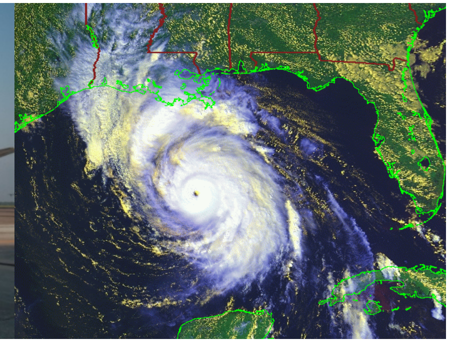
Resolving the Loop Current Complex: Implications on Hurricane Intensity Forecasting

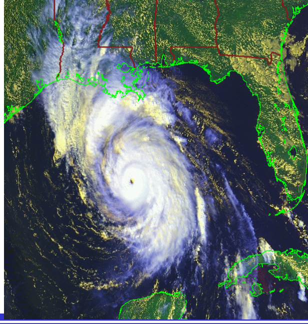


Lynn K. "Nick" Shay

Halliwell, Uhlhorn, Lumpkin, Teague, Jaimes, Meyers, Brewster, Rudzin, Hiron, McCaskill, Schuster,Wadler

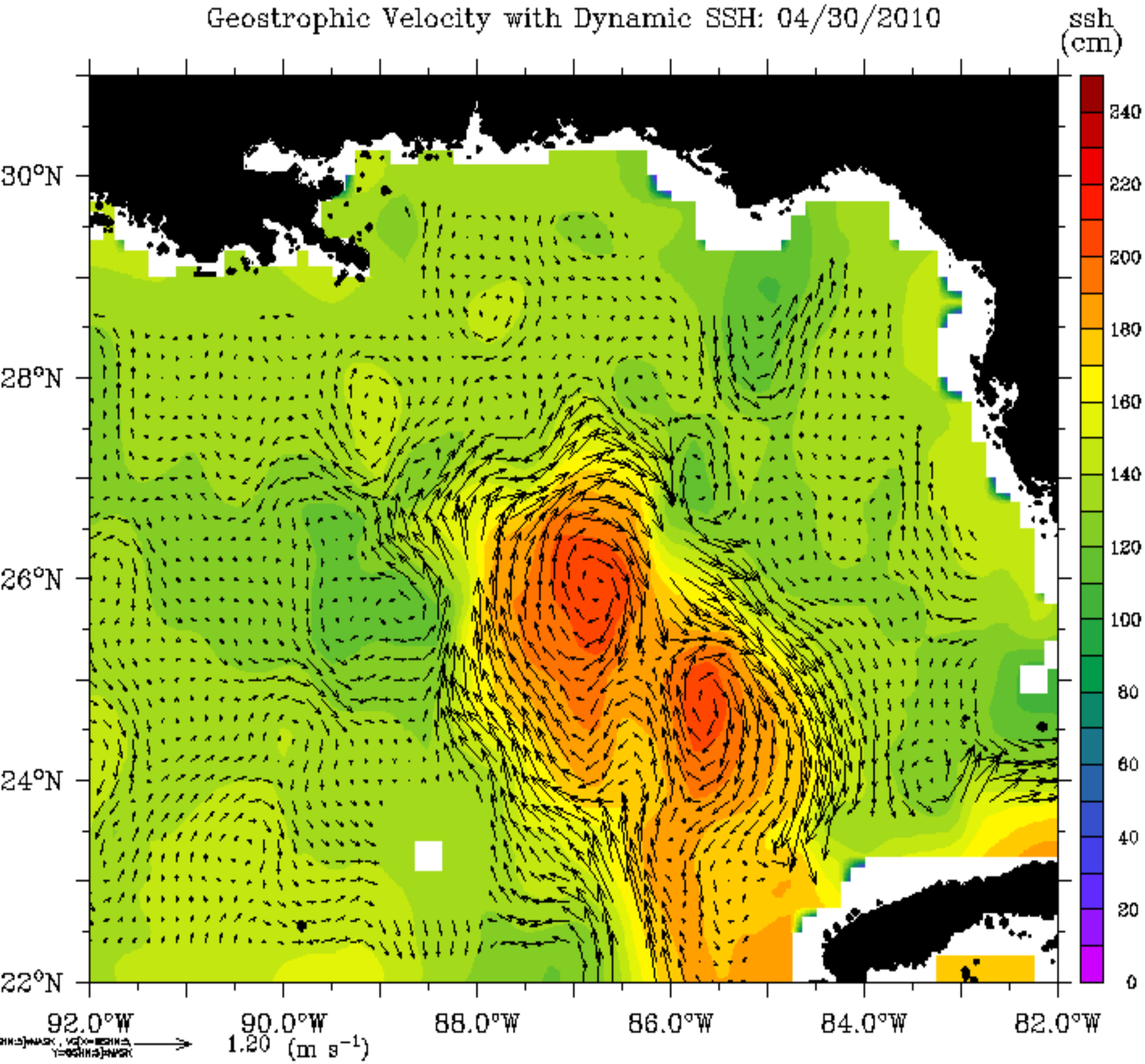
Gratefully Acknowledge NOAA's Hurricane Research Division and Aircraft Operations Center.

Outline:



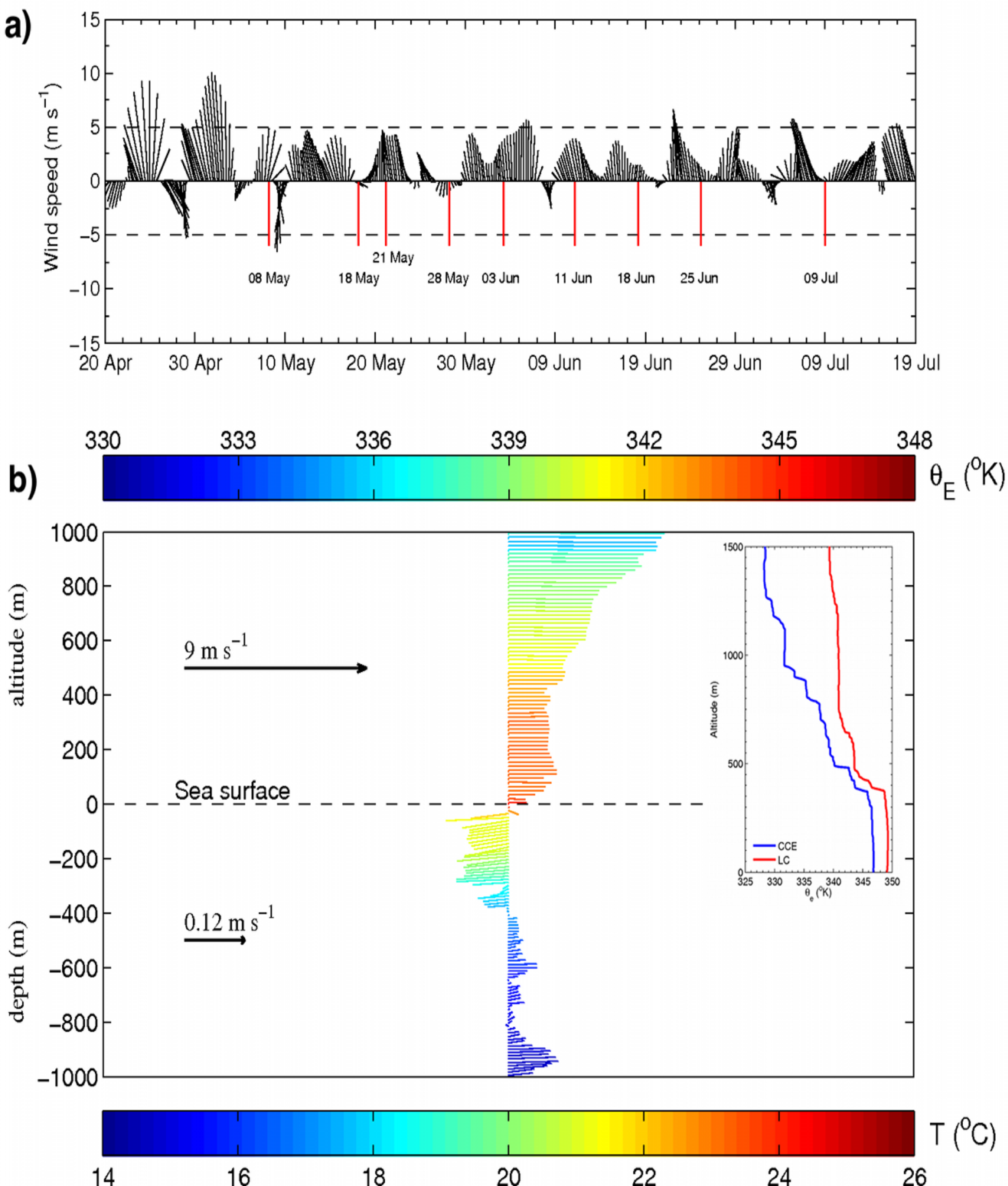
- Motivation
- Ocean Response Characteristics
- Loop Current/Warm Core Eddy Interactions (deep OML)
  1. Isidore and Lili (2002)
  2. Katrina and Rita (2005)
  3. Gustav and Ike (2008)
  4. Isaac (2012)
  5. Nate (2017)
- Cold Core Eddies (thin OML)-Ivan (2004)
- Summary

3-D ocean observations critical to improve forecasting of the coupled response during strong wind conditions.



Evolving Surface Current Structure From Altimetry (Jason-1/2) and Envisat During DwH….

What Happens in the Gulf May Not Stay in the Gulf!



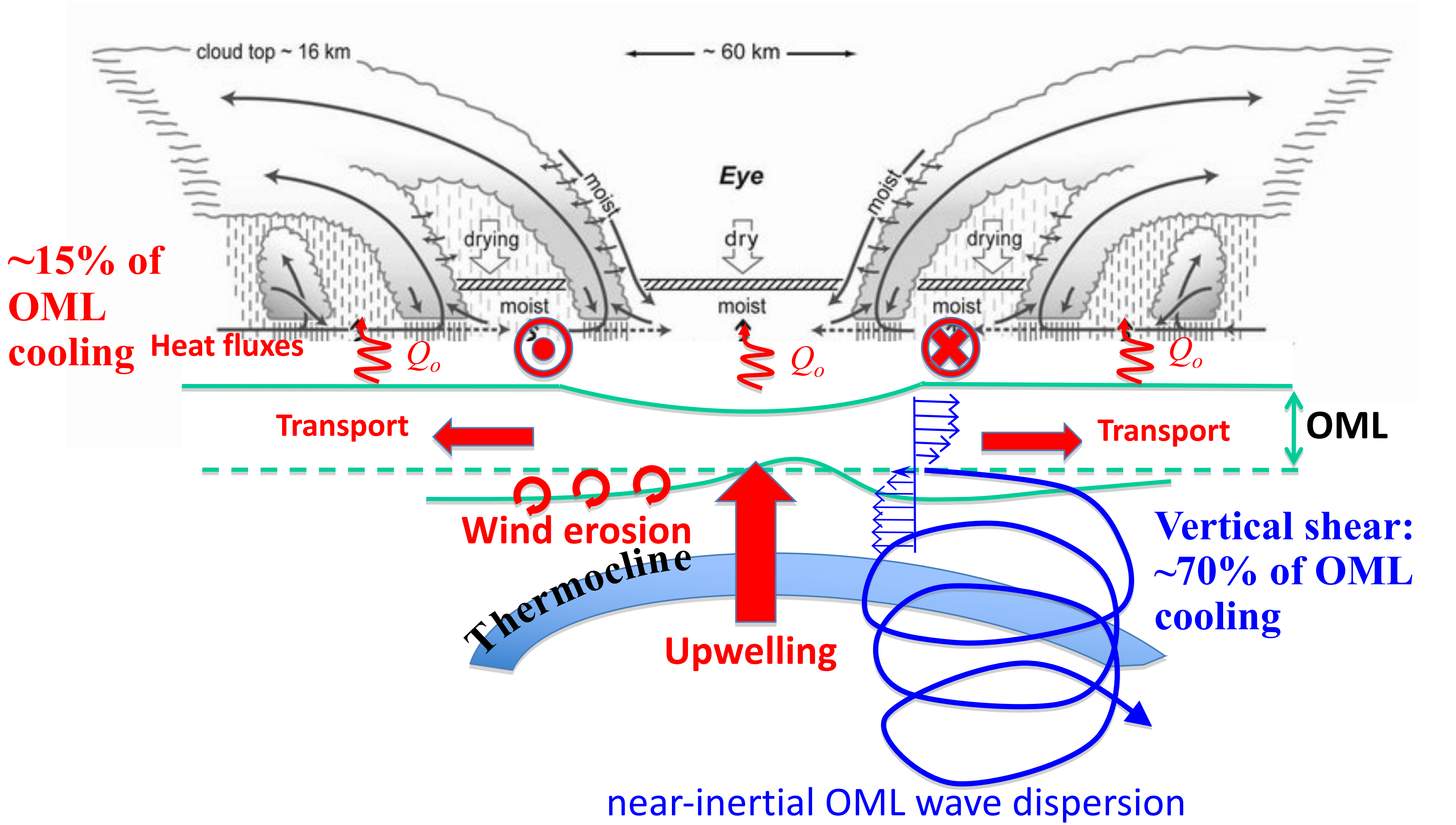
Upper: adjusted surface winds (10-m) at NOAA Data Buoy 42040 located ~55 km NE of DWH-Red lines depict day of the DwH flights.

Lower: atmospheric boundary layer winds from GPS sonde and ocean currents from an AXCP (stick plots) colored to depict equivalent potential temperature (K) and ocean temperature (C).

The OML thermal response is essentially a problem of internal ocean dynamics

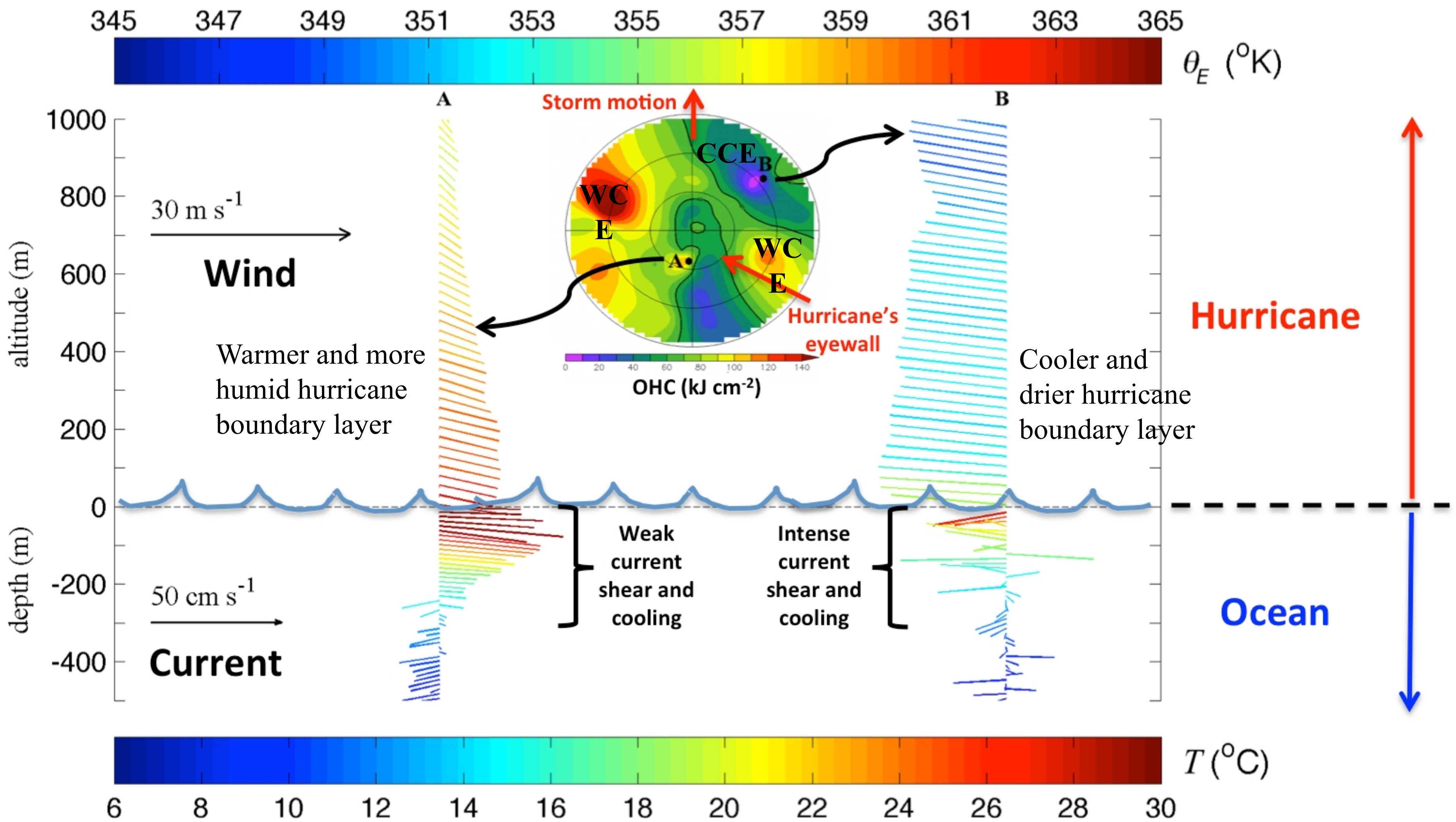
Forced stage

Relaxation stage

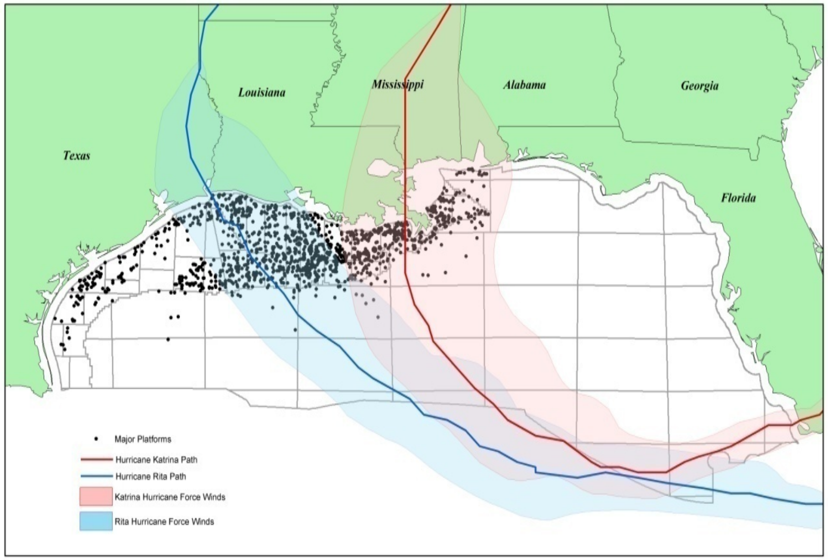


[may induce OML cooling of 65 to 80% (Jacob and Shay, JPO, 2003)]

Mesoscale Feature Effects on Vertical Shear and Mixing

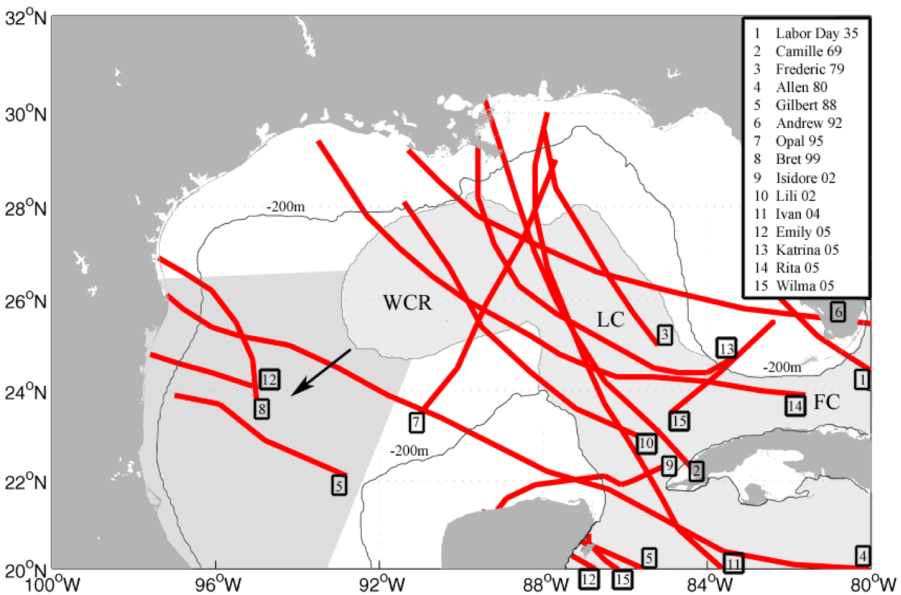


- **Wind vectors are from GPS dropsondes.**
- **Ocean currents are from Airborne eXpendable Current Profiler (AXCP).**
- **OHC: Ocean Heat Content; CCE: Cold Core Eddy (cyclone).**



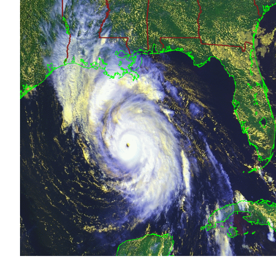
Tracks of Katrina and Rita (2005) in Northern Gulf of Mexico Relative to Oil Rigs.

