Sensitivity of Marine Boundary Layer Clouds to Idealized Climate Perturbations: The CGILS LES Intercomparison

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and CGILS LES Models and Modelers:

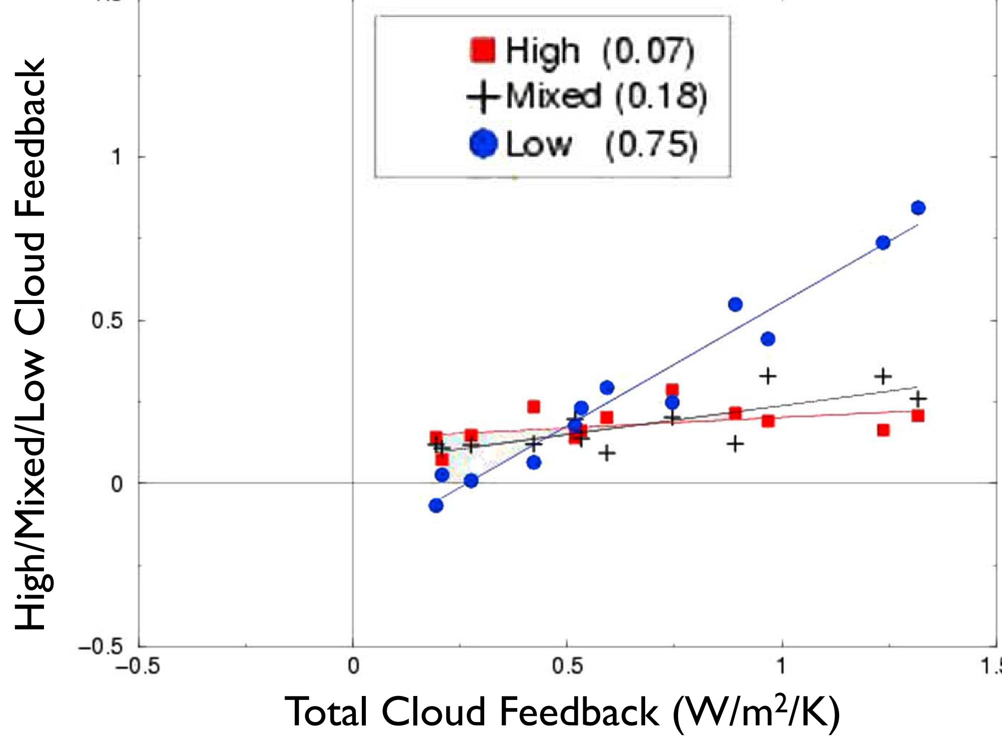
- MOLEM: Adrian Lock (UKMO),
- DALES: Stephan de Roode (Delft, the Netherlands),
- UCLA: Thijs Heus (MPIM),
- LaRC: Anning Cheng, Kuan-Man Xu (NASA LaRC, USA),
- WRF: Satoshi Endo, Yangang Liu (Brookhaven Natl Lab, USA)
- SAM: Peter Blossey (UW).

Thanks to NSF and CMMAP for support, to Marat Khairoutdinov for SAM.

Four manuscripts submitted (three to JAMES)

- M. Zhang and 39 co-authors, CGILS: First Results from an International Project to Understand the Physical Mechanisms of Low Cloud Feedbacks in General Circulation Models. *Bull. Amer. Meteorol. Soc*, Submitted 07/2012.
- M. Zhang, C. S. Bretherton, P. N. Blossey, S. Bony, F. Brient and J.-C. Golaz, The CGILS Experimental Design to Investigate Low Cloud Feedbacks in General Circulation Models by Using Single-Column and Large-Eddy Simulation Models. *J. Adv. Model. Earth Syst.*, Submitted 07/2012.
- P. N. Blossey, C. S. Bretherton, M. Zhang, A. Cheng, S. Endo, T. Heus, Y. Liu, A. Lock, S. R. de Roode and K.-M. Xu, Marine low cloud sensitivity to an idealized climate change: The CGILS LES Intercomparison. *J. Adv. Model. Earth Syst.*, Submitted 07/2012.
- C. S. Bretherton, P. N. Blossey and C. R. Jones, Mechanisms of marine low cloud sensitivity to idealized climate perturbations: A single-LES exploration extending the CGILS cases. *J. Adv. Model. Earth Syst.*, Submitted 07/2012.

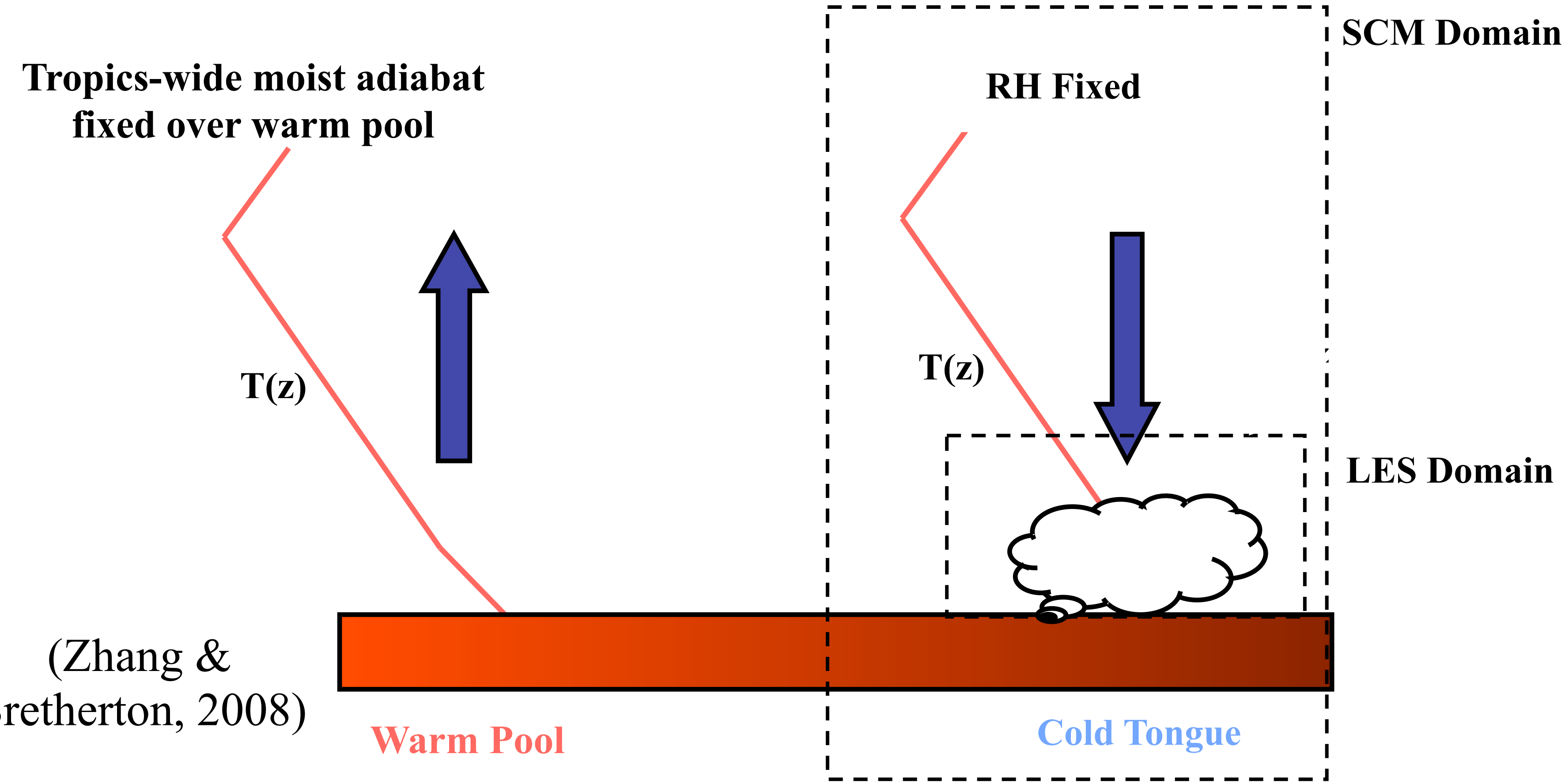
Motivation



Soden & Vecchi (2011)

- Clouds are largely subgrid-scale, parameterized features in models used for climate prediction.
- Cloud feedback is among the most uncertain components of climate sensitivity.
- Bony & Dufresne (2006): differences in tropical cloud response came mainly from shortwave in subsiding regions.
- Soden & Vecchi (2011): low cloud response largely responsible for scatter in total cloud feedback in CMIP3 models, global cloud feedbacks correlate well with those in low cloud transitions.

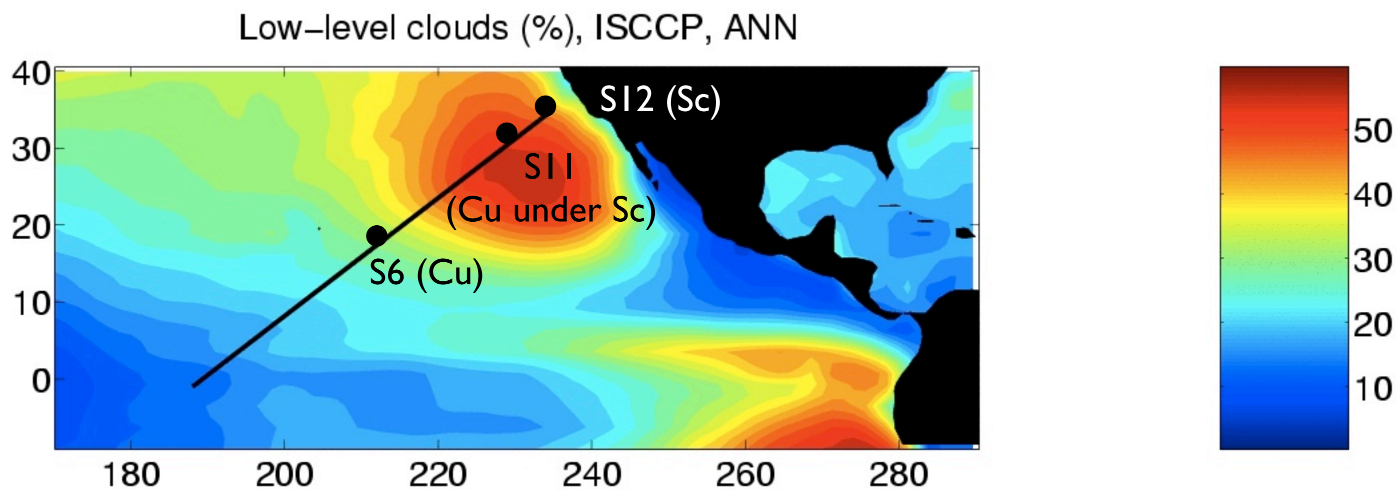
Column Modeling of Low Cloud Feedbacks



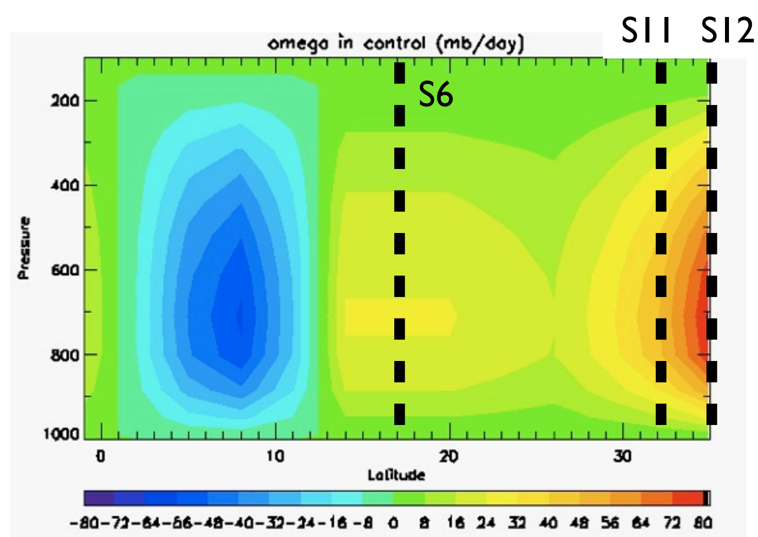
(Zhang & Bretherton, 2008)

- Simulate low cloud feedbacks in single-column setting,
- Incorporate large-scale effects of climate change,
- Use large eddy simulation (LES) models that explicitly resolve low cloud processes,
- Build confidence in results w/many models, compare w/SCMs

CGILS: CFMIP/GASS 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.



