Recent Developments of Physical Parameterizations in GFDL Atmospheric GCMs

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GFDL/NOAA, Princeton University

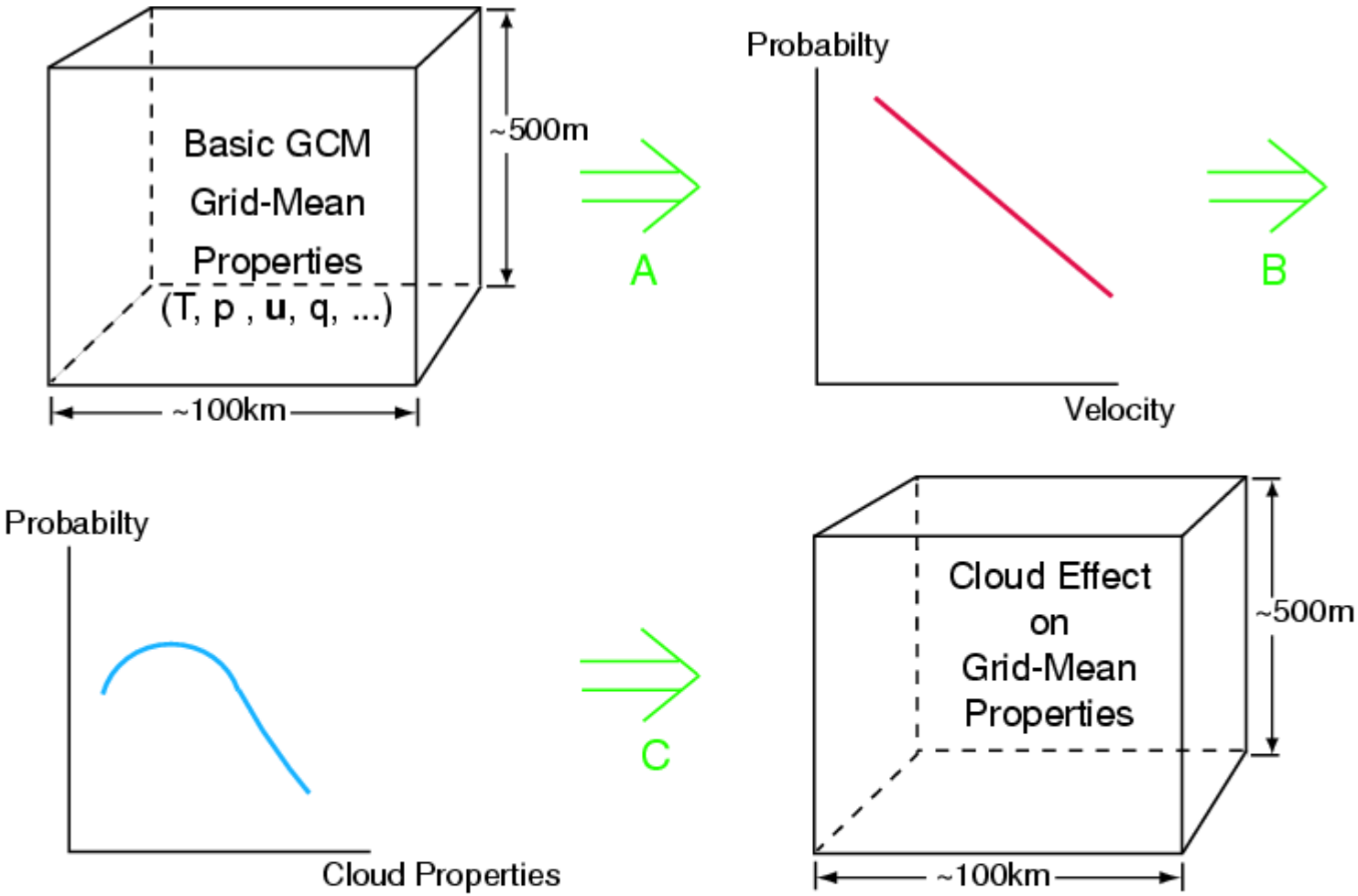
ARM RP/CM Joint Meeting, 19 November 2008, Princeton

New Science Questions for Next-Generation Model

- What are the roles of aerosol-cloud interactions in climate and climate change?
- How will land and ocean carbon cycles interact with climate change?
- To what extent is decadal prediction possible?
- What are the dominant chemistry-climate feedbacks?

Model Development to Address New Scientific Questions

- Interactive chemistry to link emissions to aerosol composition
- Sub-grid vertical velocity PDFs for convective and stratiform clouds => Supersaturation at ***cloud*** scale for aerosol activation
- Sufficiently realistic tropical land precipitation for land carbon model
- Stratospheric model for chemistry and possible links to troposphere on multi-year time scales



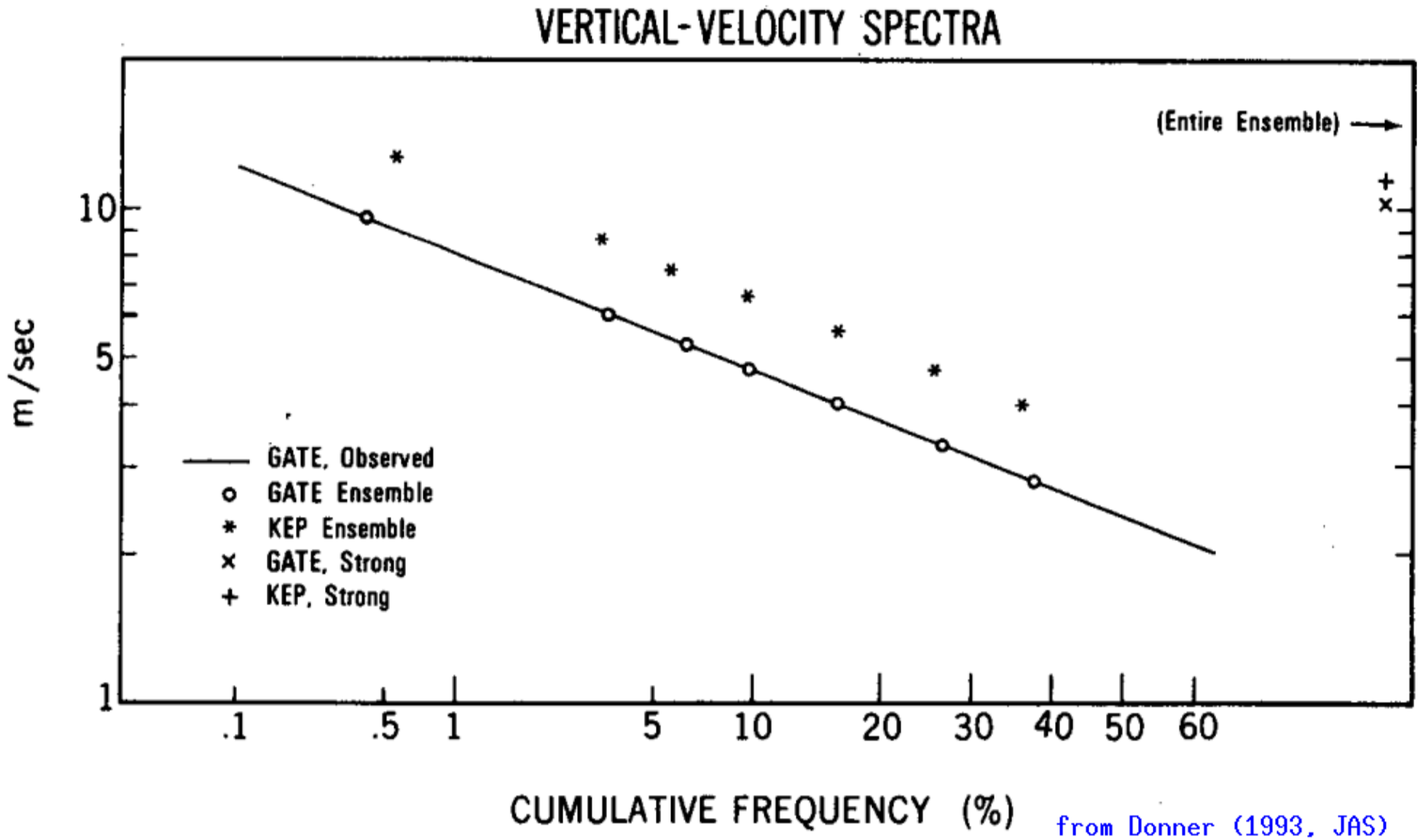
A: "Statistical" Parameterizations, e.g.
Donner (1993, *J. Atmos. Sci.*), Golaz et al. (2002, *J. Atmos. Sci.*)

B: "Classical" Process Studies, e.g., CPT, GCSS

C: Averaging

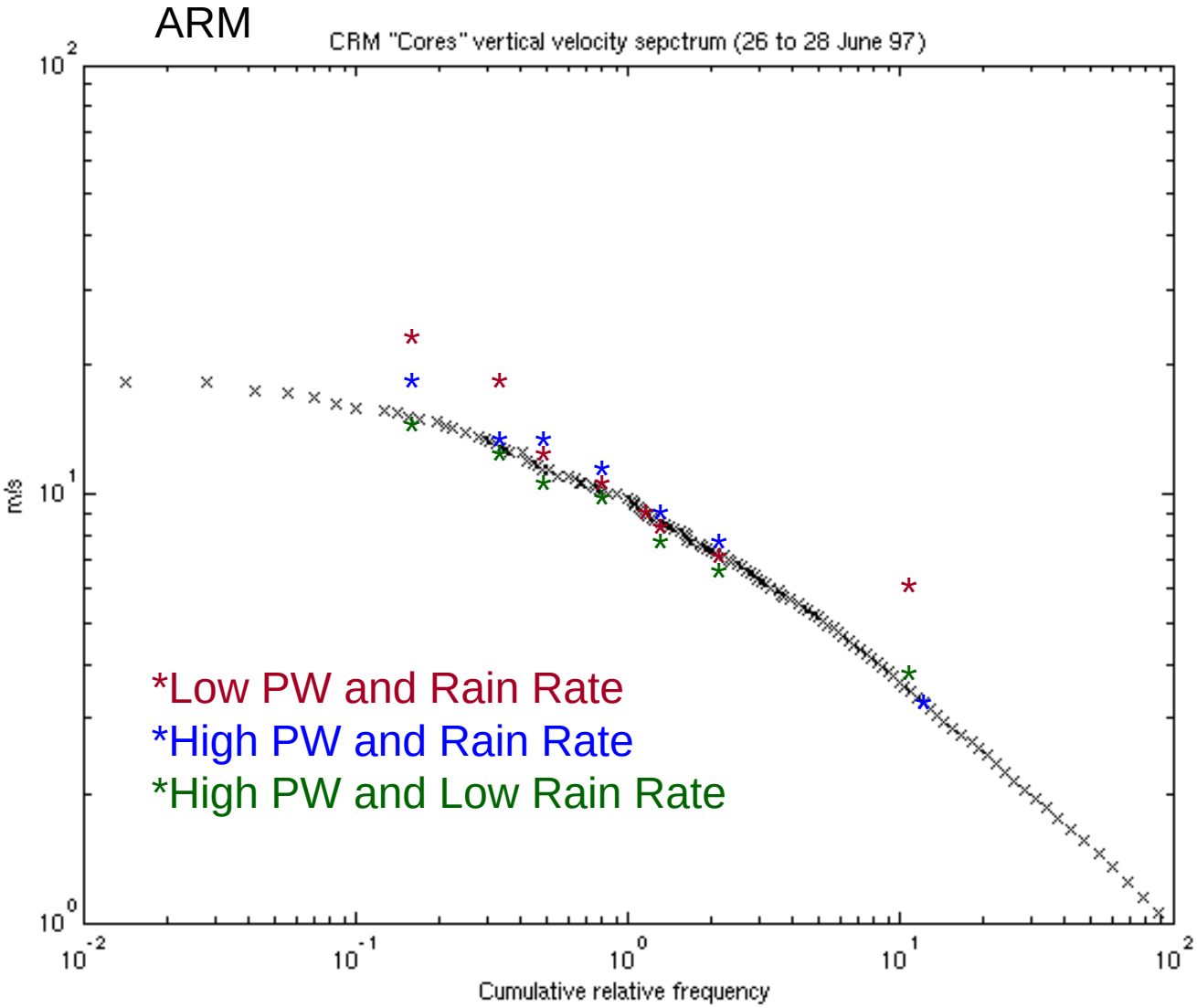
Cumulus Convection

- AM2 (IPCC AR4): Relaxed Arakawa-Schubert (Moorthi and Suarez, 1992, *Mon. Wea. Rev.*) with ensemble of deep and shallow plumes characterized by mass fluxes. Precipitation proportional to condensate.
- AM3 Deep: Donner (2001, *J. Clim.*), Wilcox and Donner (2007, *J. Clim.*) with ensemble of deep plumes with mass fluxes and vertical velocities. Simple bulk microphysics. Mesoscale updrafts and downdrafts.
- AM3 Shallow: Bretherton *et al.* (2004, *Mon. Wea. Rev.*) with buoyancy-sorting, entraining-detraining plume and vertical velocity.



from Donner (1993, JAS)

