Rapid Co-evolution of the Coastal Ocean and Atmosphere in Hurricanes and Typhoons

Contributing Scientists:
Scott Glenn, Travis Miles, Greg Seroka, Maria Aristizabal, Cliff Watkins, Sam Coakley, Alexandra Ramos Valle (Rutgers), Doug Wilson, Roy Watlington (UVI), Yi Xu (ECNU), Hak Soo Lim (KIOST)

NOAA Partners:
Avichal Mehra, Vijay Tallapragada, Hyun-Sook Kim, Gustavo Goni, Ben LaCour, Frank Marks
Hurricane Glider Picket Line - Concept of Operations

1) All Gliders monitor **Essential Ocean Features** well before a hurricane
2) Some Gliders document **Essential Ocean Processes** in a hurricane
3) Full Glider community involvement enabled by IOOS Glider DAC
Glider Tracks & ARGO Floats
2018 Hurricane Season

Total number of Glider profiles = 123335
Total number of Argo profiles = 17264

Glider Data Flow:
Operators >
IOOS Glider DAC >
NDBC > GTS >
Ops Centers

1/3 dedicated
2/3 volunteers
Glider Tracks & ARGO Floats
2019 Hurricane Season

Total number of Glider profiles = 103511
Total number of Argo profiles = 13164

Glider Data Flow:
Operators >
IOOS Glider DAC >
NDBC > GTS >
Ops Centers

1/2 dedicated
1/2 volunteers
North Atlantic Hurricanes Ocean Forecast Work Flow

Global GOFS 3.1/NCODA System  "It Starts With Us"  NCODA Incremental Insertion Window

Global RTOFS

Regional HYCOM IC used for
2019 Operational HMON/HYCOM
2019 Experimental HWRF/HYCOM
2019 Experimental HWRF/POM

2019 Operational HWRF/POM initialized with ocean climatology modified by feature models

Coming in 2020 - RTOFS-DA
Comparing Operational Hurricane Models to Glider Data

Hurricane Dorian
Aug 20 – Sep 07

GoFS
POM
Oper POM
Exp
HYCOM
Exp

Target

Full profile comparisons closest to Target
Upper ocean metrics further from Target
GOFS > HYCOM Exp > POM Exp > POM Oper
Time Series point comparison: AOML Glider SG665

Along Track comparison: Best Track

Intensity Forecast Dorian 2019082800

POM Clim - near Cat 1
POM RTOFS - near Cat 2
HYCOM RTOFS - Cat 3
**Hurricane Dorian 2019**

28 Aug to 1 Sept
TS to Cat 4
Before RI

Average forecast intensity errors for all cycles

Rapid error growth to over 20% for POM with IC from Climatology

Relatively constant error level at 10% for HYCOM with IC from RTOFS

Details in Doug Wilson’s talk in 2 weeks.
Tropical Cyclone Heat Potential – Ocean Impacts Map

But TCHP in not universal....

Irene & Sandy $87 B
Glenn et al., 2016 Nature Comms
Seroka et al., 2016 MWR
Seroka et al. 2017 JGR Oceans
Miles et al. 2017 JGR Oceans
Watkins Ph.D. Thesis
Coakley Ph.D. Thesis
Ramos-Valle Ph.D. Thesis

Harvey $128 B
Potter et al., 2019

AOML Glider Program
Many, many
Goni et al... papers
Regionally-specific Essential Ocean Features impacting Atlantic Hurricane Intensity

In biology, **co-evolution** occurs when two or more species reciprocally affect each other’s evolution...

- WIKIPEDIA

Rapid Co-evolution of the Ocean & Atmosphere in the Mid Atlantic Bight
Hurricane Irene  
August 28, 2011  
NOAA/NHC Damage:  
>$15 Billion, #15.  
Track Accurate;  
Intensity Over-predicted.


Hurricane Sandy  
October 29, 2012  
NOAA/NHC Damage:  
>$72 Billion, #5.  
Track Accurate;  
Surge Under-predicted.

Rutgers University - Coastal Ocean Observation Lab

28 Years of Continuous Observatory Operations, Data Fusion & Training

Since October 29, 1992

Satellites

HF Radar

Glider Lab

Ocean & Atmospheric Forecasts
To characterize the Cold Pool, we need ocean observations that are “fit for purpose”
Over 2 million people ordered to “flee the storm’s path”.

