MMF tropical cloud response to 4xCO2 with fixed SST - a dynamically coupled tale

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Photo courtesy Rob Wood

Cloud feedbacks in SP-CAM: An ongoing story

- Wyant et al. (2006, 2009) studied SP-CAM T42L28 cloud response to +2K SST change using 3.5-year simulations.
- Caveat: Δx = 4 km under-resolves boundary-layer Cu & Sc.
- They found strong low cloud increase in the warmer climate (negative feedback on climate change) - attributed to increased capping inversion strength and stronger clear-sky radiative cooling.
- Most conventionally-parameterized climate models do the opposite

- We have also looked at MMF 4xCO_2 cloud response with fixed SST.
- We presented tropical low cloud response at prior CMMAP workshops.
- In writing this work up for JAMES, we have realized the tale is more interesting than we initially realized, and involves the response of the 'monsoonal' (land-ocean) circulations to 4xCO_2.

Review: 4xCO_2 MMF simulation pair

- 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 by Marat used with the first ½ year discarded...short, but results hold in each of the 2 years.

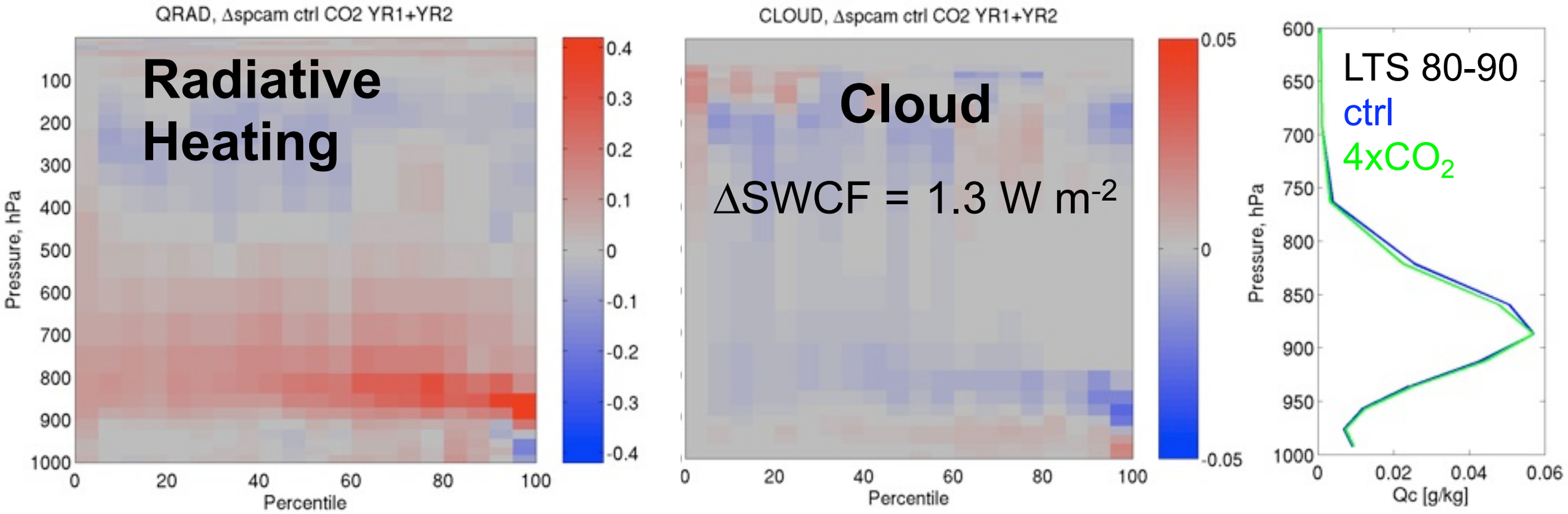
Working hypothesis:

4xCO_2 $\Rightarrow$ ~10 W m^{-2} more downwelling LW
$\Rightarrow$ Less PBL radiative destabilization
$\Rightarrow$ Less PBL cloud and entrainment
Shallower capping inversion

[This would mitigate the +2K low cloud increase]

Results (30N-S ocean-only, binned by LTS percentile)

$\Delta 4xCO_2$



MMF PBL radiative cooling decreases, low cloud subsides and |SWCF| decreases, as expected. Hypothesis confirmed!

But wait...

30S-30N ocean ΔLWCF = - 2.2 W m^{-2}. There are substantial changes in deep clouds and low clouds over warm SST as well as the changes in PBL clouds over cool SST. There is more to the tale...

CO_2 affects entire radiative cooling profile

- For a fixed atmosphere over fixed SST, more $CO_2 \Rightarrow$
  - less TOA outgoing longwave flux
  - less atmospheric column-integrated cooling
    (surface net longwave decreases much less than TOA)
  - less tropics-wide rainfall (latent heating)
  - less surface latent heat flux

For a fixed atmosphere over land, more $CO_2 \Rightarrow$

- initially, land heats up.
- promotes convection, moving rain from ocean to land.

