Tropical cyclones in high-resolution ($\Delta x \sim 10$km) climate simulations: Successes and remaining challenges

Julio Bacmeister
NCAR Earth System Lab. (NESL)

William Putman
NASA Global Modeling and Assimilation Office

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Outline

Overview
Storm tracks, intensities, and structure
– Short runs with CAM5 and GEOS5
Emphasis on potentially informative diagnostics …

Sensitivities to Model Physics
Deep Convection Scheme on/off
Condensate loading

Precipitation Objects
A promising approach to understanding cyclogenesis?

Summary and Future Directions
Simulations of Global Hurricane Climatology, Interannual Variability, and Response to Global Warming Using a 50-km Resolution GCM

MING ZHAO

University Corporation for Atmospheric Research, Boulder, Colorado, and NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

ISAAC M. HELD, SHIAN-JIANN LIN, AND GABRIEL A.VECCHI

NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

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Fig. 7. Interannual variation of hurricane numbers for North Atlantic from 1981 to 2005. IBTrACS observations (Kruk et al. 2010) (red) and four-member ensemble mean (blue); shaded area shows the simulated maximum and minimum number for each year from the four-member integrations. Model time series are normalized by time-independent multiplicative factors so as to reproduce the observed total number. Dotted lines show observed and model (ensemble mean) linear trends.
Models

CAM-5
Zhang-Macfarlane deep convection, Park-Bretherton shallow convection and moist PBL, FV-latlon dycore. Resolution shown here 0.23x0.31

GEOS-5
Relaxed Arakawa-Schubert deep convection with stochastic Tokioka limits on plume entrainment, Lock et al. PBL, FV-cubed sphere. Resolutions shown here ~28,14,7 km
TC Numbers and Tracks

Based on short runs CAM5 and GEOS5 roughly capture correct numbers of storms and distinction between active (2005) and quiet (2006) Atlantic seasons.

Distribution of tracks seems shifted to the east.
Storms with $U > 33$ $\text{ms}^{-1}$: June 1 to Nov 1 2005
Global Tropical Cyclone Tracks 2005
(May-Dec)

Observed Tracks

14-km GEOS-5
(880 hPa Deepest central pressure)

28-km GEOS-5
(890 hPa Deepest central pressure)

3 N Indian Storms

4 S Indian Storms

5 N Indian Storms

5 E Pacific Storms

9 S Indian Storms

13 Atlantic Storms

15 W Pacific Storms

17 E Pacific Storms

19 W Pacific Storms
Number of Storms in CAM (June-Nov 2005)

IBTRACS

3 default CAM runs
Tropical Cyclones 2005-2006 (May-Dec)
Atlantic Basin Intensities

- GEOS-5 captures the natural variability of tropical cyclone formation
  - In terms of intensity as well as number of storms

- GEOS-5 at high resolution (14-km) shows a capability to develop the most intense tropical cyclones
  - 7 Major Hurricanes (category 3, 4, or 5) in 2005 [7 observed]
  - 2 Major Hurricanes (category 3, 4, or 5) in 2006 [2 observed]

Above Normal Season
Below Normal Season

### 2005 Atlantic Hurricanes
- **Observed**
- **14-km GEOS-5 Nature Run**

### 2006 Atlantic Hurricanes
- **Observed**
- **14-km GEOS-5 Nature Run**
CAM also captures weak Atlantic season – somewhat stronger E. Pacific in 2006 season
TC Intensities

Intensity is more difficult to capture

Depends on “slowly” varying BCs like SST, and on noisier atmospheric quantities, e.g., shear, dry plumes ...

Models tend to produce storms that are more similar to each other than they are in nature (Zhao et al 2009)
Number of Storms in CAM

Fig. 6. A comparison of observed and model-simulated tropical storm intensity distribution as characterized by the surface maximum wind speed for the (top) North Atlantic, (middle) east Pacific, and (bottom) west Pacific. IBTrACS observations using 1-min maximum sustained wind at 10 m (black). Model simulation using 15-min (model time step) winds at the lowest model level (gray).
Time (hours) spent at Category (June-Nov 2005)

IBTRACS

3 default CAM runs
Time (hours) spent at Category (June-Nov 2005)

Hints of overactivity in intense storms?

