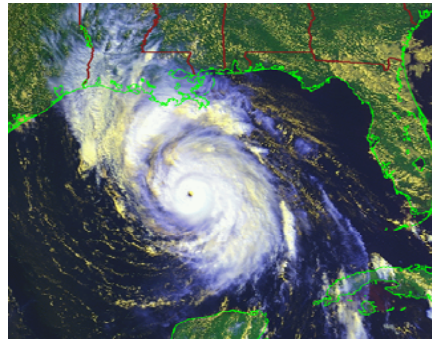


Upper Ocean Heat Variability and its Impact on Hurricane Intensity and Structure: Decadal Progress



Objective: To quantify the ocean's role on hurricane intensity and structure change from experimental, empirical, analytical and numerical perspectives aimed at improving hurricane landfall forecasts.



Lynn K. "Nick" Shay

Sponsors: NSF/NOAA/MMS/NASA

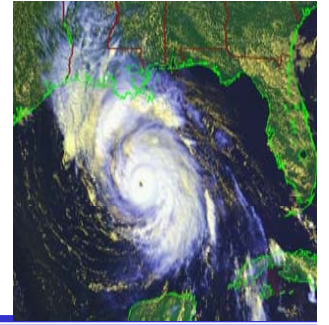
<http://isotherm.rsmas.miami.edu/~nick>

J. Brewster, W. Teague, G. Halliwell, M. Mainelli, B. Jaimes, E. Uhlhorn, C. Gentemann, P. Myers, J. Zuczek, M. Ali, I.-I. Lin, C.-C. Wu, J. Chan, M. DeMaria, J. Zhang, R. Lumpkin, J. Kaplan, D. Nolan, S. Chen, C. Lozano

The SOUTH FLORIDA cardio exercise program ...

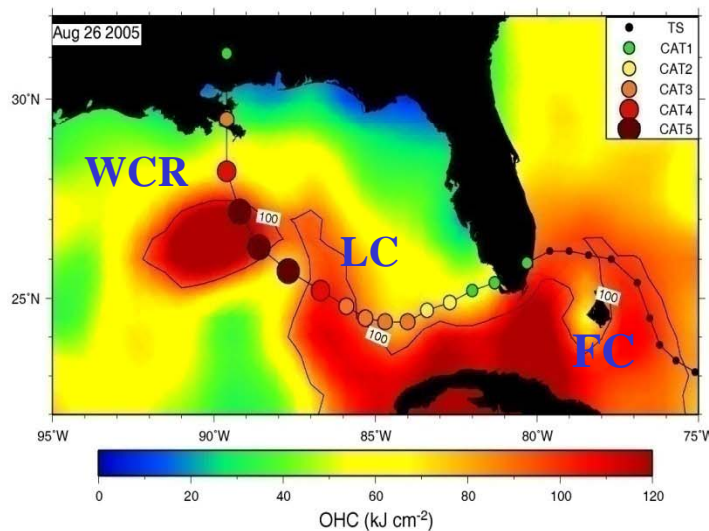
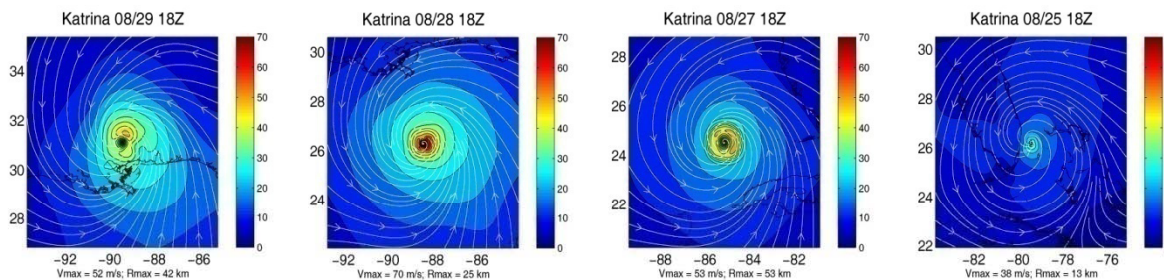
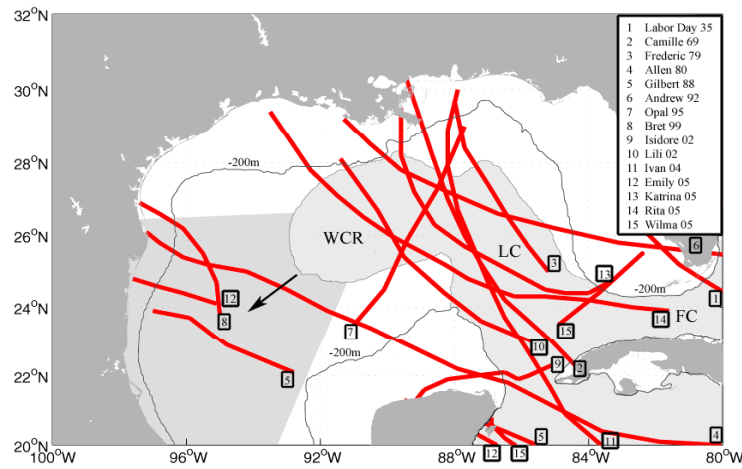


Outline:



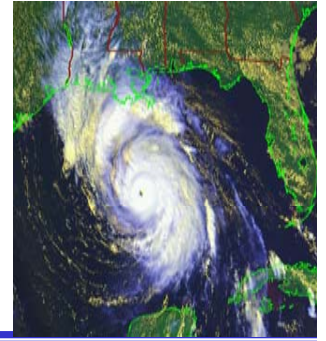
-
- Introduction
 - Motivation
 - Ocean-Atmosphere Interactions (Results from Isidore and Lili)
 - Altimetry and Oceanic Heat Content (Eastern Pacific Ocean)
 - Katrina and Rita 2005
 - Gustav and Ike 2008
 - Forecasting at TPC/NHC
 - 2009 HFP with NOAA/MMS
 - Coral Reef Challenge
 - Summary

Severe Storm (Cat 3 or above) Tracks (red) relative to the posit of the LC and WCR complex based on satellite radar data track in Aug/Sept 2005 (Shay 2008)



Altimetry data from Jason-1, GFO and Envisat data from 2005 relative to track/intensity of Katrina with HRD wind fields (Powell and Houston 1996).

Introduction:



Palmen (48), Fisher (56), Perlroth (62,65) – SST of $>26^{\circ}\text{C}$ on hurricane intensity and air-sea heat and moisture transfers.

Perlroth (68) related ocean thermal structure between the surface and 200-foot levels: Stratification (i.e. cooling and vertical mixing); and Currents (i.e. warm current advection) important.

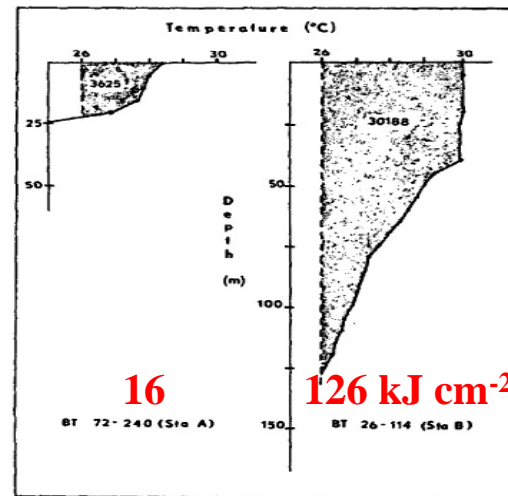
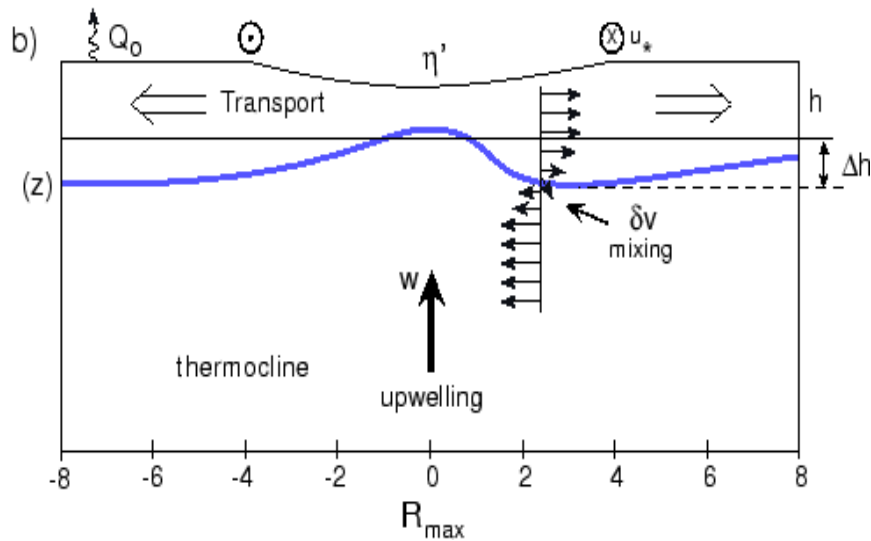
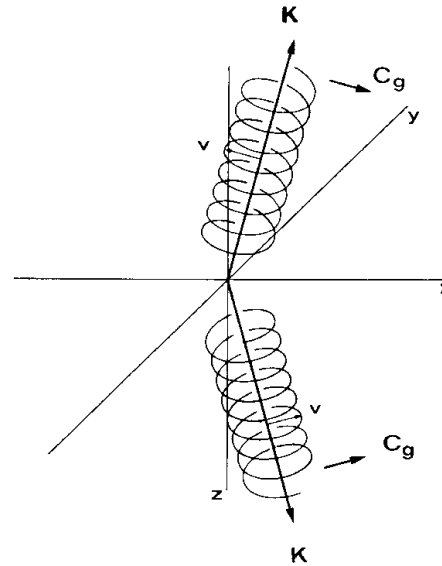
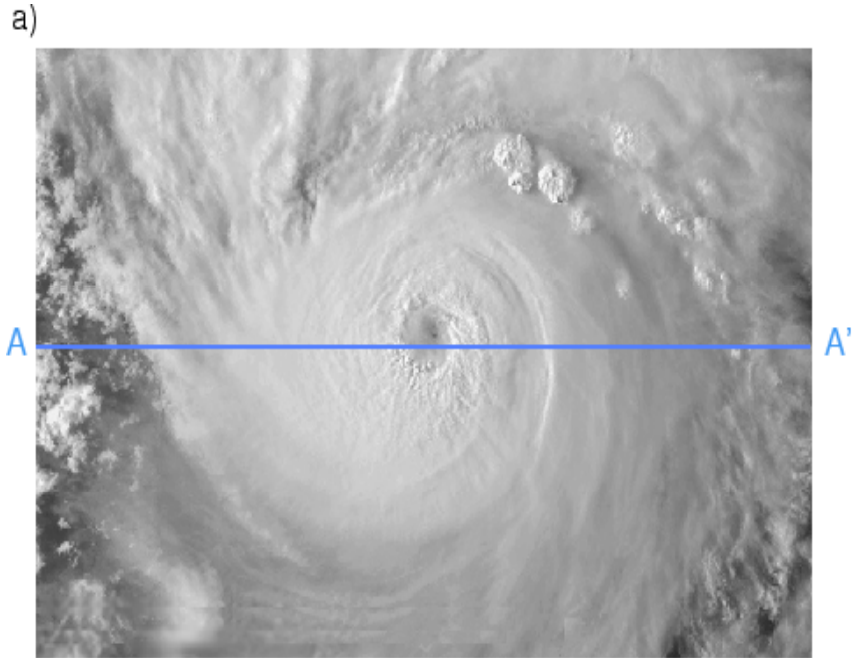
Asynoptic cruises after hurricane Hilda (64), Leipper (67) found:

- Warm ocean surface layers were advected from the storm track upwelling from about 60 m;
- SST cooling of 5°C (cold wake) and mixing within the strongly forced regime; and
- Downwelling to 100 m several R_{max} from storm center.

O'Brien and Reid (67) developed a 2-layer reduced gravity model to investigate these phenomena.

Leipper and Volgenau (72) coined the phrase: *Hurricane heat potential* to represent integrated vertical structure (pre and post hurricanes) finding the 16 kJ cm^{-2} threshold.

Leaman (1976)



Integrated thermal structure (OHC) and vertical current shear.

