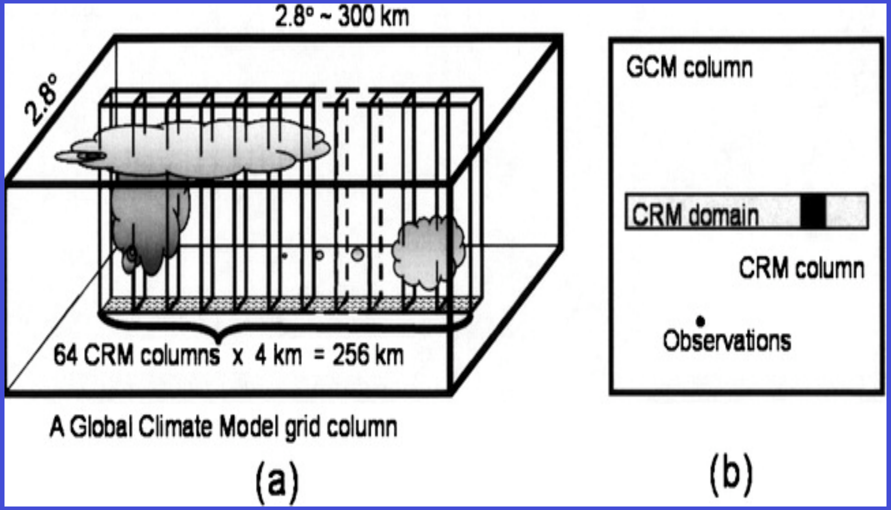
Turbulence Closure in Cloud Model and Climate Modeling – An Upgraded Multi-scale Modeling Framework (MMF)



Kuan-Man Xu

NASA Langley Research Center, USA

Objectives

- to improve the simulation of low-level clouds with the multiscale modeling framework (MMF) approach
- to evaluate and compare the performance of MMF simulations against state-of-the-art observations
- to examine climate sensitivity and cloud feedback

Cheng & Xu (2011; *JGR*): initial implementation

Xu & Cheng (2013a,b; *J. Climate*): climatology and seasonal variation

Cheng & Xu (2013a; *J. Climate*): cloud regime transition

Cheng & Xu (2013b; *JGR*): diurnal variation

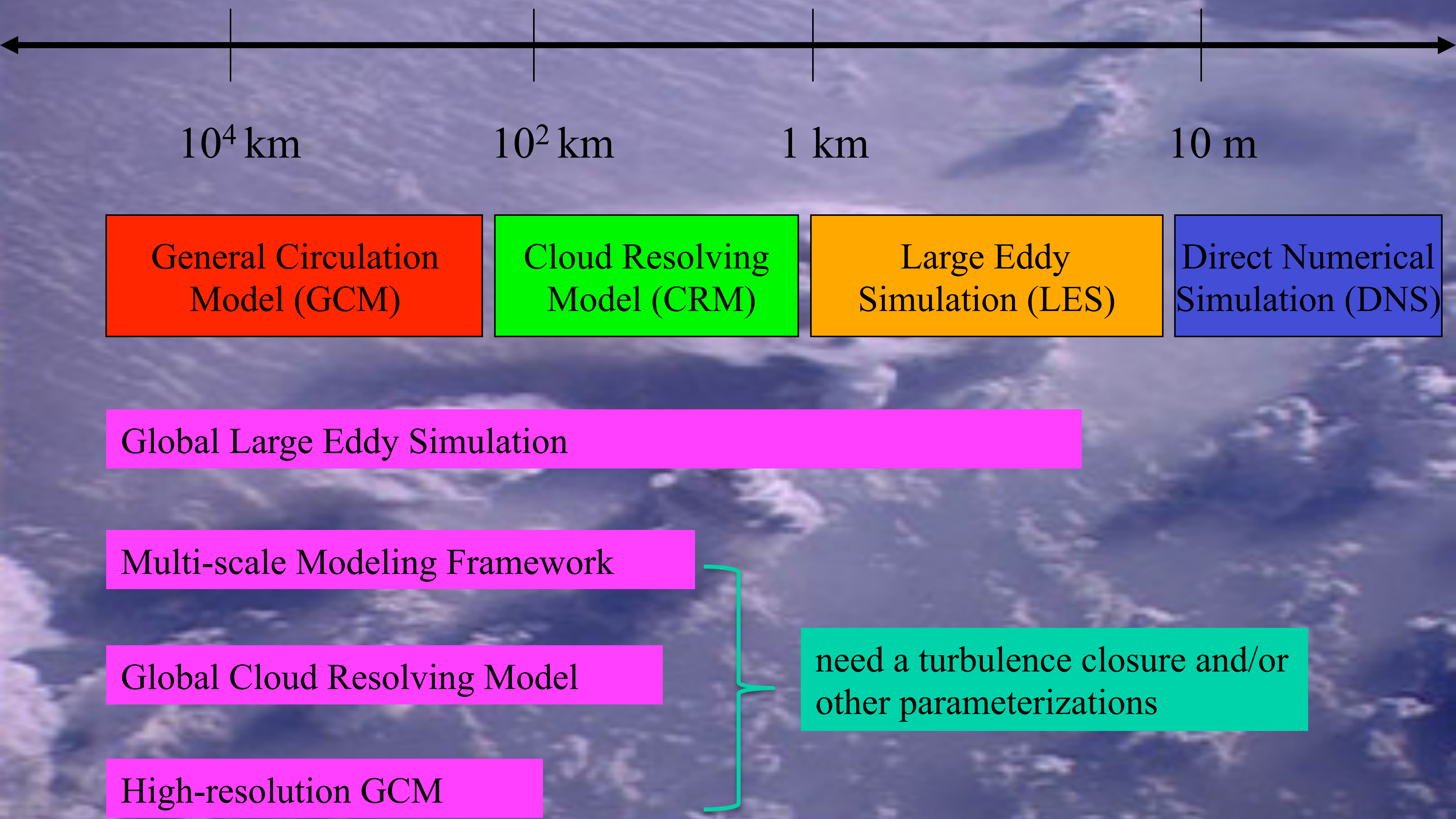
Cheng & Xu (2014; JGR): variable CRM orientation for MMF

Painemal *et al.* (2015; *J. Climate*): SE Atlantic mean & diurnal structure

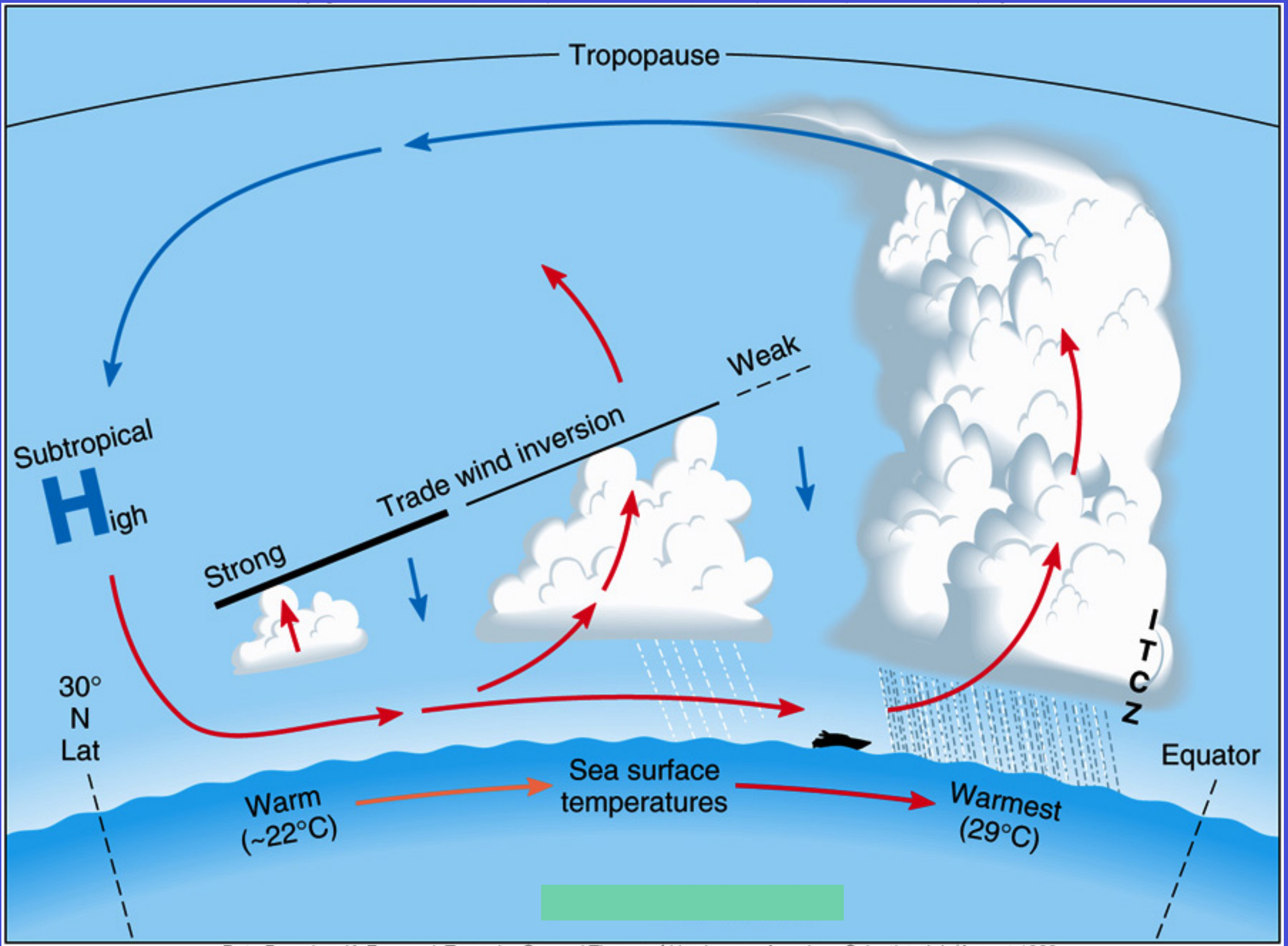
Outline

1. Introduction
2. History of cloud parameterization development
3. A higher-order turbulence closure — IPHOC
4. MMF climate simulation results
    - Climatology
    - Climate sensitivity
5. Conclusions

