Super-parametrization in climate and what do we learn from high-resolution

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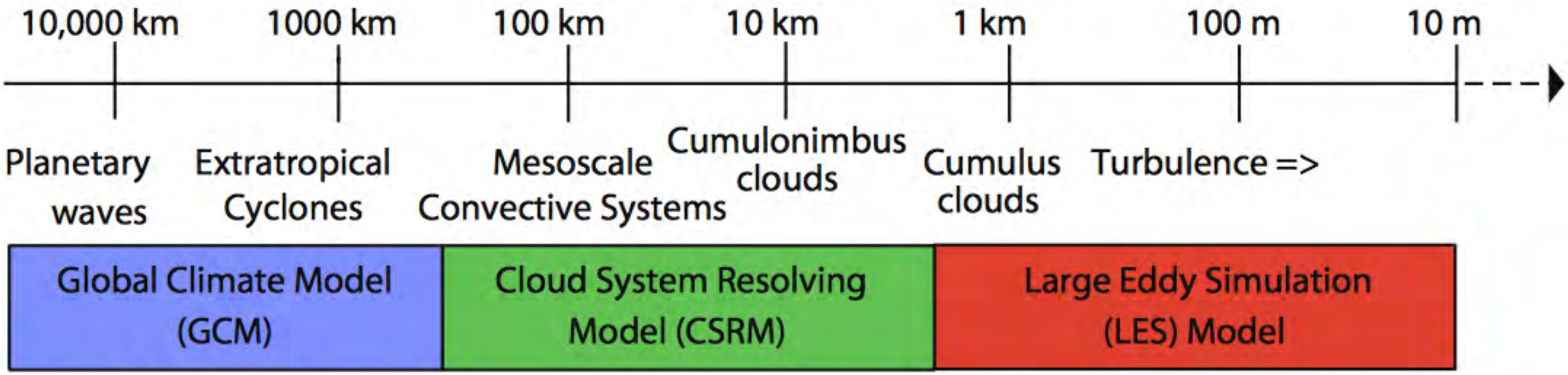
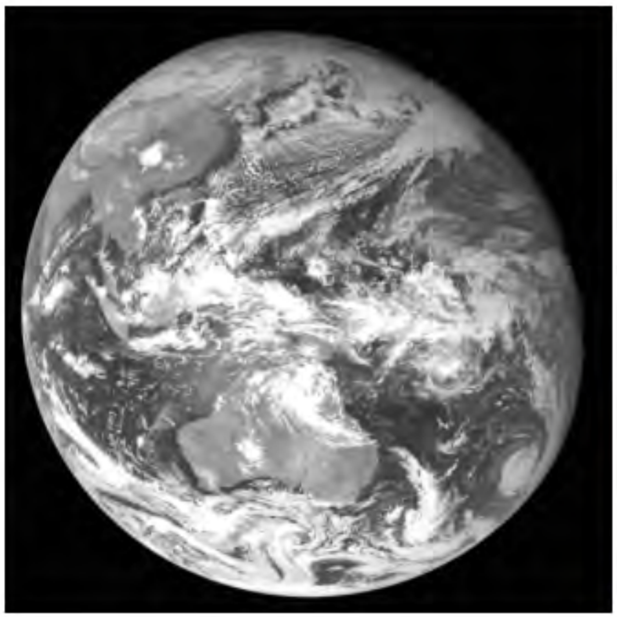
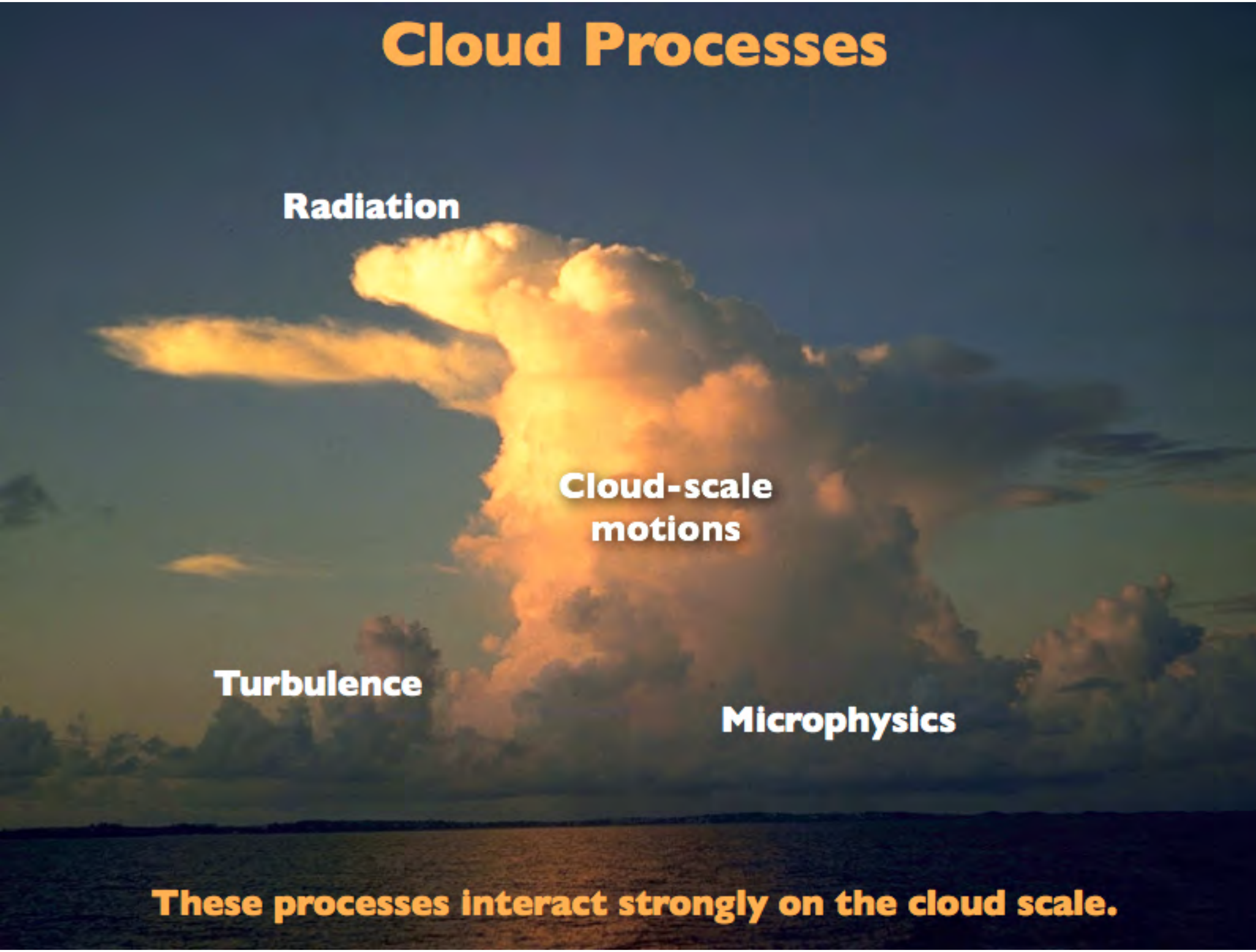
Scales of Atmospheric Motion

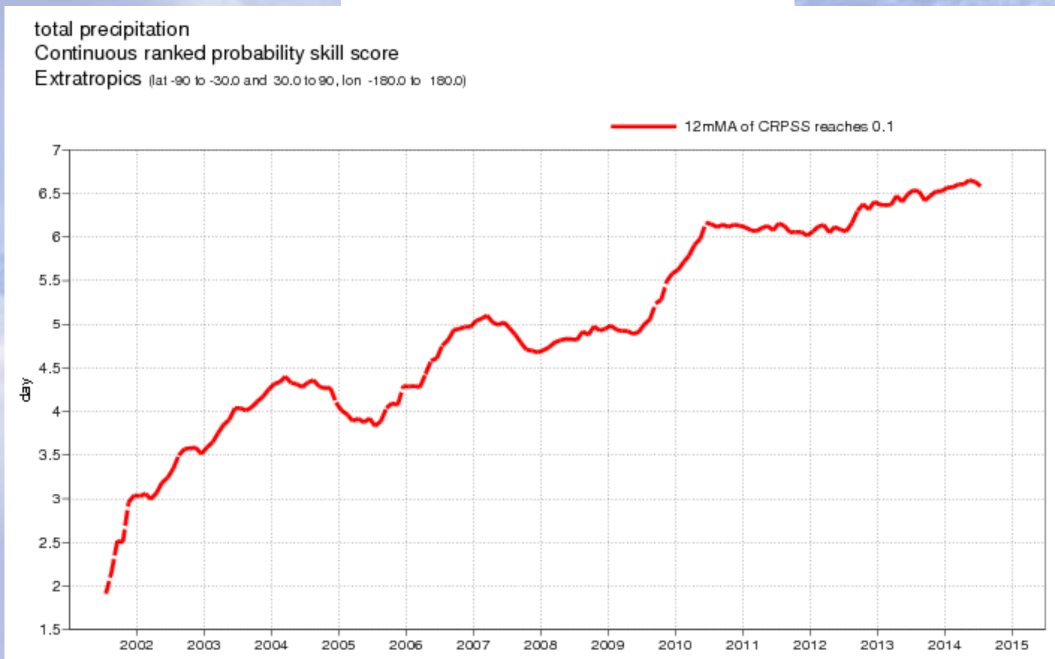


scales-separation parameterized convection



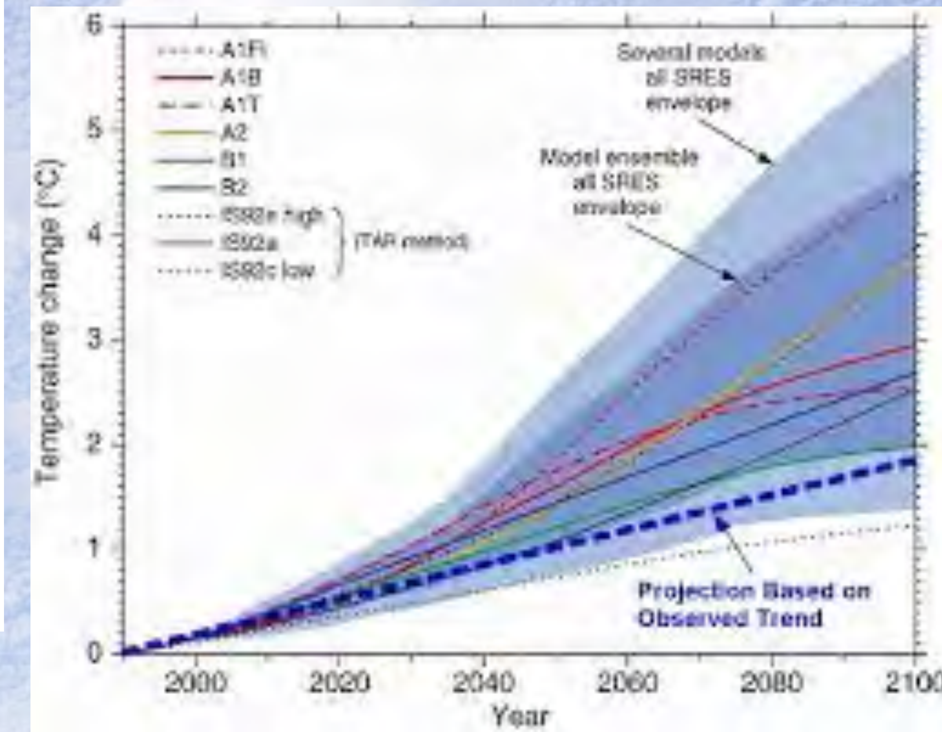

Cloud Processes
Radiation
Cloud-scale
motions
Turbulence
Microphysics
These processes interact strongly on the cloud scale.

NWP Models



- Initial conditions problem
- Confronted with truth everyday

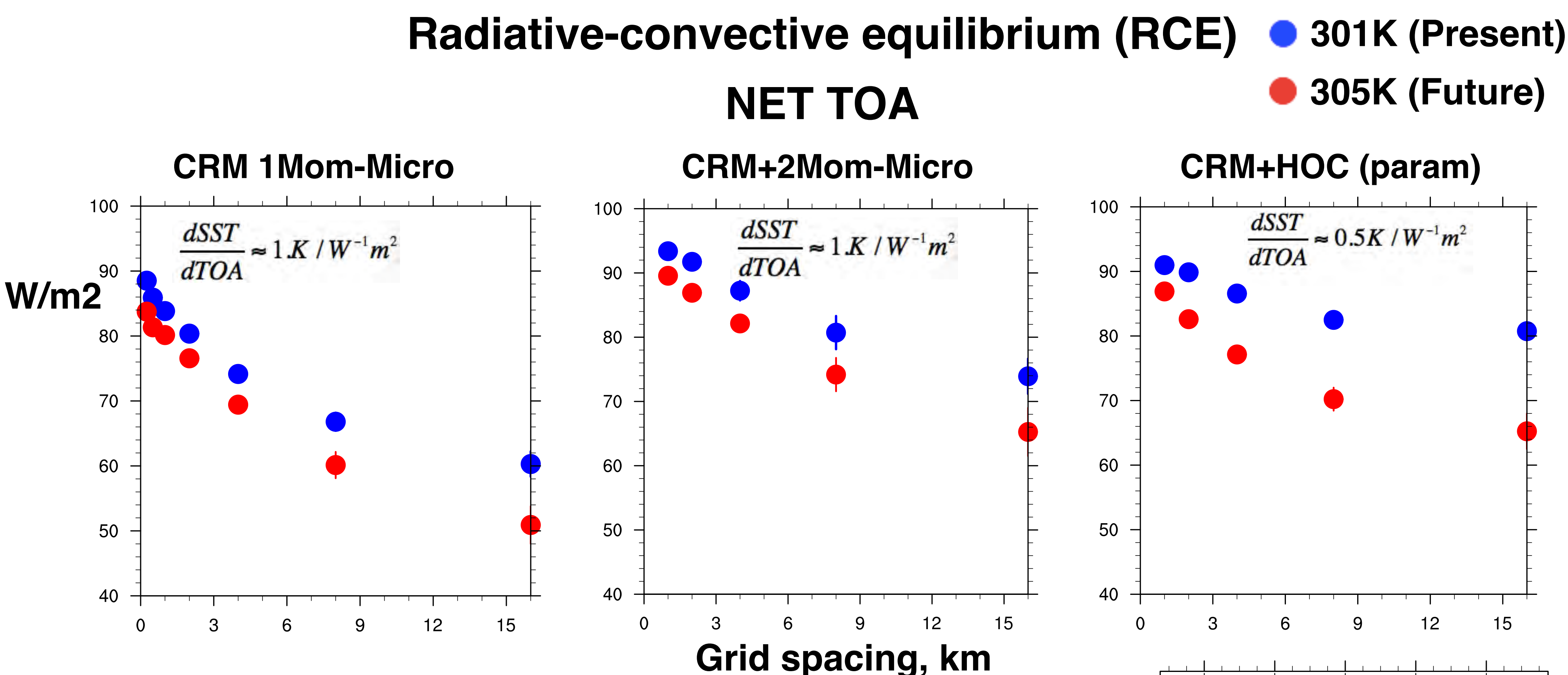
Climate Models



- Boundary conditions problem
- No truth is known
- The only hope is physical realism (resolve everything!)

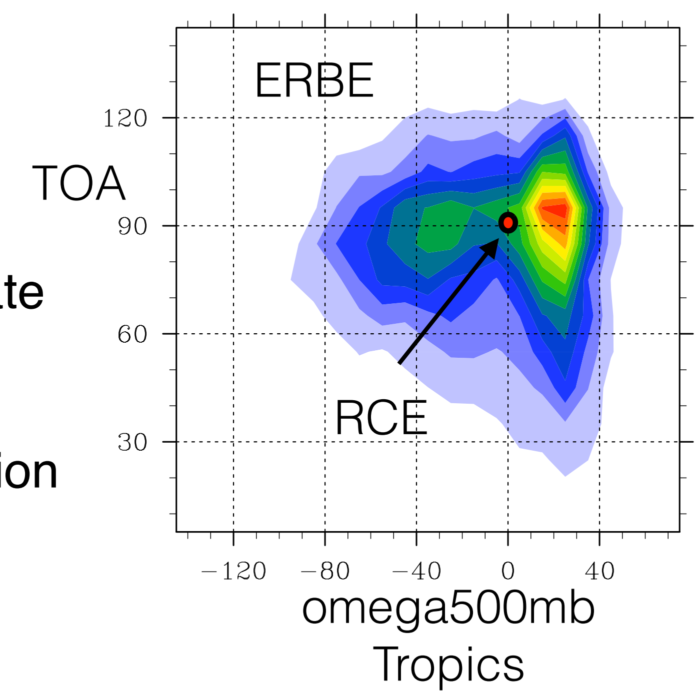
Radiative-convective equilibrium (RCE)

NET TOA

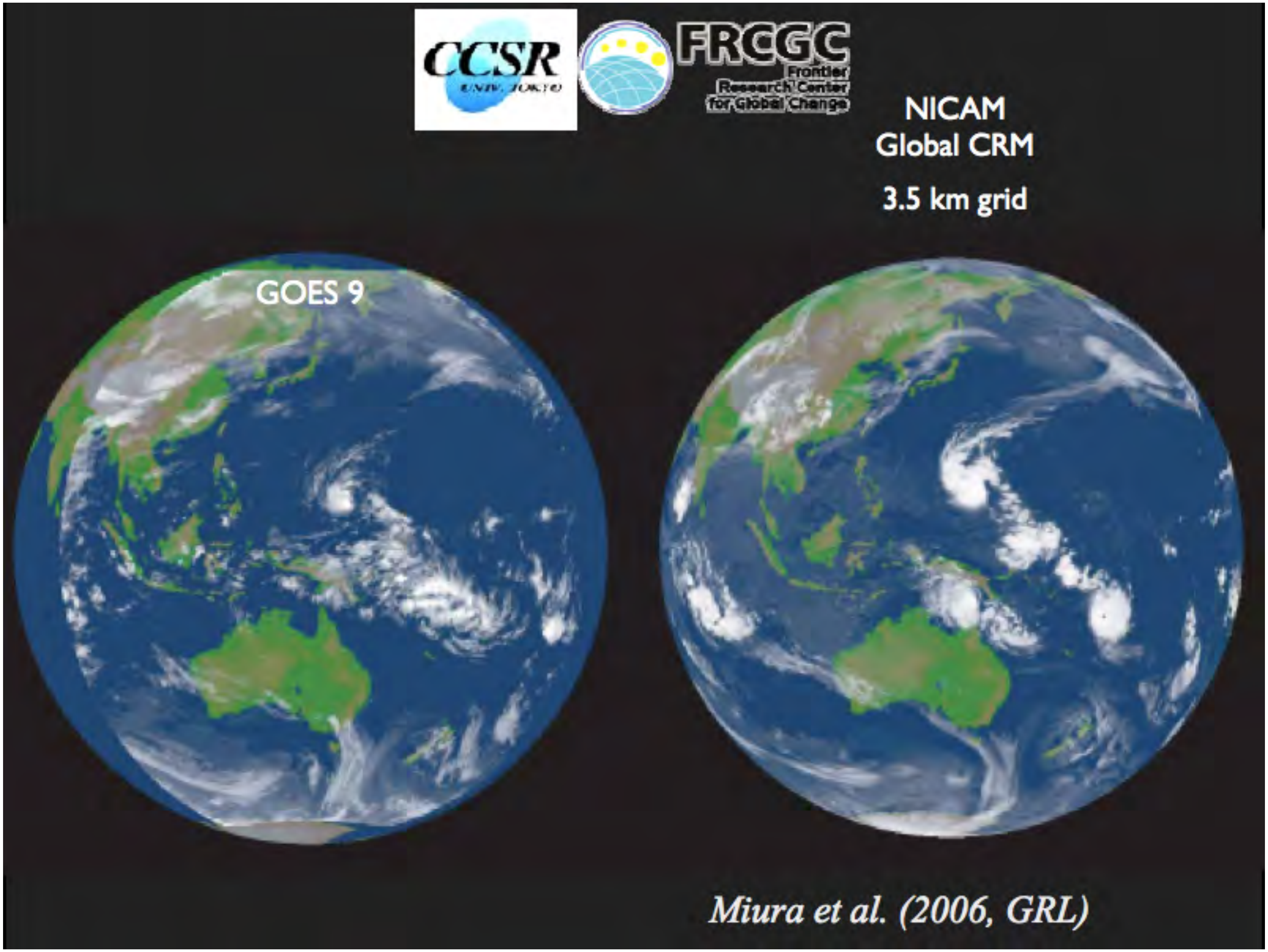


- Response to SST is not sensitive to microphysics;
- CRM+High-Order-Closure (HOC) SGS parameterization reproduces “Present”, but not “Present-minus-Future”;
- RCE with HOC has about twice as large equilibrium climate sensitivity (ECS) parameter;
- “Coarse” RCE with 4 km grid spacing appears to be the threshold when the ECS becomes invariant of the resolution

- **SGS parameterizations can significantly alter climate sensitivity**

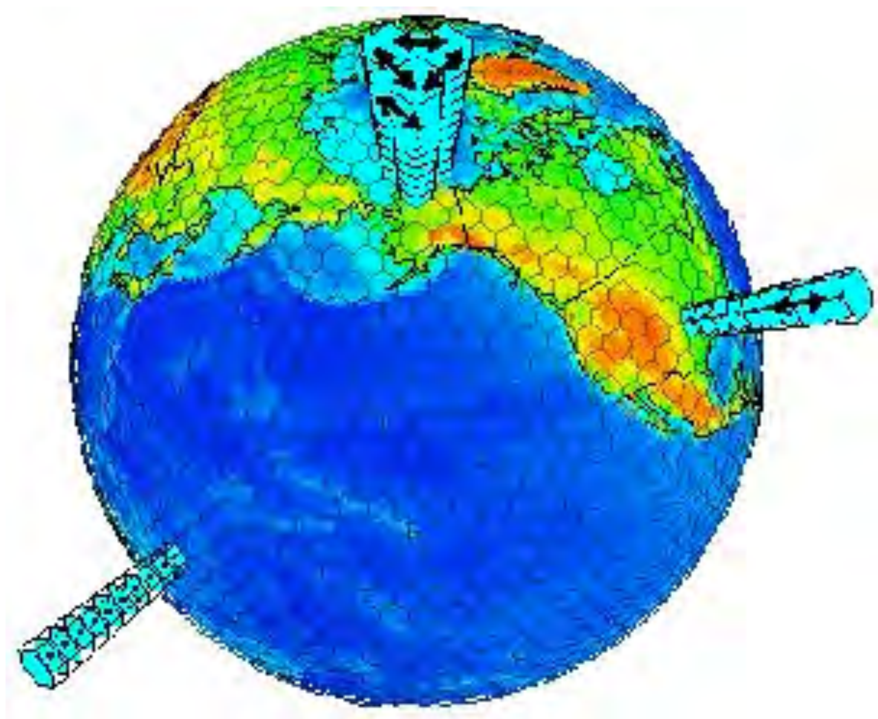


Global CRM? Resolve everything!