CRM results provide independent evaluation of entrainment PDF

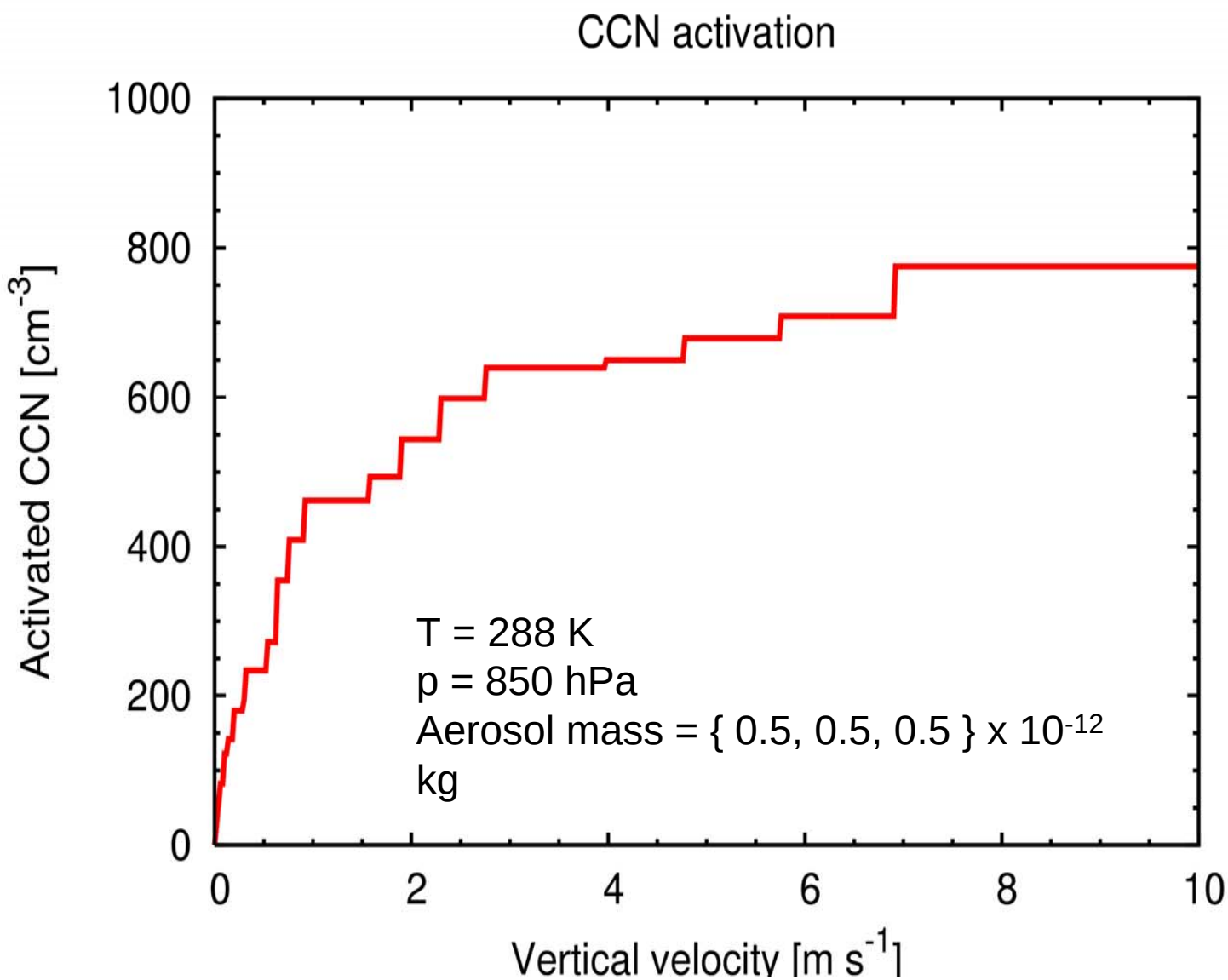


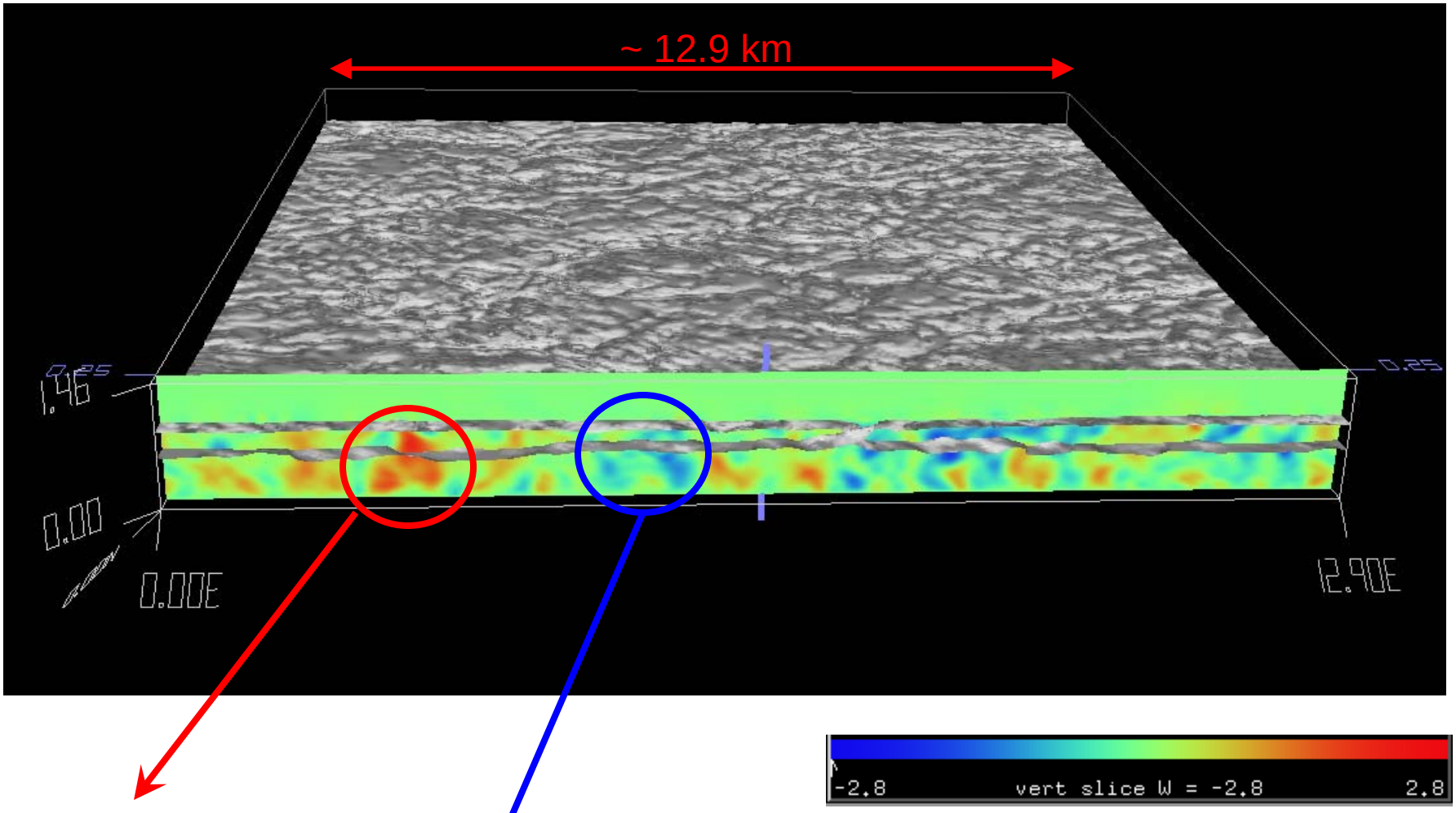
CRM results from Cris Batstone, CDC; *,*,* from Donner (1993) entrainment PDF

Vertical Velocity Variability in Stratiform Clouds

- As in AM2, basic stratiform parameterization is Tiedtke (1993, *Mon. Wea. Rev.*)
- Prognostic cloud fraction; linked to bulk microphysics (Rotstayn, 1997, *QJRMS*)
- Uniform vertical velocity (non-convective grid mean) replaced for purposes of droplet activation

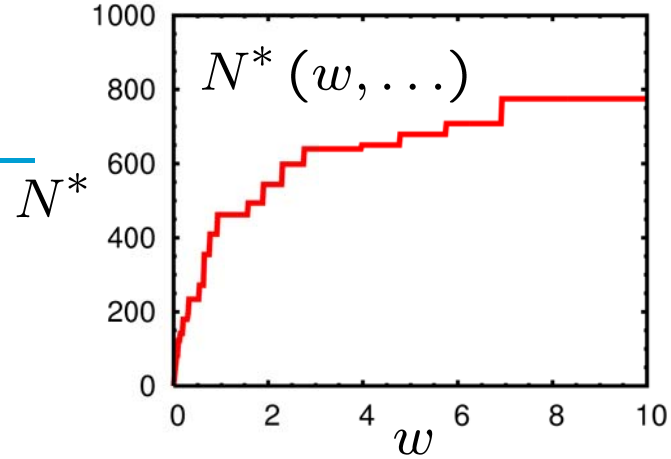
Activation (Ming *et al.*, 2006,*JAS*)





LES by Chris Golaz, GFDL

Large-scale CCN activation



Layer-averaged activation:

$$\overline{N}_{\text{activation}} = \int N^*(w, p, T)\, dx\, dy$$

Because *N** is non-linear

$$\overline{N}_{\text{activation}} \neq N^*(\bar{w}, \bar{p}, \bar{T})$$

However,

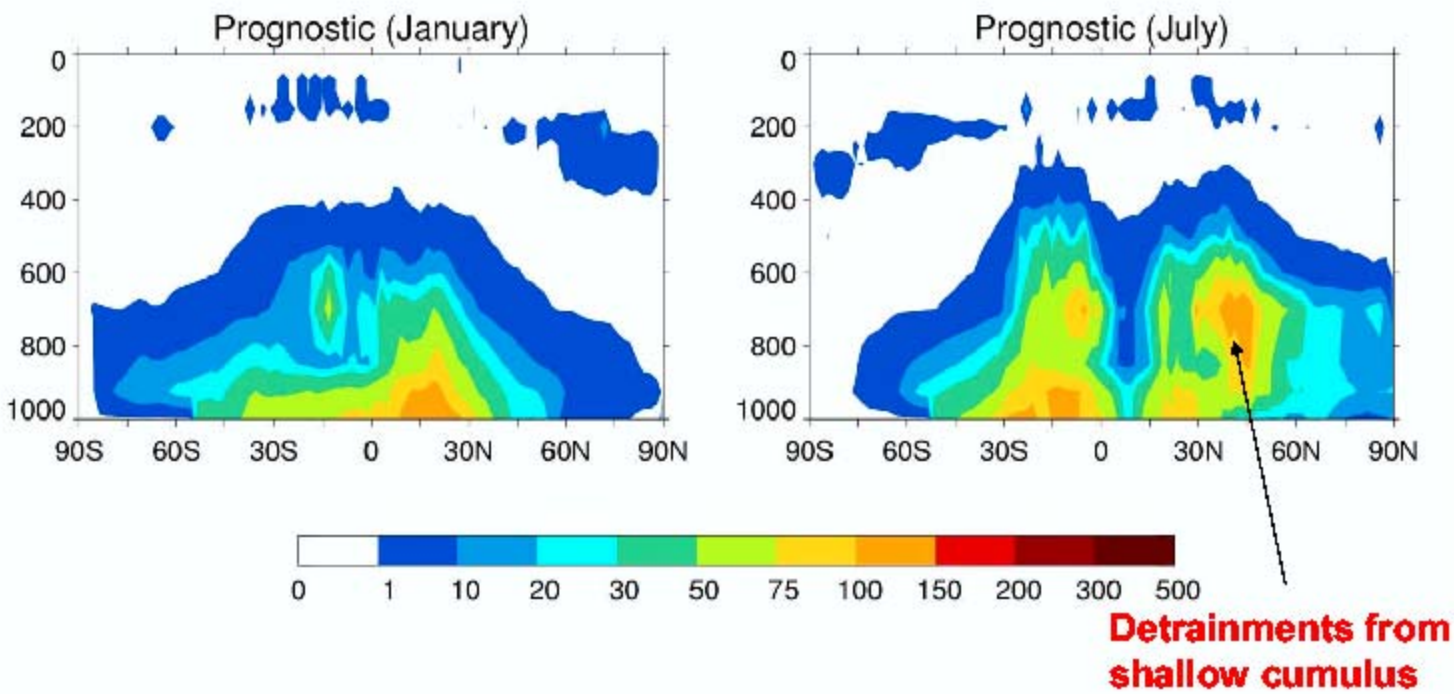
$$\overline{N}_{\text{activation}} \cong \int N^*(w, \bar{p}, \bar{T})\, pdf(w)\, dw$$

Large-scale CCN activation

- In AM2, we don't have $pdf(w)$. For now, assume a Gaussian distribution.
- Distribution width is related **empirically** to mixing coefficients Kh.

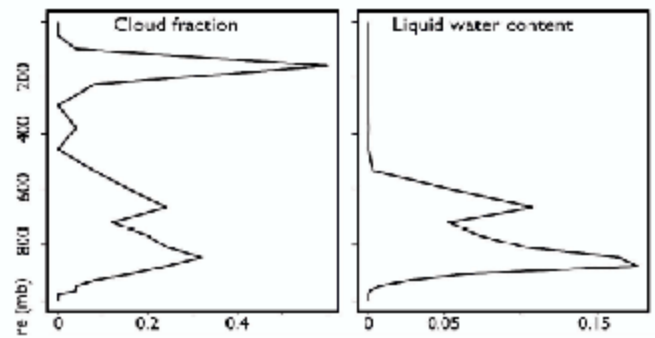
- CCN activation is computed by integration over the distribution using a Gauss-Hermite quadrature.

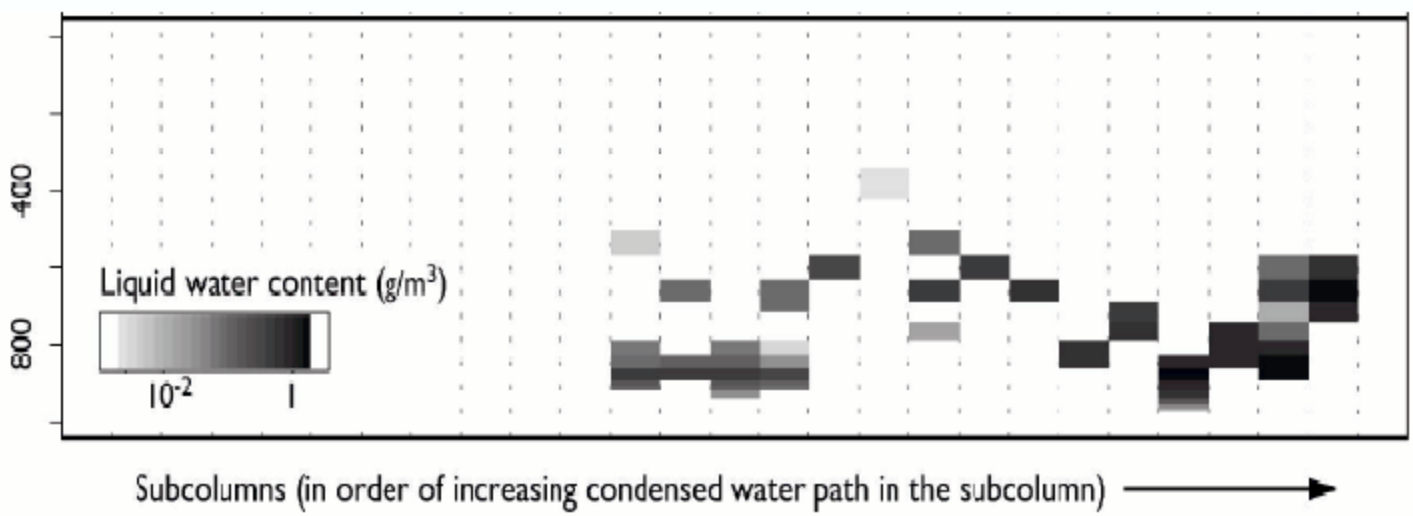
Vertical Distribution of Droplet Number Concentration (cm^{-3})