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

CGILS LES setup and sensitivity studies

Control setup at each location

- Forcings: ECMWF July mean:
  SST
  T, RH well above CTBL
  Wind profile
- CTBL horizontal T,q advection
- Idealized Subsidence Profile
- $N_d = 100\ cm^{-3}$
- Diurnally averaged summertime insolation
- Run 10 d to near steady-state
- LES models harmonized surface flux, radiation schemes

CGILS sensitivity studies

- **P2S (+2K low-lat SST increase)**
  With reduced subsidence
  Moist-adiabatic increase in warming aloft (ΔEIS ≈ 0)
  Free-trop RH unchanged

S12 only:

- **P2** (warming w/fixed subsidence)

UW only…other cloud-changing factors

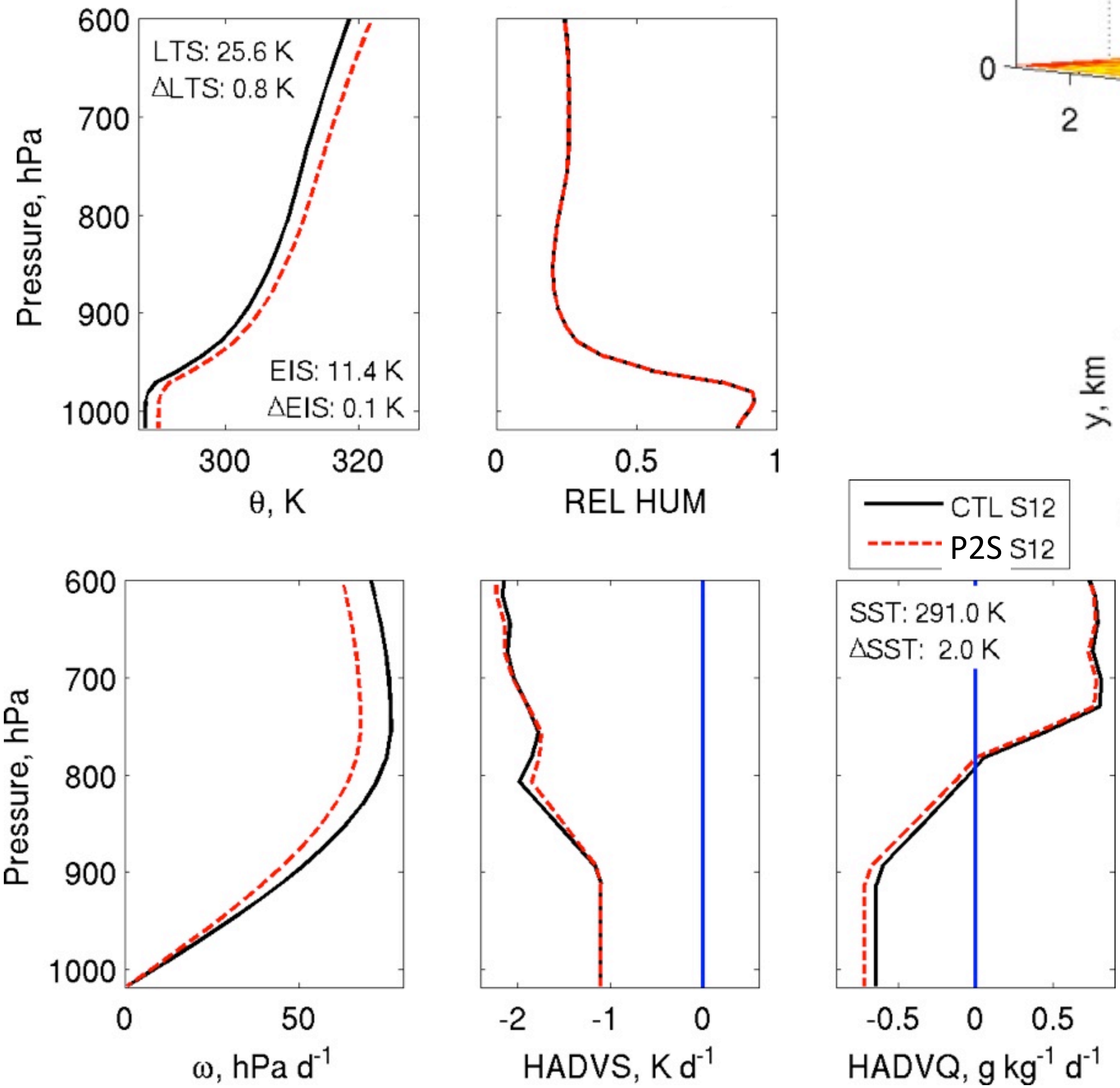
- **4xCO_2 fixed SST**
- **P2S FT** (warmer free-trop, no SST change)

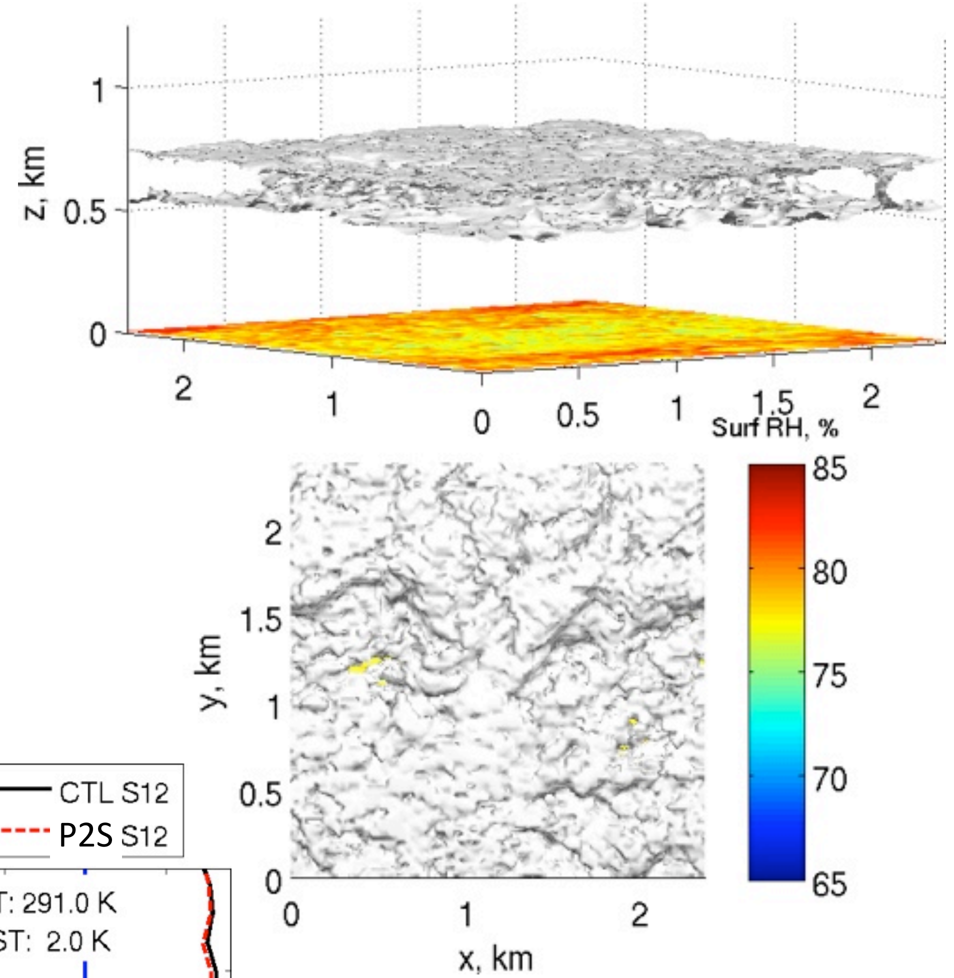
UW S12 only

- **dRH** (5% free-trop RH reduction)
- **dWS** (10% wind-speed reduction)
- **DIURN** (diurnally-varying insolation)