Great, but too expensive.

Super-parameterization roots from Single-Column Modeling (SCM)



$$\frac{\partial \bar{s}}{\partial t} = \underbrace{-\overline{\nabla s V} - \frac{\partial \bar{s}\,\bar{\omega}}{\partial p}}_{LSForcing} + \underbrace{Q_1}_{Param's}$$

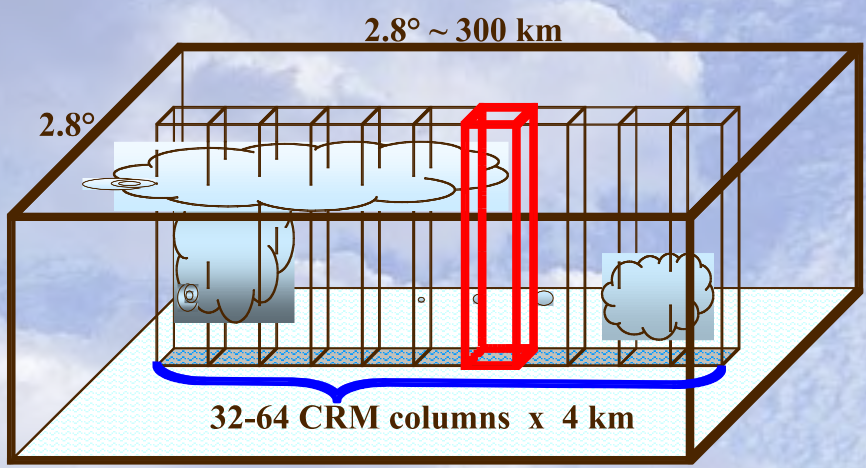
$$\frac{\partial \bar{q}}{\partial t} = \underbrace{-\overline{\nabla q V} - \frac{\partial \bar{q}\,\bar{\omega}}{\partial p}}_{LSForcing} - \underbrace{Q_2 / L}_{Param's}$$

Column-Physics Tendency (parameterizations; *No horizontal scale Δx here)*

The large-scale forcing data would come from observations (GATE, TOGA, ARM, KWAJEX, etc.)

All super-parameterization does is compute Q_1 and Q_2

Super-parametrization (SP)
Multiscale-Modeling Framework (MMF=GCM+SP)

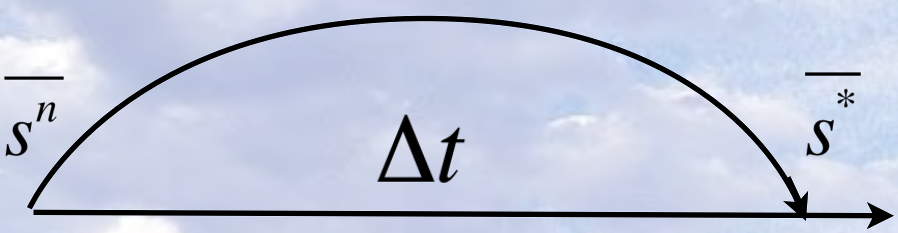


$$\frac{\partial \bar{s}}{\partial t} = -\overline{\nabla s V} - \frac{\partial \bar{s}\,\bar{\omega}}{\partial p} + Q_1$$

GCM Resolved

Column-Physics (SP)

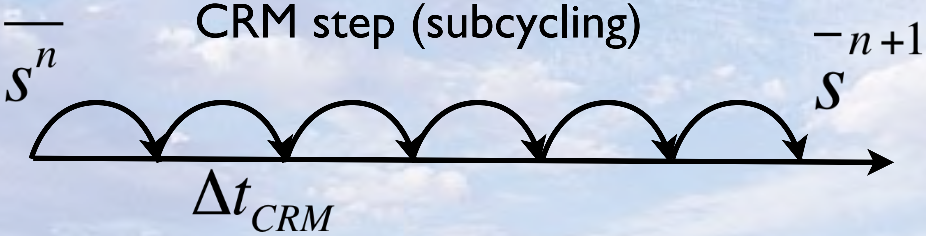
Dynamics Step:



CRM Forcing:

$$-\overline{\nabla s V} - \frac{\partial \bar{s}\,\bar{\omega}}{dp} = \frac{\overline{s}^{*} - \overline{s}^{n}}{\Delta t}$$

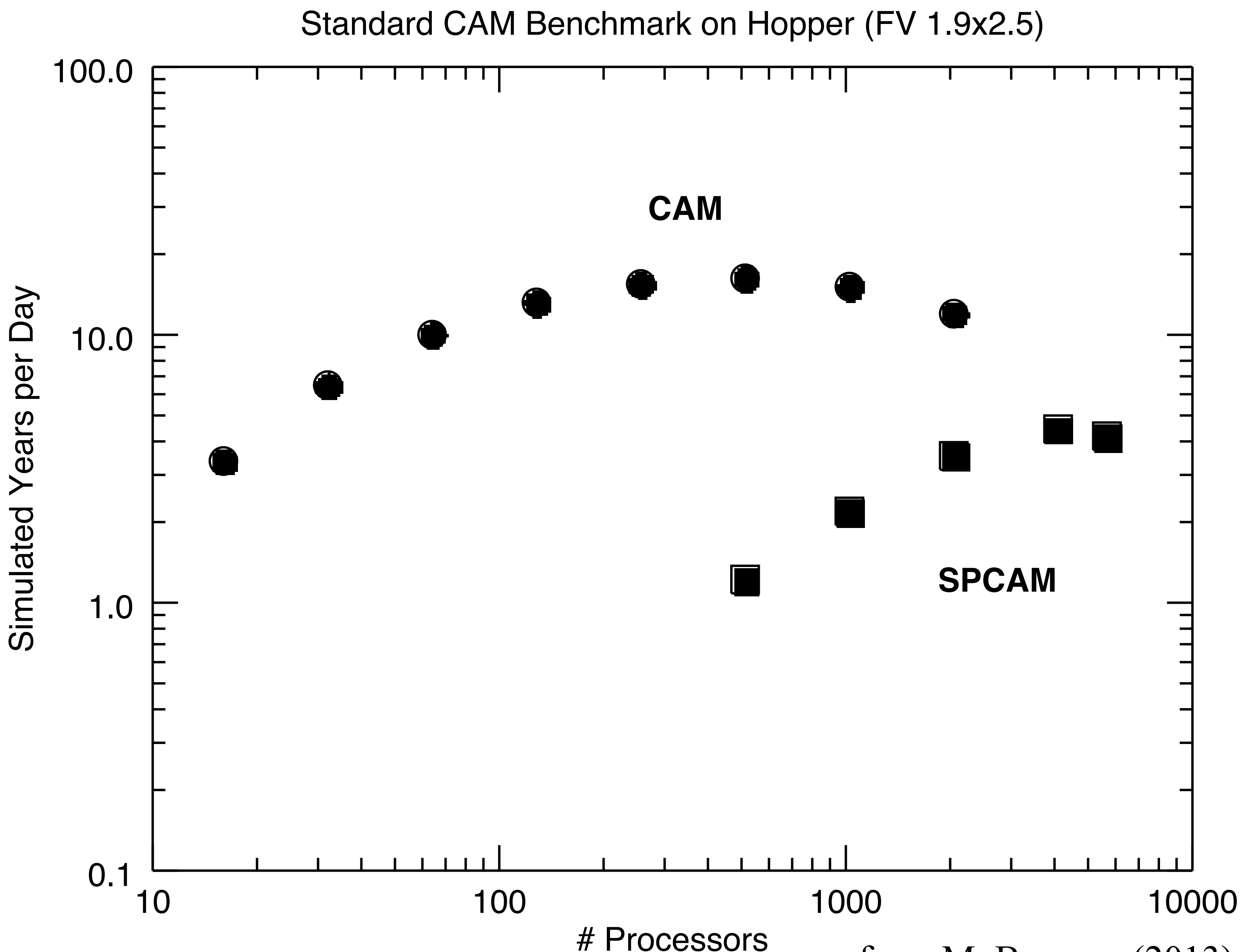
CRM step (subcycling)



CRM Tendency:

$$Q_1 = \frac{\overline{s}^{n+1} - \overline{s}^{*}}{\Delta t}$$

MMF is very expensive, but highly scalable on supercomputers



from M. Branson (2013)

Super-Parameterization - Summary

- **Runs like conventional parameterization: profile in, profile out; hence, the name, *super-parameterization* (term coined by David Randall);**
- **The CRMs do not communicate directly with each other (‘embarrassingly’ parallel problem);**
- **Radiation is usually computed on CRM grid; no cloud-overlap assumptions are needed;**
- **Momentum tendencies are not generally returned to GCM due to wrong momentum transport by 2D CRM; however use of 3D CRM is possible;**
- **Surface fluxes are still computed on GCM grid;**
- **Tendencies due to terrain are also due to GCM (no topography in CRM);**
- **PBL parameterization is generally off for scalars, but not wind;**
- **The width of the CRM domain is not tied to the GCM grid size (same way as a convective parameterization using no Δx information);**
- **GCM grid-cell should be large enough to contain large-scale convective systems.**

The super-parameterization improves variability on a wide range of time scales.

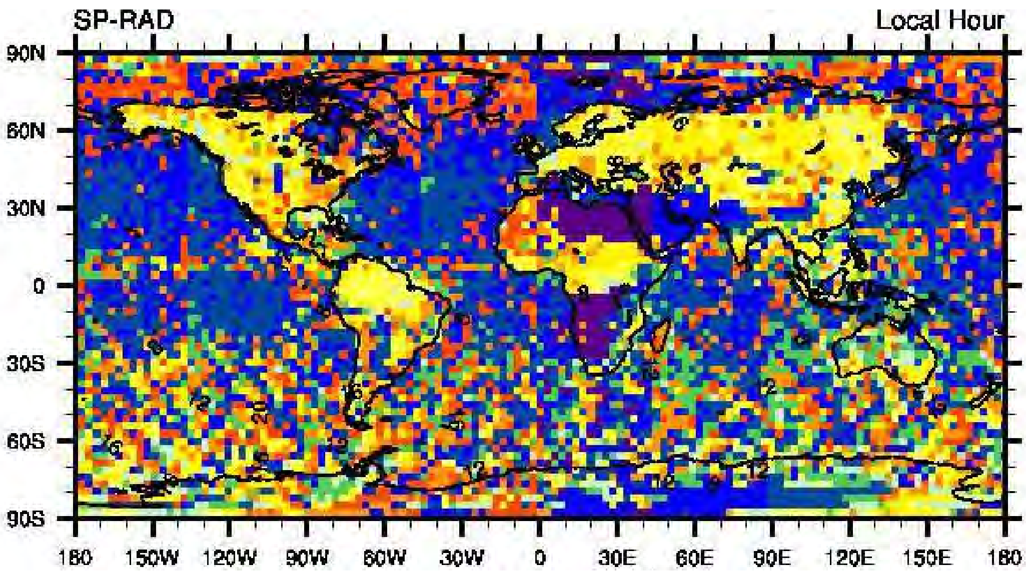
- Diurnal cycle
- Extreme Precipitation
- MJO
- African Easterly Waves
- Monsoon/BSISO
- ENSO
- ...

http://www.cmmap.org/research/pubs-mmf.html

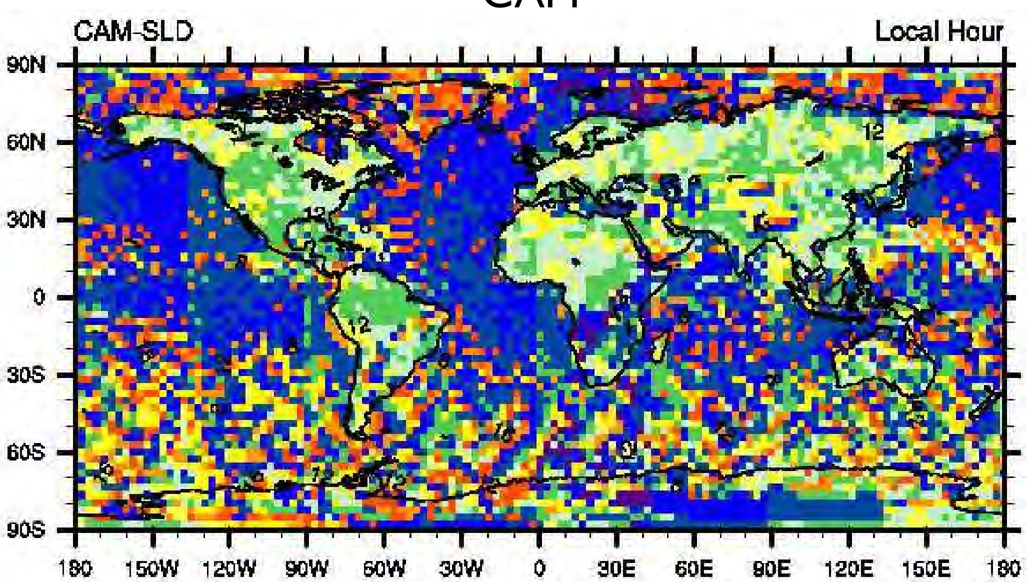
Diurnal cycle of precipitation

JJA Local Time of Precipitation Frequency Maximum

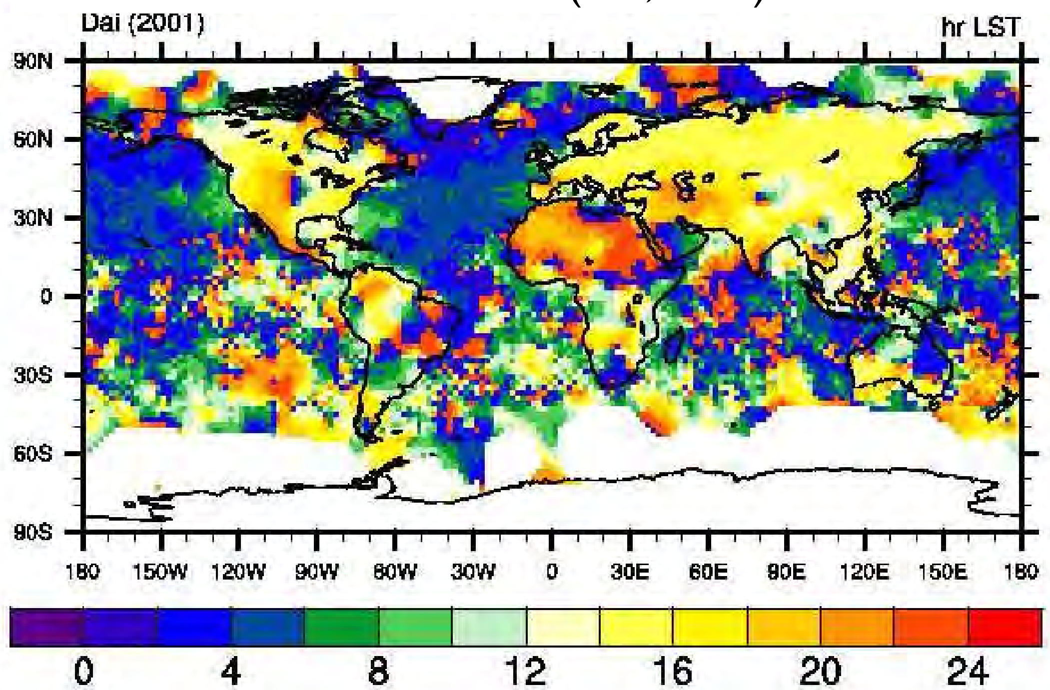
SP-CAM



CAM



Observations (Dai, 2001)

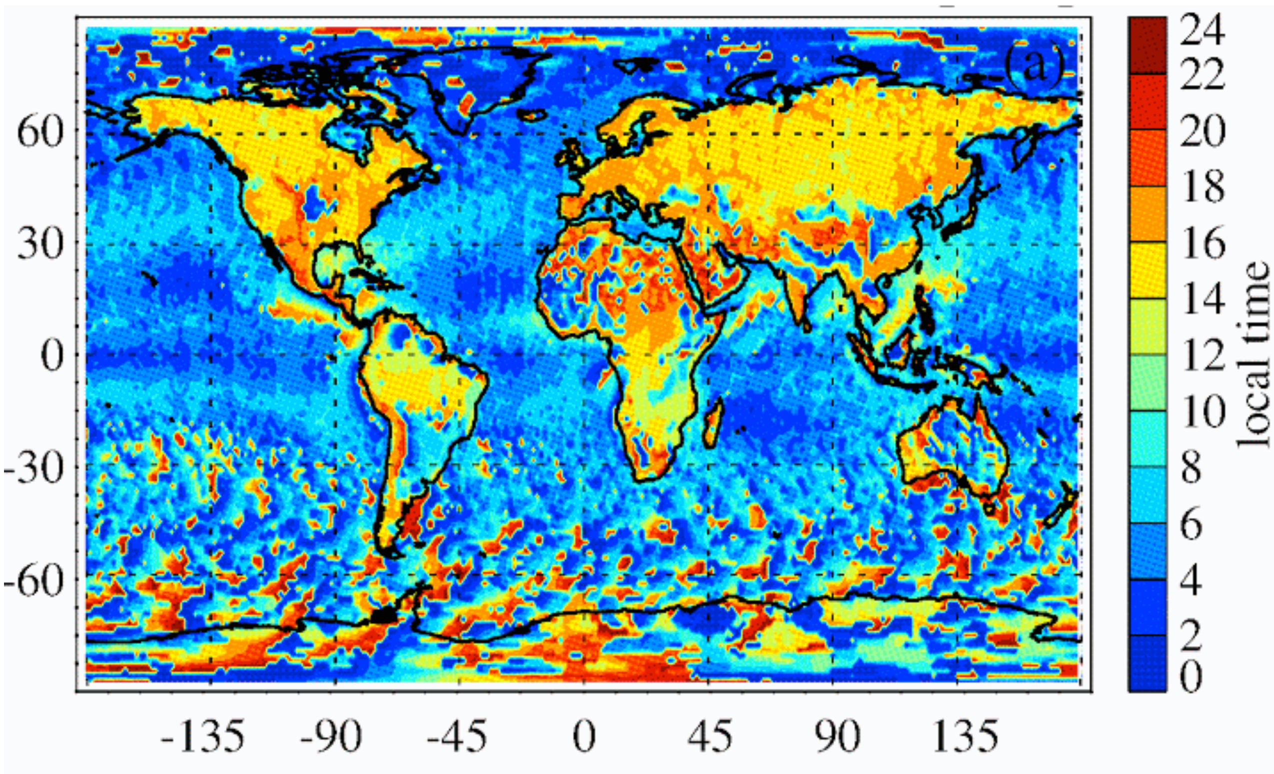


Common bias (early maximum around noon) of many climate models

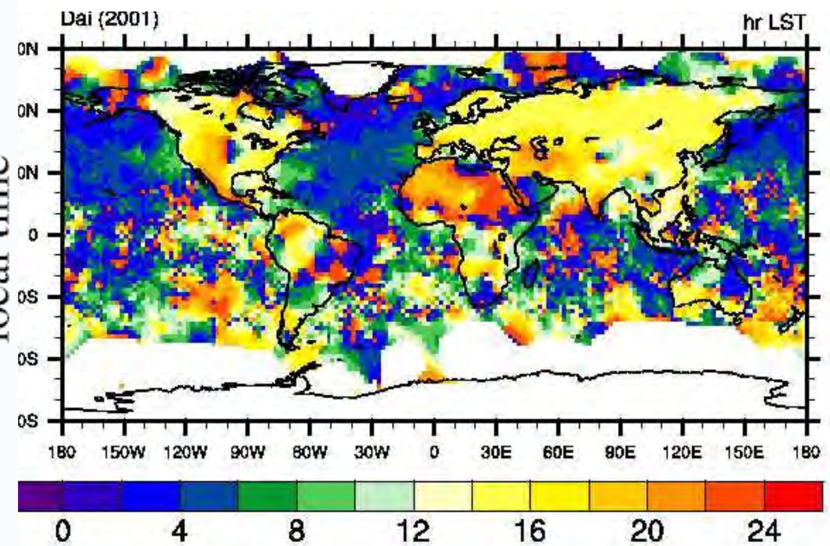
Diurnal cycle of precipitation

JJA Local Time of Precipitation Frequency Maximum

SP-CAM T85 (1.4x1.4º)