Design of a MODIS Simulator

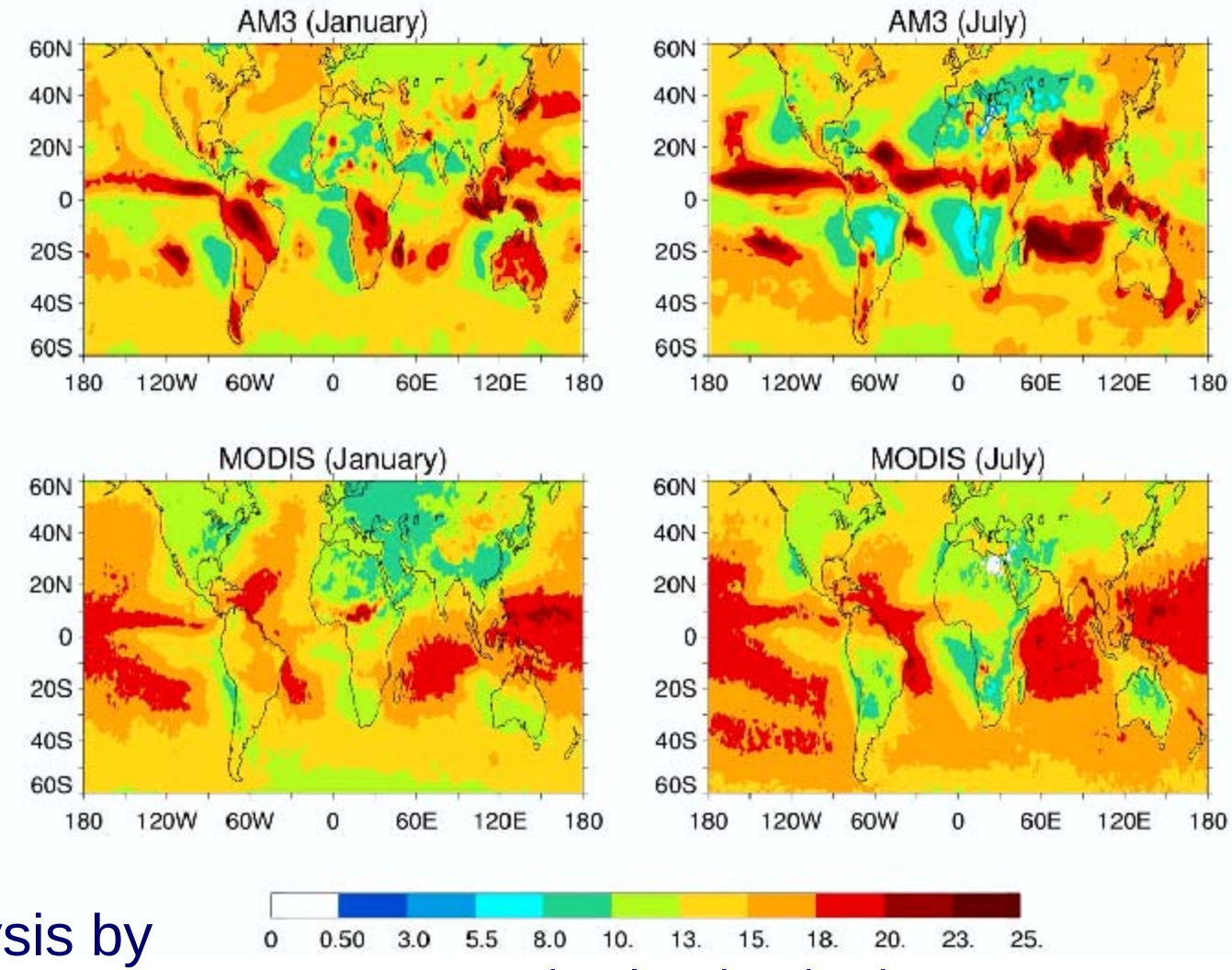
- Subcolumn sampling;
- Downward scanning of every subcolumn;
- Top two cloud optical depth;
- Liquid condensate much greater than ice.





Pincus et al., (2006, 2005)

Comparison with MODIS Retrievals



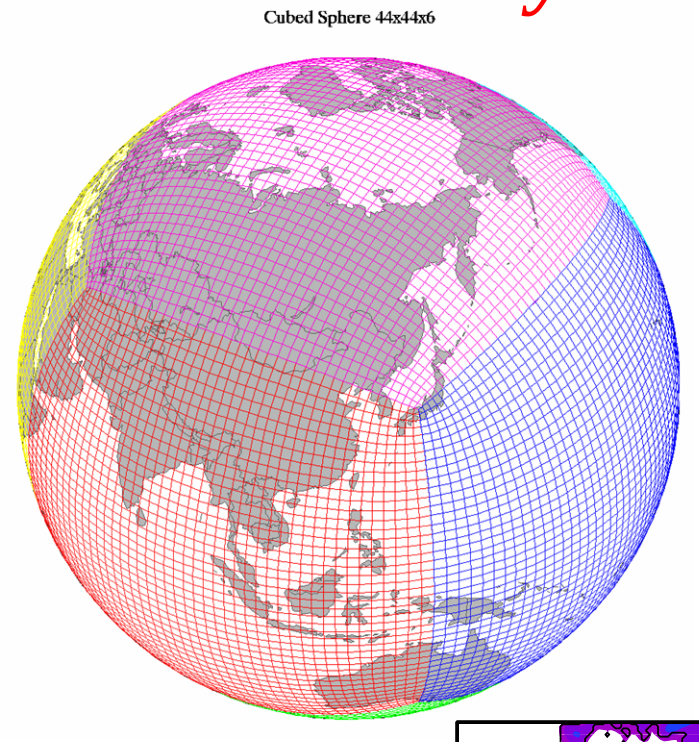
Mean droplet size (µm)

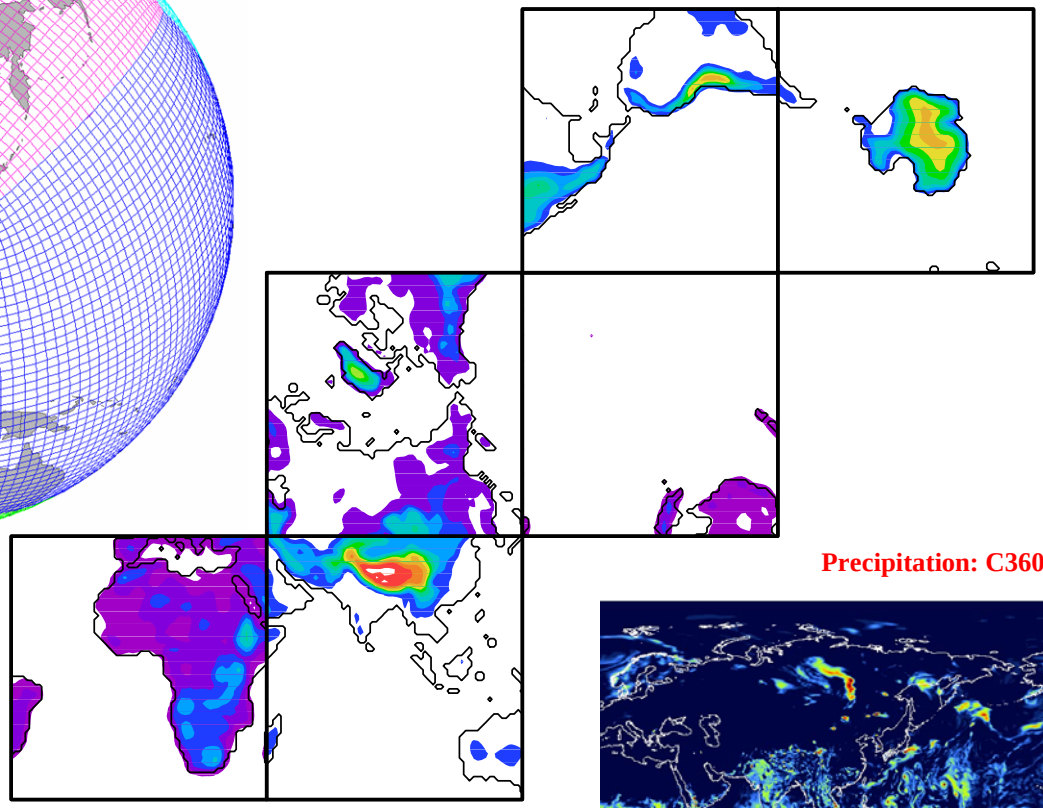
Analysis by
Yi Ming, GFDL

Dynamical Core and Boundary Layer

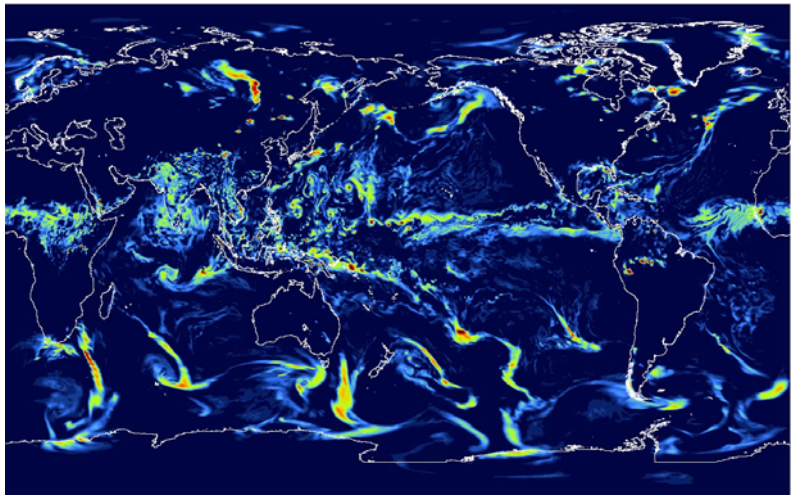
- Finite-volume dy-core (Lin, 2004, *Mon. Wea. Rev.*)
- Cubed-sphere implementation, composed of 6 rectangular domains
- No singularity associated with spherical pole
- PBL, as in AM2, follows Lock *et al.* (2001, *J. Atmos. Sci.*)

