

Improved Climate Simulations of Precipitation, Cloud and Radiation Processes with the Constraint of CRM Analysis, ARM and Satellite Observations

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Liping Deng and Sunwook Park (ISU)

Guang Jun Zhang and Xiaoliang Song (Scripps Institution of Oceanography)

Xin-zhong Liang (Illinois State Water Survey, UIUC)

Guido Vettoretti and Richard Peltier (University of Toronto)

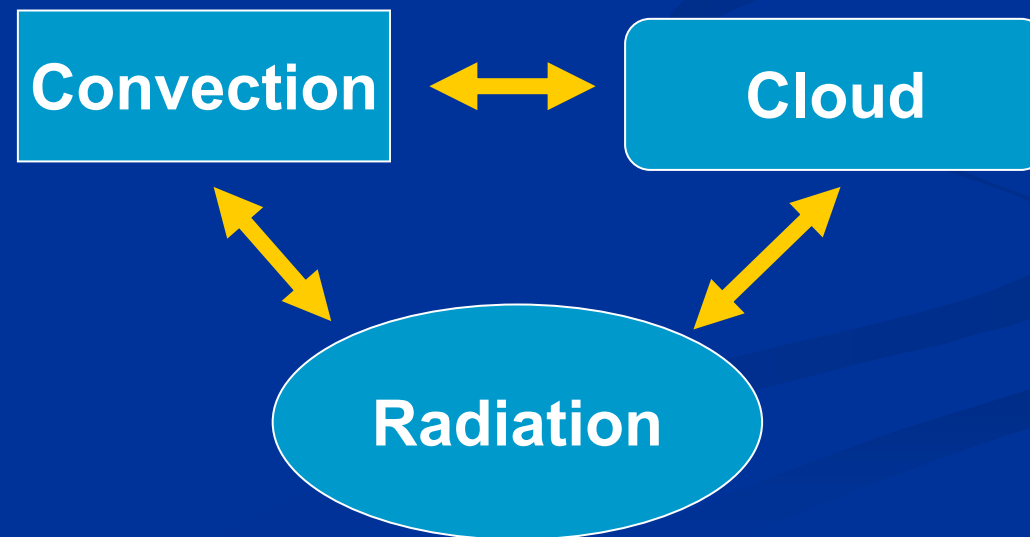
Qilong Min (State University of New York at Albany)

Partly supported by DOE ARM

Several outstanding deficiencies in coupled GCM simulations include:

- diurnal and seasonal cycle of precipitation,
- double ITCZ problem,
- weak temporal variability in tropical climate such as MJO,
- a too short and too regular ENSO periodicity,

Effects of convection, cloud and radiation processes



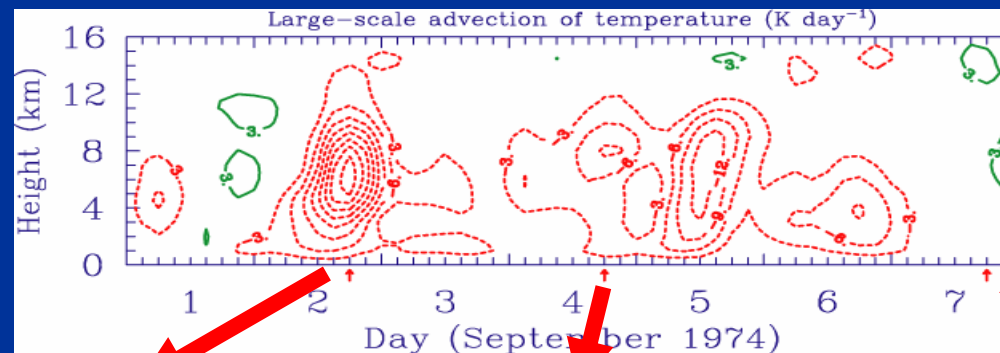
ISU Cloud-Resolving Model (CRM)

* Cloud Dynamics:

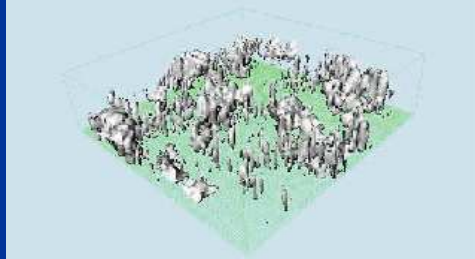
Clark-Hall finite-difference formulation of anelastic and nonhydrostatic equations (Clark et al. 1996)

* Model Physics:

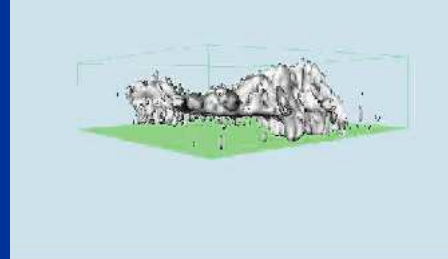
- Cloud microphysical (Kessler, 1969; Koenig and Murray, 1976)
- Radiation parameterization (Kiehl et al., 1996)
- Eddy diffusion parameterization (Smagorinsky, 1963)



Non-squall cluster



Squall cluster



Scattered convection



Grabowski, Wu and Moncrieff (1996, JAS)

Iowa State University (ISU) GCM:

Based on a version of NCAR CCSM (CCM3, CSM), but with

1. Modified Zhang-McFarlane (ZM) Convection Scheme

- Revised convection closure assumption
- Trigger condition of deep convection
- Convective momentum transport

2. Modified cloud parameterization Scheme

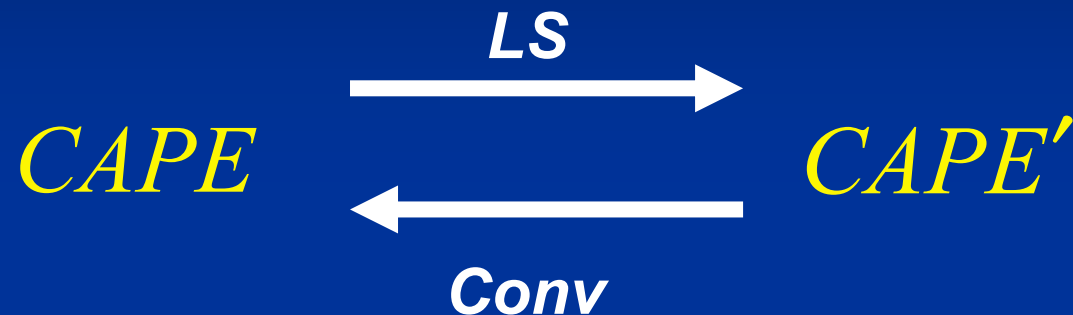
- CRM-derived vertical distribution of in-cloud water content

3. Modified Radiation parameterization Scheme

- Mosaic approach (MOS) of treating subgrid cloud variability

Revised ZM closure assumption:

Convection is tied to the destabilization of the tropospheric layer above PBL by the large-scale processes.



LS : Large-scale advection and radiative heating/cooling

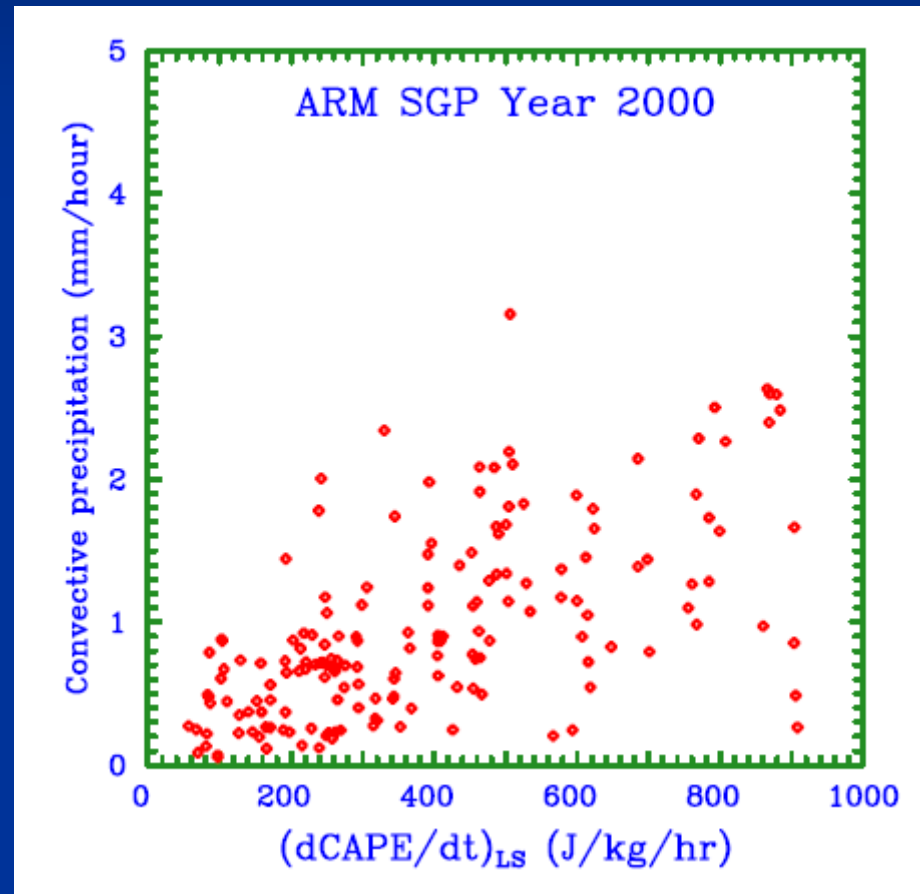
$Conv$: Convective processes

$$m_b = \frac{\langle CAPE \rangle_{LS}}{\langle CAPE \rangle_{Conv}}$$

Zhang (2002, 2003, JGR)

Trigger condition of deep convection:

Convection is activated when the increase of CAPE due to the large-scale processes exceeds certain threshold.



