# Recent Advances in Modeling Physical Processes in Climate Models: Implications for Global Space-Based Measurements

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GFDL/NOAA

NASA CERES Science Team, 24 September 2012, Princeton, NJ

# Themes

- CERES Perspective on GFDL's CMIP5 Models
- Satellite Simulators as Emerging Tools for Understanding Cloud and Aerosol Processes in Climate Models
- Cloud-Aerosol Interactions in Climate Models and Essential Related Observational Constraints

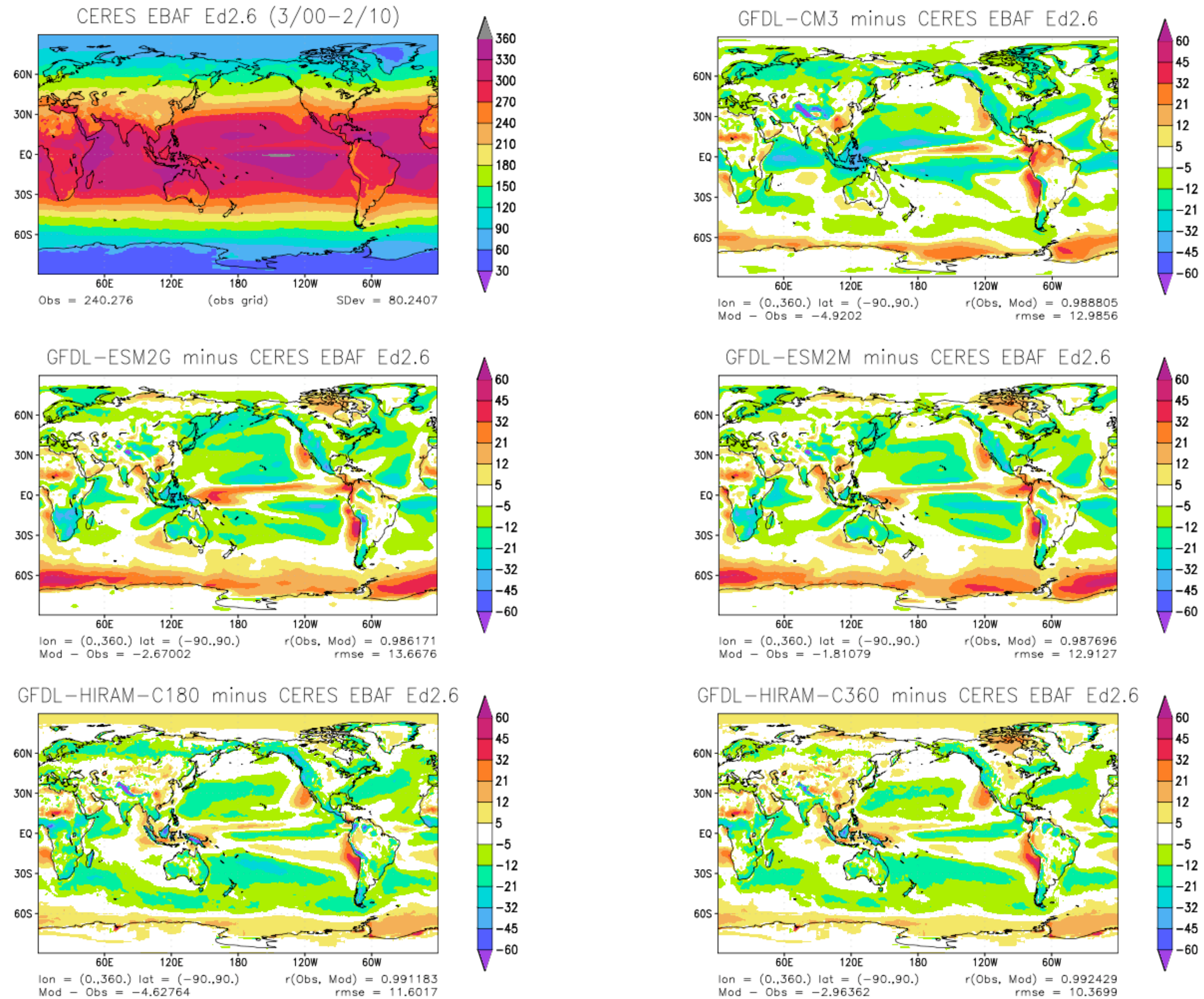
# A CERES View of GFDL's CMIP5 Models

- CM3 (Donner *et al.,* 2011, *J. Climate*): Coupled Ocean-Atmosphere Model with aerosol-cloud interactions, deep and shallow cumulus with vertical velocities, atmospheric chemistry, stratosphere (2°atmospheric horizontal resolution)
- ESM2-G and ESM2-M: Earth-System Models with isopycnal and z-coordinate ocean models, aerosol direct effects only (2° atmospheric horizontal resolution)
- HIRAM C-180 and C-360: 50-km and 25-km horizontal resolution atmosphere/land only with cloud fraction dependent on total water content, single-plume convection, aerosol direct effects only
- Details on all models at http://www.gfdl.noaa.gov/model-development

CERES EBAF Terra Edition2.6:
http://ceres.larc.nasa.gov/products.php?product=EBAF
Loeb et al. (2009), J. Climate

# ANN SWABS ($W/m^2$)

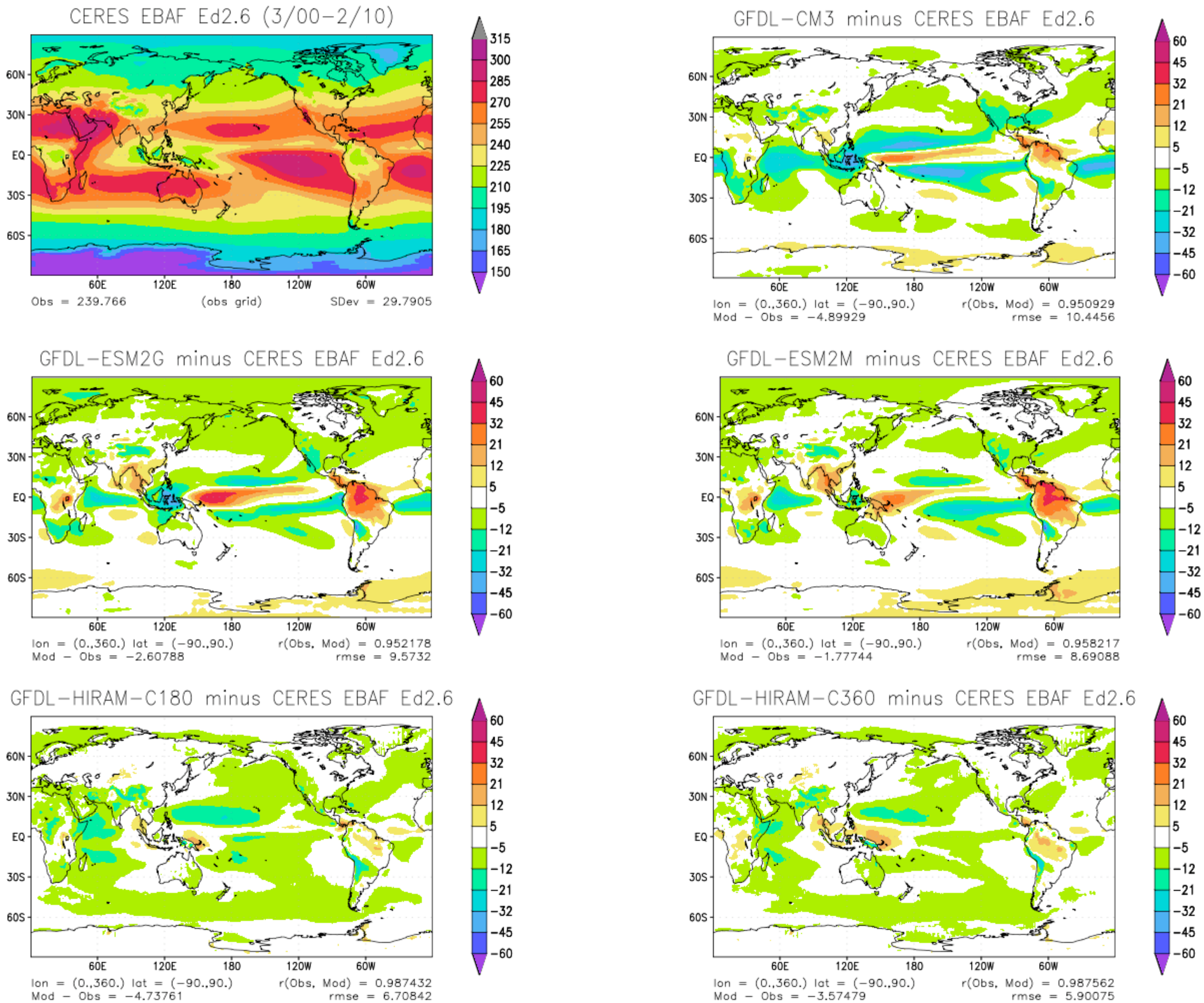
Models: 1981-2000



CERES EBAF Terra Edition2.6:
http://ceres.larc.nasa.gov/products.php?product=EBAF
Loeb et al. (2009), J. Climate

# ANN OLR (W/m²)

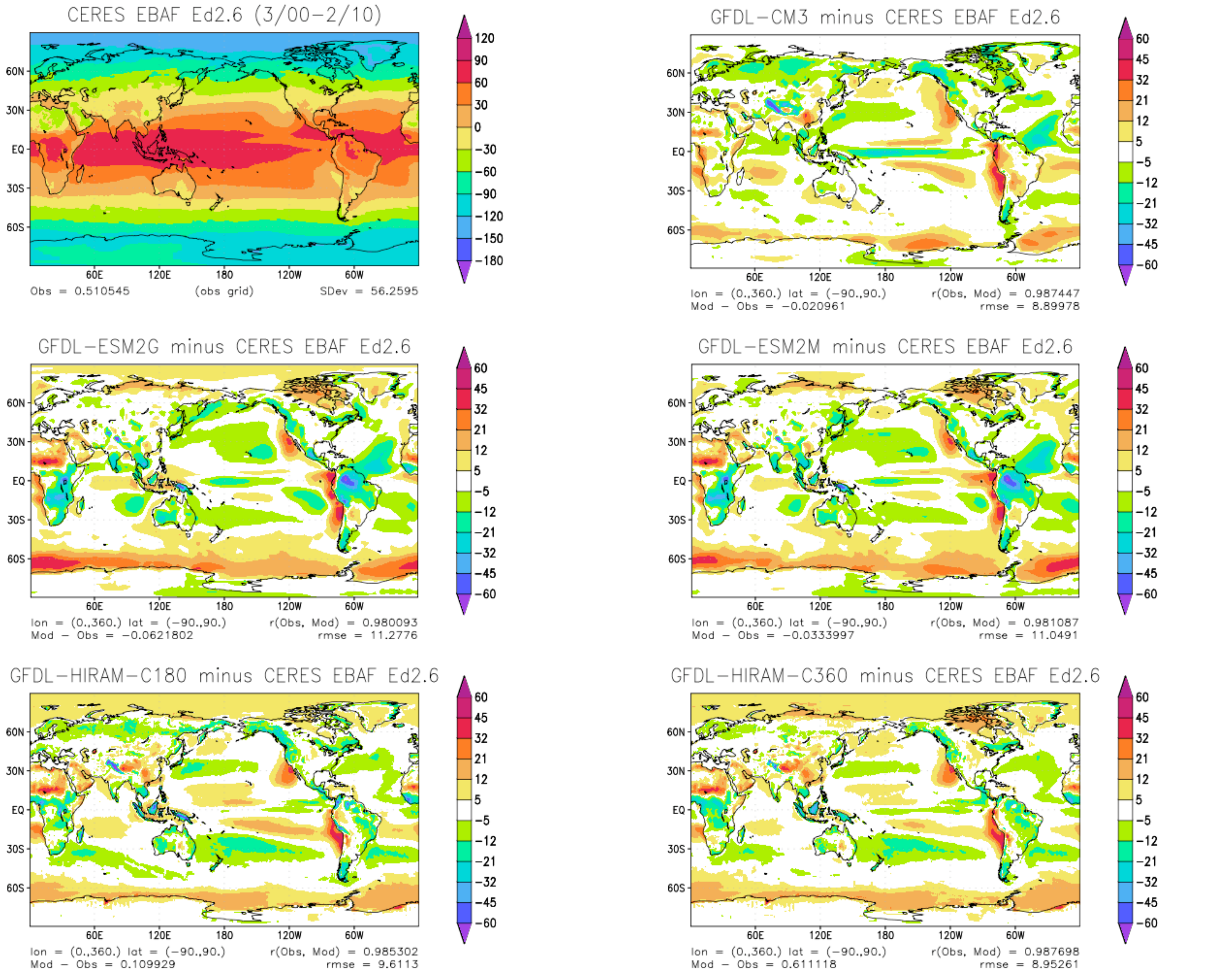
Models: 1981-2000



CERES EBAF Terra Edition2.6:
http://ceres.larc.nasa.gov/products.php?product=EBAF
Loeb et al. (2009), J. Climate

# ANN NETRADTOA (W/m²)

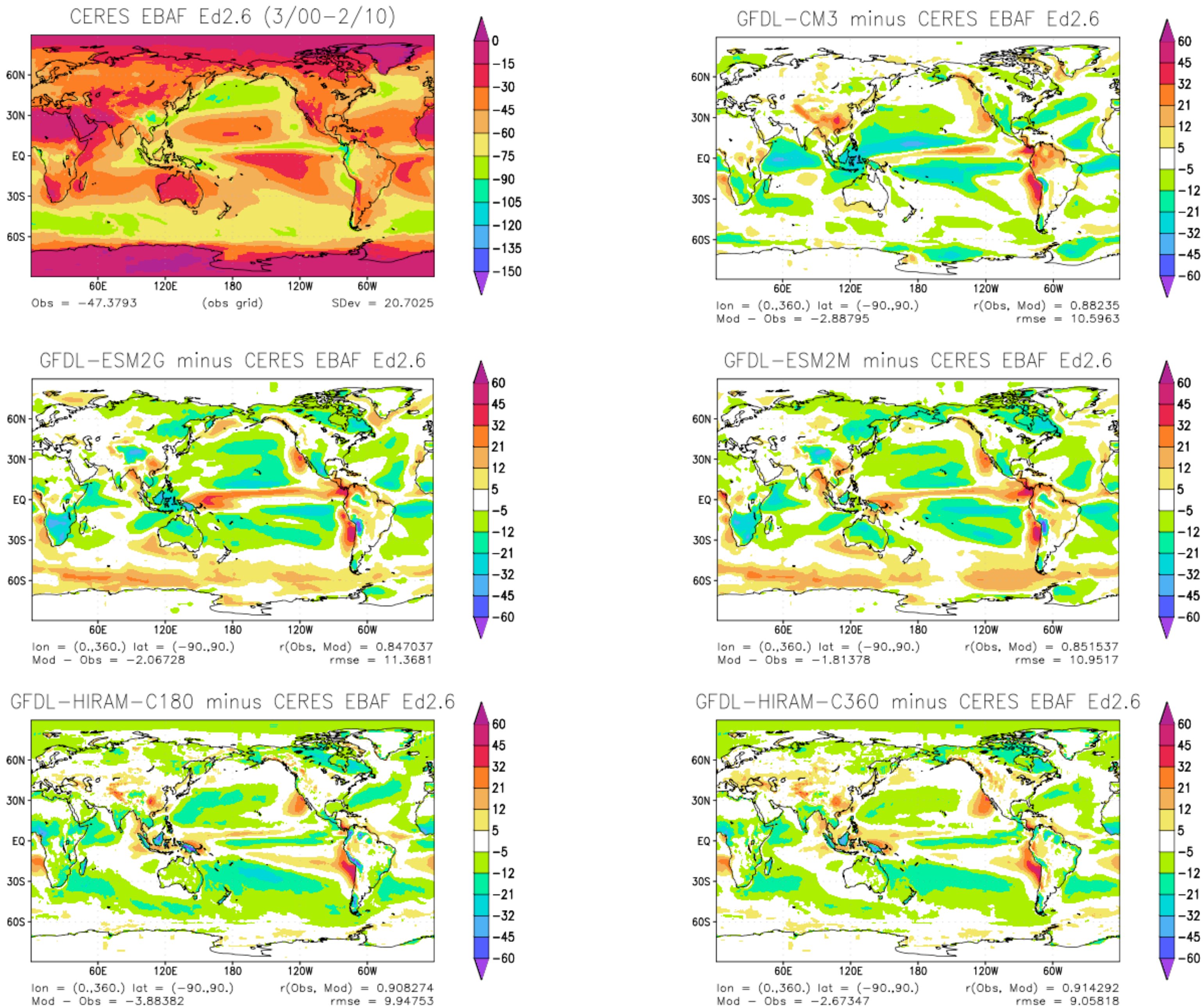
Models: 1981-2000



CERES EBAF Terra Edition2.6:
http://ceres.larc.nasa.gov/products.php?product=EBAF
Loeb et al. (2009), J. Climate

