Boundary-layer clouds in a changing climate

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Thanks: Peter Blossey, Matt Wyant, Rob Wood, Sungsu Park

Outline

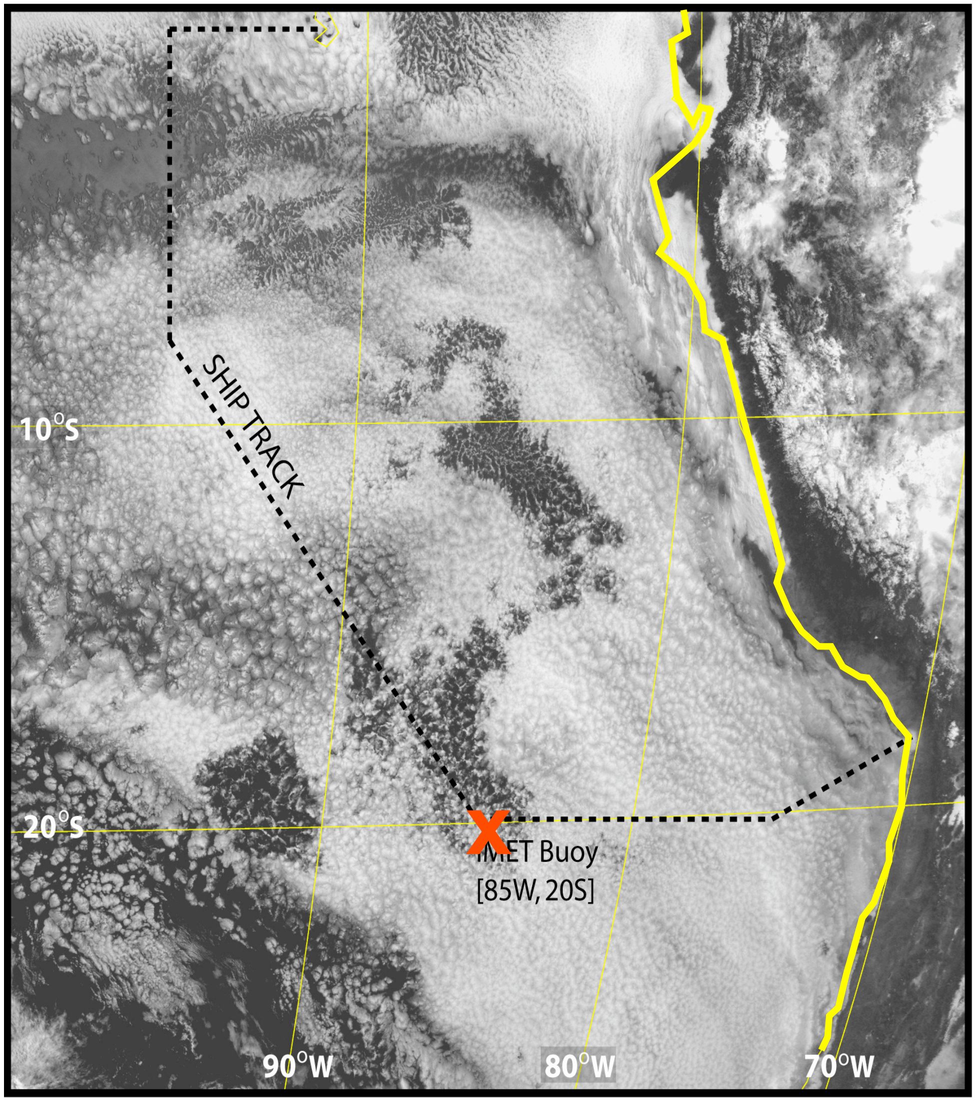
1. Boundary-layer clouds in the current climate
2. Boundary-layer cloud-aerosol interaction
3. Boundary-layer cloud feedbacks

observations ←→ process modeling ←→ global modeling

…of sensitivity to climate-change-relevant perturbations

1. Boundary-layer clouds in the current climate

GOES-10 VISIBLE IMAGE
October 17 2001, 15:00 UTC



Bretherton et al. 2004

Cloudy boundary layers important to climate

Boundary layer clouds

- Radiative impacts/surface temperature/circulation
- Vertical mixing
- Affect surface moisture/heat/momentum fluxes
- Air mass transformation
- Cloud-aerosol-chemistry interaction

Simulation challenges

- Strong internal feedbacks (cloud-radiation-turbulence, cloud-precipitation-aerosol)
- Horizontal heterogeneity
- Multiple interacting parameterizations
- Sensitive to vertical resolution

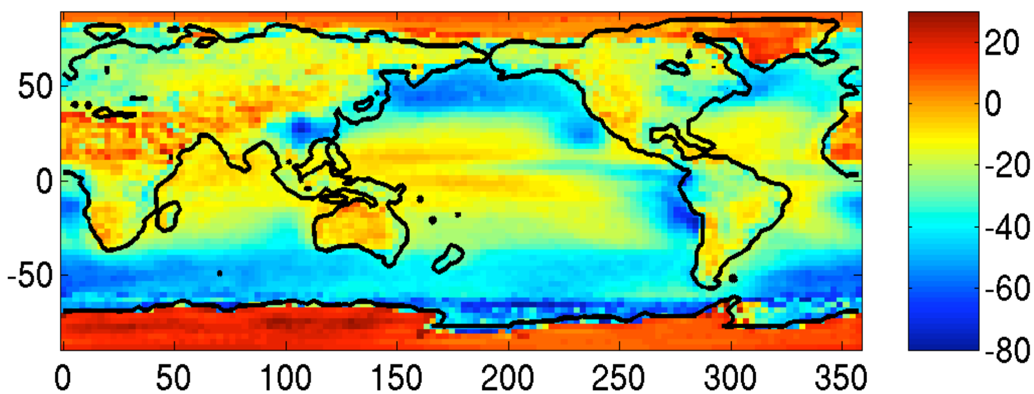
Estimated Inversion Strength (EIS)

Correlates well with spatial/seasonal/ interannual marine low cloud variations.

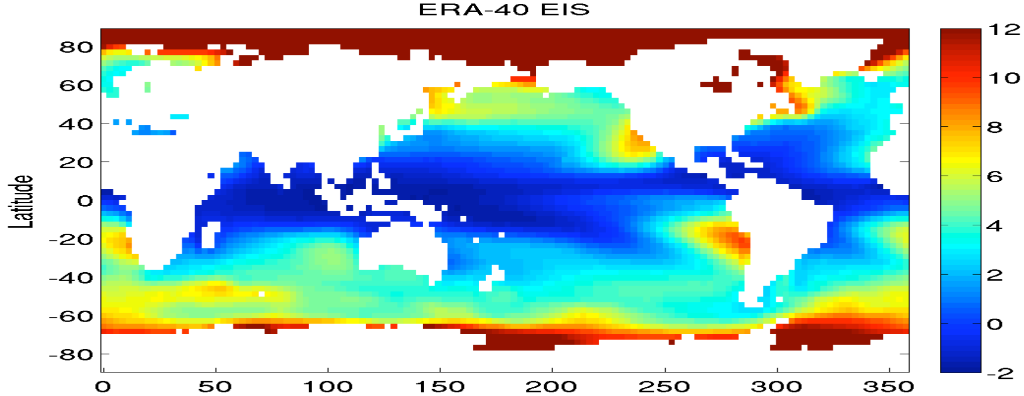
$$LTS = \theta_{700} - \theta_{1000}$$

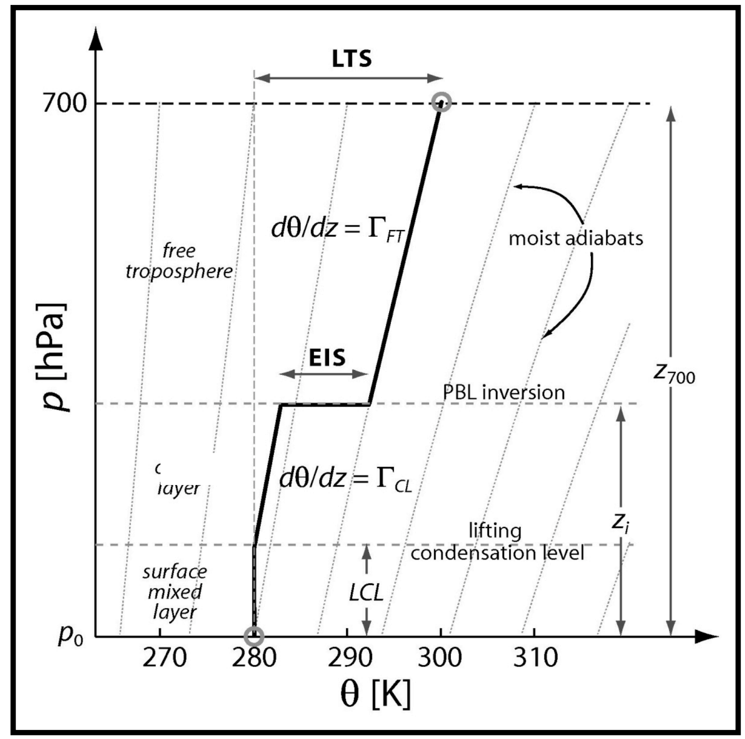
$$EIS = LTS - \Gamma_{850}^{ma}\,(z_{700} - z_{LCL})$$

