Applications of a regional coupled model to studies of global warming and hurricane-ocean interaction

Hyodae Seo
University of Hawaii

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Outline

1. **Climate simulation**: downscaling projection of global warming scenario ➔ Role of oceanic eddies and currents in Atlantic.

2. **Weather simulation**: Impact of ocean state (SST, D26, UOHC) on TC intensity ➔ Case study of Hurricane Katrina
I. *Equatorial* Atlantic Ocean’s response to global warming forcing
• CGCMs for projections of climate change need to resolve all the relevant feedback processes.
• Example: Tropical instability waves (TIWs)
• Not well-resolved in IPCC-AR4 models and their impact is unexplored.
• So we need to resolve them by downscaling.

SST snapshots from NOAA OI SST (25 km) on July 27, 2007
Model and experiments

**Scripps Coupled Ocean-Atmosphere Regional Model**

(Seo et al. 2007, *J. Climate*)

Atmosphere: Regional Spectral Model (Scripps RSM)
Ocean: Regional Ocean Modeling System (ROMS)

- **CTL**: RSM (NCEP2 6hrly) + ROMS (SODA monthly)
- 25 km ROMS + 50 km RSM
- Daily coupling based on Fairall et al. (1994)
- Atmospheric spectral nudging > 1000 km

**GW**: RSM (NCEP2 6-hrly + $\delta$) + ROMS (SODA monthly + $\delta$)

**GW-CTL**

Quasi-steady state

pseudo global warming experiment
Simulation of present-day climate

- Zonal SST gradient and equatorial cold tongue in SCOAR

GW response (GW-CTL)

- Reduced warming in the equator
- Intensified cross-equatorial meridional winds and surface divergence
Why reduced warming in cold tongue?

➔ Eg., Change in vertical temperature advection within cold tongue

\[-w \frac{\partial T}{\partial z} = -\langle w \rangle \frac{\partial T}{\partial z} - \langle w \rangle \frac{\partial T^*}{\partial z} - w^* \frac{\partial \langle T \rangle}{\partial z} - w^* \frac{\partial T^*}{\partial z}\]

1. climatological mean (CTL)
2. Perturbation from global warming (GW-CTL)

1: climatological equatorial upwelling
2: Weak warming (cooling) in the west (east) due to thermal stratification
3: Stronger cooling by increased vertical velocities

cf., an ocean dynamical thermostat in the Pacific and the Atlantic.
Change in equatorial zonal currents and equatorial instability

- $30^\circ W - 10^\circ W$
- EUC/SEC/NECC/TJ are more realistic (stronger) in SCOAR.
- Stronger northward cross-equatorial wind ➔ Stronger EUC
  (Philander and Delecluse, 1983)
Change in atmospheric circulation $\rightarrow$ changes in ocean circulation $\rightarrow$ equatorial dynamic instability

- Barotropic and baroclinic convergence are dominant energy sources for the TIWs.
- Both BT and BC are strengthened under the environmental changes associated with global warming.
Strengthening of TIWs (20-40 day band-pass filtered EKE and SST variance)

- EKE and TIW-SST variance all become stronger during the cold season (~30%).
• Equatorial upwelling (cooling) increases due to the increased vertical velocities associated with the surface divergence. cf. the tropical Pacific.

• Net eddy heat flux by TIWs is warming in CTL and increases under global warming forcing, damping the effect of increased upwelling.
Summary of Part I

• **Exploratory research**: The first coupled downscaling of climate change scenarios

• Downscaling captures equatorial currents and mesoscale variabilities

• **Upwelling increases.** **Currents intensify.** **TIWs strengthen.** Impact spatial pattern of mean state warming.

  • Need to resolve high-freq. processes in the model for global warming research.

• **Challenge**: Drift in mean state in a long-term integration.

  • Need a consistent nudging technique for large-scale circulations both of the ocean and atmosphere.
2. Impact of ocean state on TC intensity

→ Hurricane Katrina
Rapid intensification over high dynamic topography: SST alone or upper ocean heat content?

- Satellite altimeter data indicate that Katrina intensified over areas of anomalously high dynamic topography rather than areas of unusually warm surface waters.

- “SST+2°C” suggests ~10mb; cf, 50 mb increase during RI period over warm eddy.

