Sensitivity of tropical water and energy cycle to SST increase and doubling CO_2 as simulated with an upgraded Multiscale Modeling Framework

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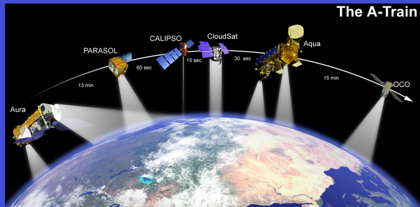
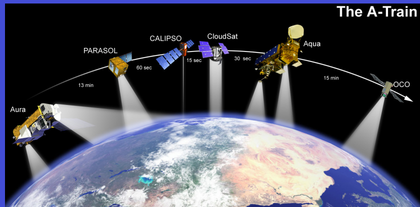


Outline

1. Why focus on low clouds?
2. Model description and simulation setup
3. Results from control and sensitivity simulations
4. Comparison with earlier studies
5. Summary and conclusions



Objectives

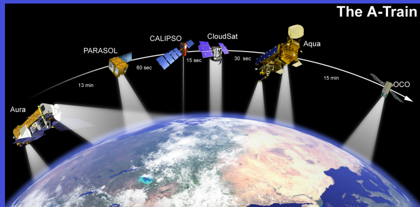
- to improve the simulation of low-level clouds using a multiscale modeling framework (MMF) with a third-order turbulence closure in its CRM component
- to understand climate sensitivity and cloud response from this MMF
- to compare with studies using an MMF with a simple first-order turbulence closure

Cheng and Xu (2011; *JGR*); Xu and Cheng (2013a,b; *J. Climate*)

Cheng and Xu (2013a; *J. Climate*); Cheng and Xu (2013b; *JGR*)

Cheng and Xu (2014, *JGR*); Painemal et al. (2015; *J. Climate)*

Cheng and Xu (2015, *J. Climate*)



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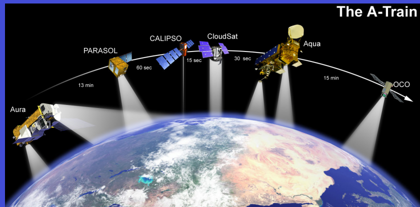
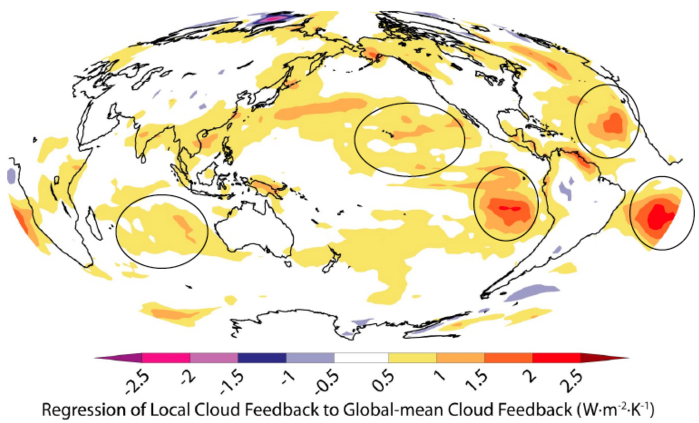


Uncertainties in cloud feedback remain in GCMs

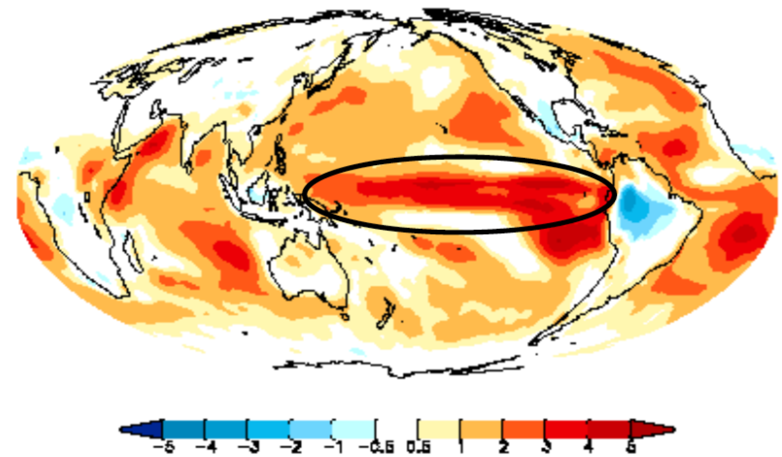
Local contribution to intermodel spread in cloud feedback: AR4



• **Most of intermodel spread arises from low stratocumulus/cumululs regions**

Soden and Vecchi (2011)

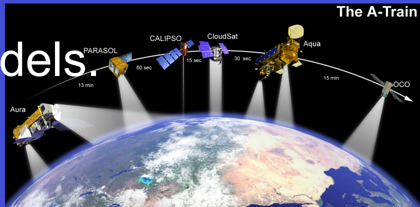
Local contribution to intermodel spread in cloud feedback: AR5



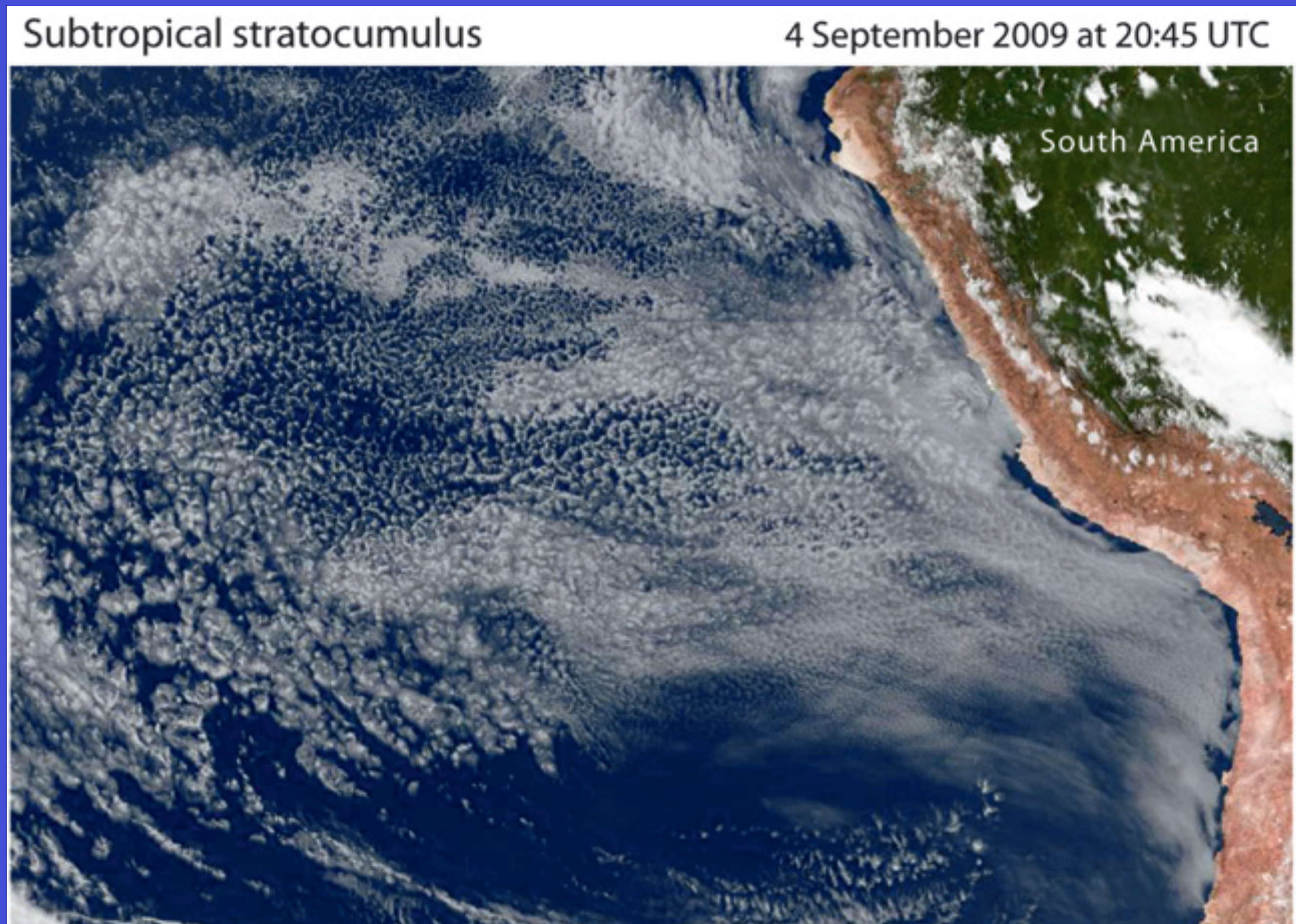
- **Low subtropical clouds still uncertain.**
- **Large contribution from equatorial Pacific.**