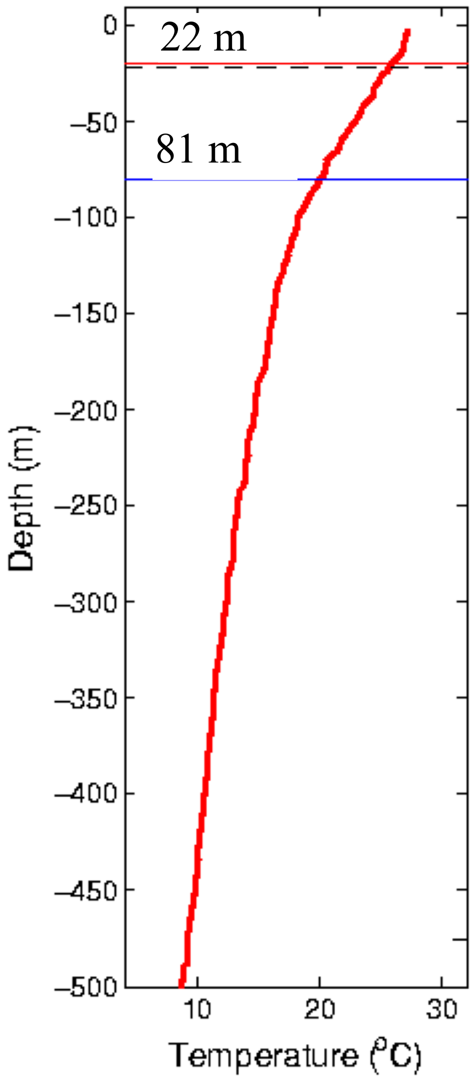
Over 35% of the Rigs were damaged or destroyed in the Gulf.
Pain at the pump!



Historical Tracks of Intense Hurricanes over the Gulf Relative to the Envelope of the LC Complex and the Movement of Warm Core Rings southwest at a few km per day.

From Jaimes and Shay (MWR, 2009)





cyclone

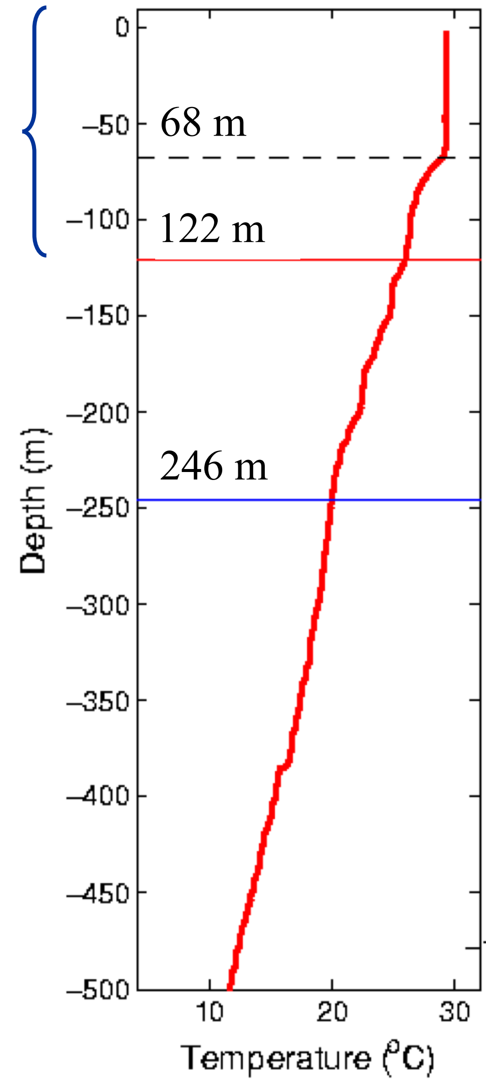
6 kJ cm^{-2}

114 kJ cm^{-2}

$$Q = c_p \int_{H26}^{\eta} \rho(z)[T(z) - 26]\, dz$$

Reduced negative feedback in warm core eddies

Hurricanes reach intensities closer to maximum potential intensity.

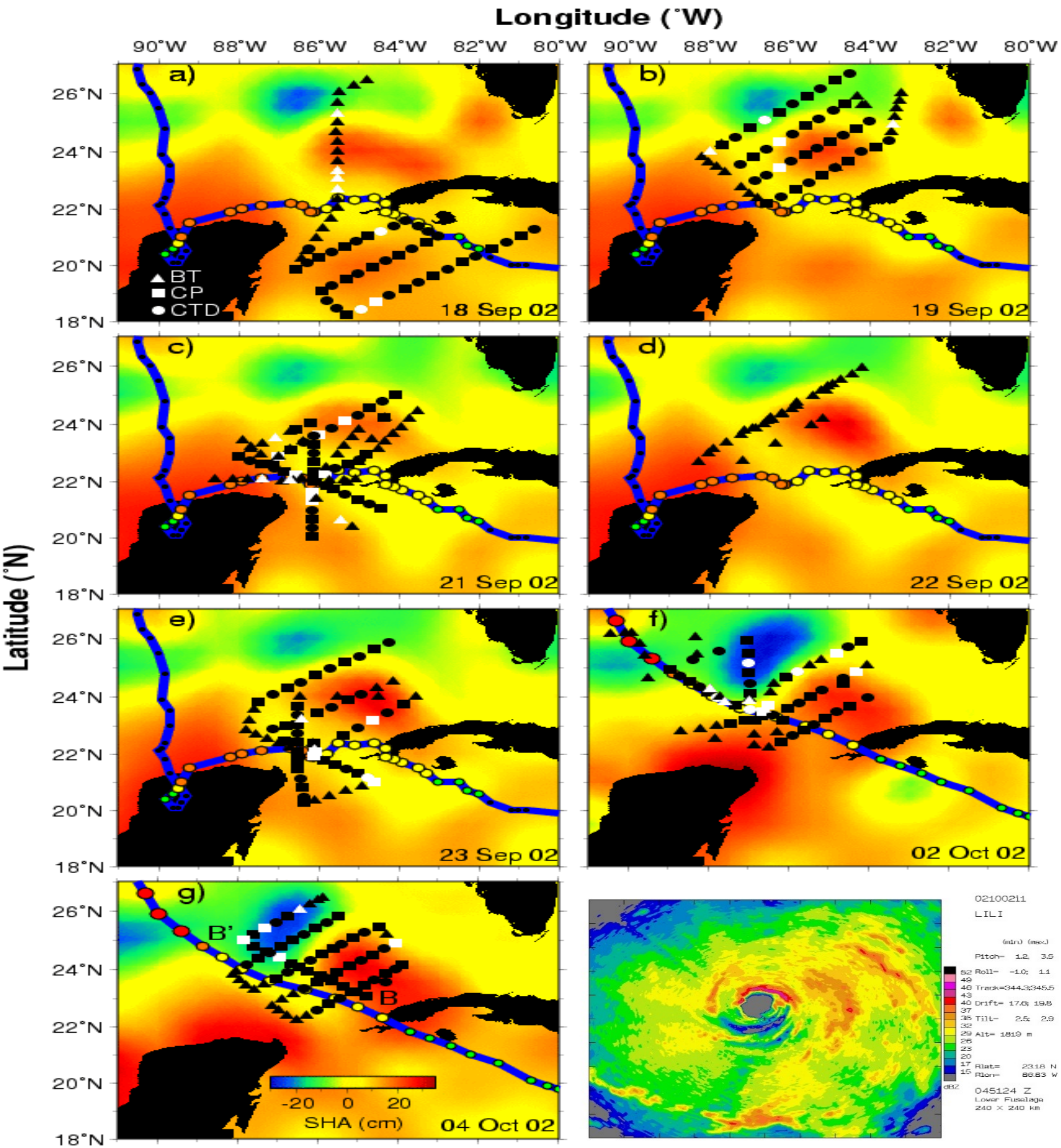


mixed layer depth

26°C

20°C

anticyclone



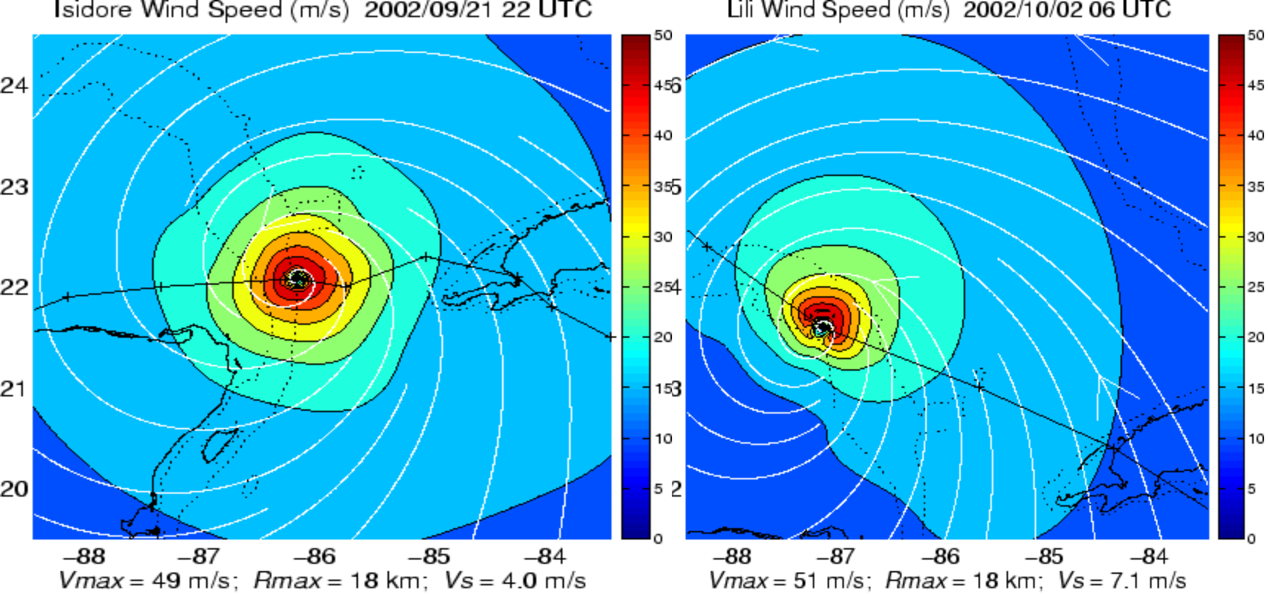
Prototype NSF/NOAA Isidore/Lili (02)”

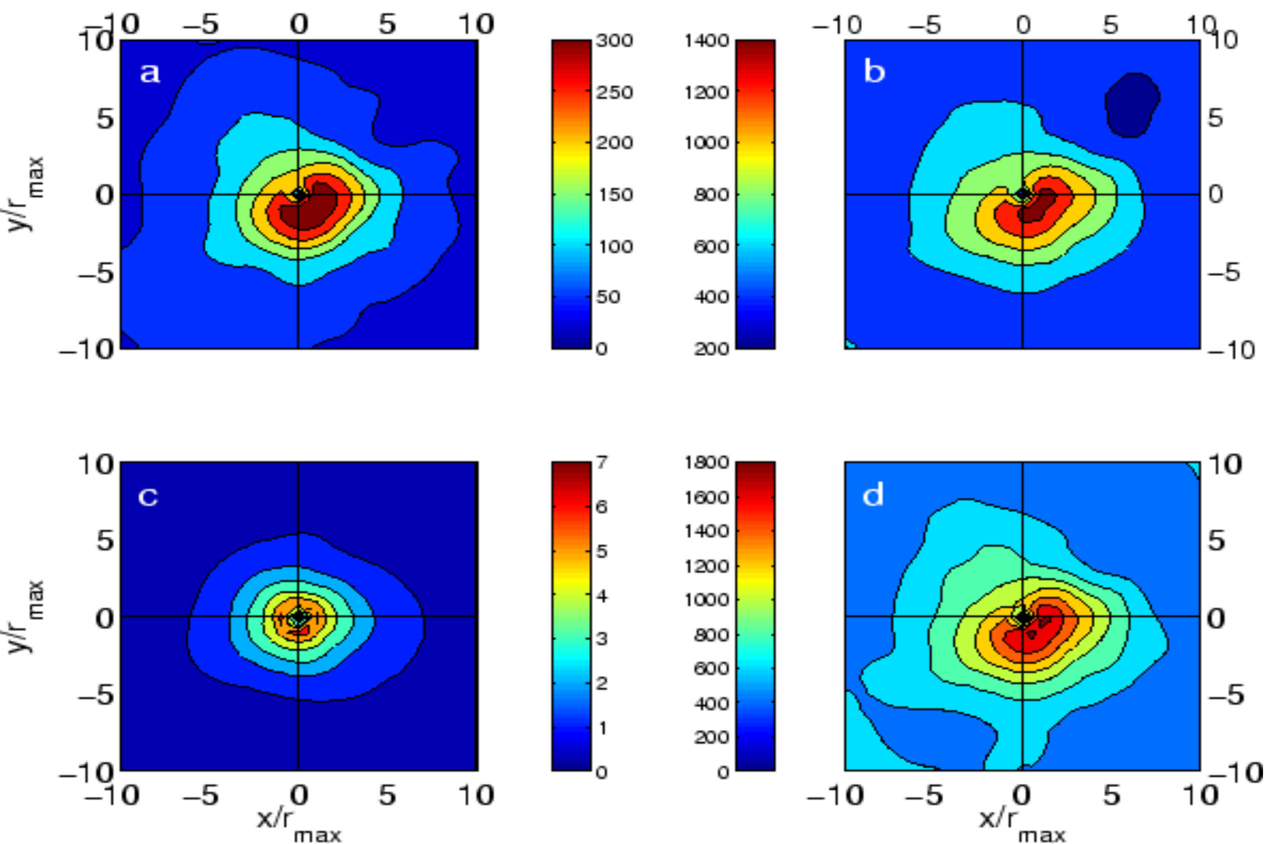
a) Caribbean (Pre)
b) GOM (Pre)
c) Isidore (Dual Aircraft)
d) Wake 1 (Post)
e) Wake 2 (Post)
f) Lili
h) Wake 1 (Post)

SHA field: TOPEX, GFO and ERS-2

Radar Composites of Lili (f)

From (Shay & Uhlhorn, MWR, 2008):

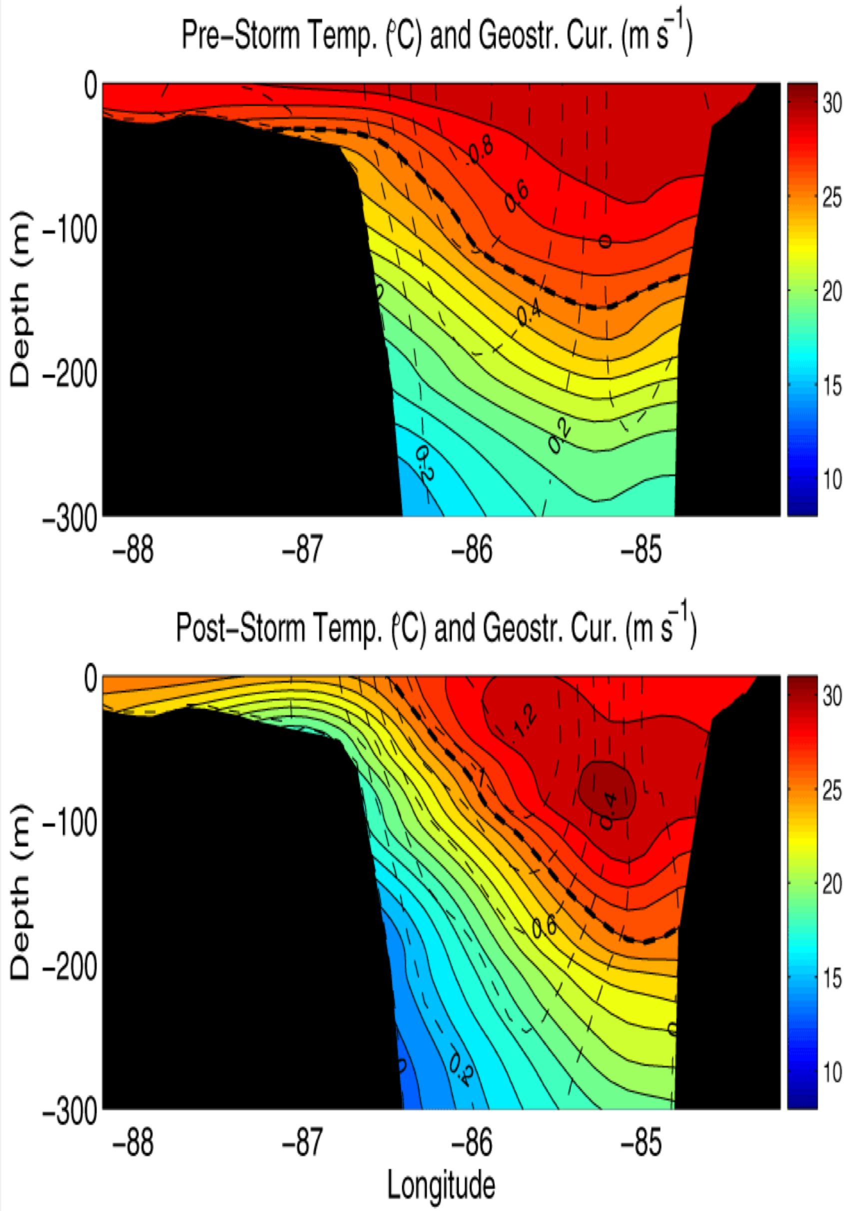


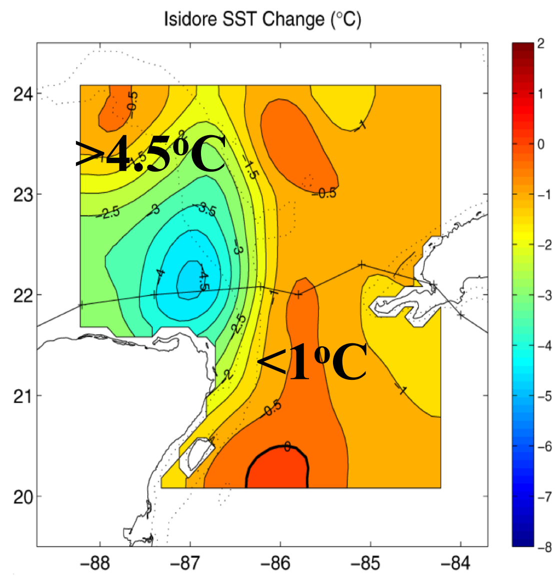


Isidore/Lili SFMR derived wind field:

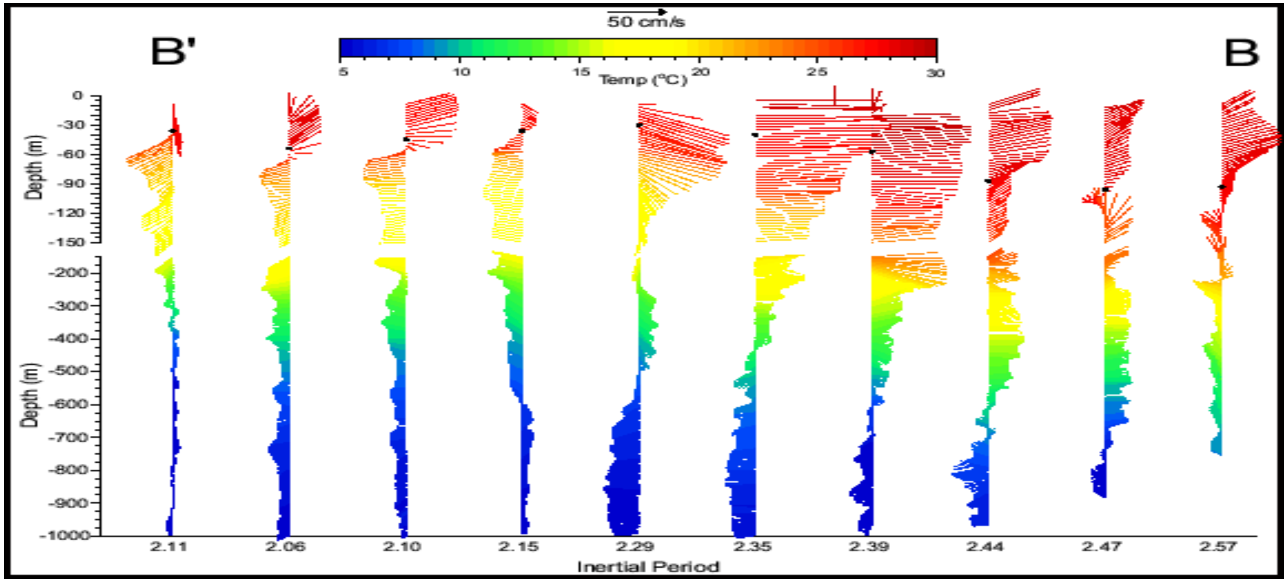
Isidore Fluxes For:
a) Sensible,
b) Latent,
c) Momentum,
d) Enthalpy.

Uses GPS, AX.., and SFMR fields.



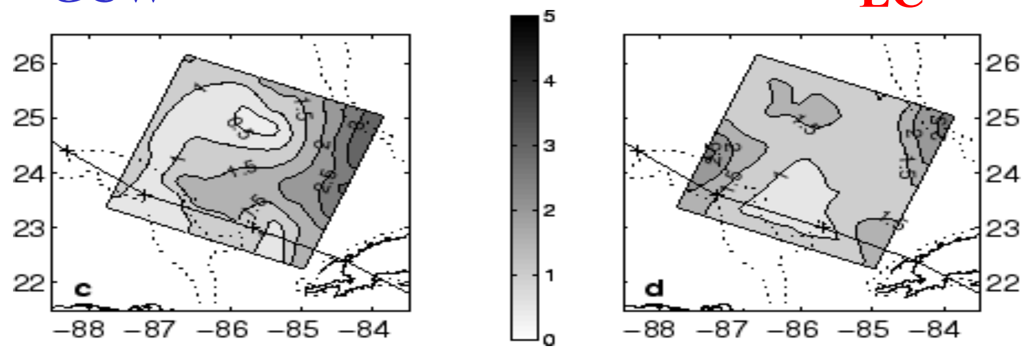


T(x,z) and V(x,z) Section (left) along 22°N and ΔSST Change (right) during after Isidore.

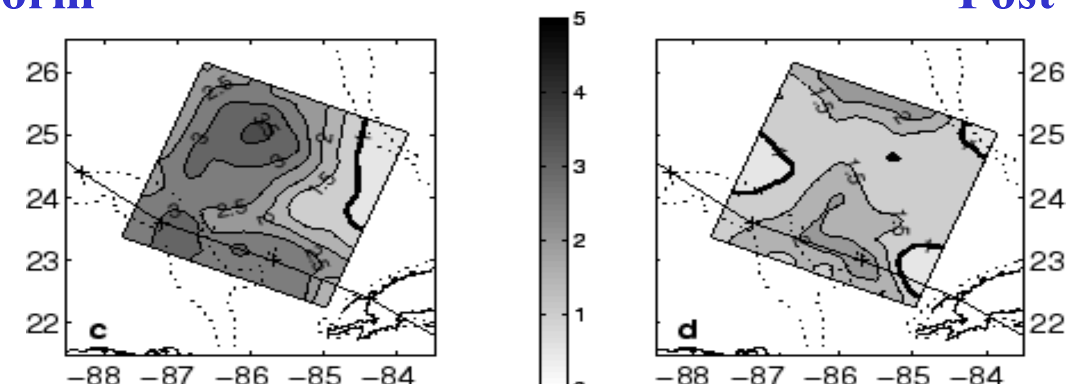


V(x,z) (upper) and T(x,z) (lower) section (left) at ~2Rmax in Lili's wake (~2 IP)

GCW **LC**



In-Storm **Post-Storm**

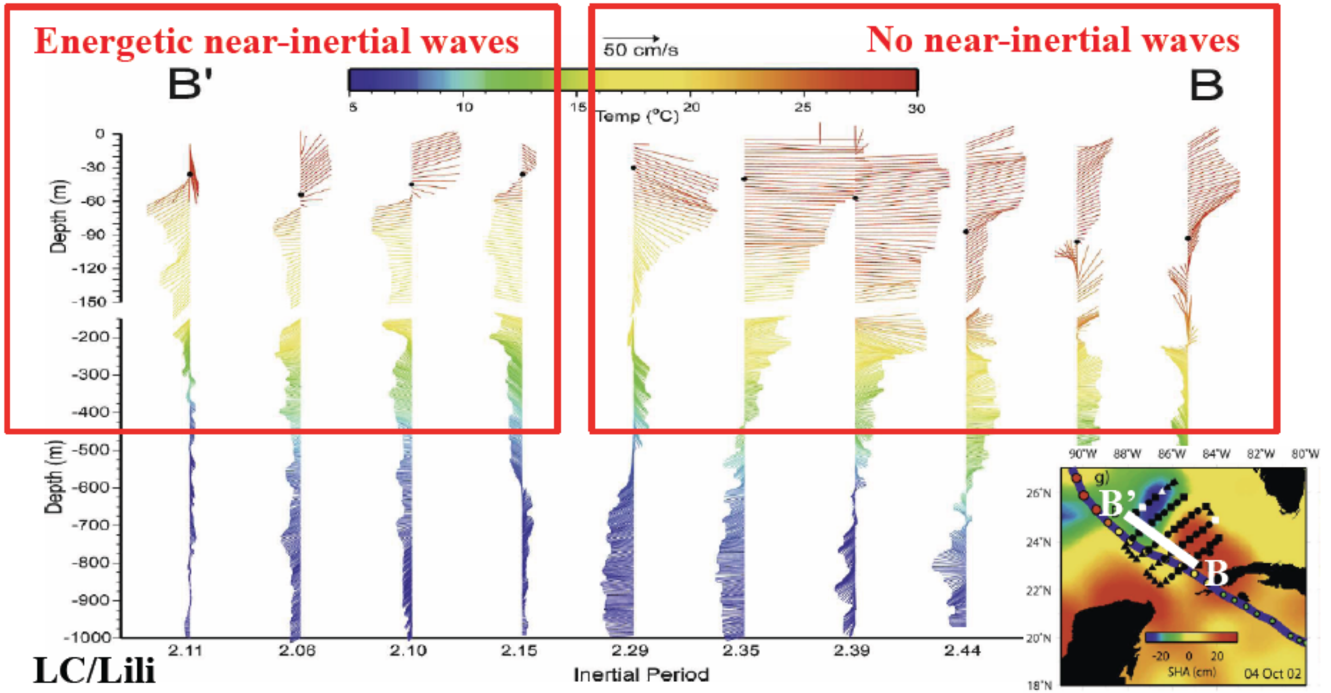


Observed velocity shears (upper) and Richardson Numbers (lower) during (panels c) and subsequent (panels d).

Vertical Structure of Near-inertial Currents

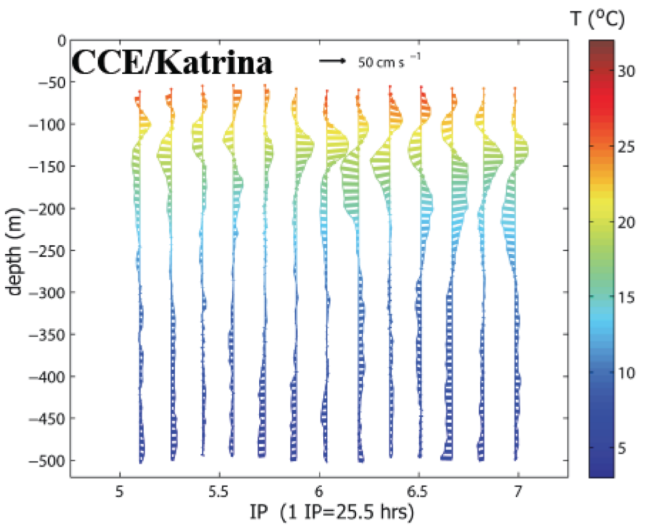
Loop Current (LC) near-inertial response to Hurricane Lili of 2002 (Shay and Uhlhorn 2008):

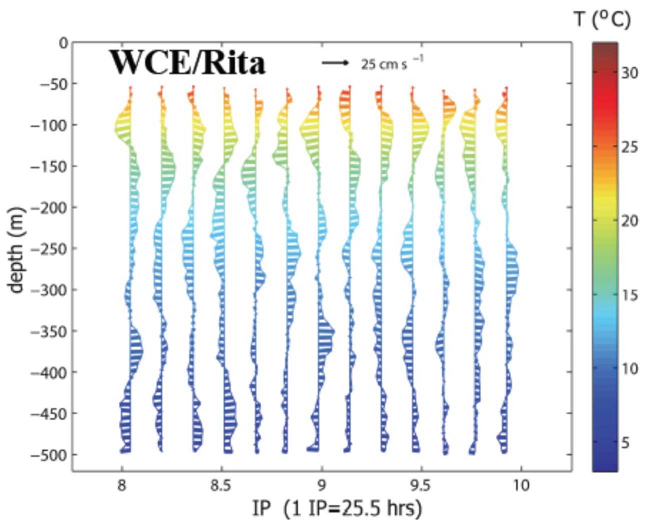
- **Energetic near-inertial response outside the LC.**
- **Weak near-inertial response inside the LC. Current shear about ½ that outside the LC.**

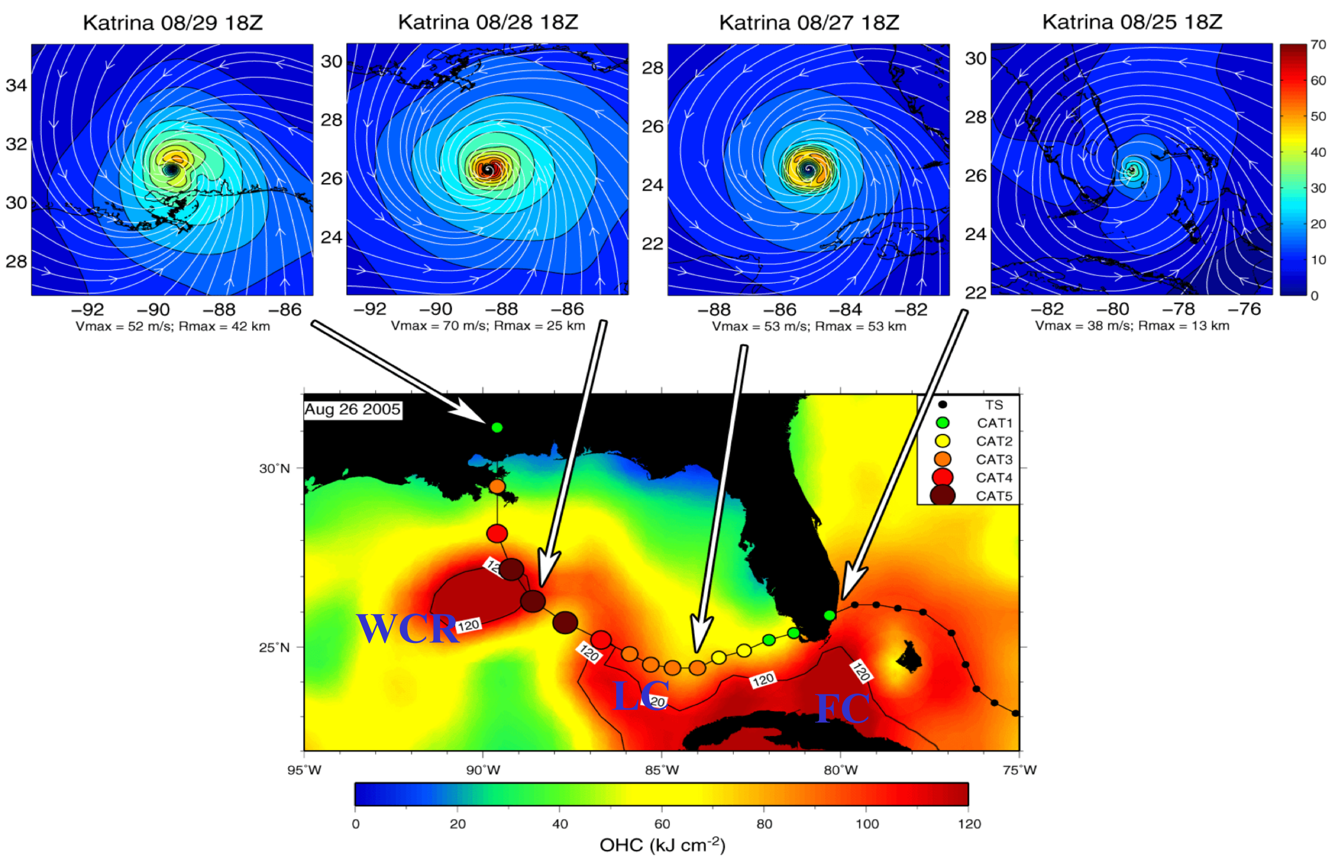


Near-inertial response to Hurricanes Katrina and Rita of 2005 (Jaimes and Shay 2010):

- **CCE: energetic near-inertial response to hurricane Katrina.**
- **WCE: weak near-inertial response to hurricane Rita.**

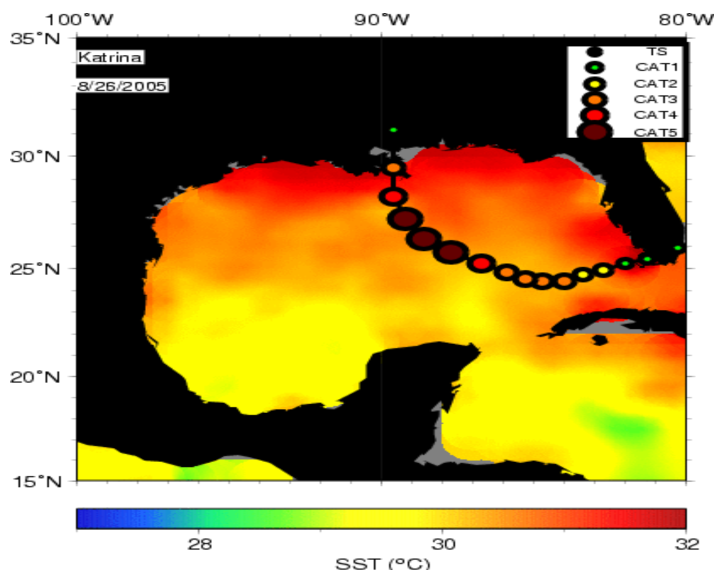






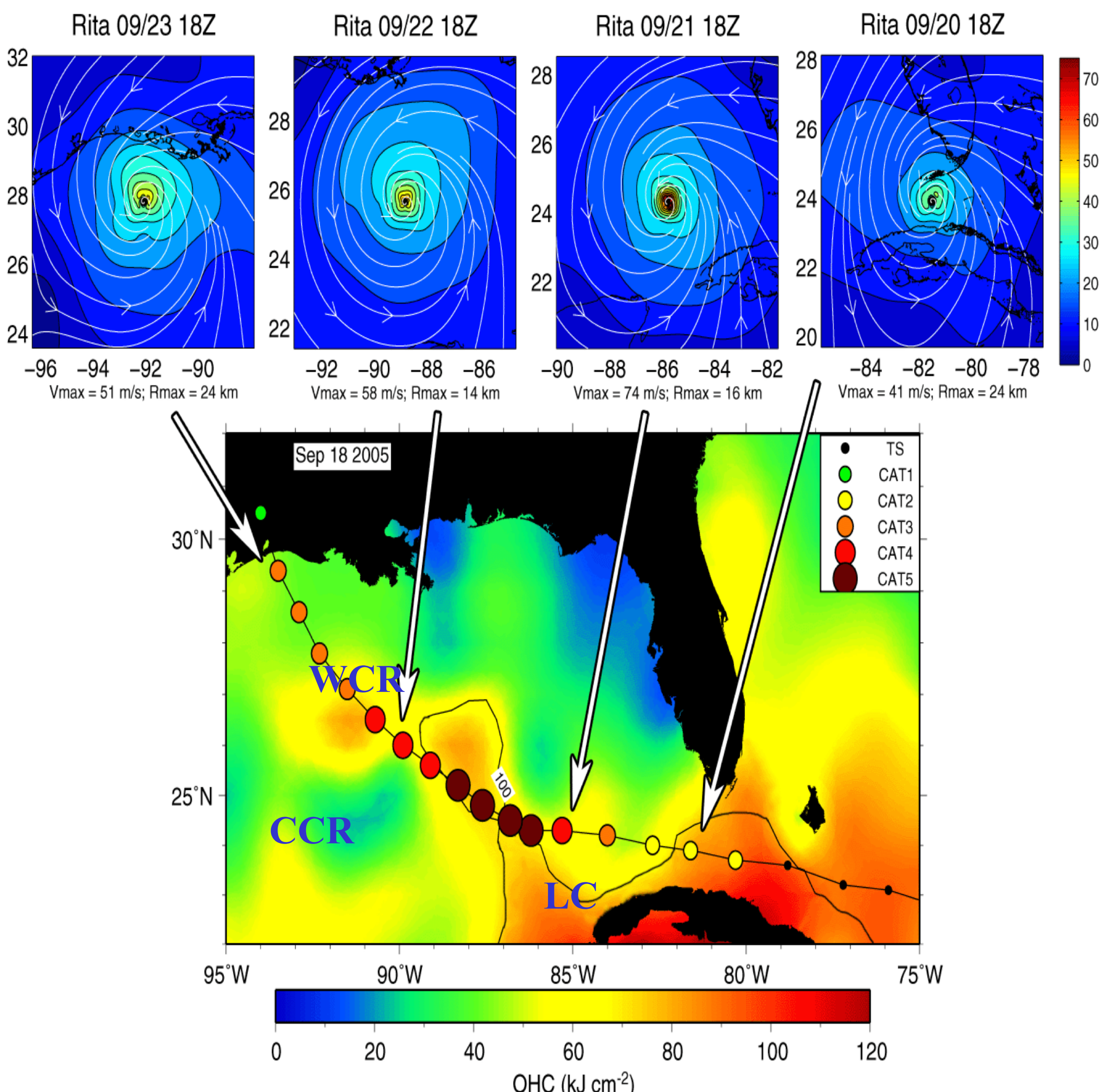
MOTIVATION: Katrina wind field with HRD wind fields (Powell et al). relative to the the LC and WCR based on satellite data in Aug 05 (Mainelli et al., WAF, 2008).

