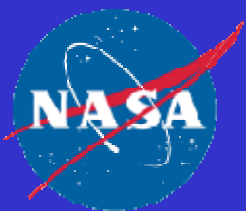


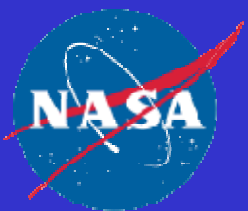
Boundary-layer Turbulence, Low Cloud and Climate Modeling: An Overview

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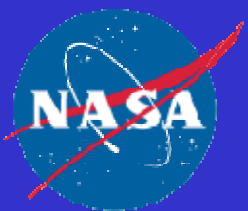
Outline

1. Introduction
2. Higher-order turbulence closure approach
3. Examples of cloud-resolving model (CRM) and multiscale modeling framework (MMF) results
 - Summary 1
4. MMF hydrological sensitivity analysis
 - Summary 2

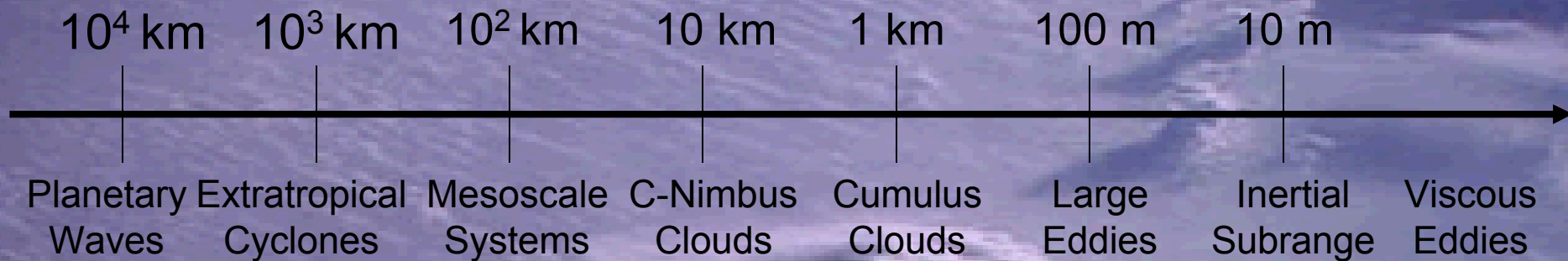


Objectives

- ✦ to improve the simulation of boundary-layer turbulence and low-level clouds with CRM and MMF
- ✦ to understand climate sensitivity, cloud feedback and hydrological sensitivity with MMF



Scales of atmospheric motion and models



General Circulation
Model (GCM)

Cloud Resolving
Model (CRM)

Large Eddy
Simulation (LES)

Direct Numerical
Simulation (DNS)