3 ways to visualize the Cubed Sphere



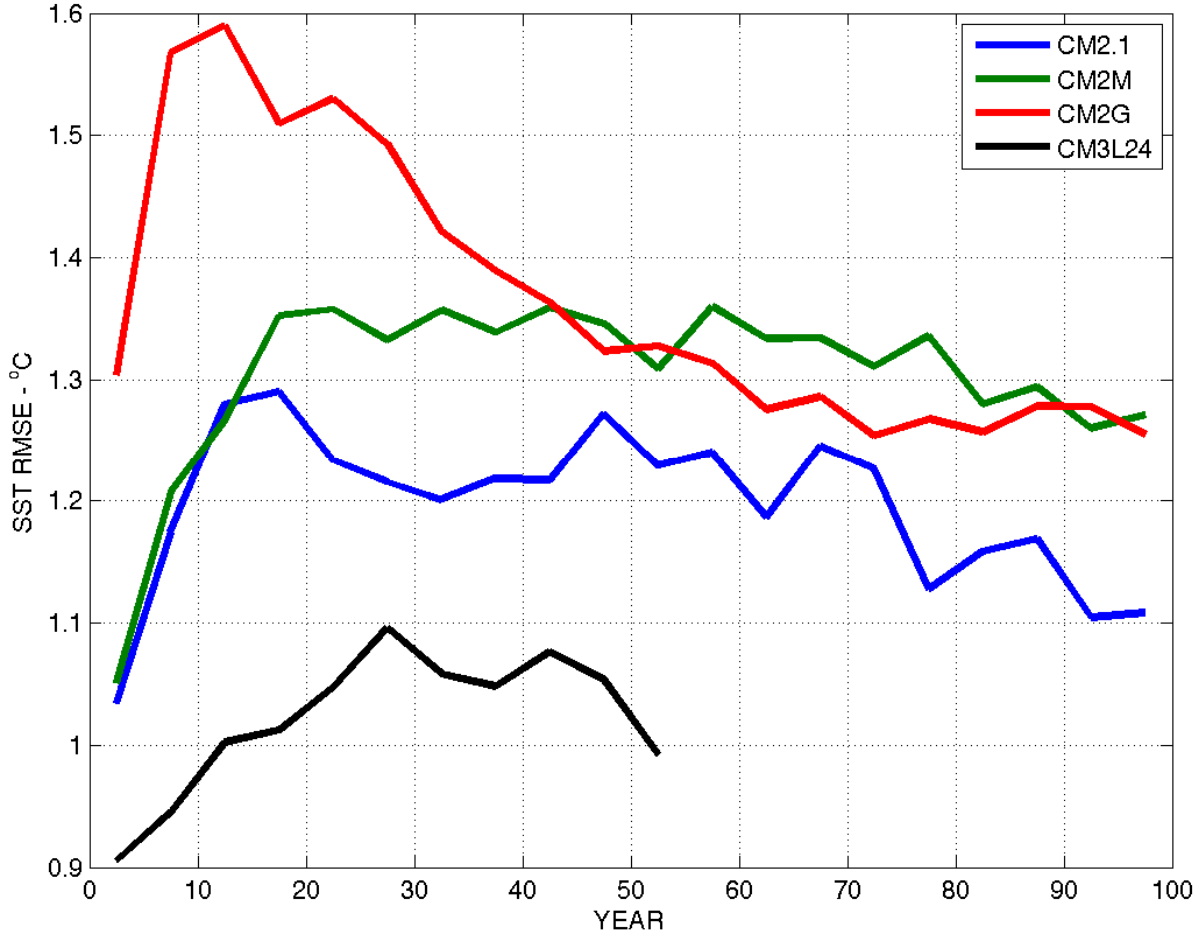


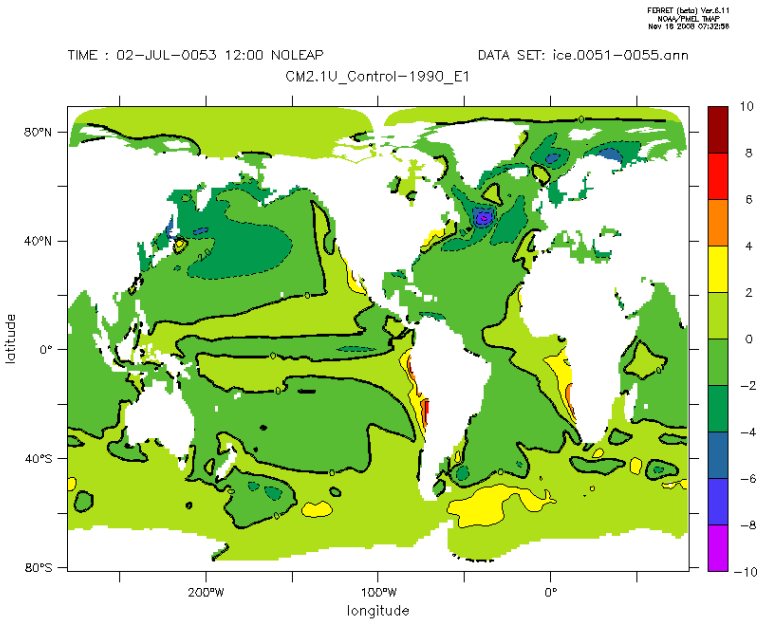
Precipitation: C360 HiRam-2

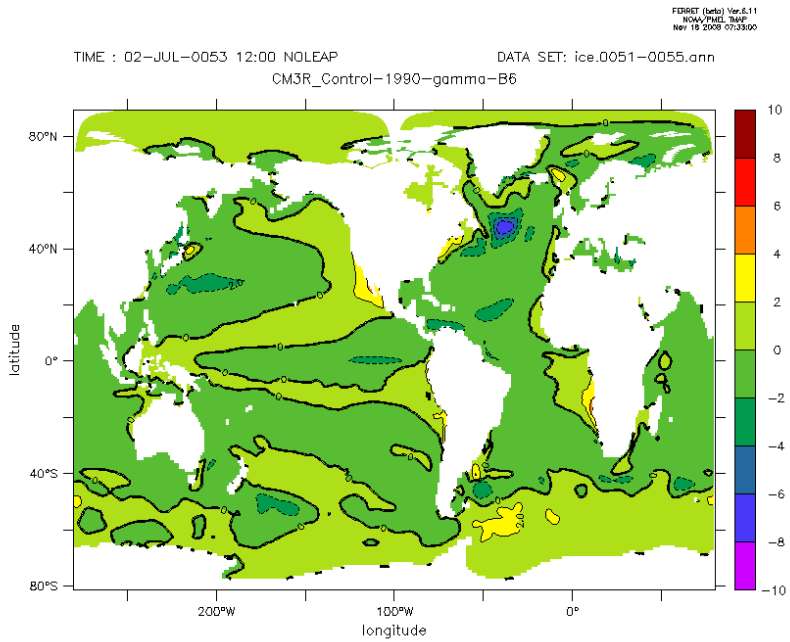


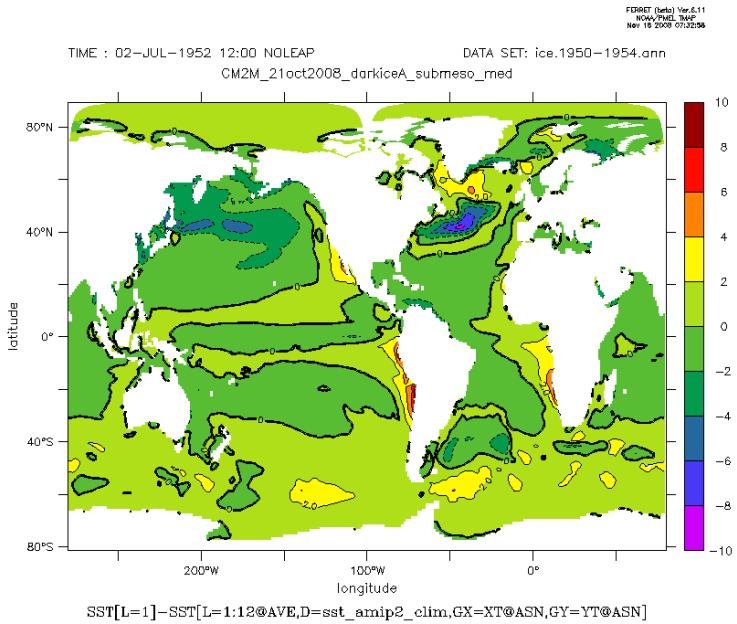
Selected Features of CM3 Climate

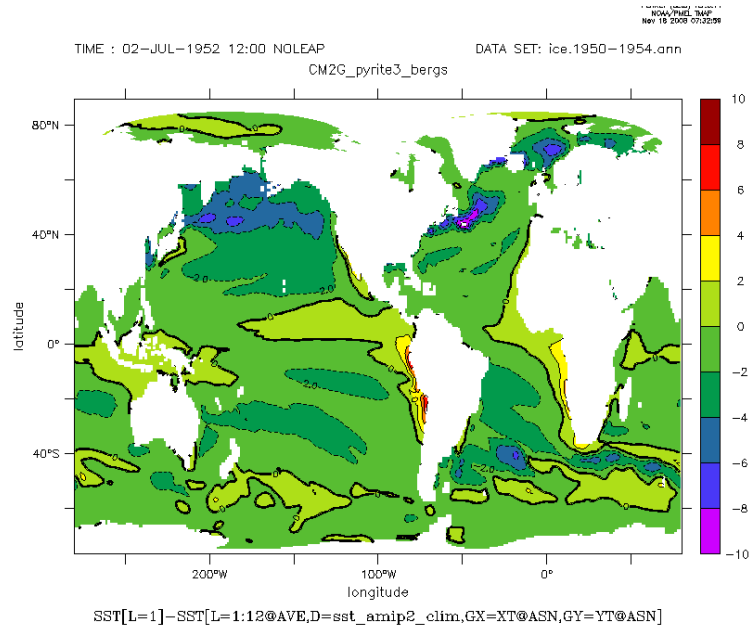
Global Mean SST Errors in CM2 and CM3



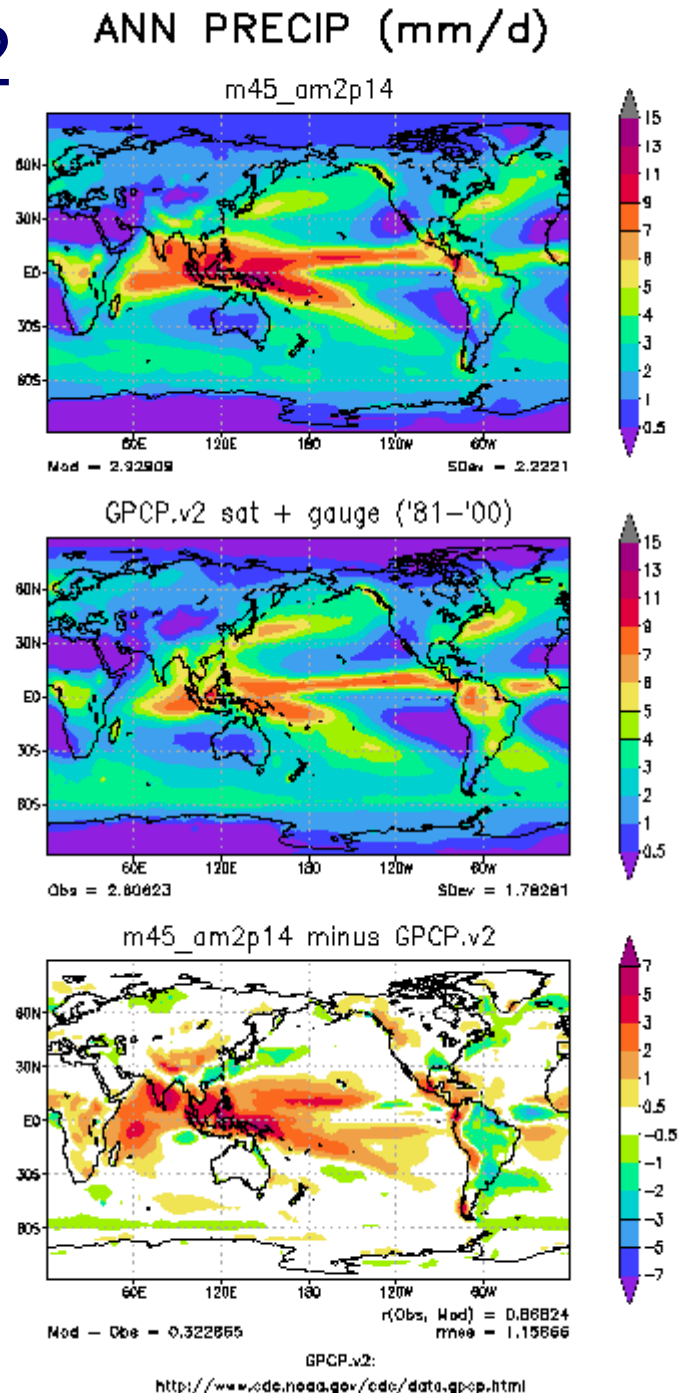

FERRET (beta) Ver.6.11
NOAA/PMEL TMAP
Nov 18 2008 07:32:58
TIME : 02-JUL-0053 12:00 NOLEAP
DATA SET: ice.0051-0055.ann
CM2.1U_Control-1990_E1
80°N
40°N
0°
40°S
80°S
latitude
200°W
100°W
0°
longitude
10
8
6
4
2
0
-2
-4
-6
-8
-10
SST[L=1]-SST[L=1:12@AVE,D=sst_amip2_clim,GX=XT@ASN,GY=YT@ASN]


FERRET (beta) Ver.6.11
NOAA/PMEL TMAP
Nov 18 2008 07:33:00
TIME : 02-JUL-0053 12:00 NOLEAP
DATA SET: ice.0051-0055.ann
CM3R_Control-1990-gamma-B6
80°N
40°N
0°
40°S
80°S
latitude
200°W
100°W
0°
longitude
10
8
6
4
2
0
-2
-4
-6
-8
-10
SST[L=1]-SST[L=1:12@AVE,D=sst_amip2_clim,GX=XT@ASN,GY=YT@ASN]

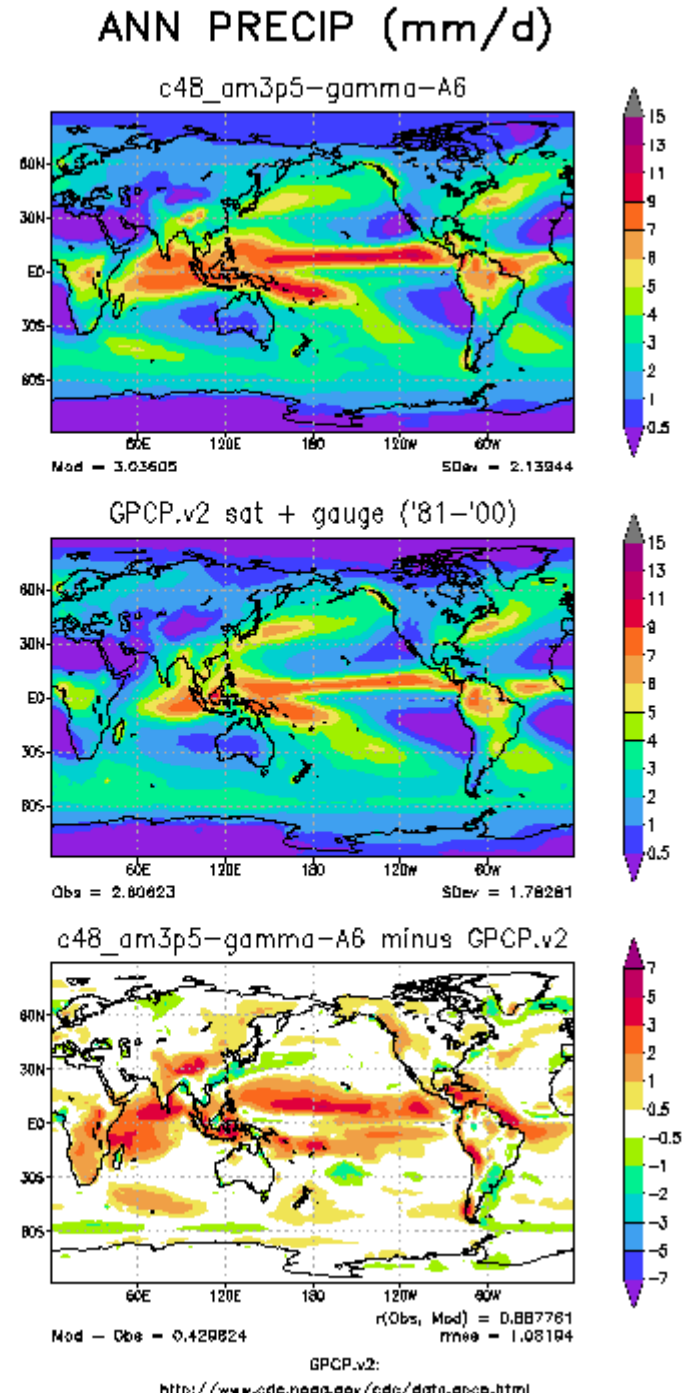

FERRET (beta) Ver.6.11
NOAA/PMEL TMAP
Nov 18 2008 07:32:56
TIME : 02-JUL-1952 12:00 NOLEAP
DATA SET: ice.1950-1954.ann
CM2M_21oct2008_darkiceA_submeso_med
80°N
40°N
0°
40°S
80°S
latitude
200°W
100°W
0°
longitude
10
8
6
4
2
0
-2
-4
-6
-8
-10
SST[L=1]-SST[L=1:12@AVE,D=sst_amip2_clim,GX=XT@ASN,GY=YT@ASN]

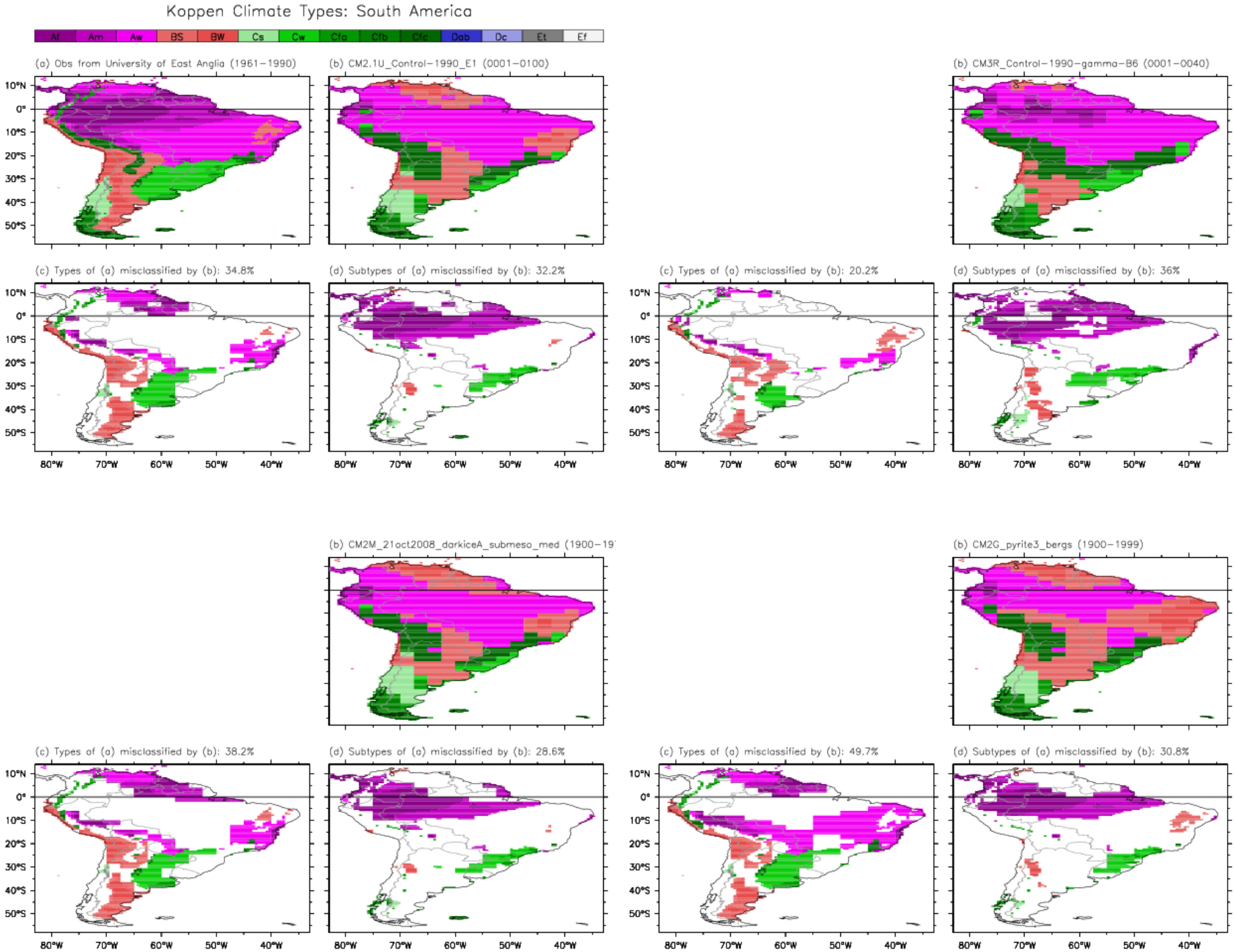

NOAA/PMEL TMAP
Nov 18 2008 07:32:59
TIME : 02-JUL-1952 12:00 NOLEAP
DATA SET: ice.1950-1954.ann
CM2G_pyrite3_bergs
80°N
40°N
0°
40°S
latitude
200°W
100°W
0°
longitude
10
8
6
4
2
0
-2
-4
-6
-8
-10
SST[L=1]-SST[L=1:12@AVE,D=sst_amip2_clim,GX=XT@ASN,GY=YT@ASN]