Wu et al. (2007, GRL)

Parameterization of convective momentum transport:

Convection redistributes the horizontal momentum through the compensating subsidence, detrainment and perturbation pressure gradient.

$$F_x = \delta(u_c - u) + M_c \frac{\partial u}{\partial z} + \frac{\sigma}{\rho} \frac{\partial p_c}{\partial x}$$

$$F_y = \delta(v_c - v) + M_c \frac{\partial v}{\partial z} + \frac{\sigma}{\rho} \frac{\partial p_c}{\partial y}$$

F_x, F_y : Convective momentum tendency

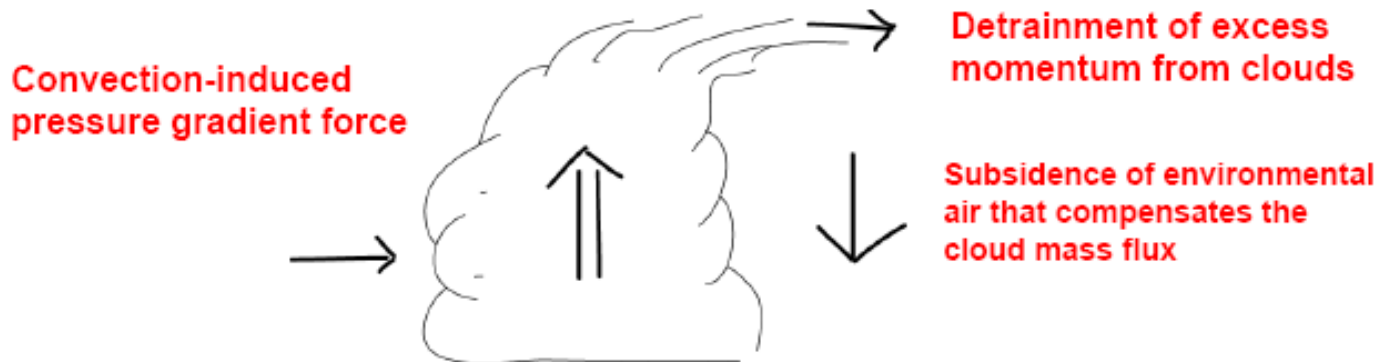
u_c, v_c : In-cloud momentum

δ : Detrainment of mass

M_c : Cloud mass flux

p_c : Cloud-scale pressure

σ_c : Fractional area of clouds



Zhang and Cho (1991, JAS)

Wu and Yanai (1994, JAS)

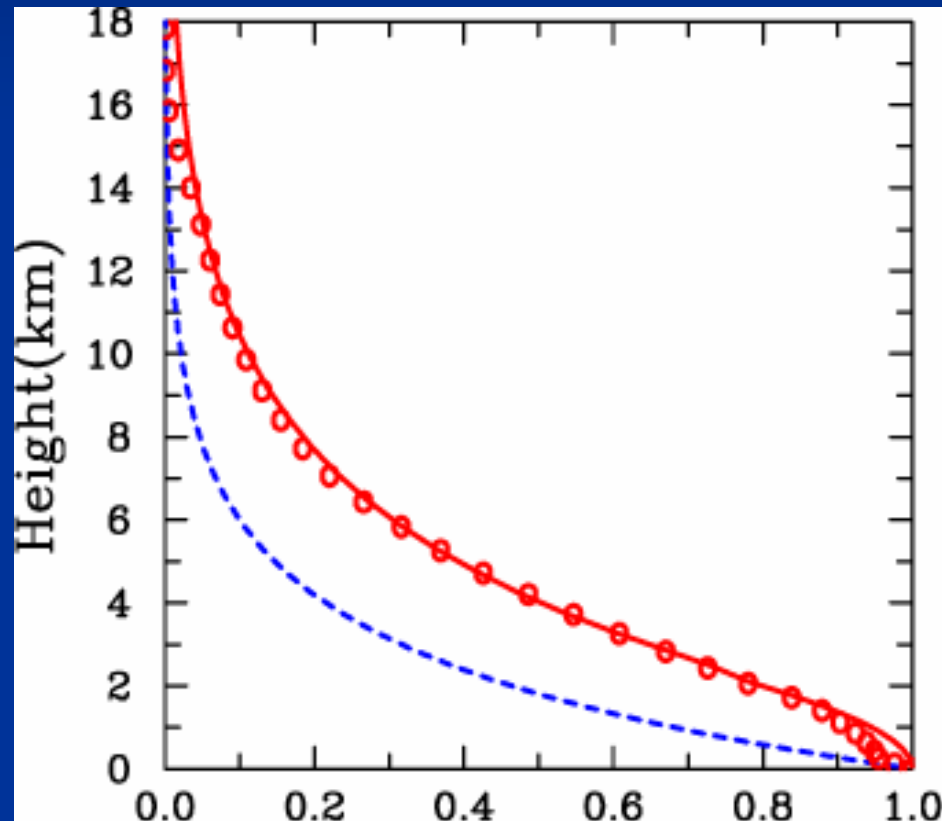
Wu, Zhang and Liang (2003, GRL)

Zhang and Wu (2003, JAS)

Song, Wu, Zhang, and Arritt (2008a, b, JC)

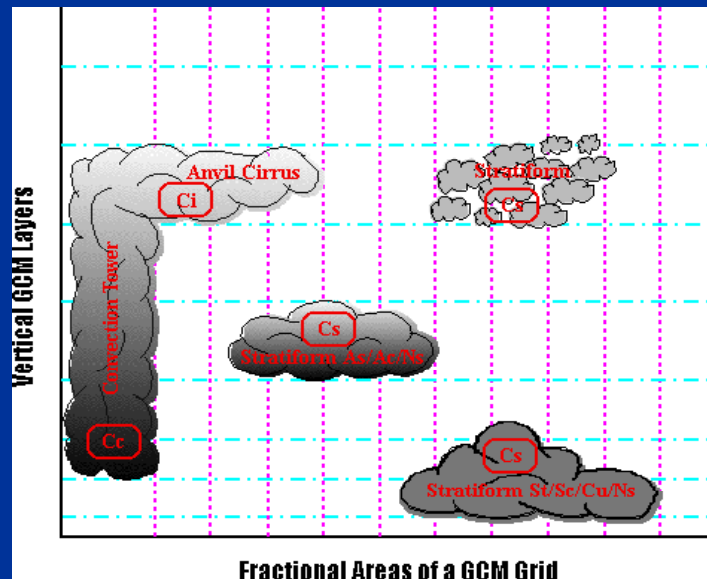
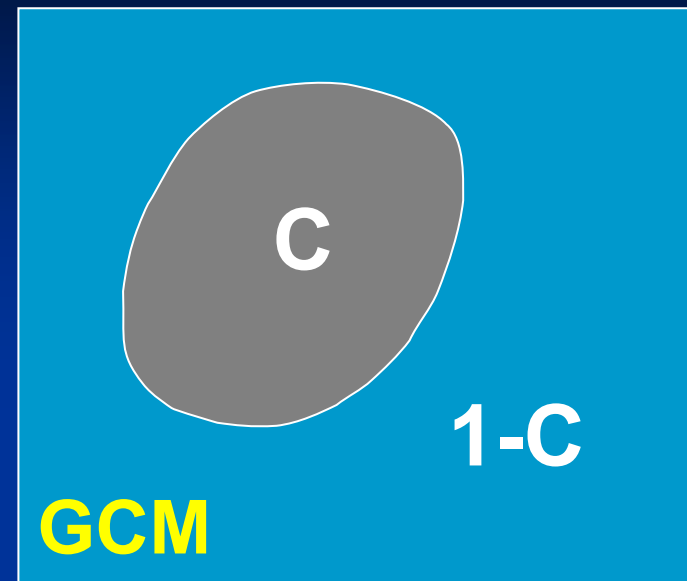
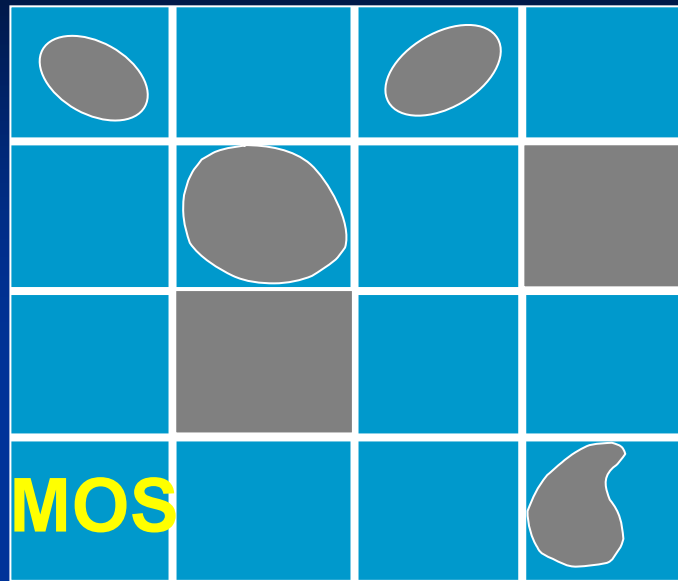
Vertical distribution of in-cloud water content:

In-cloud water content derived from the CRM simulation (solid) compares with that used by the standard CCM3 (dashed). Circles are normalized CRM cloud (liquid and ice) water content.



Wu and Liang (2005, GRL)

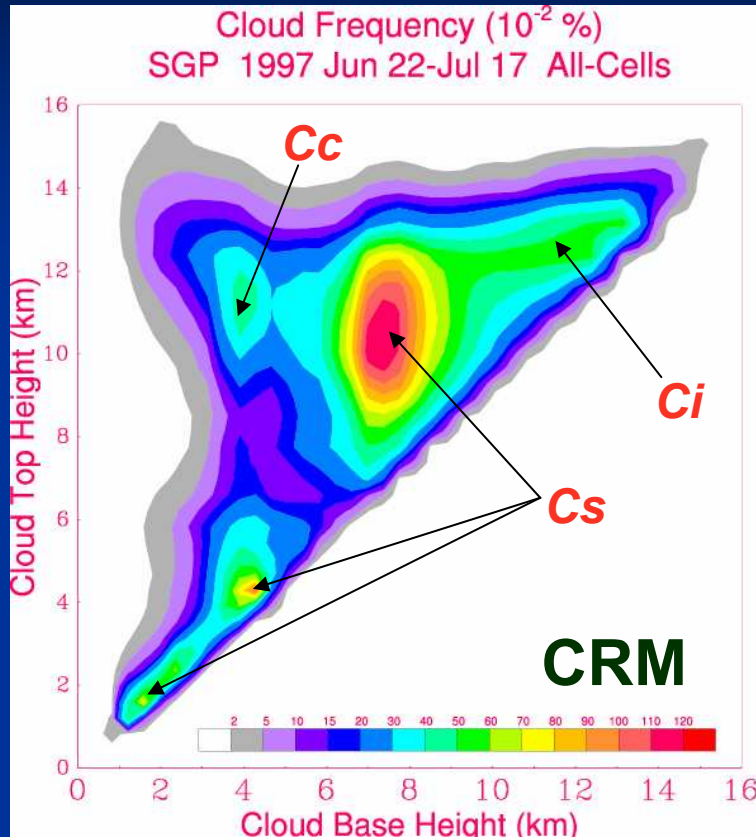
Mosaic approach (MOS) of treating subgrid cloud variability:



Liang and Wang (1997, JGR)

Cloud Frequency

Cloud Top Height



Cloud Base Height

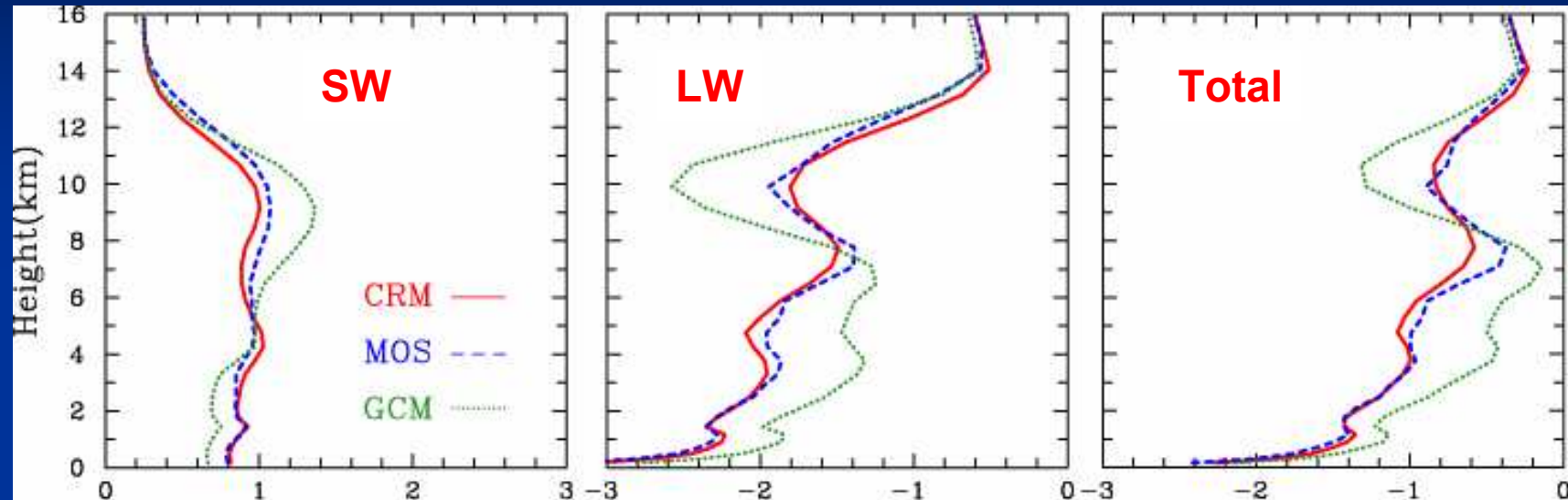
CRM simulated cloud frequency (10^{-4}) distribution as a function of the base and top heights. Four major cloud clusters are identified in the centers as deep convective tower (*Cc*), anvil cirrus (*Ci*), and stratiform cloud (*Cs*) that are distinguished by the mosaic treatment of cloud-radiation interactions.

Wu and Liang (2005, JAS)

Wu et al. (2007, MWR)

Liang and Wu (2005, GRL)