# ANN SWCF (W/m²)

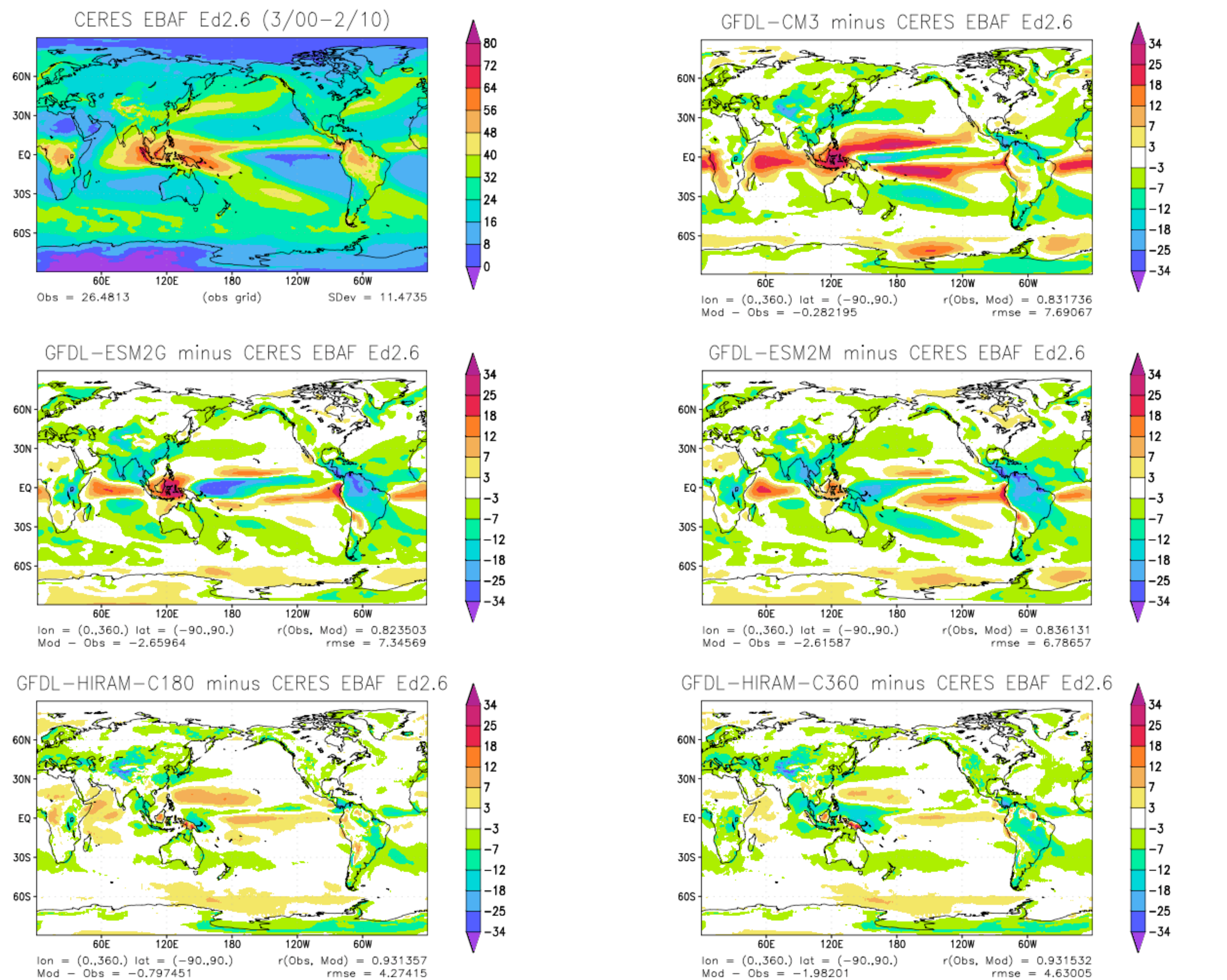
Models: 1981-2000



CERES EBAF Terra Edition2.6:
http://ceres.larc.nasa.gov/products.php?product=EBAF
Loeb et al. (2009), J. Climate

# ANN LWCF (W/m²)

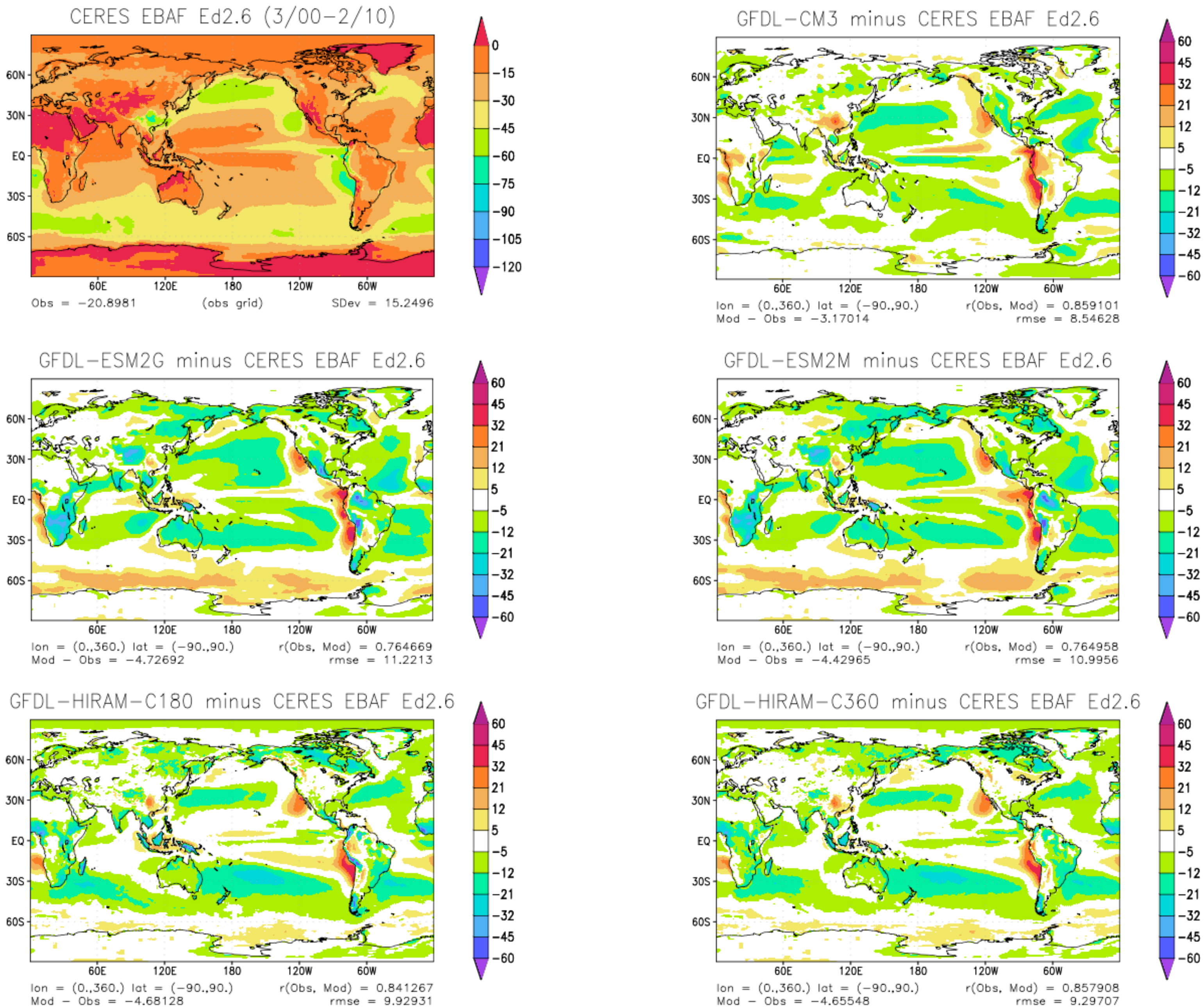
Models: 1981-2000



CERES EBAF Terra Edition2.6:
http://ceres.larc.nasa.gov/products.php?product=EBAF
Loeb et al. (2009), J. Climate

# ANN NETCF ($W/m^2$)

Models: 1981-2000



# Comments

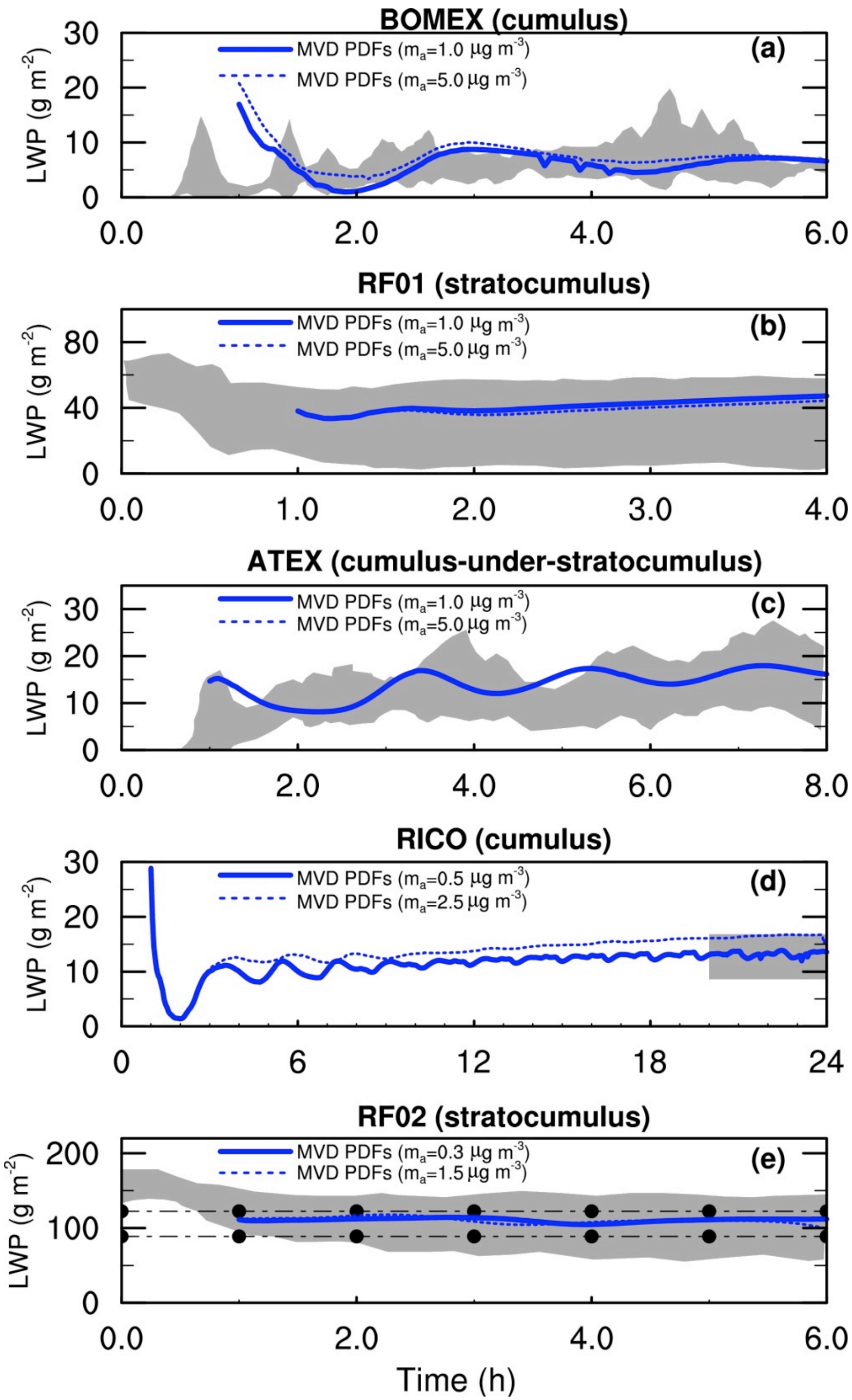
- Net radiation and CF compare best with CERES in CM3. Despite coupling and 2° resolution, CM3 better than 25-km uncoupled model with simpler physical parameterizations.
- But, longwave and shortwave components compare best for high-resolution uncoupled models. CM3 better than ESMs for shortwave; ESMs better for longwave.

# Experiments with Higher-Resolution AM3 and New Parameterization for Boundary Layers, Shallow Cumulus, Cirrus, Stratiform, and Stratocumulus Clouds

Notes: Experiments with new parameterization in early stages. Higher-resolution AM3 retains 2° parameter settings.

# Using multi-variate PDFs with dynamics (MVD PDFs) in GFDL AM3: Simulation of Marine Sc

AM3 Single Column Model using Multi-Variate Probability Density Function with Dynamics, Aerosol Activation, and Double-Moment Microphysics




"CLUBB"

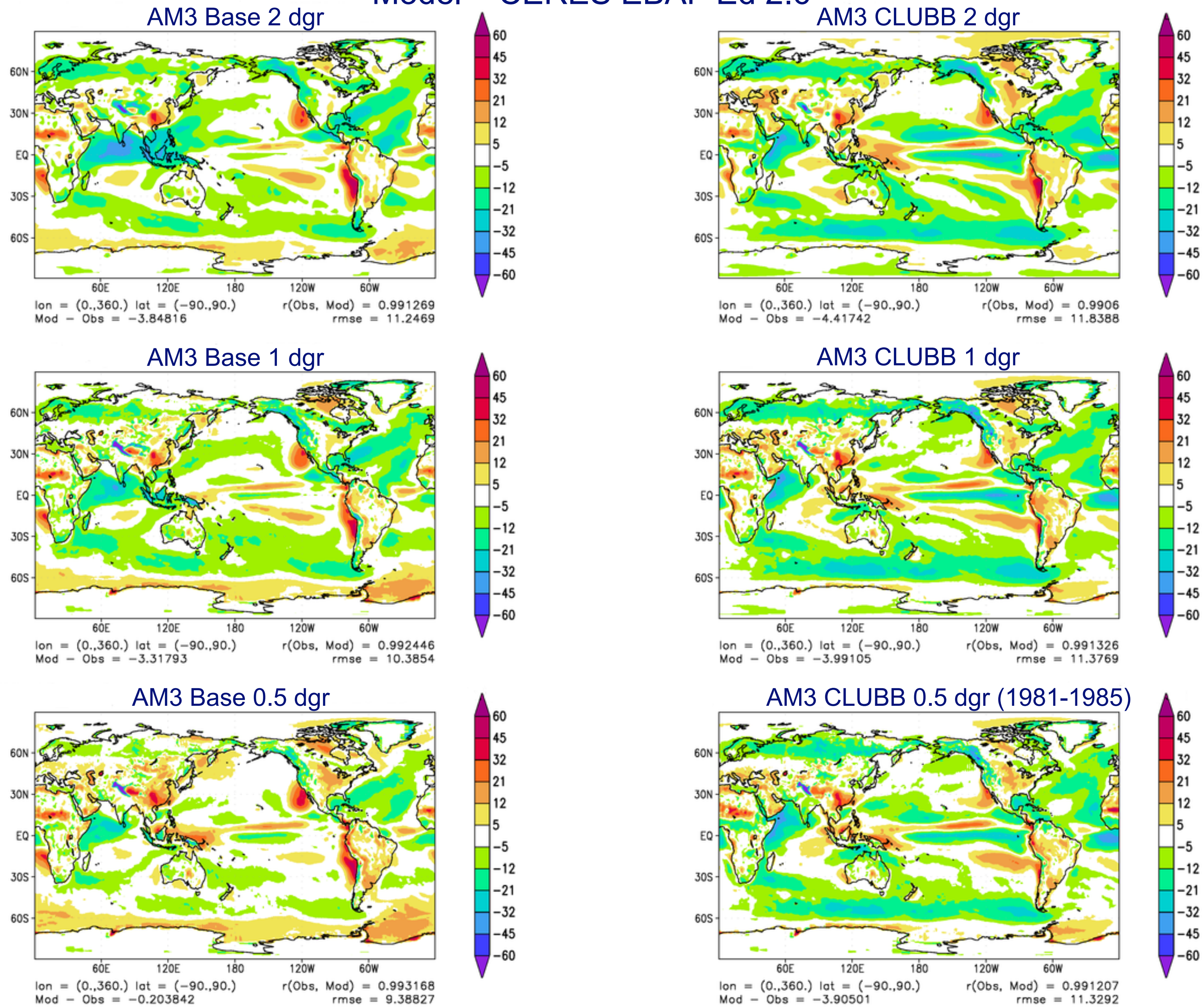
from *Guo et al.* (2010, *Geosci. Model Dev.*)

CERES EBAF Terra Edition2.6:
http://ceres.larc.nasa.gov/products.php?product=EBAF
Loeb et al. (2009), J. Climate

# ANN SWABS (W/m²)

## Model – CERES EBAF Ed 2.6

Models: 1981-2000 (except AM3 CLUBB 0.5 dgr)

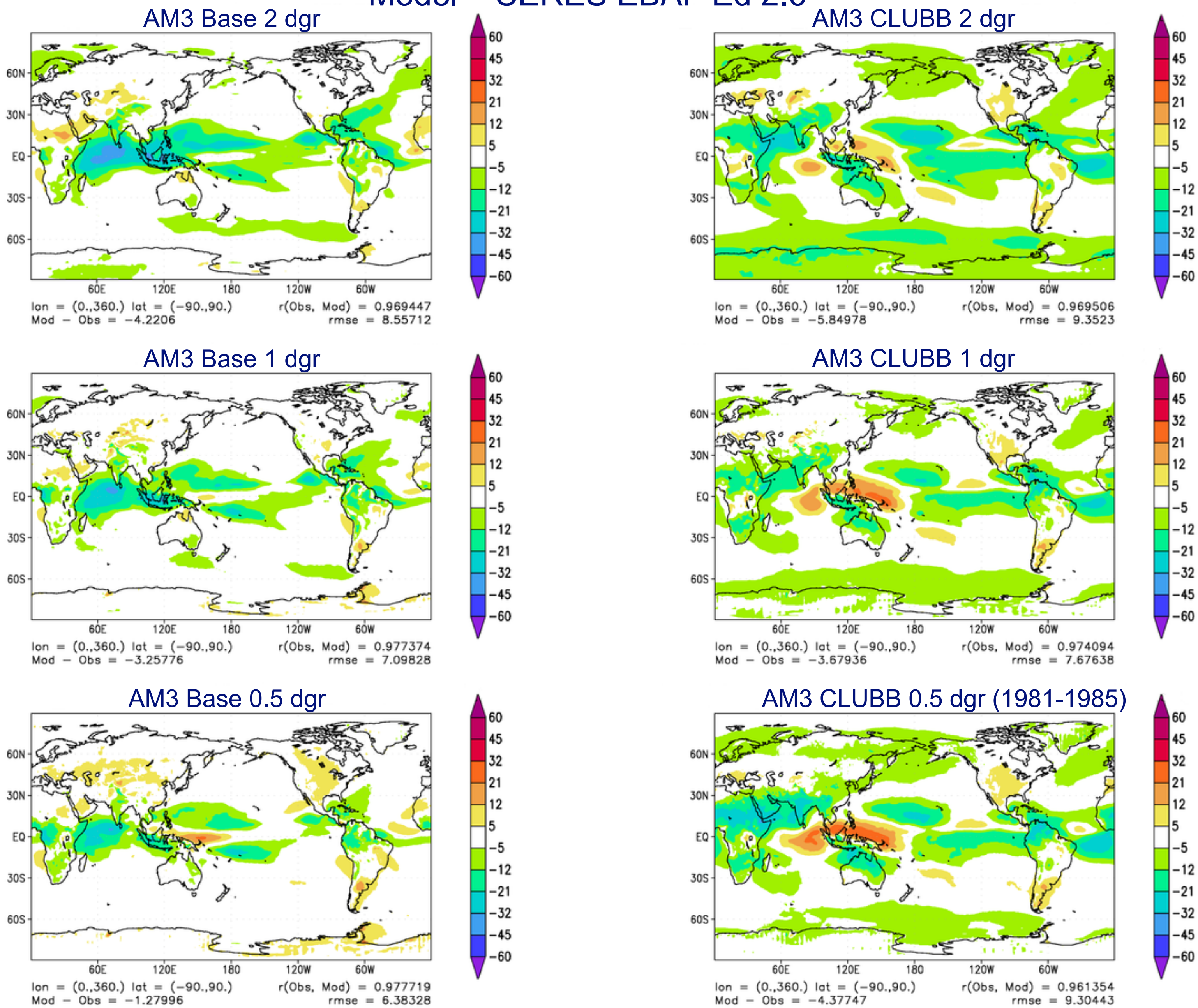


CERES EBAF Terra Edition2.6:
http://ceres.larc.nasa.gov/products.php?product=EBAF
Loeb et al. (2009), J. Climate

