Ocean Gliders in Tropical Cyclone Forecasting

EGO/UG2

21 May 2019

A growing list of collaborators…

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Leveraging Global Tropical Cyclone Expertise

National Centers for Environmental Information
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

U.S. Billion-Dollar Weather and Climate Disasters (2018)

https://www.ncdc.noaa.gov/billions/

Billion-dollar events to affect the U.S. from 1980 to 2018* (CPI-Adjusted)

DISASTER TYPE	NUMBER OF EVENTS	PERCENT FREQUENCY	CPI-ADJUSTED LOSSES *(BILLIONS OF DOLLARS)*	PERCENT OF TOTAL LOSSES	AVERAGE EVENT COST *(BILLIONS OF DOLLARS)*	DEATHS
Drought	26	10.9%	$241.3‡ CI	15.2%‡	$9.7‡	2,993†
Flooding	29	12.2%	$123.5§ CI	7.8%§	$4.3§	543
Freeze	9	3.8%	$30.0 CI	1.9%	$3.3	162
Severe Storm	101	42.4%	$223.4 CI	14.0%	$2.2	1,615
Tropical Cyclone	41	17.2%	$870.7‡ CI	54.7%‡	$21.8‡	6,436
Wildfire	16	6.7%	$54.8‡ CI	3.4%‡	$3.7‡	253
Winter Storm	16	6.7%	$47.3 CI	3.0%	$3.0	1,044
All Disasters	**238**	**100.0%**	**$1,591.0‡** CI	**100.0%**	**$6.8‡**	**13,046**

Hurricanes have caused $870.7 B in damages since 1980, more than all other natural disasters combined ($720.3 B)

National Centers for Environmental Information
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

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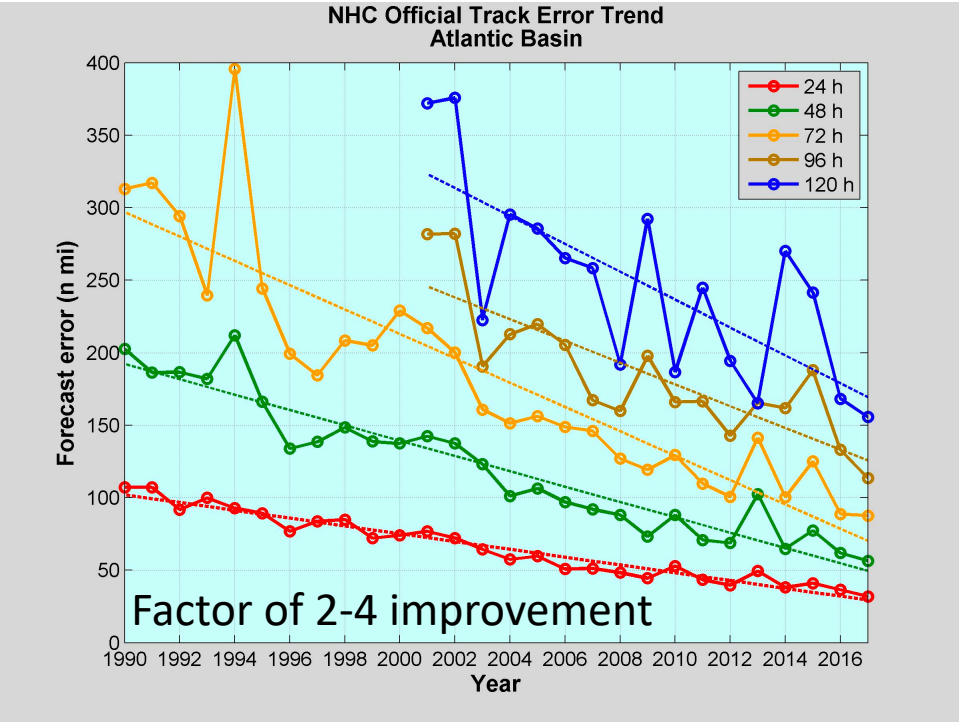
All Disasters	**238**	**100.0%**	**$1,591.0‡ CI**	**100.0%**	**$6.8‡**	**13,046**

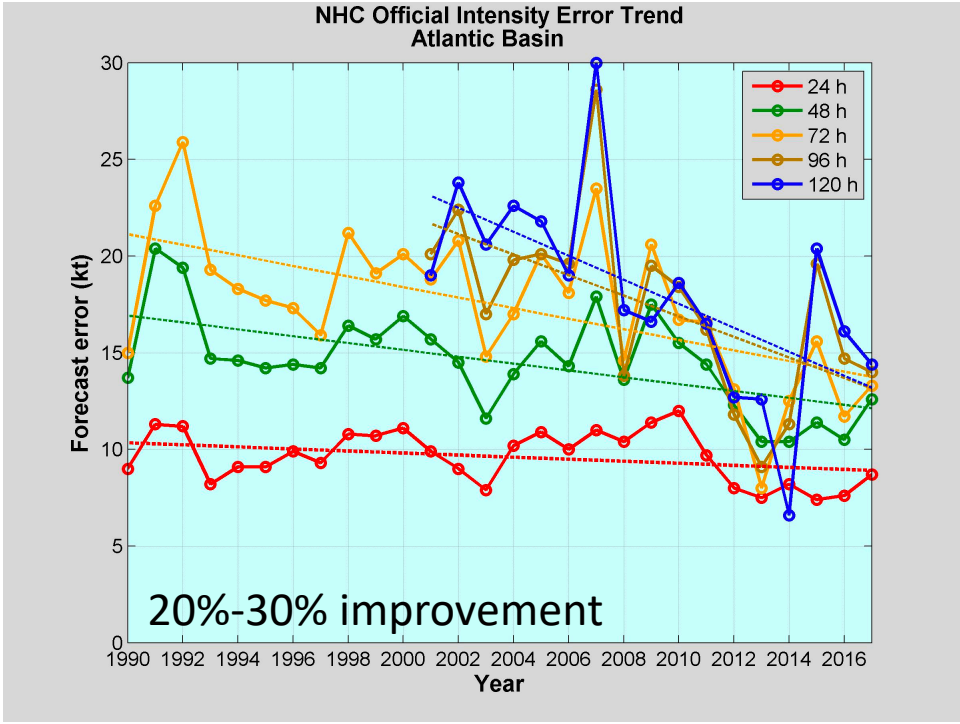
Hurricanes have caused 6,436 deaths since 1980, similar to all other natural disasters combined (6,610)

NOAA Annual Operational Suite Review

Average Track Errors: Atlantic Basin



Average Intensity Errors: Atlantic Basin



Evacuate vs **Shelter-In-Place** decisions are often made 3-5 days ahead based on the forecast intensity at landfall

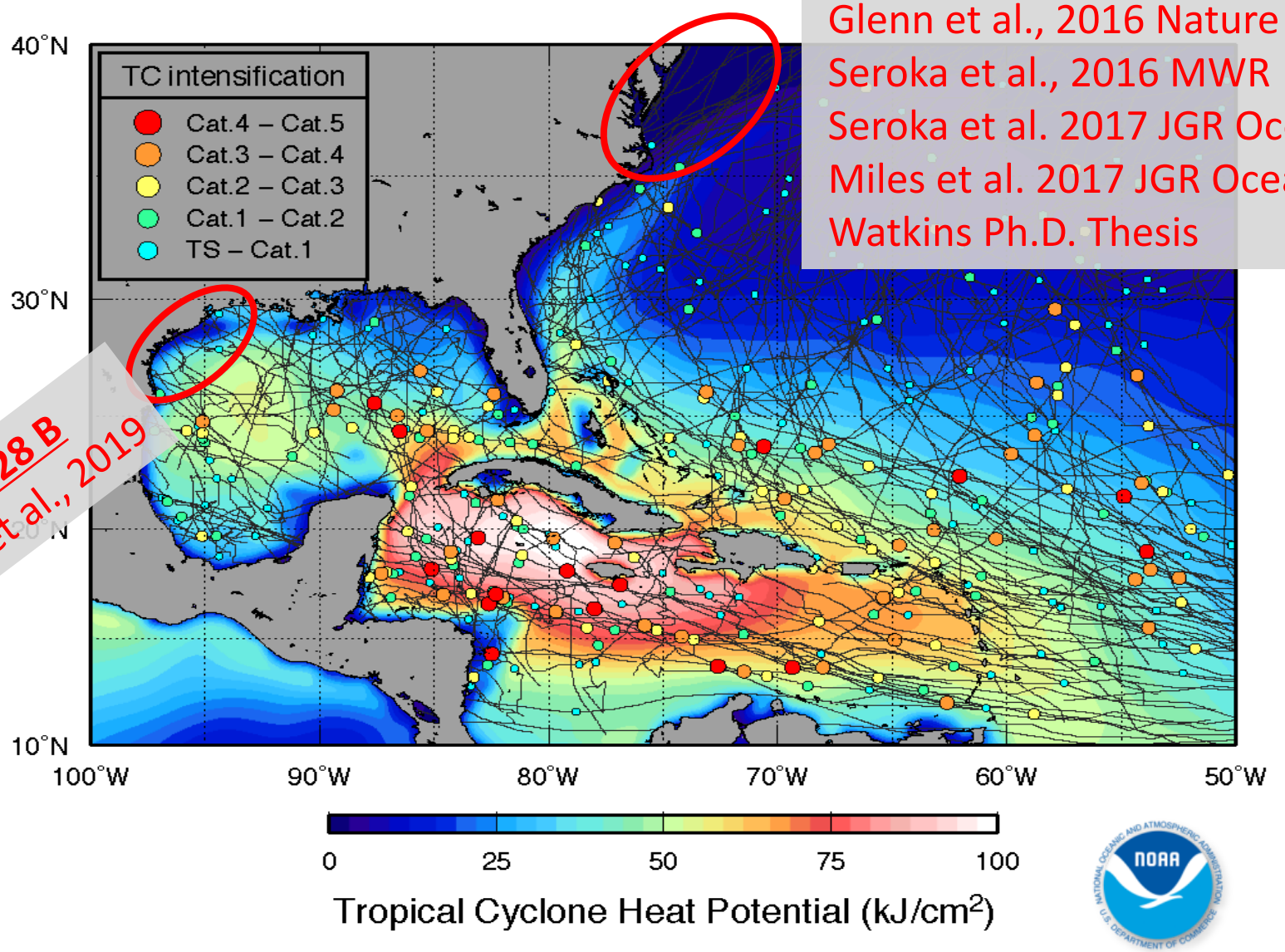
Close the gap from both sides: forecasting and response