Global Large Eddy Simulation

Multi-scale Modeling Framework

Global Cloud Resolving Model

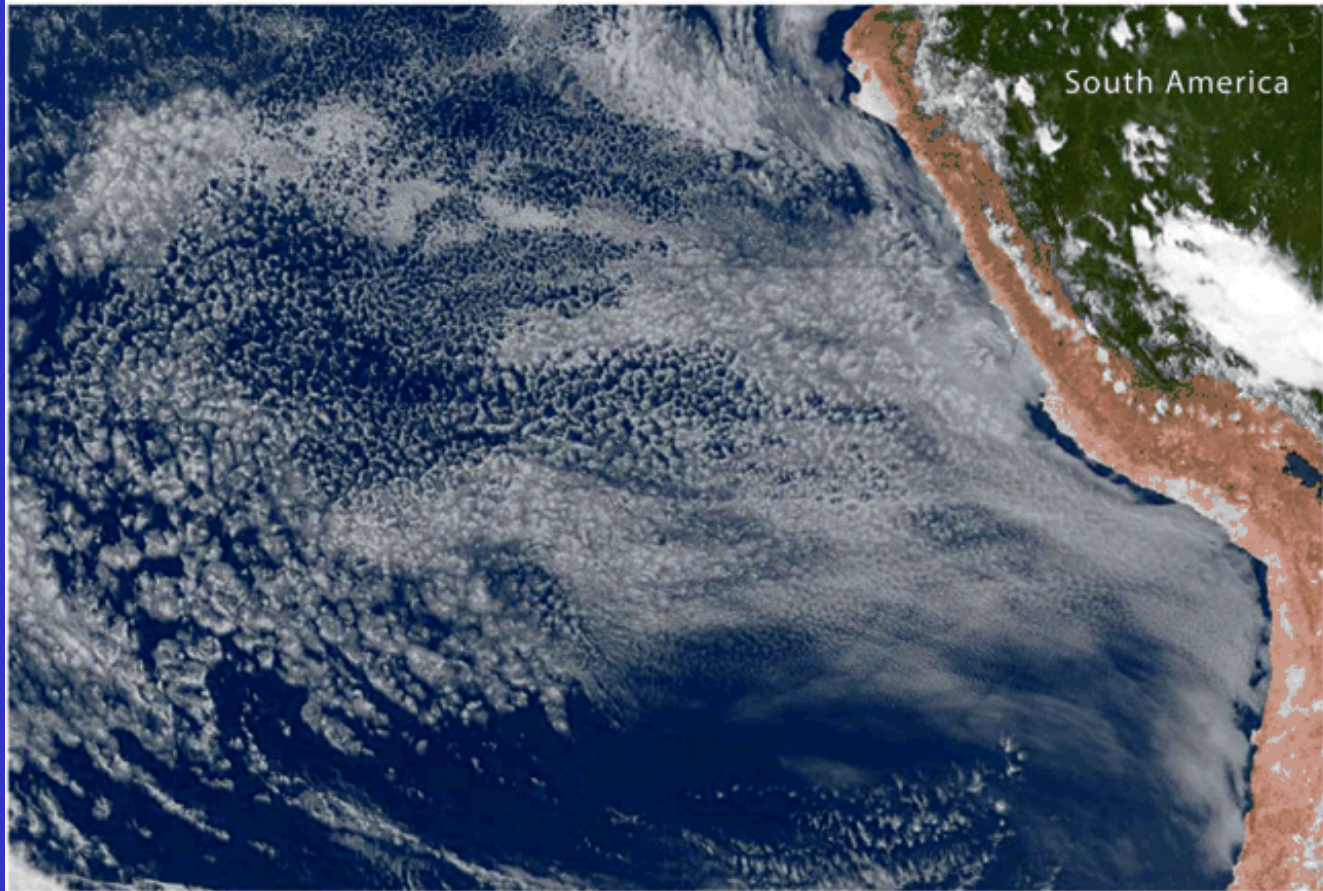
High-resolution GCM

need a turbulence closure and
other physical parameterizations

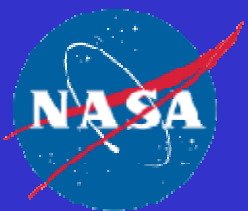
Southeast Pacific boundary-layer clouds

Subtropical stratocumulus

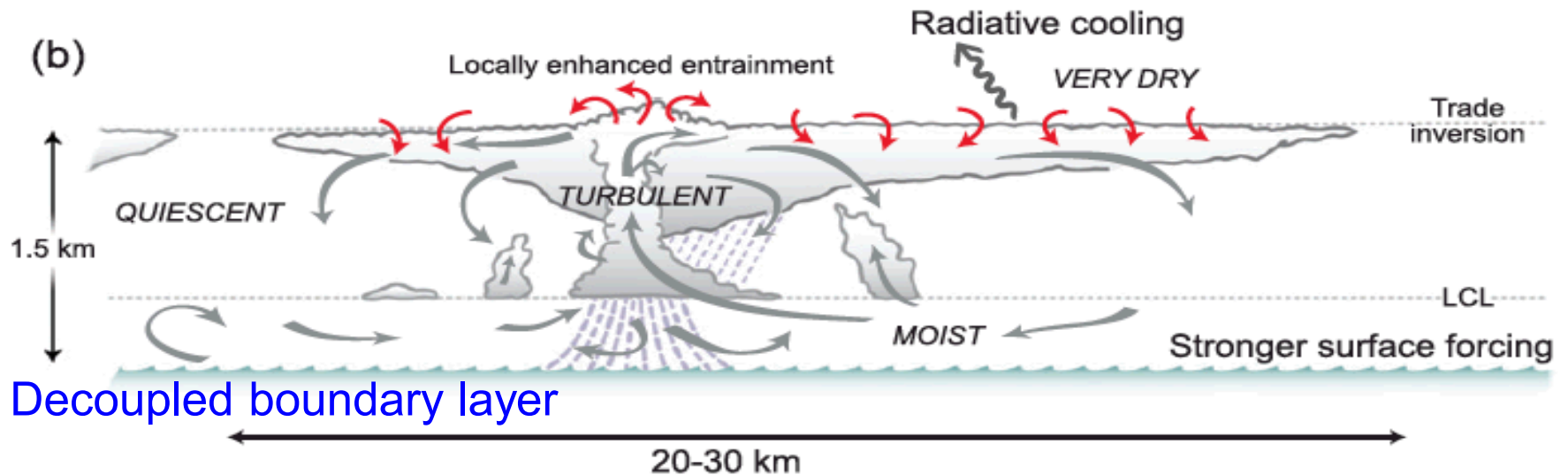
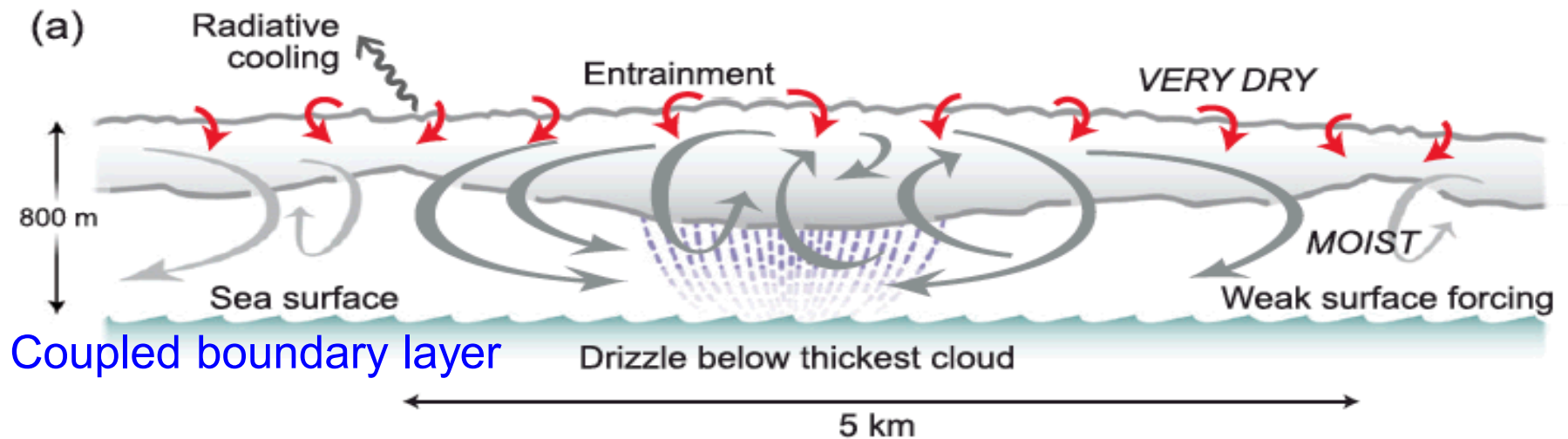
4 September 2009 at 20:45 UTC



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



Boundary-layer turbulence and clouds

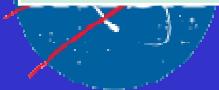


from Wood (2012; *Mon. Wea. Rev.*)



A brief history of turbulence theories and observations

1900-1910	Laminar boundary layer theory (at low Reynolds number); Laminar Ekman layer	Prandtl, Ekman
1910-1940	Turbulent mixing: mixing length theory, eddy diffusivity	Taylor, Von Karman, Prandtl, Lettau
1940-1950	Kolmogorov similarity theory of turbulence	Kolmogorov
1950-1960	Buoyancy effects on surface layer (buoy., shear)	Monin & Obukhov
1950-1960	Early field experiments (Great Plains Expt.), direct turbulent flux measurements	Lettau & Davidson
1960-1970	Observations of a variety of BL types: convective (Wangara), stable, trade-cumulus (BOMEX, ATEX)	Clarke <i>et al.</i>
1970-1980	Modeling of BL turbulence with LES; Application of higher-order turbulence closure theory	Deardorff; André <i>et al.</i> , Mellor & Yamada
1980-2000	Major field experiments for cloud-topped BL (FIRE, ASTEX, DYCOMS, ARM); <i>LES as a tool for turbulence parameterization development</i>	
2000-	Coupled with biosphere & human activity in ESMs	



Boundary-layer parameterization types

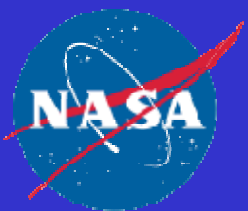
$$\left(\frac{\partial \bar{\alpha}}{\partial t}\right)_{turb} = - \frac{\partial}{\partial z}(\overline{w' \alpha'})$$

$$\frac{\partial}{\partial t}(\overline{w' \alpha'}) = - \overline{w' w'} \frac{\partial \bar{\alpha}}{\partial z} - \frac{\partial}{\partial z}(\overline{w' w' \alpha'}) + \overline{\alpha' B'} - \frac{1}{\rho} \overline{\alpha' \frac{\partial p'}{\partial z}} - \varepsilon_{w\alpha}$$

1. Eddy diffusivity (<i>K</i> -theory), $\overline{w' \alpha'} = -K_{\alpha} \frac{\partial \bar{\alpha}}{\partial z}$	2. Empirical non-local	3. Higher-order turbulence closure (HOC)
Local first-order closure: K_{α} is specified from the vertical shear and static stability	Non-local K-profile: Accounting for counter-gradient transport, $\overline{w' \alpha'} = -K_{\alpha} \left(\frac{d\bar{\alpha}}{dz} - \gamma_{\alpha} \right)$	2nd-order Mellor-Yamada (e.g., MYNN3 in WRF)
1.5-order/turbulent kinetic energy (TKE) closure: K_{α} is specified using TKE & length scale	Eddy diffusion mass-flux (EDMF): $\overline{w' \alpha'} = -K_{\alpha} \frac{d\bar{\alpha}}{dz} + \mathbf{M} (\alpha_u - \bar{\alpha})$	Full third-order (André <i>et al</i> 1976): prognostic equations of 11 2 nd -order moments & 24 3 rd -order moments
		Simplified third-order: CLUBB, IPHOC, etc.