ERBE Net Cloud Forcing, W/m²



ERA-40 EIS

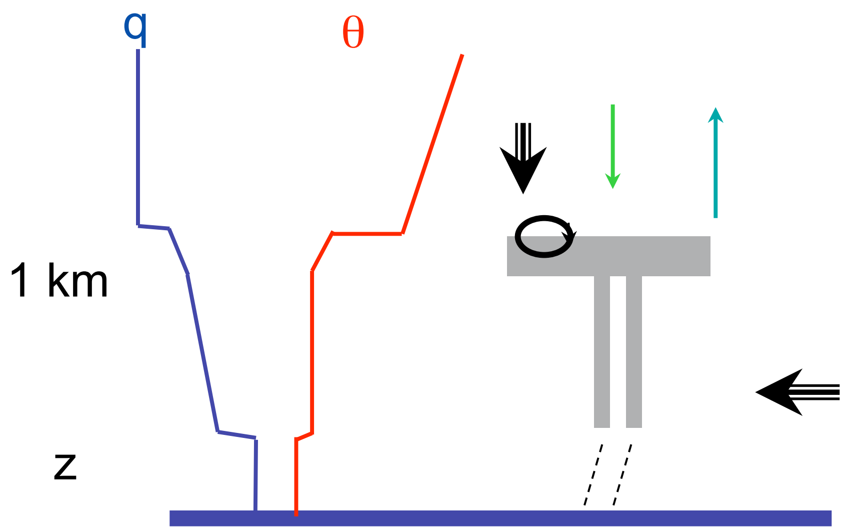


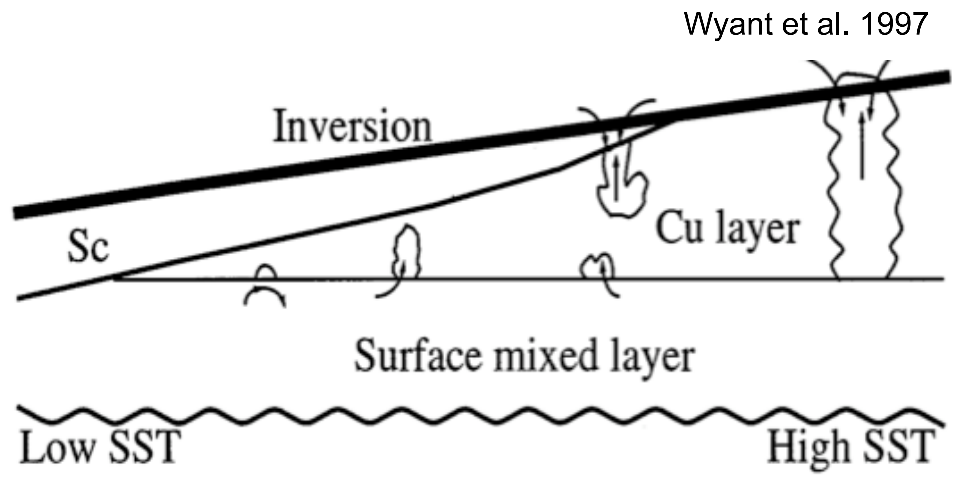


Wood and Bretherton (2006)

1 K ΔEIS ~ -8 W m^{-2} ΔCRF

Subtropical marine low cloud dynamics



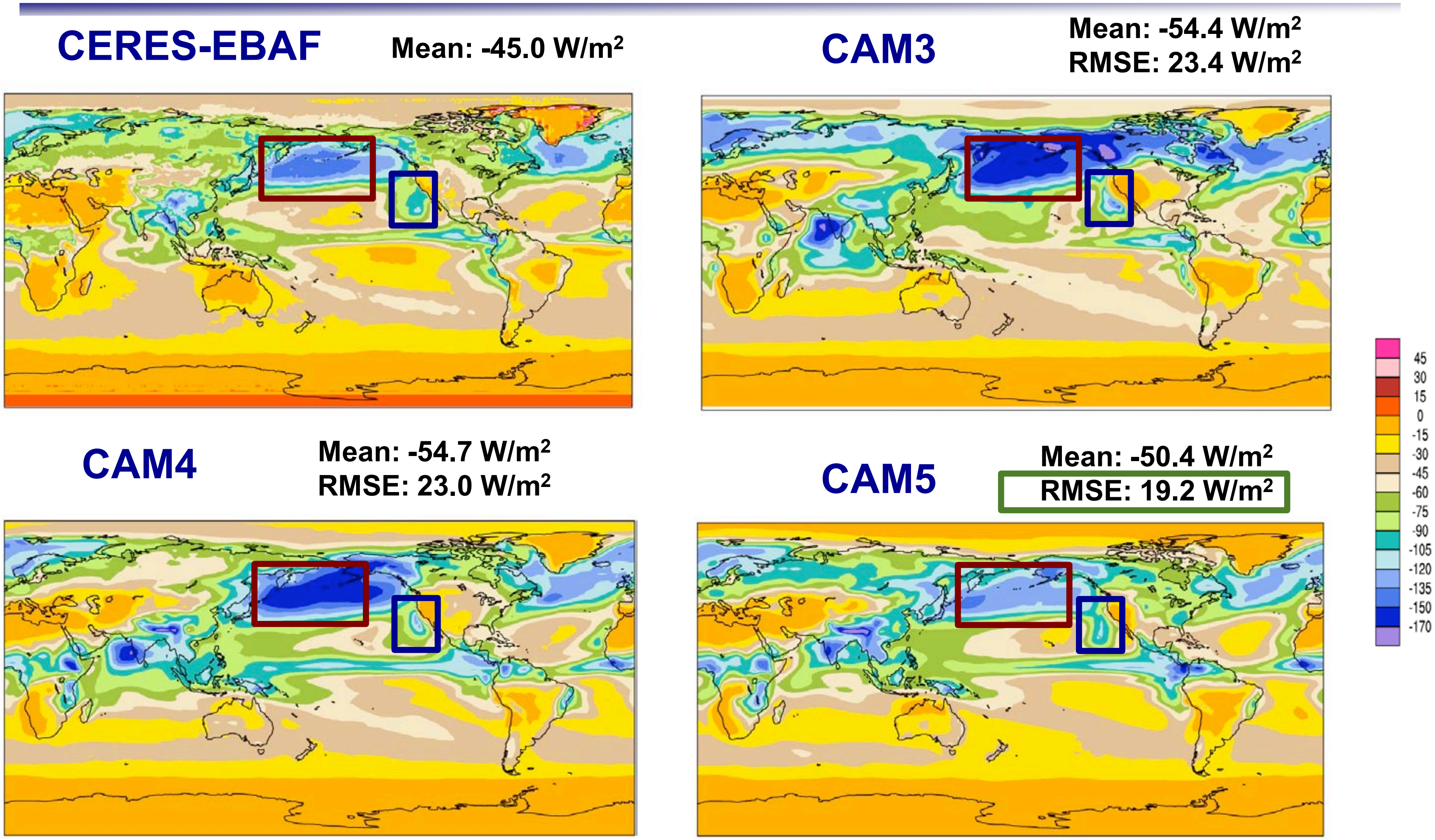


- Clouds turbulently maintained by longwave cooling and surface moistening/heating.
- Turbulence drives entrainment through capping inversion, which counteracts mean subsidence.
- Shallow PBL is well mixed with Sc, deep PBL is ‘Cu-coupled’
- Precipitation can accentuate decoupling

New parameterizations

- Careful coupling of moist turbulence (radiatively and surface-driven), shallow Cu convection, entrainment
- Lock et al. (2001): Separate sfc & Sc-driven turb layers
- Golaz et al. (2002): 2-Gaussian HOC for Sc&Cu
- Breth. et al. (2004): Shallow Cu penetrative entrainment
- Siebesma et al. (2007): Eddy Diffusion-Mass Flux
- Neggers et al. (2009): Dual-Mass Flux