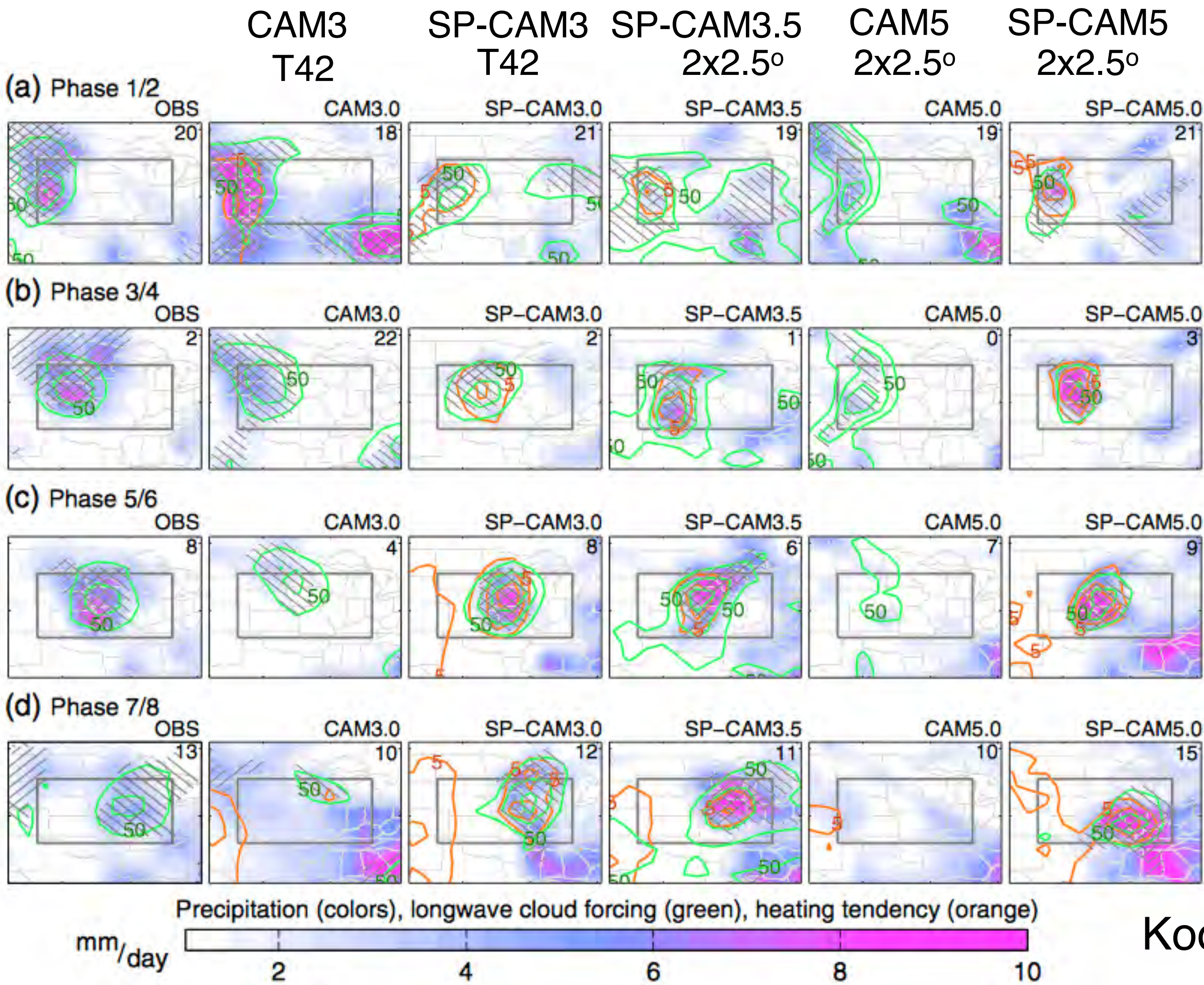


Observations (Dai, 2001)



We still don't understand why 4-km 2D CRM can do such a good job…

Eastward propagation of MCSs over US

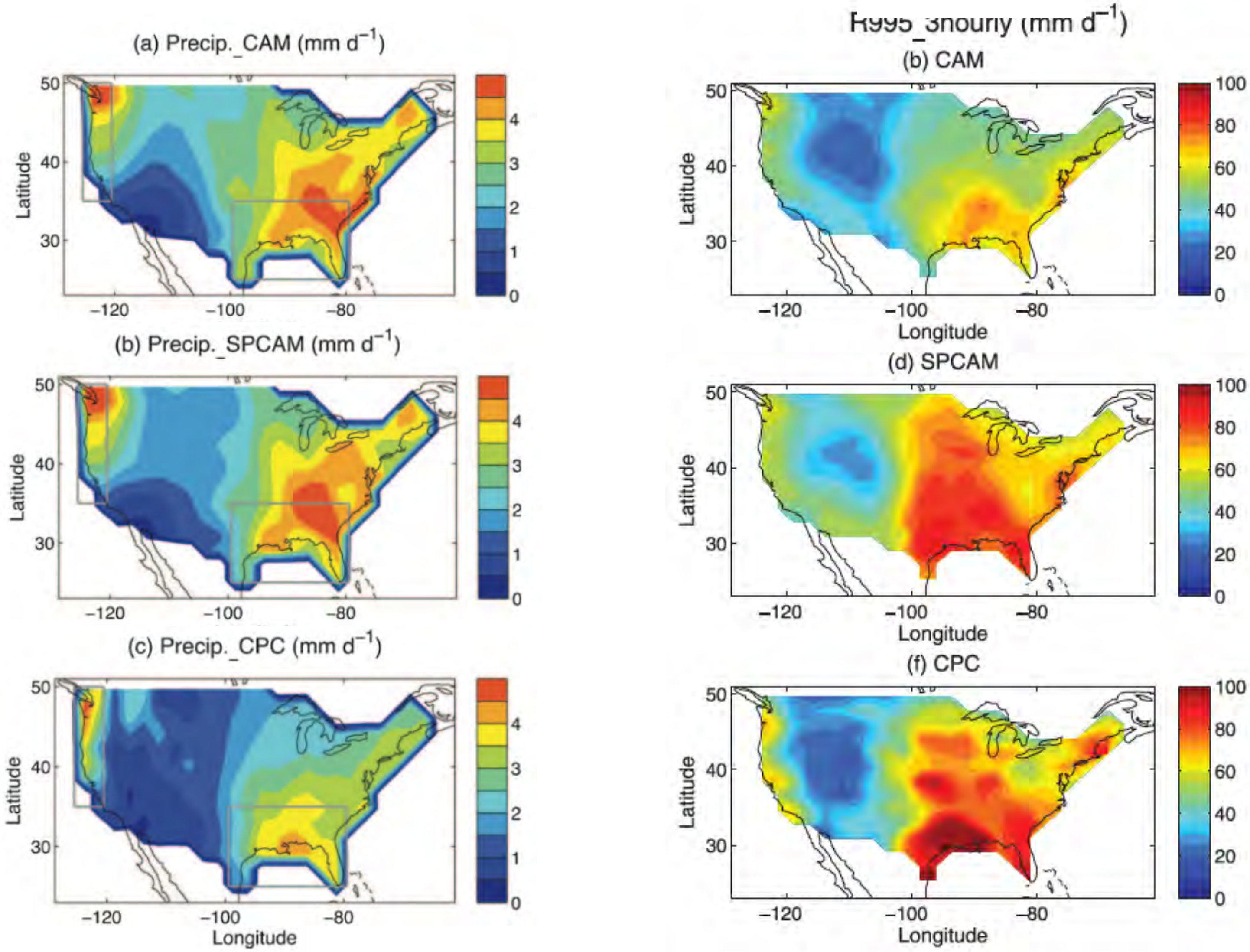


Kooperman et al 2013

Eastward propagation is robust in SP-CAM even at T42!
Only large-scale processes are responsible for propagation of MCSs.