These changes affect patterns of tropical cloudiness

Tropics-wide (30N-S) $\Delta 4xCO_2$ statistics

ΔLW_{TOA} = -8 W m^{-2} ΔLW_{sfc} = -3.3 W m^{-2} $\Delta T_{land,sfc}$ = +0.5 K

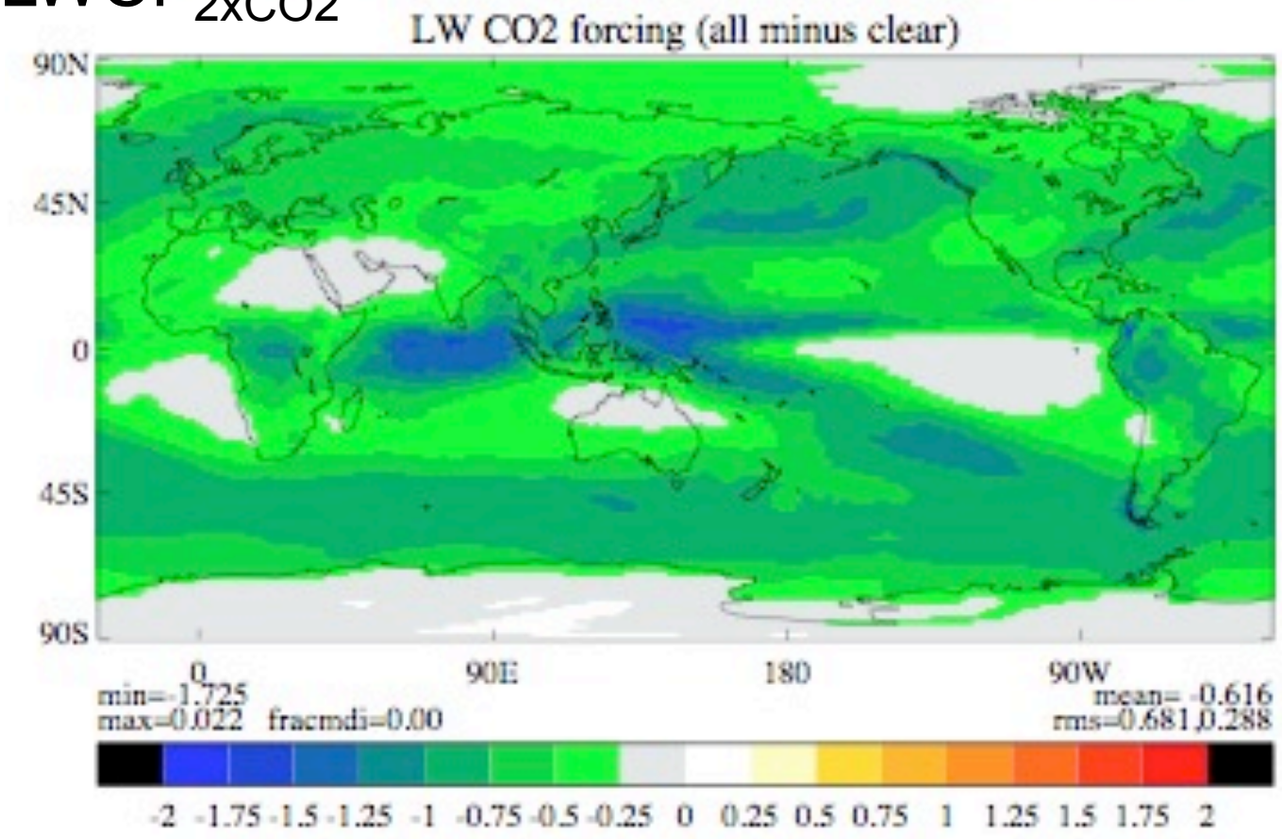
- Less LW flux divergence and an overall rainfall reduction with $4xCO_2$.

	Tropics -wide	Ocean	Land	
ΔP	-0.13	-0.25	+0.25	mm d^{-1}
ΔSWCF	+0.4	+1.3	-2.5	W m^{-2}
ΔLWCF	-1.3	-2.2	1.5	W m^{-2}

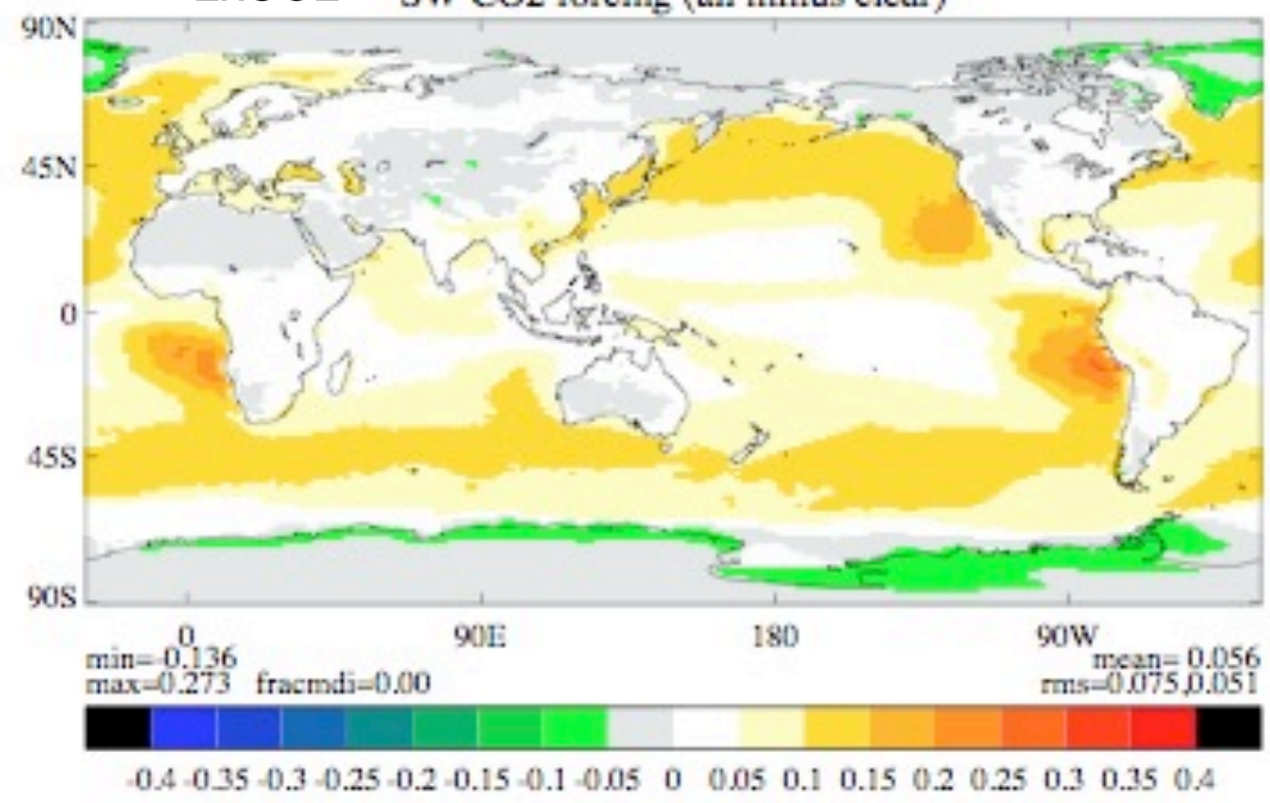
Land fraction = 0.26

- Rain and deep clouds migrate from ocean to warmer land. (SST fixed.)
- Overall reduction in cloud albedo.
- ΔLWCF mainly from ΔCO_2 rather than cloud changes (Soden et al, 2004).