# ANN OLR (W/m²)

## Model – CERES EBAF Ed 2.6

Models: 1981-2000 (except AM3 CLUBB 0.5 dgr)



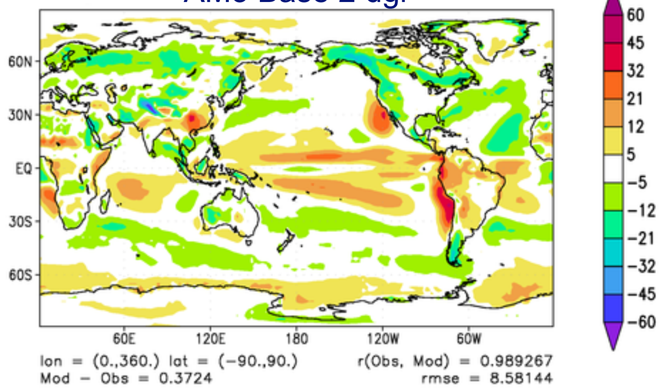
CERES EBAF Terra Edition2.6:
http://ceres.larc.nasa.gov/products.php?product=EBAF
Loeb et al. (2009), J. Climate

# ANN NETRADTOA (W/m²)

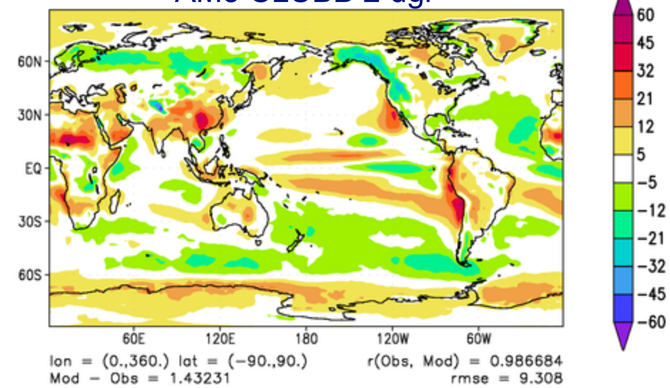
Models: 1981-2000 (except AM3 CLUBB 0.5 dgr)

## Model – CERES EBAF Ed 2.6

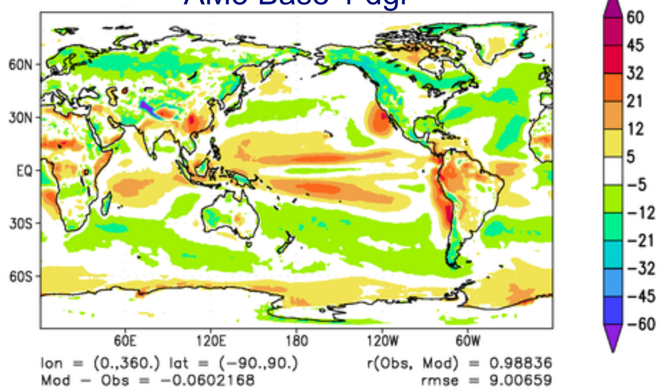
### AM3 Base 2 dgr



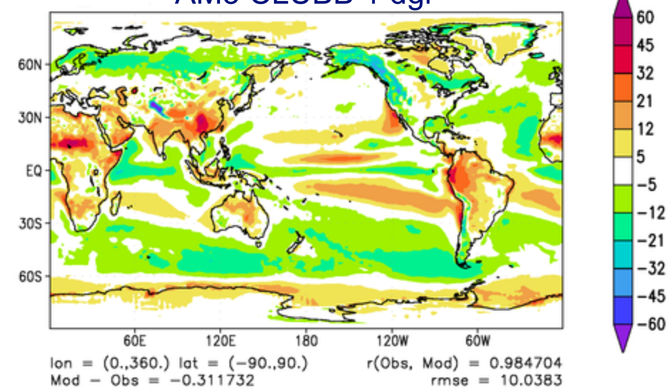

### AM3 CLUBB 2 dgr



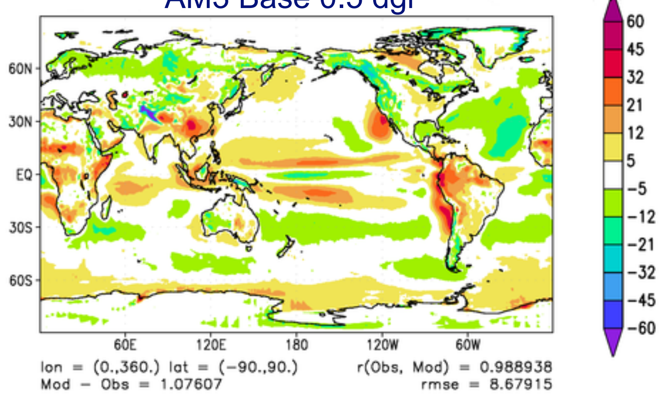

### AM3 Base 1 dgr



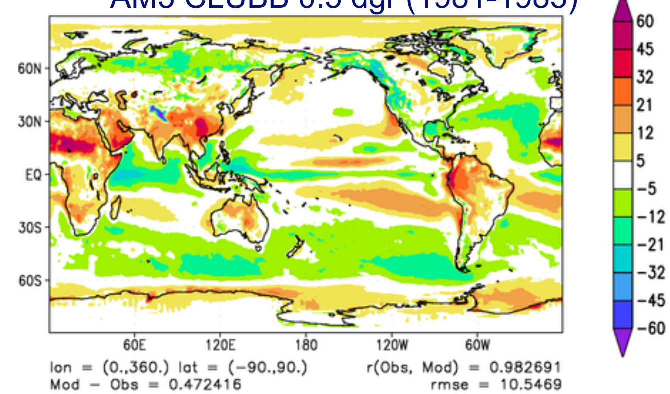

### AM3 CLUBB 1 dgr




### AM3 Base 0.5 dgr




### AM3 CLUBB 0.5 dgr (1981-1985)

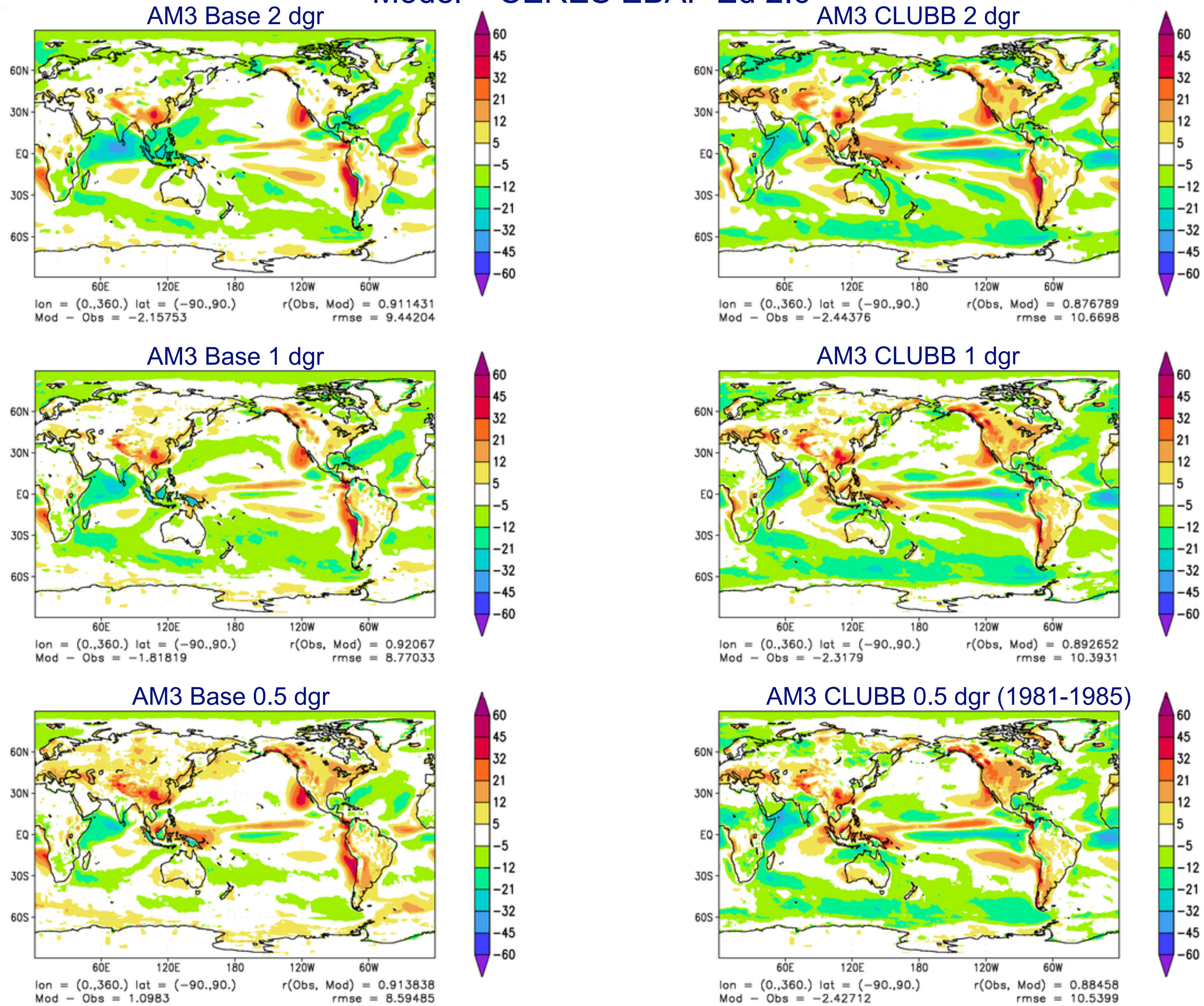


CERES EBAF Terra Edition2.6:
http://ceres.larc.nasa.gov/products.php?product=EBAF
Loeb et al. (2009), J. Climate

# ANN SWCF ($W/m^2$)

## Model – CERES EBAF Ed 2.6

Models: 1981-2000 (except AM3 CLUBB 0.5 dgr)



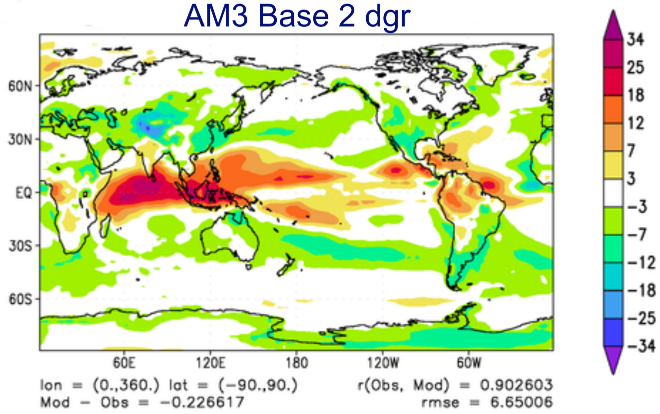
CERES EBAF Terra Edition2.6:
http://ceres.larc.nasa.gov/products.php?product=EBAF
Loeb et al. (2009), J. Climate

# ANN LWCF (W/m²)

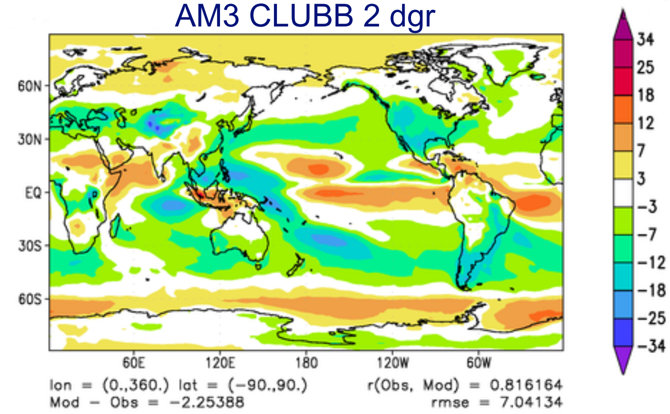
## Model – CERES EBAF Ed 2.6

Models: 1981-2000 (except AM3 CLUBB 0.5 dgr)

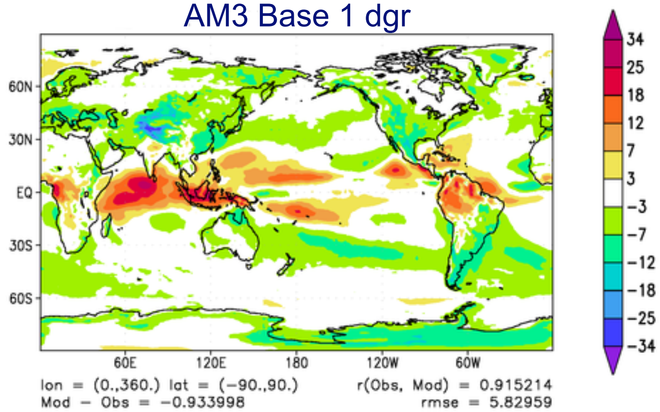
### AM3 Base 2 dgr



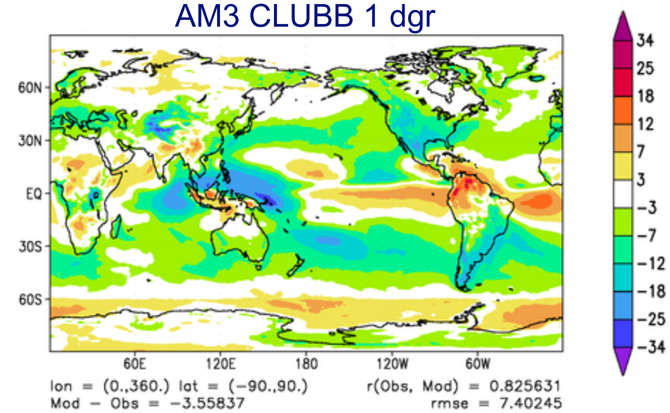

### AM3 CLUBB 2 dgr



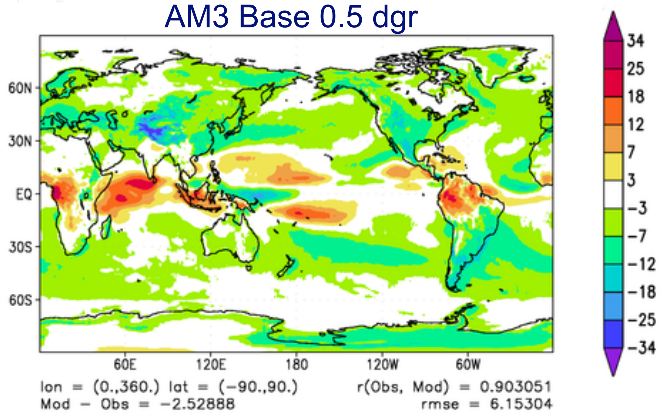

### AM3 Base 1 dgr



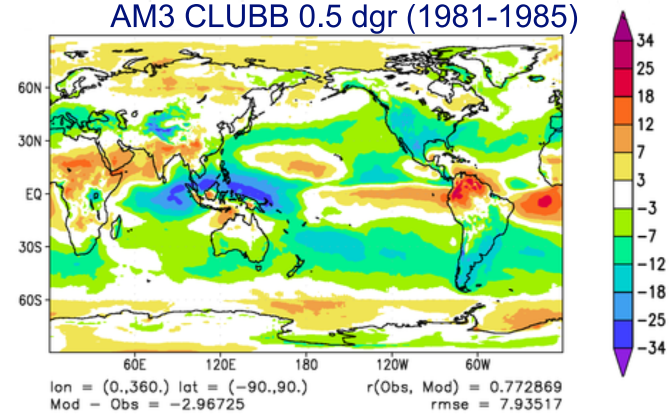

### AM3 CLUBB 1 dgr




### AM3 Base 0.5 dgr




### AM3 CLUBB 0.5 dgr (1981-1985)



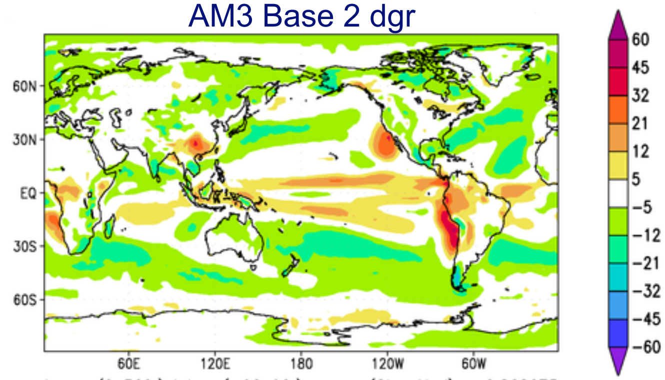
CERES EBAF Terra Edition2.6:
http://ceres.larc.nasa.gov/products.php?product=EBAF
Loeb et al. (2009), J. Climate

# ANN NETCF (W/m²)

## Model – CERES EBAF Ed 2.6

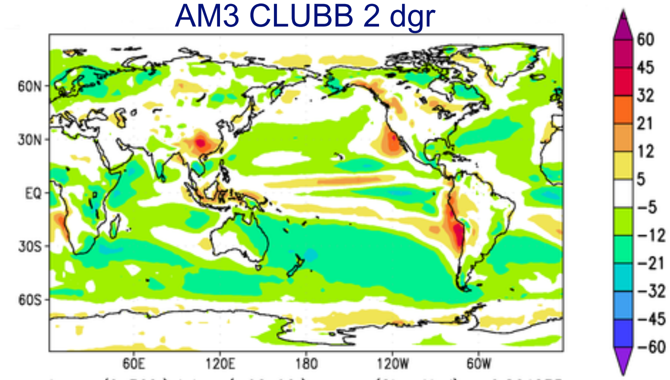
Models: 1981-2000 (except AM3 CLUBB 0.5 dgr)

### AM3 Base 2 dgr



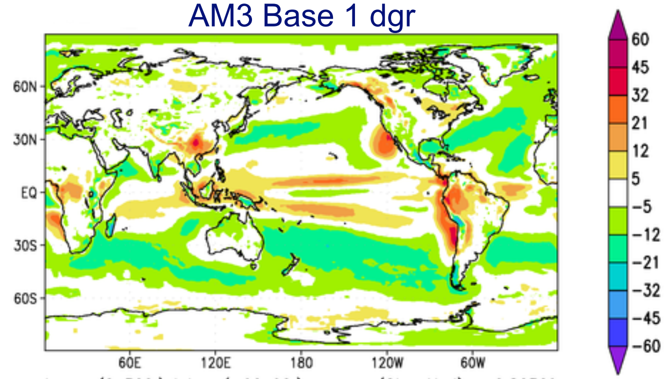

lon = (0.,360.) lat = (-90.,90.) r(Obs, Mod) = 0.862675
Mod – Obs = -2.38415 rmse = 8.56554