Tropical Cyclone Heat Potential - Rapid Intensification Proxy

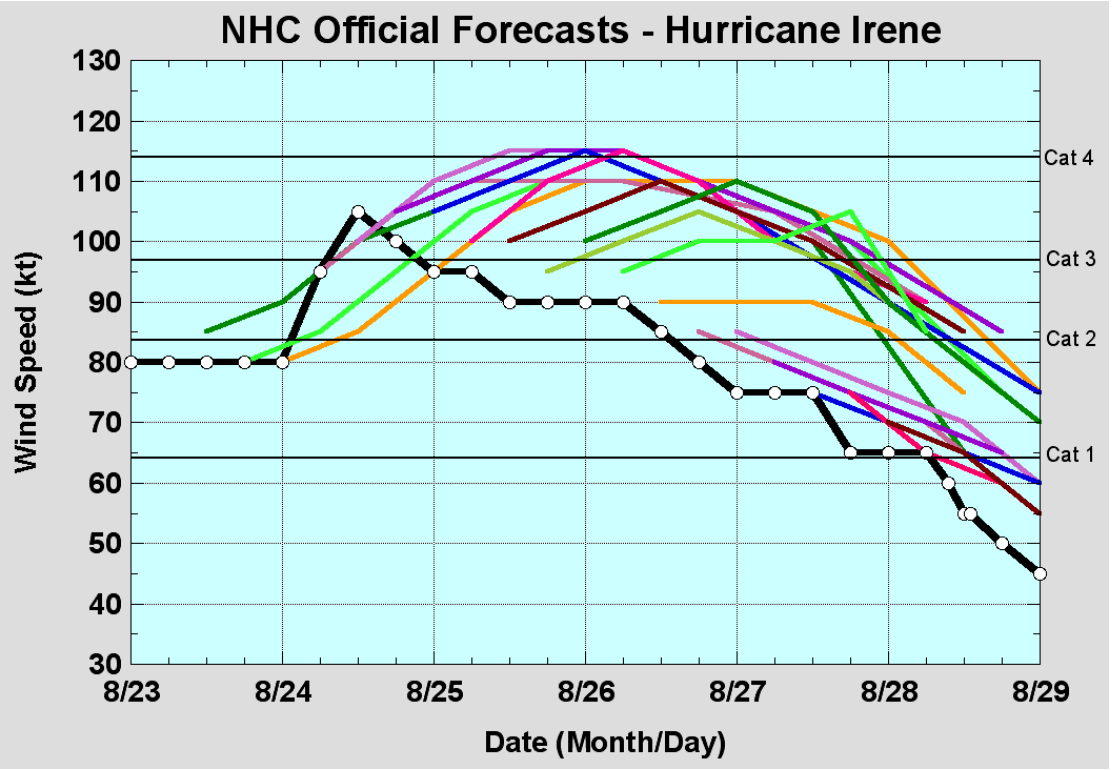
But published research shows …

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

Harvey $128 B
Potter et al., 2019



August of 2011 - Pre-Irene Forecasts and Evacuations



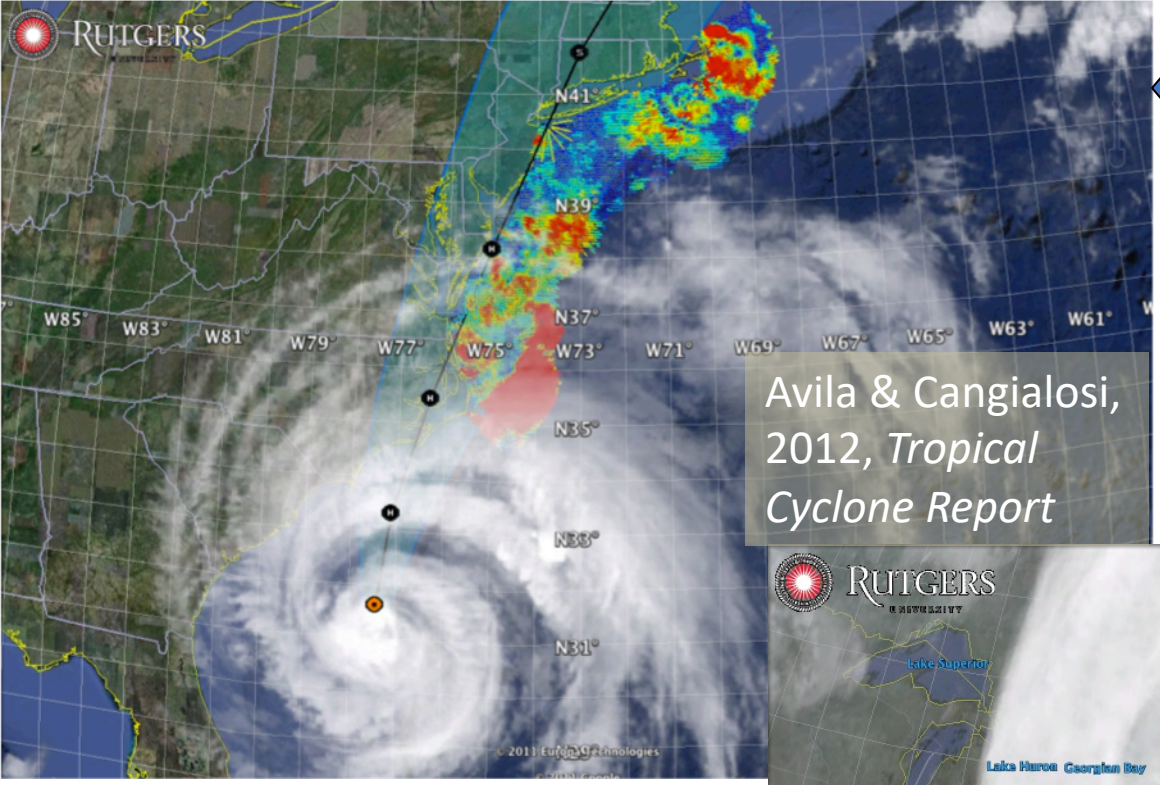
Official NHC intensity forecasts for Irene every 6 h from 1200 UTC 23 August to 0600 UTC 28 August.

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 - “This is going to be an enormous storm, and for New Jersey, something we haven’t seen in over 60 years”. “Get the hell off the beach”.

New York Mayor Bloomberg: “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.



Avila & Cangialosi, 2012, *Tropical Cyclone Report*

Hurricane Irene
August 28, 2011

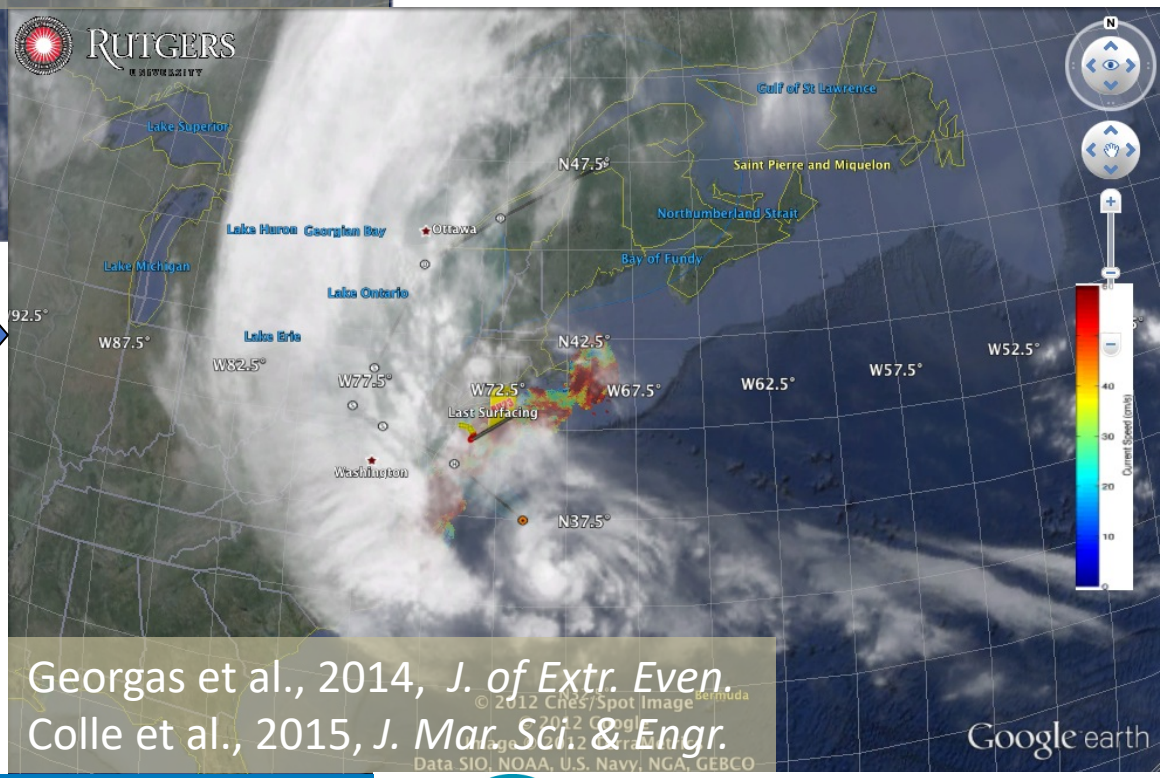
NOAA/NHC Damage:
>$15 Billion, #15.

Track Accurate;
Intensity Over-predicted.

Hurricane Sandy
October 29, 2012

NOAA/NHC Damage:
>$72 Billion, #4.

Track Accurate;
Impacts Under-predicted.



