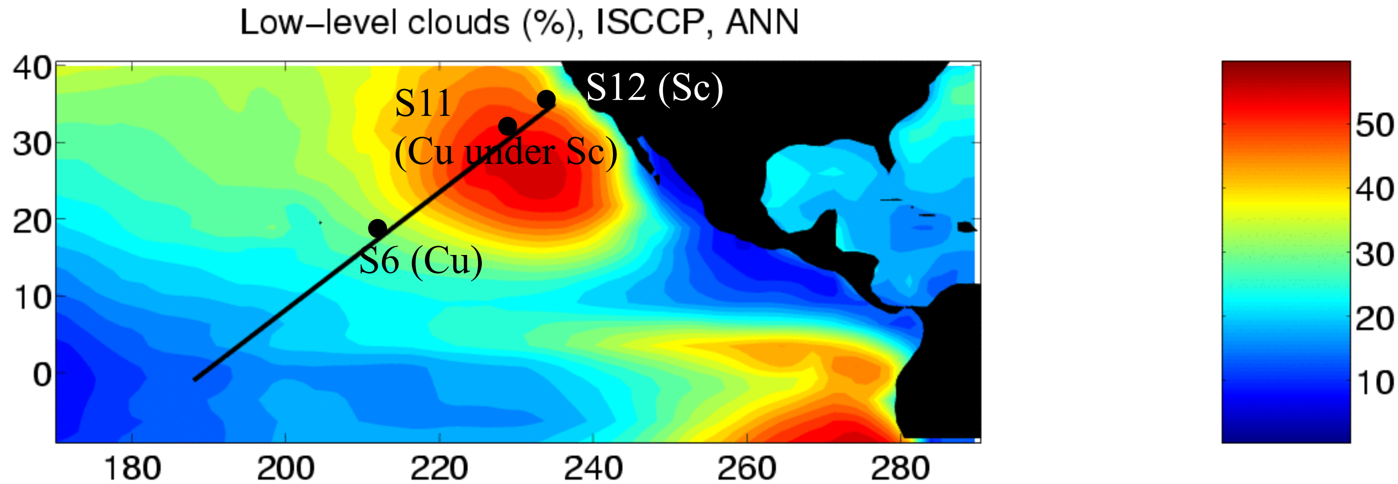
Fast adjustment:

- Shift of cloud, ascent from ocean to land
- Lower marine subtropical trade inversion

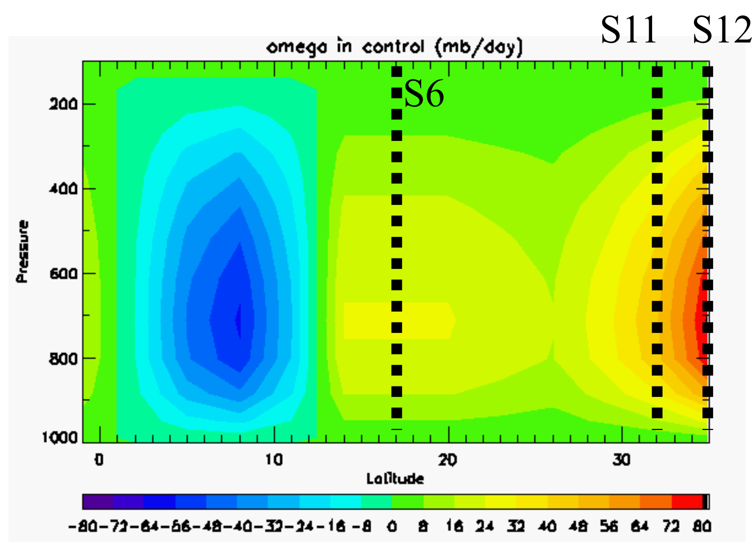
T-mediated:

- Subtropical and polar low cloud increase
- Negative global cloud feedback unlike CMIP3 GCMs

CGILS: CFMIP/GCSS Intercomparison of Large-eddy and Single-column models



- Focuses on three points along the GCSS Pacific Cross-section.
- Points range from shallow, well-mixed boundary layer near coast to deeper trade cumulus boundary layer well offshore.