Scales of Atmospheric Motion and Models

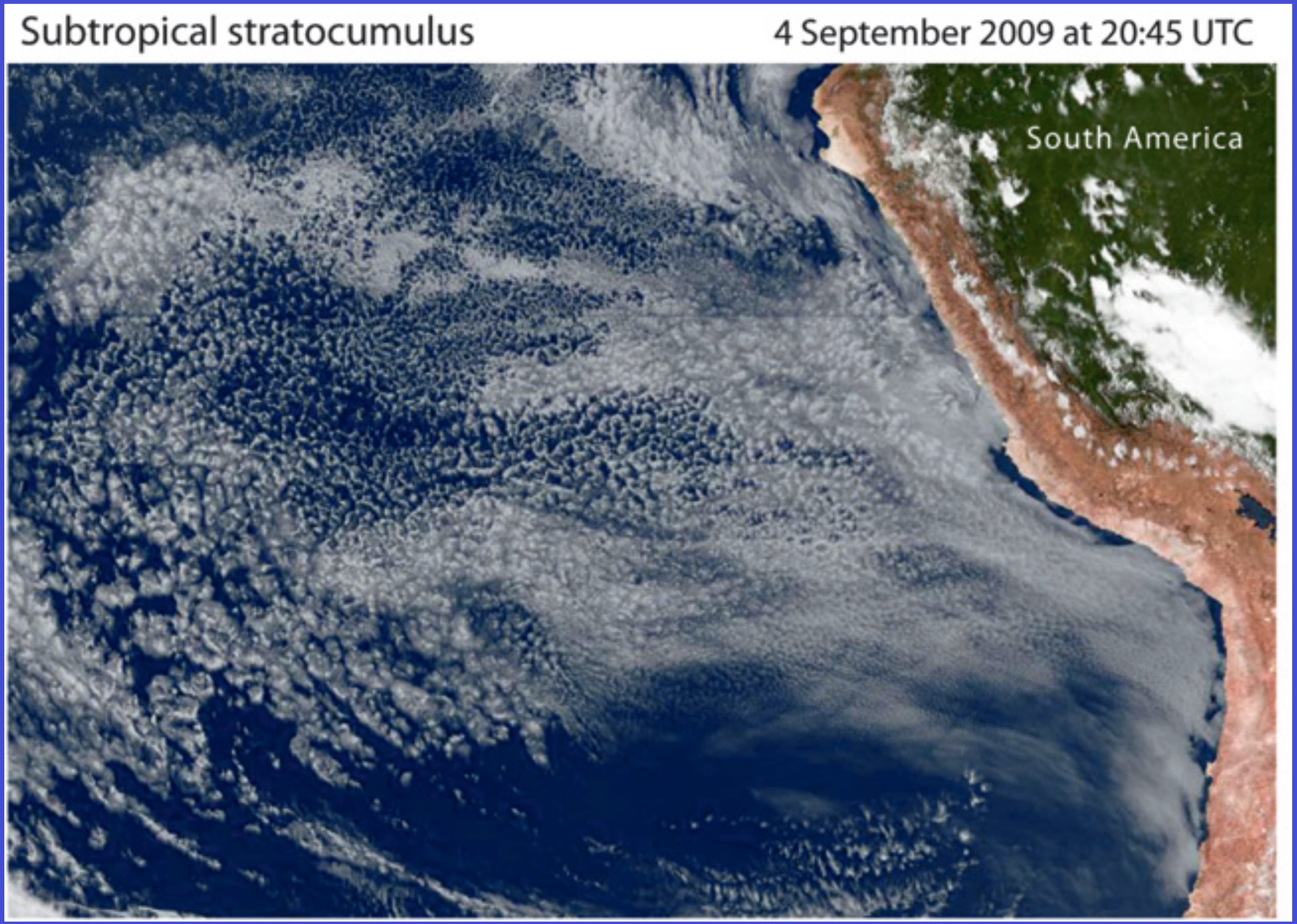


Large-scale Circulations and Cloud Systems



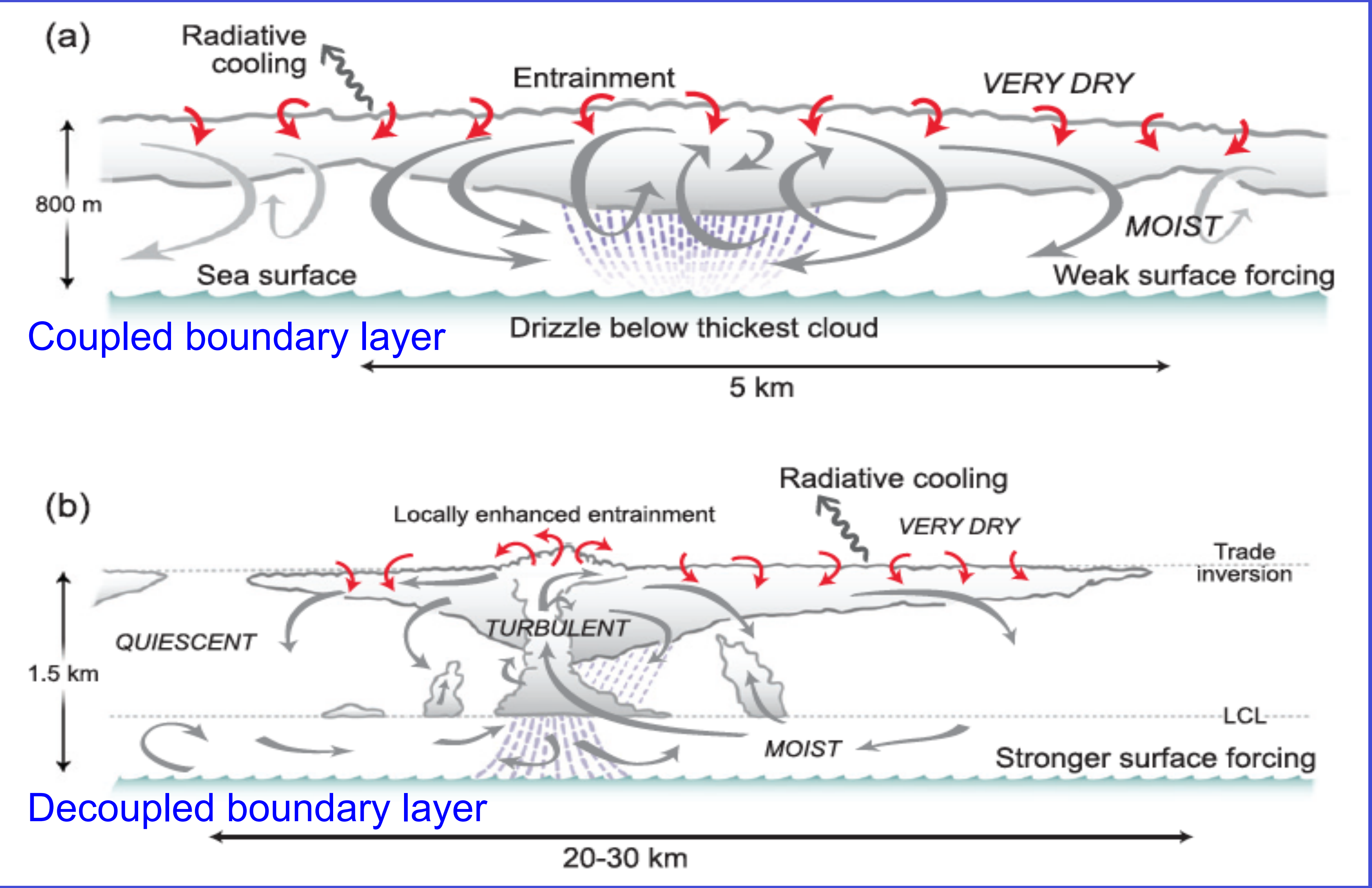
Data Based on K. Emanuel, Toward a General Theory of Hurricanes. American Scientist, July/August 1988.

Southeast (SE) Pacific Stratocumulus



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

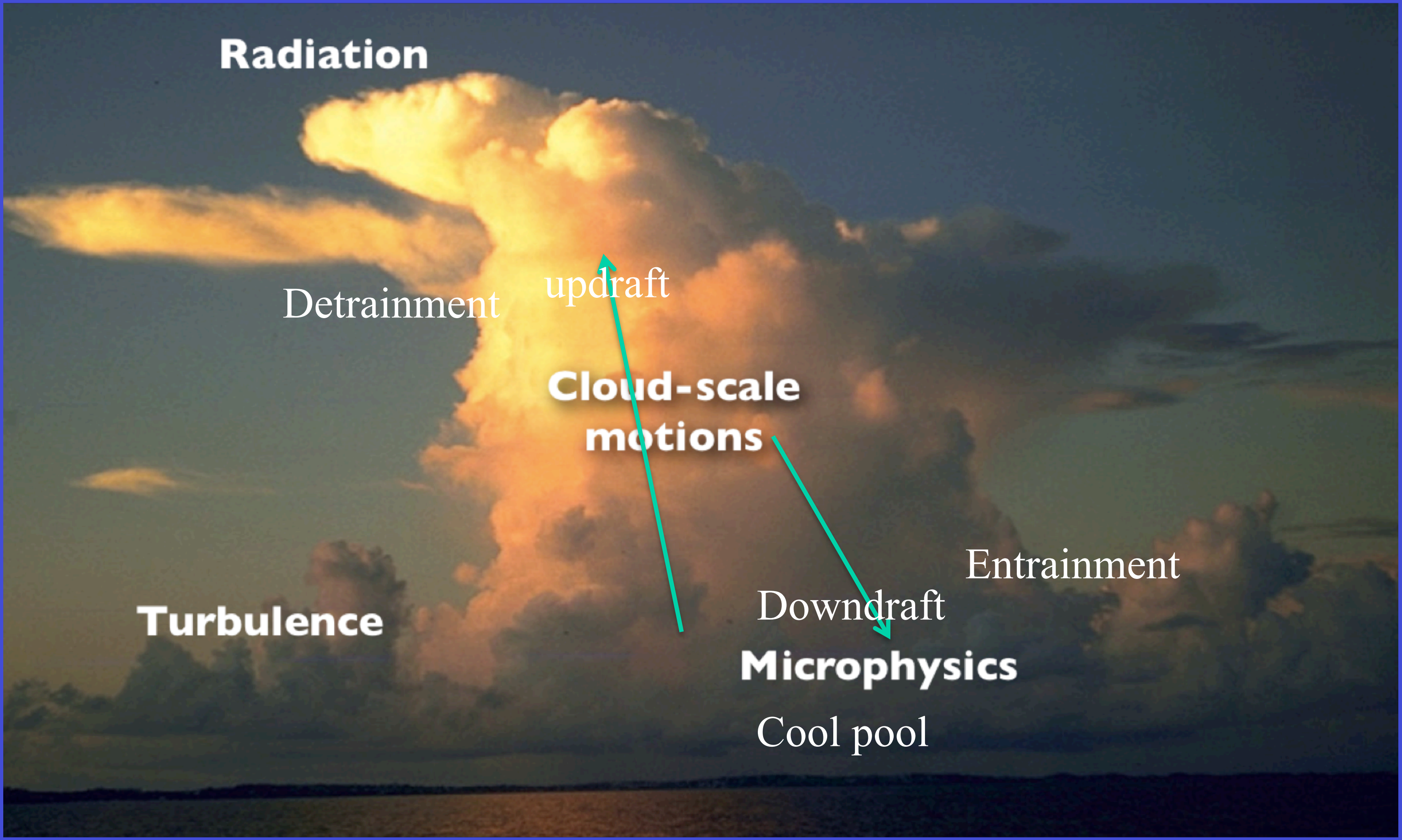
Physical Processes: Stratocumulus & PBLs



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

Physical Processes: Deep convective clouds

(c)



2. History of cloud parameterization development

The scope of cloud parameterization research

- **Theory**

  Parameterization theories

  Simple models of moist circulation systems

- **Numerical modeling**

  Simulations of large-scale circulations using parameterizations

  Cloud-system resolving models (CSRM)

- **Observations**

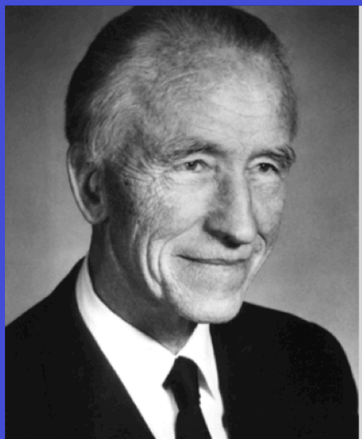
  Tests of parameterization theories

- **Practical applications**

  Climate-change simulations for policy-makers, e.g., IPCC

  Numerical weather prediction and data assimilation

Cloud parameterization history: Cumulus



Jakob Bjerknes

Updrafts and environment

The "slice" method

Bjerknes (1938)

Syukuro Manabe

Moist convective adjustment

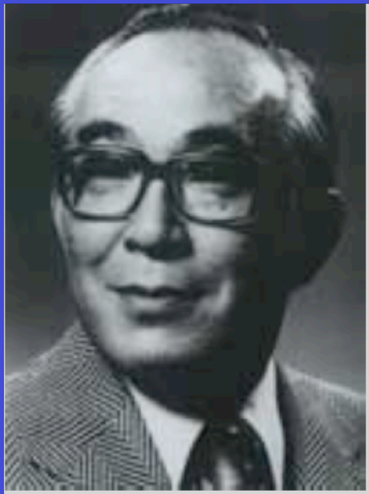
Manabe *et al.* (1965)

Hsiao-Lan Kuo

Moisture convergence to diabatic heating

Kuo (1965, 1974)

Betts & Miller (1986); Tiedtke (1989)
Kain & Fritsch (1990); Emanuel (1991)
Zhang & McFarlane (1995)
Chikira & Sugiyama (2010)



Akio Arakawa

Mass flux

Quasi-equilibrium

Coupling to the PBL

Detrainment of condensed water

Arakawa & Schubert (1974)

Xu *et al.* (1992); Xu & Arakawa (1992)
Xu (1993, 1994); Xu & Randall (1998)
Jones & Randall (2011), Liu *et al.* (2015)

Cloud parameterization history: Cloud amount

Joseph Smagorinski

Stratiform cloud amount

$\sigma = f\,(RH, RH_0)$

Smagorinsky (1960)

Hilding Sundqvist

Prognostic cloud water

Sundqvist (1978)

Michael Tiedtke

Prognostic cloud amount

Tiedtke (1993)

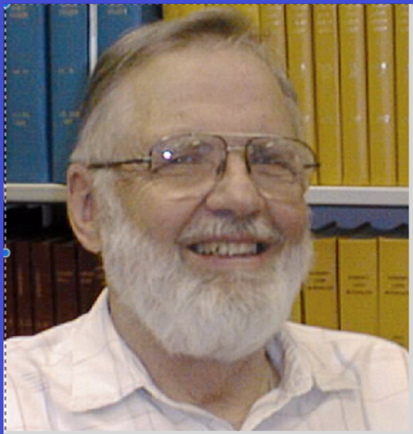
Primary motivation: Interactions with radiation

Diagnostic cloud amount parameterizations:
Smagorinsky (1960); Slingo (1980)
Xu & Krueger (1991)

Statistically-based cloud amount parameterizations:

$$\overline{\sigma} = \begin{cases} \overline{RH}^{p}\left[1-\exp\left(\dfrac{-\alpha_0 q_1}{\left[\left(1-\overline{RH}\right)q_{vs}\right]^{\gamma}}\right)\right], & \text{if } \overline{RH} < 1 \\ 1, & \text{if } \overline{RH} \geq 1 \end{cases}$$

Cloud parameterization history: PBL cloud/turbulence



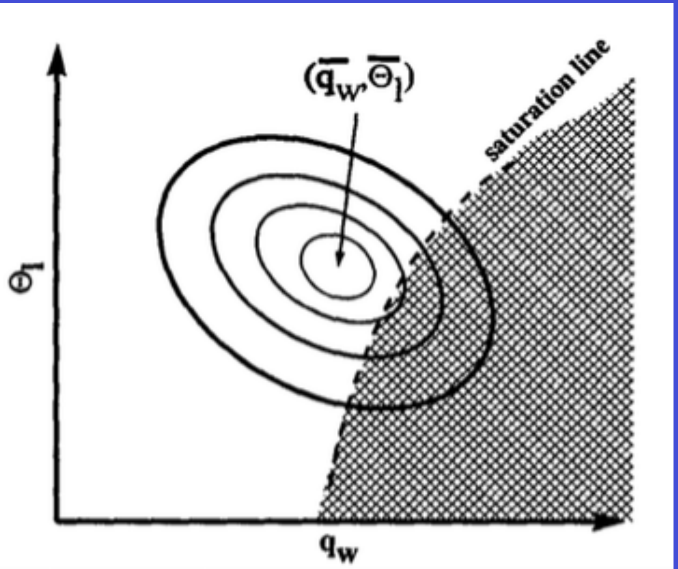
Cloud-turbulence-radiation interactions

Cloud-top entrainment

Doug Lilly

Sommeria-Deardorff-Mellor (SDM, 1977)

James Deardorff



Fully prognostic third-order turbulence closures (TOC): Dry

- Andre *et al.* (1976a, b, 1978)

with moist processes (clouds) using the SDM approach

- Bougeault (1981a, b)
- Krueger (1988)
  5 first-order moments,
  11 second-order moments, and
  24 third-order moments

Recent works: simplified TOC

Predict fewer higher-order moments

Use skewed PDFs (double Gaussian)

Golaz *et al.* (2002): $\overline{w'^3}$ (10)

Cheng & Xu (2006): $\overline{\theta_l'^3}, \overline{q_t'^3}, \overline{w'^3}$ (12)