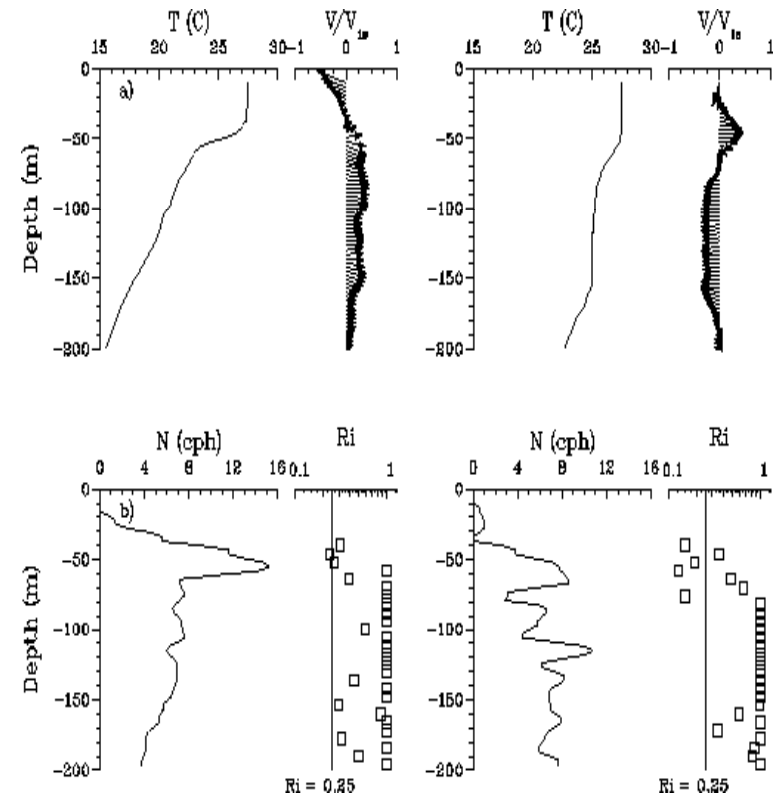
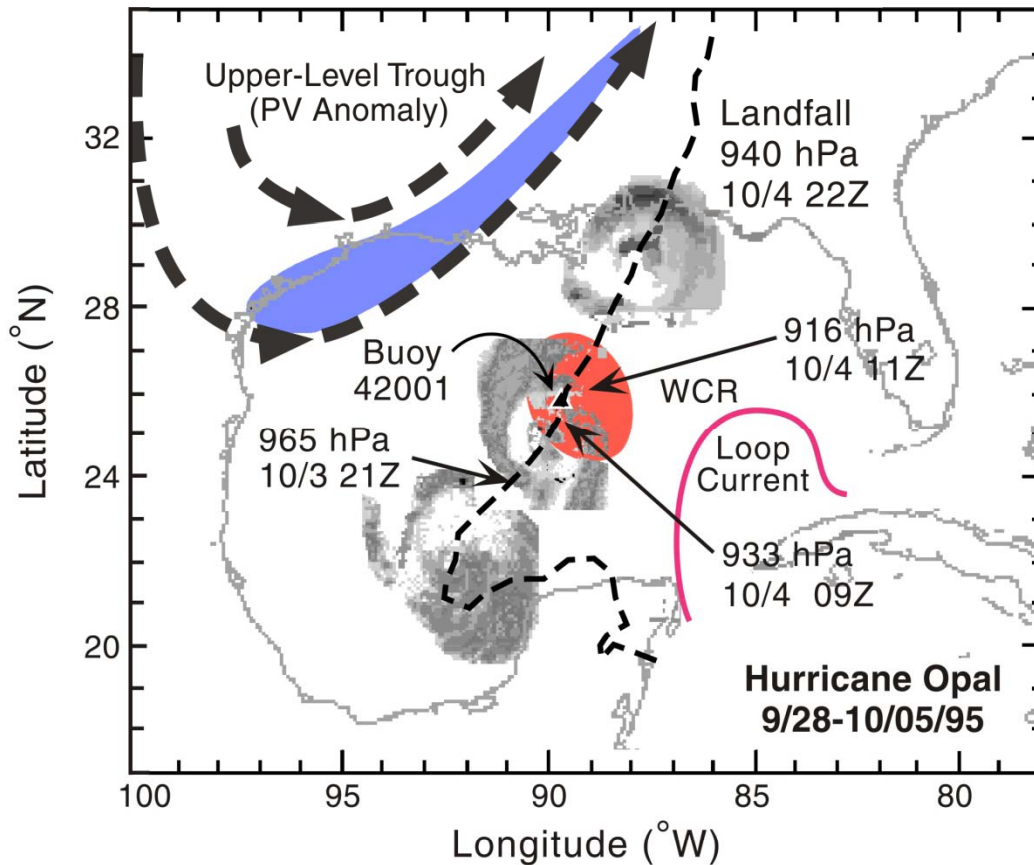
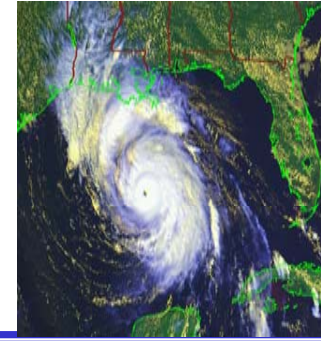
Current and shear central for mixing, cooling and, feedback to the storm.

Due to the depth of warm layers and strong background flows, minimal cooling positive feedback to TC.

Is SST Enough?

$$OHC = c_p \int_0^{D_{26}} \rho [T(z) - 26] dz,$$

Hurricane Opal: A Tipping Point? (Marks, Shay and PDT-5, BAMS, 1998)



GCW

WCR

A **tipping point** is that moment when an idea, trend, or social behavior crosses a threshold, tips, and spreads like wildfire (Gladwell 2000).

Timeline of OHC Approach:

Shay et al. (2000) used an annual climatology coupled with one altimeter cast within a reduced gravity model (Goni et al. 1996) to estimate Oceanic Heat Content (OHC) for Opal WCR under favorable atmospheric conditions (Bosart et al. 2000).

Hong et al. (2000) used a multilayer coupled model initialized with a warm eddy, Opal's intensity increased (surface pressure decreased by about 10 mb).

Mainelli (MS Thesis, 2000) assessed the validity of using a hurricane season climatology finding improved OHC values with the six month climatology.

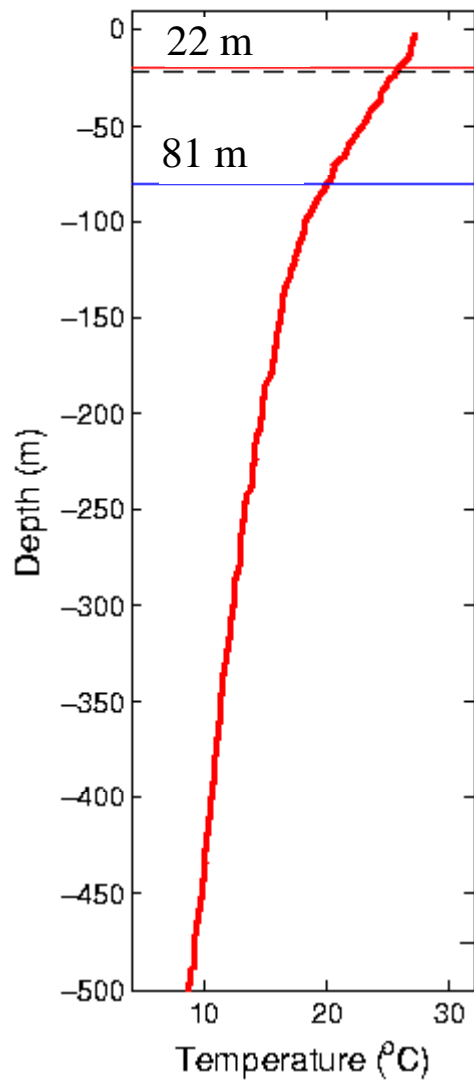
As part of the Joint Hurricane Testbed (DeMaria and Manelli in 2001), NHC and RSMAS worked out the scheme to update OHC each day with new altimetry track data that were blended and objectively analyzed using Mariano and Brown (1992).

NHC accepted the JHT results in a letter from Max Mayfield in January 2003 for use with intensity forecasts in SHIPS (DeMaria et al. 2005).

A JHT grant was awarded for OHC Estimations in the Eastern Pacific in 2006-updating the original OHC approach for use with SHIPS.

Manielli et al. (2008) showed that OHC matters for severe hurricanes (category 5).

Shay and Brewster (2009) - OHC in the East Pacific submitted to MWR.



cold cyclone

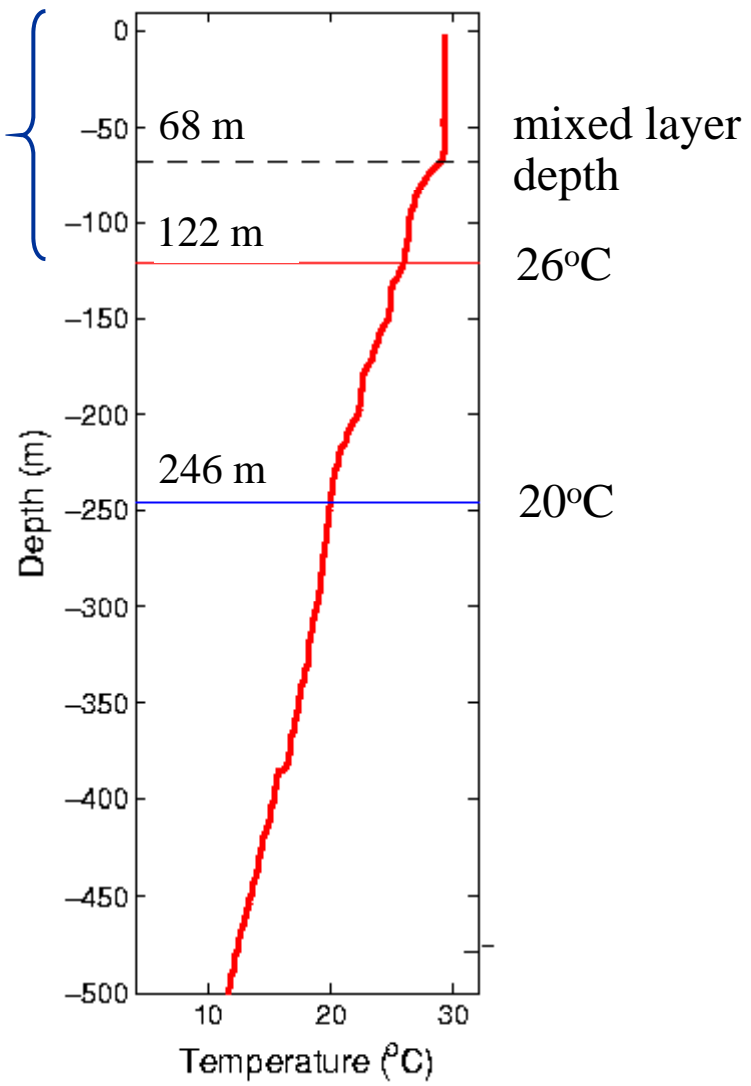
$Q = c_p \int_{H26}^{\eta} \rho(z) [T(z) - 26] dz$

6 kJ cm⁻² (indicated by a bracket from 0 to 22 m)
 114 kJ cm⁻² (indicated by a bracket from 0 to 81 m)

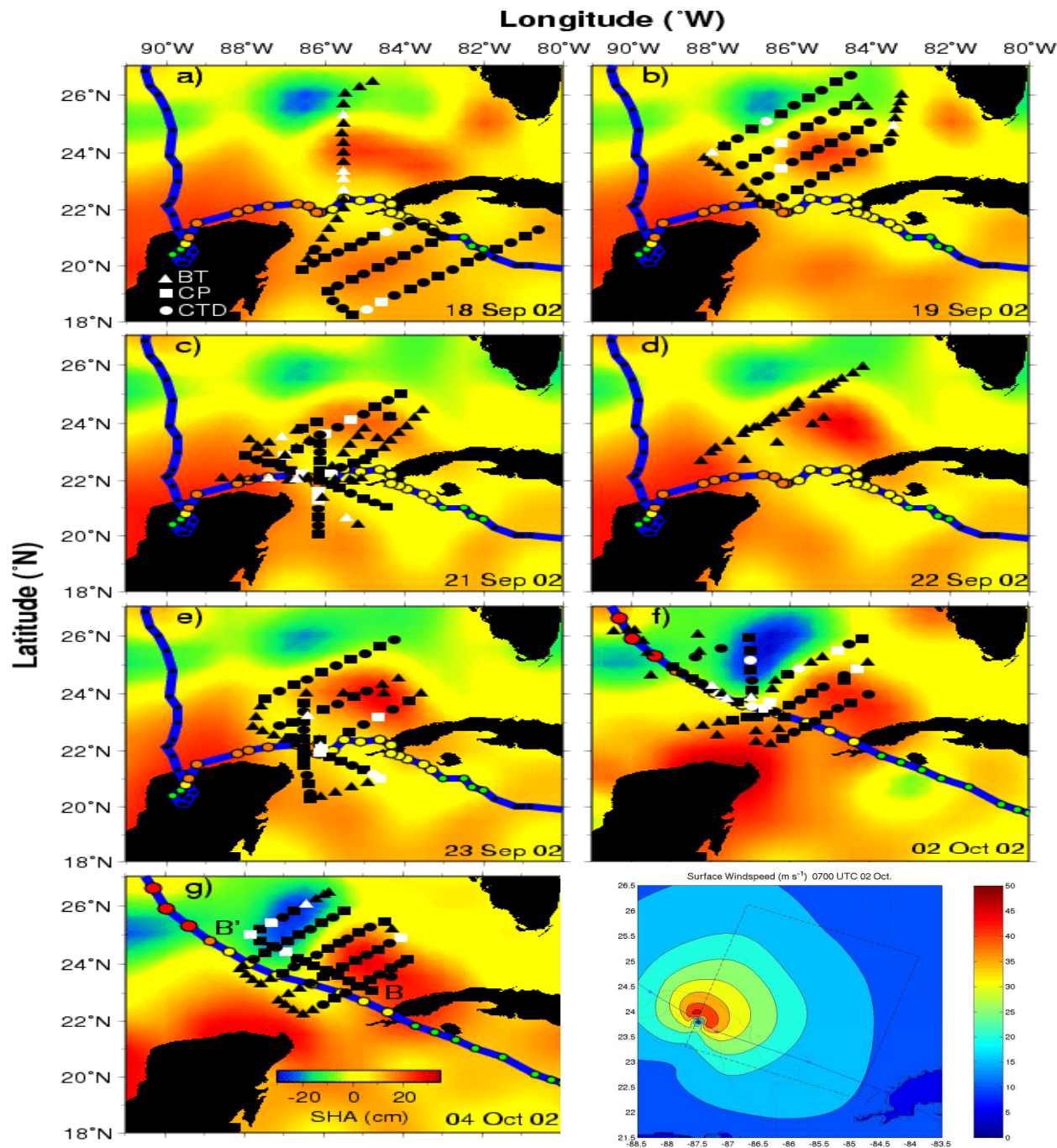
Reduced negative feedback in warm core eddies