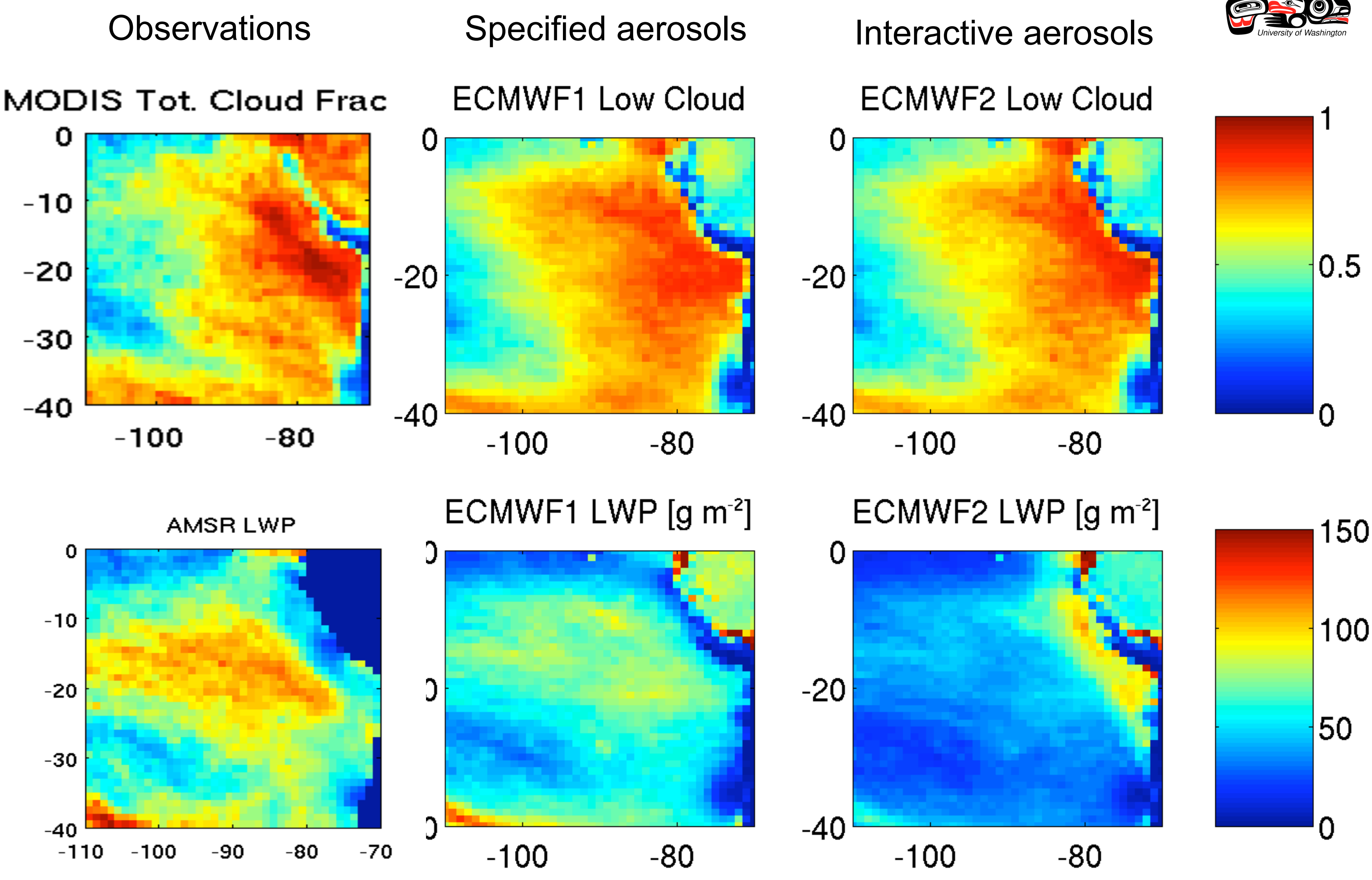
SWCF, JJA: CAM versus CERES-EBAF



- Excessive SWCF in North Pacific (in CAM3 and CAM4) is reduced in CAM5.
- CAM5 improves stratocumulus and trade cumulus
- CAM5 reduces RSME error (true even if compared to ERBE)

C. Hannay

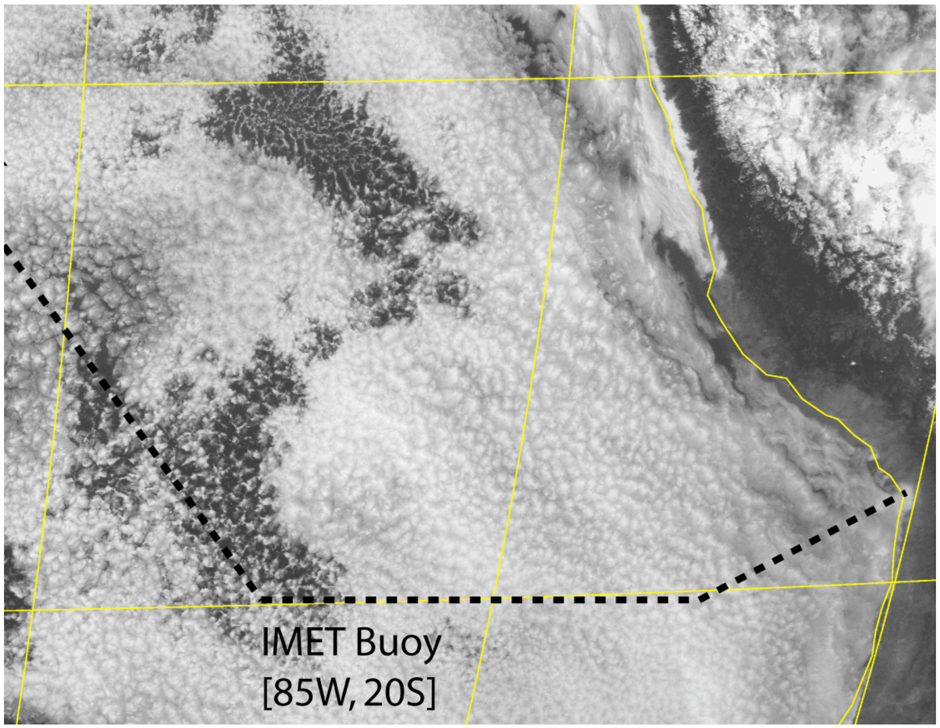
VOCA: 12-36 hr forecasts for 16 Oct-15 Nov 2008



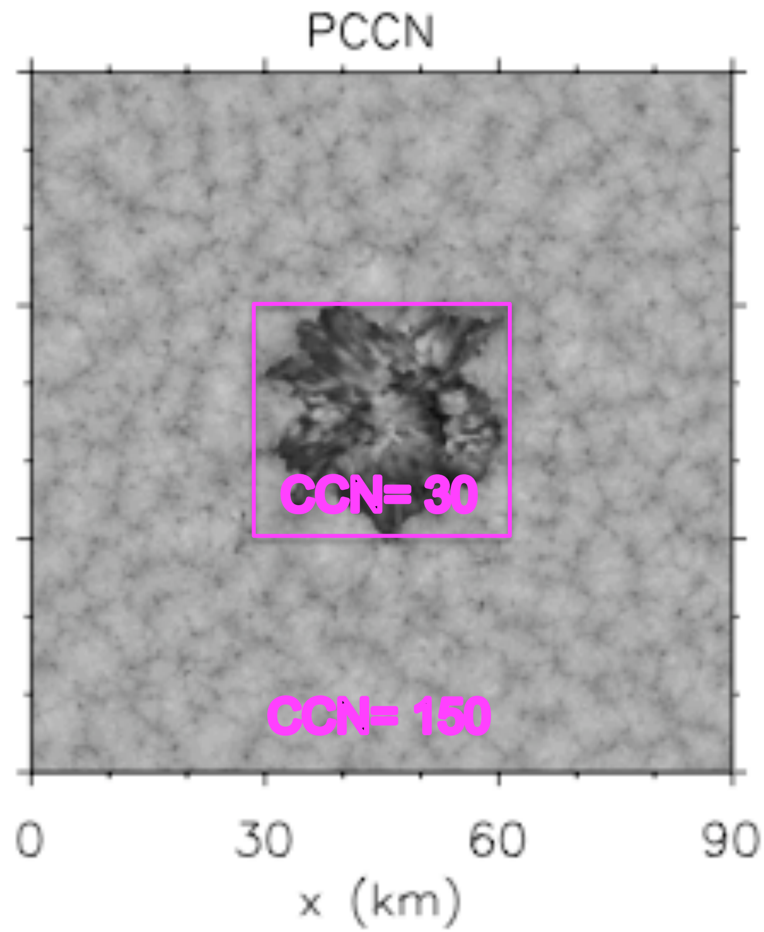
2. Boundary-layer cloud-aerosol interaction

‘Albrecht effect’: More aerosols can thicken drizzly clouds

POCS: Low CCN - drizzle - decoupling - cloud breakup



Satellite
Bretherton et al. 2004

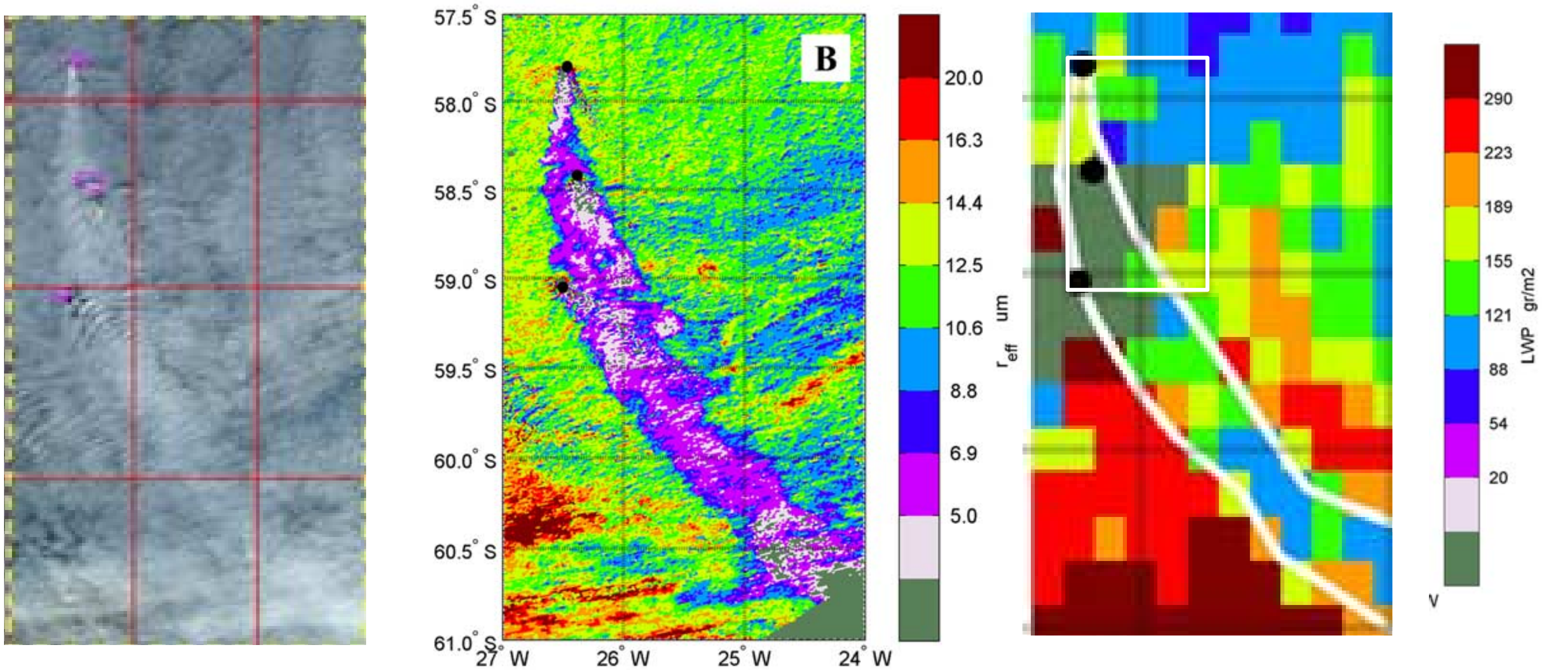


LES
Wang and Feingold 2010

…but more aerosol can **thin** non-drizzly cloud.