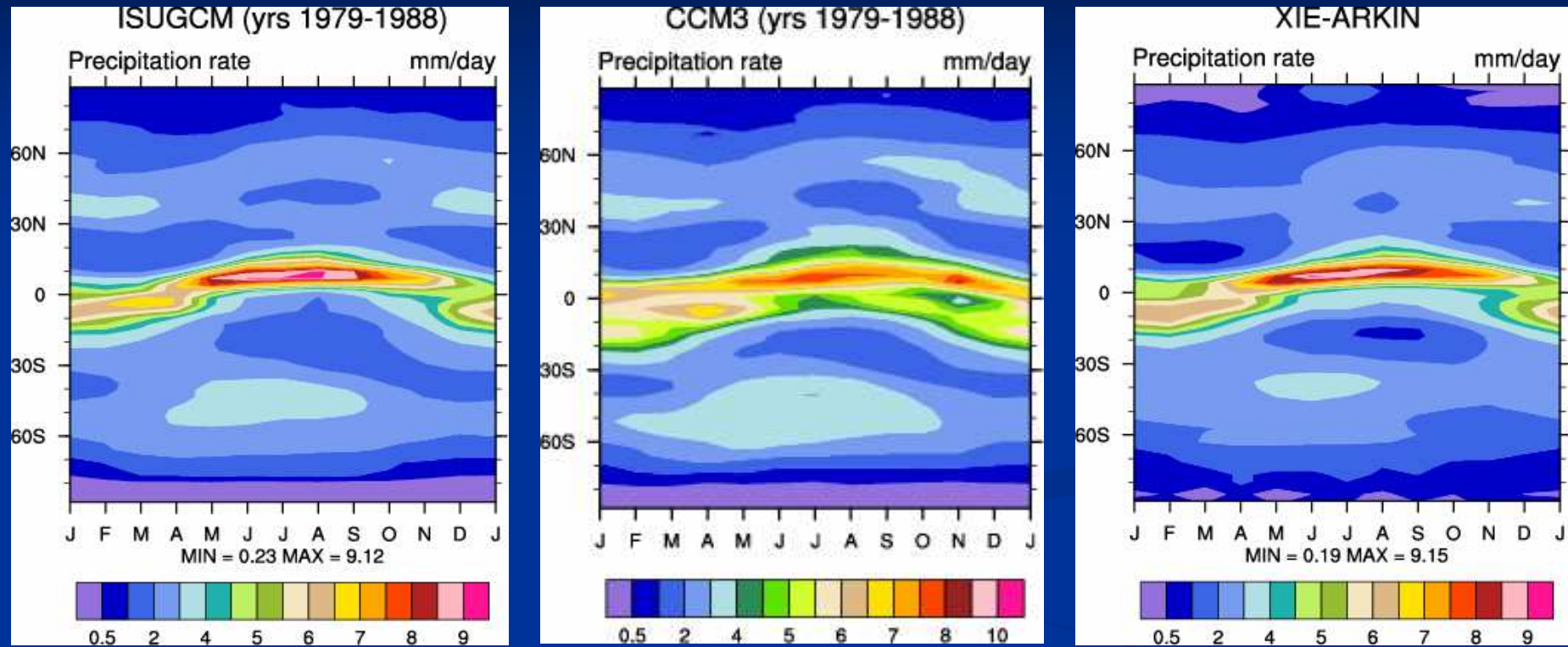
Radiative Heating Rate



Domain averaged shortwave (SW), longwave (LW) and total heating rate (K day⁻¹) profiles as simulated by the CRM and calculated by the GCM and mosaic (MOS) approaches.

Wu and Moncrieff (2001, JAS)
Liang and Wu (2005, GRL)

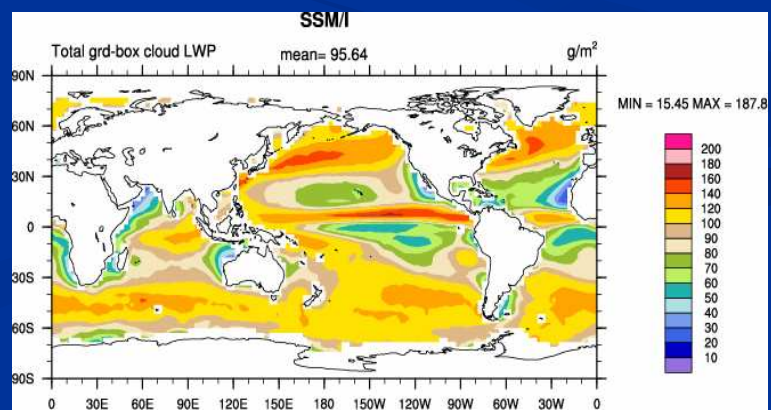
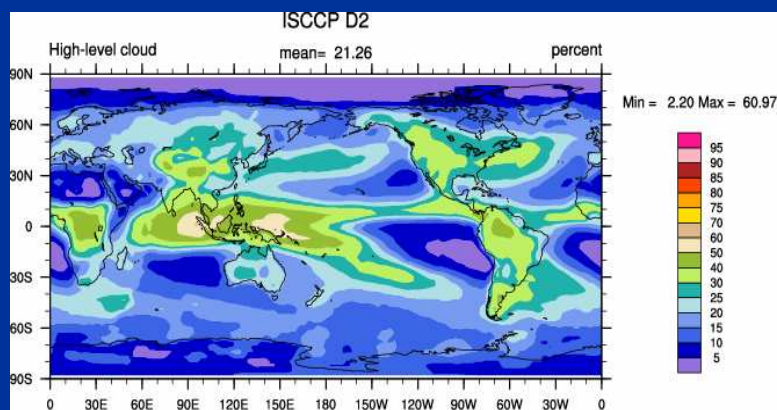
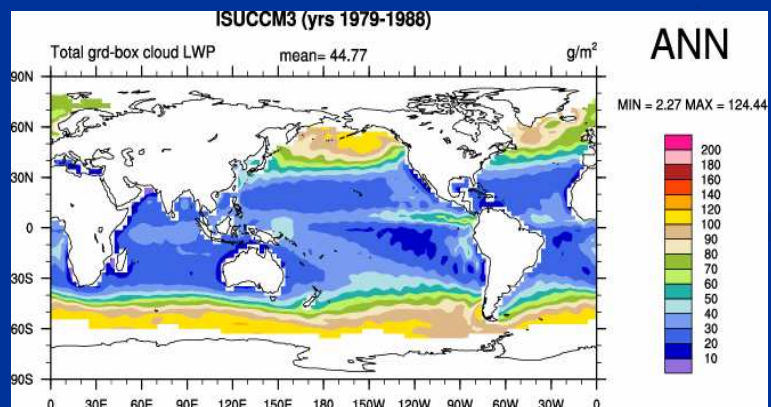
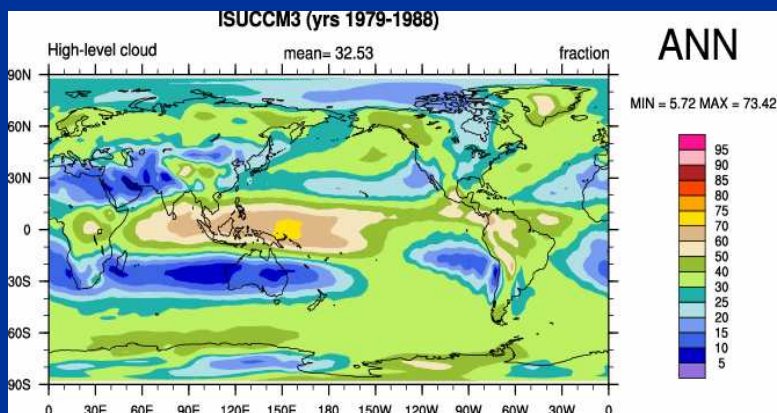
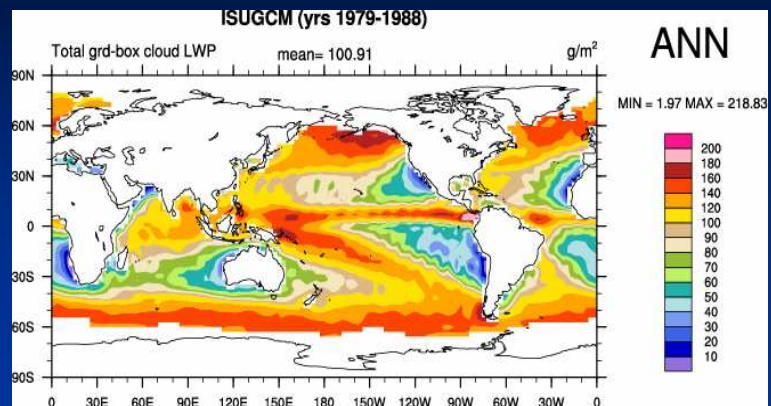
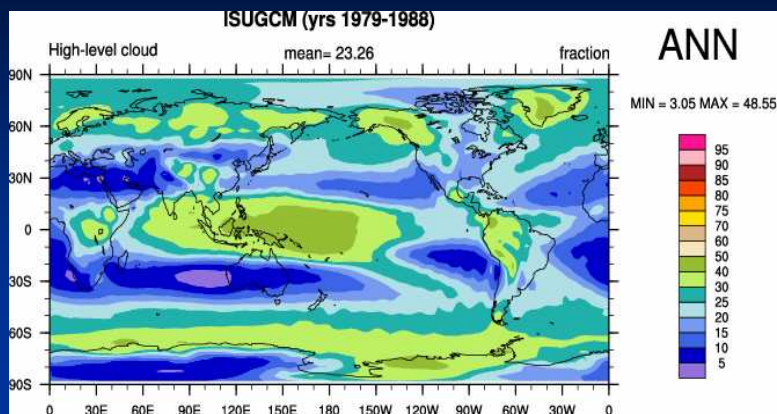
Seasonal Cycle of Precipitation



