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How Difficult is it to Reduce Low-level Cloud Biases with the Higher-order Turbulence Closure Approach in Climate Models?

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Bogenschutz, P. A., and coauthors, 2013: Higher-Order Turbulence Closure and Its Impact on Climate Simulations in the Community Atmosphere Model. *J. Climate*, 26, 9655–9676.

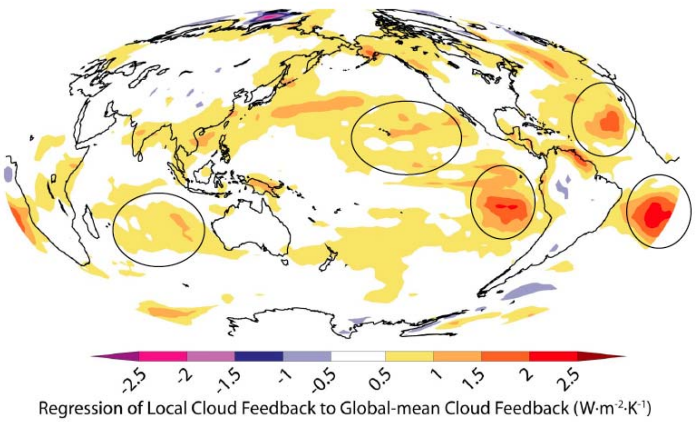
Guo, H., and coauthors, 2014: Multivariate Probability Density Functions with Dynamics in the GFDL Atmospheric General Circulation Model: Global Tests. *J. Climate*, 27, 2087–2108.

Cheng, A., and K.-M. Xu, 2015: Improved Low-Cloud Simulation from the Community Atmosphere Model with an Advanced Third-Order Turbulence Closure. *J. Climate*, 28, 5737–5762.

Guo, Z., and coauthors, 2015: Parametric behaviors of CLUBB in simulations of low clouds in the Community Atmosphere Model (CAM). *J. Adv. Model. Earth Syst.,* 7, **doi:10.1002/2014MS000405.**

Uncertainties in cloud feedback remain in GCMs

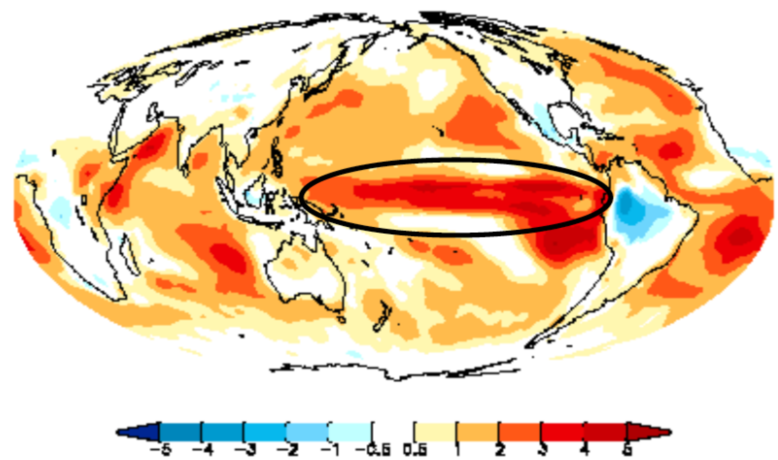
Local contribution to intermodel spread in cloud feedback: AR4