Soden and Vecchi (2011):

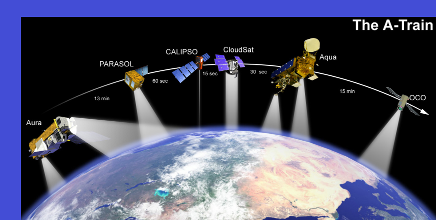
- Low cloud cover is responsible for ~3/4 of the difference in global-mean net cloud feedback among AR4 models, with the largest contributions associated with low-level subtropical marine cloud systems;
- The low-cloud inconsistency and deficiency in most of the models.



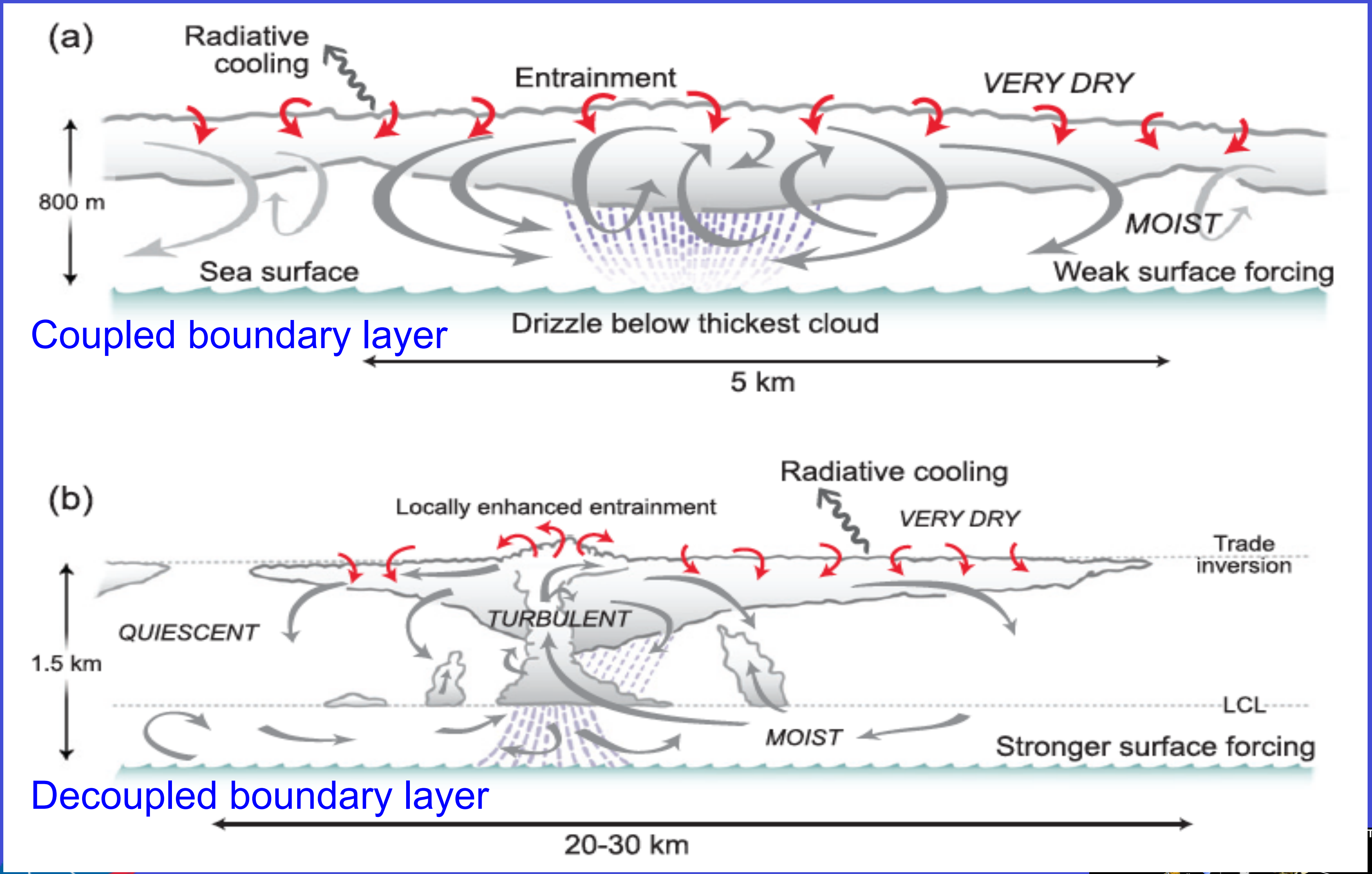
SE Pacific Stratocumulus



from Wood (2012; *Mon. Wea. Rev.*)



Processes associated with stratocumulus



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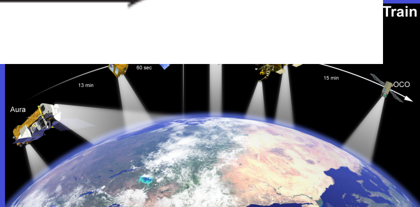

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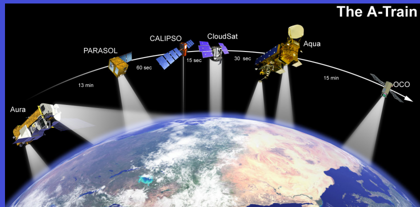
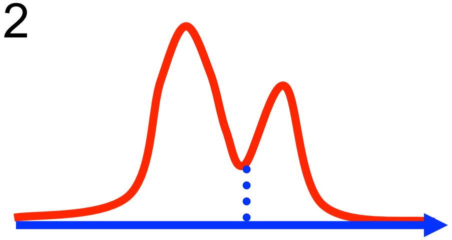