President Obama: Shaping up to be a “historic hurricane” and urged residents to “be prepared for the worst”. “Don’t wait. Don’t delay.”

New Jersey Governor Christie: Ordered evacuation of 1 million people - “Get the hell off the beach”. “Do not waste any more time working on your tan”.

New York Mayor Blumberg: “Staying behind is dangerous, staying behind is foolish, and its against the law”. “The time to leave is right now”. The bridges, streets and subways were nearly empty ahead of a nearly unprecedented mass transit shutdown.
Essential Ocean Processes:
Ahead of eye center – Vertical Shear > Mixing > Cooling > Reduced Intensity > Reduced Surge
Hurricane Irene ROMS Ocean Forecast

Satellite AVHRR vs. ROMS Model

(After – Before) SST Difference
ROMS Model Results at Glider Location

Coastal Baroclinic Circulation Enhances Mixing & Cooling

A) Temperature °C
B) Cross-shelf Velocity cm s⁻¹
C) Eddy Viscosity log₁₀(m² s⁻¹)
D) Along-shelf Velocity m s⁻¹
E) log₁₀(Ri)
F) Vertical Diffusion (°C s⁻¹)

G) Cross-shelf Momentum Balance (m s⁻²)
H) Along-shelf Momentum Balance (m s⁻²)
ROMS Model Cross-shelf Section: SST cooling, downwelling bottom T

Seroka et al. in prep.

Seroka et al. 2017
JGR Oceans
WRF Atmospheric Forecast Sensitivity Study – >130 tests

WARM OCEAN
Boundary Condition

COLD OCEAN
Boundary Condition

IMPACT?
>10 knots reduction in peak wind speed

WRF Warm SST W Spd (kts)

WRF Cold SST W Spd (kts)

Cat 1 Hurricane

Tropical Storm

MARACOOS
Ocean Information for a Changing World

IOOS
Integrated Ocean Observing System
SST within 25 km of eye & impact on air-sea heat flux

(A) AVHRR Composite SST °C 8/26
(B) AVHRR Composite SST °C 8/31

Warm
Cold

Northern Buoy
Central Buoy

26C

44009 Heat Fluxes into Atm
44065 Heat Fluxes into Atm
WRF Heat Flux
Comparison to North American Regional Reanalysis

Wind

Latent heat flux

\[ \tau = - \rho C_D U^2 \]
\[ H = - (\rho c_p) C_H (\theta_{2m} - \theta_{sfc}) \]
\[ E = - (\rho L_v) C_Q (q_{2m} - q_{sfc}) \]

Sensible heat flux
WRF Model Sensitivity Study

- Over 130 model runs
- Paired to compare sensitivities
- Central pressure & max wind
- Sensitivity to SST greatest

Pressure Sensitivity Table: 8/28 00-13 UTC

<table>
<thead>
<tr>
<th>Group</th>
<th>Name</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Setup</td>
<td>Horizontal resolution 3km vs. 6km</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical resolution 51 vs. 35 levels</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Adaptive time step on vs. off</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B.C. (Frequency) 3 hrs vs. 6 hrs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Digital Filter Initialization (DFI) on vs. off</td>
<td></td>
</tr>
<tr>
<td>Atmospheric/Model Physics</td>
<td>Microphysics 8 vs. 16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PBL scheme 5 vs. 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cumulus parameterization 1 vs. 0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SST skin on vs. off</td>
<td></td>
</tr>
<tr>
<td>Longwave radiation physics</td>
<td>1 vs. 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 vs. 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>99 vs. 4</td>
<td></td>
</tr>
<tr>
<td>Shortwave radiation physics</td>
<td>1 vs. 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 vs. 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>99 vs. 4</td>
<td></td>
</tr>
<tr>
<td>Latent heat flux &lt;0 over water</td>
<td>on vs. off (warm SST)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>on vs. off (cold SST)</td>
<td></td>
</tr>
<tr>
<td>Land surface physics</td>
<td>1 vs. 2</td>
<td></td>
</tr>
<tr>
<td>Advanced Hurricane WRF</td>
<td>Air-sea flux parameterizations 1 vs. 0 (warm SST)</td>
<td></td>
</tr>
<tr>
<td>Sea Surface Temperature</td>
<td>SST Warm vs. Cold (isftclfix=2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Warm vs. Cold (isftclfix=1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Warm vs. Cold (isftclfix=0)</td>
<td></td>
</tr>
</tbody>
</table>

