Implementing a Higher-order Turbulence Closure (IPHOC) in CAM5 and SPCAM: Issues, Successes and Remaining Challenges

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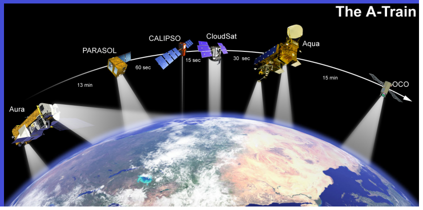
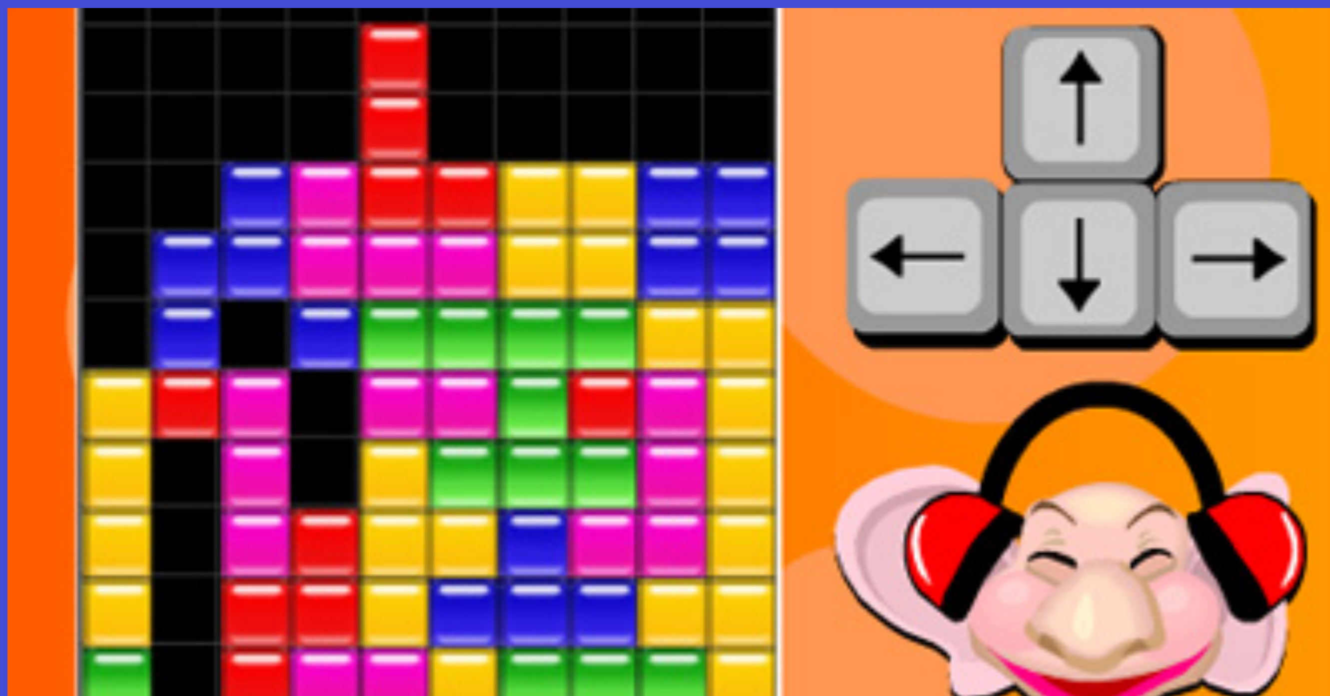
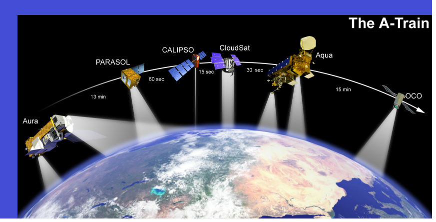


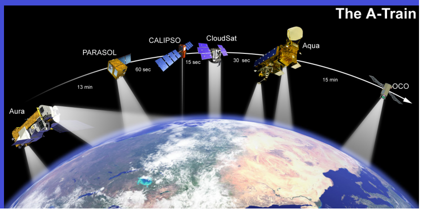
My spare time at UCLA ATM Computer Lab: playing “Tetrix” game





Outline

1. Introduction
2. Model description
3. Low-cloud climatology – the good results
4. Precipitation and energy balance – the relatively poor results
5. Remaining challenges
6. Conclusions



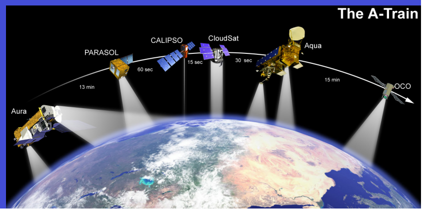
Objectives

- to improve the simulation of low-level clouds from the multiscale modeling framework (MMF) with a third-order turbulence closure in its CRM component
- to implement the same (but with more *diagnosed* moments) higher-order turbulence in CAM5 – the focus of this talk

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

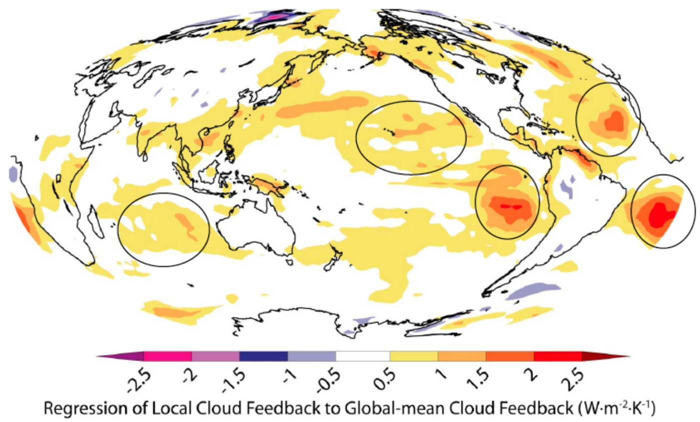
Cheng and Xu (2013a; *J. Climate*); Cheng and Xu (2013b; *JGR*)

Cheng and Xu (2014a, JGR; accepted); Cheng and Xu (2014b, in prep.)



Uncertainties in cloud feedback remain in GCMs

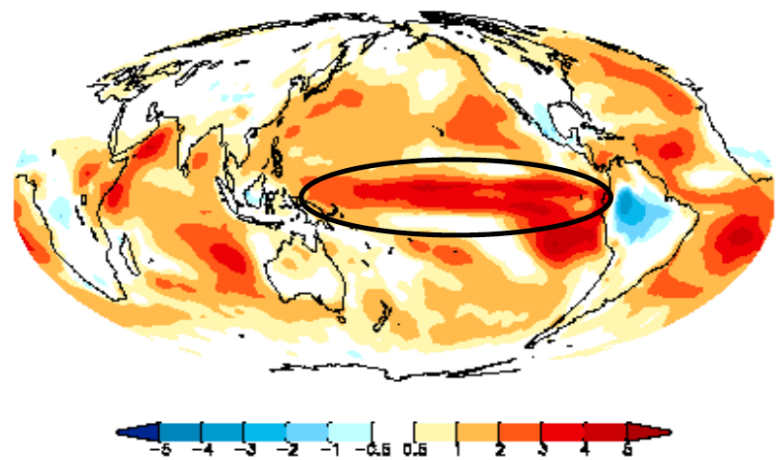
Local contribution to intermodel spread in cloud feedback: AR4



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

Soden and Vecchi (2011

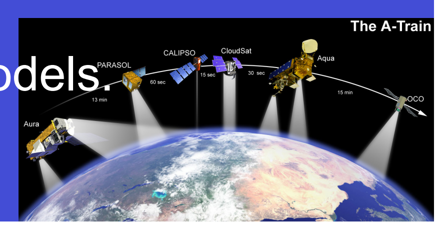
Local contribution to intermodel spread in cloud feedback: AR5



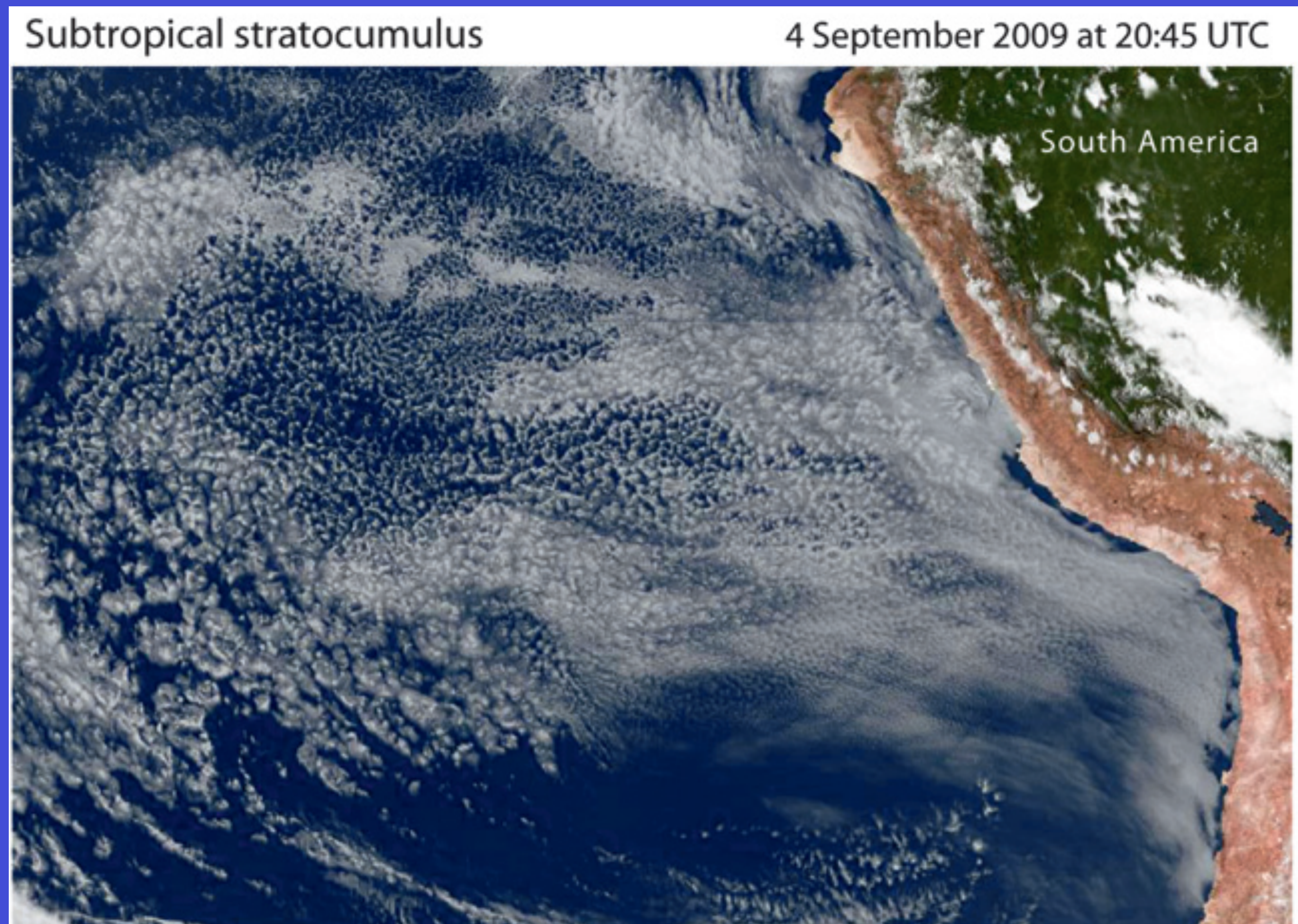
- **Low subtropical clouds still uncertain.**
- **Large contribution from equatorial Pacific.**

Soden and Vecchi (2011):

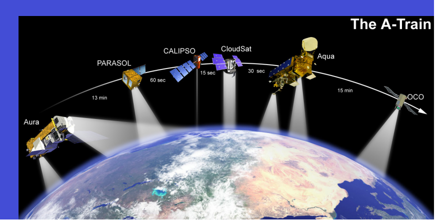
- Low cloud cover is responsible for ~3/4 of the difference in global-mean net cloud feedback among AR4 models, with the largest contributions associated with low-level subtropical marine cloud systems;
- The low-cloud inconsistency and deficiency in most of the models.



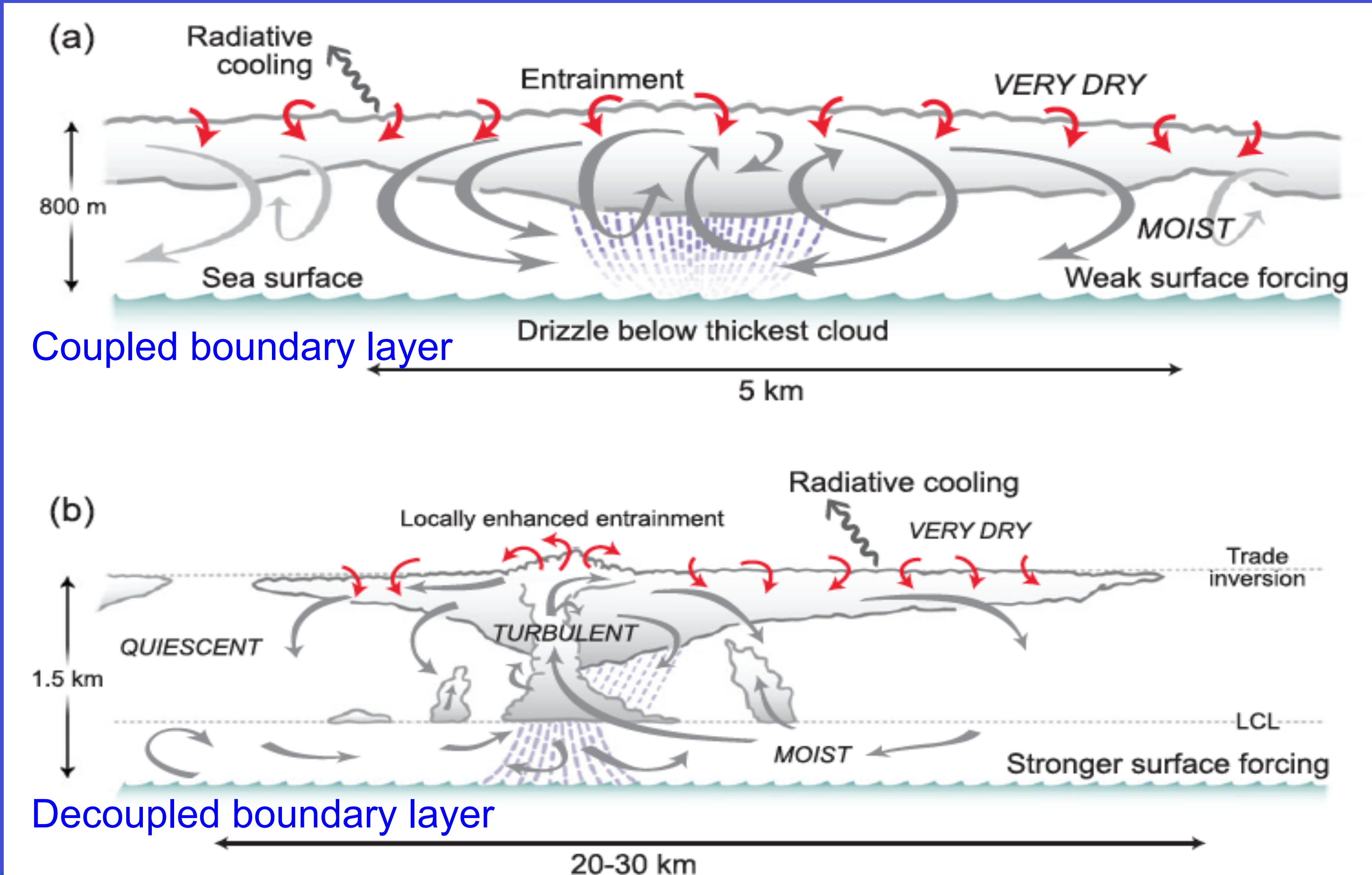
SE Pacific Stratocumulus



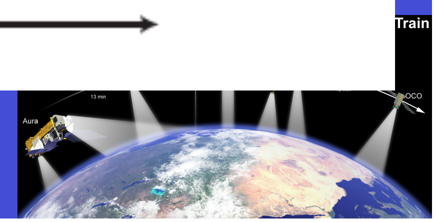
from Wood (2012; *Mon. Wea. Rev.*)