UW mixed-layer model run on all S12 cases

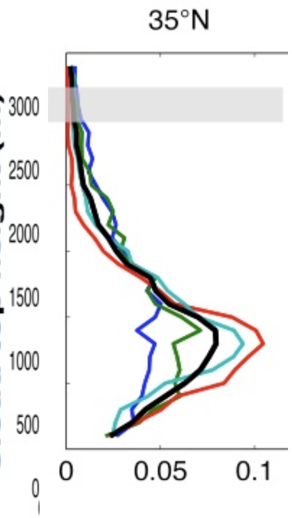
CGILS S12: Coastal Sc



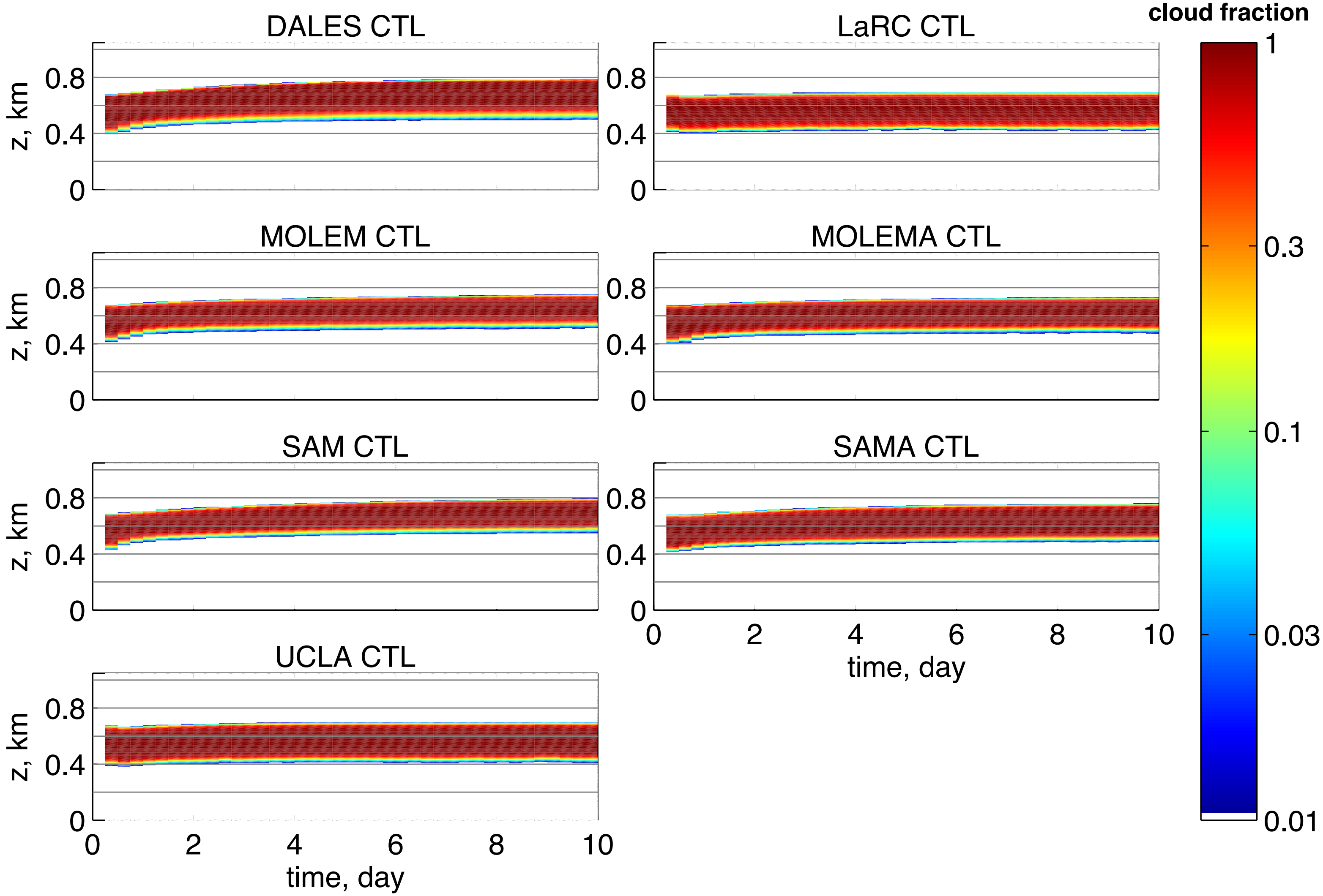


Δx = Δy = 25m
Δz = 5-15m
96 x 96 x 192
Nudged above 1200 m

S12 LES results



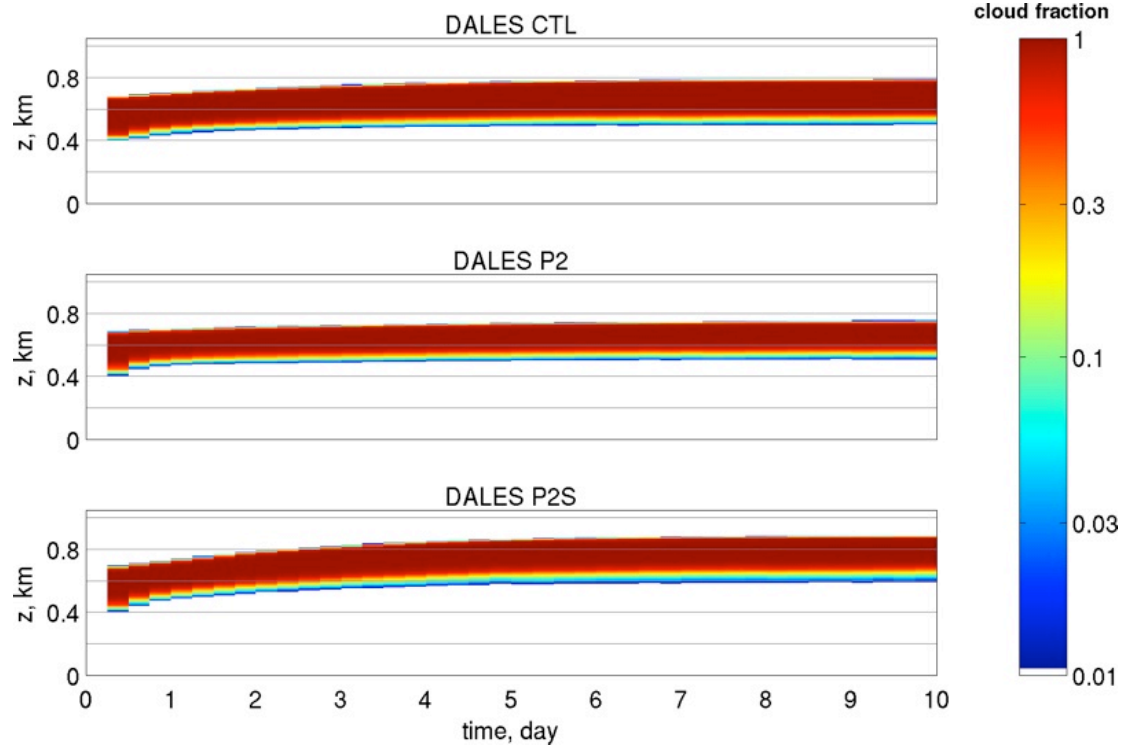
MISR Cloud Top Height PDF Courtesy of J. Karlsson.

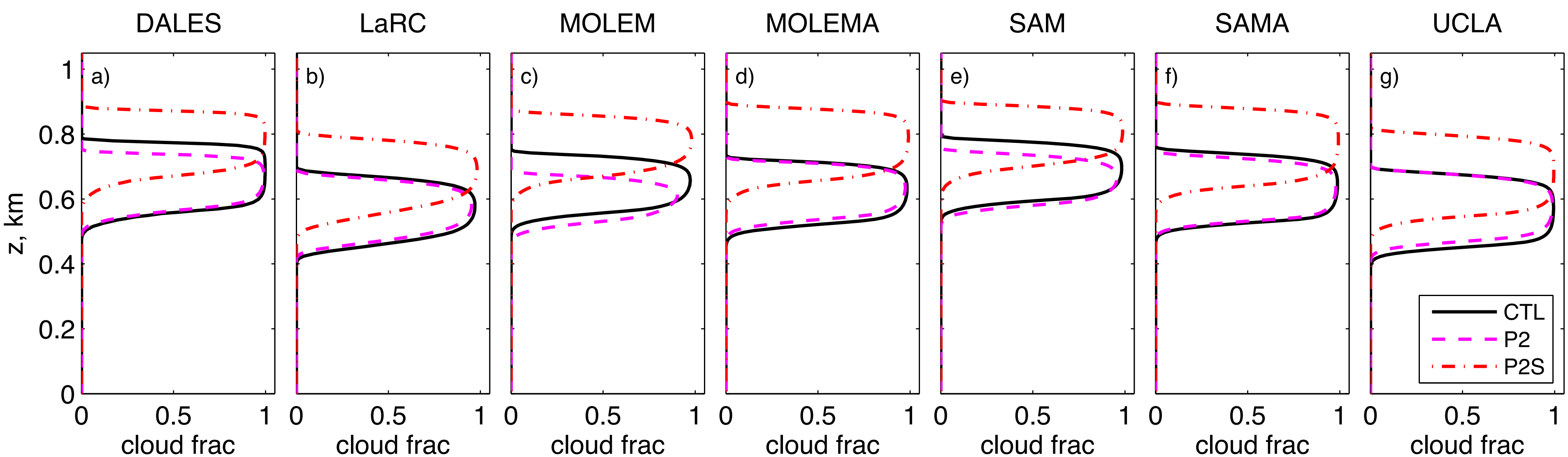


- Excellent agreement for a case with a strong inversion.
- CTL case is well-mixed, essentially non-precipitating.

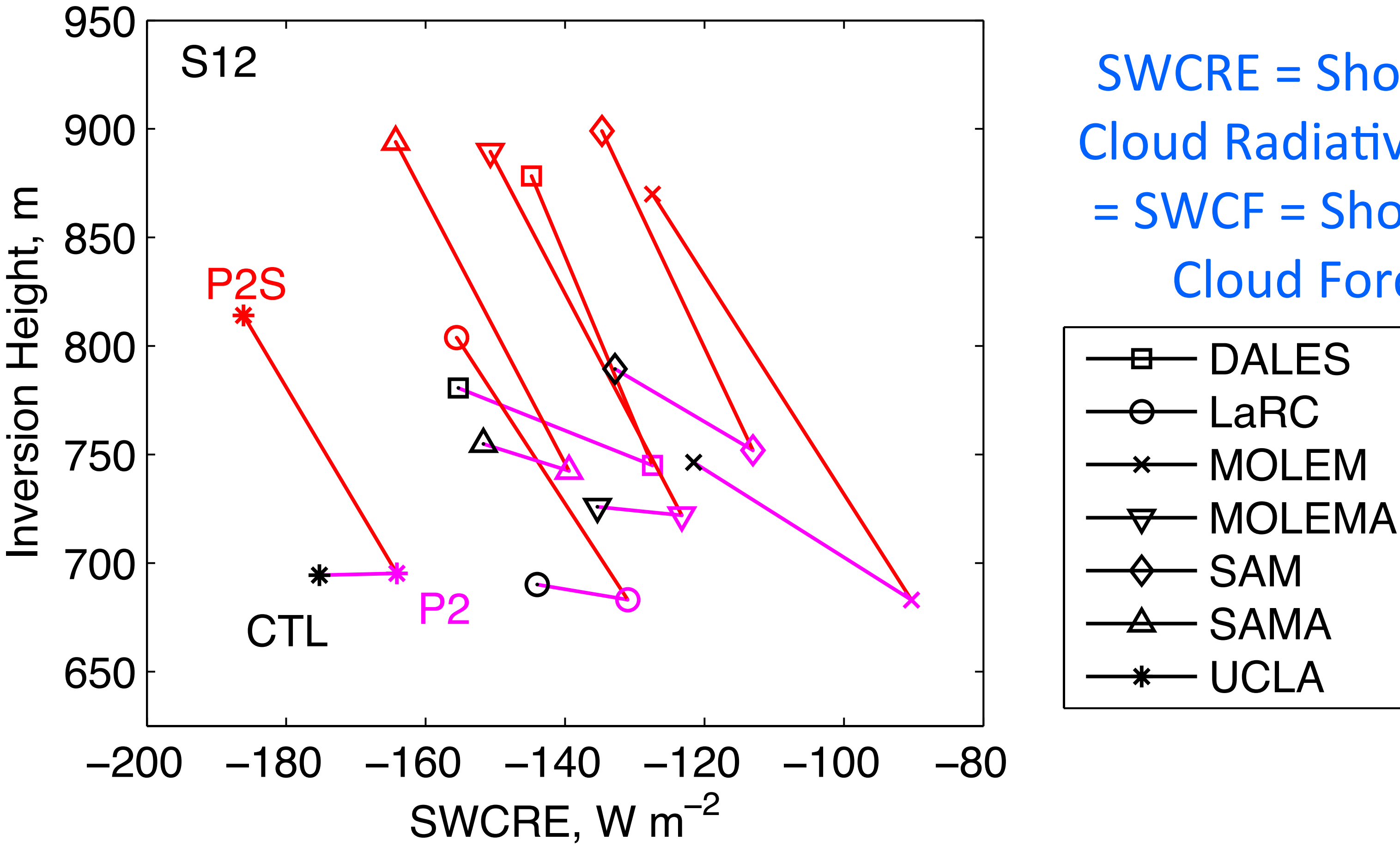
S12 Cloud Response

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





Summary of S12 cloud response



SWCRE = Shortwave Cloud Radiative Effect = SWCF = Shortwave Cloud Forcing

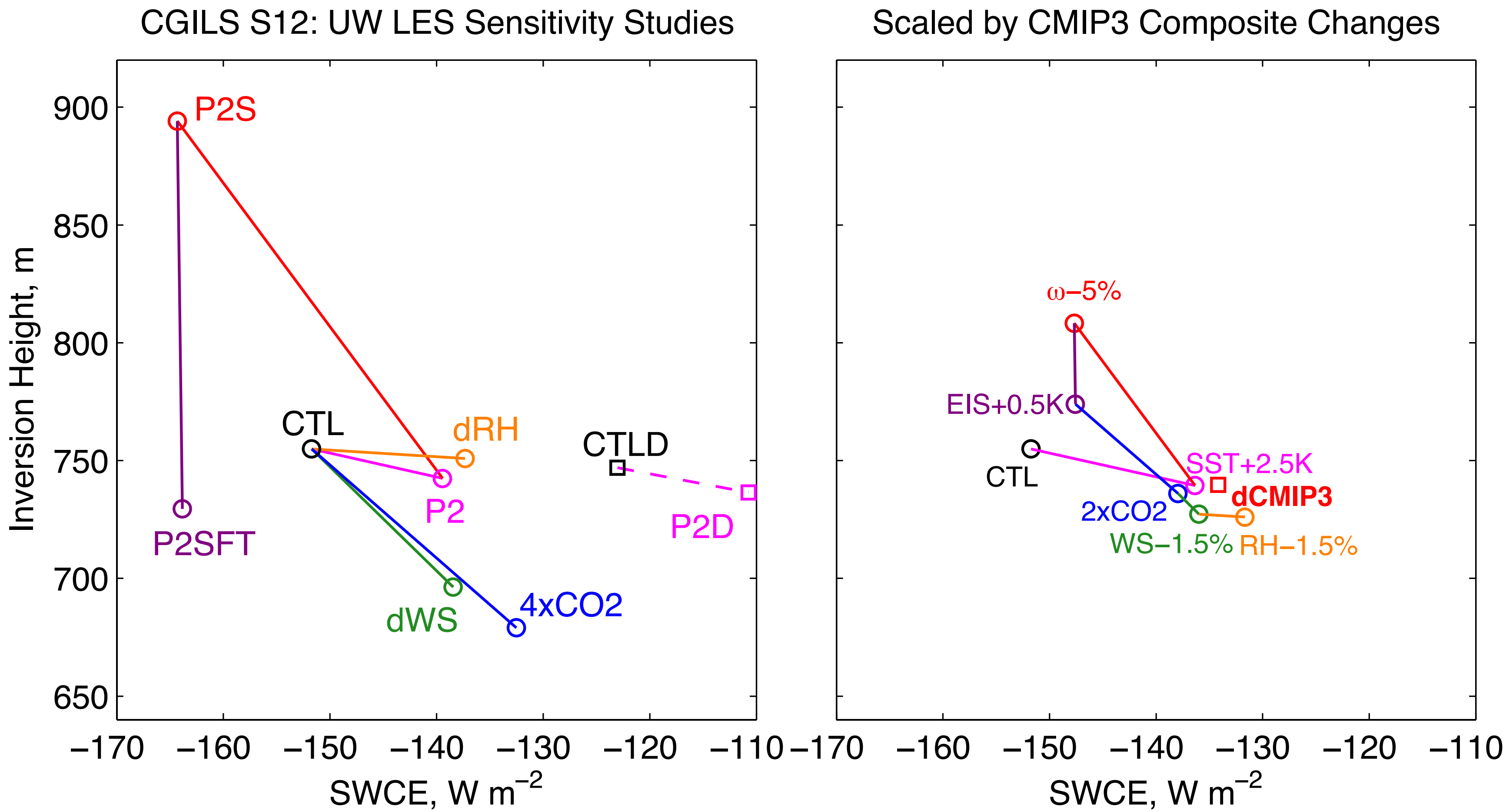
- Reasonable agreement on control cloud SWCRE
- LES all thin the cloud layer (positive feedback) in P2 case
- Cloud thickens w/deeper inversion in P2S case.

