Impact of simple parameterizations of upper ocean heat content on modeled Hurricane Irene (2011) intensity

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Image Credit: NASA/NOAA GOES Project
Motivation

• In August 2011, Hurricane Irene’s intensity was over-predicted by several hurricane models and over-forecast by the National Hurricane Center (NHC)
  • NHC final report on Irene:
    1. Consistent high bias in official intensity forecasts
      • Incomplete eyewall replacement cycle in light wind shear and over warm South Atlantic Bight waters
    2. High bias in operational analysis of intensity
      • Deep central pressure, strong flight-level winds but low surface winds
Governing factors of hurricane intensity

Did the upper ocean thermal structure and evolution (i.e. evolution of sea surface temperature, SST) contribute to Irene’s intensity over-prediction?

After Emanuel et al. (2004)
Hypothesis

We hypothesize that the models handled well:

• hurricane track (use best boundary conditions);
Hypothesis

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- vertical wind shear (TBD);
- dry air intrusion (TBD);
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Some possible reasons:

- Models have improved considerably on predicting tracks
- Atmosphere tends to receive more attention in modeling
- Models resolve large-scale processes fairly well

But models handled poorly:

- upper ocean thermal structure and evolution

This talk aims to show the relative importance of ocean prediction for intensity forecasting of Hurricane Irene.
Methods – Observations and Model

**RU16 Glider**: at 40m isobath, right of eye track

**Satellite** (“Rutgers SST”): 1km AVHRR 3-day *coldest dark pixel* SST composite (preserve cold wake); NASA SPoRT 2km SST for cloudy gaps

**Model**: 6km WRF-ARW, boundary conditions to get track correct (important because close to coast); no data assimilation
Results

1. Glider data revealed that ocean mixing and resulting surface cooling preceded the passage of the eye.

2. Improved satellite SST product revealed that this surface ocean cooling was not captured by:
   - Basic satellite products
   - Ocean models used for forecasting hurricane intensity

3. Over 100 sensitivity tests showed that Hurricane Irene intensity is very sensitive to this “ahead-of-eye” SST cooling.
1. Glider revealed “ahead-of-eye” cooling

Ocean column mixing from leading storm winds cools surface

warm SSTs before storm

passage of eye

thermocline top

thermocline bottom

onshore surface currents

offshore bottom currents

Depth (m)

August 2011 GMT

T (°C)

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JERSEY ROOTS, GLOBAL REACH
2. Improved satellite SST product revealed that this cooling was not captured by:

- basic satellite product
- ocean models used for forecasting hurricane intensity

**BEFORE IRENE**

- Rutgers SST
- RTG HR SST
- NAM model

**AFTER IRENE**

- HWRF-POM low res
- HWRF-HYCOM medium res
2. However, cooling was captured by high res ocean models

Rutgers composite showed that cooler SSTs are captured relatively well by high res coastal ocean models not specifically used for forecasting hurricanes.
3. >100 sensitivity tests showed Irene intensity very sensitive to this “ahead-of-eye” SST cooling

Over Mid-Atlantic Bight & NY Harbor

NJ landfall

Minimum Sea Level Pressure (hPa)

Sensitivity to SST (warm minus cold), isftcflx=2
Sensitivity to air-sea flux parameterization (isftcflx=1 minus isftcflx=0), warm SST
Sensitivity to air-sea flux parameterization (isftcflx=1 minus isftcflx=0), cold SST
Conclusions

- Large majority of SST cooling occurred ahead of Irene’s eye
  - Glider observed coastal downwelling, which resulted in shear across thermocline, turbulence/entrainment, and finally surface cooling
- We determined max impact of this cooling on storm intensity (fixed cold vs. fixed warm SST)
  - One of the largest among tested model parameters
- Some surface cooling occurred during/after eye passage
  - Actual impact of SST cooling on storm intensity may be slightly lower
- A 1D ocean model cannot capture 3D coastal ocean processes resulting in important “ahead-of-eye” SST cooling
- A 3D high res ocean model (e.g. ROMS) nested in a synoptic ocean model could add significant value to tropical cyclone (TC) prediction in the coastal ocean—the last hours before landfall
Future work

• Improve model spin-up issues
• Validate wind shear and dry air intrusion
• Evaluate storm size and structure
• Compare modeled to observed heat fluxes (need air T, SST)
• Move towards accurate fully coupled WRF-ROMS system
  • WRF w/ hourly ROMS SST
  • WRF coupled w/ 3D Price-Weller-Pinkel ocean model
  • WRF-ROMS
• More case studies to quantify value of 3D ocean prediction to TC intensity forecasting, eventually across season(s)
Thank You
Extra Slides
Glider, buoy, and HF radar obs.

