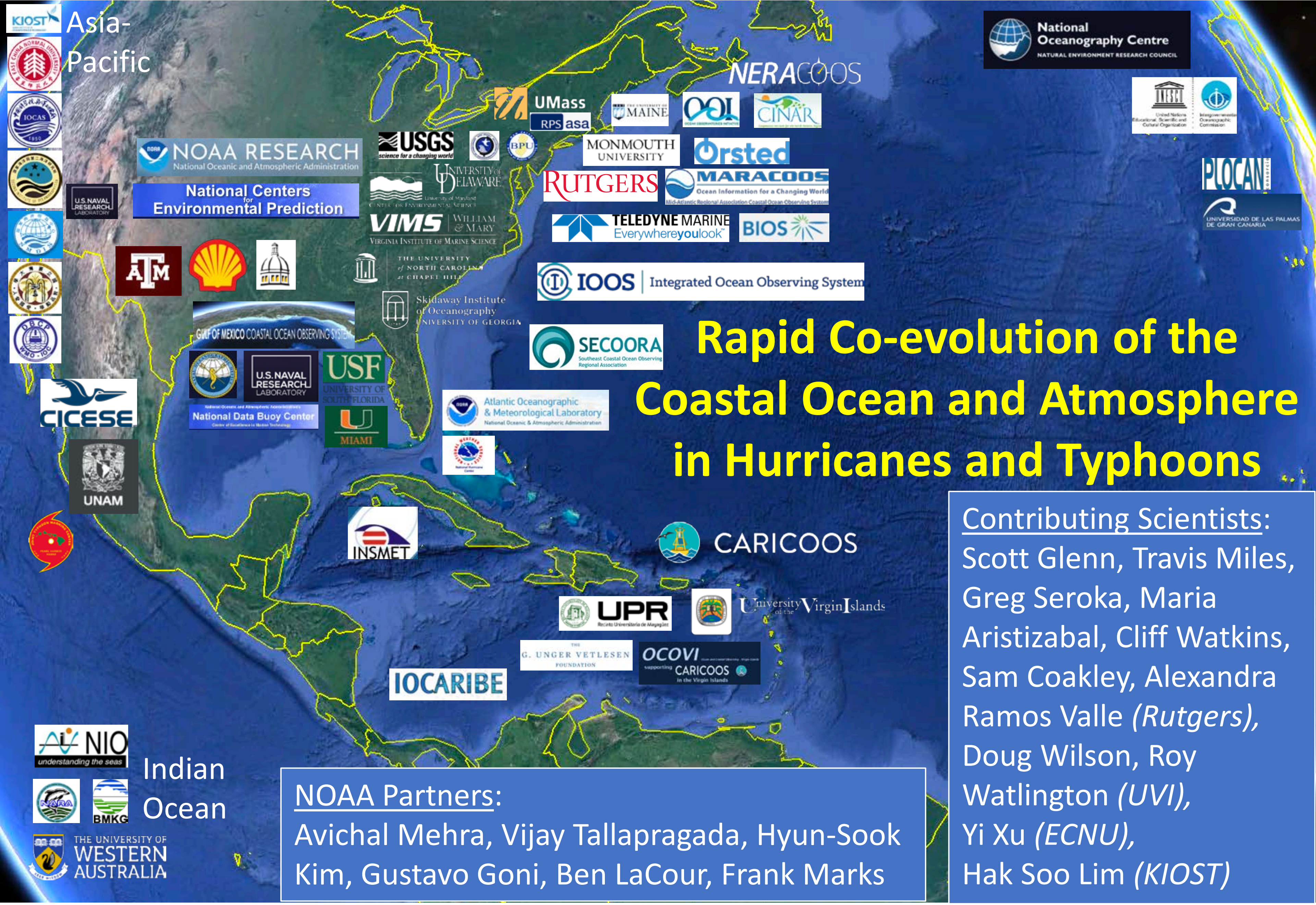
Rapid Co-evolution of the Coastal Ocean and Atmosphere in Hurricanes and Typhoons



<u>Contributing Scientists</u>:
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)*

<u>NOAA Partners</u>:
Avichal Mehra, Vijay Tallapragada, Hyun-Sook Kim, Gustavo Goni, Ben LaCour, Frank Marks

IOOS Integrated Ocean Observing System → NOAA RESEARCH National Oceanic and Atmospheric Administration → NATIONAL WEATHER SERVICE

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

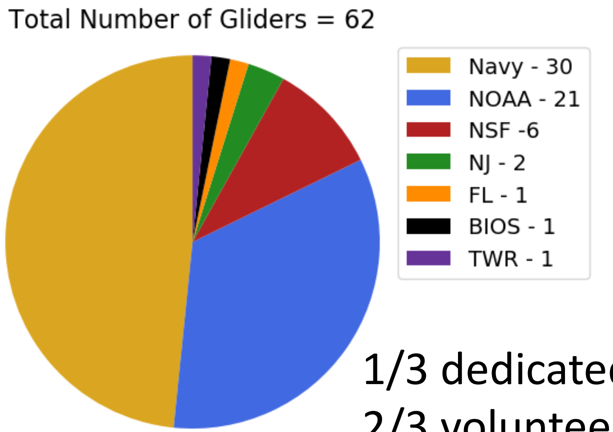
Since 1946

Since 2018

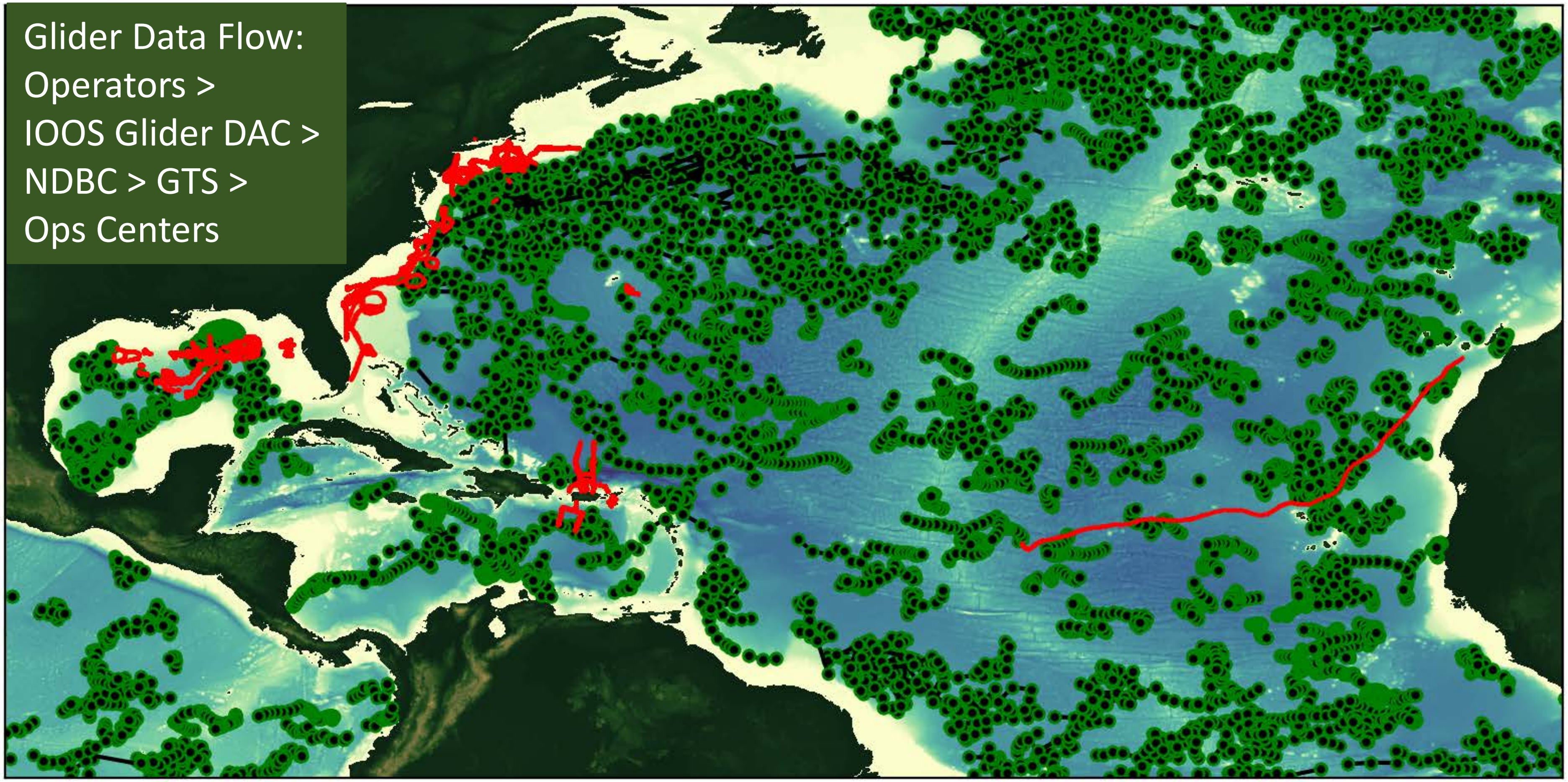
Glider Tracks & ARGO Floats
2018 Hurricane Season