IBTRACS

3 default CAM runs

TD TS Cat1 Cat2 Cat5

Cat3 Cat4
Minimum possible central pressure depends on a few parameters:
- ambient surface pressure
- ambient low-level humidity
- ambient upper-tropospheric temperature
- surface temperature in core region
This diagnostic should be relatively straightforward to calculate from re-analysis data as well as model output.
Azimuthal means of $s$, $V$ and angular mom. 

$$s = c_p \log(T) - R \log(p) + \frac{Lq}{T}$$  

(e.g. Emanuel, 2003)

**Shading** - moist entropy $s$;  
**solid contours** - angular momentum  
**dashed contours** – wind speed

**Structure at peak intensity**
Azimuthal means of $s$, $V$ and angular mom. $s = c_p \log(T) - R \log(p) + \frac{Lq}{T}$ (e.g. Emanuel, 2003)

Shading - moist entropy $s$;
solid contours - angular momentum
dashed contours - wind speed

Structure at peak intensity

Dry/cool layer around 500 hPa (freezing level?)
Precipitation time series in storm core (black), storm exterior 250-500 km + 1000 mm d\(^{-1}\) (red). Convective precip (dashed), Large-scale precip\(^1\) (solid). Thin blue lines show surface pressure.  

Note overwhelming dominance of LS in cores.
Sensitivity to use of Deep Convection Scheme

GEOS-5 attempts to hobble deep convection scheme via entrainment limits. GFDL eliminates deep scheme (with tuned shallow scheme). CAM5 precip in TC cores dominated by large-scale.

What happens if deep scheme is removed from CAM?
Storms with \(U > 33\) \(\text{ms}^{-1}\): June 1 to Nov 1 2005

- **Std CAM5 #1**
- **Std CAM5 #2**
- **Std CAM5 #3**
- **No Deep Convection Scheme**
Time (hours) at Category

IBTRACS

3 default CAM runs
IBTRACS

Legend:
- 3 default CAM runs
- No Deep scheme

Categories:
- TD
- TS
- Cat1
- Cat2
- Cat3
- Cat4
- Cat5

Time (hours) at Category

Hours
PDFs of tropical precipitation (30S-30N) rates Aug 2005

CAM5

TRMM-3B42

CAM5-No Deep scheme

**CAM5 - convective contribution (deep and shallow)**

Intensity (mm d^{-1})

Frequency
The strong influence of RAS, and a 15 minute time-step for the moist physics leads to problems within the circulation of Hurricane Bill at 7-km resolution:

- a lack of deep convective (heavy) precipitation
- an excess of shallow precipitation
- a very small eye, filled with drizzle
Using Tokioka limiter to reduce RAS, and a 120 second time-step for the moist physics improves the convection within Hurricane Bill:

- deep convective precipitation within the eye wall
- Banded structure with embedded convection
- Realistic eye diameter, clear of precipitation
Effects of Condensate Loading

Assessed using 0.5x0.5 km non-hydrostatic WRF simulation

Tropical ocean convective case (TOGA domain Feb 2006)
15-min average precipitation rate (*Hong and Lim 2006 microphysics*)

Dashed lines show 50x50 gp (25km x 25km) squares used to coarse grain WRF fields to produce “high-res AGCM” fields.
Hydrostatic Balance w/ and w/out condensate loading

\[ \pi_{hyd} = \int_{z}^{z_{top}} \frac{g}{c_{p} \Theta_{\{v,\text{cond}\}}} \, dz' + \pi_{\text{top}} \]

\[ p_{hyd} = p_{00} \pi_{hyd}^{1/\kappa} \]

w/out loading:

\[ \Theta_{v} = \Theta(1. + 0.61q) \]

with loading:

\[ \Theta_{\text{cond}} = \Theta(1. + 0.61q - q_{\text{liq}} - q_{\text{ice}} - q_{\text{rain}} - q_{\text{graup}} - q_{\text{snow}}) \]
Condensate loading matters – even in (25 km)$^2$ grid boxes
Coarse-grained to (5 km)$^2$