In 2005: Katrina (896 mb), Rita (892 mb), Wilma (882 mb) Trifecta



SST Image from TMI (lower panel).

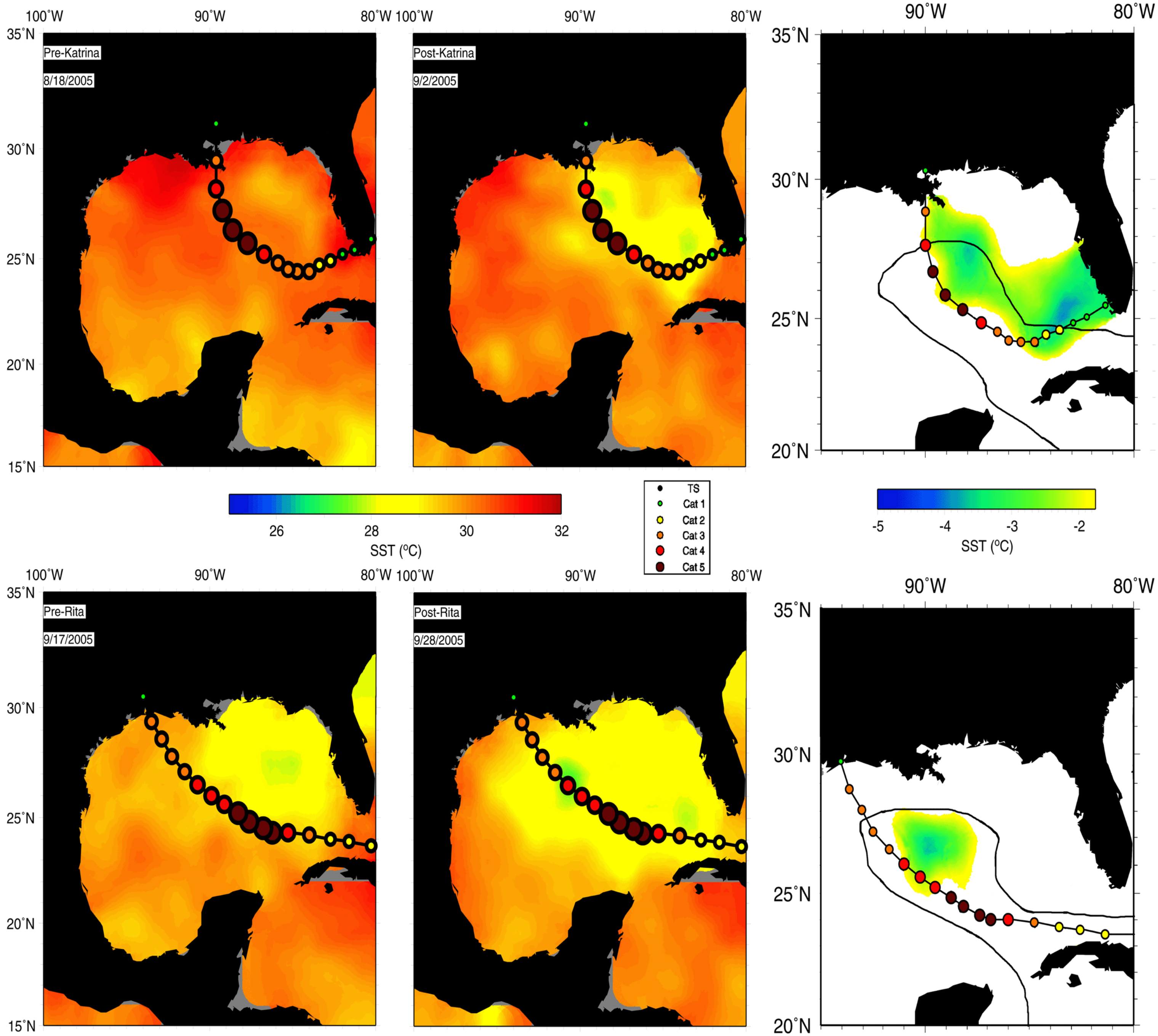
Is SST Enough?



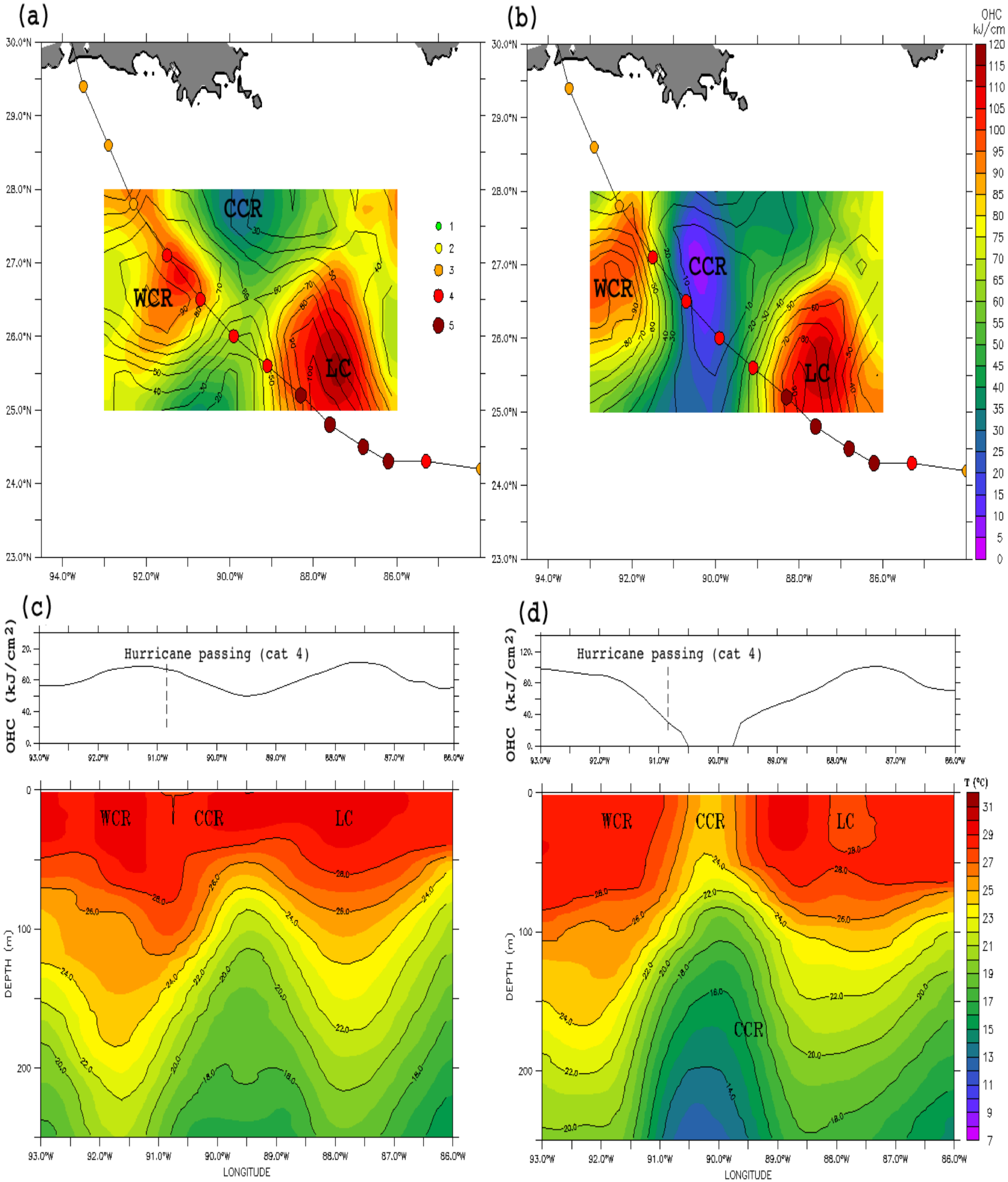
Rita's Path and Strength Relative to Pre-Storm OHC and 10-m winds from HRD HWIND Product (Mark Powell et al.)

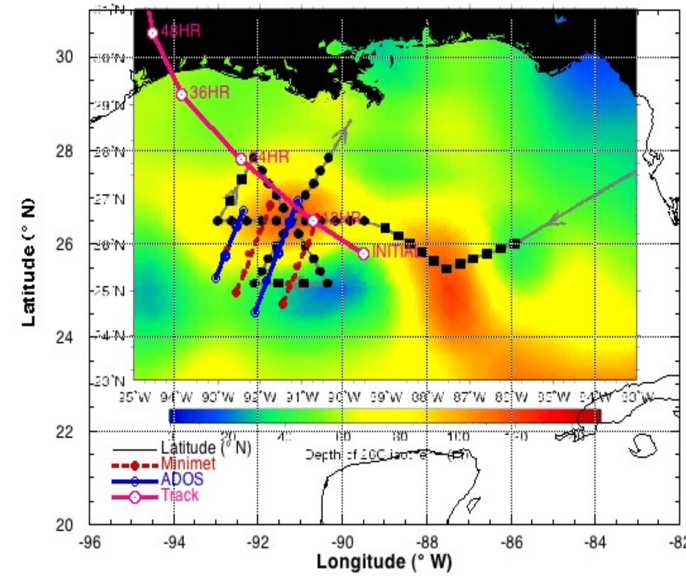
TMI Pre and Post Katrina SSTs and cooling (top);

Pre and Post Rita SSTs and cooling (bottom).



TMI Data courtesy of C. Gentemann.





Sampling Pattern: AXCTDs and Drifters relative to OHC and Rita's track.

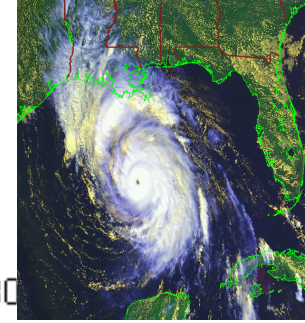
Pre (15 Sep) and Post Rita (26 Sep) WCR/CCR/ LC OHC and 26°C isotherm depth.

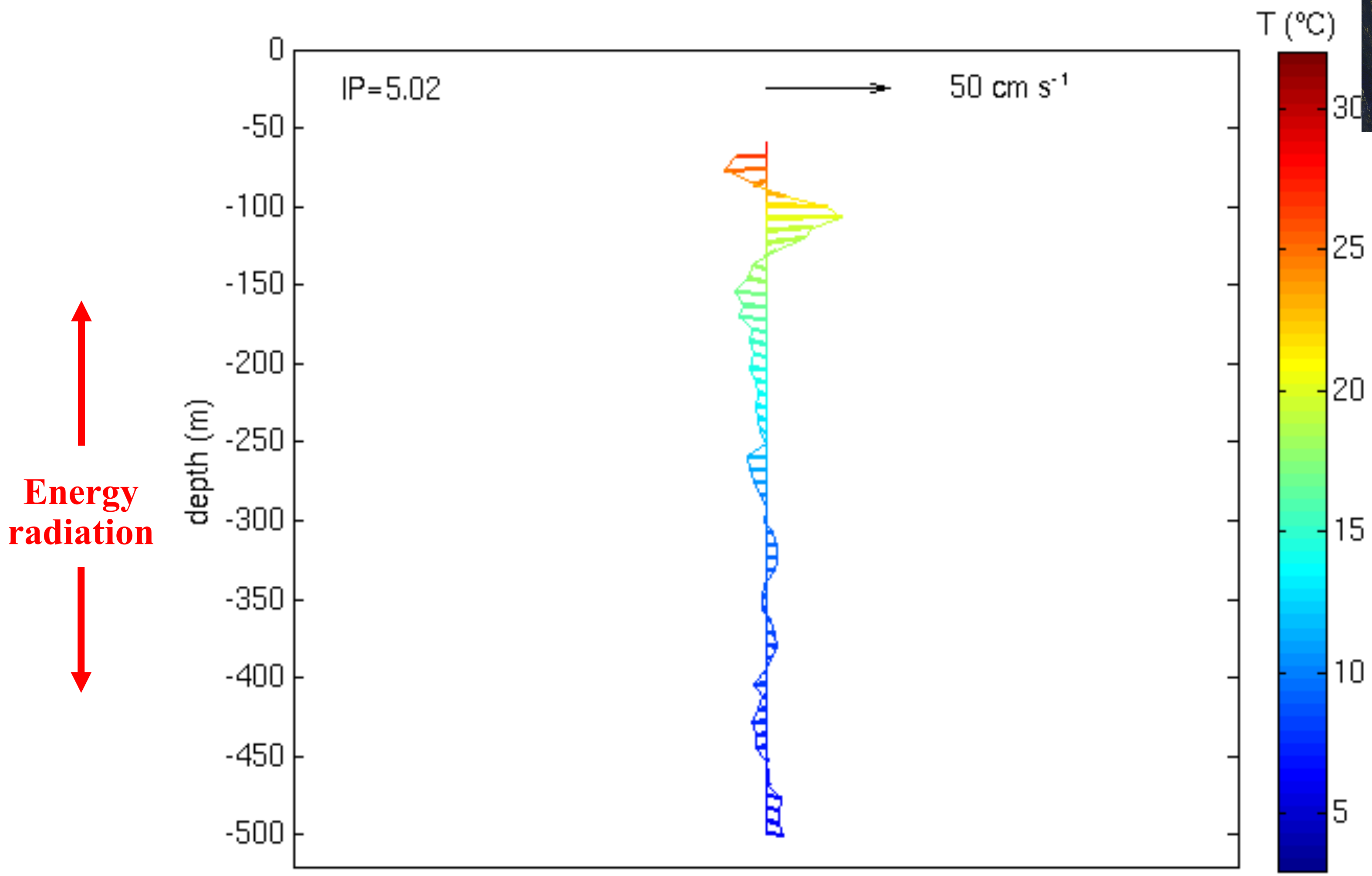
Vertical structure from AXCTDs.

Wind stress curl of Rita impacted the shedding process.

(Jaimes and Shay, MWR, 2009)

Near-inertial currents in the Katrina-forced CCE

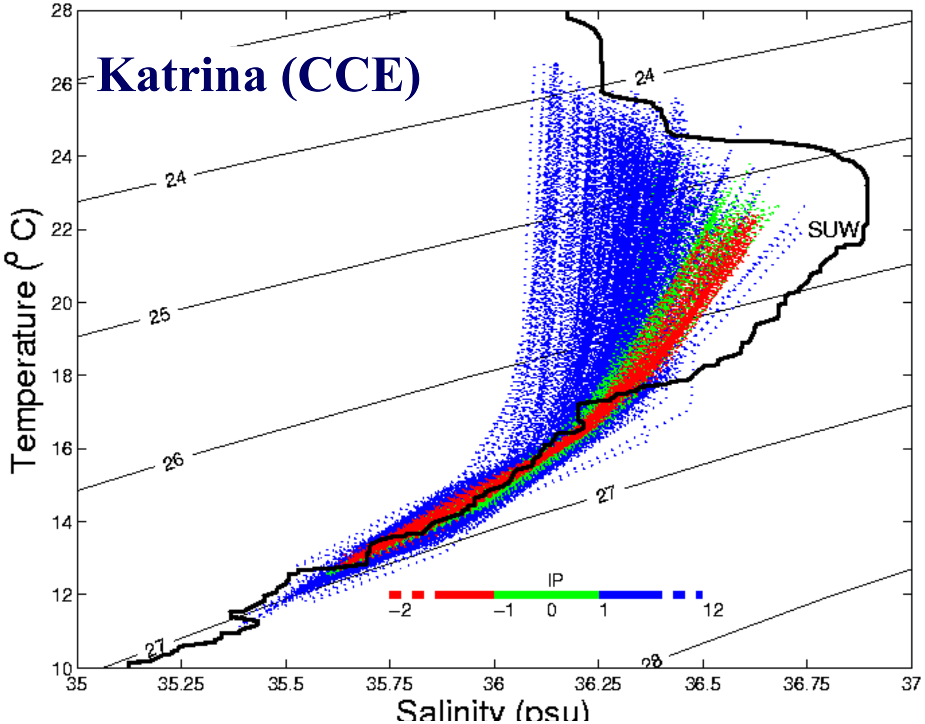




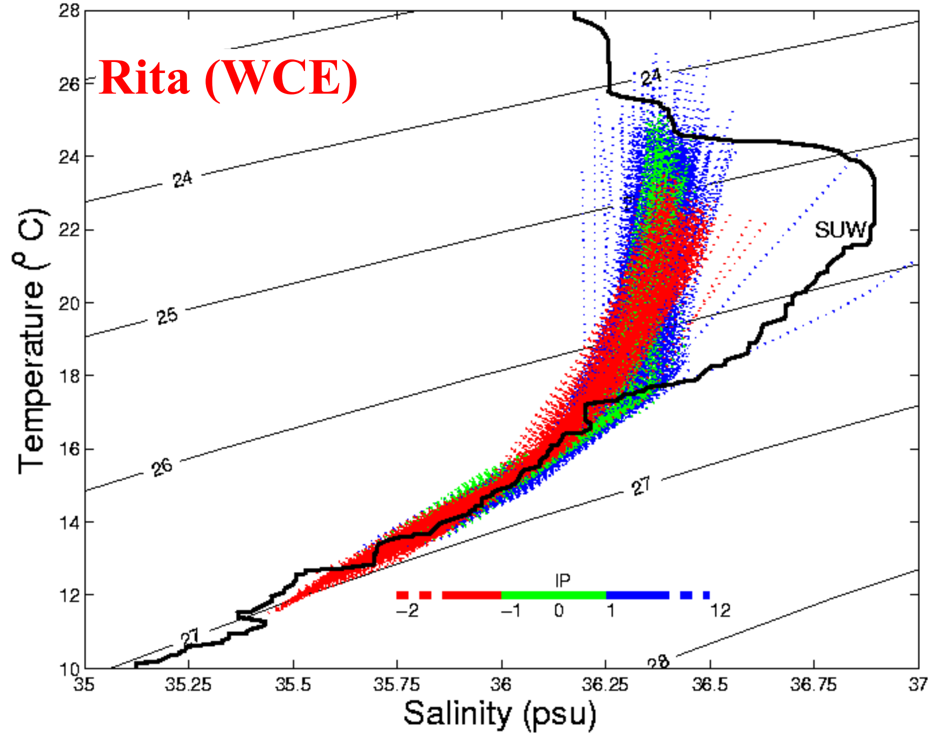
Upward amplification of upgoing energy

(as suggested by *Mied et al 1986*)