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

Soden and Vecchi (2011

Local contribution to intermodel spread in cloud feedback: AR5

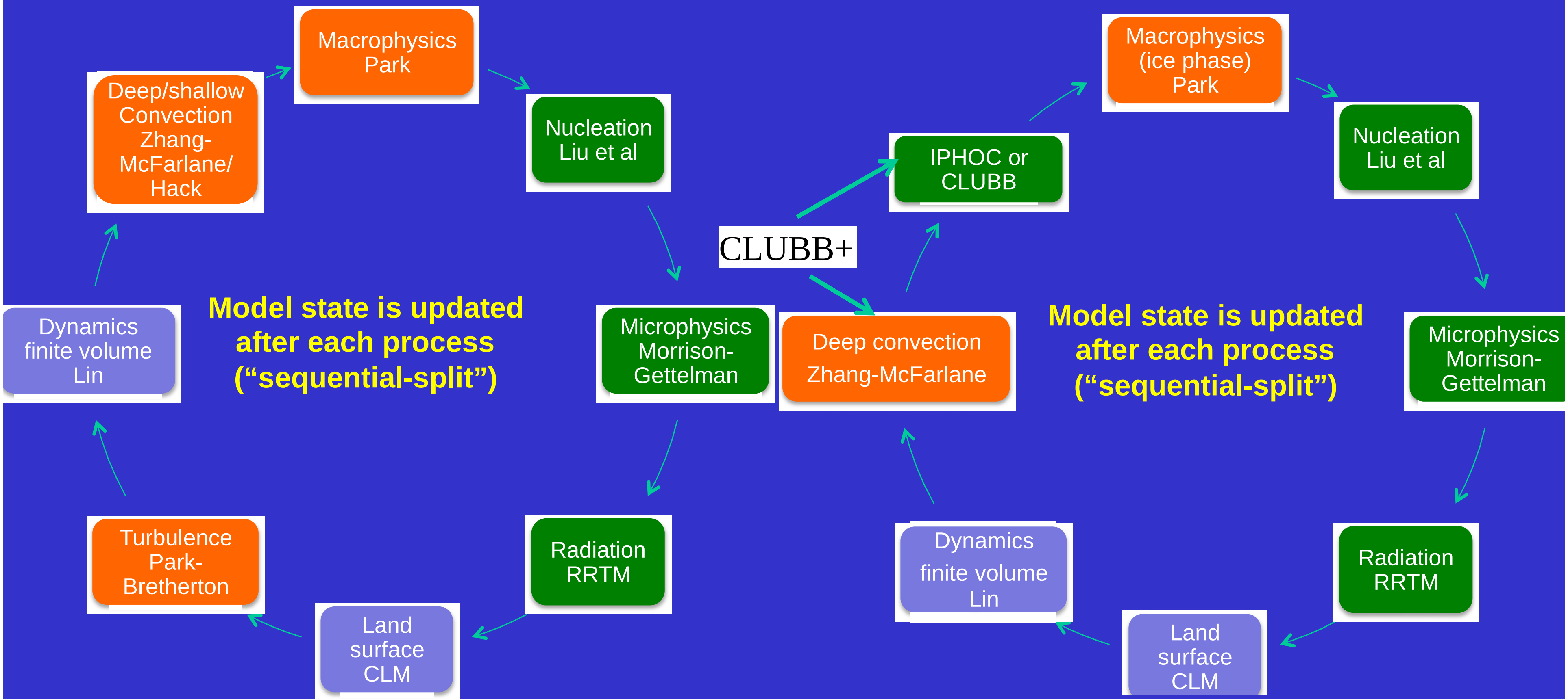


- **Low subtropical clouds still uncertain.**
- **Large contribution from equatorial Pacific.**

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.

CAM5, CAM5 (IPHOC; CLUBB), and AM3 (CLUBB, CLUBB+)

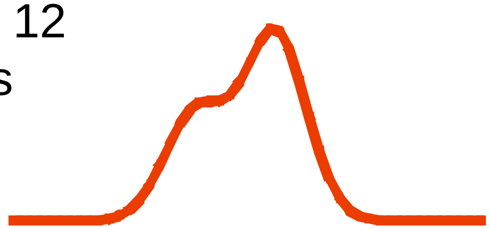


The higher-order turbulence closure approach

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



Δt

Use PDF to close higher-order moments, buoyancy terms

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

Diagnose cloud fraction, liquid water from PDF

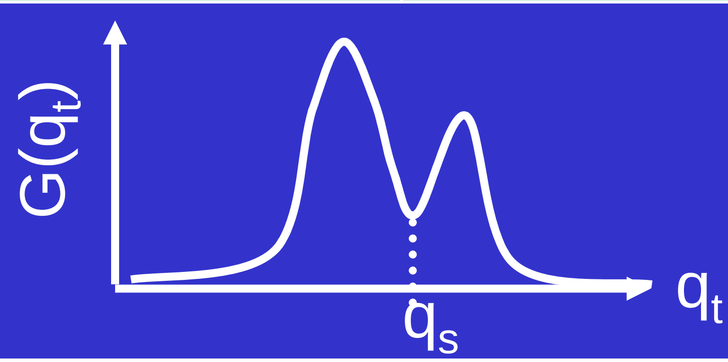
Golaz *et al.* (2002); Cheng & Xu (2006, 2011)

Differences between IPHOC and CLUBB used in GCMs?