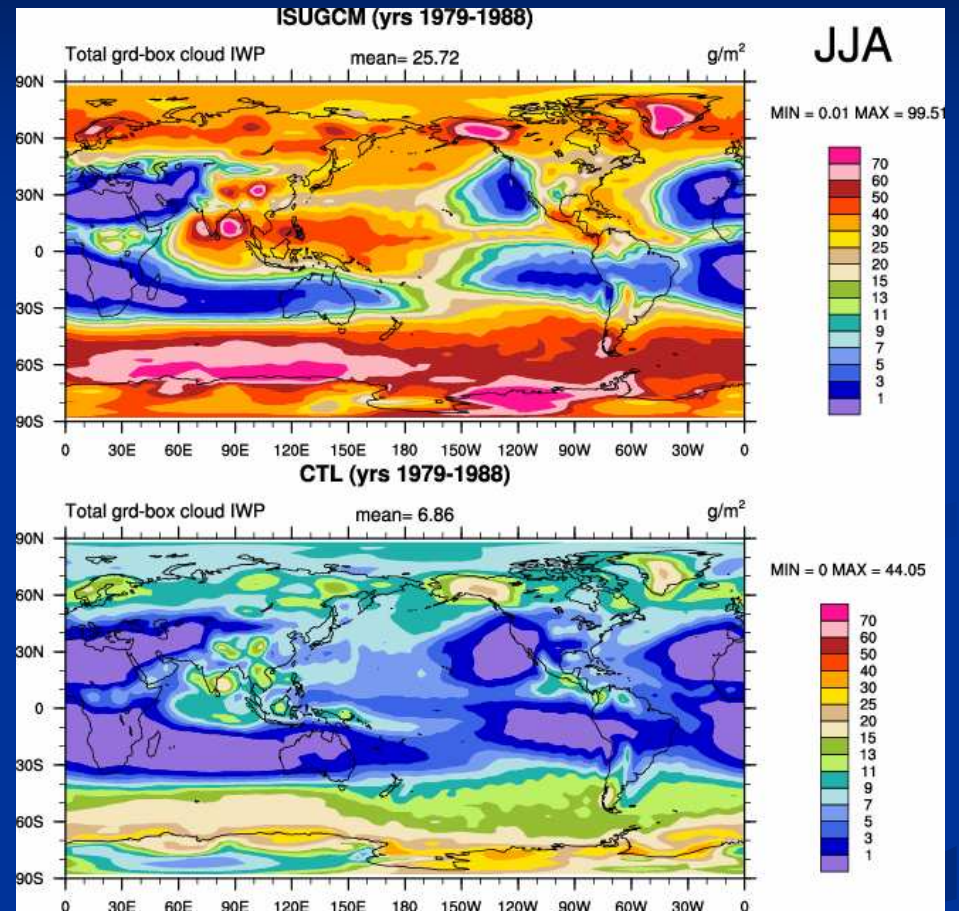
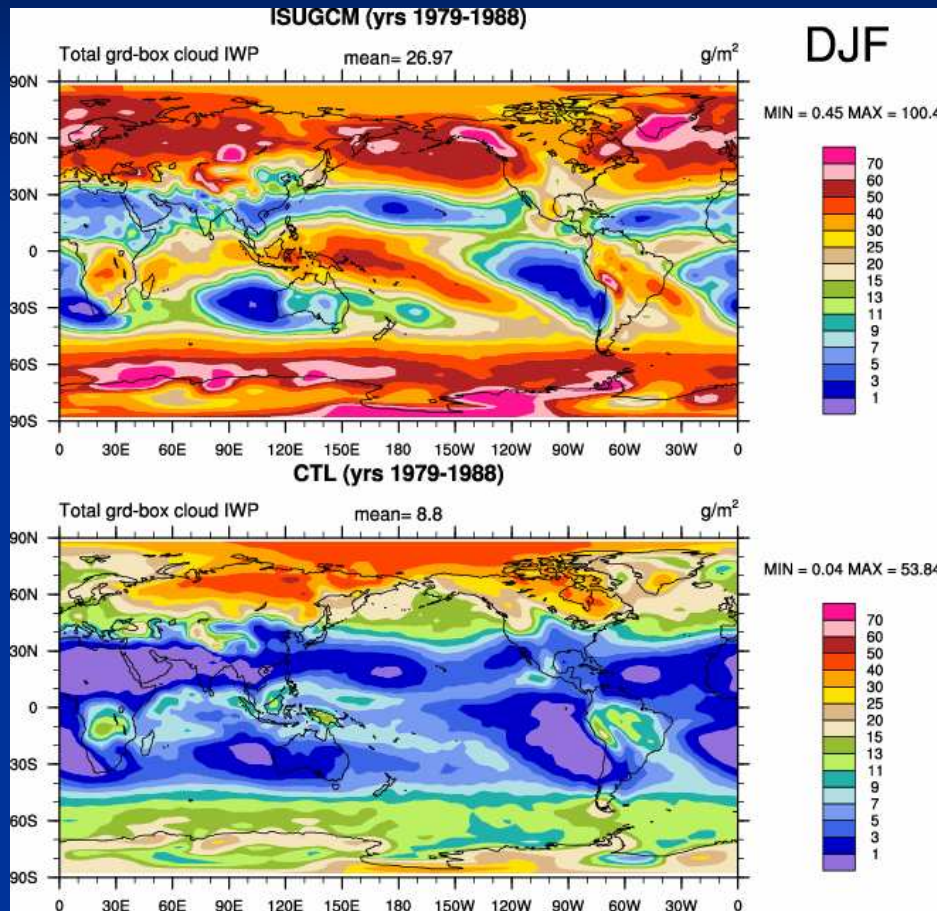
ISUGCM: CCM3 with improved convection, cloud and radiation schemes

High-level cloud amount

Liquid water path (LWP, g/m^2)



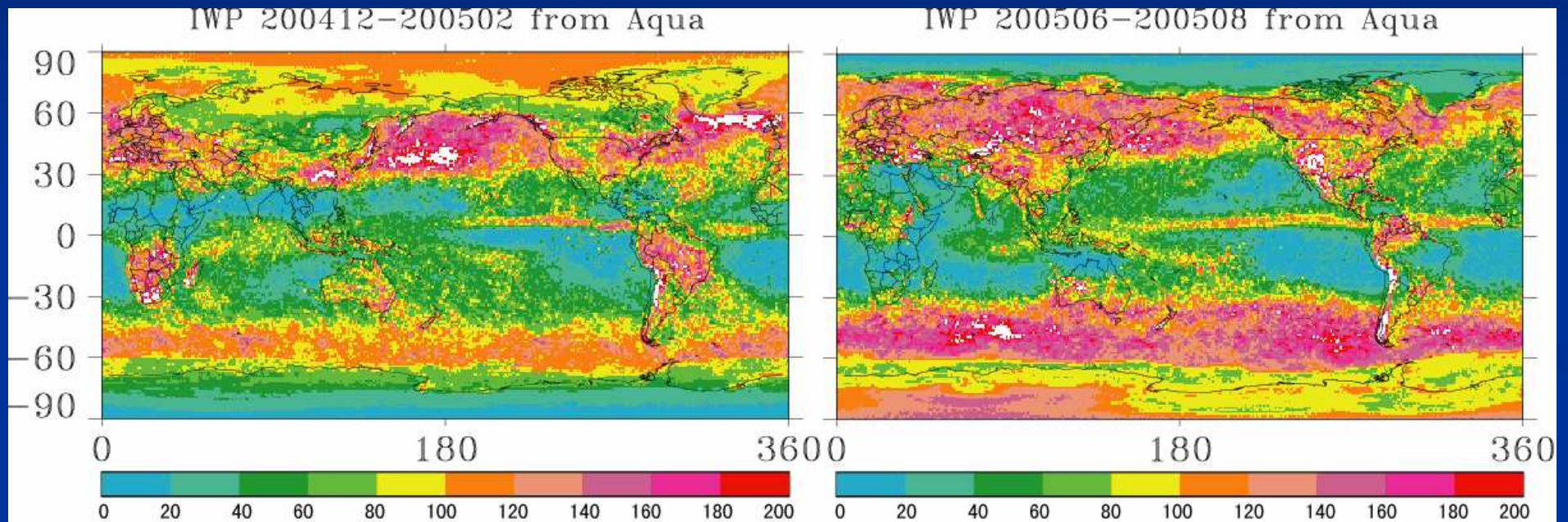
Ice water path (IWP, g m⁻²)



