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# Recent Developments of Physical Parameterizations in GFDL Atmospheric GCMs

Leo Donner, Yi Ming, Andrew Wittenberg, Mike, Winton, Bill Stern, Ming Zhao, Chris Golaz,  
Paul Ginoux, Larry Horowitz, Jeff Ploshay, S.-J. Lin, Charles Seman

GFDL/NOAA, Princeton University

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





# New Science Questions for Next-Generation Model

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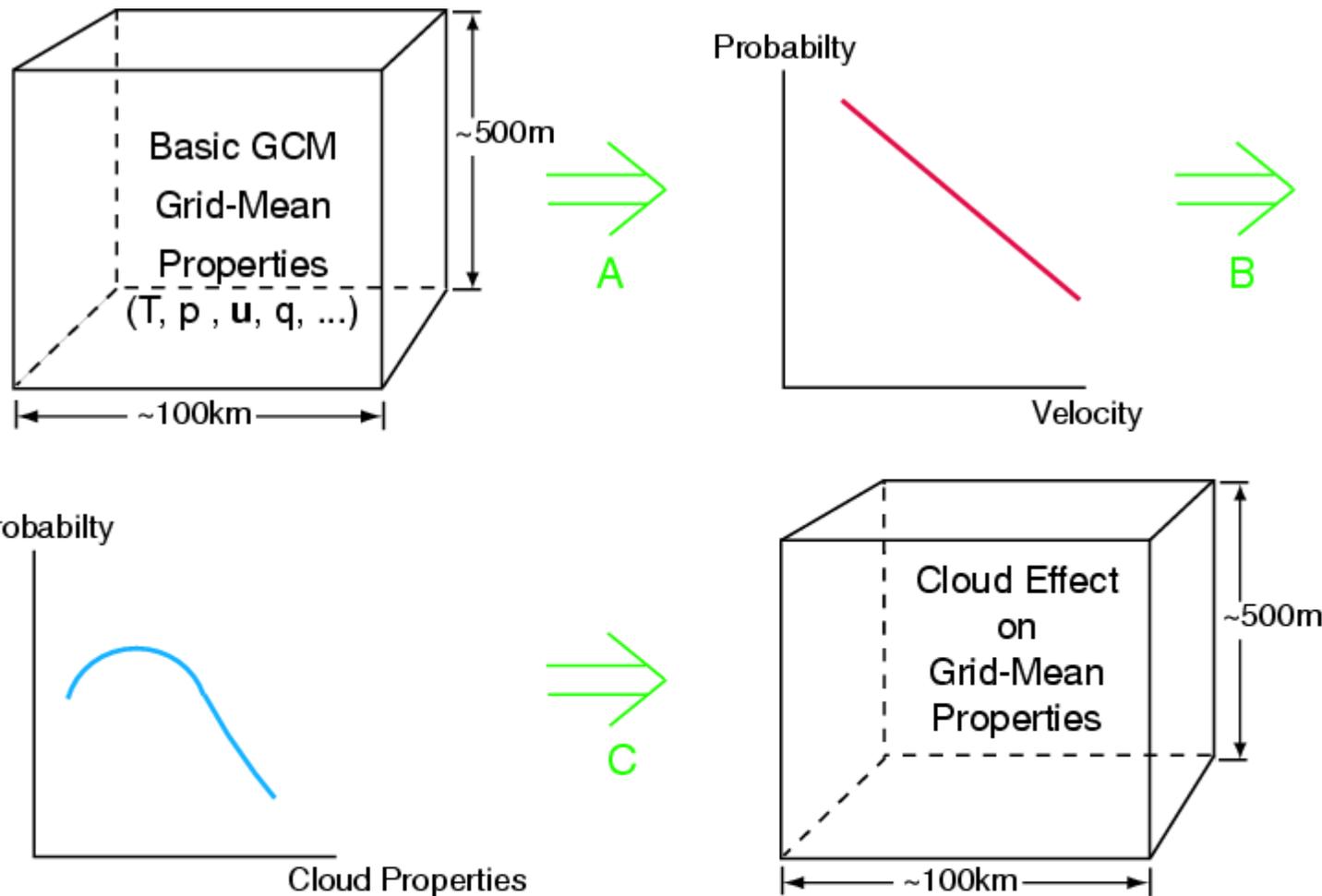
- What are the roles of aerosol-cloud interactions in climate and climate change?
- How will land and ocean carbon cycles interact with climate change?
- To what extent is decadal prediction possible?
- What are the dominant chemistry-climate feedbacks?



# Model Development to Address New Scientific Questions

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- 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



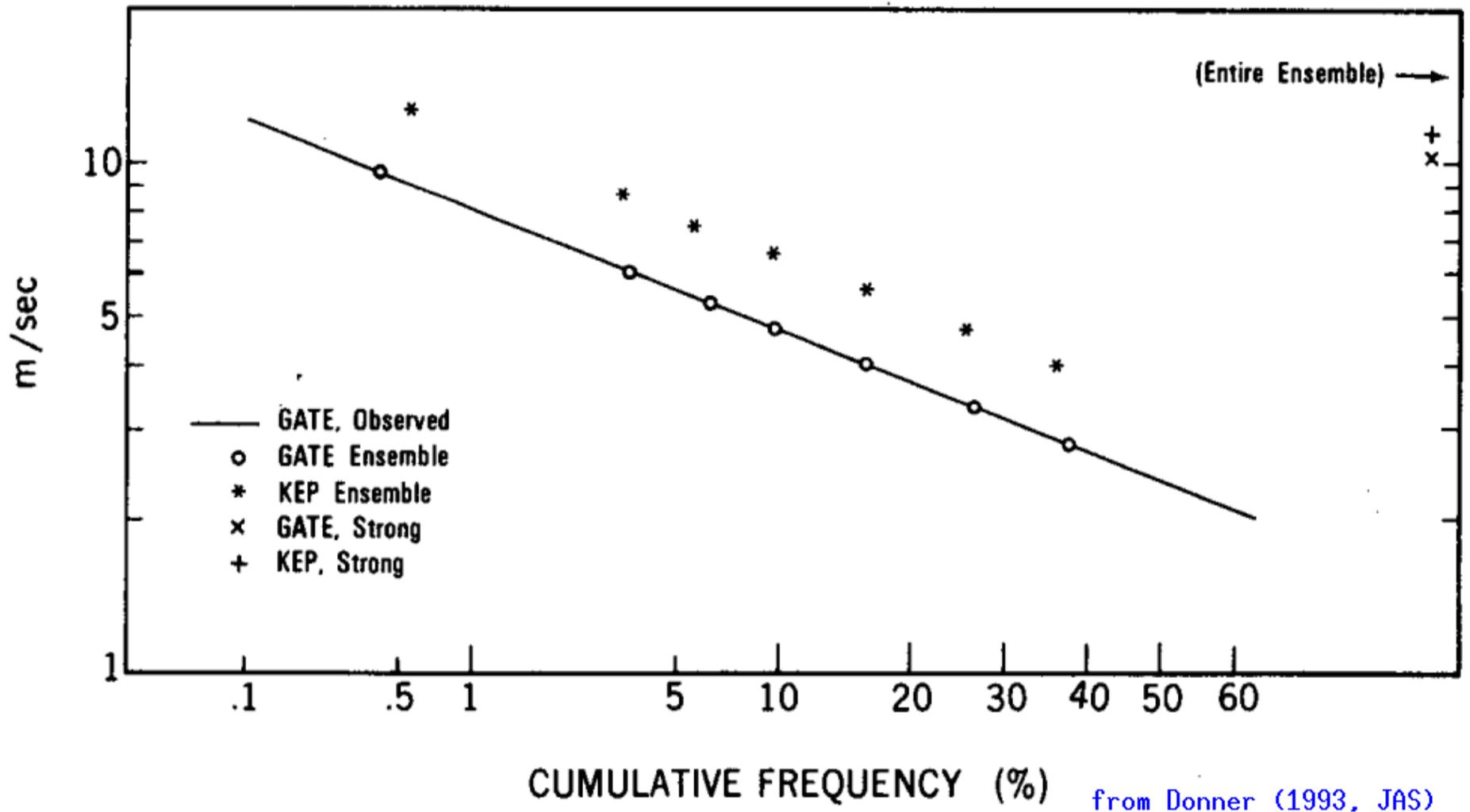


# Cumulus Convection

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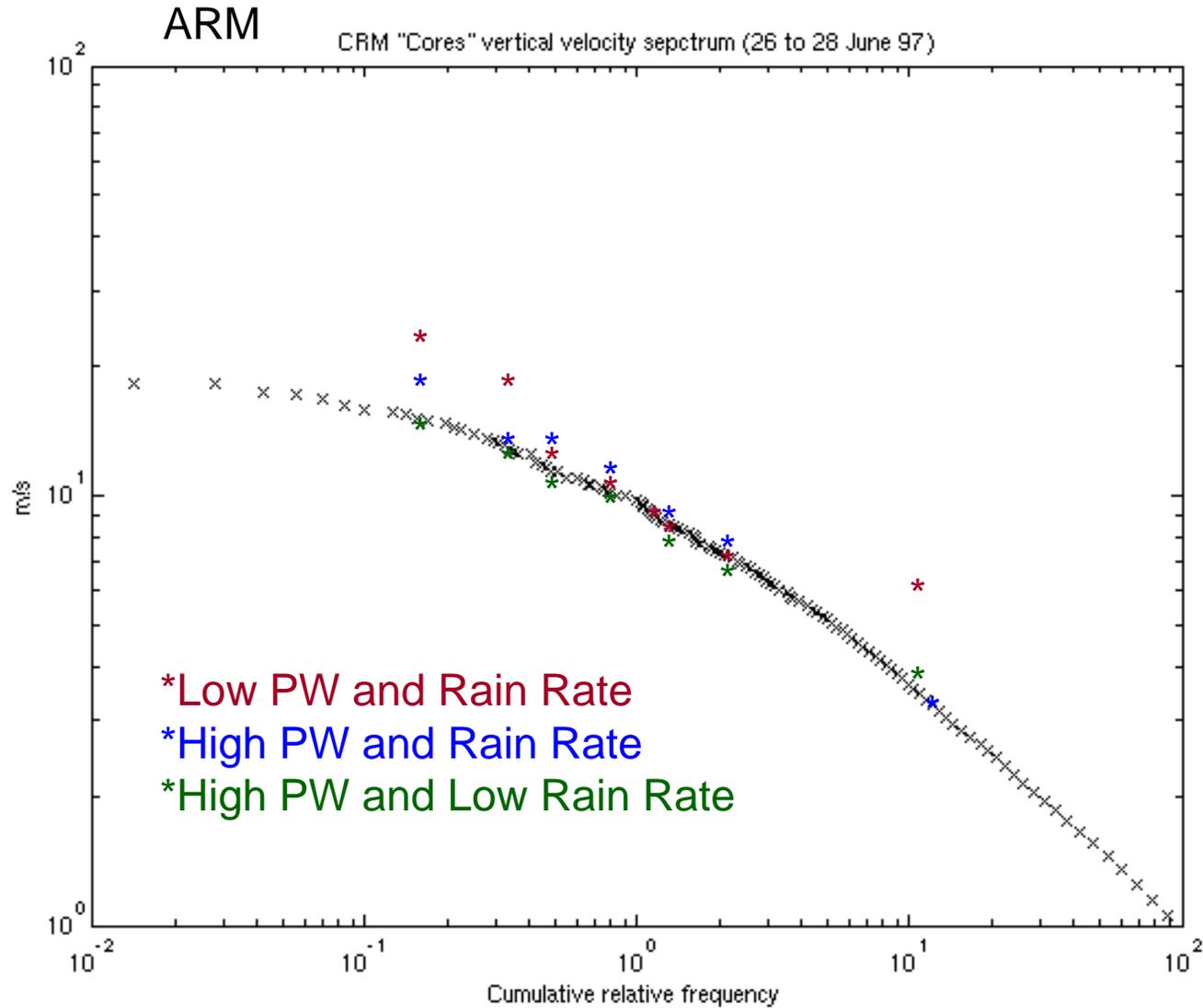
- AM2 (IPCC AR4): Relaxed Arakawa-Schubert (Moorthi and Suarez, 1992, *Mon. Wea. Rev.*) with ensemble of deep and shallow plumes characterized by mass fluxes. Precipitation proportional to condensate.
- AM3 Deep: Donner (2001, *J. Clim.*), Wilcox and Donner (2007, *J. Clim.*) with ensemble of deep plumes 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.