Higher-order turbulence closure (HOC) approach

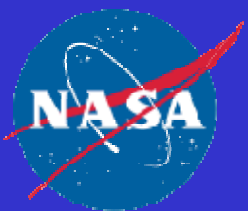
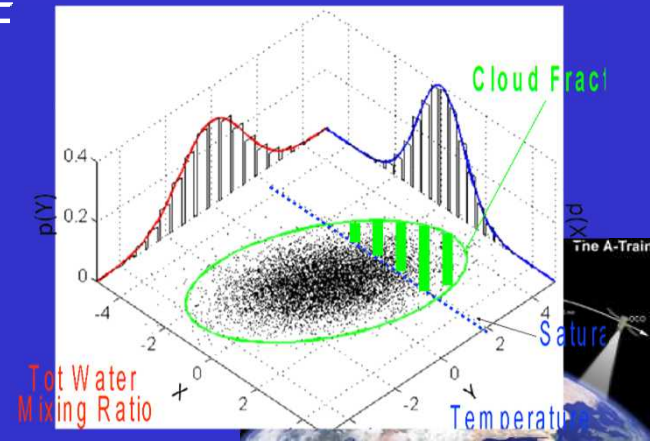
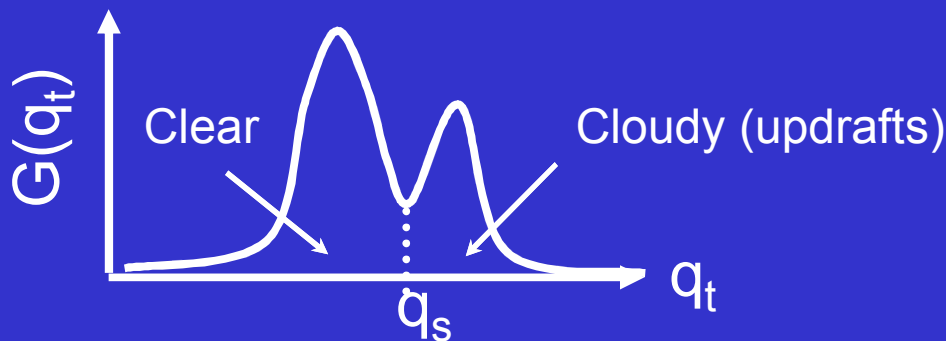
- John Lumley's "*Article of Faith*:" weak assumptions at third order are preferable to weak assumptions at second order (Randall's lecture notes)
- $$\frac{\partial}{\partial t}(\overline{w'\alpha'}) = -\overline{w'w'} \frac{\partial \overline{\alpha}}{\partial z} - \frac{\partial}{\partial z}(\overline{w'w'\alpha'}) + \overline{\alpha'B'} - \frac{1}{\rho} \overline{\alpha' \frac{\partial p'}{\partial z}} - \varepsilon_{w\alpha}$$
- The closure problem consists of
 - Parameterizing higher-order moments to predict lower-order moments
 - Pressure and buoyancy to predict statistics involving velocity components
 - Molecular viscosity and molecular conductivity (very small scales)
 - Assumptions on higher moments; e.g., $\overline{a'b'c'd'} \cong \overline{a'b'} \overline{c'd'} + \overline{a'c'} \overline{b'd'} + \overline{a'd'} \overline{b'c'}$ (*quasi-normal* assumption for fully-prog. third-order turbulence closure)
- The fully prognostic 3rd-order closure (André *et al.* 1976, 1978) was very complicated (e.g., clipping approximation) and computationally expensive
- This closure was later used in UCLA CRM (Krueger 1988) to study the interactions of boundary layer with deep convection



A new type of third-order turbulence closures

- △ “Simplification” of 3rd-order closure began in the early 2000s (e.g., Golaz *et al.* 2002; Larson *et al.* 2002; Cheng *et al.* 2004; Cheng & Xu 2006), based upon LES and field experiment data (Larson *et al.* 2002)
- △ Joint double-Gaussian distribution (PDF) of liquid-water potential temperature (θ_l), total water mixing ratio (q_t) and vertical velocity (w),

$$P(w, q_t, \theta_l) = a G_1(w, q_t, \theta_l) + (1-a) G_2(w, q_t, \theta_l)$$
- △ Fewer higher-order moments are predicted; e.g., Reynolds stress ($\overline{w'^2}$), variances ($\overline{\theta_l'^2}$, $\overline{q_t'^2}$), co-variance ($\overline{\theta_l' q_t'}$), fluxes ($\overline{w' \theta_l'}$, $\overline{w' q_t'}$), and skewnesses, $\overline{w'^3}$ (CLUBB & IPHOC), $\overline{\theta_l'^3}$, $\overline{q_t'^3}$ (IPHOC only)
- △ The rest of third- and fourth-order moments, subgrid-scale condensation and buoyancy are based on the same PDF



IPHOC: Intermediately-prognostic higher-order turbulence closure (Cheng & Xu 2006)

Advance 12 prognostic equations

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

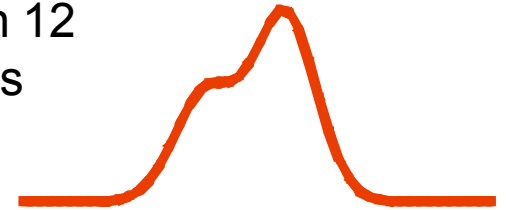
Use PDF to close higher-order moments, buoyancy terms

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

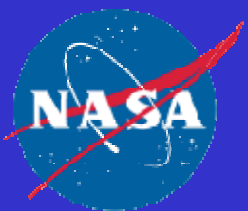
$$\overline{w'^4}, \overline{w'q_t'^3}, \overline{w'\theta_l'^3}$$