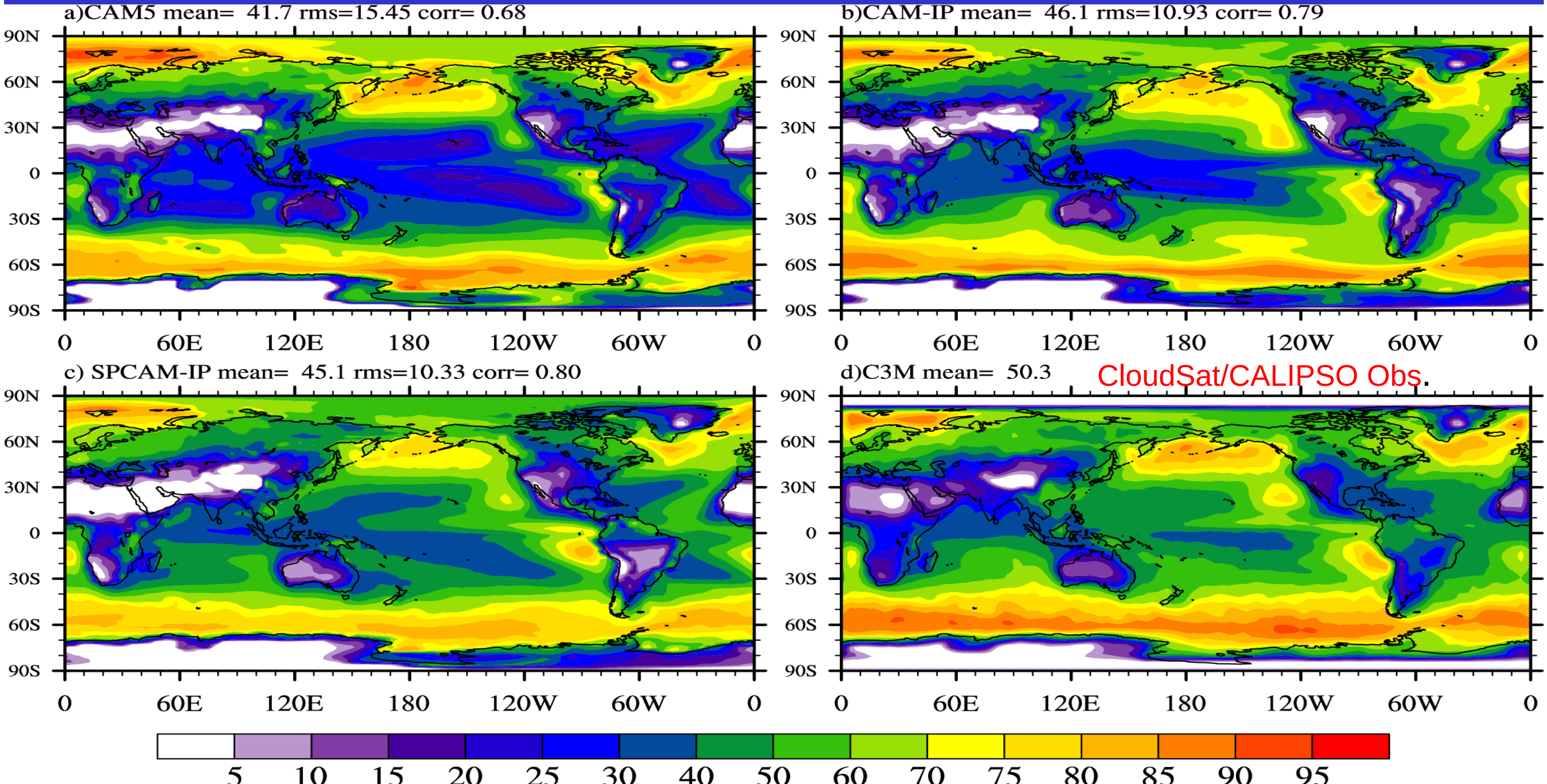
CLUBB (Cloud Layers Unified by Binormals; Golaz *et al.* 2002);

IPHOC (Intermediately Prognostic Higher-order turbulence Closure; Cheng and Xu 2008)

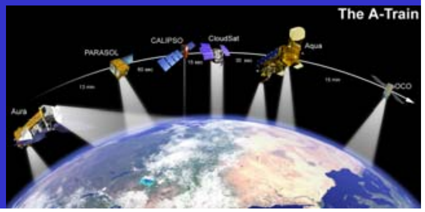
	IPHOC	CLUBB
Third-order moments	3	1
Known moments (predicted)	12 (5 in GCM; 12 in CRM)	10 (10 in GCM and CRM)
Double Gaussian	Analytical II	Analytical I
Convergence of double Gaussian	To a single Gaussian if sk=0	not
PBL height	Predicted	n/a