Total number of Glider profiles = 123335

Total number of Argo profiles = 17264

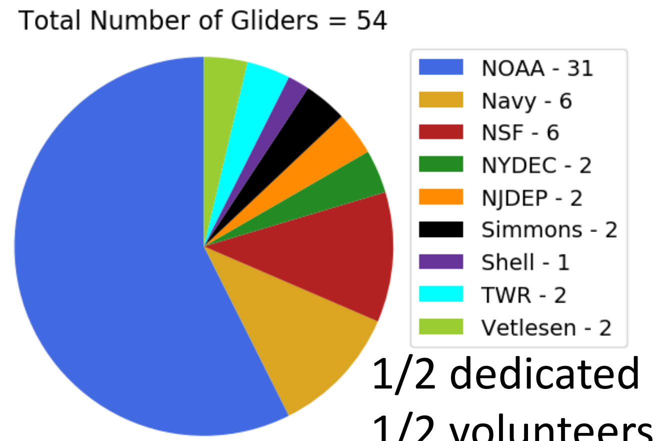


1/3 dedicated
2/3 volunteers

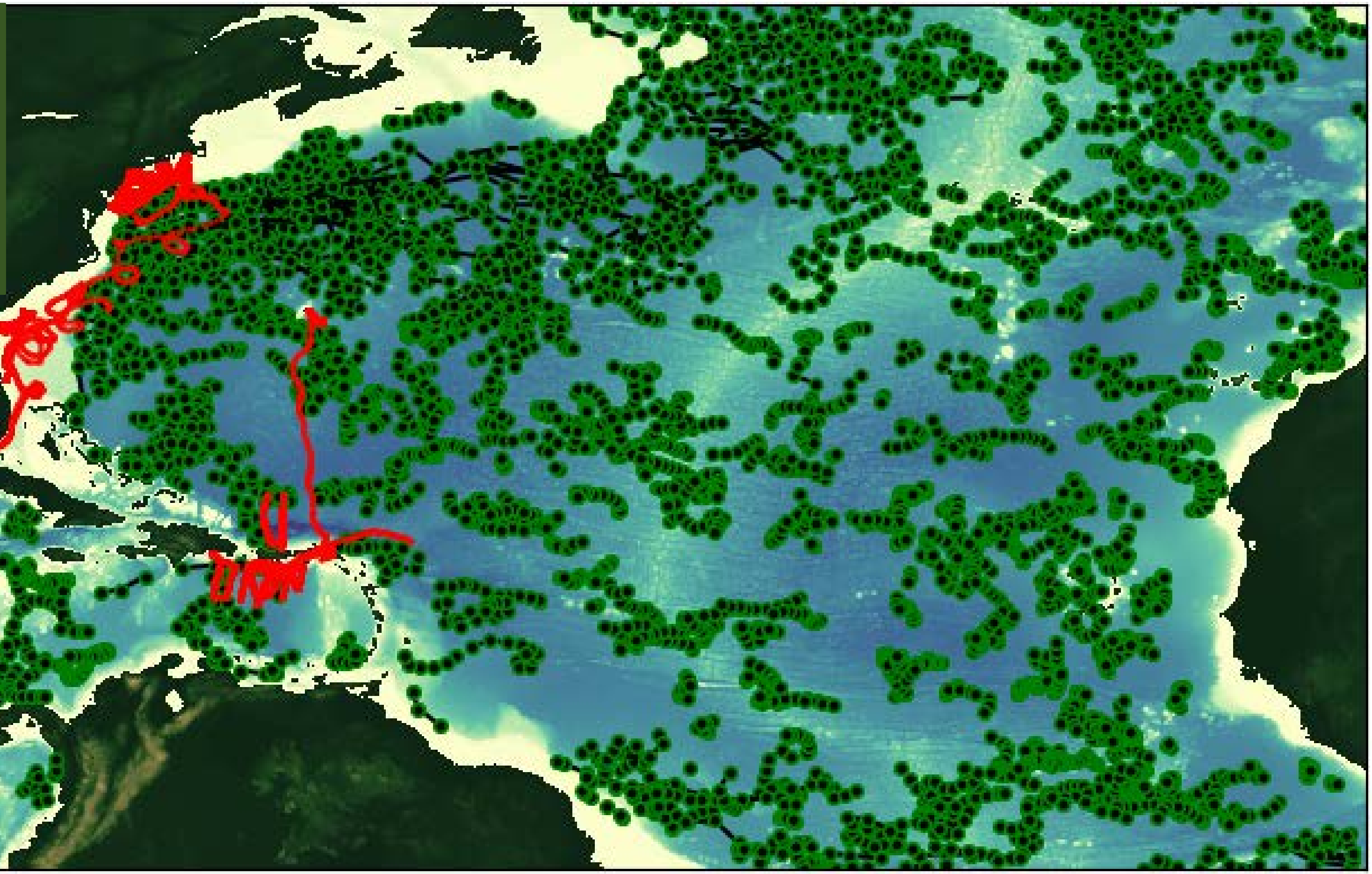


Glider Tracks & ARGO Floats
2019 Hurricane Season

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

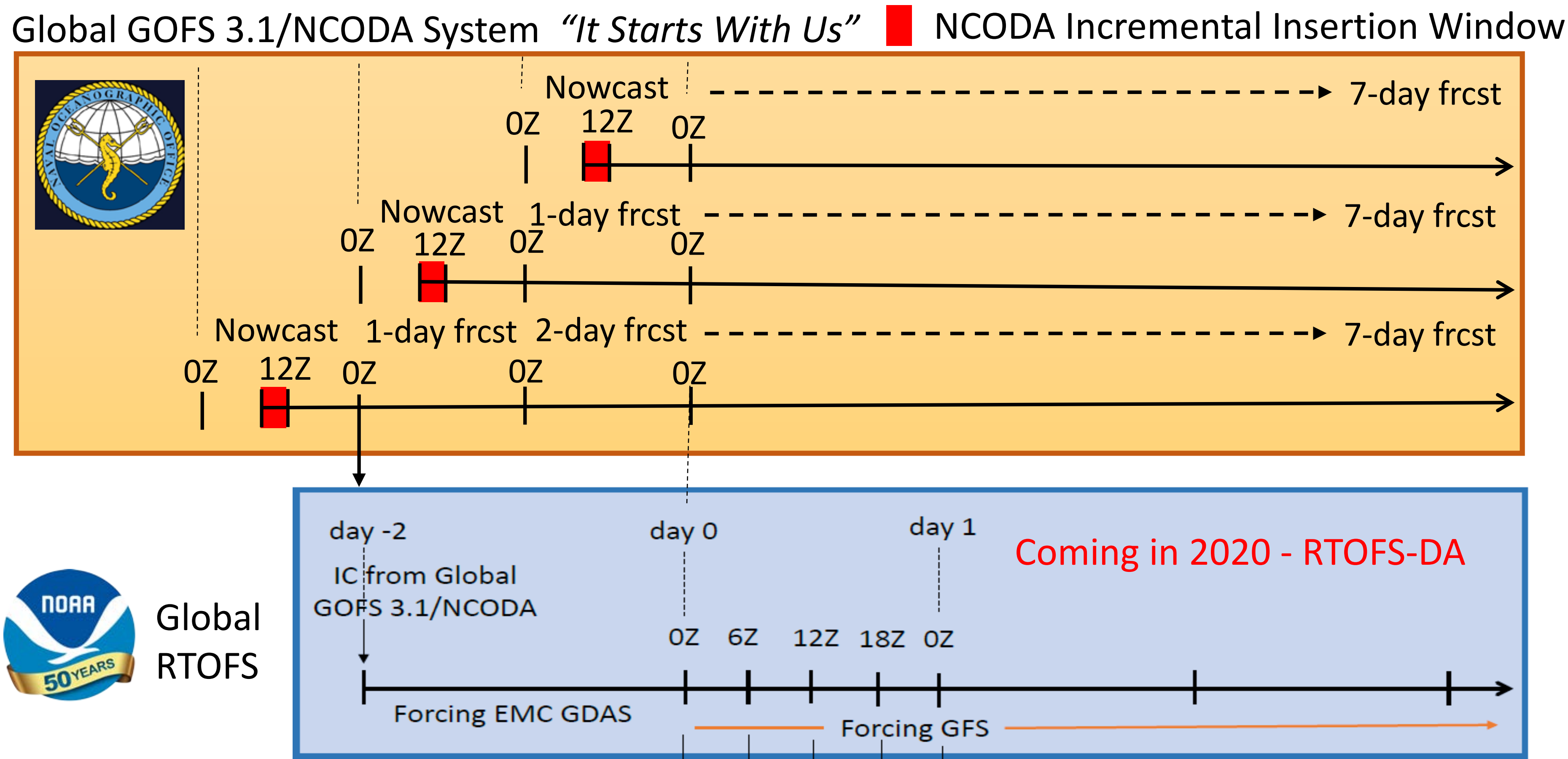


1/2 dedicated
1/2 volunteers

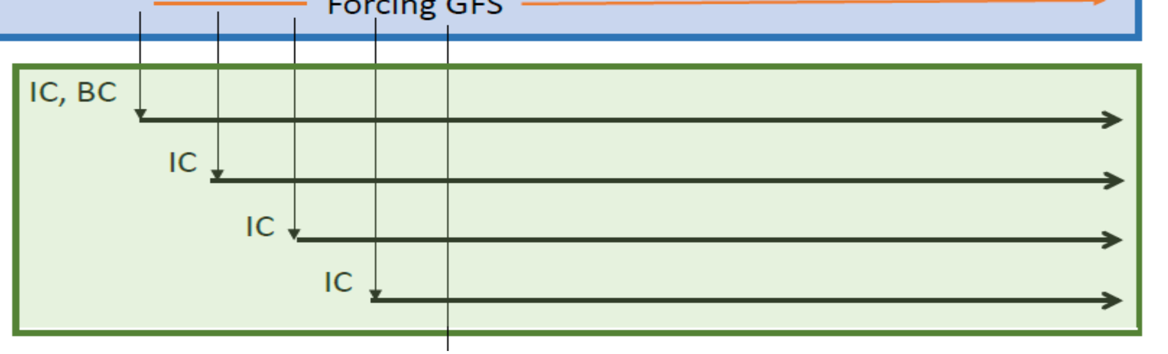


Glider Data Flow:
Operators >
IOOS Glider DAC >
NDBC > GTS >
Ops Centers

North Atlantic Hurricanes Ocean Forecast Work Flow

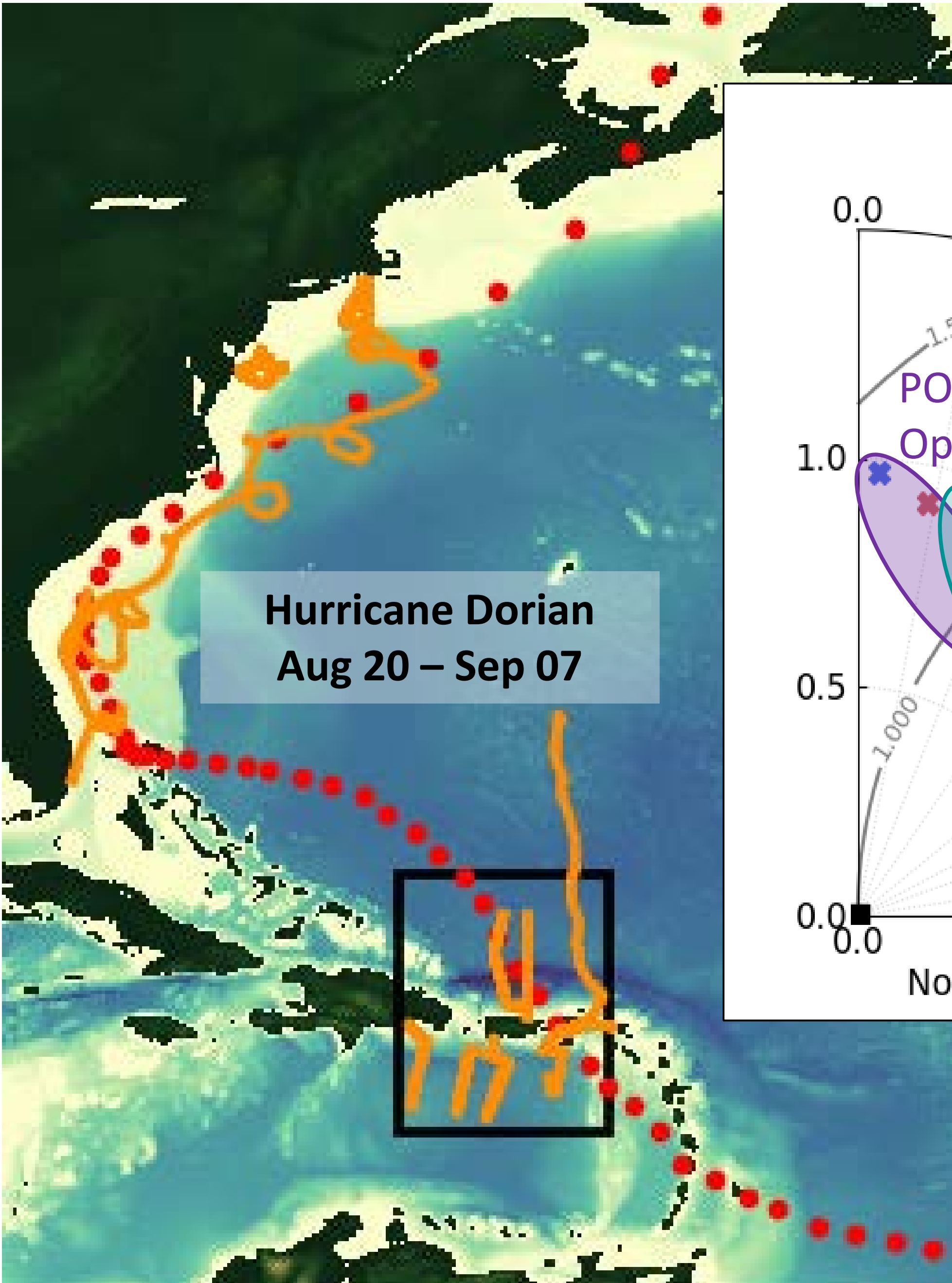


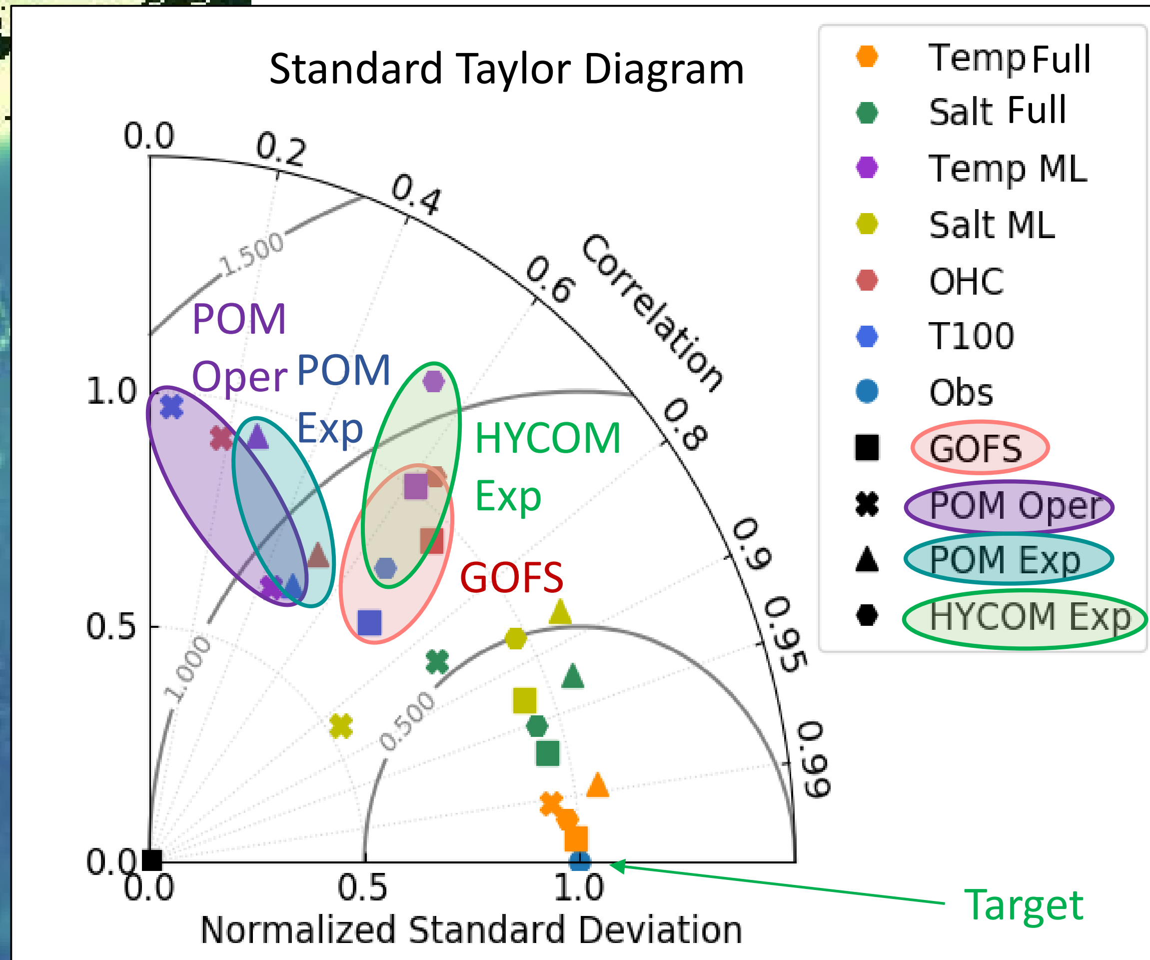
Regional HYCOM IC used for
2019 Operational HMON/HYCOM
2019 Experimental HWRF/HYCOM
2019 Experimental HWRF/POM



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

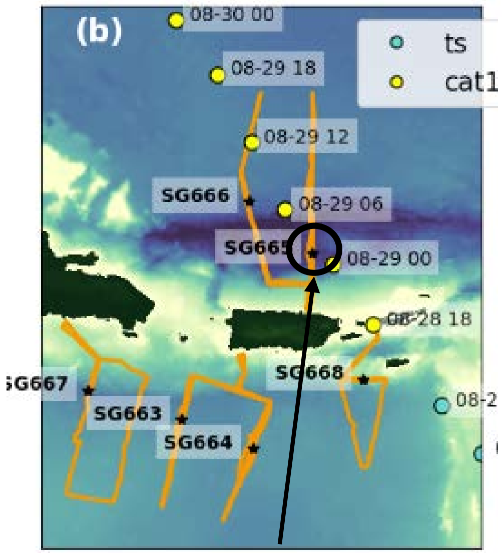
Comparing Operational Hurricane Models to Glider Data



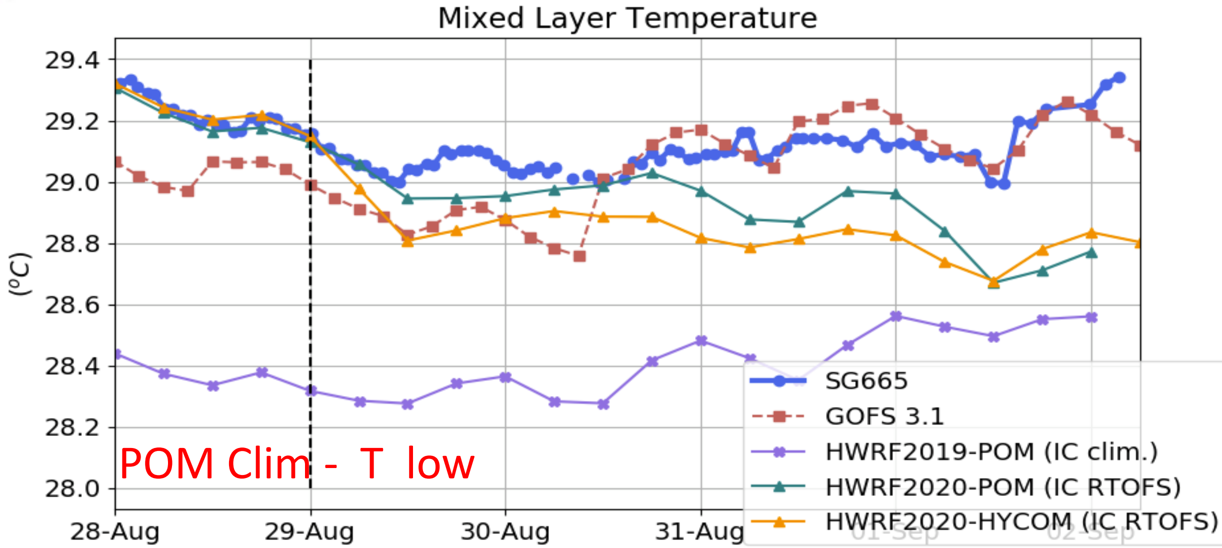


Full profile comparisons closest to Target
Upper ocean metrics further from Target
GOFS > HYCOM Exp > POM Exp > POM Oper

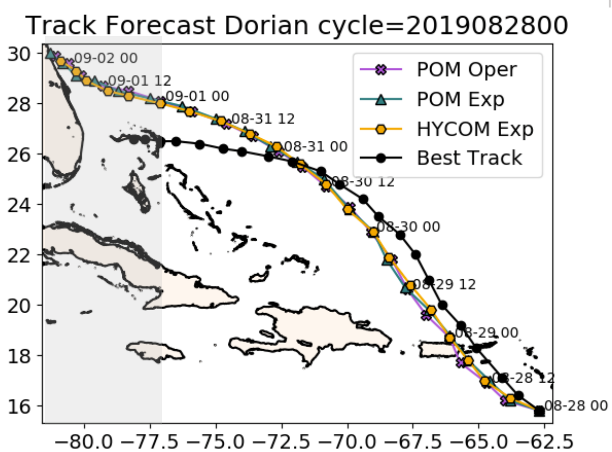
Time Series point comparison: AOML Glider SG665

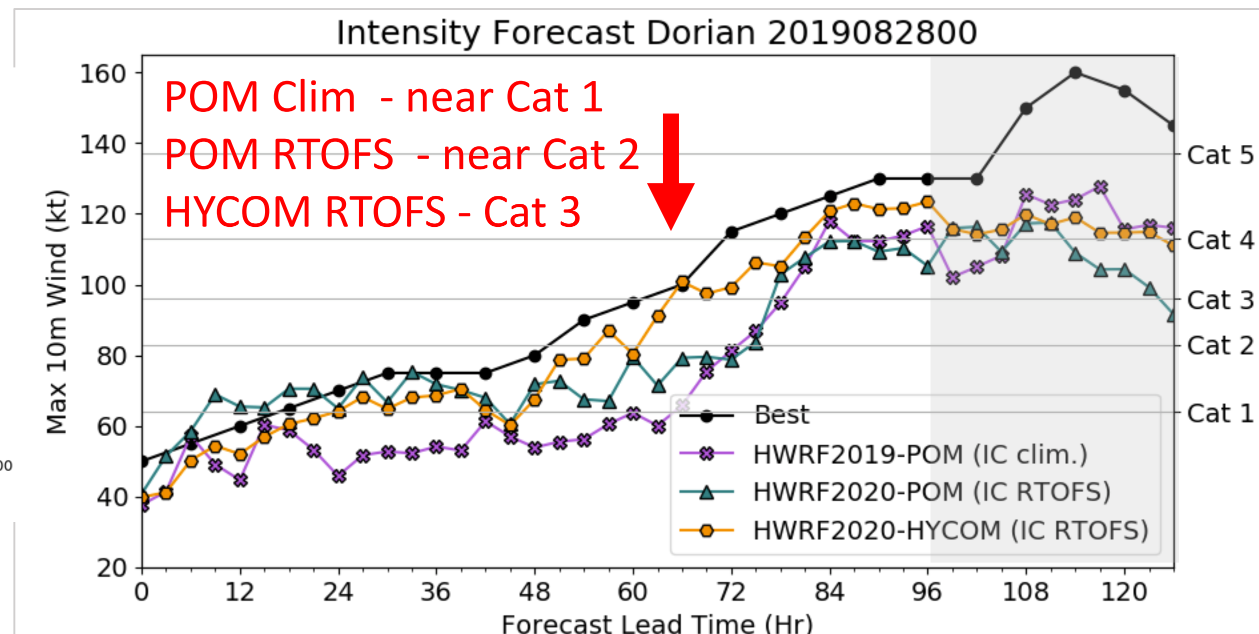


Time series location



Along Track comparison: Best Track





Hurricane Dorian 2019

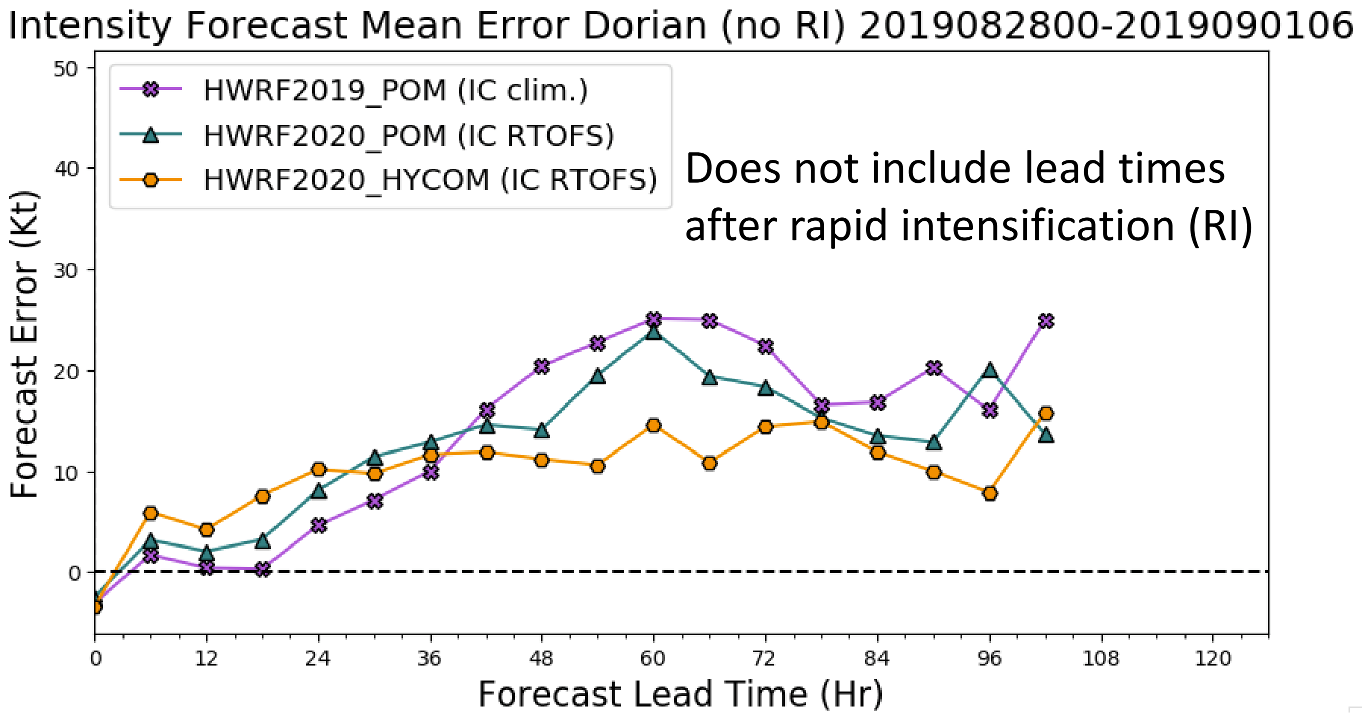
28 Aug to 1 Sept
TS to Cat 4
Before RI

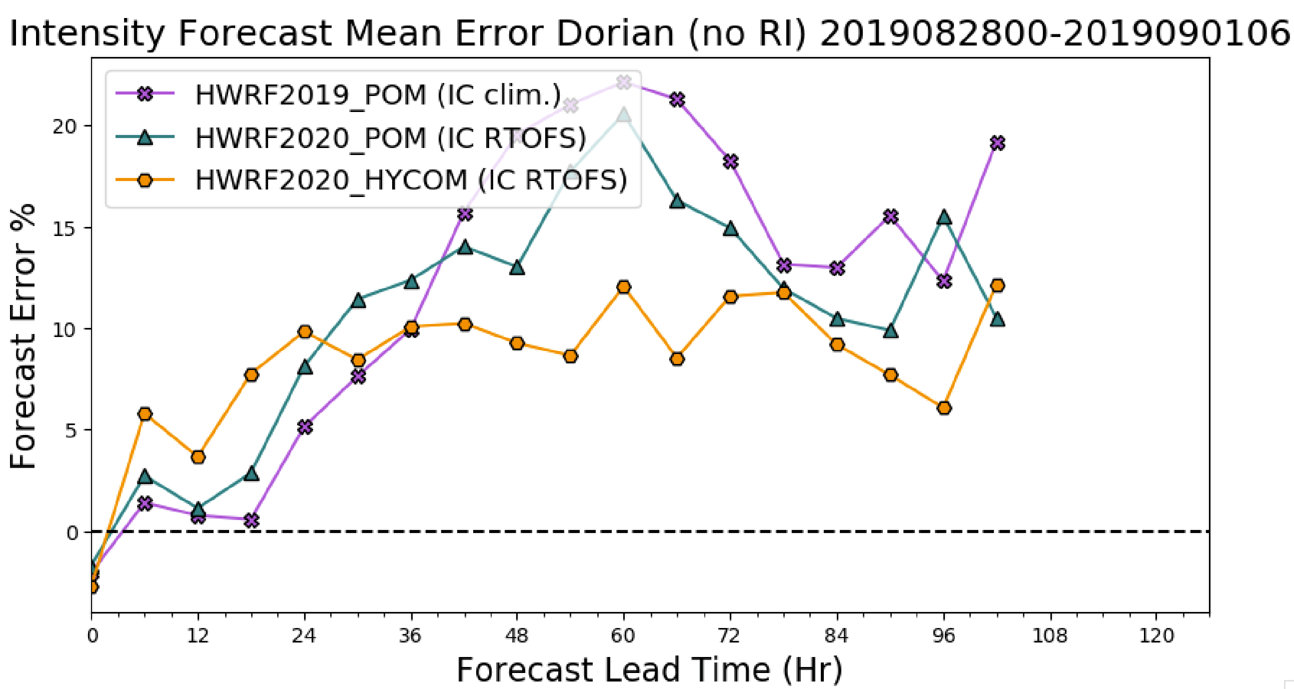
Average forecast intensity errors for all cycles

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

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

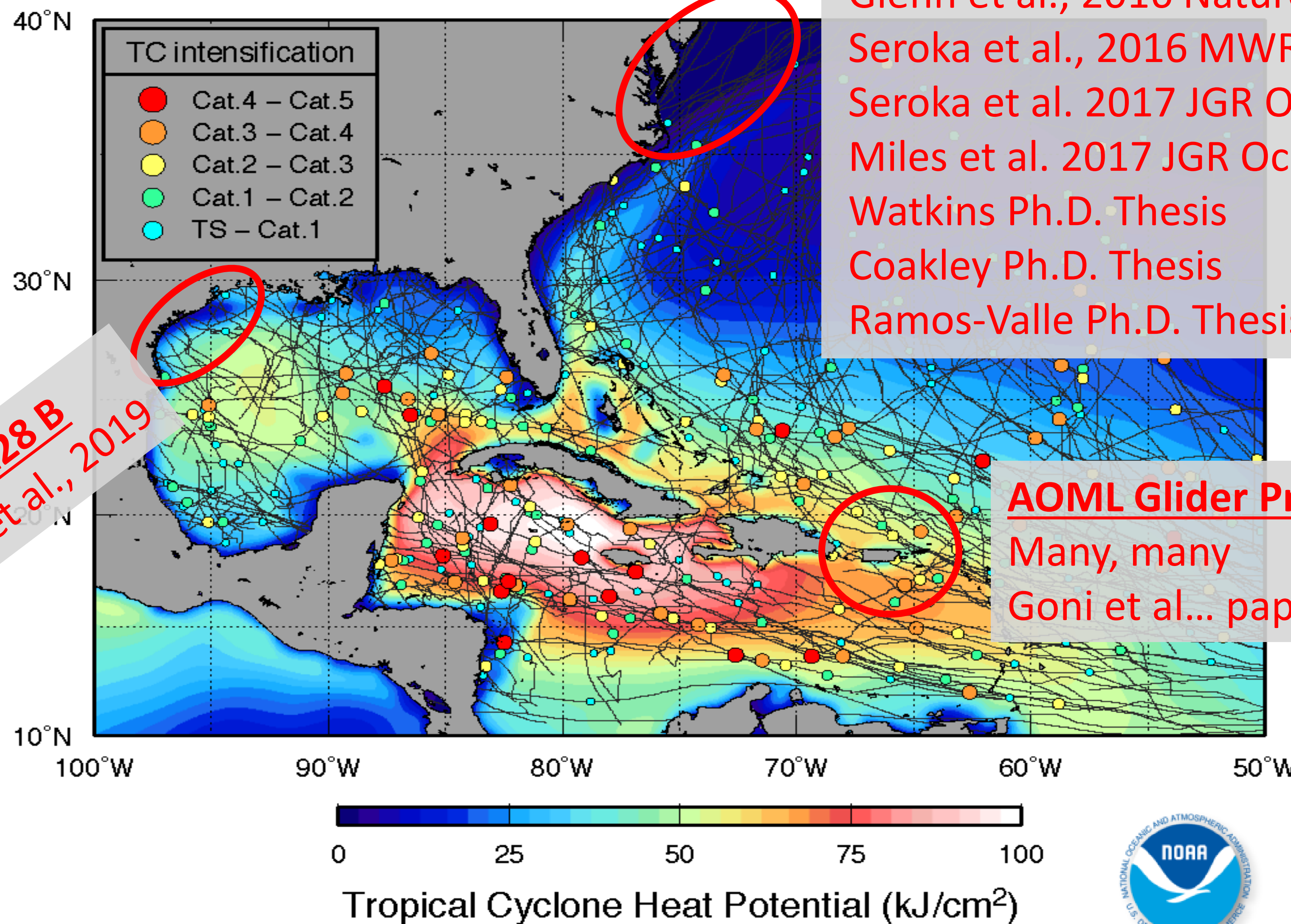
Details in Doug Wilson's talk in 2 weeks.