### AM3 CLUBB 2 dgr



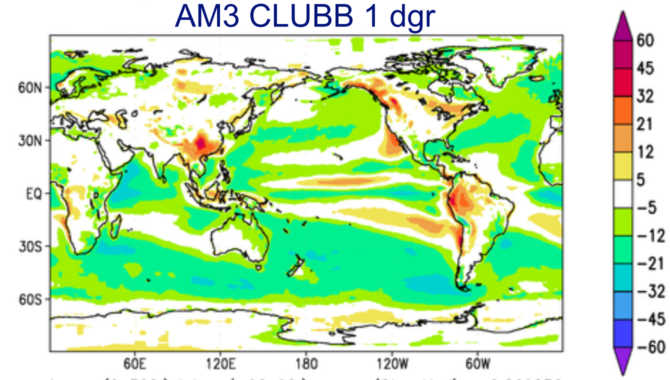

lon = (0.,360.) lat = (-90.,90.) r(Obs, Mod) = 0.864235
Mod – Obs = -4.69764 rmse = 9.75618

### AM3 Base 1 dgr



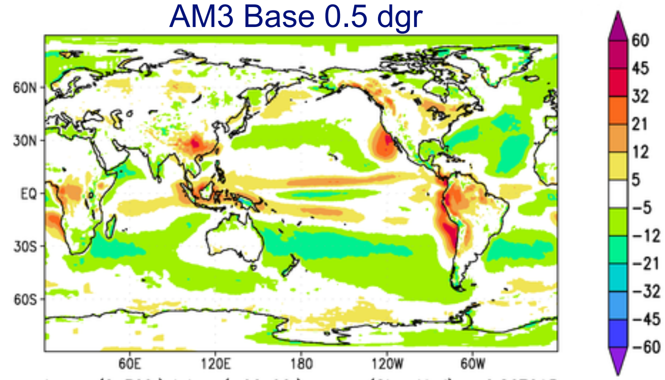

lon = (0.,360.) lat = (-90.,90.) r(Obs, Mod) = 0.86369
Mod – Obs = -2.75219 rmse = 8.95038

### AM3 CLUBB 1 dgr



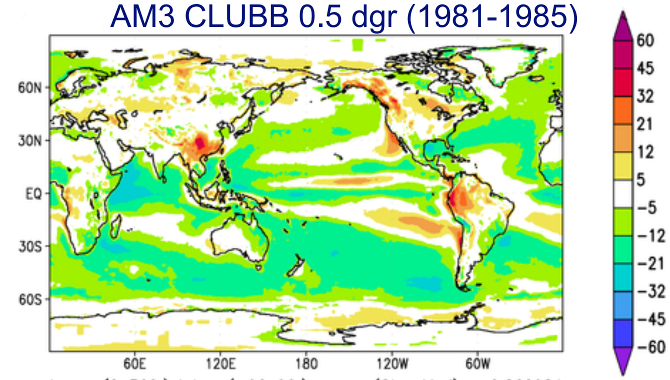

lon = (0.,360.) lat = (-90.,90.) r(Obs, Mod) = 0.869236
Mod – Obs = -5.87627 rmse = 10.8688

### AM3 Base 0.5 dgr




lon = (0.,360.) lat = (-90.,90.) r(Obs, Mod) = 0.867015
Mod – Obs = -1.43058 rmse = 8.13226

### AM3 CLUBB 0.5 dgr (1981-1985)




lon = (0.,360.) lat = (-90.,90.) r(Obs, Mod) = 0.860924
Mod – Obs = -5.39436 rmse = 10.5957

# Comments

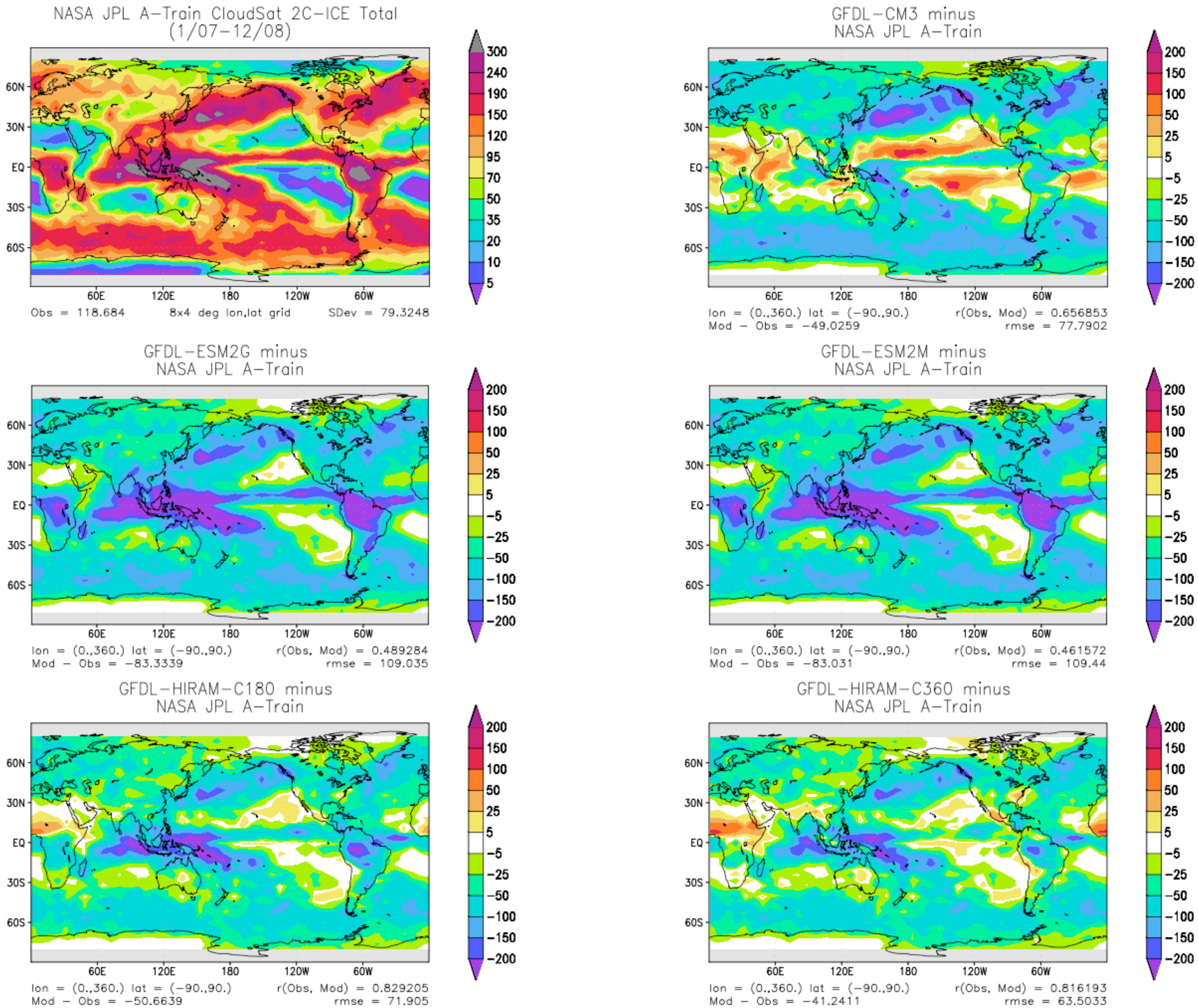
- AM3 50-km resolution matches CERES better than 50-km HIRAM for all fields except LWCF.
- SWABS, SWCF, NETRADTOA, and NETCF from 50-km AM3 match CERES better than 25-km HIRAM.
- AM3-CLUBB improves on AM3 for marine Sc at 50- and 25-km, but overall RMSEs not as good as AM3.

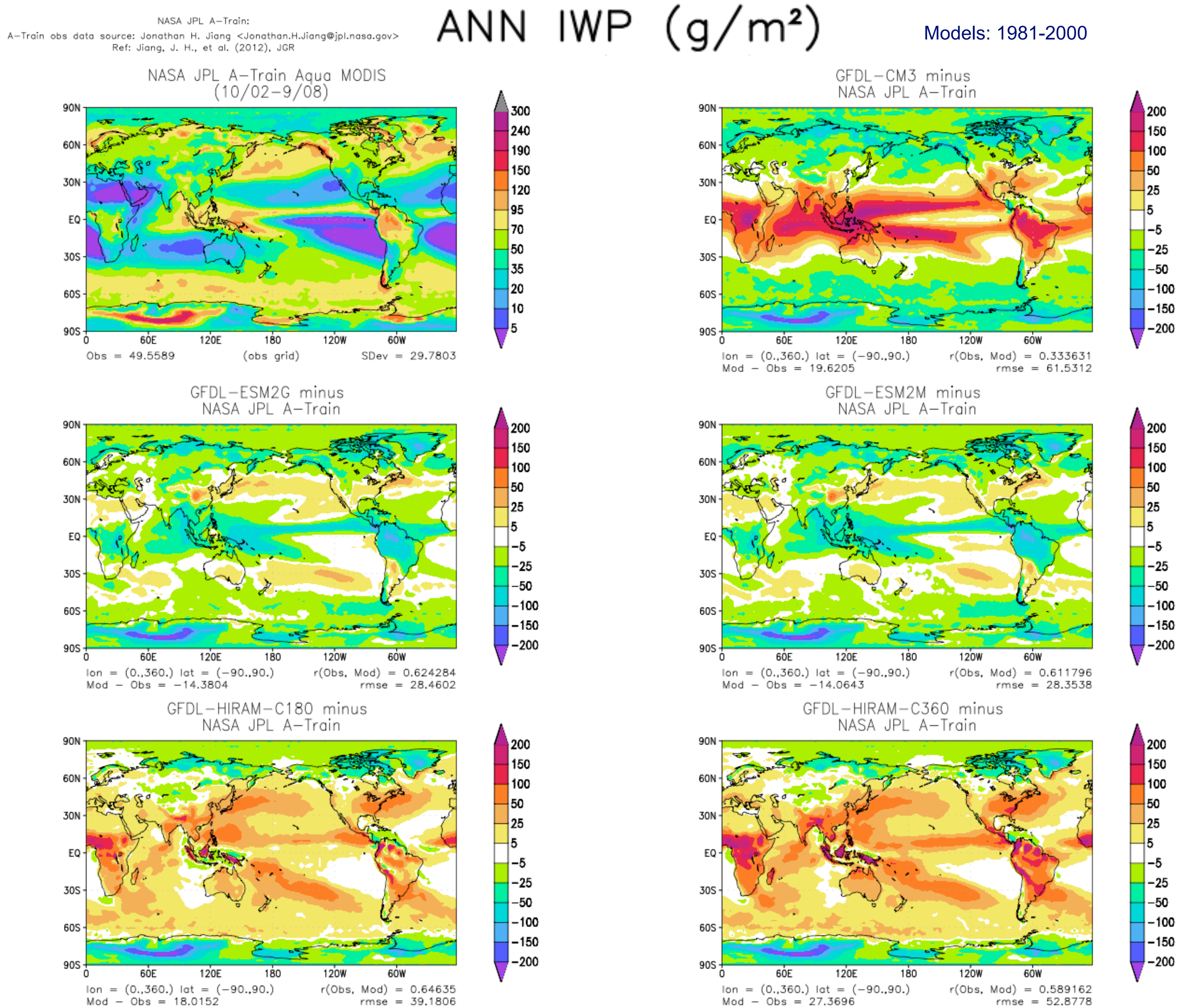
# A-Train

NASA JPL A–Train:
A–Train obs data source: Jui–Lin (Frank) Li <juilin.f.li@jpl.nasa.gov>
Ref: Li, J.–L. F., et al. (2012), JGR

# ANN IWP $(g/m^2)$

Models: 1981-2000



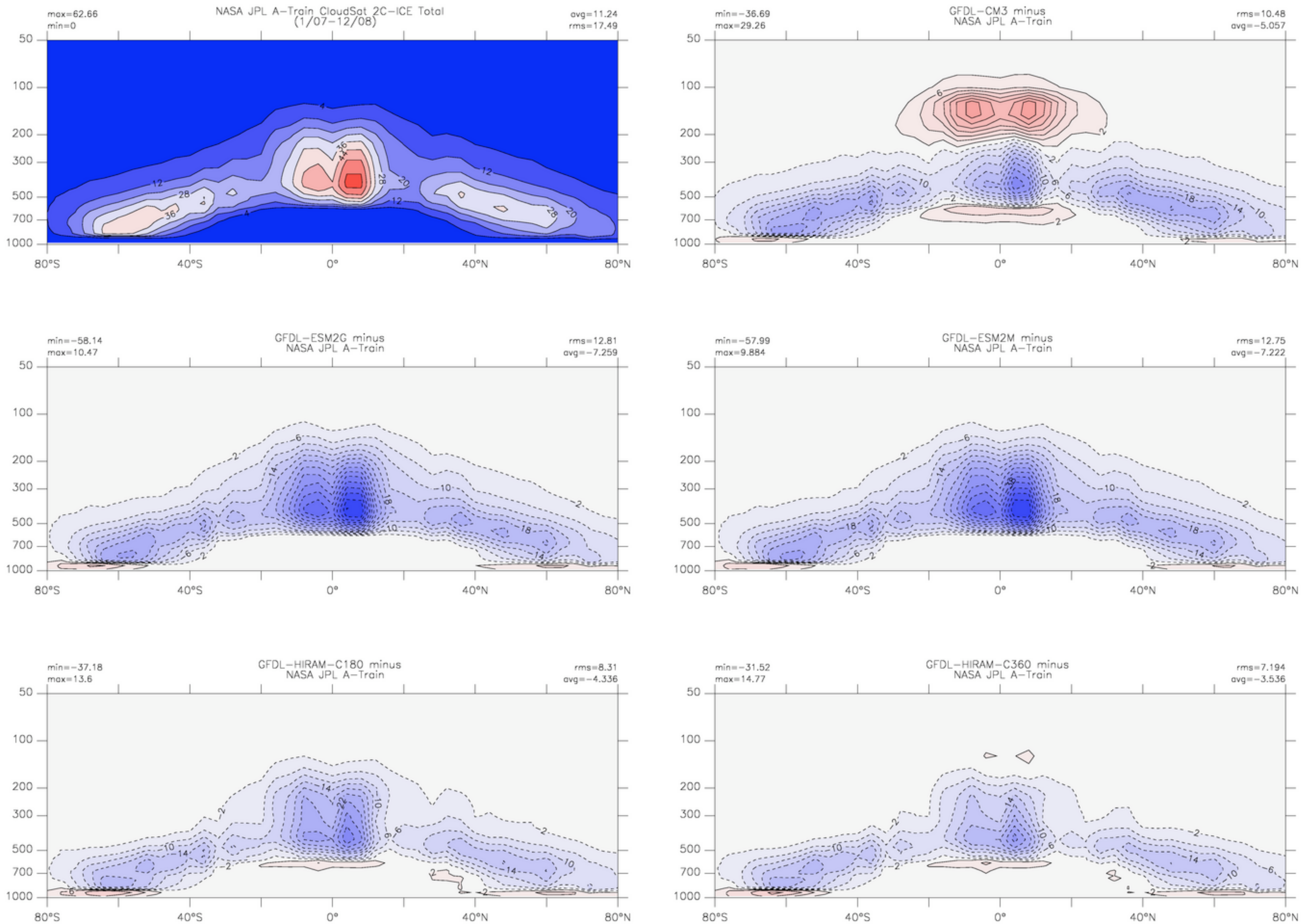


NASA JPL A-Train:
A-Train obs data source: Jonathan H. Jiang <Jonathan.H.Jiang@jpl.nasa.gov>
Ref: Jiang, J. H., et al. (2012), JGR
ANN IWP (g/m²)
Models: 1981-2000
NASA JPL A-Train Aqua MODIS (10/02-9/08)
Obs = 49.5589 (obs grid) SDev = 29.7803
GFDL-CM3 minus NASA JPL A-Train
lon = (0..360.) lat = (-90..90.) r(Obs, Mod) = 0.333631
Mod - Obs = 19.6205 rmse = 61.5312
GFDL-ESM2G minus NASA JPL A-Train
lon = (0..360.) lat = (-90..90.) r(Obs, Mod) = 0.624284
Mod - Obs = -14.3804 rmse = 28.4602
GFDL-ESM2M minus NASA JPL A-Train
lon = (0..360.) lat = (-90..90.) r(Obs, Mod) = 0.611796
Mod - Obs = -14.0643 rmse = 28.3538
GFDL-HIRAM-C180 minus NASA JPL A-Train
lon = (0..360.) lat = (-90..90.) r(Obs, Mod) = 0.64635
Mod - Obs = 18.0152 rmse = 39.1806
GFDL-HIRAM-C360 minus NASA JPL A-Train
lon = (0..360.) lat = (-90..90.) r(Obs, Mod) = 0.589162
Mod - Obs = 27.3696 rmse = 52.8778

NASA JPL A-Train obs data source: Jui-Lin (Frank) Li <juilin.f.li@jpl.nasa.gov>
Ref: Li, J.-L. F., et al. (2012), JGR

ANN [iwc] (mg kg$^{-1}$)