# VERTICAL-VELOCITY SPECTRA



from Donner (1993, JAS)

# CRM results provide independent evaluation of entrainment PDF



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



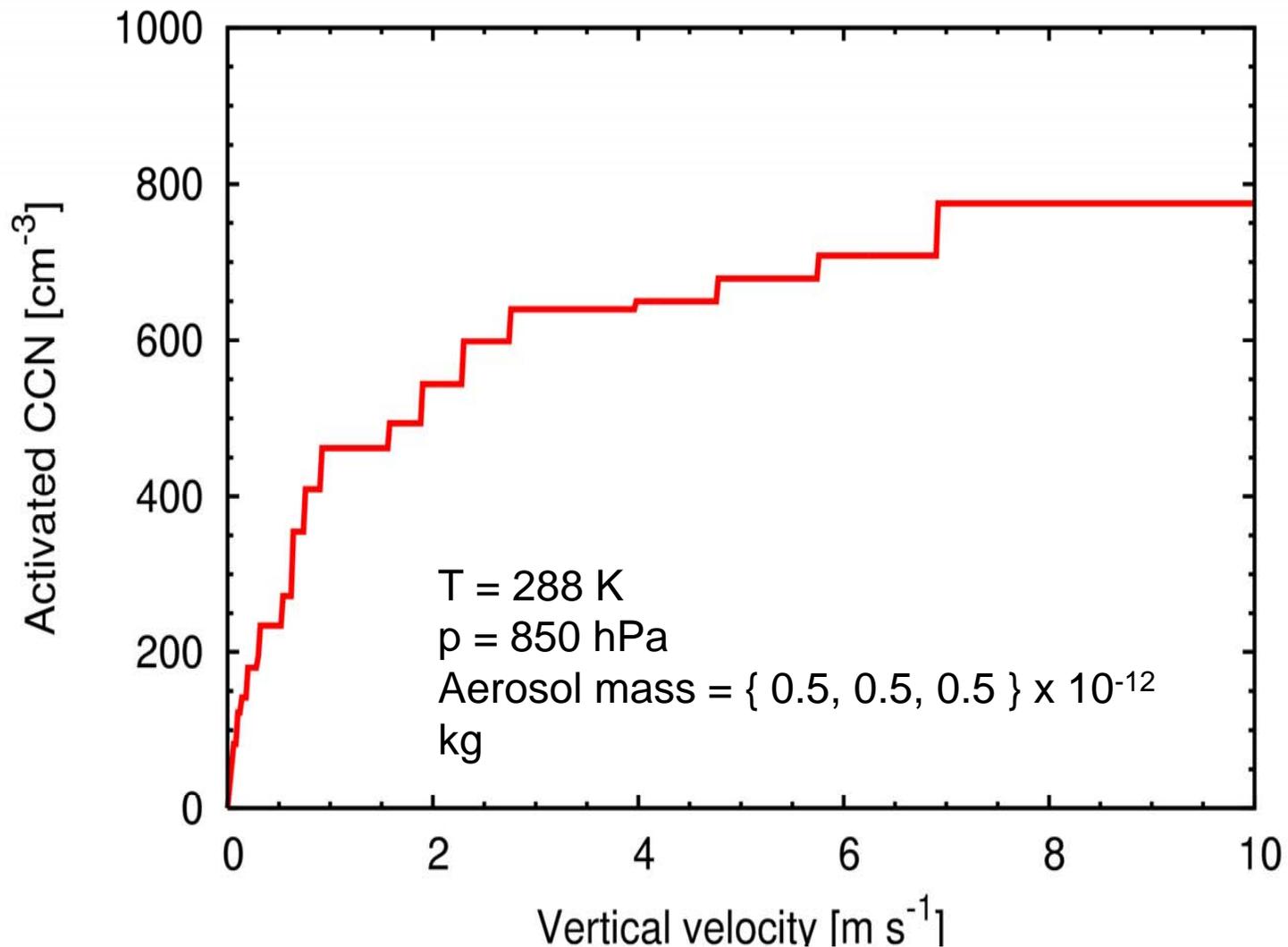
# Vertical Velocity Variability in Stratiform Clouds

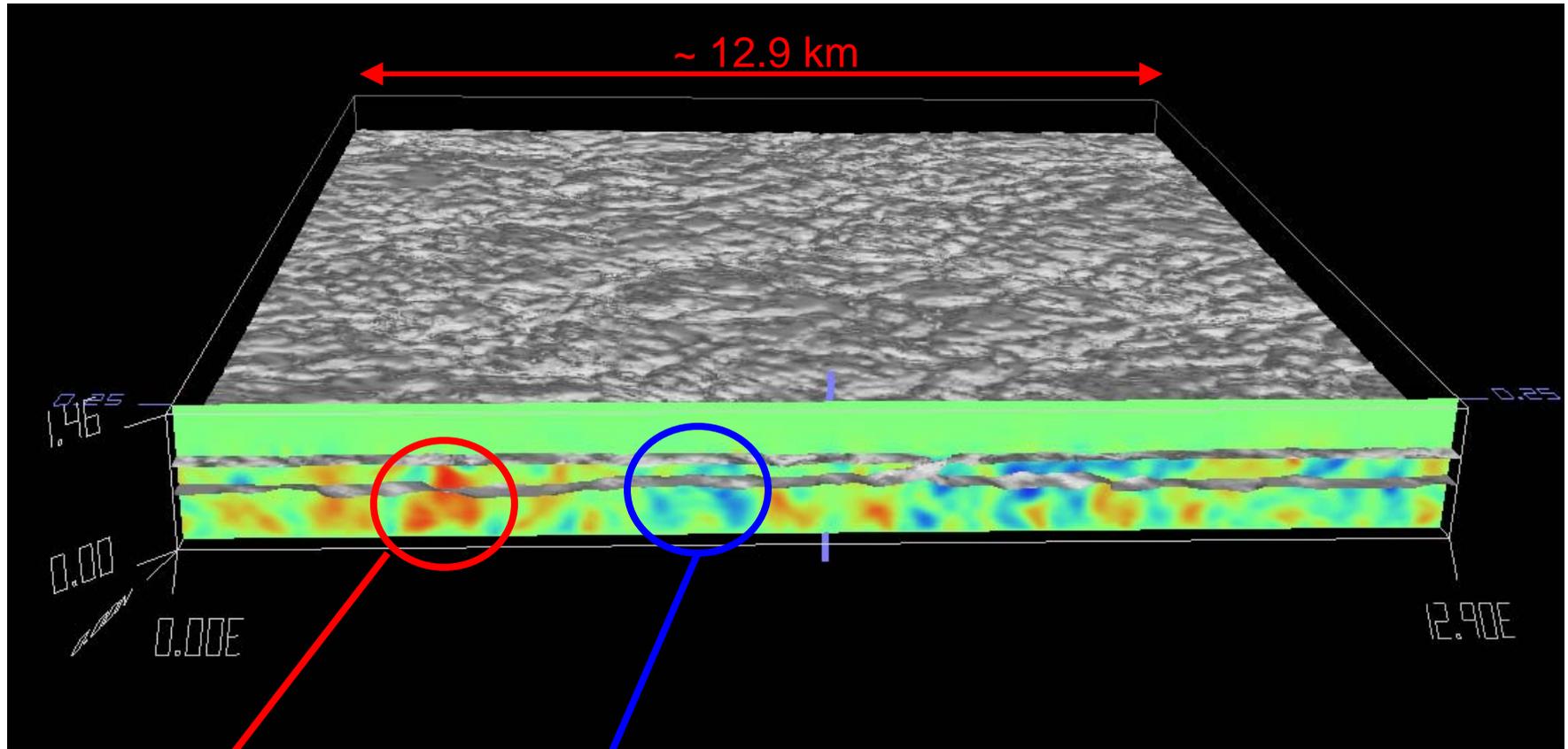
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- As in AM2, basic stratiform parameterization is Tiedtke (1993, *Mon. Wea. Rev.*)
- Prognostic cloud fraction; linked to bulk microphysics (Rotstayn, 1997, *QJRMS*)
- Uniform vertical velocity (non-convective grid mean) replaced for purposes of droplet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

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

CCN activation





updraft: activation

downdraft: evaporation

LES by Chris Golaz,  
GFDL



# Large-scale CCN activation

Layer-averaged activation:

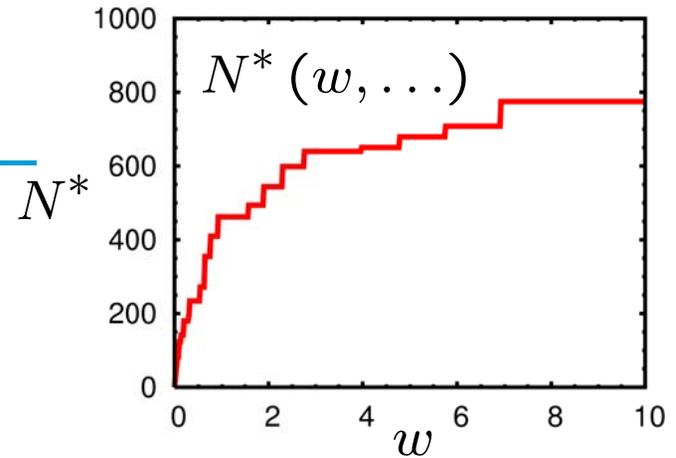
$$\bar{N}_{\text{activation}} = \int N^*(w, p, T) dx dy$$

Because  $N^*$  is non-linear

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

However,

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





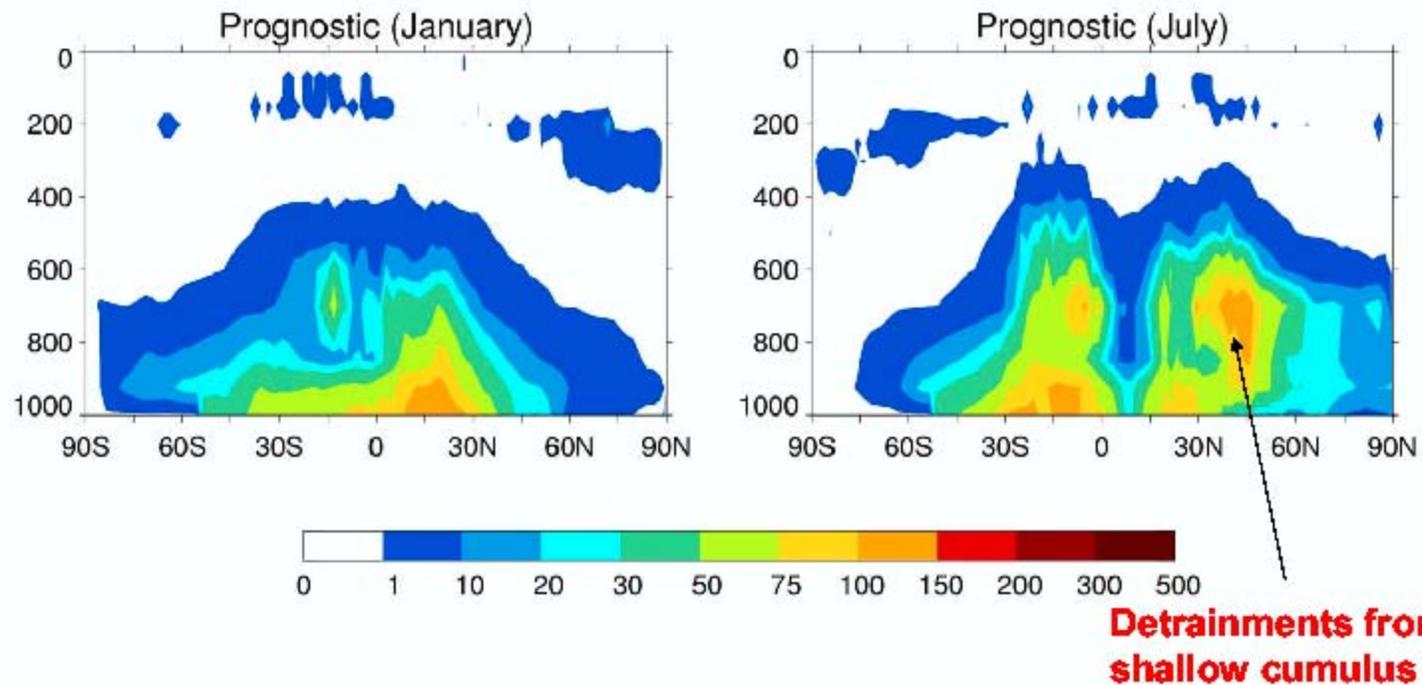
# Large-scale CCN activation

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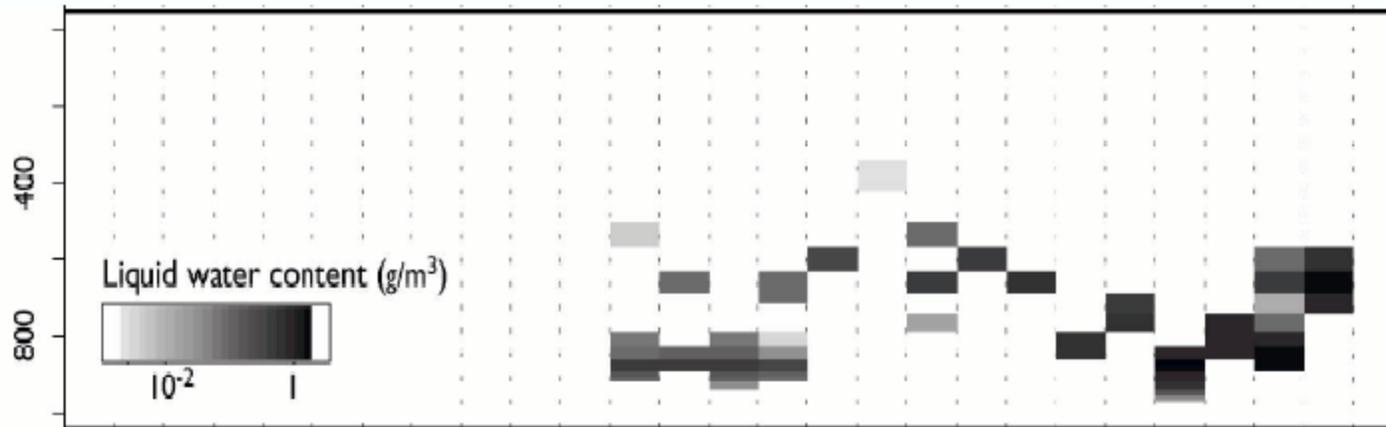
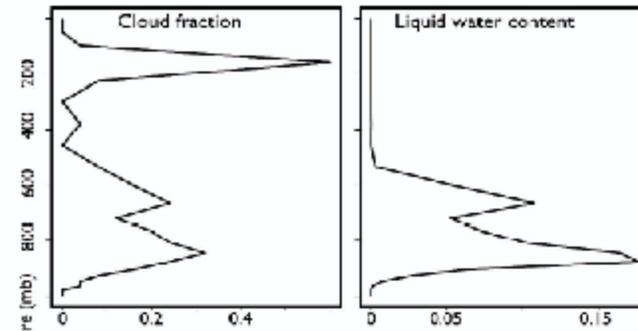
- In AM2, we don't have  $pdf(w)$ . For now, assume a Gaussian distribution.
- Distribution width is related **empirically** to mixing coefficients  $K_h$ .
- CCN activation is computed by integration over the distribution using a Gauss-Hermite quadrature.