Ice water path (IWP, g m^{-2}) from Aqua

DJF

JJA

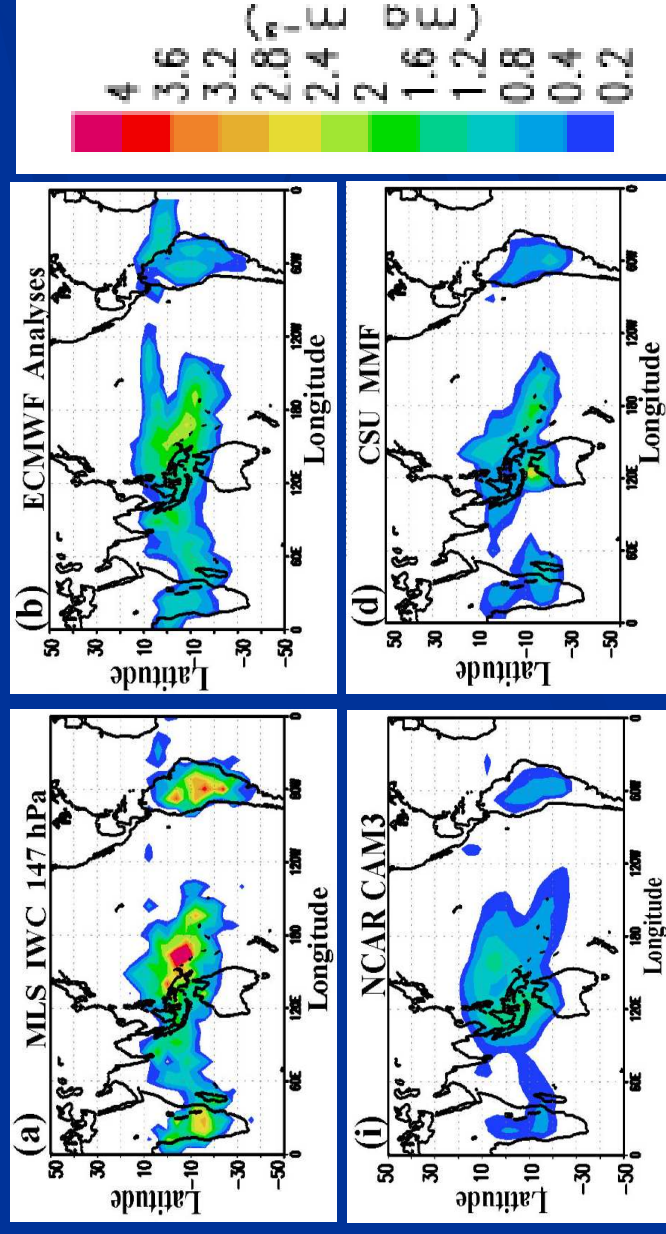


From Bing Lin and Pat Minnis (NASA/LaRC)

Comparisons of EOS MLS cloud ice measurements with ECMWF analyses and GCM simulations: Initial results

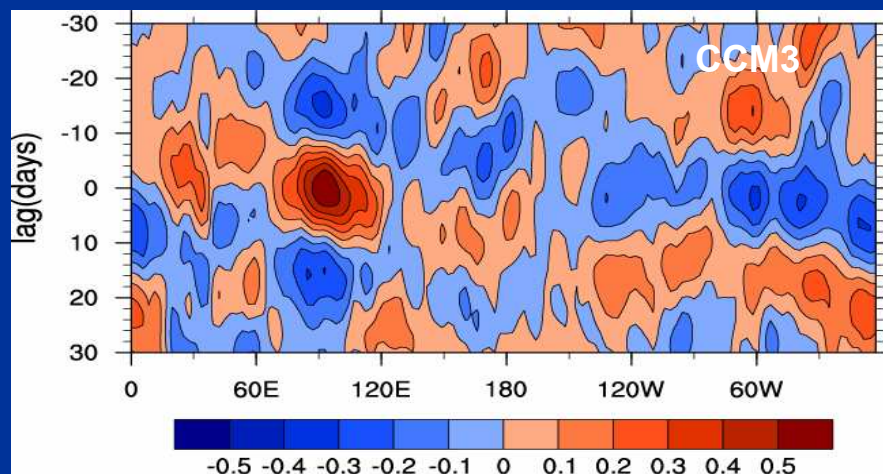
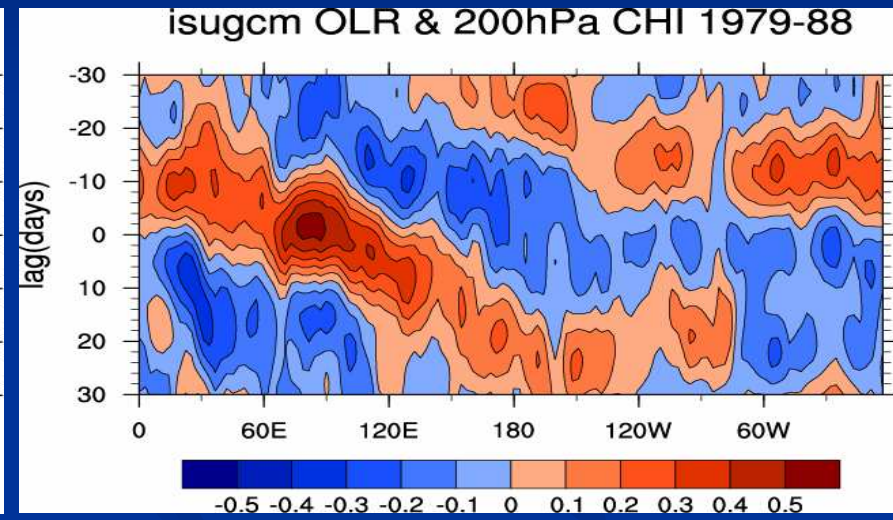
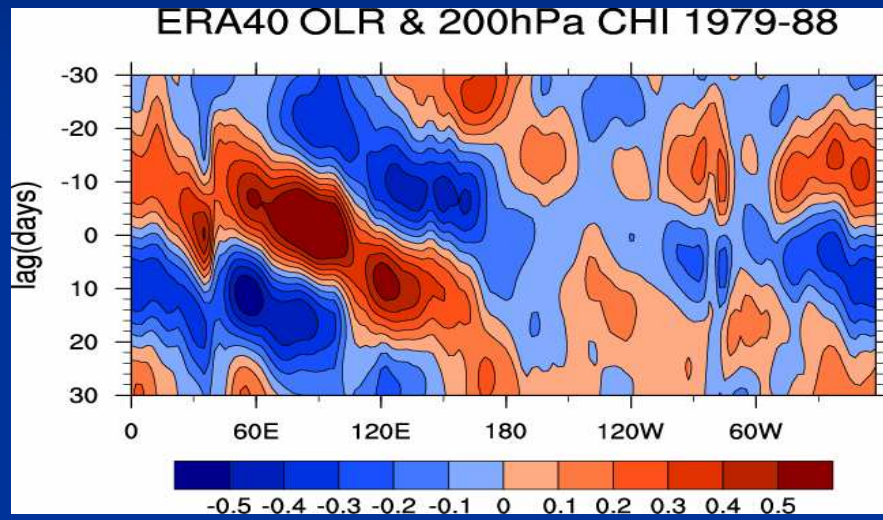
J.-L. Li,¹ D. E. Waliser,² J. H. Jiang,² D. L. Wu,² W. Read,² J. W. Waters,²
A. M. Tompkins,³ L. J. Donner,⁴ J.-D. Chern,⁵ W.-K. Tao,⁶ R. Atlas,⁶ Y. Gu,⁷ K. N. Liou,⁷
A. Del Genio,⁸ M. Khairoutdinov,⁹ and A. Gettelman¹⁰

multi-scale-modeling framework. For January 2005 monthly and daily mean values, the spatial agreement between MLS and ECMWF is quite good, although MLS estimates are higher by a factor of 2–3 over the Western Pacific, tropical Africa and South America. For the GCMs,