$\Delta LWCF_{2xCO2}$



$\Delta SWCF_{2xCO2}$



from Mark Webb (UKMO)

Direct 2xCO_2 effect on cloud forcing

Clouds compete with CO_2 as greenhouse agents.

With fixed clouds, doubling CO_2 decreases tropics-mean LWCF by 0.6 W m^{-2} with little effect on SWCF. 4xCO_2 redoubles:

Tropical-mean fixed-cloud:

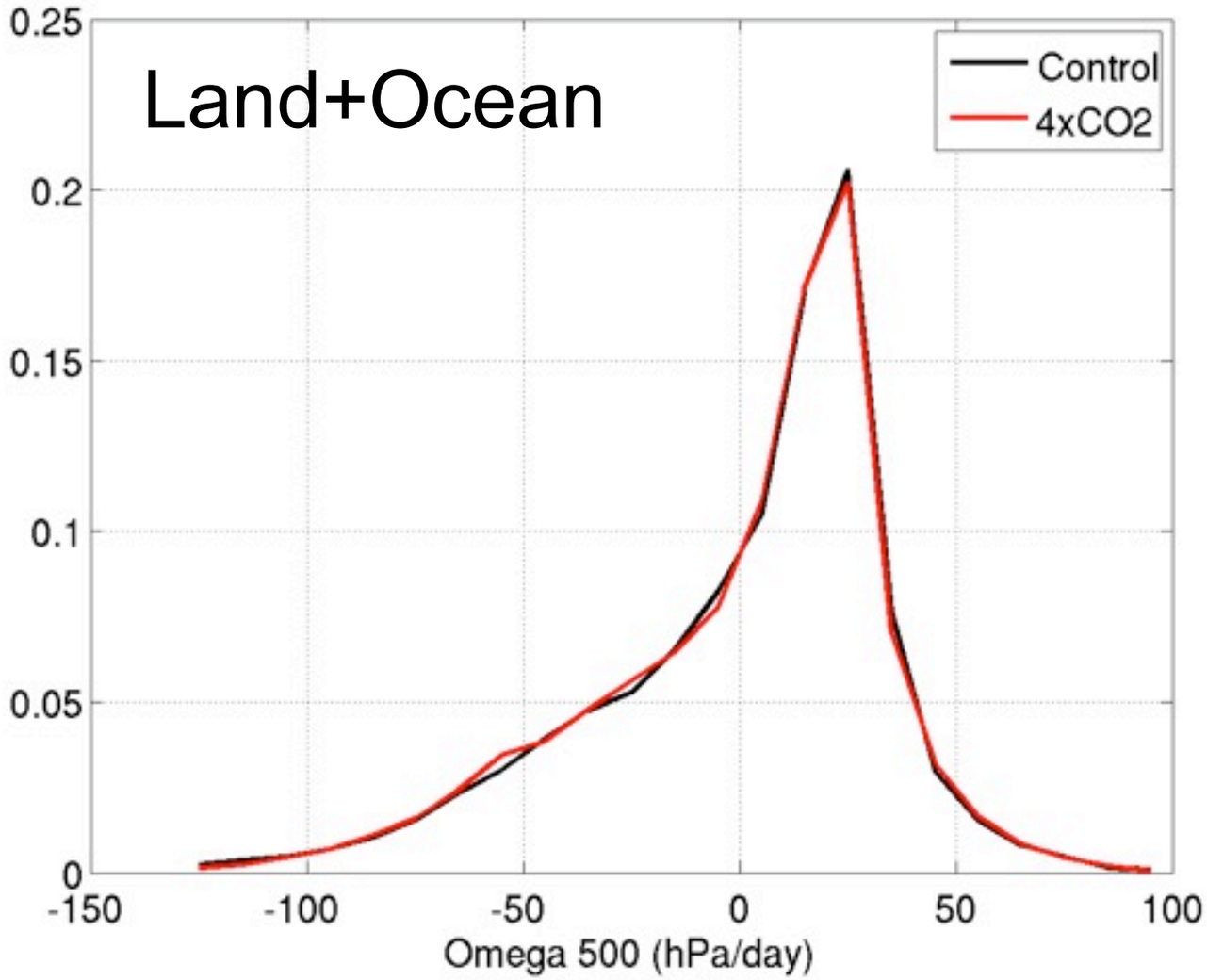
$\Delta LWCF_{4xCO2}$ = -1.2 W m^{-2}