IPHOC: Intermediately-prognostic higher-order turbulence closure for cloud-resolving model (CRM)

Advance 12 prognostic equations

$$\overline{w}, \overline{q}_t, \overline{\theta}_l, \overline{w'^2}, \overline{q_t'^2}, \overline{\theta_l'^2}, \overline{w'q_t'}, \overline{w'\theta_l'}, \overline{q_t'\theta_l'}, \overline{w'^3}, \overline{q_t'^3}, \overline{\theta_l'^3}$$

Select PDF from given family to match 12 moments



Diagnose cloud fraction, liquid water from PDF

Δt_{CRM}

Use PDF to close higher-order moments, buoyancy terms

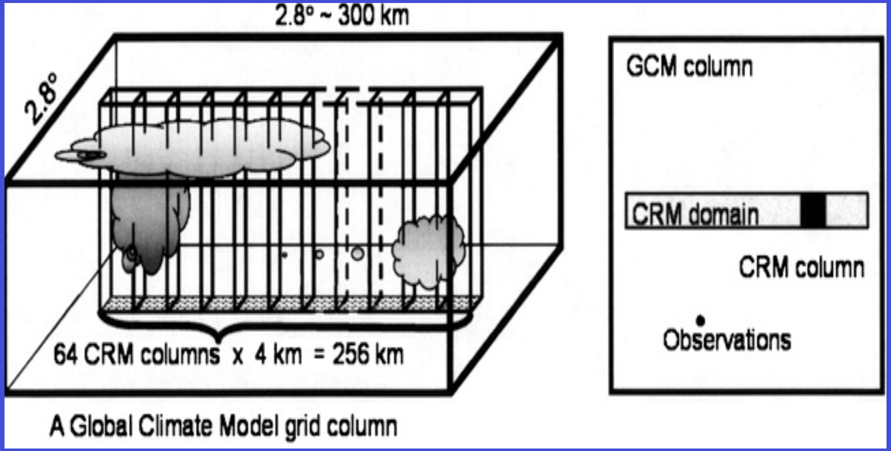
$$\overline{w'q_t'^2}, \overline{w'\theta_l'^2}, \overline{w'q_t'\theta_l'}, \overline{w'^2 q_t}, \overline{w'^2 \theta_l'},$$
$$\overline{w'^4}, \overline{w'q_t'^3}, \overline{w'\theta_l'^3}$$

Golaz *et al.* (2002); Cheng & Xu (2006, 2011)

The Multiscale Modeling Framework

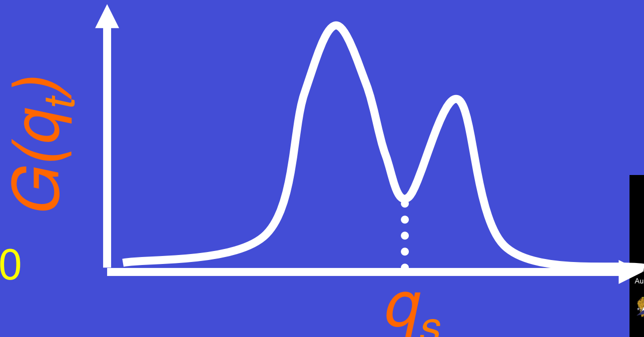
(Grabowski 2001; Khairoutdinov and Randall 2001; Cheng & Xu 2011; Xu and Cheng 2013a)

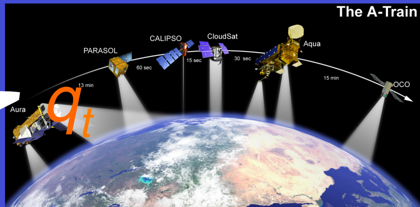
- A CRM is embedded at each grid column (~100s km) of the host GCM to represent cloud physical processes
- The CRM explicitly simulates cloud-scale dynamics (~1s & km) and processes
- Periodic lateral boundary condition for CRM (not extended to the edges)



Upgraded CRM with a third-order turbulence closure (IPHOC):

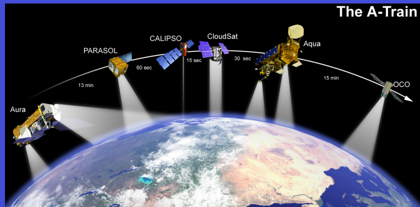
- Double-Gaussian distribution of liquid-water potential temperature (θ_l), total water mixing ratio (q_t) and vertical velocity (w), pdf = a G_1 (w, q_t, θ_l)+(1-a) G_2 (w, q_t, θ_l)
- Skewnesses, i.e., the three third-order moments, predicted
- All first-, second-, third- and fourth-order moments, subgrid-scale condensation and buoyancy based on the same PDF
- Advantages over CLUBB (Golaz *et al.*)
    1) two extra third-order moments
    2) Widths of two Gaussian unequal
    3) Merge to a single Gaussian if *sk* = 0





SPCAM-IPHOC climate simulations

- SPCAM-IPHOC
  - CAM3.5 with finite-volume dynamic core as the host GCM
  - 2-D version of System for Atmospheric Modeling (SAM) CRM with IPHOC
  - The CRM grid spacing is 4 km, with 32 columns, within a GCM grid box
  - The GCM grid spacing is 1.9°x2.5° with 32 vertical levels (12 below 700 hPa)
- Control simulation
  - Forced with climatological SST and sea ice distributions (not an AMIP-type simulation) with present-day CO_2 concentration
  - Simulation duration is 10 years and 3 months, with last nine years analyzed
- Doubled CO_2 (*2xCO_2*) simulation
  - Same as the control except that CO2 is doubled; SST and sea ice are fixed
- +2 K SST (*I2K*) simulation
  - Same as the control except that sea surface temperature is increased by 2 K