Δt

Select PDF from given family to match 12 moments

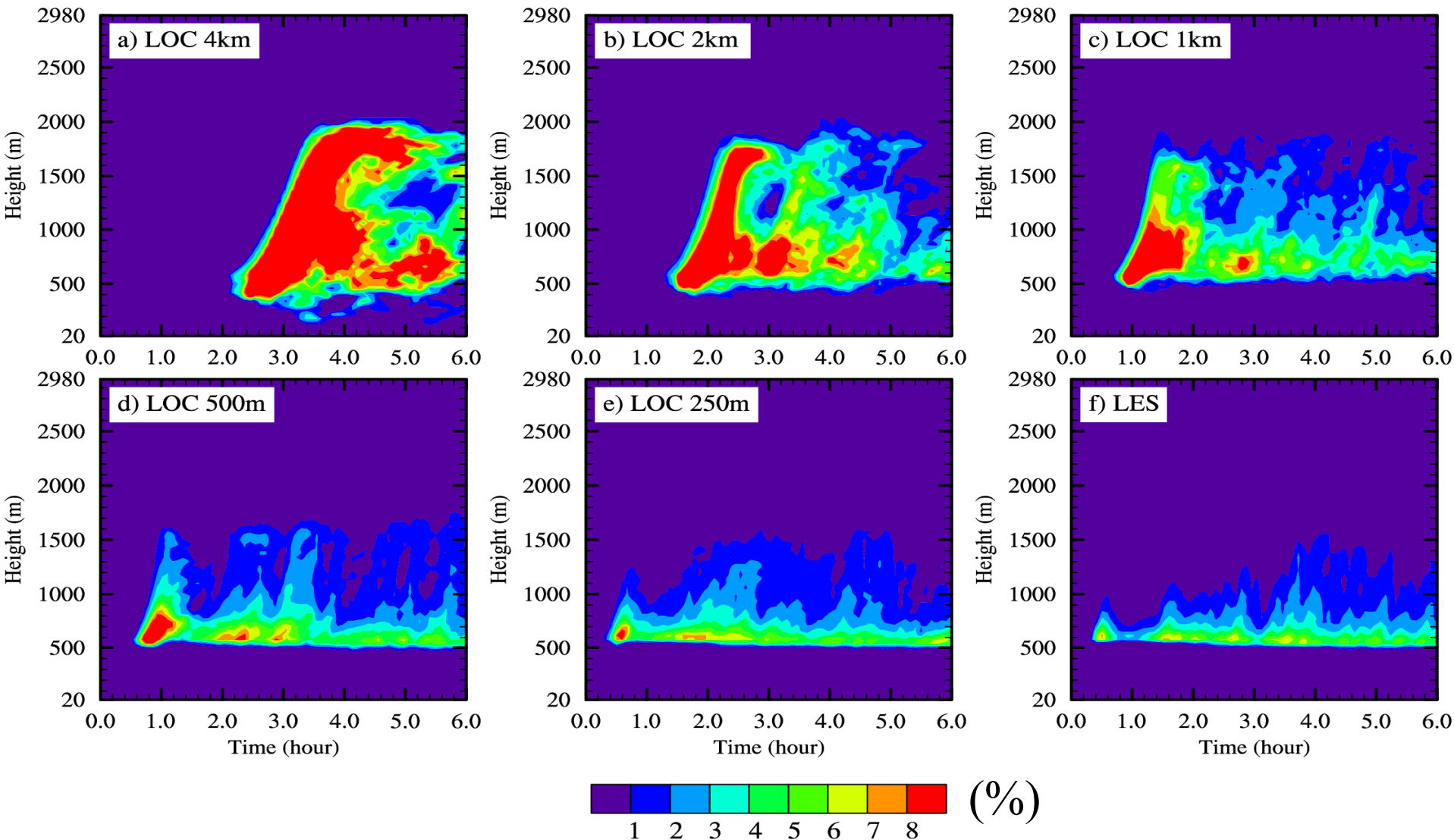


Diagnose cloud fraction, liquid water from PDF



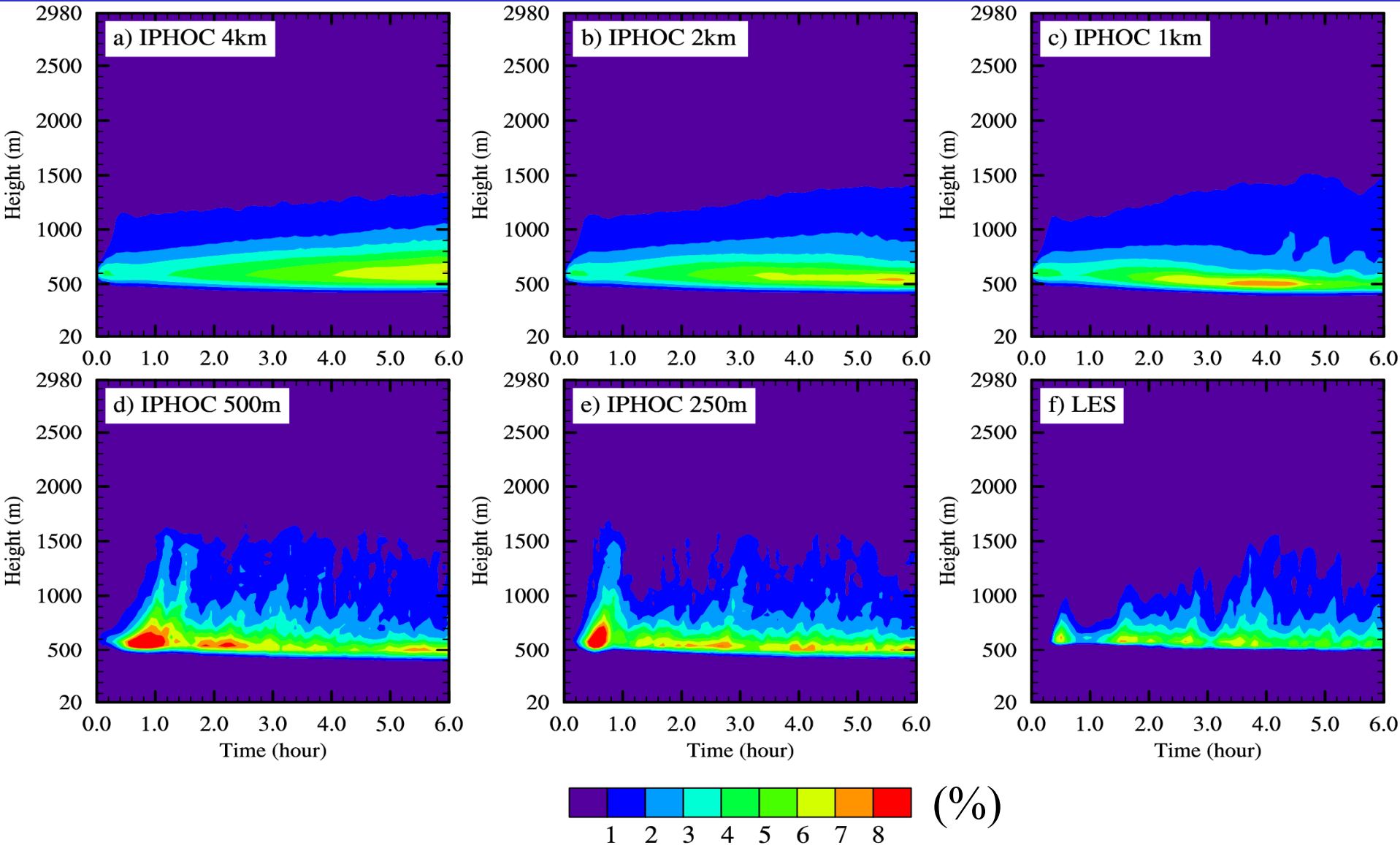
Low-order closure (LOC): CRM-simulated fractions of shallow cumuli (BOMEX case)

Cheng & Xu (2008) *J. Meteor. Soc. Jpn.*, 86A, 67-86



IPHOC: CRM-simulated fractions of shallow cumuli (BOMEX case)

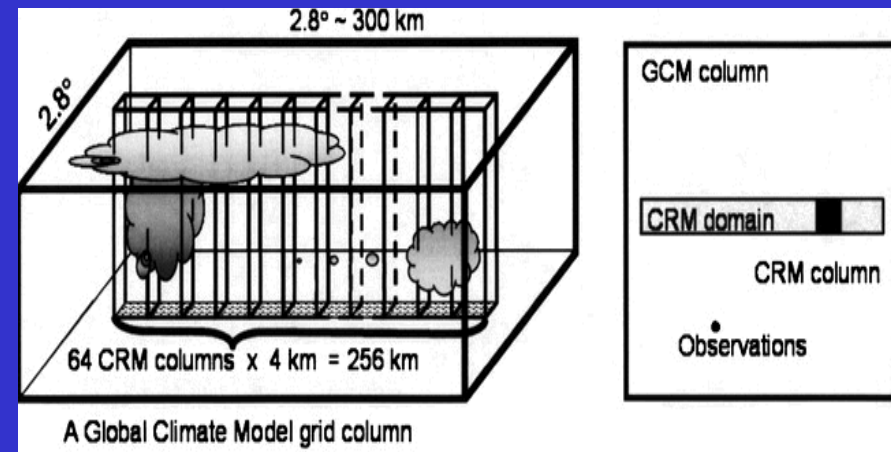
Cheng & Xu (2008) *J. Meteor. Soc. Jpn.*, 86A, 67-86



The SPCAM and SPCAM-IPHOC MMFs

(*Khairoutdinov & Randall 2001; Cheng & Xu 2011; Xu & Cheng 2013a,b*)

- ✦ Community Atmosphere Model (CAM) version 3.5 with finite-volume dynamical core as the host GCM, $1.9 \times 2.5^\circ$ grid spacing
- ✦ 2-D version of System for Atmospheric Modeling (SAM) without/with IPHOC
- ✦ CRM: 32 columns, 4 km grid spacing
- ✦ 26 layers for SPCAM, 32 for SPCAM-IPHOC; resolution below 700 hPa is doubled in the latter