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

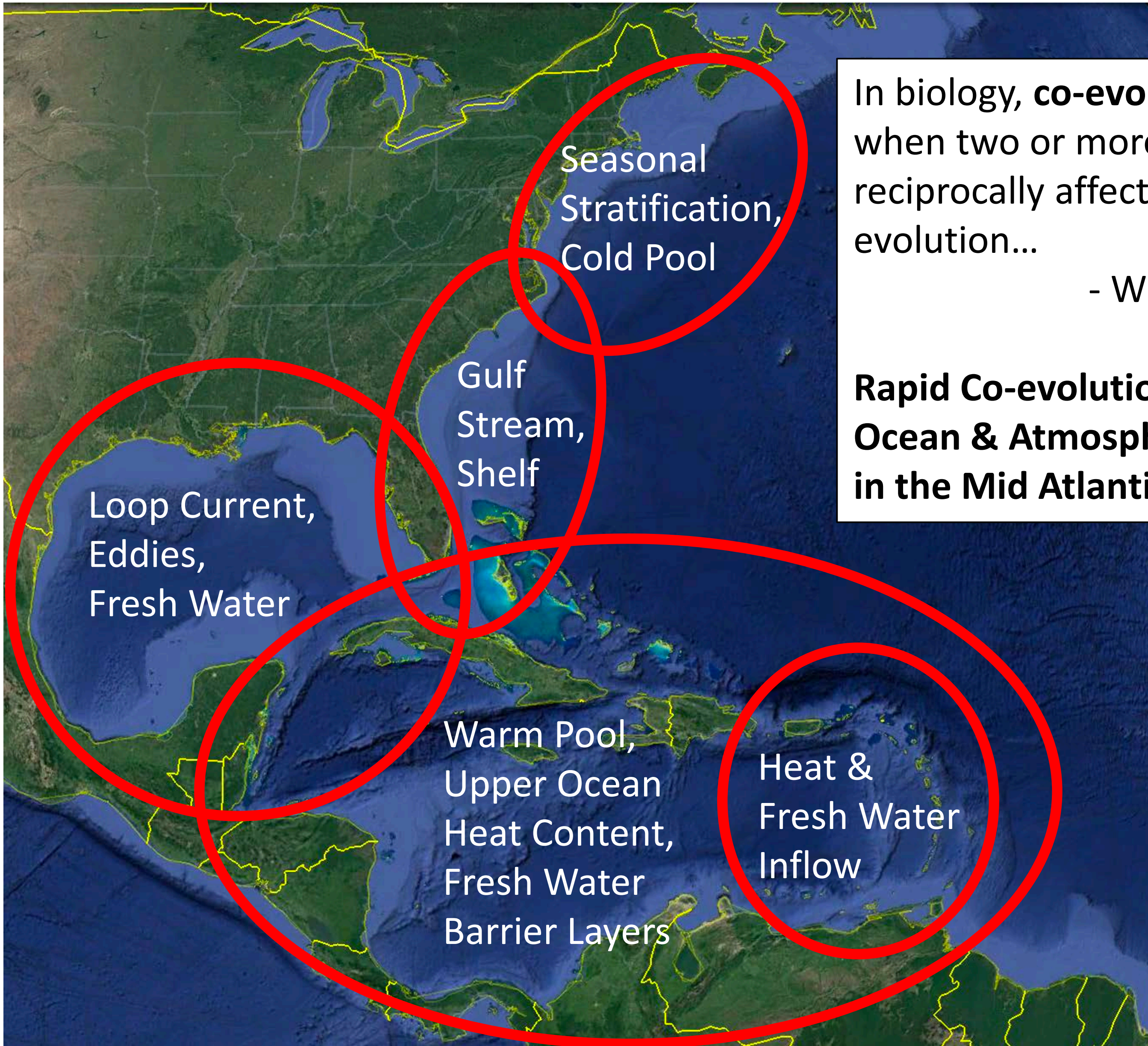
Harvey $128 B

Potter et al., 2019

AOML Glider Program

Many, many
Goni et al… papers

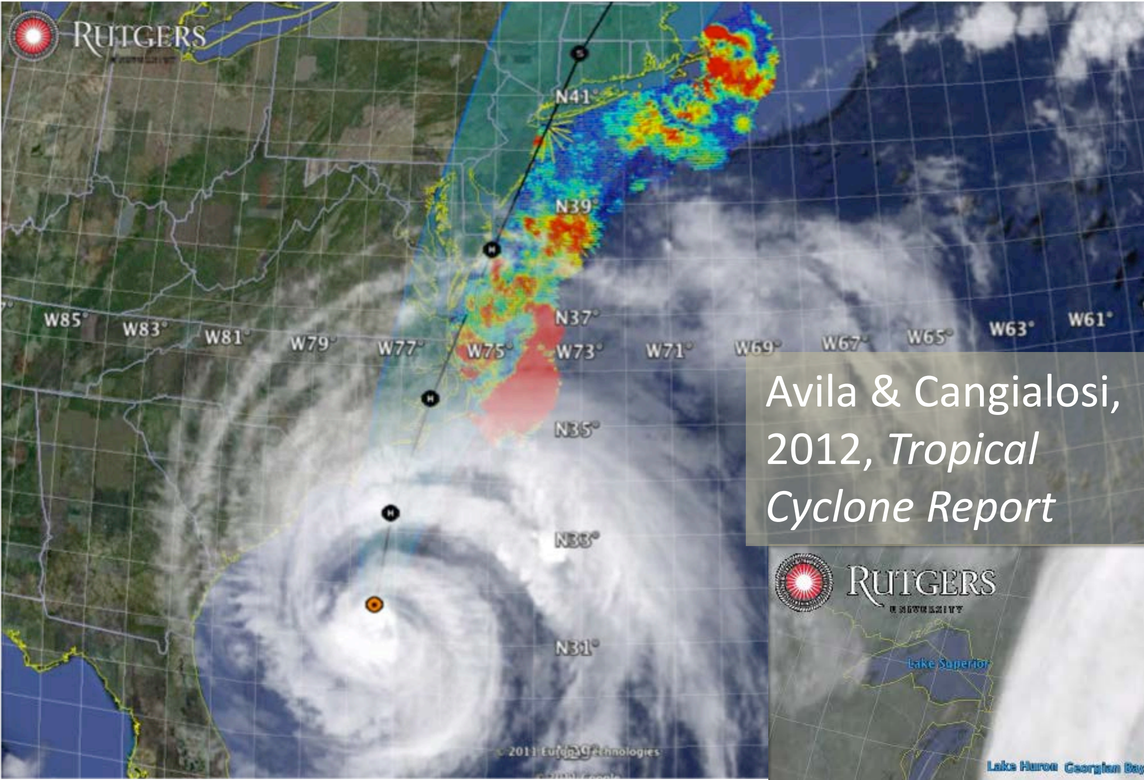
Regionally-specific Essential Ocean Features impacting Atlantic Hurricane Intensity



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

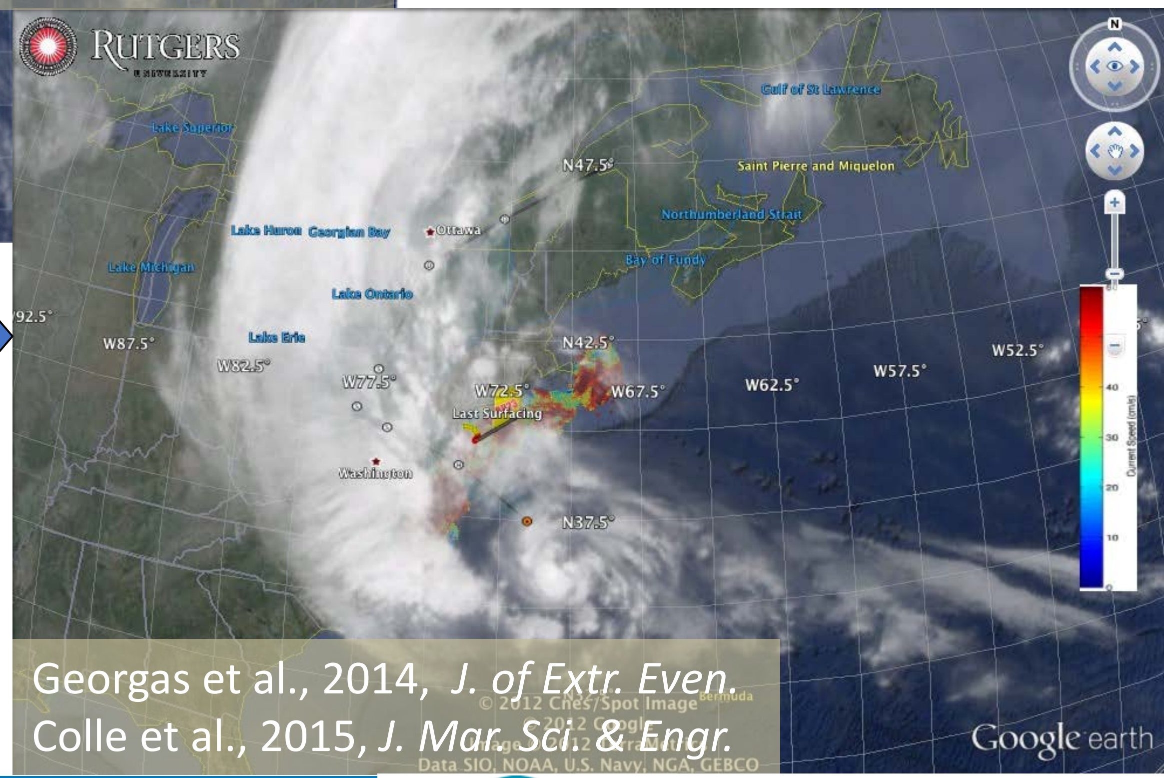


Avila & Cangialosi, 2012, *Tropical Cyclone Report*

Hurricane Irene
August 28, 2011

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

Track Accurate;
Intensity Over-predicted.



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

Hurricane Sandy
October 29, 2012

NOAA/NHC Damage:
>$72 Billion, #5.

Track Accurate;
Surge Under-predicted.

Rutgers University - Coastal Ocean Observation Lab

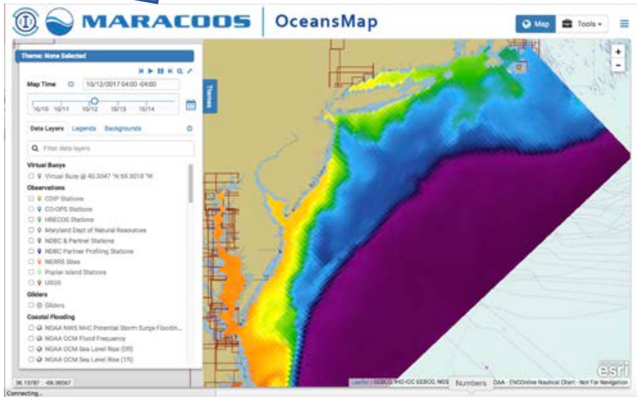
28 Years of Continuous Observatory Operations, Data Fusion & Training

Since October 29, 1992

Satellites

HF Radar

Glider Lab



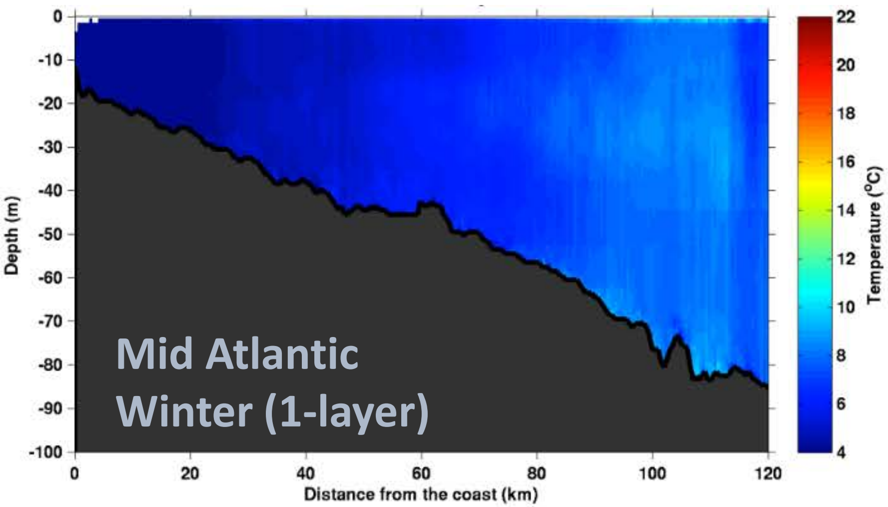
Ocean & Atmospheric Forecasts

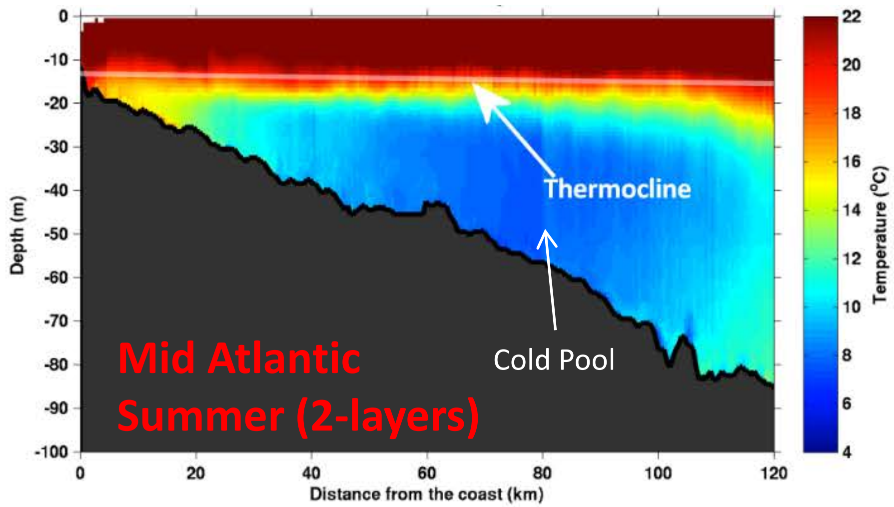
MARACOOS
Ocean Information for a Changing World

IOOS Integrated Ocean Observing System

Essential Ocean Feature - Mid-Atlantic's Cold Pool

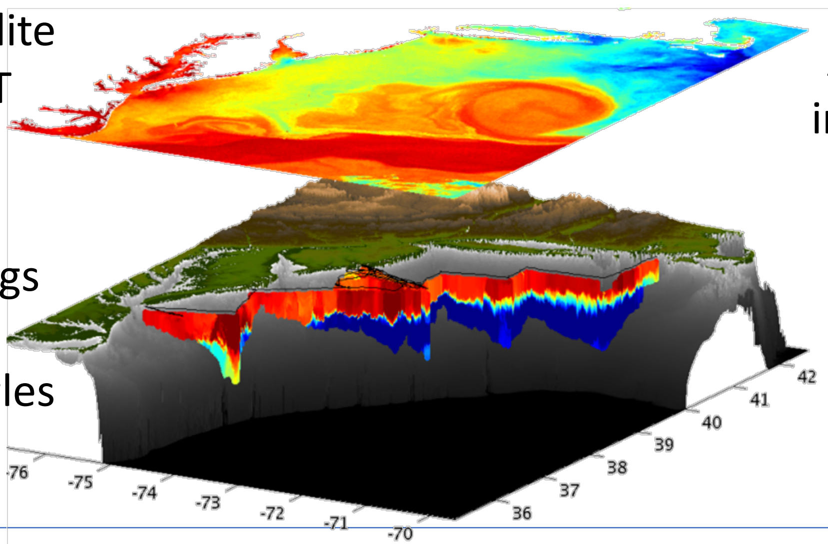
An unseen from space, cold bottom layer beneath a warm seasonal surface layer



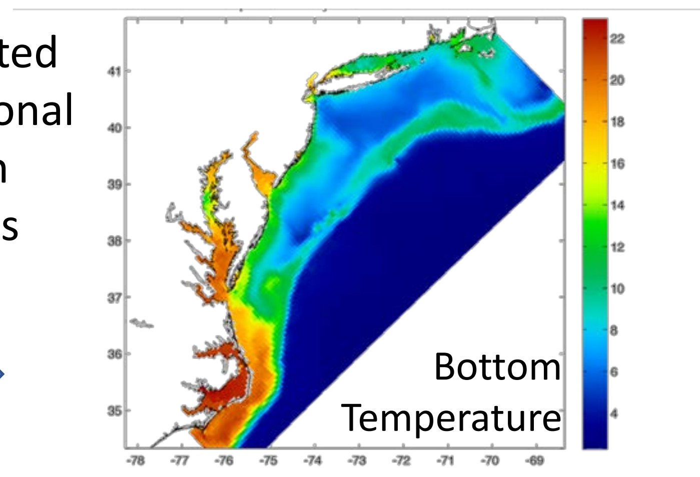


Satellite SST

Glider Zig-Zags or Triangles



Assimilated into Regional Ocean Models

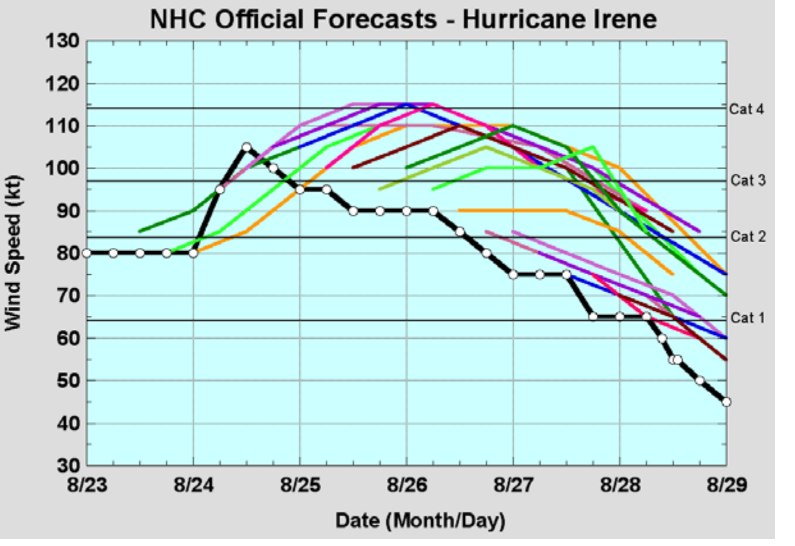


To characterize the Cold Pool, we need ocean observations that are "fit for purpose"

MARACOOS Ocean Information for a Changing World

IOOS Integrated Ocean Observing System

Pre-Irene Storm Warnings



Over 2 million people ordered to "flee the storm's path".

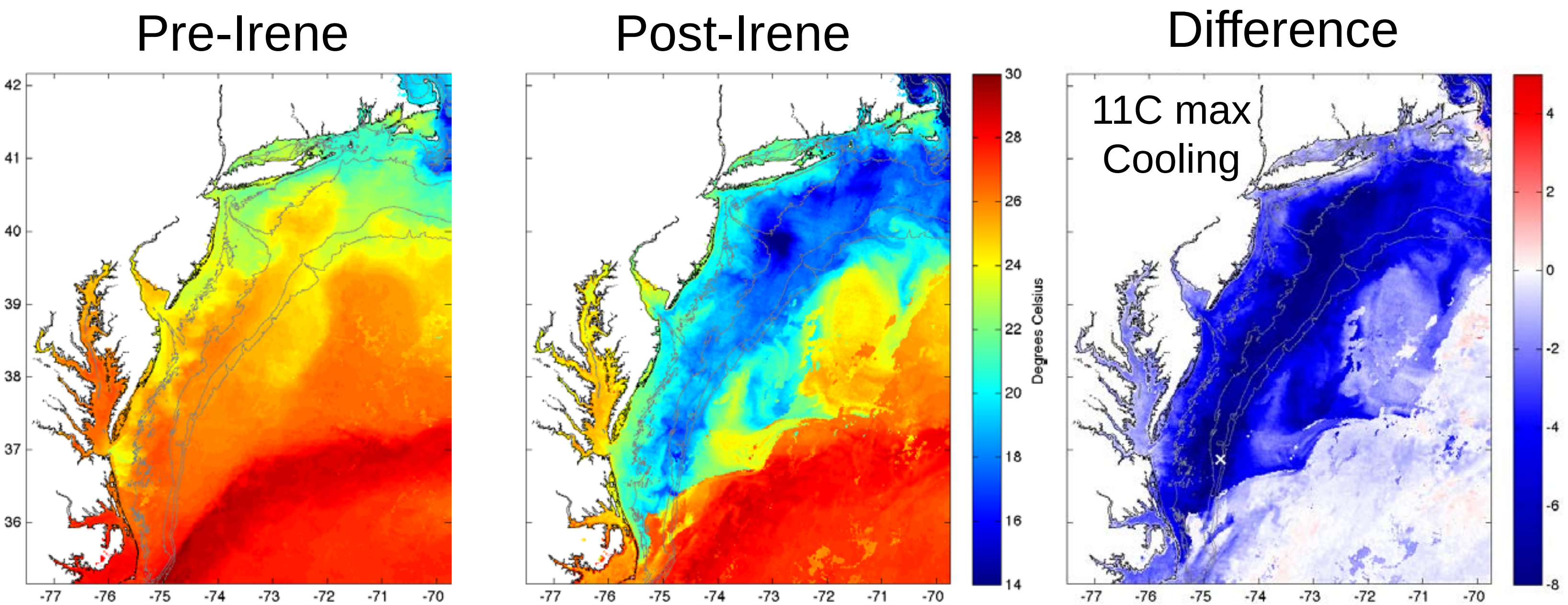
President Obama: Shaping up to be a "historic hurricane" and urged residents to "be prepared for the worst". "Don't wait. Don't delay."

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".

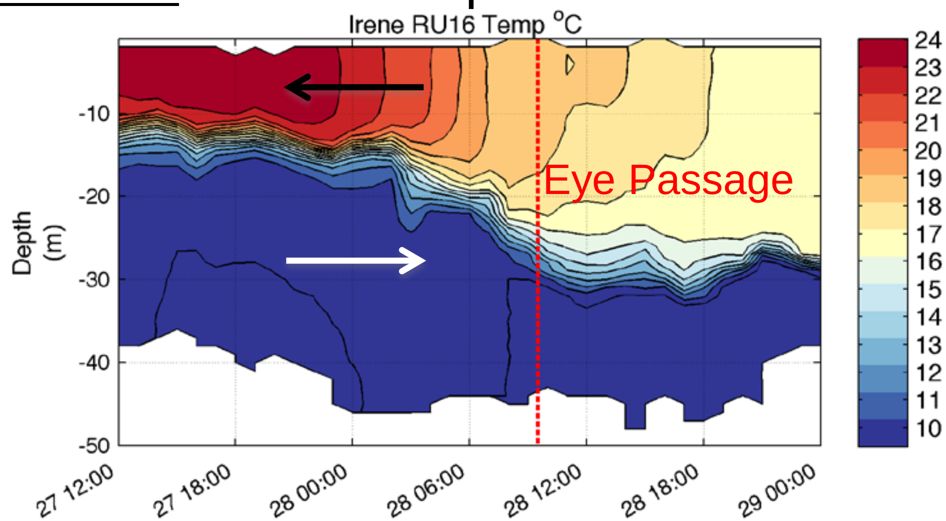
New York Mayor Blumberg: "Staying behind is dangerous, staying behind is foolish, and its against the law". "The time to leave is right now". The bridges, streets and subways were nearly empty ahead of a nearly unprecedented mass transit shutdown.

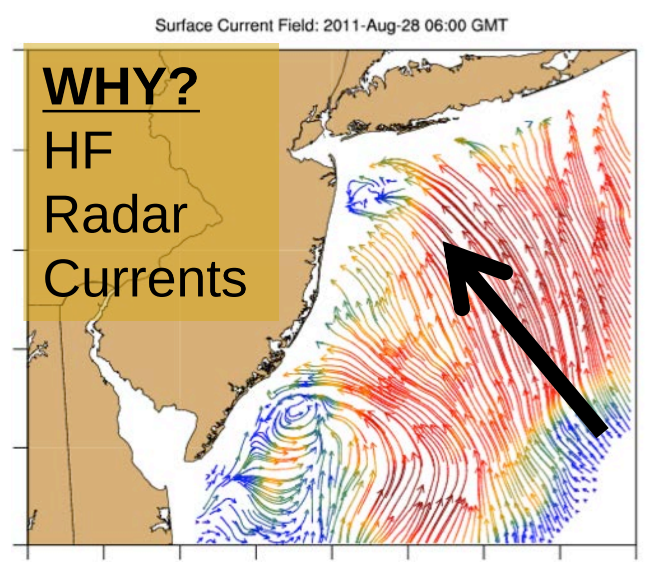
WHAT?