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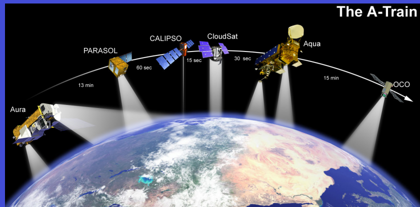
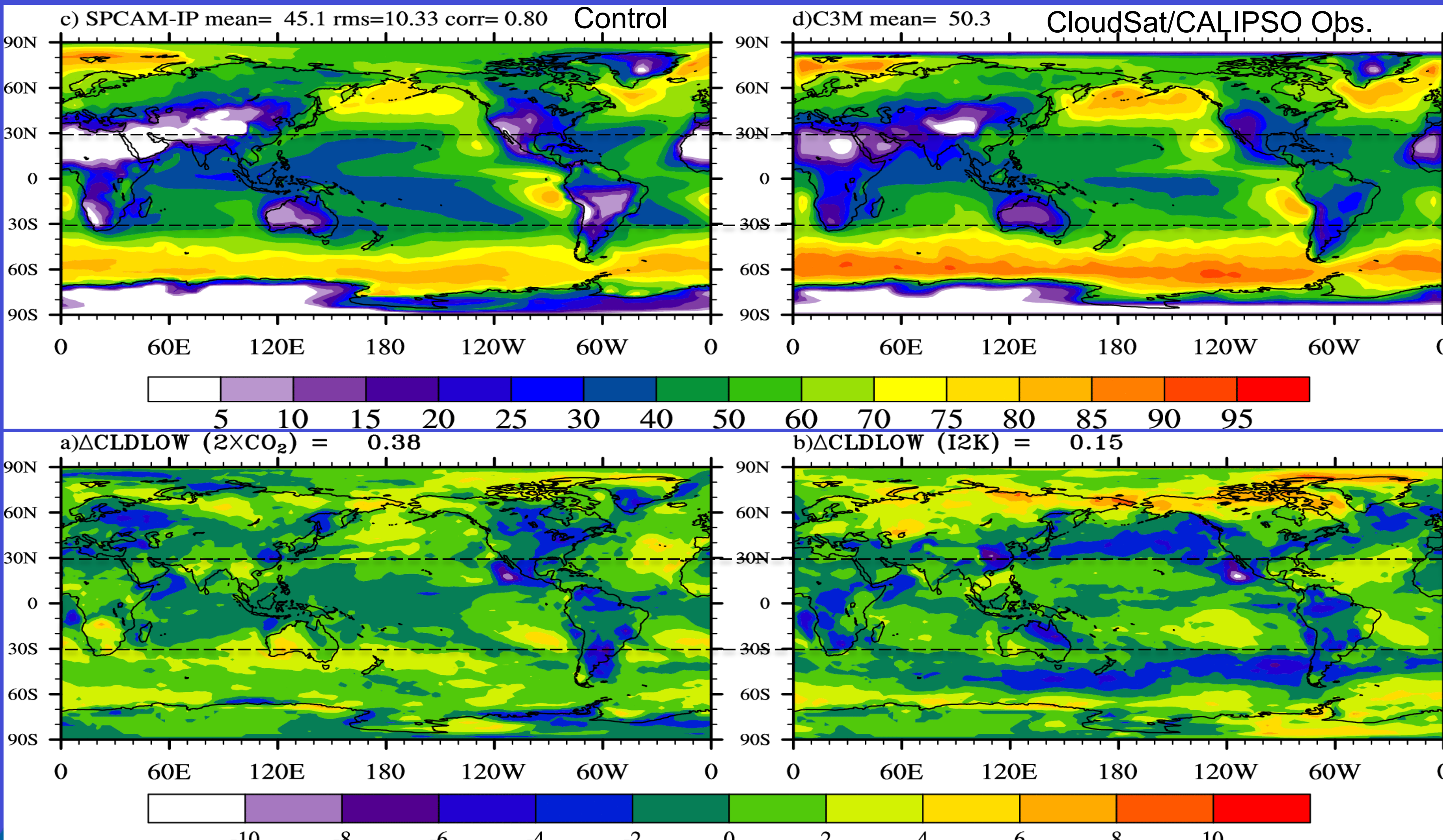
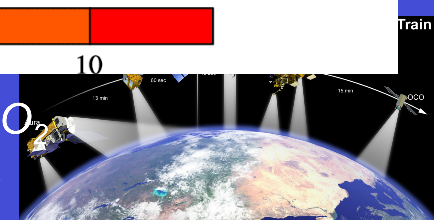


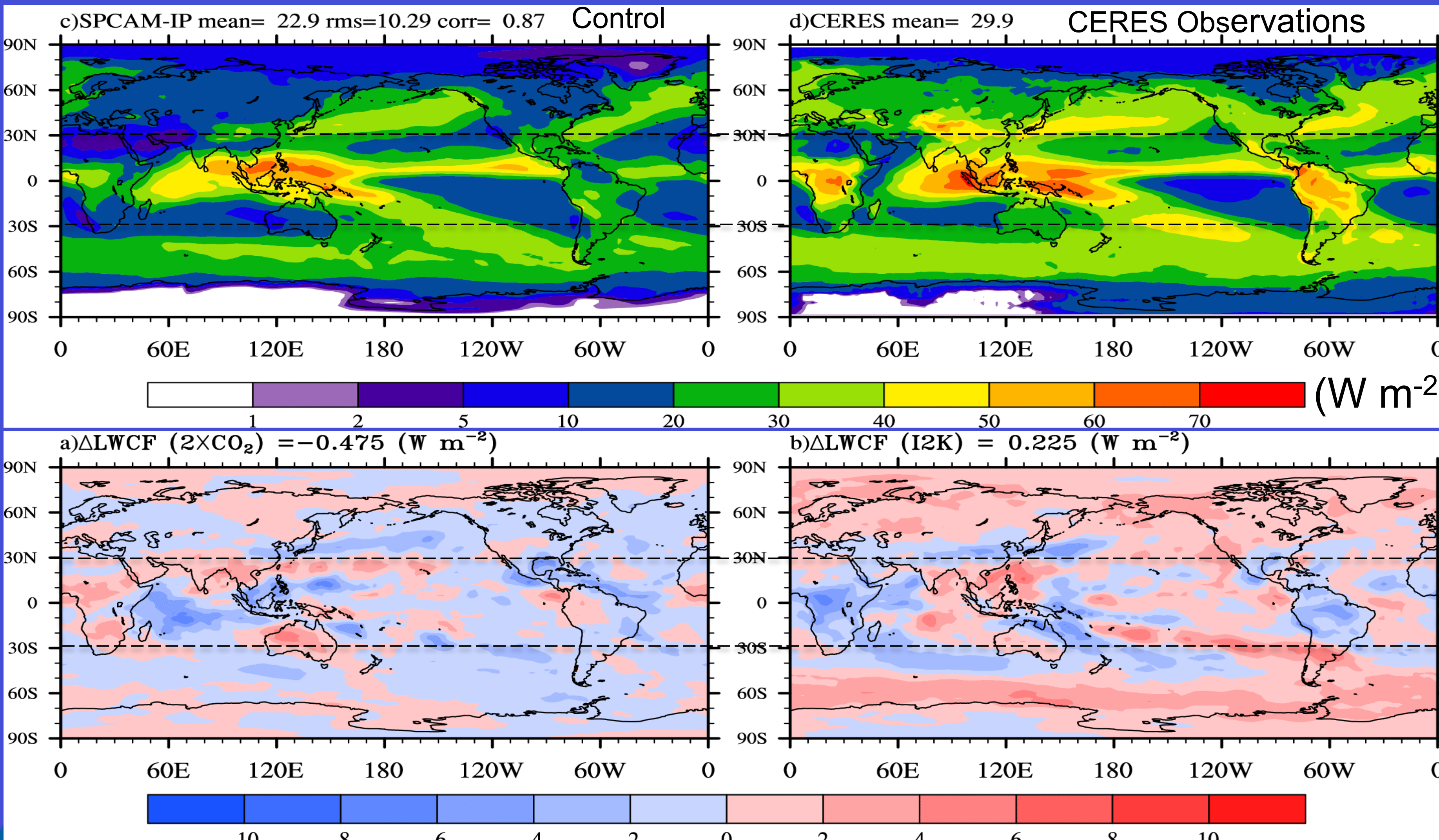
Low-level (surface -- 700 hPa) cloud fraction (%) from 10-yr control simulation and changes in sensitivity simulations