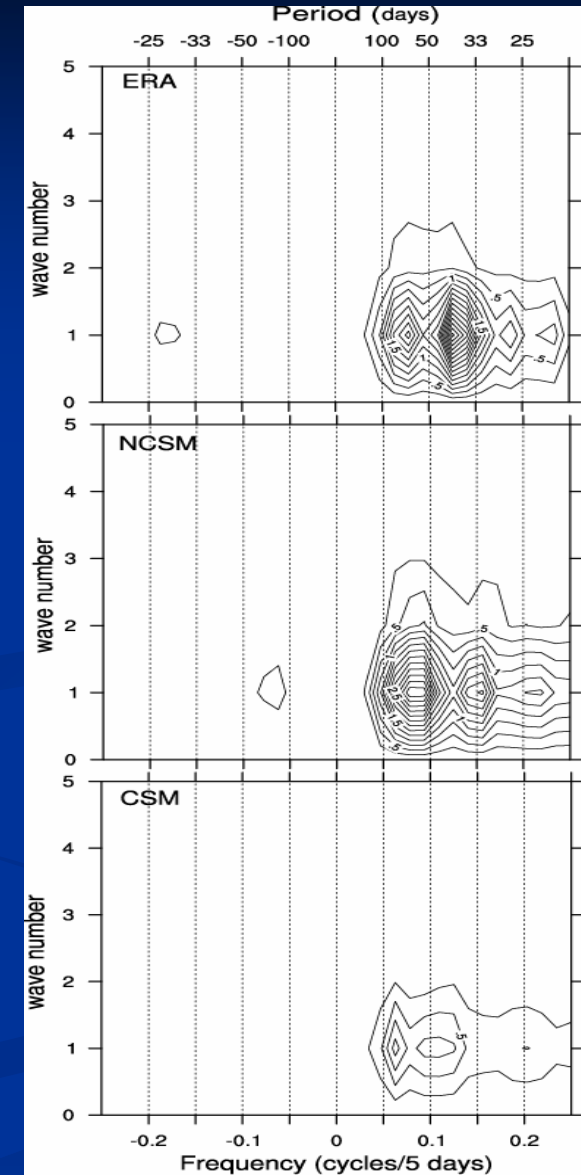
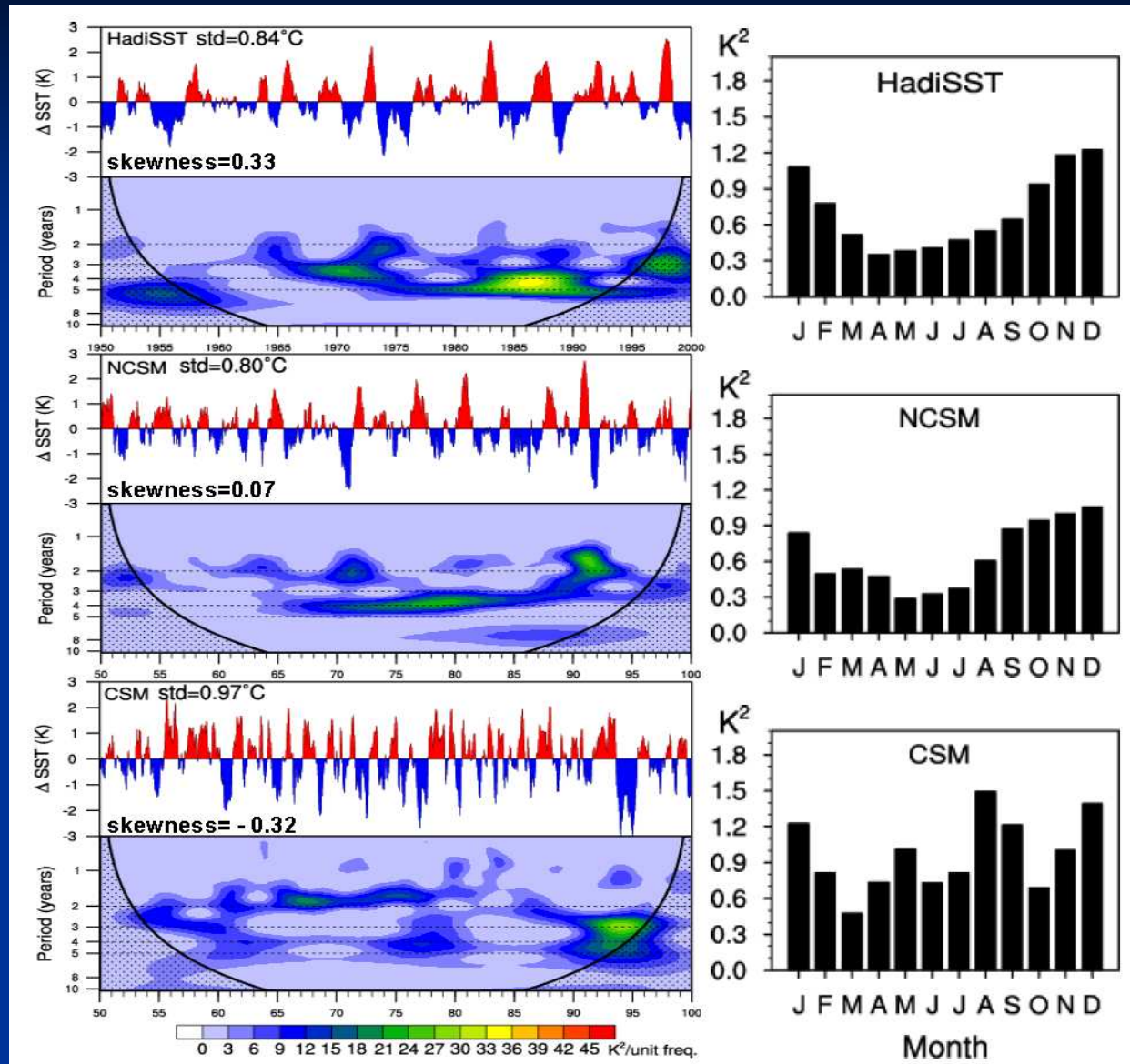
Madden-Julian Oscillation (MJO)

Lag correlations of 20-100 day filtered OLR with 200 hPa velocity potential (averaged between 10°S and 10°N) at 90°E



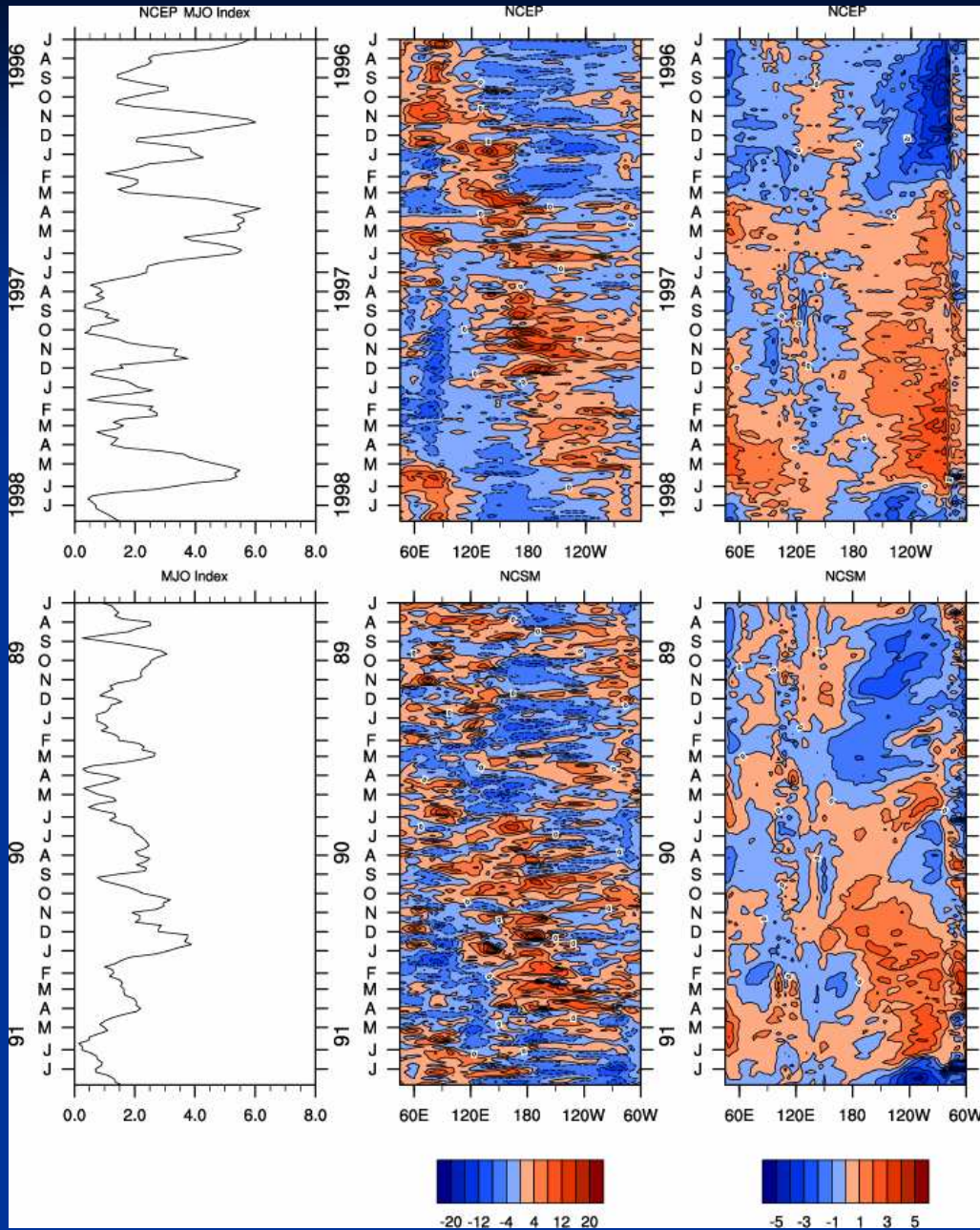
El Niño/Southern Oscillation (ENSO)