Simulation setup

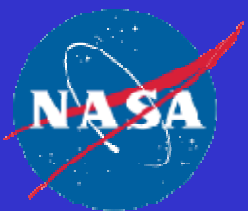
- ✦ Climatological monthly-mean SST and sea ice distributions (i.e., without interannual variation)
- ✦ Simulation duration is 10 years and 3 mos; last nine years analyzed
- ✦ Same setup for short-duration sensitivity runs with 2 yr and 3 mos duration except for the number of vertical layers and with/without IPHOC; last two year analyzed
- ✦ Climate sensitivity simulations (10 yrs and 3 mos) with uniform SST increases of 2 K or instantaneous CO₂ doubling



Short-duration sensitivity experiments

- Both the vertical resolution and IPHOC are important for simulating boundary-layer clouds

Experiment name	Feature
IP-12L	With IPHOC, 12 levels below 700 hPa
IP-6L	Same as IP-12L except for 6 layers below 700 hPa
SP-12L	Same as IP-12L except without IPHOC (i.e., with low-order closure)
SP-6L	Same as IP-6L except without IPHOC



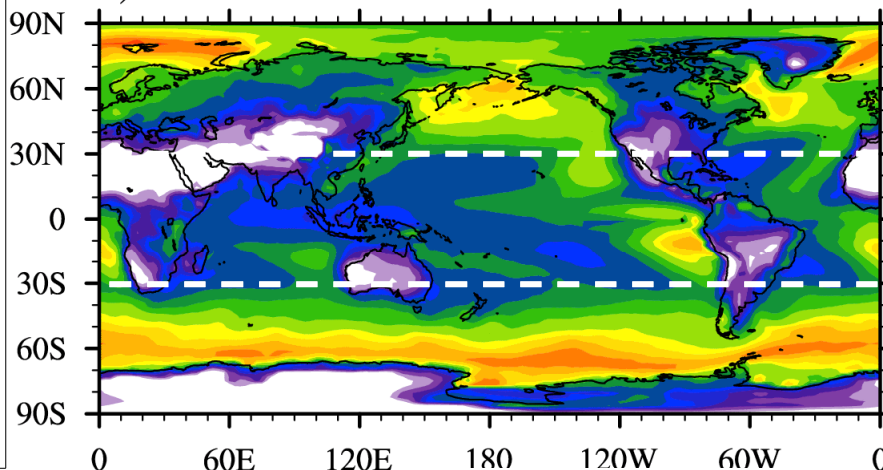
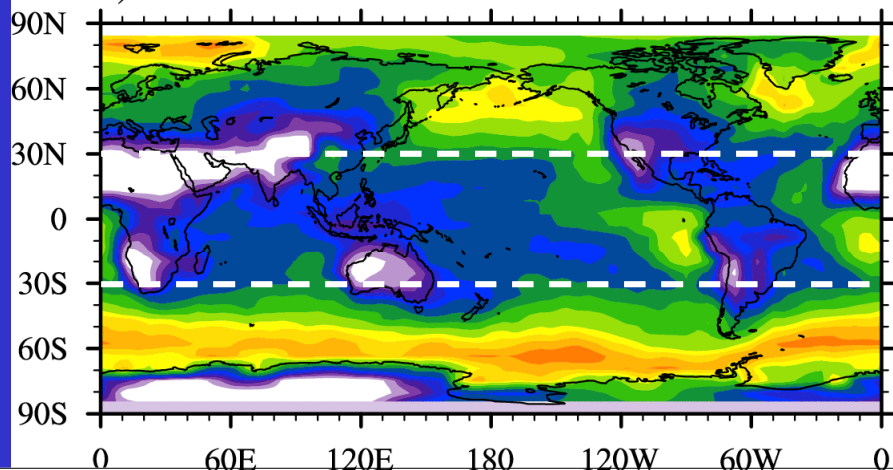
Annual-mean low-level (sfc - 700 hPa) cloud amount (%)

SPCAM (6L)

SPCAM-IPHOC (6L)

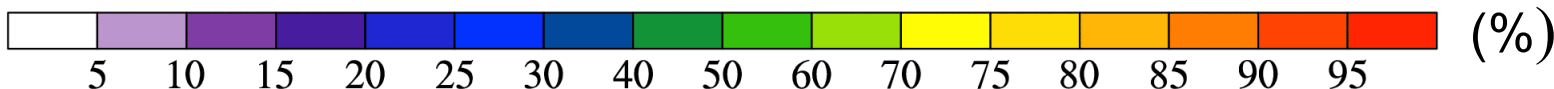
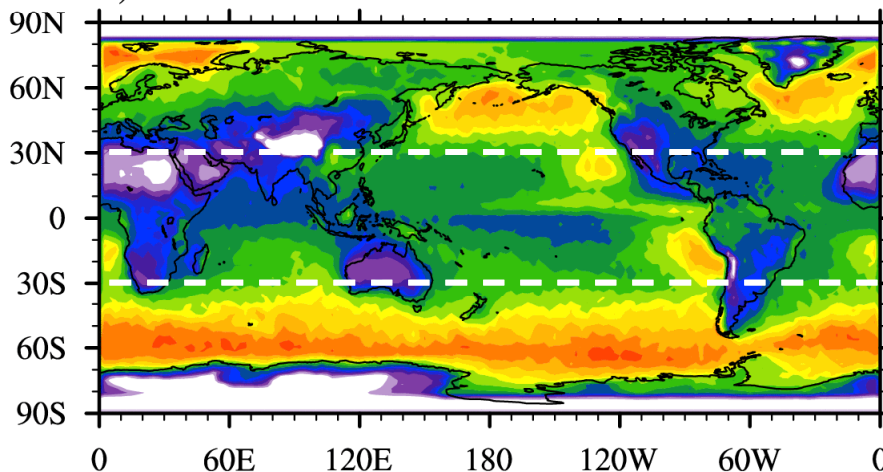
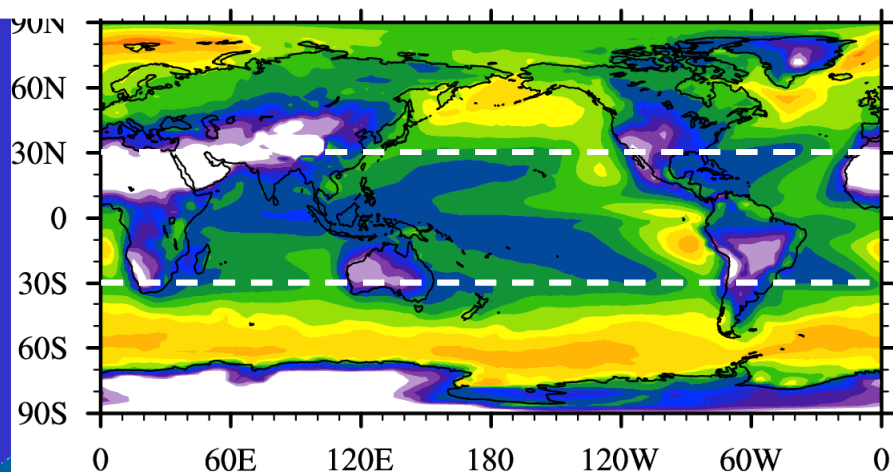
a) mean= 40.5 rms=14.4182 corr= 0.7978