$$\omega(p,lat) = \Omega(lat)\,\omega_0(p)$$

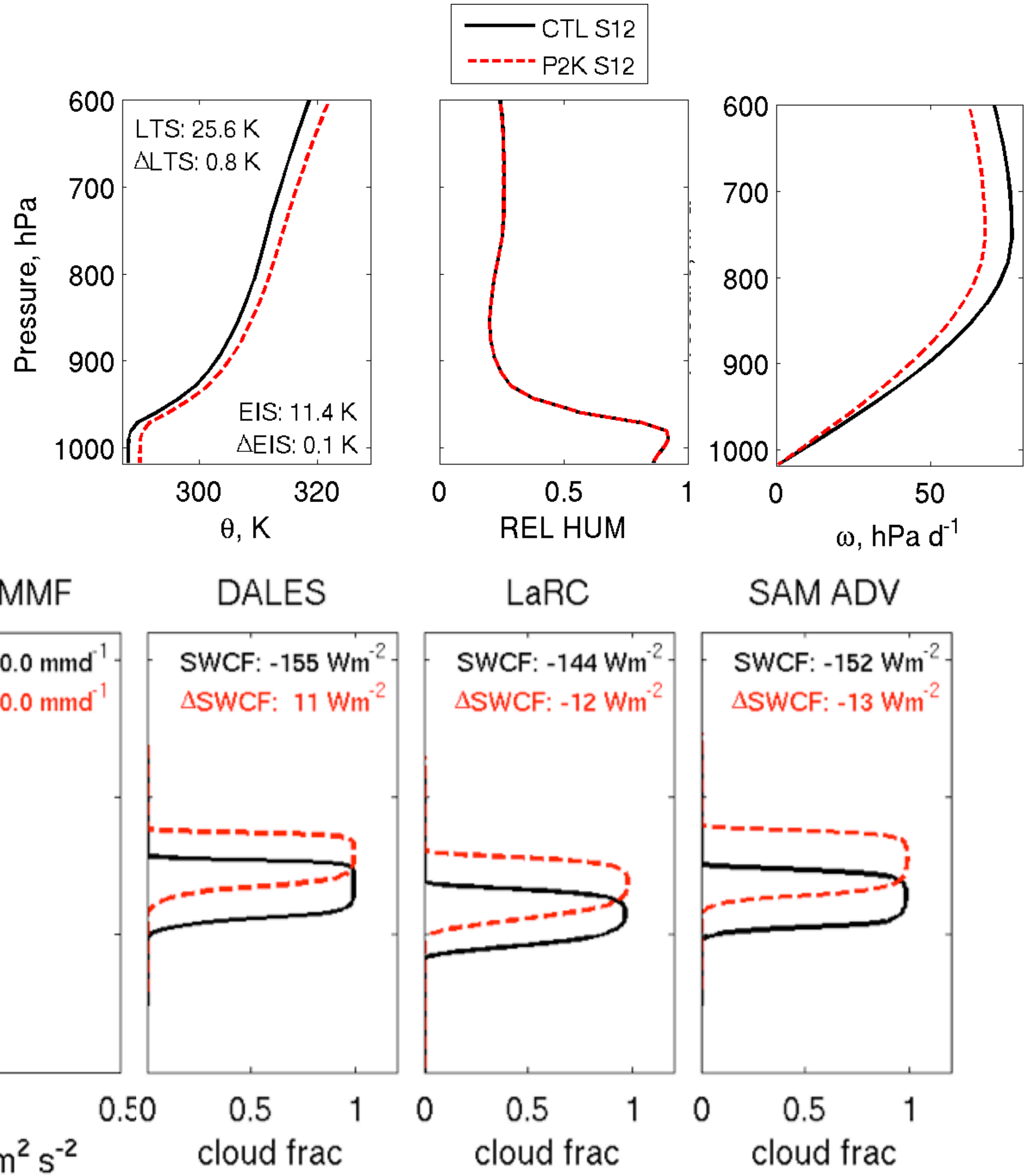
S12: Coastal SCu

LES Δx = 25m

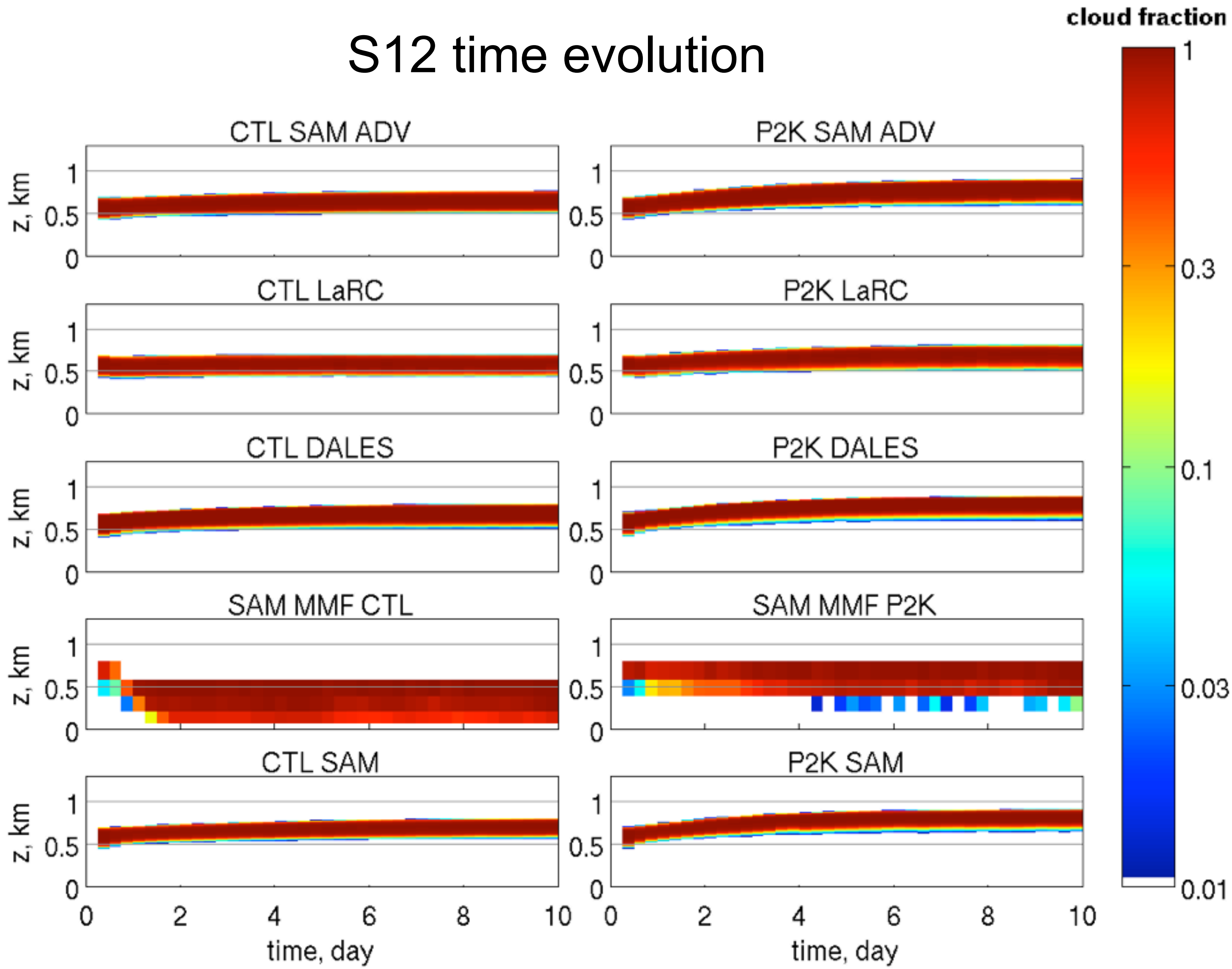
Δz = 5-15m

SPSAM Δx = 4000 m

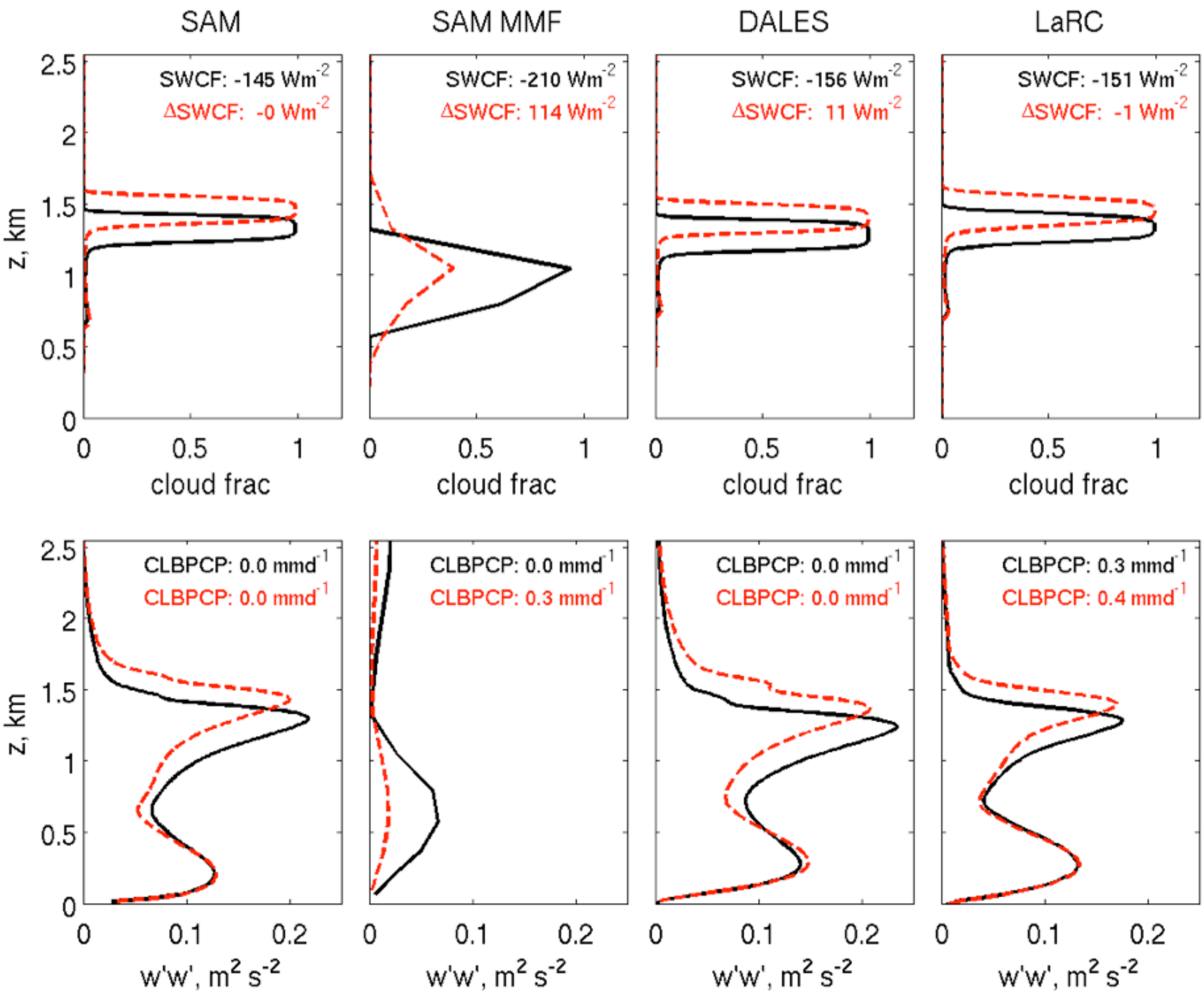