# Vertical Distribution of Droplet Number Concentration ( $\text{cm}^{-3}$ )



# Design of a MODIS Simulator

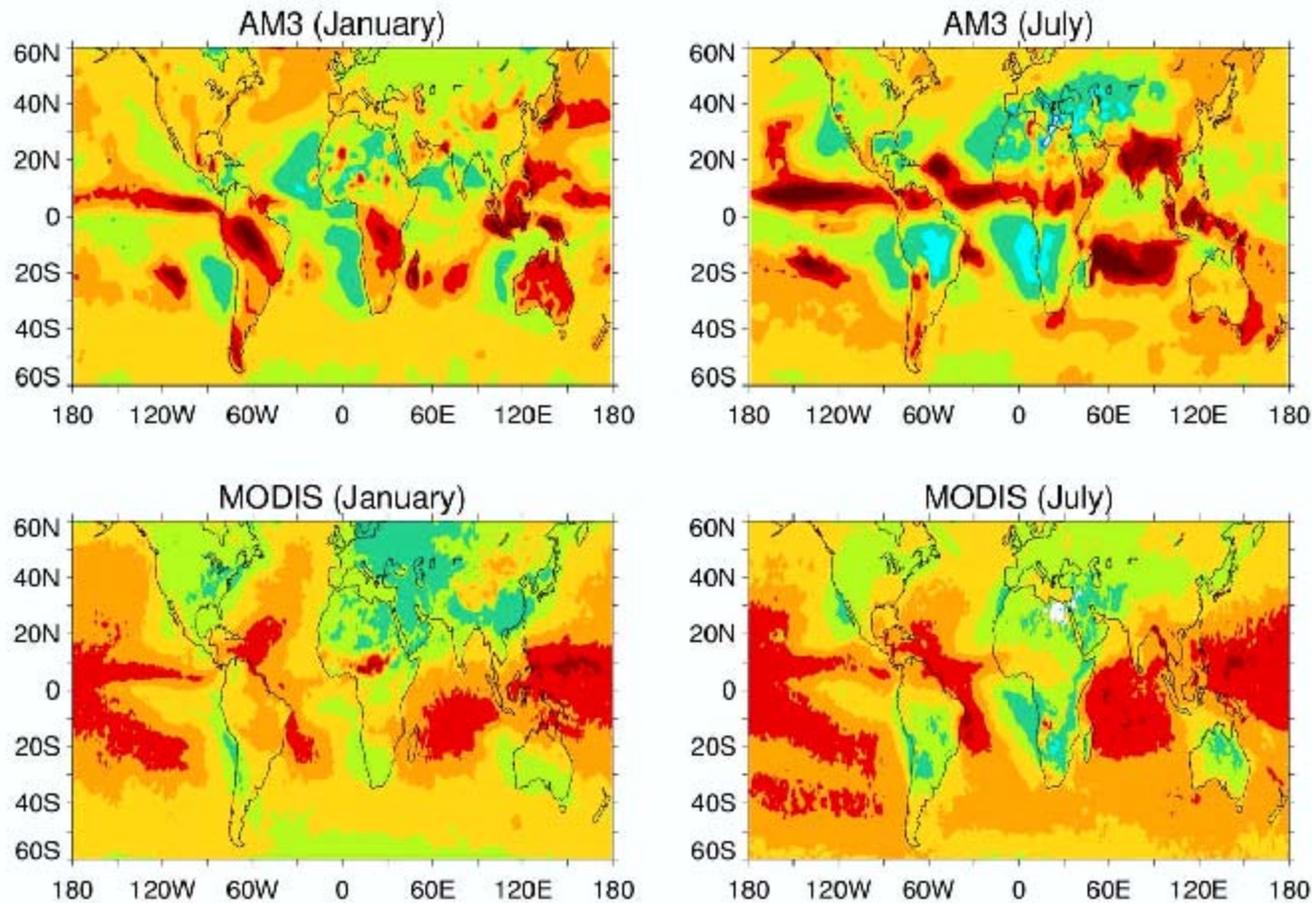
- Subcolumn sampling;
- Downward scanning of every subcolumn;
- Top two cloud optical depth;
- Liquid condensate much greater than ice.



Subcolumns (in order of increasing condensed water path in the subcolumn) →

Pincus et al., (2006, 2005)

# Comparison with MODIS Retrievals



Analysis by  
Yi Ming, GFDL





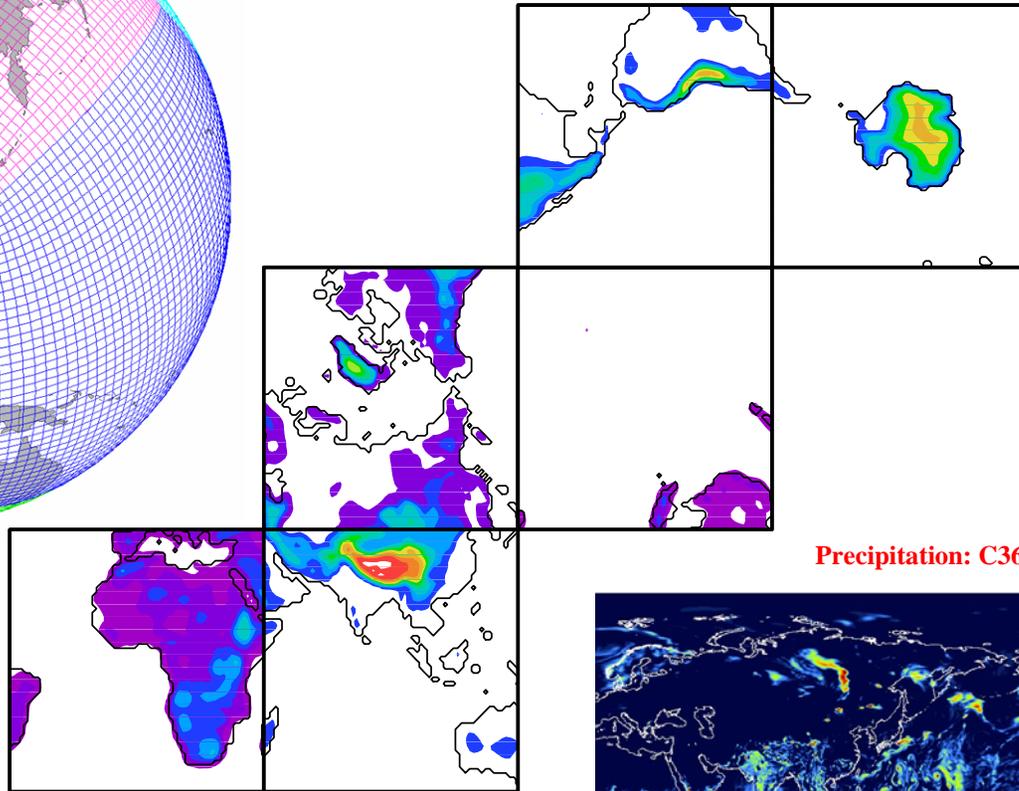
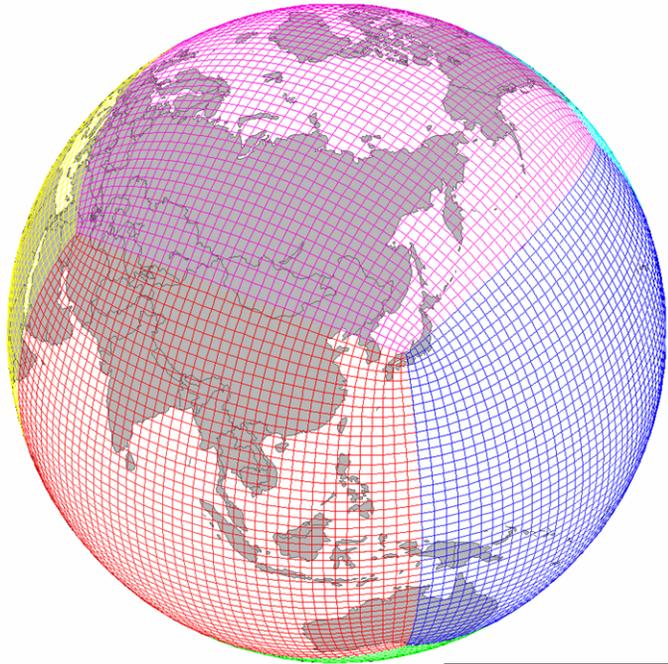
# Dynamical Core and Boundary Layer

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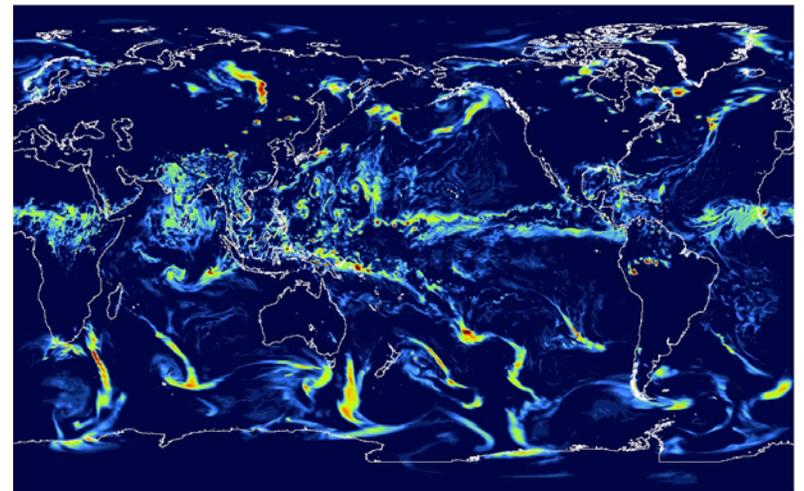
- Finite-volume dy-core (Lin, 2004, *Mon. Wea. Rev.*)
- Cubed-sphere implementation, composed of 6 rectangular domains
- No singularity associated with spherical pole
- PBL, as in AM2, follows Lock *et al.* (2001, *J. Atmos. Sci.*)

# *3 ways to visualize the Cubed Sphere*

Cubed Sphere 44x44x6



Precipitation: C360 HiRam-2





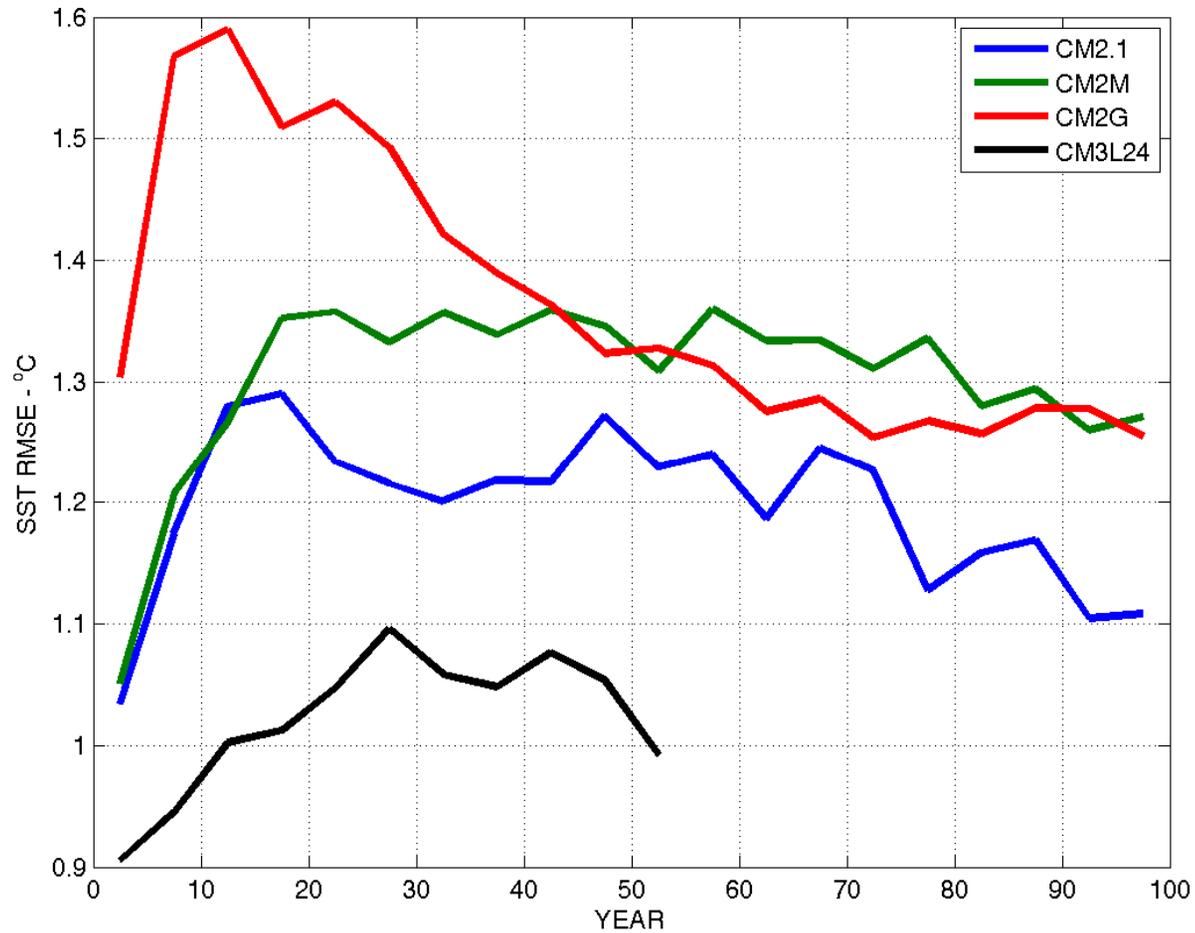
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# Selected Features of CM3 Climate



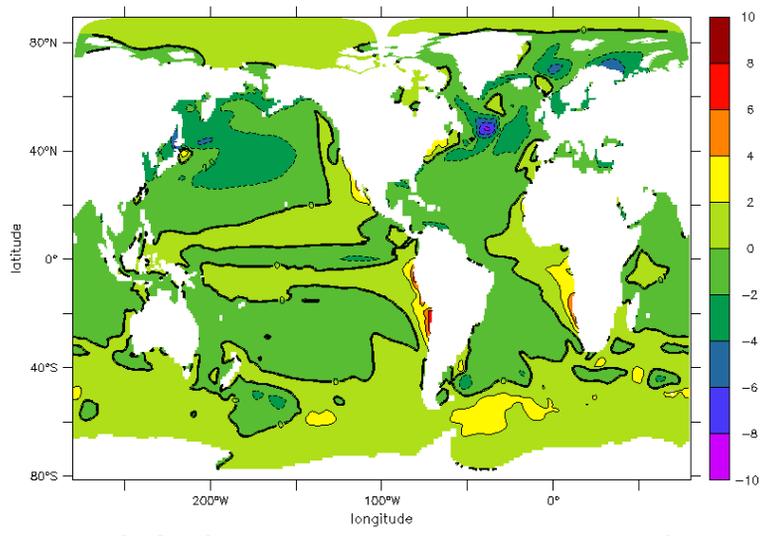


# Global Mean SST Errors in CM2 and CM3



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NOAA/PMEL TRIP  
Nov 18 2008 07:32:56