Cloud parameterization history: MMF approach

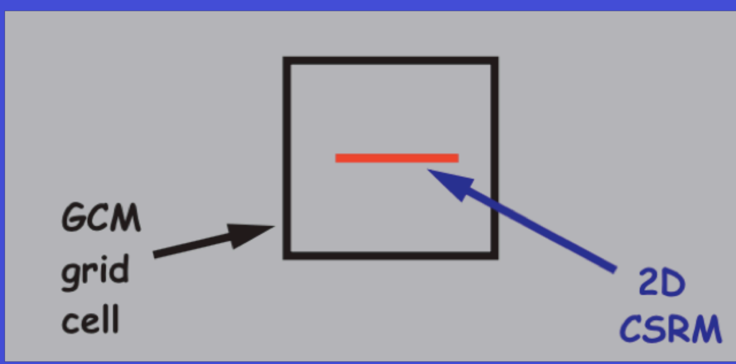
W. Grabowski

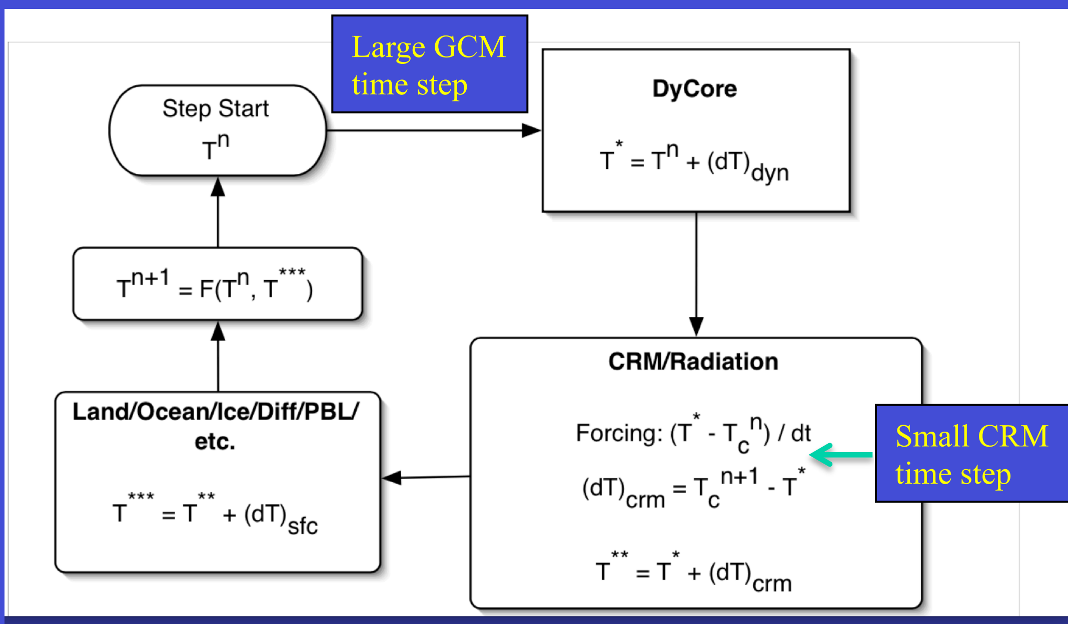
M. Khairoutdinov

David A. Randall

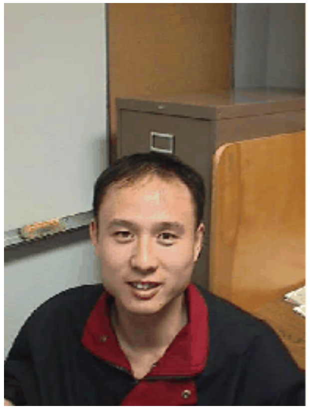
CMMAP

Reach for the sky.





3. A higher-order turbulence closure — IPHOC



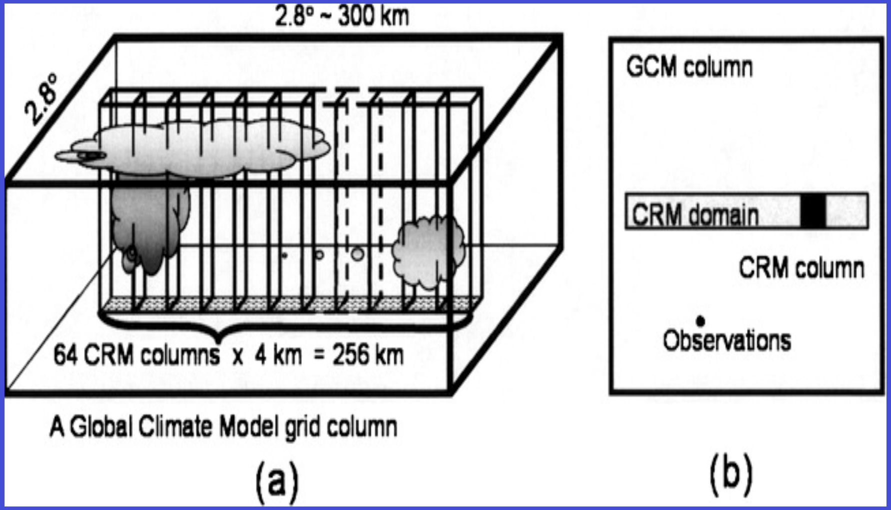
Anning Cheng

as a graduate student
(IPHOC was developed after he joined NASA).

The Multiscale Modeling Framework

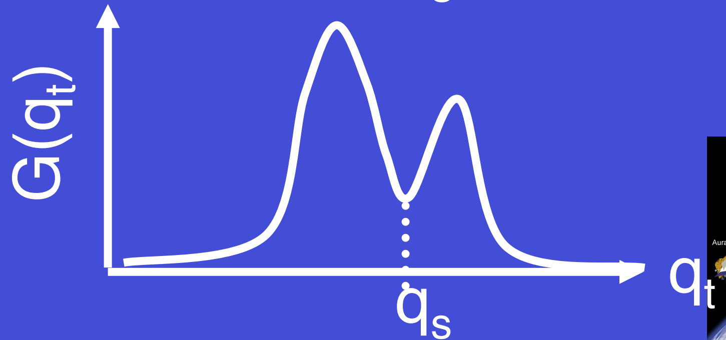
(Grabowski 2001; Khairoutdinov and Randall 2001; Cheng & Xu 2011; Xu and Cheng 2013a)

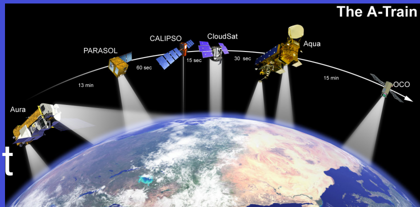
- A CRM is embedded at each grid column (~100s km) of the host GCM to represent cloud physical processes
- The CRM explicitly simulates cloud-scale dynamics (~1s km) and processes
- Periodic lateral boundary condition for CRM (not extended to the edges)



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





IPHOC: Intermediately-prognostic higher-order turbulence closure

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

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

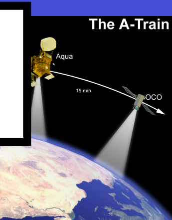
Δt

Use PDF to close higher-order moments, buoyancy terms

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have

Diagnose cloud fraction, liquid water from PDF



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

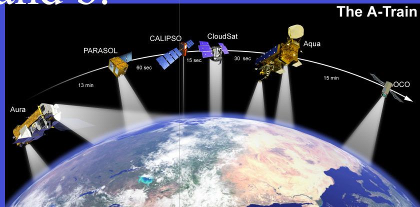
The double Gaussian PDF expression

where l, m, n = 0, 1, 2 or 3

The image cannot be displayed. Your computer may have to delete the image and then insert it again.

$$P(w, \theta_l, q_t) = aG_1(w, \theta_l, q_t) + (1 - a)G_2(w, \theta_l, q_t), \qquad (2a)$$

where ψ_i are the Gaussian mean/position; σ_ψ is the variance or the width of the Gaussian; $r_{a,b}$ is the inter-plume correlation between a and b.

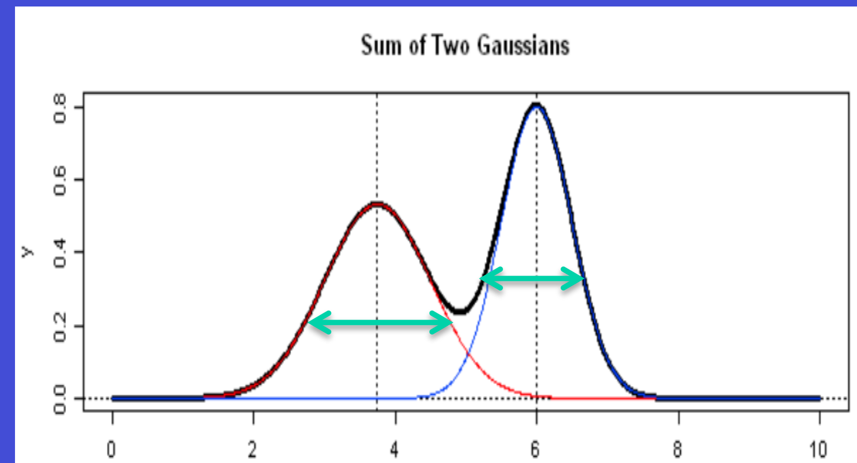


How are the Gaussian parameters determined?

$$f(w, \theta_l, q_t) = aG_1(w, \theta_l, q_t) + (1 - a)G_2(w, \theta_l, q_t),$$

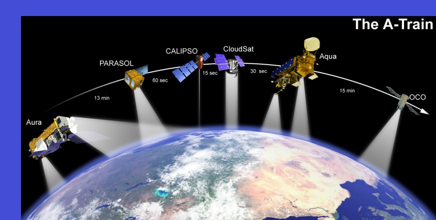
Double Gaussian parameters (19):

- Weighting of Gaussian 1 (a)
- Means (2 x 3)
- Variances (2 x 3)
- Correlations (2 x 3)



Known/predicted moments: 12 $\overline{w}, \overline{q}_t, \overline{\theta}_l, \overline{w'^2}, \overline{q_t'^2}, \overline{\theta_l'^2}, \overline{w'q_t'}, \overline{w'\theta_l'}, \overline{q_t'\theta_l'}, \overline{w'^3}, \overline{q_t'^3}, \overline{\theta_l'^3}$

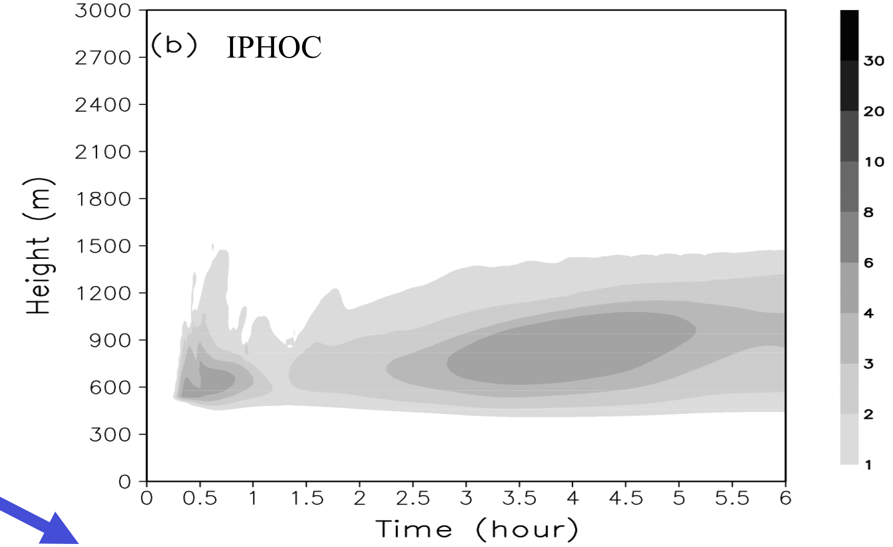
- Analytical Gaussian II (widths of two gaussians in w differ; converging to single Gaussian if skewness=0)
- Within-plume correlations are set to be equal ($r_{a,b1}=r_{a,b2}$)
- Bias between the means of two Gaussians, variance and skewness are related through $k_\alpha = \frac{Sk_\alpha \sigma_\alpha^3}{(1-a)B_\alpha^3},$
- Larson *et al.* (2002); Cheng & Xu (2006)



IPHOC removes liquid water oscillation (LWO) in a fully prognostic third-order closure

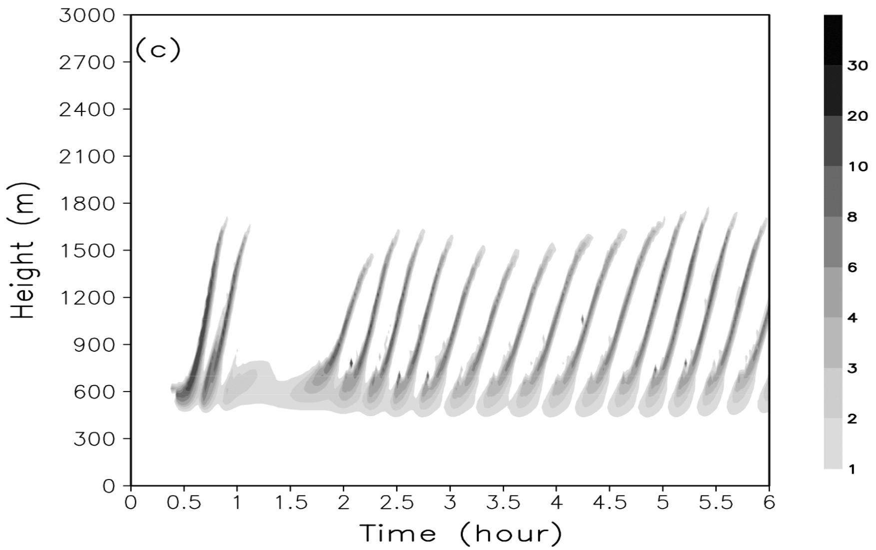
Cheng *et al*. 2004, *J. Atmos. Sci.*, 61, 1621-1629.