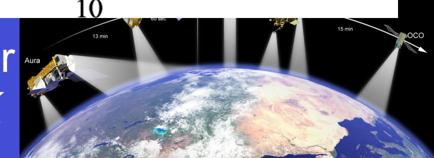


More in cumulus regions in *I2K*; but stratocumulus regions in *2xCO$_2$*
More in poleward of storm track in *I2K*, but equatorward in *2xCO$_2$*

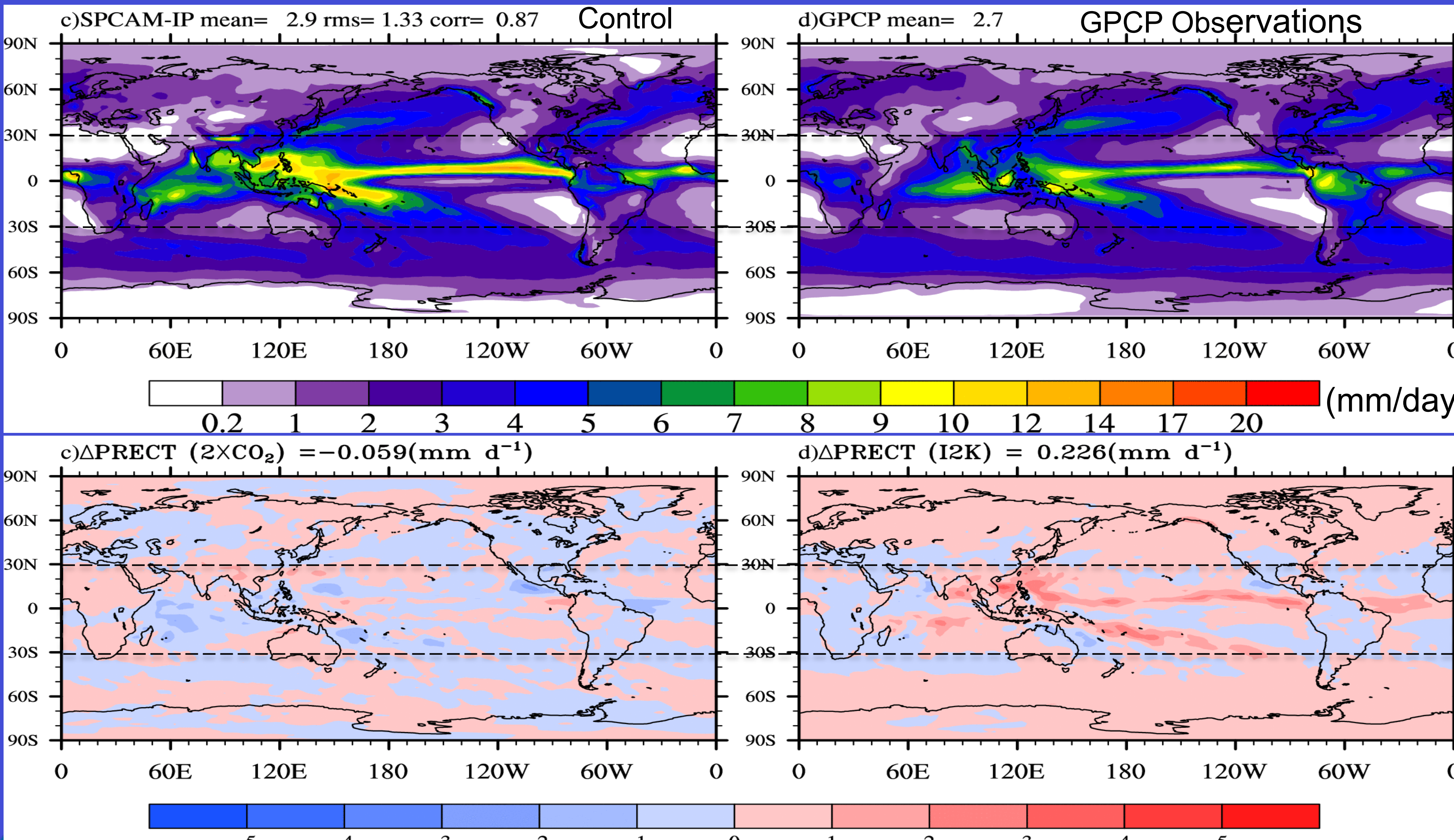
Longwave Cloud Radiative Forcing from 10-yr control simulation and changes in sensitivity simulations

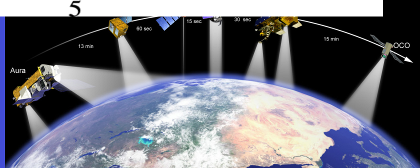


Changes in LW CRE are larger in *I2K* (higher clouds due to higher SSTs); Storm tracks moves polarwards and stronger SPCZ in *I2K*



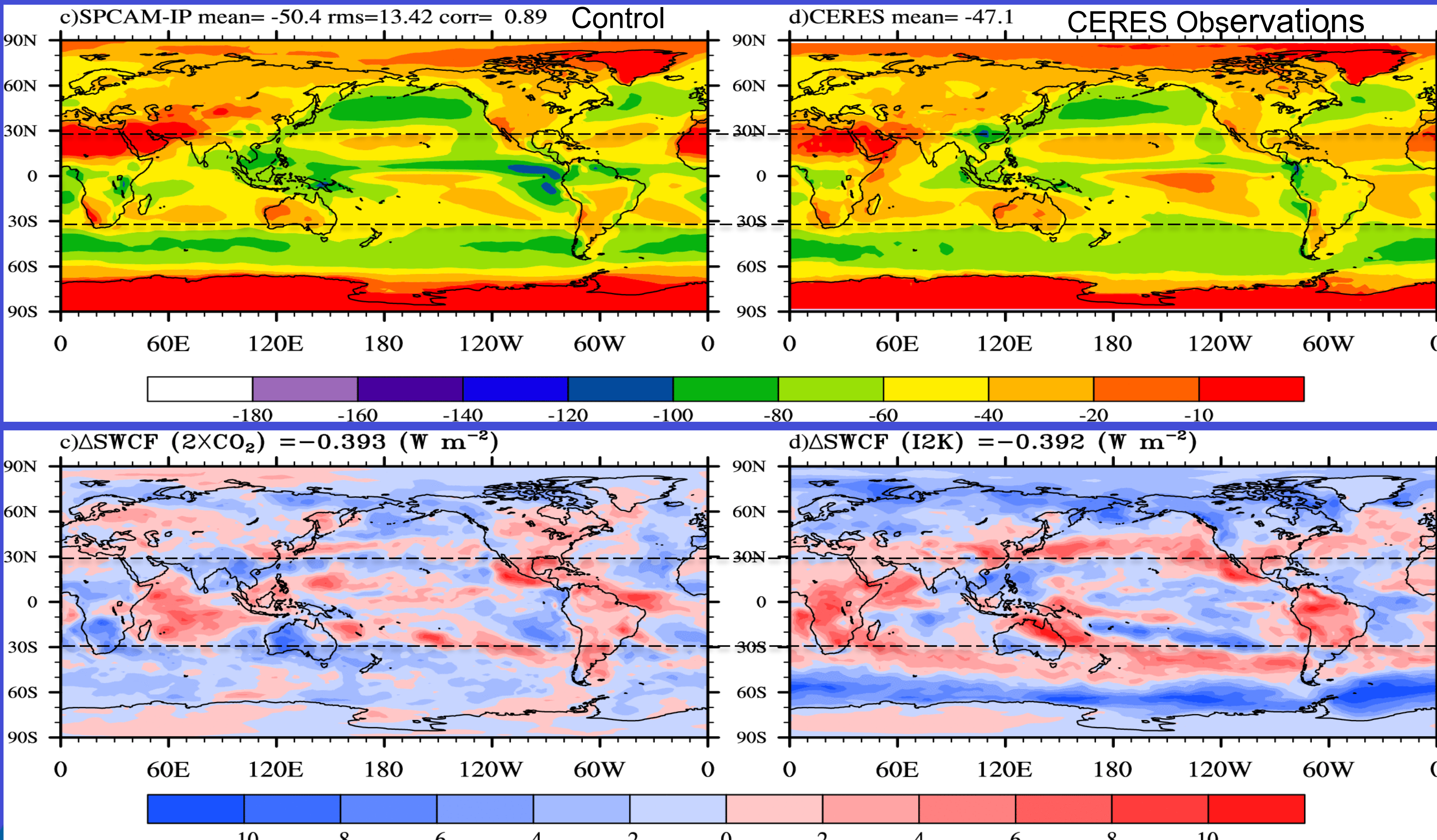
Surface Precipitation Rate from 10-yr control simulation and changes in sensitivity simulations