What about other climate perturbations (e.g., CO2)?

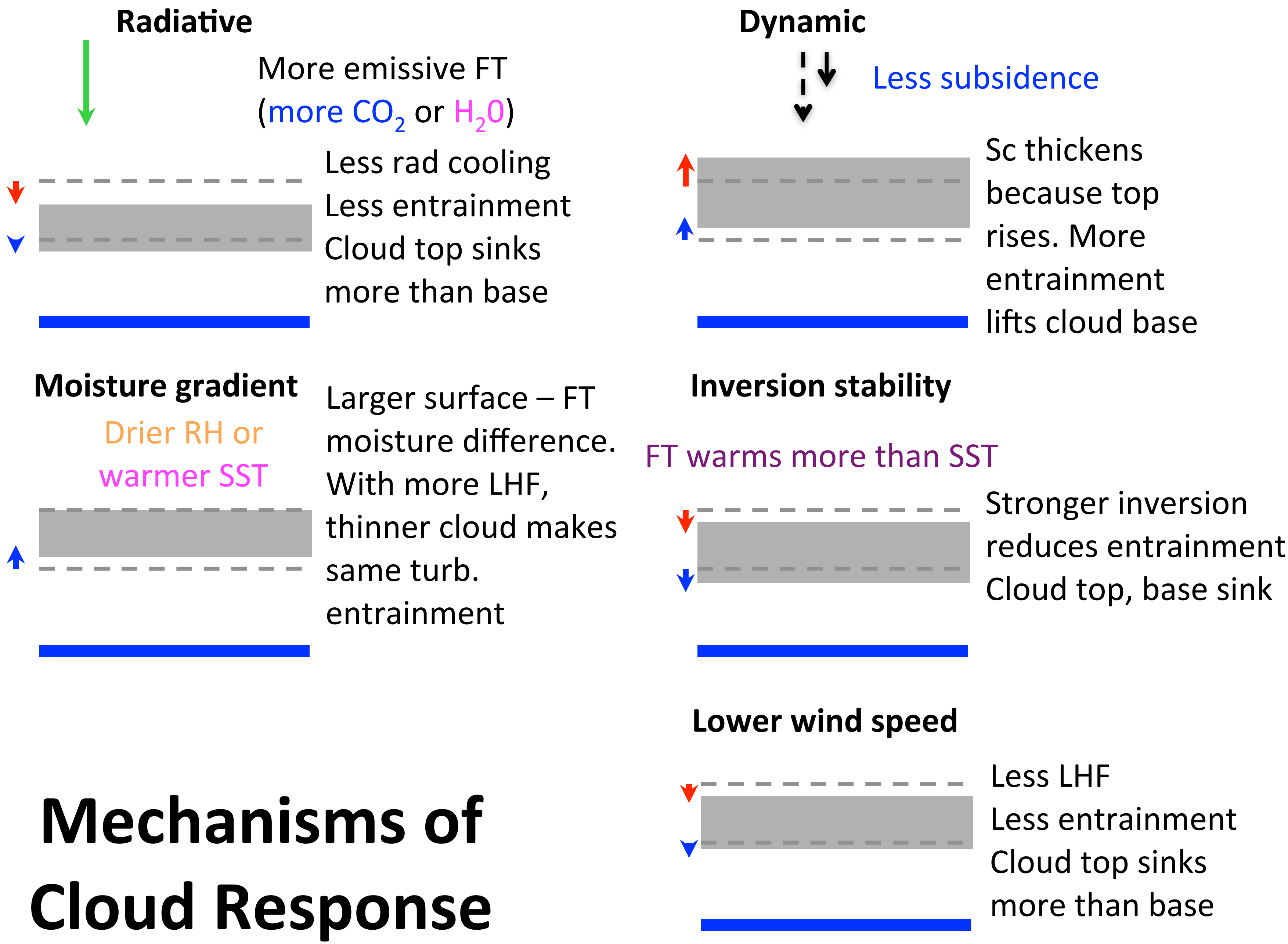
Expected 2xCO_2 subtropical forcing changes from CMIP3

Perturbation	CMIP3	Ref	CGILS	Case
δSST	2.5 ± 0.5 K	IPCC 2007	2 K	P2
δω(500 hPa)	-5 ± 3 %	Webb et al 2012	-11%	P2S - P2
δEIS	0.6 ± 0.2 K	Webb et al 2012	1.3-2.5 K	P2SFT – P2S
δRH	-1.5 ± 1 %	Sherwood et al 2009	-5 %	dRH
δ(wind speed)	-1.5 ± 1.5 %	Lu and Cai 2008	-10%	dWS

UW S12 sensitivity studies using SAMA LES

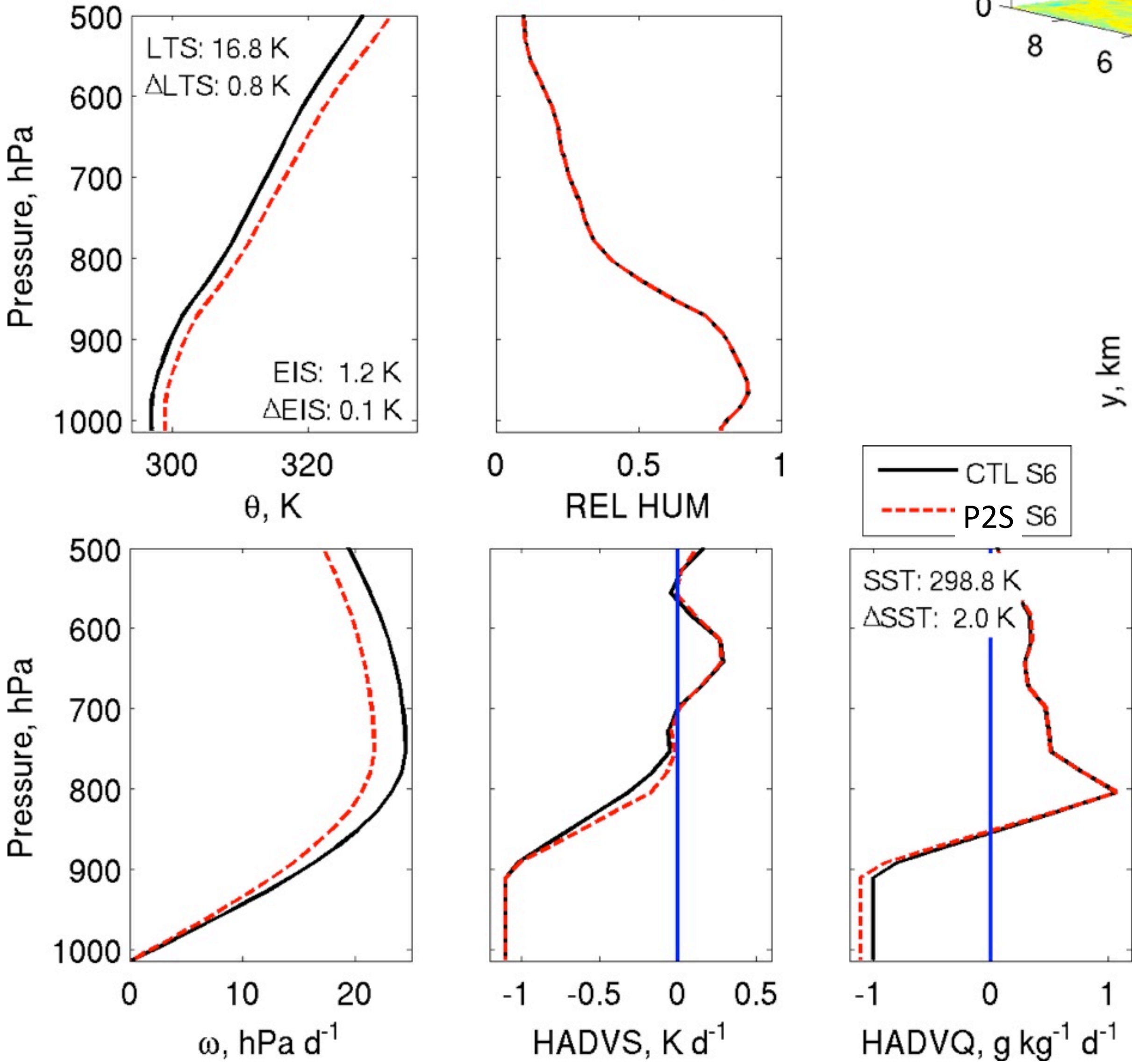


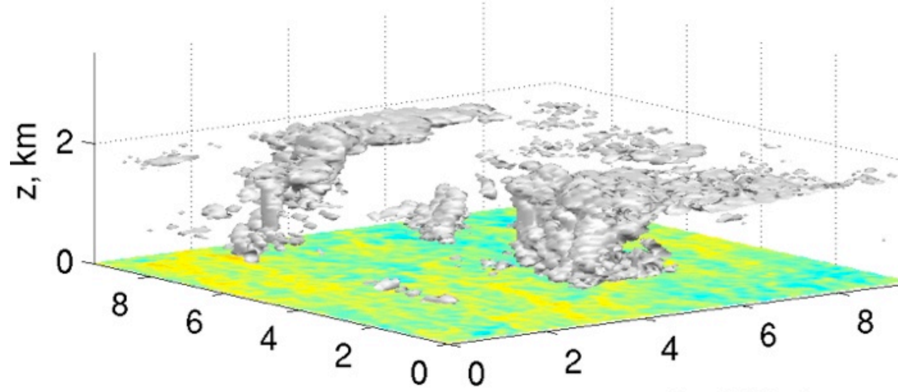
- A lot of cancellation, but net 20 W m^{-2} reduction in SWCRE for CMIP3 perturbations.
- MLM has same sensitivities as SAMA ➜ Suggests entrainment is key.