Precipitation over US

Mean **Extreme**



CAM 2x2.5°

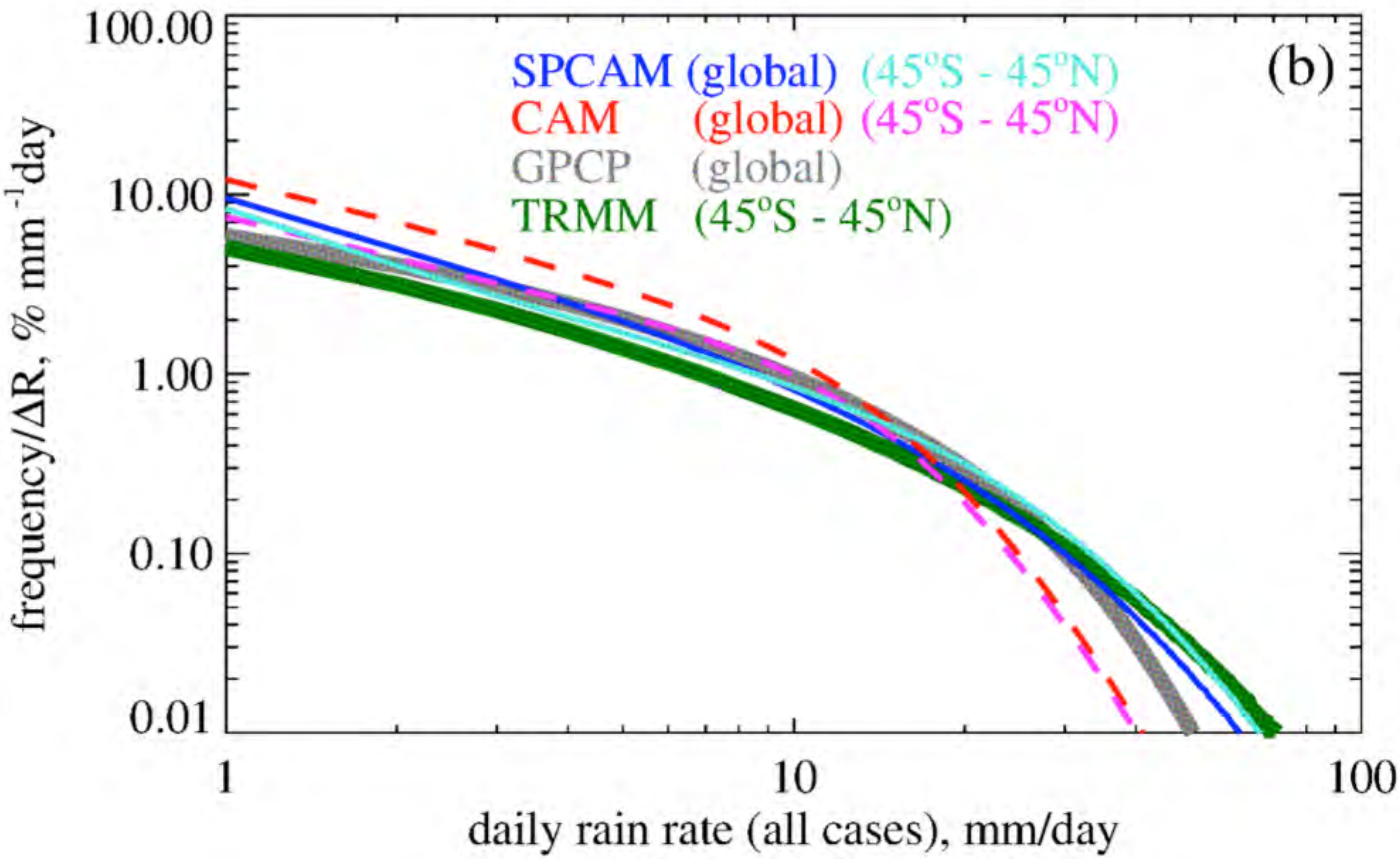
SP-CAM 2x2.5°

OBS

SP-CAM is better than CAM to simulate the extreme precipitation

Li, Rosa, Collins & Wehner, 2012

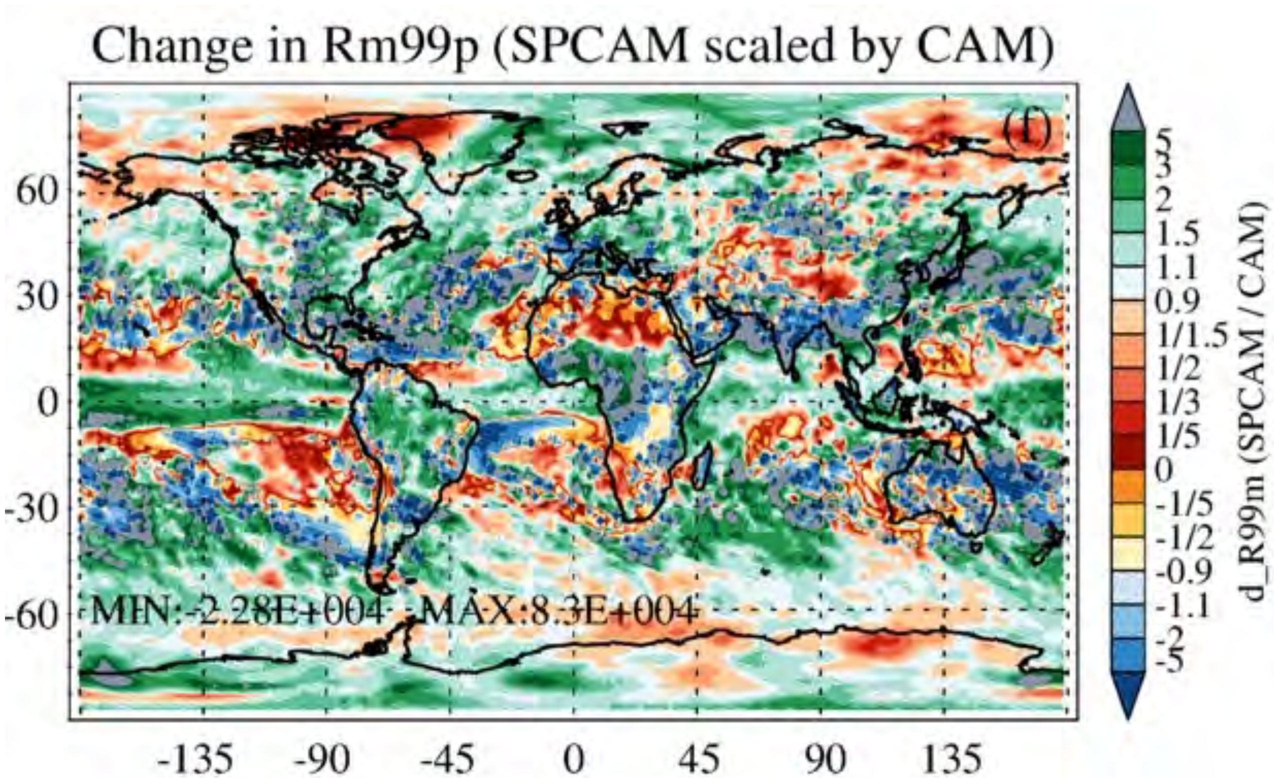
PDF of Rainfall
SP-CAM vs CAM T85

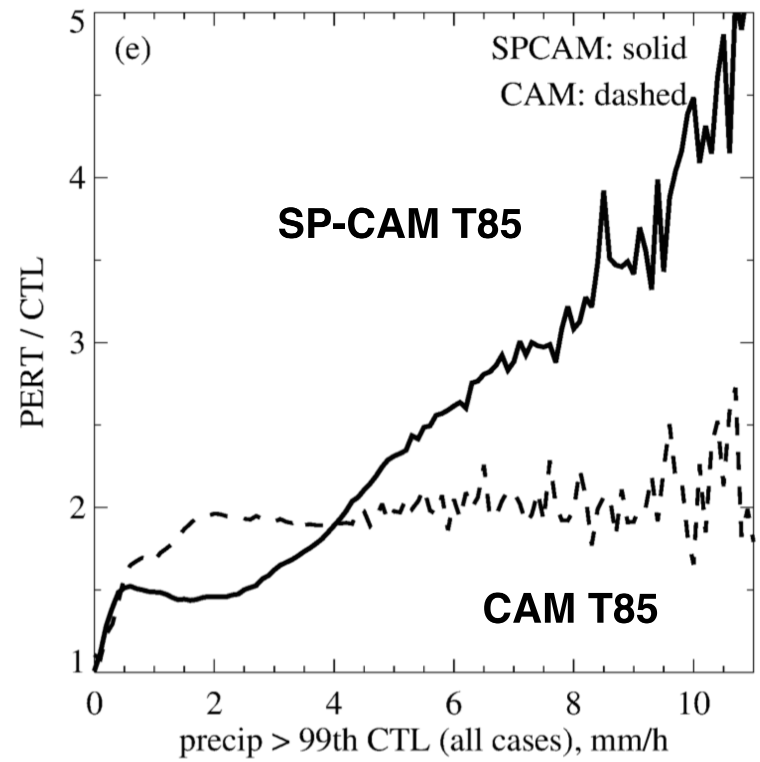


SP-CAM does better job than CAM in simulating heavy rain rates

Zhou and Khairoutdinov 2015

Change of today's extreme (99th) precipitation event frequency in RCP8.5 climate



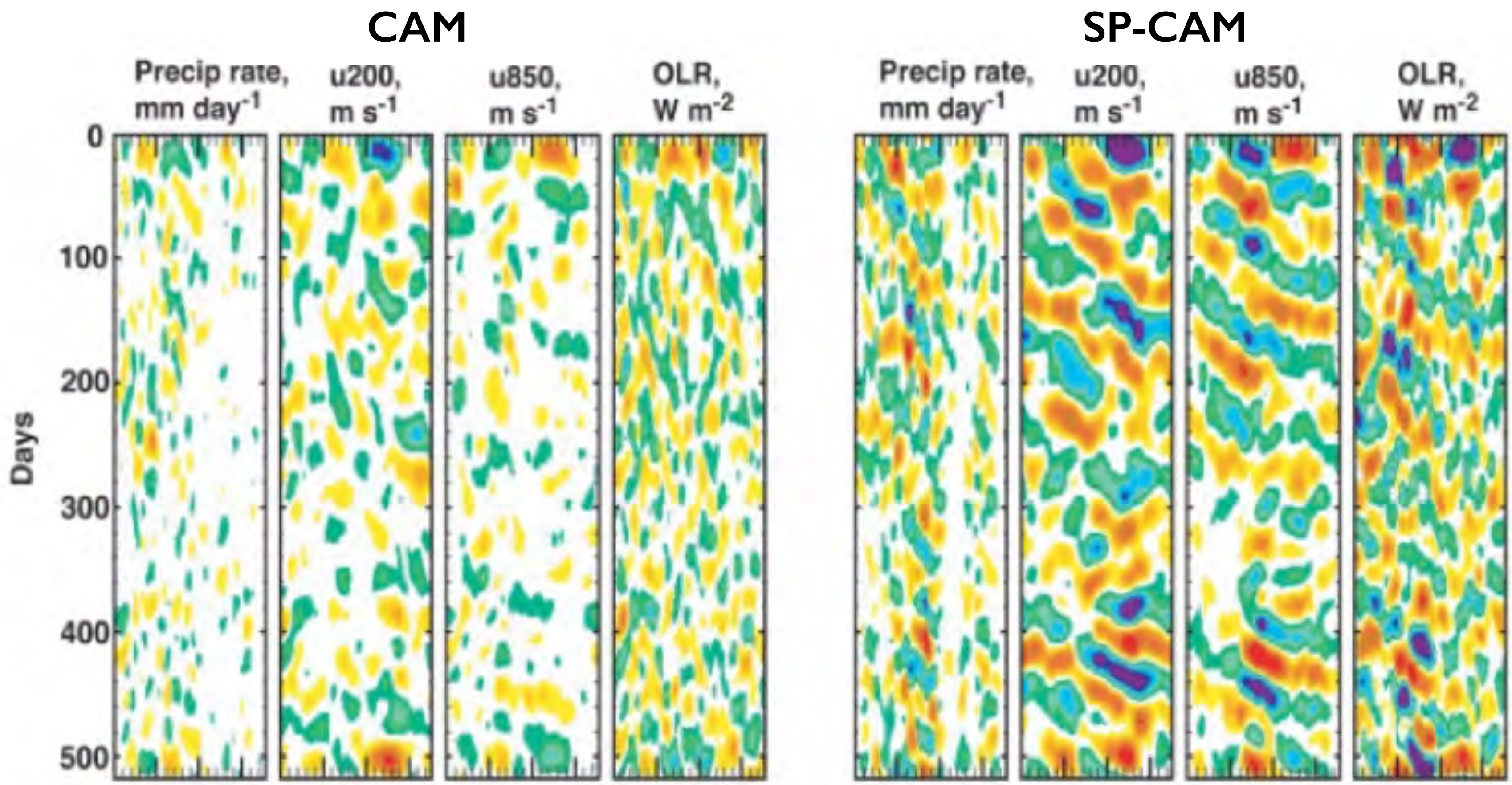


SP-CAM predicts much bigger increase in extreme precipitation frequency than CAM

Zhou and Khairoutdinov 2015


Madden-Julian Oscillation (MJO)
Осцилляция Маддена-Джулиана

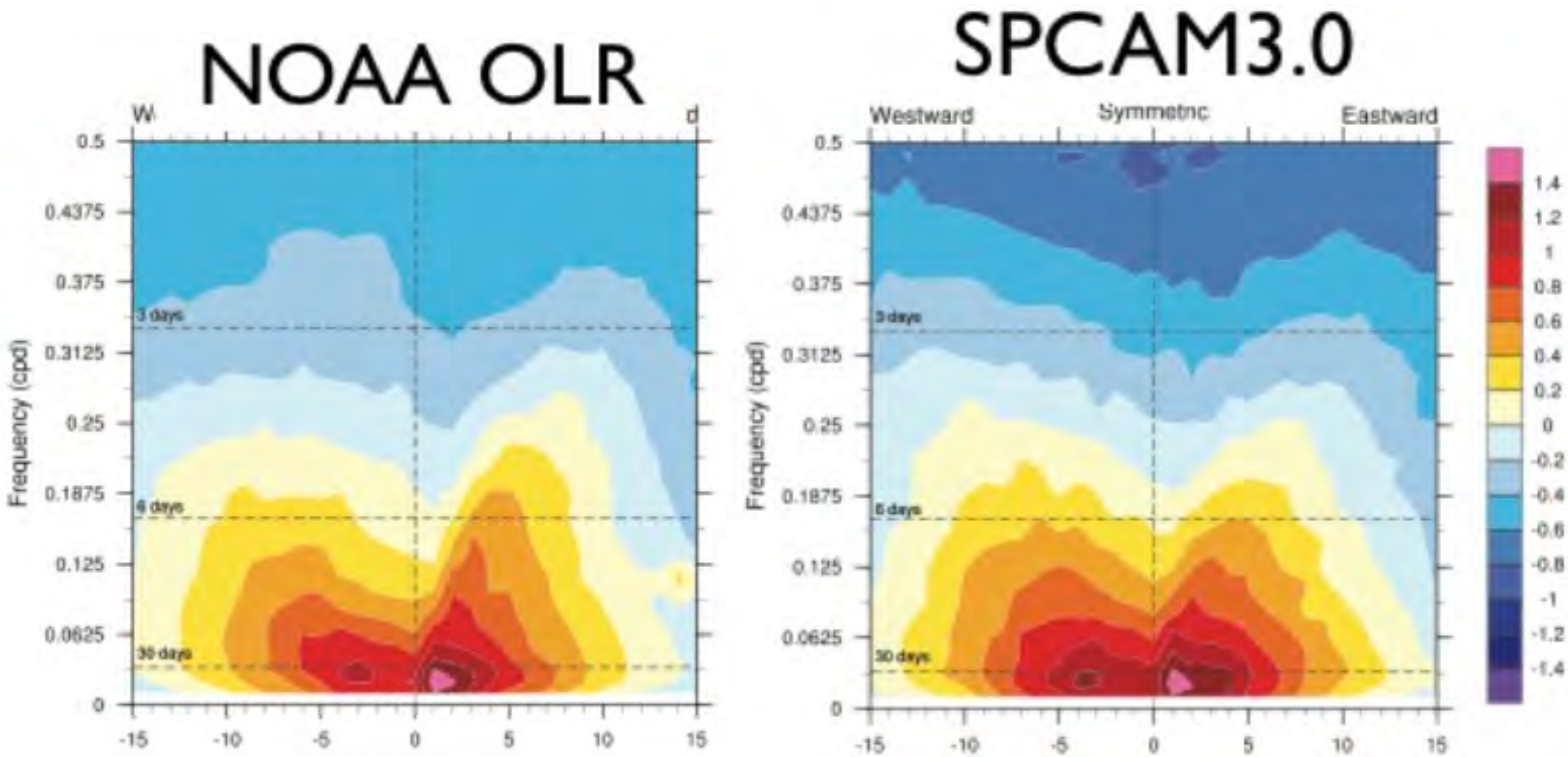
MJO in SP-CAM T21



Randall, Khairoutdinov, Arakawa, Grabowski 2003

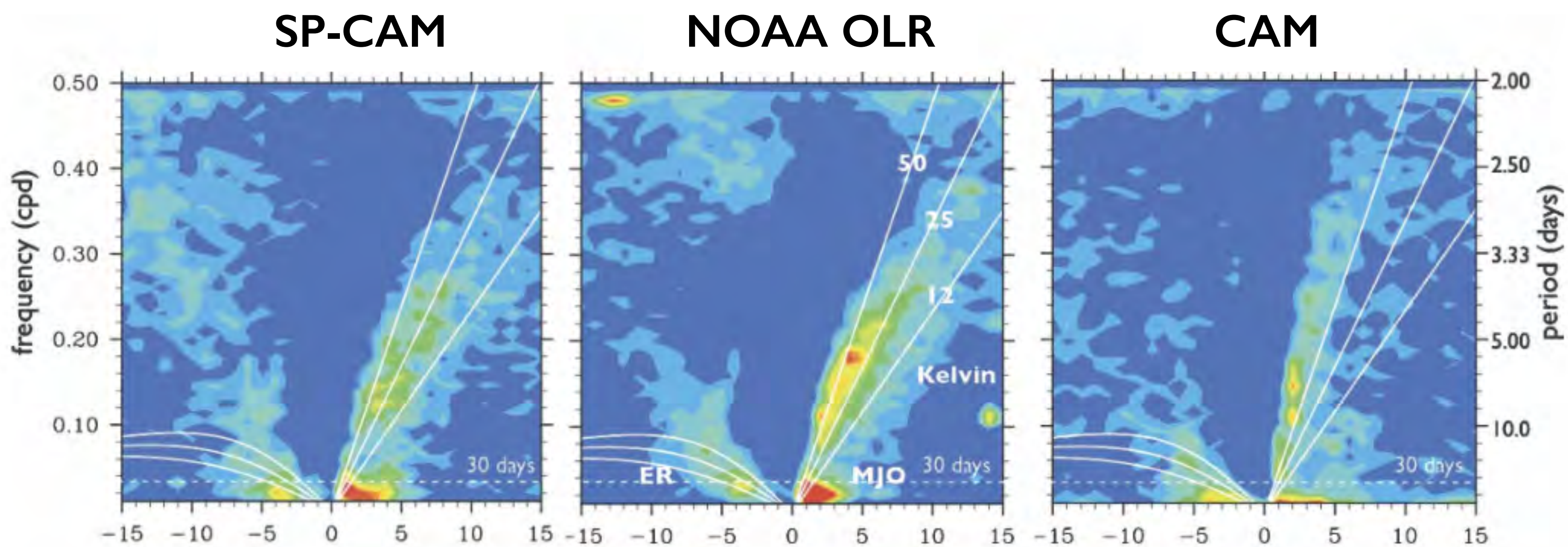
From the inception, SP-CAM/SP-CCSM has been arguably the best framework for MJO simulation