Hurricanes reach intensities closer to maximum potential intensity.



warm anticyclone



NSF/NOAA Isidore/Lili (02) Experiments (Shay and Uhlhorn 2008):

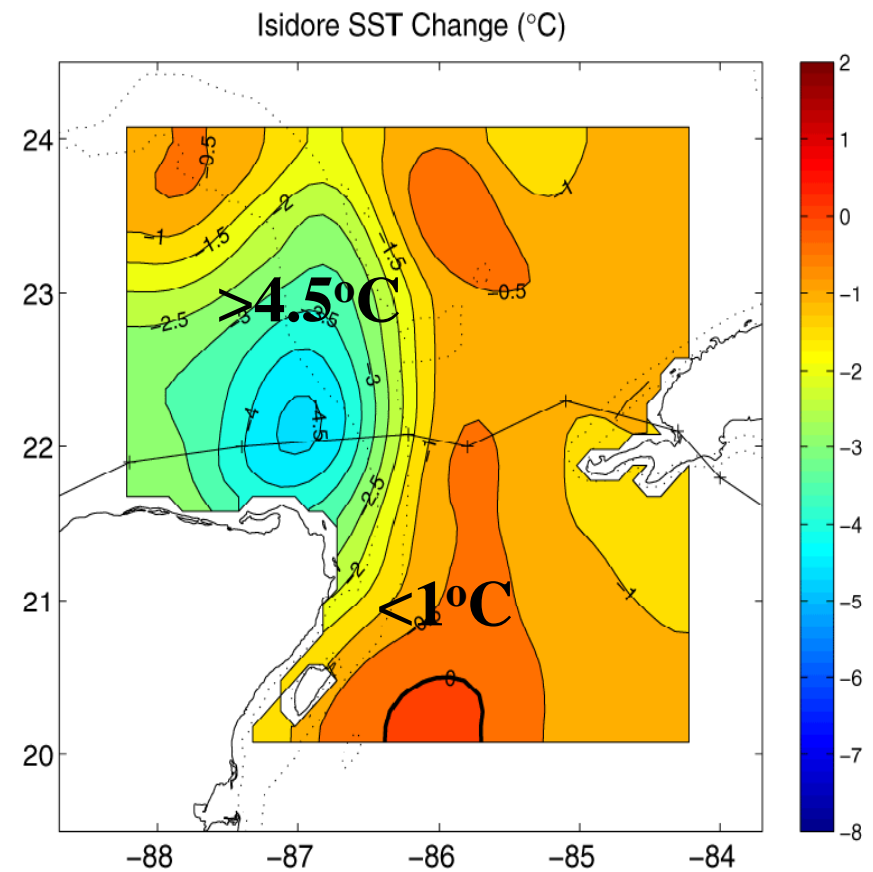
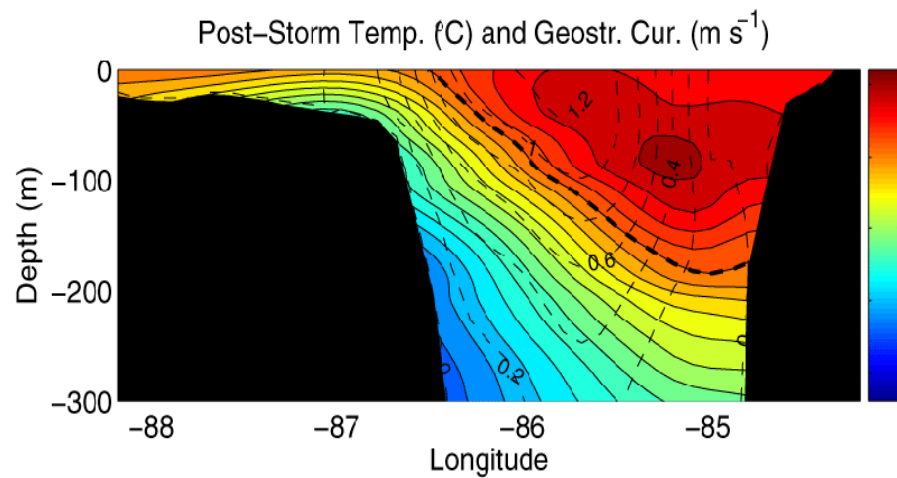
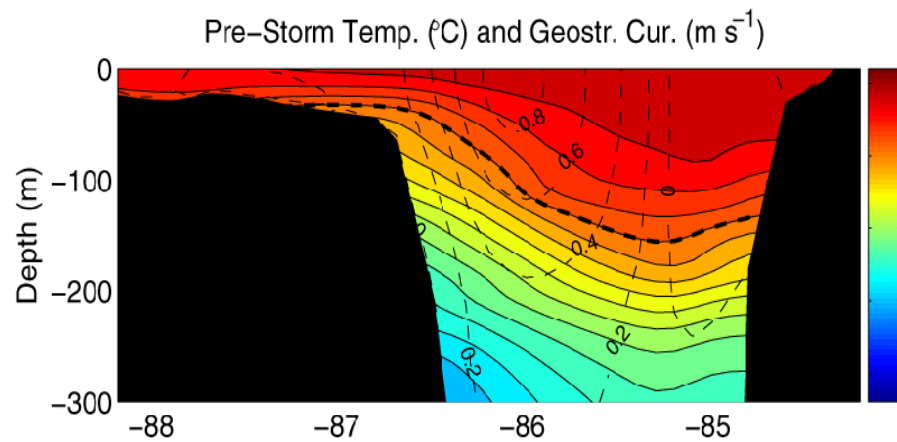
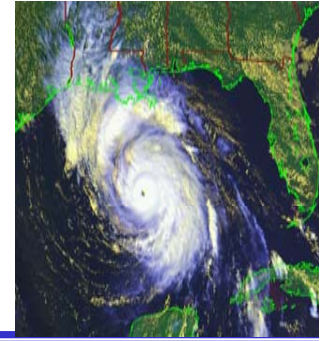
- a) Caribbean (Pre)
- b) GOM (Pre)
- c) Isidore
- d) Wake 1 (Post)
- e) Wake 2 (Post)
- f) Lili
- h) Wake 1 (Post)

SHA field: TOPEX, GFO and ERS-2

**1-Green; 2-Yellow
3-Orange; 4-Red**

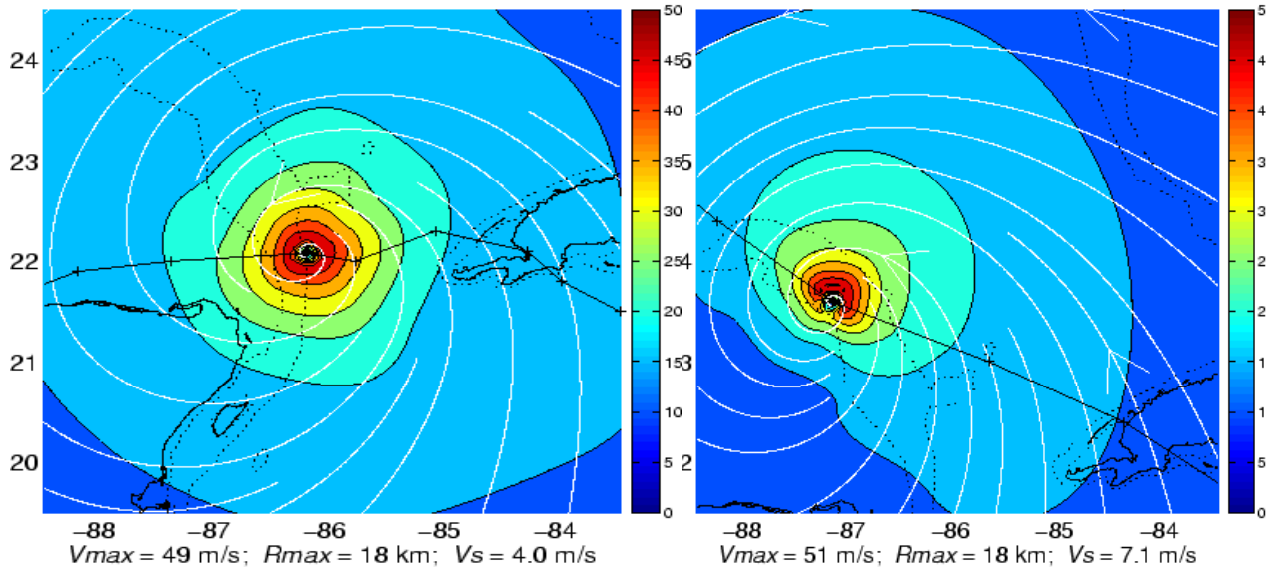
SFMR-Surface Winds (Uhlhorn et al., JAOT, 2007-B. I. Miller Award)

T(x,z) and V(x,z) Section (left) and SST Change along 22°N

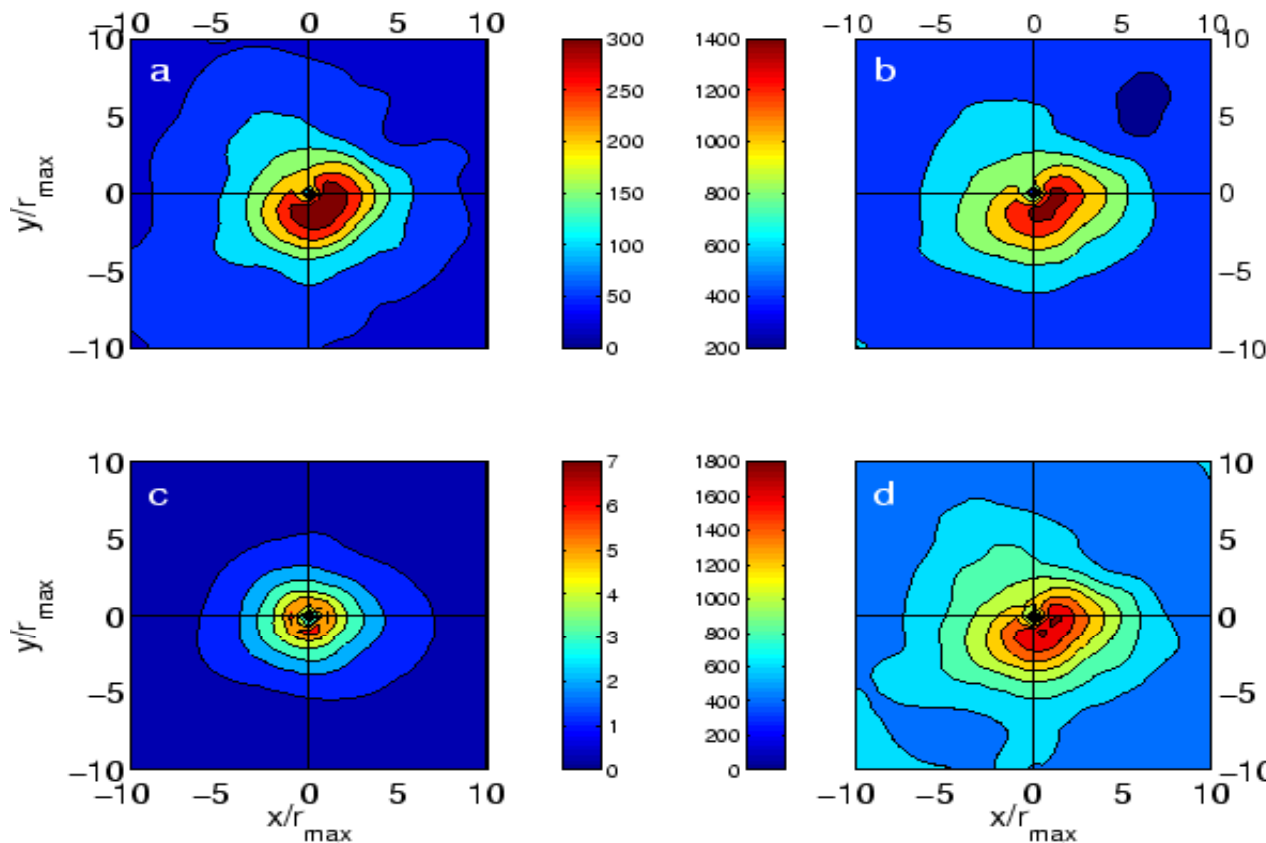


Isidore Wind Speed (m/s) 2002/09/21 22 UTC

Lili Wind Speed (m/s) 2002/10/02 06 UTC



Isidore/Lili SFMR derived wind field:

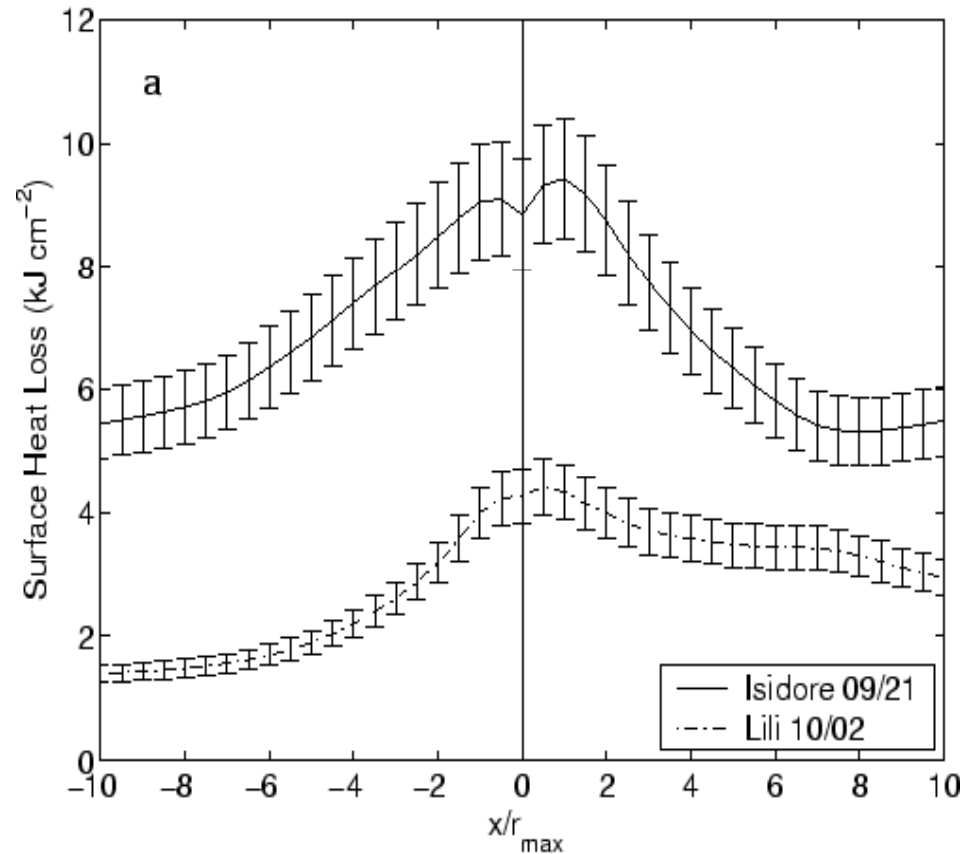
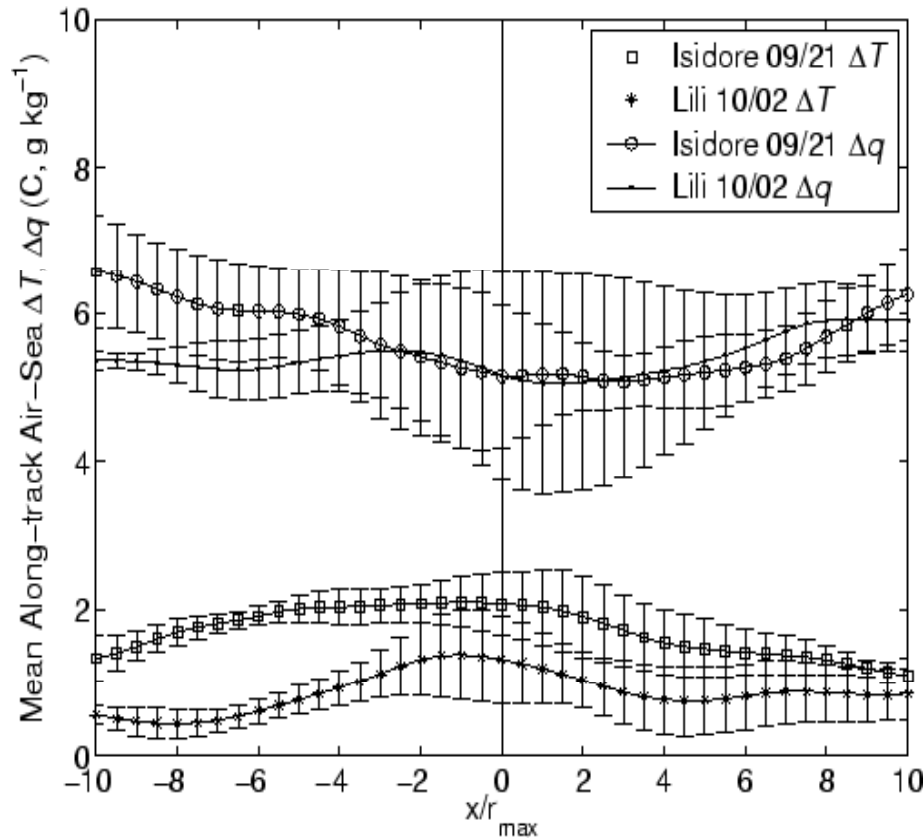
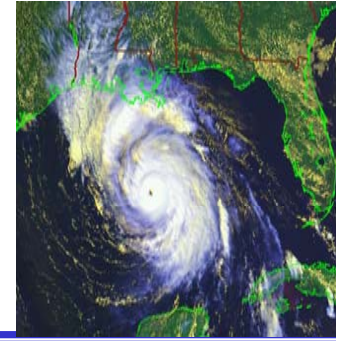


**Isidore Fluxes For:
a) Sensible,
b) Latent,
c) Momentum,
d) Enthalpy.**

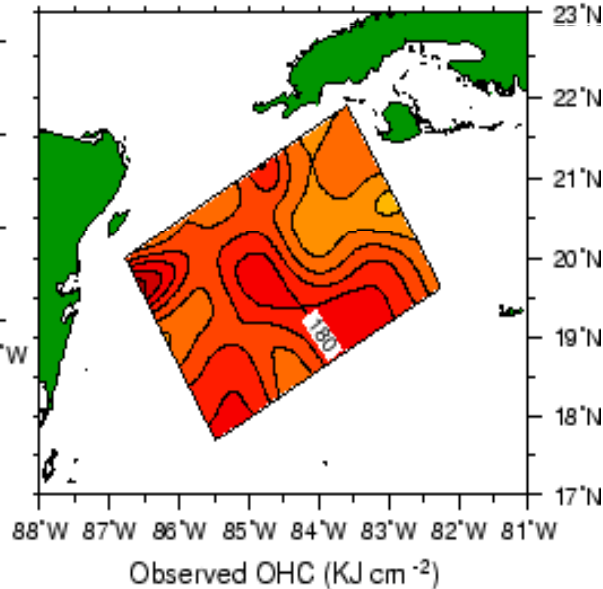
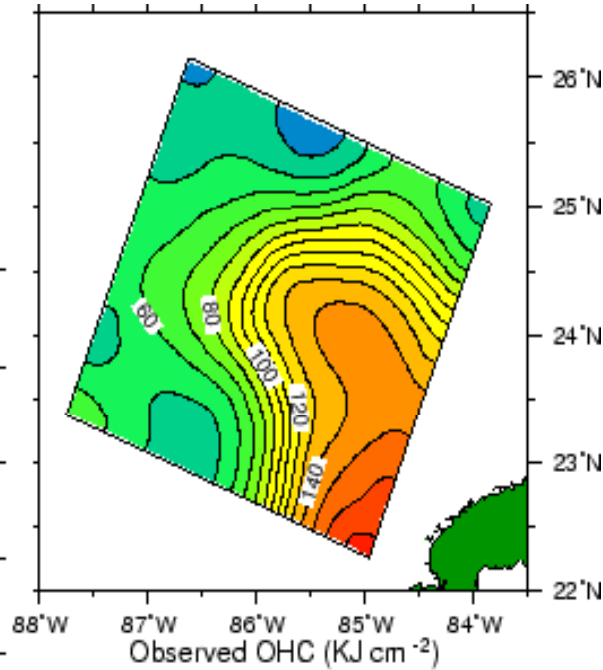
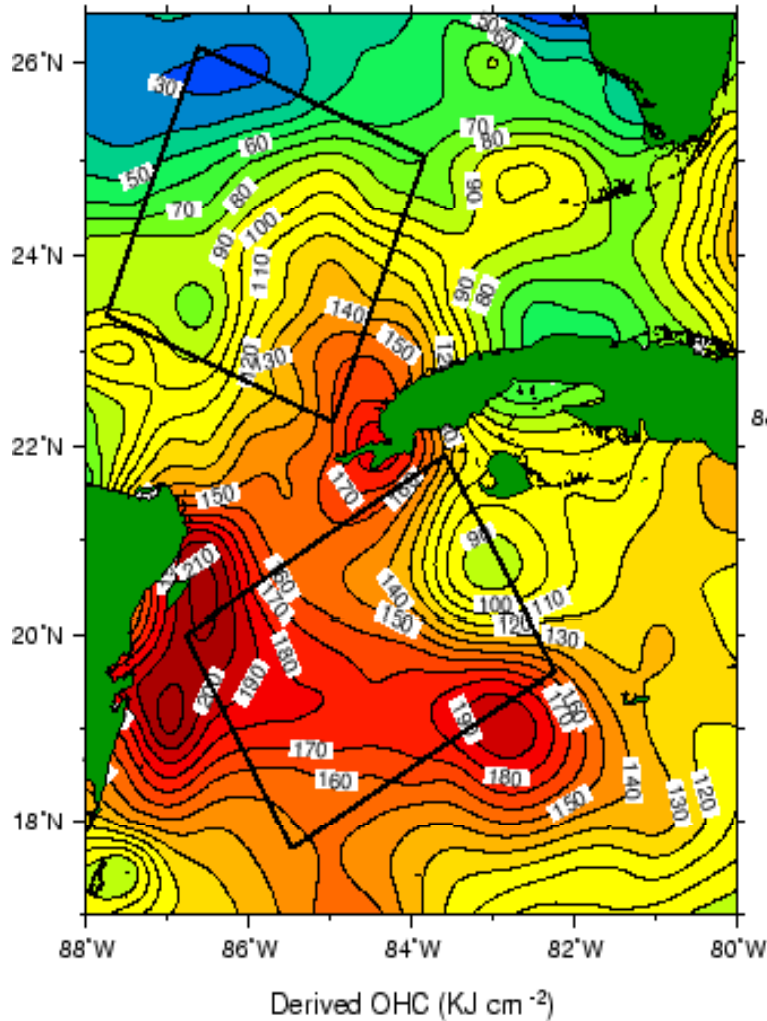
Uses GPS, AX., and SFMR fields.

(Shay and Uhlhorn, MWR, 2008)

Air-Sea Differences (left) and Surface Heat Loss (right) (From Shay and Uhlhorn, MWR, 2008)



Integrated surface heat loss over 8 hour flight-O(10 $kJ\ cm^{-2}$) from Shay and Uhlhorn (MWR, 2008) while storms went to cat-4 status!