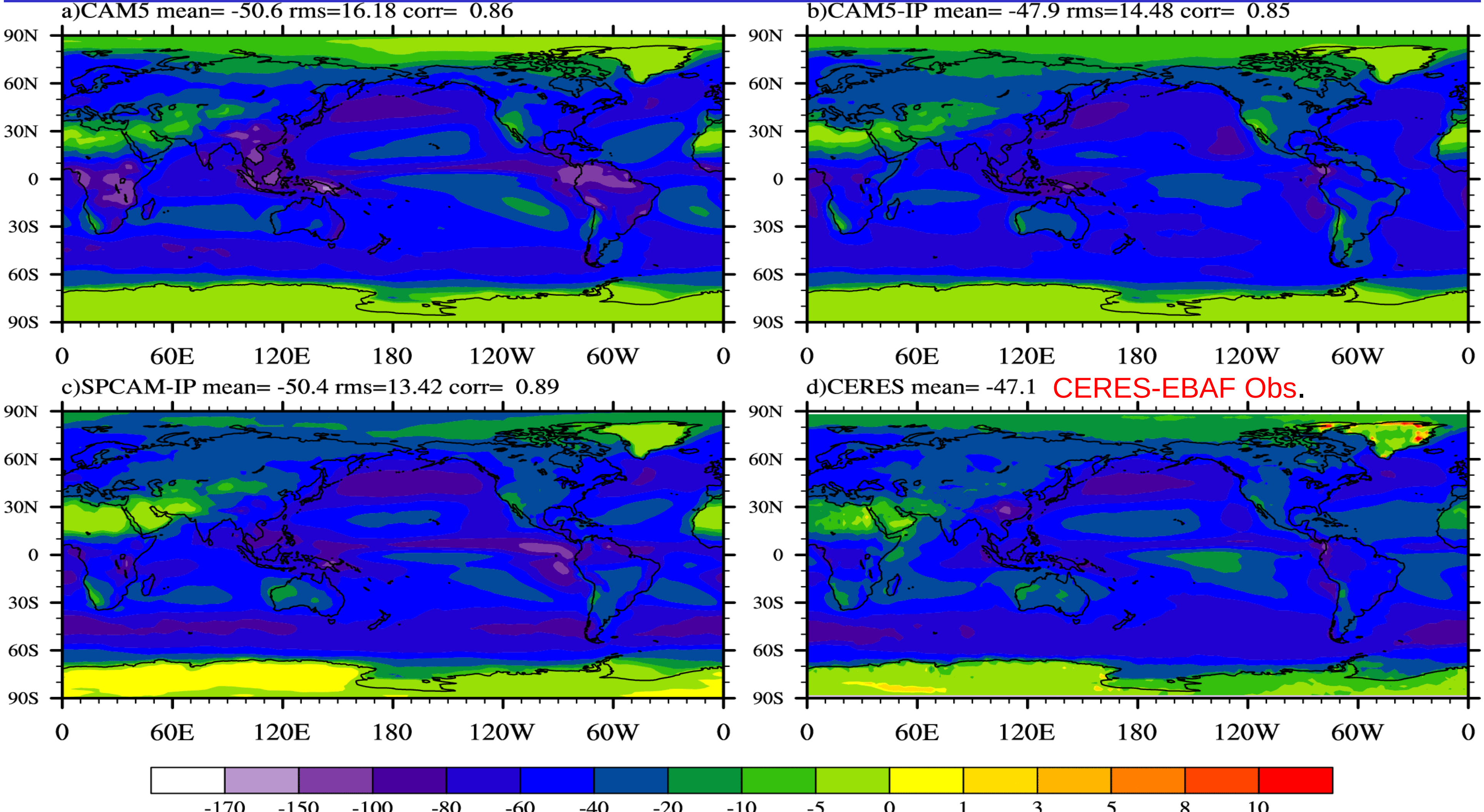
Global Distribution of Annual Mean Low Cloud Fraction -- IPHOC



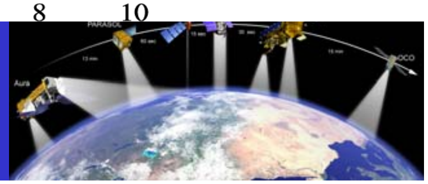
Differences in mean, RMS, correlation, subsidence regions, and storm track regions



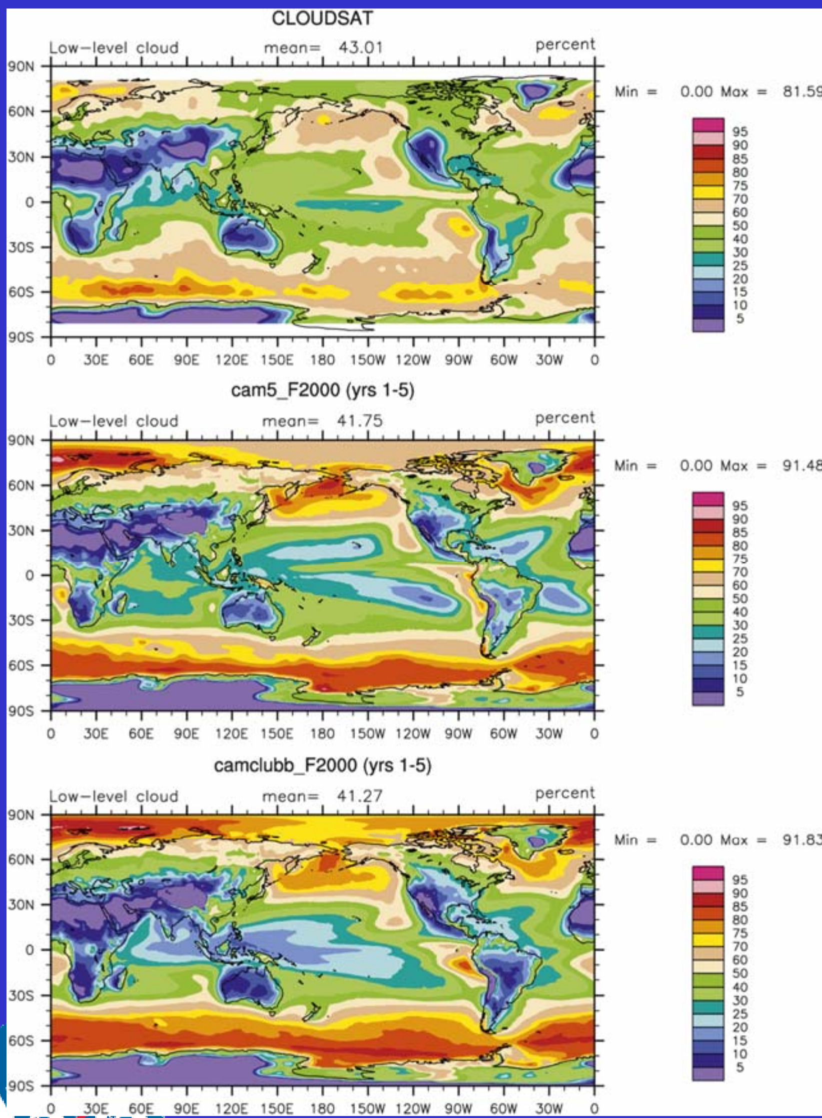
Global Distribution of Annual-Mean SW Cloud-radiative Forcing -- IPHOC