AM 2


ANN PRECIP (mm/d)
m45_am2p14
Mod = 2.92909
SDev = 2.2221
GPCP.v2 sat + gauge ('81–'00)
Obs = 2.80623
SDev = 1.78281
m45_am2p14 minus GPCP.v2
Mod – Obs = 0.322865
r(Obs, Mod) = 0.86824
rmse = 1.15666
GPCP.v2:
http://www.cdc.noaa.gov/cdc/data.gpcp.html

AM 3

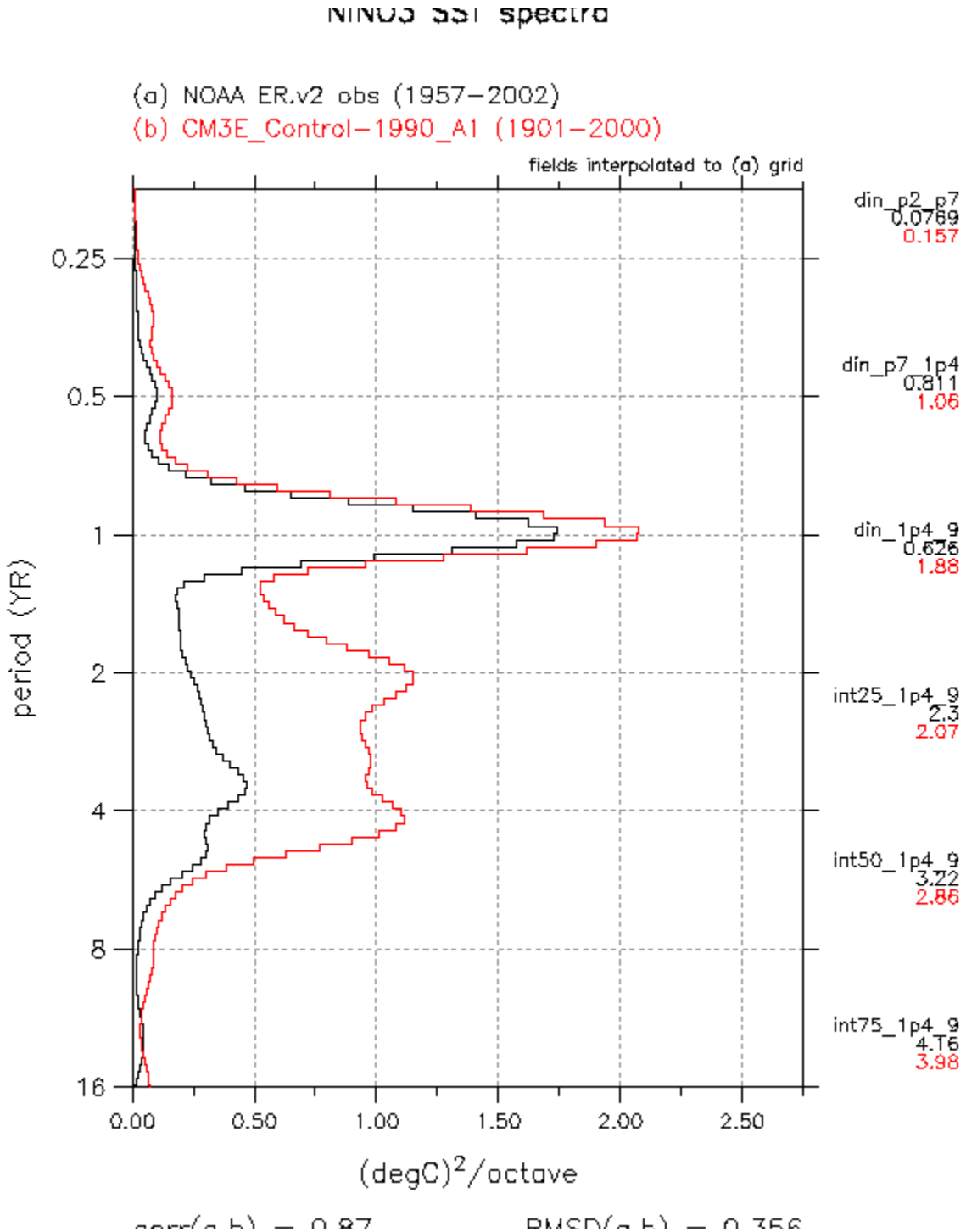

ANN PRECIP (mm/d)
c48_am3p5–gamma–A6
Mod = 3.03605
SDev = 2.13944
GPCP.v2 sat + gauge ('81–'00)
Obs = 2.80623
SDev = 1.78281
c48_am3p5–gamma–A6 minus GPCP.v2
Mod – Obs = 0.429824
r(Obs, Mod) = 0.887761
rmse = 1.08194
GPCP.v2:


Koppen Climate Types: South America
Af
Am
Aw
BS
BW
Cs
Cw
Cfa
Cfb
Cfc
Dab
Dc
Et
Ef
(a) Obs from University of East Anglia (1961–1990)
(b) CM2.1U_Control-1990_E1 (0001–0100)
(b) CM3R_Control-1990-gamma-B6 (0001–0040)
(c) Types of (a) misclassified by (b): 34.8%
(d) Subtypes of (a) misclassified by (b): 32.2%
(c) Types of (a) misclassified by (b): 20.2%
(d) Subtypes of (a) misclassified by (b): 36%
(b) CM2M_21oct2008_darkiceA_submeso_med (1900–19
(b) CM2G_pyrite3_bergs (1900–1999)
(c) Types of (a) misclassified by (b): 38.2%
(d) Subtypes of (a) misclassified by (b): 28.6%
(c) Types of (a) misclassified by (b): 49.7%
(d) Subtypes of (a) misclassified by (b): 30.8%
10°N
0°
10°S
20°S
30°S
40°S
50°S
80°W
70°W
60°W
50°W
40°W

Transients are exhibiting strong dependence on details of closure for cumulus parameterization