Processes associated with stratocumulus



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

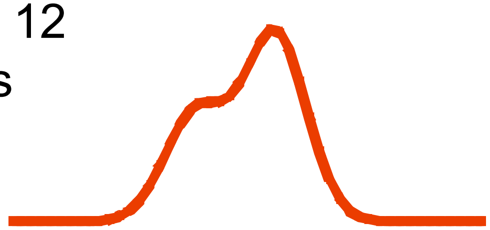


IPHOC: Intermediately-prognostic higher-order turbulence closure in SPCAM via SAM CRM

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

Use PDF to close higher-order moments, buoyancy terms

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

Δt_{CRM}

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

IPHOC implemented in CAM5, replacing all BL (turbulence, Cu & Sc) parameterizations

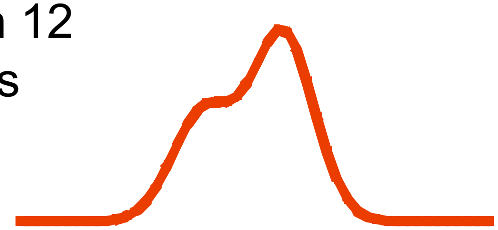
Advance 5 prognostic equations

$$\bar{w}, \bar{q}_t, \bar{\theta}_l, \overline{w'q_t'}, \overline{w'\theta_l'}$$

Diagnose 7 moments

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

Select PDF from given family to match 12 moments



Diagnose cloud fraction, liquid water from PDF

Use PDF to close higher-order moments, buoyancy terms

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

Δt_{GCM_sub}

Golaz *et al.* (2002); Cheng & Xu (2006)
Cheng and Xu (2014b; in prep.)

CAM5 (Community Atmosphere Model version 5)

Macrophysics
Park

Nucleation
Liu et al

Microphysics
Morrison-Gettelman

Radiation
RRTM

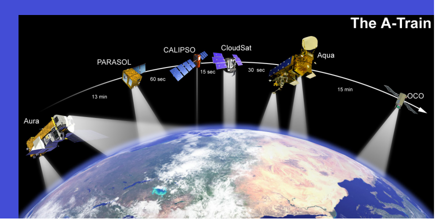
Land surface
CLM

Turbulence
Park-Bretherton

Dynamics
finite volume
Lin

Deep/shallow Convection
Zhang-McFarlane/Hack

Model state is updated after each process ("sequential-split")



CAM5 with IPHOC

Macrophysics (ice phase) Park

Nucleation Liu et al

Microphysics Morrison-Gettelman

Radiation RRTM

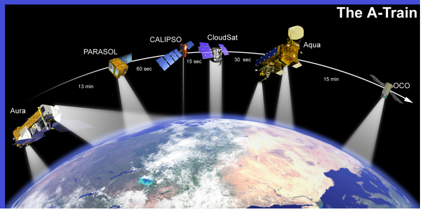
Land surface CLM

Dynamics finite volume Lin

Deep convection Zhang-McFarlane

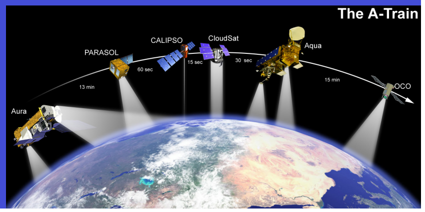
IPHOC

Model state is updated after each process (“sequential-split”)



Issues related to IPHOC implementation

- Common issues for both SPCAM and CAM5
  - Added computational cost: 100% for SPCAM and 50% for CAM5
- Issues specific to SPCAM
  - Difficult to tune the model for energy balance
  - 9 extra predictive equations and storage for other higher-order moments
- Issues specific to CAM5
  - Large time step: using sub-step (30 sec) for prognostic equations; diagnosis of most second and all third moments
  - Vertical resolution: adding a diagnostic equation for PBL height to better represent the sharp gradient
  - Coupling with other model parameterization components (e.g., ice-phase macrophysics, deep convection)

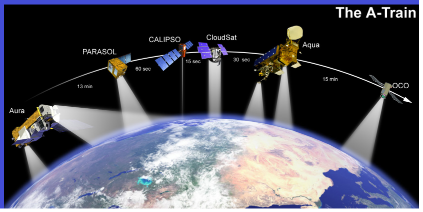


CAM5, CAM5-IPHOC, SPCAM-IPHOC climate simulations

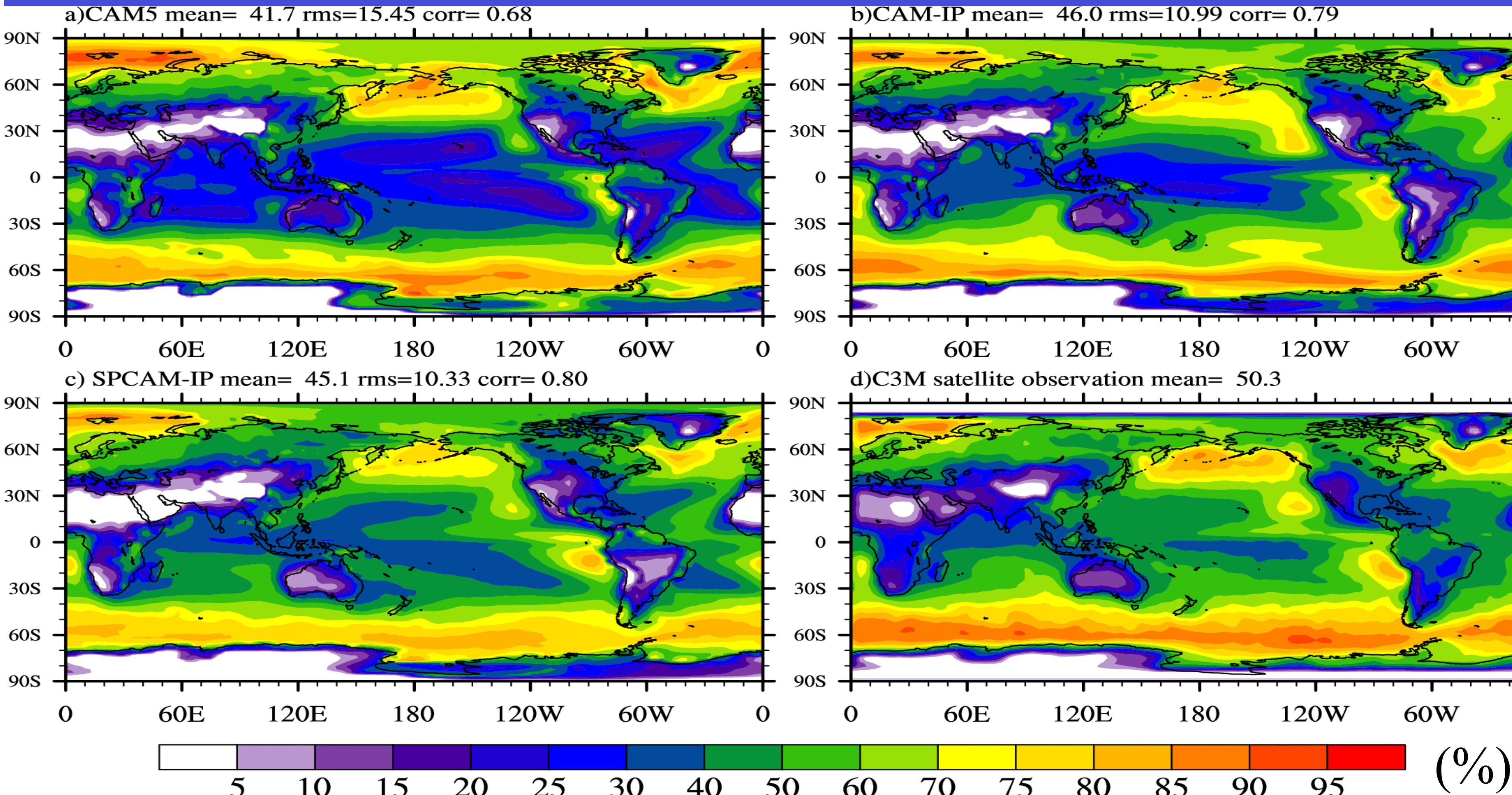
- SPCAM-IPHOC
  - CAM3.5 with finite-volume dynamic core as the host GCM
  - 2-D version of System for Atmospheric Modeling (SAM) CRM with IPHOC
  - The CRM grid spacing is 4 km, with 32 columns, within a GCM grid box
  - The GCM grid spacing is 1.9°x2.5° with 32 vertical levels (12 below 700 hPa)
- CAM5 and CAM5-IPHOC GCMs
  - CAM5 with finite-volume dynamic core without/with IPHOC
  - Grid spacing is 1.9°x2.5°; 30 vertical levels (10 below 700 hPa)

All simulations:

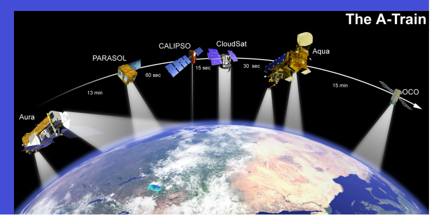
- The simulations are forced with climatological SST and sea ice distributions (not an AMIP-type simulation)
- Simulation duration is 10 years and 3 months, with last nine years analyzed



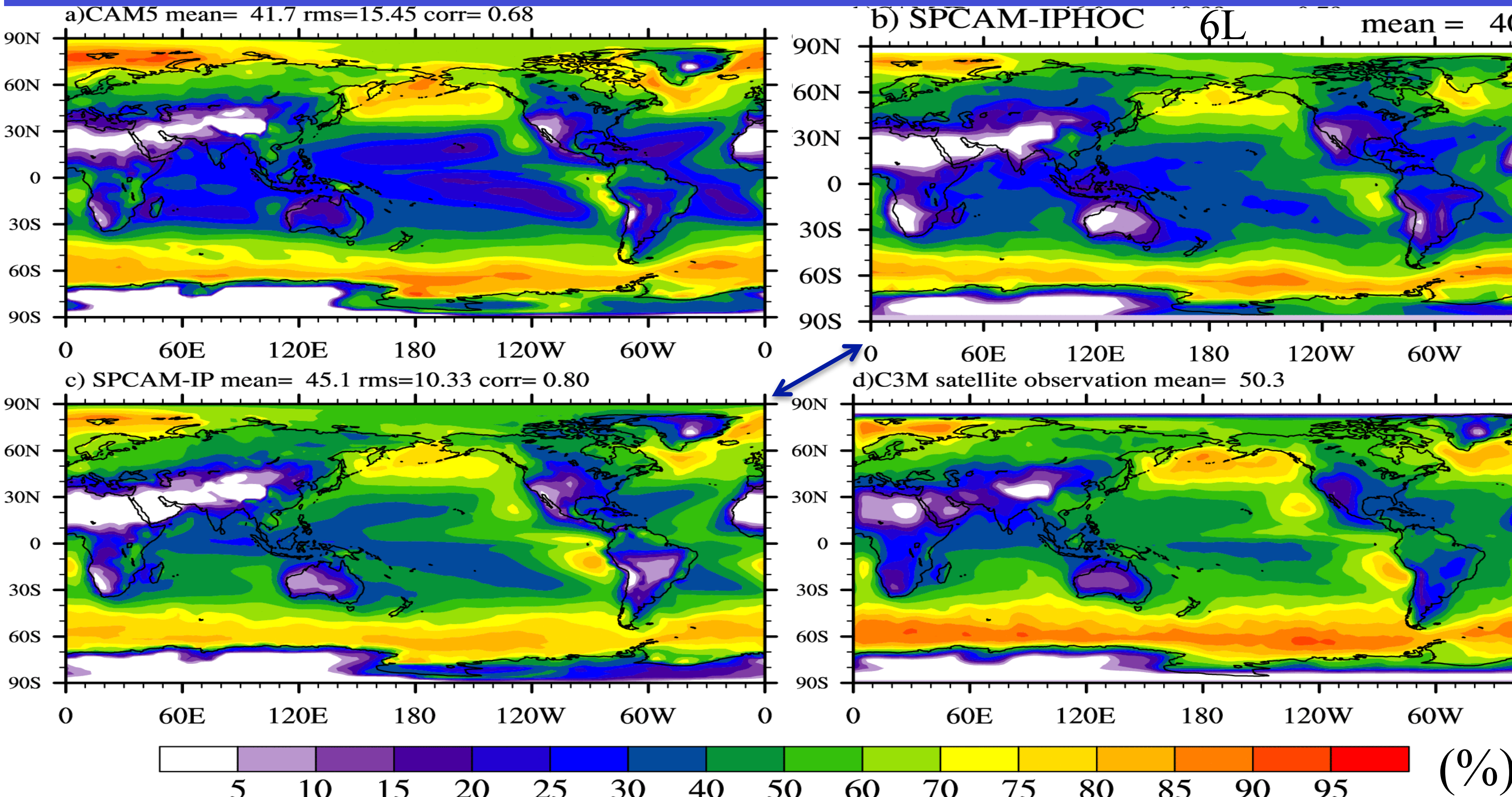
Global distribution of annual mean low cloud fraction (top > 700 hPa)