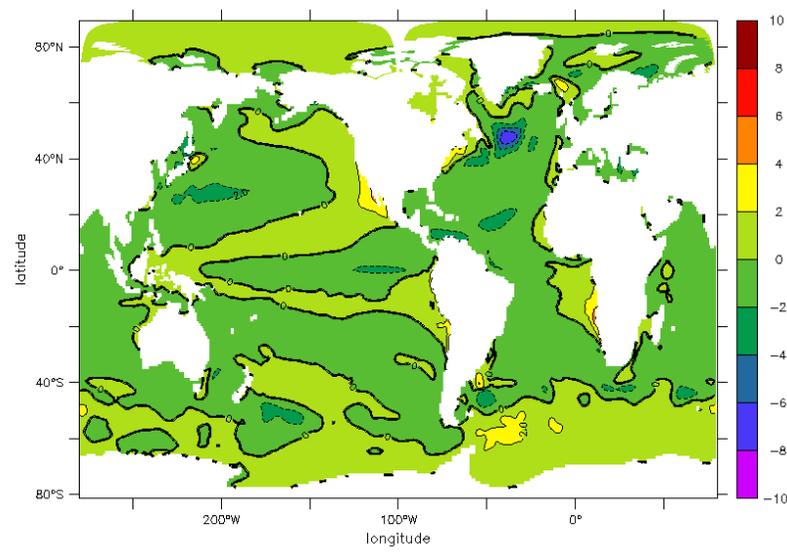
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DATA SET: ice.0051-0055.ann  
CM2.1U\_Control-1990\_E1



SST[L=1]-SST[L=1:12@AVE,D=sst\_amp2\_clim,GX=XT@ASN,GY=YT@ASN]

FERRET (beta) Ver.6.11  
NOAA/PMEL TRIP  
Nov 18 2008 07:32:56

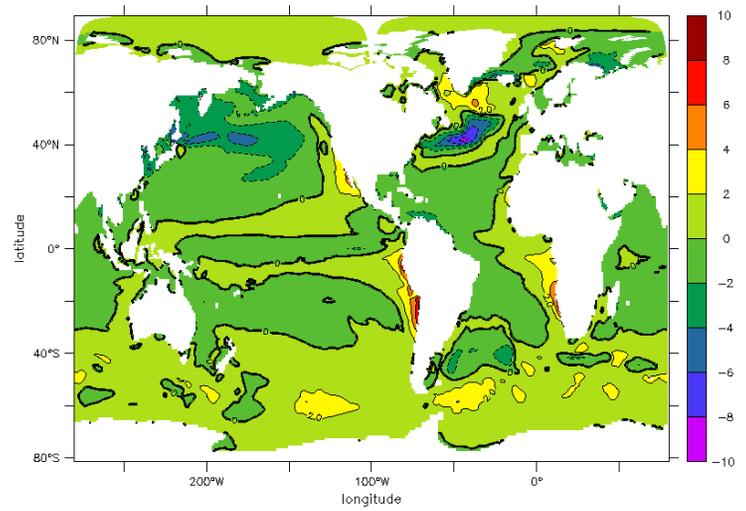
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DATA SET: ice.0051-0055.ann  
CM3R\_Control-1990-gamma-B6



SST[L=1]-SST[L=1:12@AVE,D=sst\_amp2\_clim,GX=XT@ASN,GY=YT@ASN]

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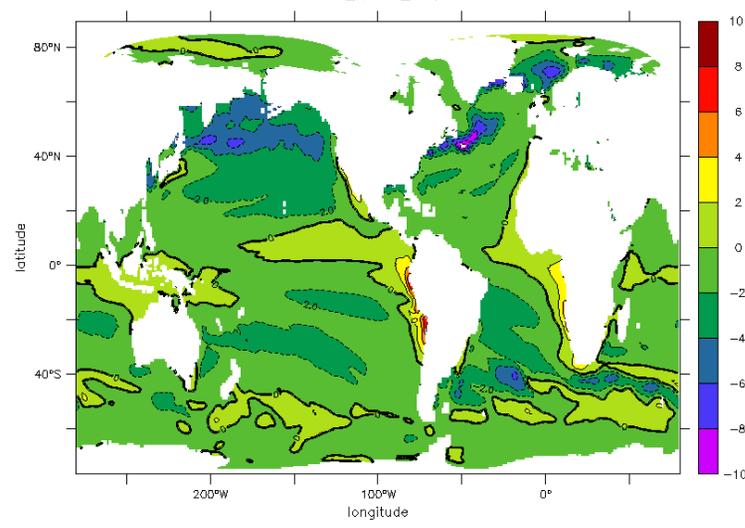
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DATA SET: ice.1950-1954.ann  
CM2M\_21oct2008\_darkiceA\_submeso\_med



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FERRET (beta) Ver.6.11  
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DATA SET: ice.1950-1954.ann  
CM2G\_pyrite3\_bergs

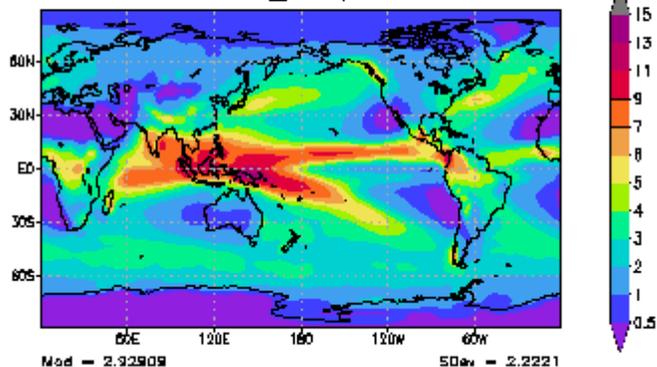


SST[L=1]-SST[L=1:12@AVE,D=sst\_amp2\_clim,GX=XT@ASN,GY=YT@ASN]

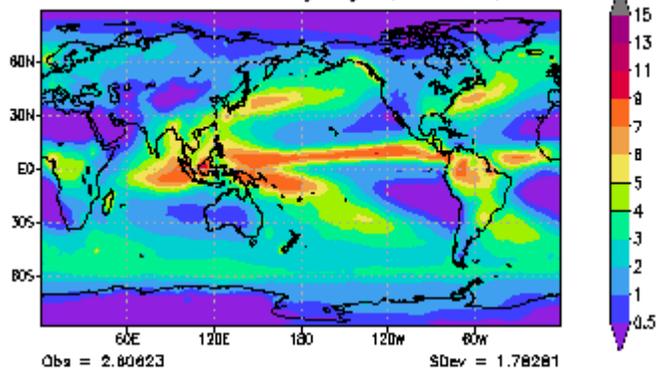
# AM 2

## ANN PRECIP (mm/d)

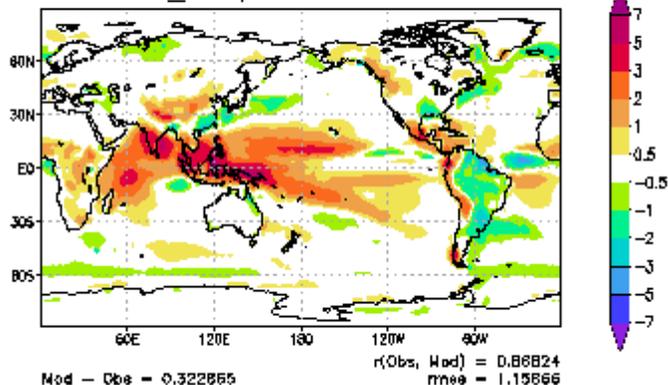
m45\_am2p14



GPCP.v2 sat + gauge ('81-'00)



m45\_am2p14 minus GPCP.v2



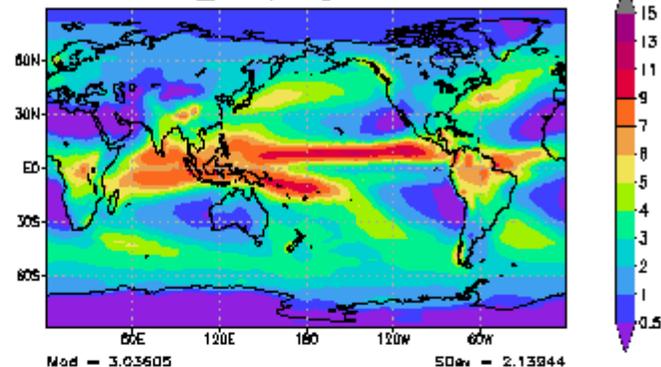
GPCP.v2:

<http://www.cgd.noaa.gov/cgd/data/gpcp.html>

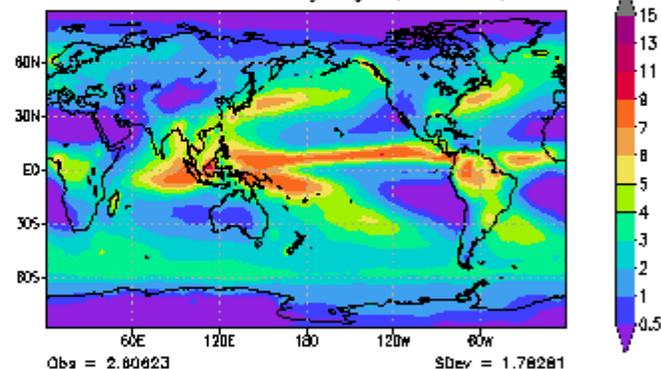
# AM 3

## ANN PRECIP (mm/d)

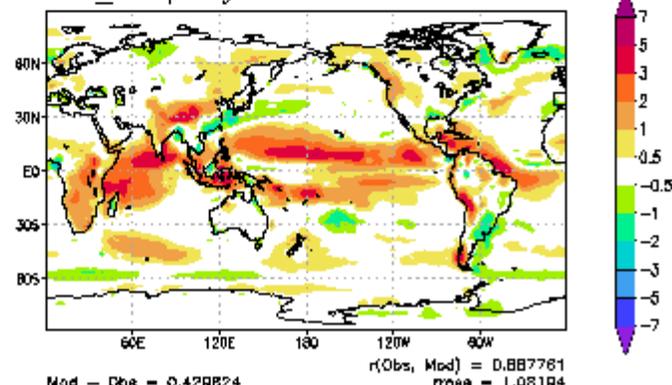
c48\_am3p5-gamma-A6



GPCP.v2 sat + gauge ('81-'00)



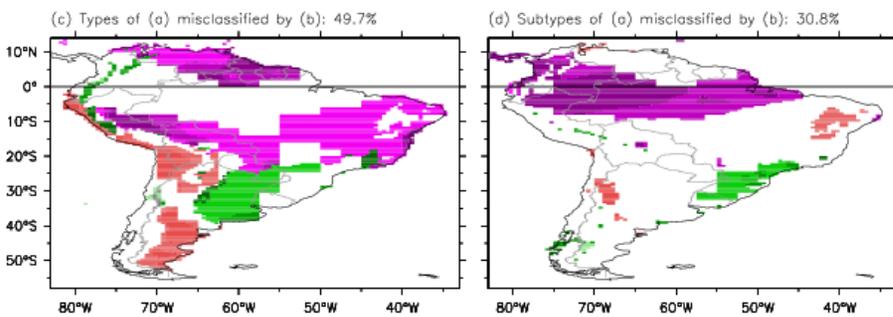
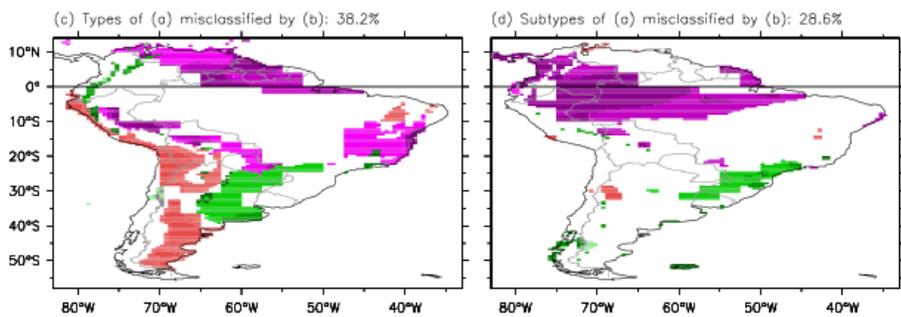
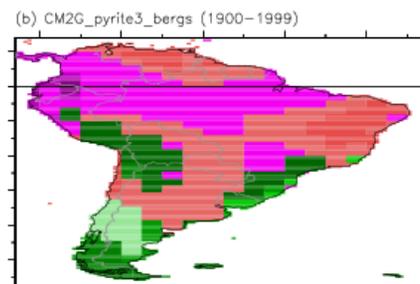
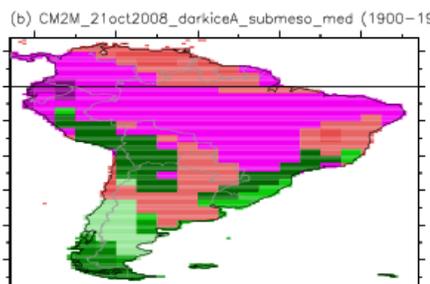
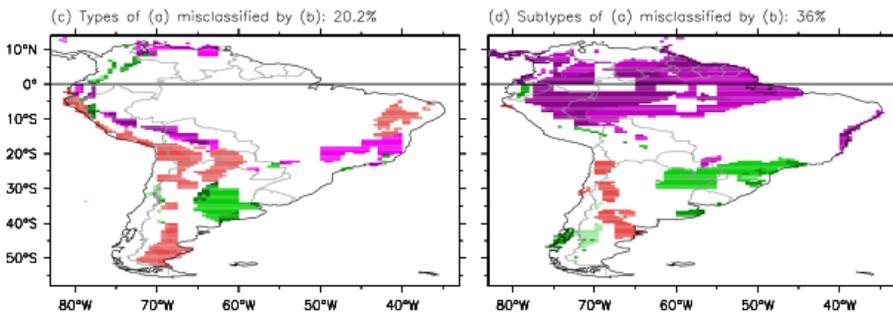
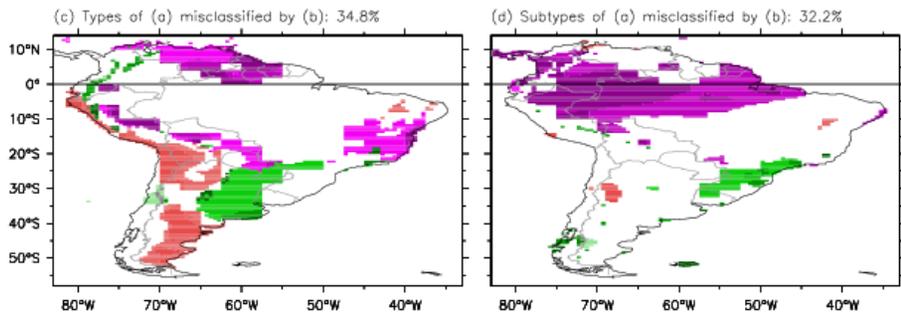
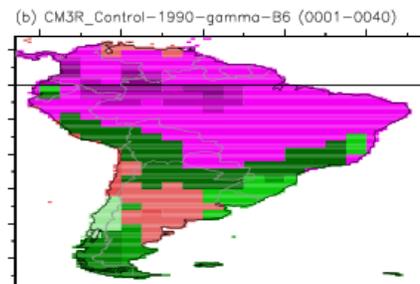
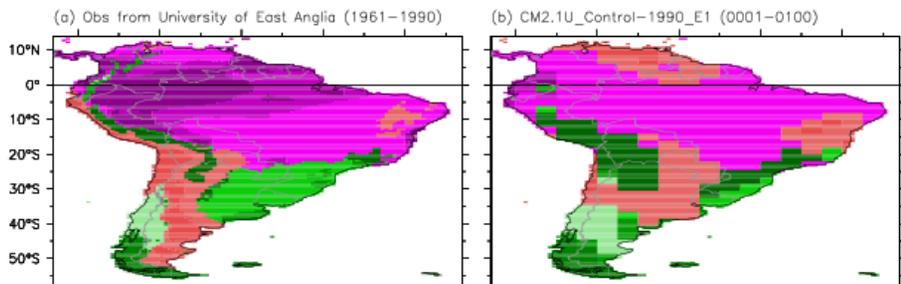
c48\_am3p5-gamma-A6 minus GPCP.v2