Georgas et al., 2014, *J. of Extr. Even.*
Colle et al., 2015, *J. Mar. Sci. & Engr.*

MARACOOS
Ocean Information for a Changing World

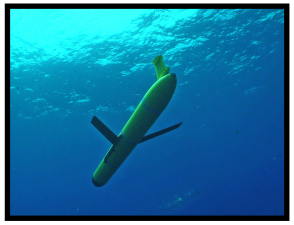
CERTIFIED

IOOS
Integrated Ocean Observing System

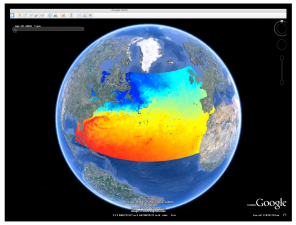
MARACOOS - Operations Center
Rutgers University - Center for Ocean Observing Leadership

L-Band & X-Band Satellite Receivers

46 Site CODAR Network



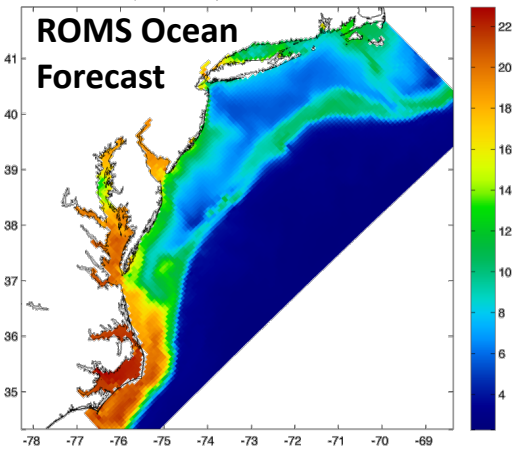
>479 Glider Deployments

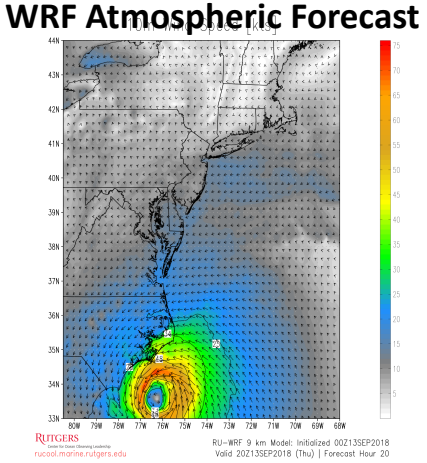


Ocean & Atmos. Forecasts

REGIONAL INFORMATION COORDINATION ENTITY
CERTIFIED
2016

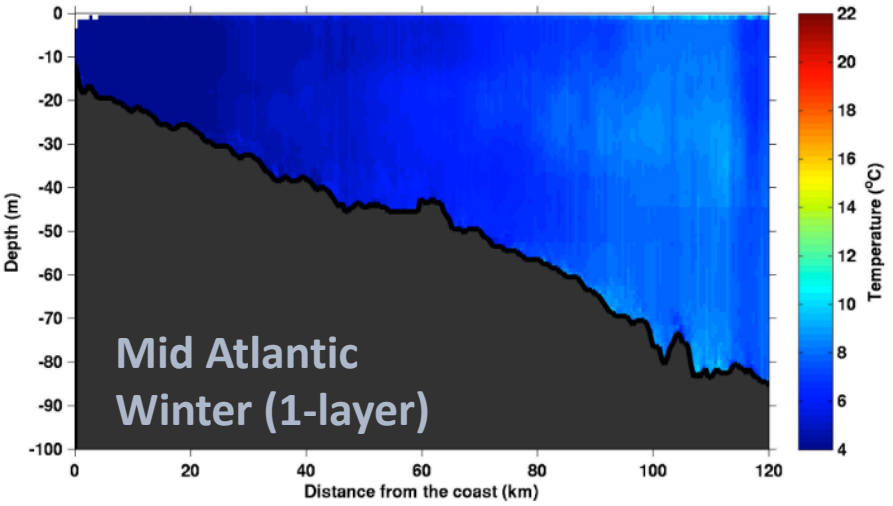
MARACOOS is an IOOS Certified RICE

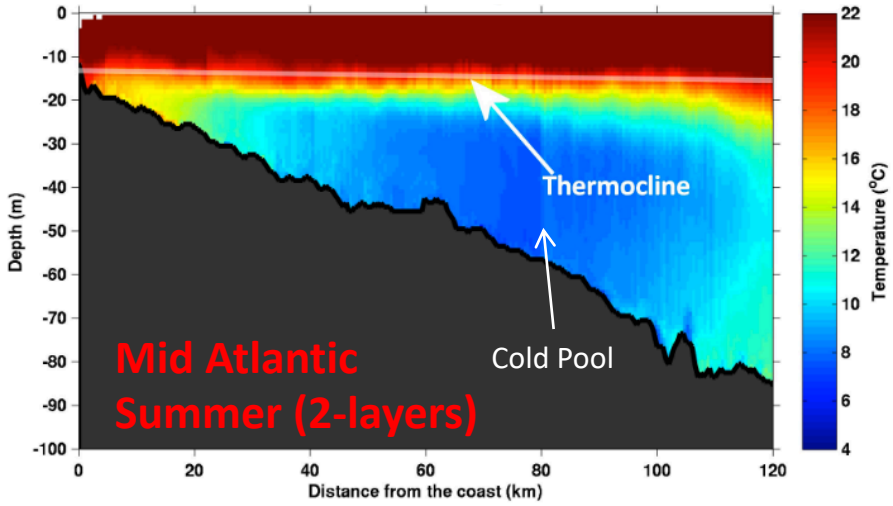




Essential Ocean Feature - Mid-Atlantic's Cold Pool

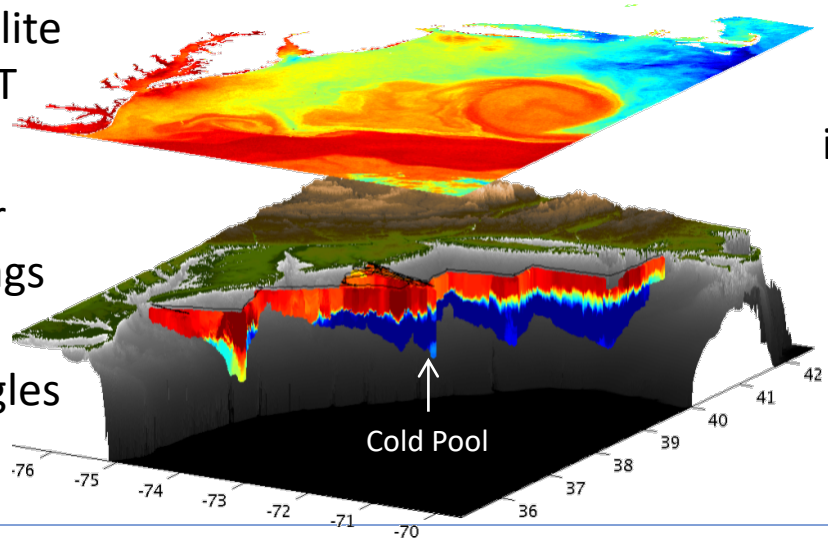
A continental shelf-wide cold bottom layer beneath a warm summer surface layer





Satellite SST

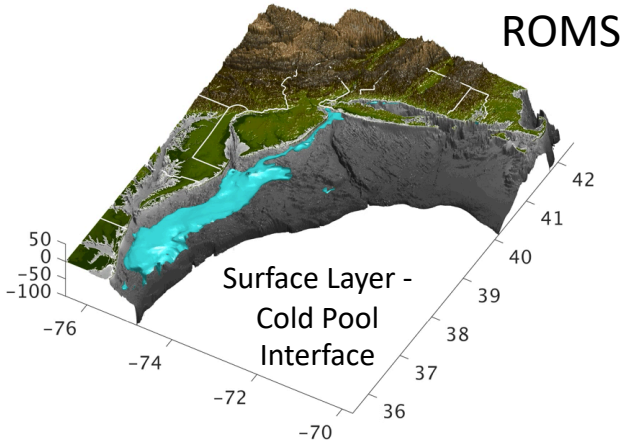
Glider Zig-Zags or Triangles



Assimilated into Regional Ocean Models

12° C on May 15, 2017

ROMS



The Cold Pool is not monitored from space – we use Gliders, HF Radar, and Models

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IOOS
Integrated Ocean Observing System