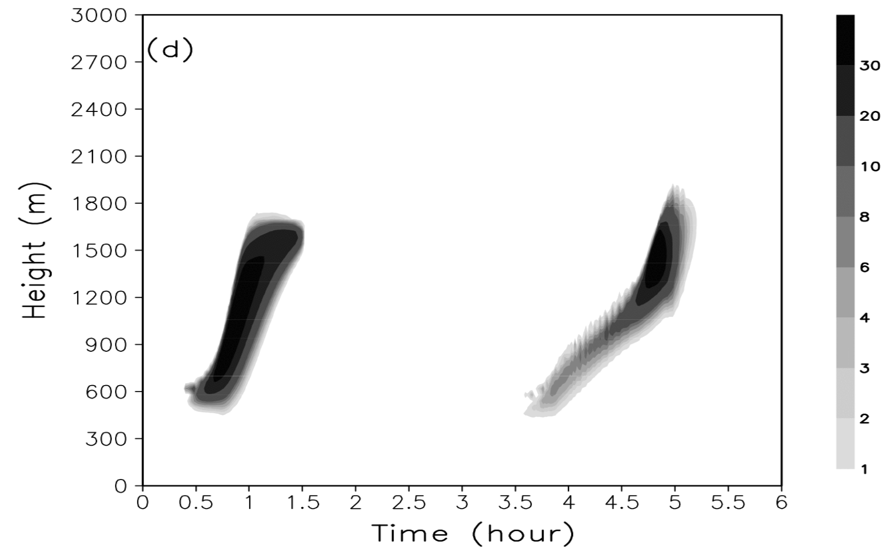
Properly parameterized LWB



Neglected liquid water buoyancy (LWB)

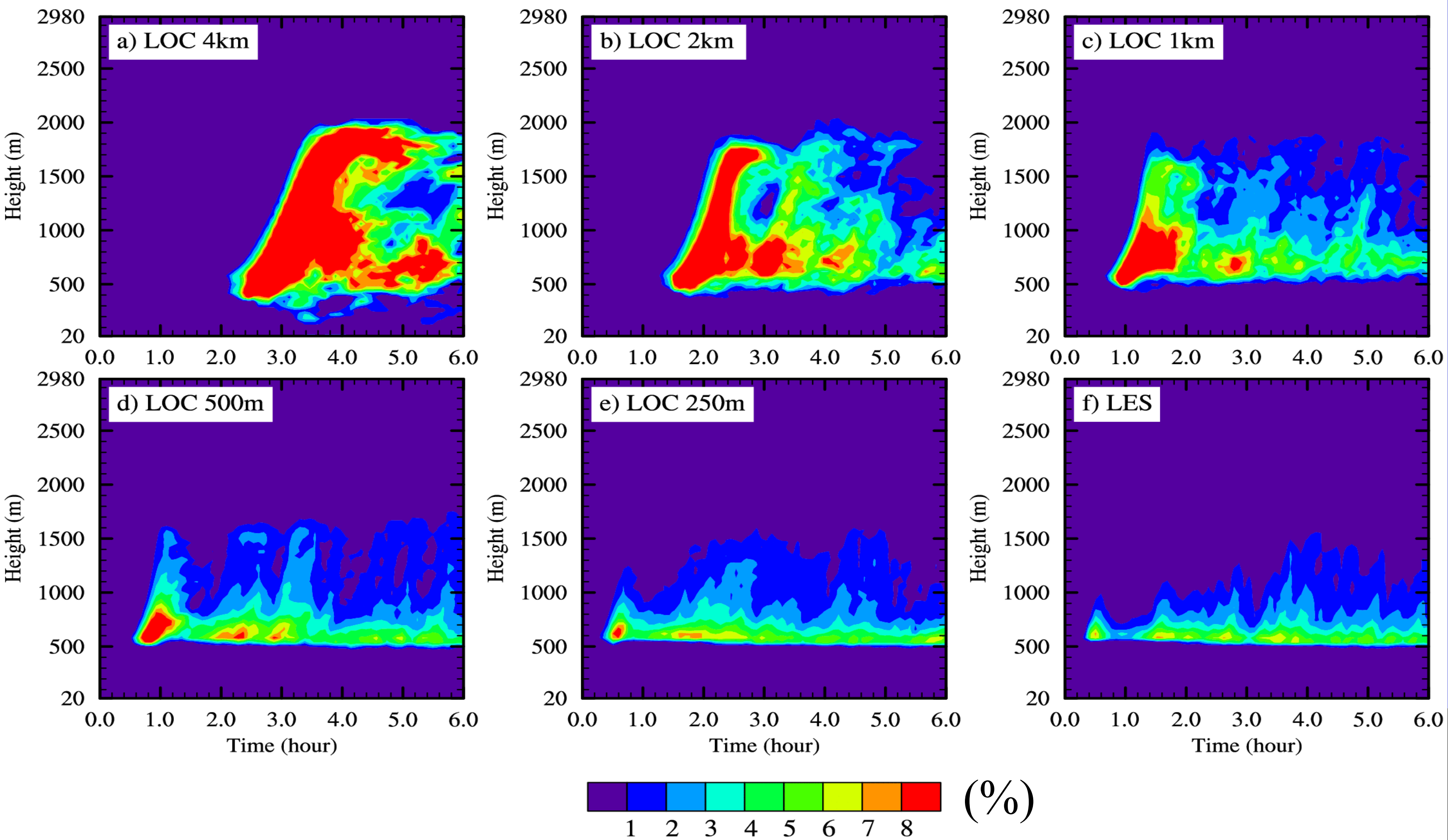
LWO





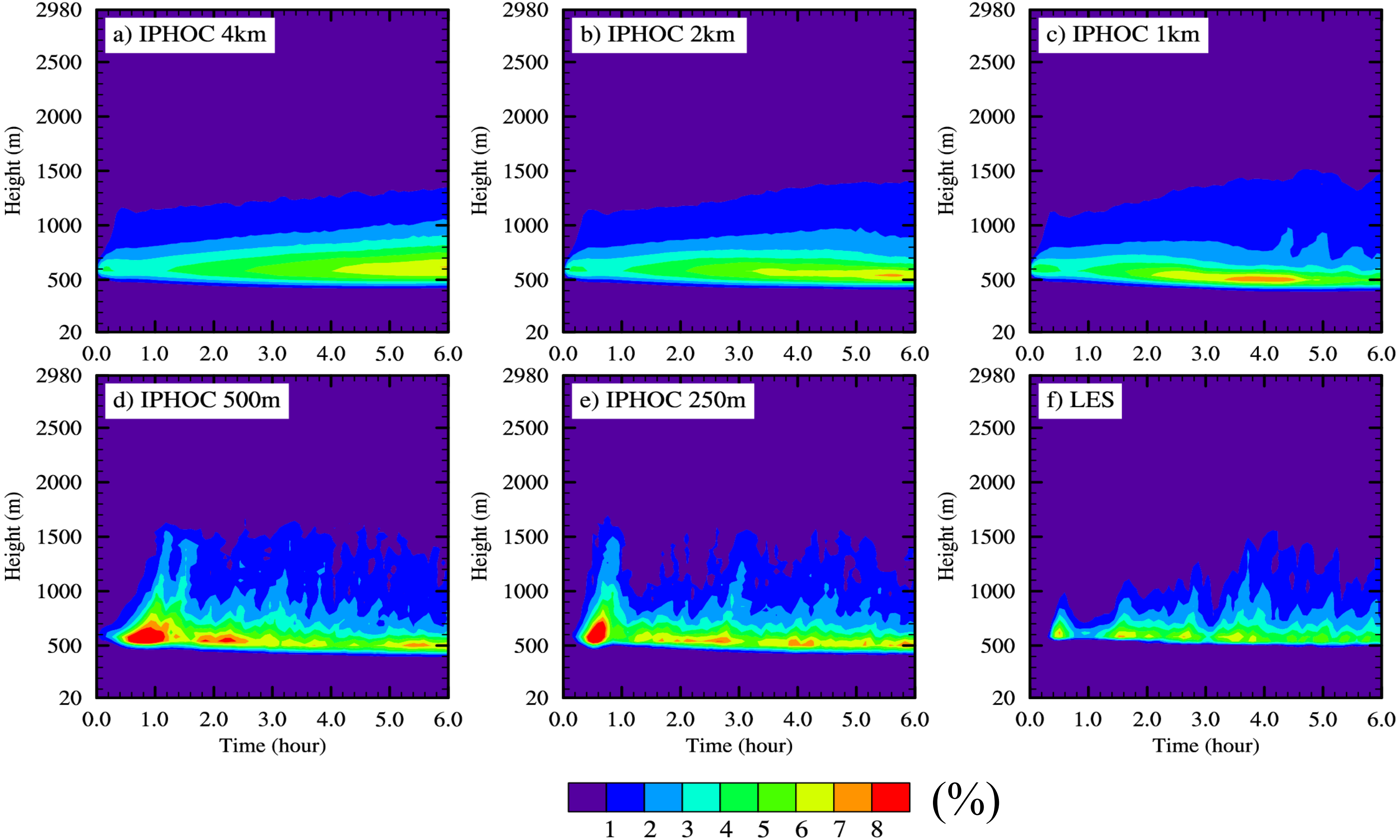
Low-order closure (LOC): CRM-simulated fractions of shallow cumuli (BOMEX case)

Cheng A., & K.-M. Xu, 2008, *J. Meteor. Soc. Jpn.*, 86A, 67-86



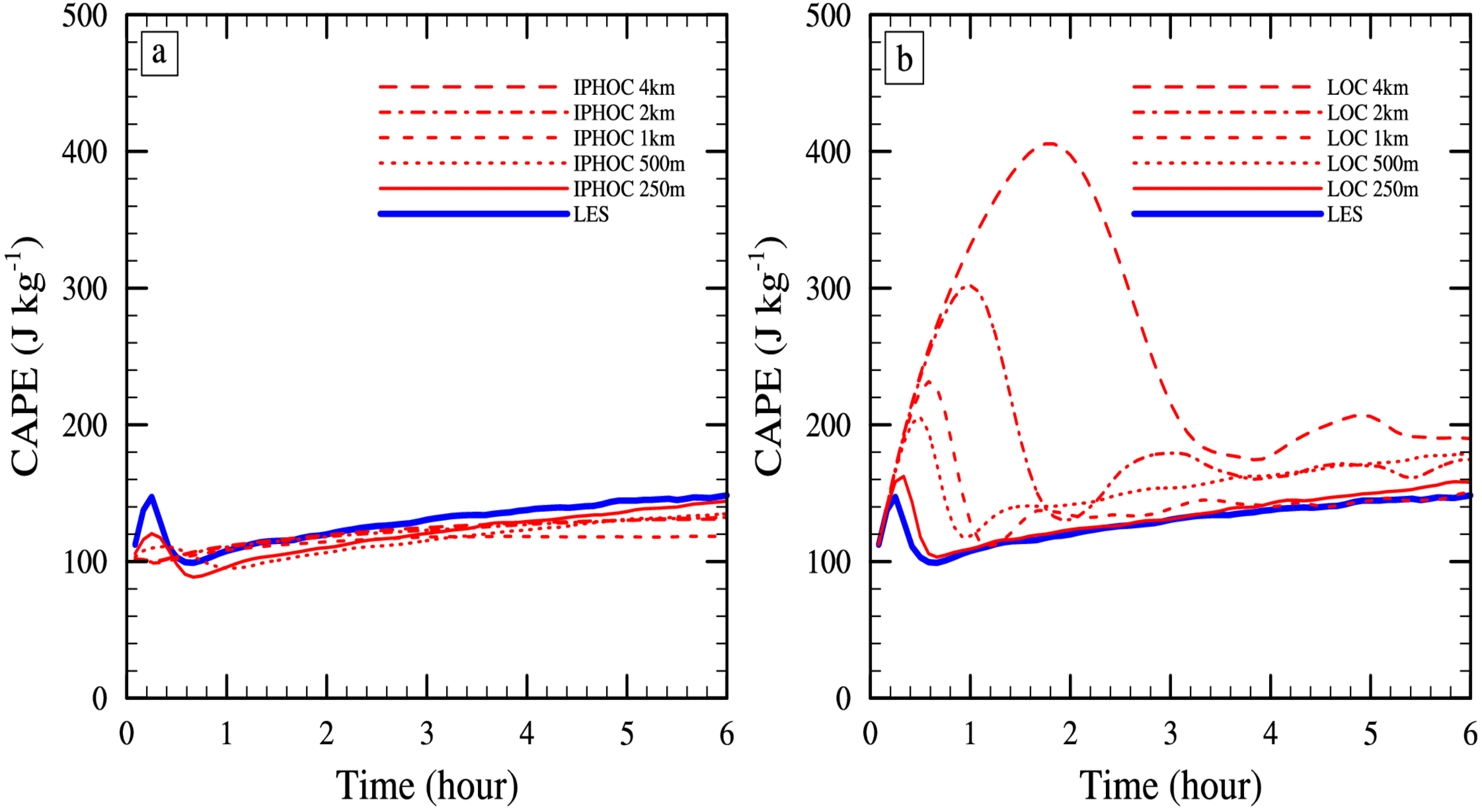
IPHOC: CRM-simulated fractions of shallow cumuli (BOMEX case)

Cheng A., & K.-M. Xu, 2008, *J. Meteor. Soc. Jpn.*, 86A, 67-86



Insufficient SGS transports from low-order closure (LOC) cause initial build-up of CAPE (convective available potential energy)

Cheng A., & K.-M. Xu, 2008, *J. Meteor. Soc. Jpn.*, 86A, 67-86 .



