Global Modeling of Tropical Cyclone Activities and Response to 21st Century Warming Using a 50km Resolution GFDL HIRAM

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with Isaac Held, Shiann-Jiann Lin, and Gabriel Vecchi
How may tropical cyclones respond to warming?

Knutson et. al 2010 (Nat. Geosci., WMO assessment)

Examples of most recent studies based on CMIP5:
Knutson et. al 2013 (J. Climate) – dynamical downscaling
Camargo 2013 (J. Climate) – explicit simulation and GPI/PI
Emanuel 2013 (PNAS) – simplified dynamical downscaling

Atlantic Tropical Cyclones Composite for 2004 and 2005

It would be very difficult to answer it without using a high resolution GCM. Resolution is a key, although not the only key!
Challenges in modeling the TC-climate connections

CHALLENGES:
- Resolution
- Domain size
- Integration length
- Ensemble size
- Physics complexity

COMPROMISE!
- 50km
- Global
- 20-30 year
- 1-5 realization
- AMIP + sim.physics

→ A 50km HIRAM

Present-day simulations (coupled or prescribed SSTs)
- Evaluate simulated present-day variability in frequency, intensity, size/structure/energetics

Future projection simulations (coupled or prescribed SSTs)
- Understand the simulated changes in frequency, intensity and size/structure/energetics

Idealized models to improve our understanding
HIRAM simulated global hurricane climatology, seasonal cycle, inter-annual variability, and decadal trends (Zhao et. al 2009)

Hurricane Tracks (1981-2005)

OBS

HiRAM

Seasonal Cycle

Inter-annual variability

NATL

EPAC

WPAC

Red: observations
Blue: HiRAM ensemble mean
Shading: model spread
Shaevitz et al. (2014 JAMES) conclude: "Overall the models were able to reproduce the geographic distribution of TC track density in the observations, with the HIRAM, in particular, demonstrating the most similarity to observations."

Model resolutions range from 28km to 130km.

HIRAM performs well in the GCMs participating in the US CLIVAR Hurricane Working Group (Figure: for TC track density)
HIRAM performs well in the GCMs participating in the US CLIVAR Hurricane Working Group (Figure: seasonal cycle of TC frequency)

Shaevitz et. al 2014 JAMES
Animation of various dynamical and thermo-dynamical fields following a single TC simulated in a 50km HIRAM
TC size and precipitation statistics in a 50km HIRAM

Fields averaged over all simulated TCs for the N. Atlantic, E. Pacific and W. Pacific basins. Model captures the geographical distribution of TC size and precipitation.
Comparison of the 50km HIRAM simulated and ISCCP observed LW and SW cloud radiative effects associated with TCs.
Key aspects of the HIRAM for realistic TC simulation

- Advanced finite volume cube-sphere dynamical core
- Less-intrusive convection scheme
  - better simulations of mean climate state and easterly waves
  - participating in IPCC AR5 high-res simulation

Why non-intrusive convection parameterization?

- More systematic avenue towards consistency and convergence as model resolution becomes finer.
- More realistic representation of organized convective system.
- More realistic representation of cloud precipitation microphysics.
- Enhanced tropical transient activity and tropical cyclones.
- Avoid many artifacts in deep convective parameterization.
- One can obtain a high quality simulation with such a scheme in an AGCM forced by observed SSTs.
Sensitivity of global TC frequency to cumulus entrainment rate and divergence damping parameters

Increasing cumulus mixing

Increasing divergence damping

Zhao, Held and Lin 2012 (JAS)
The derived maximum wind speed relationship is approximately bi-linear

\[ I_{fit} = I_T + \alpha (I_{GCM} - I_T); I_{GCM} \leq I_T \]
\[ I_{fit} = I_T + \beta (I_{GCM} - I_T); I_{GCM} > I_T \]

\[ \alpha = 1.22; \beta = 3.15; I_T = 34 \text{ m/s} \]

Zhao and Held 2010, J. Climate
The simple statistical adjustment allows the model to capture variability of Atlantic major hurricanes

Zhao and Held 2010, J. Climate
Projections for future TC frequency

Future projections using a time slice method

\[ \delta N = \frac{\partial N}{\partial GHG} \delta GHG + \frac{\partial N}{\partial SST} \delta SST + \frac{\partial N}{\partial RSST} \delta RSST \]

1. Response to changes in greenhouse gases \( \delta GHG \)
2. Response to changes in global tropical mean SST \( \delta SST \)
3. Response to changes in relative SST (RSST) \( \delta RSST \)

CNTL \rightarrow +2K (P2K) \rightarrow +2K and 2xCO2 (BOTH) \rightarrow 9 coupled model projected SST anomalies

2xCO2
Global TC frequency response to uniform 2 degree SST warming and doubling of atmospheric CO2 concentration

Sugi and Yoshimura 2004, Held and Zhao 2011, J Climate
Global TC frequency response to 2K SST warming and CO2 doubling from the US CLIVAR HWG models

Changes in global TC frequency

Fractional changes in global TC frequency

Zhao et. al 2013, CLIVAR newsletter
Mid-tropospheric convective mass flux best explains the simulated TC frequency response for most HWG models.