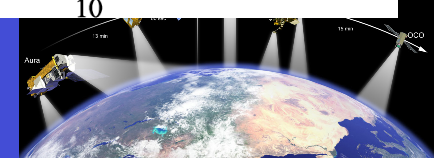




Increases at ITCZ and SPCZ (polarward movements) in *I2K;*
General small decreases in tropics and over lands in *2xCO_2*

Shortwave Cloud Radiative Forcing from 10-yr control simulation and changes in sensitivity simulations





Changes in SW CRE reflect mostly the changes in low cloud fraction in both sensitivity simulations; some due to high clouds

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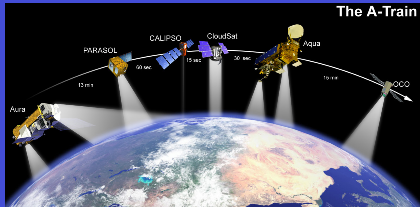
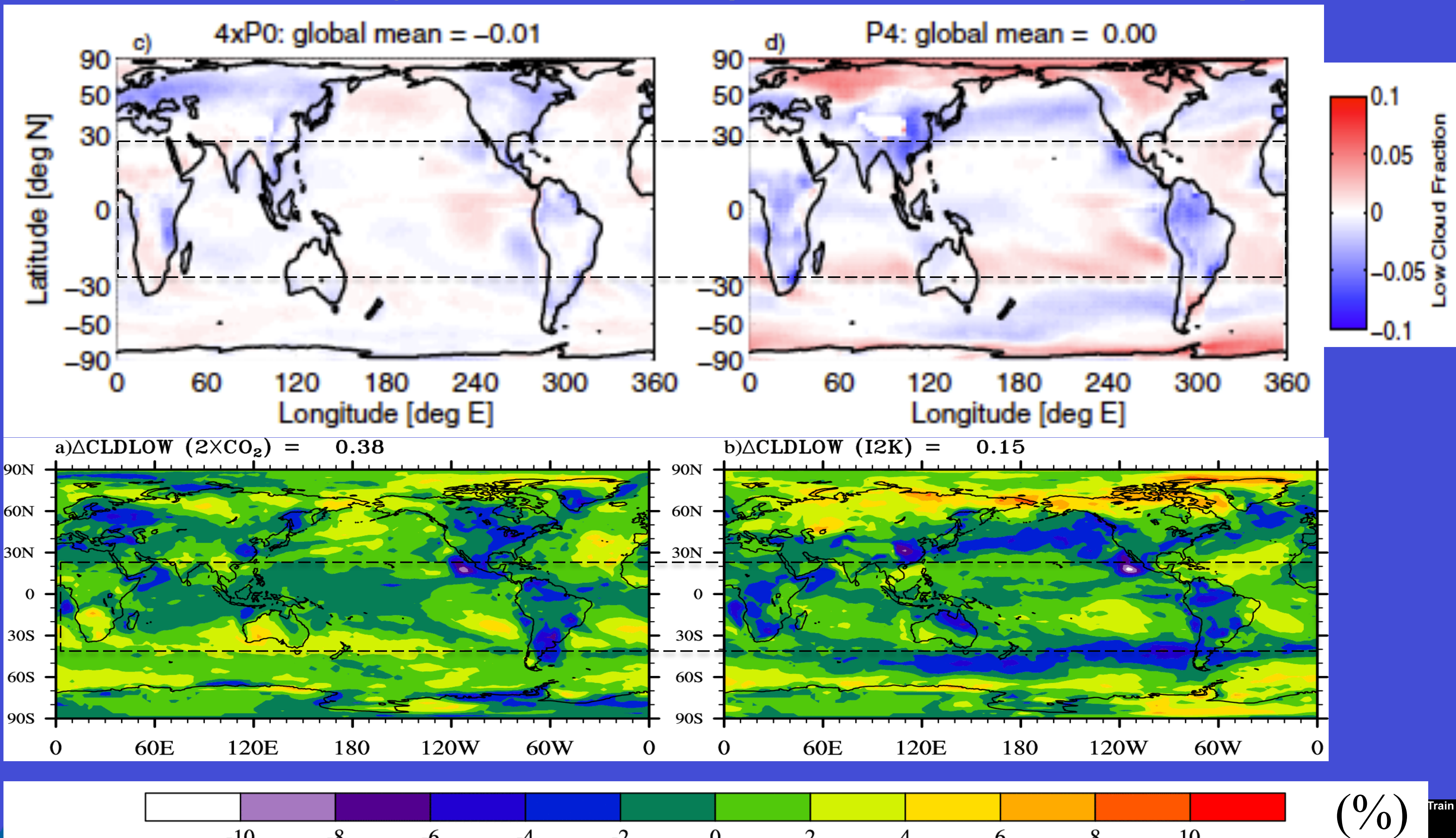
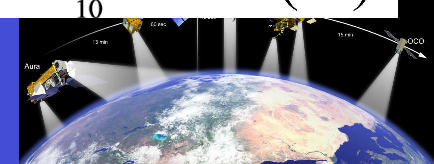