Global mean from CAM5-IP is the closest to CERES
slightly weaker negative forcing from low clouds



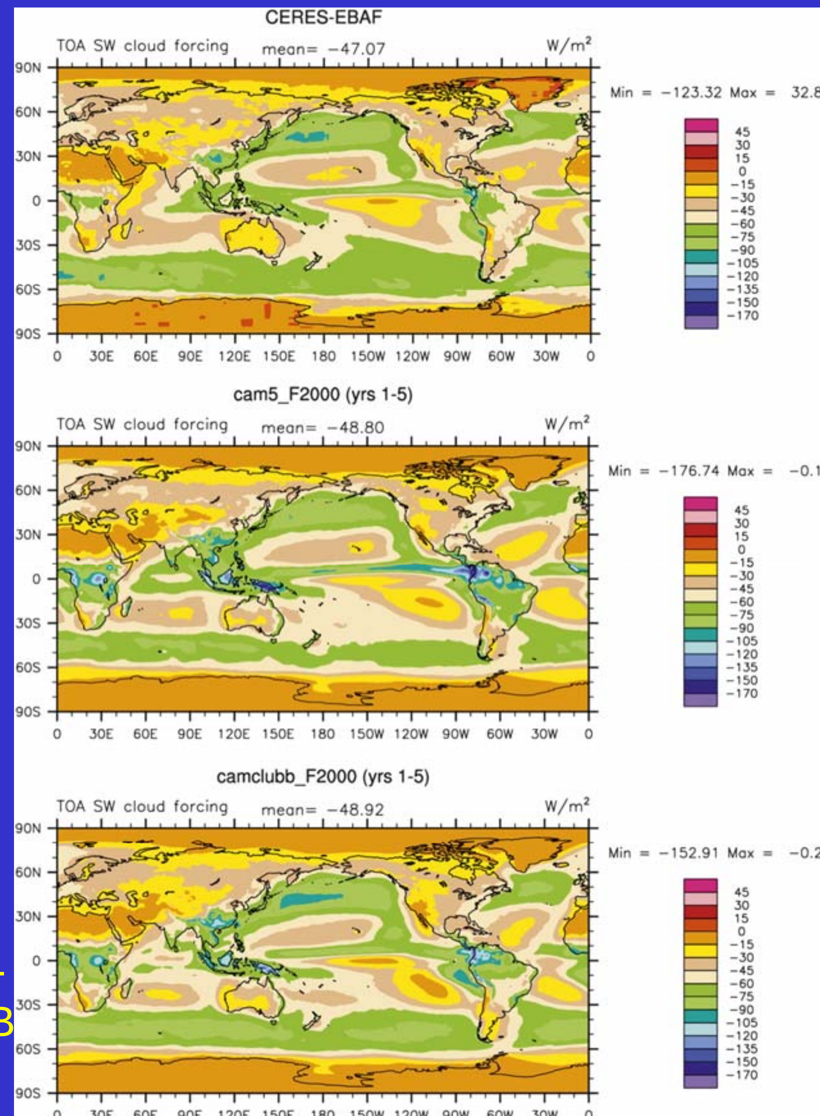
CAM5, CAM5-CLUBB (tuned) cloud fraction and SW cloud radiative forcing

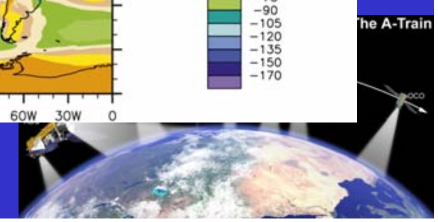


OBS.