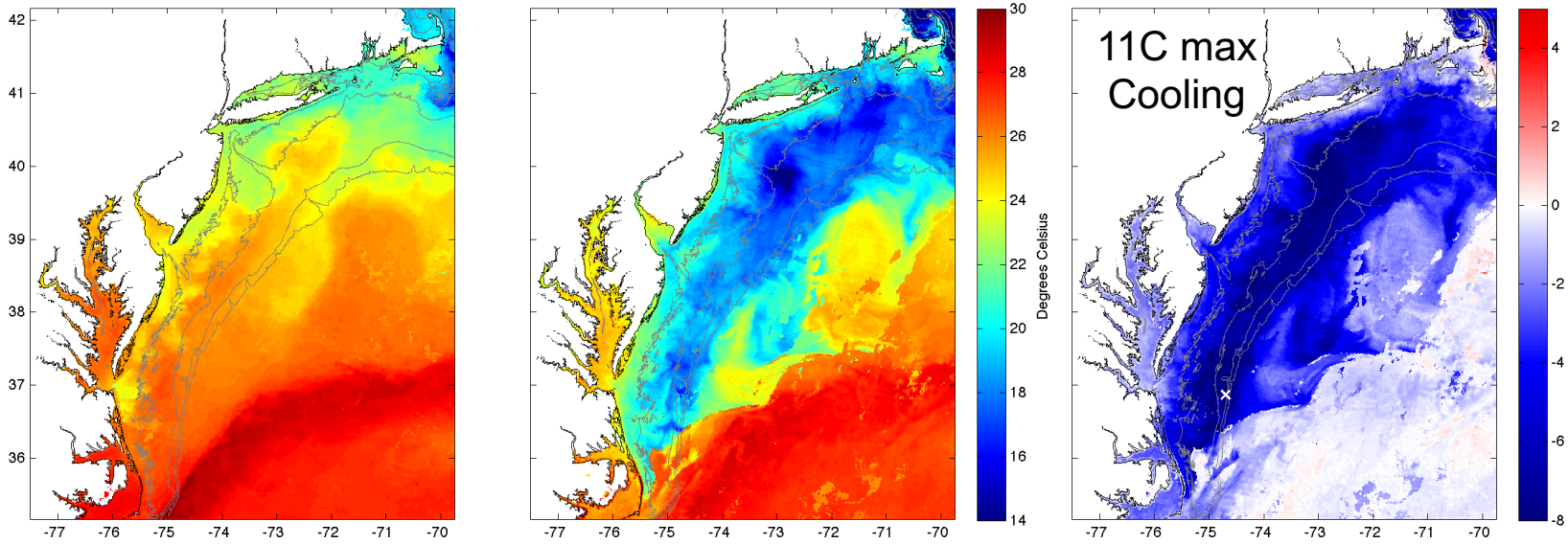
Pre-Irene

Post-Irene

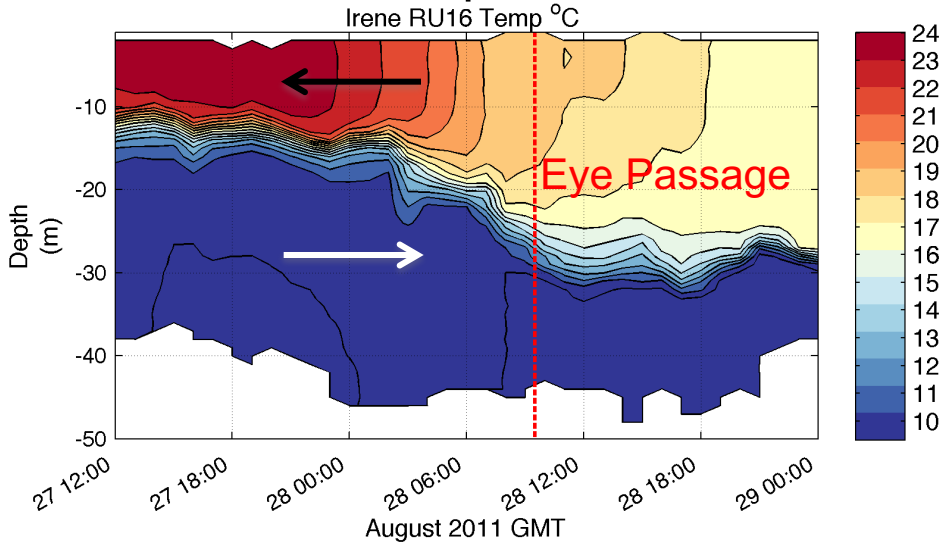
Difference

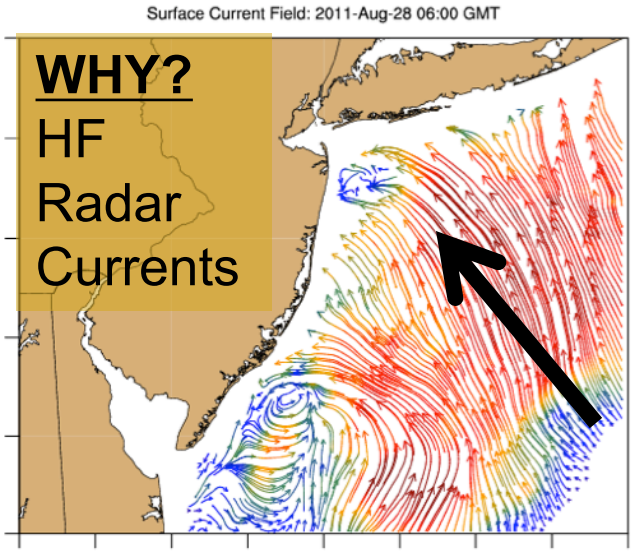
WHAT?

Satellite SST



WHEN? Glider Temperature





Glenn et al., Nat Comms, 2016

Essential Ocean Processes in Hurricane Irene:

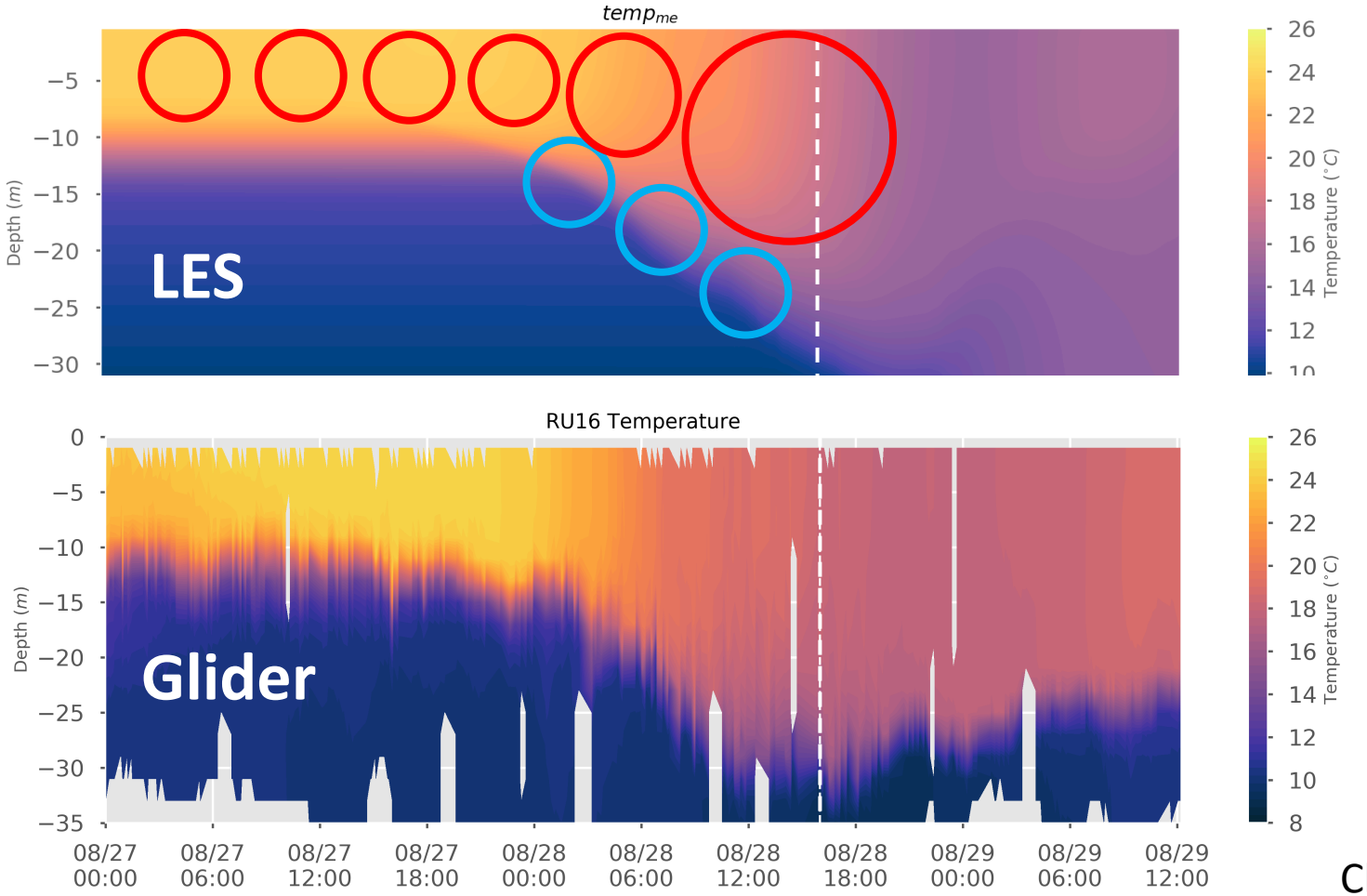
Ahead of eye center – Vertical Shear > Mixing > Cooling > Weakening

Large Eddy Simulations (LES) of vertical mixing in Irene

Mixed-mode Instabilities – combination of:

1. Wind-induced surface instabilities plus

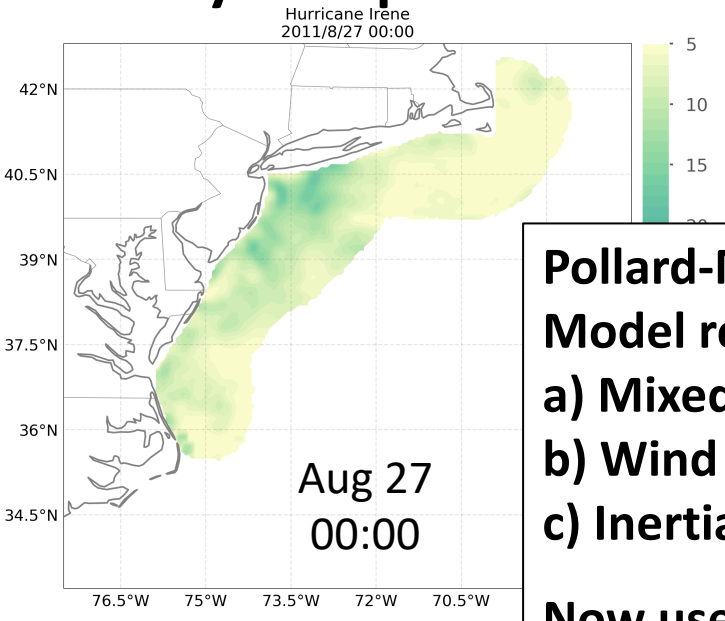
2. Shear induced pycnocline instabilities



LES versus RU-16 Temperature profiles

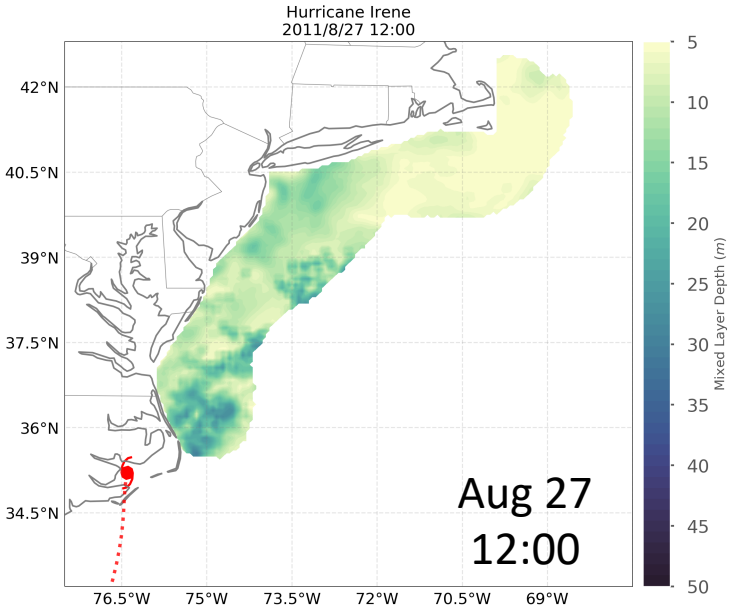
Cliff Watkins
Thesis Chapter 2

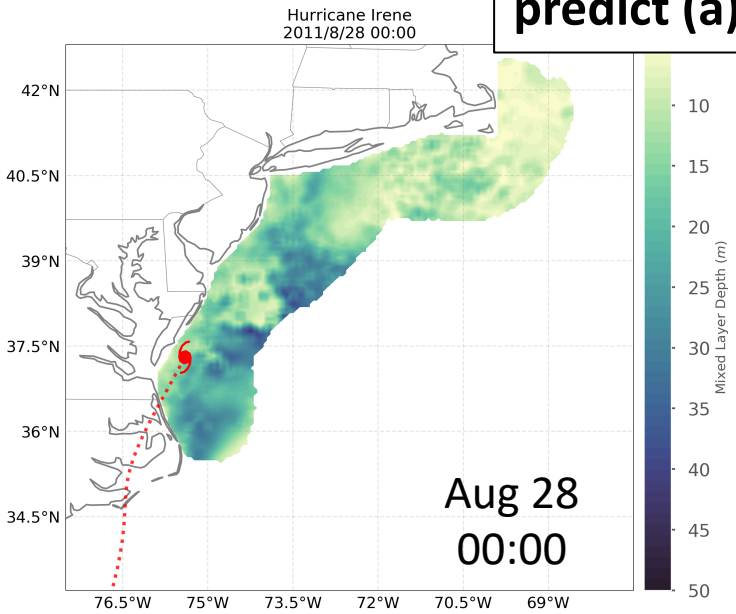
Mixed Layer Depth from HF Radar Inertial Response & Wind Forecast