Non-hydrostatic effects become detectable
Parameterized precipitation loading

Surface precip rate $R_{\text{surf}}$ used to diagnose precipitating condensate density $\rho_{\text{prec}}$

For $z < 7000m$

$$\rho_{\text{prec}}(x, y, z, t) = \frac{R_{\text{surf}}(x, y, t)}{w_{\text{fall}}}$$

$$p_{\text{prec}}(x, y, z, t) = \int_{z}^{7000m} g\rho_{\text{prec}} dz'$$

Extra condensate pressure is added to “real” model pressure right before horizontal gradients are calculated, then removed.
Net loading at surface (in Pa) as a function of surface precipitation rate – for $(25\text{km})^2$ resolution

$D_{\text{prec}} = 7000m$

$w_{\text{fall}} = 2.5\text{ m s}^{-1}$

Dashed red line shows net parameterized pressure loading from precipitating condensate as implemented in CAM5.
PDFs of tropical precipitation (30S-30N) rates Aug 2005

Parameterized precip loading in CAM5 (green line) removes extreme rates
PDFs of tropical precipitation (30S-30N) rates Aug 2005

Parameterized precip loading in CAM5 (green line) removes extreme rates
Annual mean precipitation

CAM5 control

w/ parameterized precipitation loading

Bad news: TC number also decreases
Storms with $U > 33 \text{ ms}^{-1}$: June 1 to Nov 1 2005

Std CAM5 #1

Std CAM5 #2

Std CAM5 #3

w/ parameterized precip loading
Time (hours) at Category

IBTRACS

3 default CAM runs

No Deep scheme

Parameterized loading

Hours

TD  TS  Cat1  Cat2  Cat3  Cat4  Cat5
Precipitation Loading in perspective

Relatively small perturbation to pressure field in precipitating regions seems to have large effect.

Same pressure increase could be achieved by re-evaporating about 1/8-th of condensate column
Analysis using Precipitation Objects

with
Gregor Skok,
University of Ljubljana
Joe Tribbia
NCAR AMP/CGD
Thresholding only

Raw precipitation (snapshot)

Smoothing with convolution

Thresholding after convolution
Objects are tracked in time using overlaps. Could be modified to include search radius.
Hope to see transitions from clusters of convection to tropical cyclones (eventually). Analysis just begun.
“Feature” tracks June 1 to Nov 1 2005

Precipitation object tracks (that contained winds $> 33 \text{ ms}^{-1}$ at some point)

Surface pressure based hurricane/TC tracks (winds $> 33 \text{ ms}^{-1}$ somewhere)
Precip object tracks September 2005 (originating 10S-25N)

0 < Max wind < 17 ms\(^{-1}\)

17 < Max wind < 33 ms\(^{-1}\) (TS)

33 ms\(^{-1}\) < Max wind (TC/hurricane)
PDFs of object area

- Default CAM
- No deep scheme
- With parameterized loading
PDFs of object mean vertical motion

- Blue: Default CAM
- Red: No deep scheme
- Black: With parameterized loading

Y-axis: Frequency
X-axis: Pa s^{-1}
Summary and future directions

Models with $\Delta x \sim 10\text{km}$ can capture many important aspects of TC climatology but answer depends sensitively on physics tuning.

Time to focus on cyclogenesis processes in $\sim 10\text{ km}$ models.

Tracks and intensities may have similar biases in current models, e.g., eastward shift in tracks, not enough variability in intensity.
Convection and Clouds in the Tropics

2009-Aug-20 21z  72-hour Forecasts

- East Pacific ITCZ
- Atlantic Hurricane Bill
- African Deep Convective Clusters
- Indian Monsoon
- Pacific Warm Pool

28 km GEOS-5

3.5 km GEOS-5

GOES IR
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   To provide facility support to the wider community; and,
   To apply the results to benefit society.

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