4. MMF climate simulation results – experiments

Experiment name	Other name/ duration	Feature
IP-12L	Control experiment (SPCAM-IPHOC); 10 yrs and 3 mos	With IPHOC, 12 levels below 700 hPa
IP-6L	SPCAM-IPHOC (6L); 2 yrs and 3 mos test	Same as IP-12L except for 6 levels below 700 hPa
SP-12L	SPCAM (12L); 2 yrs and 3 mos test	Same as IP-12L except without IPHOC (i.e., with low-order closure)
SP-6L	SPCAM (6L); 2 yrs and 3 mos test	Same as IP-6L except without IPHOC

MMF "control" climate simulation

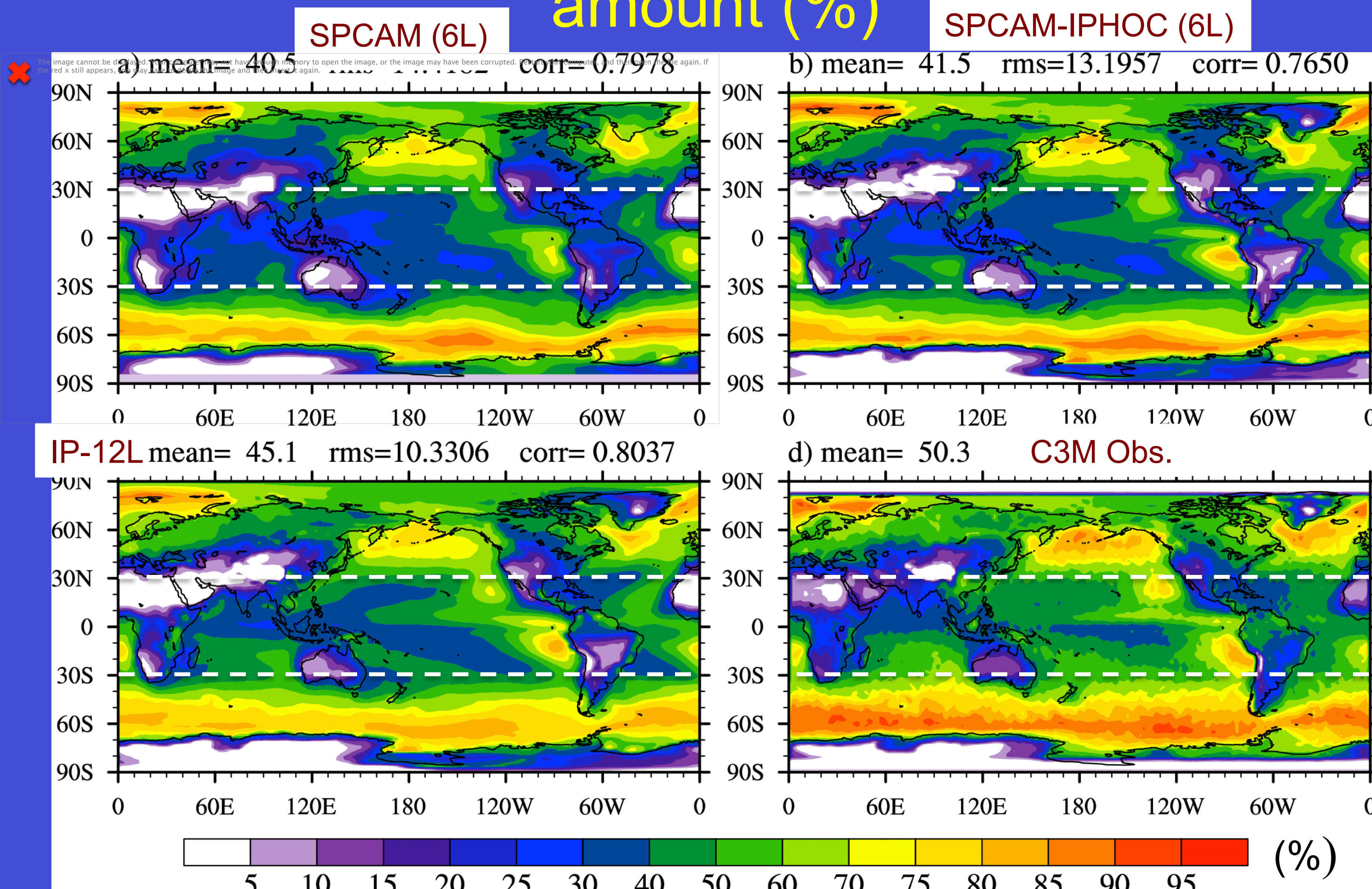
- The model, SPCAM-IPHOC, is Community Atmosphere Model (CAM) version 3.5 with finite-volume dynamical core as the host GCM.
- The CRM is the 2-D version of System for Atmospheric Modeling (SAM) with IPHOC higher-order turbulence closure, the grid spacing is 4 km, with 32 columns within a GCM grid box.
- Grid spacing of the host GCM is 1.9°x2.5°; doubling the number of levels below 700 hPa (6 to 12) from the standard CAM configuration; the total number of vertical layers is 32.
- The simulation is forced with 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 for climatology and seasonal cycle; last year analyzed for diurnal variability due to availability of hourly model output.
- Same setup for sensitivity runs with 2 yr and 3 mos duration except for the number of vertical layers and with/without IPHOC.

Datasets used in evaluating the simulation

- Precipitation observations (32-yr; 1979-2011): Global Precipitation Climatology Project (GPCP; Adler et al. 2003)
- Low-level/total cloud amount and liquid water content (4-yr; 2006-10): CloudSat, CALIPSO, CERES and MODIS merged data (C3M; Kato et al. 2010, 2011)
- Cloud radiative effects at the TOA and surface (10-yr; 2000-10): CERES EBAF version 2.6r (TOA; Loeb et al. 2009) and surface EBAF2.6 (Kato et al. 2012)
- Precipitable water (13-yr; 1988-2001): NASA Water Vapor Project (NVAP)
- Meteorological state variables (10-yr; 2000-10): ECMWF Interim Re-Analysis or ERA40

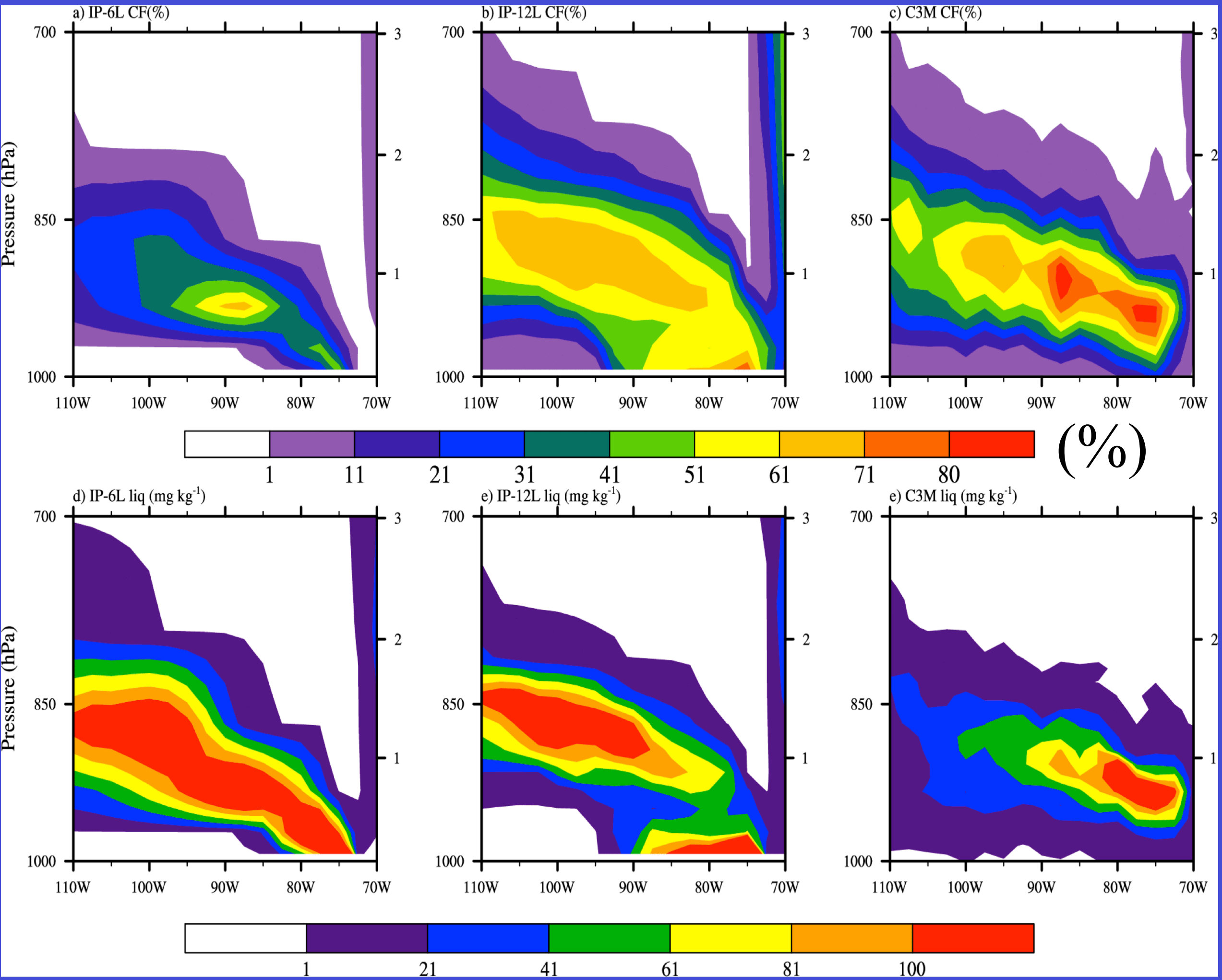
4. MMF climate simulation results:
a) Climatology

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



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

IP-6L IP-12L (C3M Obs.)



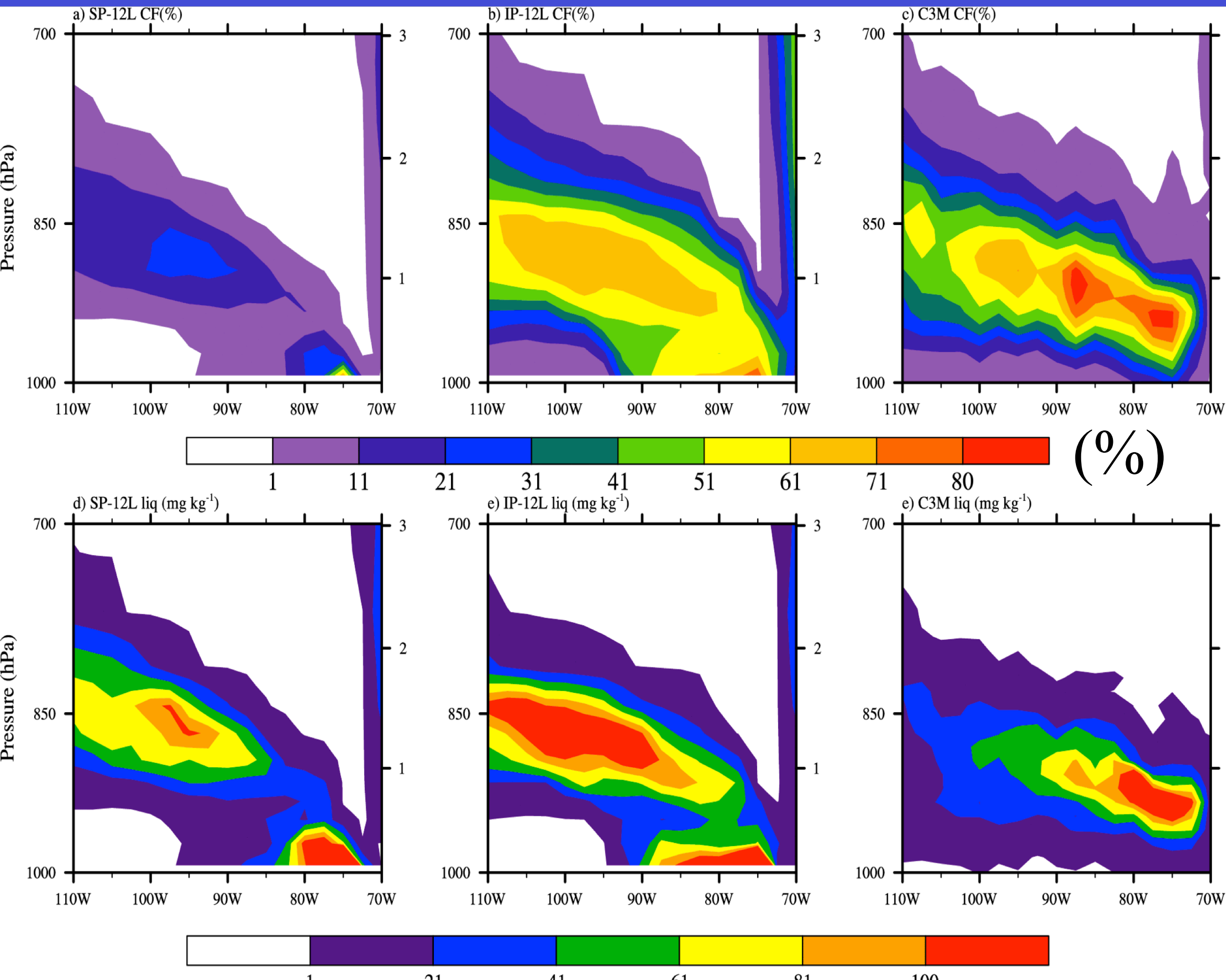
Cloud liquid water (mg kg^{-1})

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 pronounced.

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

SP-12L IP-12L (C3M Obs.)

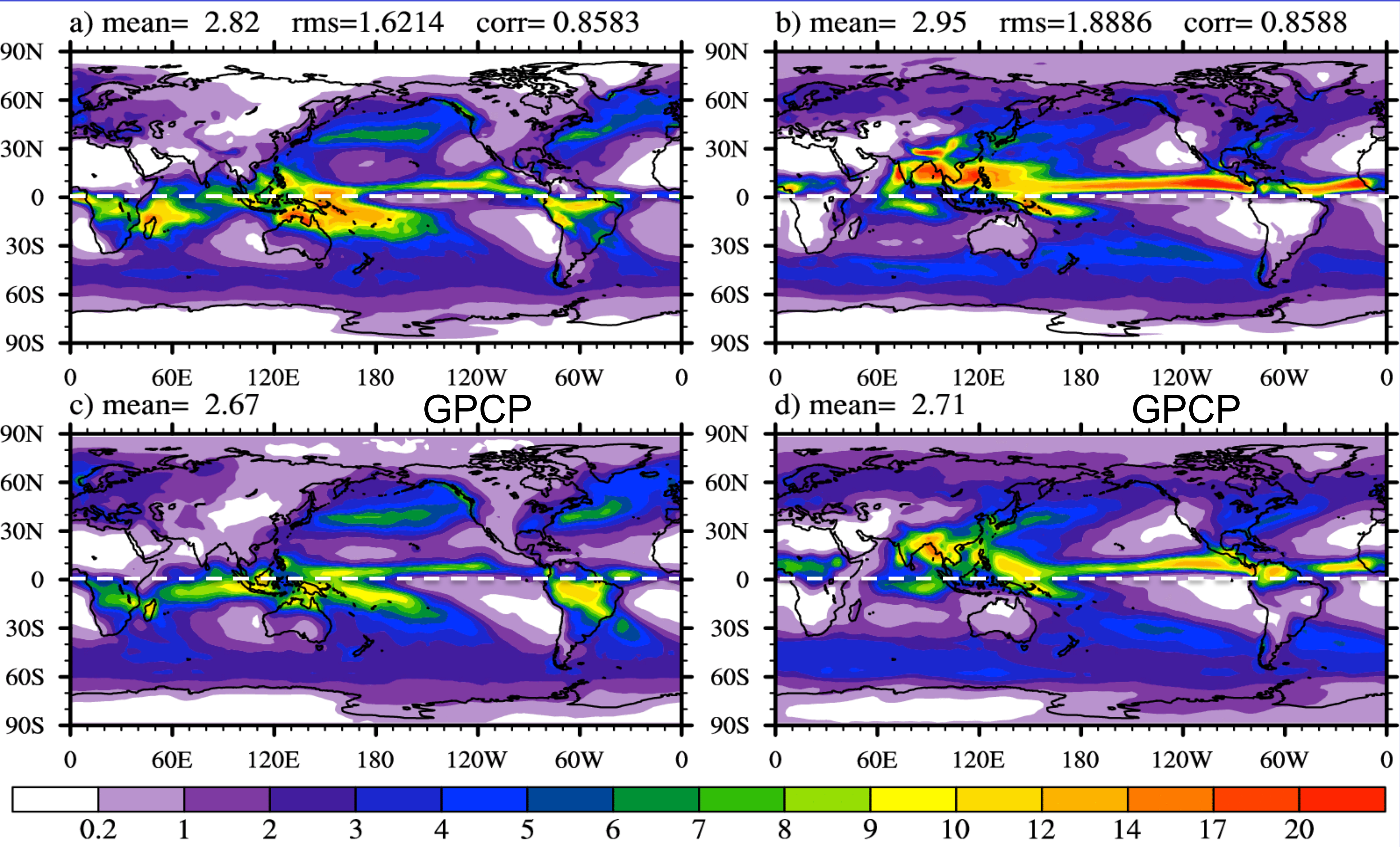


Cloud liquid water (mg kg^{-1})

Both SPCAM and SPCAM-IPHOC runs, with 12 levels below 700 hPa.