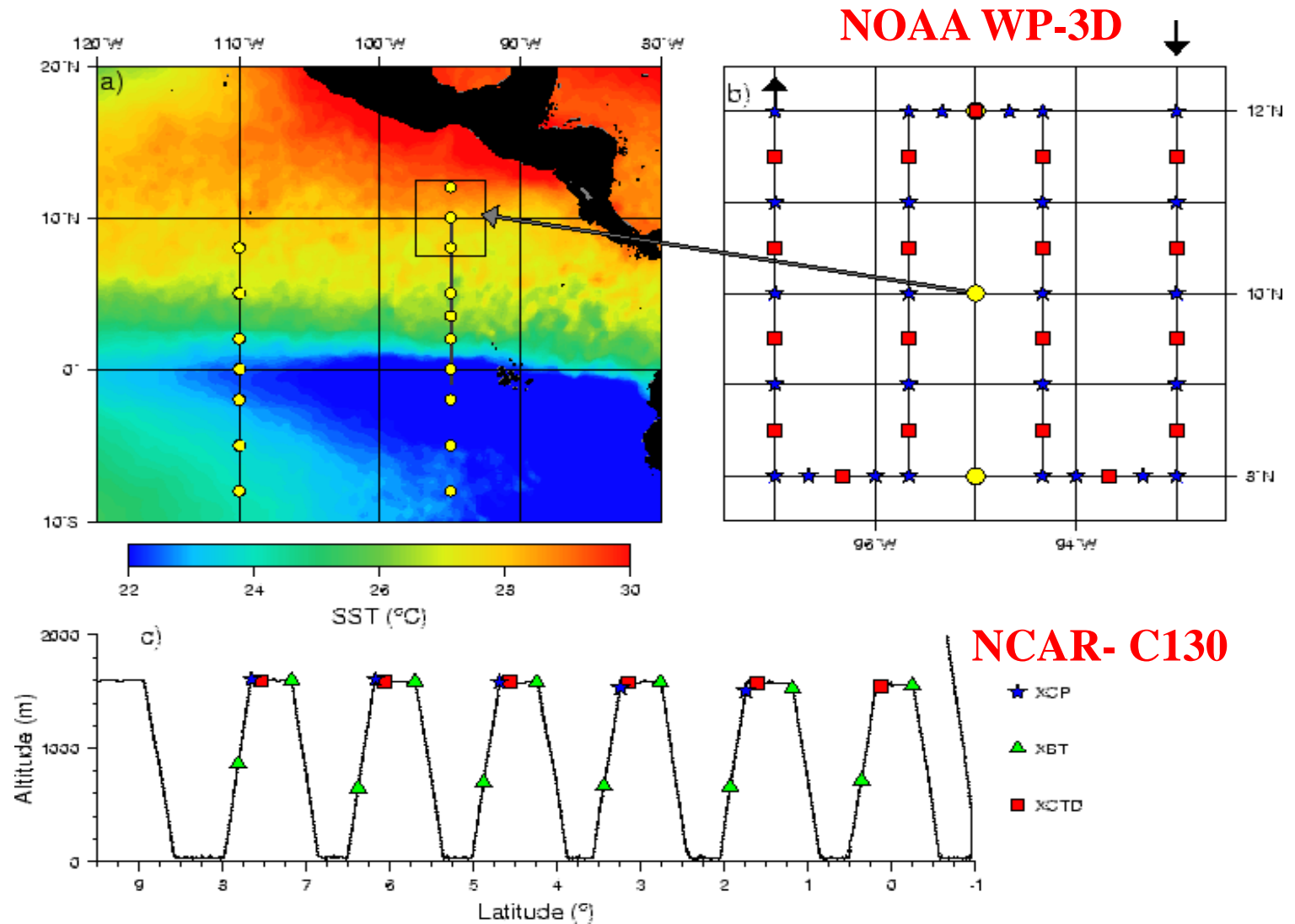
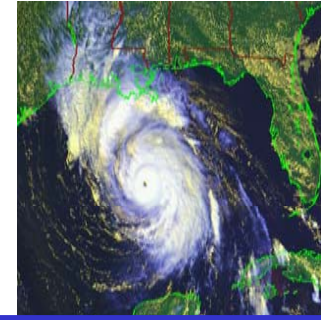


Sat-Derived OHC (left) estimates and two Pre-Isidore OHC snapshots (right) in Sept 02 in the NW Caribbean and GOM basins.

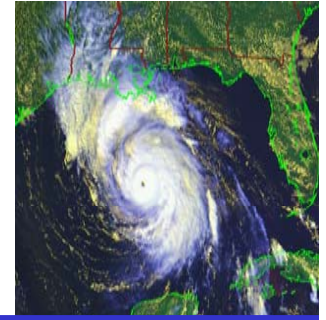
Satellite estimate based on a 7-day Reynolds and Topex/ERS-2 altimeter SHA data.

Product Transitioned 02 at TPC-NOAA Joint Hurricane Testbed Grant (Mainelli and Shay).

NSF/NOAA Aircraft and TAO Buoys Sample Strategy (Raymond et al., BAMS, 2004)

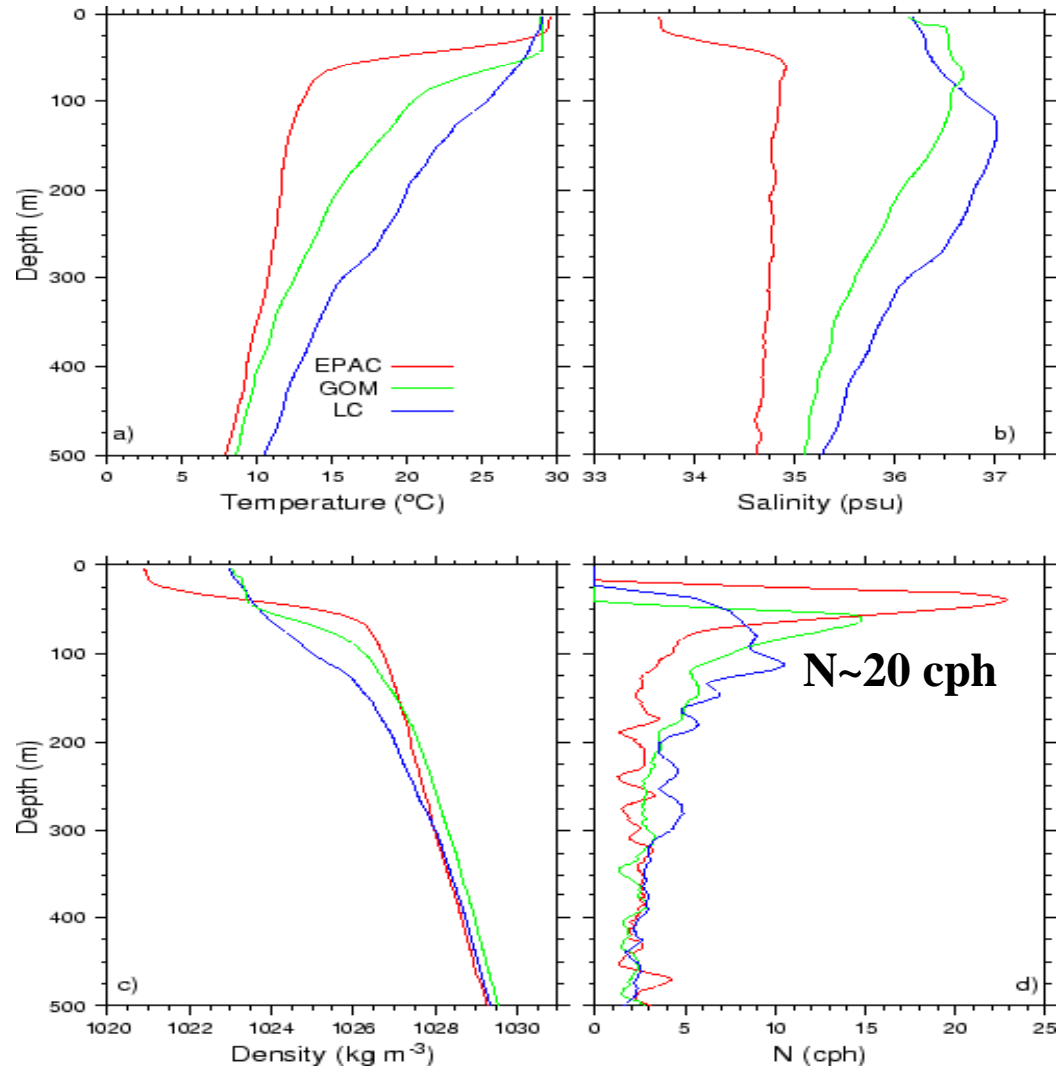


EPAC Paradox

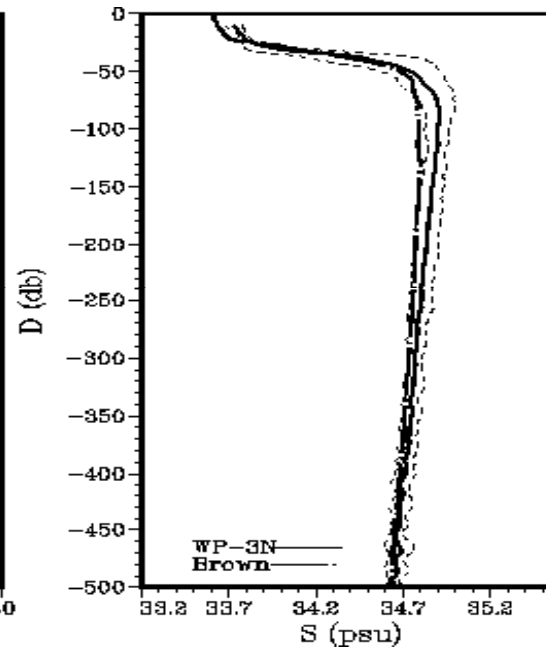
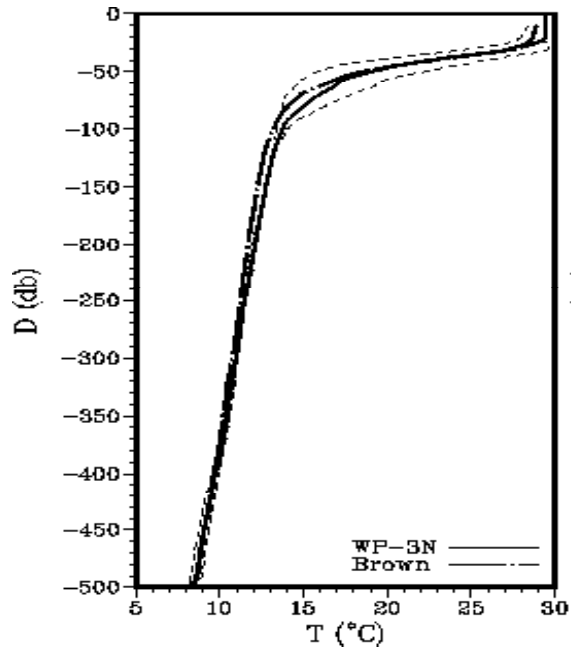


Strong vertical temperature, salinity and density gradients at base of OML in EPAC...

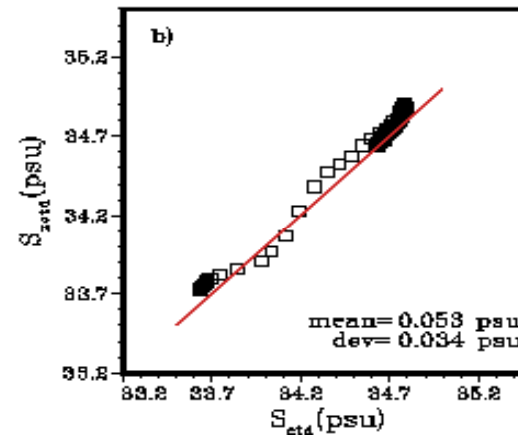
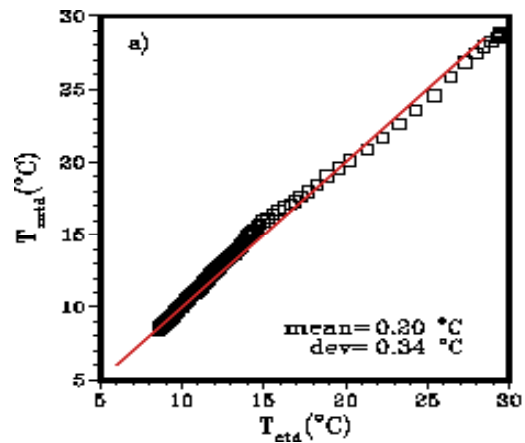
Implications for mixing...and ocean (SST) cooling.



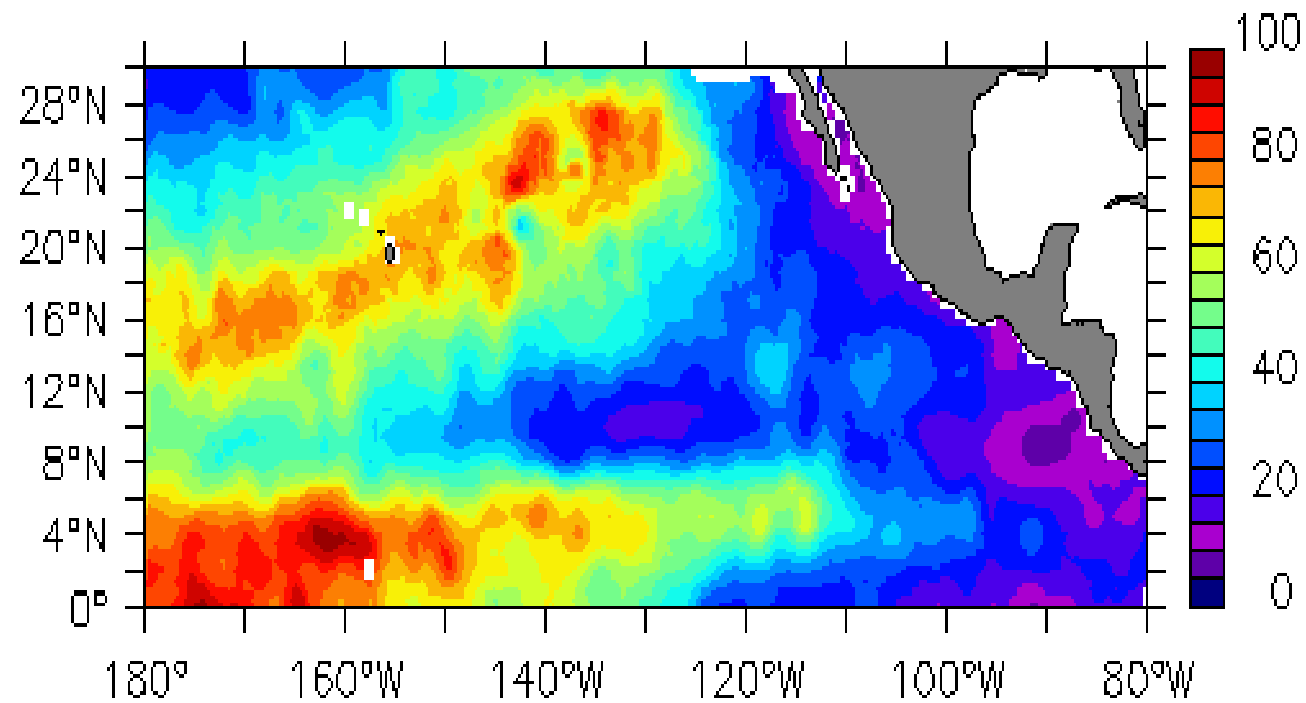
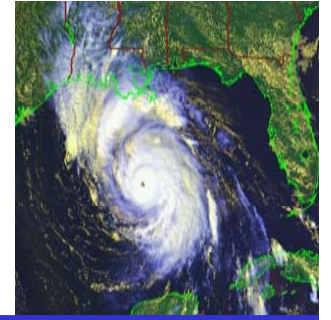
NOAA R/V Brown Versus WP-3D CTDs -10N