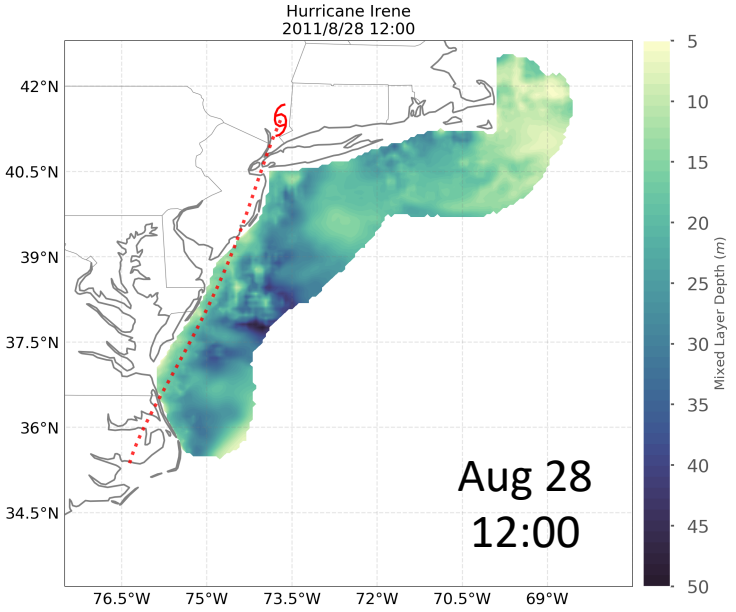


Pollard-Millard (1970)
Model relates:
a) Mixed layer depth
b) Wind forcing
c) Inertial response

Now use (b) & (c) to predict (a)



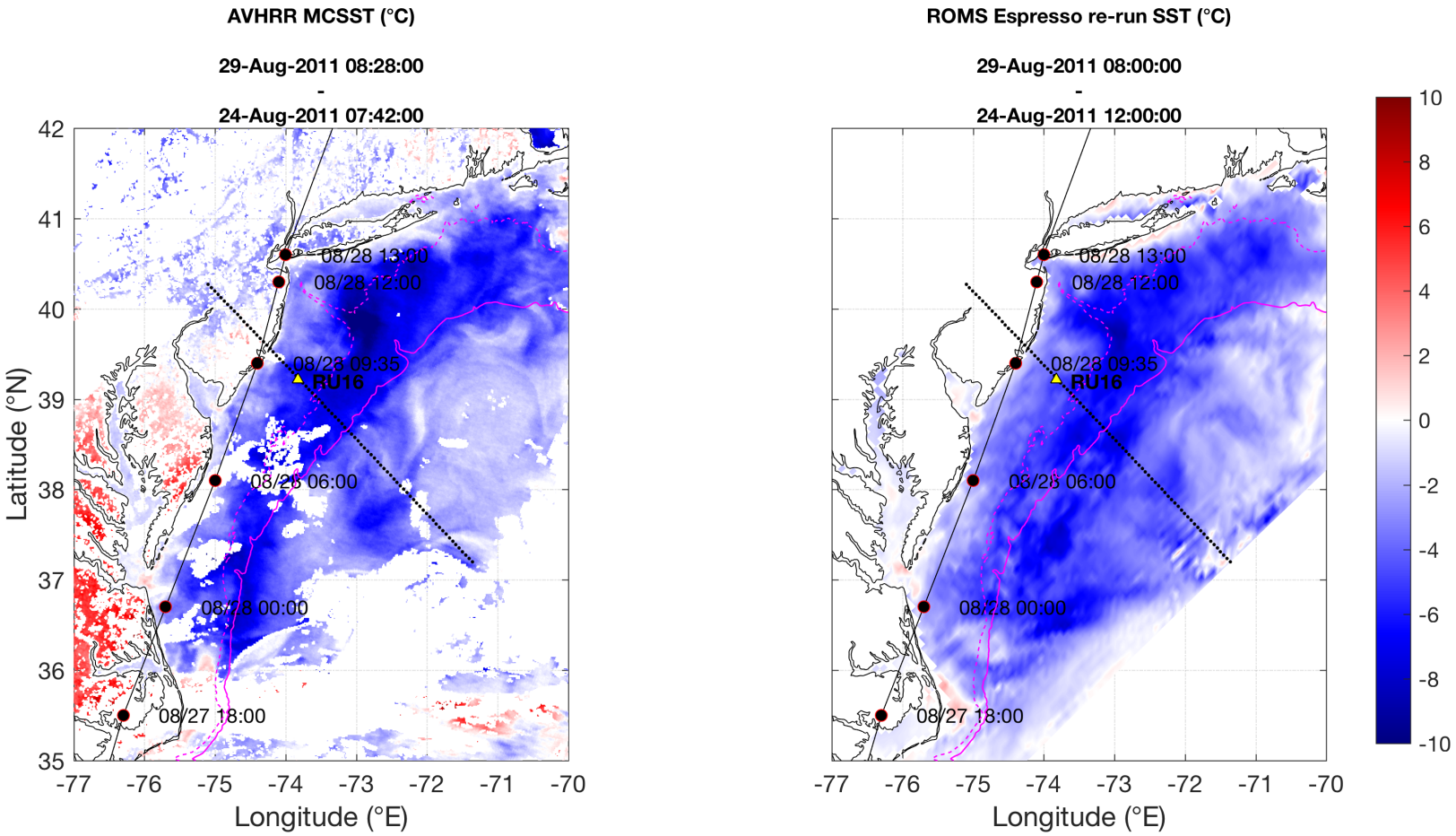




Cliff Watkins, Thesis Chapter 1

Hurricane Irene SST Difference (Before-After)

Satellite AVHRR vs. ROMS Model

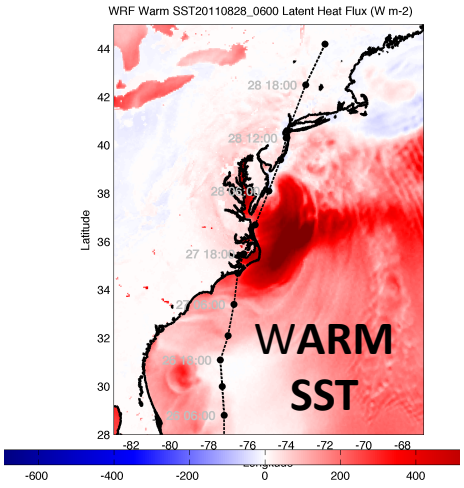


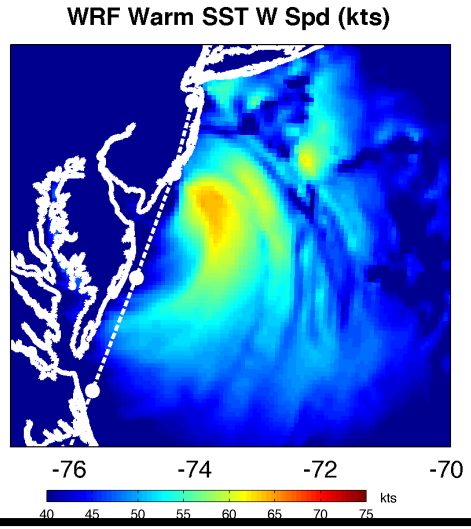
Difference

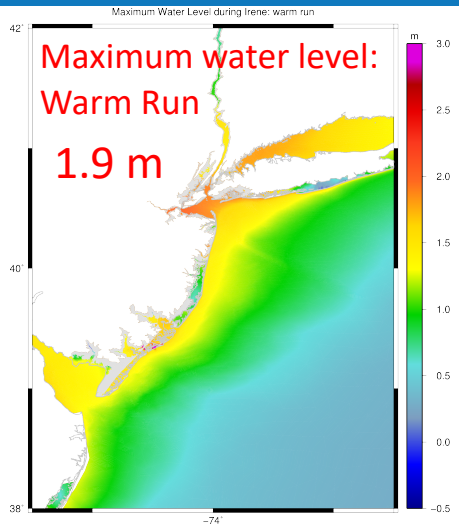
Significant shelf-wide cooling ahead-of-eye-center observed & forecast