Δz ~ 200 m



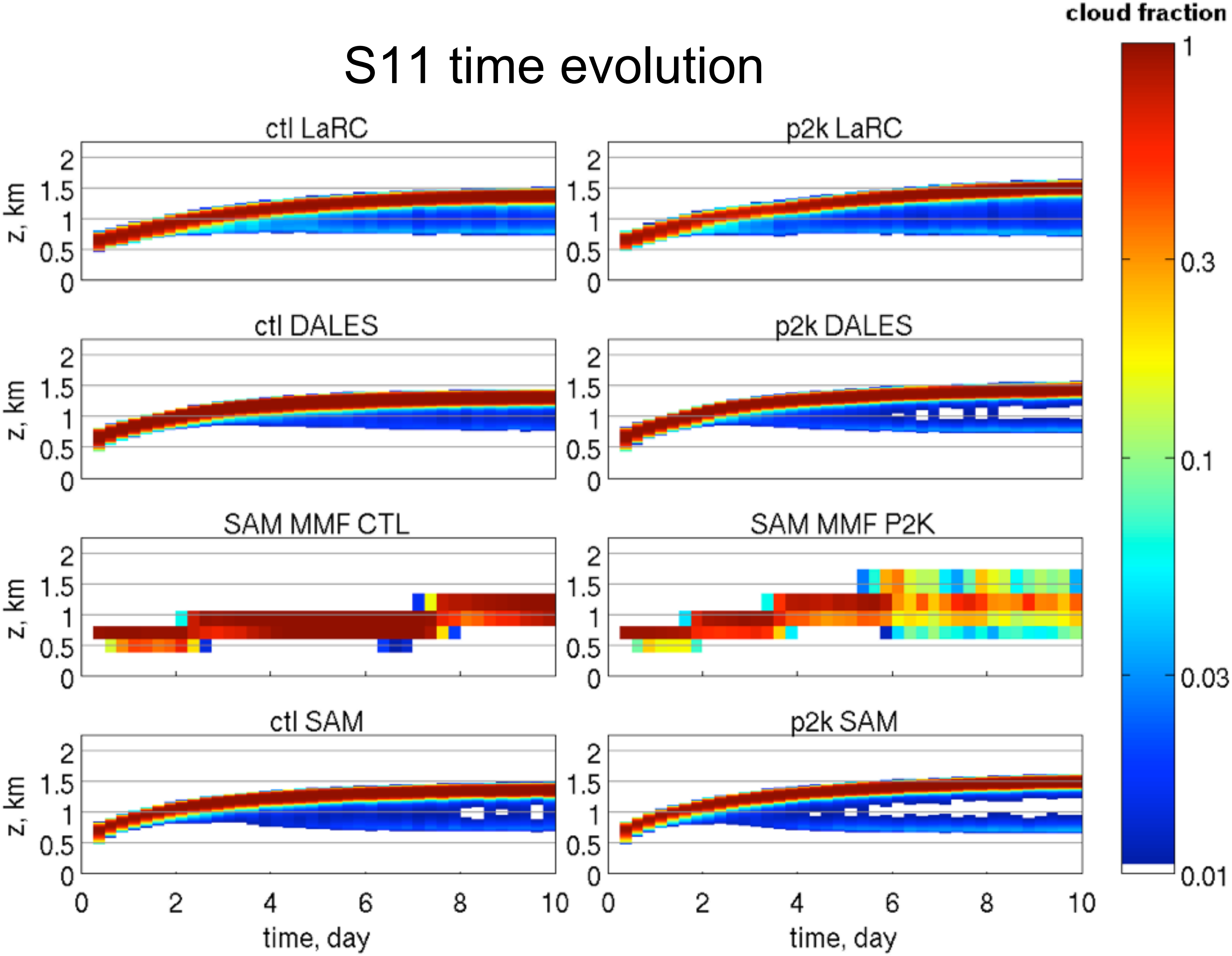
S12 time evolution



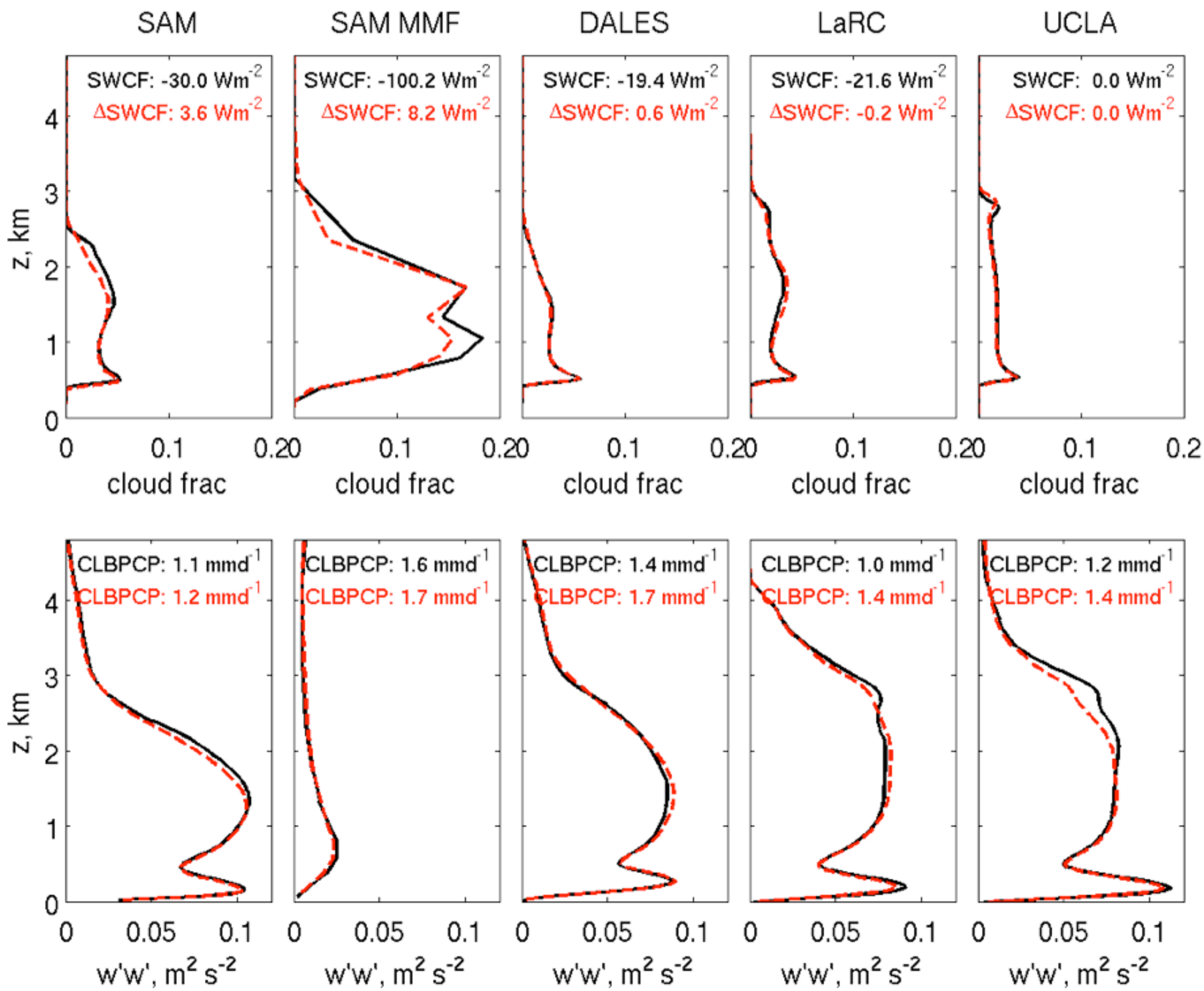
S11: Decoupled Sc



S11 time evolution

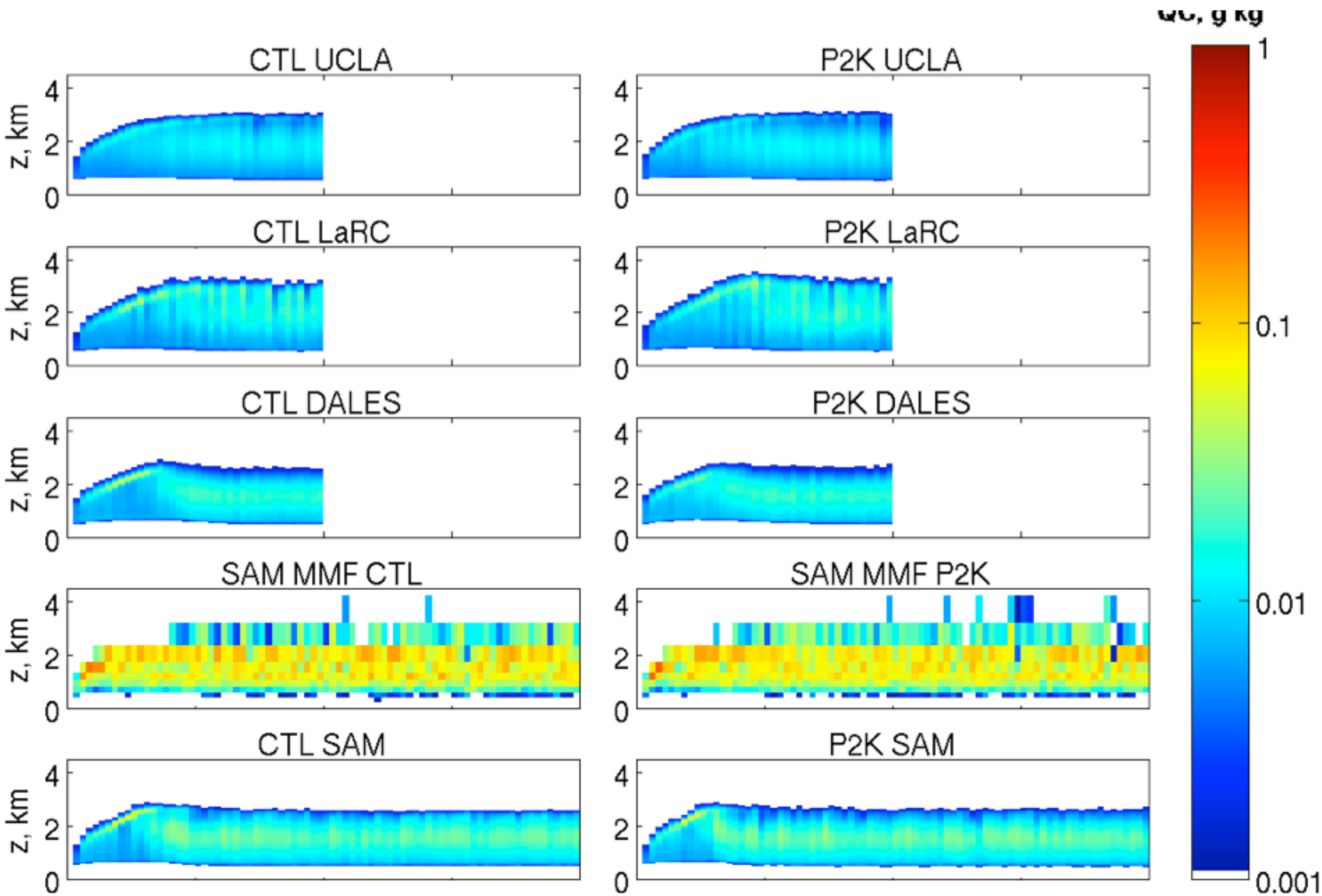


S6: Trade Cu