GPCP.v2:

<http://www.cgd.noaa.gov/cgd/data/gpcp.html>

# Koppen Climate Types: South America





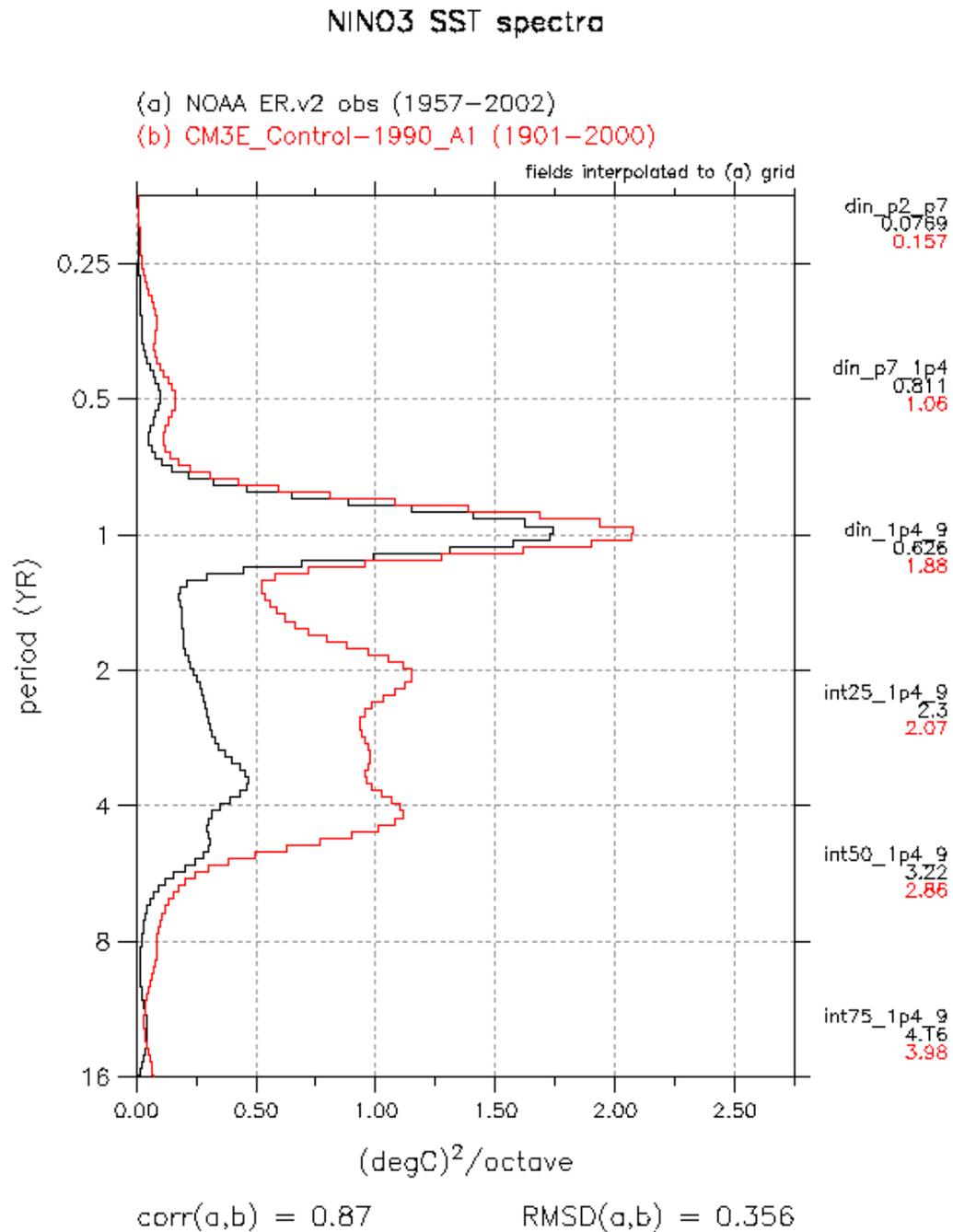
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Transients are exhibiting strong dependence on details of closure for cumulus parameterization

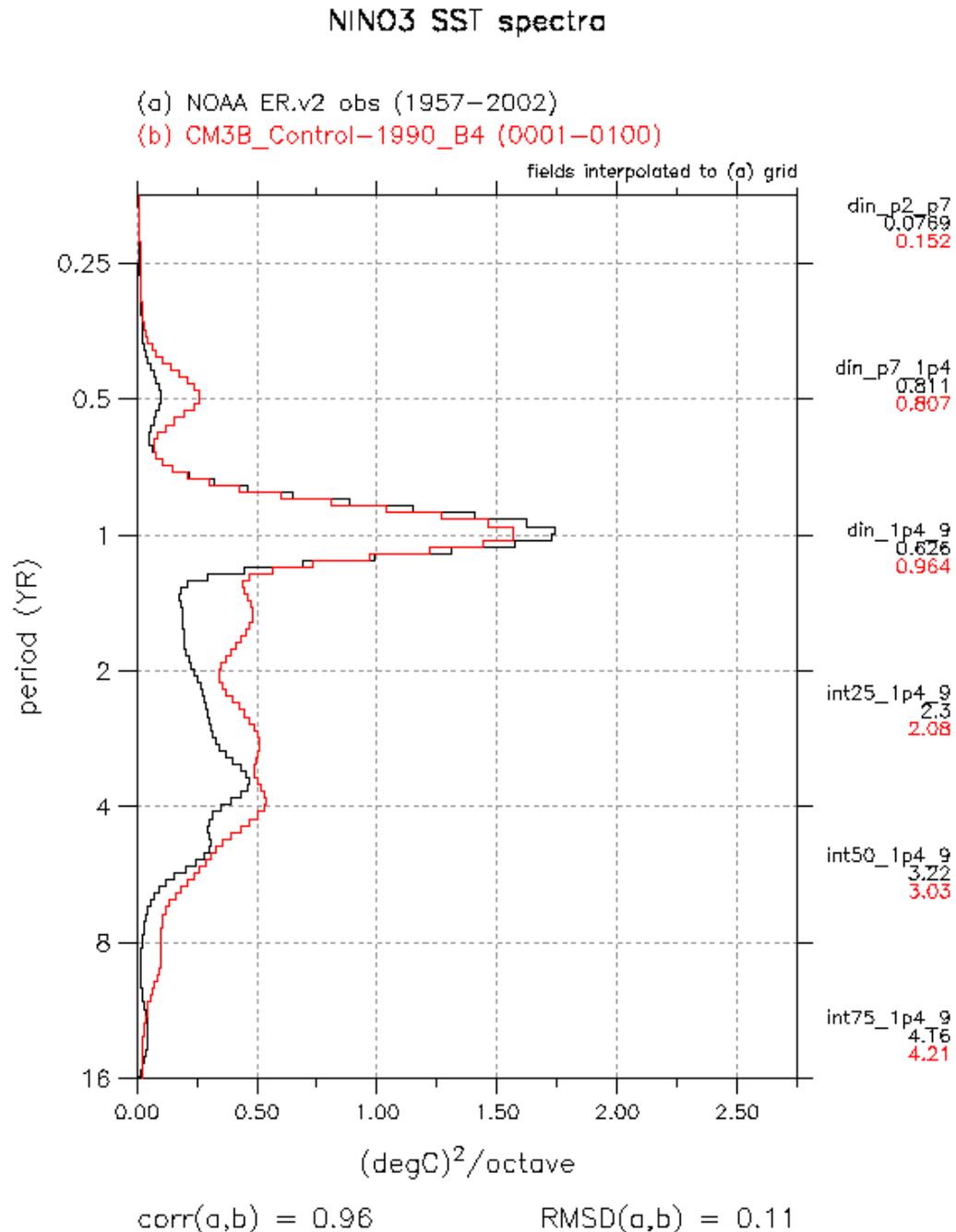


# CAPE relax closure

# Ocean Coupling



Zhang  
(2002,  
*JGR*)  
closure  
  
Ocean  
Coupling



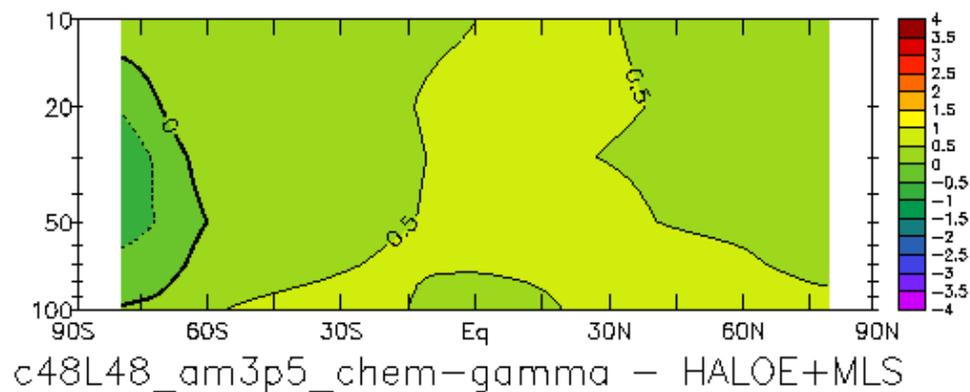
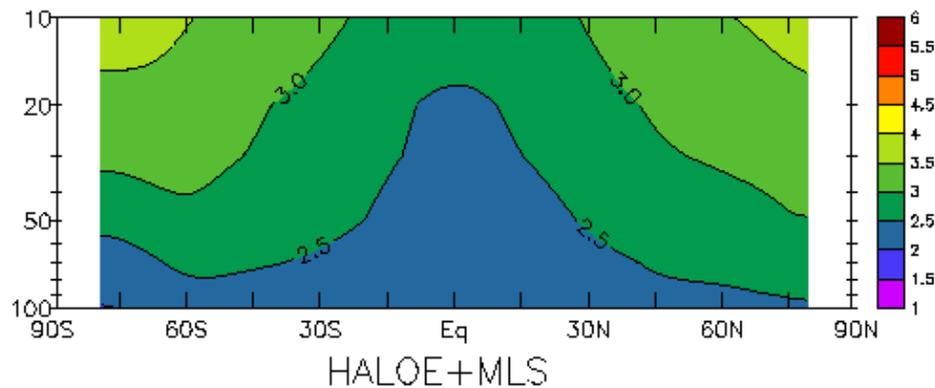
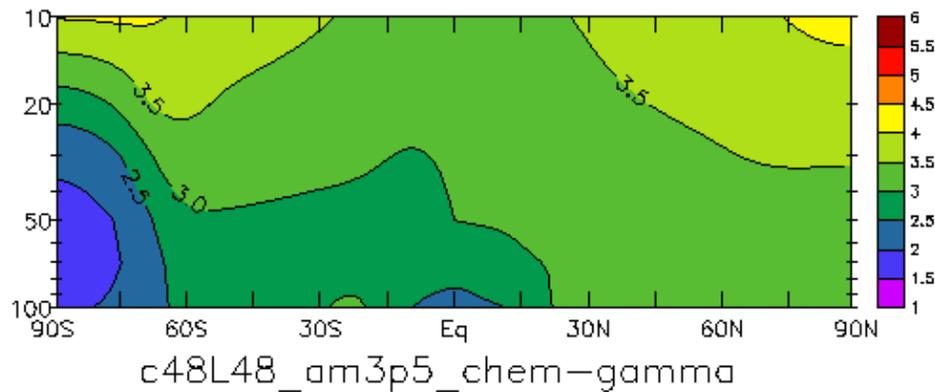


# Development Issues-Injection of Water Vapor into Stratosphere

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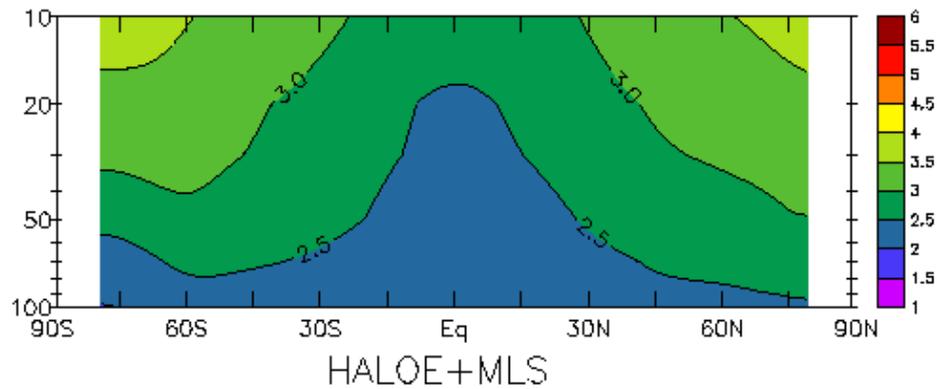
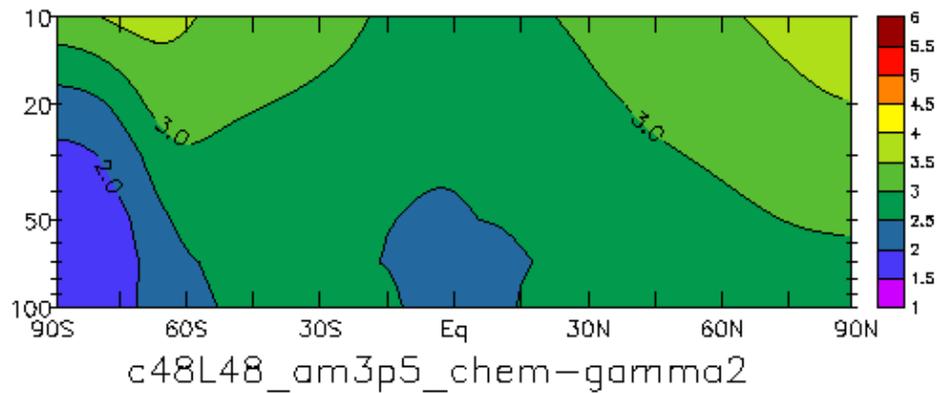
- Donner (2003, *J. Clim.*) cumulus parameterization allows overshooting towers and stratospheric water vapor injection
- Stratospheric water vapor sensitive to details of cumulus closure

