Climate Models and Tropical Cyclones: Idealized Models of the Climatology of Cyclogenesis

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Thanks to Ming Zhao, Tim Merlis, Andrew Ballinger, Wenyu Zhou
Claim:

we are poised for rapid progress in our understanding of the tropical cyclone climate based on simulation of tropical cyclones in global models

analogous to the transition in the 1970-80's in simulations of midlatitude baroclinic eddies in global models

(models are far from perfect but good enough that we feel justified in manipulating them to better understand the factors that control these storms)
All results here based on a single atmospheric model HiRAM (Zhao, et al, J. Clim. 2009) with 25 or 50km resolution but using geometries/boundary conditions with different levels of idealization

Realistic version
prescribed sea surface temperatures - SSTs

Aqua-planet:
zonally symmetric boundary conditions
slab ocean (Merlis et al, GRL, 2013)
fixed SSTs (Ballinger et al, JAS, 2015)

Spherical rotating radiative-convective equilibrium
uniform SSTs in latitude and longitude
(Merlis et al GRL 2016)

f-plane rotating radiative convective equilibrium:
fixed SSTs (Zhou et al, JAS, 2014)
slab ocean (Zhou et al, JAMES, 2017)
hurricane tracks (1981-2005) upper: obs, lower: model

Zhao et al, JAS, 2009
Model captures the seasonal cycle of hurricane frequency over various ocean basins

Zhao et al, JAS, 2009
Model captures ENSO effect on hurricane genesis frequency

El-Nino years minus La-Nina years (observation)

El-Nino years minus La-Nina years (C180HiRAM)

Zhao et al, JAS, 2009
Raw model output cannot be used to study intensity

pdf of max lifetime wind speed

HIRAM (50km grid)
Observation
raw global model output cannot be used for quantitative info on intensity but a statistical adjustment captures observed variability of storm mean intensity

Mean intensity is obtained by averaging the maximum intensity of each storm over all TCs in given years

Change in mean intensity of Atlantic TCs La Nina minus El Nino

Zhao and Held, 2010, J. Clim
Global mean reduction is due in part to $\text{CO}_2$ increase with fixed SSTs.

P2K: uniform SST increase of 2K
    no change in CO2

2xCO2: double CO2
    no change in SST

Contribute about equally to global mean reduction in frequency

Held and Zhao, J. Climate, 2011
When HiRAM is run with change in SSTs over 21\textsuperscript{st} century simulated by 8 of world’s climate models

Change in Atlantic Hurricane numbers correlated with warming in Atlantic SST relative to mean tropical warming
Effect of change in convection scheme on TCs in HiRAM

Inhibiting parameterized convection =>

Zhao, Held, Lin JAS 2012
Aquaplanet over slab ocean (20m deep), 50km resolution, zonally symmetric climate, no seasonal cycle

Merlis, et al, GRL, 2013
Moving ITCZ by changing prescribed cross-equatorial “oceanic” energy flux

Poleward ITCZ more favorable for cyclogenesis.
Merlis, et al, GRL, 2013

Moving ITCZ by changing prescribed cross-equatorial “oceanic” energy flux

Poleward ITCZ more favorable for cyclogenesis.
ITCZ & TC genesis shifts poleward with warming!
Typically, number of TCs decreases with uniform warming with realistic boundary conditions.

But in this aqua-planet configuration, the number increases because ITCZ and genesis move poleward.
Typically, number of TCs decreases with global warming with realistic boundary conditions.

But in the aqua-planet configuration, the number increases because ITCZ moves poleward.

Understanding this result has at least 3 distinct parts:
-- how does the ITCZ move with warming
-- how does the TC number change with ITCZ latitude
-- how does the TC number change with warming with fixed ITCZ latitude

\[ N = f(Q, T) = g(ITCZ(Q, T), T) \]

\[ \frac{\partial f}{\partial T} > 0; \quad \frac{\partial g}{\partial T} < 0 \]
adding zonal variations
SST = SST_0(y) + (1.5K)sin(kx)

Andrew Ballinger, in prep
Genesis frequency

$k = 1$

$k = 2$

$k = 3$
Rotating radiative-convective equilibrium on a sphere
Uniform SSTs – Uniform insolation
(eliminates midlatitude baroclinic eddies)

SST = 297 K
Near surface wind speed

SST = 305 K

tropical genesis => beta drift => polar accumulation

Merlis, et al GRL, 2015
SST = 307K

Merlis, et al 2015
TC decreases as temperature increases in rotating radiative-convective equilibrium.
Rotating Radiative Convective Equilibrium
Identical model except for $f$-plane doubly-periodic geometry and homogeneous forcing and SSTs

Also referred to as “TC World” and “Diabatic Ekman Turbulence”

Surface wind speed

Zhou et al., 2014, JAS
Lots of interesting parameter dependencies:

distance between storms increases with SST: NH/f ?, u*/f ?

Lots of interesting parameter dependencies:

distance between storms decreases with rotation rate: \( \frac{NH}{f} \), \( \frac{u^*}{f} \)

\[ f = 5 \quad \text{vs.} \quad f = 20 \]

Potential Intensity:

\[ C_D V^3 \sim Q(\Delta T / T) \sim C_H V (k^* - k)(\Delta T / T) \]

\[ \Rightarrow V^2 \sim \left( C_H / C_D \right) (k^* - k)(\Delta T / T) \]
Radius of maximum winds

![Graph showing the relationship between SST (K) and RMW (km)]

- Median of all
- Mean of the strongest
Rotating radiative-convective equilibrium on an f-plane with a slab ocean of depth $H$ (energetically closed – prognostic SSTs)

$H = 0.1 \text{ m}$

$H = 20 \text{ m}$
Even as energy content of “ocean” – the depth of the slab approaches zero, tropical storms survive and fill domain.

Depth = 0.1 m

Depth = 20 m
There is great opportunity for a new generation of scientists with solid foundations in both tropical cyclone (TC) research and in global climate modeling to increase our fundamental understanding of the TC climatology and improve our simulations and predictions of its variability and sensitivity.