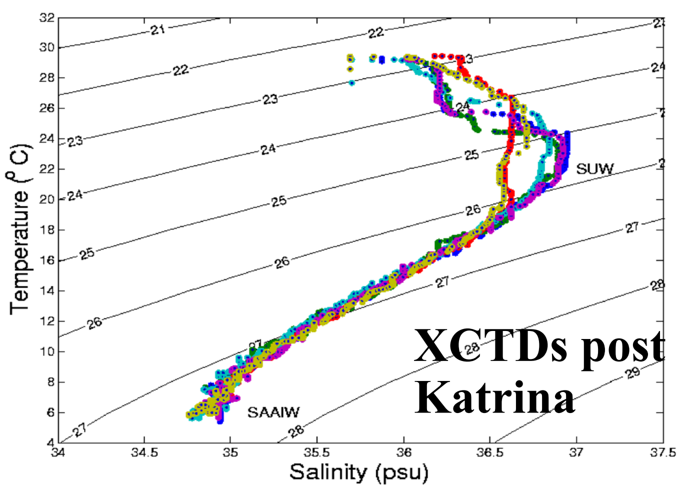
Water mass transformation by near-inertial current mixing



Stronger mixing

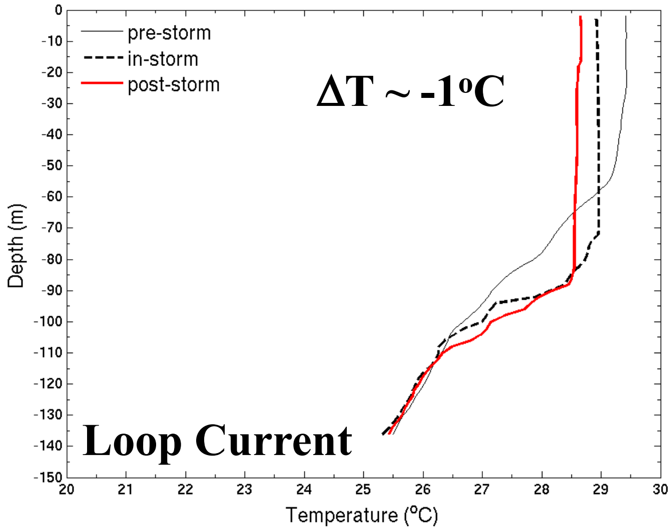


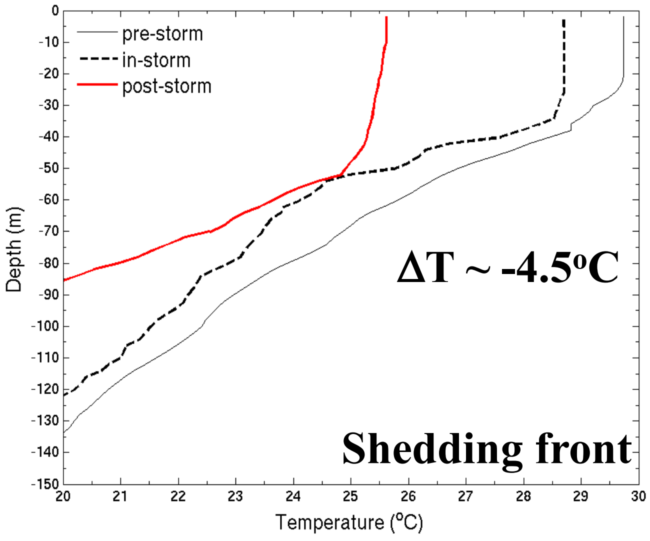
Reduced mixing

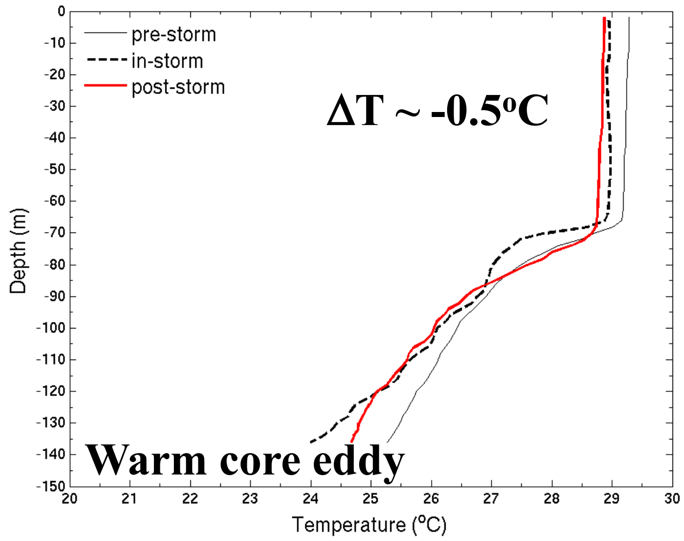


- Mixing driven by vertical shear of near-inertial currents.
- Mixing confined to waters lighter than $\sigma_t = 27$ (reduced ventilation of the thermocline)

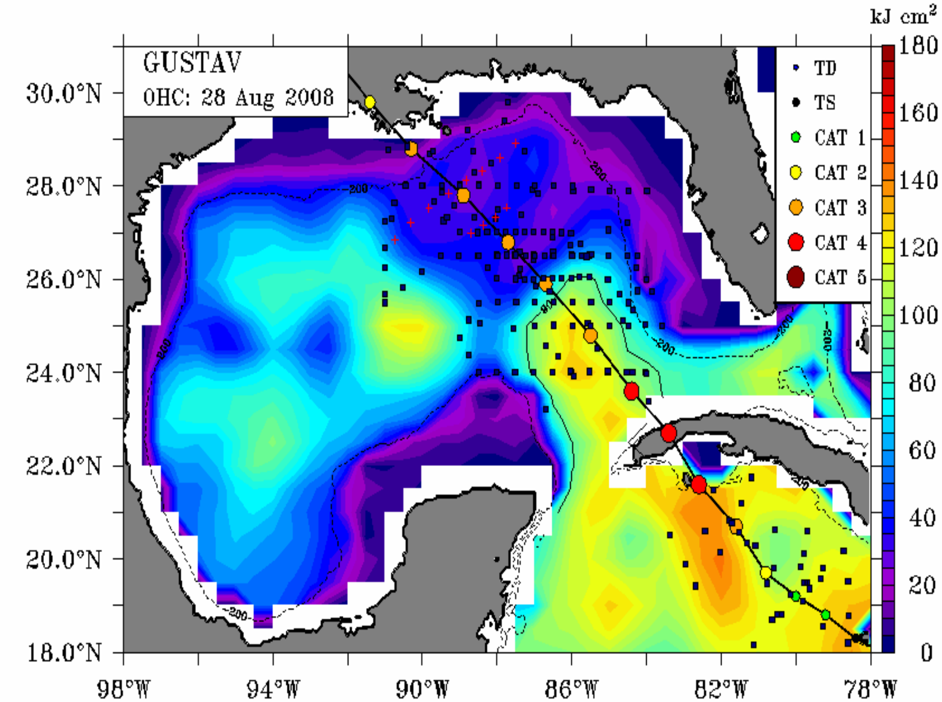
Differentiated cooling in the LC system (Jaimes and Shay, MWR, 2009)

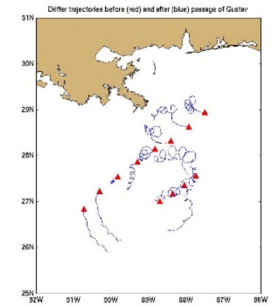


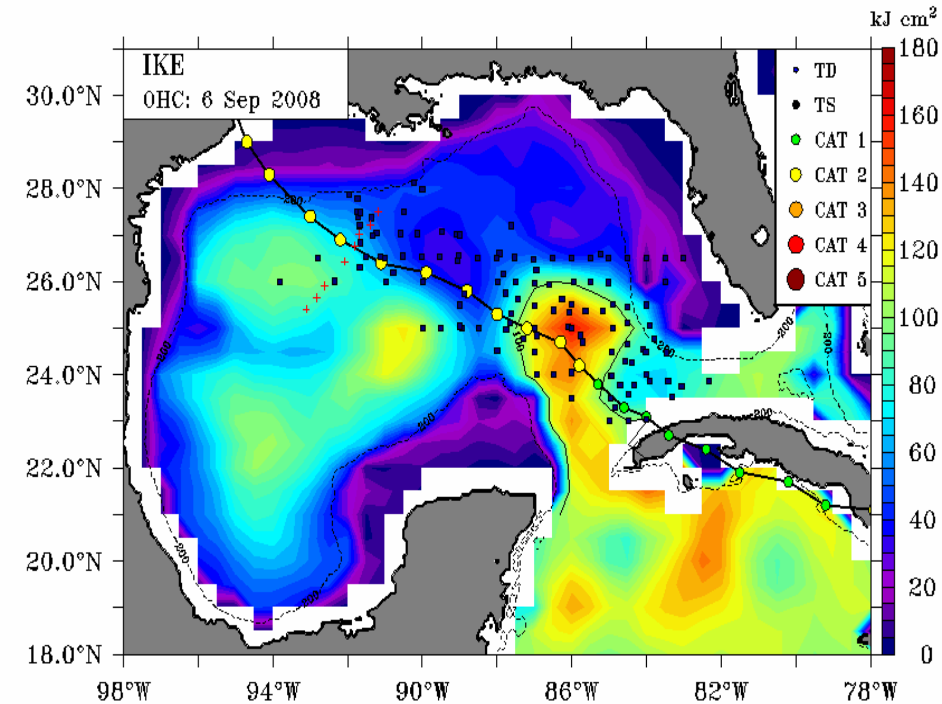


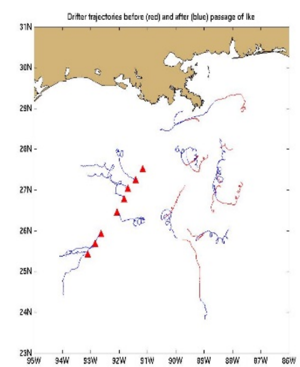


Cluster-averaged temperature profiles









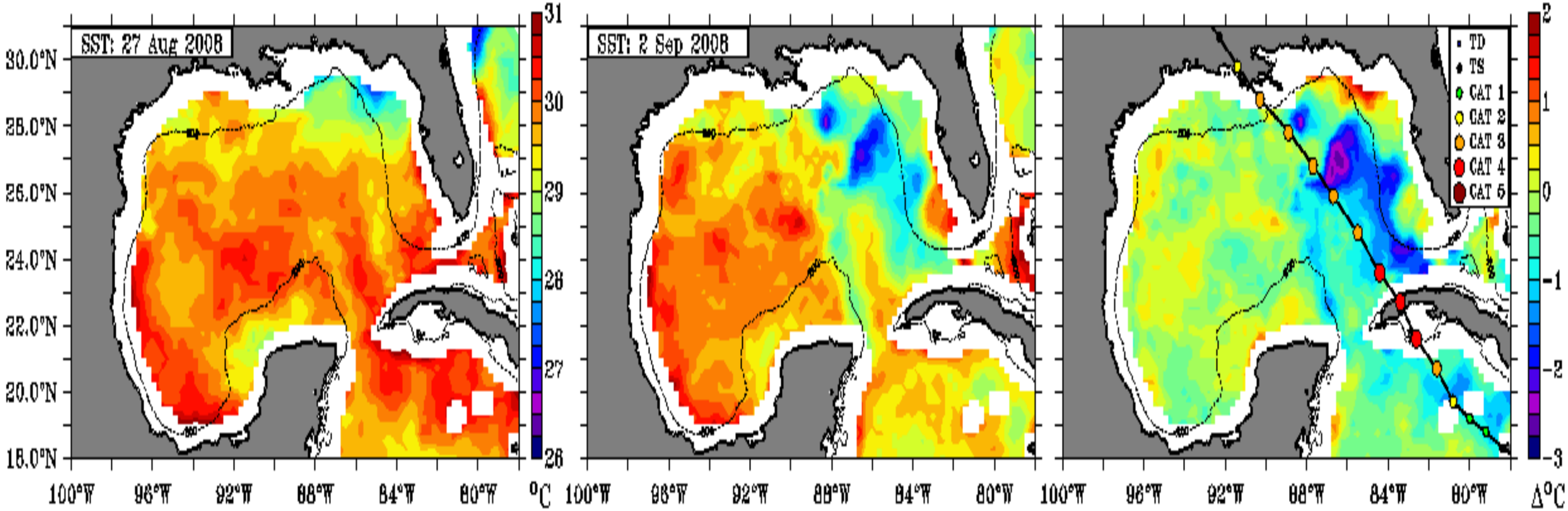
Track and Intensity of TC's Gustav and Ike (08) Versus AXBTs relative to OHC and 26°C Isotherm Depth.

Gustav: 191 AXBTs
111 GPS Drifters
Floats

Ike : 216 AXBTs
111 GPS Drifters
Floats

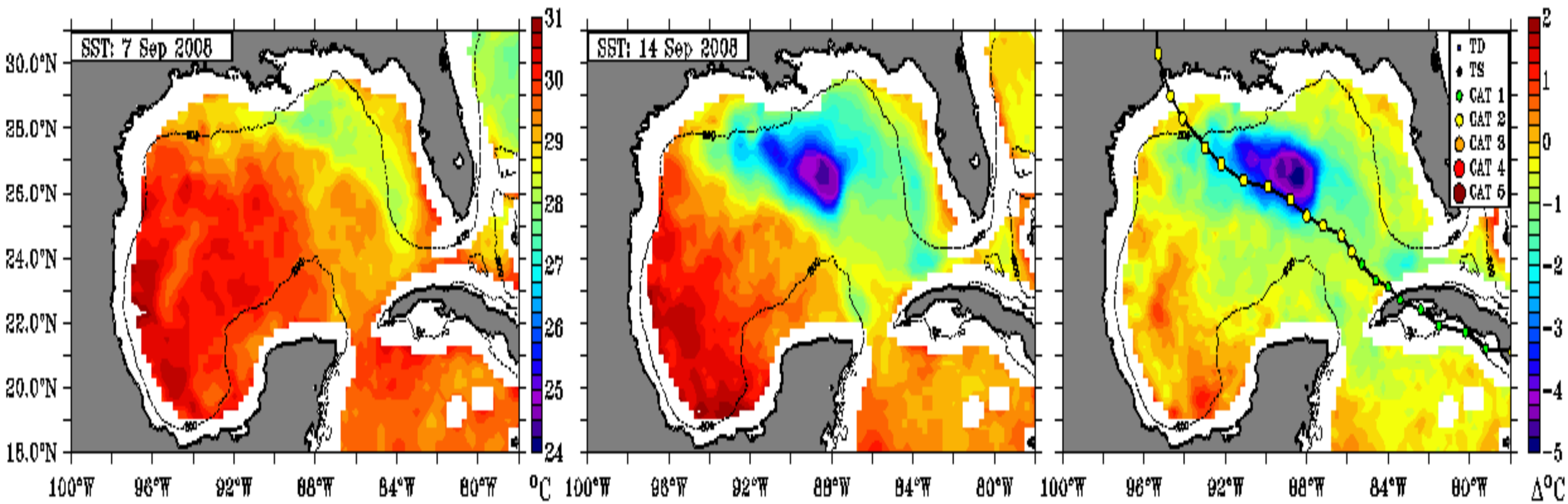
From Meyers et al., JGR, (2016).

Rick Lumpkin provided drifter data.



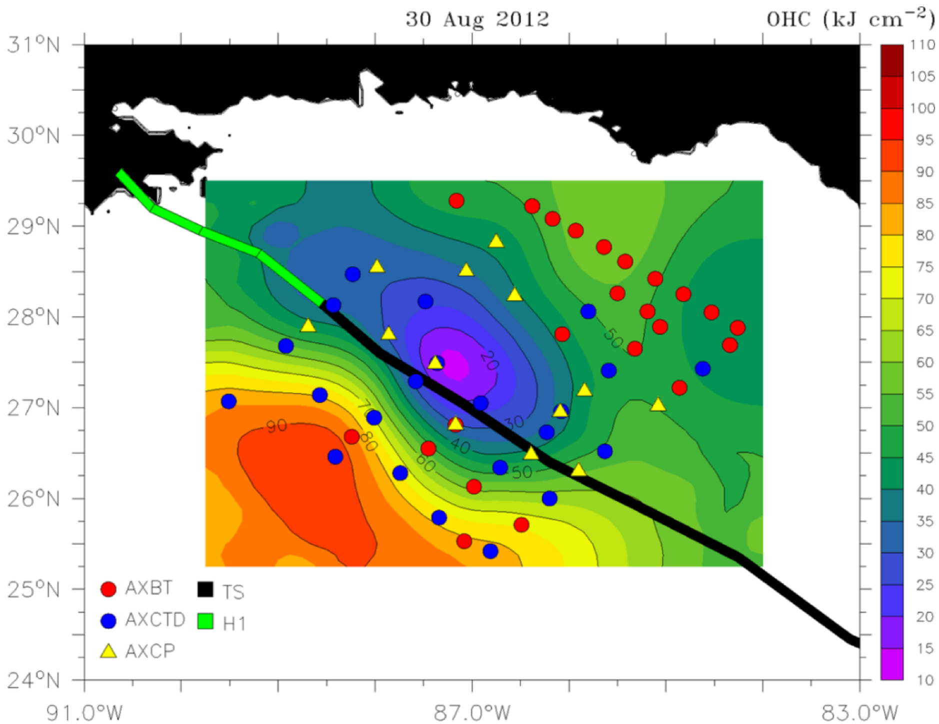
Pre-Storm Post-Storm Change in SST

Data courtesy of Remote Sensing Systems



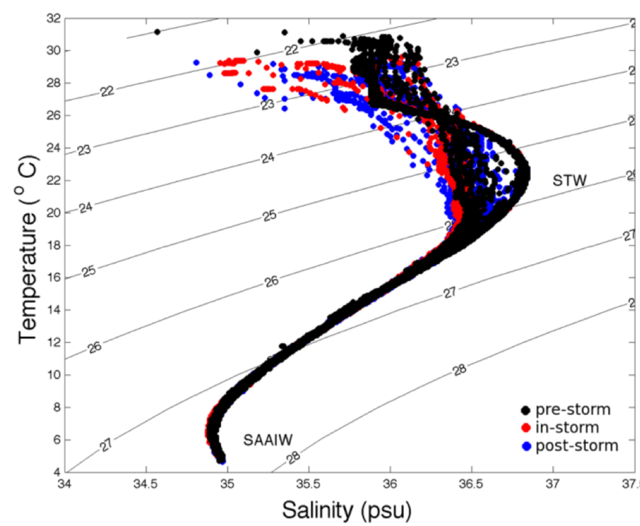
Post-Isaac flight (30 Aug)

	Deployed	Good	Bad	Success
AXBTs	23	20	3	87%
AXCTDs	24	23	1	96%
AXCPs	20	17	3	85%
Overall	**67**	**60**	**7**	**90%**