Zonal mean specific humidity (mg/kg), ann

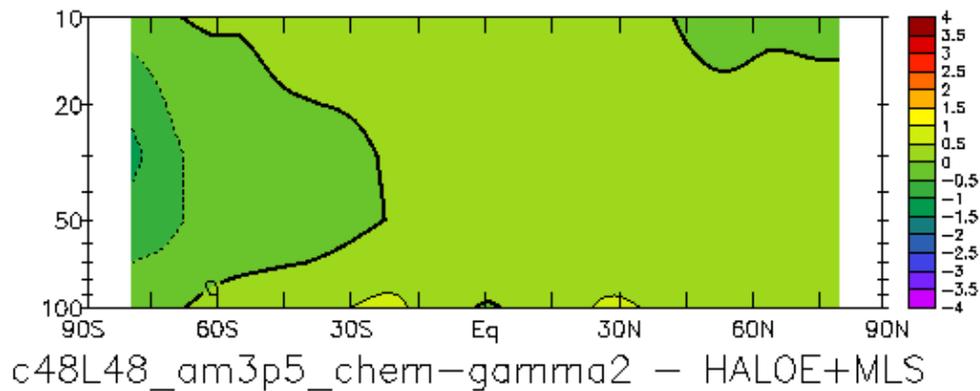


Convective cells and mesoscale circulations allowed to puncture tropopause.

Zonal mean specific humidity (mg/kg), ann



Convective cells allowed to puncture tropopause





# “Indirect Effect” and 20<sup>th</sup> Century Climate

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



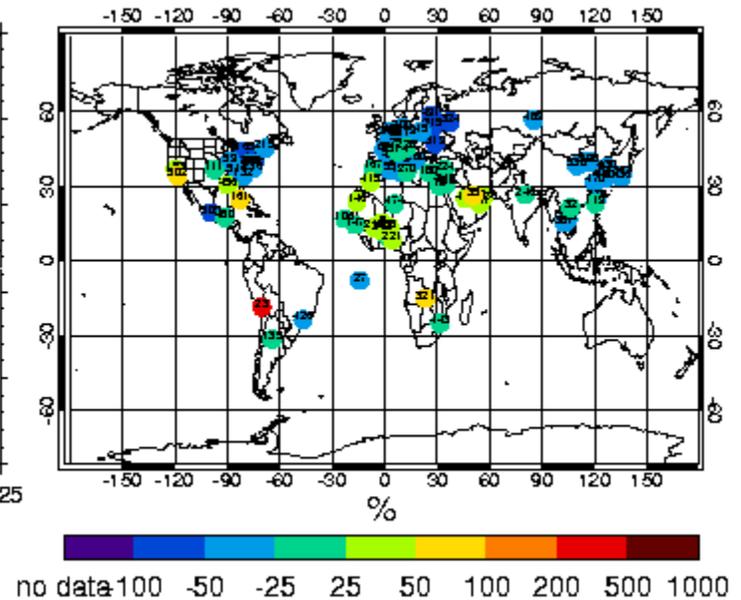
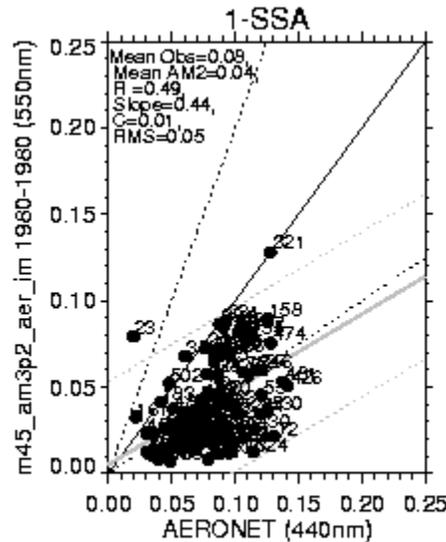
# AM2 and AM3: Indicators of 20<sup>th</sup> Century Warming

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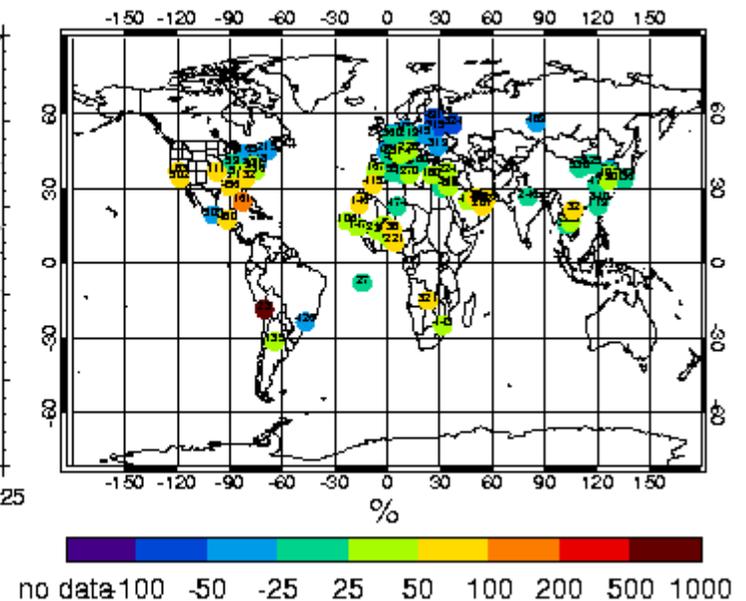
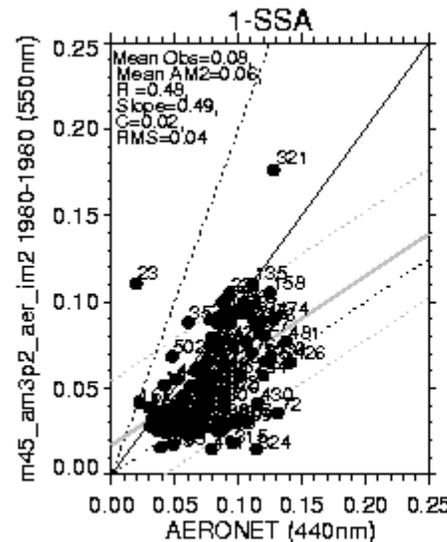
- AM2 RFP:  $1.3 \text{ W m}^{-2}$  (GHG:  $2.1 \text{ W m}^{-2}$  ; Aerosol:  $-0.8 \text{ W m}^{-2}$  )
- AM2 Cess Sensitivity:  $1.6 \text{ W m}^{-2} \text{ K}^{-1}$
- AM2 RFP/Sensitivity:  $0.8 \text{ K}$
- AM3 RFP:  $0.9 \text{ W m}^{-2}$  (GHG:  $2.5 \text{ W m}^{-2}$  ; Aerosol:  $-1.6 \text{ W m}^{-2}$  )
- AM3 Cess Sensitivity:  $1.3 \text{ W m}^{-2} \text{ K}^{-1}$
- AM3 RFP/Sensitivity:  $0.7 \text{ K}$
- 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

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- 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

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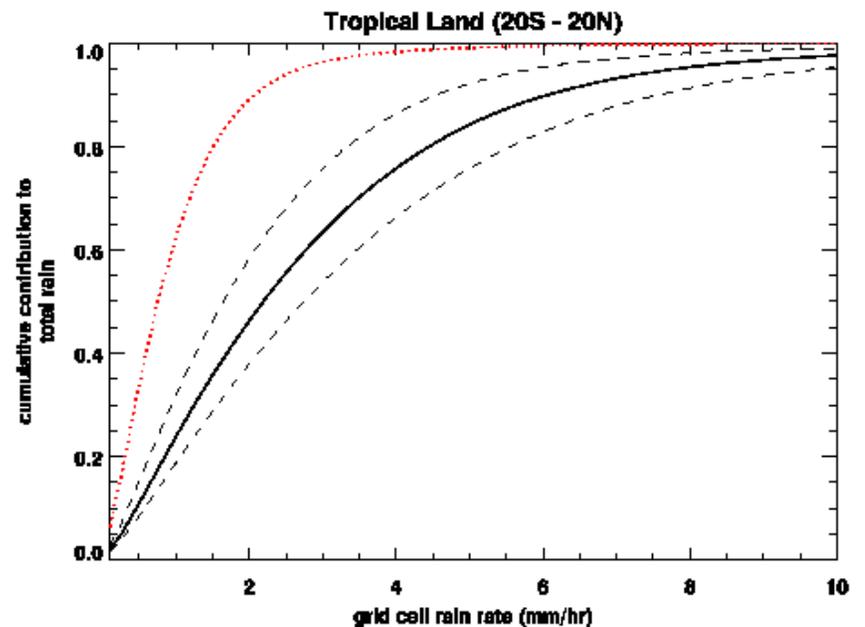
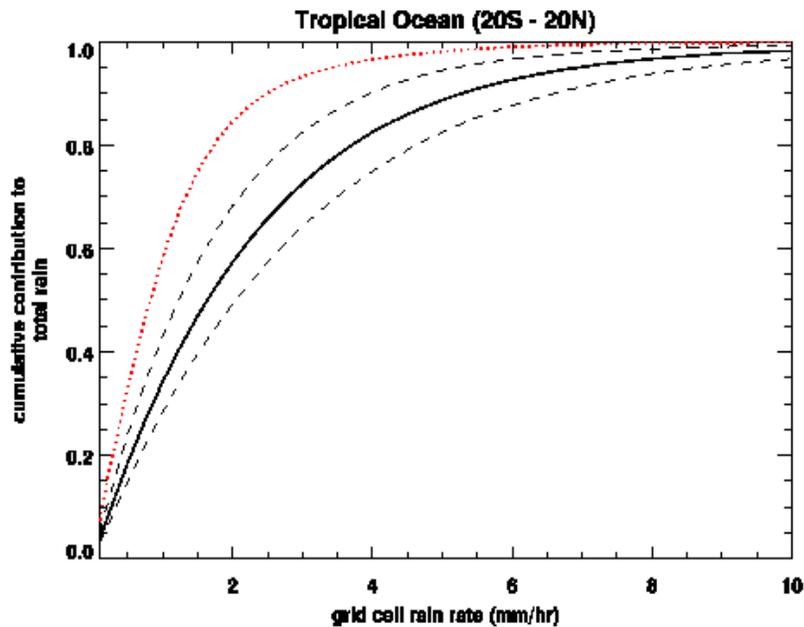
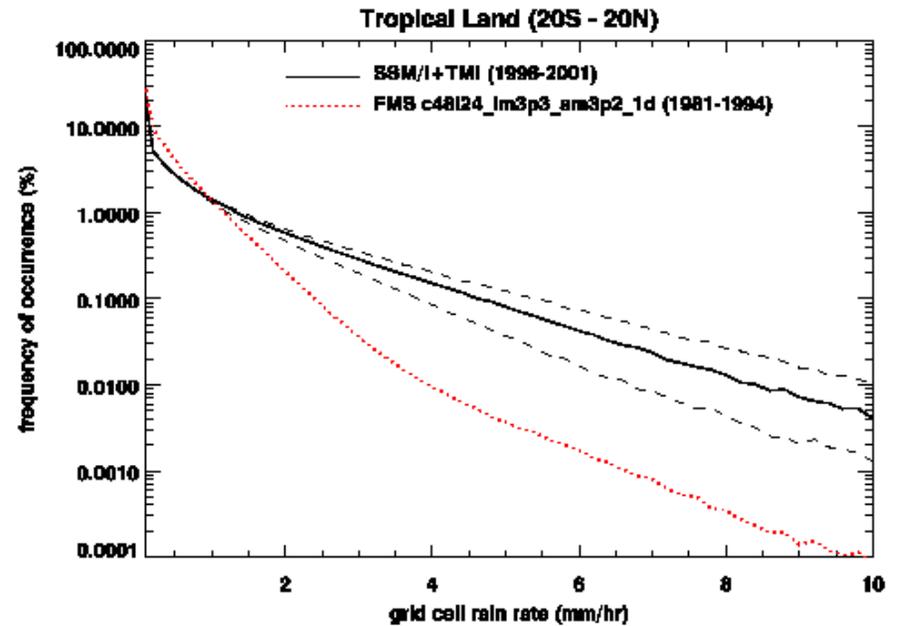
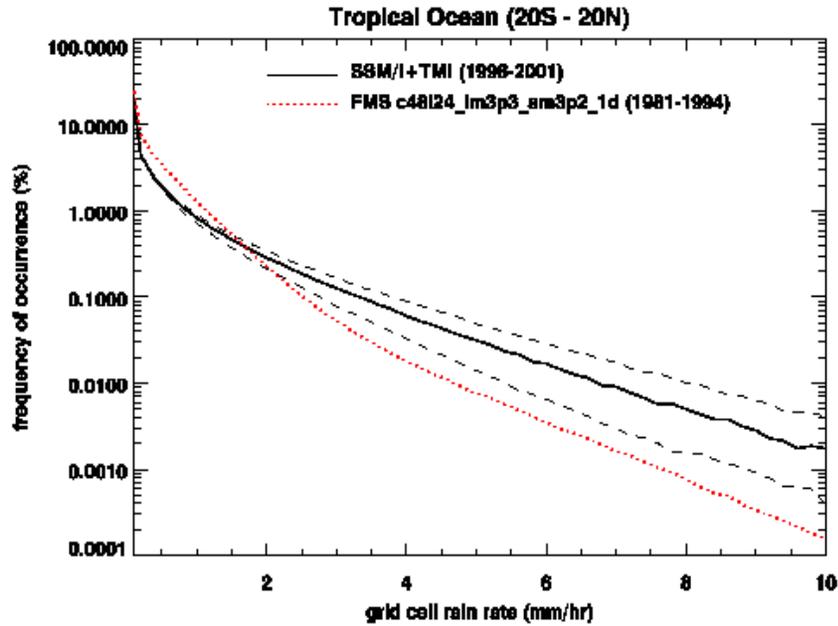
- Cloud-aerosol interactions (“indirect effect”), atmospheric chemistry, and increased troposphere-stratosphere coupling are key developments in GFDL AM for AR5
- Physics changes required for cloud-aerosol interaction include macrophysics (sub-grid vertical velocity PDFs) for convective and stratiform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