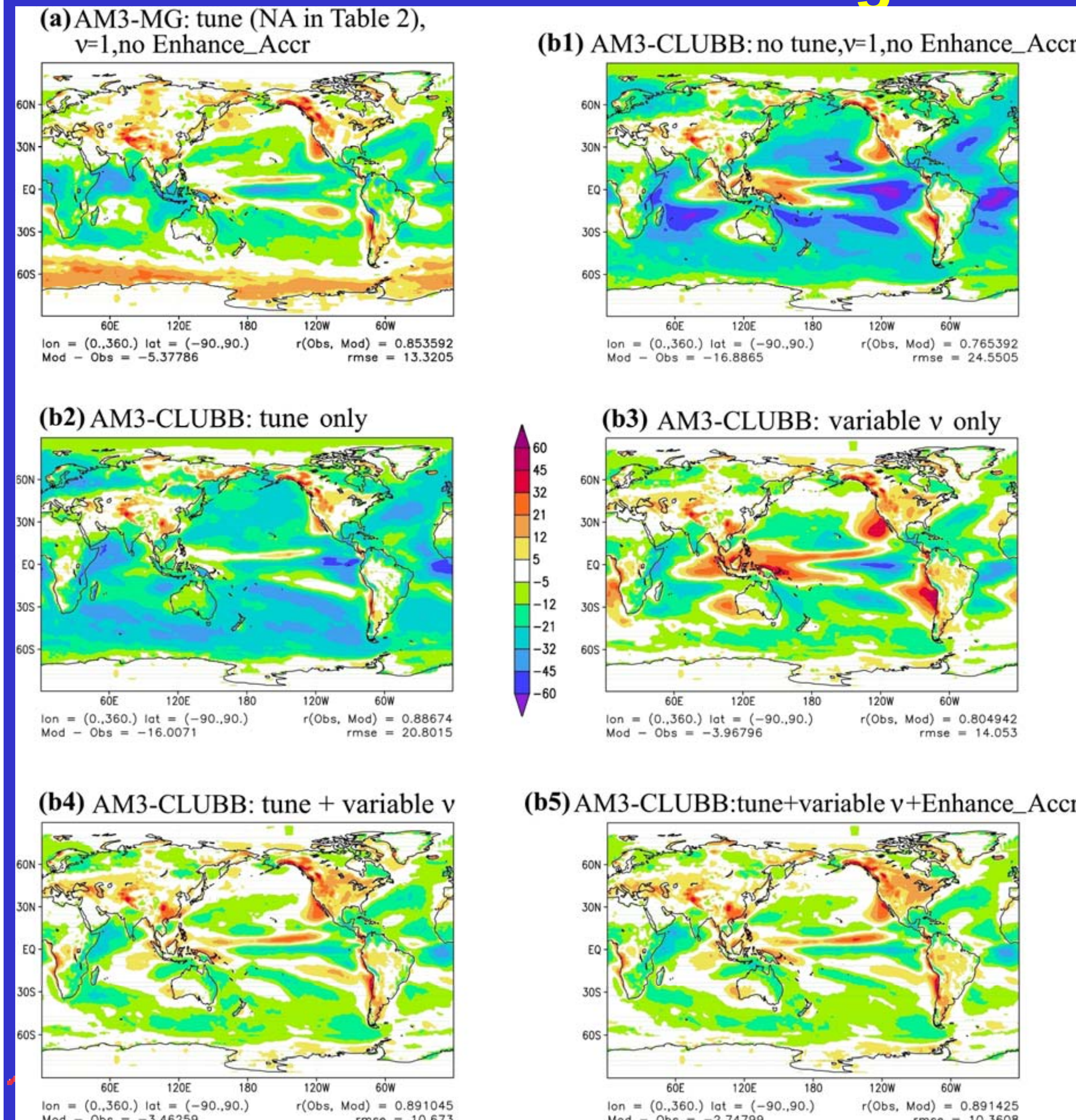
CAM5

CAM5-CLUBB



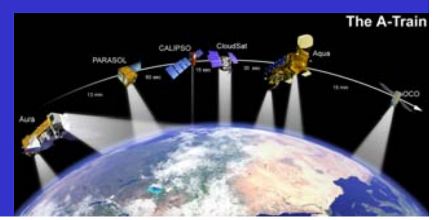


GFDL AM3, AM3-CLUB and tuned versions
SW Cloud radiative forcing differences from CERES