b) mean= 41.5 rms=13.1957 corr= 0.7650



IP-12L mean= 45.1 rms=10.3306 corr= 0.8037

d) mean= 50.3 C3M Observations

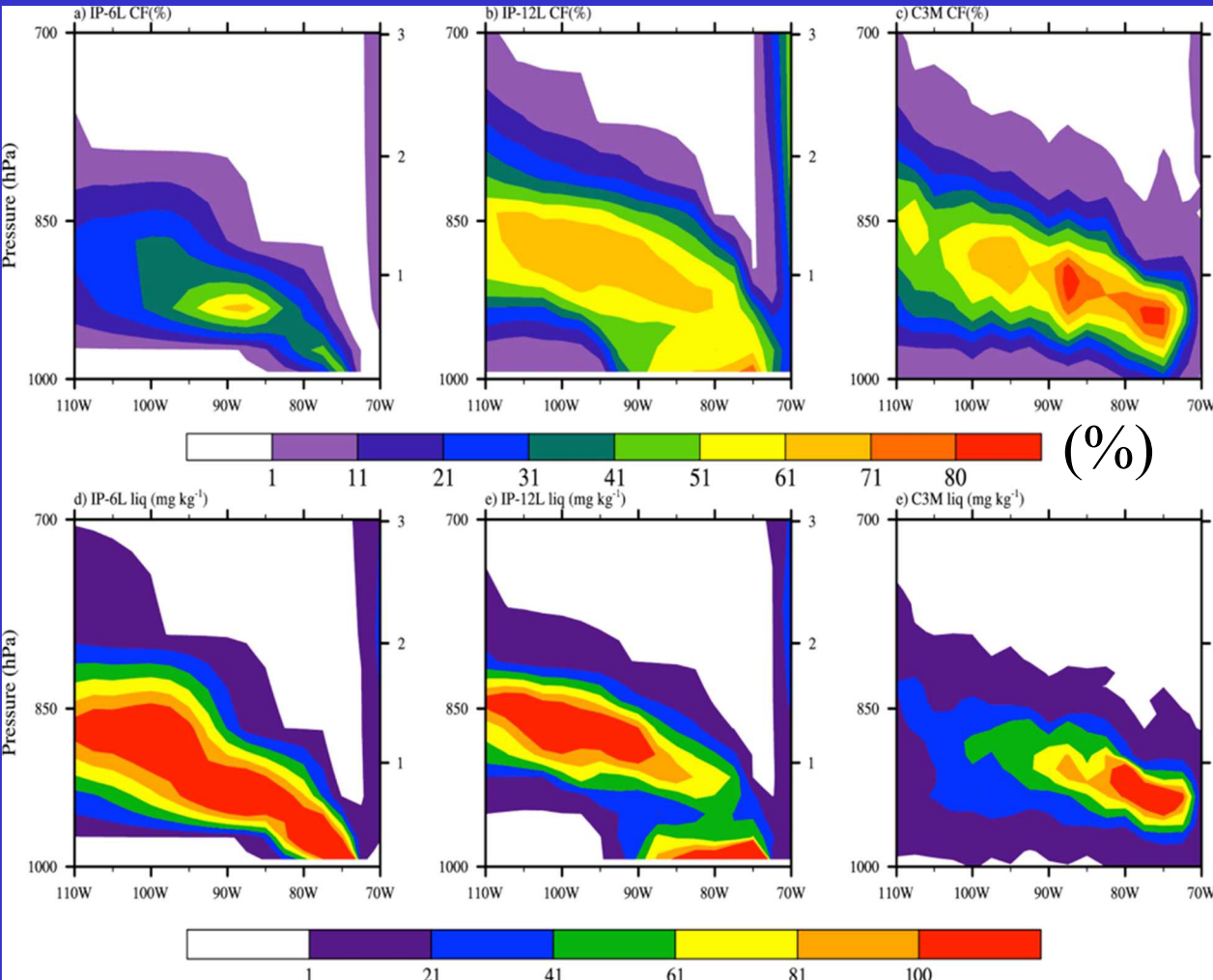


Annual-mean cloud fraction (top) and cloud liquid water (bottom) west of S. America at 18°S

IP-6L

IP-12L

(C3M Obs.)



SPCAM-IPHOC runs with 6 levels or 12 levels below 700 hPa

The increased vertical resolution improves the agreement with observations, but overestimate of cloud water is still pronounced.

Observations are from the merged Cloudsat, CALIPSO, CERES and MODIS (C3M) product



Cloud liquid water (mg kg⁻¹)

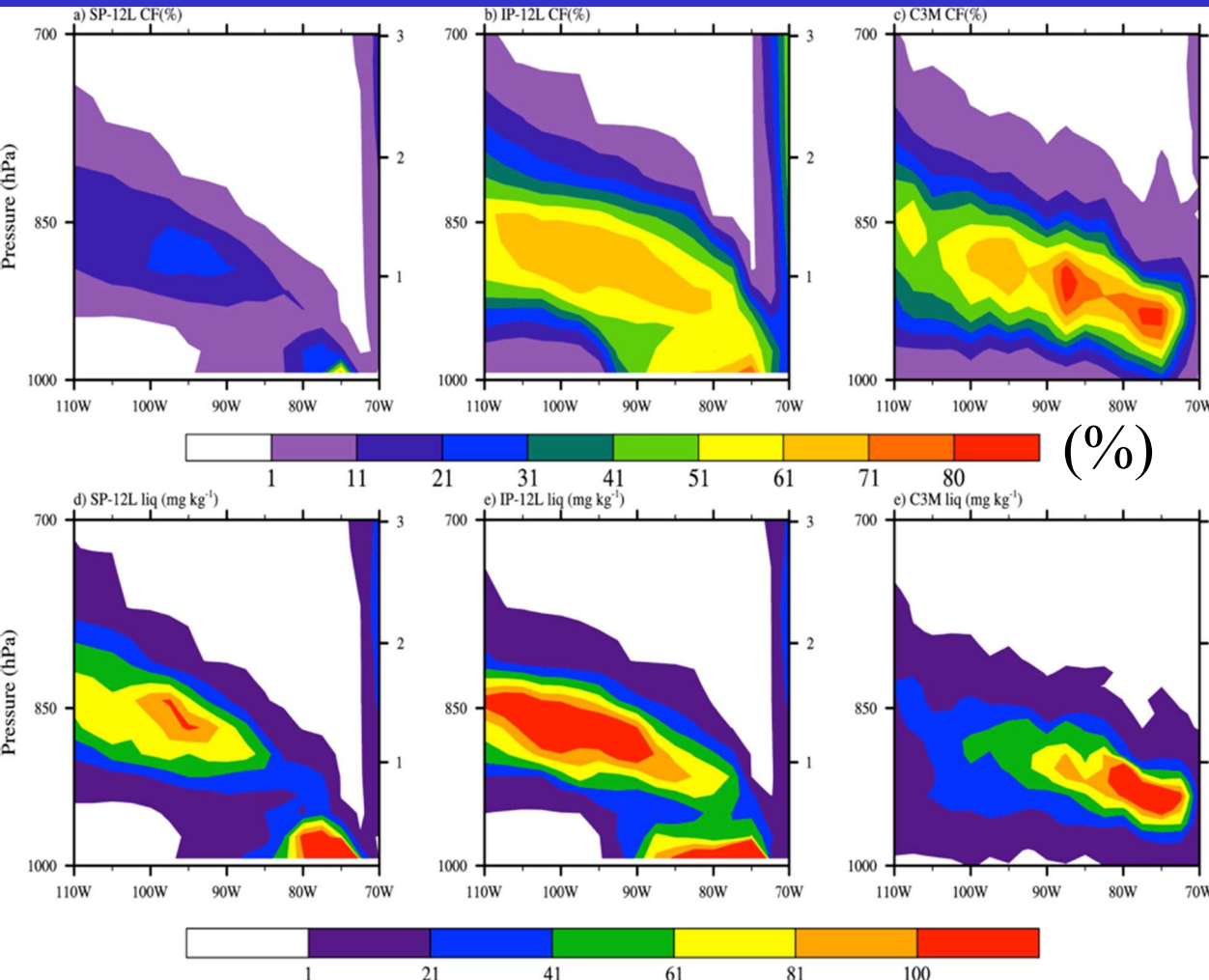


Annual-mean cloud fraction (top) and cloud liquid water (bottom) west of South America at 18°S

SP-12L

IP-12L

(C3M Obs.)