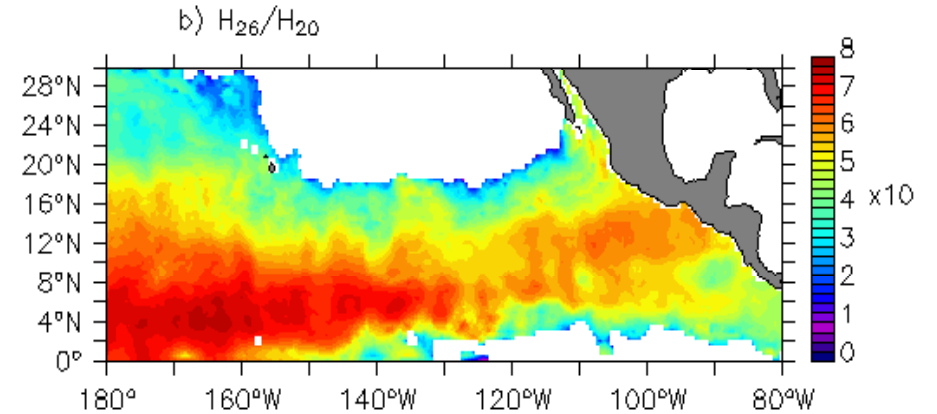
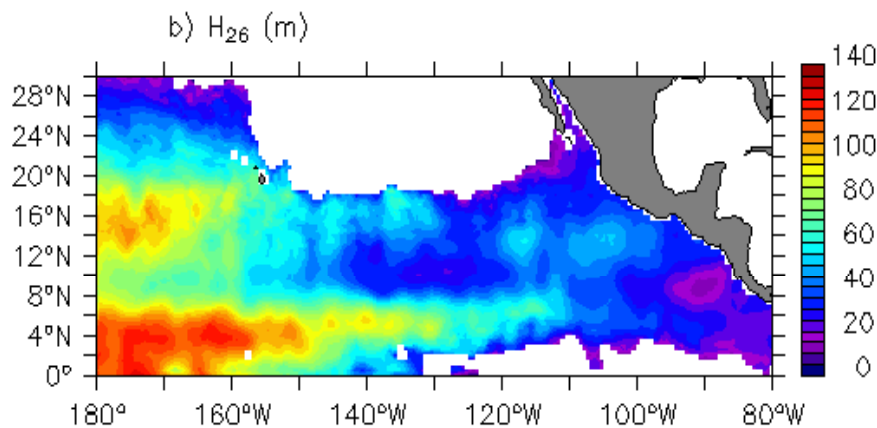
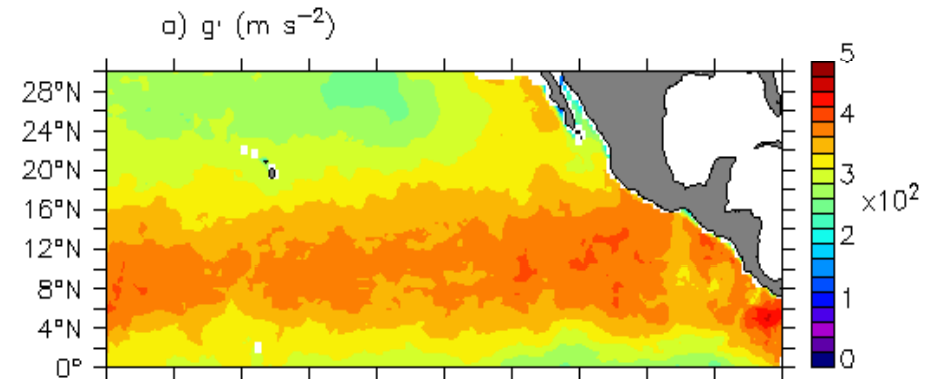
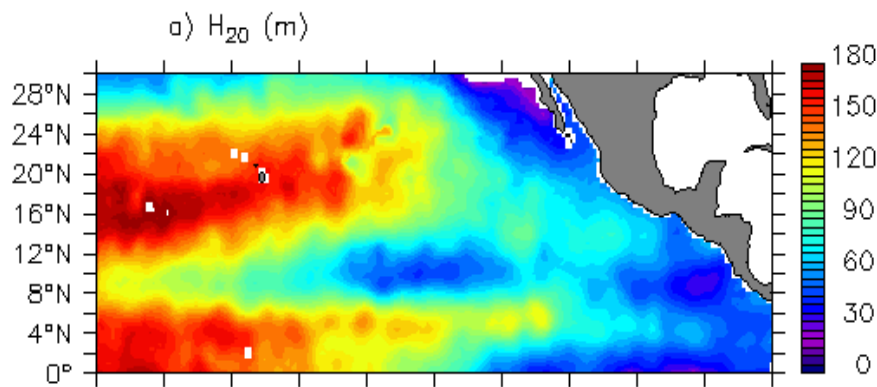
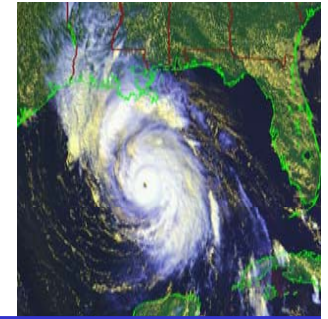
**Airborne
Oceanography
Works!**



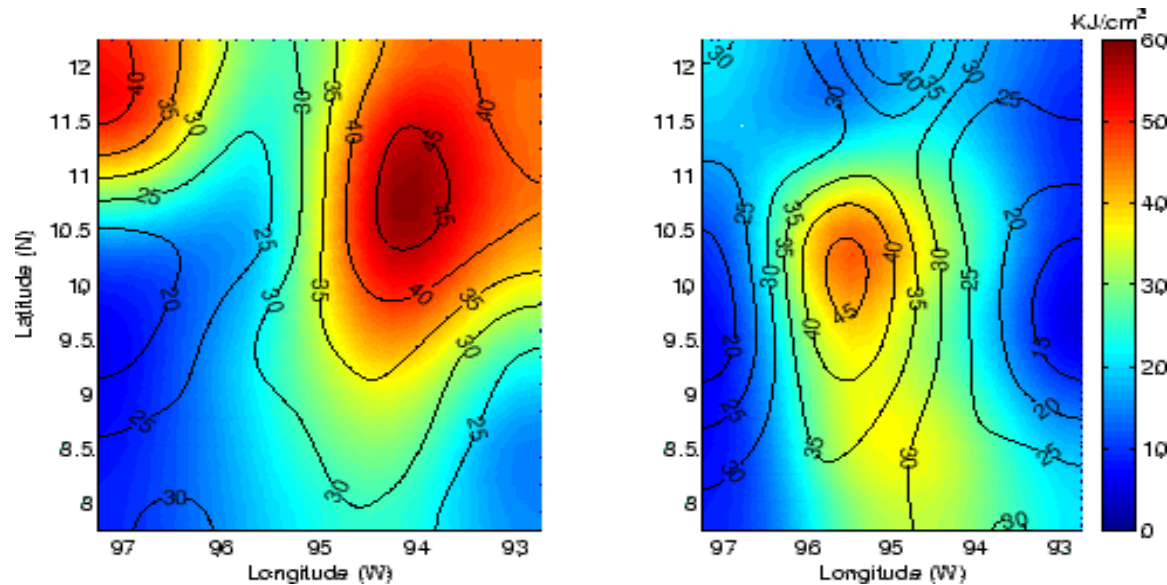
Depth of the Climatological Ocean Mixed Layer (m) GDEM.



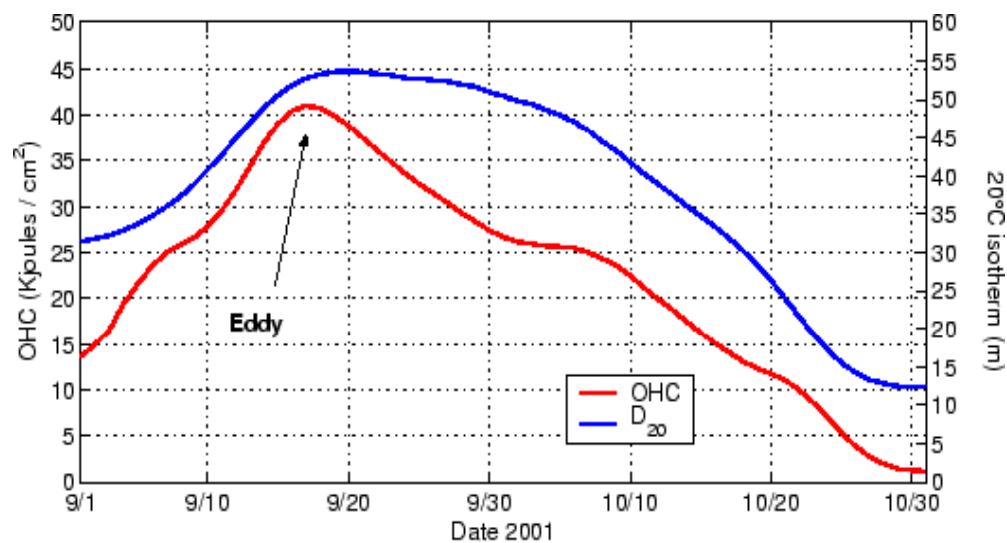
Mean Isotherm Depths (left) & Reduced Gravity and Ratio (right)



Costa Rica Dome.