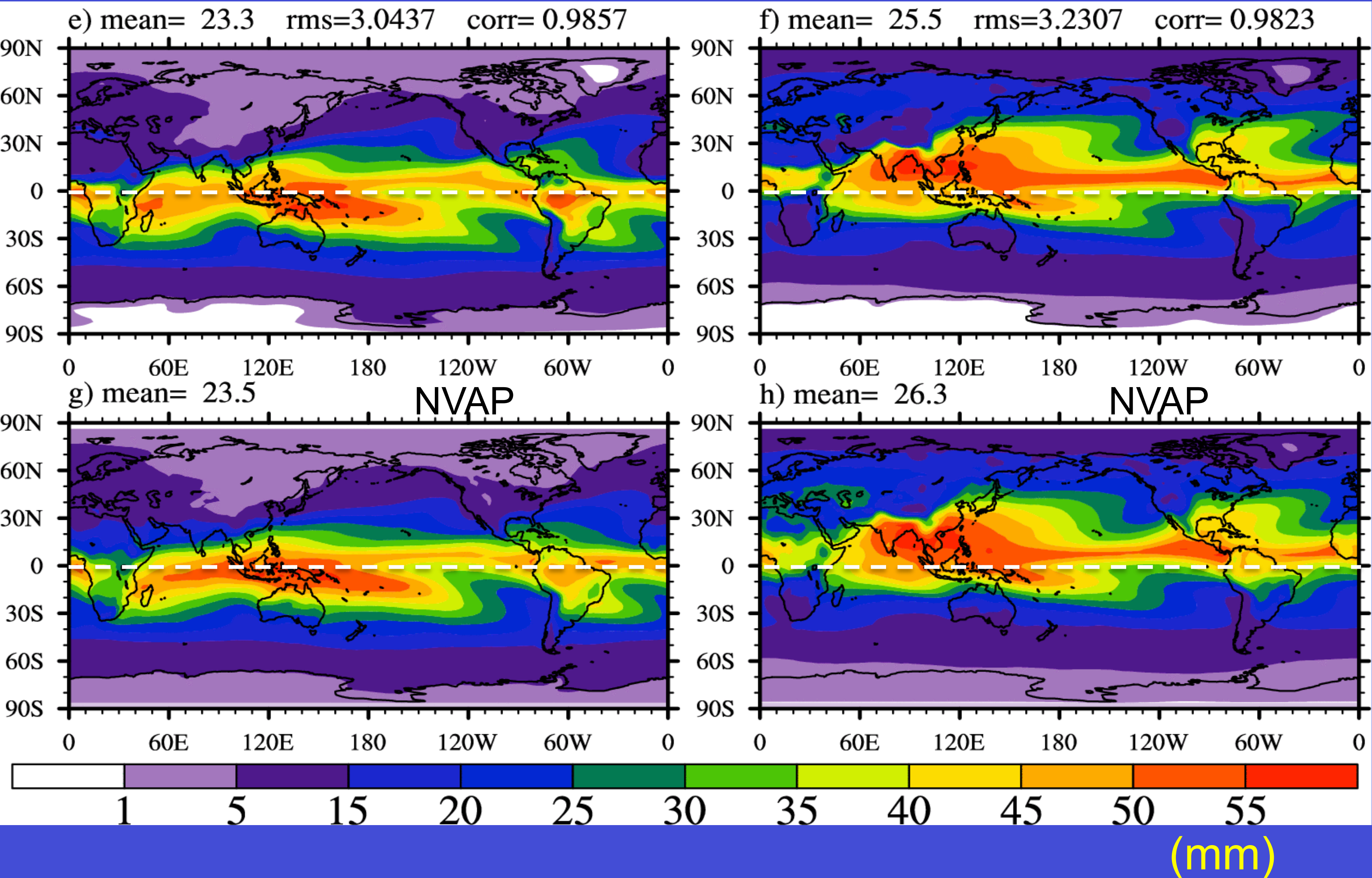
- SPCAM: clouds are produced only through grid-scale condensation;
- SPCAM-IPHOC: subgrid scale condensation
- The inclusion of IPHOC helps the simulation

Surface precipitation rate (left—DJF; right—JJA)

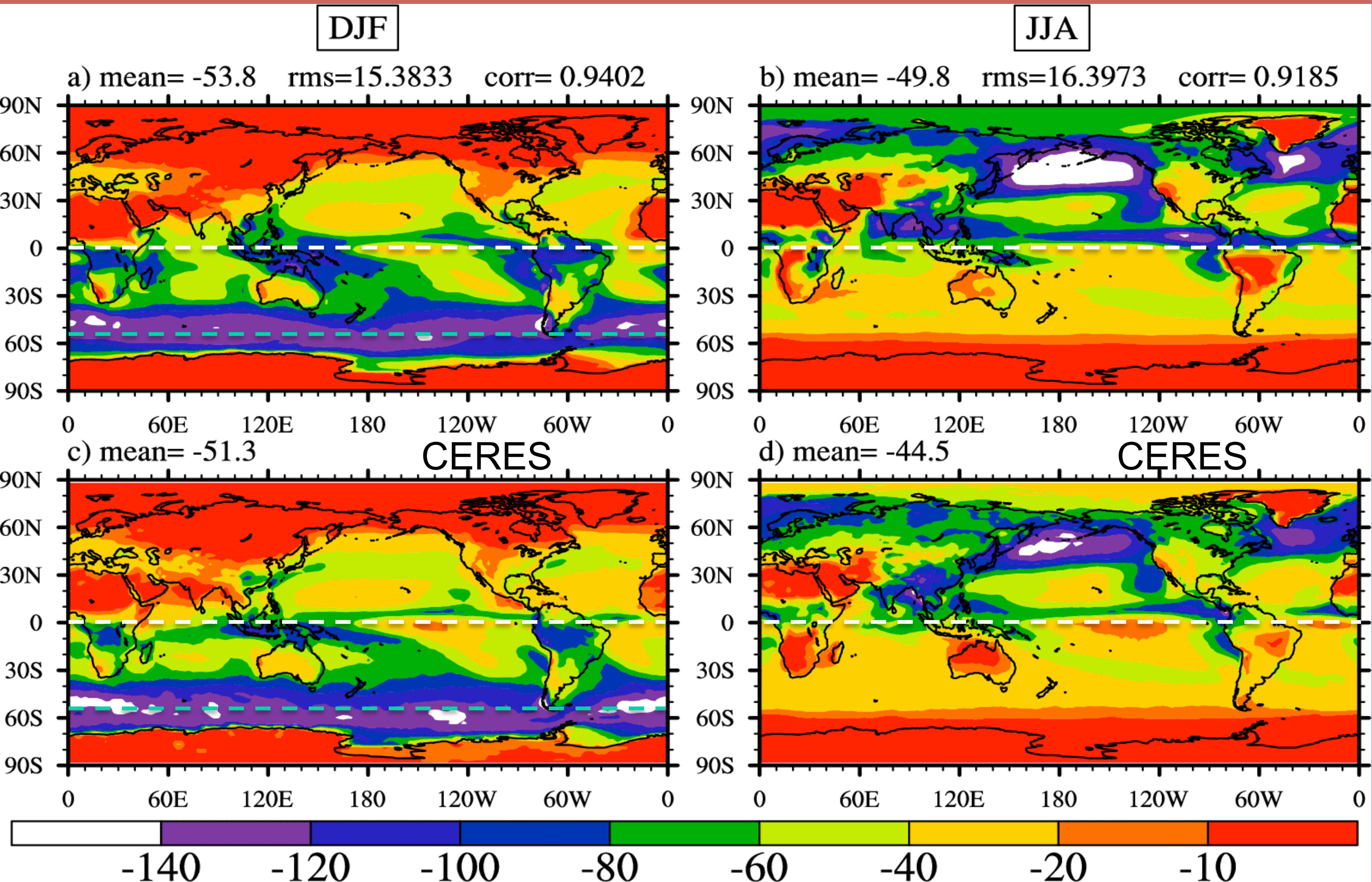


(mm/day)

Column-integrated vapor (left—DJF; right—JJA)

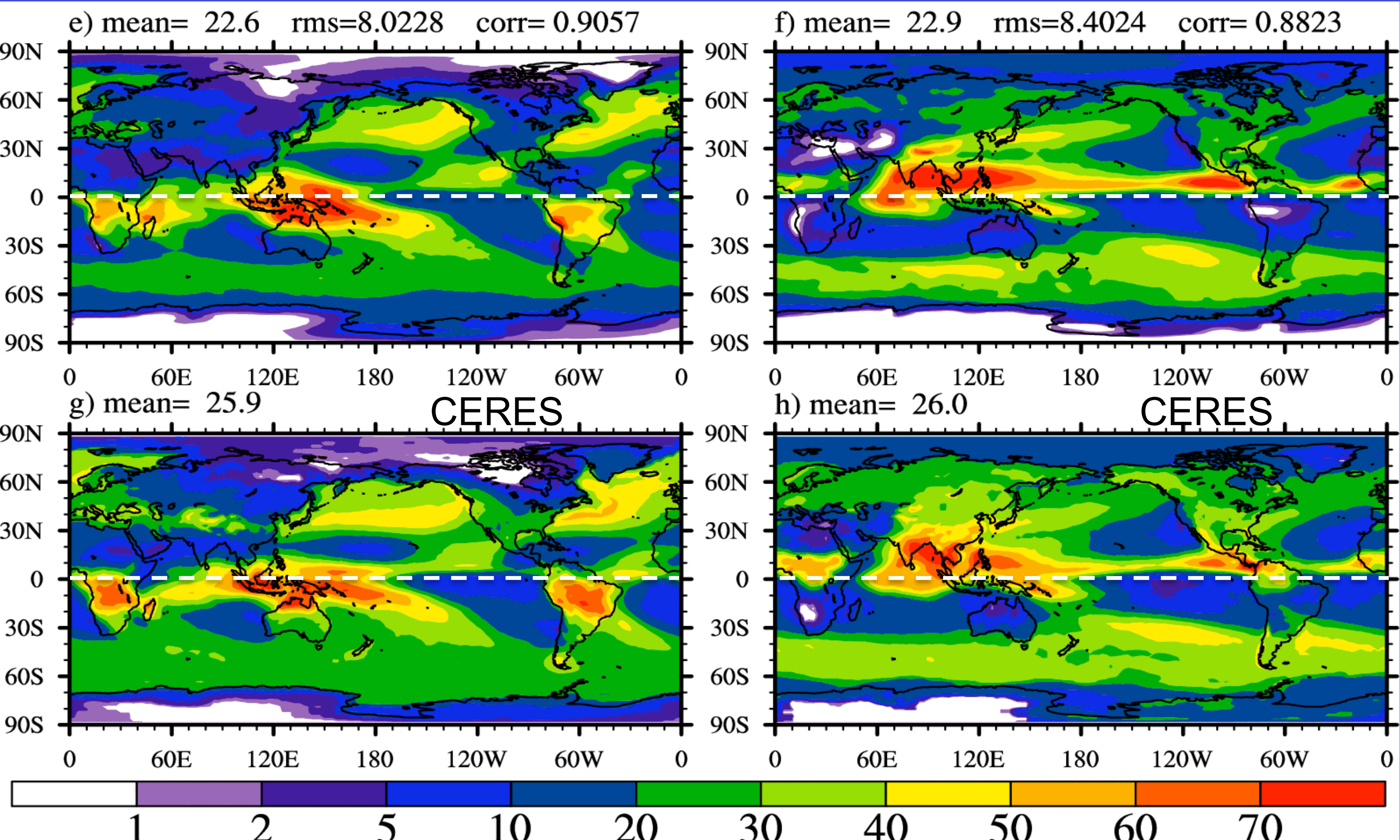


TOA SW Cloud Rad. Eff. (left—DJF; right—JJA)



Cloud radiative effect = radiative flux (cloudy sky – clear sky) (W m^{-2})

TOA LW Cloud Rad. Eff. (left—DJF; right—JJA)