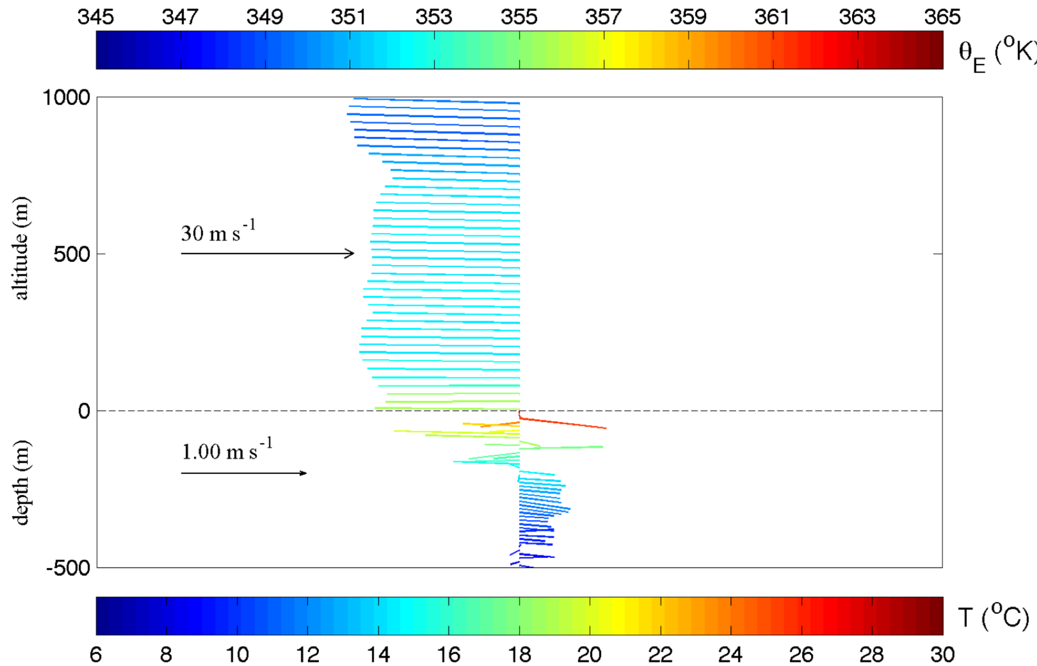
Isaac Flight Summary

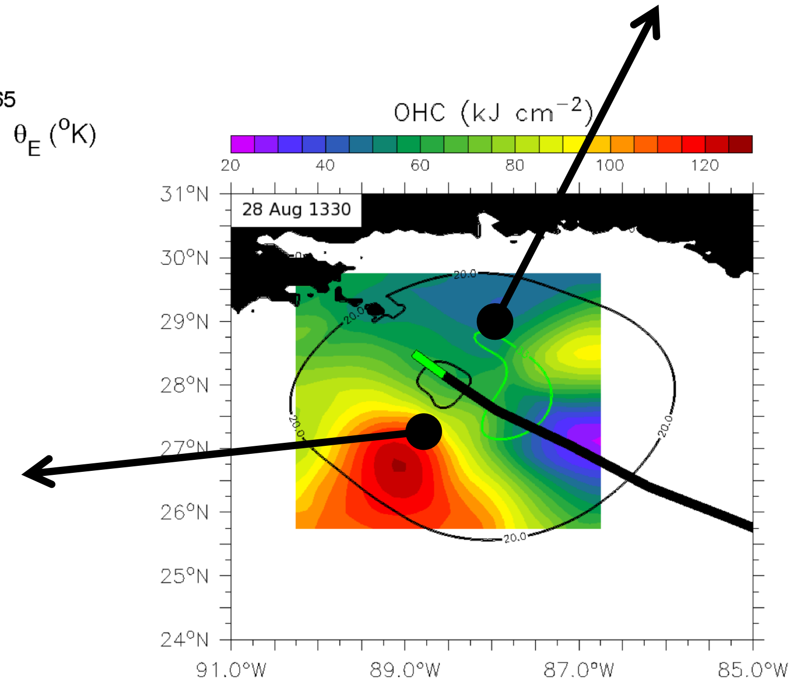
- **58 AXBTs deployed in other 3 in-storm flights (97%)**
- **218 Ocean probes**
- **overall success: 88% during six flights**
- ***Below are the T/S curves from XCTDs prior, during and after Isaac.***

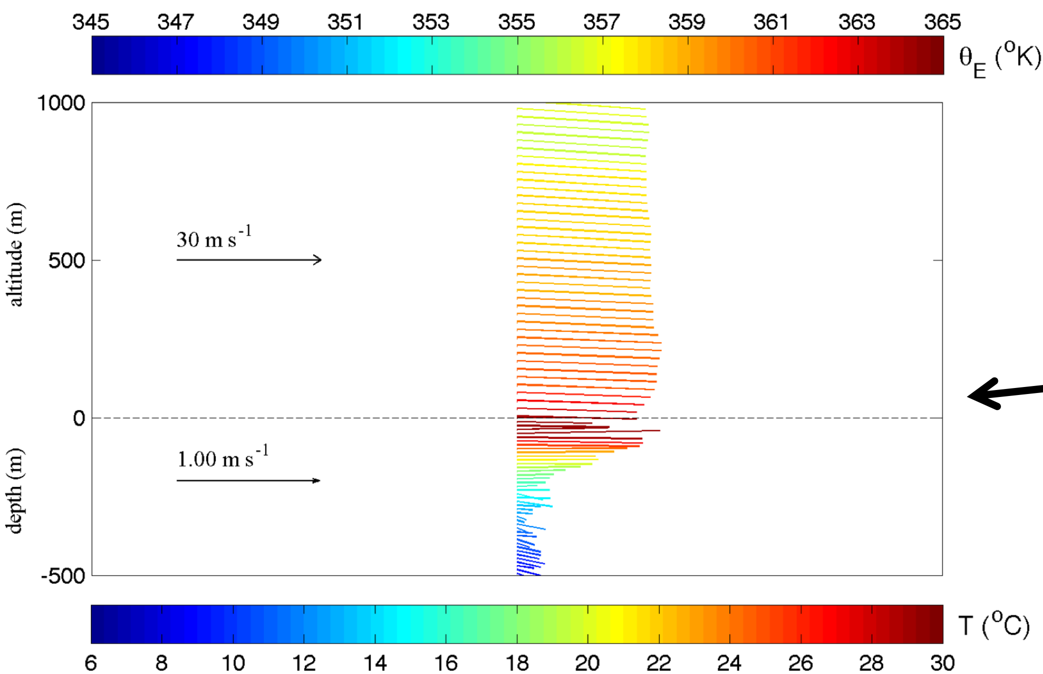


Contrasting ocean response in oceanic geostrophic features.

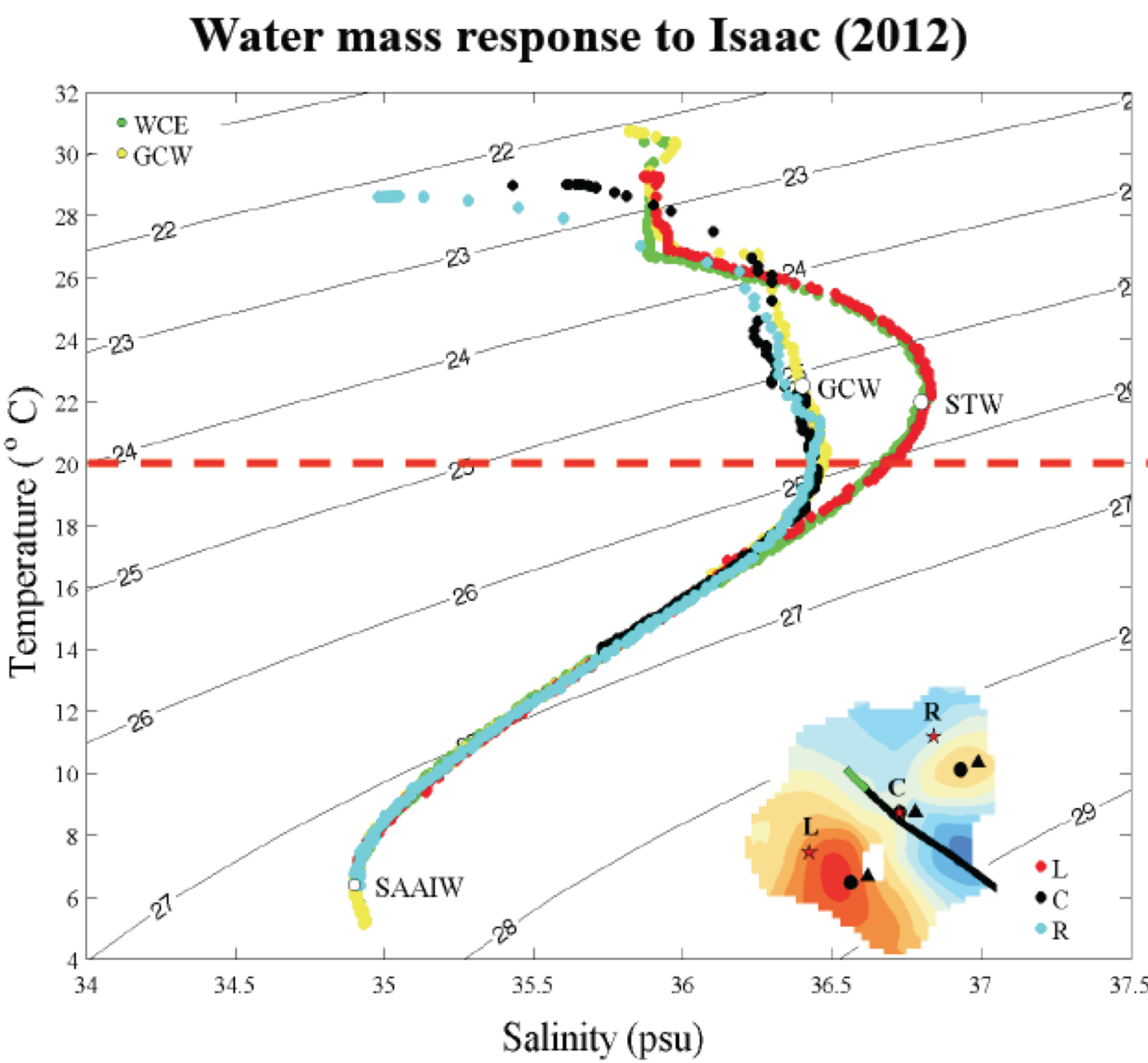
Contrasting distribution of θ_E as a function of underlying oceanic features.







Upwelling and Mixing Regimes



Upwelling and Mixing

Diabatic cooling regime (influenced by vertical mixing)

Pure Upwelling

Adiabatic cooling regime (vertical mixing vanishes)

Pure upwelling responses (adiabatic reversible process) can be evaluated in terms of fluctuations in the 20°C isotherm's depth (h_{20}).

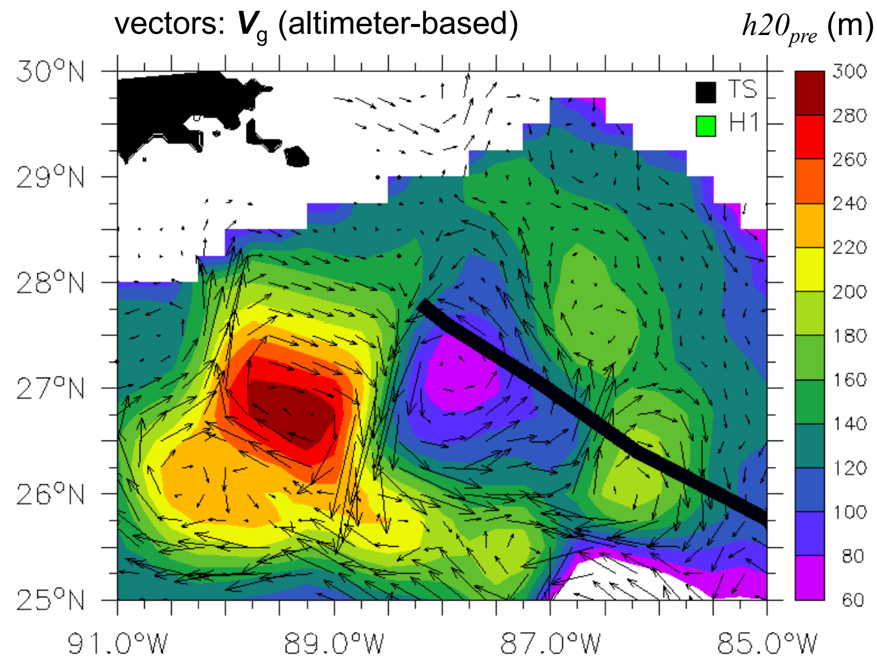
Jaimes and Shay (2015)

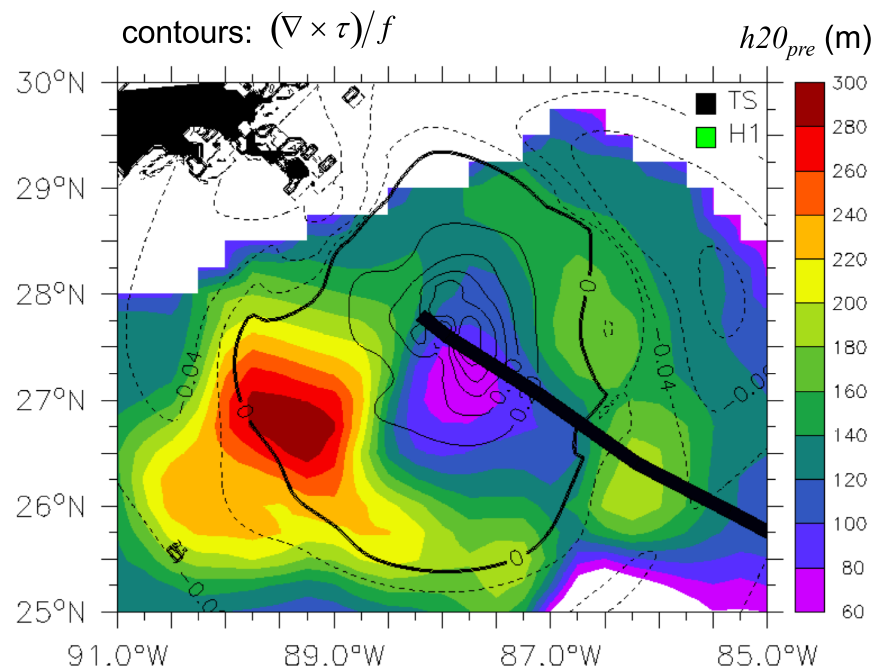
Isaac moved over and intense geostrophic oceanic eddy field in the eastern Gulf of Mexico.

During intensification to hurricane (28 Aug), the cyclonic curl of the wind stress extended over a region of more than 300 km in diameter ($4R_{max}$ to $5R_{max}$).

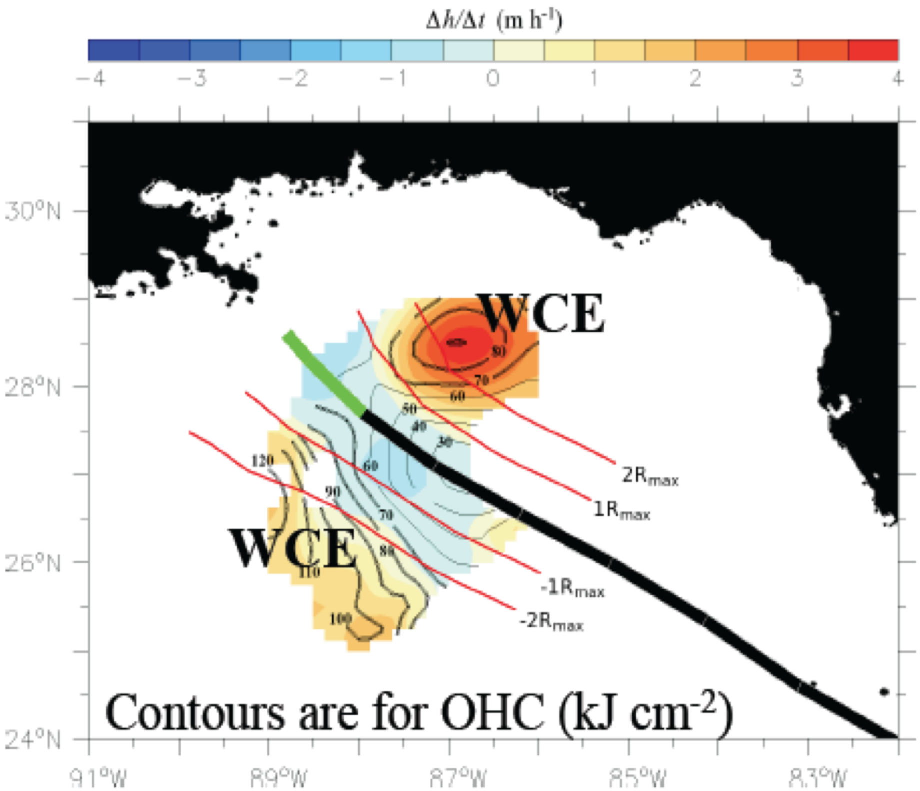
Vertical velocity associated with isopycnal displacements are a function both the geostrophic current vorticity and the curl of the wind stress (Jaimes et al., DAO, 2011).