SPCAM and SPCAM-IPHOCC runs with 12 levels below 700 hPa

- SPCAM: clouds are produced only through grid-scale condensation
- SPCAM-IPHOCC: subgrid scale condensation
- The inclusion of IPHOCC helps the simulation

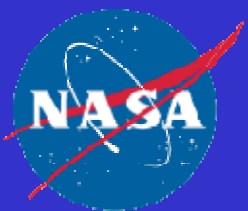


Cloud liquid water (mg kg^{-1})

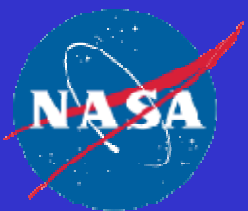


Summary, 1

- 1) The higher-order turbulence closure approach has undergone a rapid development in the past two decades
- 2) It can now serve as a unified parameterization of boundary-layer turbulence and low-level clouds in CRM, MMF and conventional GCM (for deep convection; see Thayer-Calder *et al.* 2015)
- 3) Both a higher-order turbulence closure and higher vertical resolution are needed to simulate boundary-layer turbulence and clouds



MMF climate sensitivity studies



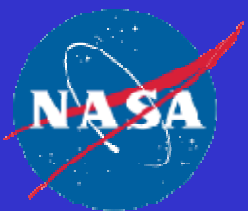
Why is hydrological sensitivity (HS) different among GCMs and much lower than moisture increase?

- Lower tropospheric moisture increases at $6.5\text{--}7\% \text{ K}^{-1}$ (Clausius–Clapeyron relation) with anthropogenic warming
- GCMs produce $2.52 \pm 0.22\% \text{ K}^{-1}$ increase in global-mean precipitation
- Sensitivity of longwave (LW) cooling (a major contributor to HS) to moisture increase depends on the (horizontal/vertical) distribution of moisture and clouds, which MMF simulates at every GCM grid cell

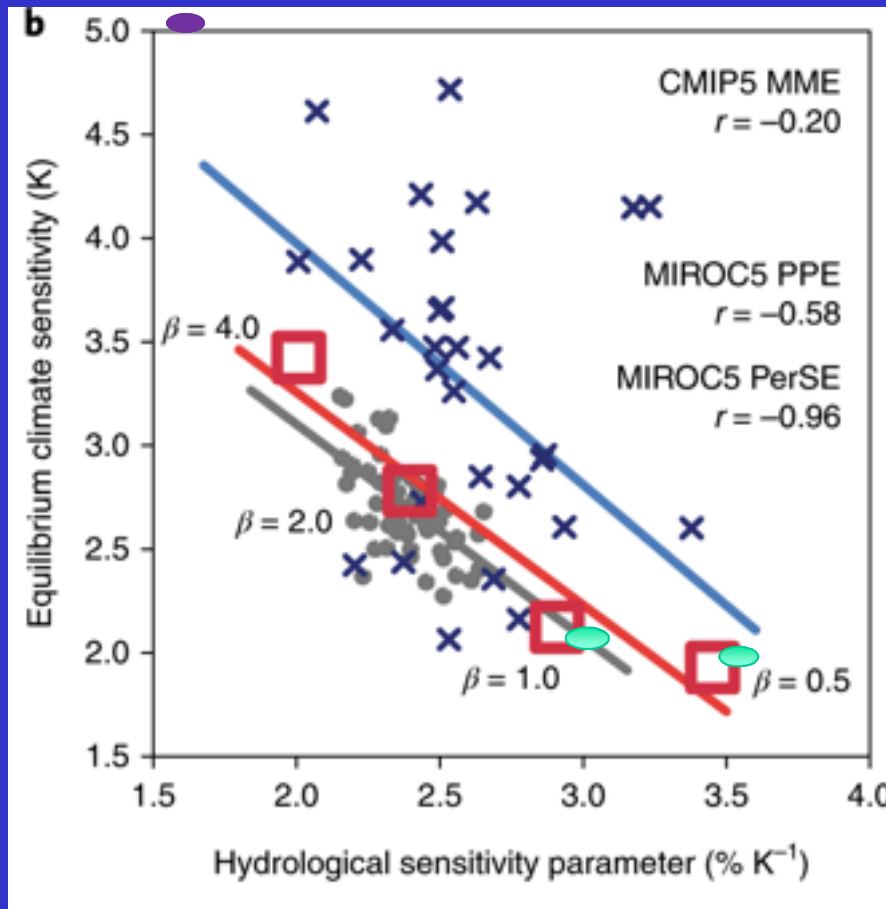
Plausible explanations include

1. Lack of *the iris effect* in GCMs, which increases longwave radiative cooling (LWC) as the clearsky area expands with warming (Mauritsen & Stevens 2015) – **TOA**
2. Change in surface LW cloud radiative forcing/effect (CRE) due to *low cloud change* (Watanabe *et al.* 2018) – **Surface**

HS depends upon an accurate description of clouds



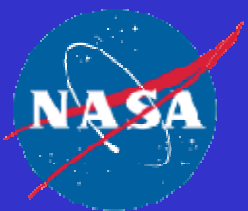
A hydrological sensitivity explanation



Watanabe *et al.* (2018), Low clouds link equilibrium climate sensitivity (ECS) and hydrological sensitivity (HS), *Nature Climate Change*.

Negative correlation between ECS and HS; if low cloud cover declines with global warming, it will increase ECS while suppressing the increase in global mean precipitation

	ECS (K)	HS ($\% K^{-1}$)	P ($mm h^{-1}$)
SPCAM	2.1	3.0	2.87
SPCAM-IPHOC	2.0	3.6	2.86
E3SM	5.2	1.6	3.06



The energetic constraint

(e.g., Newell *et al.* 1975; Mitchell *et al.* 1987)

Vertical integration of the heat budget equation yields

$LP = LWC - SWA - SH - H$ (convergence of dry static energy)

Average over the globe: $LP = LWC - SWA - SH$

LP: latent heating from precipitation (P)