Cloud radiative effect = radiative flux (cloudy sky – clear sky) $(W\ m^{-2})$

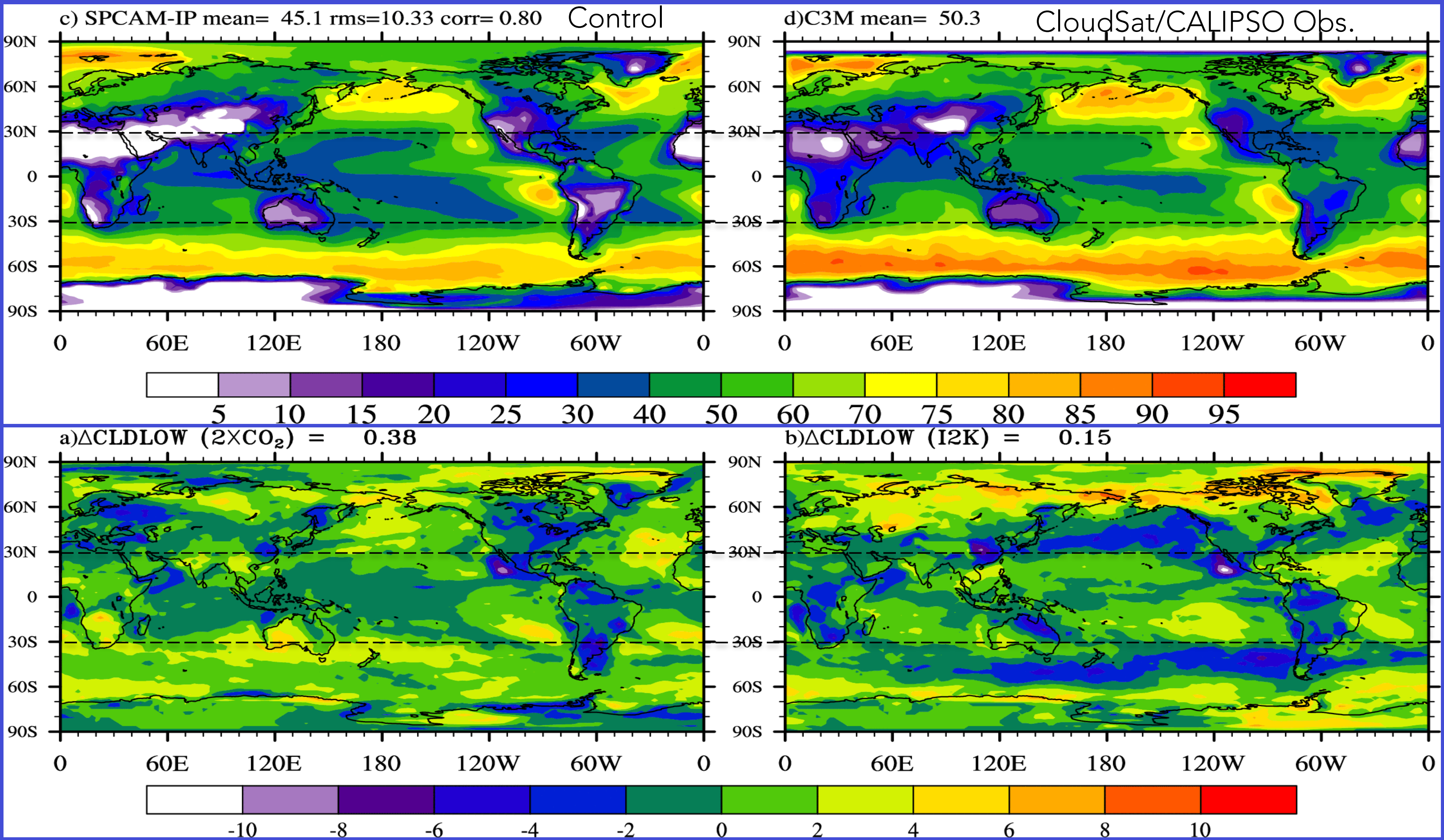
4. MMF climate simulation results:

b) Climate sensitivity

Why climate sensitivity study with MMF?

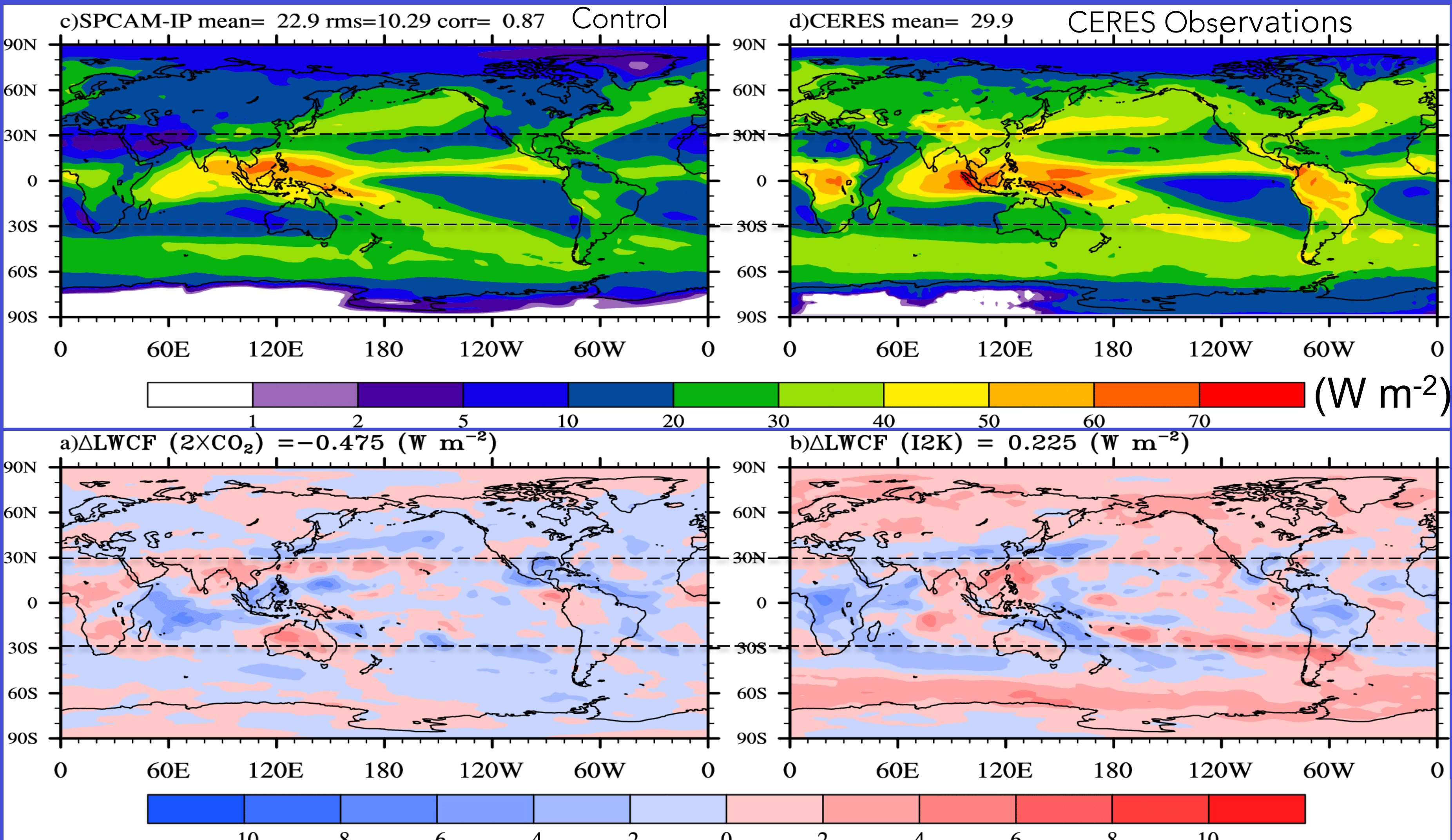
- Conventional GCMs do not simulate low clouds well
- Low clouds remains the largest uncertainty in cloud feedbacks and climate projection
- The version of MMF simulates realistic low clouds
- Control simulation
  - Forced with climatological SST and sea ice distributions (not an AMIP-type simulation) with present-day CO_2 concentration
  - Simulation duration is 10 yrs and 3 mos, with last 9 yrs analyzed
- Doubled CO_2 ($2xCO_2$) simulation
  - Same as the control except that CO_2 is doubled at the beginning of the simulation but SST and sea ice are fixed as the control
- +2 K SST (I2K) simulation
  - Same as the control except that SST is increased by 2 K

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



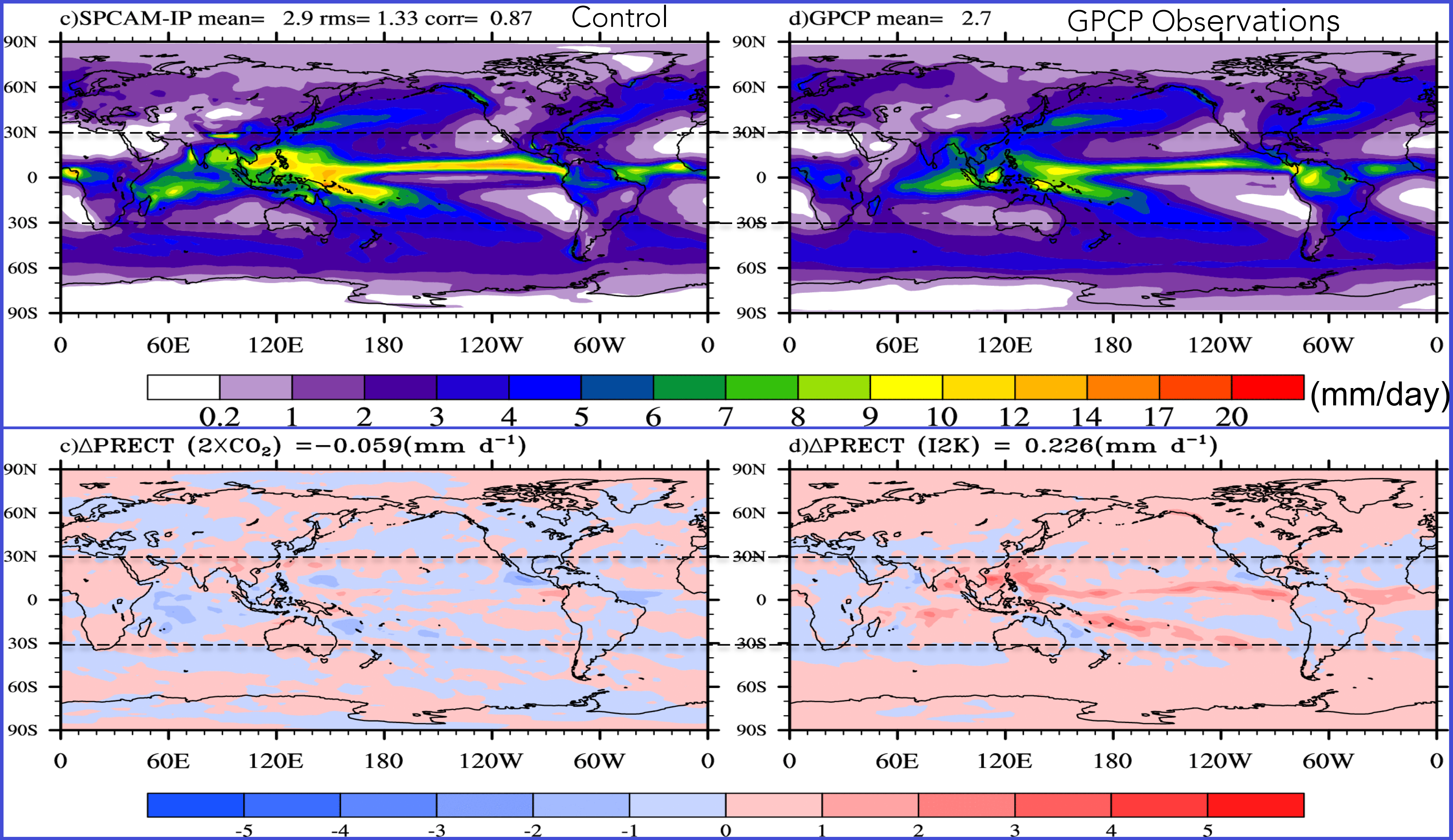
More in cumulus regions in *I2K*; but stratocumulus regions in *2xCO_2*
More in poleward of storm track in *I2K*, but equatorward in *2xCO_2*

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



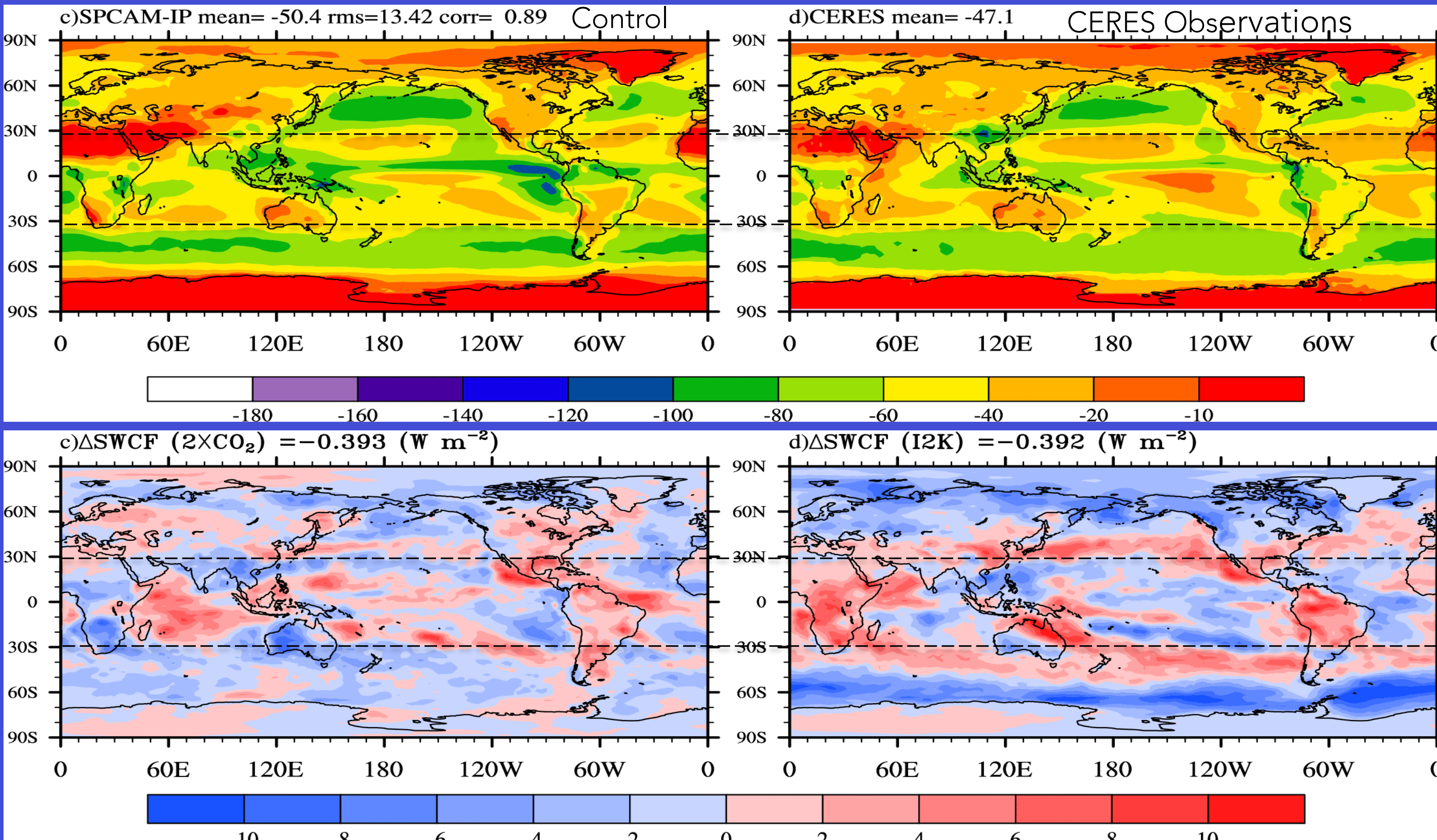
Changes in LW CRE are larger in *I2K* (higher clouds due to higher SSTs); Storm tracks moves polarwards and stronger SPCZ in *I2K*