A ‘volcano track’ from the South Sandwich Islands, 27 Apr 2006 (Gasso 2008)

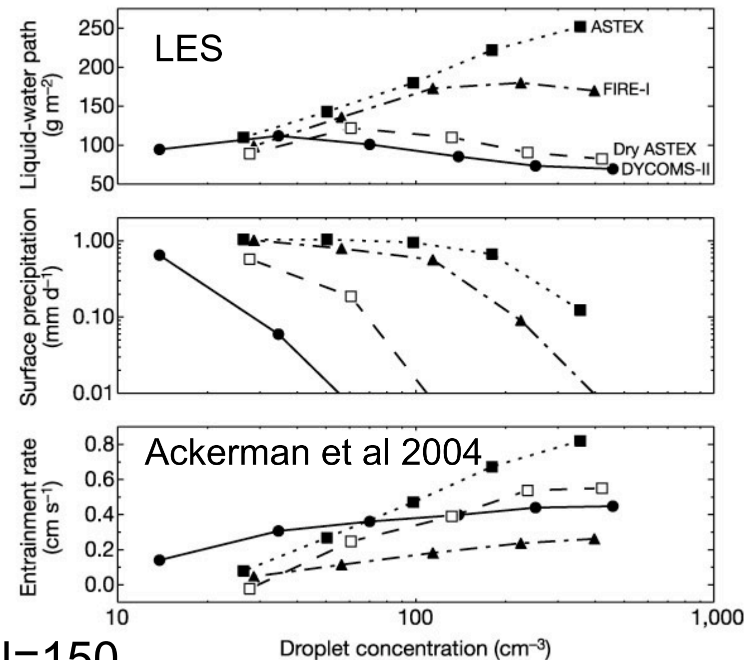
VIS r_{eff} LWP

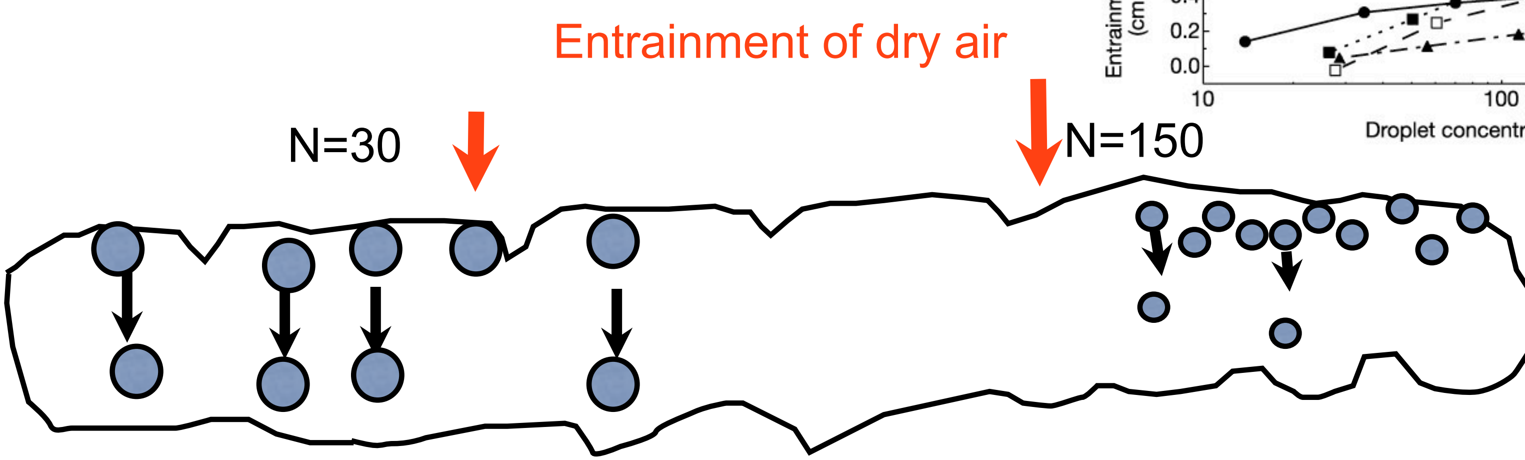


Factor of 2 LWP reduction in the track almost cancels out brightening of the clouds due to the high CCN producing smaller droplets.

Less droplet sedimentation enhances entrainment

- More aerosol
- Smaller, slower falling cloud droplets
- Droplets stay in entrainment zone where they evaporatively cool entrained dry air
- More entrainment, thinner cloud





Ackerman et al. 2004; Bretherton et al. 2007

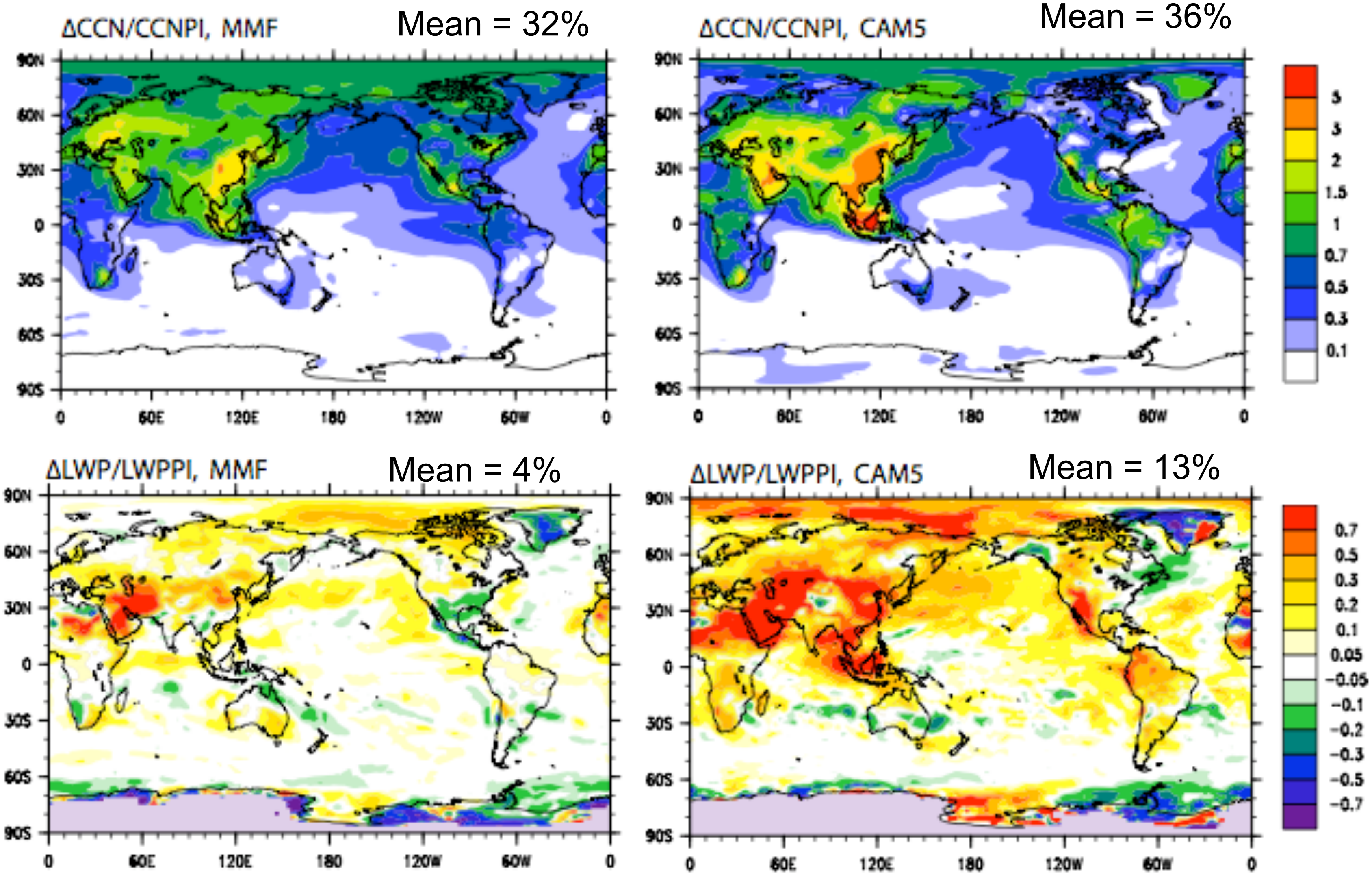
This effect is not well represented in most climate models