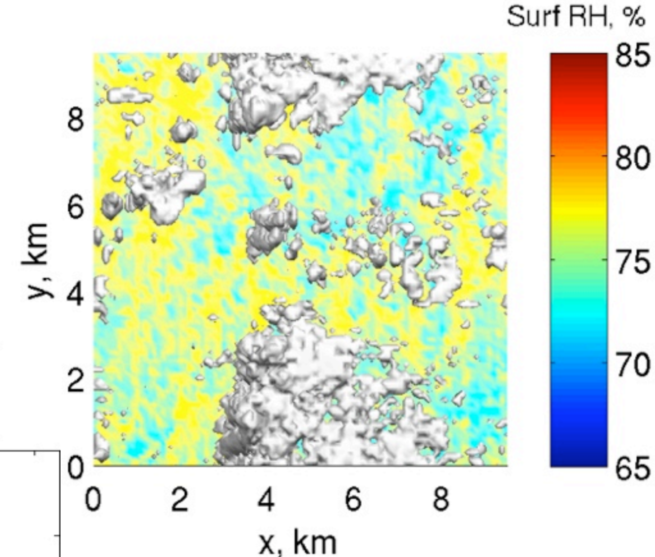


Radiative
More emissive FT
(more CO_2 or H_20)
Less rad cooling
Less entrainment
Cloud top sinks
more than base
Dynamic
Less subsidence
Sc thickens
because top
rises. More
entrainment
lifts cloud base
Moisture gradient
Drier RH or
warmer SST
Larger surface – FT
moisture difference.
With more LHF,
thinner cloud makes
same turb.
entrainment
Inversion stability
FT warms more than SST
Stronger inversion
reduces entrainment
Cloud top, base sink
Lower wind speed
Less LHF
Less entrainment
Cloud top sinks
more than base
Mechanisms of
Cloud Response

S6: Trade cumulus regime







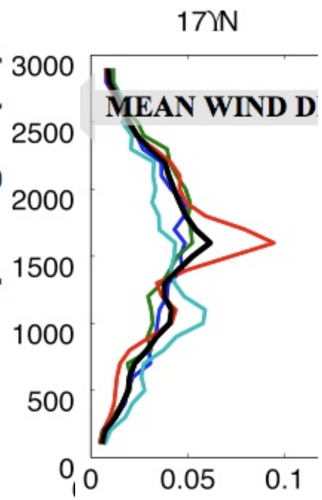
Δx=100m

Δz=40m

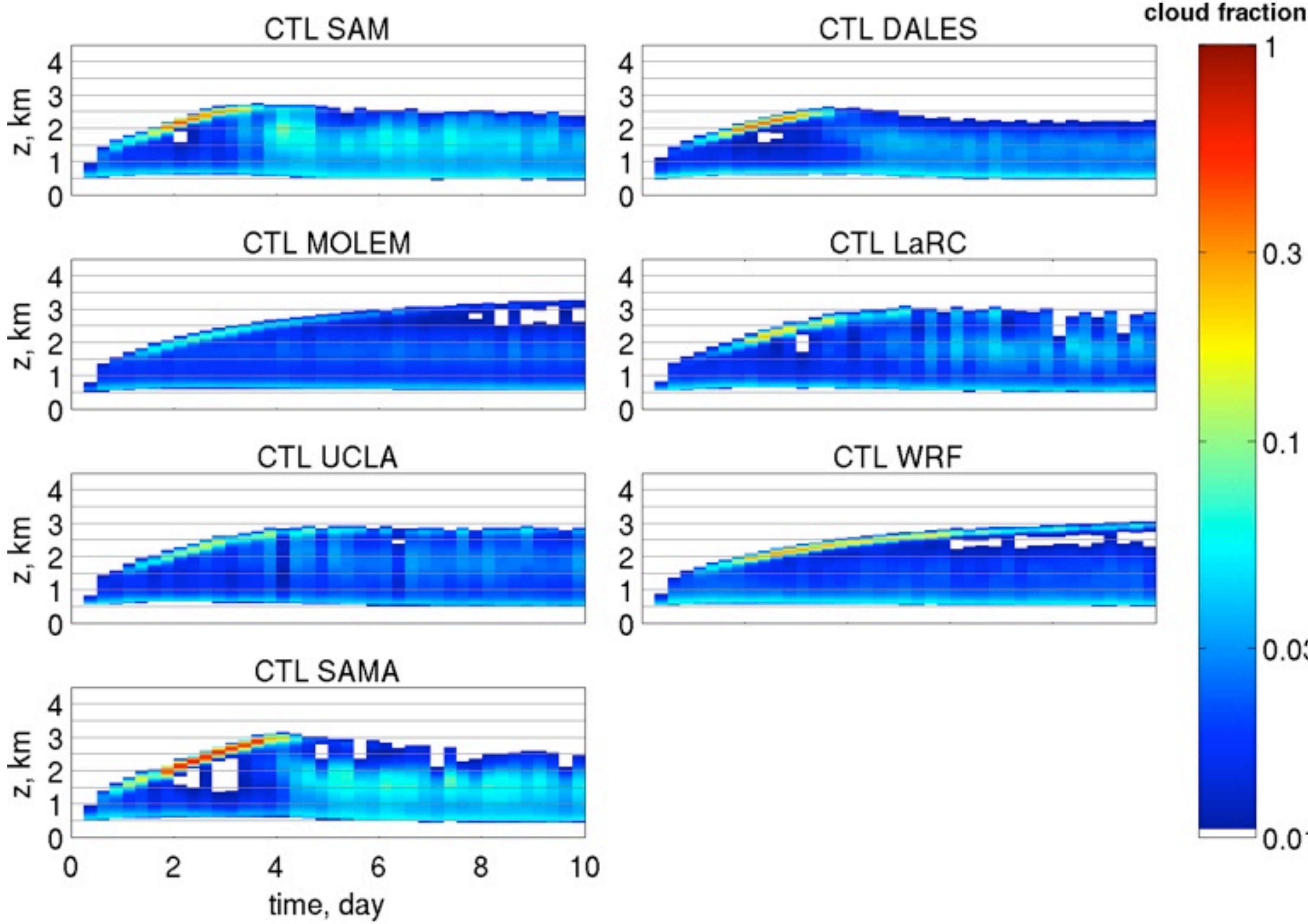
96x96x128

Nudged above 4km

S6: Cloud Fraction

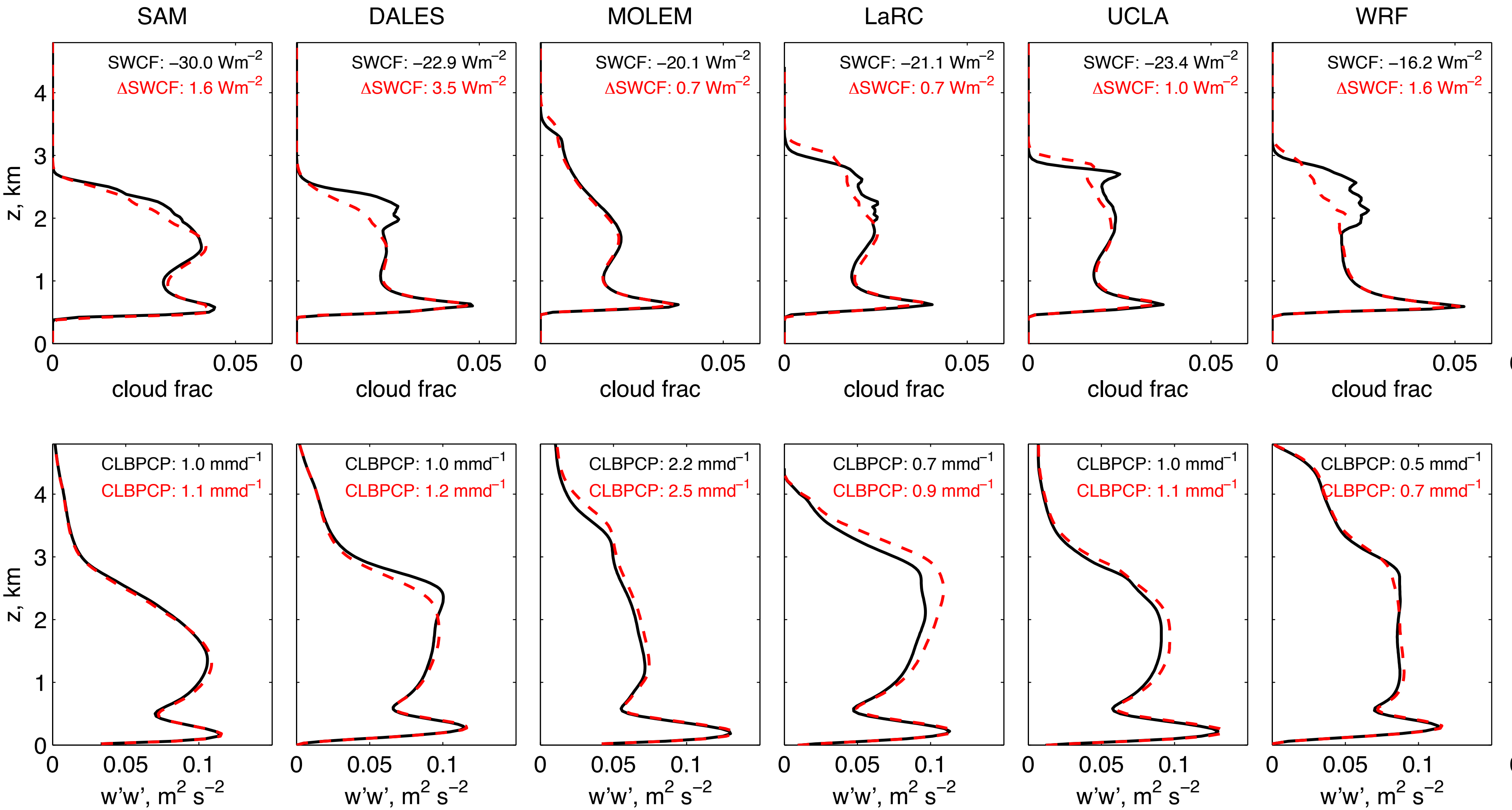


MISR Cloud Top Height PDF Courtesy of J. Karlsson.



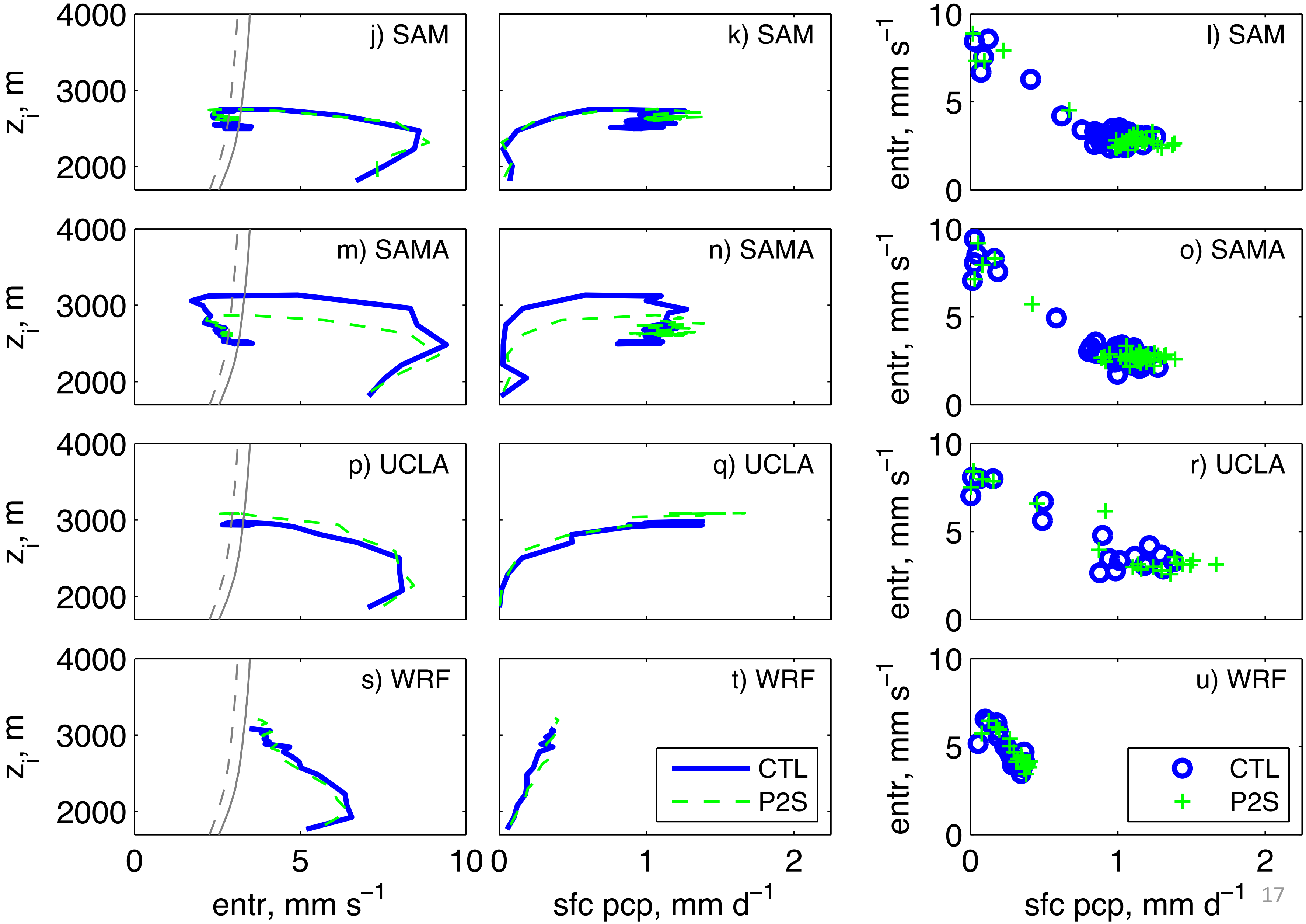
- Fair agreement between LES models in BL structure, depth.
- Initial Sc-over-Cu layer deepens and transitions to a Cu-only layer.
- +2K changes are weak; cloud layer depth is regulated by precipitation