Intraseasonal Variability in Tropics



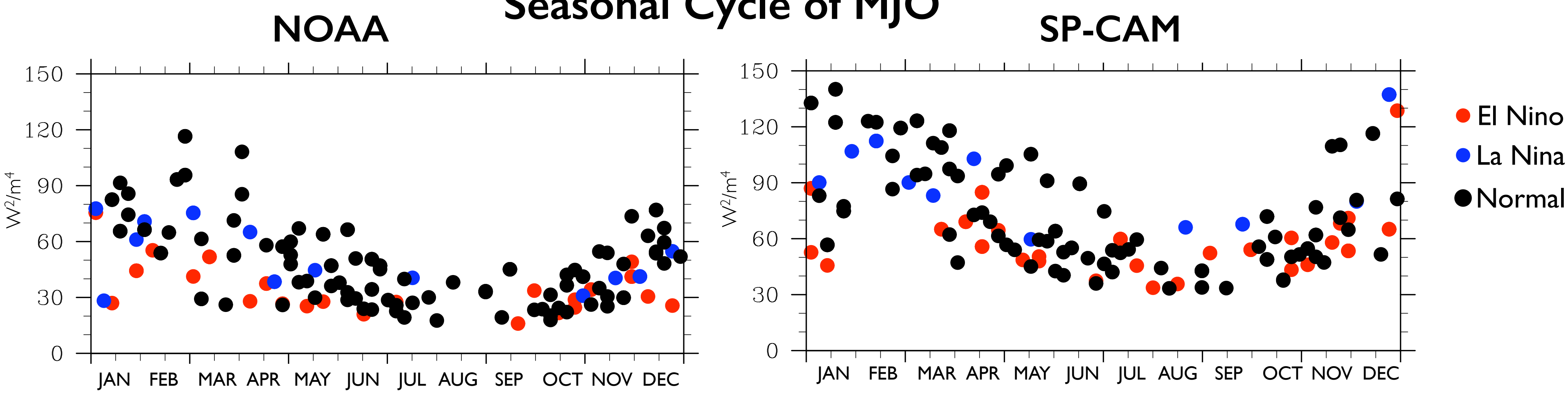
Pritchard 2012

Inraseasonal Variability in Tropics

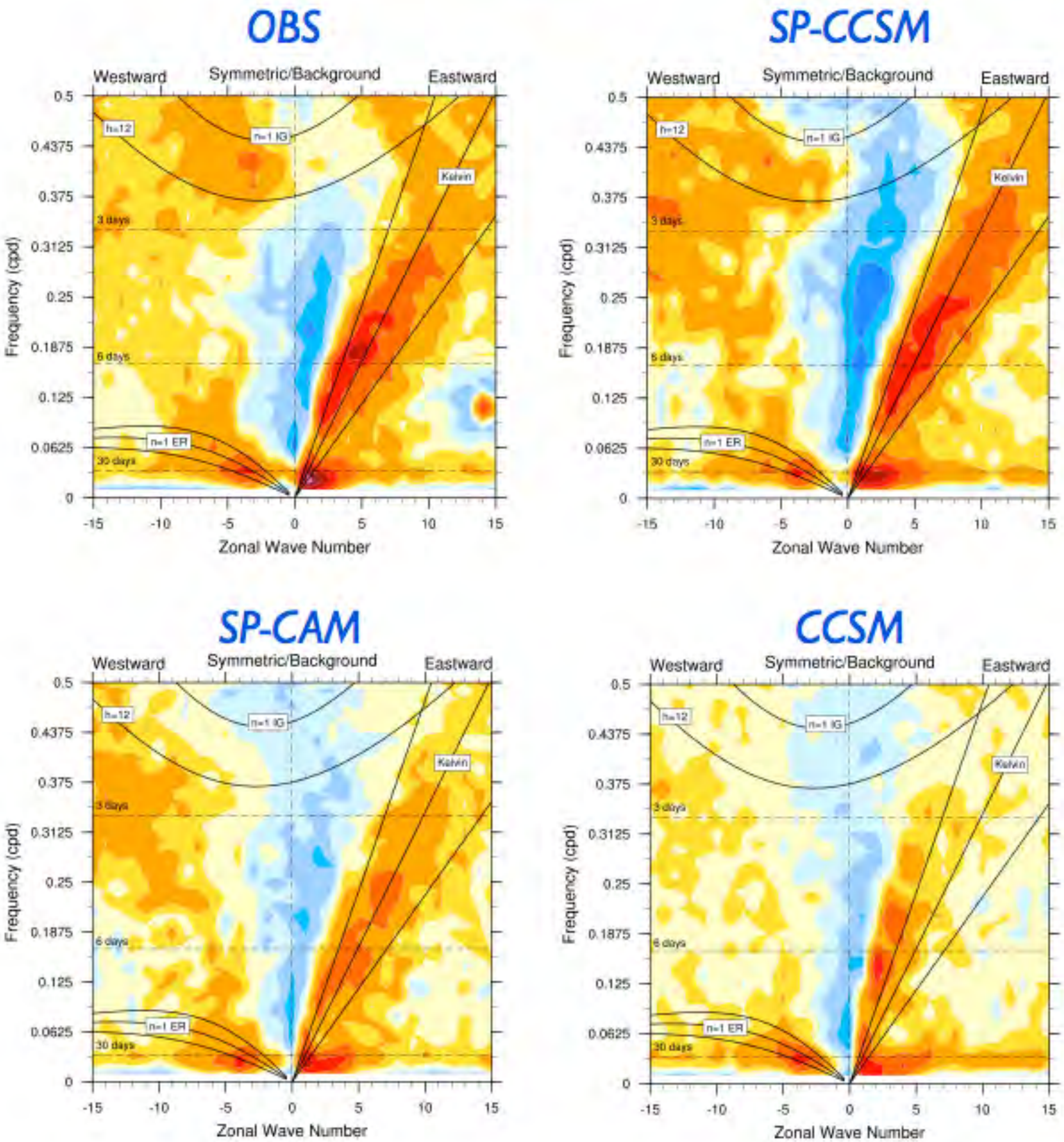


Khairoutdinov, DeMott, Randall 2008

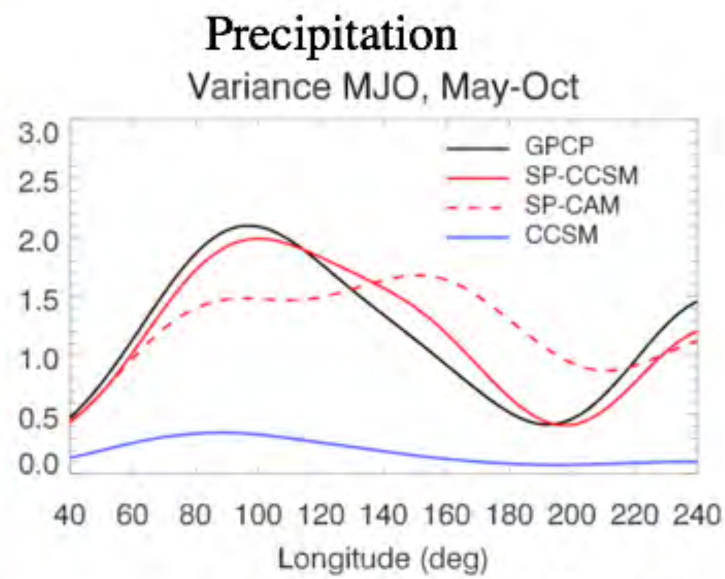
Seasonal Cycle of MJO



Coupled SP-CCSM

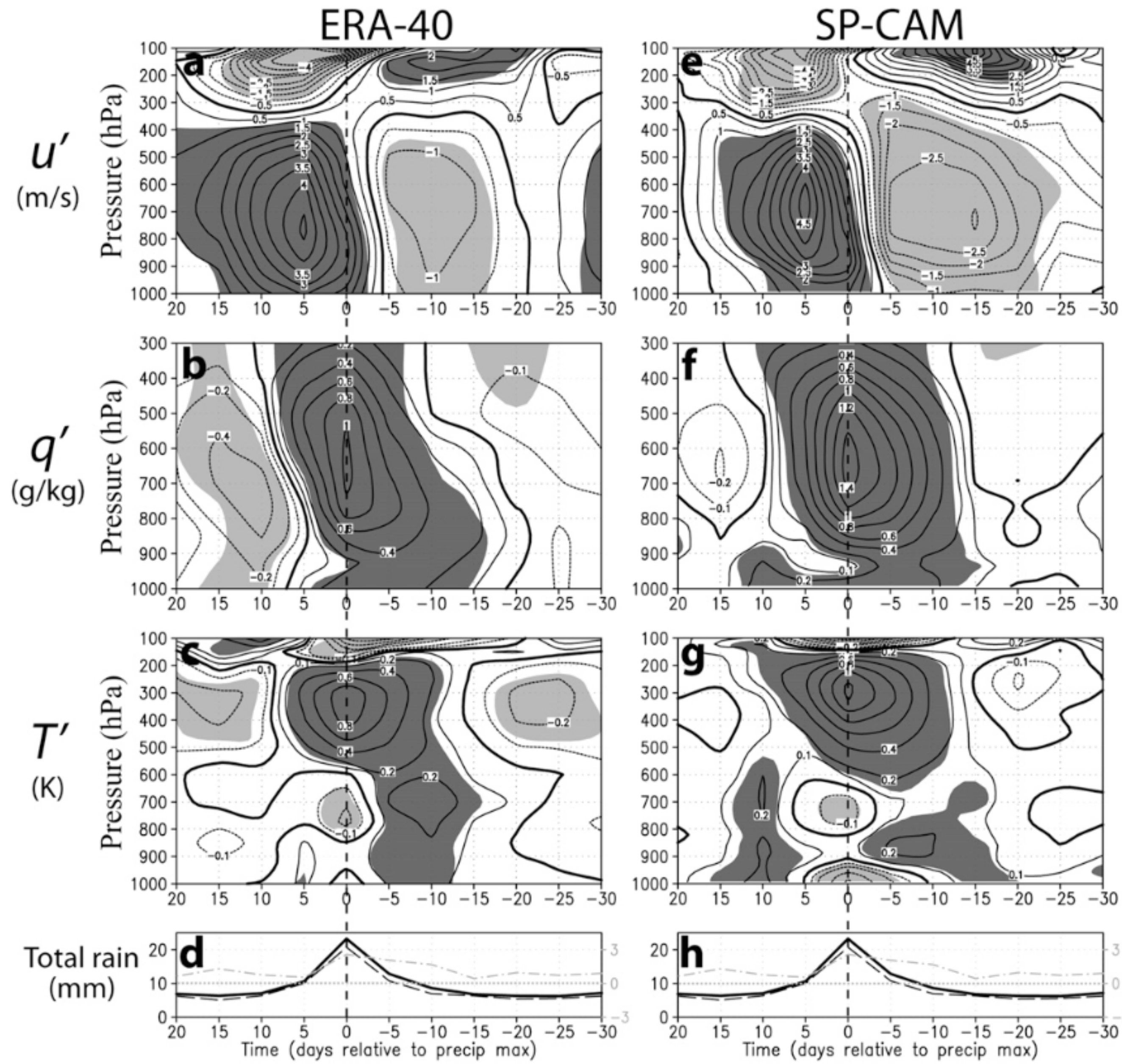


Coupling to the ocean improves subseasonal variability



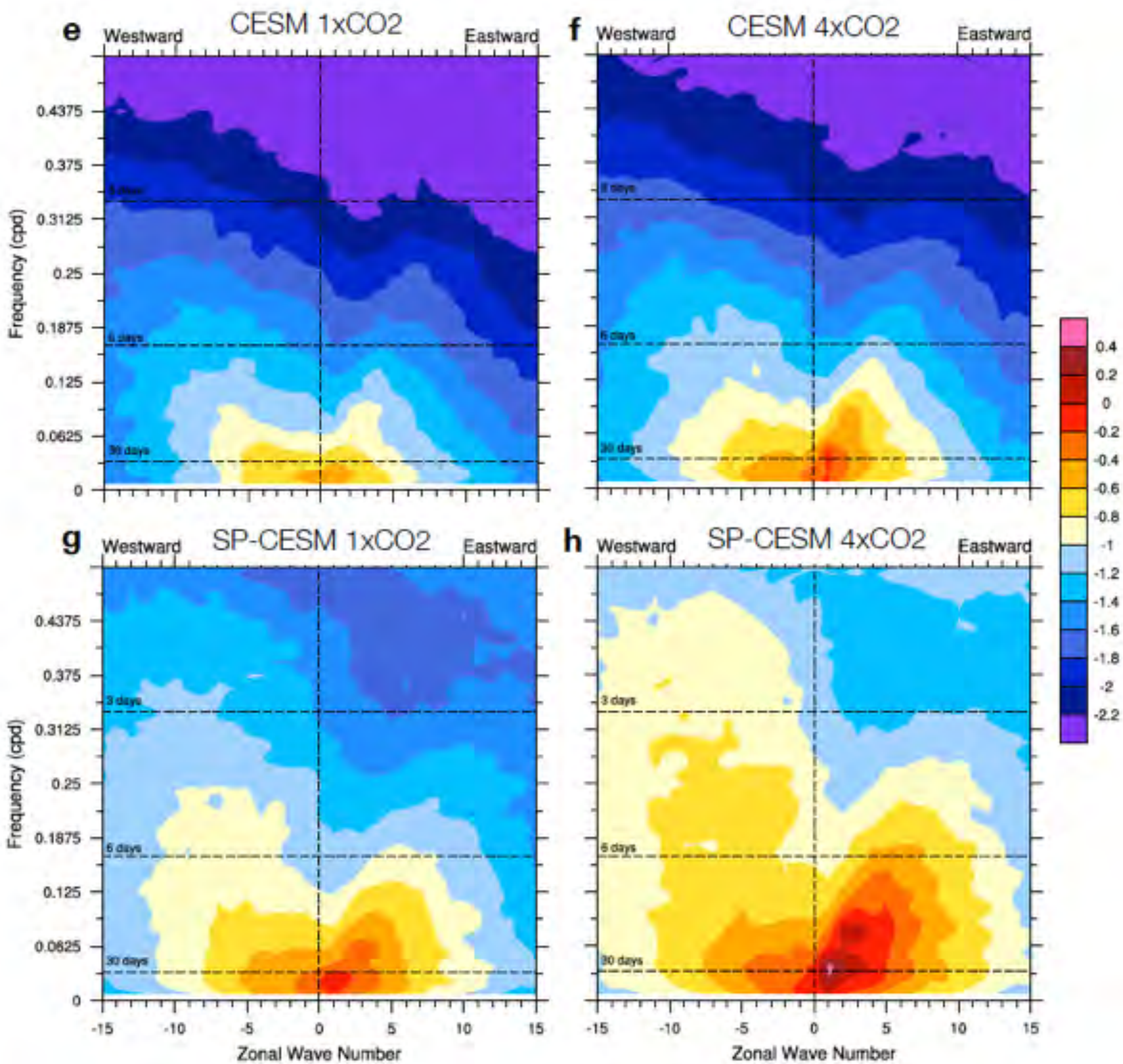
DeMott et al (2011)

Zonal cross-section of MJO



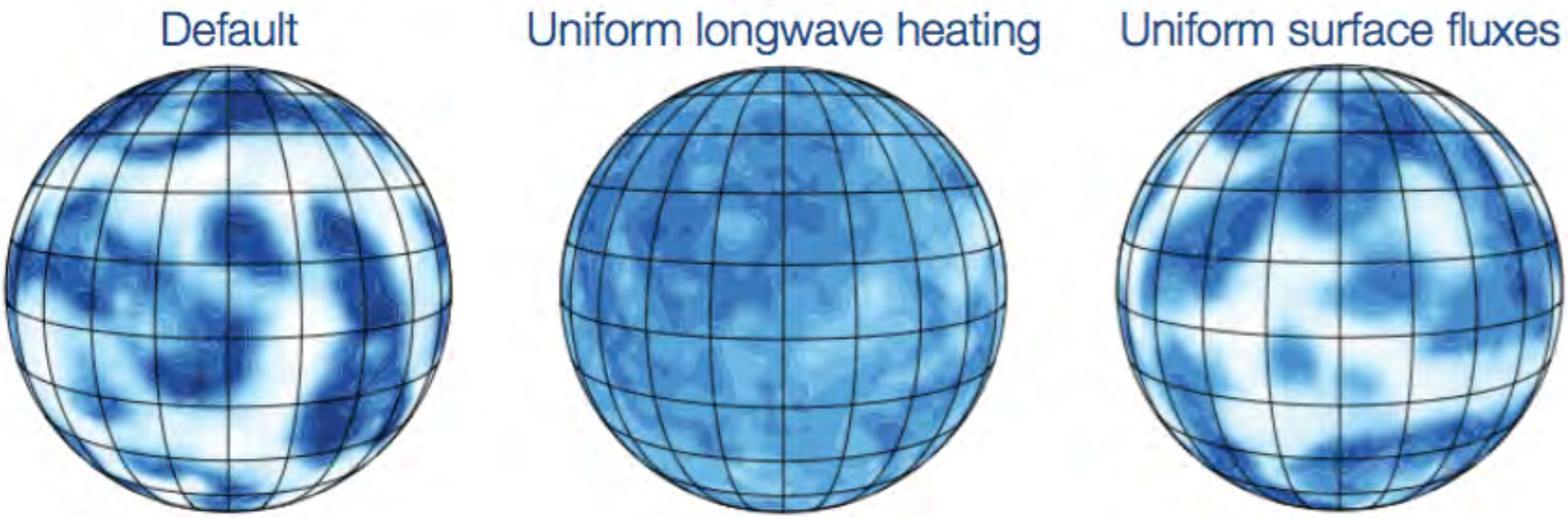
Benedict and Randall 2008

Large increase of MJO in warmer climate



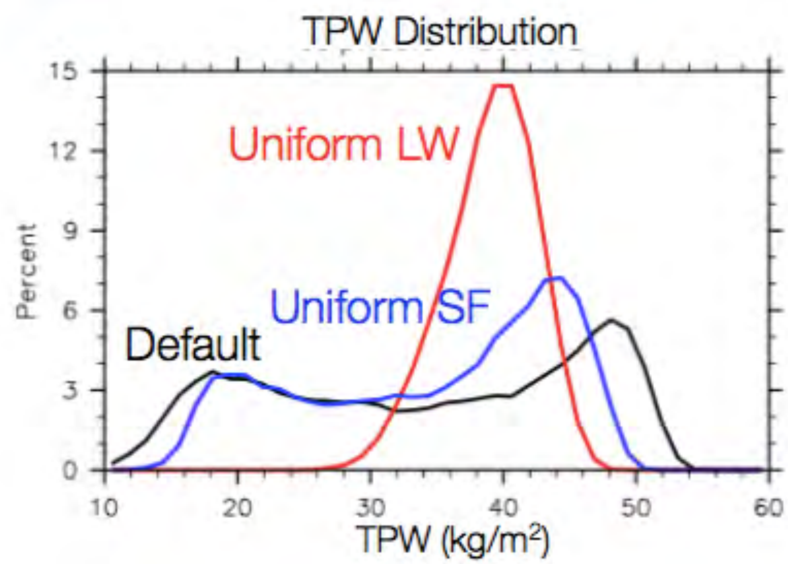
Arnold et al, PNAS 2014

Self-aggregation of convection on sphere
SST=const, Solar=const, f=0



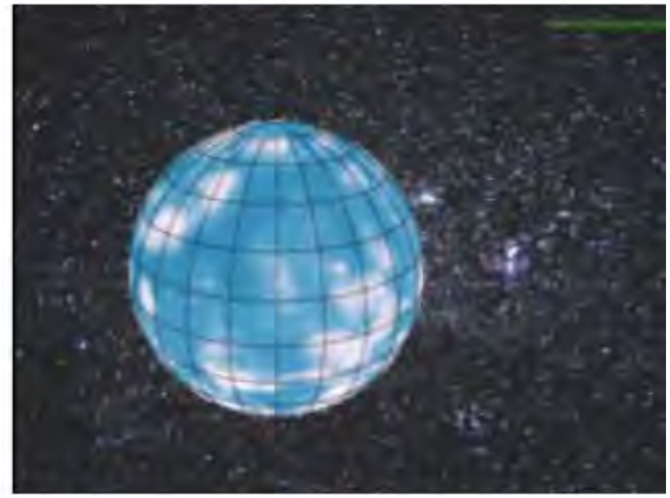
Aggregation does not occur without interactive longwave!

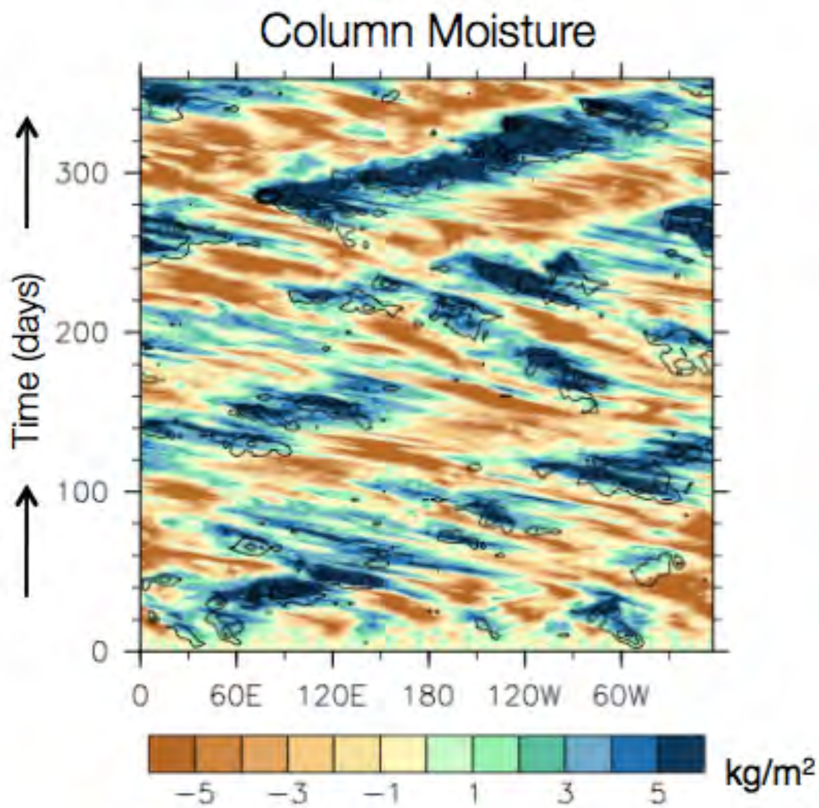
Surface fluxes help, but are not essential.

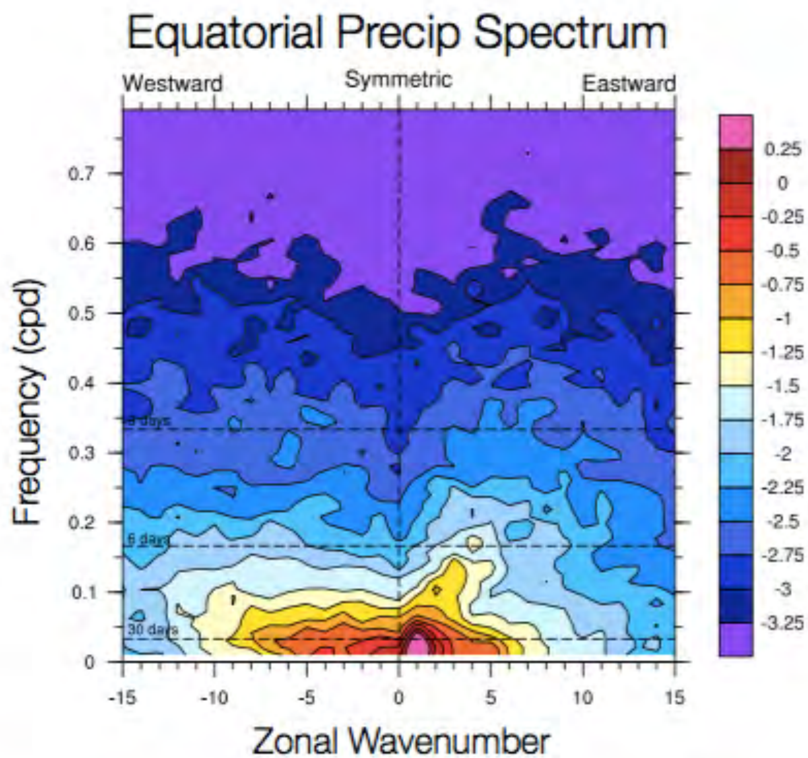


Arnold and Randall (2015)

Restoring full rotation: Model produces an "MJO"



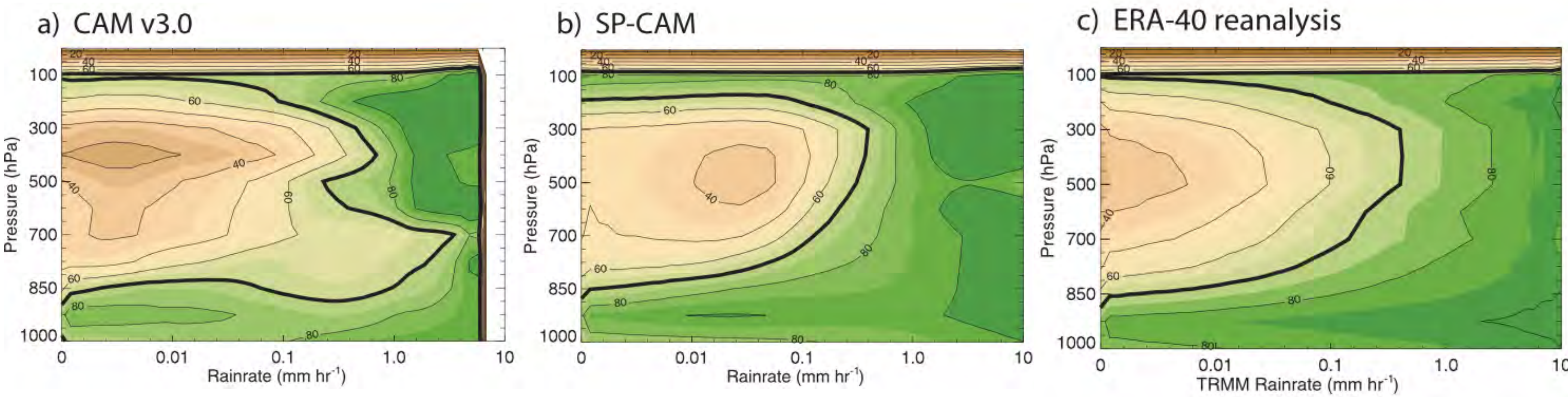




See also: Grabowski (2003/04)

Arnold and Randall (2015)

Tropospheric moisture in Tropics binned by rainfall rate



In Obs and SP-CAM, heavy rainfall corresponds to regions with high humidity, especially in low-to-mid troposphere.

Is high sensitivity of precipitation to humidity the key for simulating MJO?

Thayer-Calder and Randall (2009)

African Easterly Waves

AEWs are well simulated in SP-CCSM, but virtually missing in CCSM

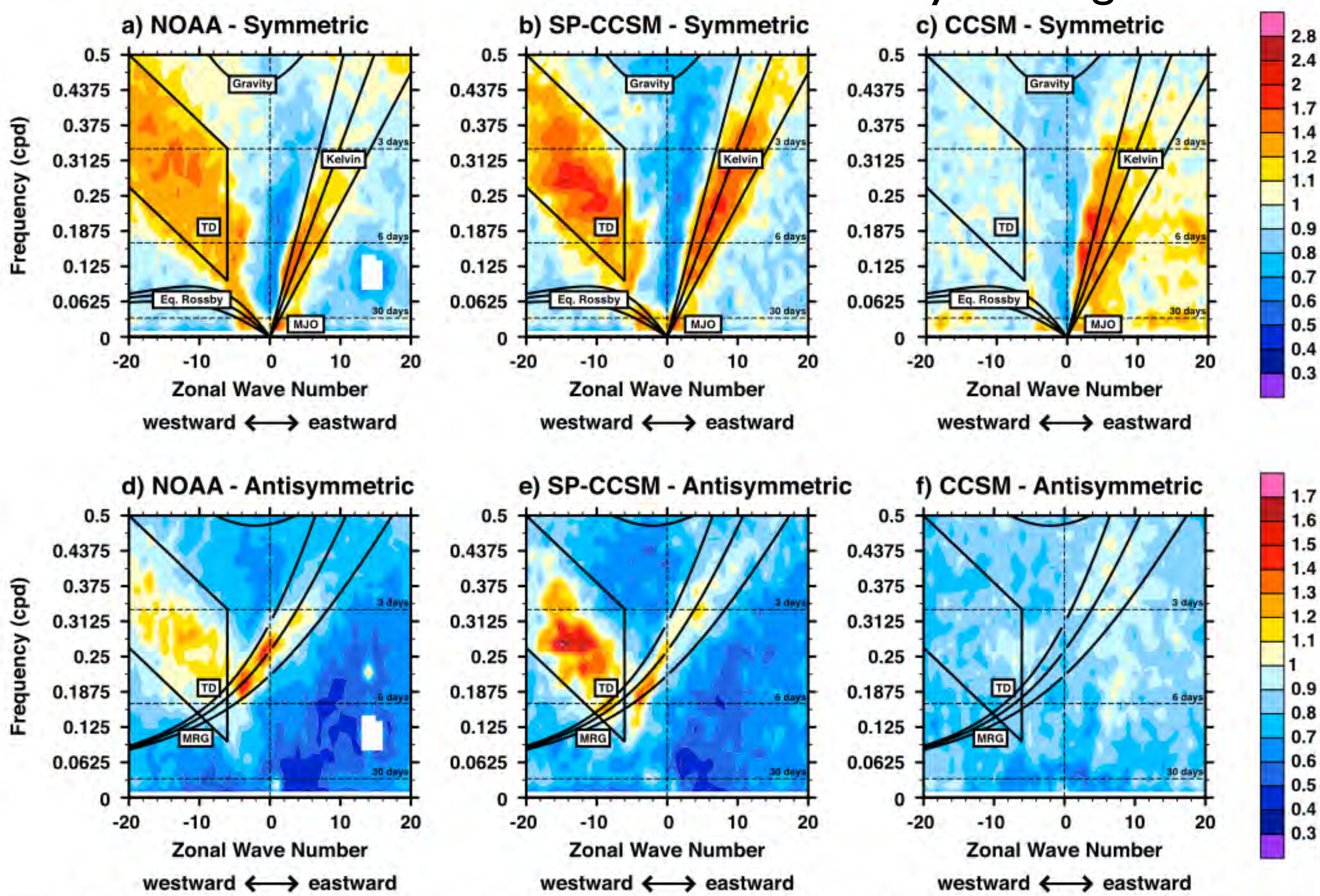


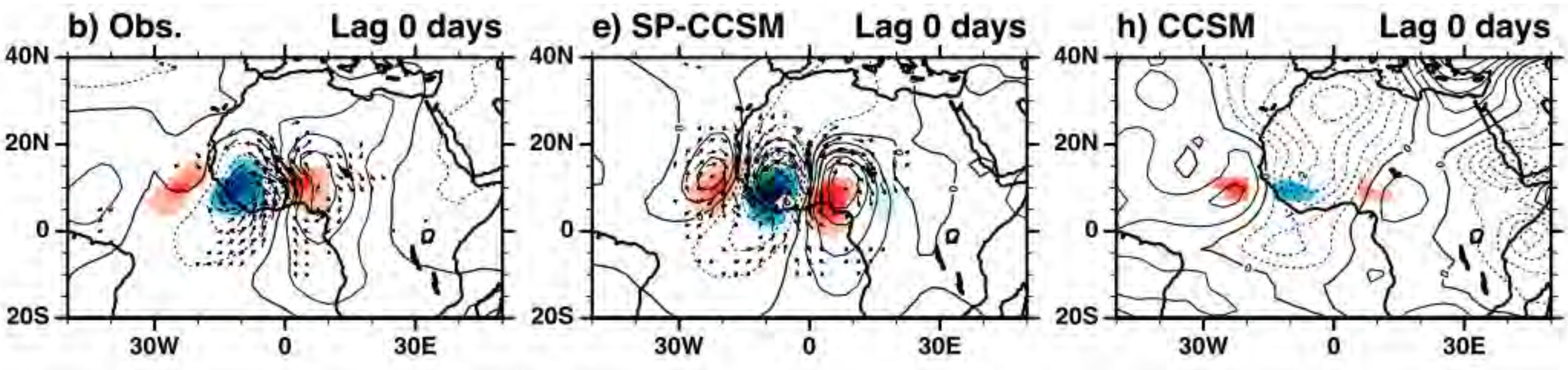
FIG. 2. Average JJAS signal-to-noise space–time spectra averaged between 15°S and 15°N at all longitudes for disturbances that are (a)–(c) symmetric and (d)–(f) antisymmetric about the equator from (left) observations, (middle) SP-CCSM, and (right) CCSM.