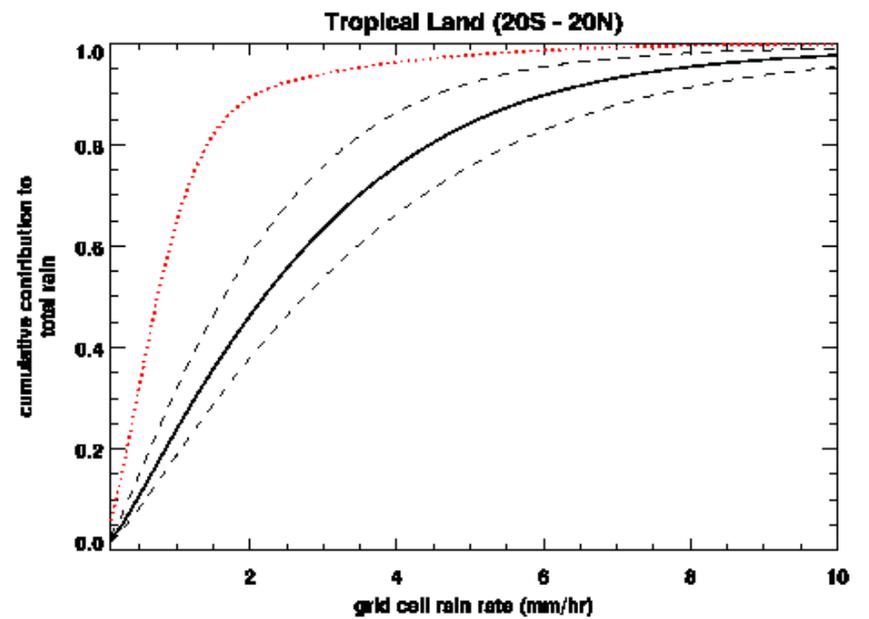
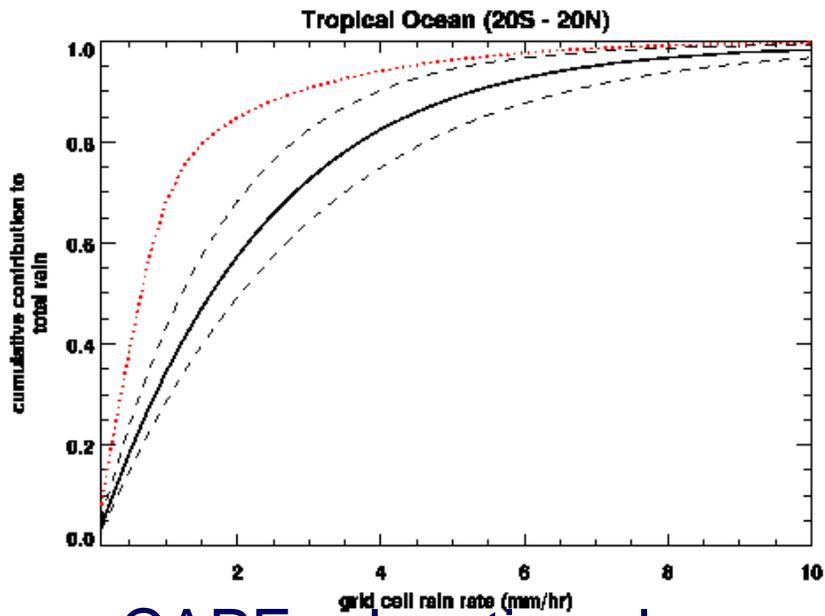
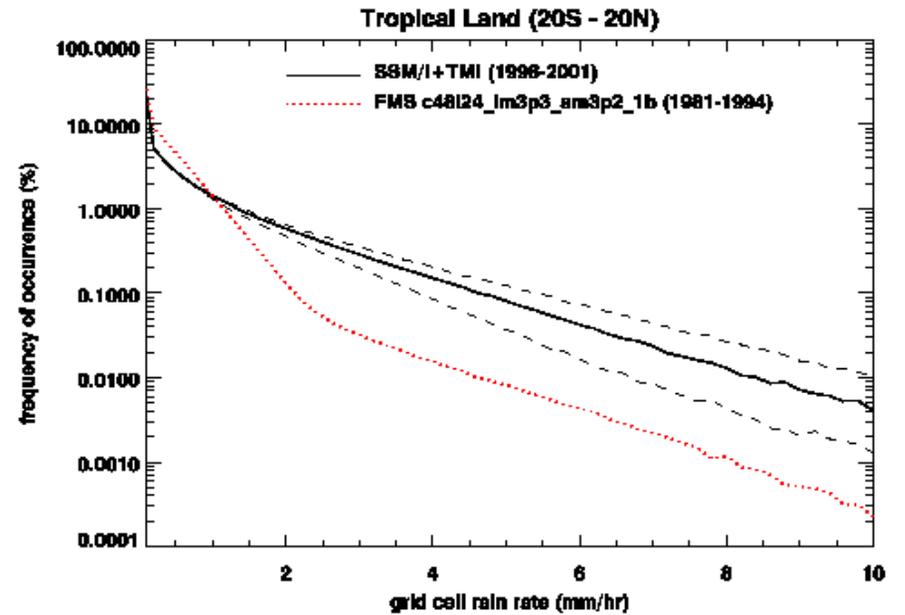
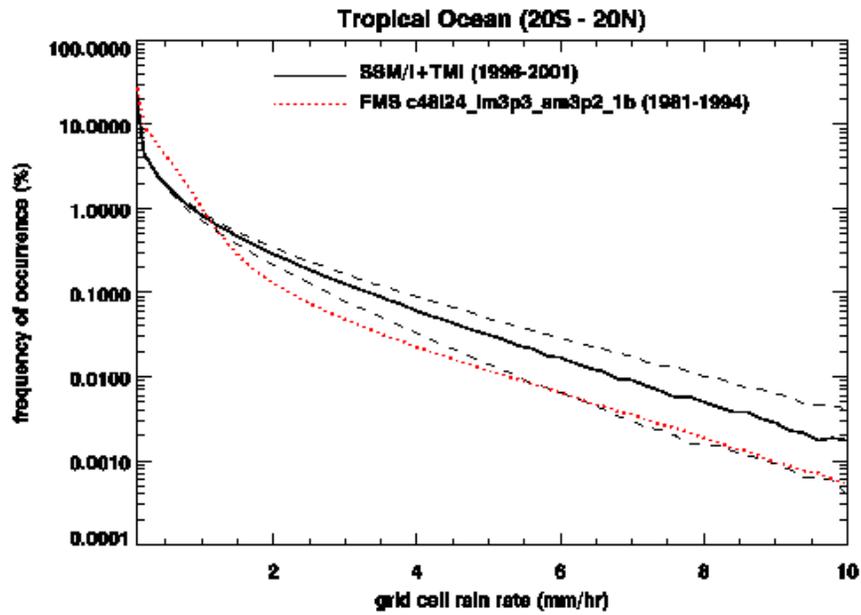
# Excessive Cooling by Indirect Effect (Lohmann *et al.*, 2007, *BAMS*) ?

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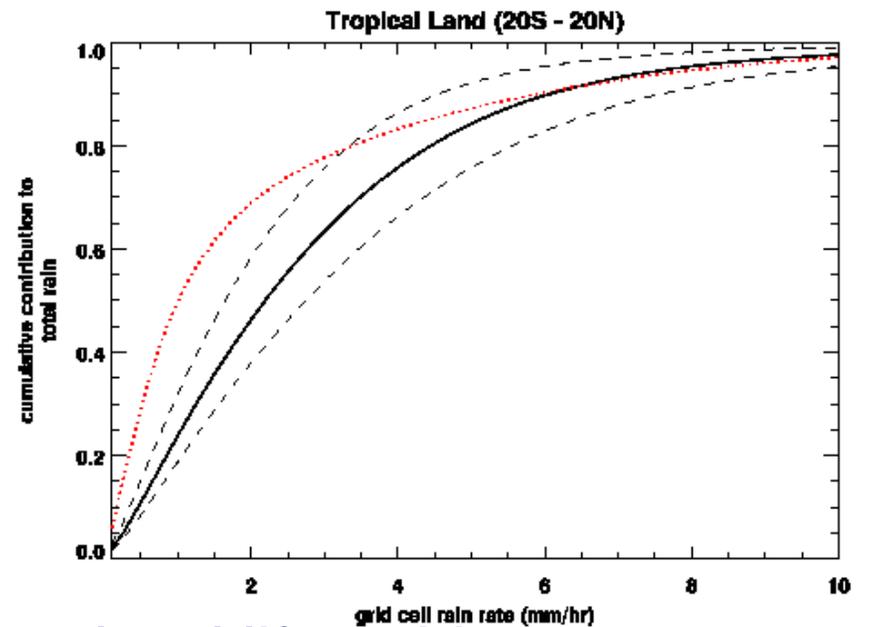
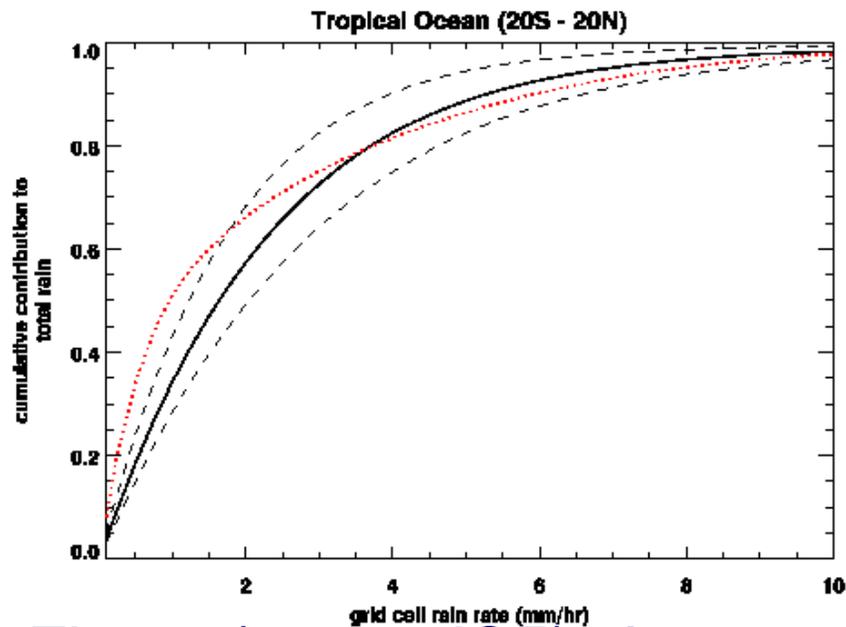
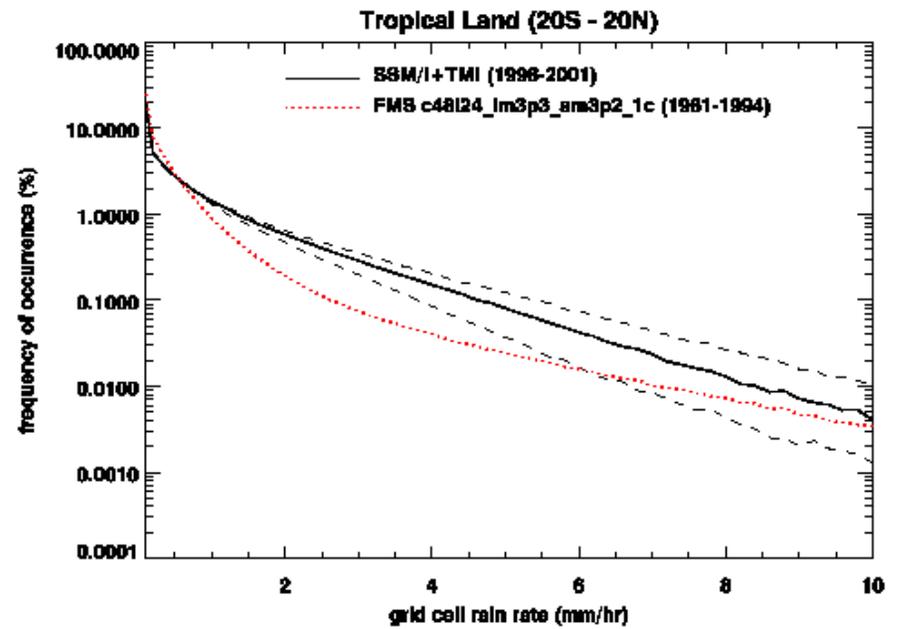
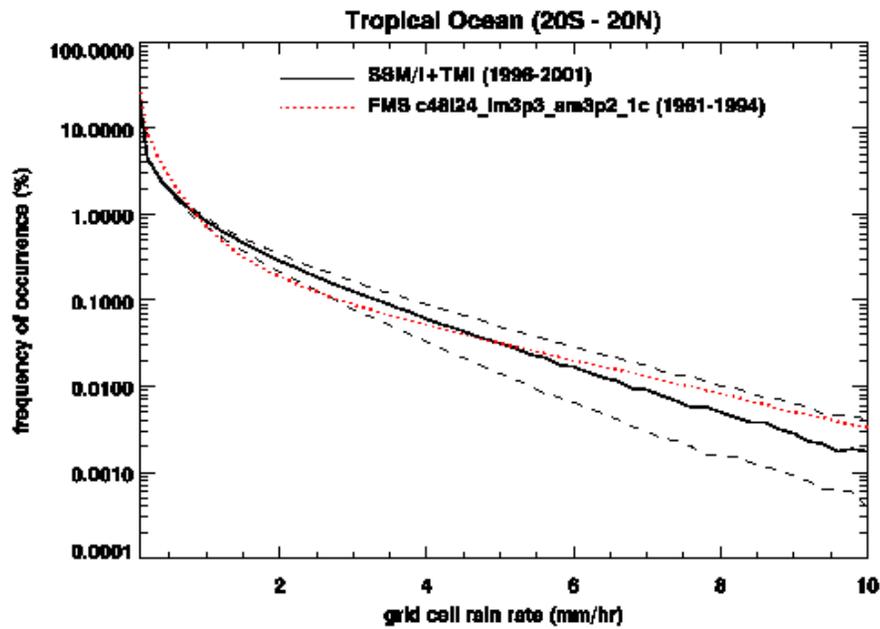
- Less direct effect (internal mixing)
- Extent of warm-cloud nucleation by organics
- PI – PD aerosol concentrations
- Warming by ice cloud-aerosol interactions
- Dispersion and other microphysics
- Cloud-scale instabilities limiting increased liquid at high aerosol (Ackerman *et al.*, 2004, *Nature*)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