SAM
SAM MMF
DALES
LaRC
UCLA
SWCF: -30.0 Wm-2
ΔSWCF: 3.6 Wm-2
SWCF: -100.2 Wm-2
ΔSWCF: 8.2 Wm-2
SWCF: -19.4 Wm-2
ΔSWCF: 0.6 Wm-2
SWCF: -21.6 Wm-2
ΔSWCF: -0.2 Wm-2
SWCF: 0.0 Wm-2
ΔSWCF: 0.0 Wm-2
z, km
cloud frac
CLBPCP: 1.1 mmd-1
CLBPCP: 1.2 mmd-1
CLBPCP: 1.6 mmd-1
CLBPCP: 1.7 mmd-1
CLBPCP: 1.4 mmd-1
CLBPCP: 1.7 mmd-1
CLBPCP: 1.0 mmd-1
CLBPCP: 1.4 mmd-1
CLBPCP: 1.2 mmd-1
CLBPCP: 1.4 mmd-1
w'w', m2 s-2

S6 time evolution



Synopsis of CGILS tests

- SP-SAM captures basic character of cloud in all 3 cases
- Too much cloud in all three cases
- +2K sensitivity tests affected by grid-locking in SP-SAM and suggest positive low cloud feedback, unlike full model run!
- As Kuan-Man, Anning, my group and others have noted, vertical velocity variance is not resolved in SP-SAM.
- An SP-SAM with a better subgrid scheme (e.g. IPHOC) would probably perform better, at least for control case.