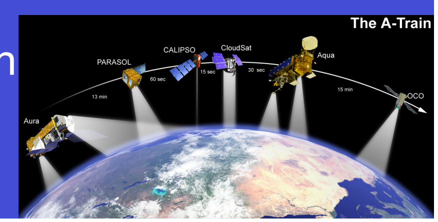
Improvement from CAM5-IP in mean, RMS, correlation;
Increases in coastal subsidence and SH storm track regions



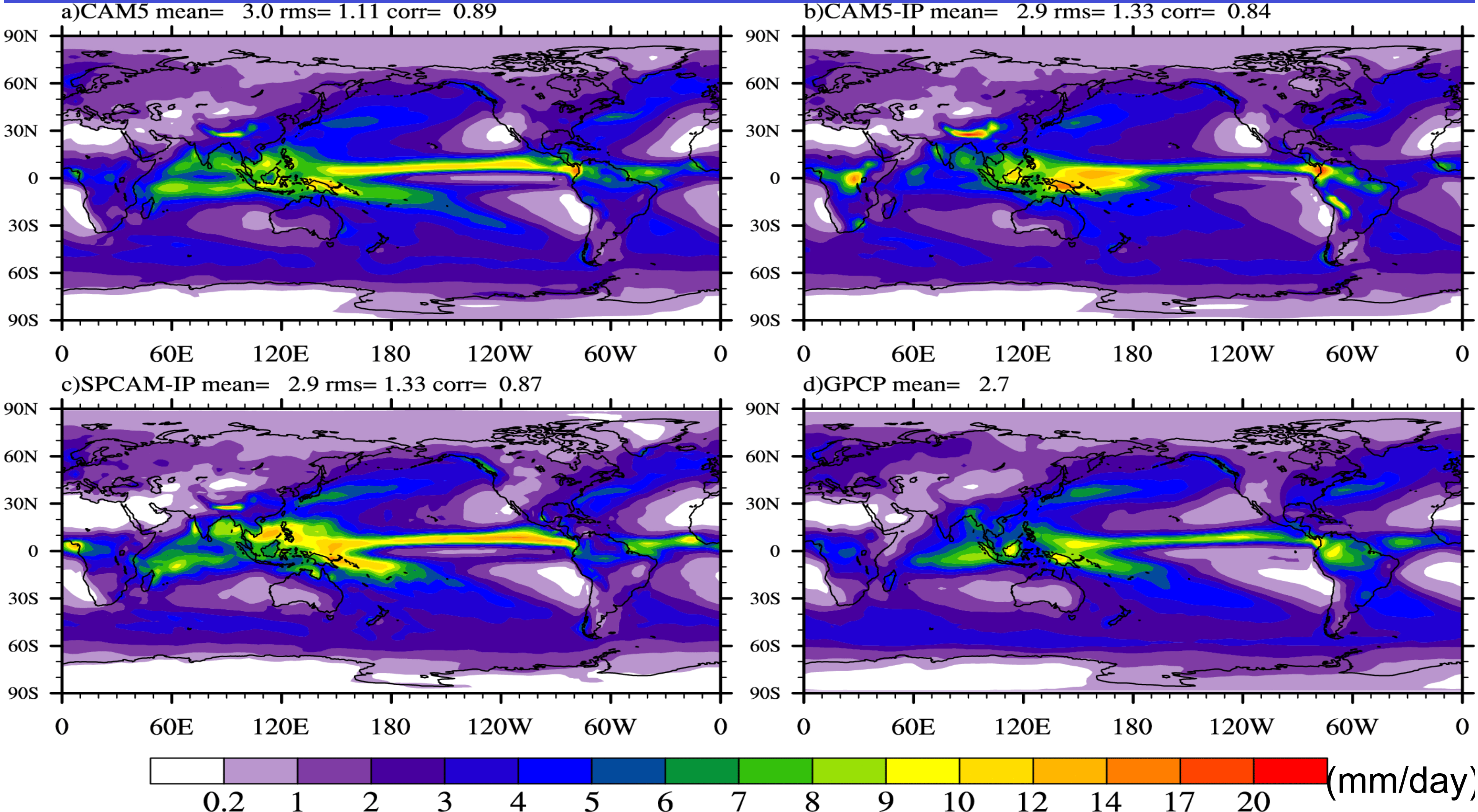
Global distribution of annual mean low cloud fraction (top > 700 hPa)



For SH storm track low clouds, the decrease of vertical resolution increases the cloud fraction for SPCAM-IPHOC

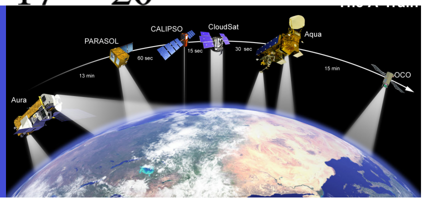


Global distribution of annual mean surface precipitation

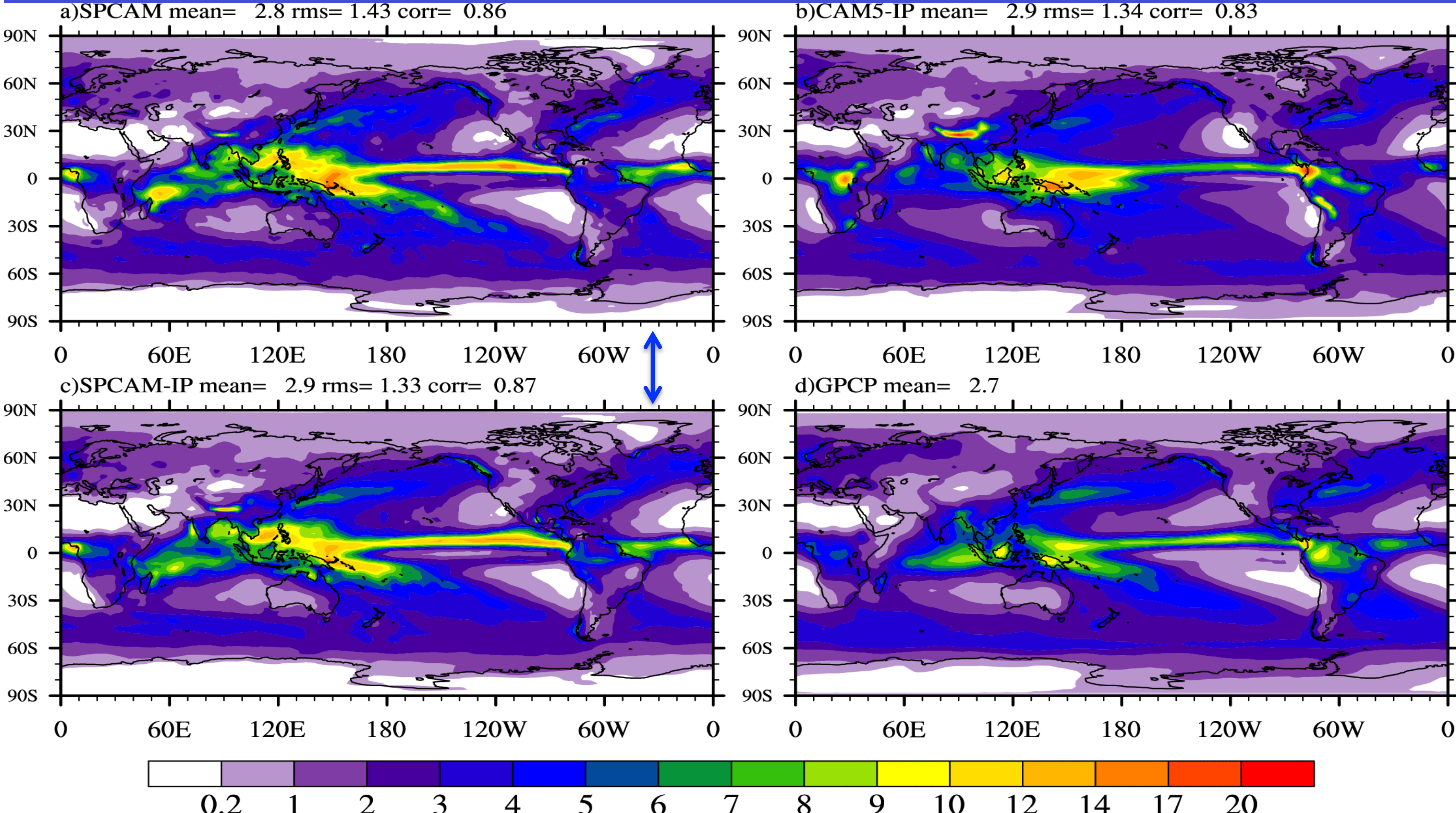


Reduced precipitation in eastern Pacific, but lack of SPCZ, ITCZ over the Indian Ocean in CAM5-IP; overestimates over lands

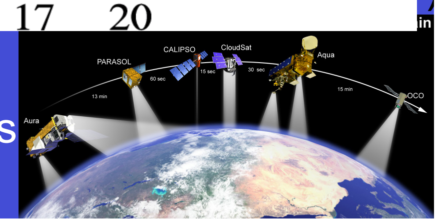
SPCAM-IPHOC: lack of convection over land, microphysics?



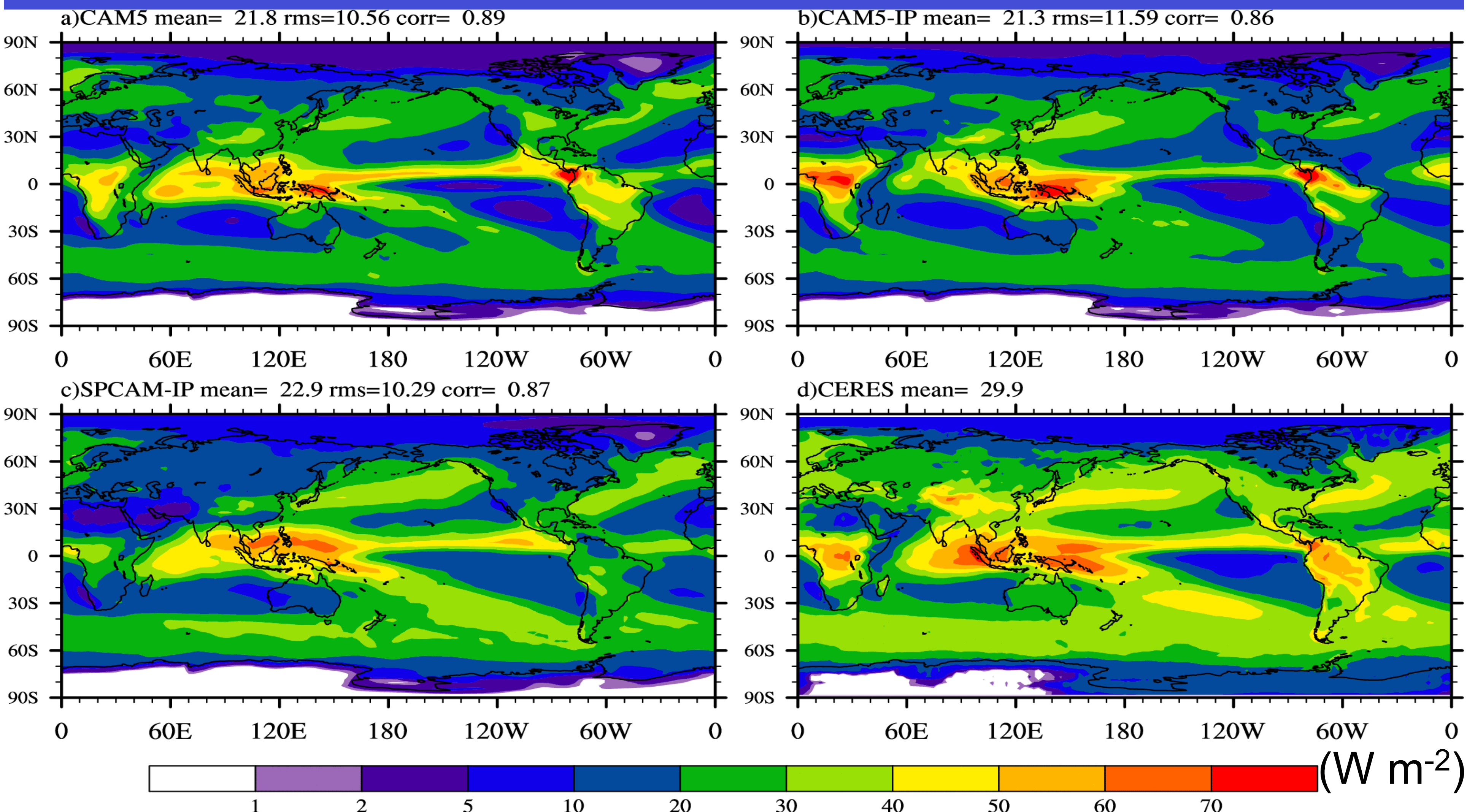
Global distribution of annual mean surface precipitation



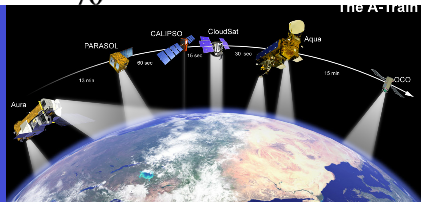
SPCAM-IPHOC: lack of convection over land, microphysics?
"Pledge the 5th:" IPHOC did not change the precipitation patterns of SPCAM, especially, over lands (2 yrs 3 mos. sensitivity runs)