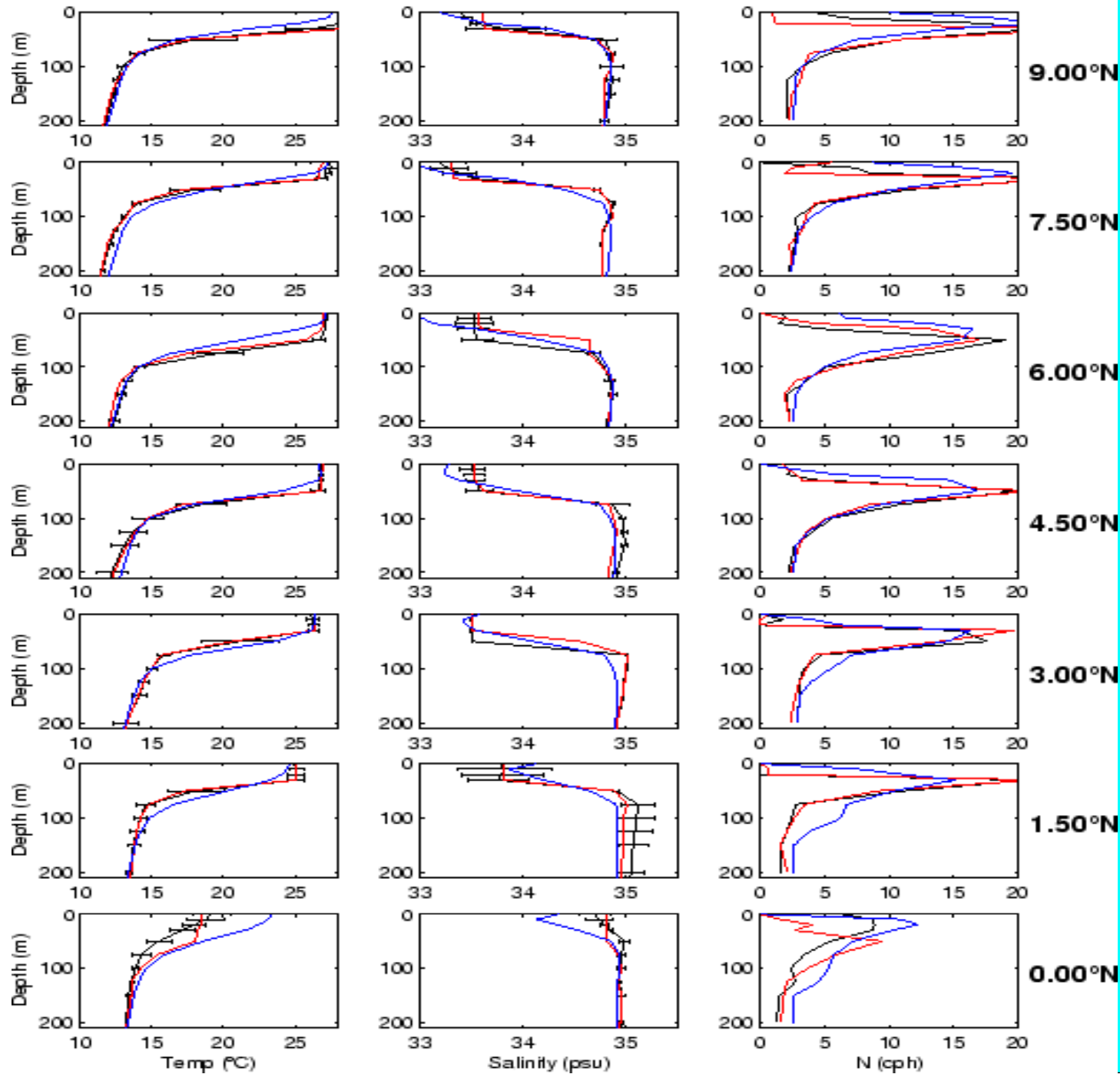


Sept (left) and Oct (right) OHC of Warm Core Eddy

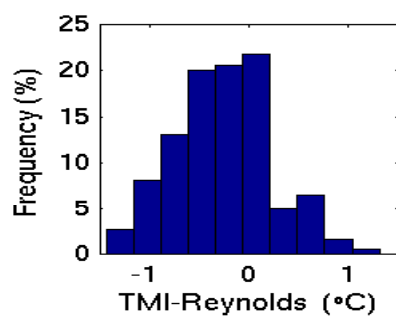
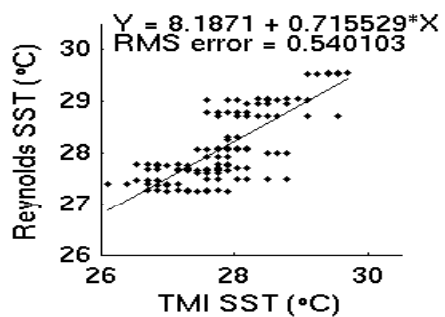
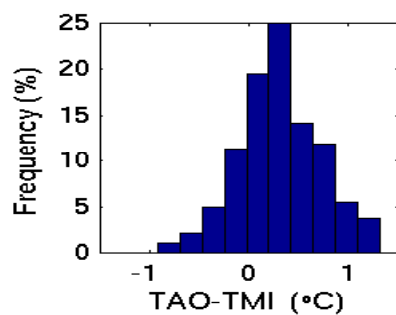
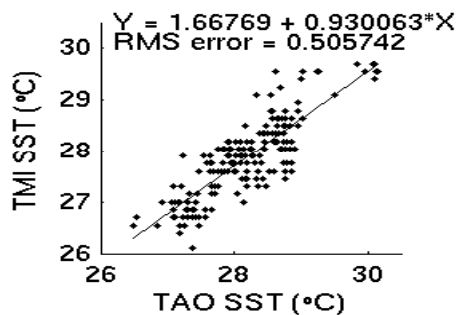
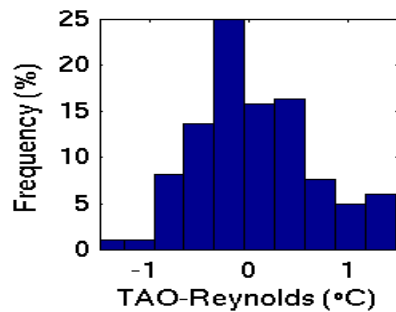
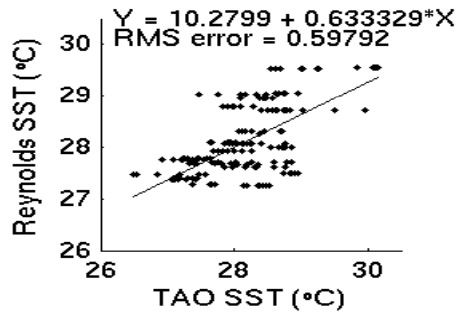


10°N TAO Mooring OHC and D₂₀°C. The shallow isotherm depths may be an indication of the Costa Rica Dome.

October: Black-EPIC, Red-Ron Brown, Blue-GDEMv3



**95°W
Ocean
Structure:
EPIC**



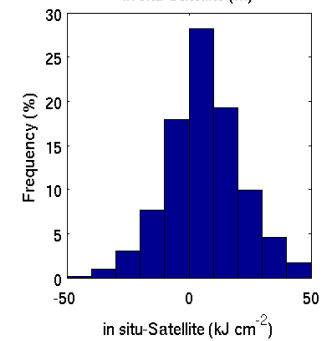
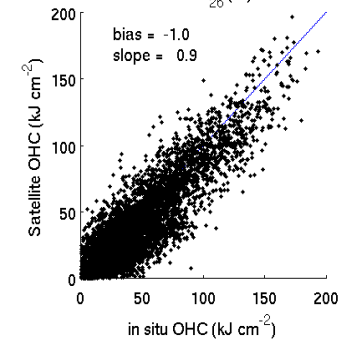
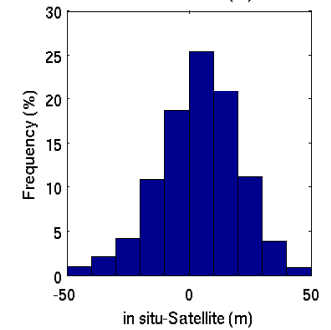
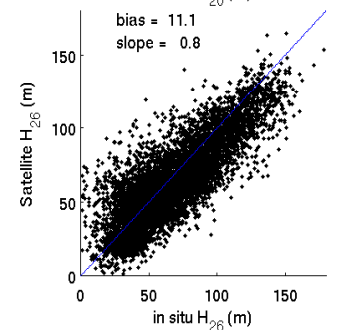
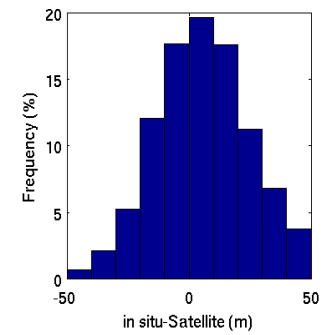
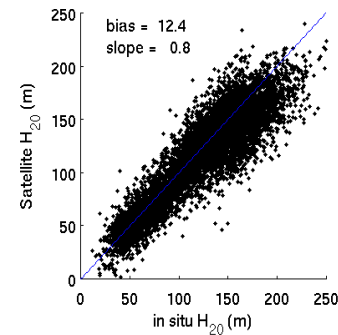
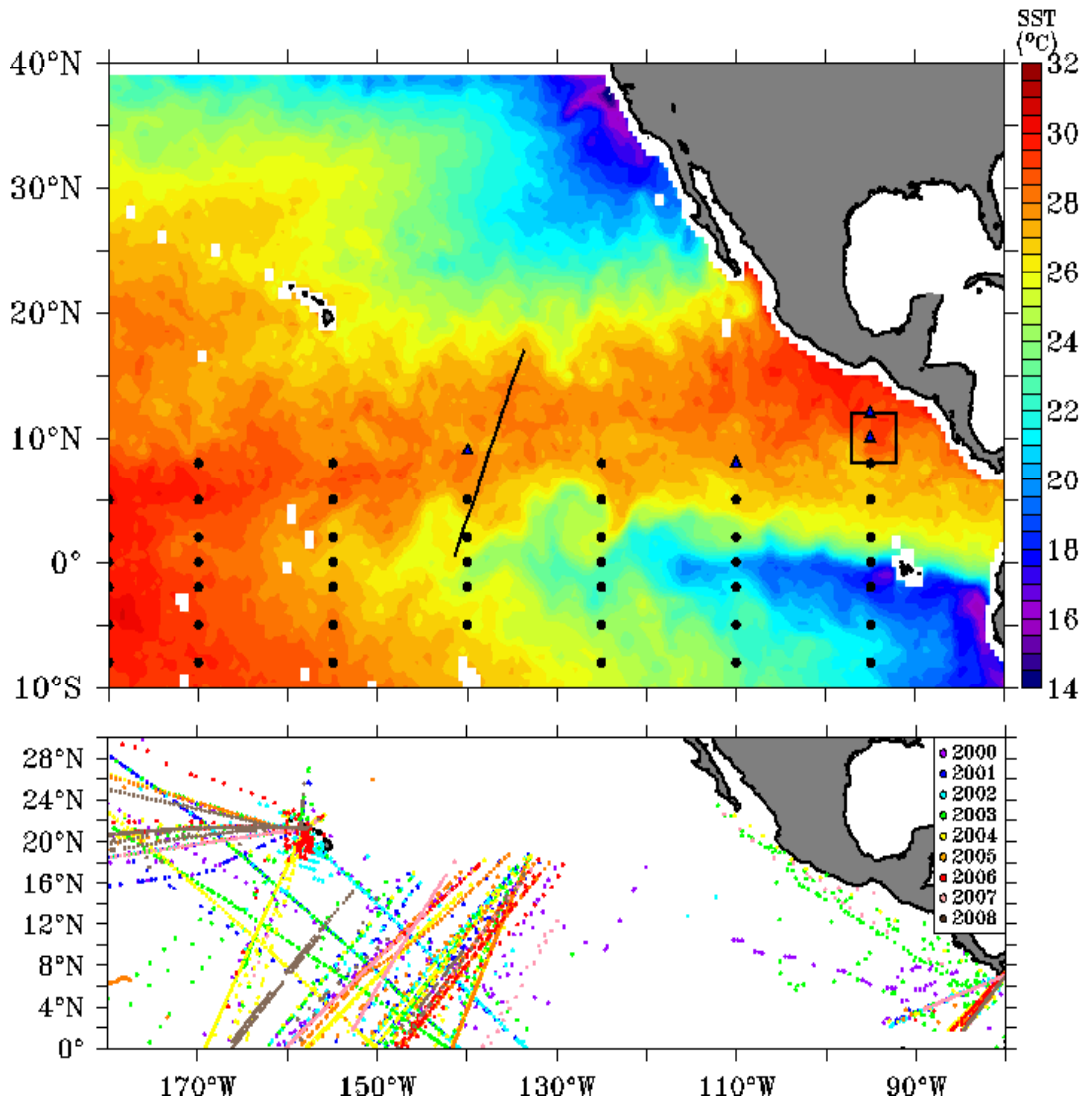
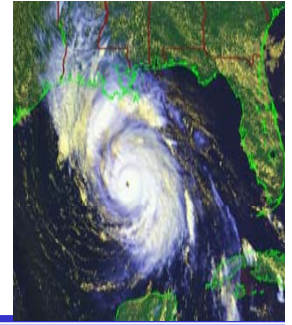
**SSTs at 10°N,
95°W:
SST Product
Choice?**

TMI/AMSR-E

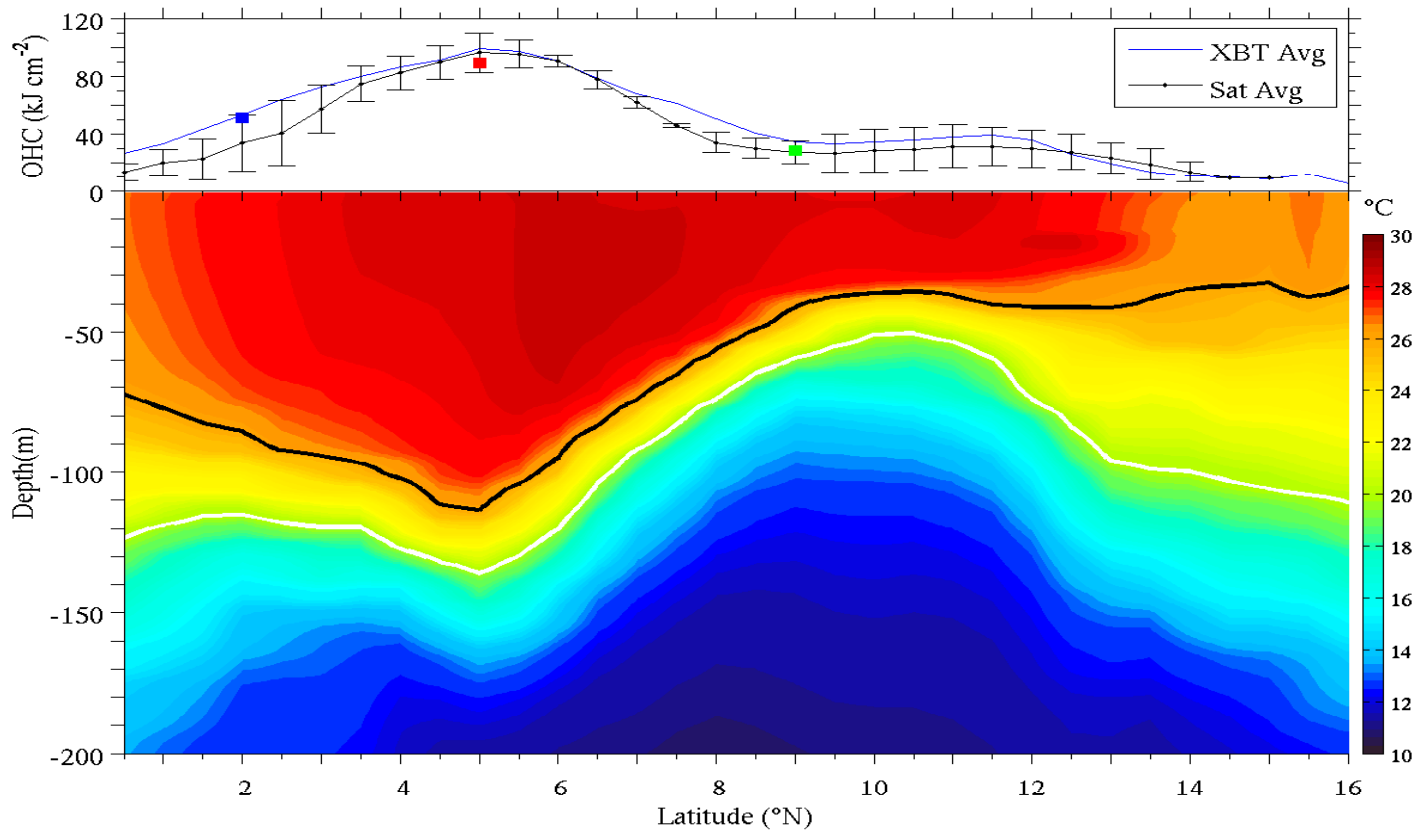
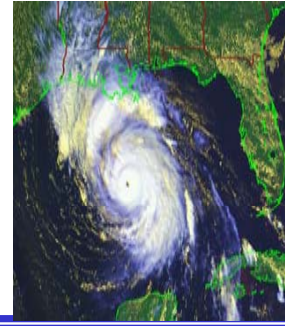
**Courtesy of
Remote
Sensing
Systems.**

East Pacific Ocean 00-08 XBT Transects

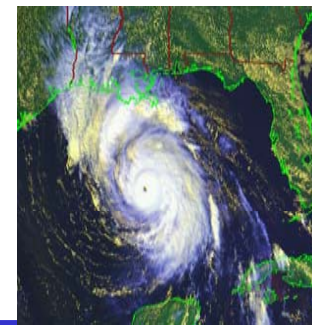
(from <http://www.aoml.noaa.gov/phod/trinanes/SEAS>).