Seroka, Miles, Xu, Kohut, Schofield & Glenn, Hurricane Irene Sensitivity to Stratified Coastal Ocean Cooling, Monthly Weather Review, 2016
WRF Model Sensitivity Study

- Over 130 model runs
- Paired to compare sensitivities
- Central pressure & max wind
- Sensitivity to SST greatest

Using this as a benchmark for Coupled model development

WRF – ROMS in ESMF/NUOPC Framework

- Allow for coupled regional coupled modeling by NOAA NOS/EMC/Others
ADCIRC Storm Surge Model driven by RUWRF winds

- Barotropic 2D depth integrated version
- Cold start: no tidal forcing
- Waves included
  - SWAN+ADCIRC coupling
  - SWAN passes information to ADCIRC every 10 min
- Simulation length: 2 days
- Model time step = 1s
- Variable Coriolis
- Quadratic bottom friction parameterization

Courtesy of PhD candidate Alexandra Ramos Valle

In prep
ADCIRC Storm Surge Model driven by RUWRF winds

Maximum water level:
- Warm Run: 1.9 m
- Cold Run: 1.4 m

Water Level Difference (m)
- Warm - Cold

In prep

Courtesy of PhD candidate Alexandra Ramos Valle
Summer Tropical Cyclones Tracks over the Continental Shelf

Yellow Sea
26 Typhoons
since 1985

Mid Atlantic Bight
11 Hurricanes
since 1985
### Historical Hurricanes Crossing the MAB in Stratified Season

**Observed Ahead-of-Eye-Center Cooling**

<table>
<thead>
<tr>
<th>Storm Name</th>
<th>Buoy</th>
<th>Water Depth (m)</th>
<th>Ahead-of-Eye Cooling (°C)</th>
<th>Total Cooling (°C)</th>
<th>% Ahead-of-Eye</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arthur (2014)</td>
<td>44014</td>
<td>48</td>
<td>1.4</td>
<td>2.4</td>
<td>58%</td>
</tr>
<tr>
<td>Irene (2011)</td>
<td>44100</td>
<td>26</td>
<td>6.8</td>
<td>7.2</td>
<td>94%</td>
</tr>
<tr>
<td>Barry (2007)</td>
<td>ALSN6</td>
<td>29</td>
<td>5.1</td>
<td>5.1</td>
<td>100%</td>
</tr>
<tr>
<td>Hermine (2004)</td>
<td>44009</td>
<td>31</td>
<td>0.9</td>
<td>1.1</td>
<td>82%</td>
</tr>
<tr>
<td>Allison (2001)</td>
<td>CHLV2</td>
<td>14</td>
<td>2.3</td>
<td>2.6</td>
<td>88%</td>
</tr>
<tr>
<td>Bonnie (1998)</td>
<td>CHLV2</td>
<td>14</td>
<td>4.2</td>
<td>4.2</td>
<td>100%</td>
</tr>
<tr>
<td>Danny (1997)</td>
<td>44009</td>
<td>31</td>
<td>2.1</td>
<td>3.6</td>
<td>58%</td>
</tr>
<tr>
<td>Arthur (1996)</td>
<td>44009</td>
<td>31</td>
<td>2.3</td>
<td>3.5</td>
<td>66%</td>
</tr>
<tr>
<td>Emily (1993)</td>
<td>44014</td>
<td>48</td>
<td>2.3</td>
<td>2.8</td>
<td>82%</td>
</tr>
<tr>
<td>Bob (1991)</td>
<td>44025</td>
<td>41</td>
<td>2.1</td>
<td>4.6</td>
<td>46%</td>
</tr>
<tr>
<td>Charley (1986)</td>
<td>44009</td>
<td>31</td>
<td>2.7</td>
<td>5.4</td>
<td>50%</td>
</tr>
</tbody>
</table>

**Average**

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>31</td>
<td>2.9</td>
<td>3.9</td>
<td></td>
<td>75%</td>
</tr>
<tr>
<td>STD</td>
<td>11</td>
<td>1.7</td>
<td>1.7</td>
<td></td>
<td>20%</td>
</tr>
</tbody>
</table>

Buoy data from the 30-year NOAA NDBC Archive
Typhoon Muifa: Ahead-of-Eye-Center Cooling observed by Coastal Buoy