$\Delta SWCF_{4xCO2}$ = +0.1 W m^{-2}

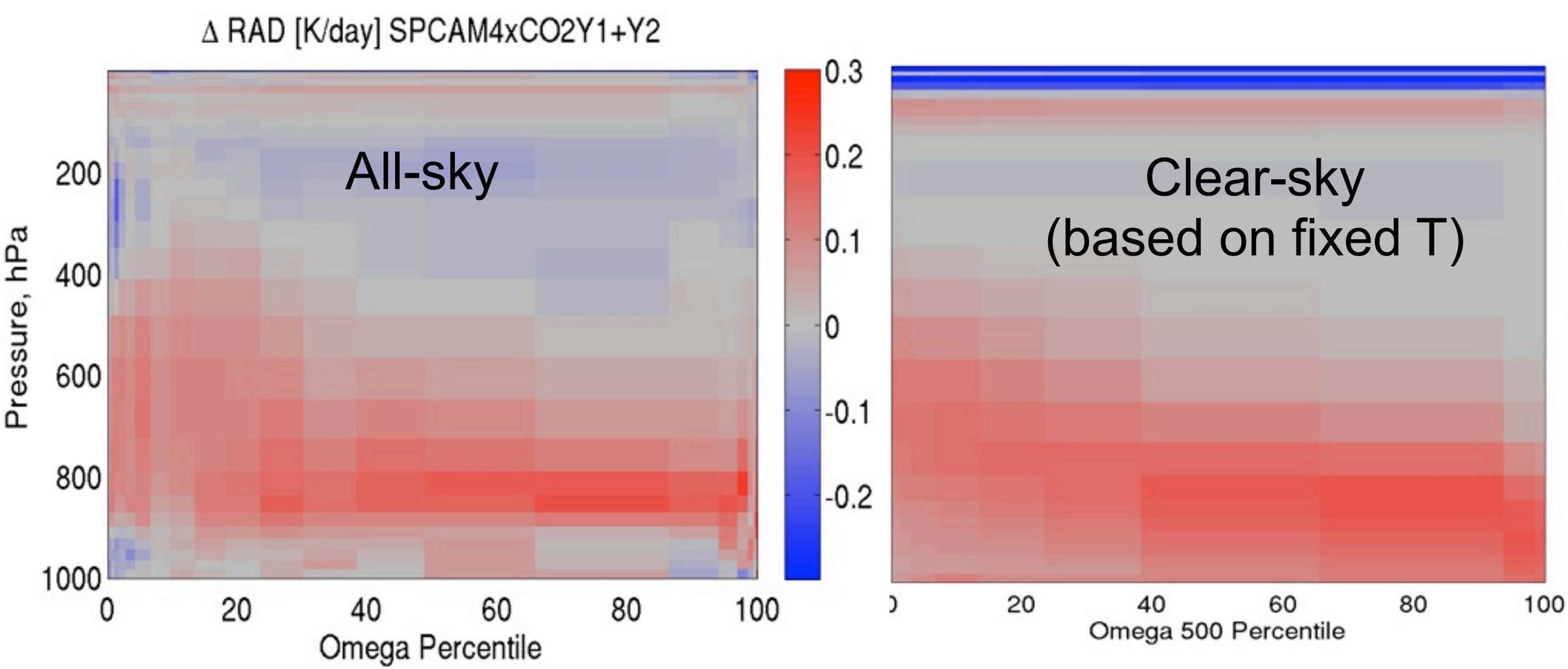
This explains the entire 4xCO_2 ΔLWCF signal (i. e. no Δ(high cloud) required.

4xCO2 tropical circulation changes

- Bin using monthly ω_{500} (rather than LTS) to include land regions
- Binning extracts robust results from 2 years of output
- No overall change to tropical overturning circulation!