At surface

Below surface
Cross-shelf Transects

Explanation of Air-Sea Flux Changes in WRF

- \( \tau = -\rho u^* \Delta x = -\rho C_D U^2 \) 
  momentum flux (\( \tau \))
- \( H = -\rho c_p u \Delta \theta = -\left( \rho c_p \right) C_H U \Delta \theta \) 
  sensible heat flux (H)
- \( E = -\rho L v u \Delta q = -\left( \rho L_v \right) C_Q U \Delta q \) 
  latent heat flux (E)

\( \rho \): density of air 
\( (u^*, \theta^*, q^*) \): friction velocity, surface layer temperature and moisture scales 
U: 10m wind speed 
\( c_p \): specific heat capacity of air, \( L_v \): enthalpy of vaporization 
\( \Delta (\theta, q) \): temperature, water vapor difference between \( z_{ref} = 10m \) and \( z = sfc \)

In neutrally stable surface layer within TC eyewall (e.g. Powell et al. 2003):

- \( C_D = k^2/\ln(z_{ref}/z_0)^2 \) 
  drag coefficient
- \( C_H = (C_D^{\frac{3}{2}}) \times k/\ln(z_{ref}/z_T) \) 
  sensible heat coefficient
- \( C_Q = (C_D^{\frac{3}{2}}) \times k/\ln(z_{ref}/z_Q) \) 
  latent heat coefficient
- \( C_k = C_H + C_Q \) 
  moist enthalpy coefficient

\( k \): von Kármán constant 
\( z_{ref} \): (usually 10m) reference height

<table>
<thead>
<tr>
<th>WRF isftcflux</th>
<th>( z_0 ): momentum roughness length</th>
<th>( z_T ): sensible heat roughness length</th>
<th>( z_Q ): latent heat roughness length</th>
<th>Dissipative heating?</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( z_0 = 0.0185u^*2/g + 1.59E-5 )</td>
<td>( z_0 )</td>
<td>( z_Q = (z_0^{-1} + ku*K_a^{-1})^{-1} ) Carlson &amp; Boland (1978)</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Charnock (1955)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>See Green &amp; Zhang (2013) for eq.</td>
<td>10^{-4} m</td>
<td>10^{-4} m</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>Same as ( z_0 ) for Option 1</td>
<td>( z_T = z_0 \exp[k(7.3Re^{\frac{3}{4}}Pr^{\frac{1}{2}}-5)] )</td>
<td>( z_Q = z_0 \exp[-k(7.3Re^{\frac{3}{4}}Sc^{\frac{1}{2}}-5)] )</td>
<td>Yes</td>
</tr>
</tbody>
</table>

\( K_a = 2.4E-5 \) m²s⁻¹ (background molecular viscosity) 
\( Re = u.Z_0/\nu \) (Roughness Reynolds number), \( Pr = 0.71 \) (Prandtl number), \( Sc = 0.6 \) (Schmidt number)

After Green & Zhang (2013)
Plot of Resulting Exchange Coefficients

After Zhang et al. (2012)
Presentation for HFIP
1D ocean model

H0ML = 10 m
Gamma = 1.6 C/m

H0ML from HYCOM
Gamma = 1.6 C/m
Results:

C. Maximum Sustained 10m Wind Speed (m/s)

D. Difference in Maximum Sustained 10m Wind Speed (m/s)

E. Error (m/s) 2011 Aug 28 00:00-13:00
Sensitivity tables: 110 runs

- Bad B.C.
- Bad forecast of wind
- Max wind largest sensitivity to SST
- Diff. init. time
- Bad B.C.
- Bad forecast of pressure
- Min SLP large sensitivity to SST

Parameterized Upper Ocean Heat Content
ROMS simulation results

(A) Temperature

(B) Vertical Velocity

(C) Vertical Advection

(D) Momentum Balance

(E) Crossshore Velocity

(F) Eddy Viscosity

(G) Vertical Diffusion

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Simple **Uncoupled** WRF Hindcast Sensitivities:

**SST Setup**

- Modify SST input to “simulate” SST cooling:
  - From fixed warm pre-storm SST (e.g. NAM, GFS) to what?
- 2 methods to determine optimal timing of SST cooling:
  1. When did models show mixing in southern MAB?
  2. When did “critical mixing” wind speed occur in southern MAB? *(Critical mixing w.s. = w.s. observed at buoys and modeled at glider when sea surface cooled). Assumes similar stratification across MAB.*

- Cooling Time = 8/27 ~10:00 UTC
- Model Init. Time = 8/27 06:00 UTC
- Used fixed cold post-storm SST
Model Validation

- Height 9.08m (obs) vs. 10m (WRF) [log law]
- Averaging time 2-min (land stations)*, 8-min (buoys) vs. instantaneous (WRF) [obs gusts]
- Validate at 44014, 44009, 44065, and tall met towers (for boundary layer shear profile- NHC indicated it as large during Irene)

*OYC: 15-min, Stafford Park: 10- and 60-min
Model Validation