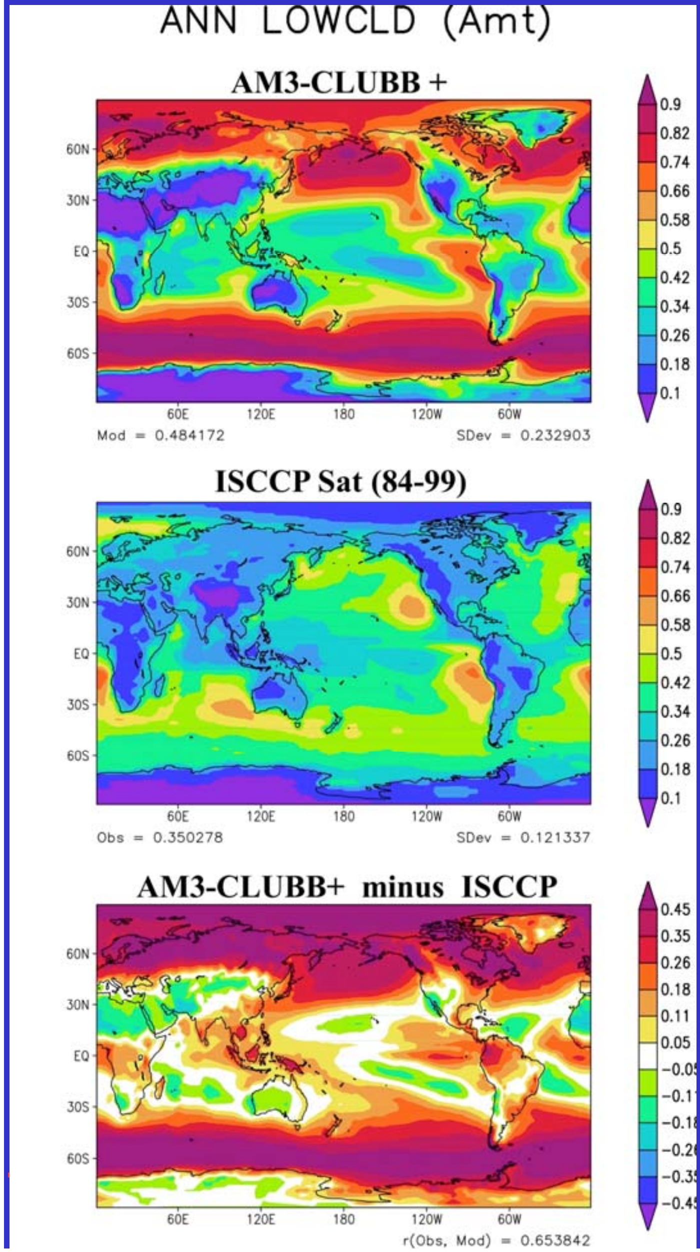


Parameter	Tuned	Original
C1	1.0	2.5
C4	1.0	5.2
C5	0	0.3
C6	0.5	4.0
C7	0.8	0.5
C11b	0.15	0.35
Wpxp_L	150	60
C6_Lscale0	30	14
C7_Lscale0	0.99	0.85

Variable *v*: cloud water variance from CLUBB (0.001-10)
Enhanced accretion rates (10%)

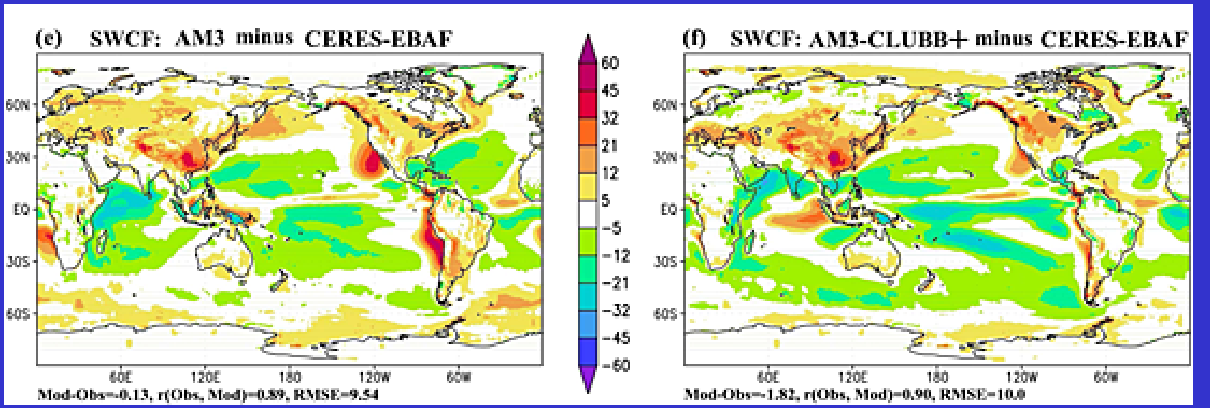


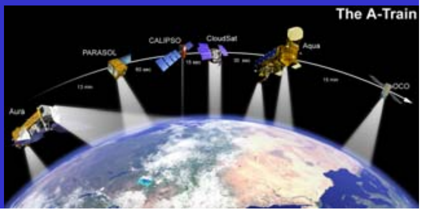
GDFL AM3 united parameterization, CLUBB+