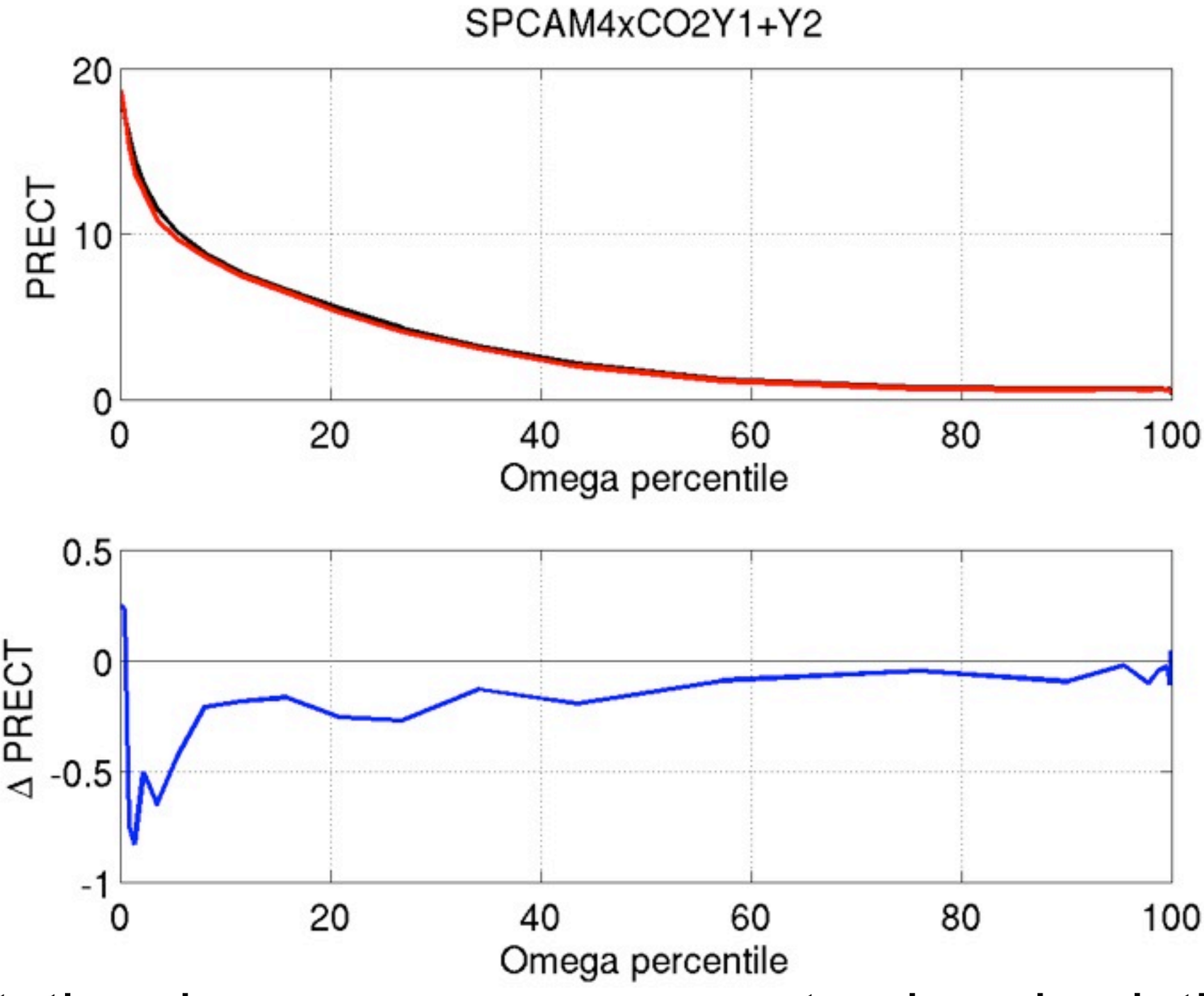


Radiative heating changes mainly due to clear-sky



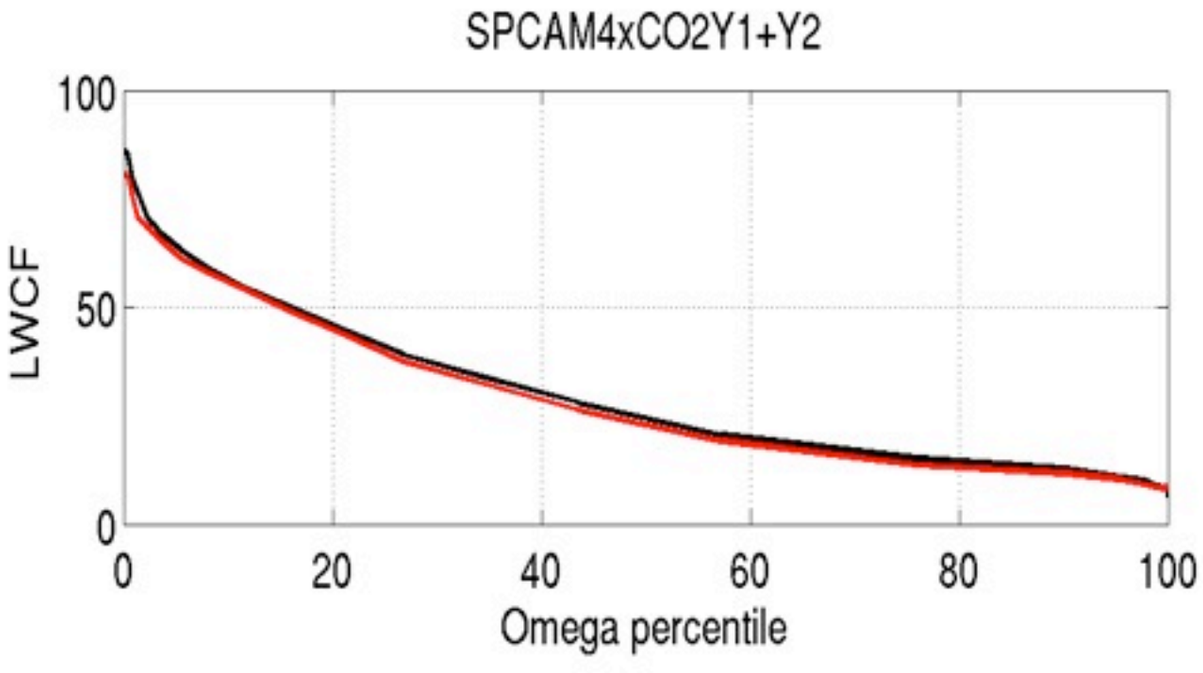
- $4xCO_2$ reduces lower-tropospheric radiative cooling
- $4xCO_2$ cools stratosphere, slightly raising tropopause.