S6: Cloud Fraction



- Fair agreement between LES models in BL structure, depth.
- +2K changes are weak; cloud layer depth is regulated by precipitation

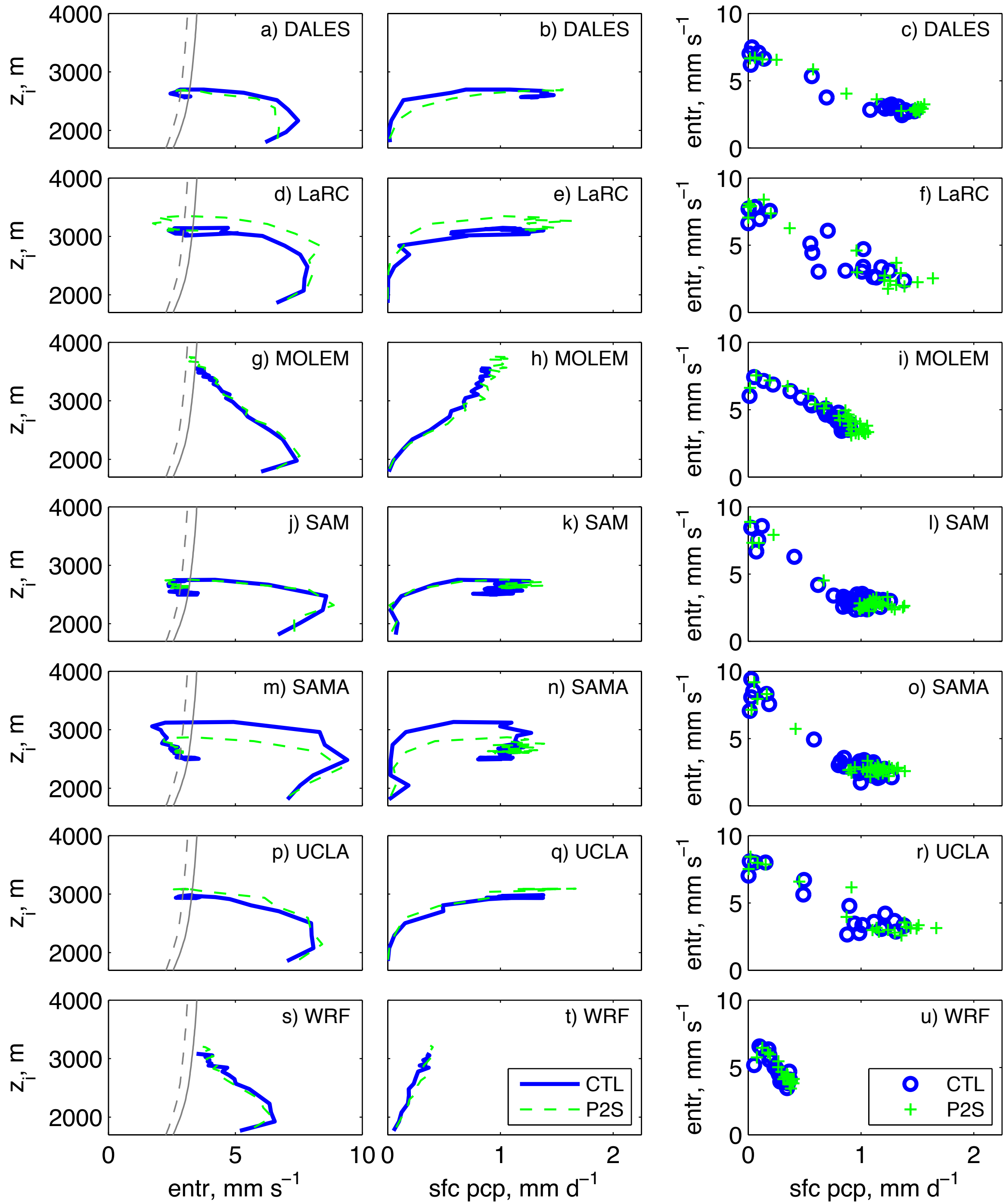
Precipitation-Entrainment Feedbacks



CGILS LES conclusions

- Four competing effects of climate perturbations on Sc clouds:
  1. Larger surface – free trop moisture jump thins Sc
  2. More emissive free trop (CO_2, H_20) or less wind thins Sc
  3. Less subsidence thickens Sc (mostly for S12)
  4. Stronger inversion thickens Sc (mostly for S11, not shown)

  Effect 1 has largest ΔSWCRE , but 2 and 3 nearly as important.
- For P2S case, LES don't agree on sign of ΔSWCRE.
- However, for combined CMIP3 2xCO2 forcing changes, LES suggest Sc ΔSWCRE > 0 (+ cld feedback) at S11 and S12.
- For shallow Cu case, precipitation buffers cloud depth/response, yielding slight positive ΔSWCRE > 0.



a) DALES
b) DALES
c) DALES
d) LaRC
e) LaRC
f) LaRC
g) MOLEM
h) MOLEM
i) MOLEM
j) SAM
k) SAM
l) SAM
m) SAMA
n) SAMA
o) SAMA
p) UCLA
q) UCLA
r) UCLA
s) WRF
t) WRF
u) WRF
CTL
P2S
z_i, m
entr, mm s^{-1}
sfc pcp, mm d^{-1}

Summary of S12 cloud response

	CTL		P2K OM0		P2K	
LES	LWP g m^{-2}	SWCRE W m^{-2}	ΔLWP g m^{-2}	ΔSWCRE W m^{-2}	ΔLWP g m^{-2}	ΔSWCRE W m^{-2}
DALES	51	−155	−17	+28	−6	+10
LaRC	48	−144	−7	+13	+13	−12
UCLA	57	−175	−7	+11	+16	−10
SAM	35	−133	−9	+20	+2	−2
SAMA	49	−152	−7	+12	+14	−13

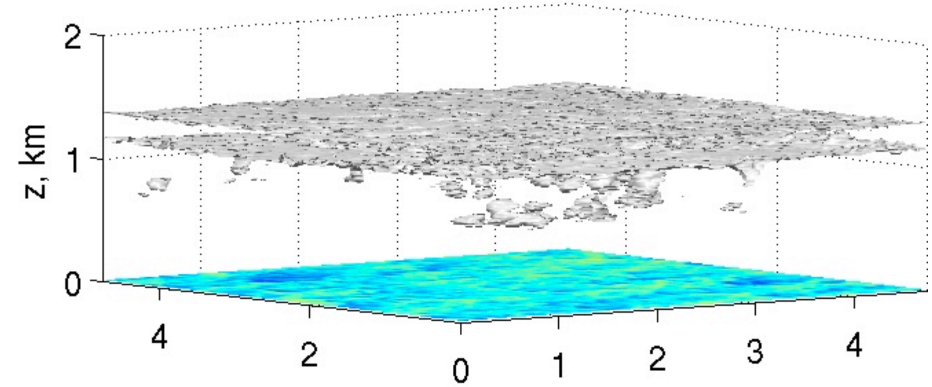
- Good agreement on control cloud thickness
- LES all thin the cloud layer (positive feedback) in OM0
- P2K response mixed (marginal decoupling in SAM, DALES)

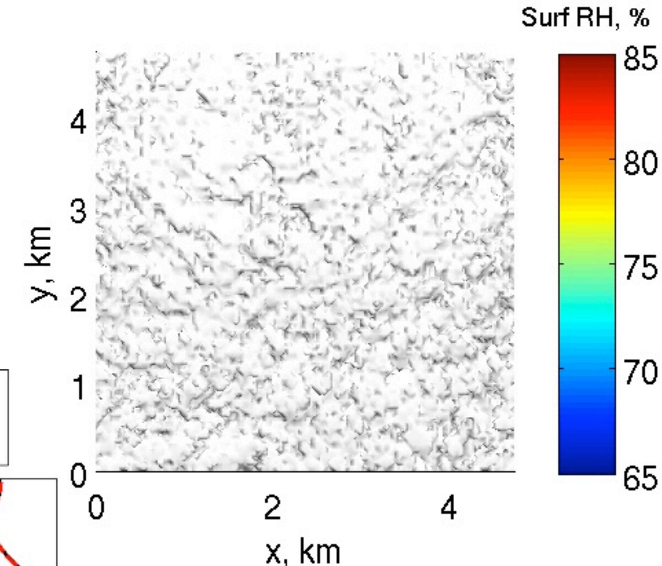
Summary of S11 cloud response

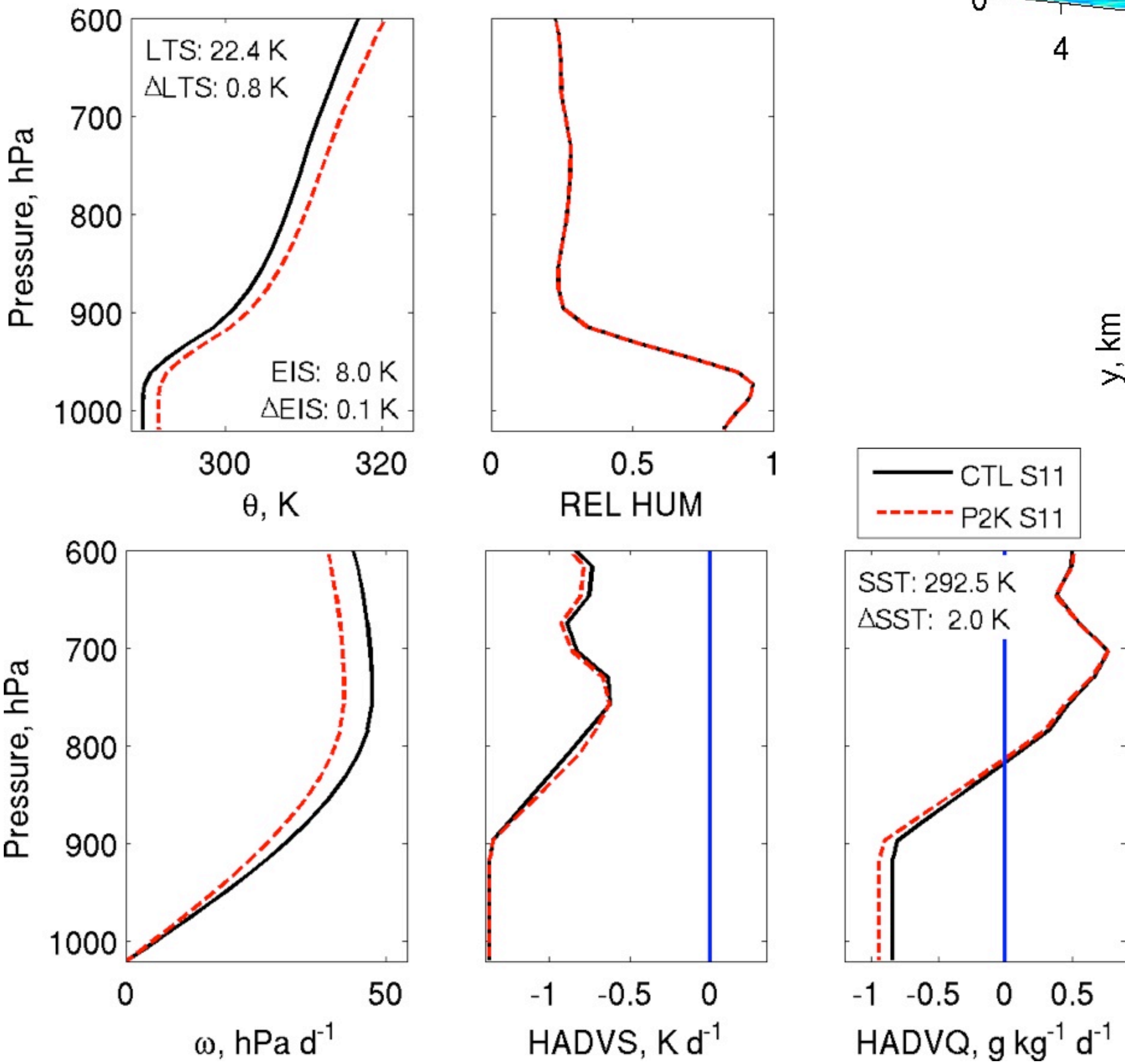
	CTL		P2K	
LES	LWP g m^{-2}	SWCRE W m^{-2}	ΔLWP g m^{-2}	ΔSWCRE W m^{-2}
DALES	52	−156	−6	+11
LaRC	50	−175	+2	0
SAM	43	−145	+1	0
SAMA	63	−152	−1	+4