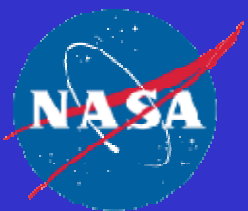
LWC: longwave cooling in the atmosphere

SWA: shortwave absorption (heating) in the atmosphere

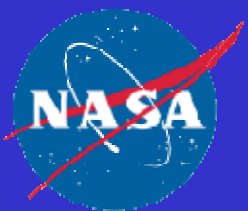
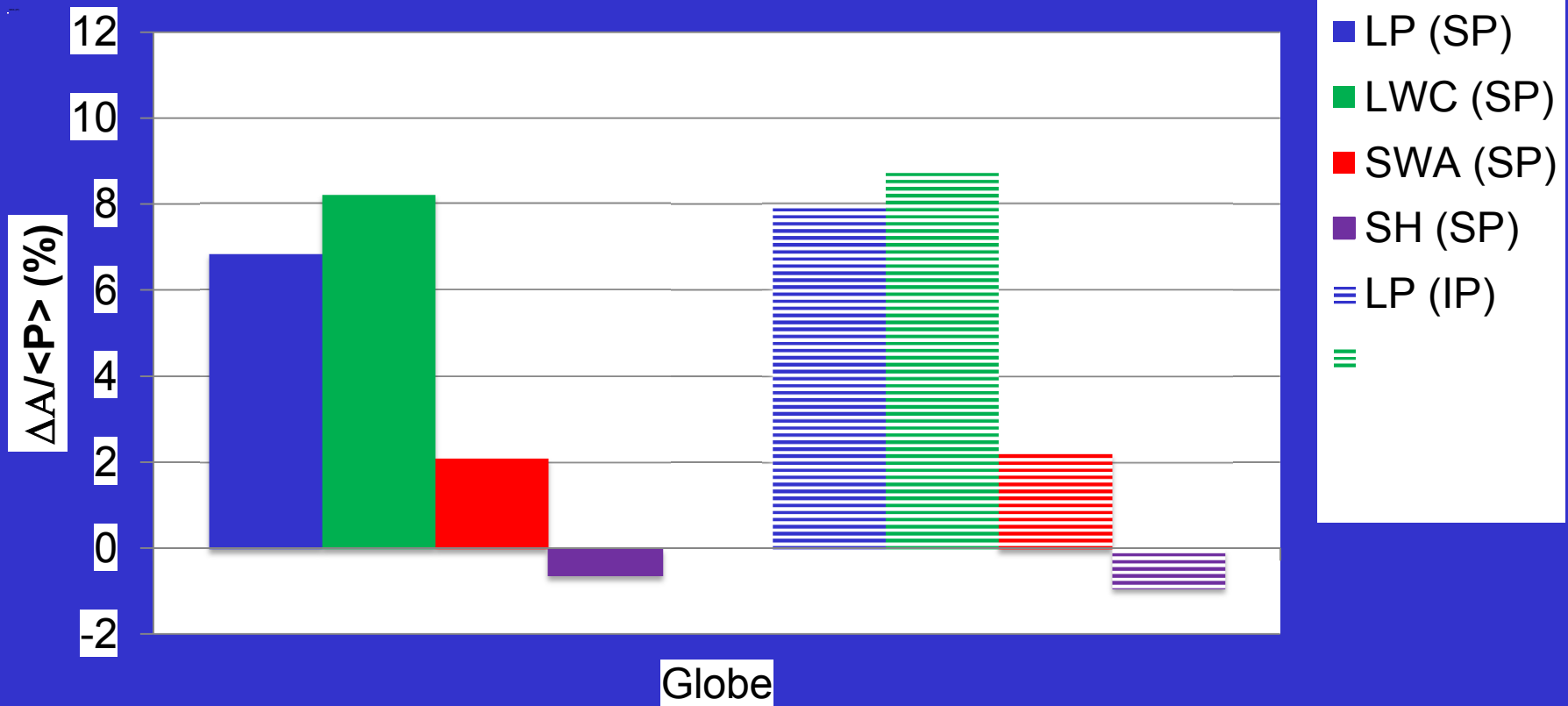
SH: surface sensible heating

H: convergence of dry static energy

LP (W m ⁻²)	LWC	SWA	SH
82.8	182.7	78.8	23.4

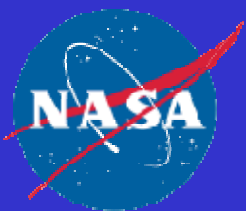
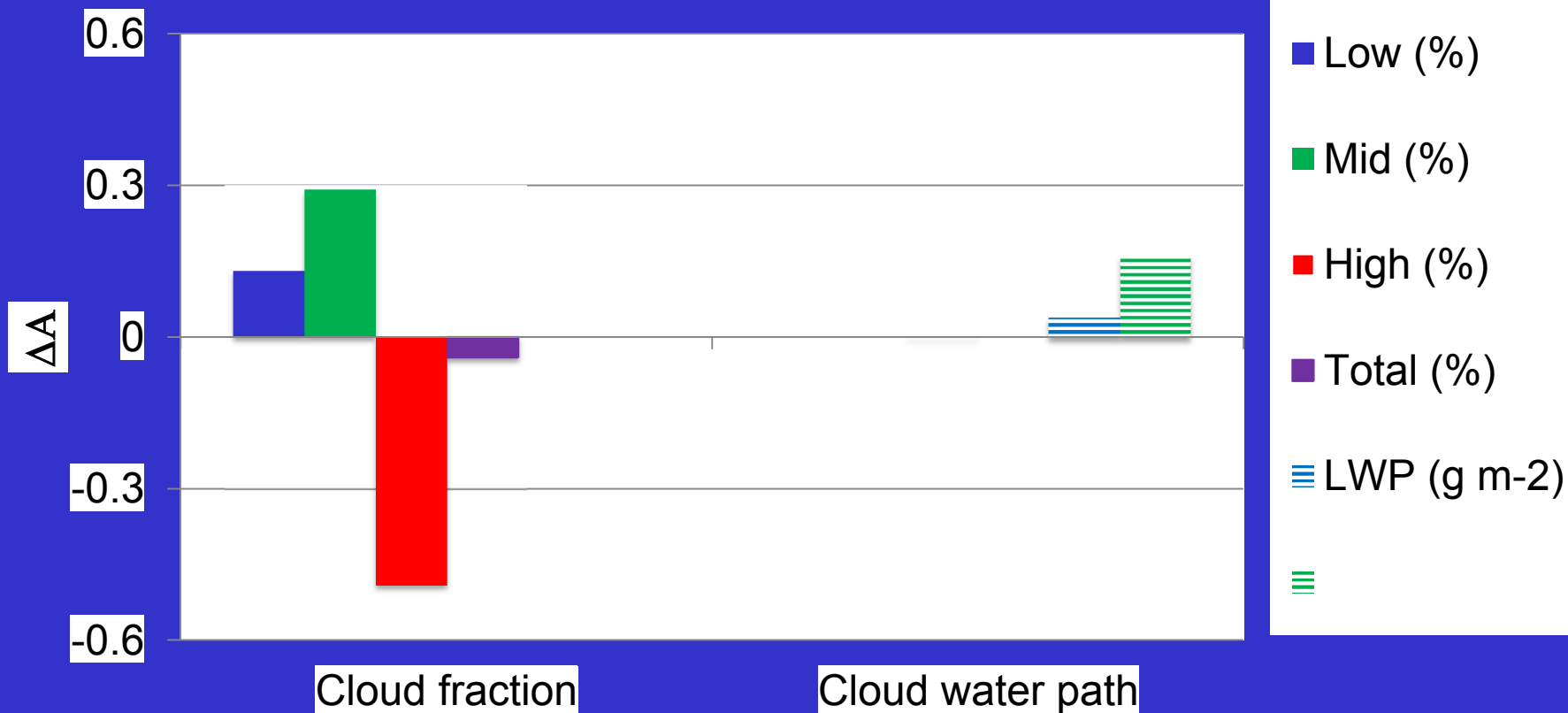


Changes in global energetic components (+2 or +4 K SST – control runs)



(from cloud in robotics and middle cloud in extra-robotics)
NASA: both low and middle clouds are higher in 1992
Midlatitude air is being heated by greenhouse gases
Surface air is being heated by greenhouse gases

Differences in cloud fraction and water path changes between +SST and ctrl runs



Summary, 2

- 1) Both SPCAM and SPCAM-IPHOC MMFs simulate less muted global hydrological responses than conventional GCMs
- 2) SPCAM-IPHOC simulates higher global hydrological sensitivity. Its difference from SPCAM is close to the spread of conventional GCMs
- 3) Longwave cooling (LWC) contributes half of the difference in precipitation sensitivity, due to differences in cloud radiative heating between the two MMFs (less cloud heating in the atmospheric column of SPCAM-IPHOC) that are contributed from the surface related to more low and middle clouds
- 4) Surface sensible heating (SH) contributes slightly less, due to more stable boundary layer over ocean in SPCAM-IPHOC