GCM differences in AIE depend on LWP response

PNNL-MMF
AIE = 0.8 W m^{-2}

CAM5
AIE = 1.4 W m^{-2}

Wang et al. 2011



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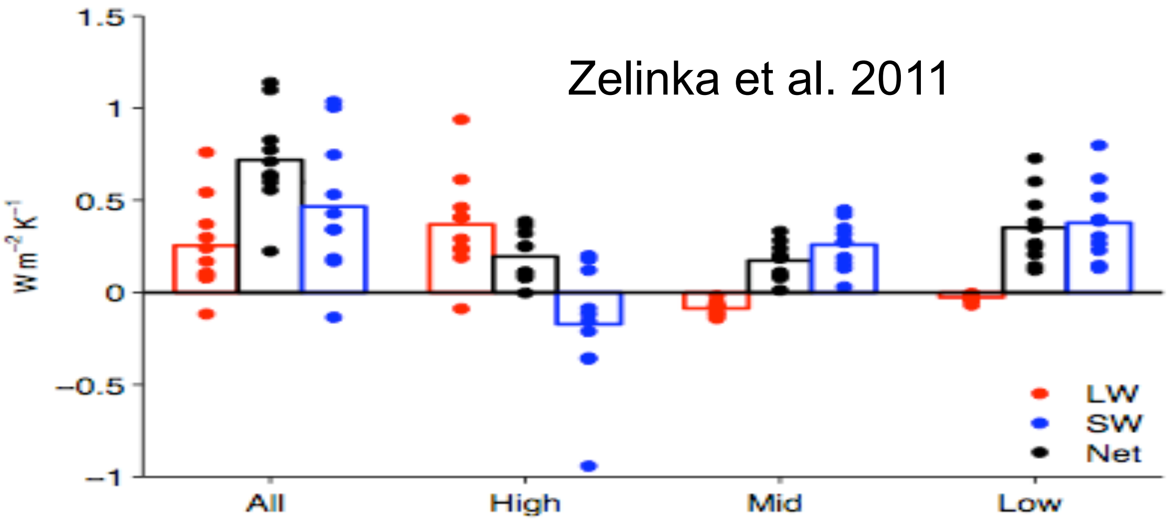
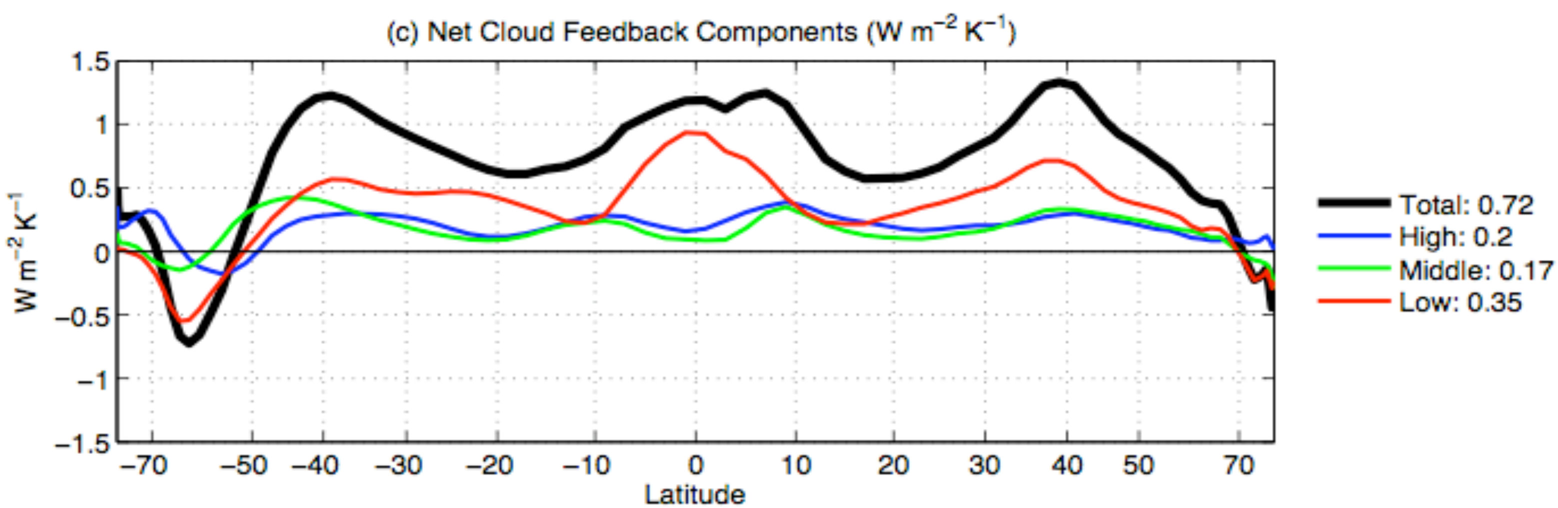
Boundary-layer cloud feedbacks

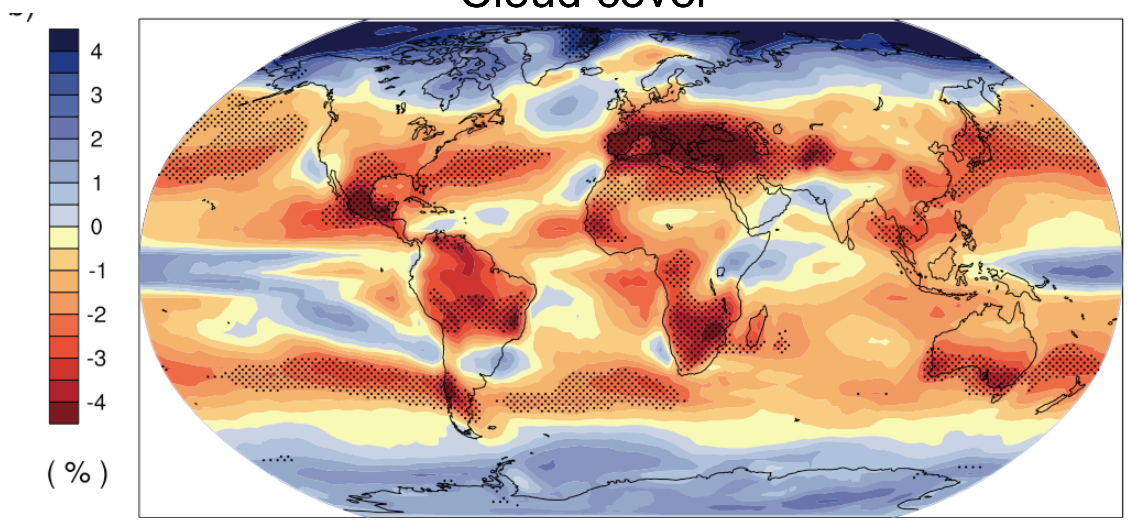
- Largest cause of intermodel spread in climate sensitivity
- Important to Arctic sea-ice loss



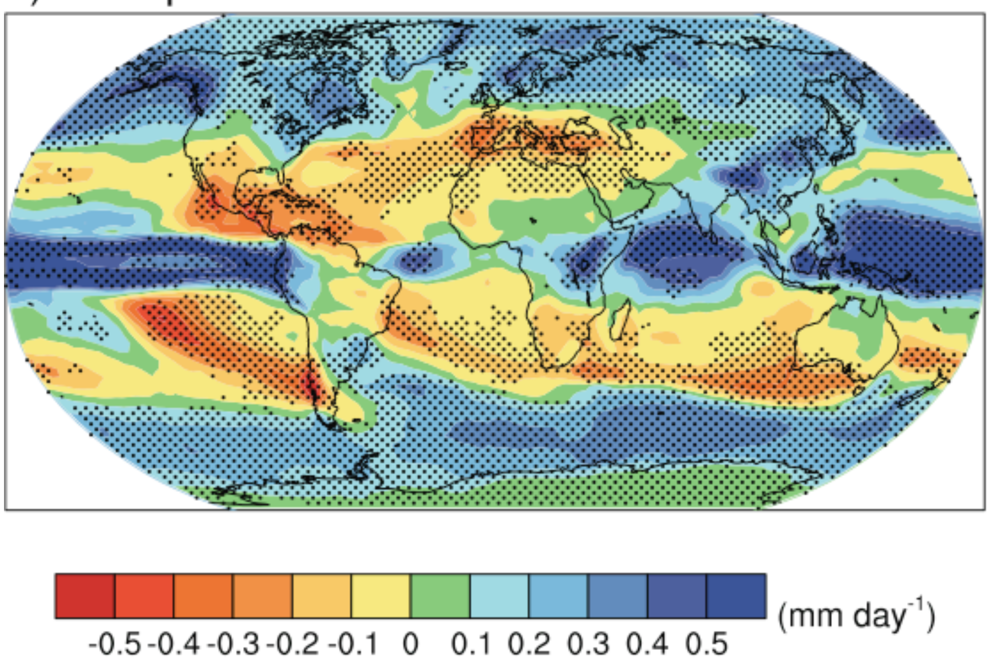


Cloud and precipitation trends are related

Cloud cover



a) Precipitation



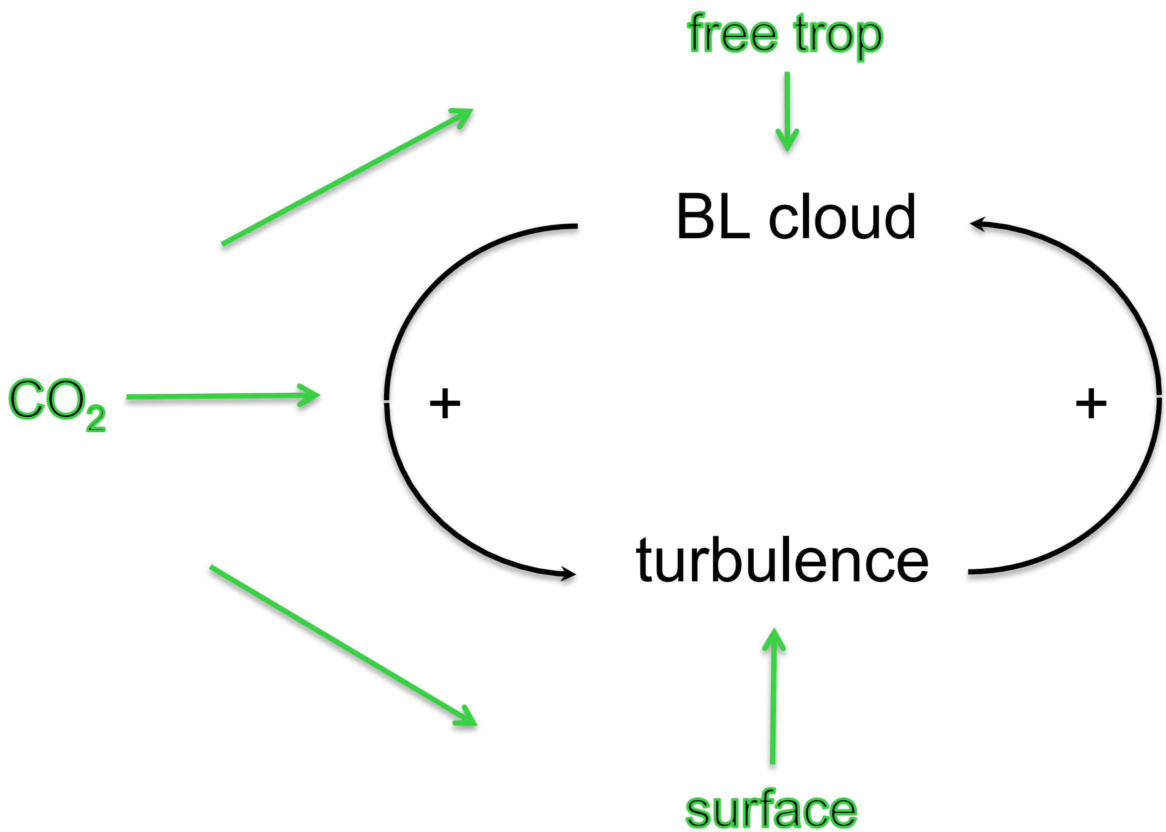
Multimodel average reflects circulation shifts (Held and Soden 2006)

Cloud decrease is more pervasive than rainfall decrease

For deep clouds, this is due to weakening vertical mass fluxes. For boundary layer clouds, still no accepted physical explanation.