- Very good agreement on control cloud thickness
- P2K response: neutral to positive ΔSWCRE

CGILS S11:
Cu under SCu



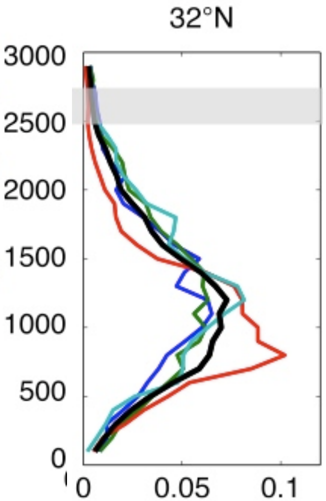




Δx=50m

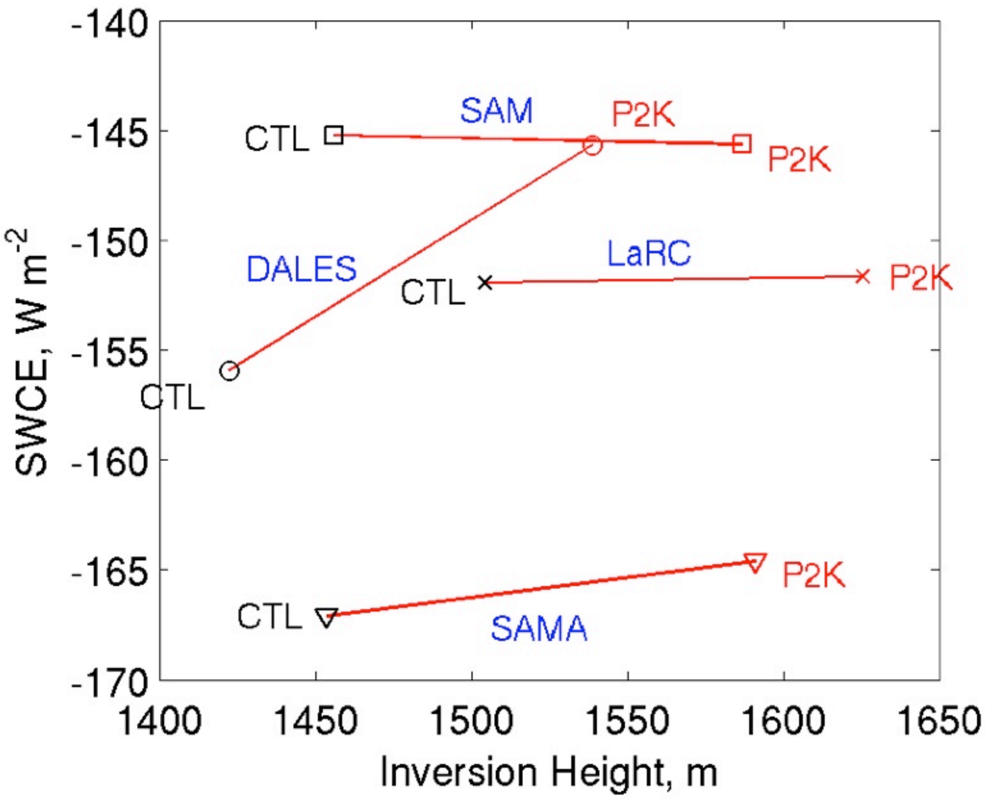
Δz=5-25m

S11 results



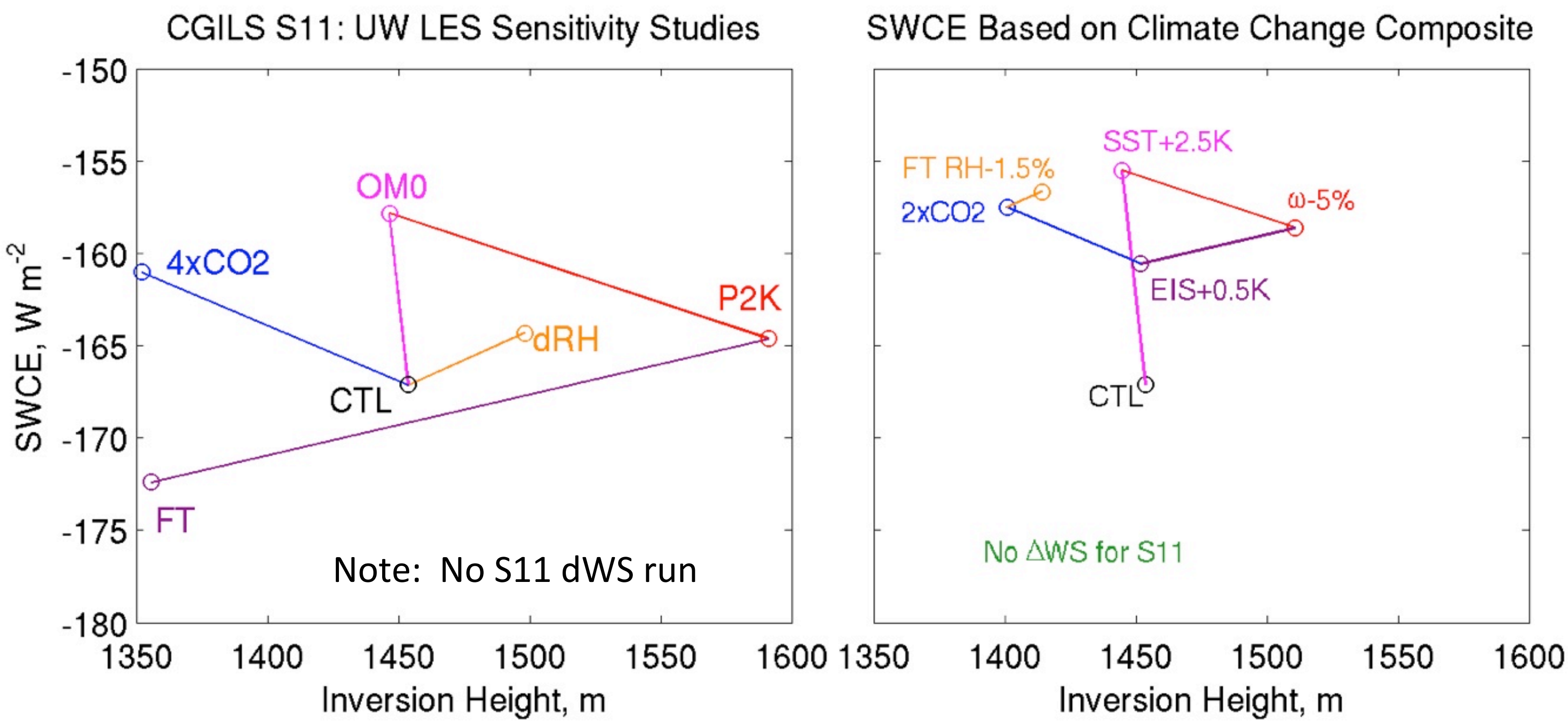
MISR Cloud Top Height PDF Courtesy of J. Karlsson.

Summary of S11 cloud response



- Very good agreement on control cloud thickness
- P2K response: neutral to positive ΔSWCRE

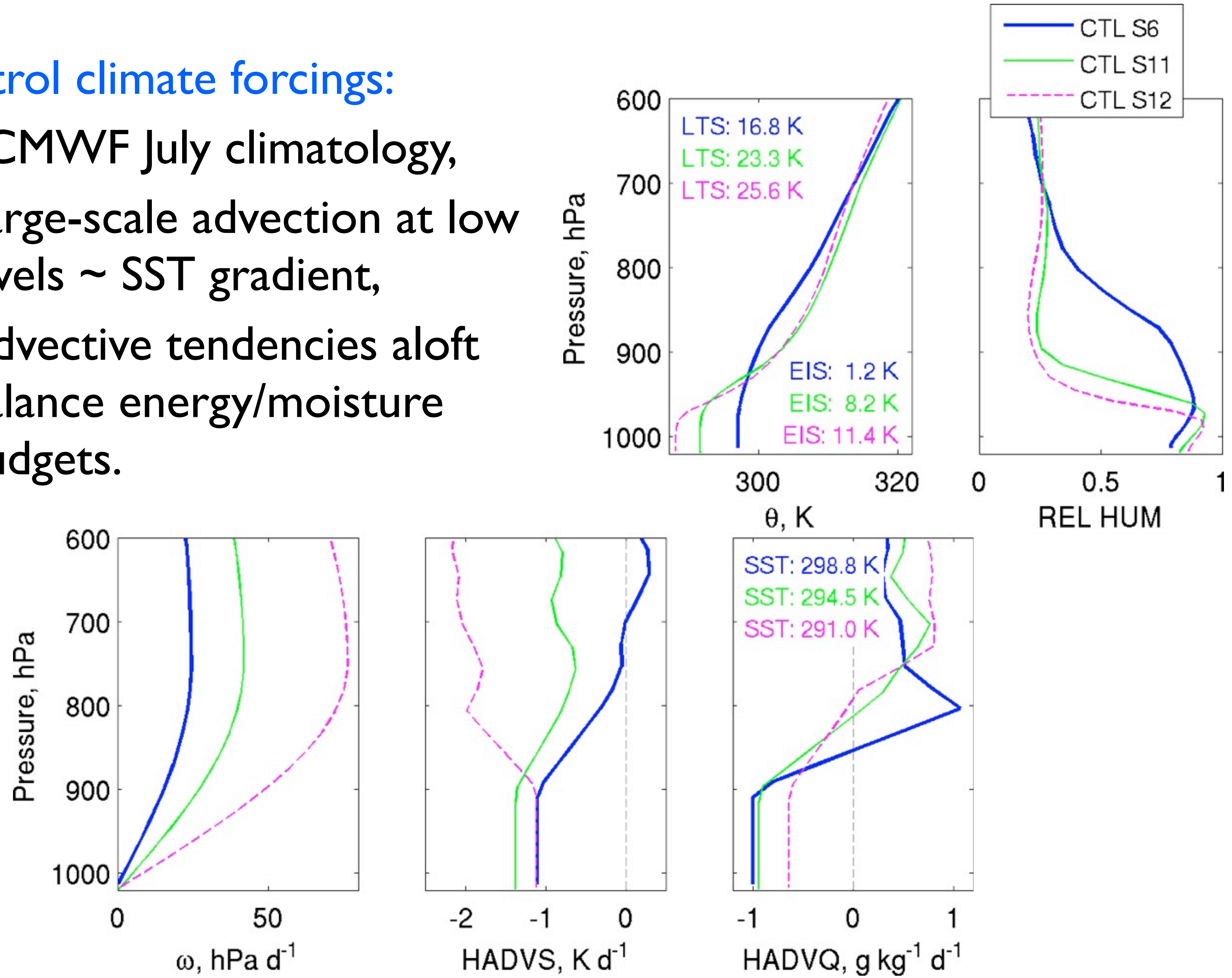
UW S11 sensitivity studies using SAMA LES



- Net 9 W m^{-2} reduction in SWCRE for CMIP3 perturbations.
- Less cloud thinning than S12 due to CO_2, less thickening from ω
- As with S12, positive cloud feedback is mostly from 2K SST increase.