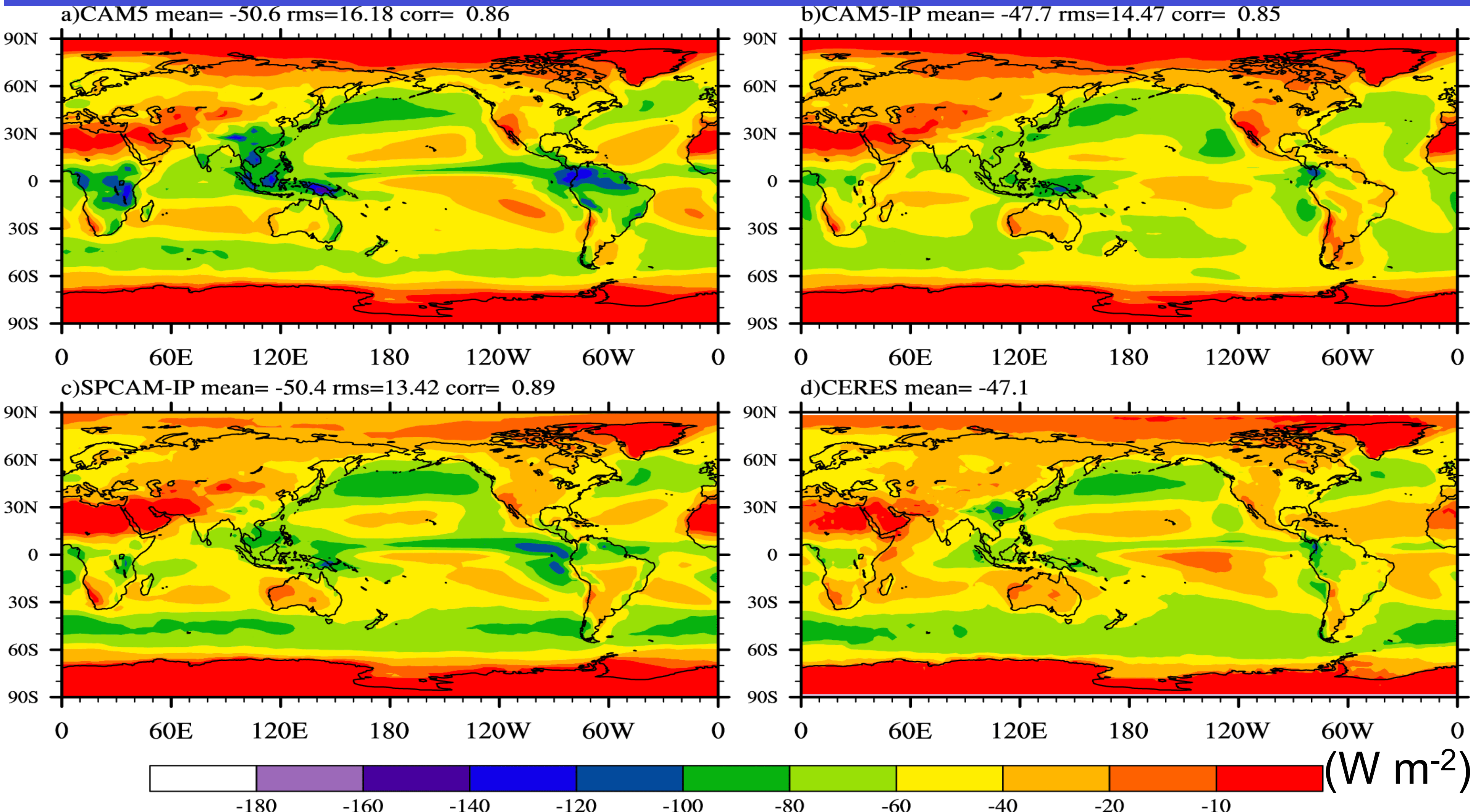
Global distribution of annual mean LW CRF



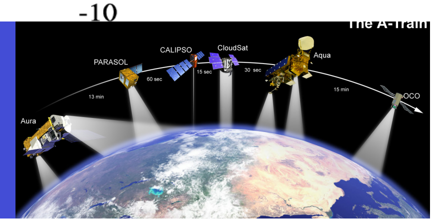
Stronger LW CRF in tropical regions compared with CAM5;
Lack of SPCZ, overestimates in Africa and S. America



Global distribution of annual mean SW CRF

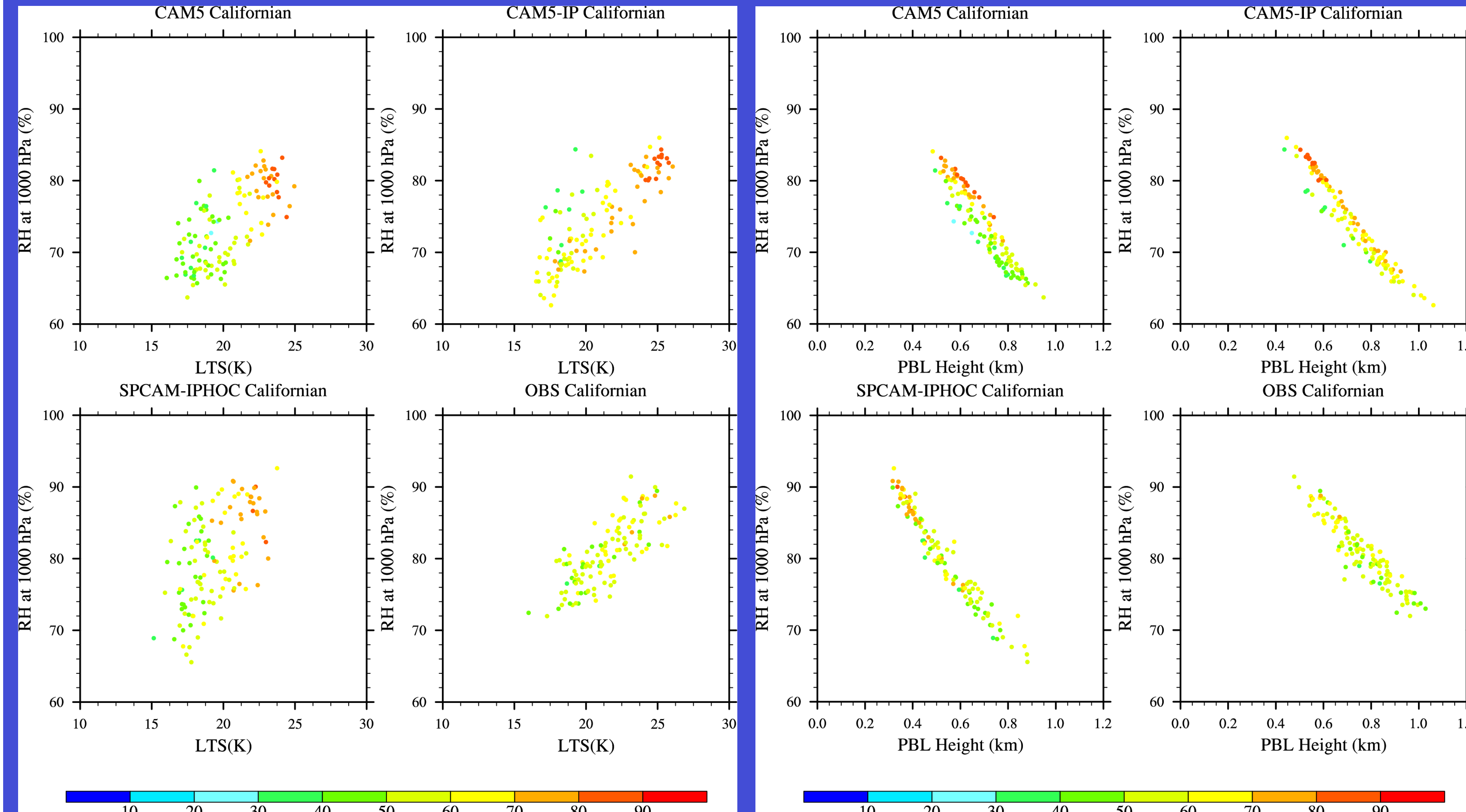


Global mean from CAM5-IP is the closest to CERES
Strong negative cloud radiative forcing (CRF) from low clouds

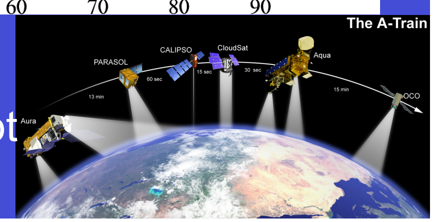


Low cloud, LTS, PBL height and RH_s –Californian

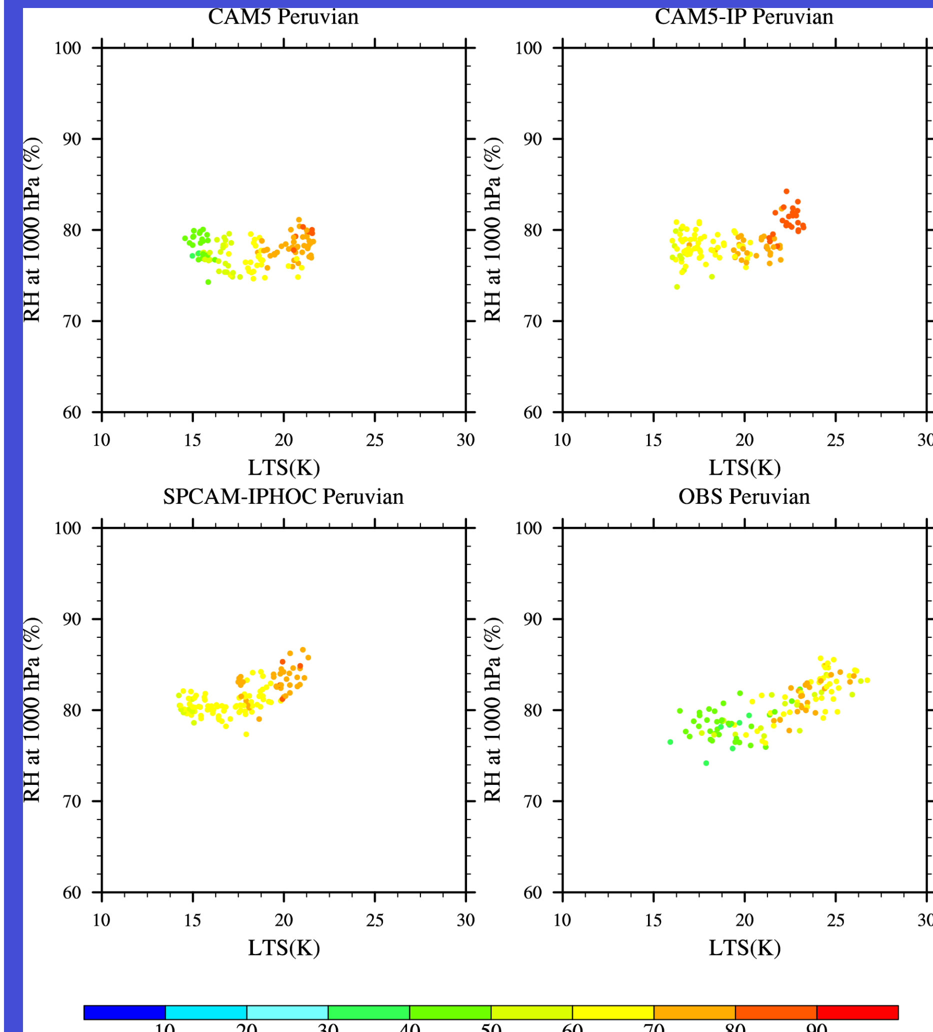
[see DeMott et al. (2010) for CAM3 and SPCAM]

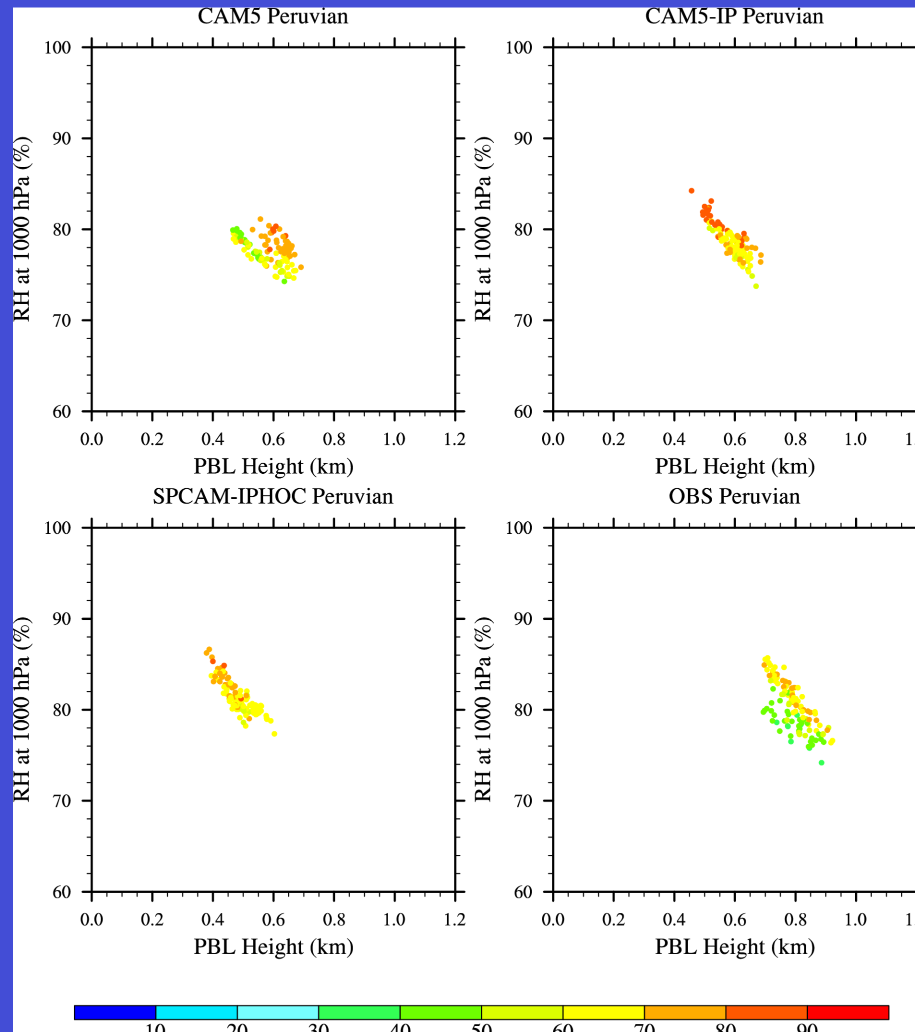


CAM5-IP simulates larger LTS and deeper PBL situations; most consistent with “observations” (CloudSat/CALIPSO & ERAI) except for excessive cloudiness