Satellite SST



WHEN? Glider Temperature



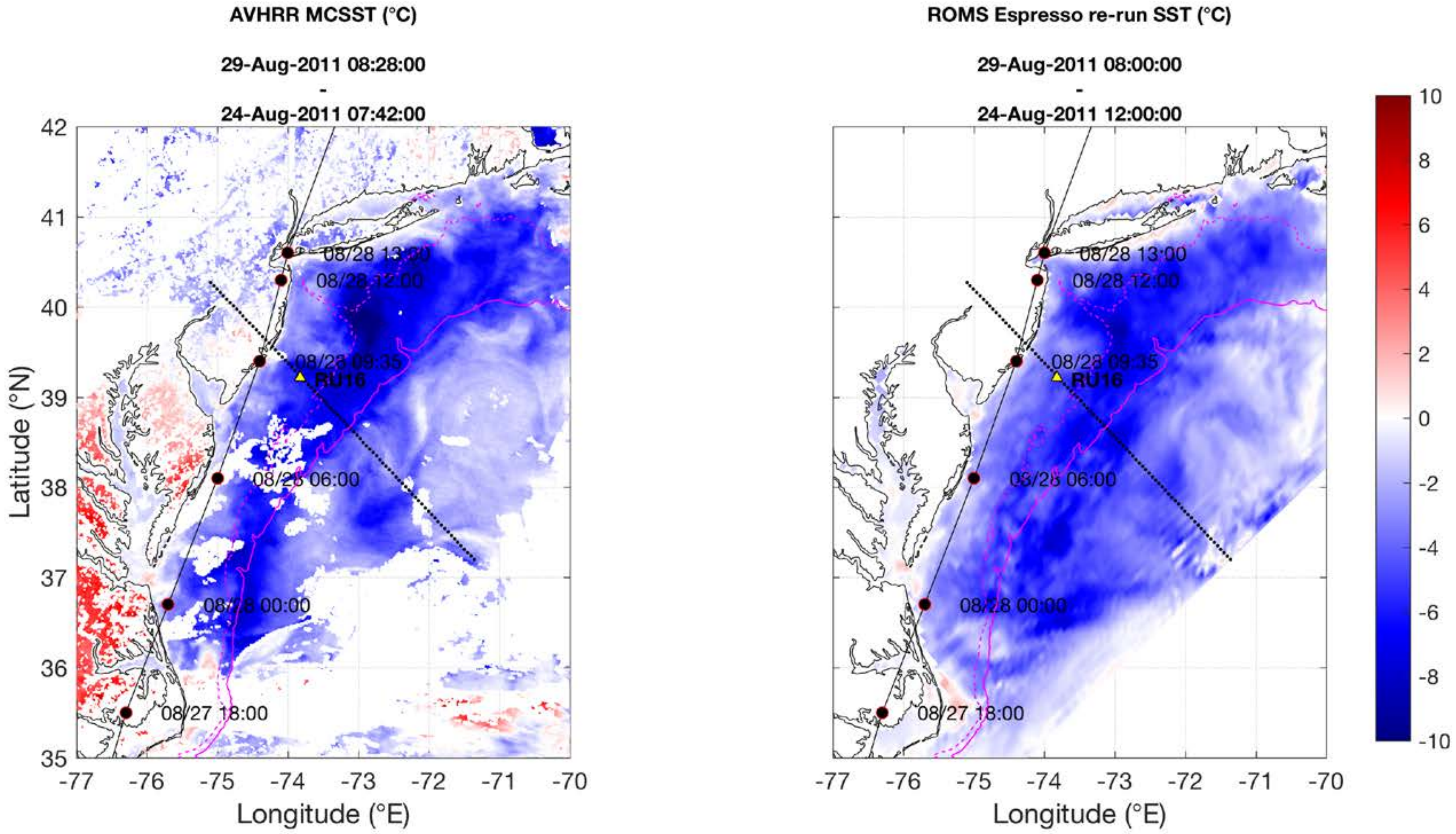


Essential Ocean Processes:

Ahead of eye center – Vertical Shear > Mixing > Cooling > Reduced Intensity > Reduced Surge

Hurricane Irene ROMS Ocean Forecast

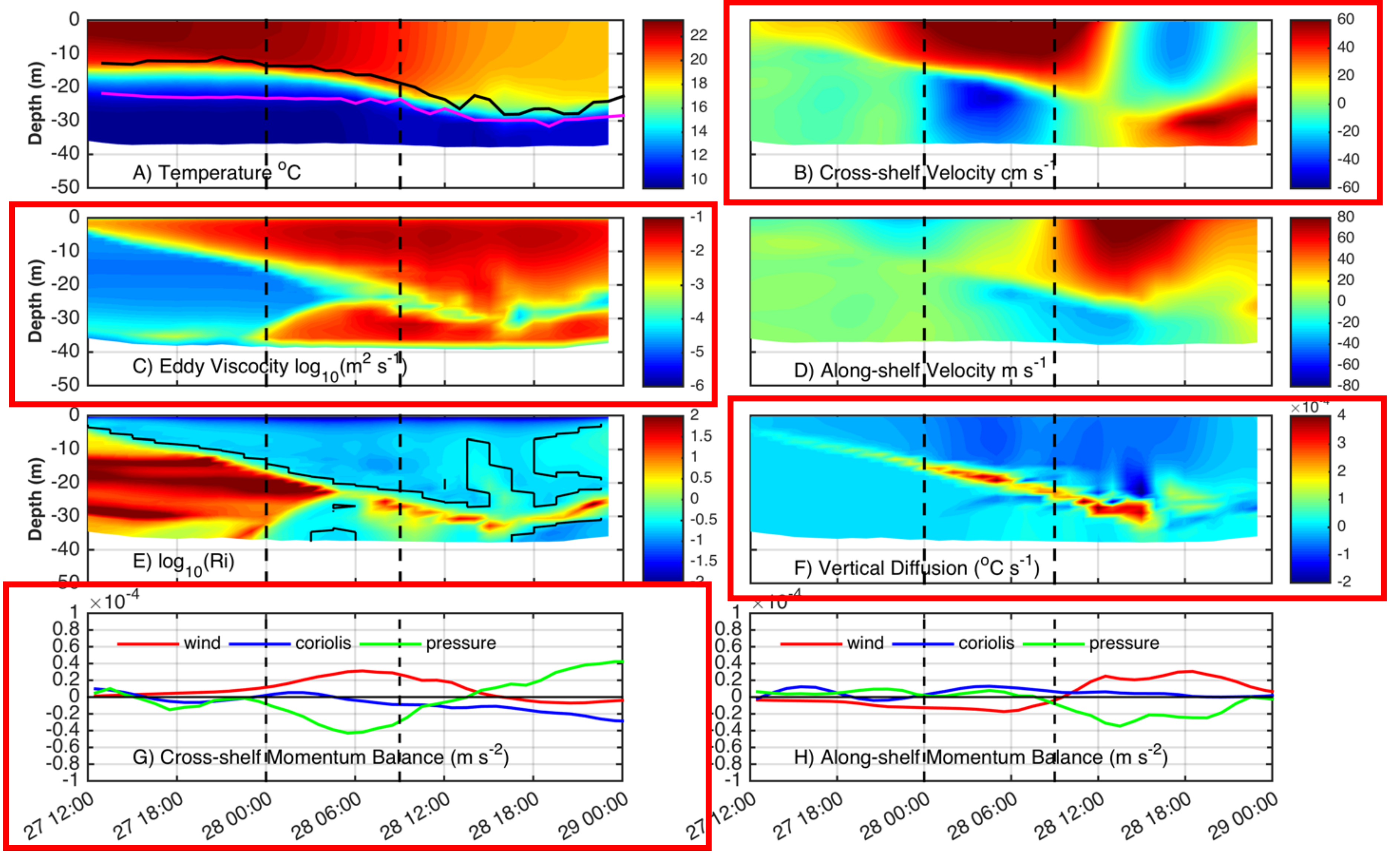
Satellite AVHRR vs. ROMS Model



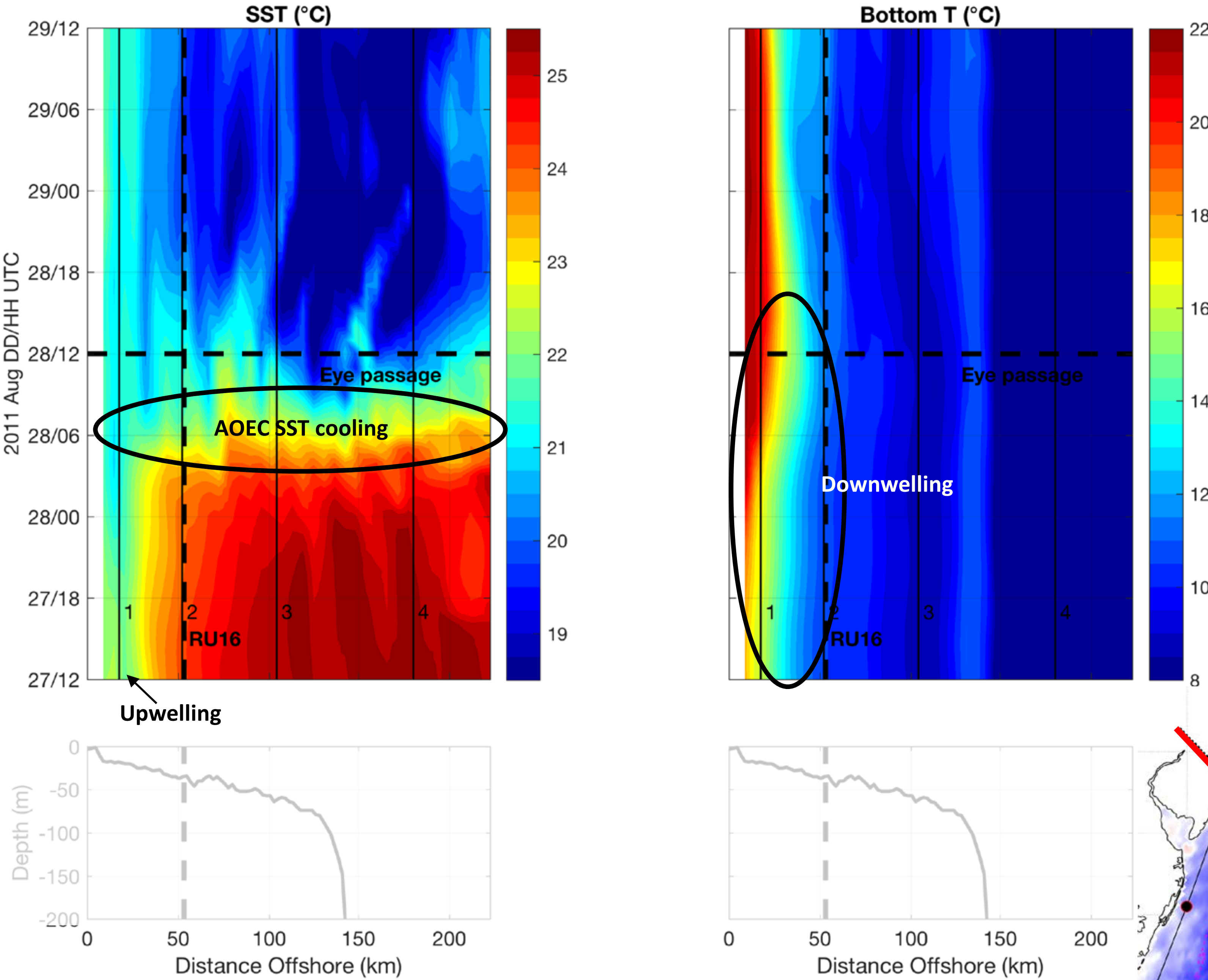
(After – Before) SST Difference

ROMS Model Results at Glider Location

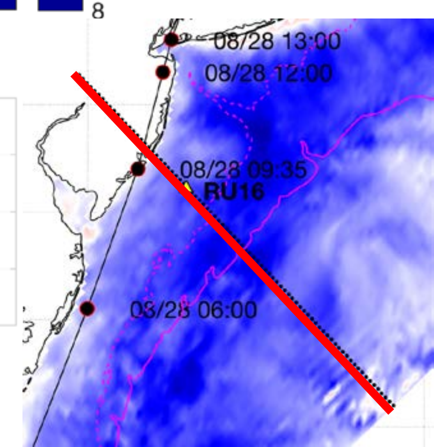
Coastal Baroclinic Circulation Enhances Mixing & Cooling



ROMS Model Cross-shelf Section: SST cooling, downwelling bottom T

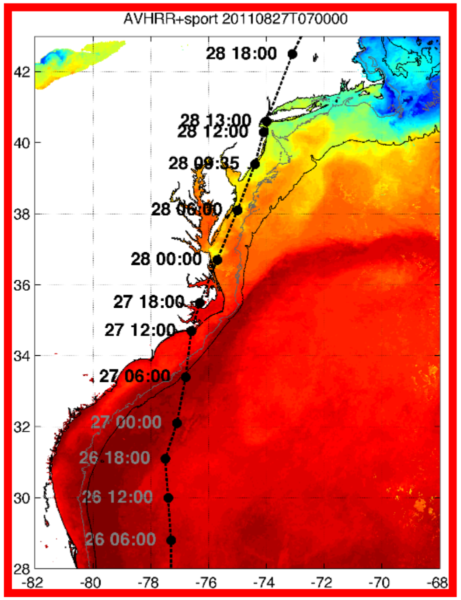


Seroka et al. 2017 JGR Oceans

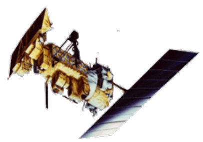


Seroka et al. in prep.

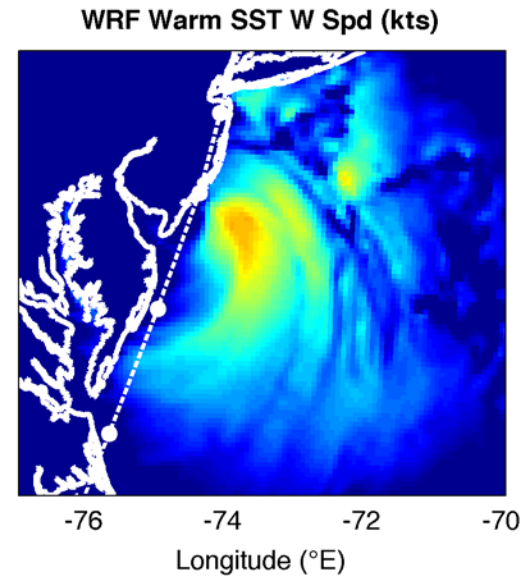
WRF Atmospheric Forecast Sensitivity Study – >130 tests

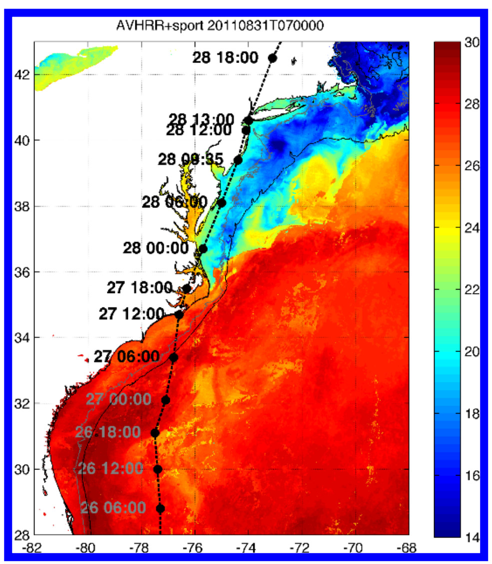


Warm Ocean Boundary Condition



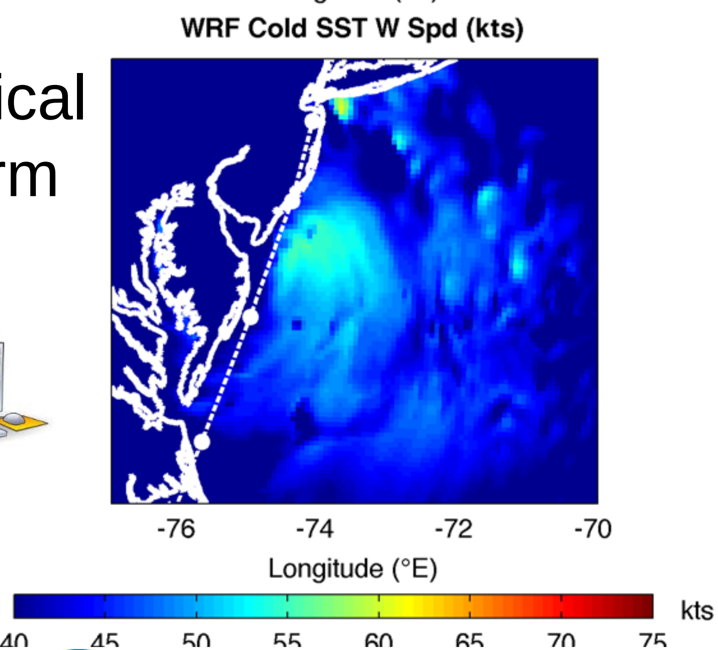
Cat 1 Hurricane





Cold Ocean Boundary Condition

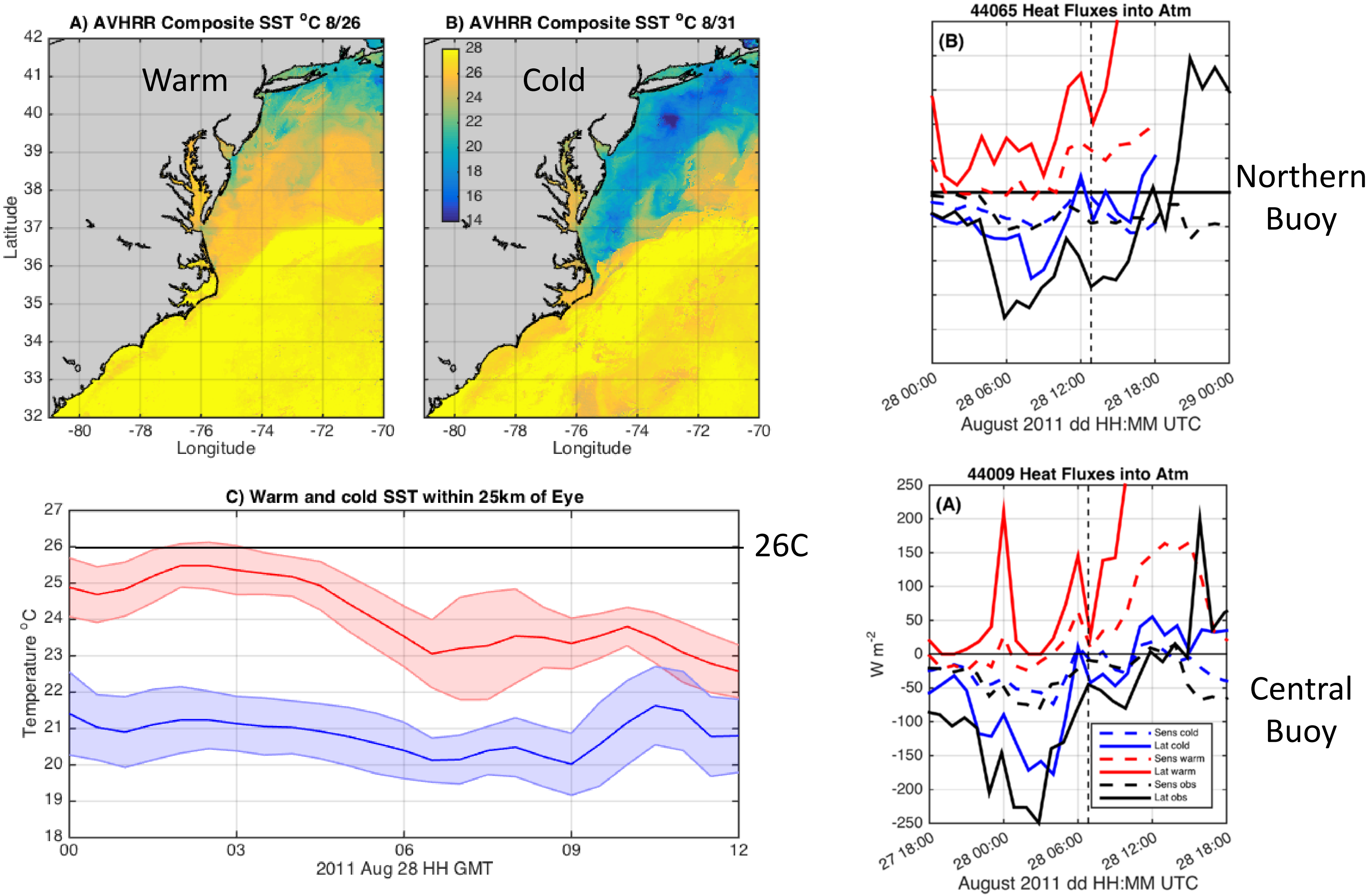
Tropical Storm



IMPACT?