Changes in global TC frequency

Zhao et al. 2013, CLIVAR newsletter

An index for seasonal-scale convective mass flux measured by 500mb omega weighted by TC genesis frequency from the control simulation.

Changes in 500mb omega
Mechanisms for global mean reduction

Future projections

\[
\delta N = \frac{\partial N}{\partial \text{GHG}} \delta \text{GHG} + \frac{\partial N}{\partial \text{SST}} \delta \text{GSST} + \frac{\partial N}{\partial \text{RSST}} \delta \text{RSST} \ (x, y)
\]

\[
= \frac{\partial N}{\partial M_c} \frac{\partial M_c}{\partial \text{GHG}} \delta \text{GHG} + \frac{\partial N}{\partial M_c} \frac{\partial M_c}{\partial \text{SST}} \delta \text{GSST} + \frac{\partial N}{\partial M_c} \frac{\partial M_c}{\partial \text{RSST}} \delta \text{RSST} \ (x, y)
\]

\[\delta M_c \downarrow \text{GLOBAL} \quad \delta M_c \downarrow \text{GLOBAL} \quad \delta M_c \uparrow \text{REGIONAL}\]

\[
P = M_c q_b \Rightarrow \frac{\delta M_c}{M_c} = \frac{\delta P}{P} - \frac{\delta q_b}{q_b} = \frac{\delta Q_{rad}}{Q_{rad}} - \frac{\delta q_b}{q_b} < 0
\]

Held & Soden (2006)

\(\delta M_c\) is non-uniform, monsoonal-like response may be important, significant precipitation move from ocean to land for 2xCO2 case and opposite for the +2K case, causing more uncertainty across models

Zhao et. al 2013, CLIVAR newsletter
Regional TC frequency response to coupled model projected 21st century warming

Key points:

- Quantify the uncertainty due to spatial pattern of SST warming?

- What features of SST distributions are important?

- Atmospheric mechanisms that translate the SSTs into processes that directly control regional TC activities?

SST warming anomalies:

0. 18 model ensemble mean
1. GFDL CM2.0
2. GFDL CM2.1
3. UKMO HADCM3
4. UKMO HADGEM1
5. MPI-ECHAM5
6. CCCMA
7. MRI-CGCM
8. MIROC-HI
9. 2K UNIFORM WARMING

CO2 is doubled for all cases
HiRAM simulated hurricane frequency response to 21st century warming projected by IPCC AR4 coupled models

For each basin, there is large inter-model spread in the magnitude and even the sign of the hurricane frequency response. The differences are entirely due to the different SST projections. (Zhao and Held, 2012, J. Climate)
Indices of SSTs and atmospheric properties relevant to hurricane genesis frequency

SSTs $\rightarrow$ atmospheric properties $\rightarrow$ hurricanes

\[ RSST(m, x, y) : \text{relative SST} = \text{local} - \text{tropical mean SST} \]
\[
RSST(x, y) = \frac{\sum_{m} RSST(m, x, y)G(m, x, y)}{\sum_{m} G(m, x, y)}
\]

\[ G(m, x, y) : \text{climatological storm genesis frequency from the control simulation.} \]
\[ m = 1-12, \ x = \text{lon}, \ y = \text{lat} \]

\[ \omega_{500}(m, x, y) : \text{mid-troposphere vertical velocity} \]
\[ \text{(Zhao and Held, J. Climate 2012)} \]
Most inter-model variation can be explained by the simple relative SST index in the N. Atlantic, E. Pacific and S. Indian Ocean.

Scatter plots of fractional change in hurricane count vs change in relative SST.

R: correlation coefficient

(Zhao and Held, 2012, J. Climate)
Mid-tropospheric vertical velocity is skillful in explaining the simulated hurricane response for all basins.

Scatter plots of fractional change in hurricane count vs change in mid-troposphere vertical velocity (hPa/day).

R: correlation coefficient
(Zhao and Held, 2012, J. Climate)
The eastward migration of TC genesis frequency can be explained by changes in mid-troposphere vertical velocity.

Change in hurricane genesis frequency (unit: #/year/4°x5°)

Change in mid-troposphere vertical velocity

Color: average from 8 individual models; stipple: area where 6 out of the 8 models agree on the sign of change. (unit: hPa/day)
Summary

A 50km HiRAM forced by the observed SSTs appears to realistically simulate many aspects of TC frequency variability. The advanced dynamical core and convection representation are key toward the success. The results further suggest:

- decoupling between simulations of TC frequency and intensity
- strong relationship between SST and TC frequency variability
- justifying time-slice method for studying future change in TC frequency

For future TC change, it is useful to decompose total response into 3 components: changes due to 1) GHG increase, 2) global mean SST increase, 3) changes in spatial pattern of SSTs. Results suggest:

- Robust reduction in global mean frequency to GHG increase
- Less robust reduction in global TC count to global mean SST warming
- Large uncertainties at basin scale due to different SST pattern change.

All 3 aspects of the response suggest the importance of changes in large-scale convective overturning motion in predicting TC responses.
End
HIRAM performs well in the GCMs participating in the US CLIVAR Hurricane Working Group (Figure: TC genesis density)

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