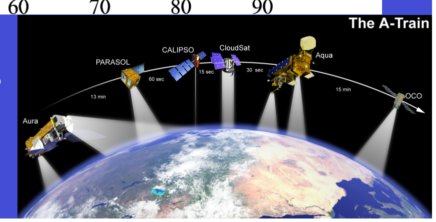


Low cloud, LTS, PBL height and RH_s -- Peruvian

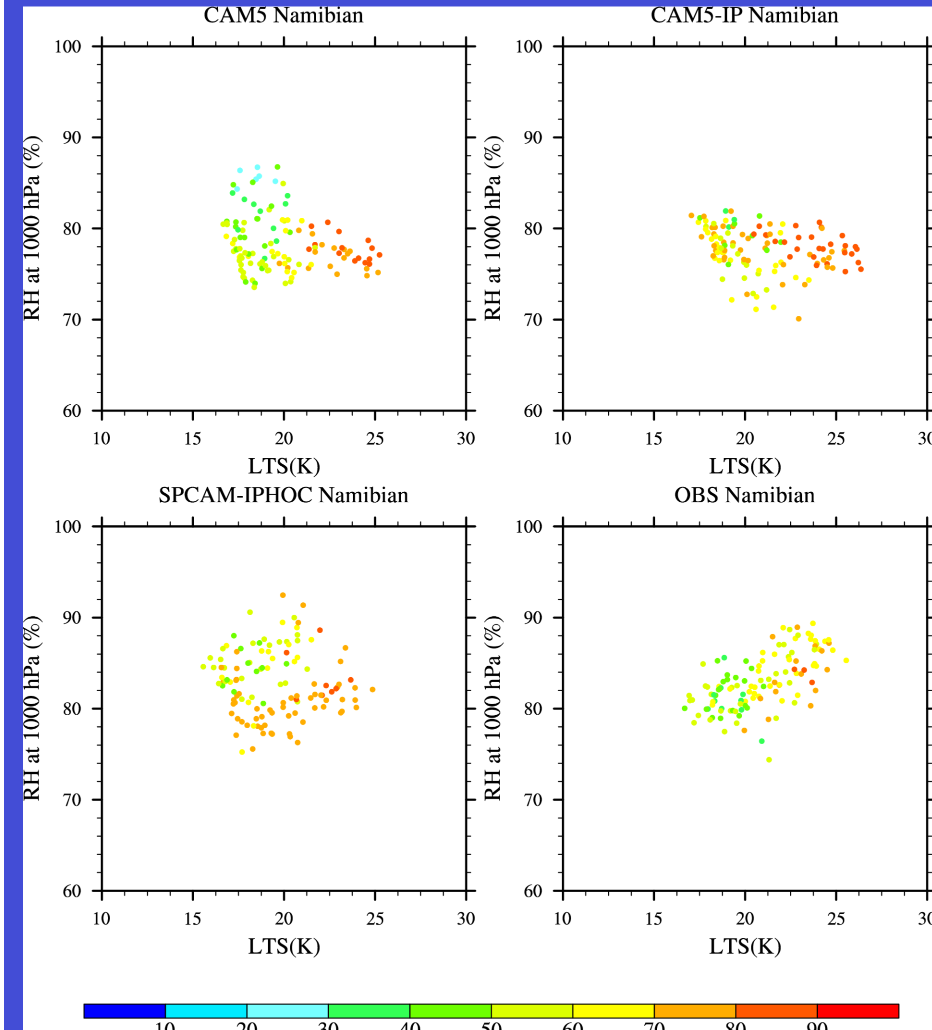


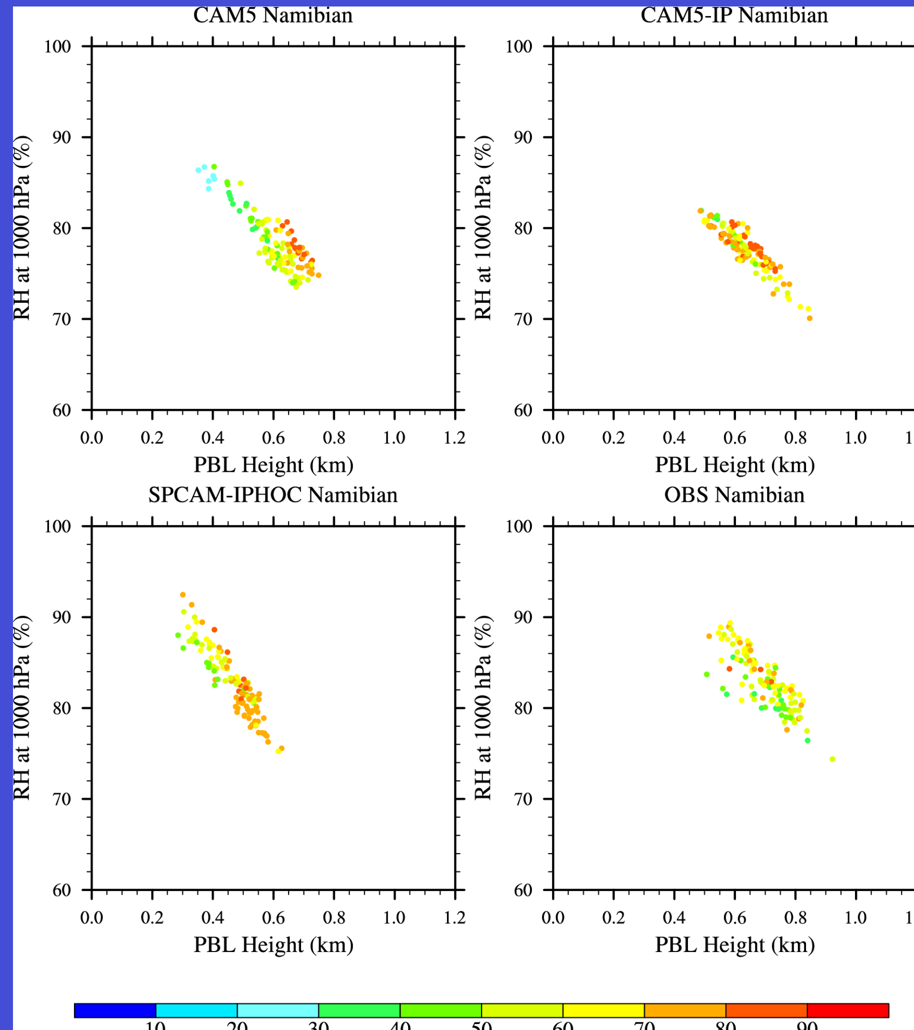


Narrower LTS ranges simulated by all models; smaller cloud variations for both models w/ IPHOC (lower PBLs); shallower PBLs for higher cloudiness in CAM5, opposite to other models and "observations"

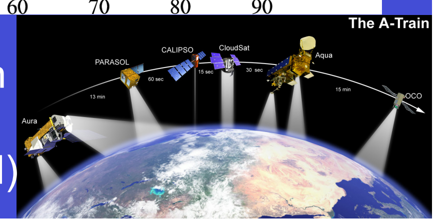


Low cloud, LTS, PBL height and RH_s -- Namibian

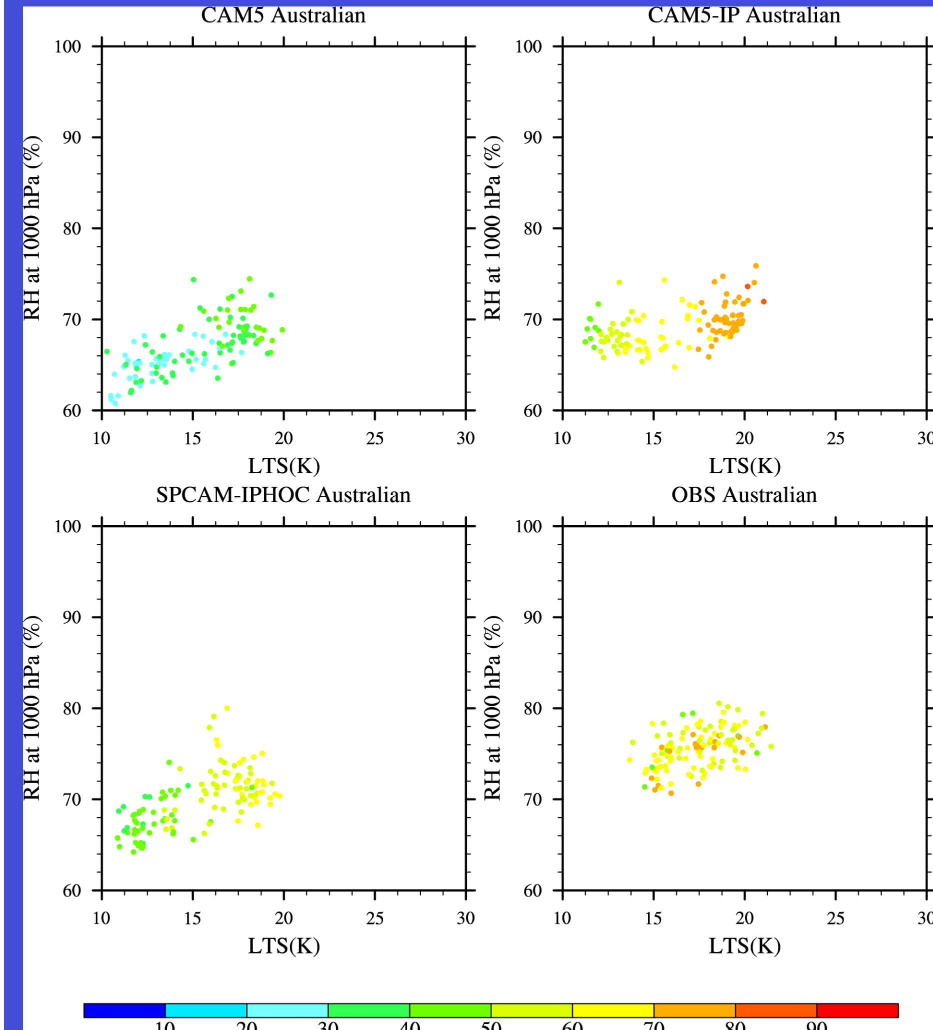


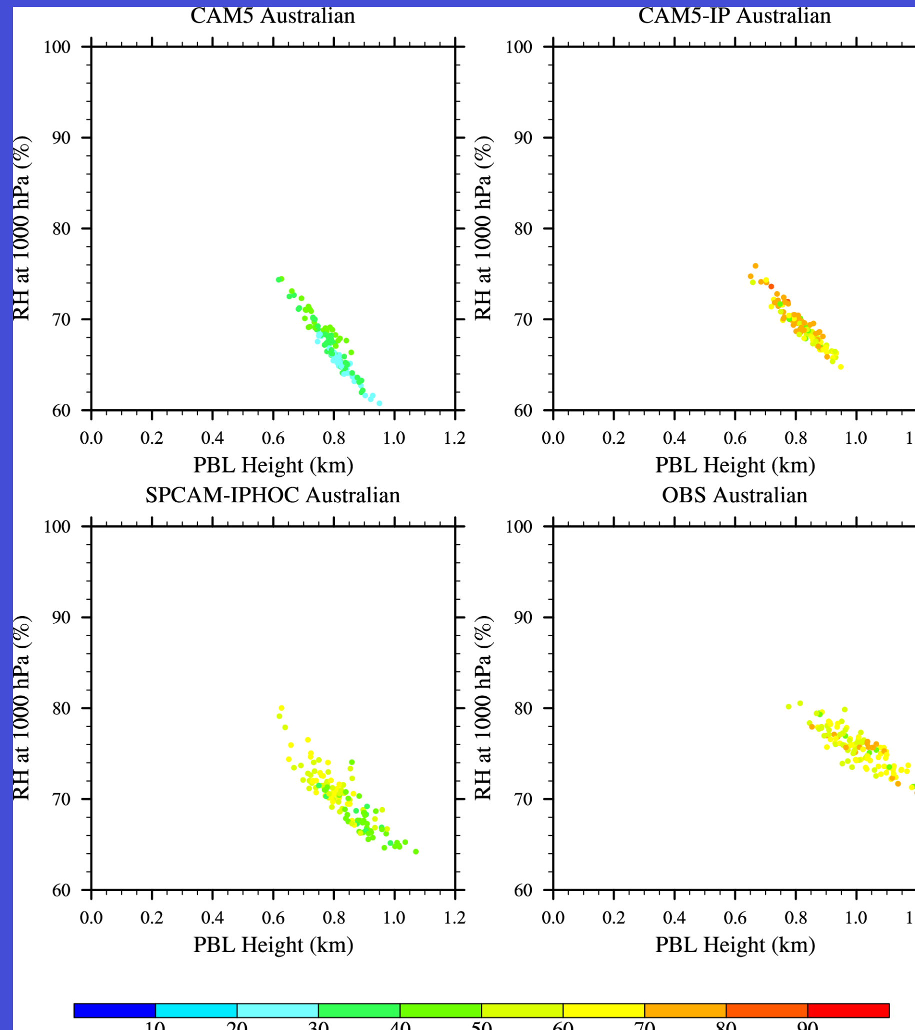


Similar to Peruvian region except for the lacking of correlation between LTS and cloudiness or between RHs and cloudiness; PBL height variation cannot explain the cloudiness variation (lower PBL in SPCAM)