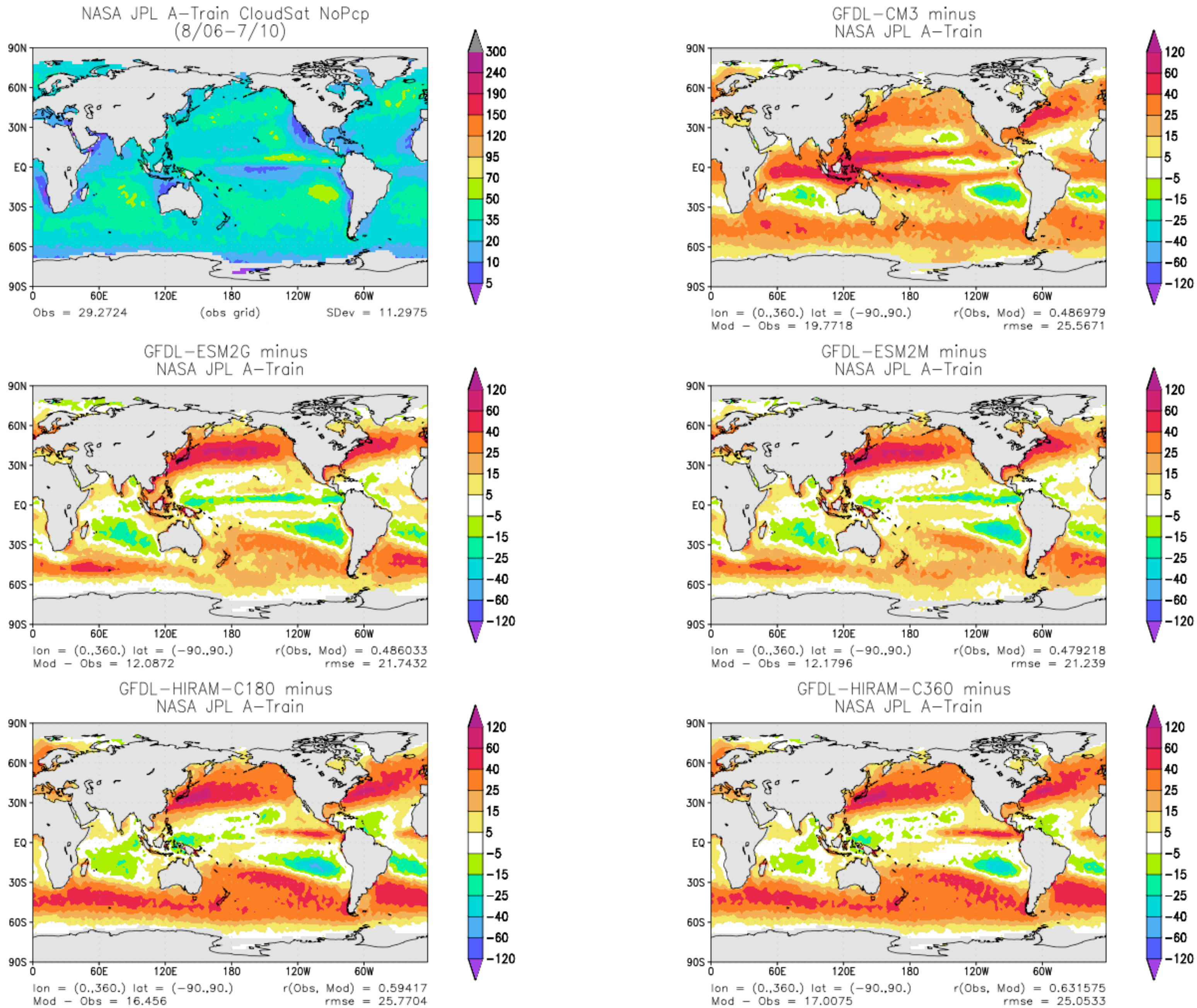
Models: 1981-2000



NASA JPL A–Train:
A–Train obs data source: Jonathan H. Jiang <Jonathan.H.Jiang@jpl.nasa.gov>
Ref: Jiang, J. H., et al. (2012), JGR

# ANN LWP (g/m²)

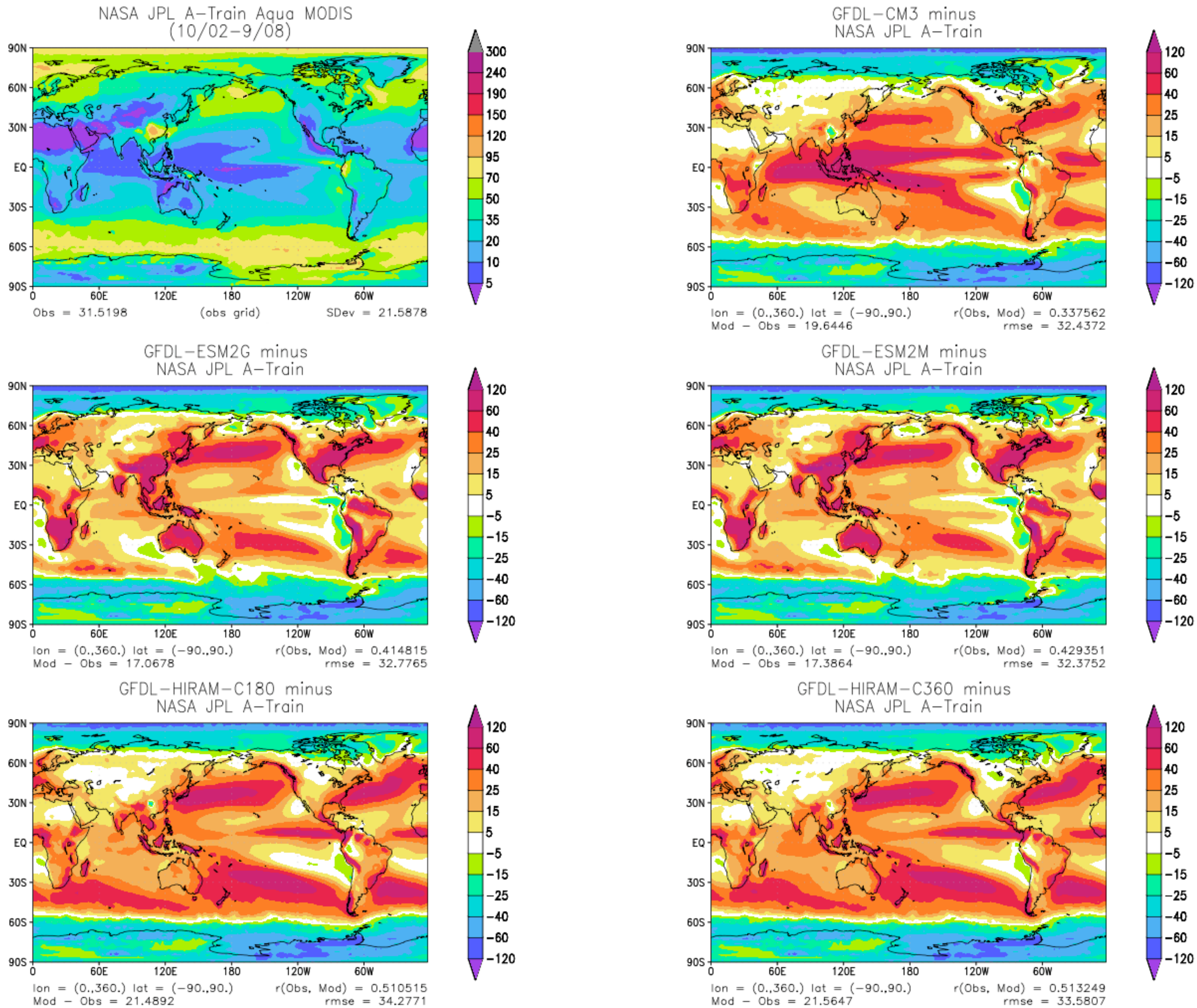
Models: 1981-2000



NASA JPL A−Train:
A−Train obs data source: Jonathan H. Jiang <Jonathan.H.Jiang@jpl.nasa.gov>
Ref: Jiang, J. H., et al. (2012), JGR

# ANN LWP ($g/m^2$)

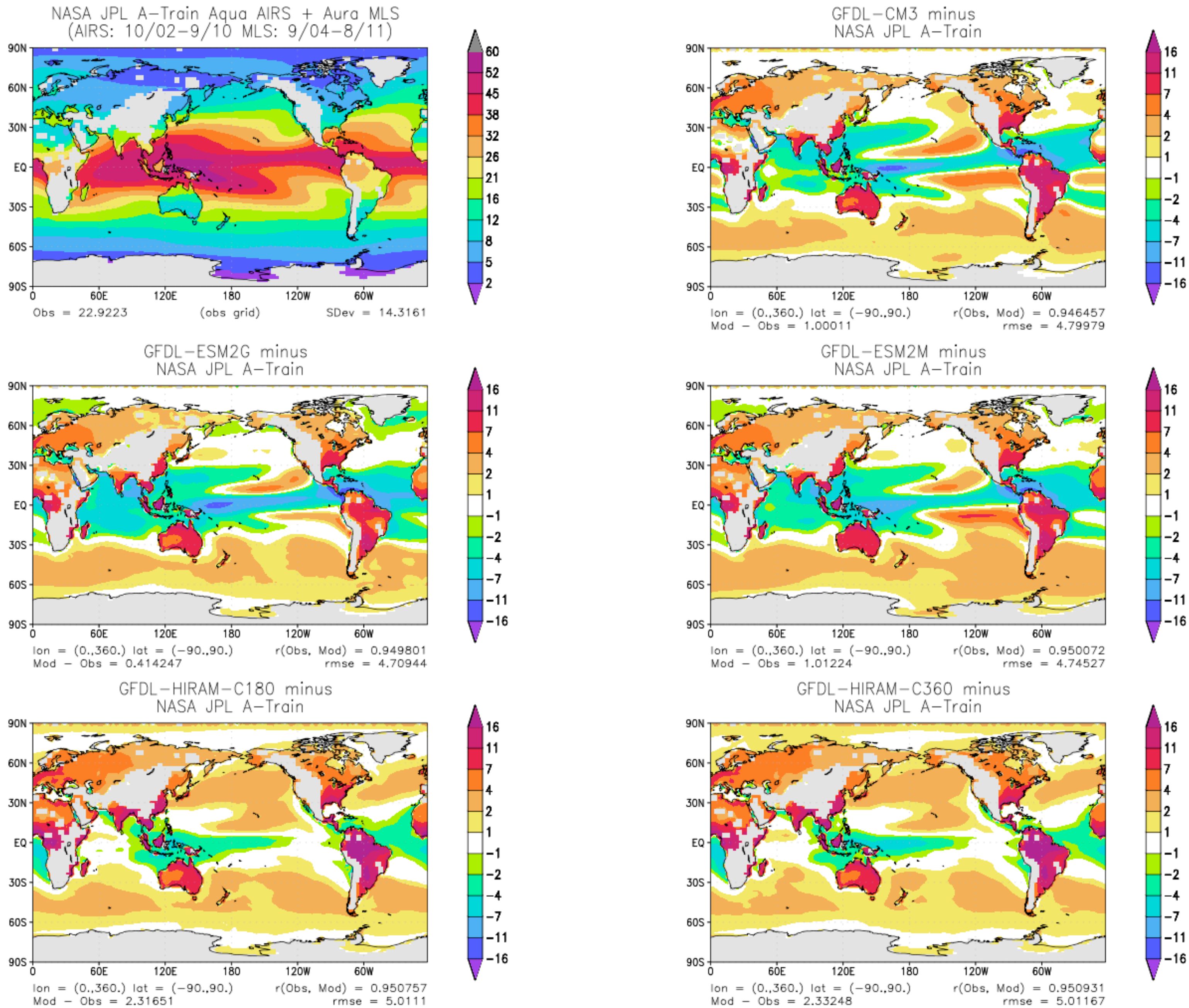
Models: 1981-2000



NASA JPL A–Train:
A–Train obs data source: Jonathan H. Jiang <Jonathan.H.Jiang@jpl.nasa.gov>
Ref: Jiang, J. H., et al. (2012), JGR

# ANN PRW (kg/m²)

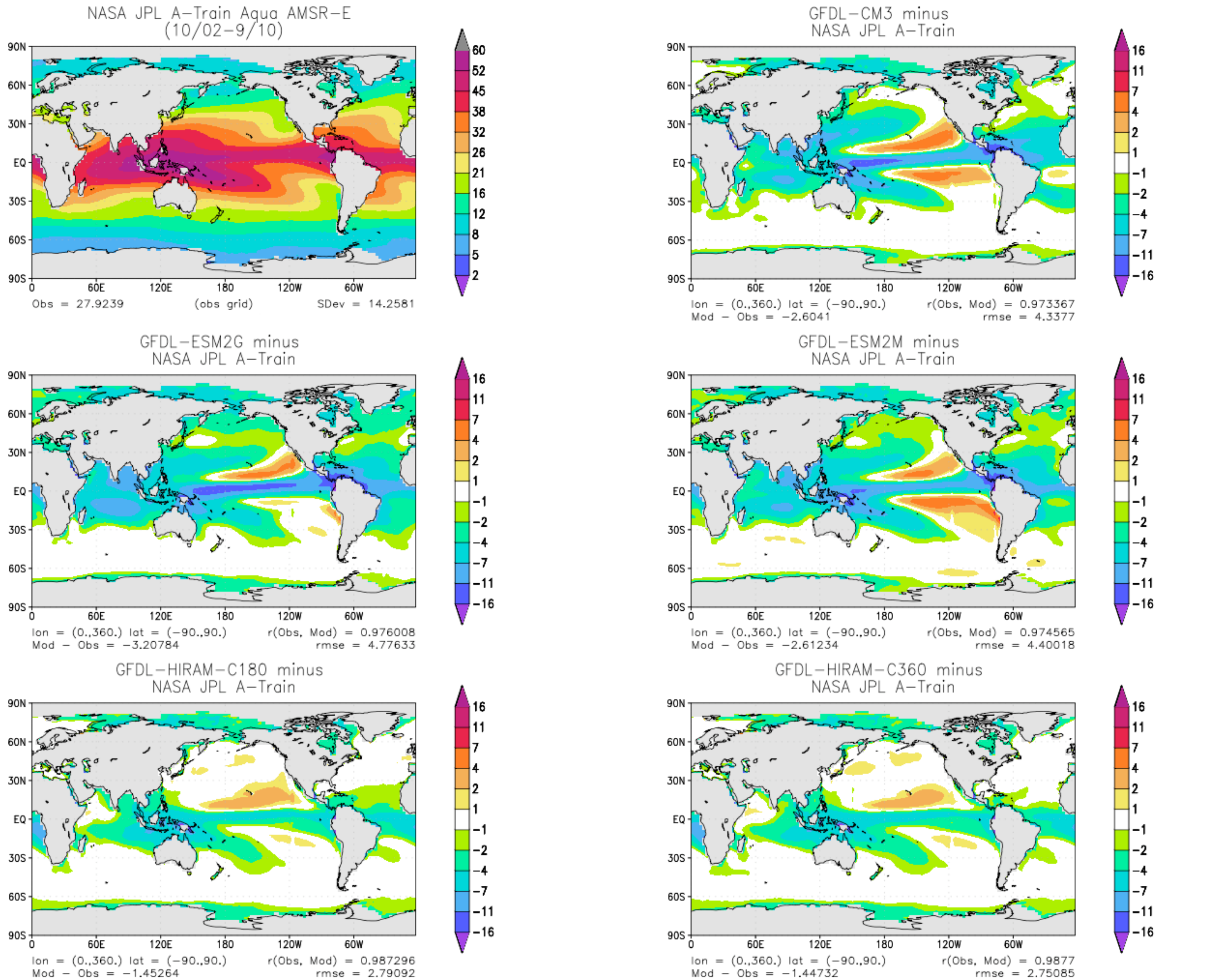
Models: 1981-2000



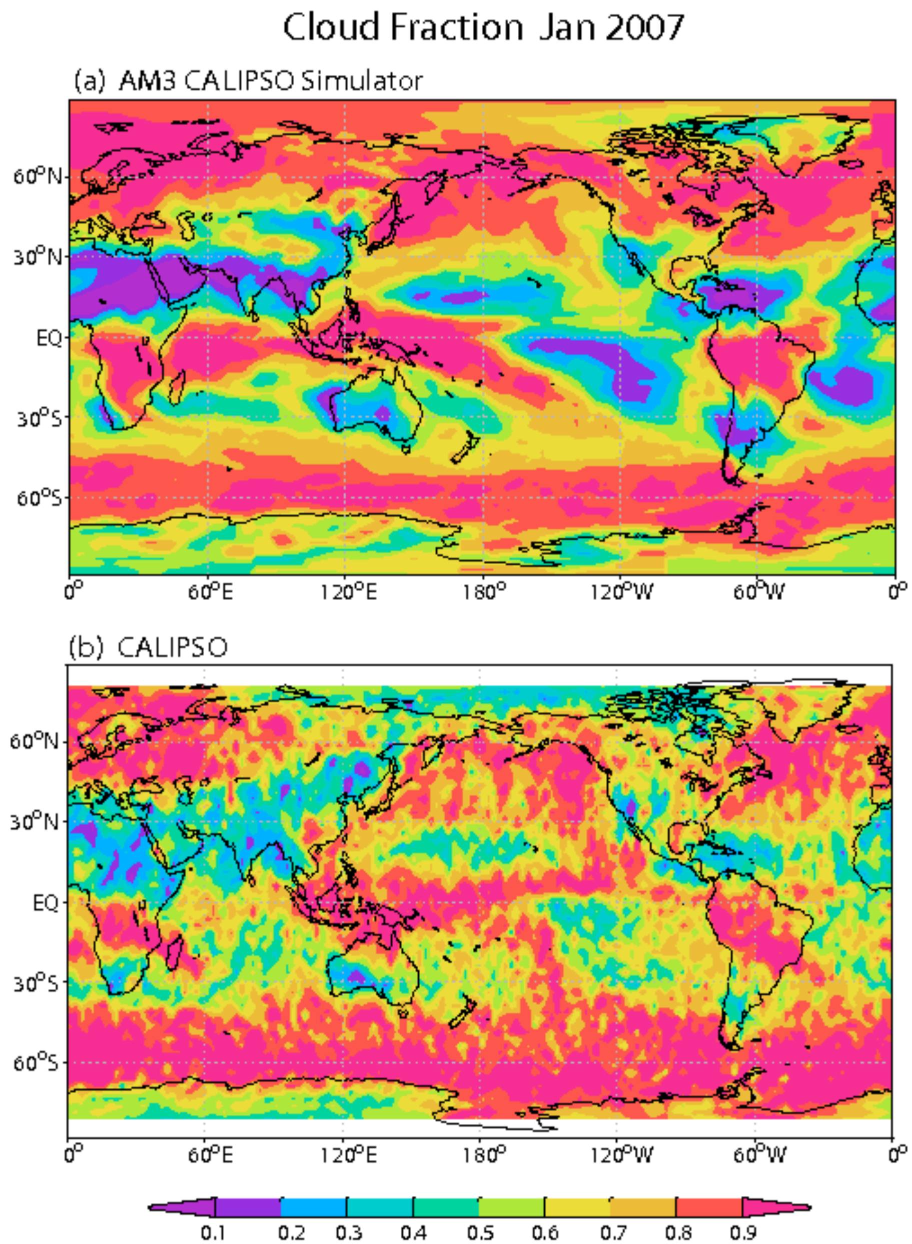
NASA JPL A-Train:
A-Train obs data source: Jonathan H. Jiang <Jonathan.H.Jiang@jpl.nasa.gov>
Ref: Jiang, J. H., et al. (2012), JGR