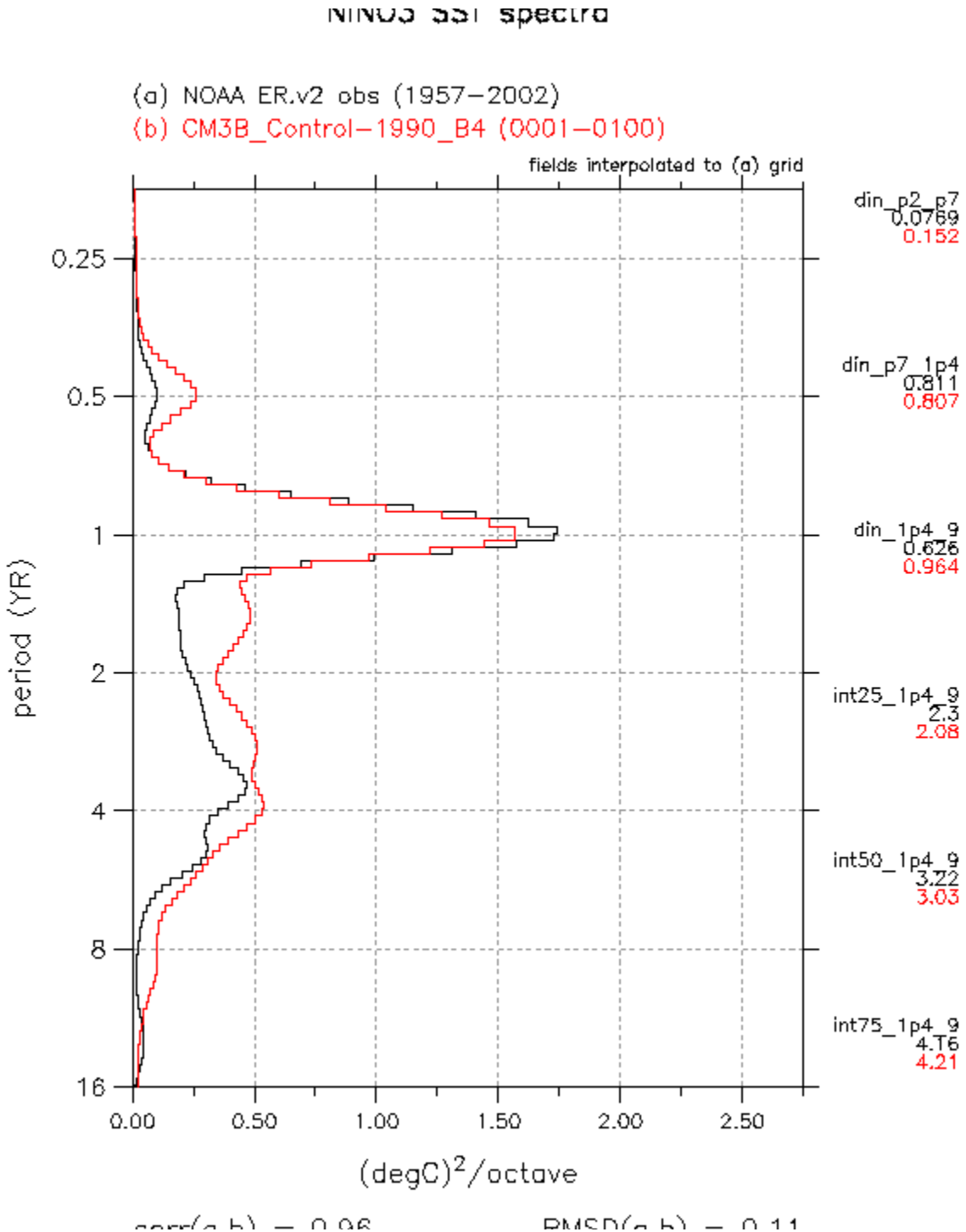
CAPE relax closure

Ocean Coupling



Zhang (2002, *JGR*) closure

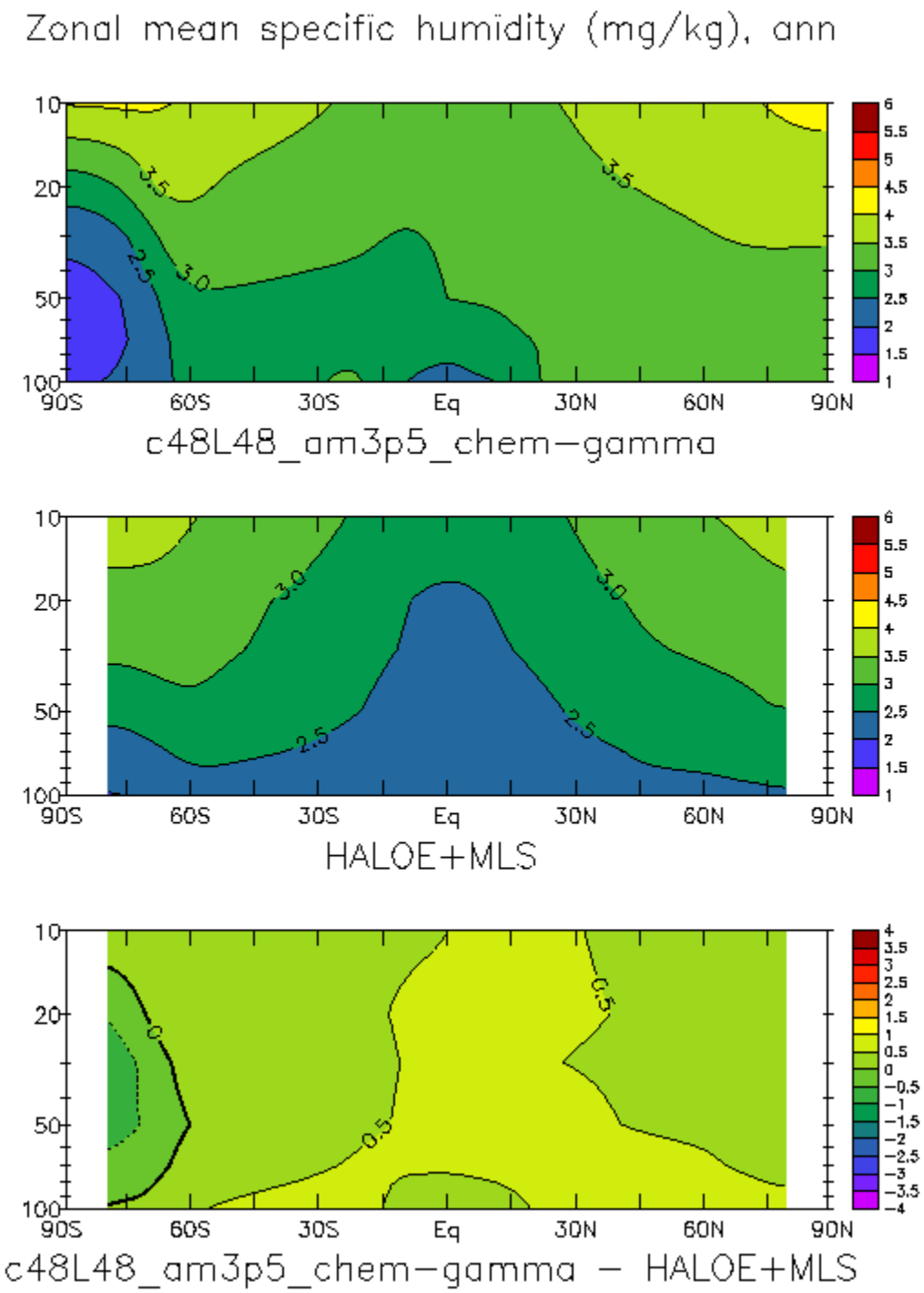
Ocean Coupling



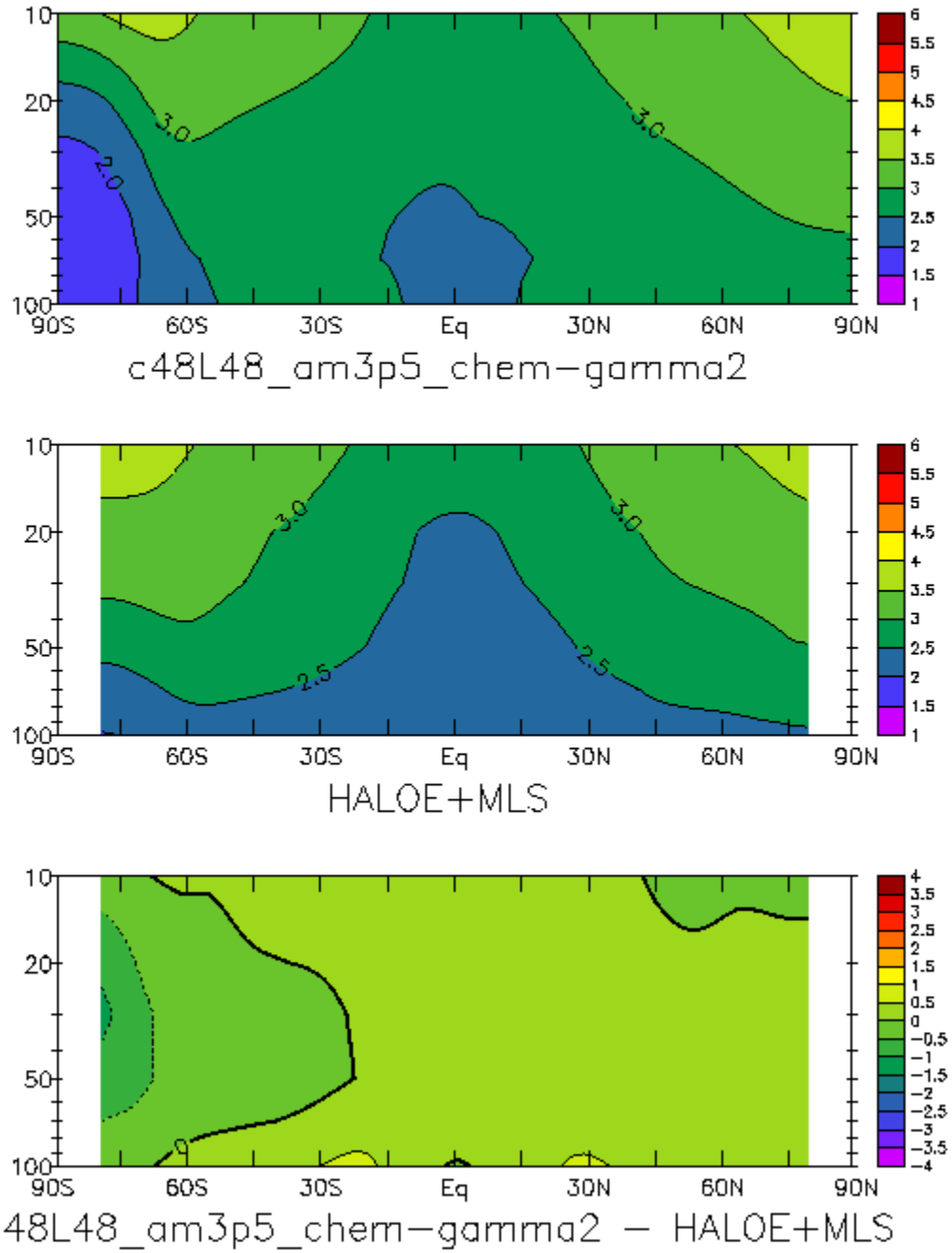
Development Issues-Injection of Water Vapor into Stratosphere

- Donner (2003, *J. Clim.*) cumulus parameterization allows overshooting towers and stratospheric water vapor injection
- Stratospheric water vapor sensitive to details of cumulus closure

Convective cells and mesoscale circulations allowed to puncture tropopause.



Zonal mean specific humidity (mg/kg), ann



Convective cells allowed to puncture tropopause

"Indirect Effect" and 20th Century Climate

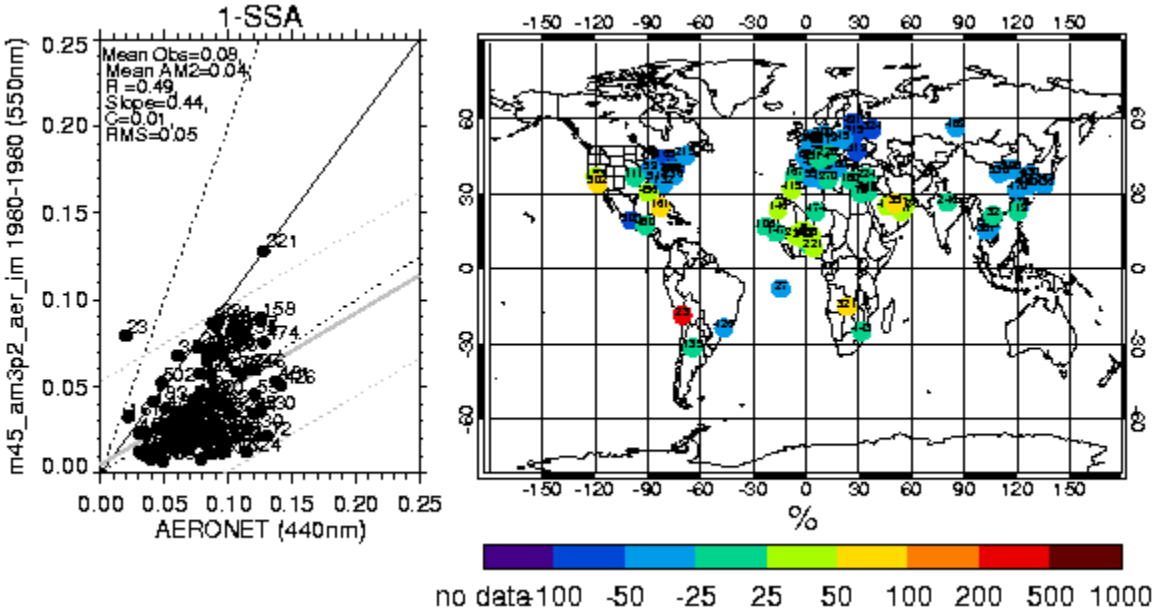
- AM2 (IPCC AR4) Sulfate+OC+BC forcing ~ -0.4 W m^{-2} (external mix)
- AM2 Sulfate+OC+BC Pre-Industrial -> Present-Day Radiative Flux Perturbation (RFP) ~ -0.8 W m^{-2} (external mix)
- Aerosol-cloud interaction AM with external mix RFP ~ -3.0 W m^{-2}
- Aerosol-cloud interaction AM with sulfate-hydrophilic carbon internal mix ~ -1.6 W m^{-2}

AM2 and AM3: Indicators of 20th Century Warming

- AM2 RFP: 1.3 W m^{-2} (GHG: 2.1 W m^{-2} ; Aerosol: -0.8 W m^{-2})
- AM2 Cess Sensitivity: 1.6 W m^{-2} K^{-1}
- AM2 RFP/Sensitivity: 0.8 K
- AM3 RFP: 0.9 W m^{-2} (GHG: 2.5 W m^{-2} ; Aerosol: -1.6 W m^{-2})
- AM3 Cess Sensitivity: 1.3 W m^{-2} K^{-1}
- AM3 RFP/Sensitivity: 0.7 K
- RFP is PI -> PD TOA radiative flux perturbation with fixed PD SST

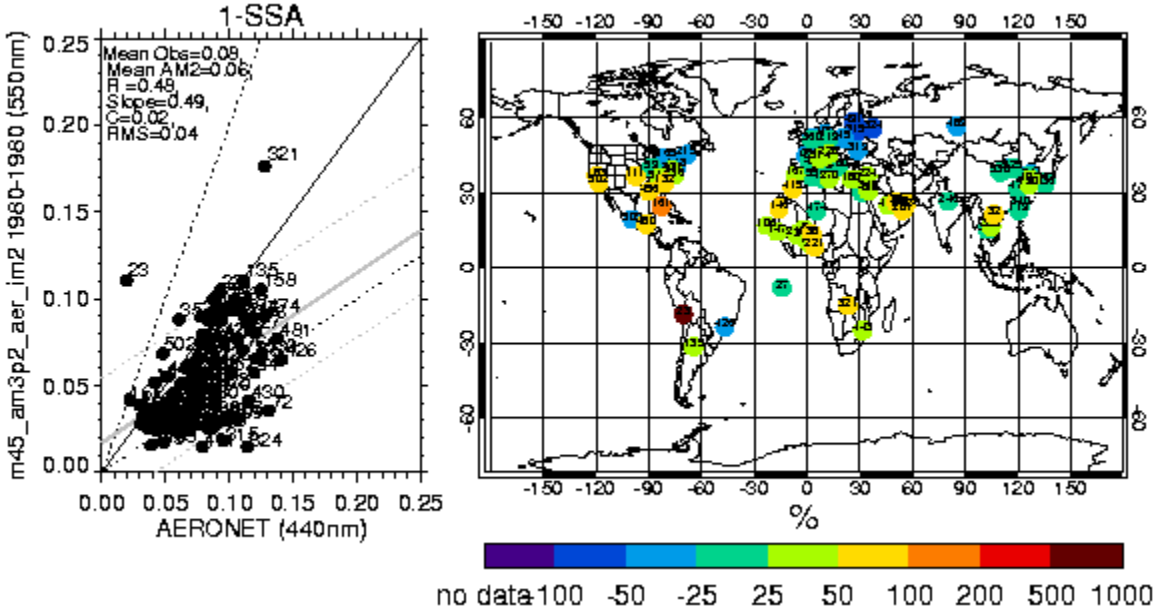
External Mixture

Increased absorption using internal mixture agrees better with Aeronet.



Internal Mixture-Sulfate and Hydrophilic Carbon

Analysis by Paul Ginoux, GFDL



ARM Interactions

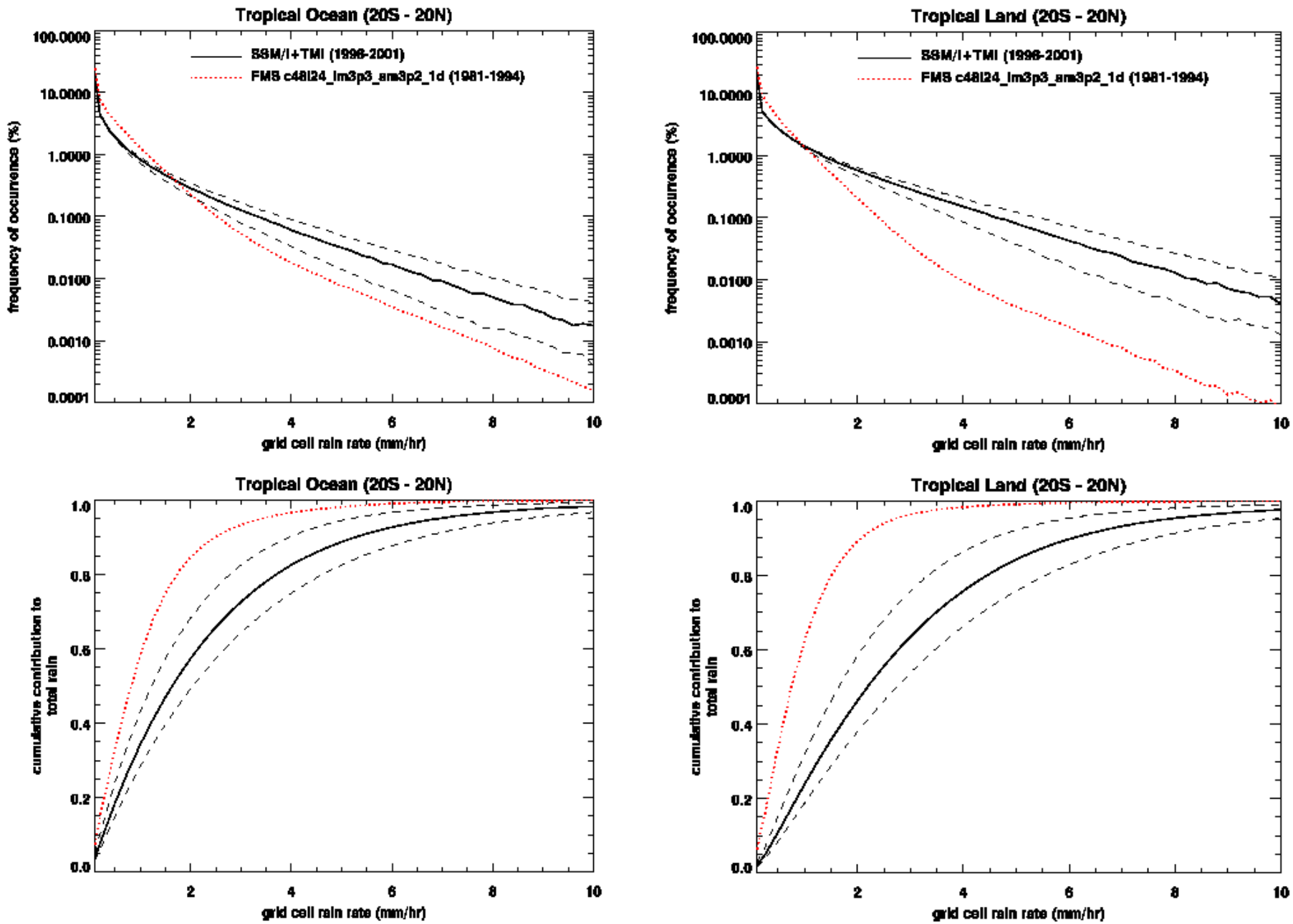
- Vertical velocity spectra are now key elements of parameterizations for convective and stratiform clouds. Candidates for testing with ARM cloud vertical velocities.
- SCM tests of new parameterizations with ARM cases.
- CSRM integrations for ARM cases. Evaluation of physical processes in GCM parameterization against CSRM.
- CAPT evaluations.

