Understanding the Role of Tropical Cyclones in the Climate System with Simplified Climate Models

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Motivation: 1 hurricane = millions of atomic bombs

Coastal communities in Mexico Beach, FL before and after Hurricane Michael (2018)

[Source: NOAA]
Question: Do tropical cyclones affect climate system energy transport?

- For the Equable Climates, 146-34 Myr B.P. (Cretaceous - Eocene): tropical cyclones hypothesized to keep the poles warmer by **enhancing ocean heat transport** (Emanuel, 2002; Korty et al., 2008)
- For current and future climates: Can tropical cyclones be a significant agent of energy transport? If so, how?
Observation: Tropical cyclones may contribute \(\sim 15\%\) to ocean heat transport

- Earlier estimates: anywhere between 5-50\%
- Mei et al. (2013): Northern Hemisphere TCs contribute \(0.32 \pm 0.15\) PW \((\sim 15 \pm 7\%)\) to poleward ocean heat transport
- BUT global tropical ocean heat transport \((2.3 \pm 0.4\) PW\) has a substantial error margin (Ganachaud and Wunsch, 2003)
Conventional climate modeling: Tropical cyclones represented at high resolution

- NCAR’s Community Atmosphere Model at ~28 km horizontal resolution

- Tropical cyclone (TC) precipitation and wind field capturing the interaction with mountainous island

- Biases in simulated TC statistics, especially for the Western North Pacific (Bacmeister et al., 2018; Wu et al., submitted)
Conventional climate modeling: Ocean response to TC captured

[Li and Sriver, 2018; Bock, 2017]
Conventional climate modeling: Biases in TC climatology

CAM5-only decadal (1980-2005) climatology:
- Global TC frequency: ~70% of observation
- Western North Pacific: ~40% of observation

[Observations, n = 2422]

[Simulations, n = 1603]

[Obs., n = 2422]

[N = 465]

[N = 191]

[Bacmeister et al., 2018; Wu et al., submitted]
Gap: Uncertainty and complexity

• Observation:
  - Limited records of TCs, especially of the ocean
  - Large error margin in ocean heat transport

• Conventional climate modeling:
  - Uncertainty from limited skills (atmosphere and ocean)
  - Computationally expensive due to complex components
Approach: A hierarchy of simpler models

- Human
- Mouse
- Fruit fly

[Prokop, 2015]
Approach: A hierarchy of simpler models

- Complex boundary forcing
- Idealized boundary forcing
- Surface Temperature (K)
- Total precipitable water (kg/m²)
- Poleward Energy Transport
- Observations
- Atmosphere
- Total
- Ocean
- Aquaplanet

Conventional Climate Model

- Complex climate
- Total precipitable water (kg/m²)

Simplified Climate Model

- Idealized climate
- Total precipitable water (kg/m²)

Figures:
- (a) Conventional Climate Model
- (b) Complex climate
- (c) Poleward Energy Transport
- (d) Simplified Climate Model
- (e) Idealized climate
- (f) Aquaplanet

References:
- Ferreira et al., 2010
Proposed Hypotheses

• H1: TCs contribute a significant fraction (>10%) to ocean heat transport (cf. Mei et al. 2013).

• H2: TCs contribute a significant fraction (>10%) to oceanic overturning circulation in the tropics (cf. Shi and Bretherton 2014).

• H3: The impact of TCs is enhanced in the presence of western boundary currents (cf. Li and Sriver 2018a).

RIDGE: aquaplanet with a strip of pole-to-pole continent

Ocean dynamics leads to western boundary currents, like the Atlantic Gulf Stream or Pacific Kuroshio

[DiNezio, 2019]
Experiment 1: Low-resolution coupled simulation

Atmosphere ~1° + Ocean ~2°, fully coupled ~4000 yrs

AQUA sea surface temp.

RIDGE sea surface temp.

- Western Pacific warm pool
  - Related to cold tongue to the east.
  - No cold tongue in the Indian Ocean because of absolute westerlies

- Independent Atlantic

- Equatorial cold tongue,
  - Weak equatorial trades,
  - Trade winds converging off the equator at about 10°.

- Localization of deep sinking and overturning in narrow basin
  - (Ferreira et al. 2010; Nilsson et al. 2013)

- Role of continents in heat transport
  - (Enderton & Marshall 2009)

- Role of continents in freshwater transport
  - (Ferreira and Marshall 2015)

- AMOC's role in ITCZ location
  - (Marshall et al. 2014)

- Role of subtropical cells in ITCZ sensitivity to interhemispheric forcing
  - (Green and Marshall 2017)
Experiment 2: High-resolution atmosphere-only simulation

Atmosphere model ~0.25°
Forced by prescribed sea surface temperature
~30 yrs

AQUA atmosphere
RIDGE atmosphere
Experiment 3: High-resolution ocean-only simulation

TC-filtering of atmosphere bottom layer
Ocean model ~1°, forced by atmosphere with and without TCs

[Li and Sriver, 2018]

Diagnostics and Analysis
Computational highlights

Climate model development
- Bringing together idealized atmosphere and ocean
- Collaboration and community

High-performance computing
- Order of 1,000,000 core hours on supercomputer Cheyenne
- Innovation for potentially high-resolution coupling

Data analysis
- Output order of 10 TB
- Parallel processing for TC-tracking
- Interactive diagnostics and visualization in development
Timeline: 1.5 – 2 years

- Summer 2019: Low-res. coupled simulation
- Fall 2019: High-res. atmosphere-only simulation
- Fall-Winter 2019: High-res. ocean-only simulation
- Spring 2020 and beyond:
  - Data analysis and interpretation
  - Additional experiment: High-res. coupled simulation
  - Presentations and publications
Broader Impacts: Advancing Climate Science and Modeling

$1$ investment in natural hazard mitigation $= \$11$ in national benefit
[the National Institute of Building Sciences, 2019]

[Satellite image: NASA]