SP-CCSM @ T42

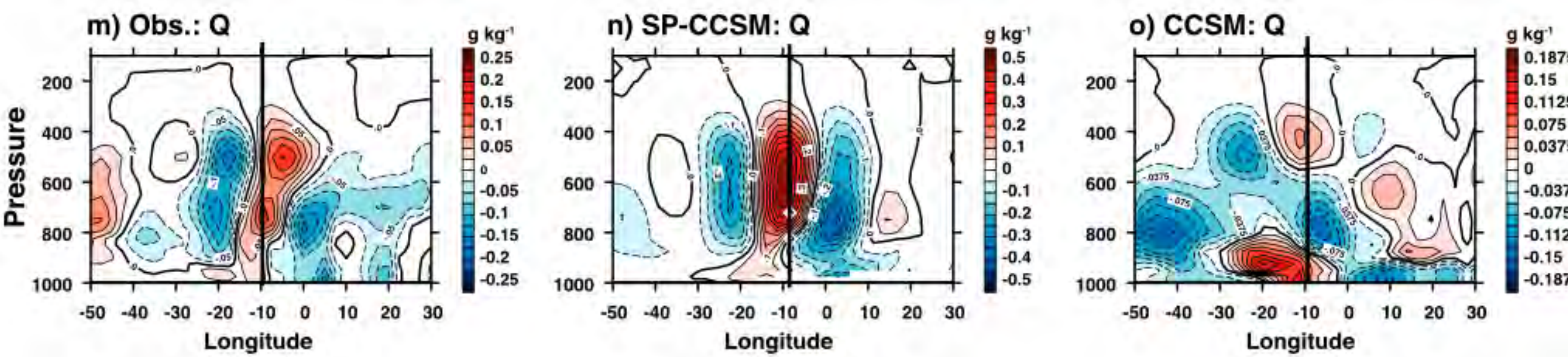
McCary, Randall, Stan 2014

African Easterly Waves

OLR anomalies and 850 mb streamfunction and winds



Zonal cross-section of moisture anomalies

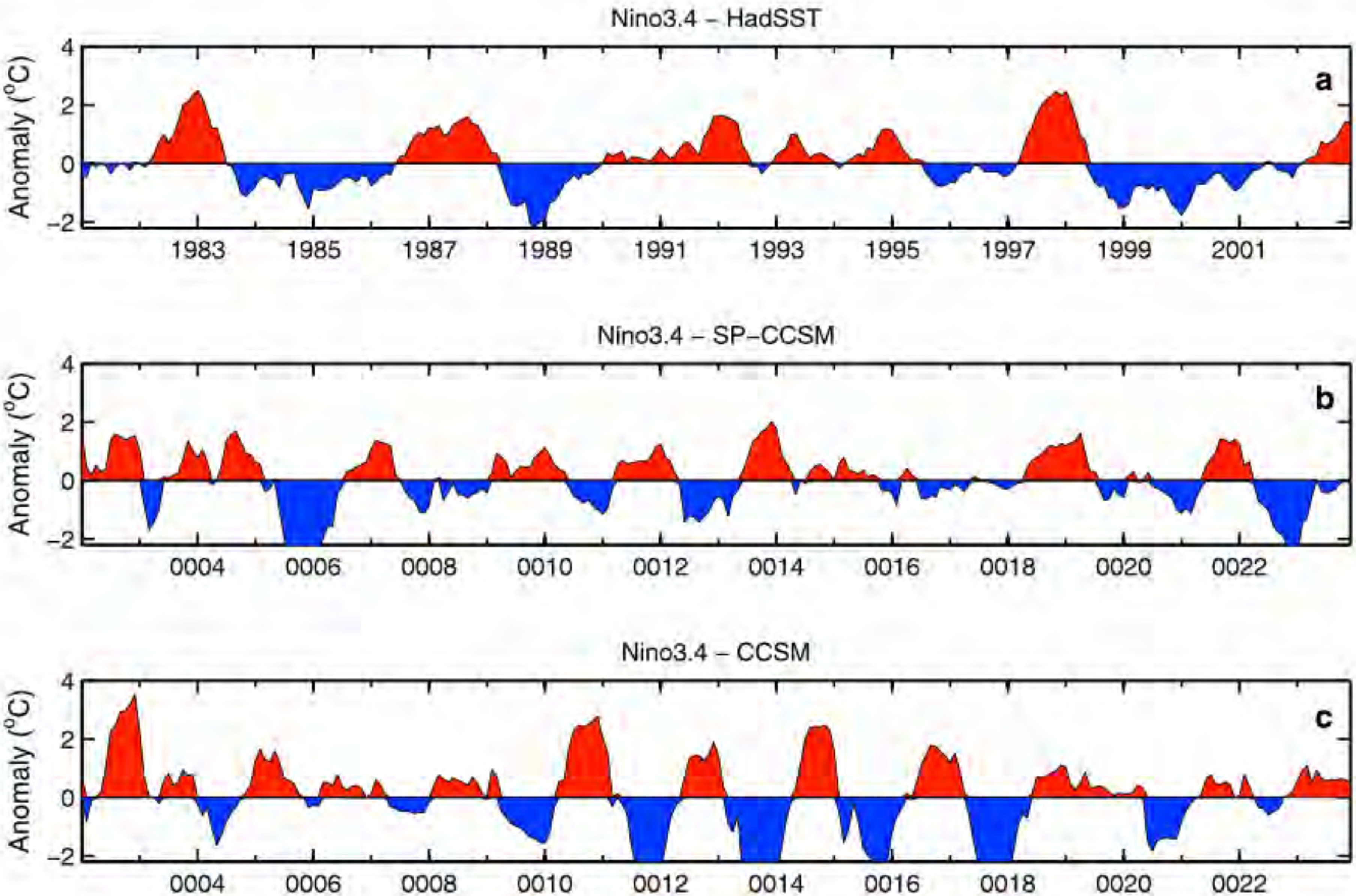


SP-CCSM couples convection and waves right to simulate AEWs even at T42!
Again, as in MJO, mid-tropospheric moisture anomaly appears to be the key to simulating AEWs.

McCary, Randall, Stan 2014

ENSO

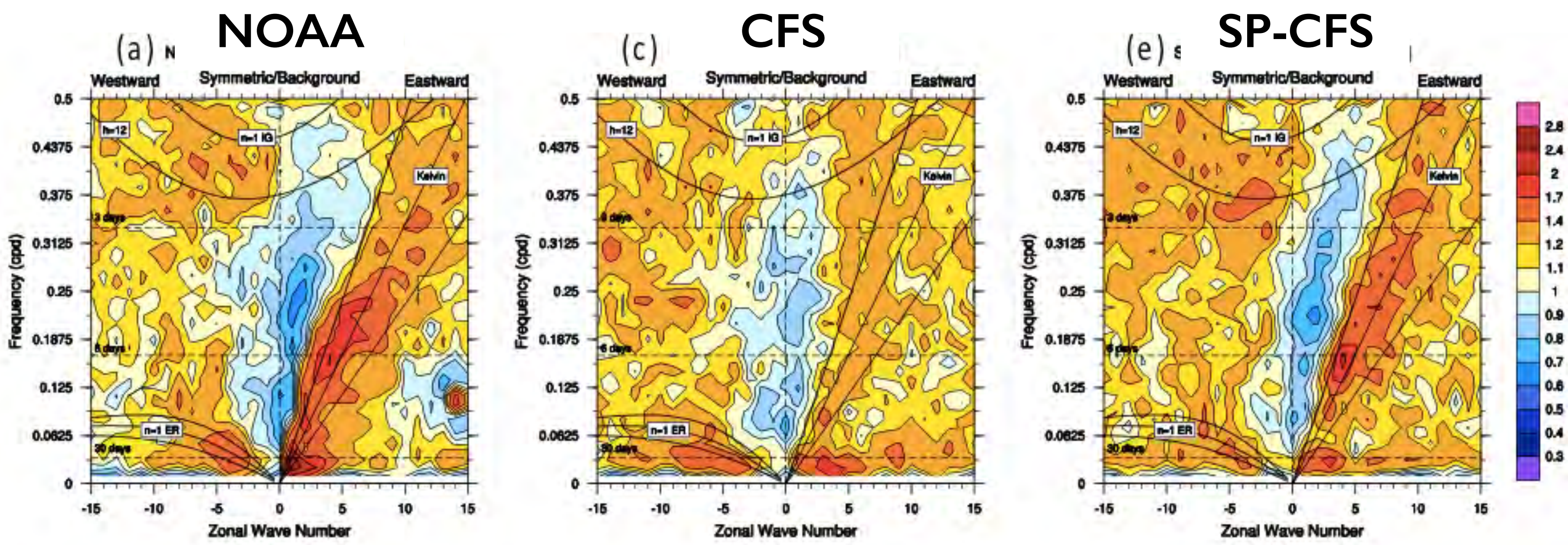
El Nino amplitude and periodicity is better simulated by SP-CCSM

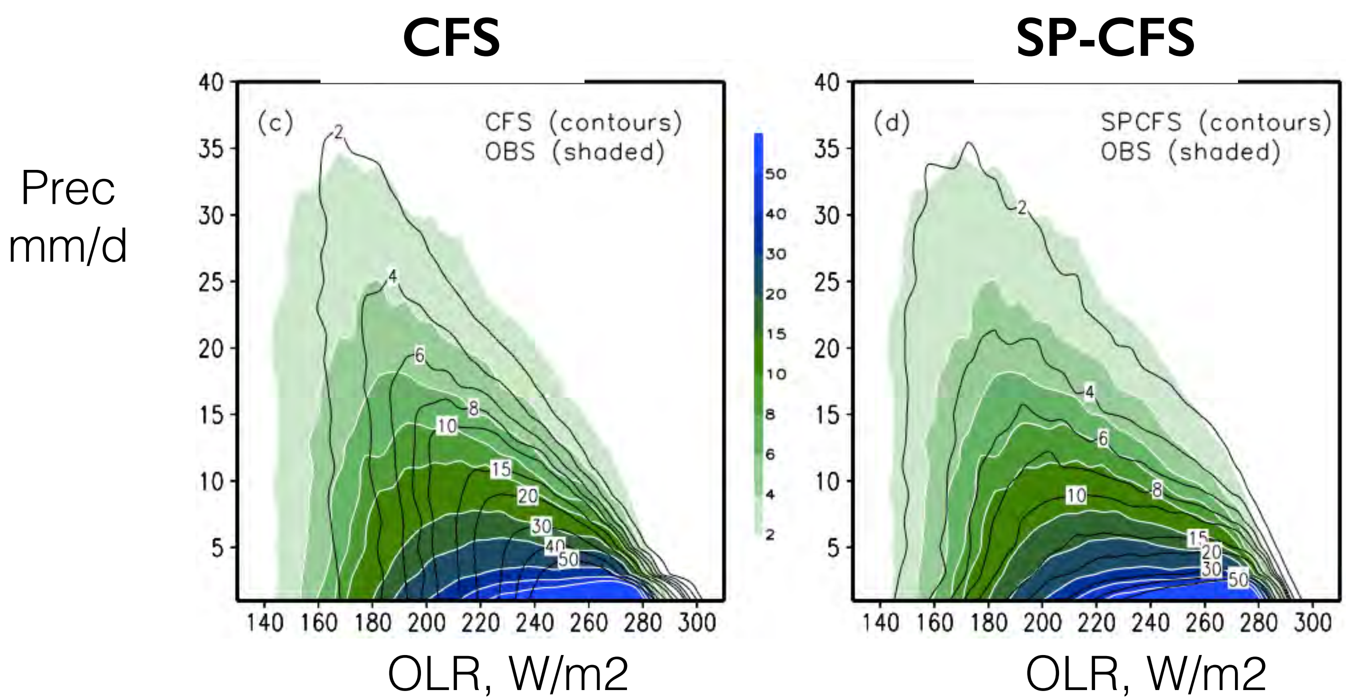


Super-parameterized GCMs

- **2001: SP-CAM**
- **2007: SP-fvGCM: NASA GSFC (Wei-Kuo Tao)**
- **2010: SP-WRF: (Stefan Tulich)**
- **2011: SP-CFS: Indian Institute of Tropical Meteorology**
- **2014: SP-IFS: ECMWF**

SP-CFS (IITM)





Goswami et al, JC (2015)

SP-IFS - Super-parameterized IFS

Thanks to

Anton Beljaars
Peter Bechtold
Filip Vana
Glenn Carver

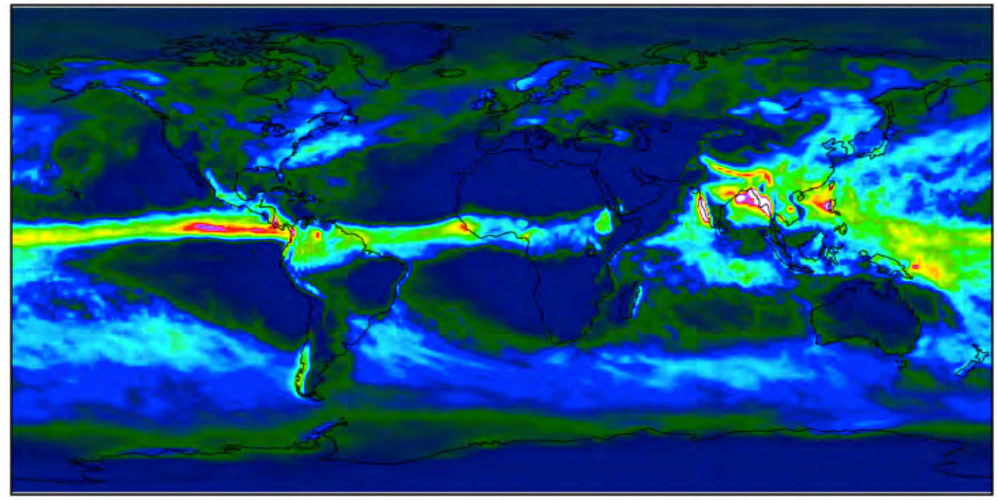
- **First implemented in OpenIFS, which is a free running IFS (cycle 38R1), but without data assimilation system;**
- **Summer 2014: T159 (~1.125° x 1.125°) 3-year runs with SP-OIFS;**
- **Fall 2014: SP is implemented in IFS CY40R3.**
- **Fall 2014: SP is in IFS Single-Column Model CY40R1;**
- **Currently, implemented in CY41R3 and can be run using prepIFS system.**

Preliminary results using T159 SP-OpenIFS

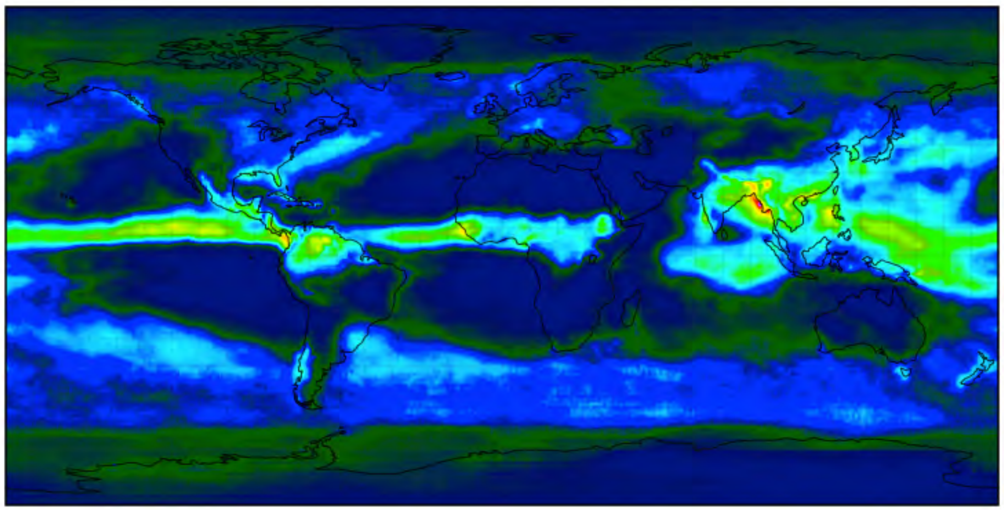
- **SP: 32 x 74; Δx=4 km; Δt=20s;**
- **All IFS cloud and convective parameterizations are off;**
- **PBL/mixing parameterizations are allowed;**
- **Radiation coupling through SP's *mean* profiles (not on CRM grid as done in SP-CAM);**
- **Free continuous climate run for 3 years starting Aug 2000.**

JJA Precipitation
T159

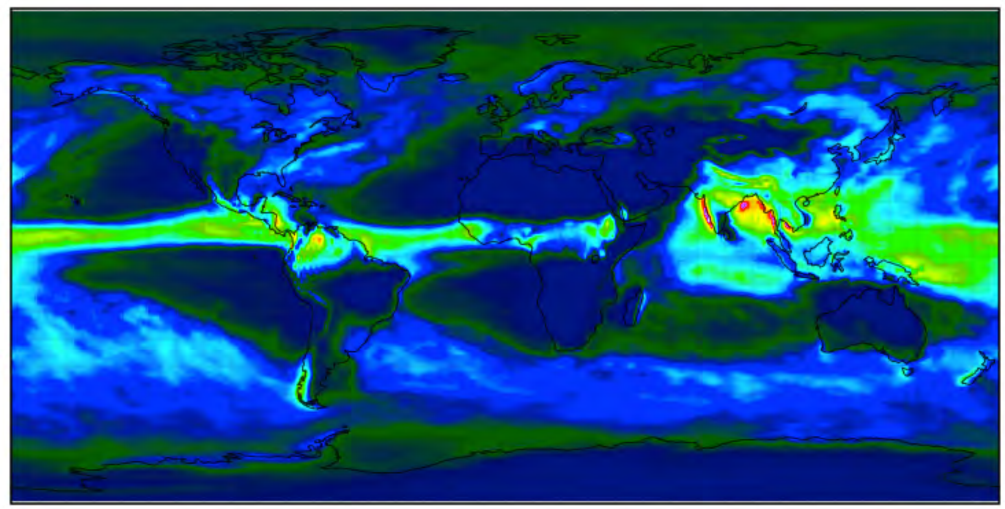
SP-OIFS



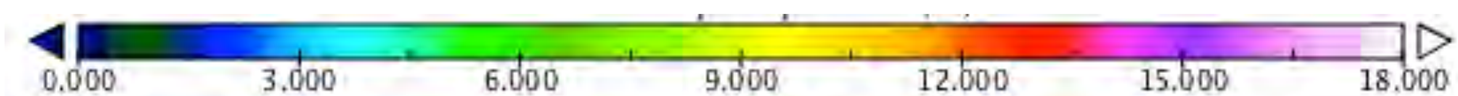
GPCP (OBS)



OIFS

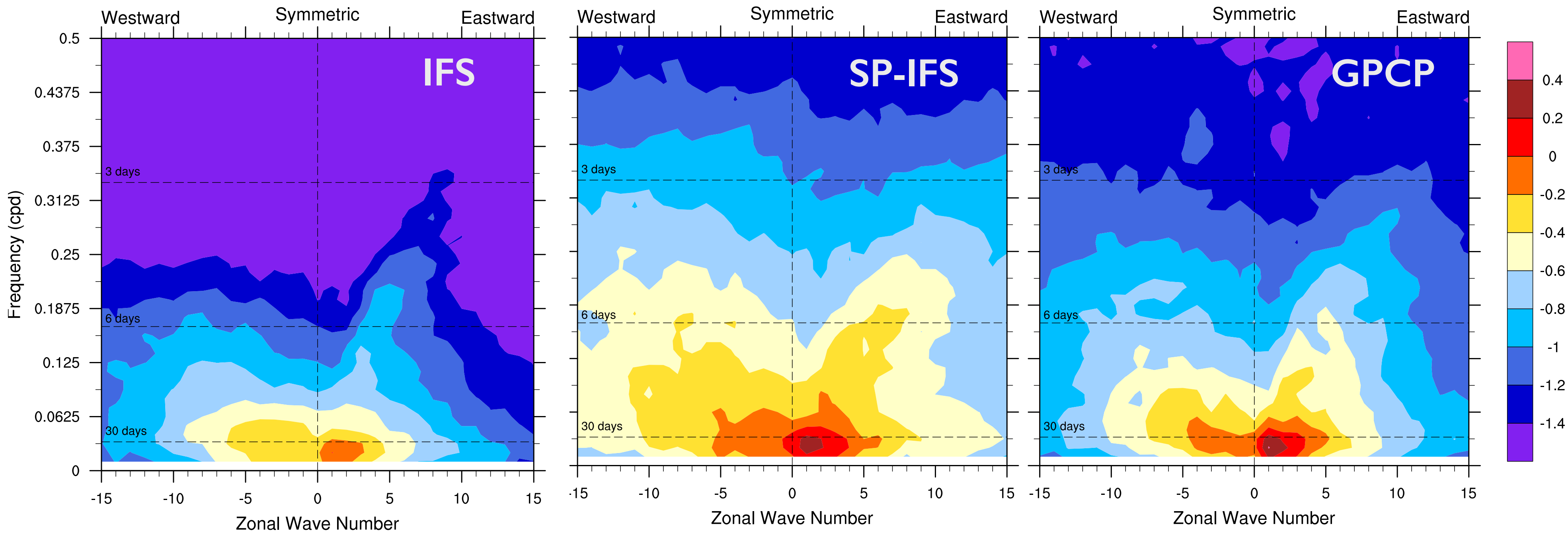


Mean climatology of SP-IFS doesn’t look bad for a model which hasn't been properly tuned.