Madden-Julian Oscillation



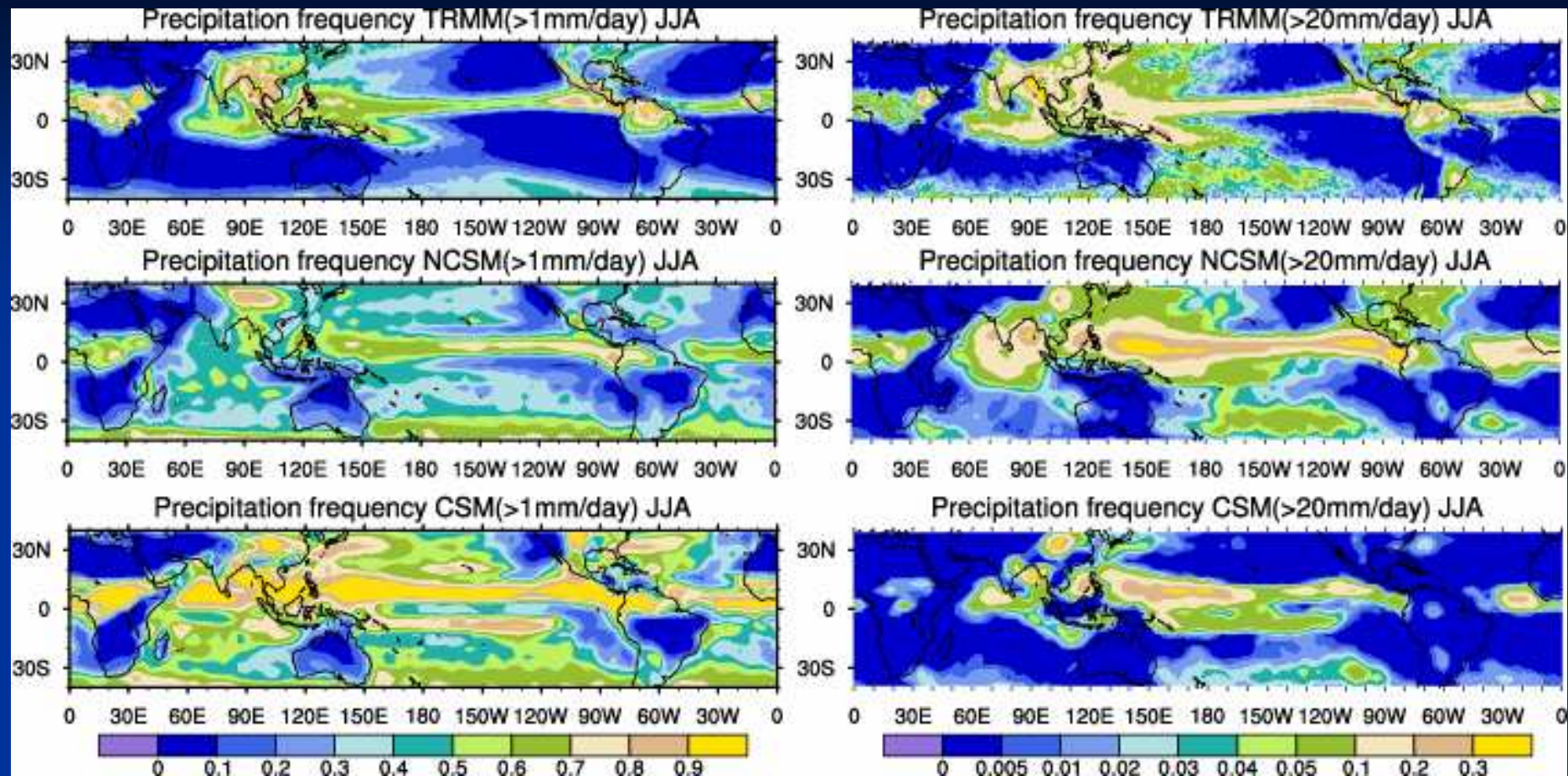
Wu et al. (2007, GRL)

1997/98 El Niño Event



Wu et al. (2007, GRL)

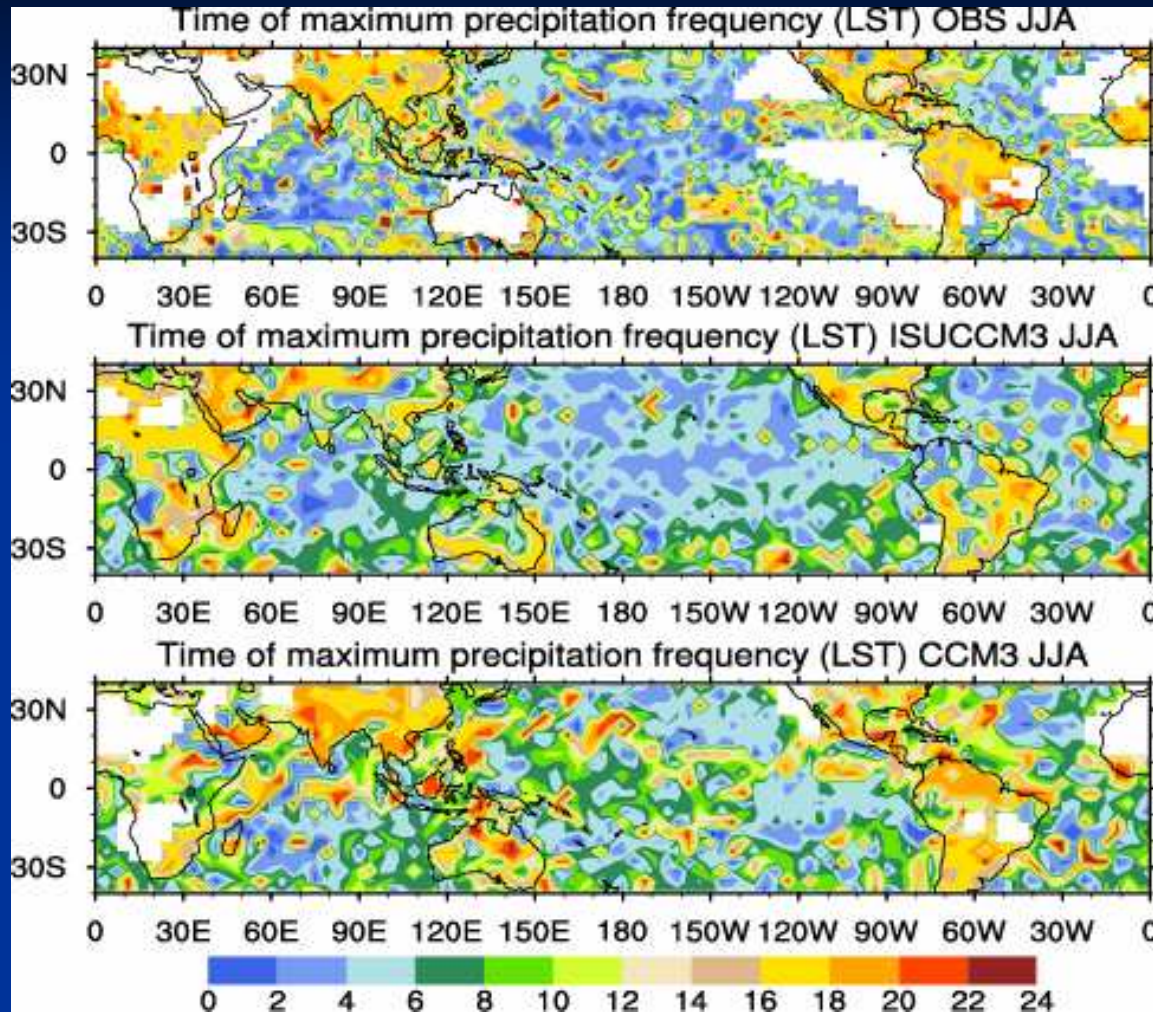
Precipitation Frequency



JJA (June, July and August) daily precipitation (>1 mmday⁻¹, left; >20 mmday⁻¹, right) frequencies (%) from TRMM (Tropical Rainfall Measuring Mission) 3B42 satellite observations (1998-2003, top), the NCSM with the modified ZM convection scheme (years 80-89, middle), and the standard CSM (years 80-89, bottom).

Wu et al. (2007, GRL)

Diurnal Cycle of Precipitation



Time of maximum precipitation frequency (in Local Solar Time) for JJA from TRMM observations (OBS), uncoupled ISU GCM at T31 resolution with the modified ZM convection scheme (ISUCCM3), and standard NCAR CCM3 at T31 (CCM3).

Remarks

- **Statistical analysis of ARM-validated CRM simulations together with the theoretical consideration of subgrid-scale processes offer a unique opportunity to improve the representation of convection, cloud and radiation processes and the GCM simulations of climate mean state and variability.**
- **Moist convection simulated by the ISU GCM with the improved convection scheme occurs less frequent but better organized and is more consistent with observations, which results in increased MJO activity. The organized convection and clouds within MJO affect ENSO events through the influence on the Hadley and Walker circulations and tropical surface energy budget, and the atmosphere-ocean coupling.**
- **The retrievals of satellite observations provide an opportunity to systematically and consistently evaluate all aspects of precipitation, cloud liquid and ice water properties, and radiative fluxes, and impose a constraint on the formulation of convection, cloud and radiation processes in the GCM simulations.**