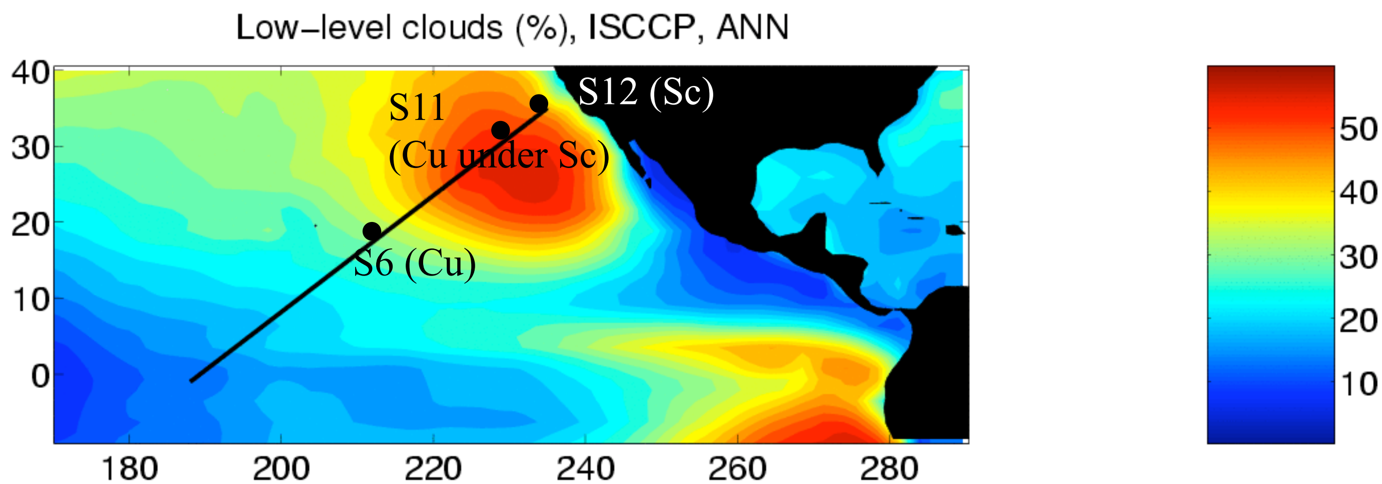
IPCC 2007

Cloud-radiation-turbulence feedback in CTBLs

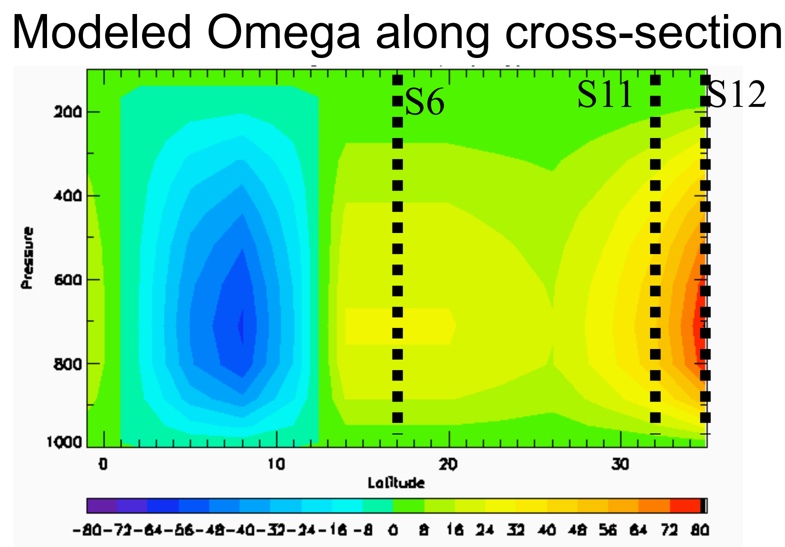


Challenge: positive feedback involving small-scale processes that has not usefully been constrained by observations.