Summary

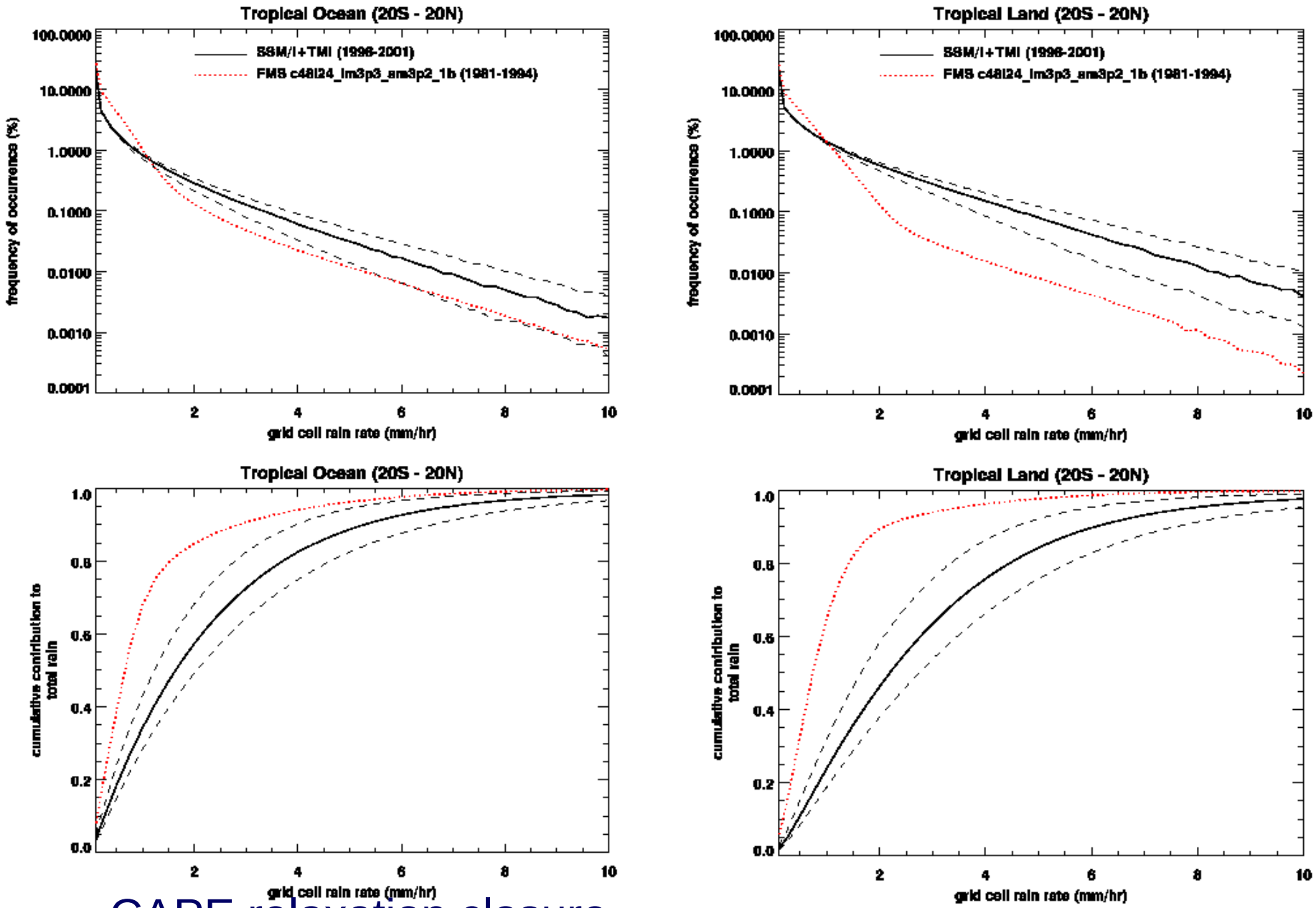
- Cloud-aerosol interactions ("indirect effect"), atmospheric chemistry, and increased troposphere-stratosphere coupling are key developments in GFDL AM for AR5
- Physics changes required for cloud-aerosol interaction include macrophysics (sub-grid vertical velocity PDFs) for convective and stratiform clouds and microphysics (aerosol activation)
- Increased vertical resolution and chemistry for stratosphere-troposphere coupling

Excessive Cooling by Indirect Effect (Lohmann *et al.*, 2007, *BAMS)* ?

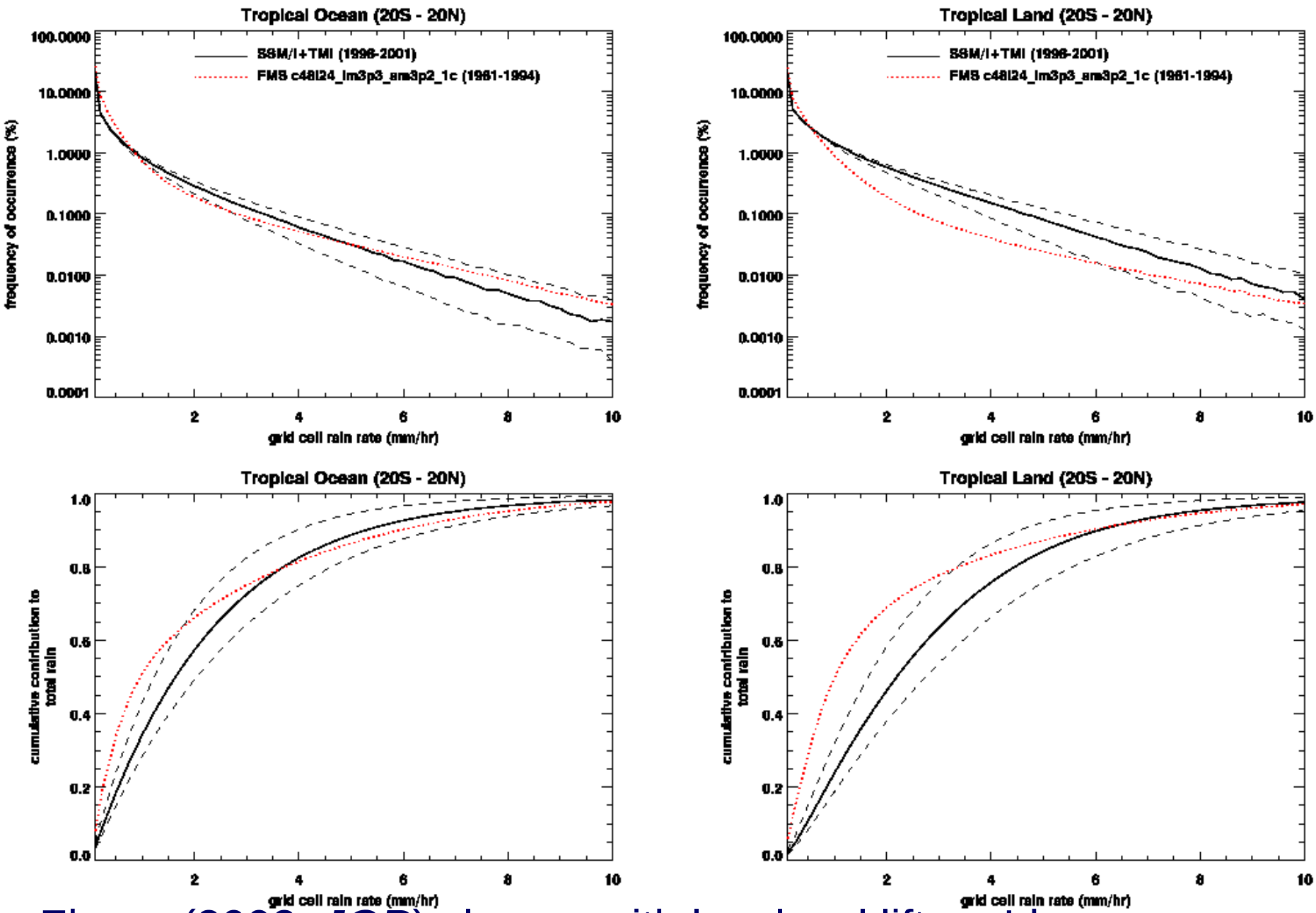
- Less direct effect (internal mixing)
- Extent of warm-cloud nucleation by organics
- PI – PD aerosol concentrations
- Warming by ice cloud-aerosol interactions
- Dispersion and other microphysics
- Cloud-scale instabilities limiting increased liquid at high aerosol (Ackerman *et al.,* 2004, *Nature)*
- Fundamental issues with cloud macrophysics, N.B., ERBE net cloud forcing ~ -20 W m^{-2}



Zhang (2002, *JGR*) closure without low-level lift req'd

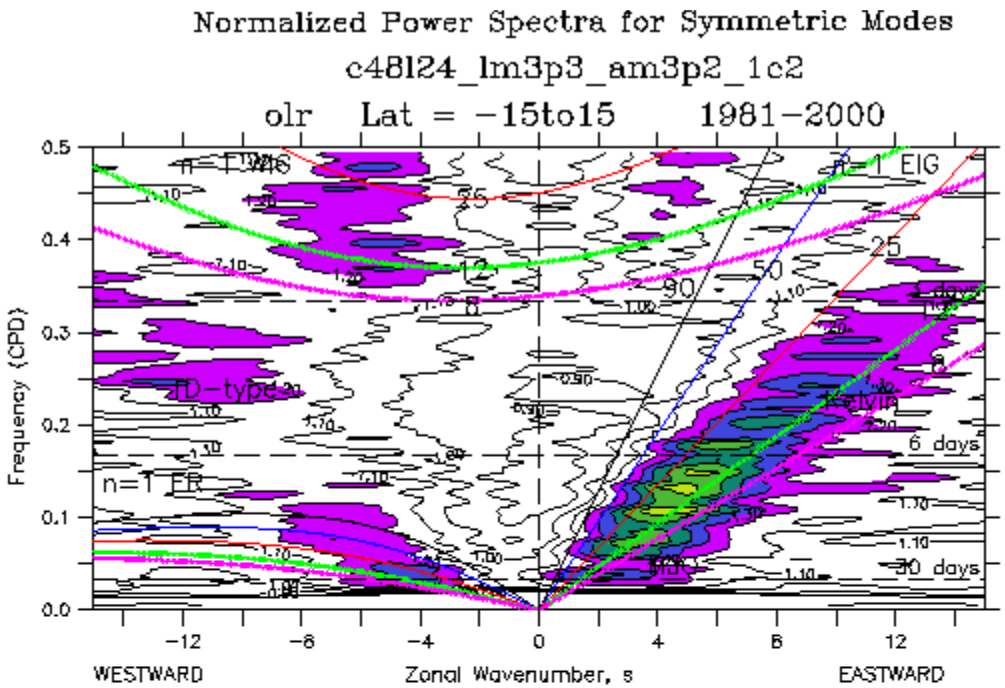


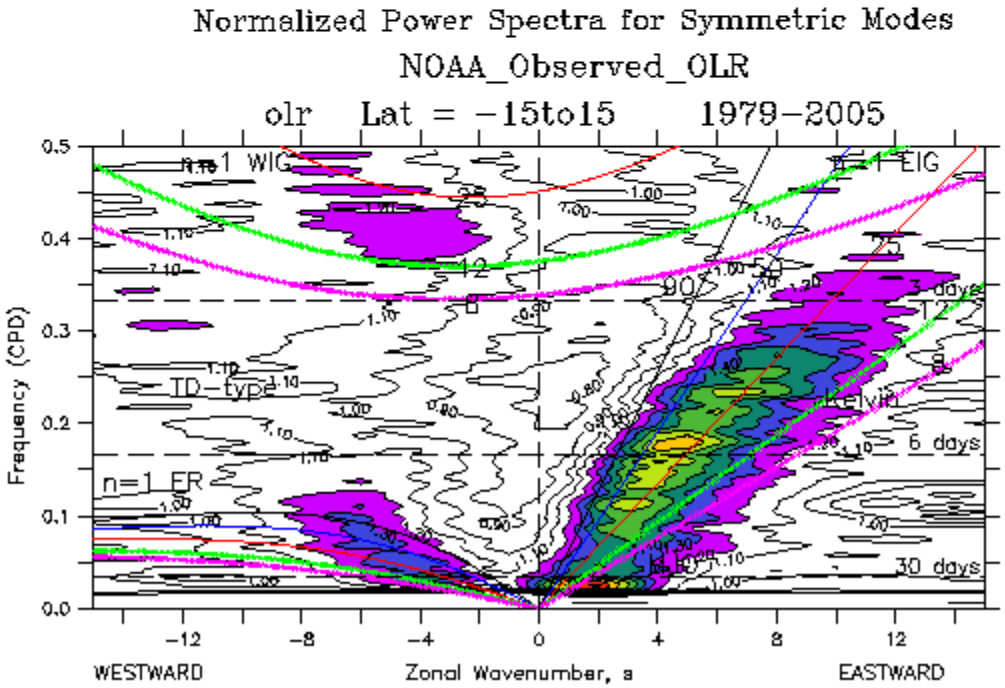
CAPE relaxation closure



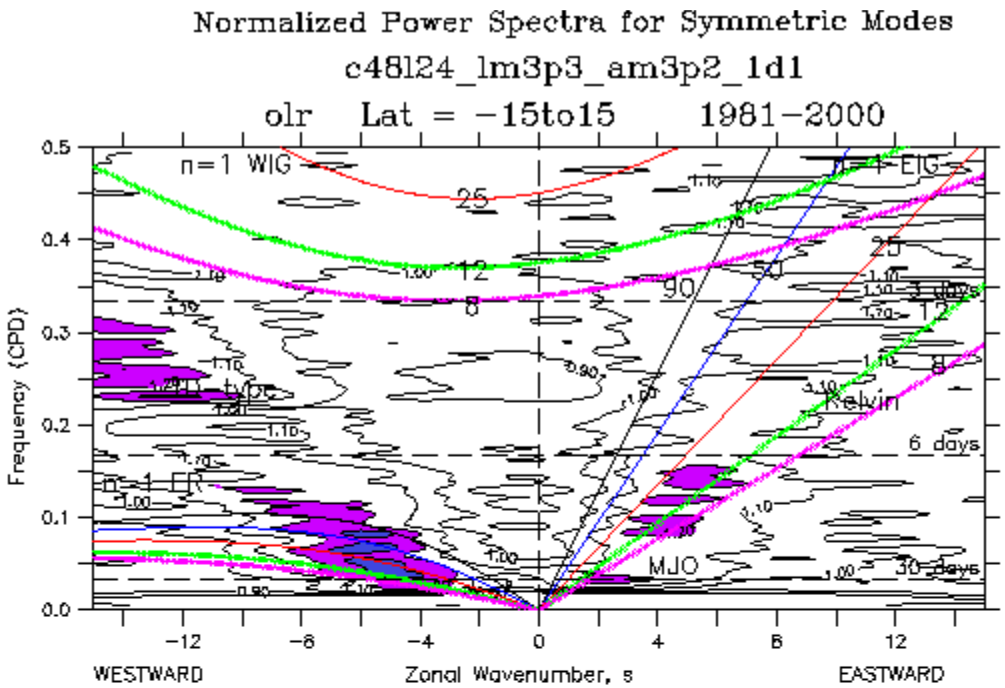
Zhang (2002, *JGR*) closure with low-level lift req'd

