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

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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](http://www.gfdl.noaa.gov/model-development)
ANN SWABS (W/m²)  

CERES EBAF Ed2.6 (3/00-2/10)

GFDL–CM3 minus CERES EBAF Ed2.6

GFDL–ESM2G minus CERES EBAF Ed2.6

GFDL–ESM2M minus CERES EBAF Ed2.6

GFDL–HIRAM–C180 minus CERES EBAF Ed2.6

GFDL–HIRAM–C360 minus CERES EBAF Ed2.6
CERES EBAF Ed2.6 (3/00–2/10)

GFDL–CM3 minus CERES EBAF Ed2.6

GFDL–ESM2G minus CERES EBAF Ed2.6

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CERES EBAF Ed2.6 (3/00–2/10)

GFDL-CM3 minus CERES EBAF Ed2.6

GFDL-ESM2G minus CERES EBAF Ed2.6

GFDL-ESM2M minus CERES EBAF Ed2.6

GFDL-HIRAM-C180 minus CERES EBAF Ed2.6

GFDL-HIRAM-C360 minus CERES EBAF Ed2.6

Obs = 0.510545  (obs grid)  SD = 5.25595

Ron (Obs, Mod) = 0.898225  r(Cer, Mod) = 0.988497

Mod - Obs = -0.120861  rmse = 8.59975

Ron (Obs, Mod) = 0.885392  r(Cer, Mod) = 0.987998

Mod - Obs = 0.061111B  rmse = 8.95261

Ion - (0.360) lat = (-90,90)
ANN SWCF (W/m²)  


CERES EBAF Ed2.6 (3/00-2/10)

GFDM-CM3 minus CERES EBAF Ed2.6

GFDM-ESM2G minus CERES EBAF Ed2.6

GFDM-ESM2M minus CERES EBAF Ed2.6

GFDM-HIRAM-C180 minus CERES EBAF Ed2.6

GFDM-HIRAM-C360 minus CERES EBAF Ed2.6

CERES EBAF Ed2.6 (3/00–2/10)

GFSL–CM3 minus CERES EBAF Ed2.6

GFSL–ESM2G minus CERES EBAF Ed2.6

GFSL–ESM2M minus CERES EBAF Ed2.6

GFSL–HIRAM–C180 minus CERES EBAF Ed2.6

GFSL–HIRAM–C360 minus CERES EBAF Ed2.6
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.)
Models: 1981-2000 (except AM3 CLUBB 0.5 dgr)

Model – CERES EBAF Ed 2.6

ANN SWABS (W/m²)

AM3 Base 2 dgr

AM3 Base 1 dgr

AM3 Base 0.5 dgr

AM3 CLUBB 2 dgr

AM3 CLUBB 1 dgr

AM3 CLUBB 0.5 dgr (1981-1985)
Models: 1981-2000 (except AM3 CLUBB 0.5 dgr)

AM3 Base 2 dgr

AM3 Base 1 dgr

AM3 Base 0.5 dgr

AM3 CLUBB 2 dgr

AM3 CLUBB 1 dgr

AM3 CLUBB 0.5 dgr (1981-1985)
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)
Models: 1981-2000 (except AM3 CLUBB 0.5 dgr)

Model – CERES EBAF Ed 2.6

ANN SWCF (W/m²)

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)
ANN LWCF (W/m²) Model – CERES EBAF Ed 2.6

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

- AM3 Base 2 dgr
- AM3 Base 1 dgr
- AM3 Base 0.5 dgr
- AM3 CLUBB 2 dgr
- AM3 CLUBB 1 dgr
- AM3 CLUBB 0.5 dgr (1981-1985)
ANN NETCF (W/m²) Model – CERES EBAF Ed 2.6

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

- AM3 Base 2 dgr
- AM3 Base 1 dgr
- AM3 Base 0.5 dgr
- AM3 CLUBB 2 dgr
- AM3 CLUBB 1 dgr
- AM3 CLUBB 0.5 dgr (1981-1985)
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
ANN LWP (g/m²) Models: 1981-2000

NASA JPL A-Train CloudSat NaPcp (8/06-7/10)

GFDT-CM3 minus NASA JPL A-Train

GFDT-ESM2M minus NASA JPL A-Train

GFDT-HIRAM-C160 minus NASA JPL A-Train
CFMIP2 and Satellite Simulators
Cloud Fraction Jan 2007

(a) AM3 CALIPSO Simulator

(b) CALIPSO

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)
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

20th Century Surface Temperature

Global Temperature Anomalies
from 1850-1899 average

from Rich Neale, NCAR
GFDDL CM3 has more realistic aerosol distribution than GFDDL 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)

Platnick, GFDL 31 March 2011
In CM3, aerosols are more realistic, but 20\textsuperscript{th} 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 ($\tau_a$)

<table>
<thead>
<tr>
<th>Relationship</th>
<th>Terra</th>
<th>Aqua</th>
<th>CAM</th>
<th>GFDL</th>
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</thead>
<tbody>
<tr>
<td>$N_d$-$\tau_a$</td>
<td>land</td>
<td>0.083</td>
<td>0.078</td>
<td>0.180</td>
</tr>
<tr>
<td></td>
<td>ocean</td>
<td>0.256</td>
<td>0.251</td>
<td>0.408</td>
</tr>
<tr>
<td>LWP-$\tau_a$</td>
<td>land</td>
<td>0.074</td>
<td>0.100</td>
<td>3.064</td>
</tr>
<tr>
<td></td>
<td>ocean</td>
<td>0.134</td>
<td>0.093</td>
<td>3.615</td>
</tr>
</tbody>
</table>

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

Solid: MVD PDFs

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

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

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

Uncertainty in precipitation observations impacts model development.
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)
Mean precip bias about 4% greater with parcel-environment equilibrium (Benedict et al., 2012, J. Climate, in press)

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.