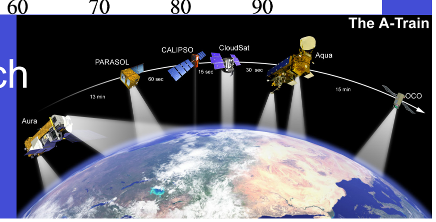


Low cloud, LTS, PBL height and RH_s -- Australian

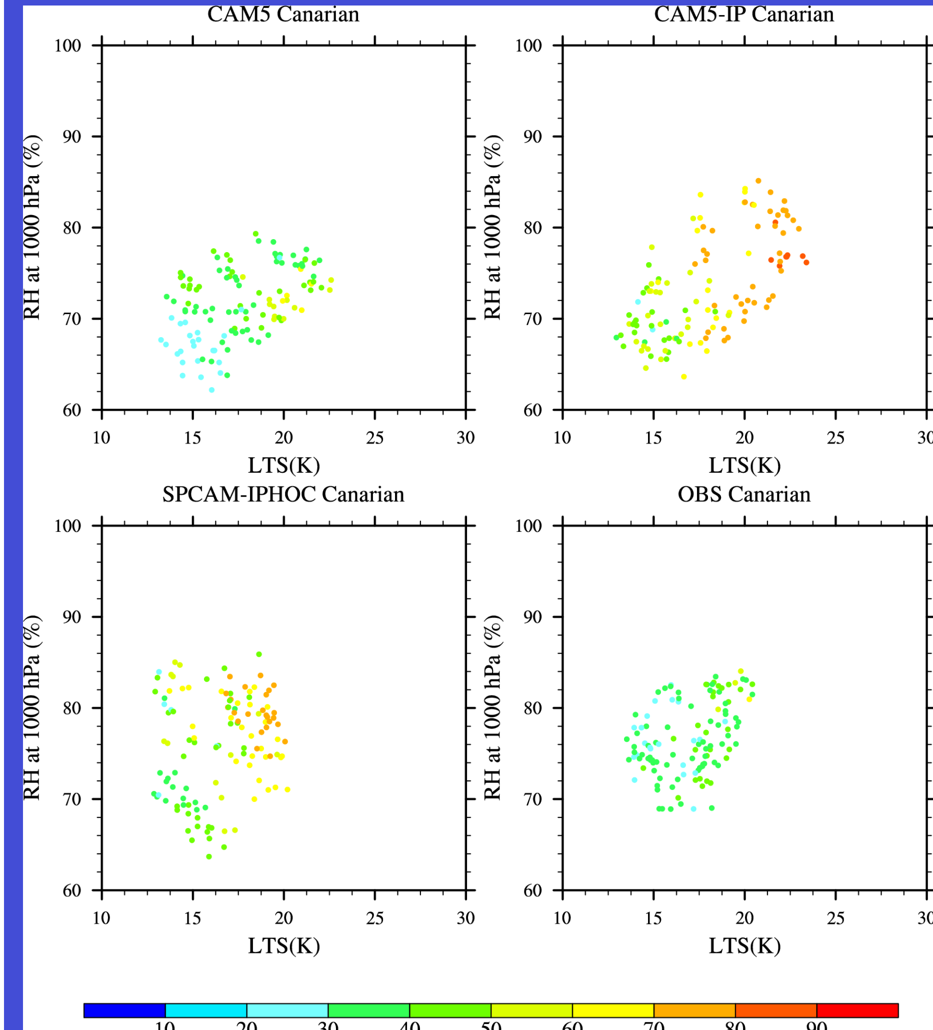


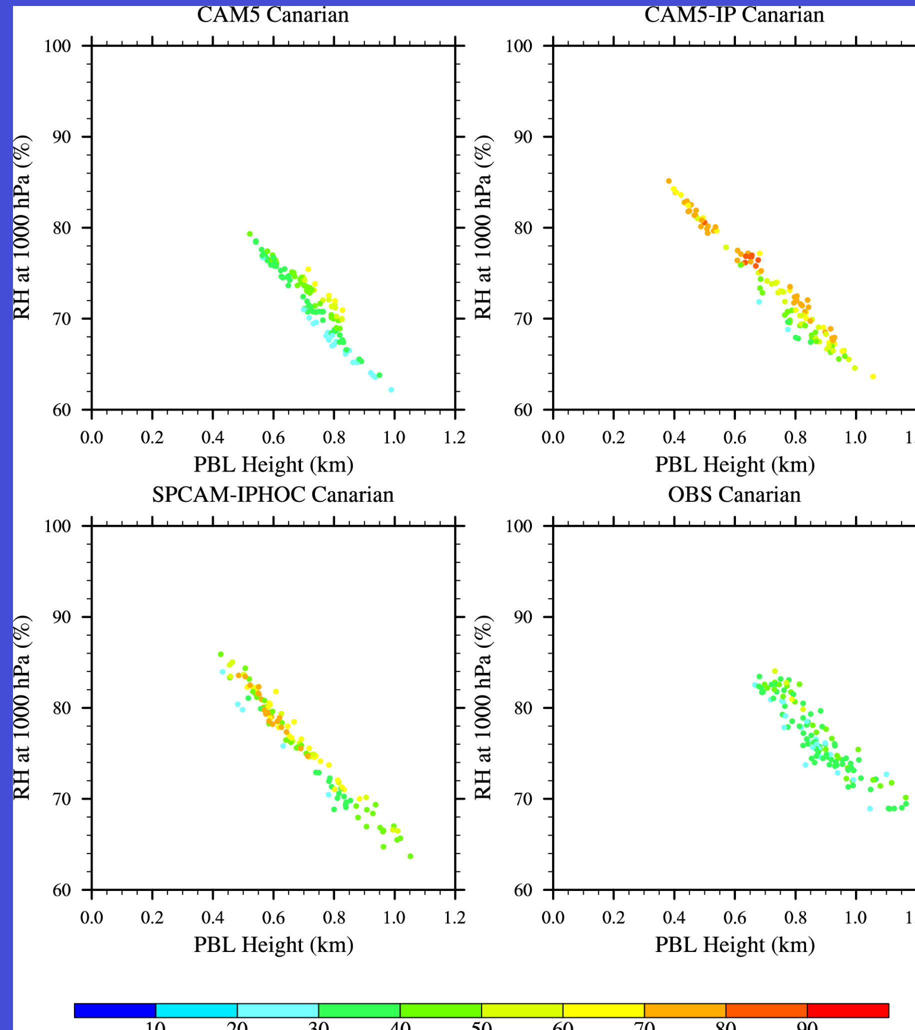


Much smaller LTS values, yet CAM5-IP overestimates cloudiness; much lower PBL heights in all models, but lowest cloudiness in CAM5



Low cloud, LTS, PBL height and RH_s -- Canarian





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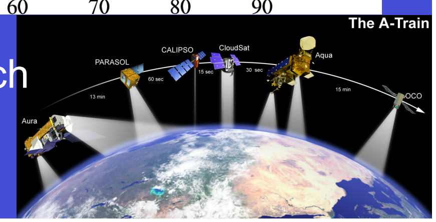
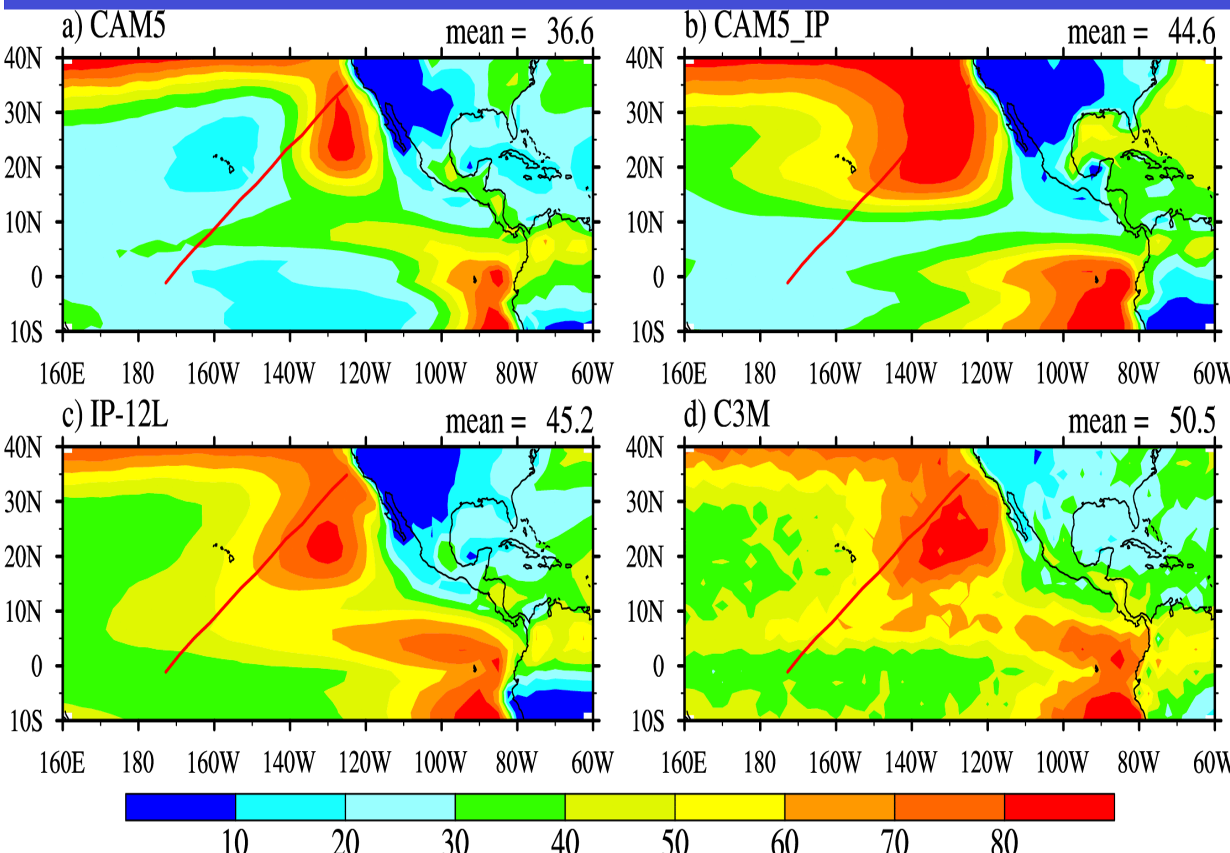
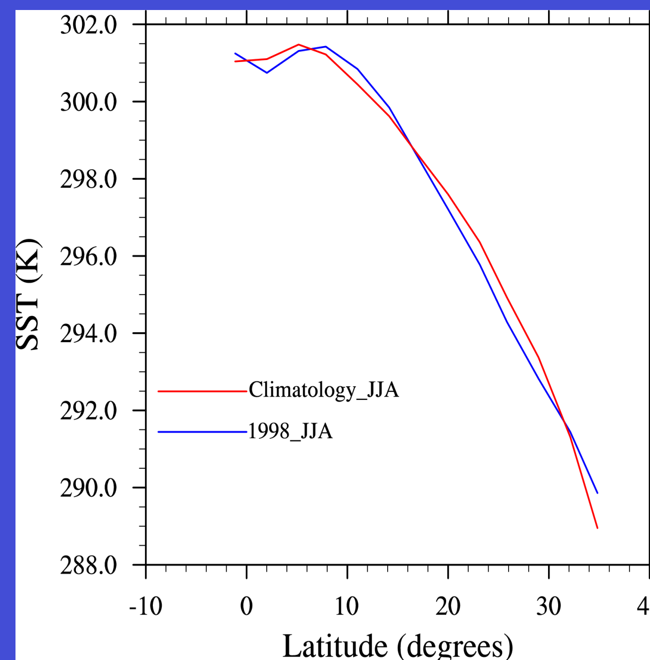


Why the GPCI transect? Transitions from tropical deep convection, tradewind cumulus to stratocumulus

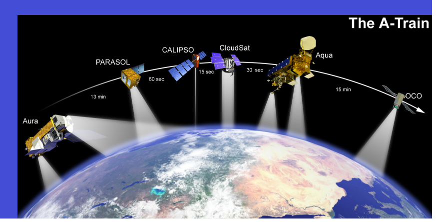
Low cloud cover for June-July-August (JJA)