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



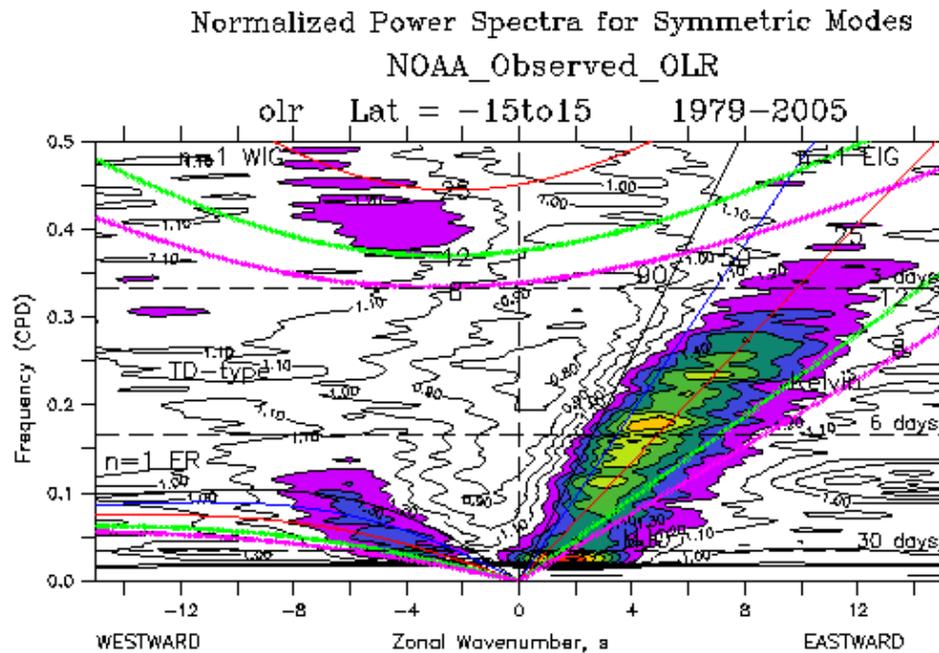
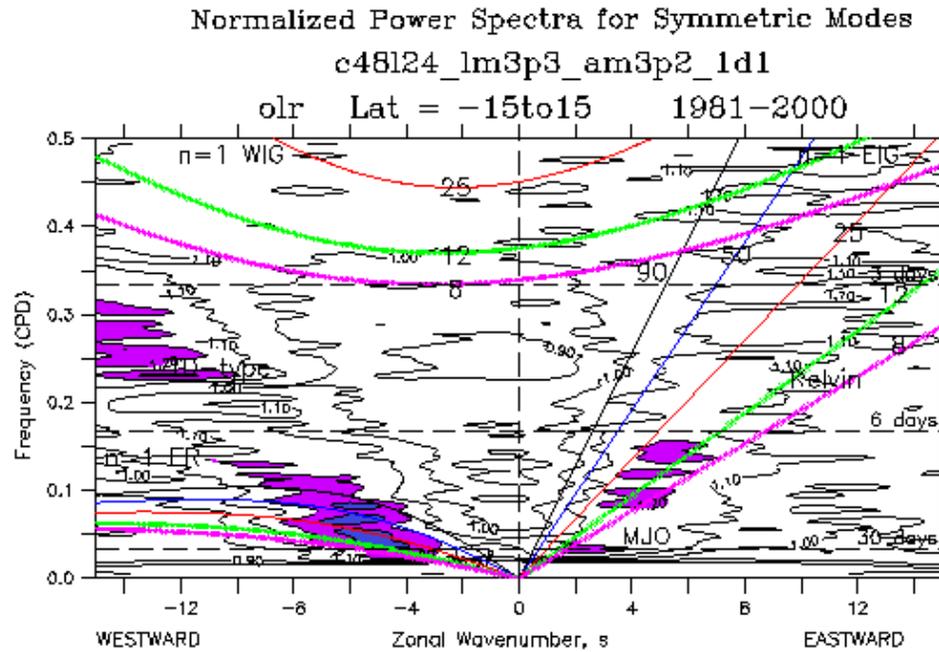
CAPE relaxation closure



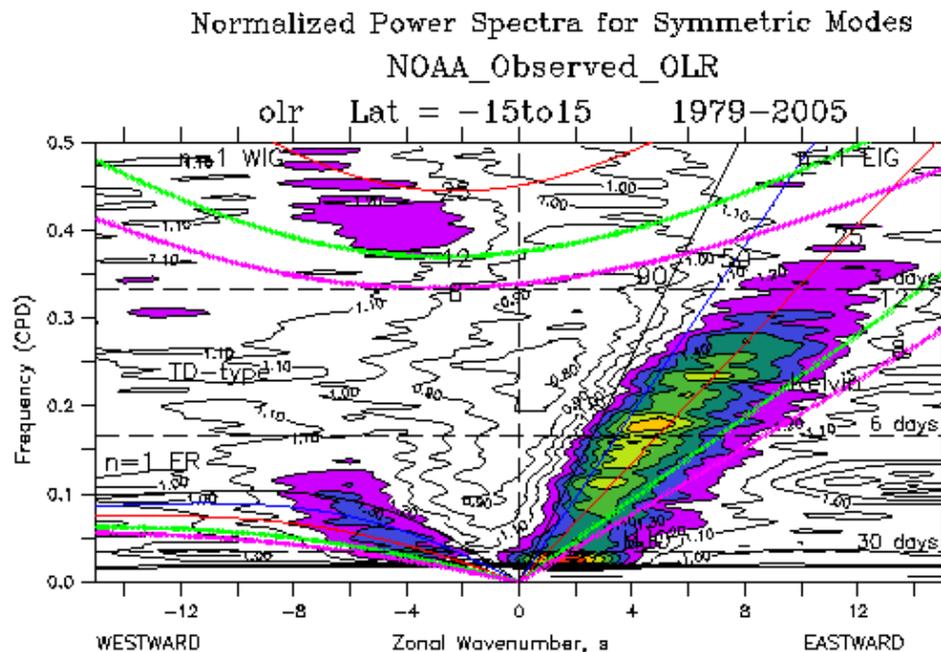
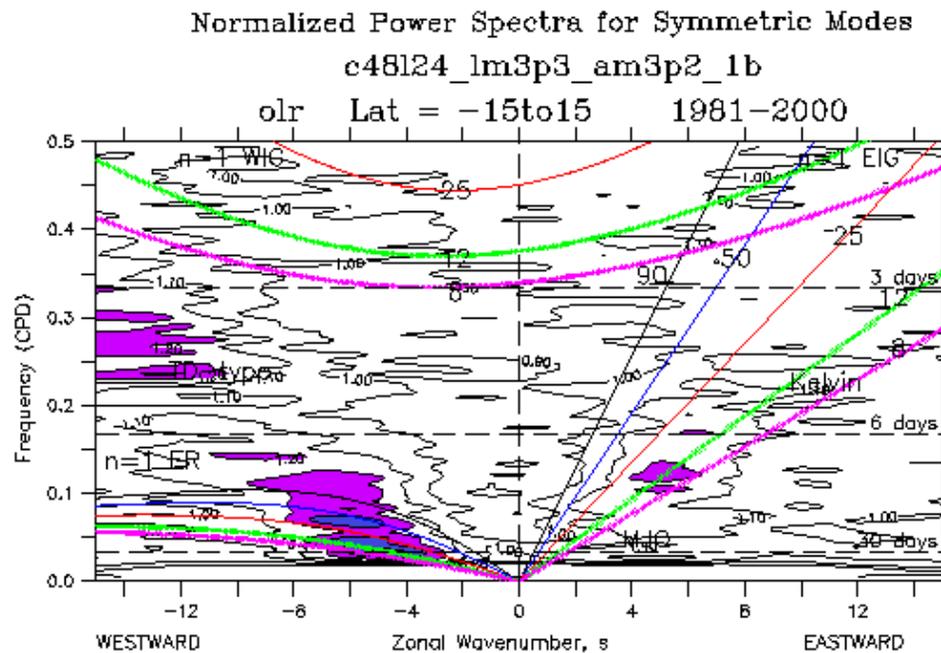
Zhang (2002, *JGR*) closure with low-level lift req'd



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



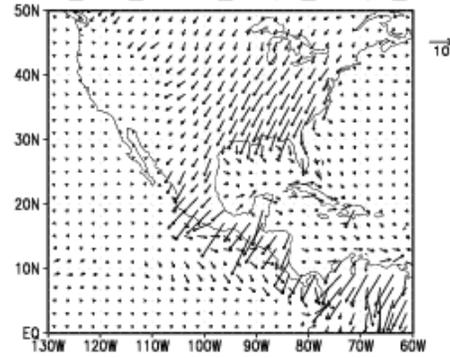
# CAPE relaxation closure



# CAPE relaxation closure

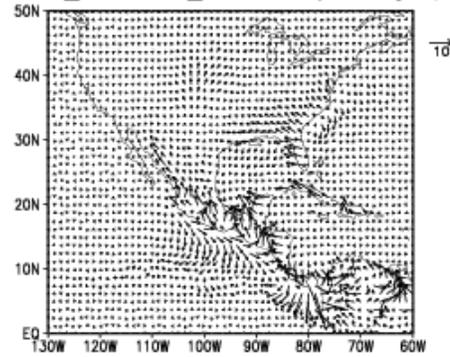
Diurnal Harmonic Vectors: Precip(JJA)

AM3\_M45\_c48I24\_lm3p3\_am3p2\_1b

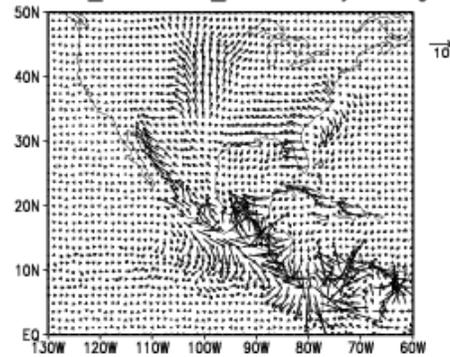


00  
18 ← → 06  
12  
local time

TRMM\_obs 1998\_2006 every 5th gridpt

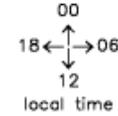
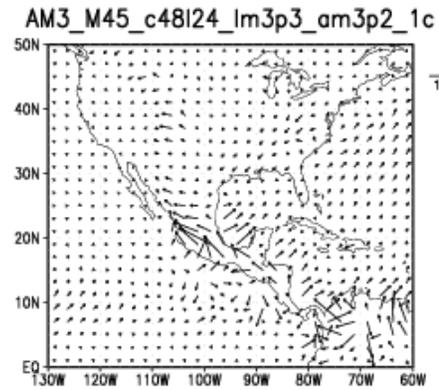


PERSIANN\_obs 2002\_2005 every 5th gridpt

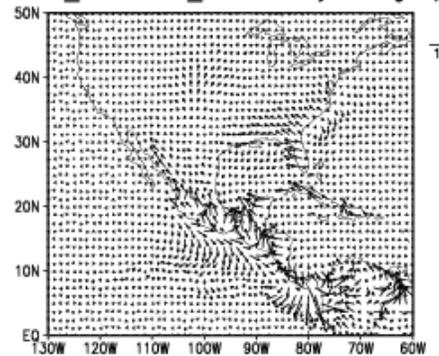


Zhang  
(2002,  
*JGR*)  
closure  
with low-  
level  
lift req'd

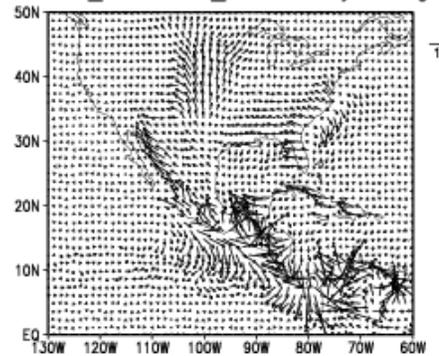
Diurnal Harmonic Vectors: Precip(JJA)



TRMM\_obs 1998\_2006 every 5th gridpt



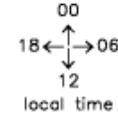
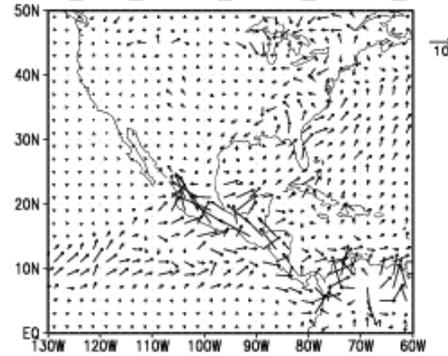
PERSIANN\_obs 2002\_2005 every 5th gridpt



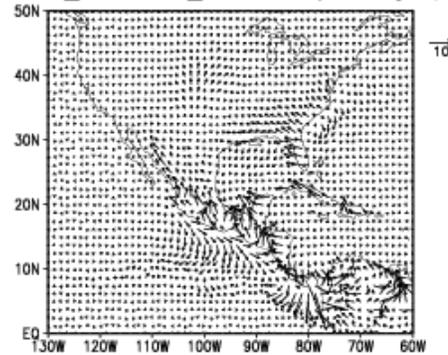
Zhang  
(2002,  
*JGR*)  
closure  
without  
low-level  
lift req'd

Diurnal Harmonic Vectors: Precip(JJA)

AM3\_M45\_c48124\_lm3p3\_am3p2\_1d



TRMM\_obs 1998\_2006 every 5th gridpt



PERSIANN\_obs 2002\_2005 every 5th gridpt