# ANN PRW ($kg/m^2$)

Models: 1981-2000

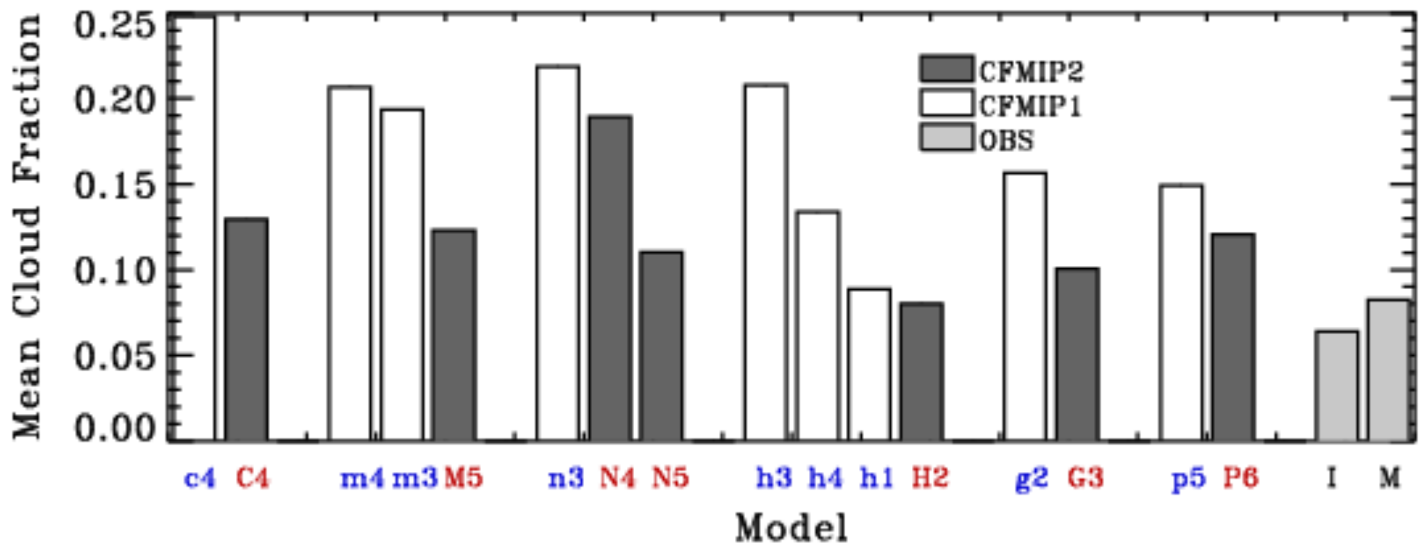


# CFMIP2 and Satellite Simulators



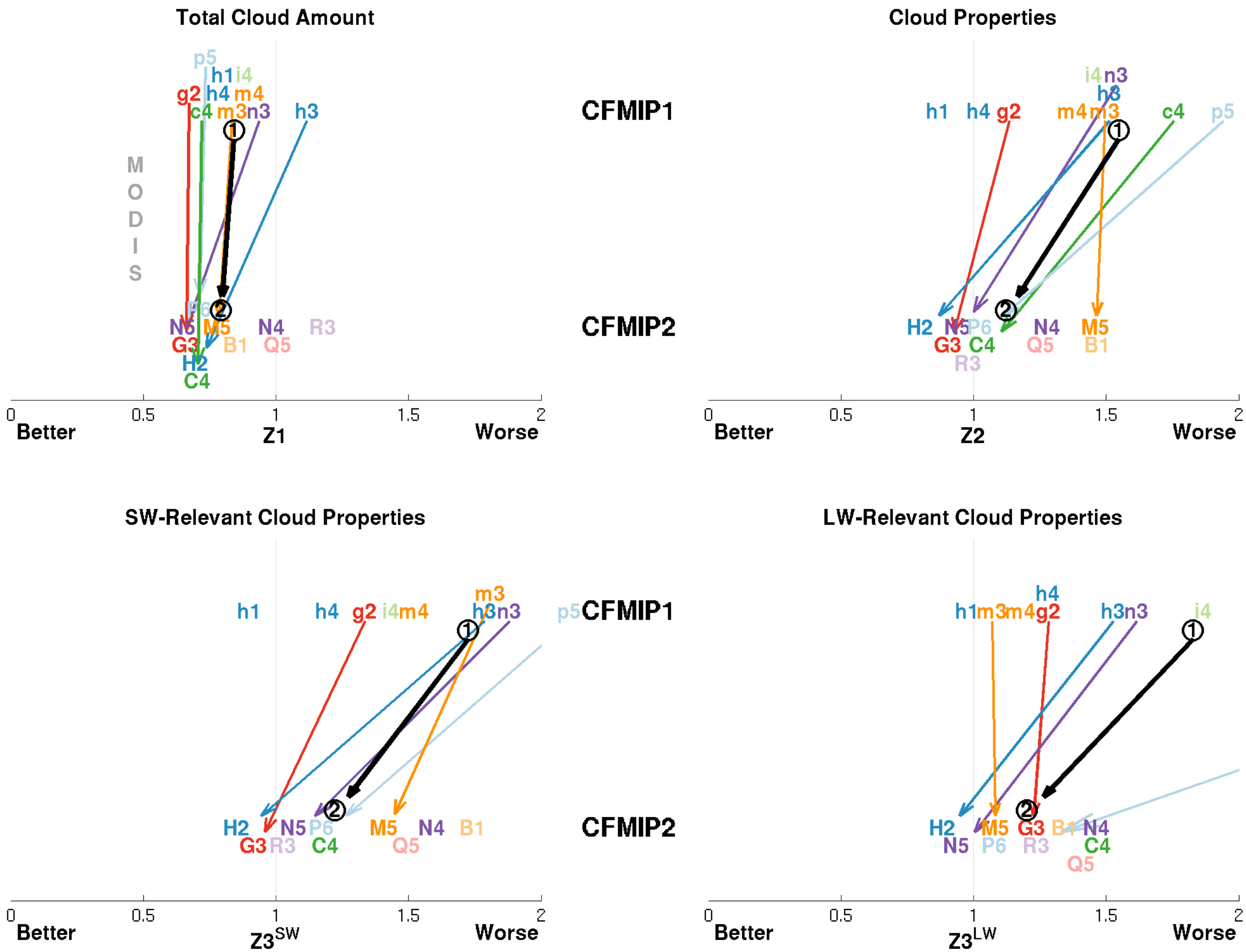

from Donner *et al.* (2011, *J. Climate*)

## Simulator Mean Cloud Fraction for Optical Depths > 23
## CMIP3 and CMIP5 Models




c4,C4: Canadian Centre for Climate Modeling and Analysis
M4,m3,M5: MIROC, U. Tokyo
n3,N4,N5: NCAR CCSM/CESM
h3, h4, h1, H2: Hadley Centre
g2,G3: GFDL CM2.1,CM3
p5,P6: MPI-ESM-LR
I: ISCCP, M: MODIS
(from Klein *et al.,* 2012, *JGR,* in revision)

# Scalar Measures of Model Skill *vs.* ISCCP (from Klein *et al.*, 2012, *JGR*, in rev.)

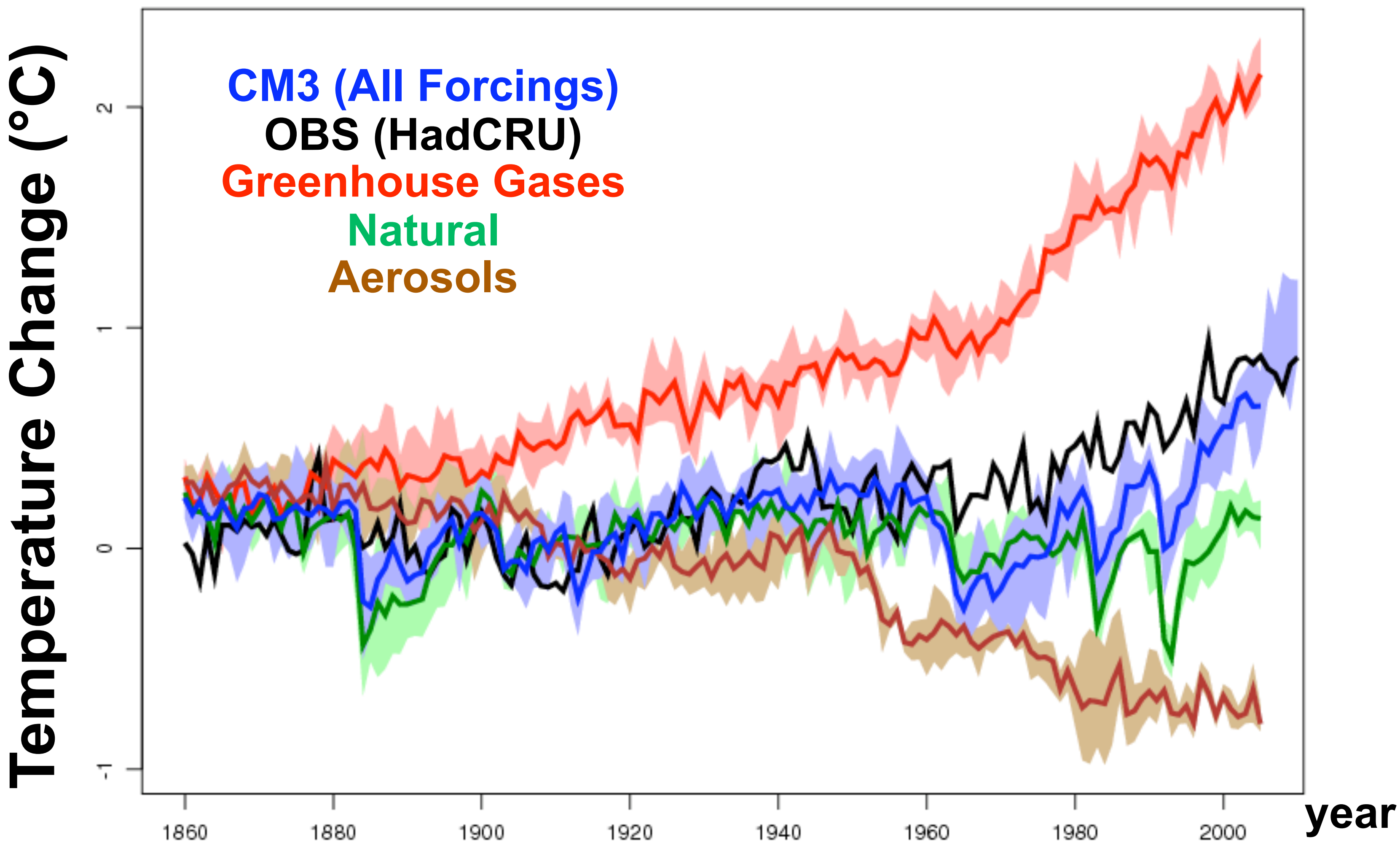



Q: CNRM (France); R:MRI(Japan)

# Cloud-Aerosol Interactions: Critical Needs for Space-Based Observational Contraints

- Physically based treatments of aerosol-cloud interactions included in GFDL CM3 and NCAR CAM5.
- 20th century warming reduced in CM3 and CAM5, relative to earlier models without aerosol-cloud interactions.
- Interactions among aerosols, precipitation, and cloud dynamics limit cooling by aerosol-cloud interactions and  could improve realism of climate models including aerosol-cloud interactions.
- Global observations of cloud microphysical properties and their relationship to aerosols are essential for constraining global models.