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



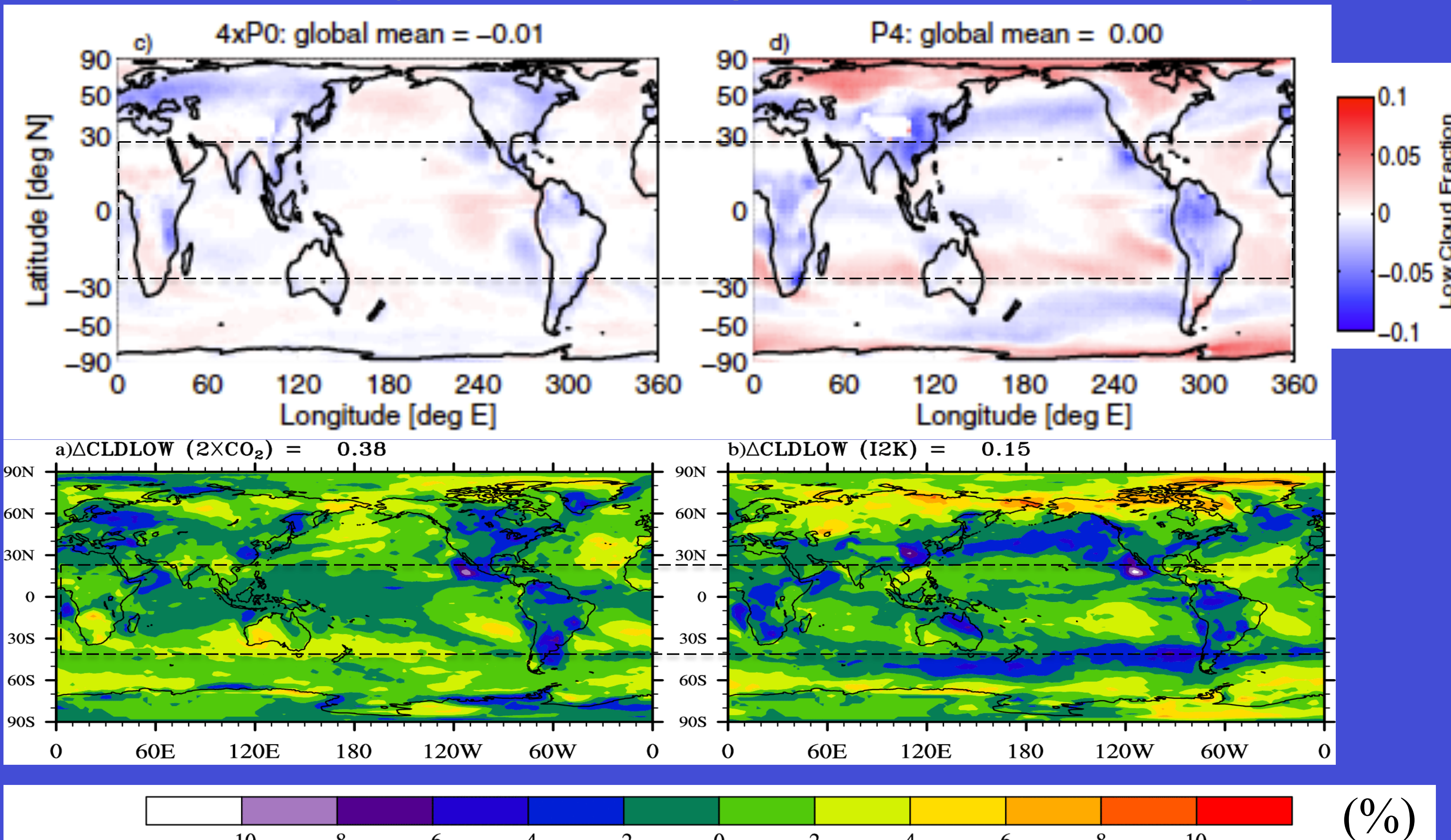
Increases at ITCZ and SPCZ (polarward movements) in *I2K;*
General small decreases in tropics and over lands in *2x*CO_2

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

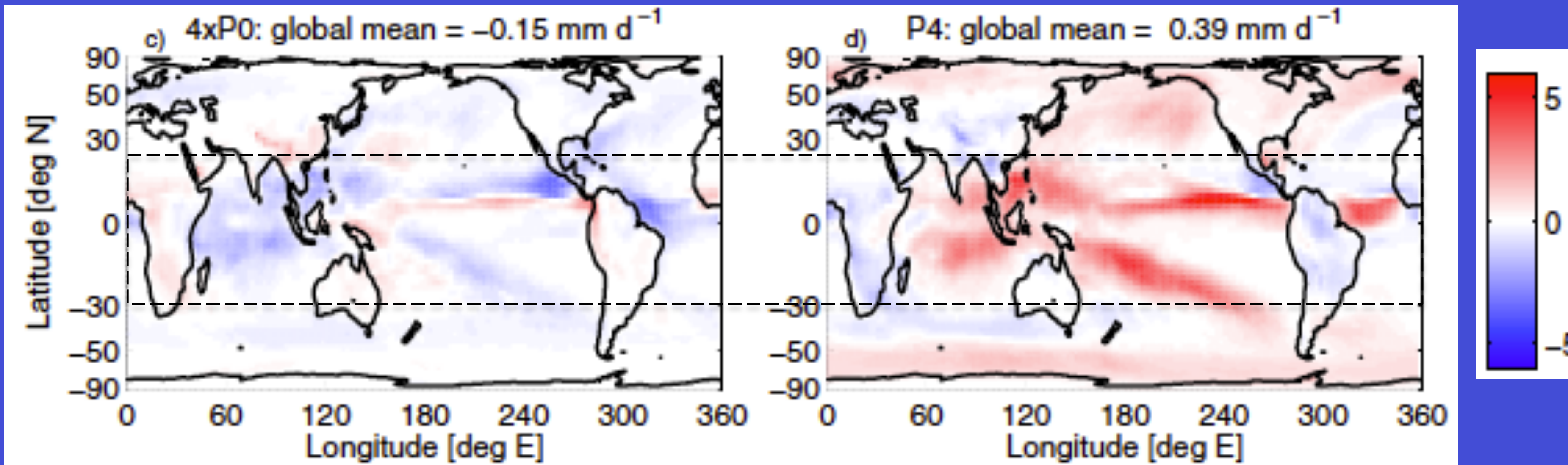
Low-level (surface -- 700 hPa) cloud fraction (%) changes in sensitivity simulations (Bretherton *et al.* 2014)

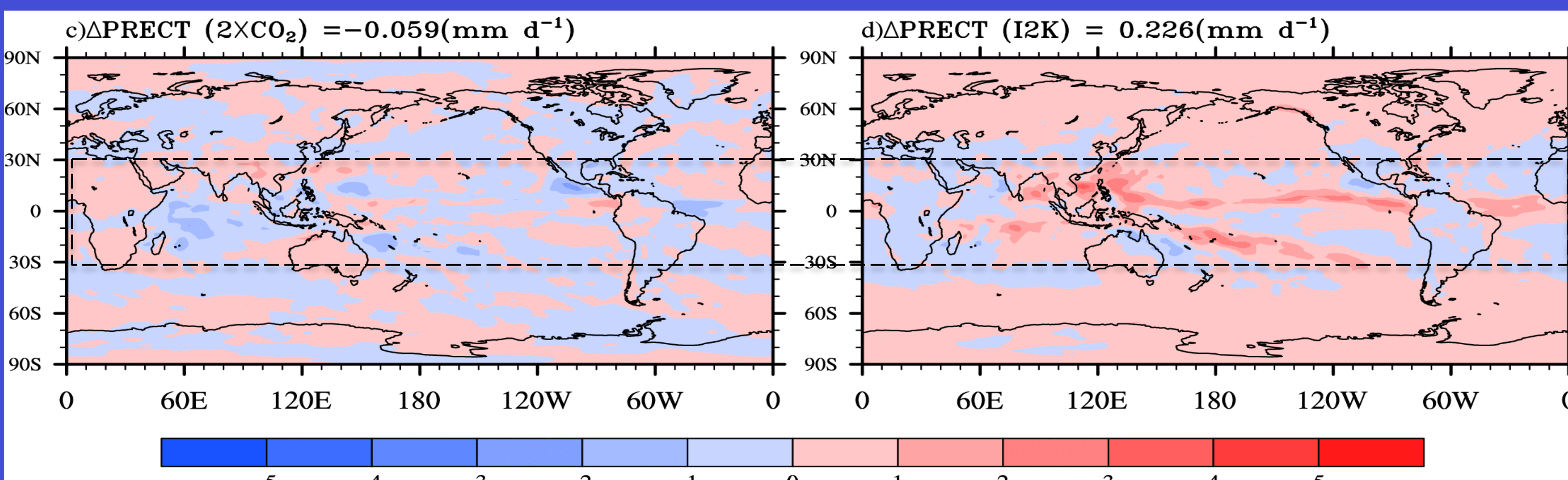


Differences appear in cumulus regions in +SST simulations

There are large differences in CO_2 simulations everywhere

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

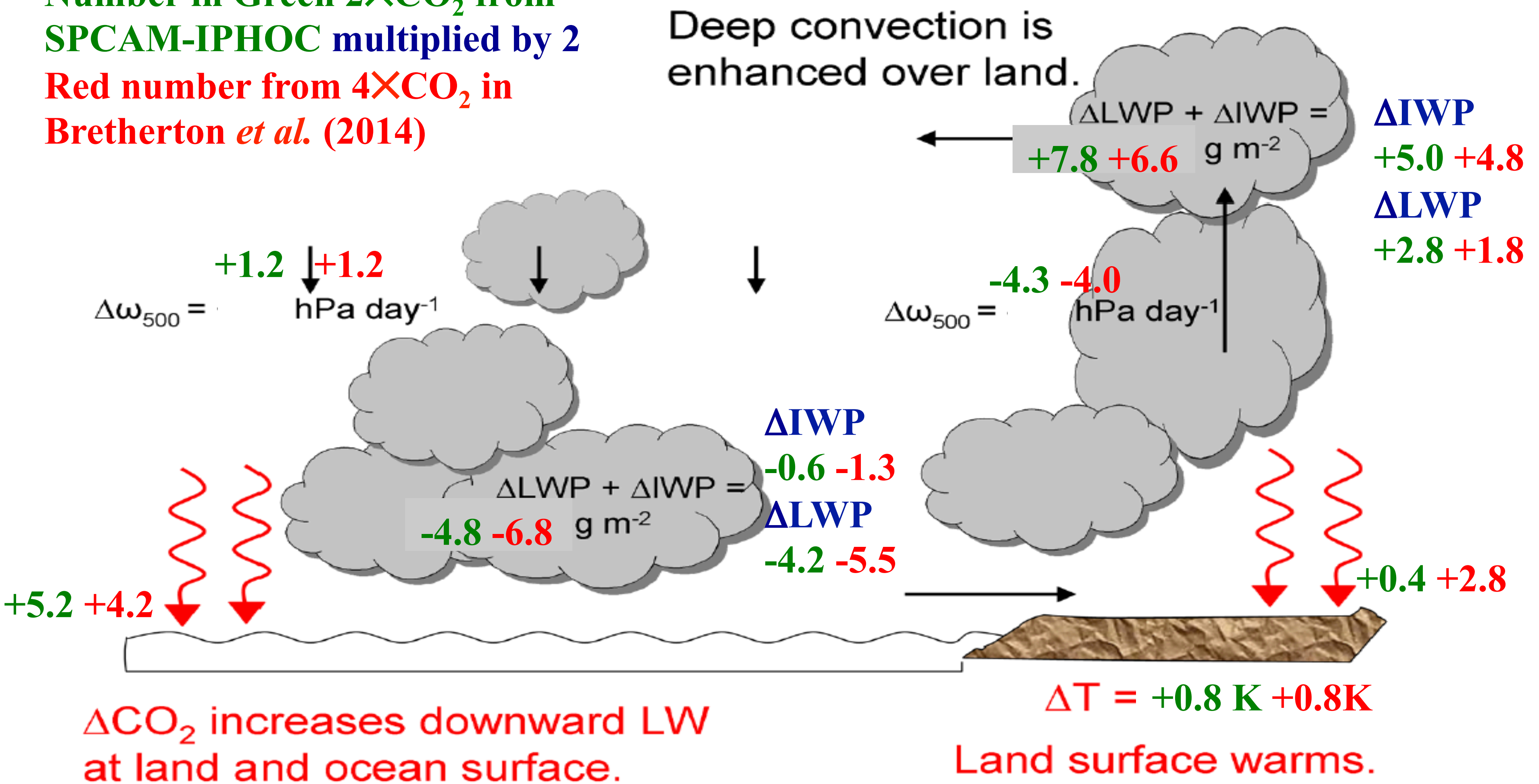




Similar increases at ITCZ and SPCZ in +SST simulations*;*
More increases over lands in *2x*CO_2 than in *4x*CO_2

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

Number in Green 2×CO_2 from SPCAM-IPHOC multiplied by 2
Red number from 4×CO_2 in Bretherton *et al.* (2014)



Summary and conclusions

- The MMF climate simulation greatly reduces regional biases associate with low-level clouds
- The simulated climatology agree with observations in many aspects, but not perfect everywhere
- The low cloud fractions increase in the tropics/subtropics in both sensitivity simulations, but for different reasons
- 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 2xCO2 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