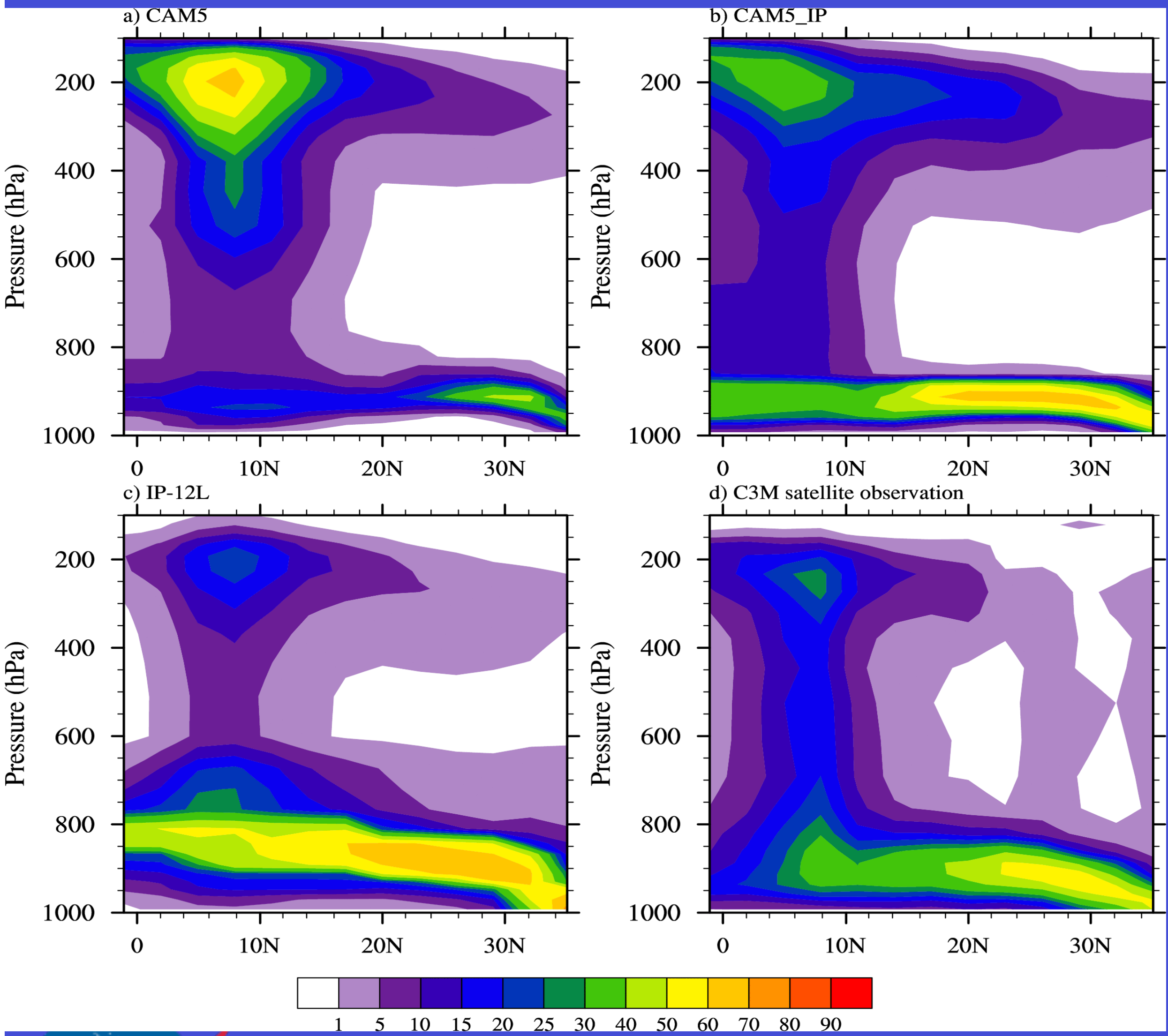
Sea surface temperature



Slow down the sharp transition (Sc to Cu) in CAM5-IP

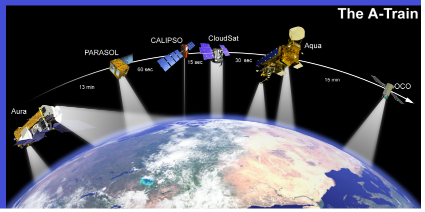


Cloud fraction cross-section along GPCI

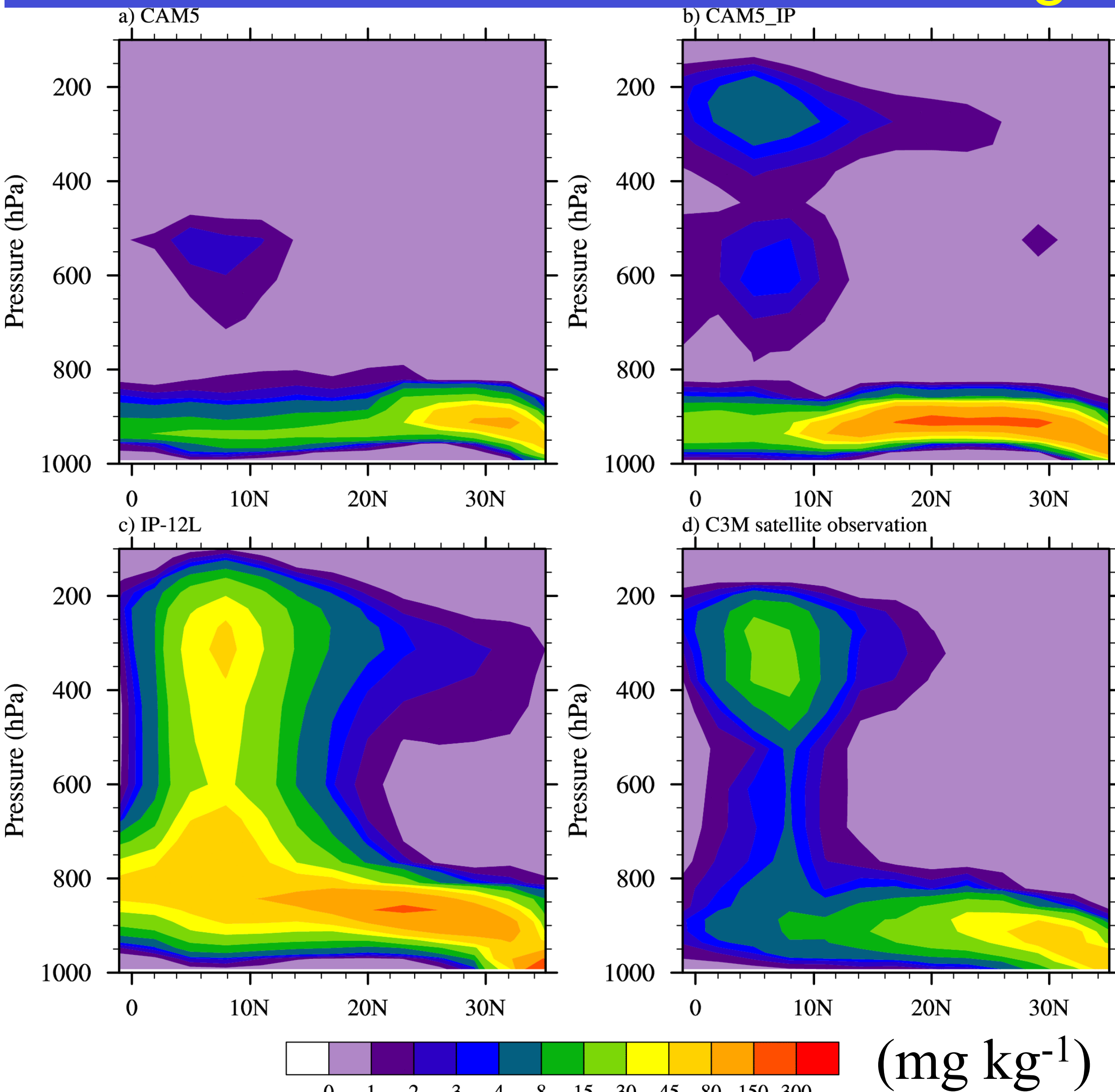


(%)

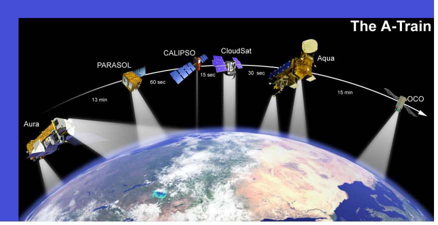
- CAM5-IP produces realistic low-level, middle level, and high-level clouds;



Total cloud condensate (liquid + ice) cross-section along GPCI

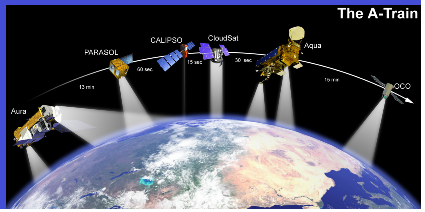


- CAM5-IP produces more condensate in middle and upper troposphere than CAM5, and in low level than SPCAM-IPHOC



Remaining challenges

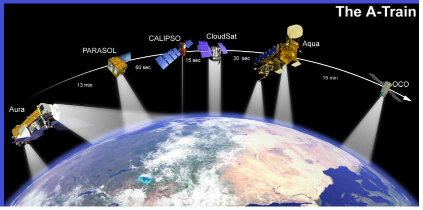
- TOA and surface energy balance
- Coupling of IPHOC with other physical parameterizations
- Reducing computational costs
- Improve the reality of the simulation – reducing regional biases



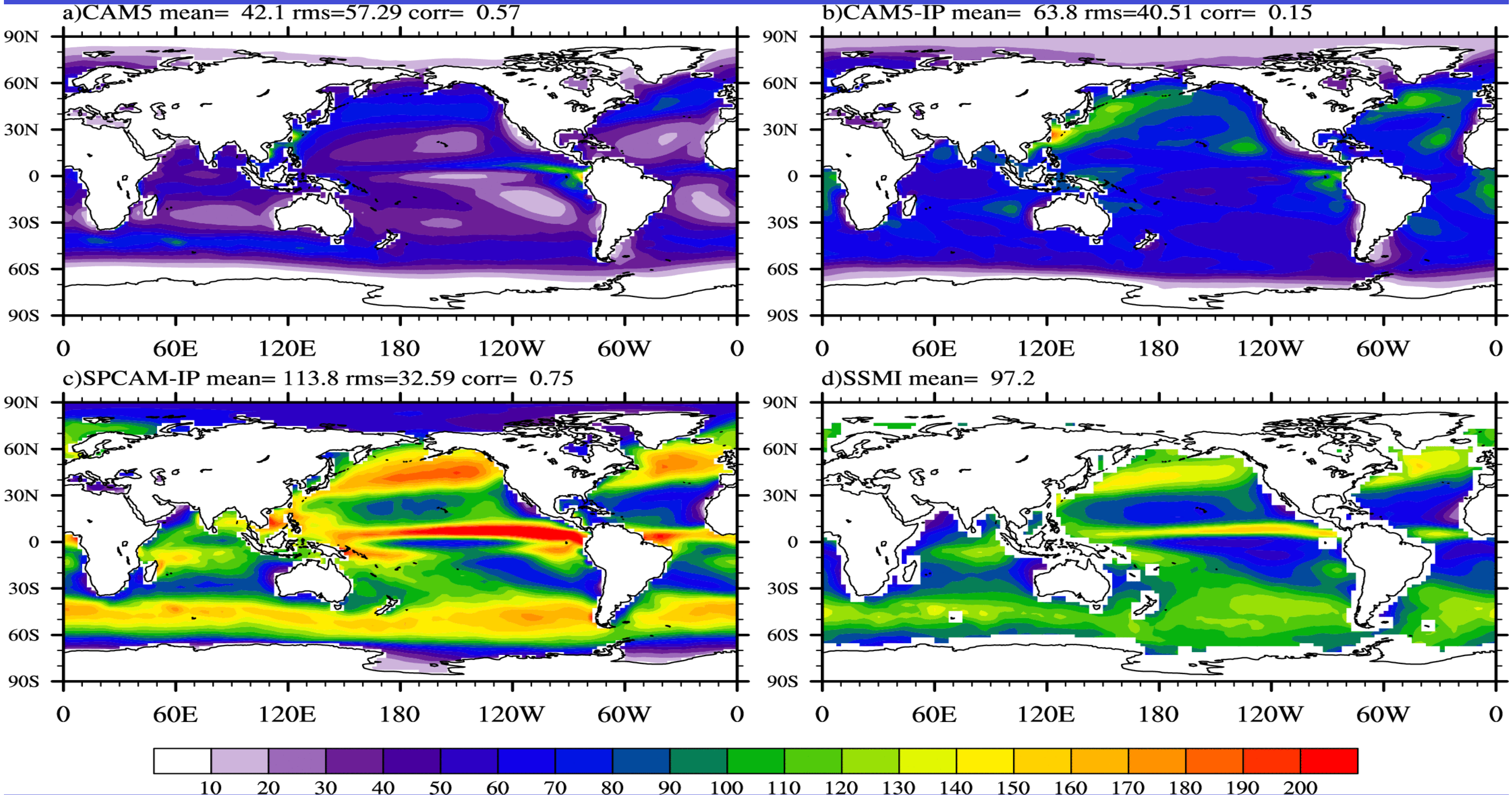
TOA and surface energy balance

	SW	LW	Imbalance
SPCAM-IPHOC	240.40	240.60	-0.20
CAM5	240.01	234.82	5.19
CAM5-IPHOC	239.52	237.02	2.50
CERES-EBAF	239.60	240.20	-0.60

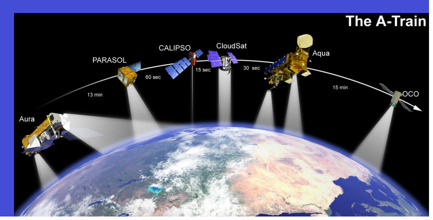
	SW-sfc	LW-sfc	LH	SH	Imbalance
SPCAM-IPHOC	161.98	57.66	88.31	23.52	7.51
CAM5	160.95	54.19	86.17	17.97	-2.62
CAM5-IPHOC	157.00	54.54	82.94	19.33	-0.19
OBS.	162.98	54.47	87.94	19.37	1.20