>10 knots reduction in peak wind speed

SST within 25 km of eye & impact on air-sea heat flux



WRF Heat Flux Comparison to North American Regional Reanalysis

Wind

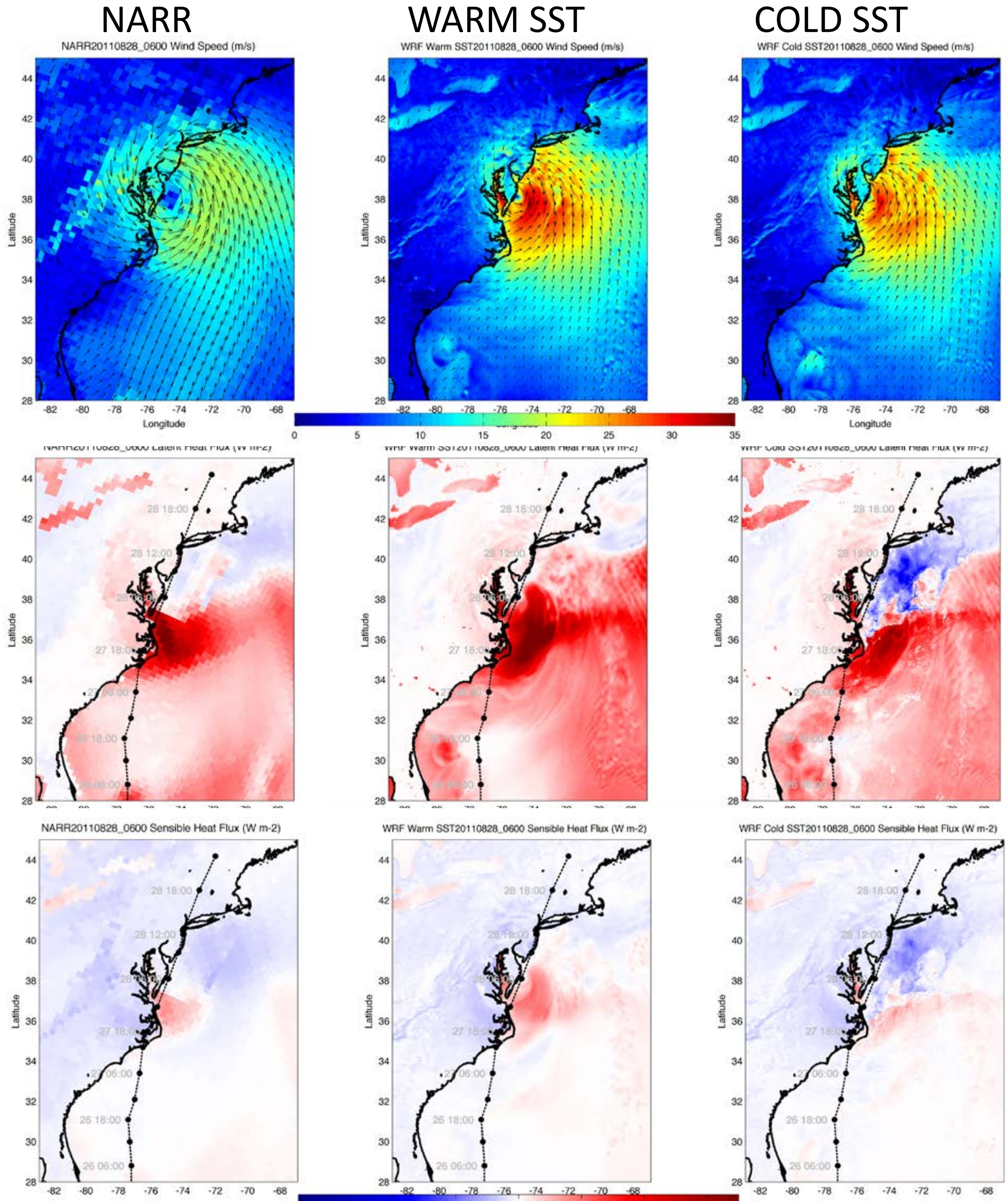
Latent heat flux

$$\tau = -\rho C_D U^2$$

$$H = -(\rho c_p) C_H U(\theta_{2m} - \theta_{sfc})$$

$$E = -(\rho L_v) C_Q U(q_{2m} - q_{sfc})$$

Sensible heat flux

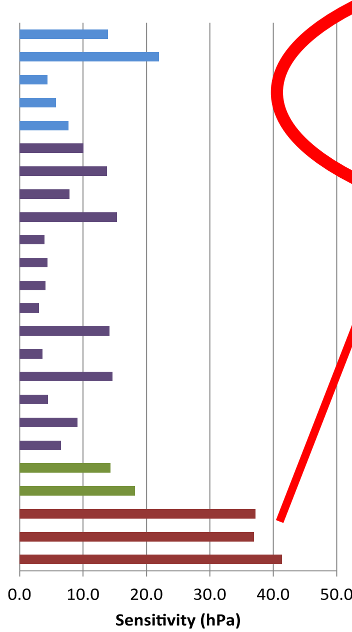


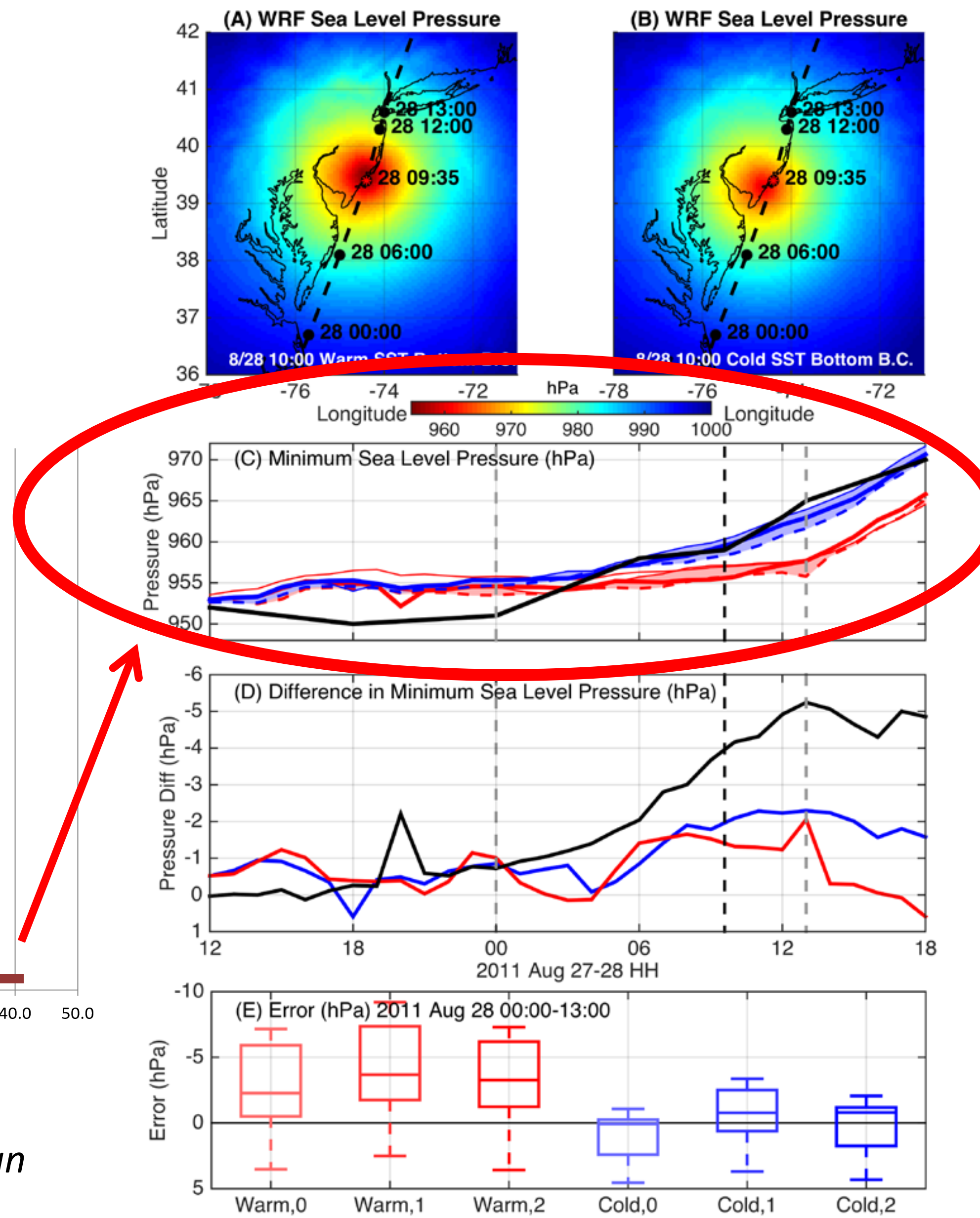
WRF Model Sensitivity Study

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

Pressure Sensitivity Table: 8/28 00-13 UTC

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





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

WRF Model Sensitivity Study

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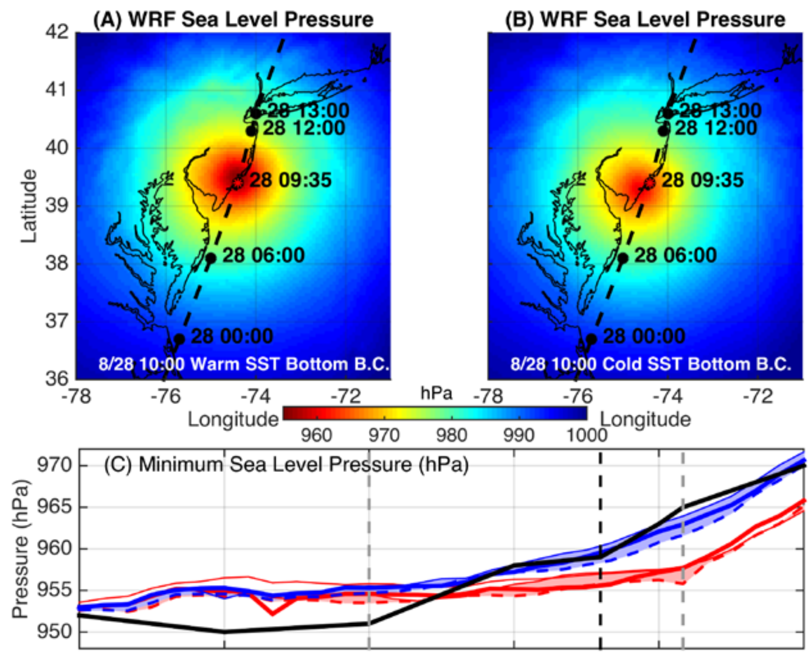
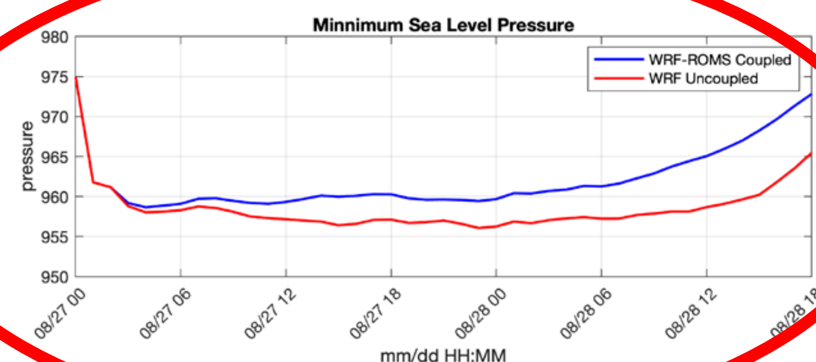


Using this as a benchmark for Coupled model development

WRF – ROMS in ESMF/NUOPC Framework

- Allow for coupled regional coupled modeling by NOAA NOS/EMC/Others



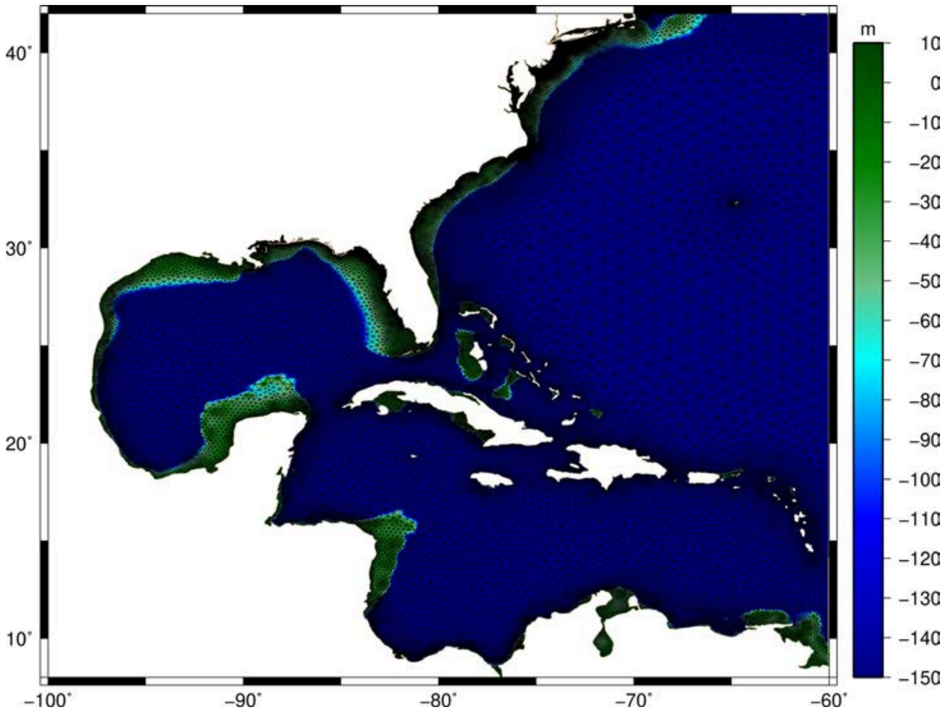
NUOPC

ESMF

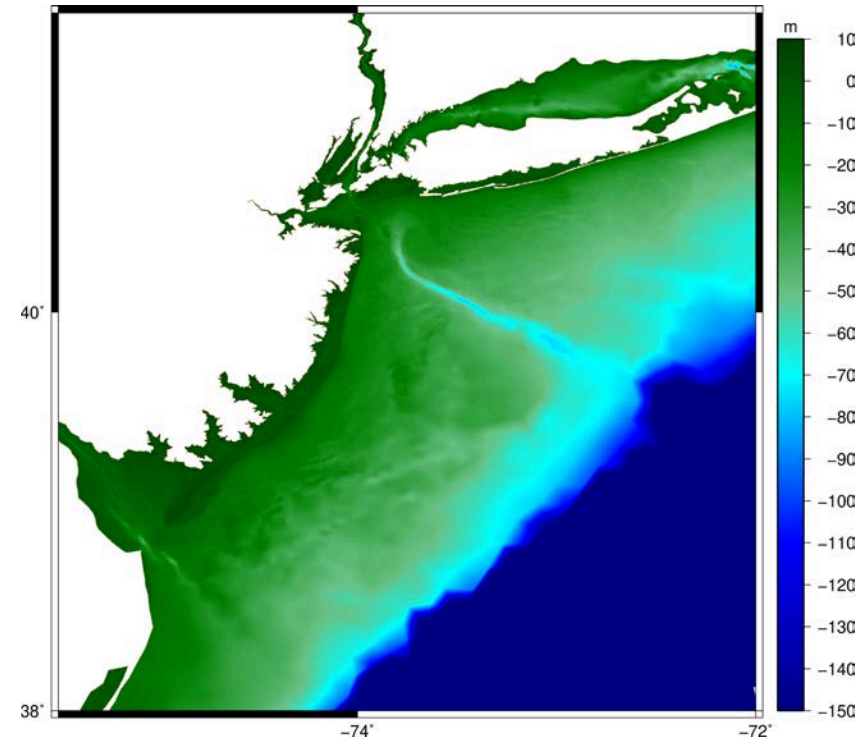
IOOS | Integrated Ocean Observing System

Community Infrastructure for Building and Coupling Models

ADCIRC Storm Surge Model driven by RUWRF winds



High resolution NJ & NY



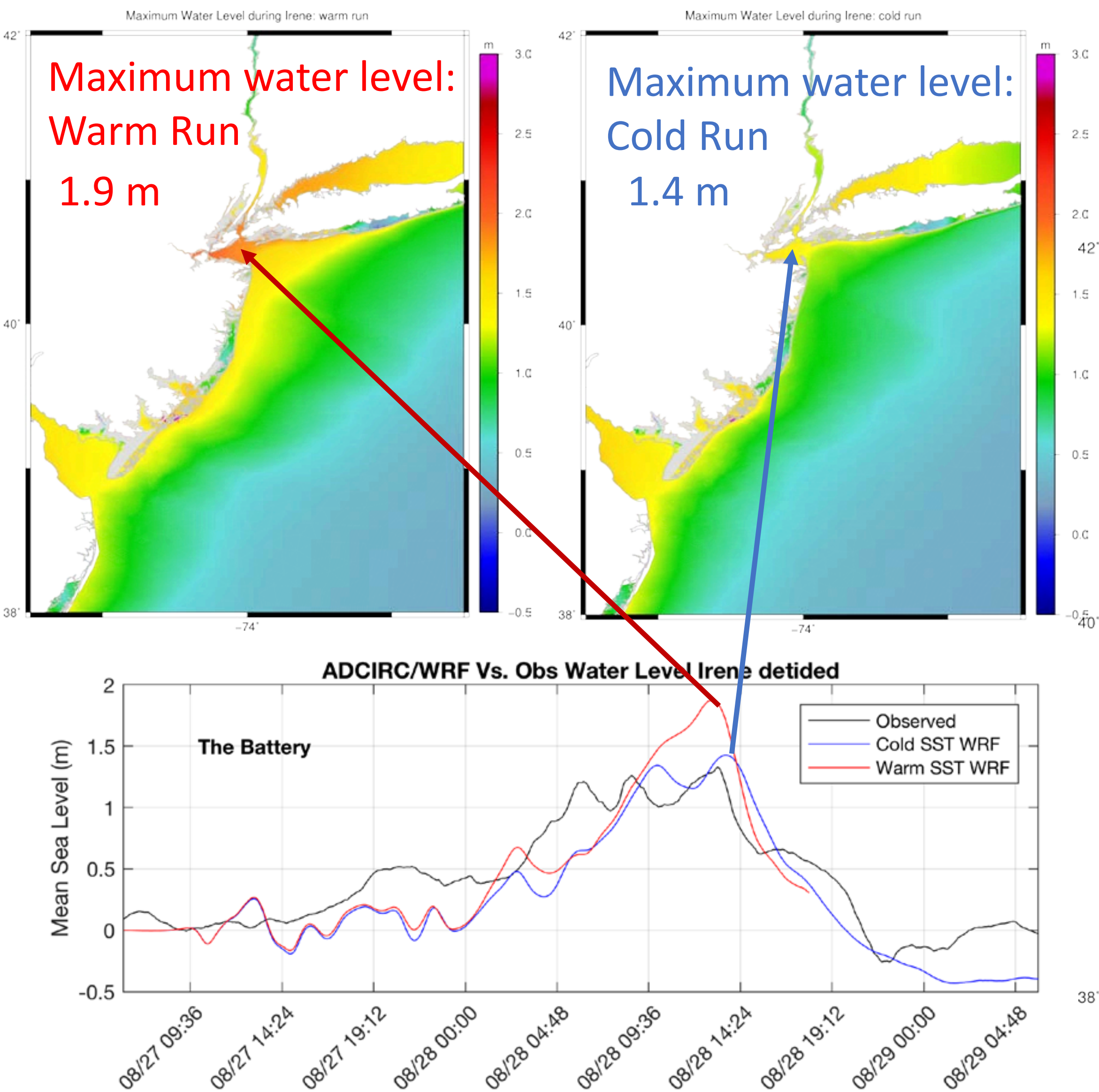
- Barotropic 2D depth integrated version
- Cold start: no tidal forcing
- Waves included
  - SWAN+ADCIRC coupling
  - SWAN passes information to ADCIRC every 10 min

- Simulation length: 2 days
- Model time step = 1s
- Variable Coriolis
- Quadratic bottom friction parameterization

Courtesy of PhD candidate Alexandra Ramos Valle

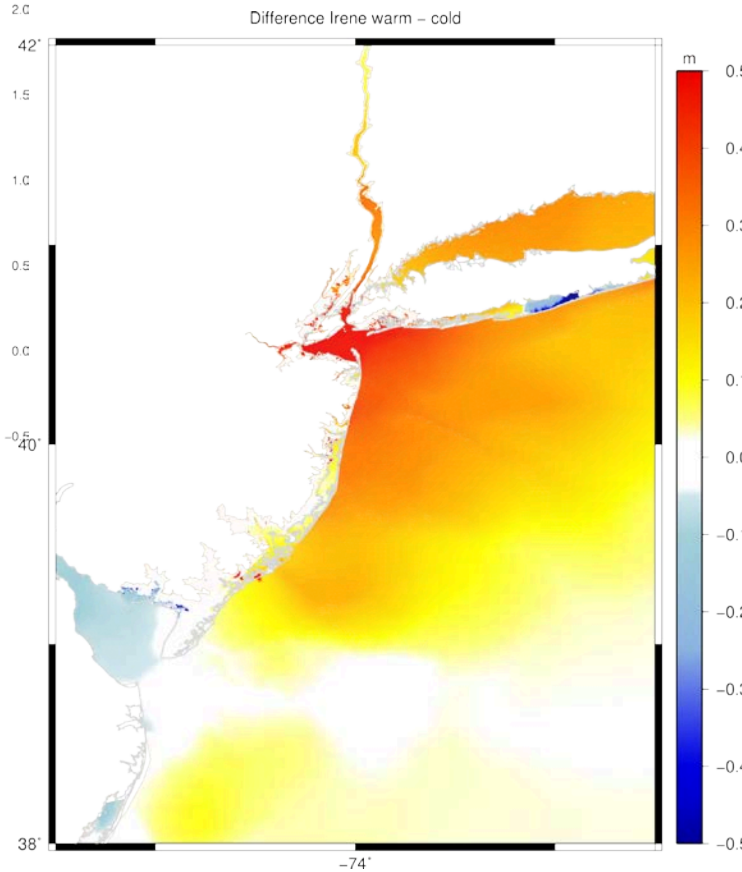
In prep

ADCIRC Storm Surge Model driven by RUWRF winds



Water Level Difference (m)