Low cloud fraction

SW cloud radiative forcing difference

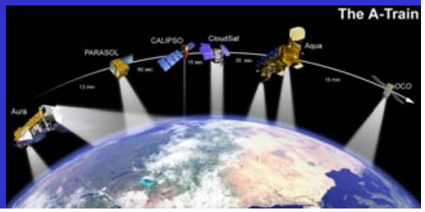




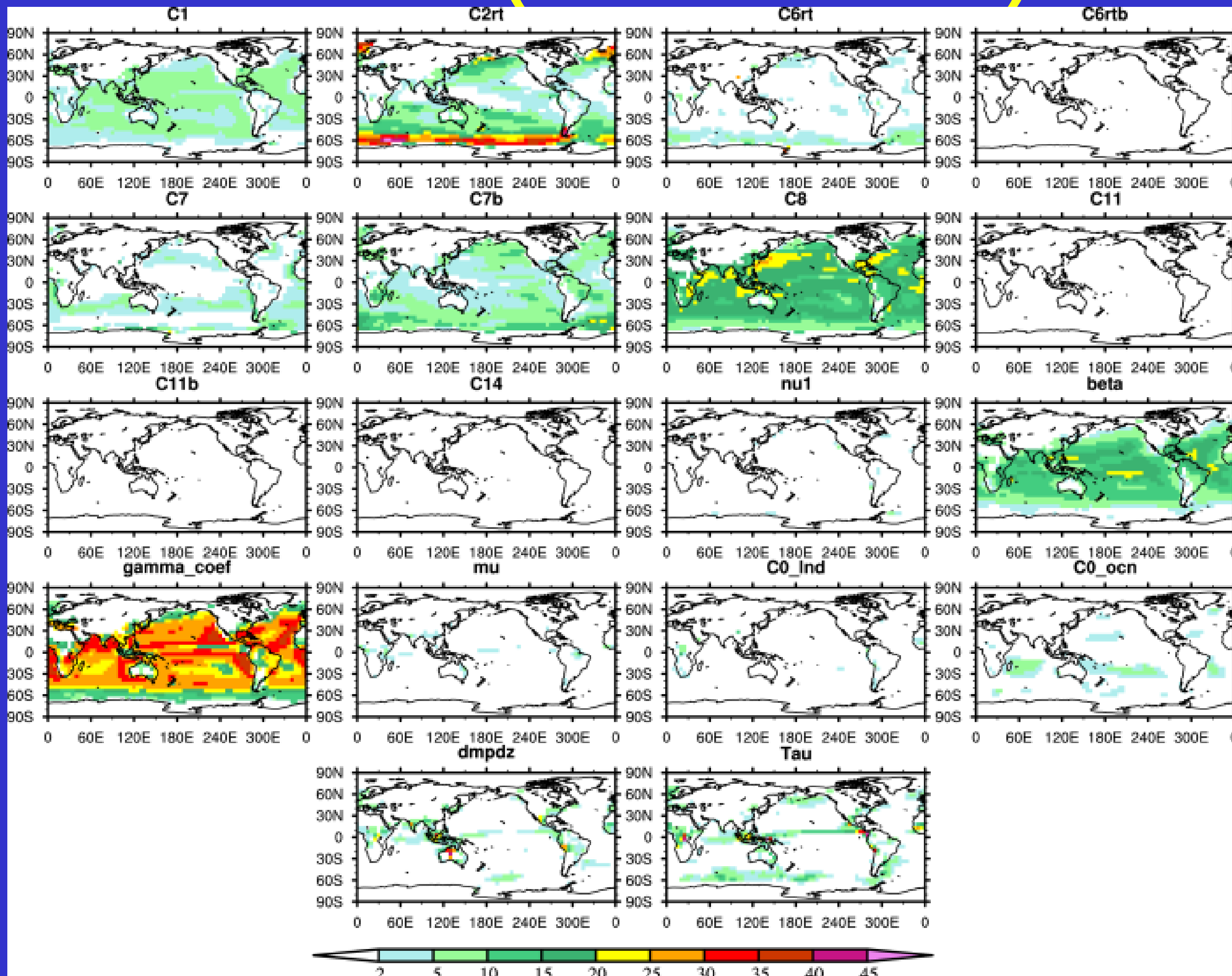
Tuned parameter tests in CAM5-CLUBB (Guo *et al.* 2015)

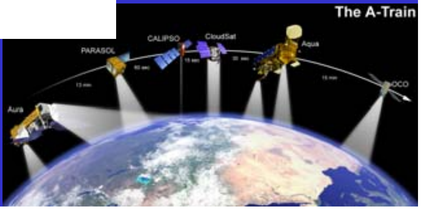
Table 1. Tunable Parameters of CLUBB and ZM

Parameter	Description	Default Value	Investigated Range
C1	Constant associated with $\overline{w'^2}$ dissipation	2.5	1.25–5
C2rt	Constant associated with $\overline{q_t'^2}$ dissipation	1.0	0.5–2
C6rt	Low skewness of Newtonian damping of water flux	4.0	3.0–8.0
C6rtb	High skewness of Newtonian damping of water flux	6.0	3.0–8.0
C7	Low skewness of buoyancy damping of water flux	0.8	0.25–1.0
C7b	High skewness of buoyancy damping of water flux	0.65	0.25–1.0
C8	Constant associated with Newtonian damping of $\overline{w'^3}$	3.0	1.5–6.0
C11	Low skewness of buoyancy damping of $\overline{w'^3}$	0.8	0.0–1.0
C11b	High skewness of buoyancy damping of $\overline{w'^3}$	0.65	0.0–1.0
C14	Constant of Newtonian damping of $\overline{u'^2}$ and $\overline{v'^2}$	1.0	1.0–2.0
ν (nu)	Background coefficient of eddy diffusion	20.0	10.0–40.0
β (beta)	Constant related to skewness of θ_l and q_t	1.75	0.0–3.0
γ (gamma_coef)	Constant of the width of PDF in w-coordinate ($\tilde{\sigma}_w^2$)	0.32	0.1–0.6
μ (mu)	Parcel entrainment rate (1/m)	0.001	$0.5–2.0 \times 10^{-3}$
C0_lnd	ZM precipitation efficiency over land	0.0059	0.003–0.09
C0_ocn	ZM precipitation efficiency over ocean	0.045	0.003–0.09
dmpdz	Entrainment rate of ZM	-10^{-3}	-0.2 to -2×10^{-3}
tau	CAPE consumption time scale (s)	3600 s	1800–10,800



Sensitivity to Tuning parameter tests in CAM5-CLUBB (Guo *et al.* 2015)





Summary and conclusions

- The higher-order turbulence closure approach offers a promising approach to subgrid-scale variability.
- The low-level clouds are improved in different GCM simulations and the biass in SW cloud radiative forcing are reduced.
- The potential for realistic simulation of cloud processes is great with the higher-order turbulence closure approach, for example, coupling with cloud microphysics, and unified low and deep convection parameterization.
- Sensitivity to parameters are especially strong for skewness-related parameters. A better constraint is needed from global observations.