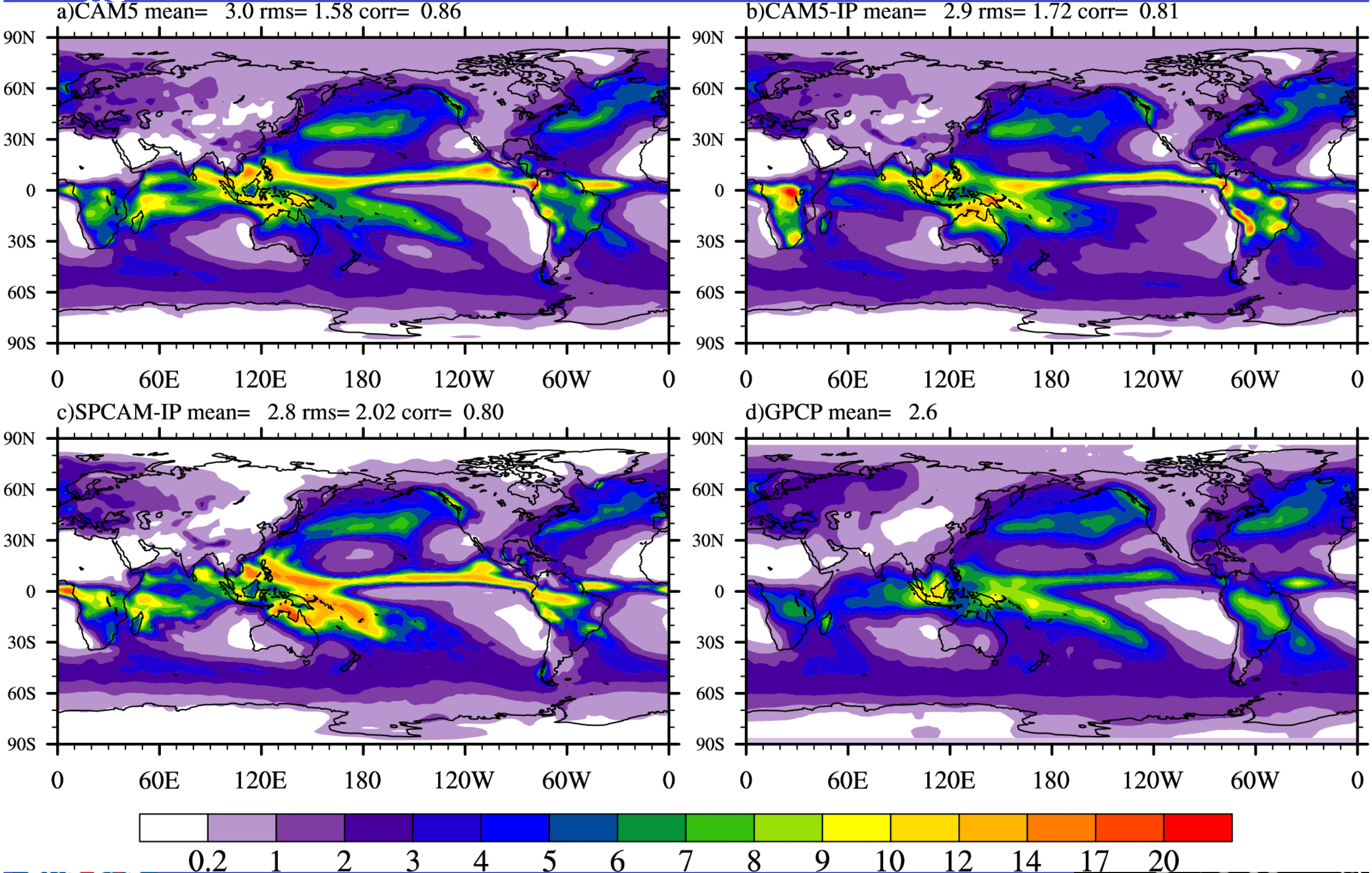
Global distribution of annual mean LWP



Relatively small Liquid water path in ITCZ from CAM5-IP

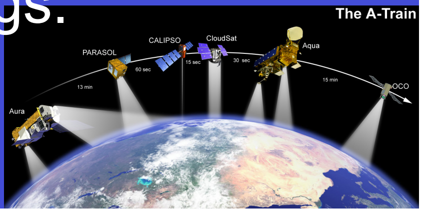


Monthly surface precipitation rate

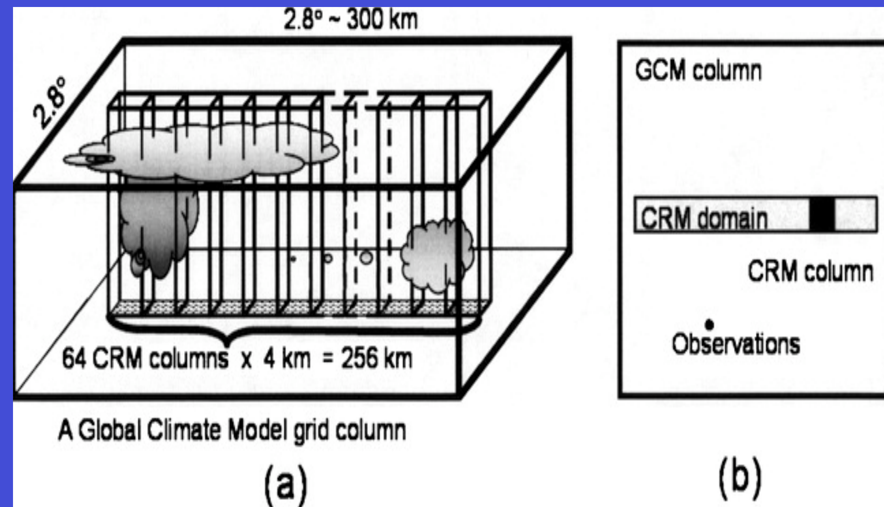


Summary and conclusions

- The global and annual mean low cloud fraction from CAM5-IPHOC is within 5% of C3M observations. The spatial distributions of low clouds are realistic in several ocean basins.
- The global and annual liquid water water path increases compared with CAM5, but the correlation with SSM/I decreases. The liquid water path in ITCZ is relatively small.
- The southeast Pacific convergence zone (SPCZ) from CAM5-IPHOC is also weaker compared with other two models.
- The LWCF and SWCF are realistic compared with CERES. The effects of low clouds can clearly seen from SWCF.
- A reasonable cloud regime transition from CAM5-IPHOC is produced. The vertical structures in cloud fraction and condensate are improved compared with CAM5.
- The potential for realistic simulation of cloud processes is great with the IPHOC approach. Some deficiencies may be related to parameterizations beyond the IPHOC or their couplings.



Multiscale Modeling Framework
(Grabowski 2001; Khairoutdinov and Randall 2001)



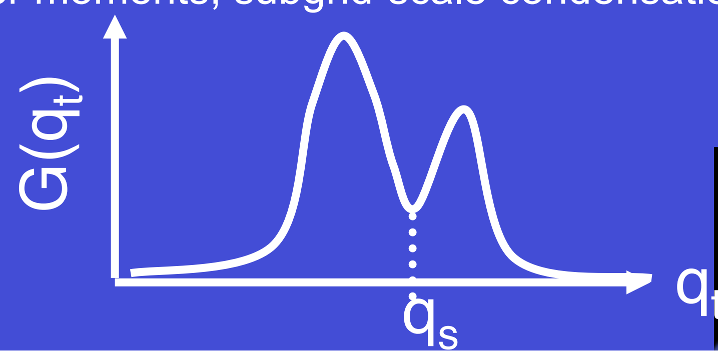
SPCAM: SAM CRM

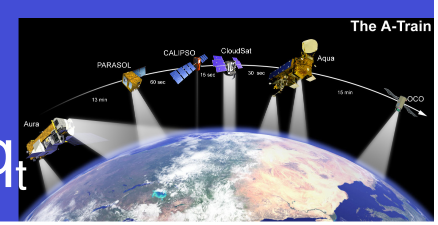
- A CRM is embedded at each grid column (~100s km) of the host GCM to represent cloud physical processes
- The CRM explicitly simulates cloud-scale dynamics (~1 km) and processes
- Periodic lateral boundary condition for CRM (not extend to the edges)

SPCAM-IPHOC: SAM CRM

upgraded with a third-order turbulence closure (IPHOC)

- Double-Gaussian distribution of liquid-water potential temperature, total water mixing ratio and vertical velocity
- Skewnesses, i.e., the three third-order moments, predicted
- All first-, second-, third- and fourth-order moments, subgrid-scale condensation (cloud fraction) and buoyancy based on the same PDF





CAM5
(Community Atmosphere Model version 5)

CAM5:

- ✦ Park-Bretherton macrophysics and turbulence, Zhang-McFarlane deep convection, Morrison-Genttleman microphysics, Liu et al. nucleation, RRTM radiation, CLM, and Lin finite-volume dynamic core
- ✦ Model state is updated sequentially after each physical process

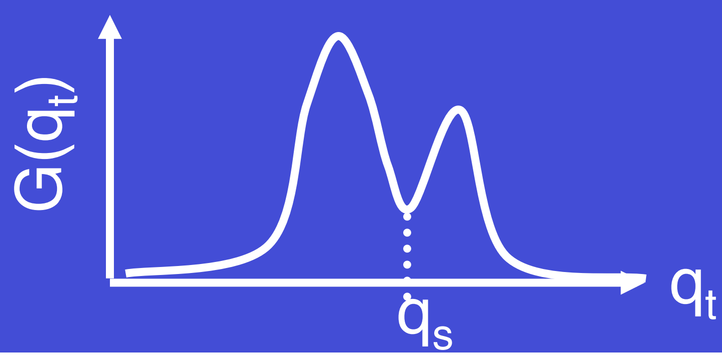
CAM5-IPHOC:

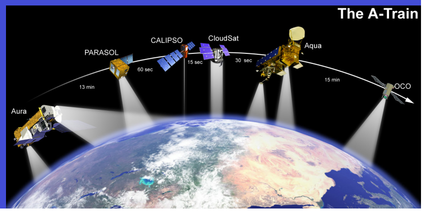
A third-order turbulence closure (IPHOC) replaces macrophysics, shallow cumulus and stratocumulus, and turbulence parameterization

✦Double-Gaussian distribution of liquid-water potential temperature, total water mixing ratio and vertical velocity

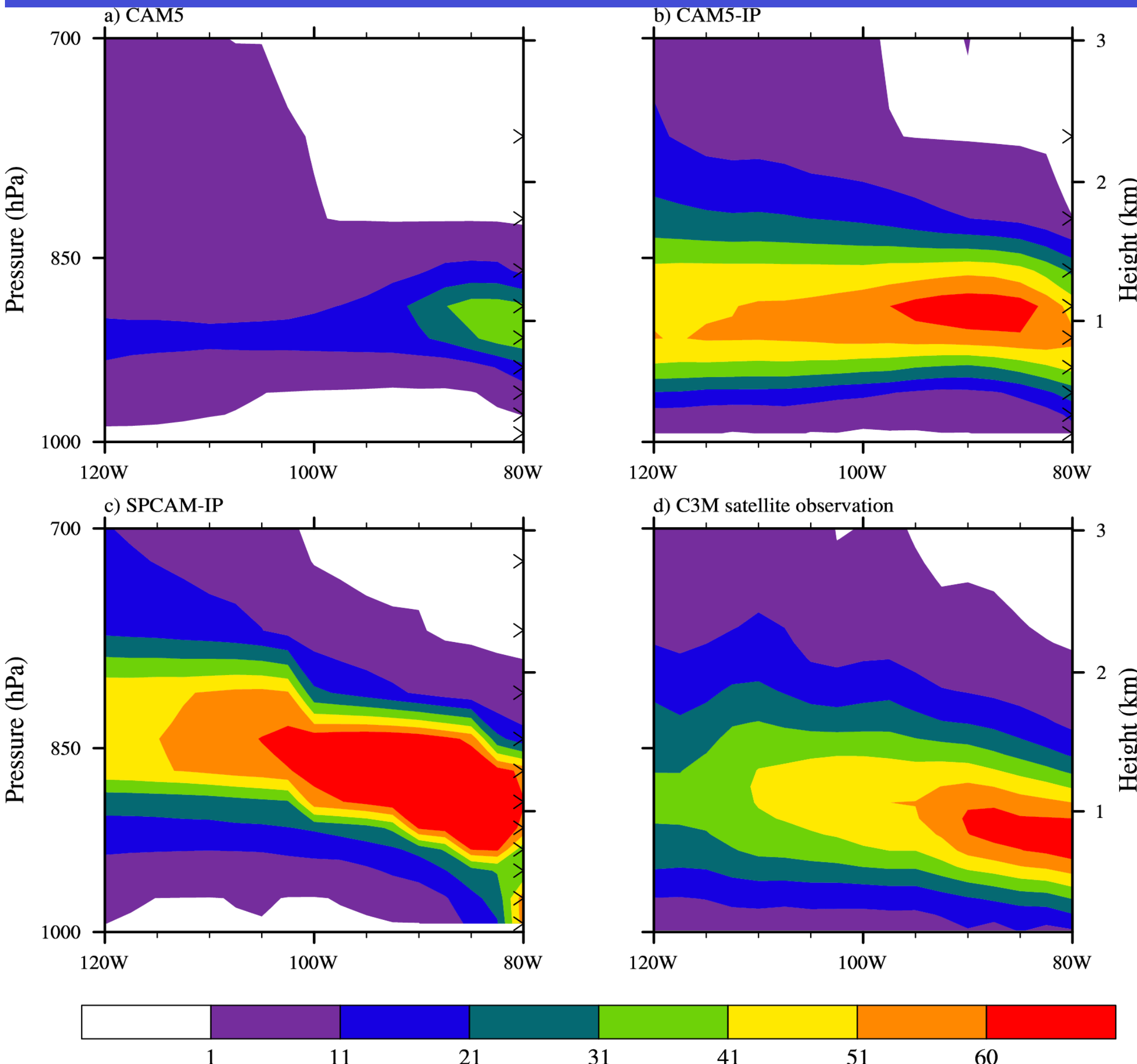
✦Skewnesses, i.e., the three third-order moments, the second moments of liquid-water potential temperature and total water mixing ratio, and PBL height diagnosed; Fluxes and second moment of vertical velocity predicted.

✦All first-, second-, third- and fourth-order moments, subgrid-scale condensation (cloud fraction) and buoyancy based on the same PDF



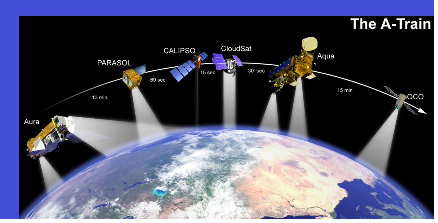


Cloud fraction cross-section along 20°S

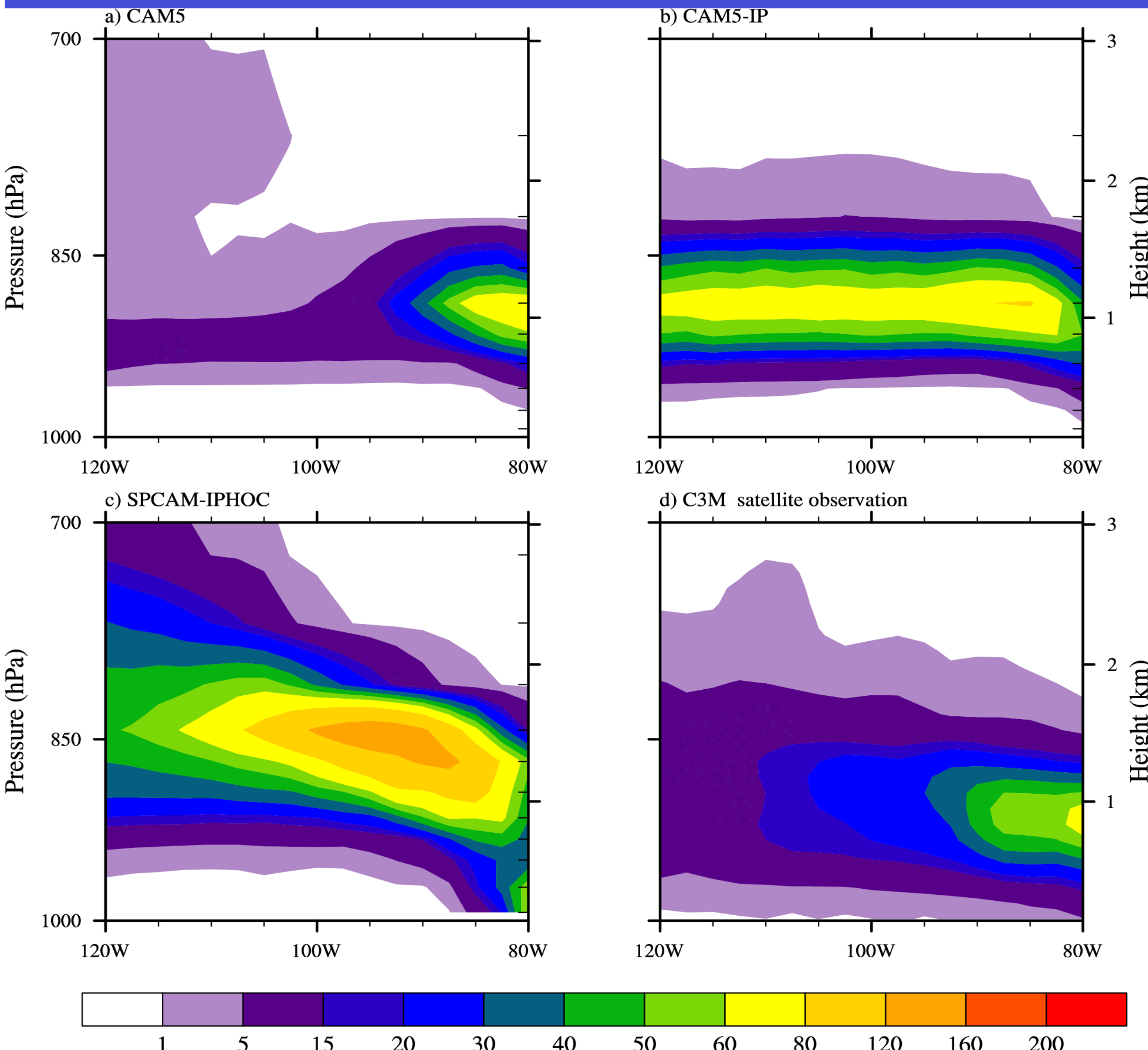


(%)

- CAM5-IP produces realistic stratocumulus and shallow cumulus clouds off south America.



Cloud liquid water cross-section along 20°S



(mg kg^{-1})

- CAM5-IP produces more condensate off the coast, but the increase of cloud base height from Sc to Cu is minimal