Warm - Cold

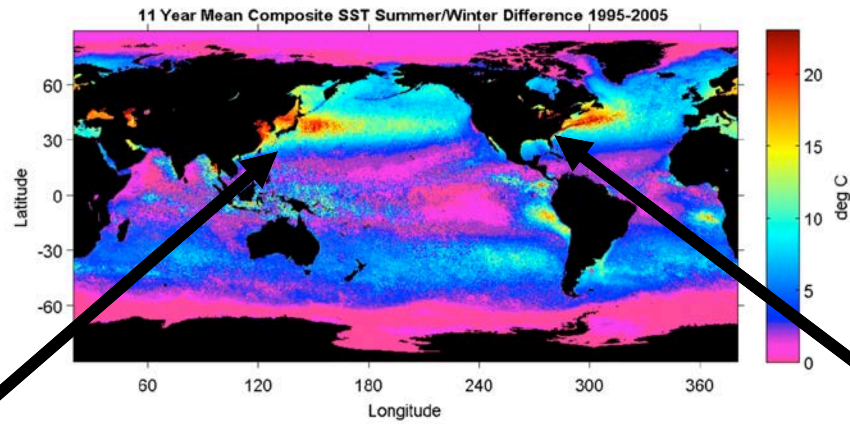


Courtesy of PhD candidate Alexandra Ramos Valle

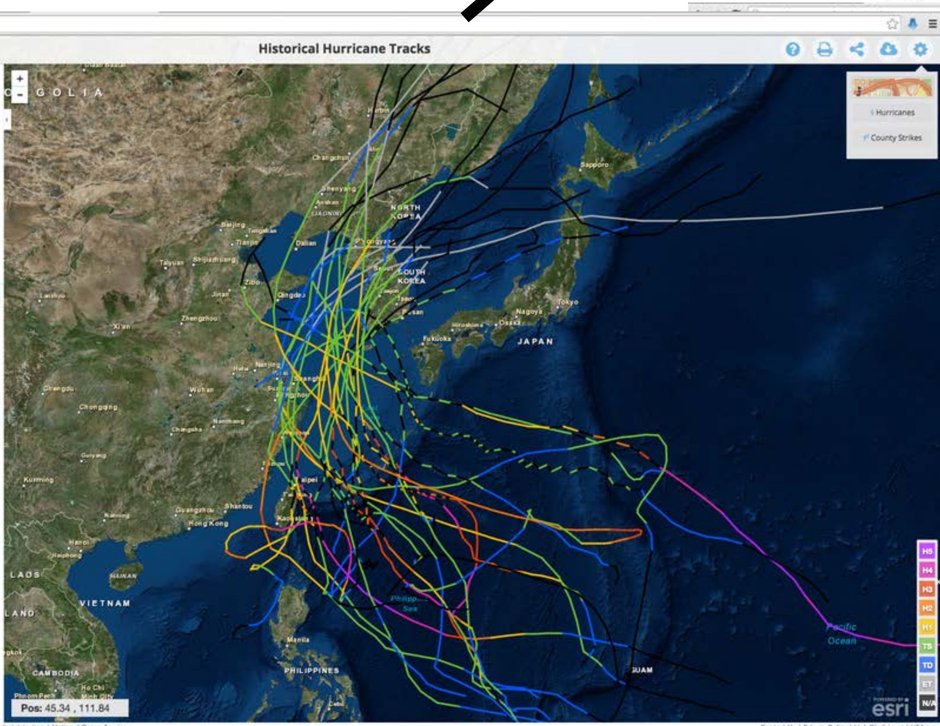
In prep

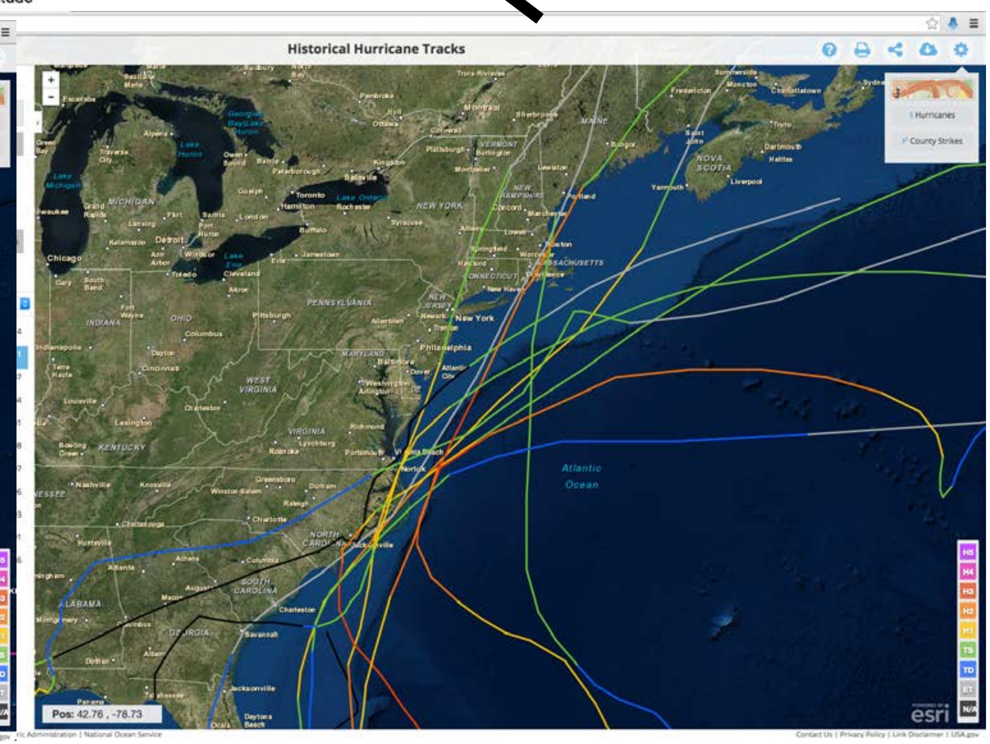
Summer Tropical Cyclones Tracks over the Continental Shelf

Yellow Sea
26 Typhoons
since 1985



Mid Atlantic Bight
11 Hurricanes
since 1985



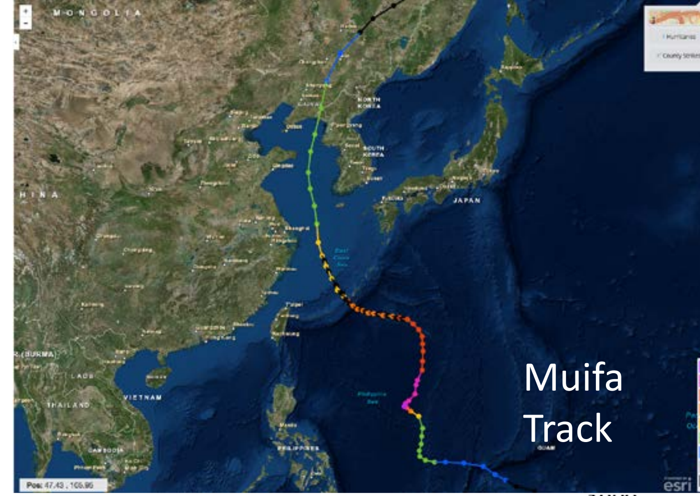


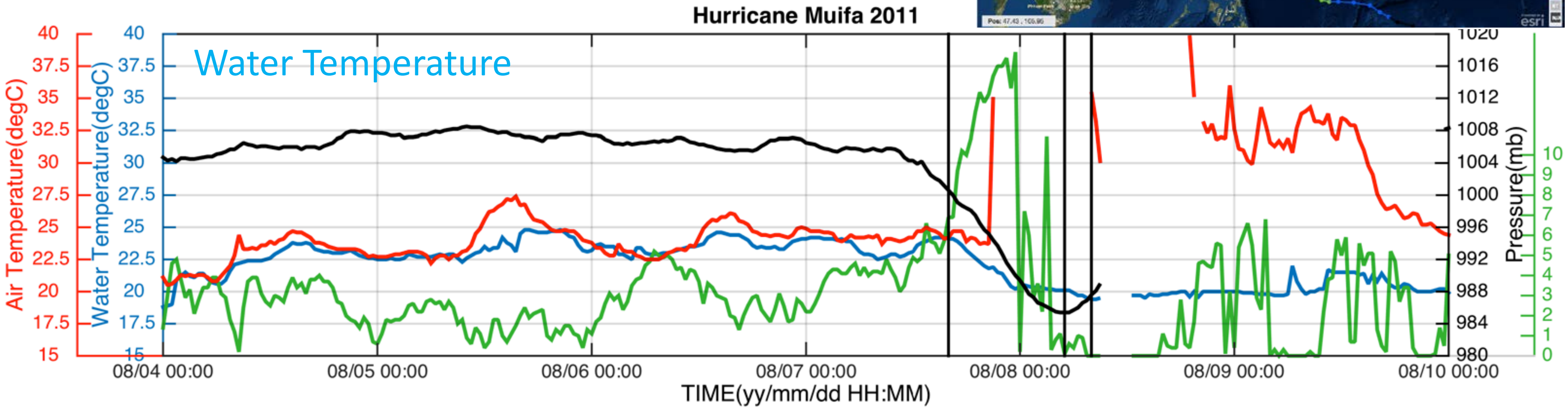
Historical Hurricanes Crossing the MAB in Stratified Season Observed Ahead-of-Eye-Center Cooling

Storm Name	Buoy	Water Depth (m)	Ahead-of-Eye Cooling (°C)	Total Cooling (°C)	% Ahead-of-Eye
Arthur (2014)	44014	48	1.4	2.4	58%
Irene (2011)	44100	26	6.8	7.2	94%
Barry (2007)	ALSN6	29	5.1	5.1	100%
Hermine (2004)	44009	31	0.9	1.1	82%
Allison (2001)	CHLV2	14	2.3	2.6	88%
Bonnie (1998)	CHLV2	14	4.2	4.2	100%
Danny (1997)	44009	31	2.1	3.6	58%
Arthur (1996)	44009	31	2.3	3.5	66%
Emily (1993)	44014	48	2.3	2.8	82%
Bob (1991)	44025	41	2.1	4.6	46%
Charley (1986)	44009	31	2.7	5.4	50%
Average		**31**	**2.9**	**3.9**	**75%**
STD		**11**	**1.7**	**1.7**	**20%**

Buoy data from the 30-year NOAA NDBC Archive

Typhoon Muifa: Ahead-of-Eye-Center Cooling observed by Coastal Buoy

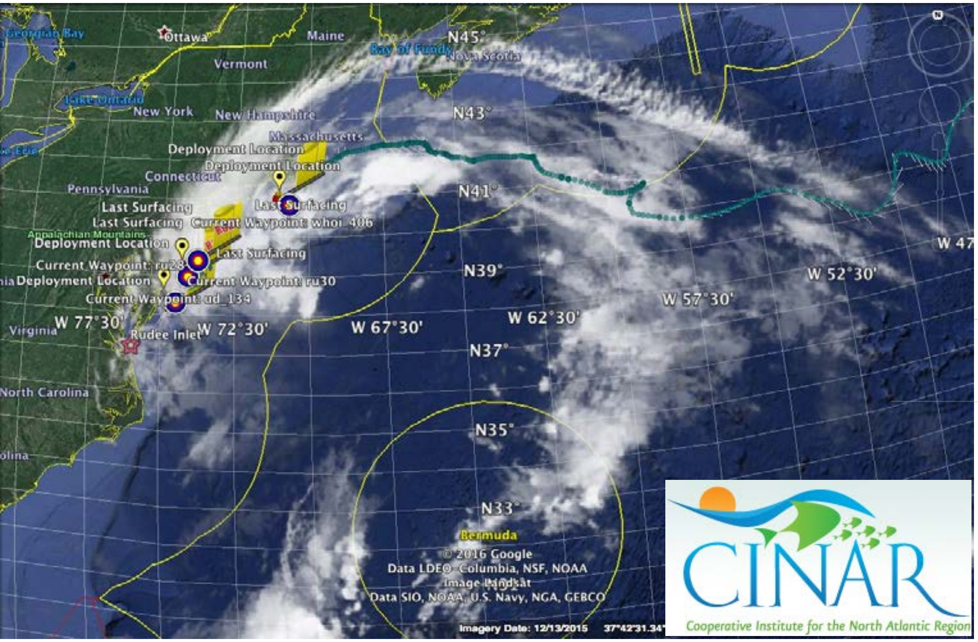


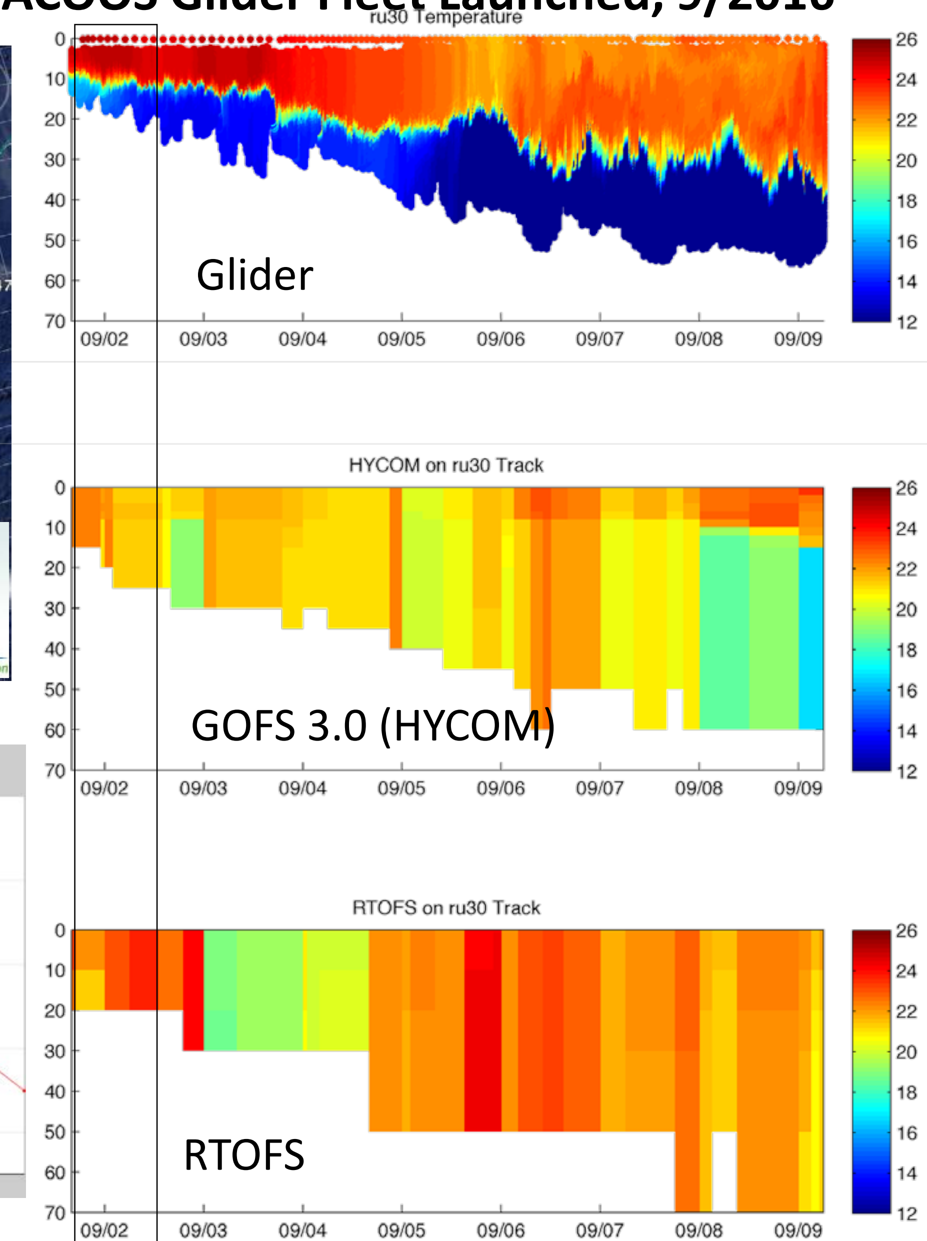


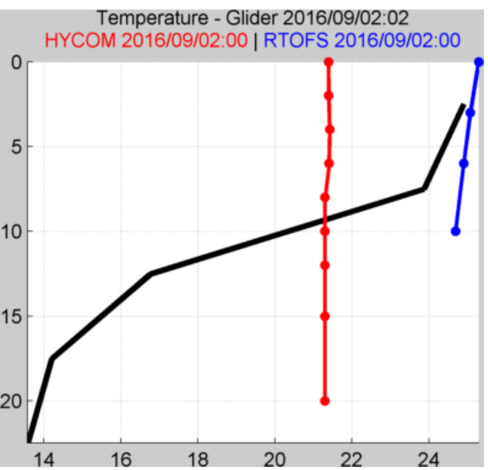
From: Fei Yu, Institute of Oceanology, Chinese Academy of Sciences
Yi Xu, State Key Laboratory of Estuarine & Coastal Research, East China Normal University
Nature Communications, 2016

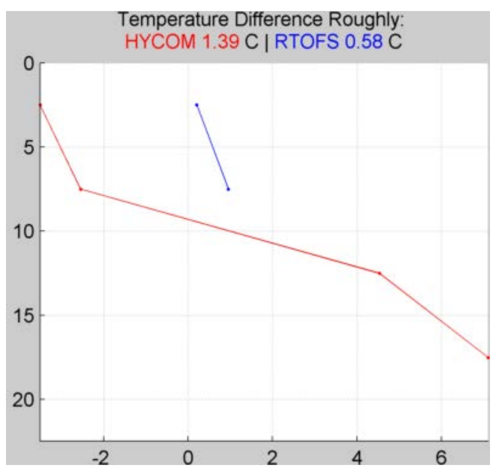
Storm Name	Buoy	Water Depth (m)	Ahead-of-Eye Cooling (°C)	Total Cooling (°C)	% Ahead-of-Eye
Muifa (2011)	37.0445N 122.6558E	31	4.1	4.8	85%

Hurricane Hermine Response: CINAR/MARACOOS Glider Fleet Launched, 9/2016





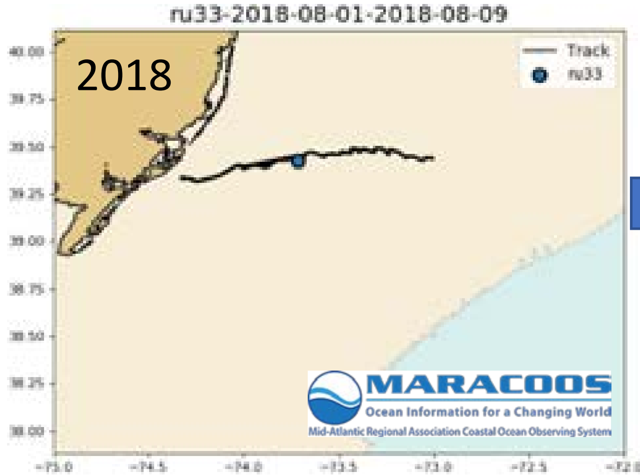


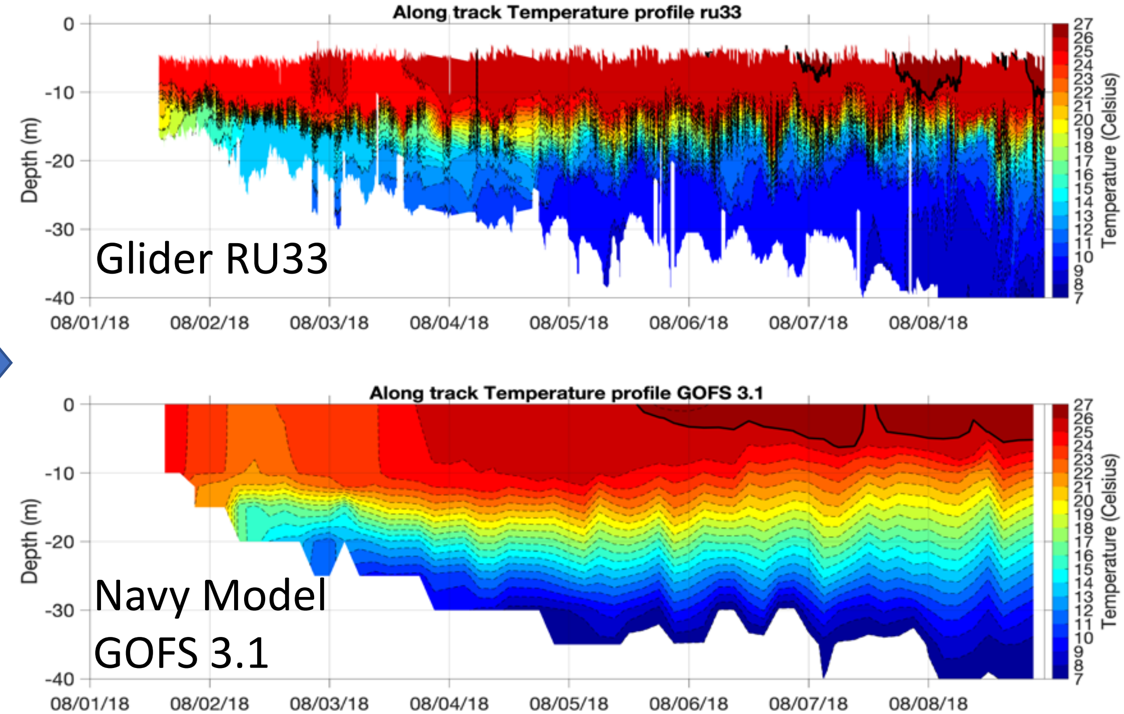


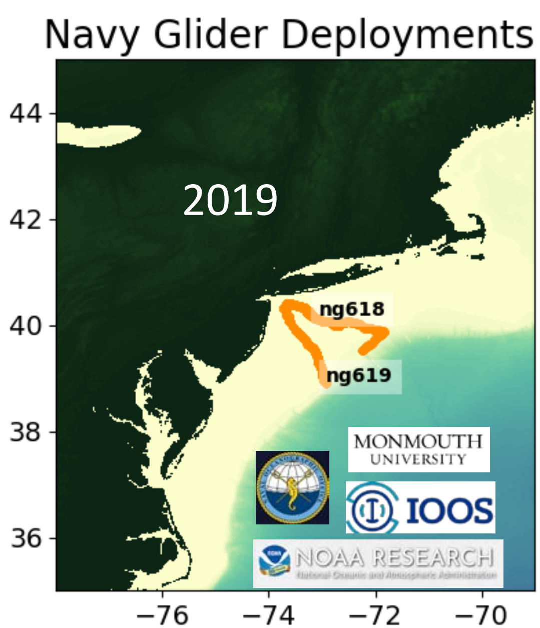
Forecast Models Lack an Essential Ocean Feature - Cold Pool