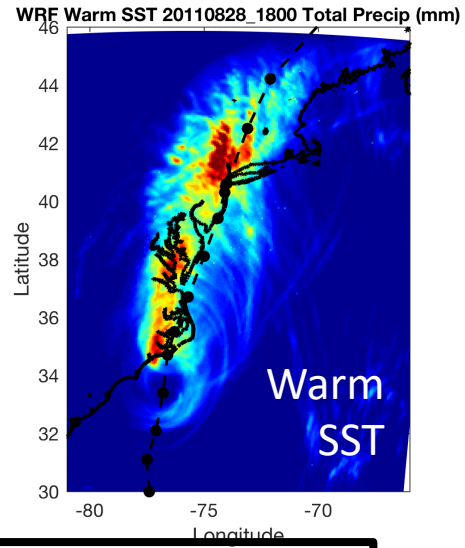
Seroka et al., JGR, *2017*

Irene - Impacts of Warm (top row) vs Cold (bottom row) SST

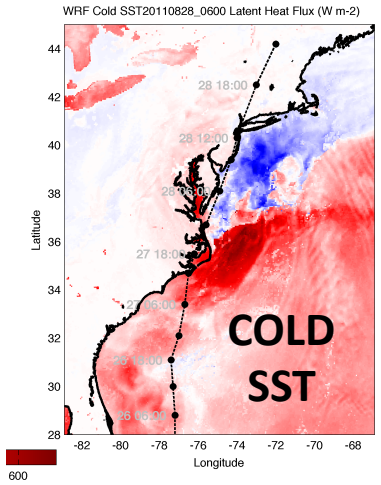


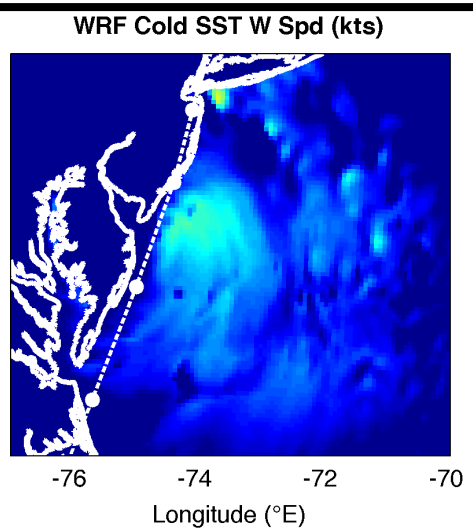


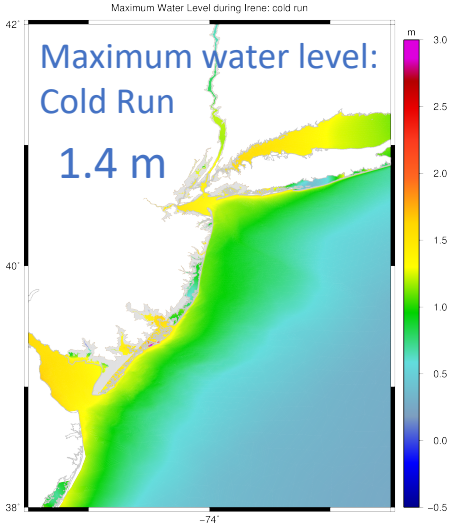


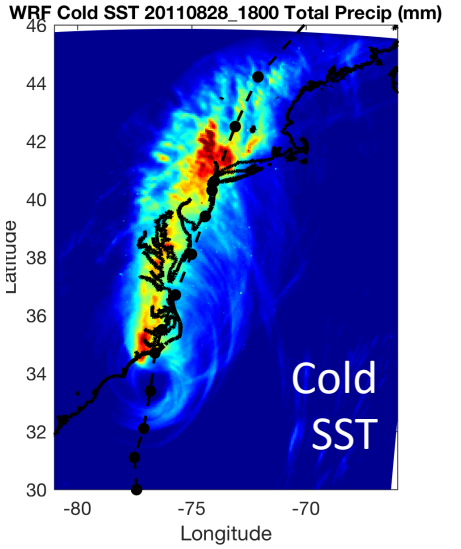


Surface Heat Flux **Wind Speed** **Storm Surge** **Total Rainfall**









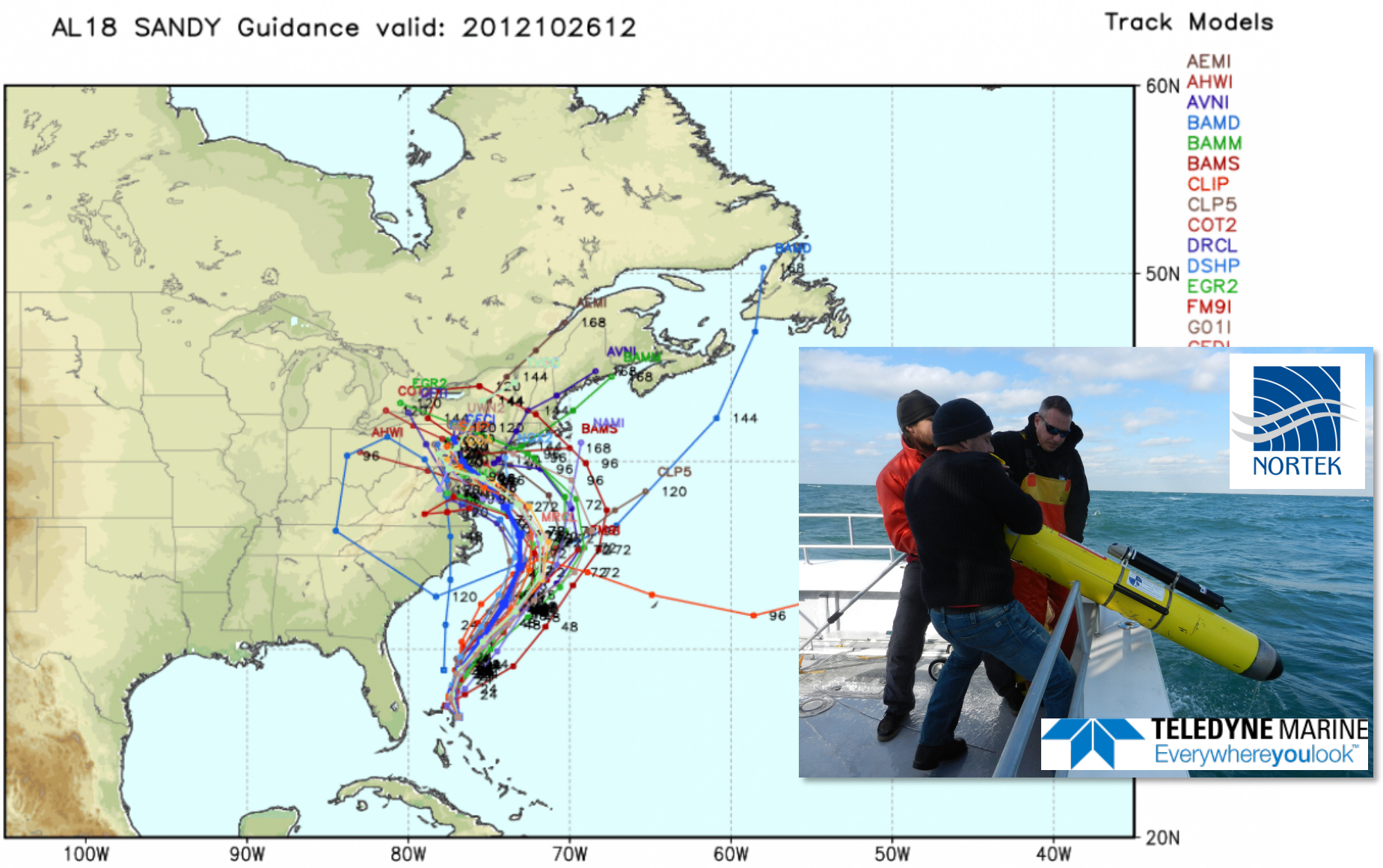
Sign Change as observed

10 knot reduction to observed

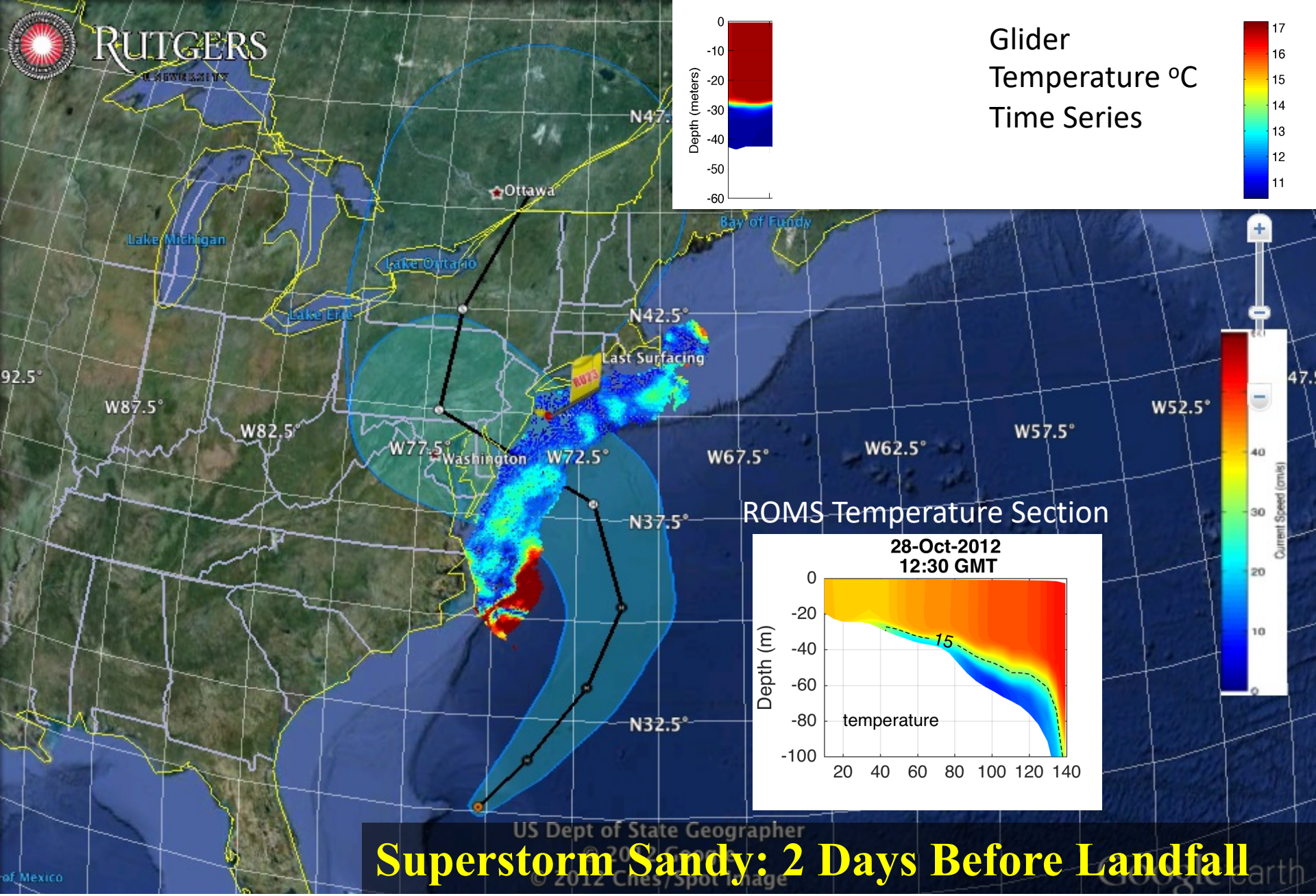