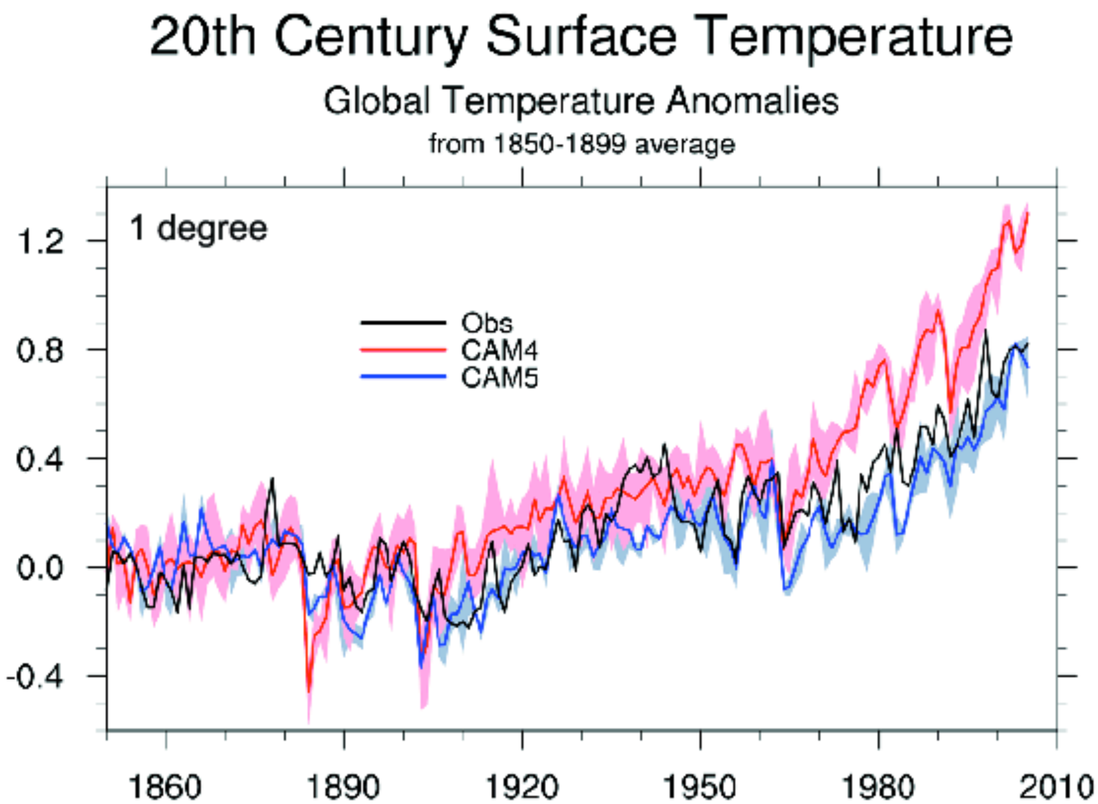
# CM3 Surface Air Temperature Change



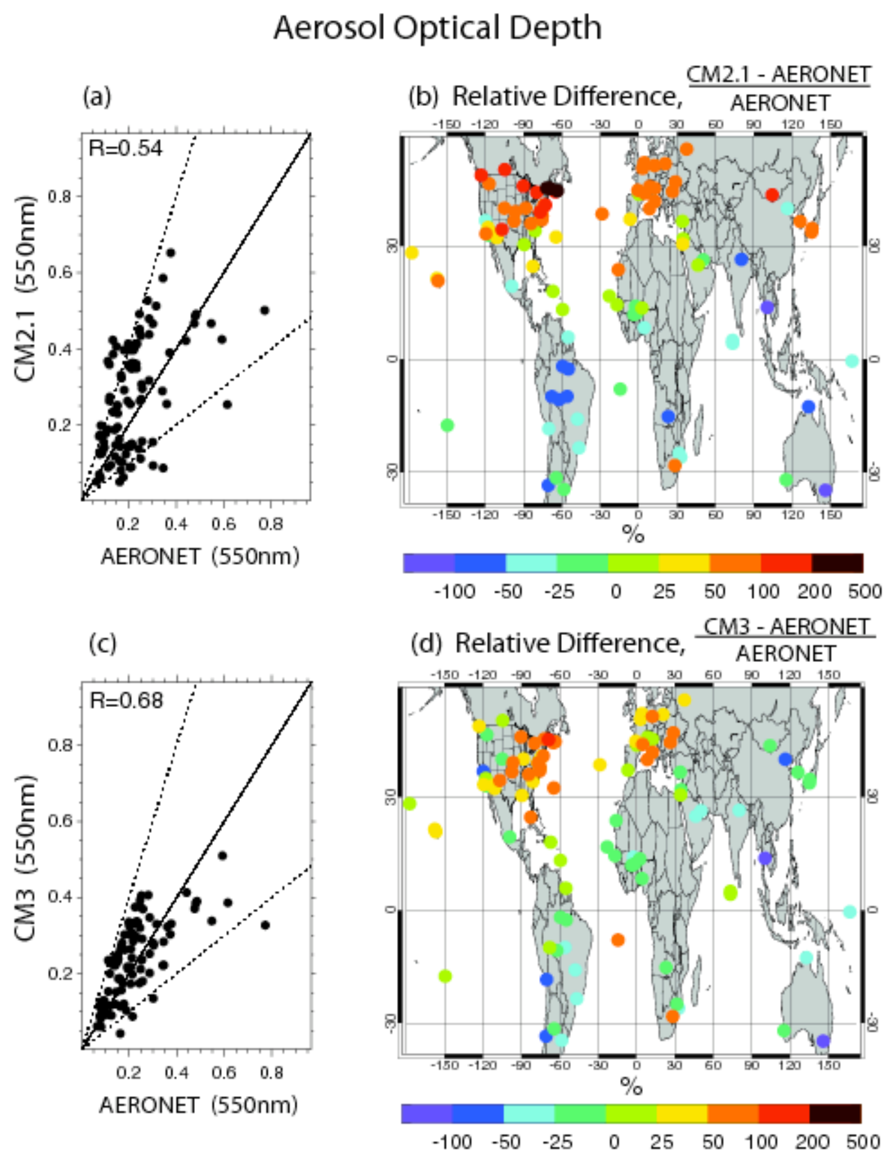

**Strong cooling from aerosols (and volcanoes) in late 20th century**

analysis by Larry Horowitz, GFDL

# CESM(CAM5.1) 20th Century

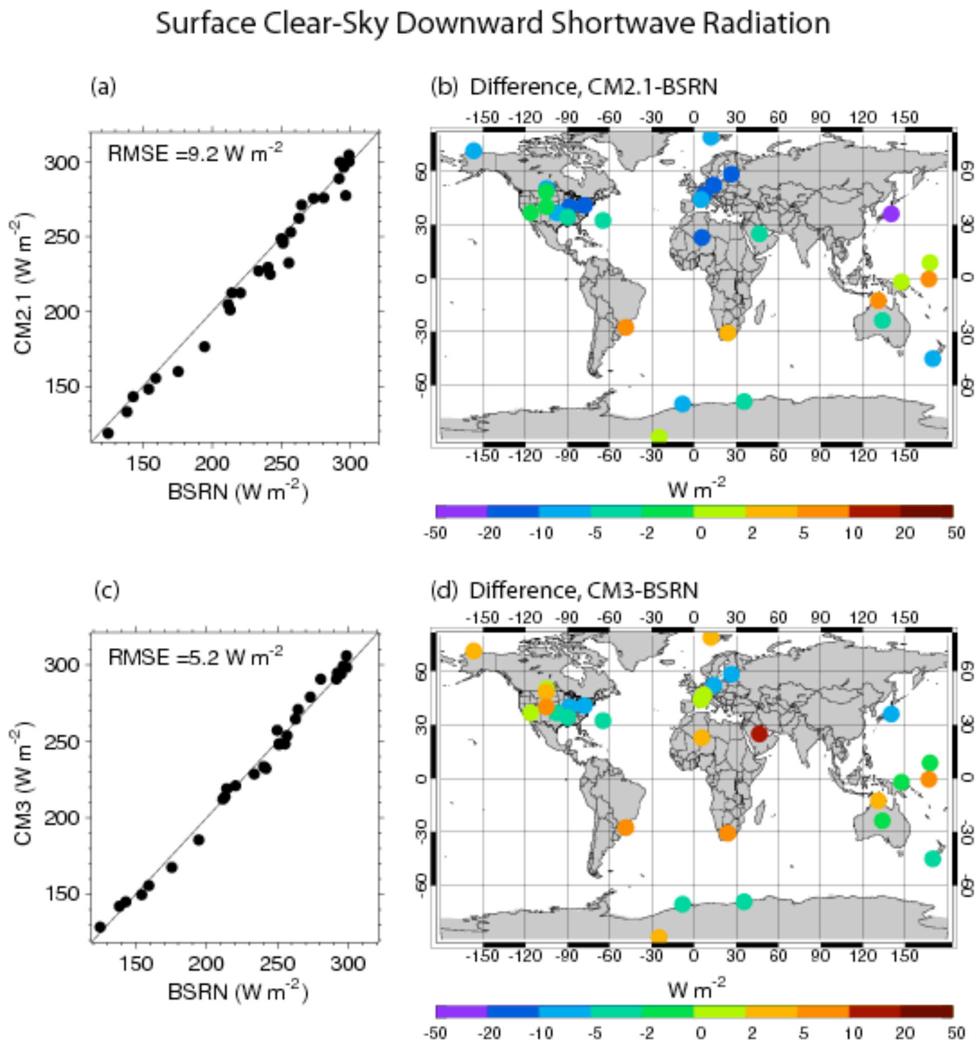



from Rich Neale, NCAR



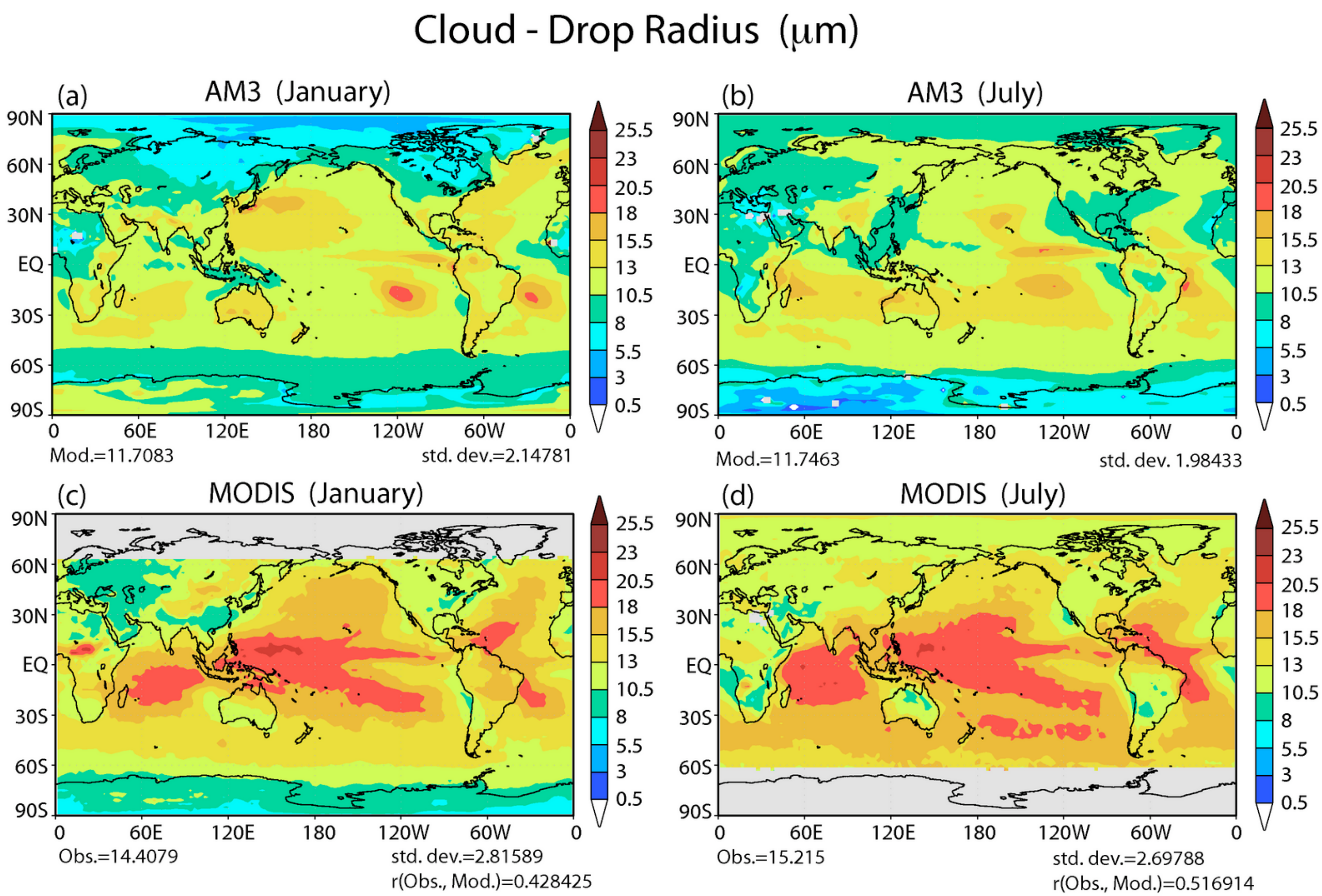

GFDL CM3 has more realistic aerosol distribution than GFDL CM2.1

from Donner *et al.* (2011, *J. Climate*)

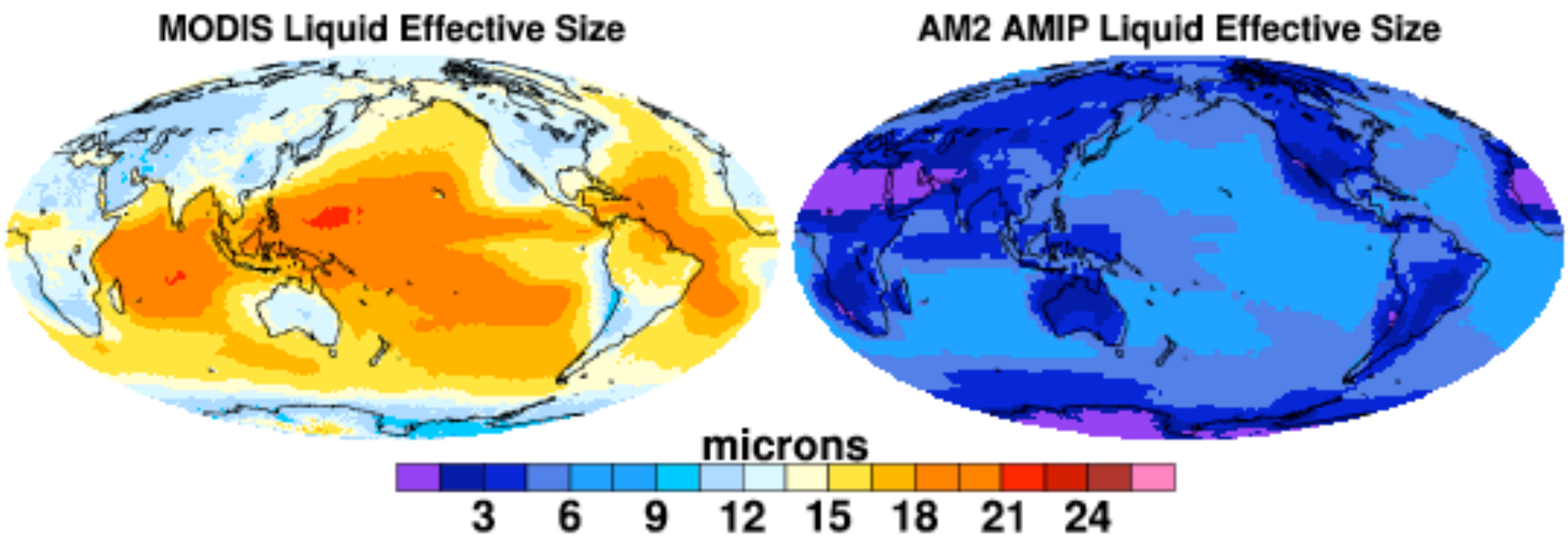



More realistic aerosol distribution in CM3 improves downward surface clear-sky shortwave fluxes.

from Donner *et al.* (2011, *J. Climate*)



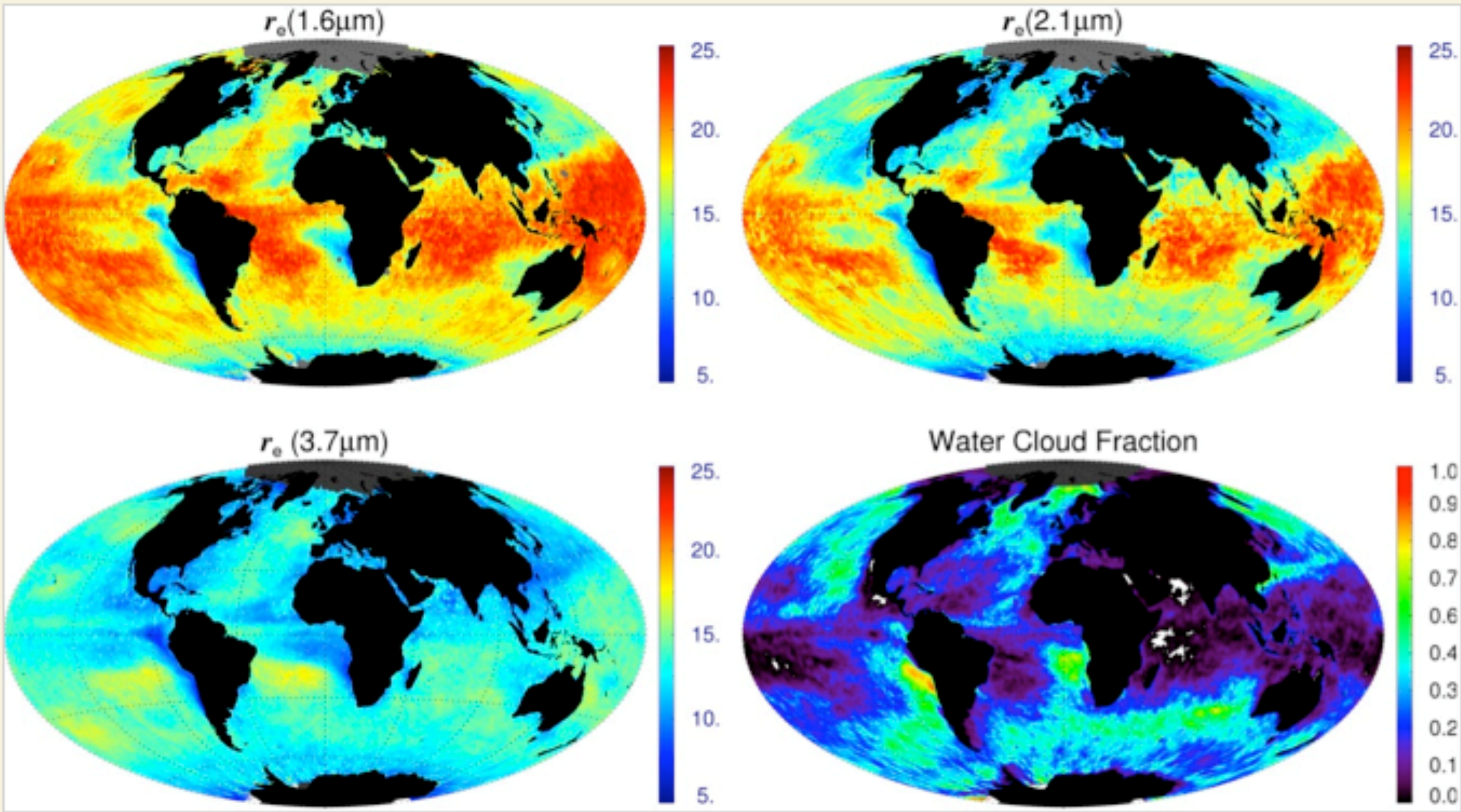

from Donner *et al.* (2011, *J. Climate*)




from Ben Hillman, U. Washington

# Monthly Mean Cloud Effective Radius: 2.1 vs. 3.7 μm

(Terra MODIS April 2005, C6 Test3, L3 unweighted means, liquid water clouds)



In CM3, aerosols are more realistic, but 20th century temperature simulation is less so. Cloud radiative and dynamical responses to aerosols may be responsible.

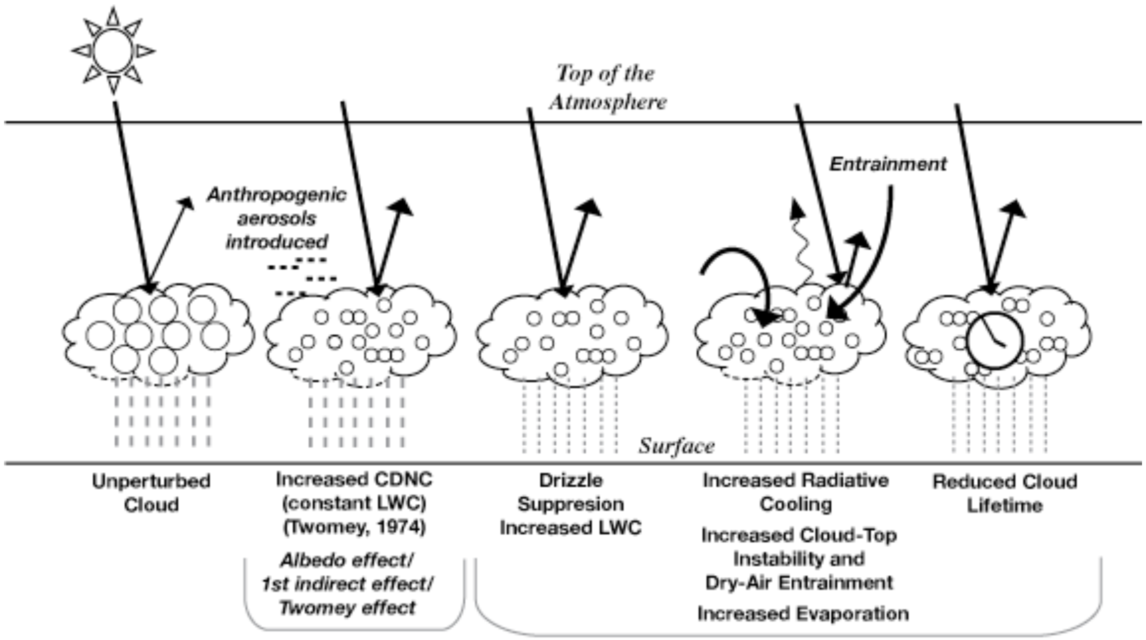
# Linear Regressions between Logarithms of Droplet Number ($N_d$) /Liquid Water Path (LWP) and Aerosol Optical Depth ($\tau_a$)

| Relationship | | Terra | Aqua | CAM | GFDL |
|---|---|---|---|---|---|
| $N_d$-$\tau_a$ | land | 0.083 | 0.078 | 0.180 | 0.375 |
| | ocean | 0.256 | 0.251 | 0.408 | 0.155 |
| LWP-$\tau_a$ | land | 0.074 | 0.100 | 3.064 | 1.557 |
| | ocean | 0.134 | 0.093 | 3.615 | 1.422 |

from Quaas *et al.* (2009, *Atmos. Chem. Phys.*)

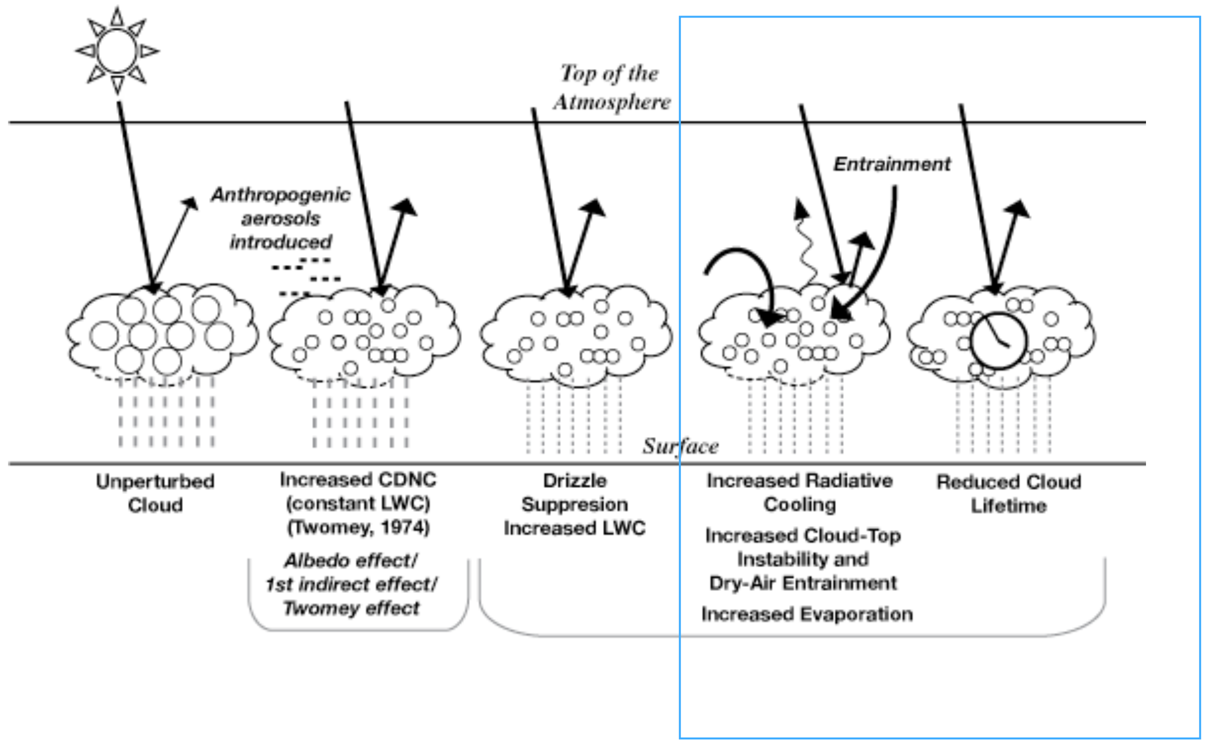
Globally averaged drop number/aerosol relationships are within a factor of two of satellite estimates, but liquid water path/aerosol relationships are 15 to 30 times stronger than satellite estimates. Wang *et al.* (2012, *Geophys. Res. Lett.*) have also found most model overestimate LWP response to aerosol perturbation.