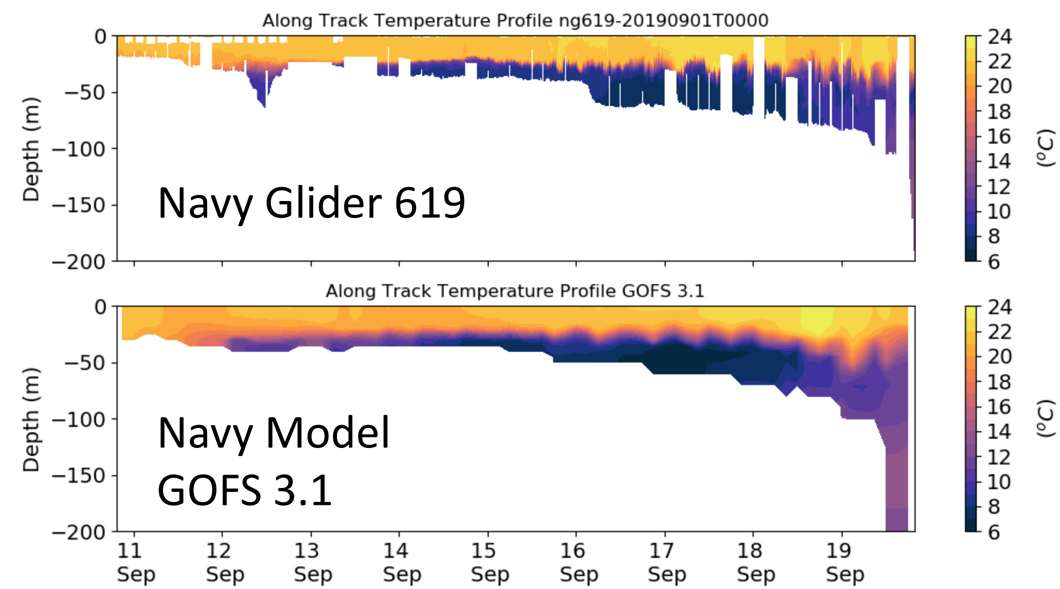
Glider data rejected for assimilation – too far from the model “truth”

Essential Ocean Features in new Navy GOFS 3.1









Slab Lagged Inertial Model (SLIM) Formulation

Governing Equations – Wind Forced **Slab**

$$\frac{\partial u}{\partial t} - fv = F^x_{wind} - cu$$

$$\frac{\partial v}{\partial t} + fu = F^y_{wind} - cv,$$

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

$$F^{x,y}_{wind}(t) = \frac{\rho_a C_D U(t)^2}{\rho_w Z_o}(\cos\theta(t), \sin\theta(t)),$$

Friction: 2-5 days typical

c^{-1} as the e-folding decay time,

Start with a typical mixed layer depth (Zo=10m), calculate predicted inertial signal **Uo**

Cost function – **Uo** scaled (Zo/Z) & time **lagged** (φ) fit to HF Radar observed inertial currents

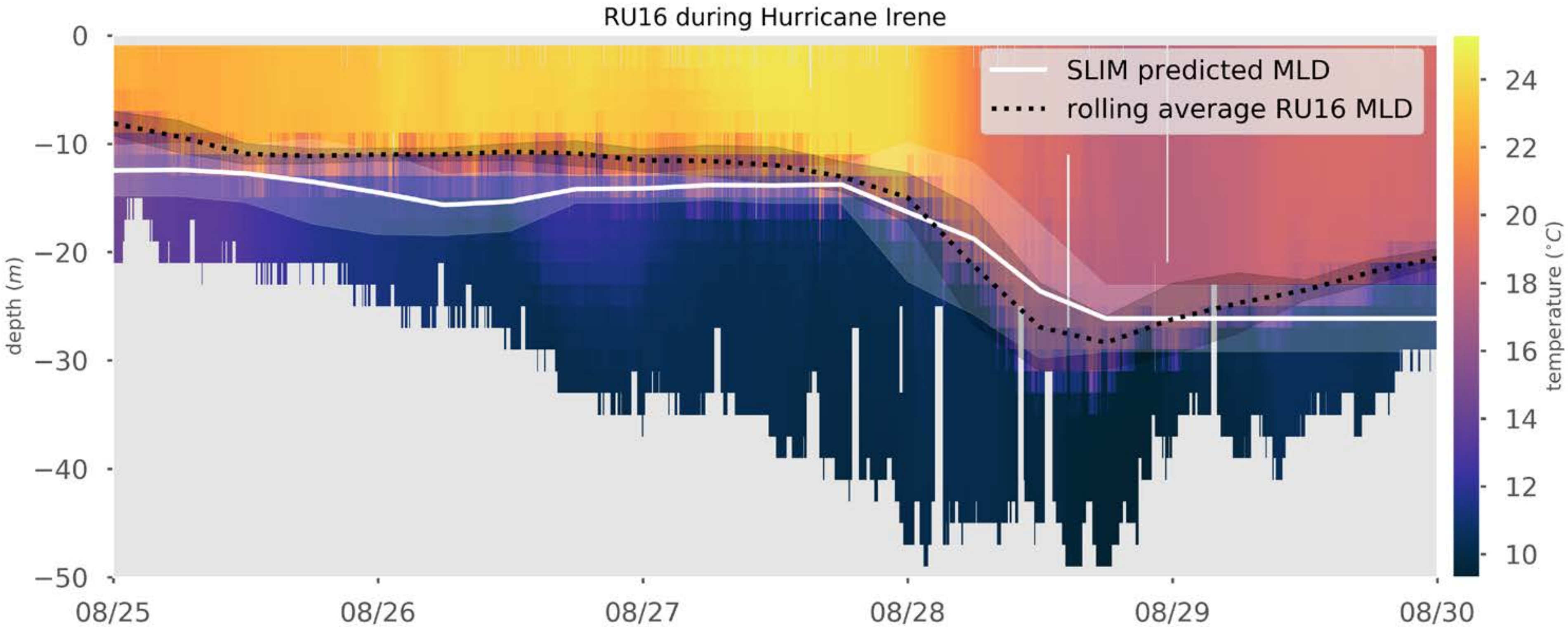
$$\mathbf{J}(Z,\phi) = \sum w\left(U_{radar}(t) - \mathbf{U}_o(t-\phi)\frac{Z_o}{Z}\right),$$

Z is best fit thermocline depth

w is a gaussian in time weighting function centered on a 2-day sliding window

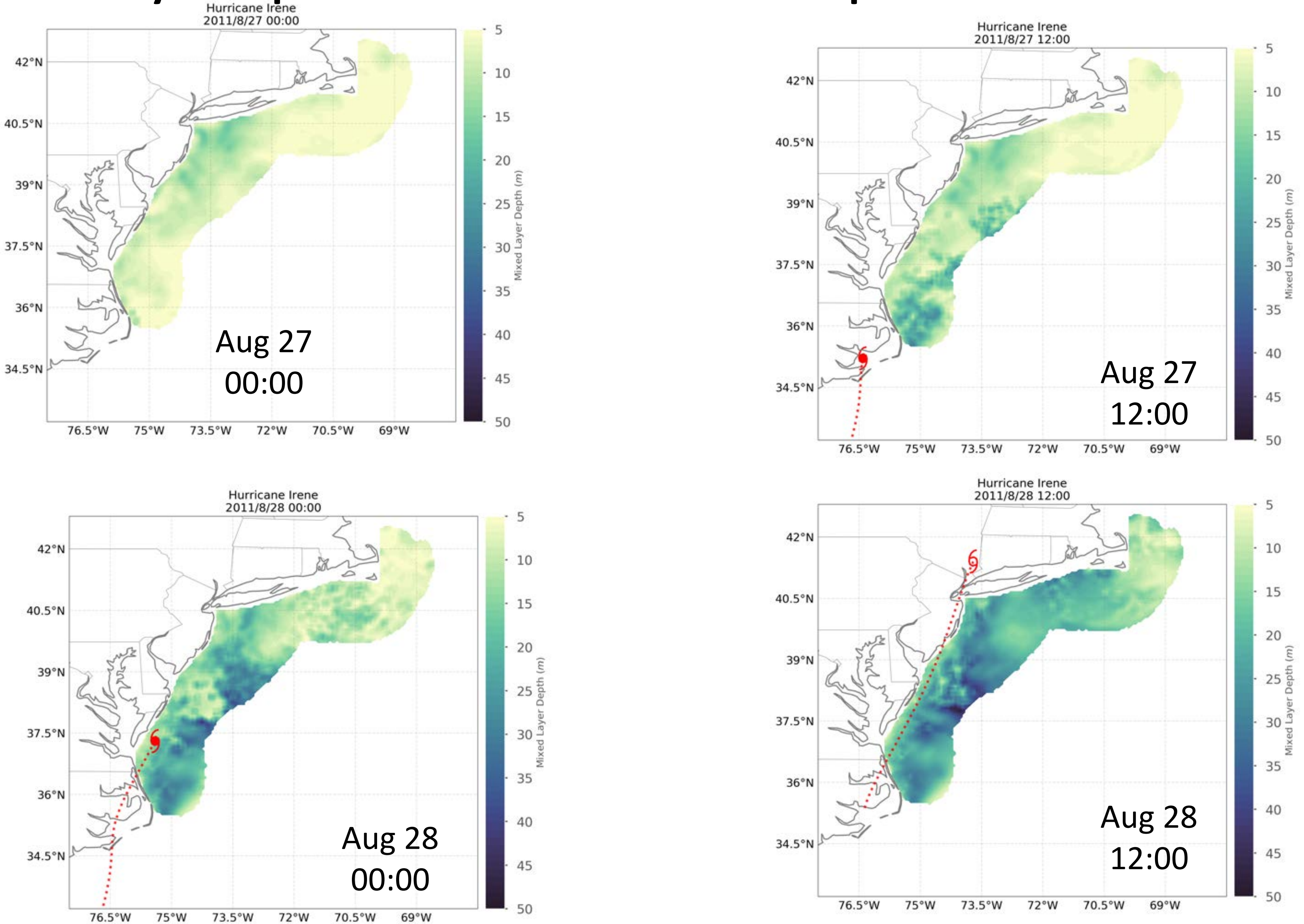
Hurricane Irene –

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

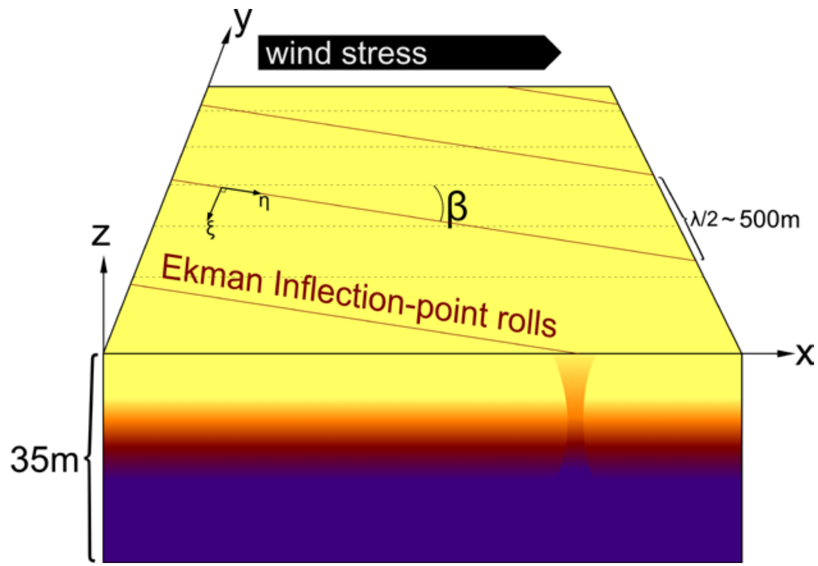
Mixed Layer Depth from HF Radar Inertial Response & Wind Forecast



Cliff Watkins, Thesis Chapter 1

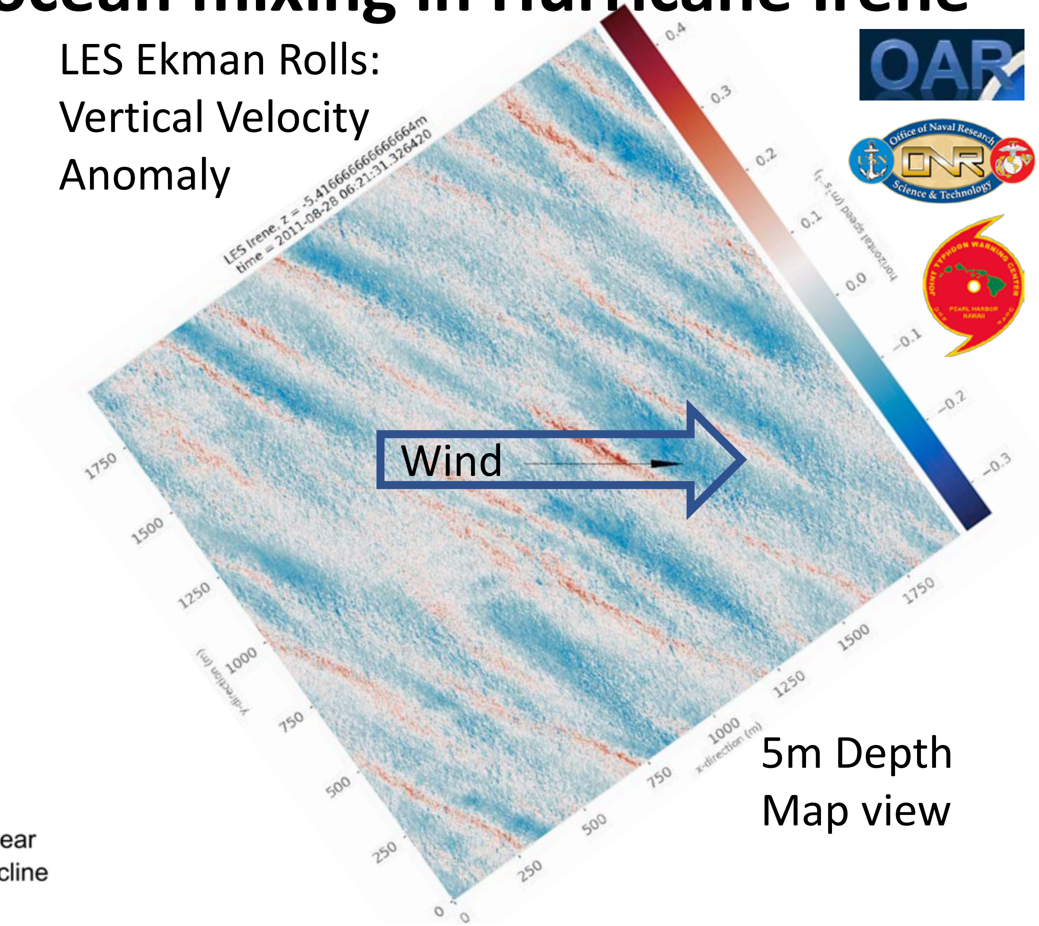
But what mixing processes are causing the MLD deepening?

Large Eddy Simulation of ocean mixing in Hurricane Irene

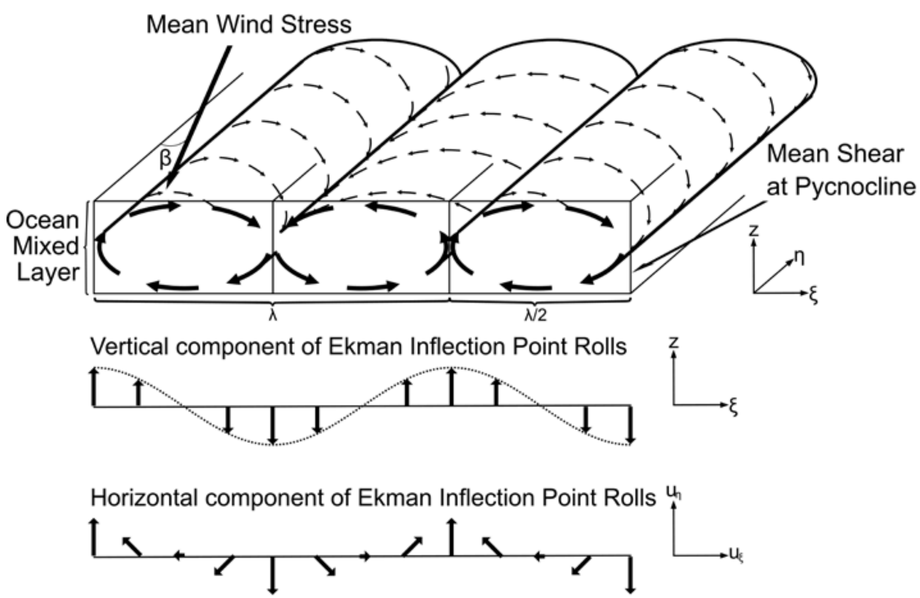


LES Model Set Up

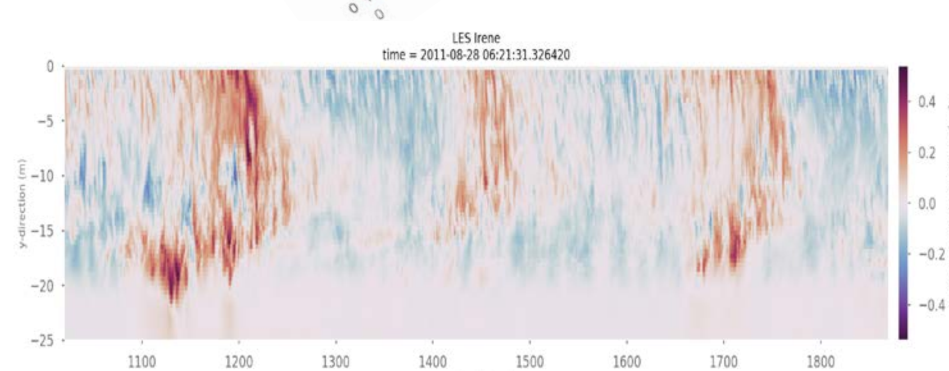
LES Ekman Rolls: Vertical Velocity Anomaly



5m Depth Map view



Idealized Ekman Roll Structures

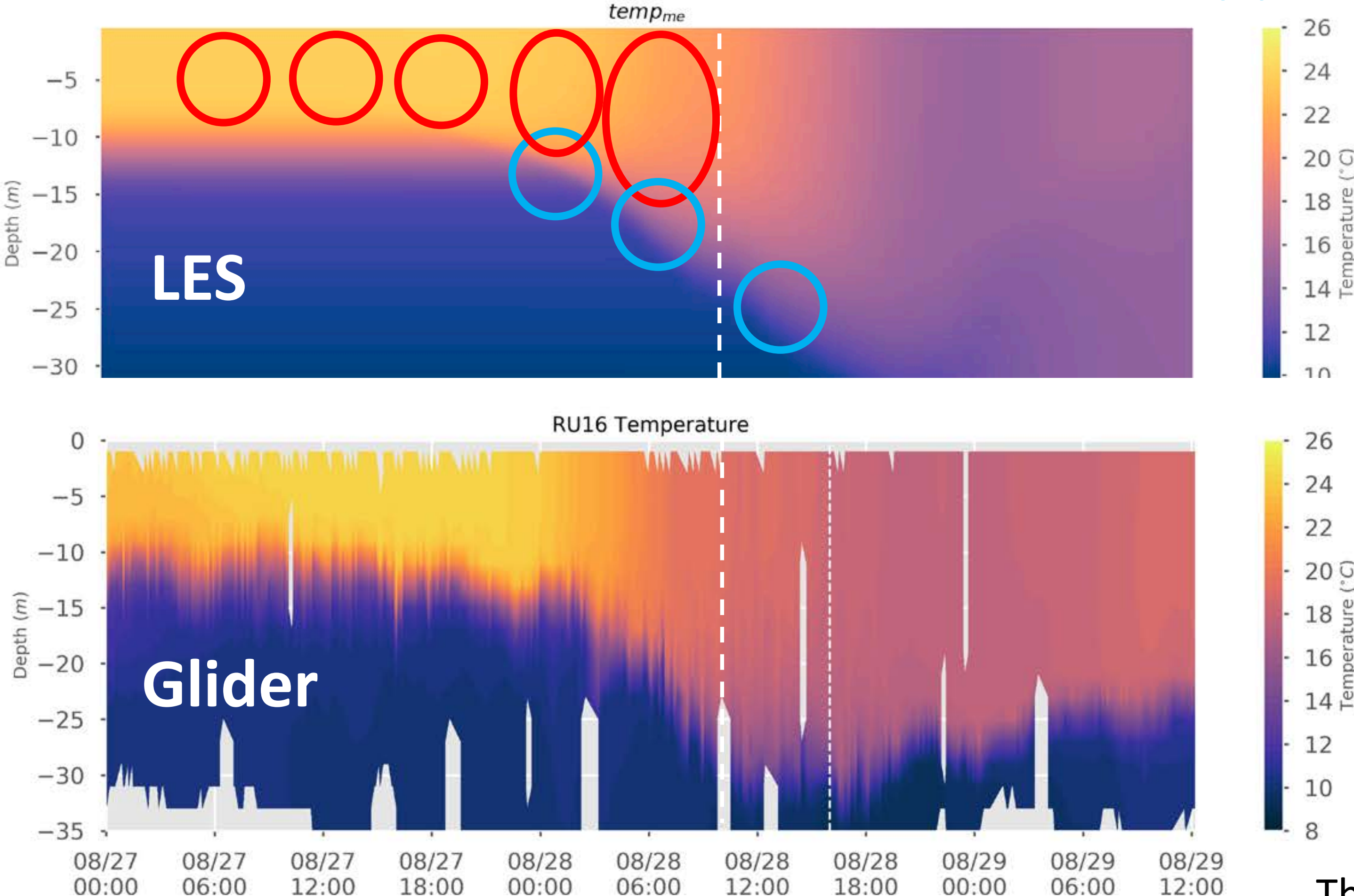


Vertical Section View

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



LES versus RU-16 Temperature profiles

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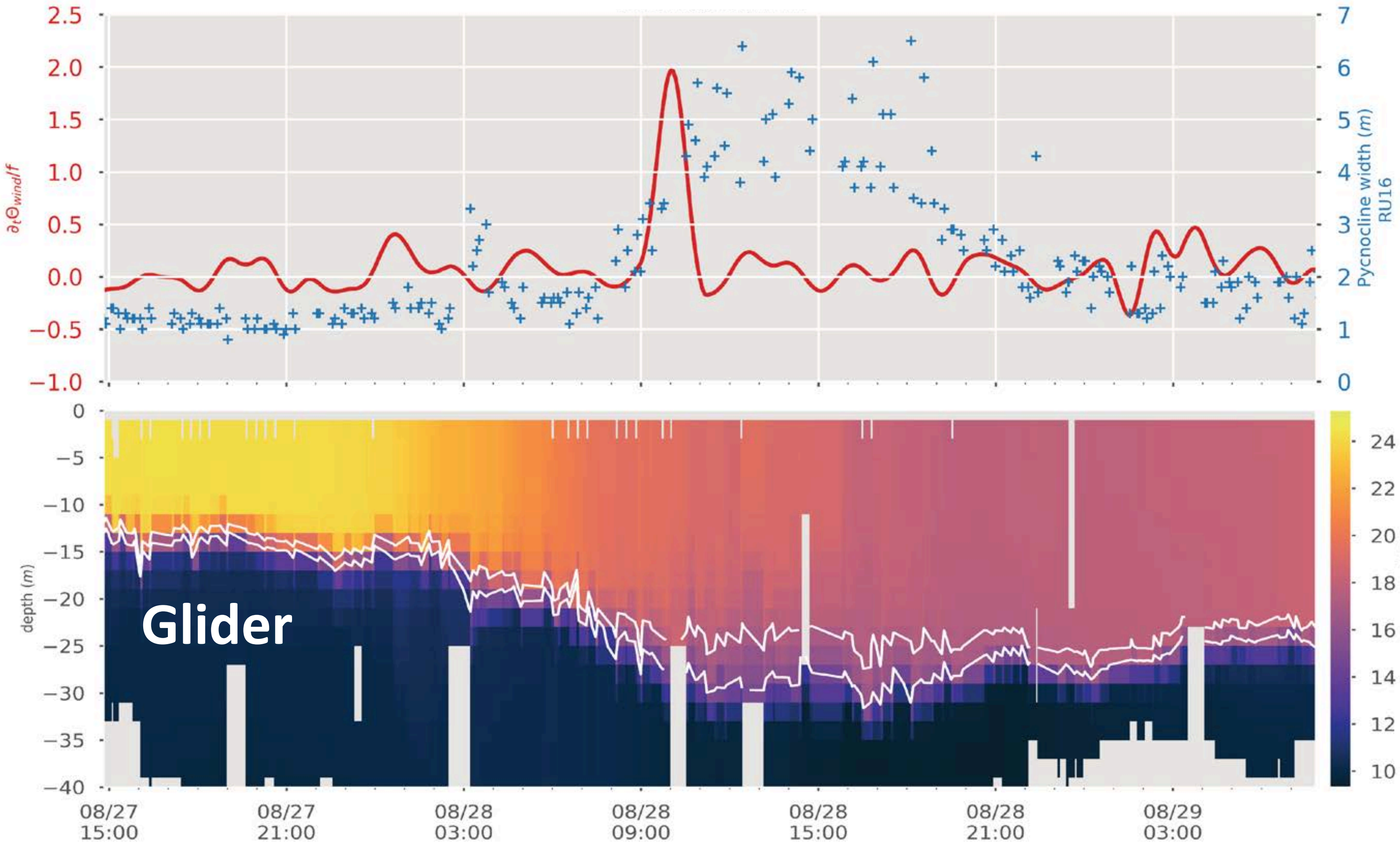
Thesis Chapter 2