- $h20_{pre}$ is from SMARTS (25 Aug)
- τ is from Hwind (1030z, 28 Aug)

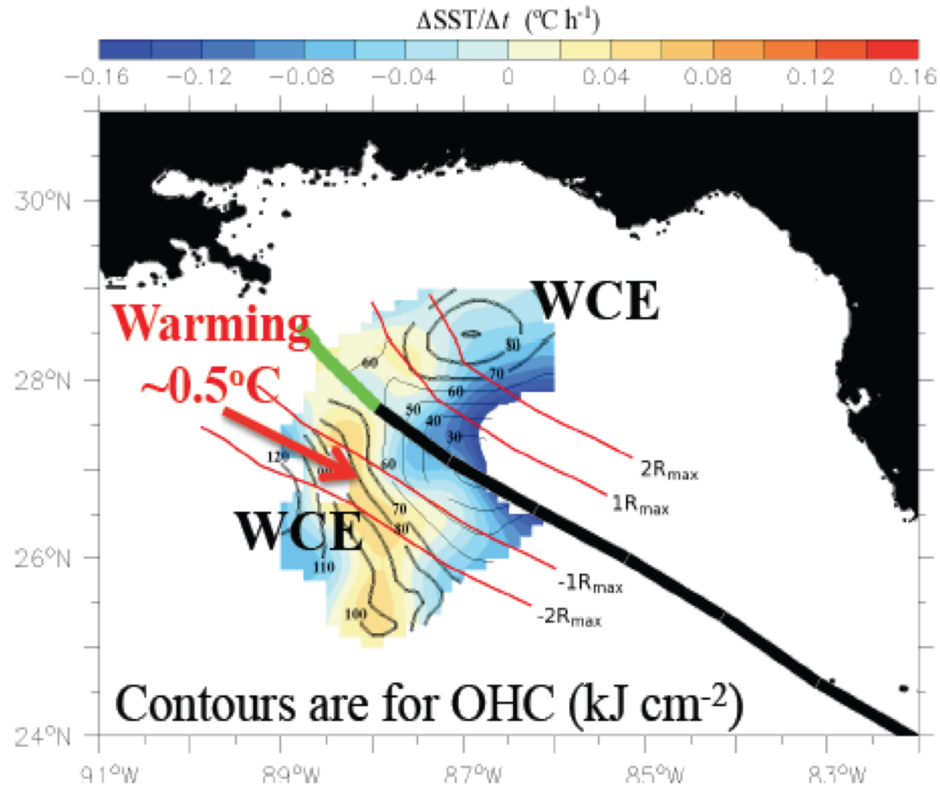




Ocean Mixed Layer and SST Response During Isaac (12) (Jaimes et al., DAO, 2016)



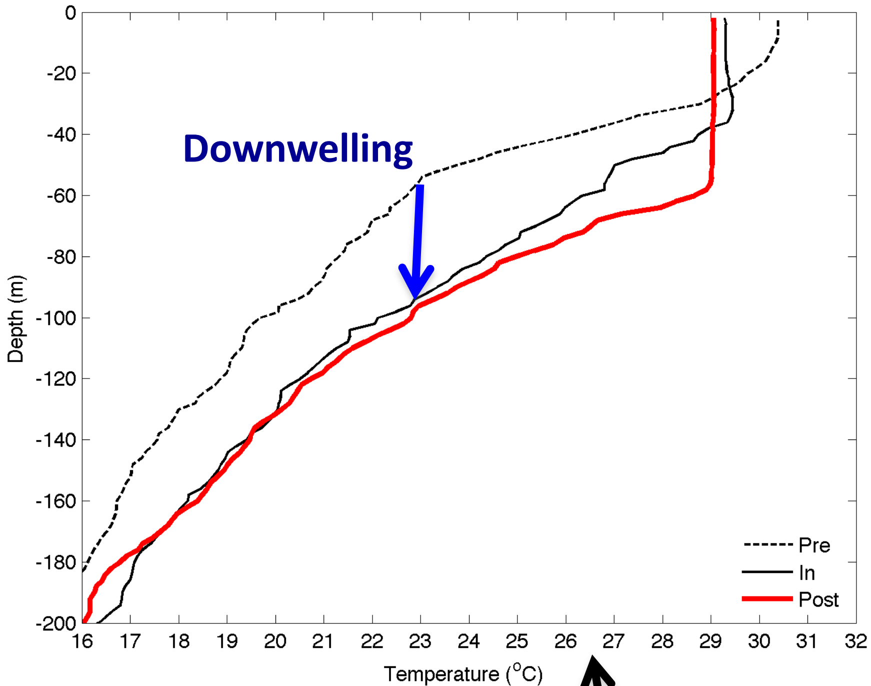
In- storm (12 h interval) Ocean Mixed layer (OML) deepening; h is OML depth.

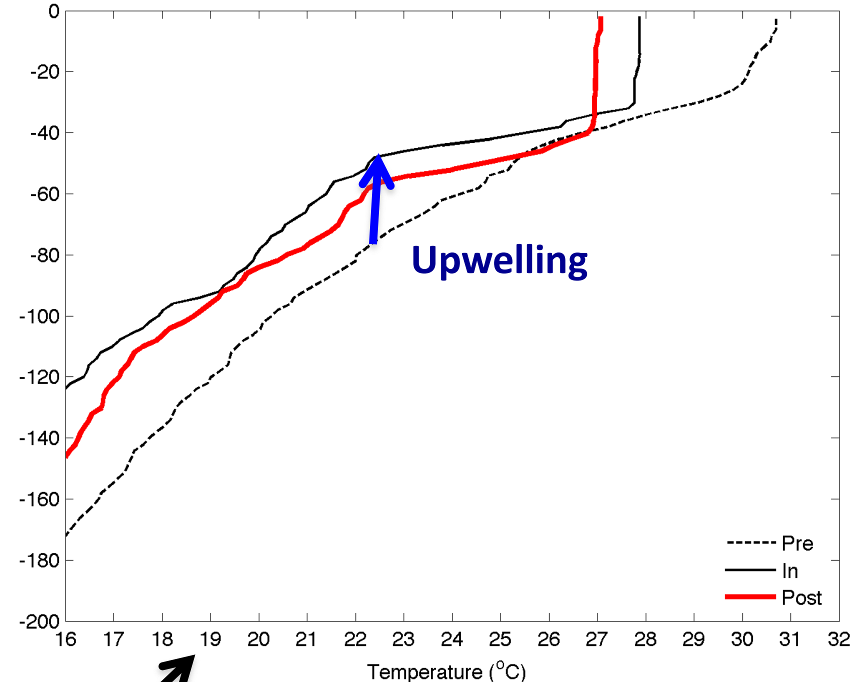


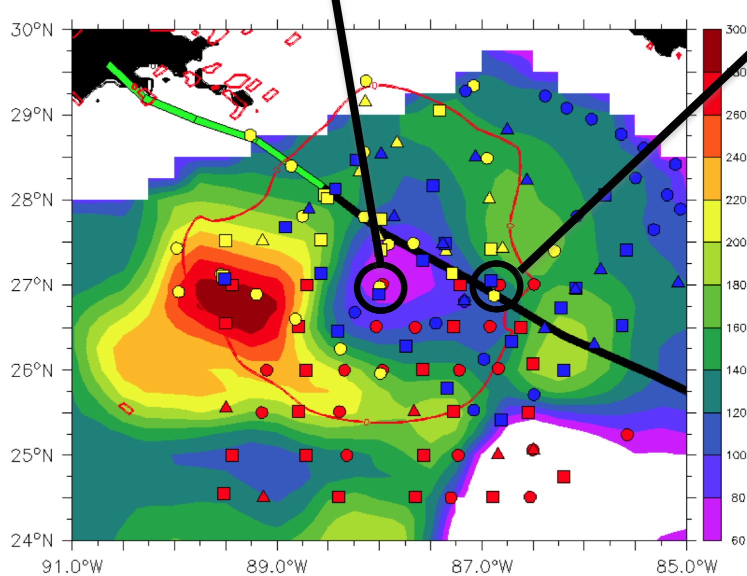
In- storm (12 h interval) sea surface cooling; SST: sea surface temperature.

Jaimes et al. (2016)

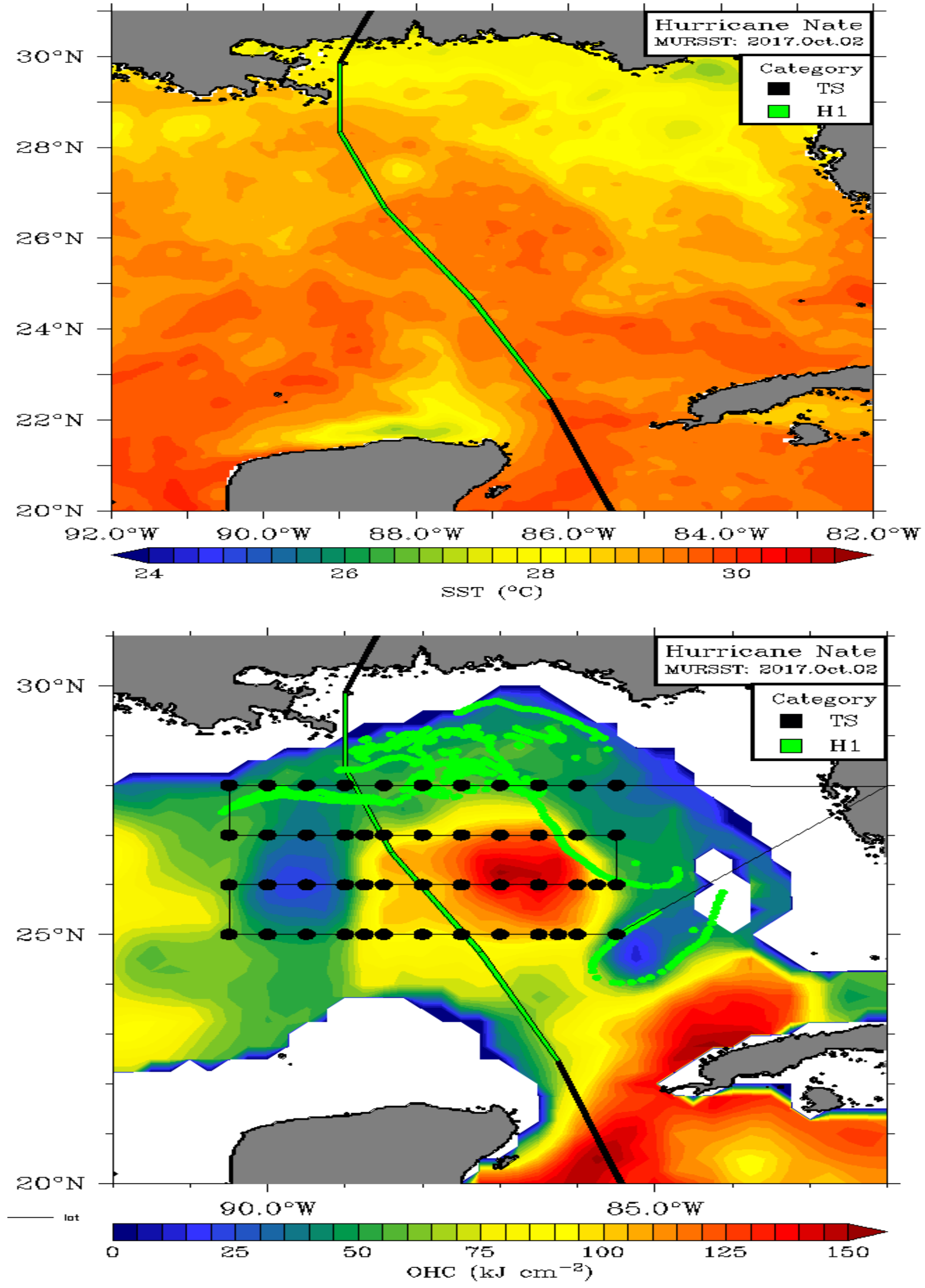
Contrasting upwelling and cooling inside the region of cyclonic wind stress curl







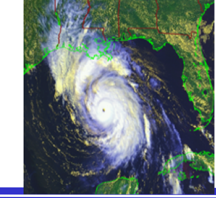
In-storm data is from the 28 August morning flight (during intensification to hurricane level)

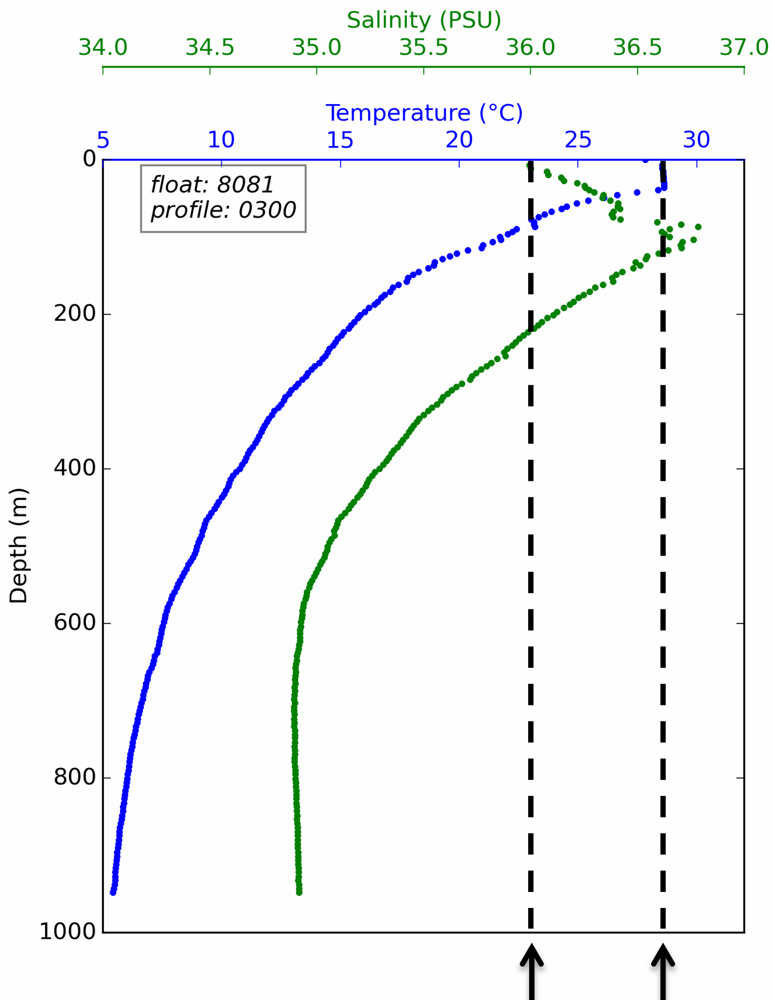


SST (**color**) prior to Nate in the GoM relative to track and intensity of Nate. Note Nate moved over the Gulf at speeds of more than 10 m/s (20 knts). Roughly 83% of the storms over the GoM move at speeds less than 5.8 m/s (~11 knts).

OHC (**color**) relative to pre-storm ocean grid (dots) of expendables deployed from NOAA WP-3D and Nate's track. Light **green** represents data from *state-of-the-art* profiling floats with physical and biochemical sensors deployed as part of GoMRI project that uses the APEX-EM platform (Sanford et al., GRL, 2007).

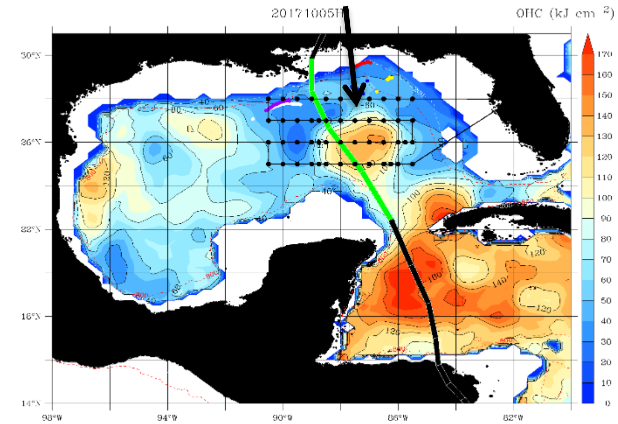
Temperature, Salinity and Current Response (Float Data) to Nate

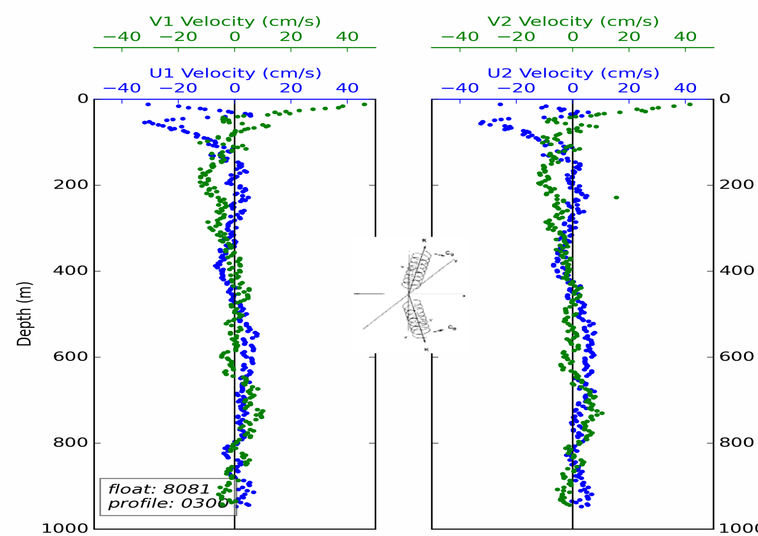




Pre-storm conditions

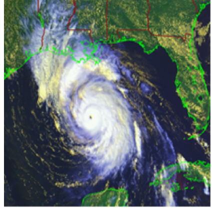
Data from this APEX-EM float

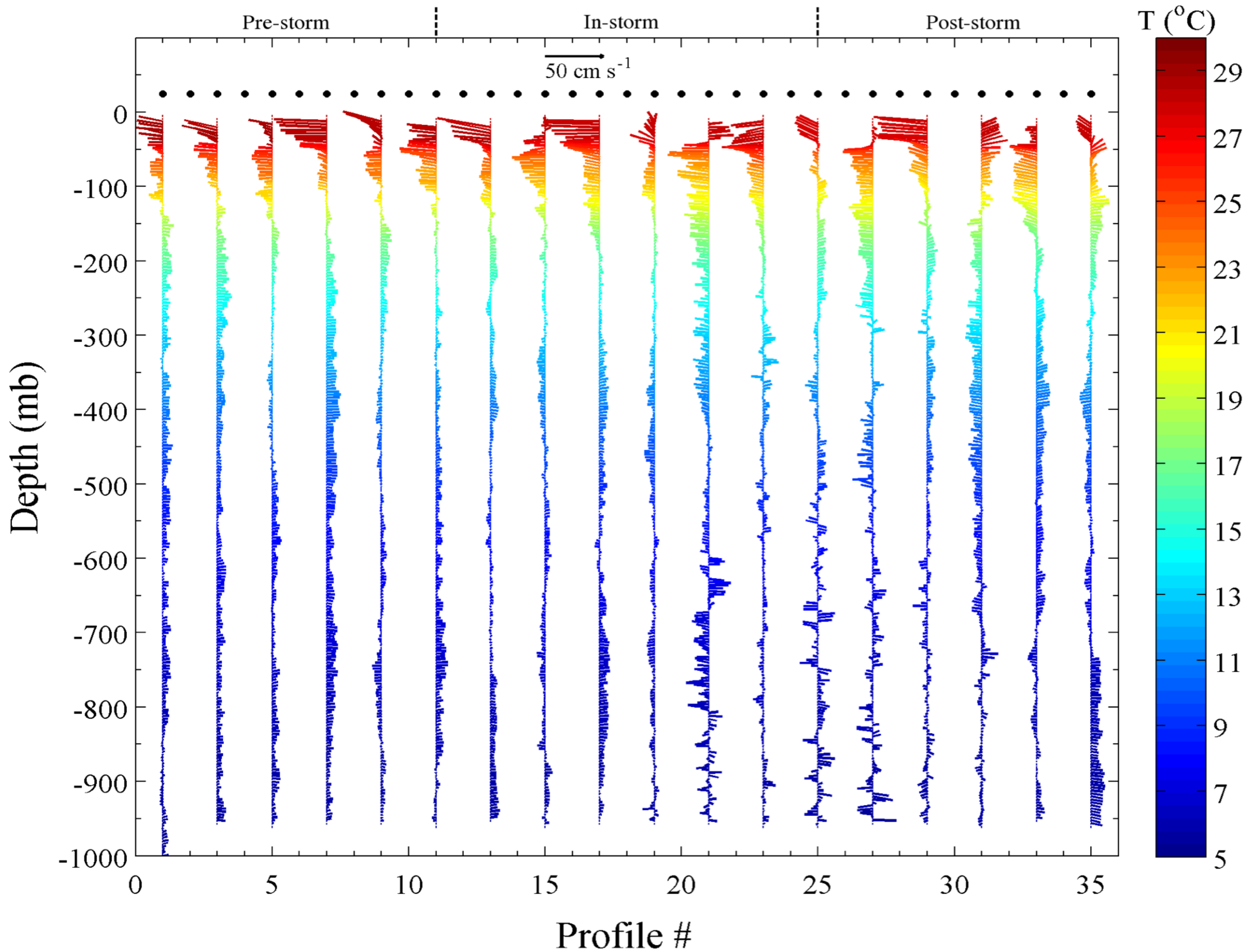




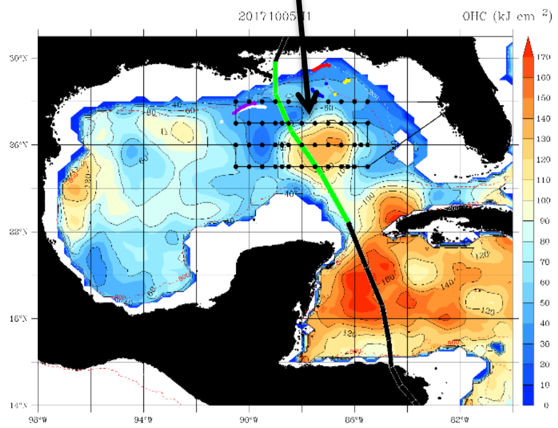
GULF OF MEXICO RESEARCH INITIATIVE

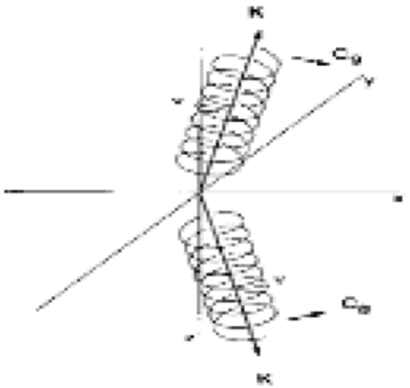
Nate's Velocity Response (Float Data) as part of GoMRI Project.