# Schematic View of Aerosol-Cloud Interactions in Boundary-Layer Clouds



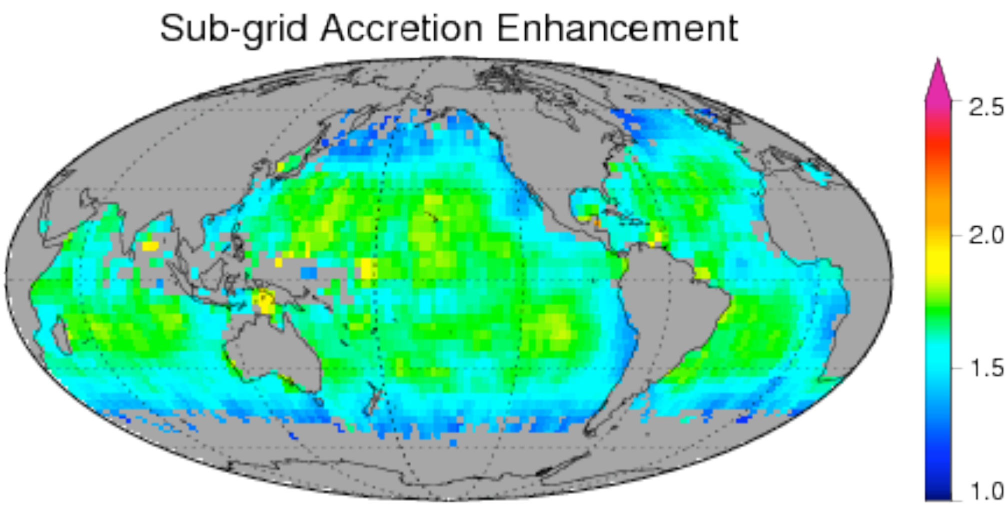

from Haywood et al. (2009, *Clouds in the Perturbed Climate System*)

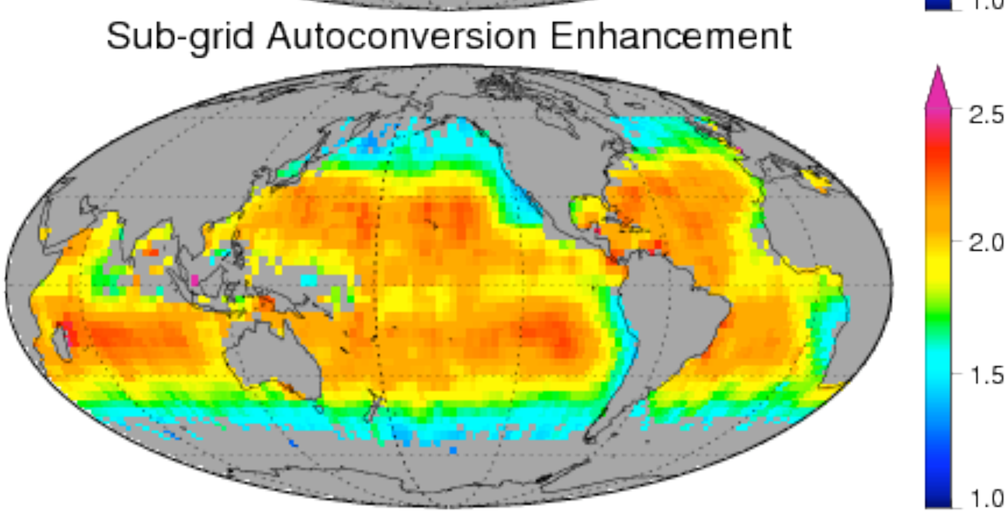
# GFDL CM3 cloud macrophysics does not treat cloud-top instability and dry-air entrainment realistically.




from Haywood et al. (2009, *Clouds in the Perturbed Climate System*)

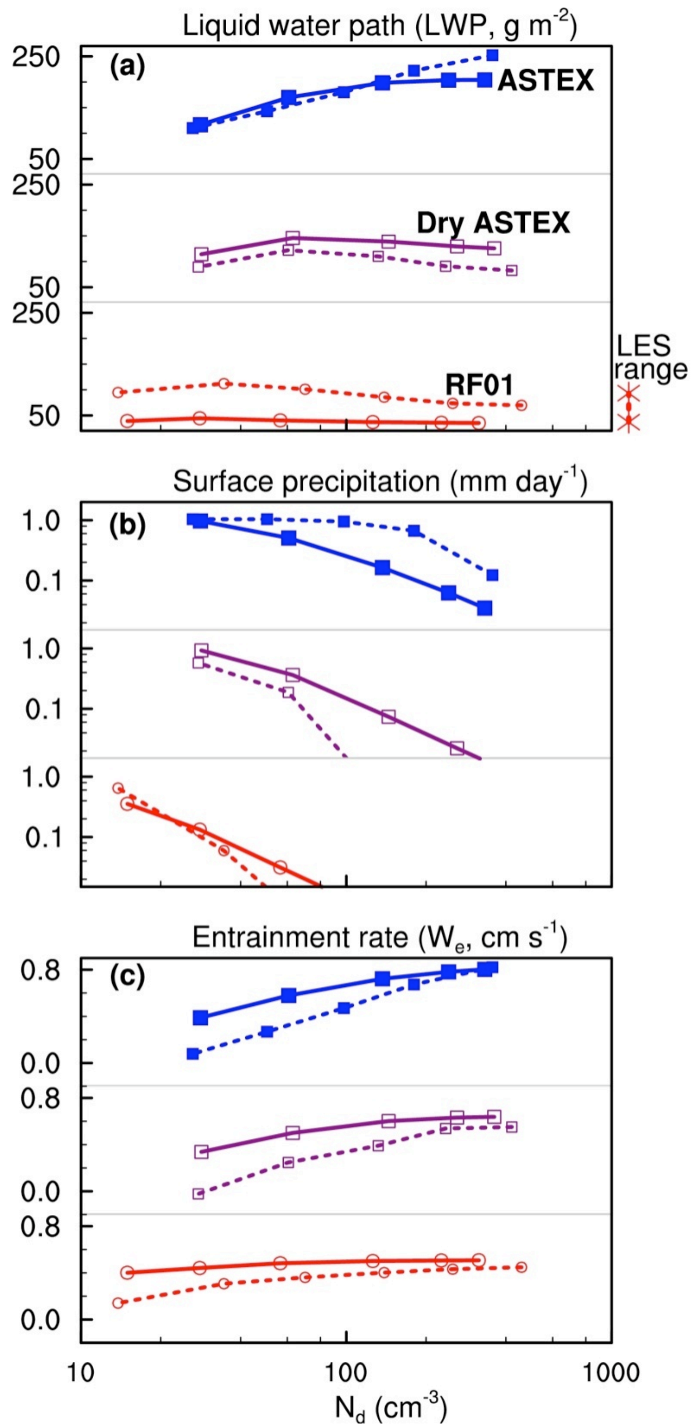
# Accretion and Autoconversion Enhancement by Sub-Cloud Co-Variability in Cloud Liquid and Rain (analysis by Matt Lebsock, JPL)




Microphysical properties impact aerosol-cloud interactions strongly, e.g., Golaz *et al.* (2011, *J. Climate*) on effect of autoconversion threshold.

# Physics of entrainment-aerosol interaction similar in CLUBB and LES



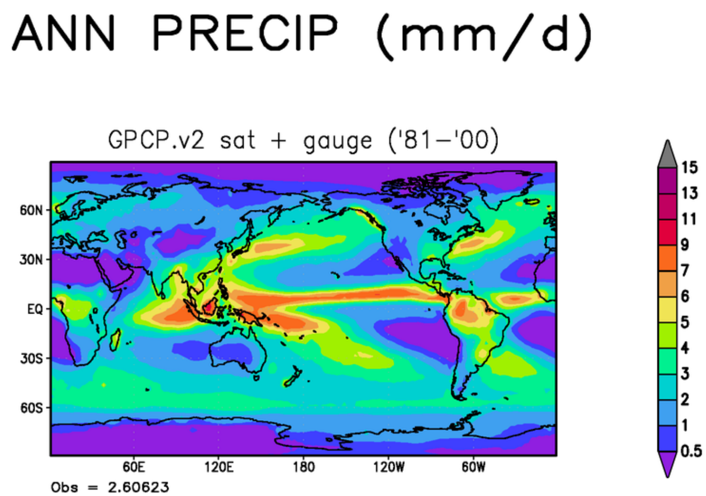

LES range from Guo *et al.* (2010, *GMD*)

Solid: MVD PDFs

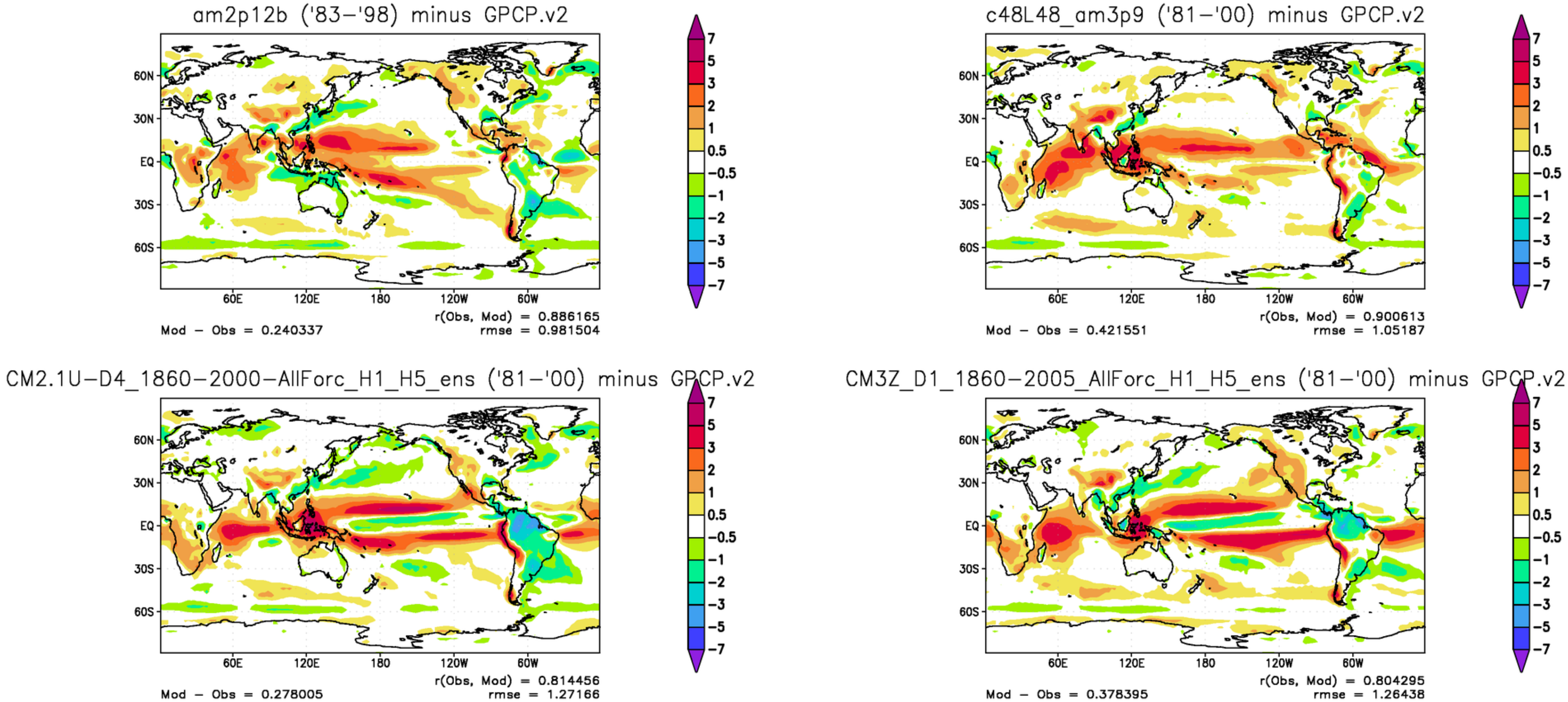
Dashed: LES from Ackerman *et al.* (2004, *Nature*)

cf., Guo *et al.* (2011, *GRL*)

Uncertainty in precipitation observations impacts model development.

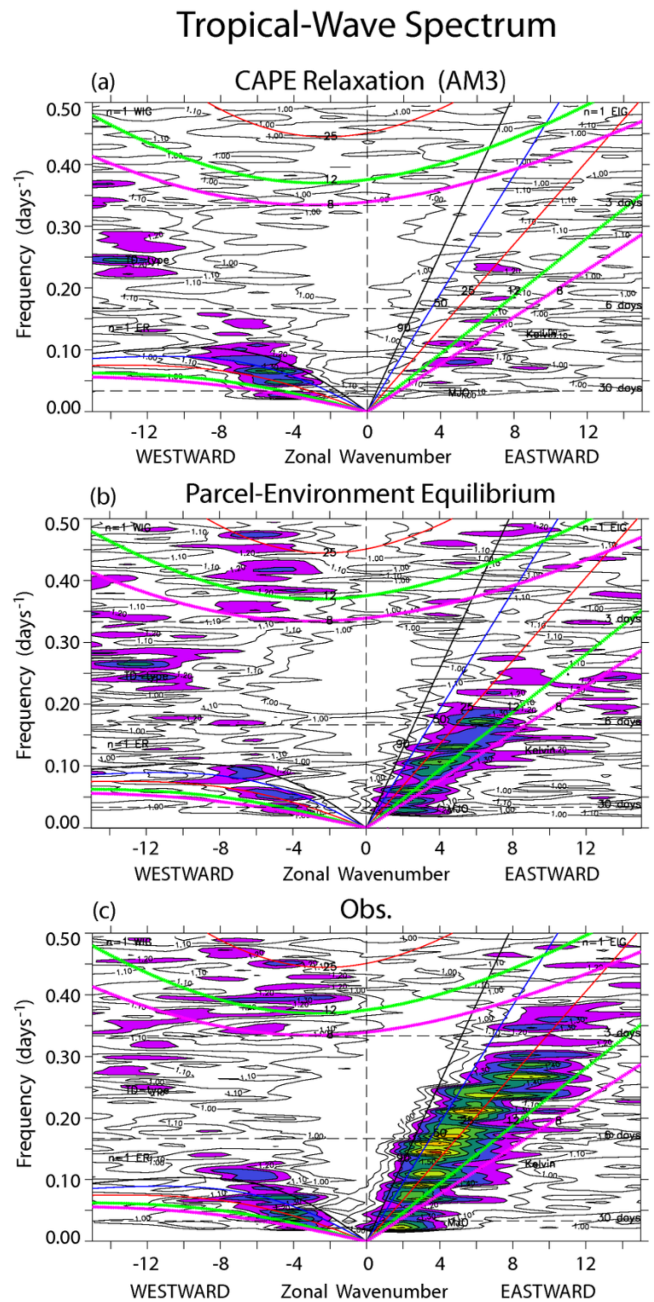



Kato *et al.* (2011, *J. Geophys. Res.*) indicate GPCP precipitation may be biased 15% to 20% low.

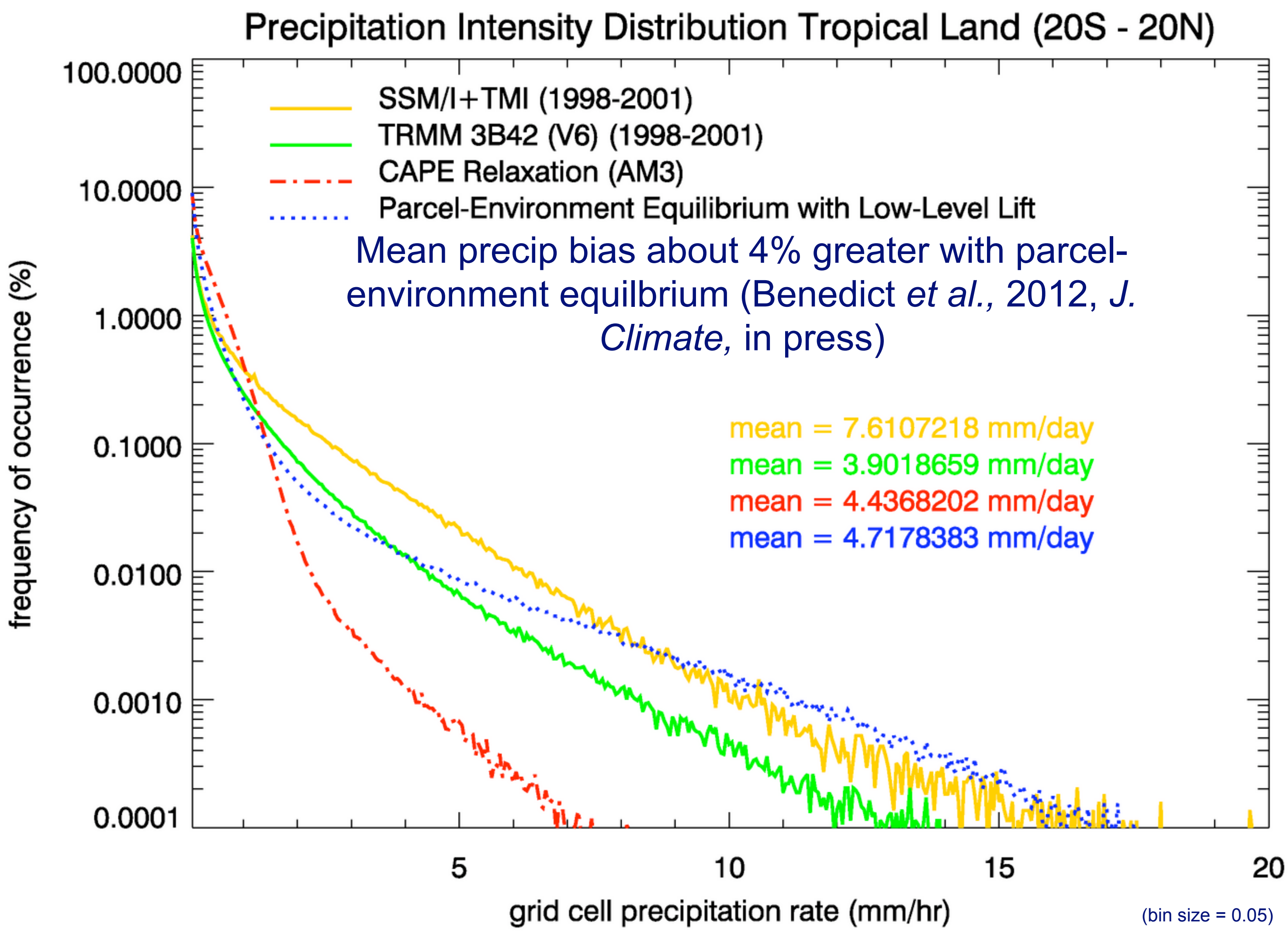



GPCP.v2:
http://www.cdc.noaa.gov/cdc/data.gpcp.html
Adler, et al, Journal of Hydrometeorology, December 2003, p 1147–1167

Mean Precipitation Bias about 4% greater than for CAPE Relaxation (Benedict *et al.*, 2012, *J. Climate,* in press)




from Donner *et al.* (2011, *J. Climate*)




reconstruction of Figure 26 in Donner *et al.* (2011, *J. Climate*)
with linear x-axis and SSM/I+TMI observations

# Summary

- CERES, A-Train valuable evaluation tools for model development. Both physical parameterization and model resolution improve simulations.
- Satellite simulators in models provide new perspectives. Encouraging improvement in model cloud properties between CMIP3 and CMIP5.
- Modeling aerosol-cloud interactions in climate models: Significant first efforts but major challenges representing all relevant processes. Global, space-based process-related metrics will be crucial to moving forward.