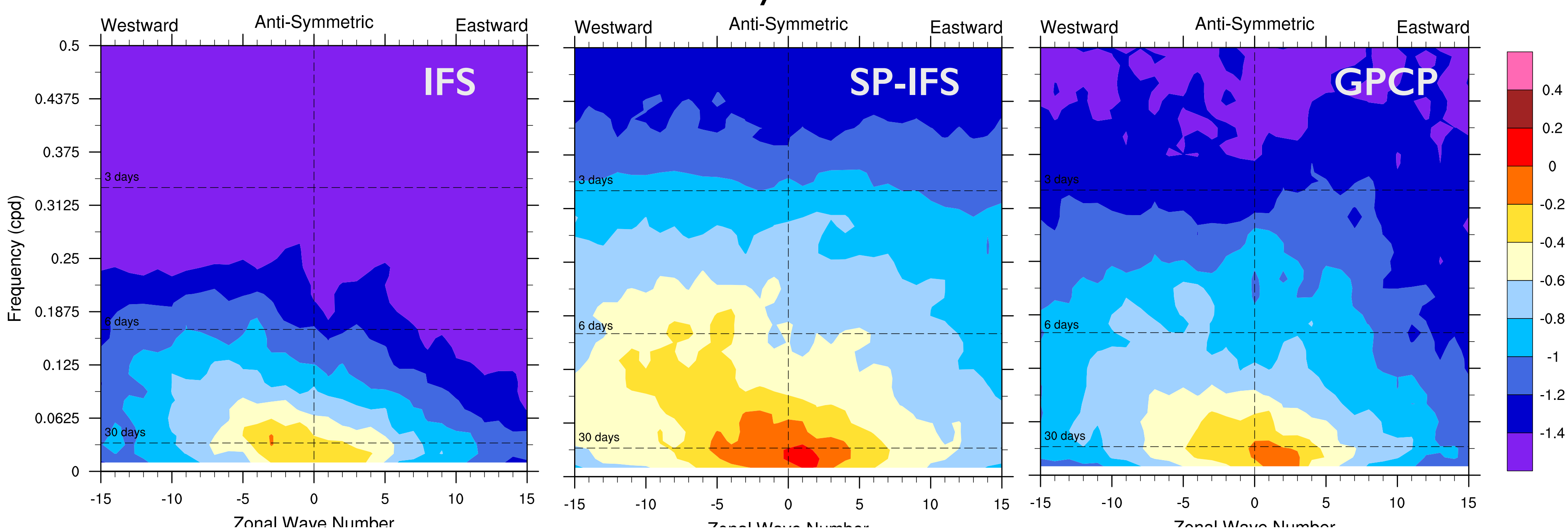


Frequency Spectrum (Subseasonal): Precipitation in Tropics (15°S-15°N)

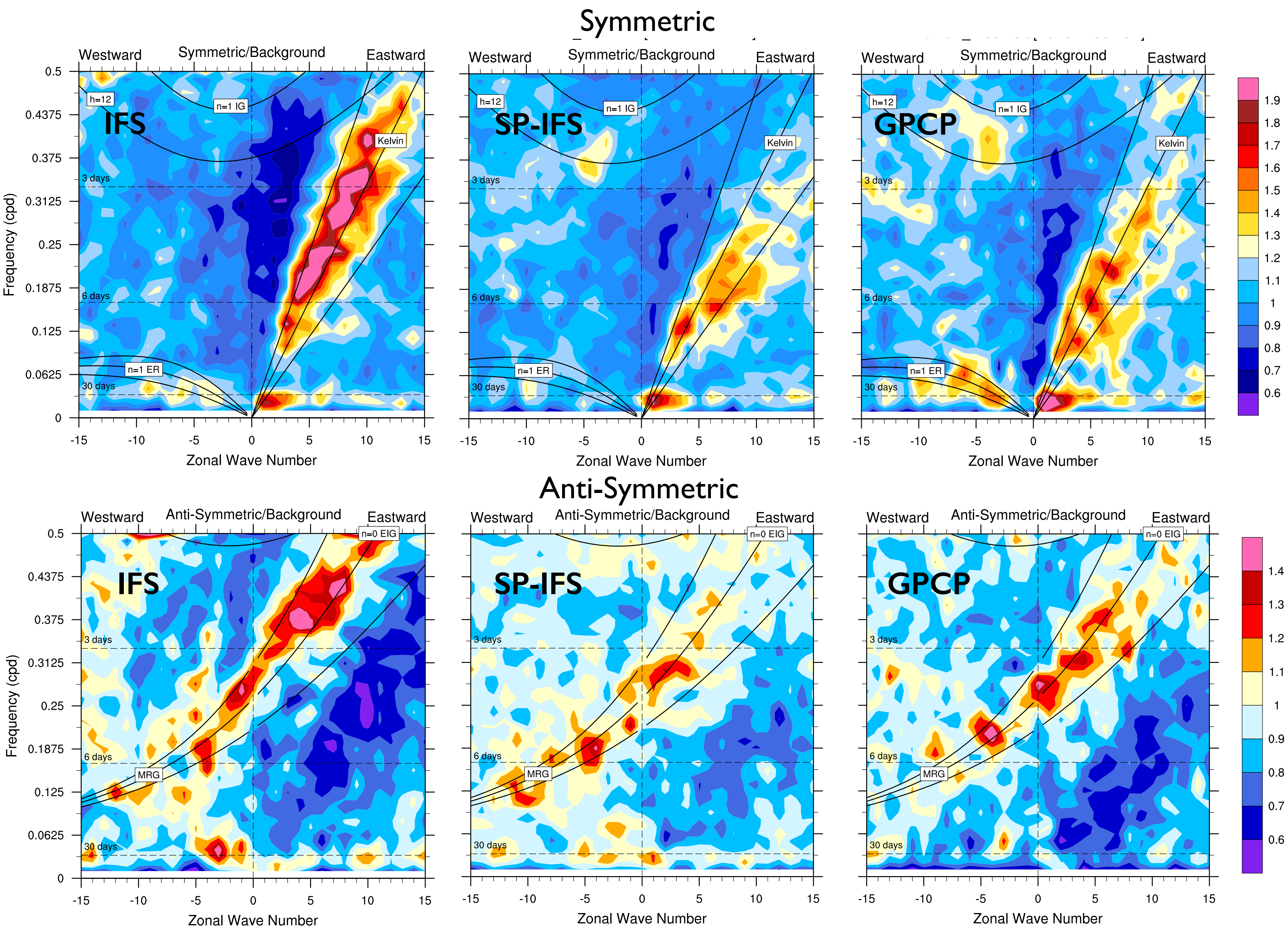
Symmetric



Anti-Symmetric

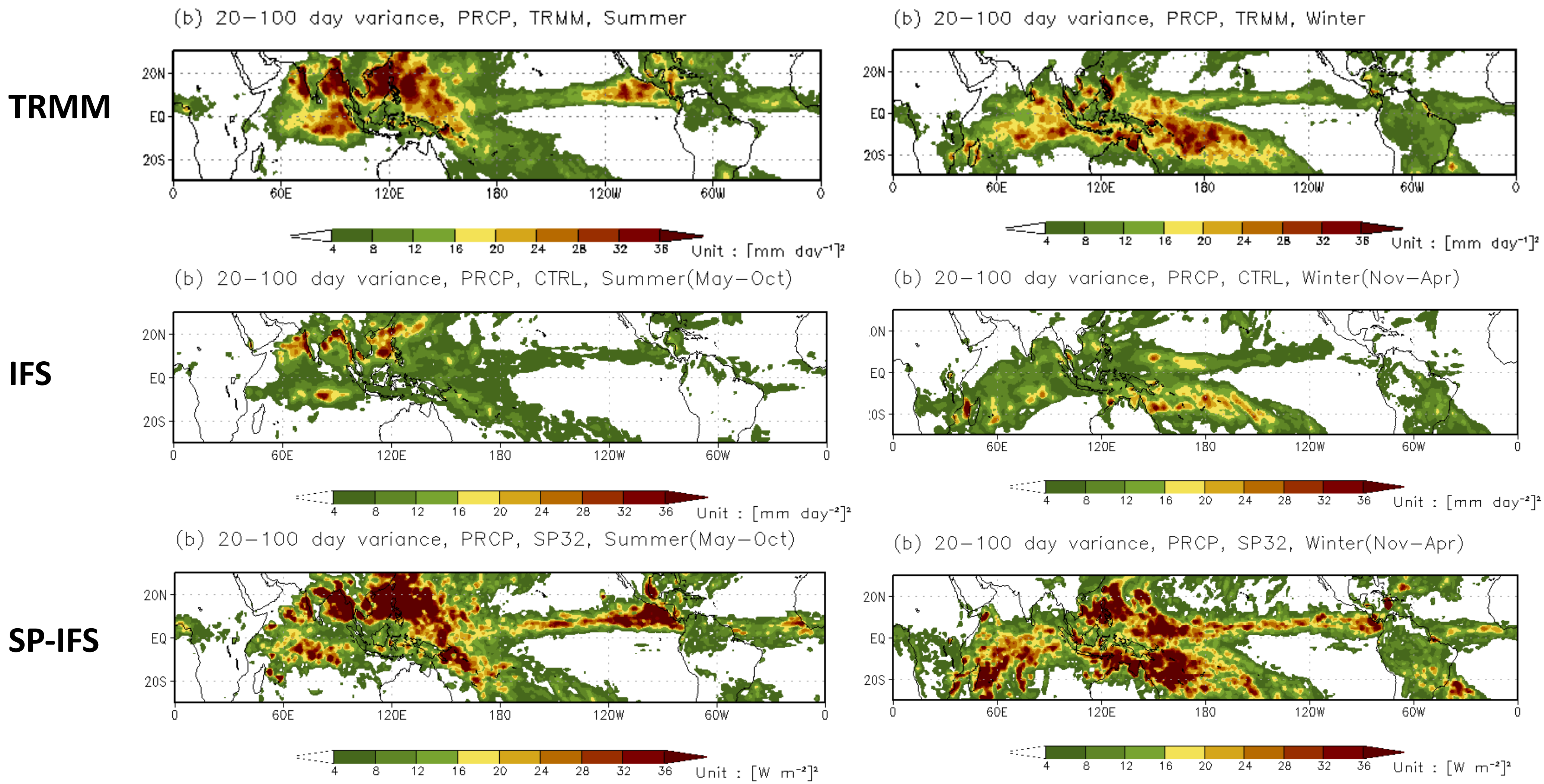


Frequency Spectrum (S/N): Precipitation in Tropics (15ºS-15ºN)



Variance: 20-100 day filtered precipitation

Summer (May-Oct) **Winter (Nov-Apr)**



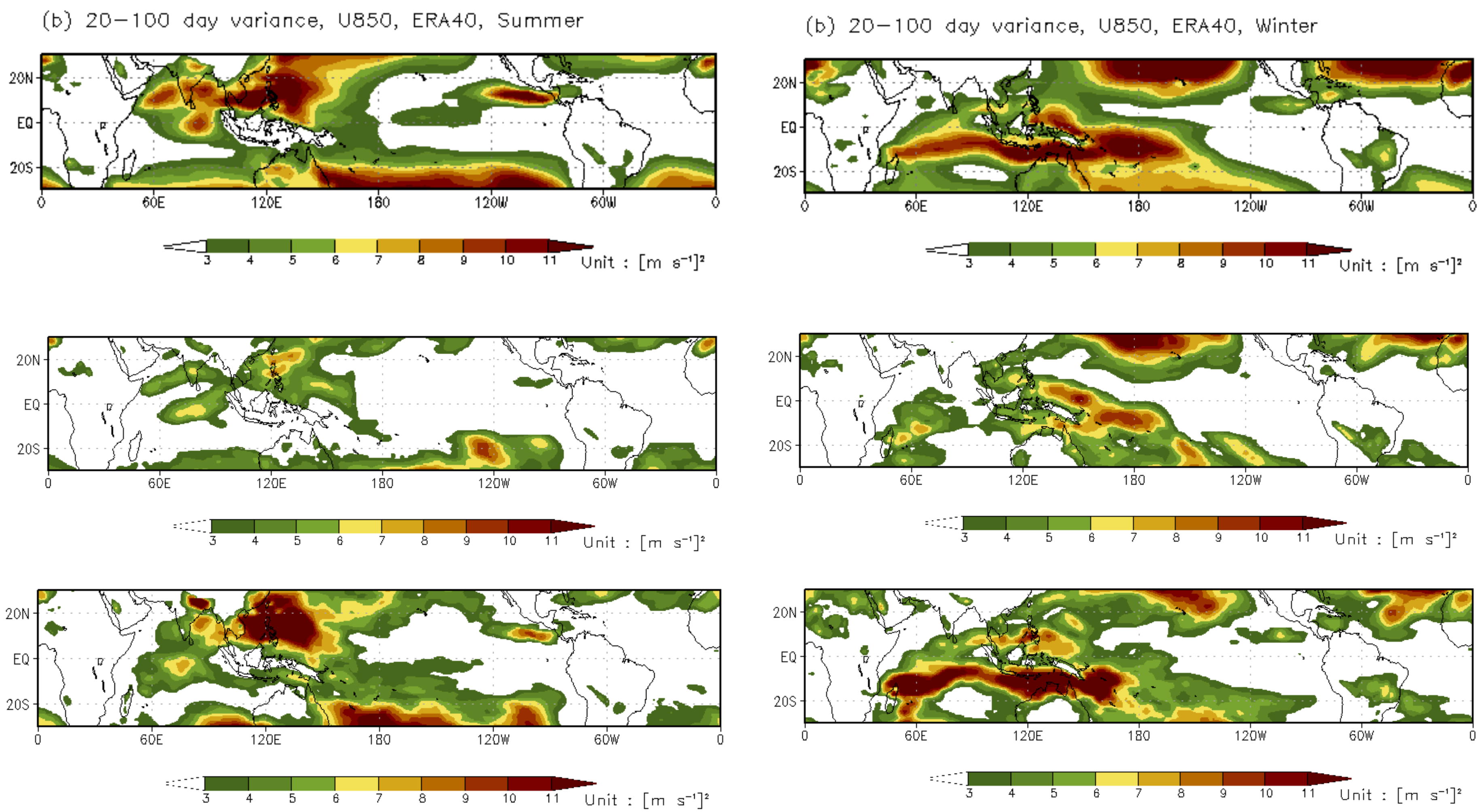
Variance: 20-100 day filtered U850

Summer (May-Oct) | **Winter (Nov-Apr)**

ERA40

IFS

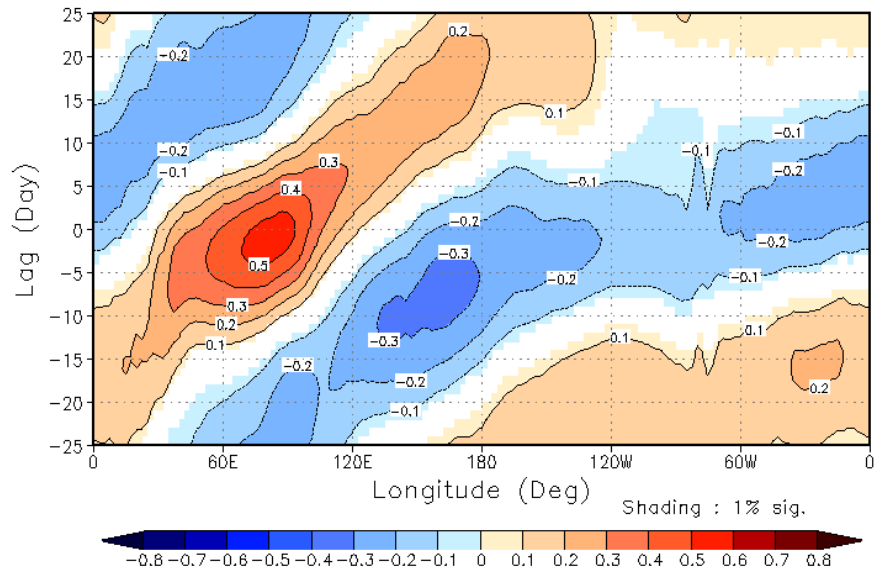
SP-IFS



MJO eastward propagation

Lag correlation (U850, Winter)