- How much of intensification of Katrina in 2005 was due to ocean impact (SST, D26, UOHC)? Can we quantify this?
Coupled experiment: *Scripps Coupled Ocean-Atmosphere Regional Model*

- RSM (NCEP2 6hrly) + ROMS (ECCO kf066b 10-daily $1^\circ \times 1^\circ$)
- 15 km ROMS + 15 km RSM with matching grids
- 1-hourly coupling based on Fairall et al. (1994)
- 120-hr. integration: Aug. 26 00Z - Aug. 31,00Z, 2005

Simulated Katrina is weak.

- Rapid intensification is underestimated
  - Need enough time for the storm to spin-up from the initial fields.
  - We need a good initial maximum wind speed. Bogussing the initial vortex in the NCEP is needed.
\( \Delta \text{SLP} \) (each year minus 2005) after 74 hrs from initialization

- The same Katrina of 2005, is coupled to ocean states of different years (1993 to 2008).

- Katrina is generally weaker compared to 2005.

- Indicating that 2005 ocean state was favorable to the intensification of Katrina. \( \Rightarrow \) “The Perfect Ocean” for Katrina.

- So, is weaker Katrina in other years due to SST or UOHC? \( \Rightarrow \) We have to look at the oceanic initial conditions.
Sensitivity of Katrina intensity to ocean states in different years

- Intensity of storm is more sensitive to the initial SST, rather than D26 or UOHC;
- Range of SLP variation due to SST is ~5 mb.
Interannual variability of ECCO D26 is underestimated.

- Interannual variability of D26/SSH in ECCO is too weak compared to that of SODA and AVISO altimeter data.

- SODA suggests interannual variability of D26 of ~30 meters where Katrina passed over.

<table>
<thead>
<tr>
<th>ECCO</th>
<th>SODA</th>
<th>AVISO</th>
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<tr>
<td>D26 [m]</td>
<td>SSH [cm]</td>
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<tr>
<td>ECCO: 1X1,10-daily; kf066b</td>
<td>SODA: 0.5X0.5, monthly, No assimilation of altimeter data</td>
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Alter D26 in initial conditions without changing SST

- Alter depth of 26°C isotherm, increasing/decreasing the heat content of the ocean.
- ±30 m change in D26 gives >15 mb change in SLP in 2005 → Corresponds to 30% of SLP reduction in CTL case.
• TC intensity is negatively correlated with D26.

• Variability is greater in warmer ocean conditions than colder ocean conditions.

→ Sensitivity of storm intensity is greater for warmer ocean.
Min. SLP and initial ocean state

- Interannual SST variation is negatively correlated to storm intensities; the range of SLP sensitivity is ~5-15 mb depending on D26.
- However, the same SST can cause large SLP variation depending on D26.
- Interannual D26 variation has an incorrect correlation with the SLP.
- However, when interannual D26 variability is increased to match the observations, then SLP has a robust negative correlation with SLP with >25 mb.
- UOHC reflects these two features.
Summary of Part 2

• For strong TCs, UOHC (D26+SST) is an useful predictor, than SST alone, for the intensification.

• Inclusion of dynamic topography in the statistical prediction model improves intensity forecast; NHC (up to ~20%) and JTWC (~1%).

• Ocean dynamical topography may give wide range of predictability of intense TCs from weekly to interannual.

• In this set of experiments, D26 produces wider ranges of intensity response of TCs than SSTs.
  • Since an intense TC interacts with ocean more strongly, the estimate here is likely higher with stronger storms -- work in progress to add realistic initial maximum wind speed.
  • Need better oceanic initialization; other oceanic analyses products with better information of dynamic topography.
Outlook

• Understanding of regional processes in a changing climate is important.
  
  • The US west coast and other coastal upwelling regions are good initial targets because of important interactions involving ocean dynamics, coastal meteorology, air-sea coupling and bio-geochemistry.

• As the WRF is being embedded within CCSM to produce stronger TCs, it is important to provide ocean feedback on more appropriate spatial scales (e.g., reduced self-induced cooling).

  • We need the generalized oceanic nested grids within POP in coordination with WRF/CAM for key regions of cyclogenesis of the global ocean.
Thanks