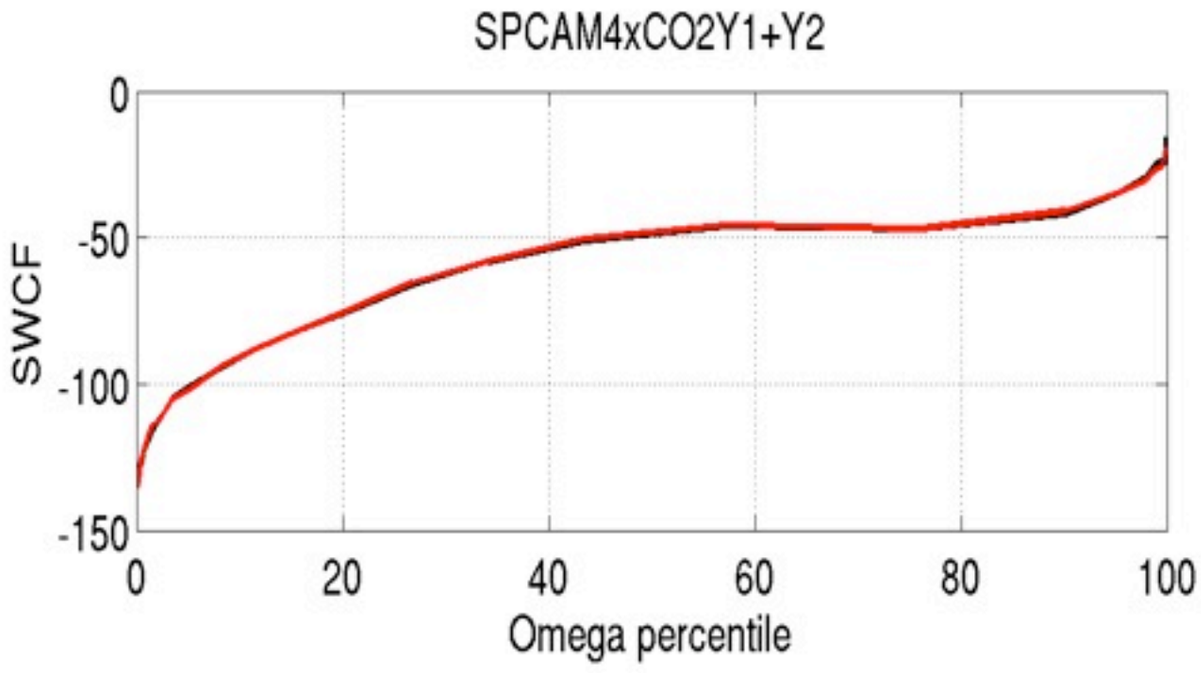
Binned precipitation

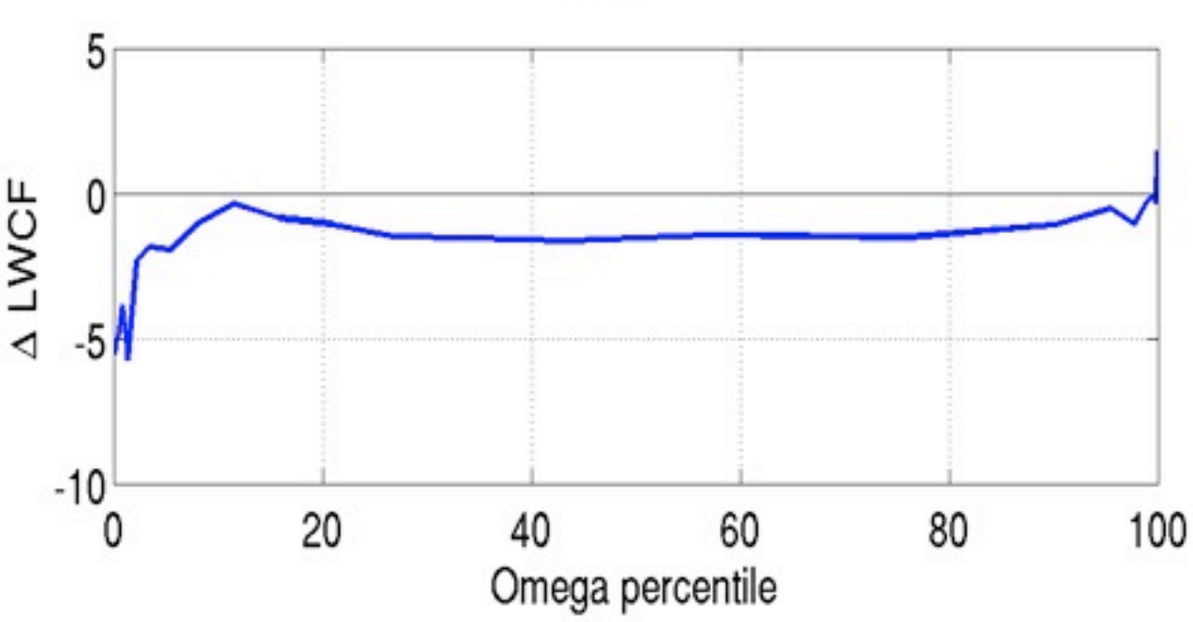


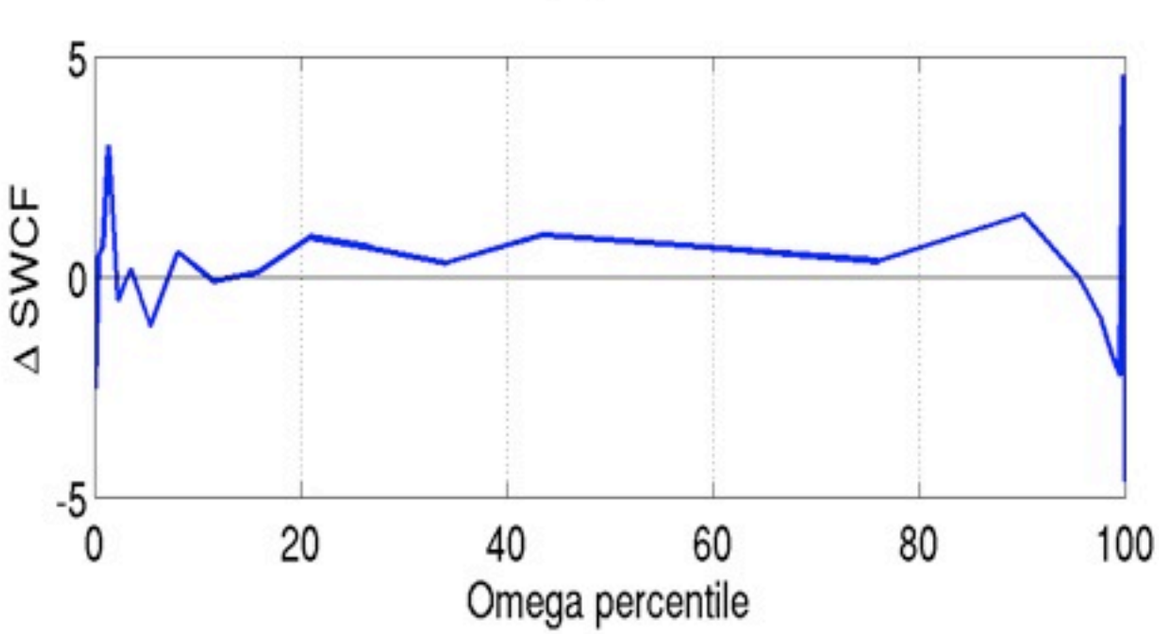
Precipitation decreases even as overturning circulation does not, due to reduced surface latent heat flux.