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

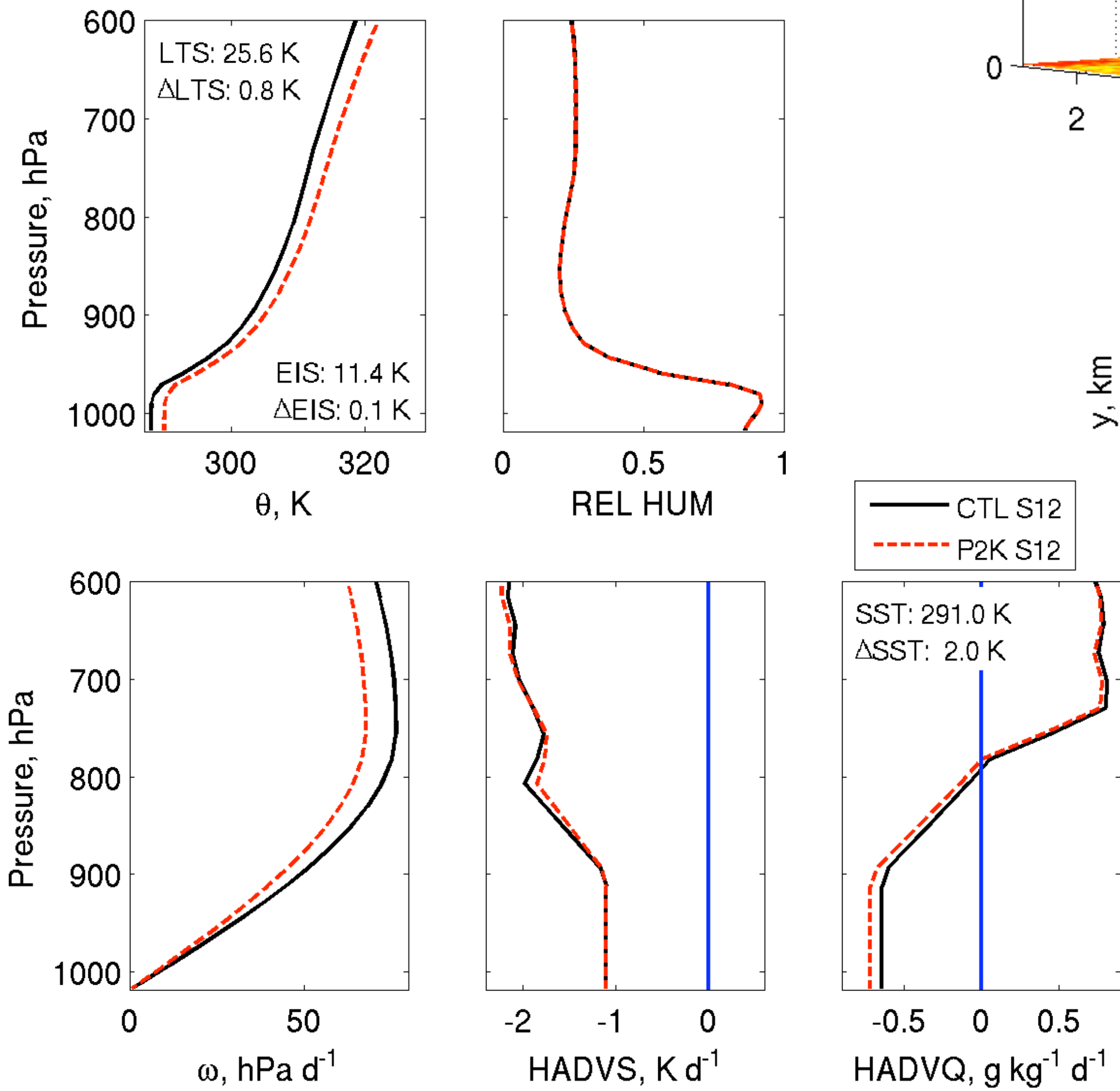


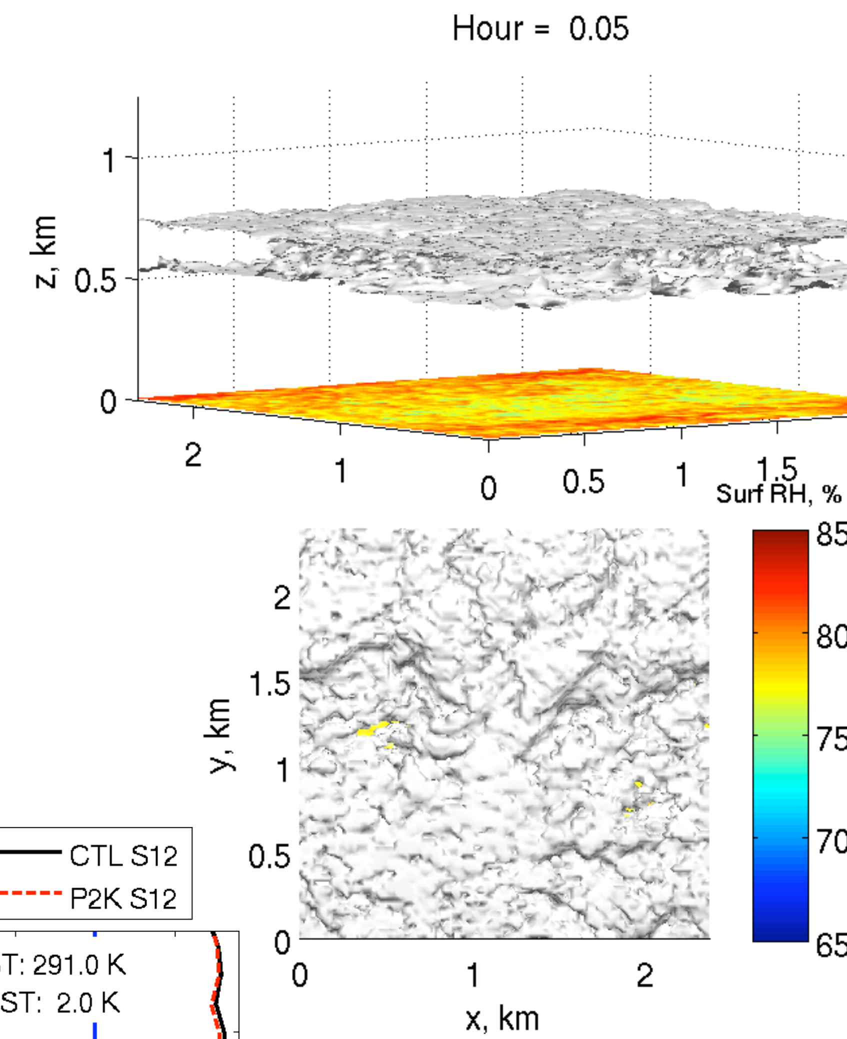
- Focuses on three points along the GCSS Pacific Cross-section.
- Points range from shallow, well-mixed boundary layer near coast to deeper trade cumulus boundary layer well offshore.
- Five LES models and 20+ single column models participating.



Coordinators: Minghua Zhang, Chris Bretherton, Peter Blossey, Stephan de Roode

CGILS S12: Coastal SCu



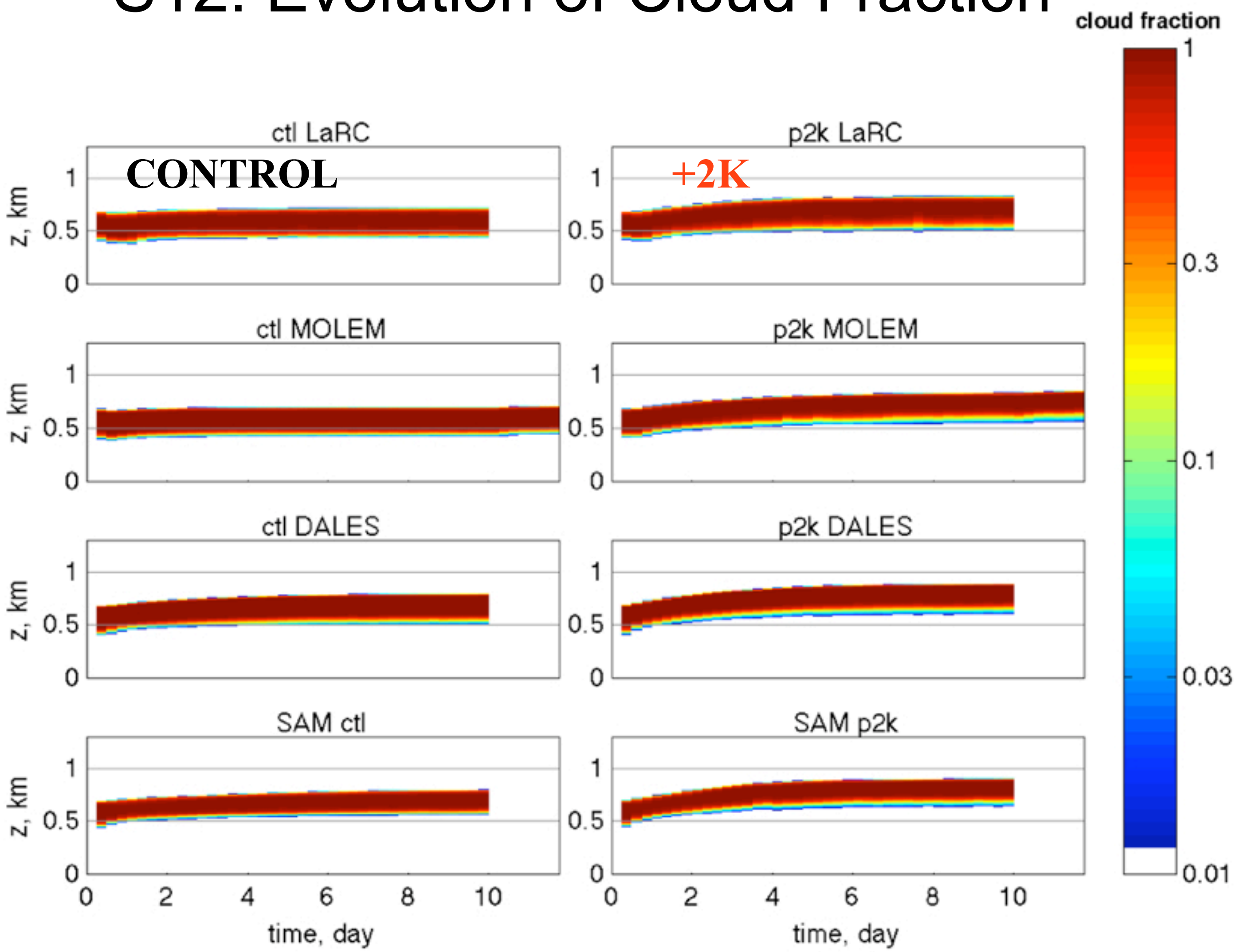


Δx=25m

Δz=5-15m

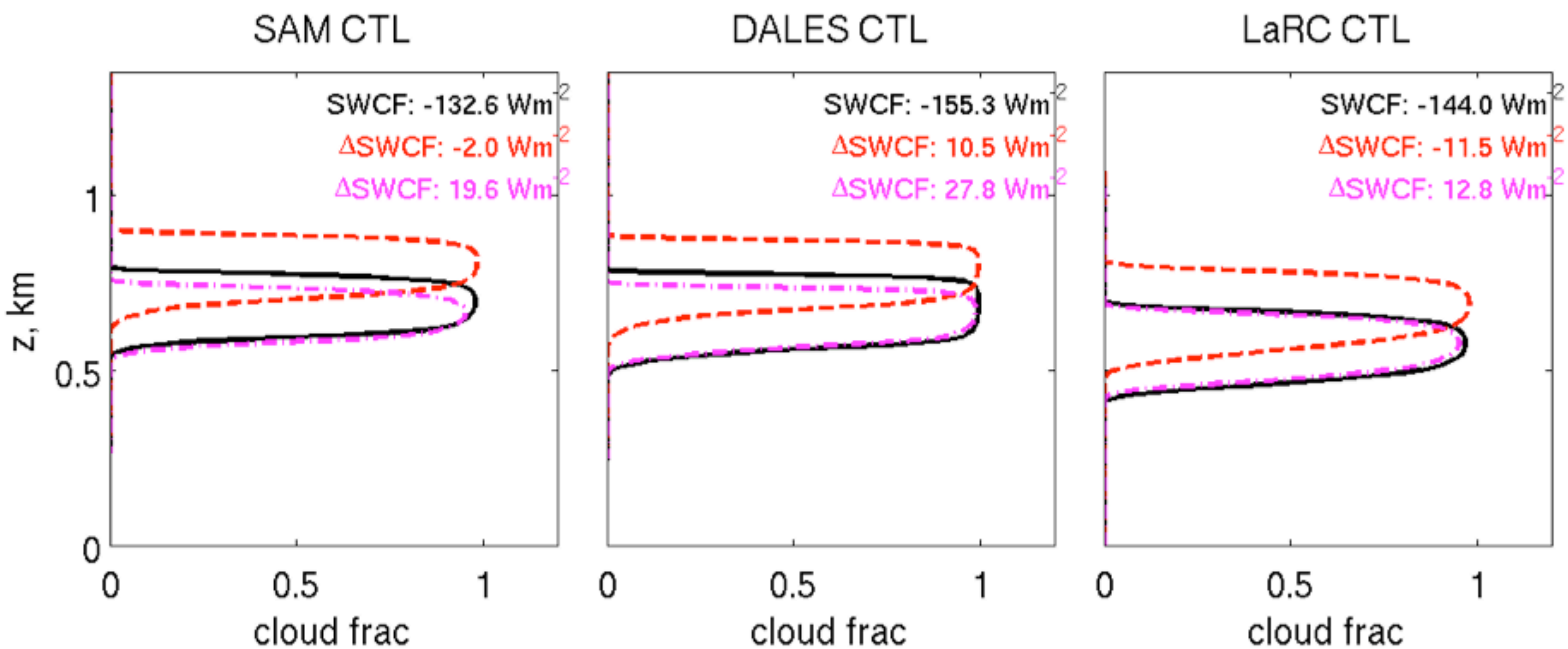
ΔEIS ~ 0

S12: Evolution of Cloud Fraction



- Models agree well: Control case well-mixed, +2K runs deepen.
- Differences mainly due to advection schemes at sharp inversion