TELEDYNE MARINE Everywhereyoulook

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 -

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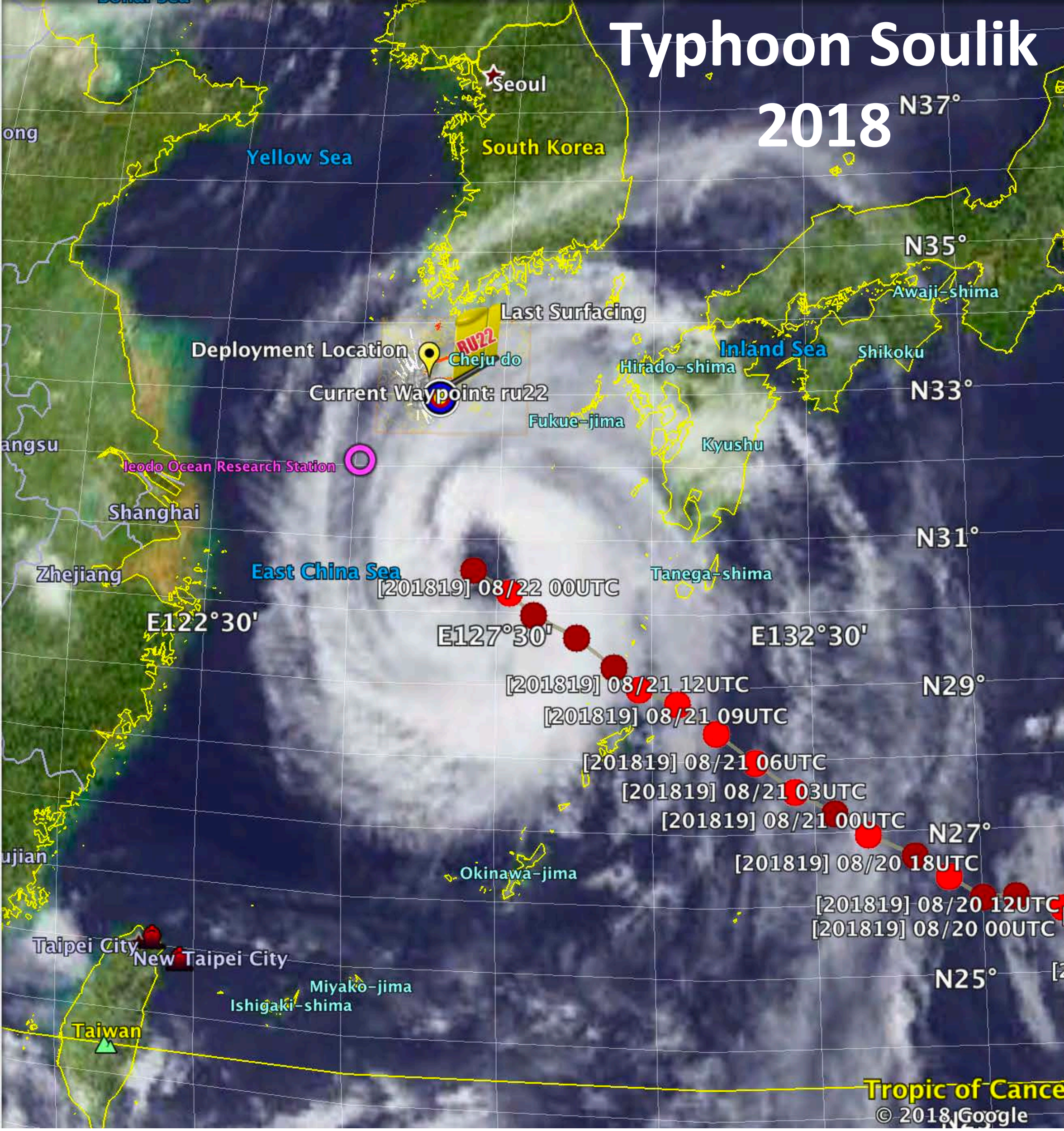
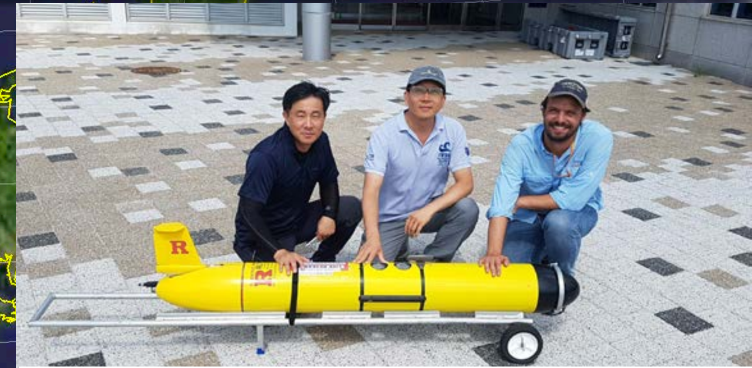
TELEDYNE MARINE Everywhereyoulook™

Typhoon Soulik 2018





Jeju Is. Pre-deployment & Recovery

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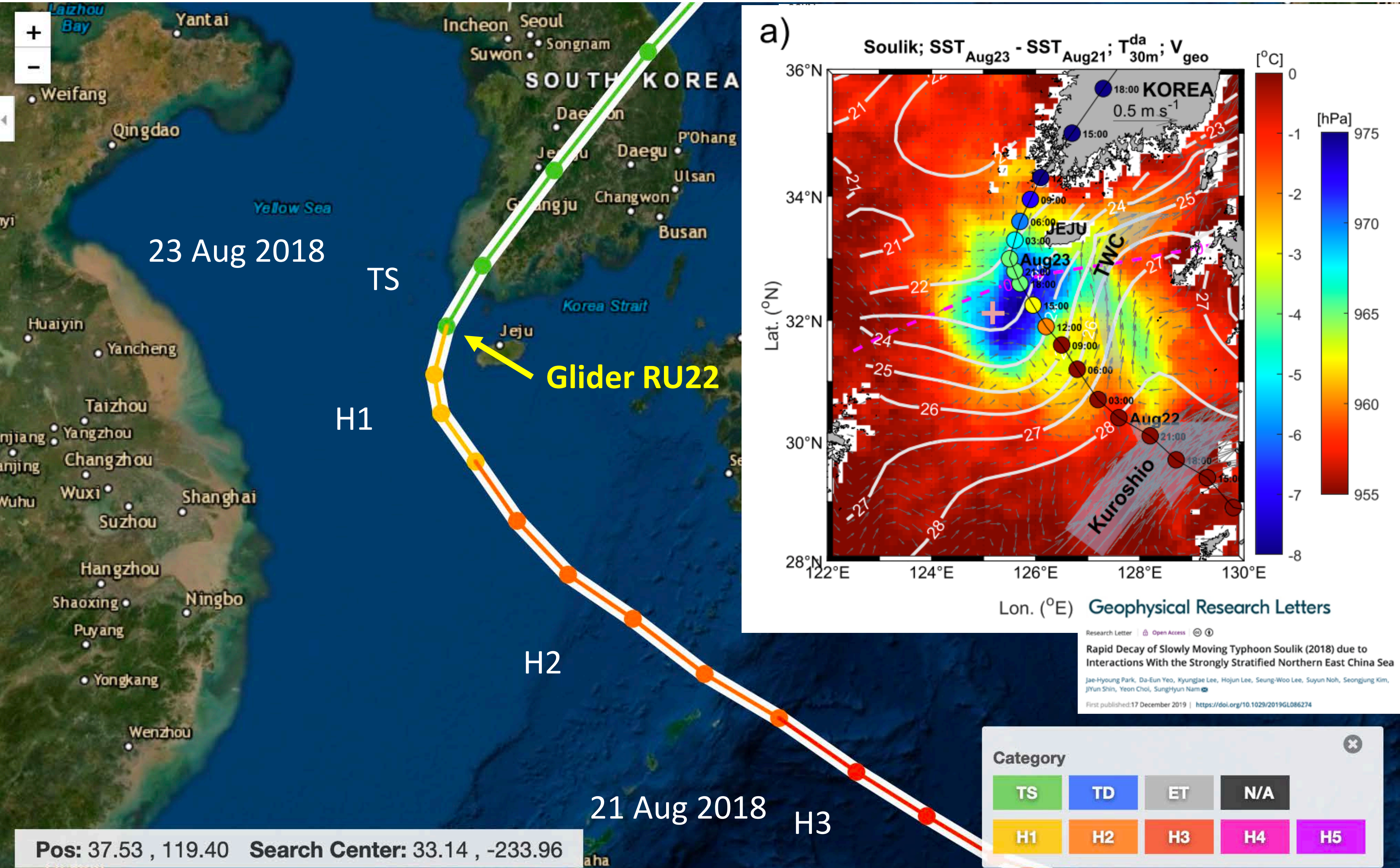
NOAA RESEARCH National Oceanic and Atmospheric Administration

Rapid Coevolution of Typhoon Soulik & Stratified Yellow Sea



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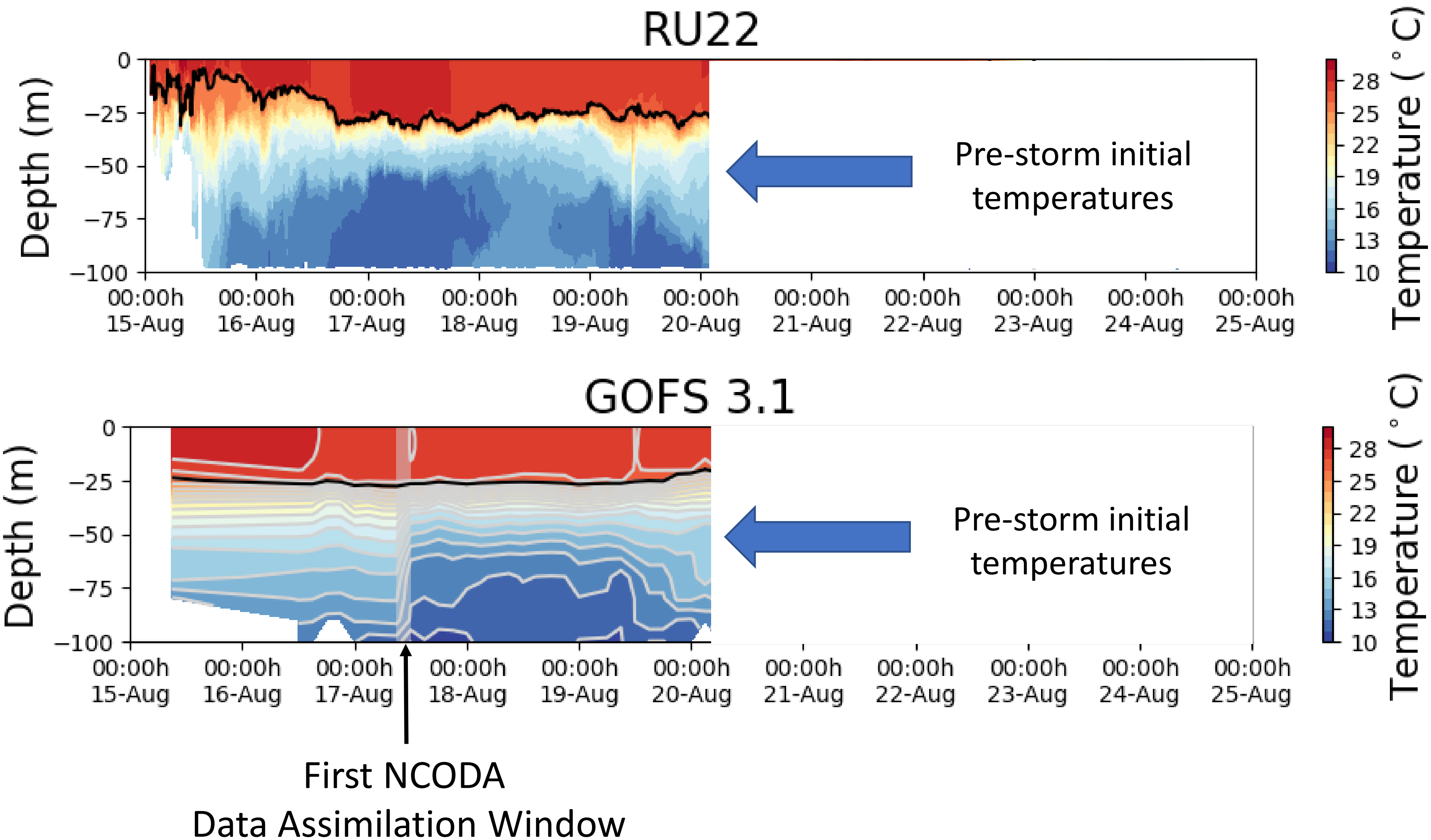
Typhoon Soulik – Glider Comparisons with Global Model



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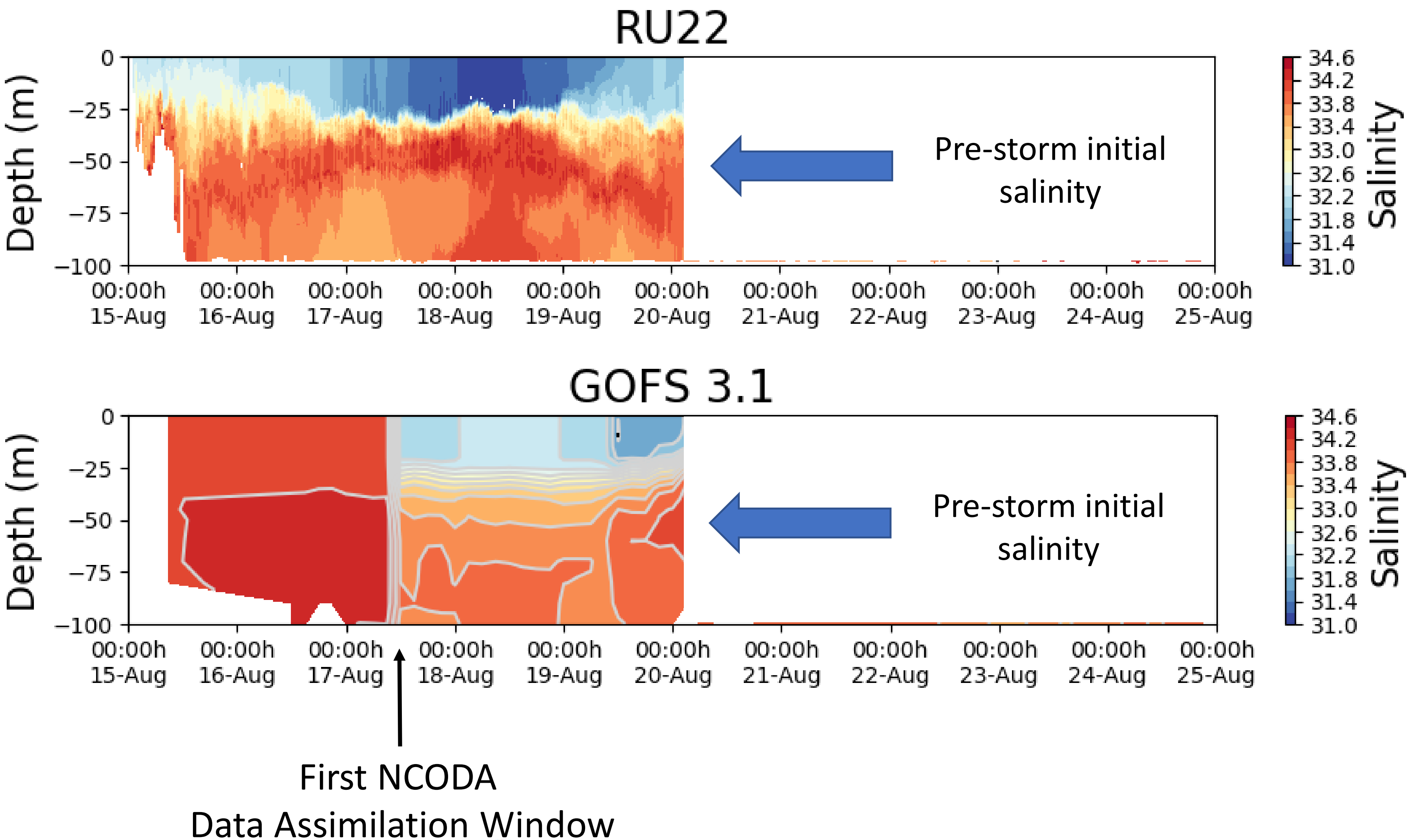
Typhoon Soulik – Glider Comparisons with Global Model



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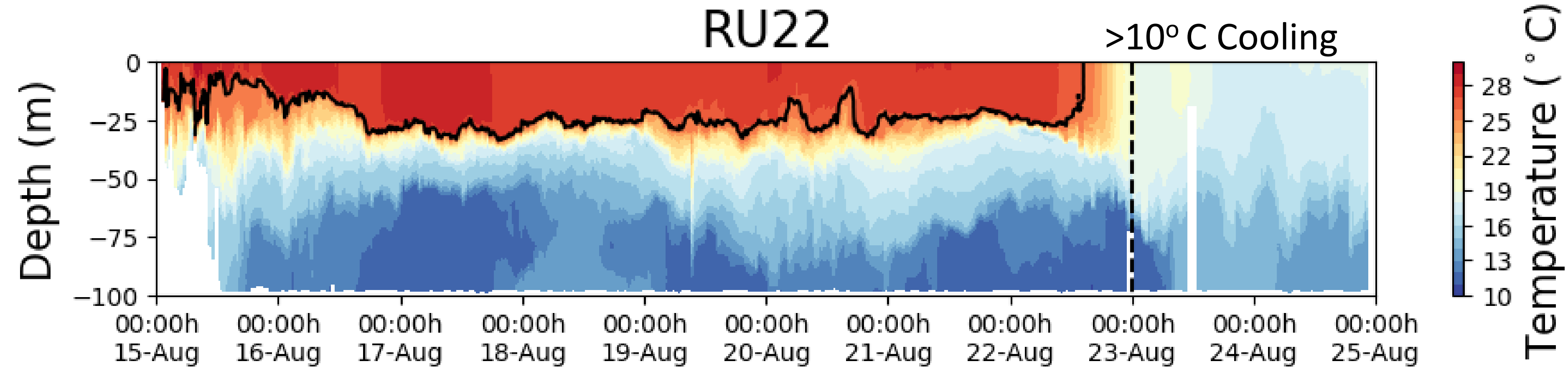

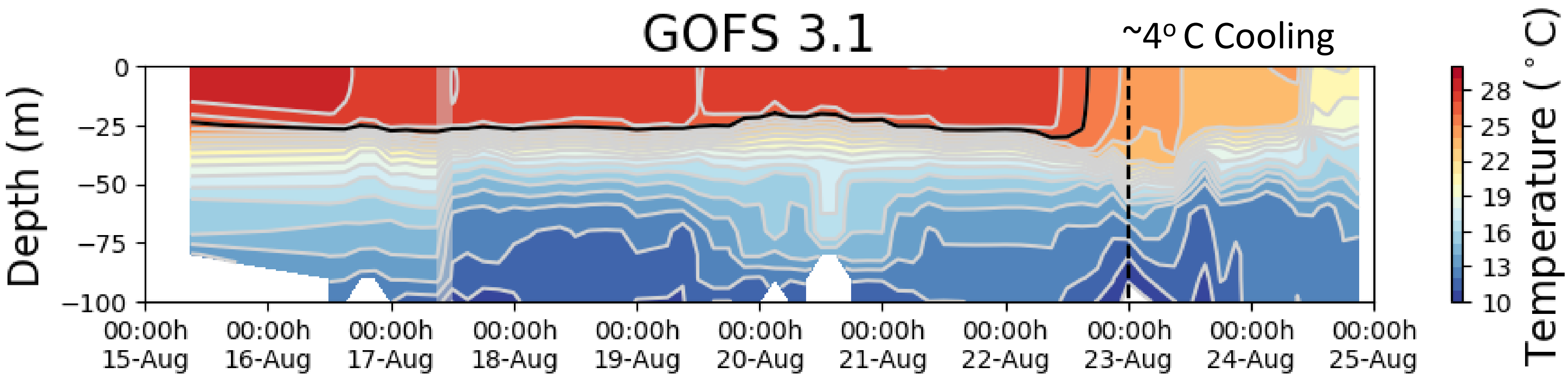

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Conclusions

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