Binned CRF changes



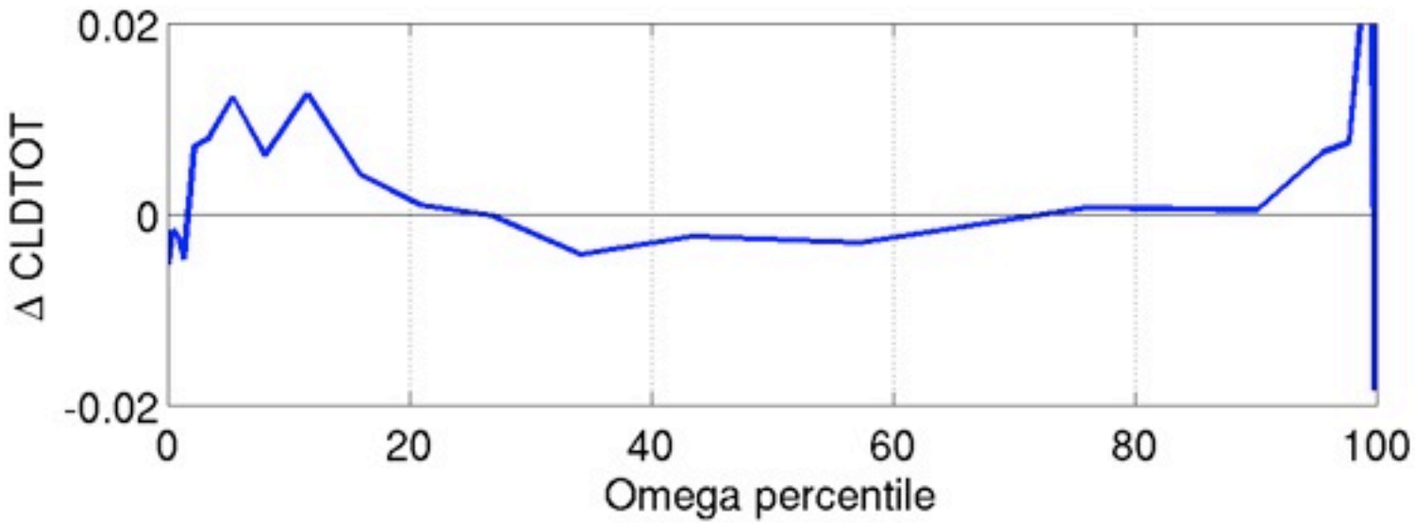




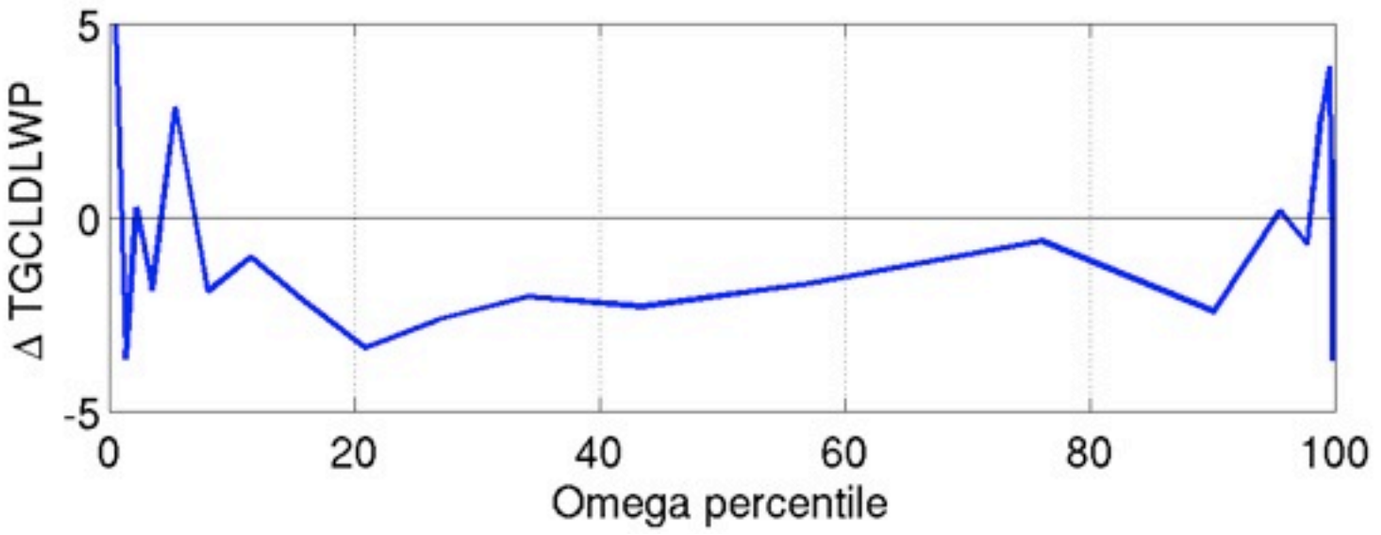


- Roughly compensating 1 W m^{-2} reductions in LWCF, SWCF except in extreme percentiles.
- ΔLWCF mainly due to ΔCO_2 with fixed clouds.