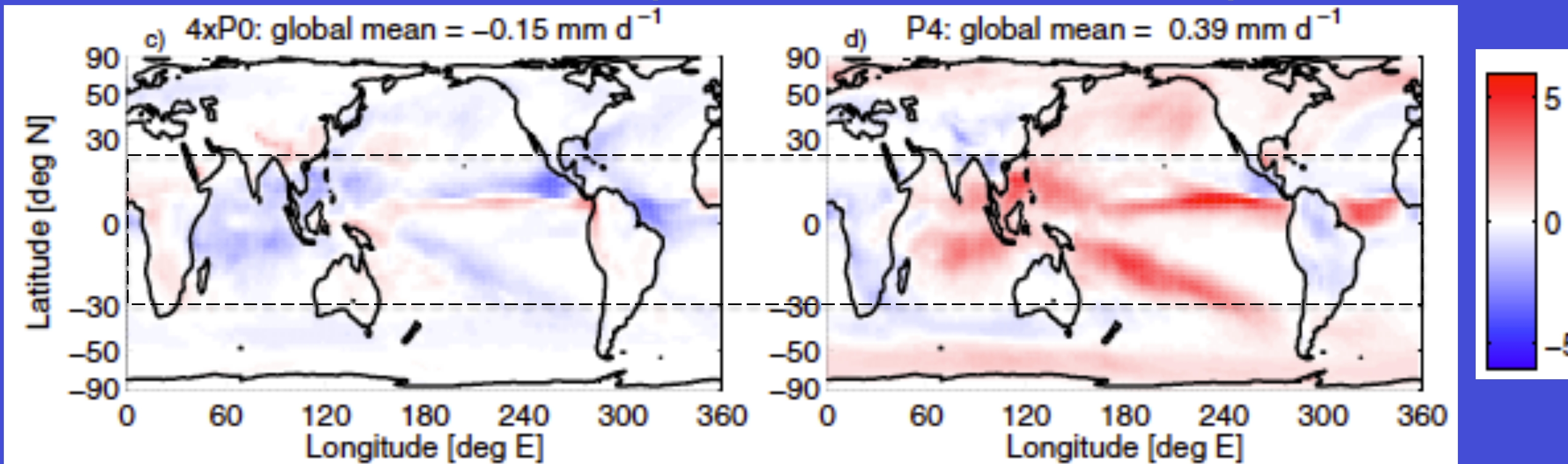
Low-level (surface -- 700 hPa) cloud fraction (%) changes in sensitivity simulations (Bretherton *et al.* 2014)

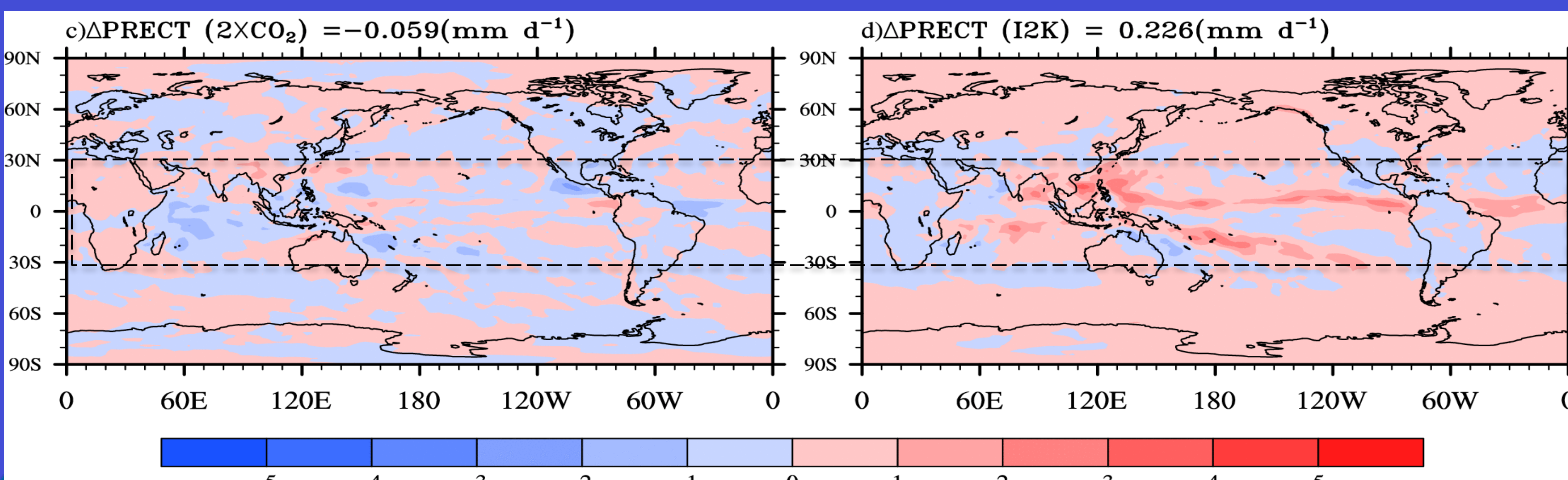


Differences appear in cumulus regions in +SST simulations
There are large differences in CO_2 simulations everywhere

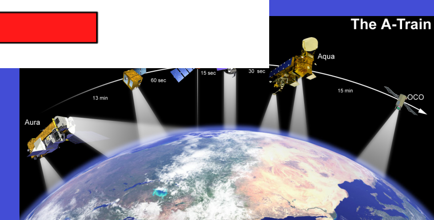


Surface Precipitation Rate changes in sensitivity simulations (Bretherton *et al.*, 2014)