7.5-10 day means with/without +2K ω reduction



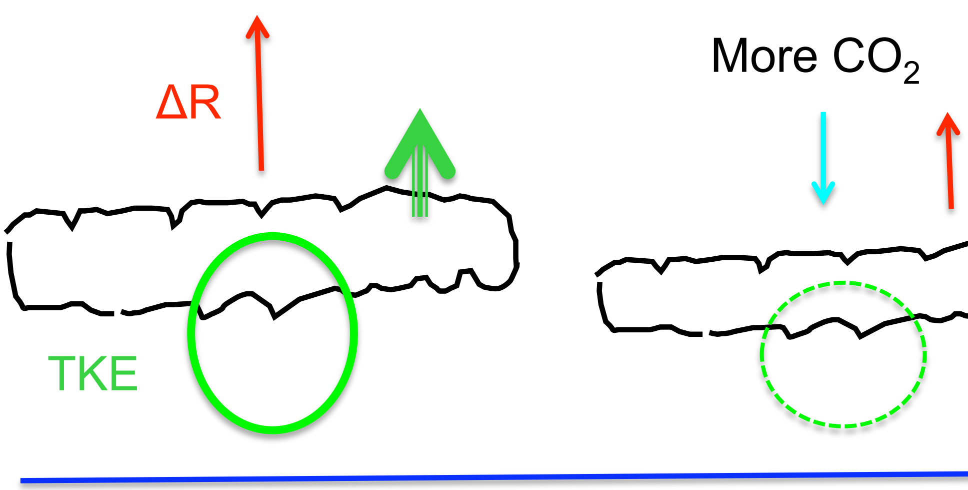
with Δω: Inversion deepening, mixed cloud response
without Δω: Slight inversion thinning, distinct cloud thinning

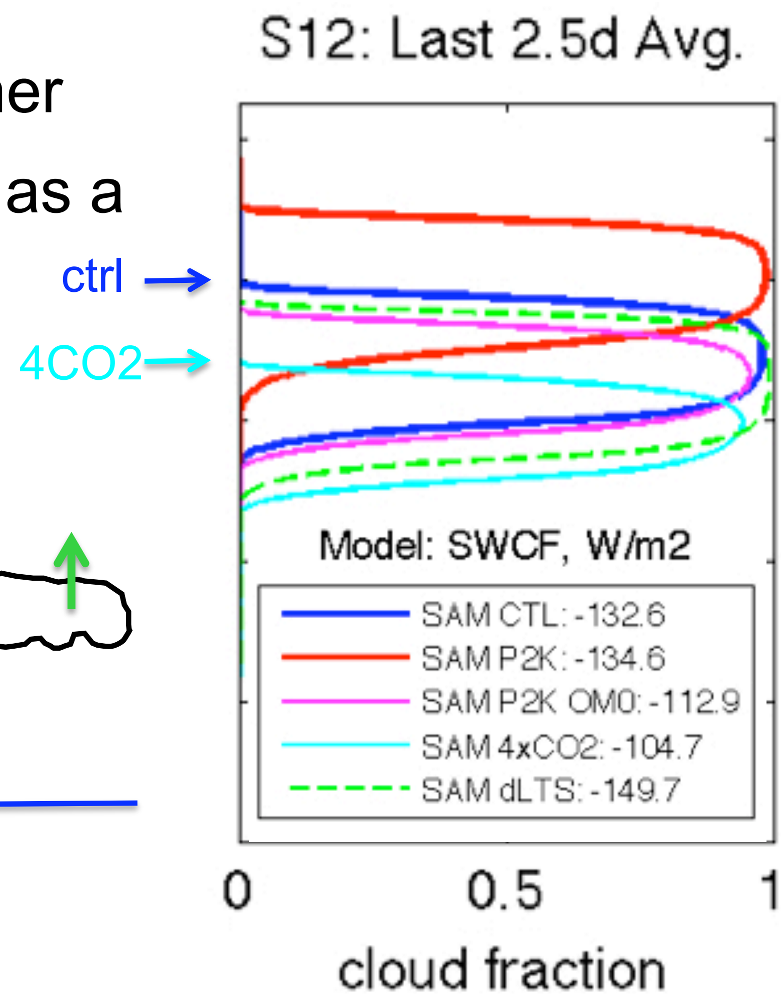
Δω more important than ΔEIS to boundary-layer cloud feedback?
Sat obs of same sensitivity to Δω: Myers & Norris A48B poster

Radiative effect of CO_2 on boundary-layer cloud

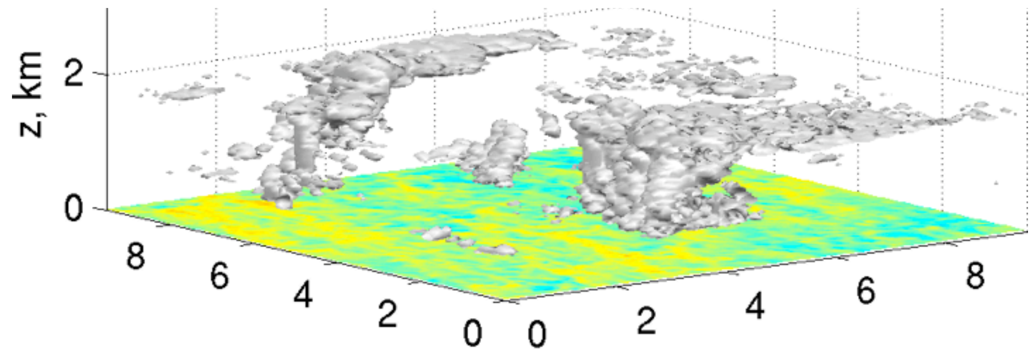
- Quadruple CO_2 without changing free-trop T,q profiles

- Inversion lower and cloud thinner
- ΔSWCF = +28 W/m^2 as strong as a ΔEIS of 3.5 K.

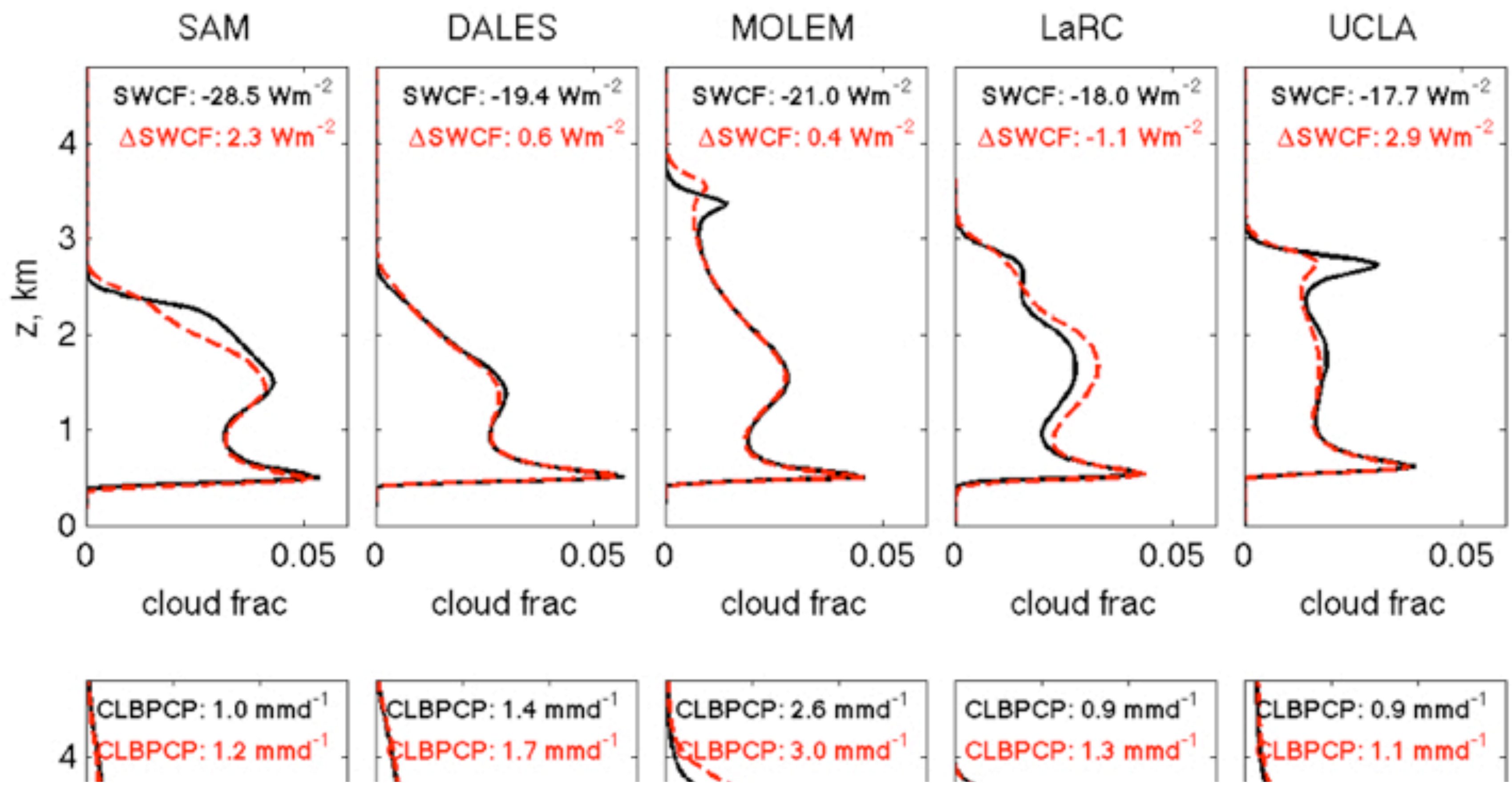




S6 trade cumulus case



- Cloud layer deepens until precipitation strengthens
- +2K has only weak impact on layer depth or cloud forcing



Conclusions

- Interplay of observations, process models and parameterization development makes better GCMs and climate predictions
- Factors controlling mean cloud distribution may be less important for its climate response
- Nondrizzling and drizzling BL clouds respond oppositely to aerosol increases.
- In global average, LES suggest boundary layer cloud feedbacks may have more to do with changes in radiative destabilization and subsidence than changes in stratification.
- Overall, LES support moderate positive subtropical cloud feedback in Sc regions, weaker feedback in Cu regions.