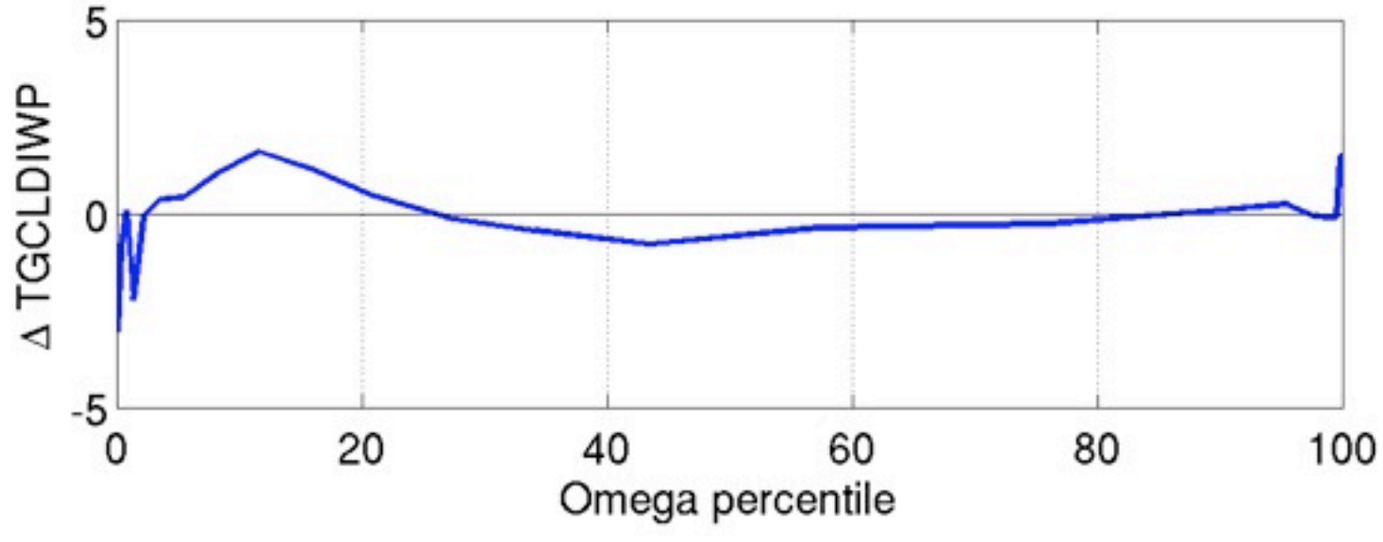
Changes in cloud fraction, LWP, IWP



Little change

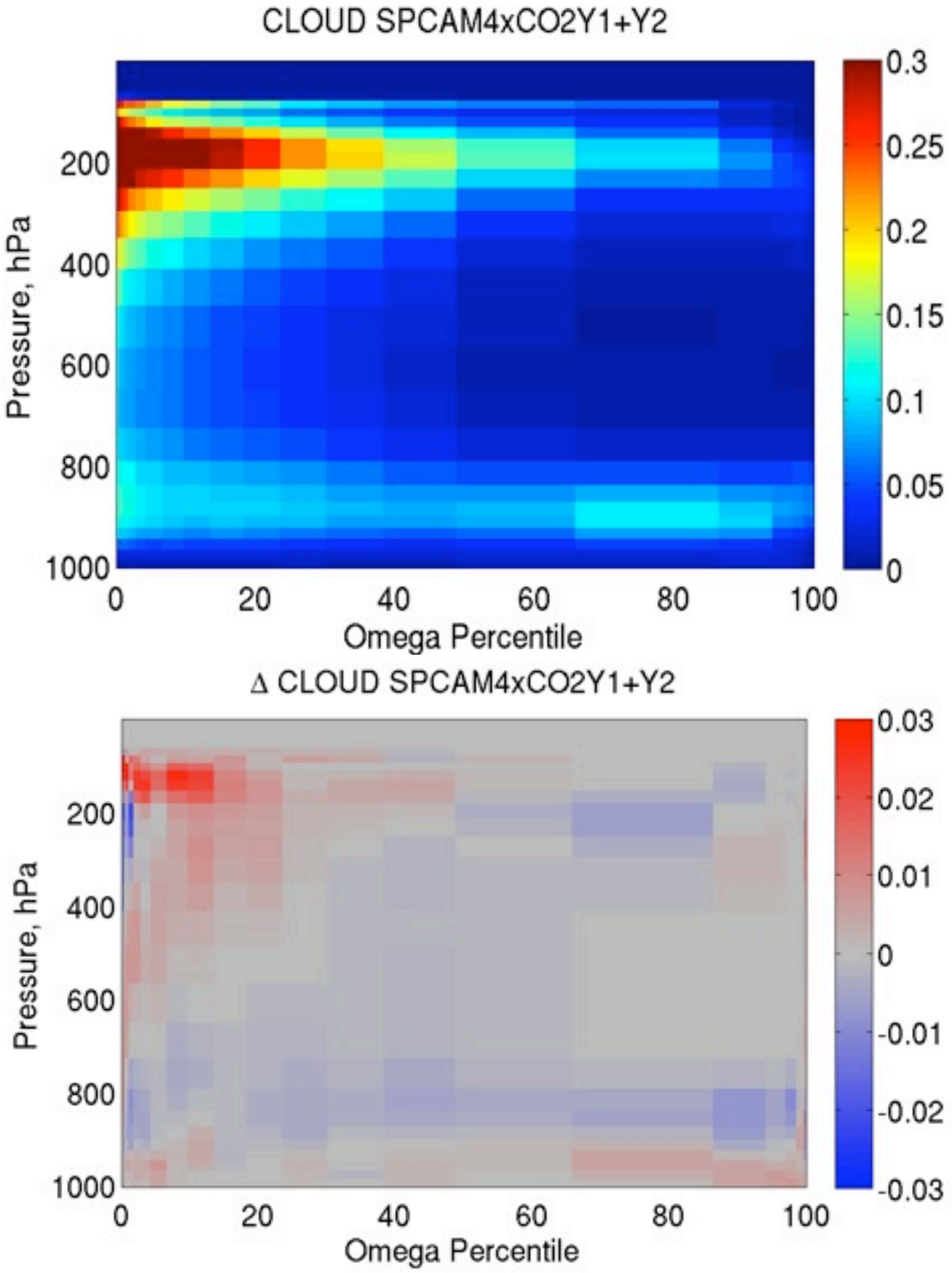


Reduction



Little change

Cloud and condensate changes



Changes in cloud:

- Higher tropopause anvil tops
- Reduced low cloud/LWP everywhere.

Summary

Quadrupling CO2 with fixed SST:

- Reduces atmospheric radiative cooling
- Decreases low cloud and liquid water path
- Lowers trade inversion in cool-SST regions
- Warms land, moving deep convection there
- Decreases rainfall and LHF but not overturning circulation
- Has mixed effects on deep cloud.
- Can decrease LWCF by ~1 W m^{-2} even with fixed cloud.

The tropics-mean 4xCO_2 cloud response is mainly due to low-cloud changes that are thermodynamically driven.

The regional 4xCO_2 cloud response must be interpreted in the context of overall tropical circulation changes.