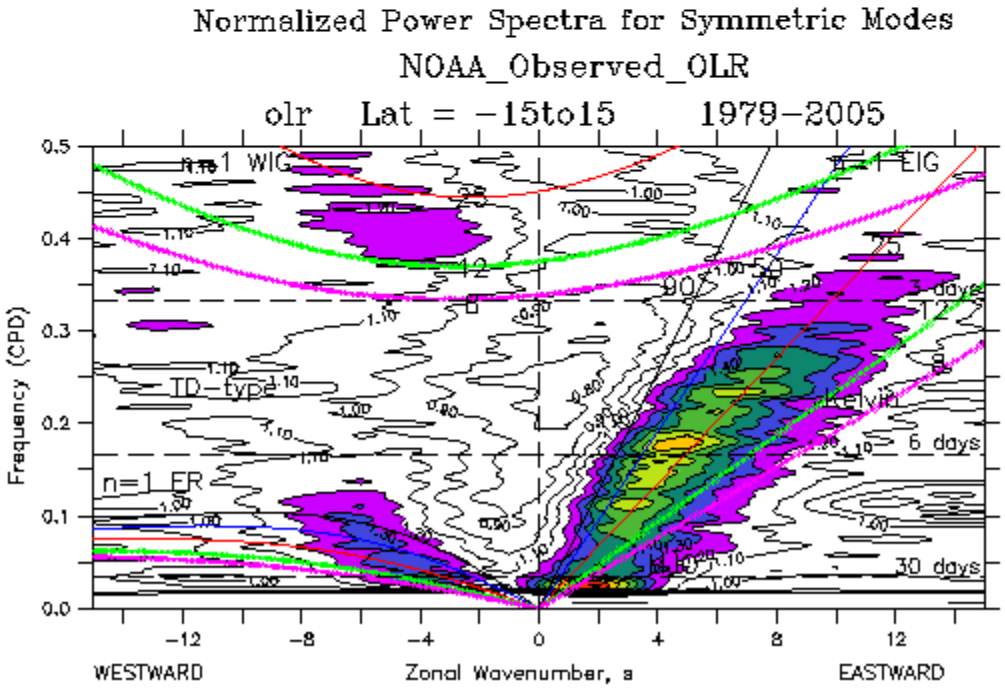
Zhang (2002, *JGR*) closure w/ low-level lift req'd



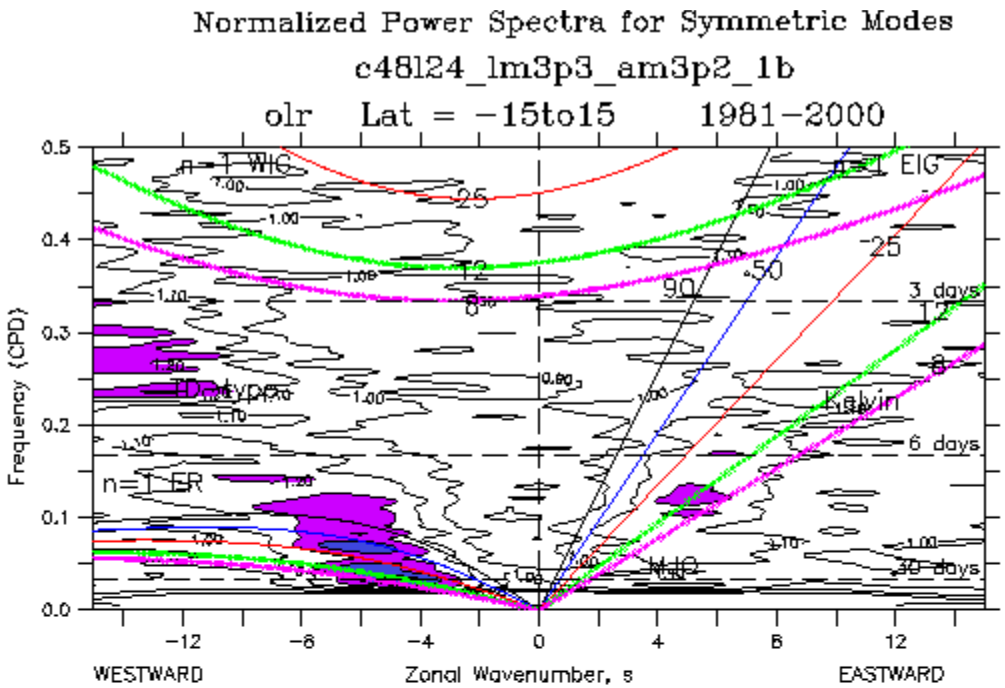


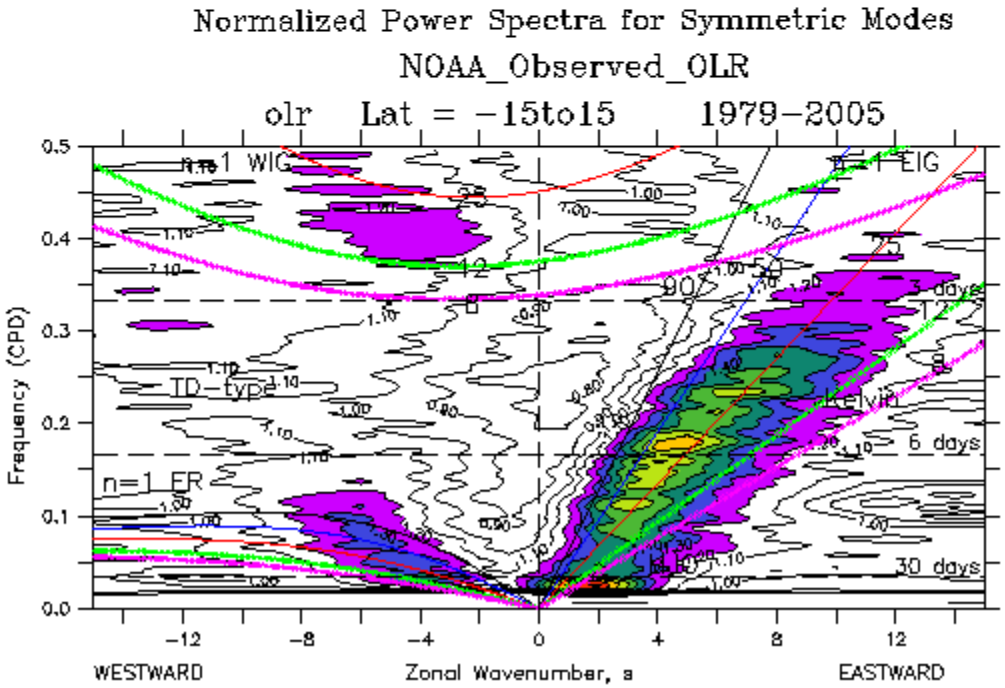
Zhang (2006, *JGR*) without low-level lift req'd



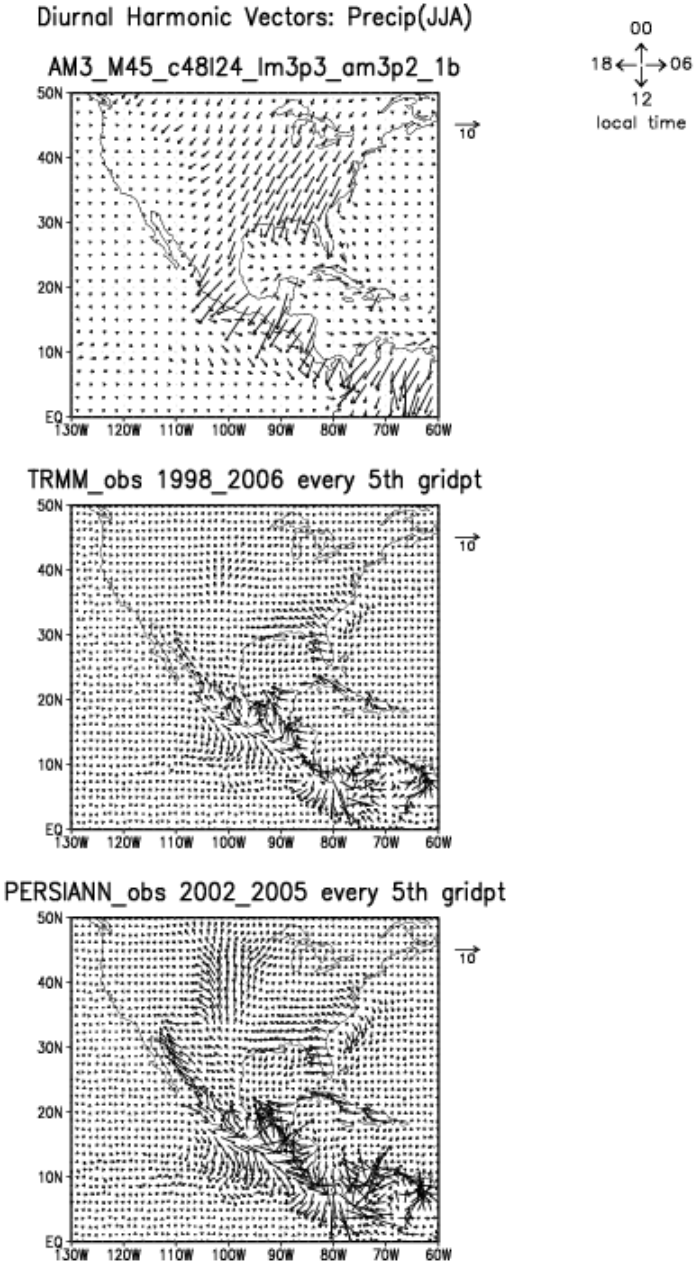


CAPE relaxation closure

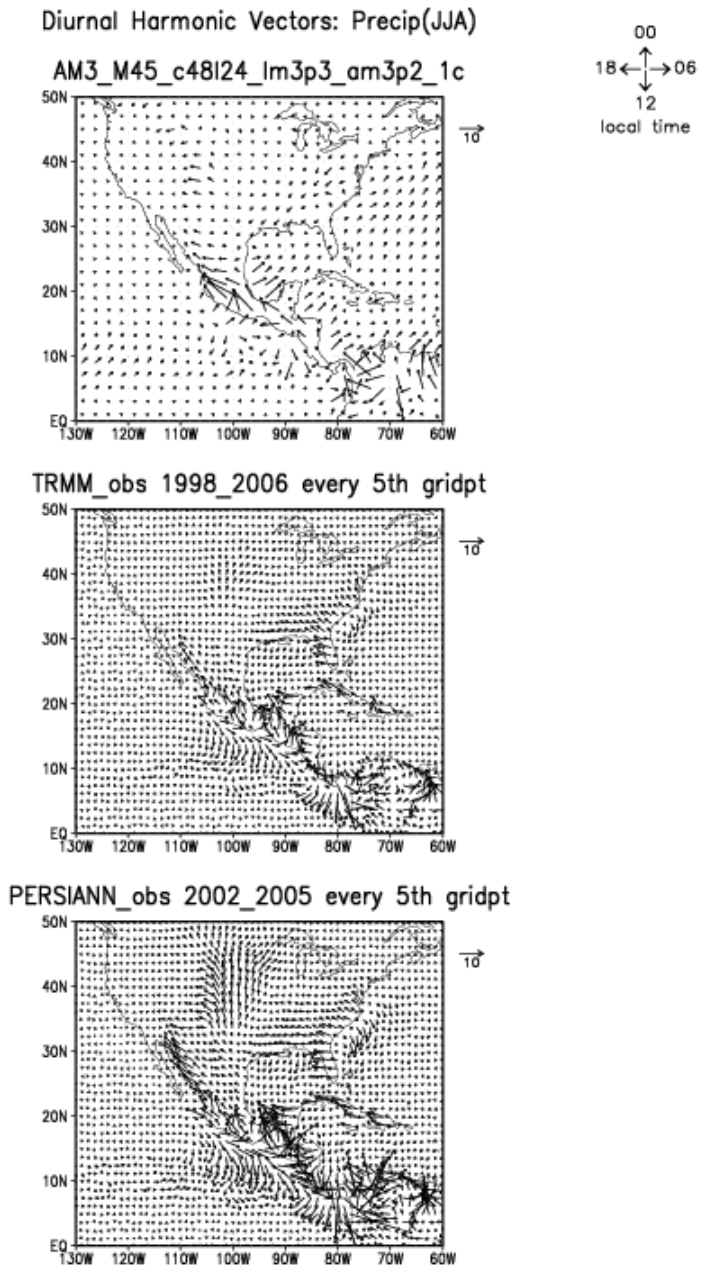
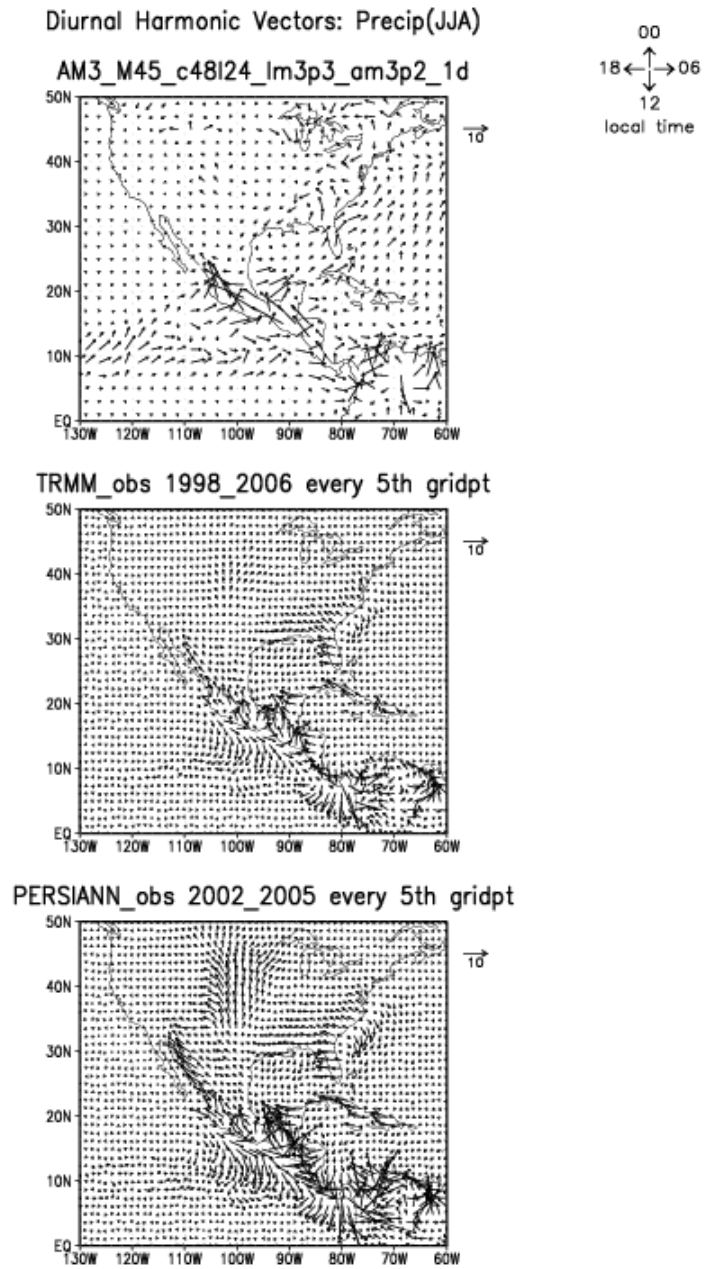




CAPE relaxation closure



Zhang (2002, *JGR*) closure with low-level lift req'd



Zhang (2002, *JGR*) closure without low-level lift req'd