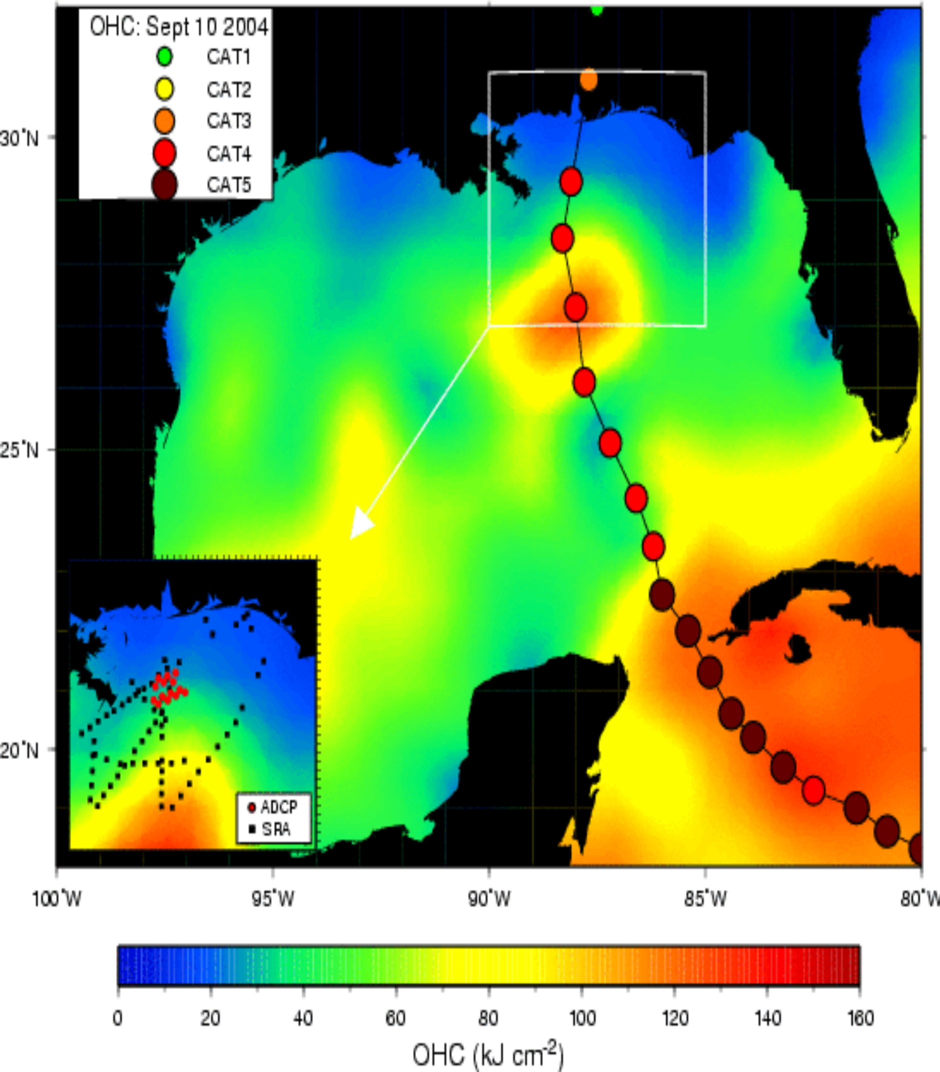
Data from this float

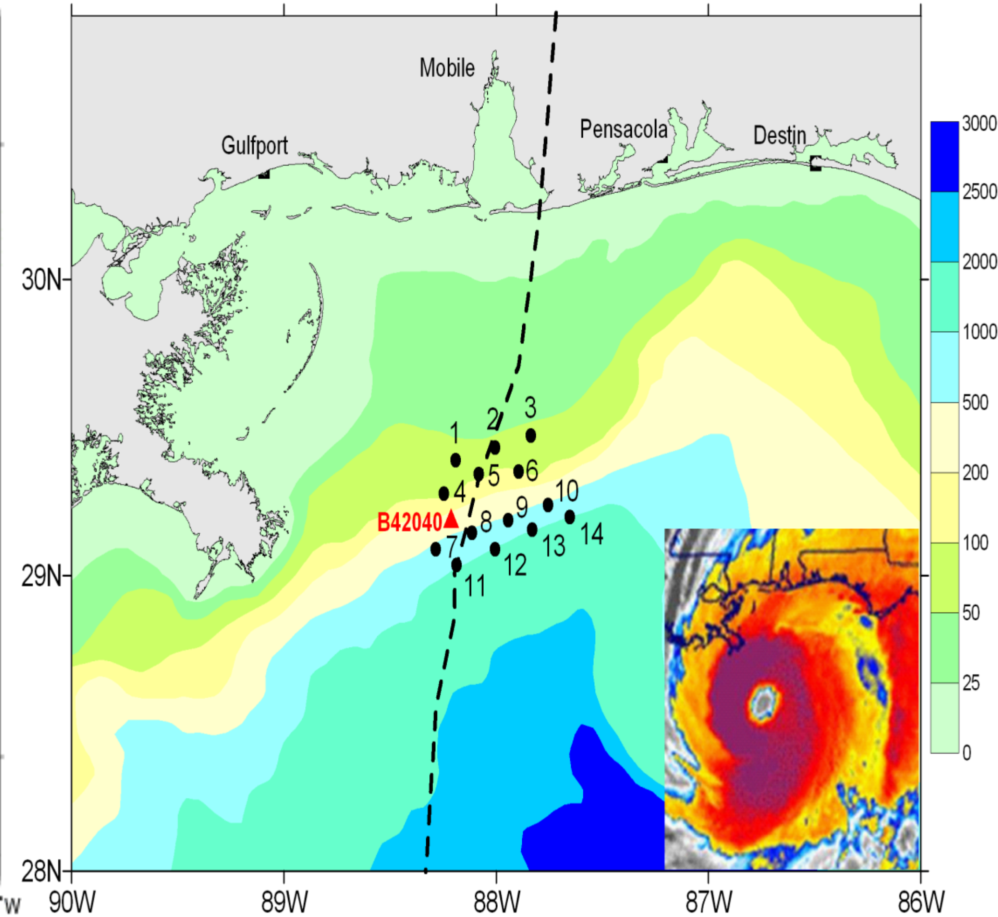




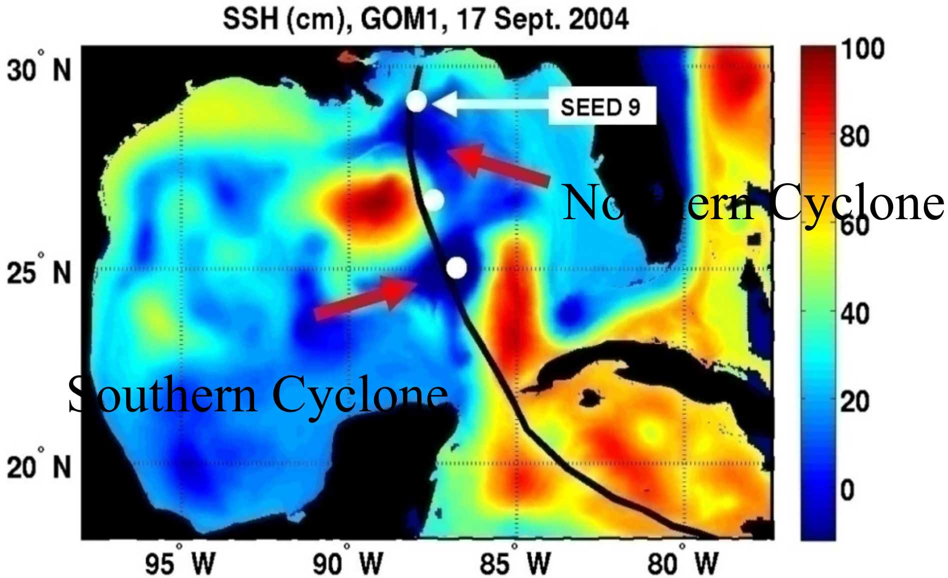
(Leaman and Sanford, JPO, 1976)

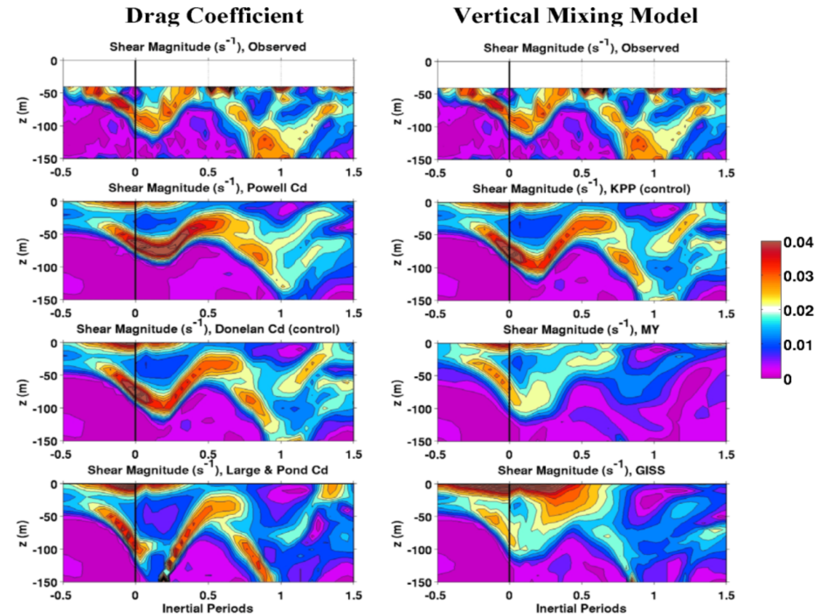
Ivan's Track and Intensity Relative to OHC (left) NRL SEED Mooring Locations in Northern Gulf of Mexico Relative to Bottom Depth (Right) (*Teague et al., JPO, 2007*).

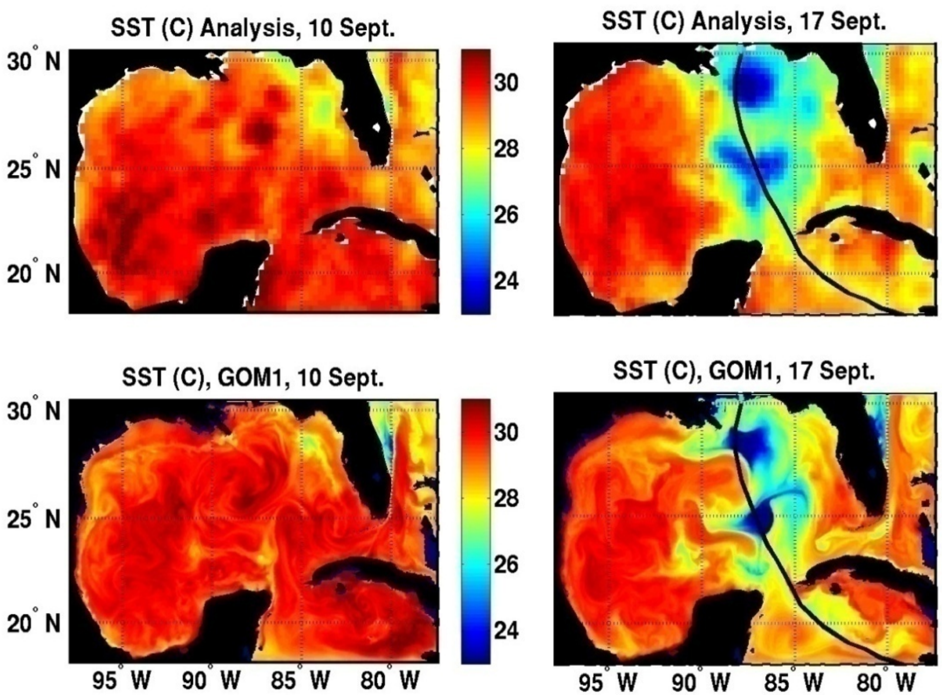




14 ADCP moorings- Focus here in Array 9.





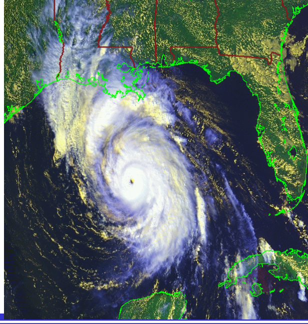


Observed and simulated *TC Ivan (2004) current shear response at NRL SEED Moorings along the Northern GOM shelf (Teague et al., JPO, 2007).*

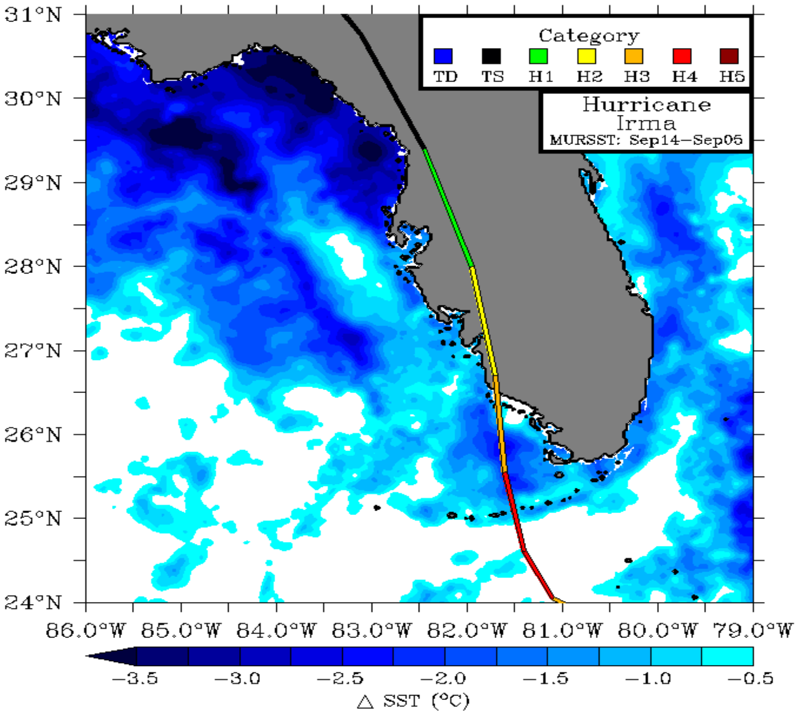
Observed (TMI) and Model SST Analyses relative to Ivan's track.

From Halliwell *et al.* (MWR, 2011)

SST Response to Slow Moving Irma Over WFS (2017)

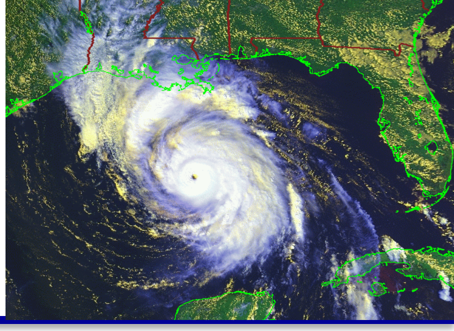


- SST Response of 3 to 3.5C Due to Slow Moving (Broad) Wind Field.
- Forces Off-Shore Transport and Upwelling of cooler water.
- Broad Wind Fields Affecting The Shelf: Frederic (1979); Dennis and Katrina (05)
- Major Red Tide Outbreaks in 1980, 2006 and 2018.
- Hurricane Passage Pre-conditioning the Shelf With Upwelling and Suspension of organisms such as K-Breve?



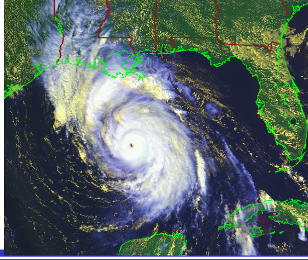
GRHSST Data Product From NASA JPL

Airborne Oceanographic Surveys Using AXCP/EM APEX Sensors In Storms



Survey(s)	Basin	Year	Sensors	References
Norbert	EPAC	1984	AXCP	Sanford *et al.* (1987)
Josephine	WATL	1984	AXCP	Sanford *et al.* (1987)
Gloria	WATL	1985	AXCP Drifters	Black *et al.* (1988); Price *et al.* (1994)
Gilbert	GOM	1988	AXCP	Shay *et al.* (1992)
Dennis	WATL	1998	OML Floats	D'Asaro (2003)
EPIC/Juliette	EPAC	2001	AXCP AXCTD	Raymond et al. (2004); Shay and Brewster (2010)
Isidore /Lili	GOM	2002	AXCP AXCTD	Shay and Uhlhorn (2008); Uhlhorn and Shay (2012)
Frances	WATL	2004	EM/APEX OML floats	Sanford *et al.* (2007); D'Asaro *et al.* (2007)
Katrina/Rita	GOM	2005	AXCTD AXCP	Jaimes and Shay (2009)
Gustav and Ike	GOM	2008	EM/APEX OML floats	Meyers *et al*. (2015)
ITOP	WPAC	2010	EM/APEX OML floats	D'Asaro *et al.* (2013)
DwH	GOM	2010	AXCTD AXCP	Shay et al. (2011)
Isaac	GOM	2012	AXCTD AXCP	Jaimes and Shay (2015)
Edouard	WATL	2014	AXCTD AXCP	Uhlhorn et al. (2015)

Where is the Loop Current!



LC Complex provides positive feedback to hurricanes through sustained heat and moisture fluxes due to warm layer depth (e.g. 26C water). Observed SST cooling less than 1.5C.

SST modulated by warm and cold ocean features that have to be properly initialized in models and complex mixing processes impact fluxes.

Momentum (current shear) response drives the mixing or lack thereof in LC; geostrophic currents/vorticity enhance upwelling and downwelling process.

In forecast (coupled) models, largest uncertainties in model initializations, and mixing and air-sea parameterizations. Evolving 3-D data are crucial.

Negative feedback (cooling/mixing induced by strong winds and CCR) as opposed to **positive feedback** **over the LC/ WCR.**

Targeted obs (storm-coordinate system) of temperatures, salinities and currents needed to assess mixing schemes and evaluate initialization schemes. Expendables (AXCP, AXCTD), drifters, EM-APEX floats and gliders are needed for satellite and coupled model evaluations.