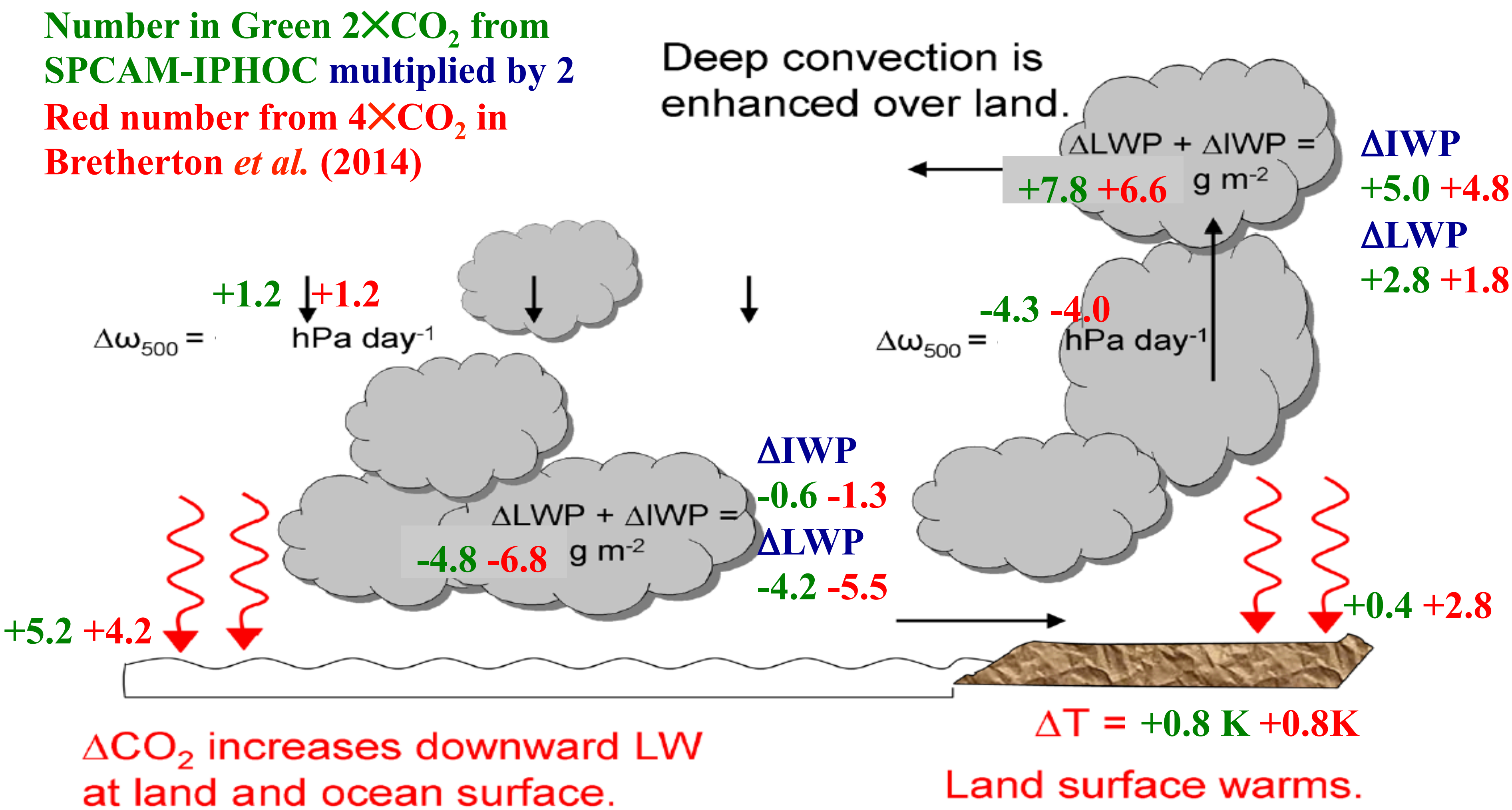




Similar increases at ITCZ and SPCZ in +SST simulations*;*
More increases over lands in *2xCO_2* than in *4xCO_2*

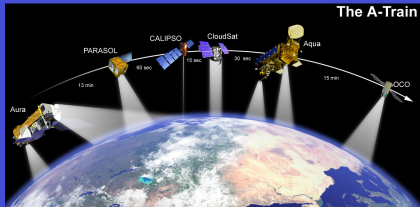


Changes in the tropical land and ocean (30° N/S) from CO_2 sensitivity simulations

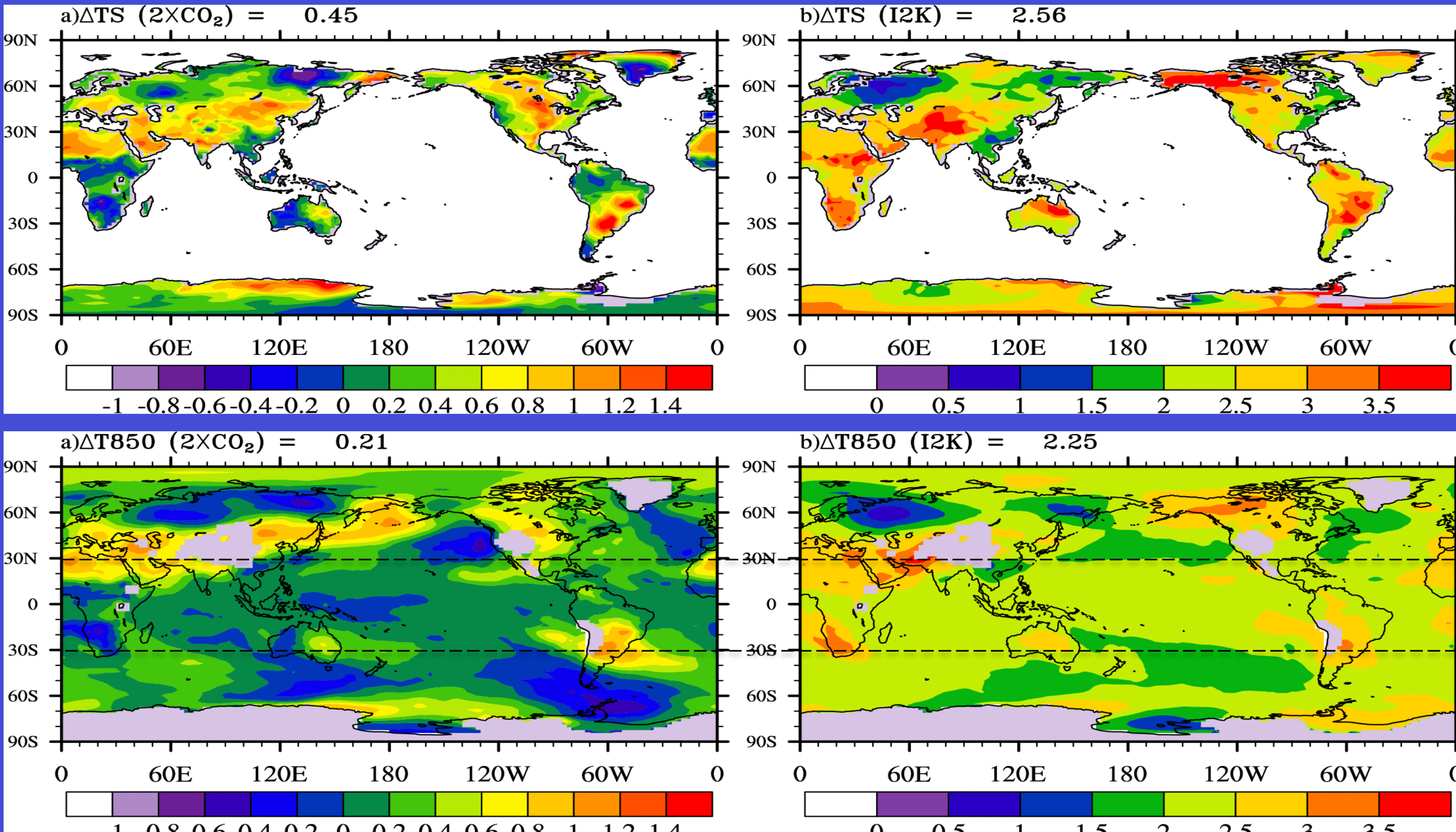


Summary and conclusions

- The low cloud fractions increases in the tropics/subtropics in both sensitivity simulations, but for different reasons.
  - Enhanced inversion strength due to free tropospheric warming from $2XCO_2$;
  - Increased instability results in more shallow convection in +2K SST
- The polarward displacement of storm tracks results in large changes (+ve polarward and –ve equatorward) in cloud fraction and cloud radiative effects in +2K SST simulation
- Precipitation increases in +2K SST are pronounced, especially ITCZ and SPCZ, but almost no increases in the global mean of *$2xCO_2$* simulation, in which the local changes are dis-similar to those of +2K SST in most continents
- There are many similarities with the MMF without the higher-order turbulence closure, but there are some differences
  - shallow cumulus increase more over ocean
  - stronger convection over lands and weaker convection over ocean
  - stronger lower tropospheric moisture transport over land is the reason



Temperature differences at surface and 850 hPa between sensitivity and control simulations



Increased stability in the stratocumulus regions of *2xCO$_2$*
But the cumulus regions in *I2K* do not show much change