0.5 m reduction to observed

35 mm reduction to observed

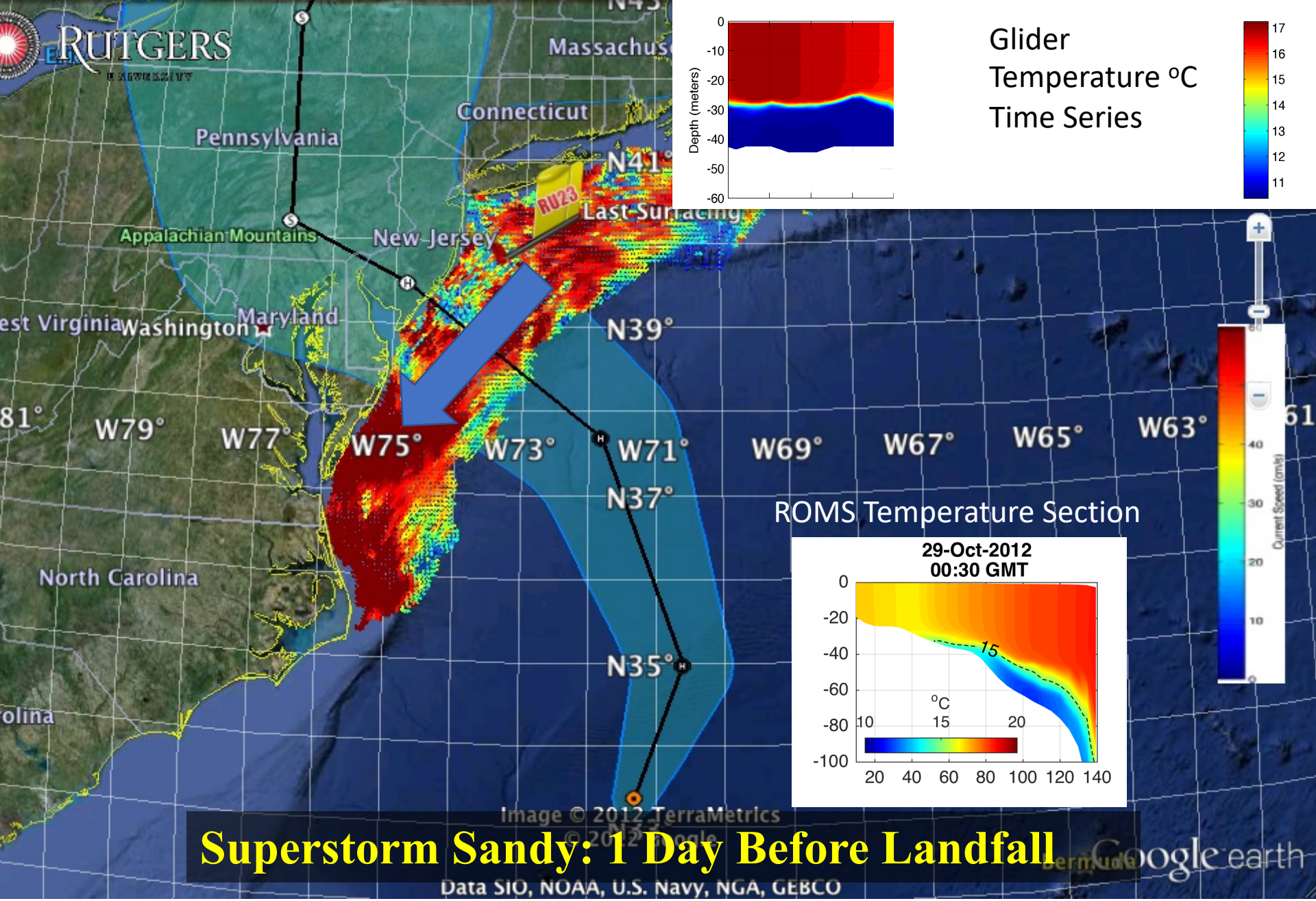
Hurricane Sandy – 1 year later



Miles et al., J. of Geophys. Res. Oceans (2015) *and* (2017)

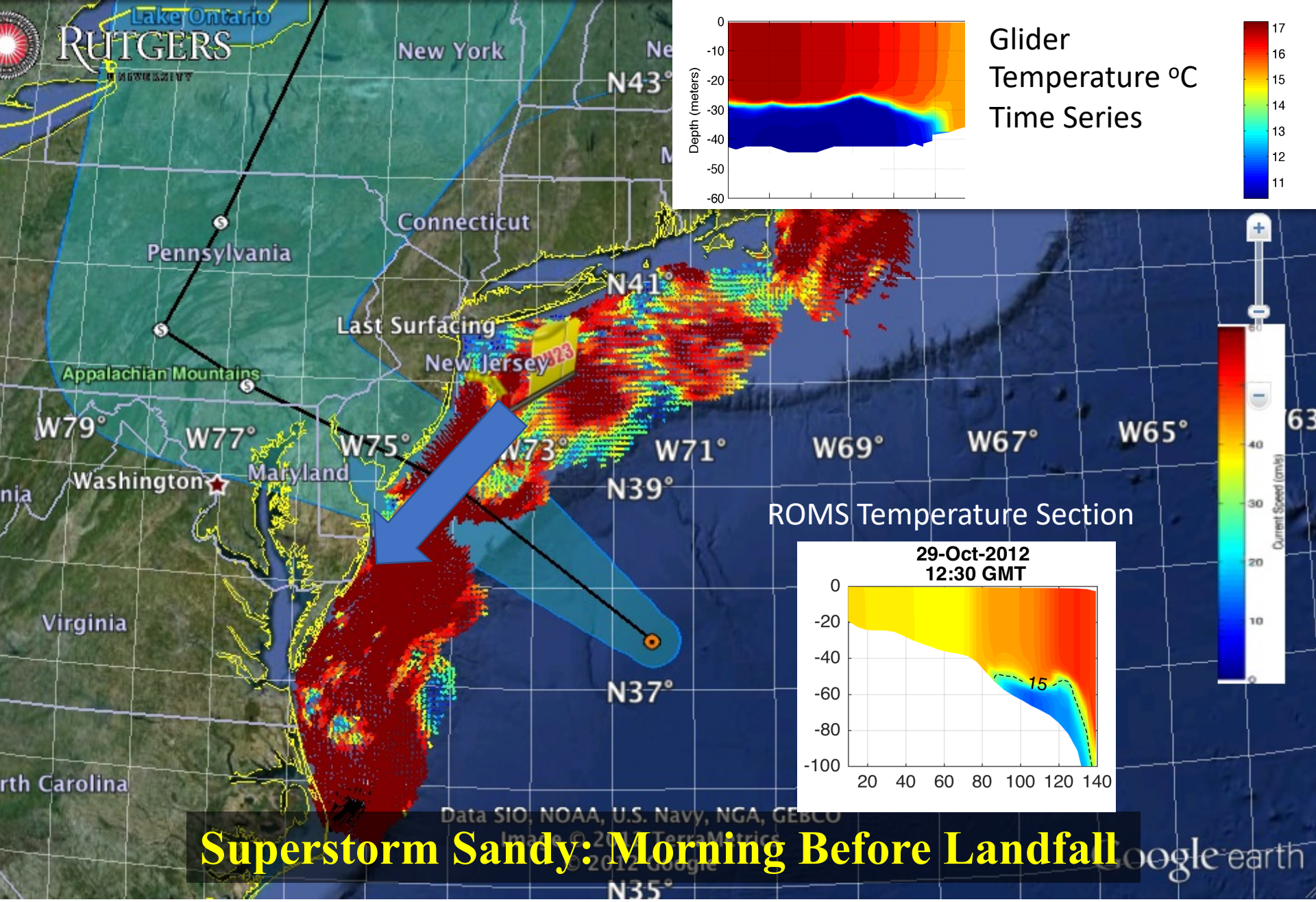


Miles et al., J. of Geophys. Res. Oceans (2015) *and* (2017)



Superstorm Sandy: 1 Day Before Landfall

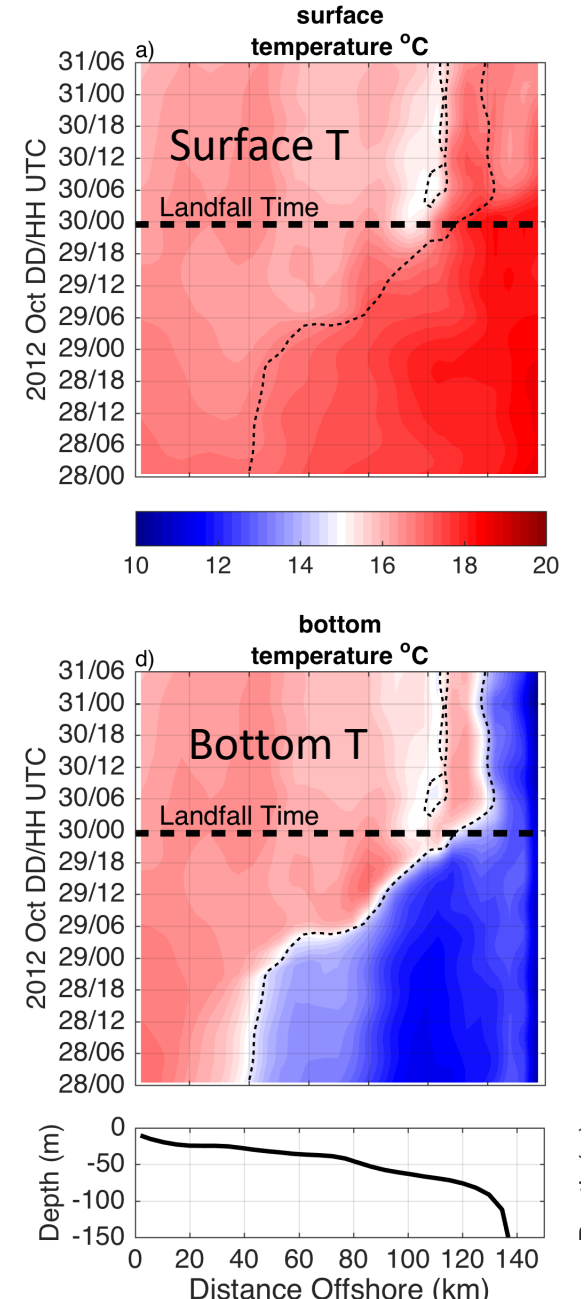
Miles et al., J. of Geophys. Res. Oceans (2015) *and* (2017)



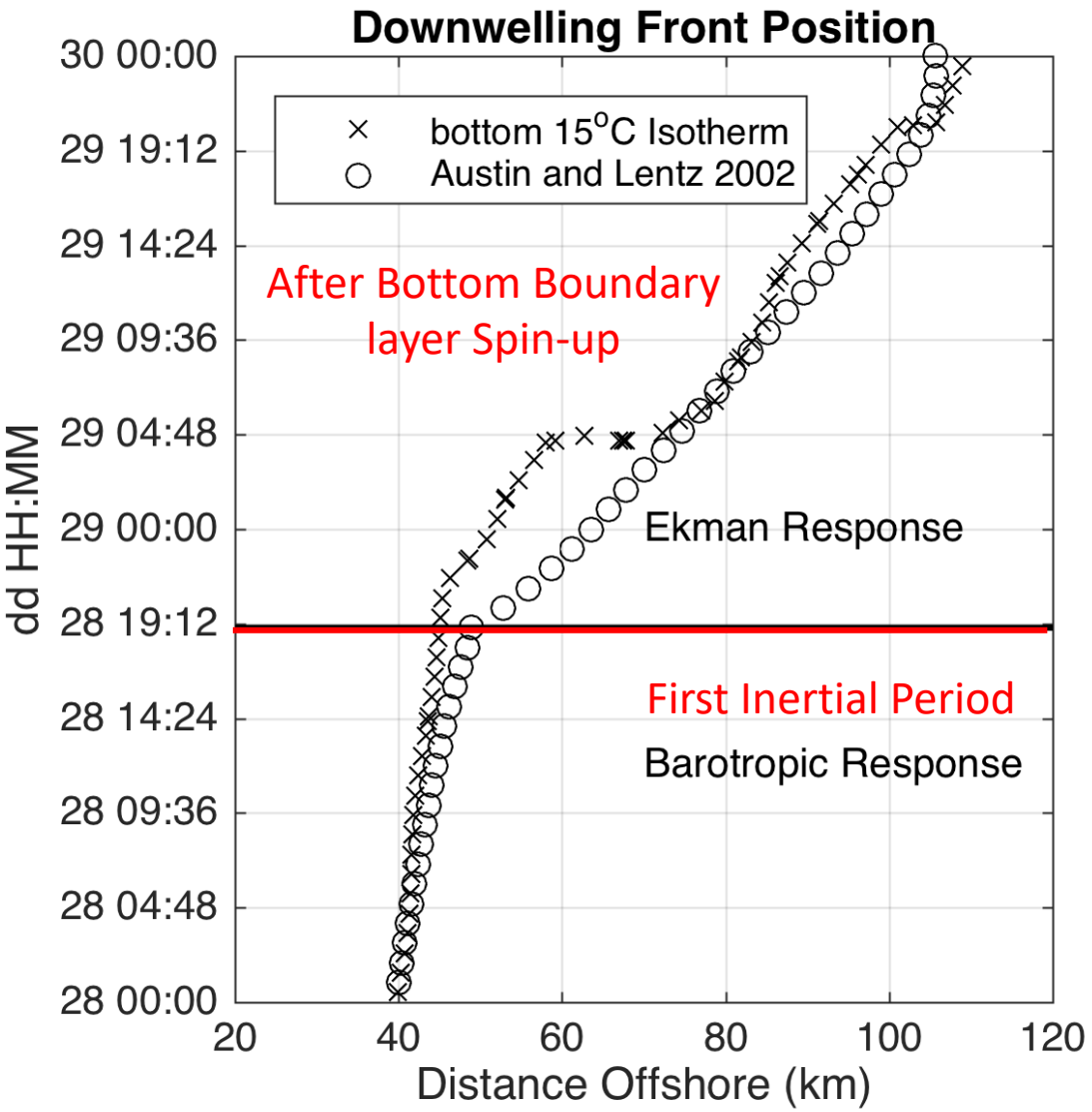
Superstorm Sandy: Morning Before Landfall