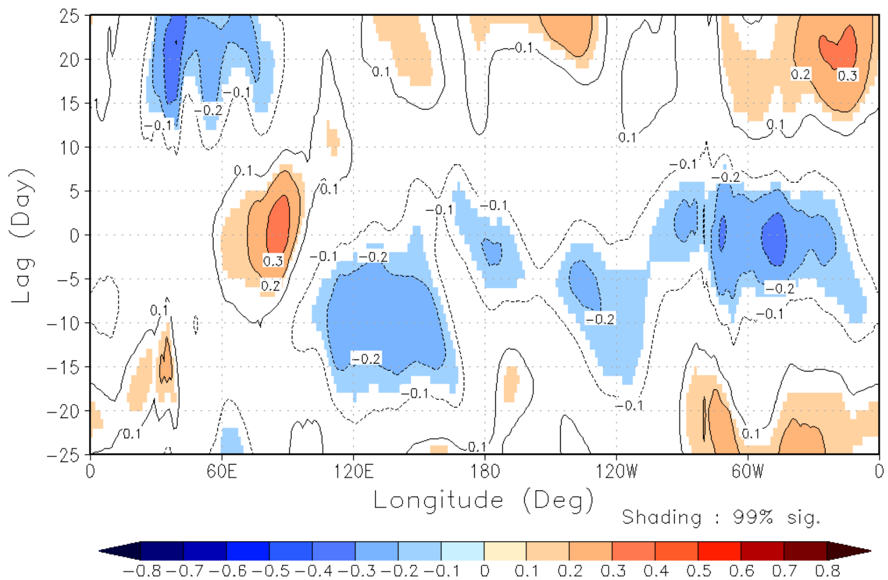
ERA40



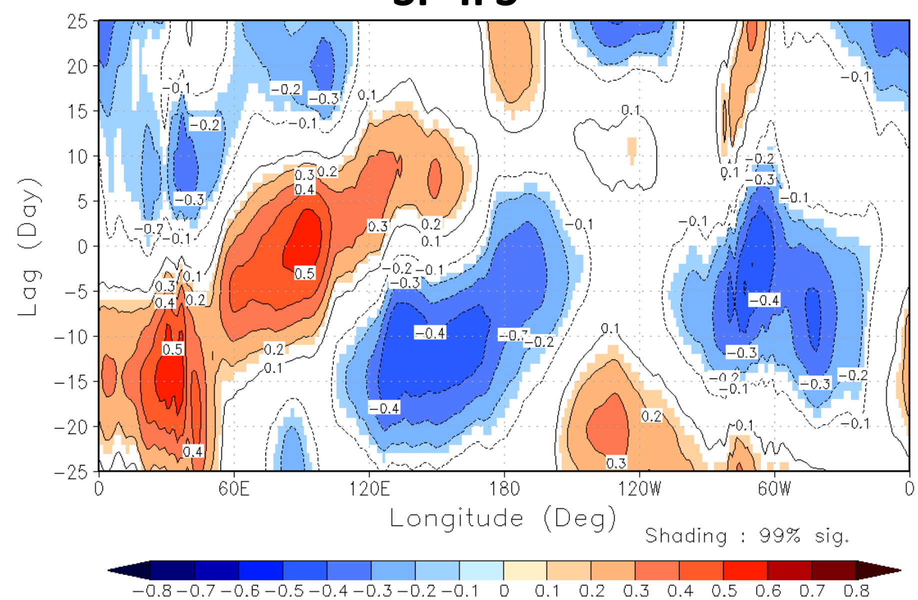
Reference domain:
1.25S-16.25N, 68E-96E

* US CLIVAR MJO Diagnostic metrics

IFS



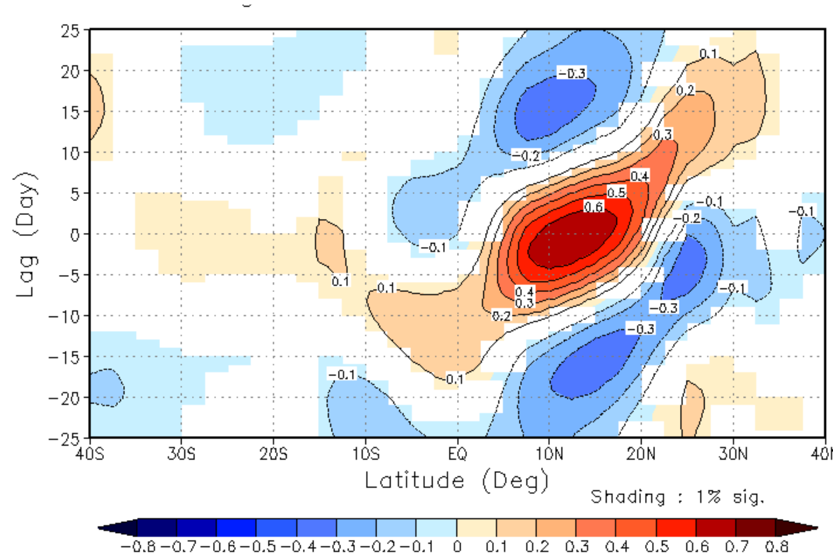
SP-IFS



Summer ISO northward propagation

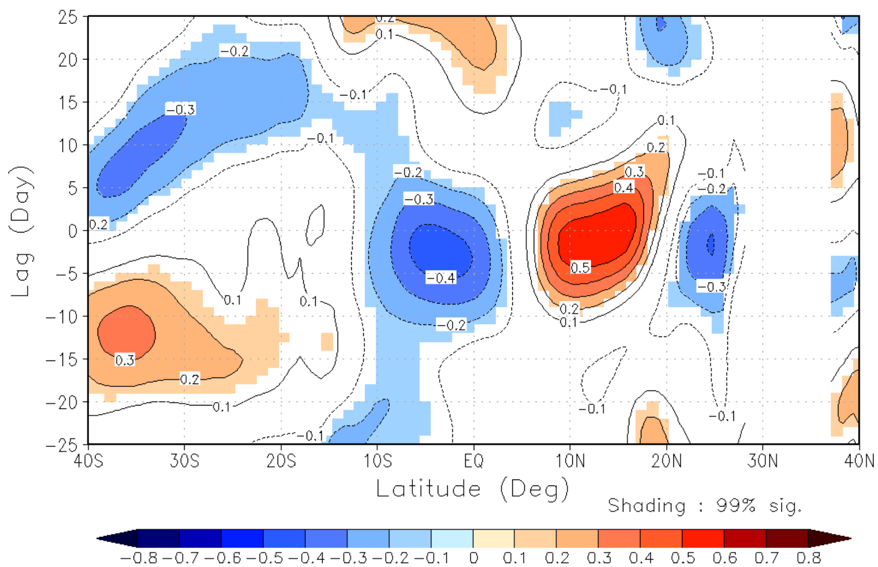
Lag correlation (U850, Summer)

ERA40

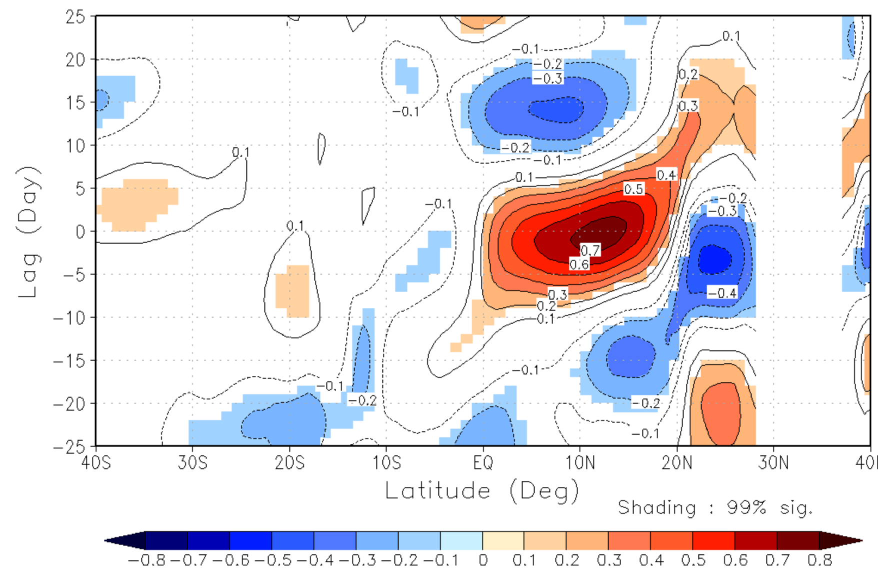


Reference domain: 3.75N-21.25N, 68E-96E

IFS

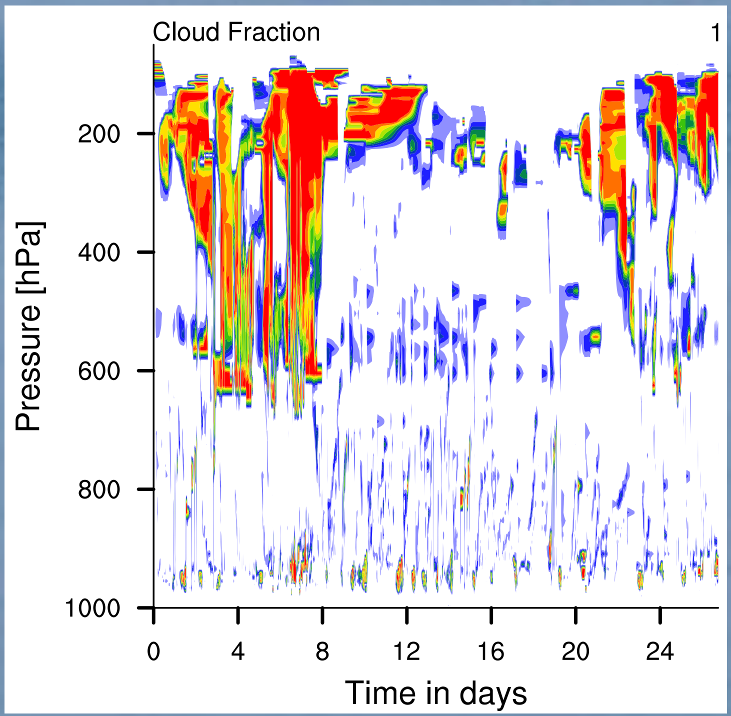


SP-IFS

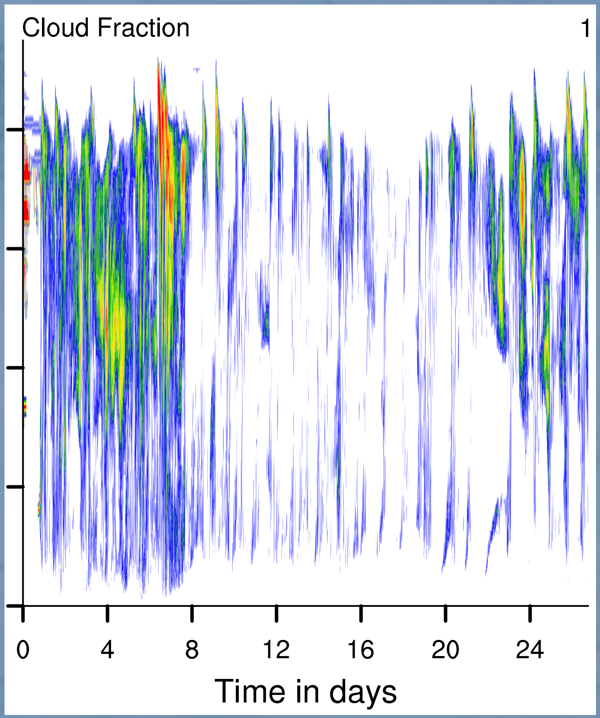


Tuning for cloud fraction using SCM IFS (TWP ICE case)

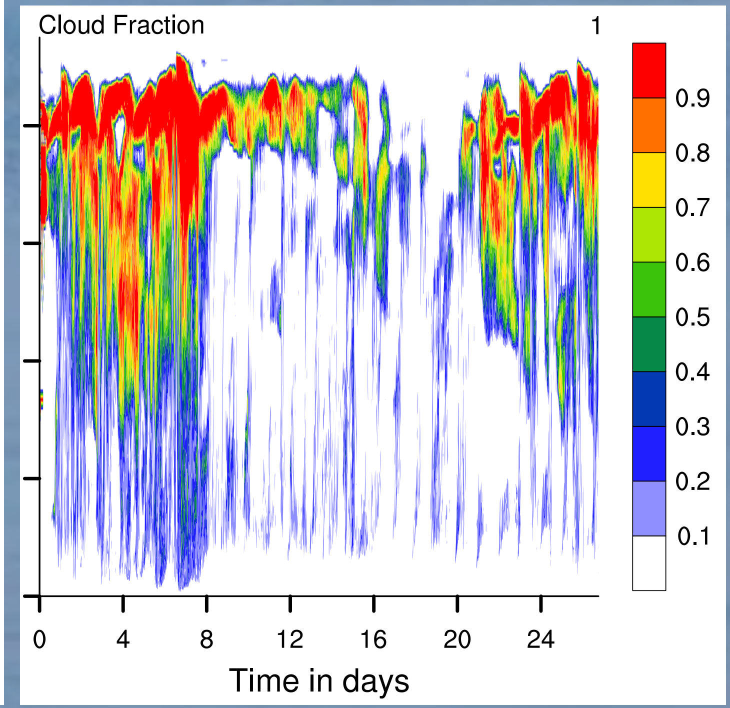
IFS



SP-IFS (control)

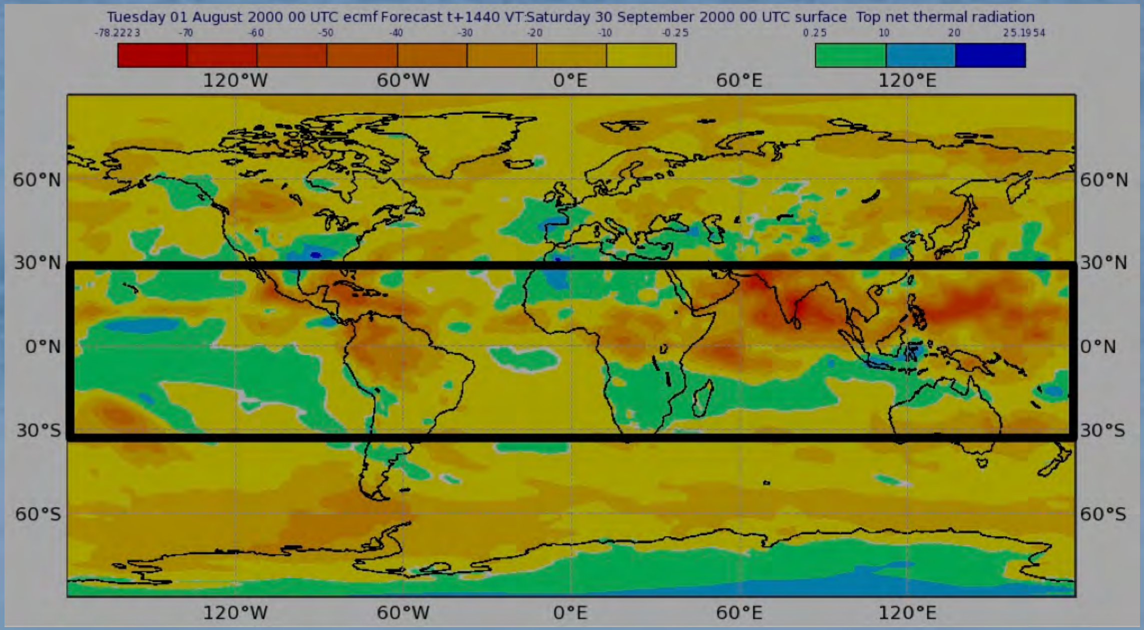


SP-IFS (tuned)

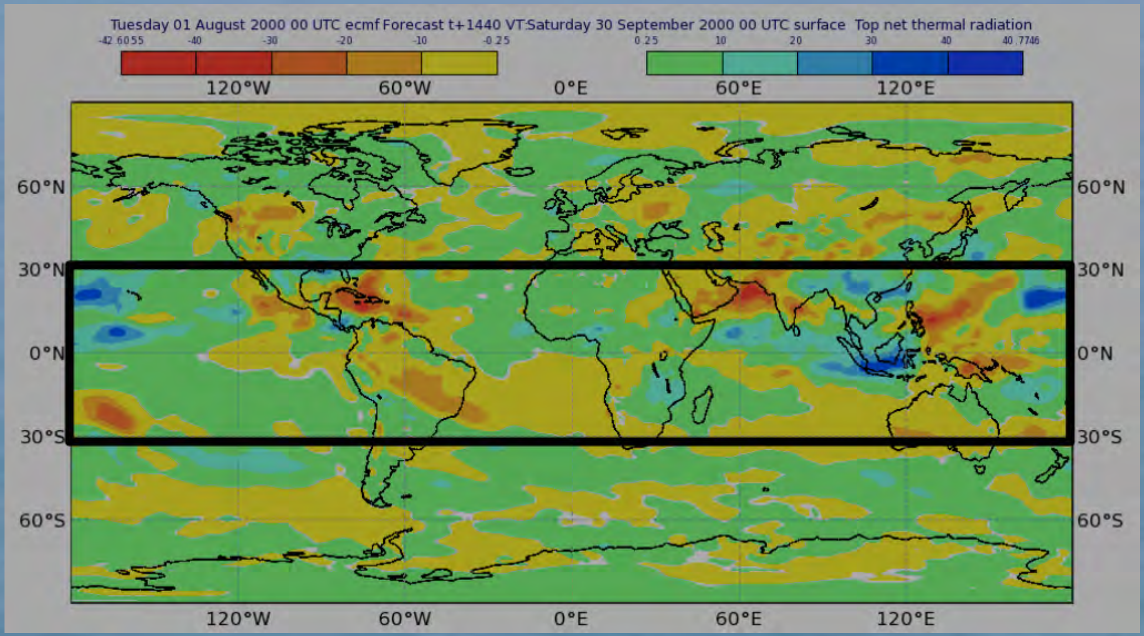


Bias in OLR in SP-IFS CY40R1 forecast

SP-IFS (before tuning)

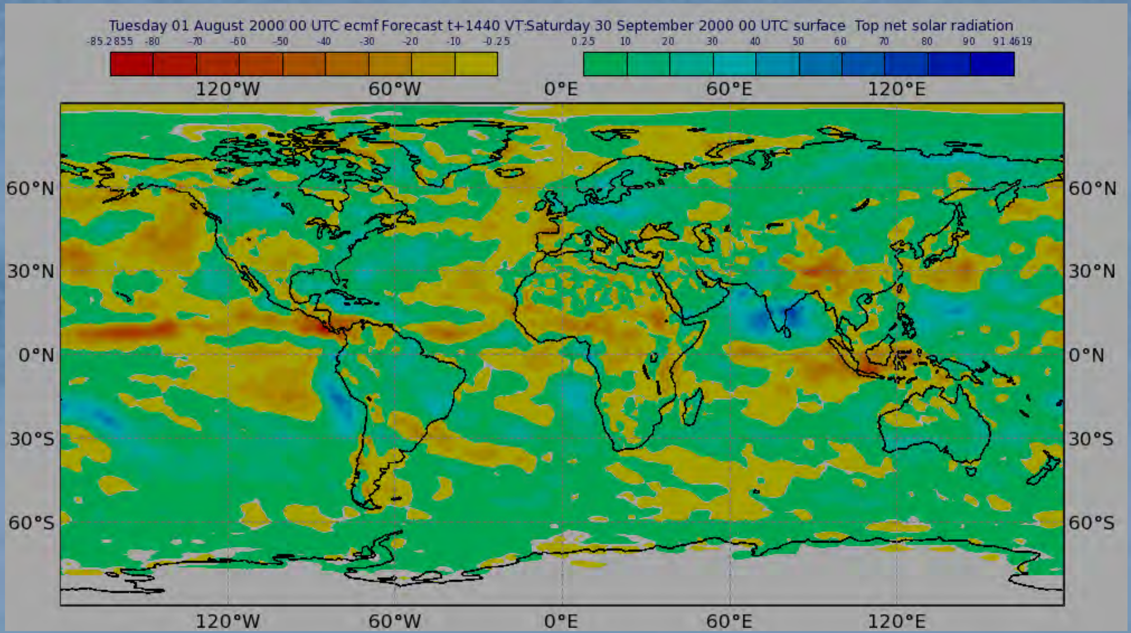


IFS



Bias in OLR in SP-IFS CY40R1 forecast

SP-IFS (after tuning)



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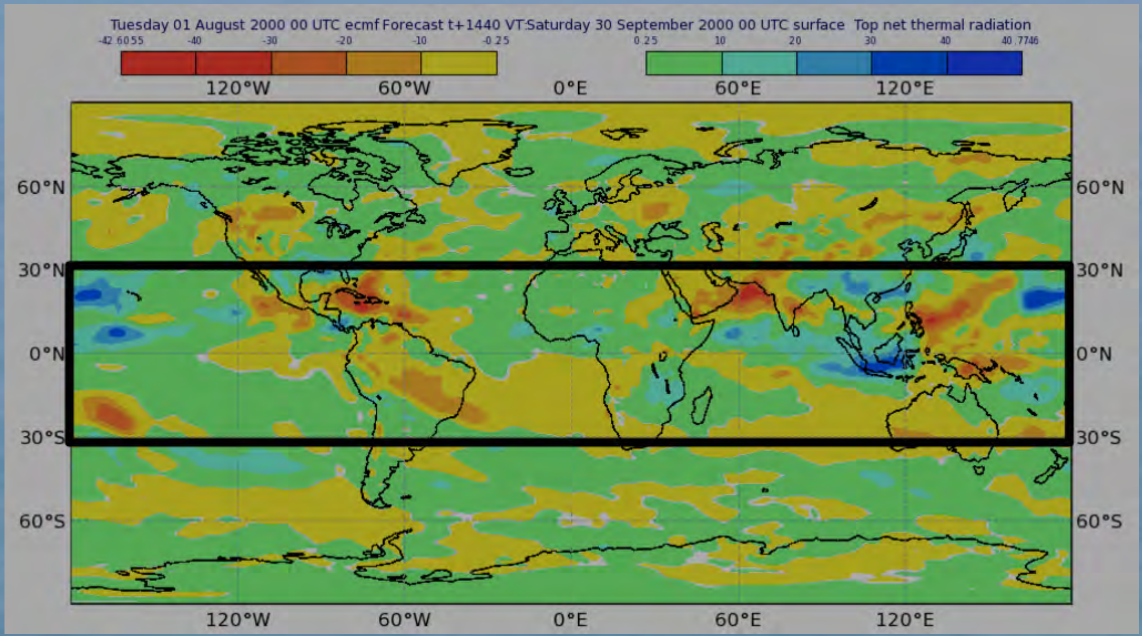

What have we learnt from SP?

- **Even small-domain 2D CRM works better than current convective parameterizations to represent variability of climate system on various timescales.**
- **We know much more about MJO now thanks to the SP.**
- **As the SP interacts with a GCM as an ordinary parameterization (1D profile in, 1D profile out), it is in principle possible to develop a parameterization that works as well as the SP.**

Lots of MMF publications:

http://www.cmmap.org/research/pubs-mmf.html