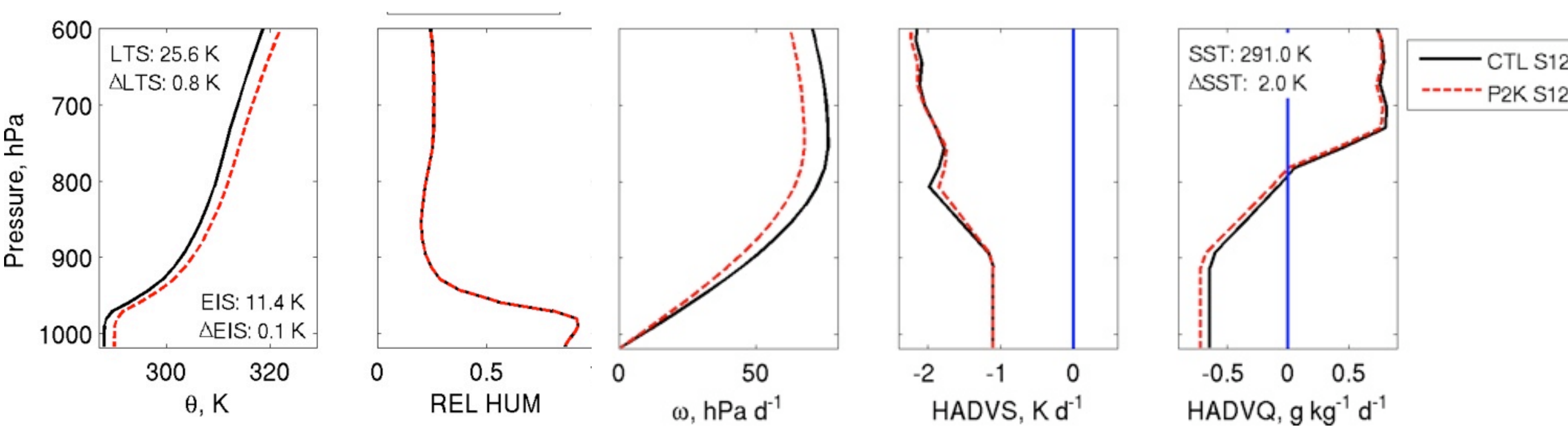
Column Cloud Feedbacks

- Control climate forcings:
  - ECMWF July climatology,
  - Large-scale advection at low levels ~ SST gradient,
  - Advective tendencies aloft balance energy/moisture budgets.



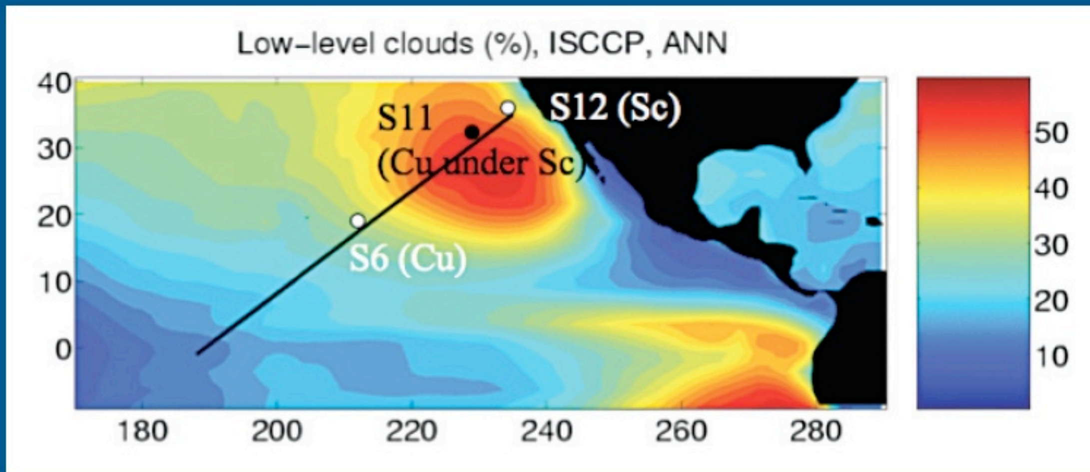
Column Cloud Feedbacks

- Idealized +2K climate perturbation:
  - SST increases by 2K (no CO_2 perturbation),
  - moist adiabatic warming of T sounding aloft,
  - free tropospheric RH unchanged in warmer climate,
  - omega (LS subsidence) decreases by about 11%,
  - LS advective cooling of BL unchanged,
  - LS advective drying of BL scales with Clausius-Clapeyron.

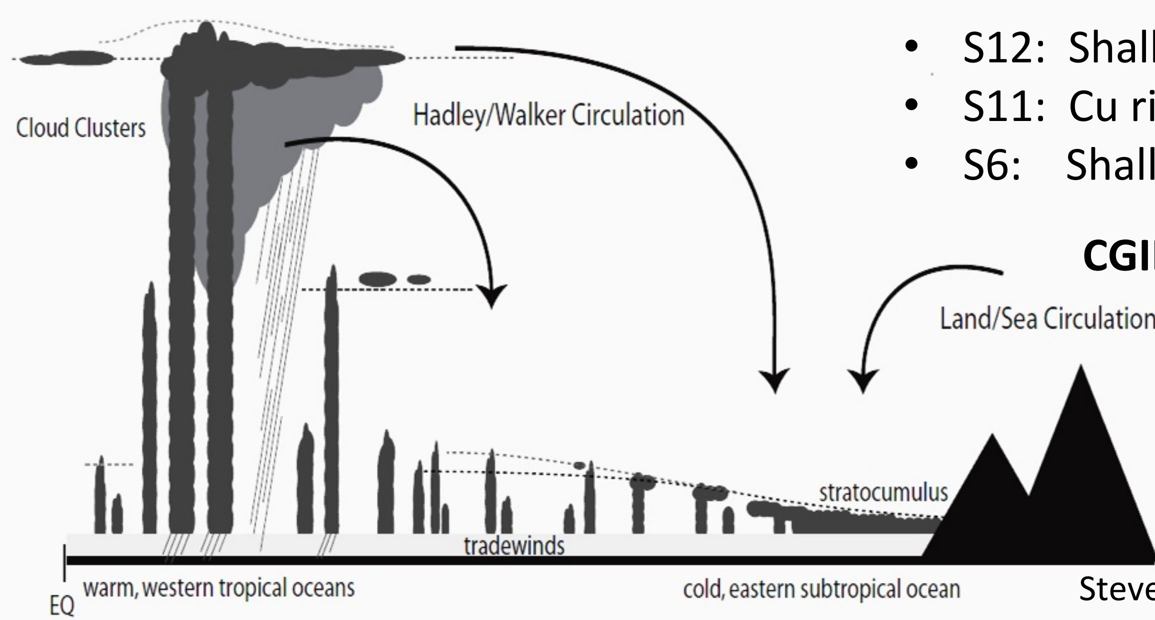


Sensitivity of Marine Boundary Layer Clouds to Idealized Climate Perturbations

Zhang et al (2010)



The CGILS intercomparison transect overlaid on the Northeast Pacific annual-mean low cloud amount. Initially, CGILS focused on location S11 (32°N, 129°W) near the northern end of the GCSS Pacific Cross-Section Intercomparison study region. The other two locations are S6 and S12. S11 is near the climatological summertime maximum of low-level cloud cover. S6 is characterized by shallow cumuli, and S12 by shallow coastal stratocumulus.



- S12: Shallow, well-mixed stratocumulus (Sc)
- S11: Cu rising into Sc
- S6: Shallow Cu

CGILS Goal: Compare LES and SCM CTBL simulations of these locations under large-scale forcings representative of present and perturbed climates

Stevens 2006

CGILS LES update

Peter Blossey and Chris Bretherton, Univ. Washington

DALES:	Stephan DeRoode, TU-Delft
LaRC:	Anning Cheng/Kuan-Man Xu, NASA-LaRC
MOLEM:	Adrian Lock, UKMO
SAM:	Peter Blossey, U. Washington
UCLA:	Thijs Heus, MPI-Hamburg
WRF:	Satoshi Endo/Yangang Liu, Brookhaven Natl. Lab (S6)

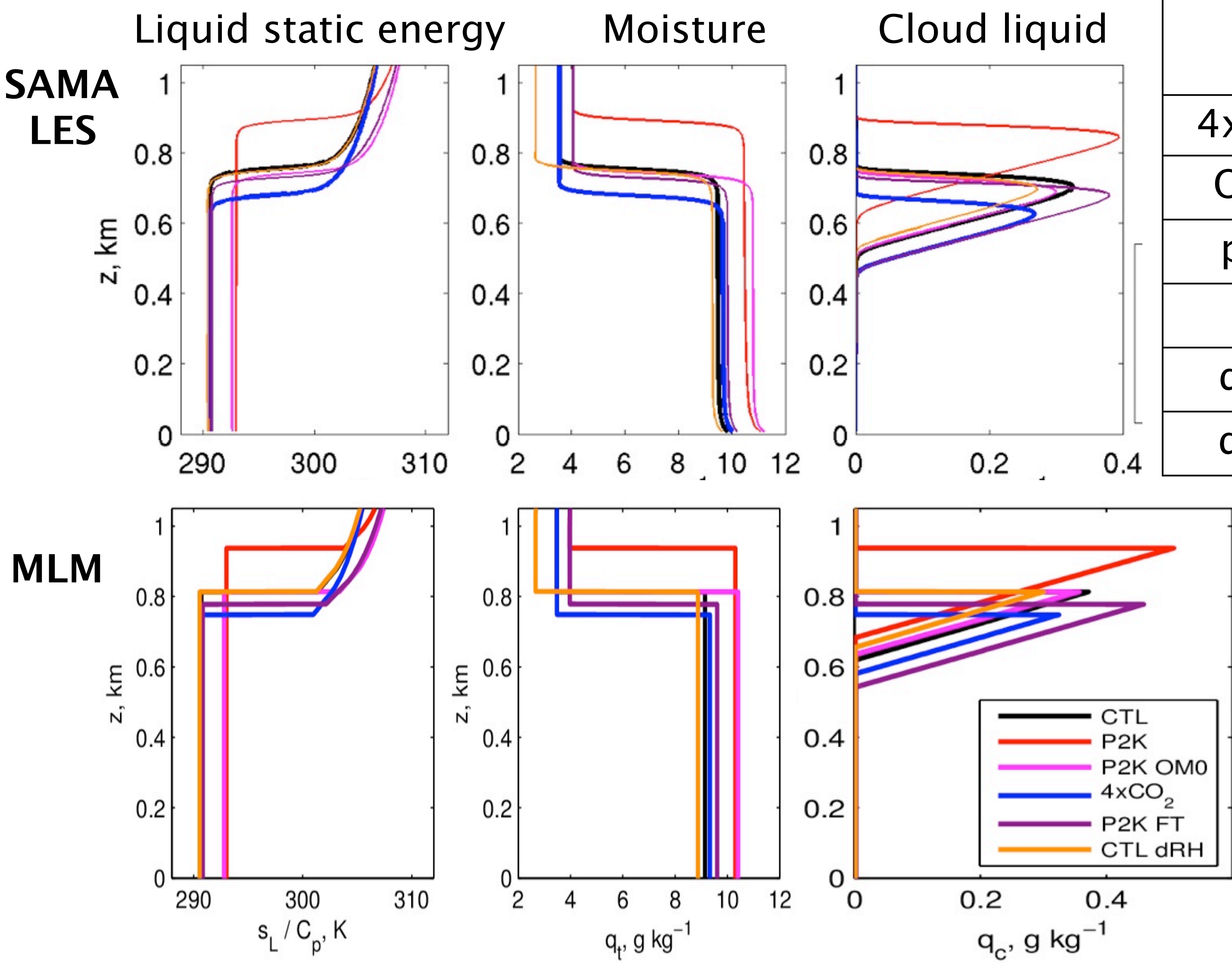
Intercomparison Status

April 2012: All groups have submitted final results

July 2012: Planned CGILS LES paper submissions

Sept 2012: Pan-GASS meeting – CGILS Phase II strawman?

Comparison with MLM



7.5-10 day avg	ΔSWCRE W m^{-2}	
	MLM	SAMA
4xCO_2	+16	+19
OM0	+10	+12
p2K	−29	−13
FT	−21	−12
dRH	+21	+14
dWS	+26	+14

MLM has similar sensitivities as SAM ➔ Entrainment is key.