From: Fei Yu, Institute of Oceanology, Chinese Academy of Sciences
Yi Xu, State Key Laboratory of Estuarine & Coastal Research, East China Normal University

Nature Communications, 2016

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<th>Total Cooling (°C)</th>
<th>% Ahead-of-Eye</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muifa (2011)</td>
<td>37.0445N 122.6558E</td>
<td>31</td>
<td>4.1</td>
<td>4.8</td>
<td>85%</td>
</tr>
</tbody>
</table>
Forecast Models Lack an Essential Ocean Feature - Cold Pool
Glider data rejected for assimilation – too far from the model “truth”
Essential Ocean Features in new Navy GOFS 3.1

Glider RU33

Navy Model GOFS 3.1

Navy Glider Deployments

Navy Glider 619

Navy Model GOFS 3.1
Slab Lagged Inertial Model (SLIM) Formulation

Governing Equations – Wind Forced \textbf{Slab}

\[ \frac{\partial u}{\partial t} - fu = F_{\text{wind}}^x - cu \]

\[ \frac{\partial v}{\partial t} + fu = F_{\text{wind}}^y - cv, \]

\textbf{Inertial} Response = Forcing - Friction

Pollard & Millard, 1970:
- Given a wind time series and a slab mixed layer depth, estimate the velocity of the inertial oscillations.

Cliff Watkins et al., 2020:
- Given a wind time series and an inertial wave velocity time series from HF Radar, estimate the depth of the mixed layer.

Forcing: Winds from North American Rapid Refresh

Friction: 2-5 days typical

\[ F_{\text{wind}}^{x,y}(t) = \frac{\rho_a C_D U(t)^2}{\rho_w Z_o} (\cos \theta(t), \sin \theta(t)), \]

\[ c^{-1} \text{ as the e-folding decay time,} \]

Start with a typical mixed layer depth (Zo=10m), calculate predicted inertial signal \textbf{Uo}

Cost function – \textbf{Uo} scaled (Zo/Z) & time \textbf{lagged} (\phi) fit to HF Radar observed inertial currents

\[ J(Z, \phi) = \sum w \left( U_{\text{radar}}(t) - U_o(t - \phi) \frac{Z_o}{Z} \right), \]

\[ Z \text{ is best fit thermocline depth} \]

\[ w \text{ is a gaussian in time weighting function centered on a 2-day sliding window} \]
Hurricane Irene –
Comparison of SLIM predicted and Glider observed Mixed Layer Depth

Mid-Atlantic HF Radar network + Windfields + SLIM provide the means to map MLD co-evolution in hurricanes
But what mixing processes are causing the MLD deepening?
Large Eddy Simulation of ocean mixing in Hurricane Irene

LES Model Set Up

LES Ekman Rolls:
Vertical Velocity Anomaly

5m Depth Map view

Vertical Section View
Large Eddy Simulations (LES) of vertical mixing in Irene

Mixed-mode Instabilities – combination of:
1. Wind-induced Ekman rolls in surface layer plus
2. Shear induced Kelvin-Helmholtz rolls in pycnocline

Cliff Watkins
Thesis Chapter 2
Hurricane Irene Observations –
Change in Wind Direction compared to Thermocline Width

Essential Ocean Processes –
1) Rapid wind direction change shuts down the Ekman Rolls in surface layer
2) Vertical shear driven Kelvin Helmholtz rolls persist -
Typhoon Soulil
2018

Jeju Is. Pre-deployment & Recovery
Rapid Coevolution of Typhoon Soulik & Stratified Yellow Sea

Glider RU22
25.8 km
H2
23 Aug 2018
TS
H1
Glider RU22
21 Aug 2018
H3
Pre-storm initial temperatures

First NCODA Data Assimilation Window

Typhoon Soulik – Glider Comparisons with Global Model
Typhoon Soulik – Glider Comparisons with Global Model

RU22

Pre-storm initial salinity

GOFS 3.1

Pre-storm initial salinity

First NCODA Data Assimilation Window
Conclusions

• Glider Picket Line ConOps enable community participation in the acquisition of unique profile data for hurricane forecasting & research.
• Scientists are identifying *Essential Ocean Features* and *Essential Ocean Processes* impacting hurricane intensity that are regionally dependent.
• Rapid Co-evolution documented in MAB & Yellow Sea.
• RTOFS DA & beyond will benefit from regional science experience.
• EPIC could enable greater oceanographic participation in R2O.