Miles et al., J. of Geophys. Res. Oceans (2015) *and* (2017)

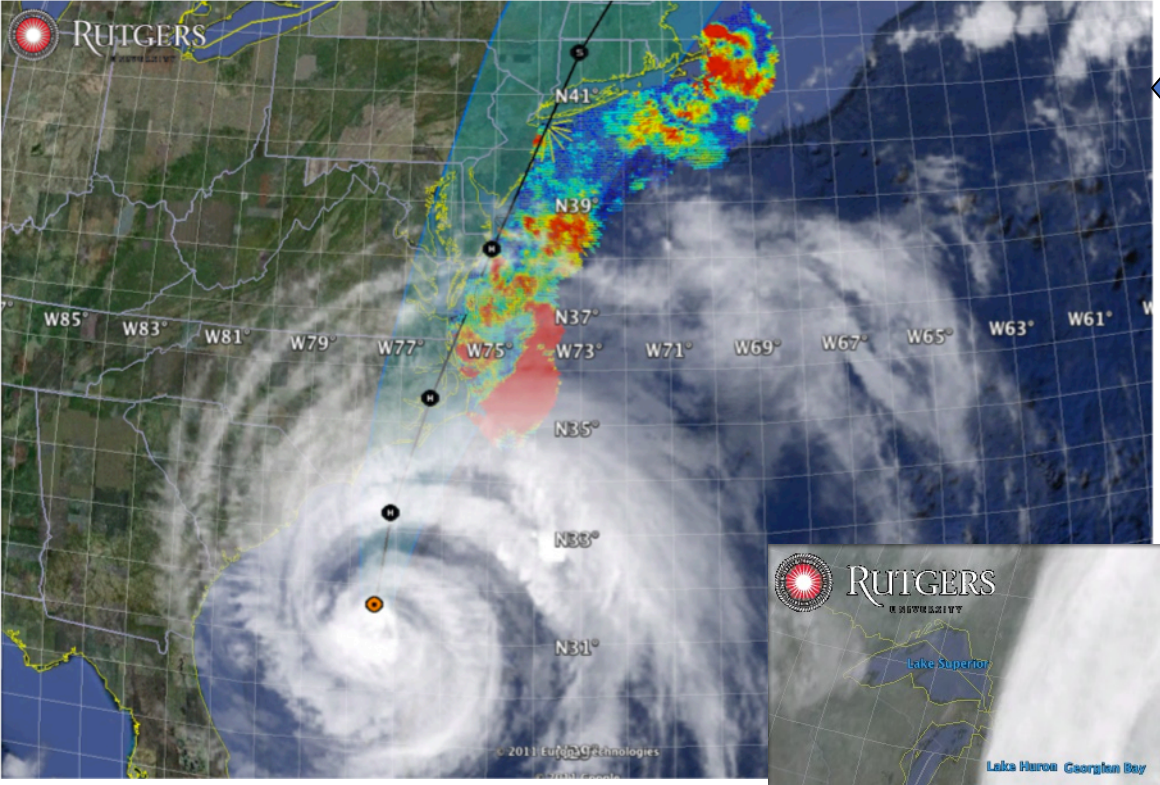
Hurricane Sandy Hovmoller Diagrams Surface and Bottom Temperature



time



Miles et al., J. of Geophys. Res. Oceans (2017)



Irene-Class Essential Ocean Processes

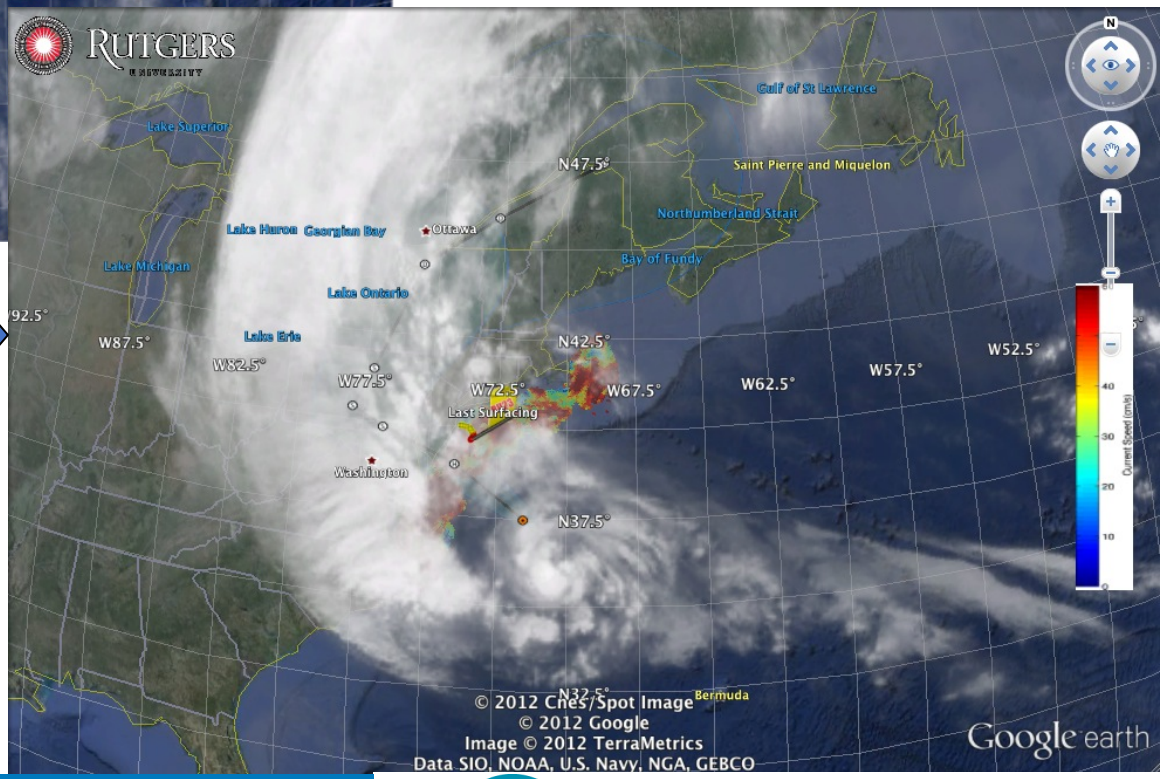
Ahead-of-eye mixing/cooling also observed in:

- 10 MAB Hurricanes
- 2 Yellow Sea Typhoons

Sandy-Class Essential Ocean Processes

Ahead-of-eye downwelling also observed in:

- Hurricane Jose in 2017



New Scientific Understanding:

- Two types of coastal ocean response to Mid Atlantic hurricanes discovered

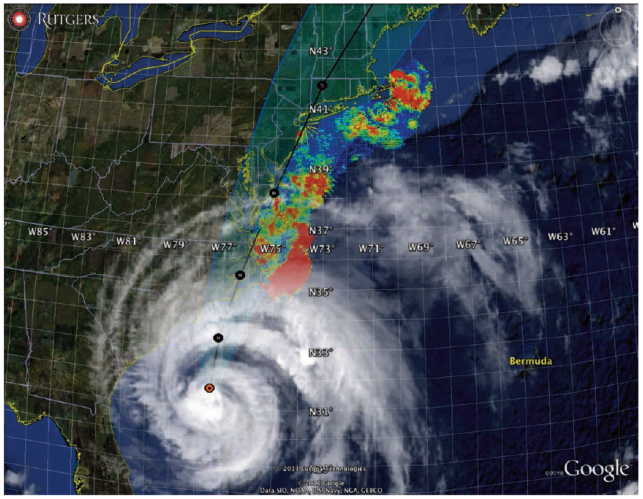
- The essential ocean features are
  - Seasonally warmed surface water
  - Persistent Cold Pool bottom water

- The essential ocean processes are
  - (a) ahead-of-eye mixing/cooling
  - (b) ahead-of-eye downwelling

nature COMMUNICATIONS
March 8, 2016
www.nature.com/ncomms

Stratified coastal ocean interactions with tropical cyclones

S.M. Glenn, T.N. Miles, G.N. Seroka, Y. Xu, R.K. Forney, F. Yu, H. Roarty, O. Schofield & J. Kohut



+ Monthly Weather Review (2016)
+ JGR-Oceans (2017)
+ JGR-Oceans (2017)

OCEANIC & ATMOSPHERIC Research
CINAR
Cooperative Institute for the North Atlantic Region

- The essential ocean feedbacks on the atmosphere are
  - (a) ocean mixing/cooling reduces storm intensity - **Irene**
  - (b) offshore advection of cold bottom water leaves a warm surface layer that acts to increase intensity - **Sandy**

Conclusions

- Gliders are an increasingly valuable platform for hurricane research and forecasting
- Used to identify essential ocean features & processes in each Atlantic region that forecast models must include
- Glider-enabled storm science motivated a 2018 community response through the IOOS Glider DAC
- New Glider datasets are pushing the limits of our operational data assimilation capabilities