XBT Transect and Moorings (dots) from 5-years of measurements relative to sat average-East Pacific

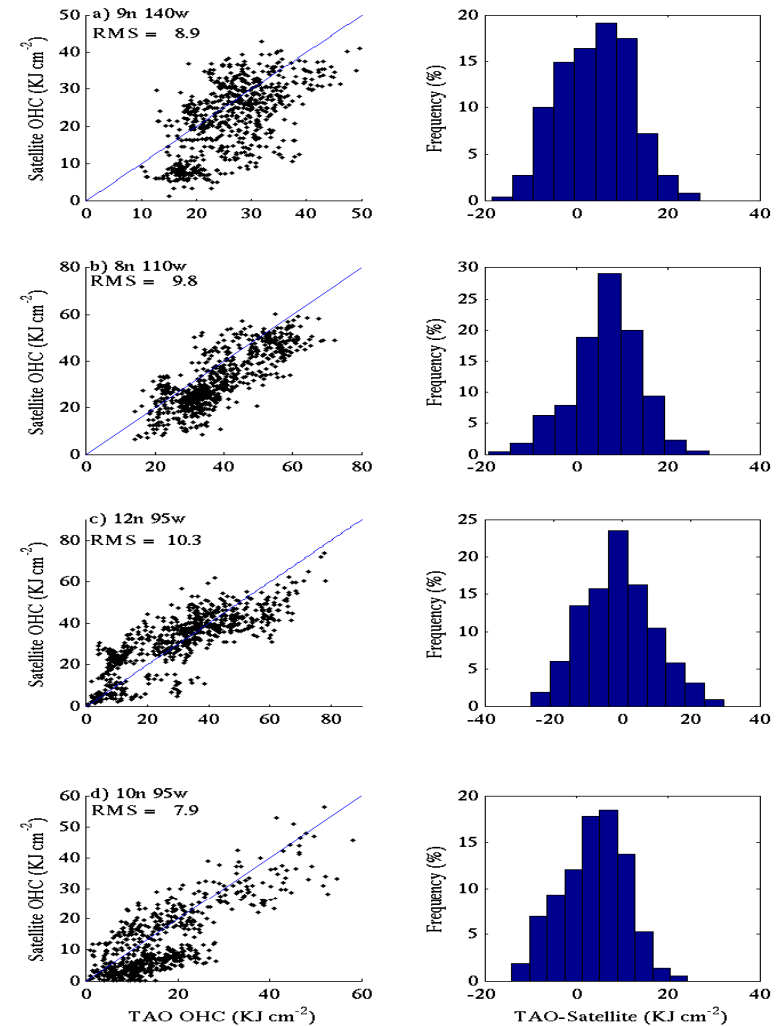
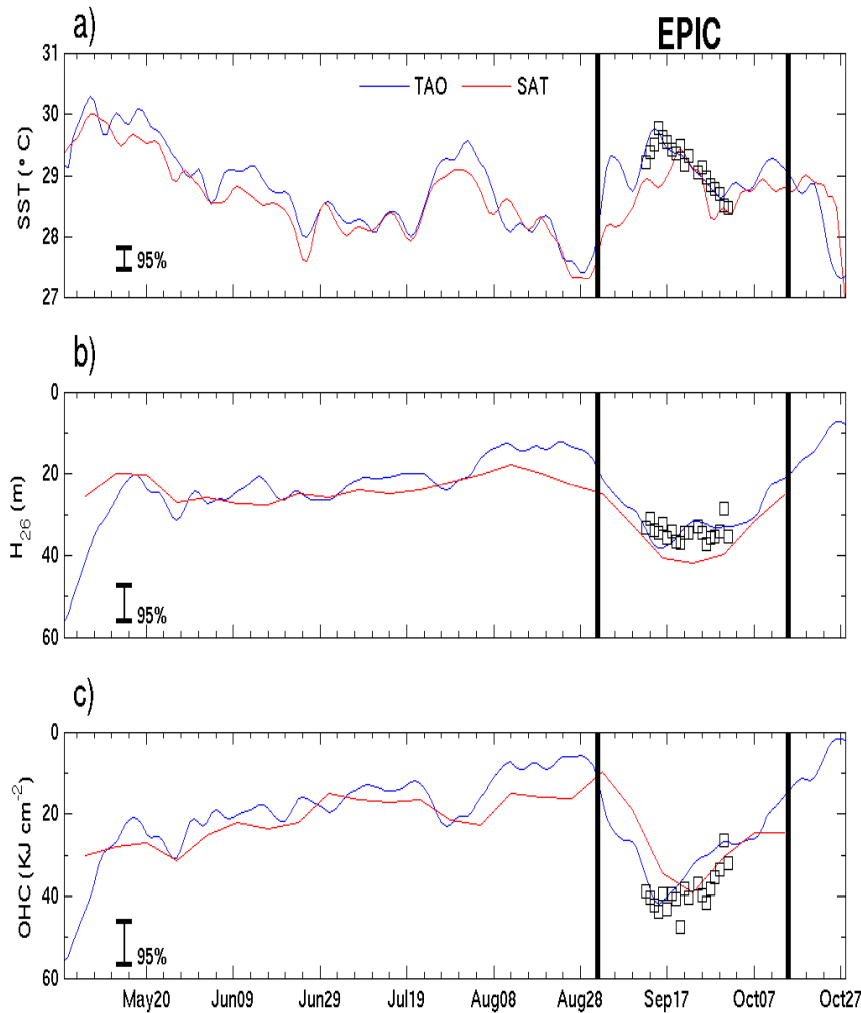


Statistics (2000-2008)

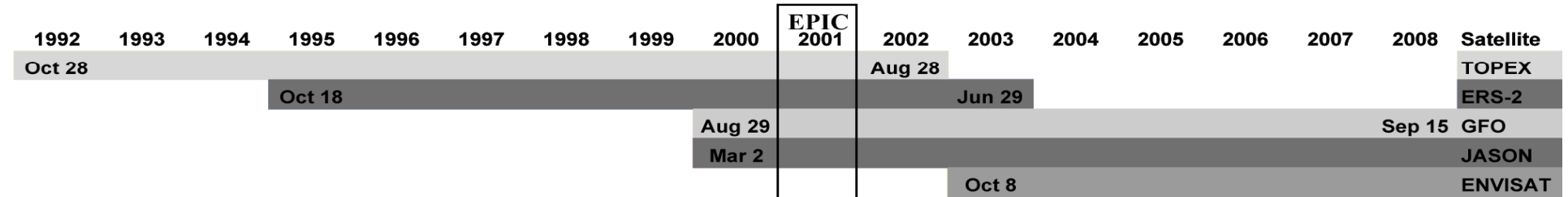
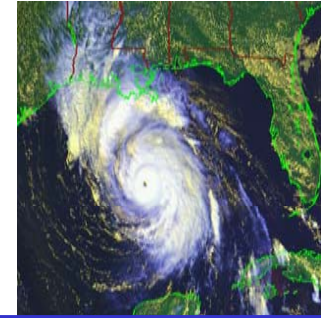


	00	01	02	03	04	05	06	07	08	All
n	434	637	730	1168	1142	824	609	446	460	6420
H₂₀ (m)										
bias	16	12	11	8	8	23	12	13	11	12
slope	0.8	0.8	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8
RMS	21	20	24	22	21	22	24	23	22	22
Depth	208	209	219	230	239	218	215	211	190	220
H₂₆ (m)										
Bias	9	11	13	6	8	18	15	8	13	11
Slope	0.8	0.7	0.7	0.9	0.8	0.7	0.7	0.8	0.8	0.8
RMS	17	19	22	17	17	17	18	18	16	18
Depth	140	157	158	154	170	150	138	128	141	157
OHC (kJ cm⁻²)										
Bias	4	-3	9	-2	1	1	-2	3	3	1
Slope	0.7	0.8	0.9	0.8	0.9	0.9	0.9	0.8	0.9	0.9
RMS	15	20	21	19	15	16	15	15	13	17
Value	116	180	190	168	180	150	150	113	104	180

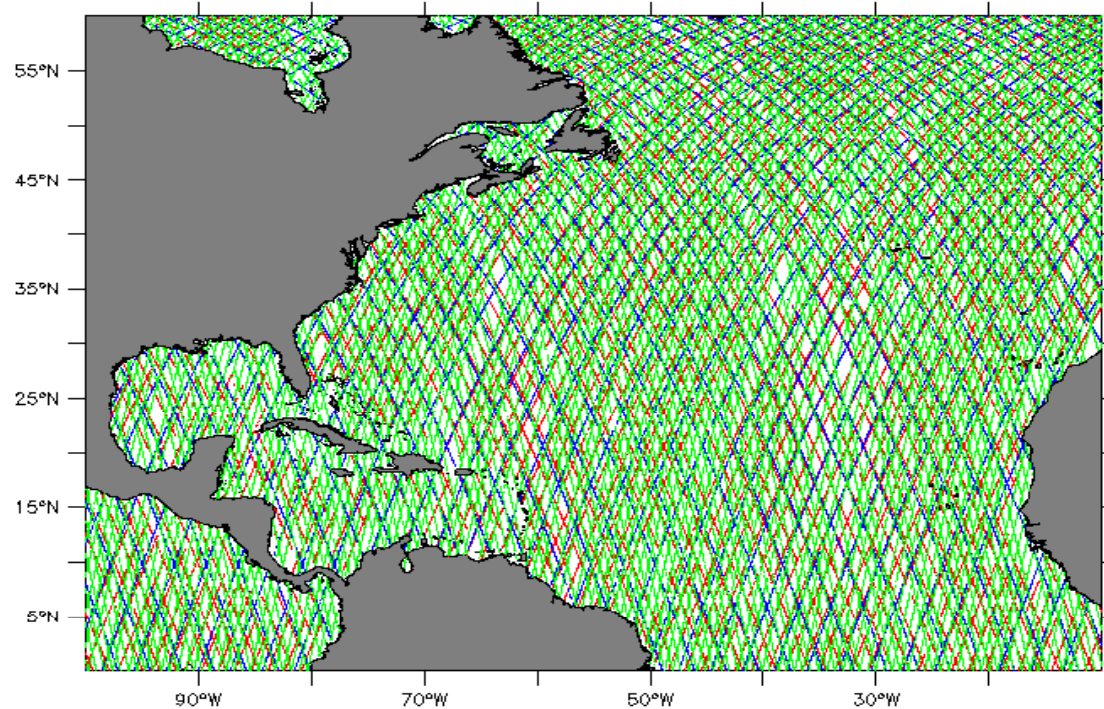
Time Series (left) of a) SST, b) H_{26} & c) OHC from TAO (blue), Sat (red) and *R/V Ron Brown* During EPIC and OHC Comparisons (right) at Four TAO Moorings



Altimetry Availability Since 1992

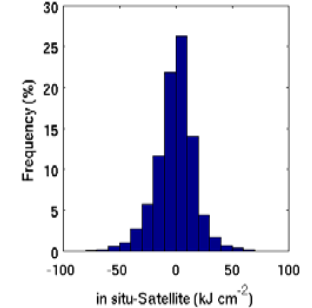
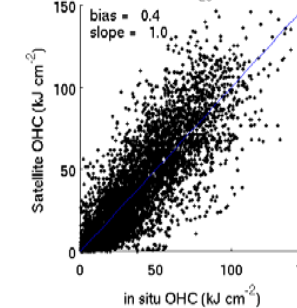
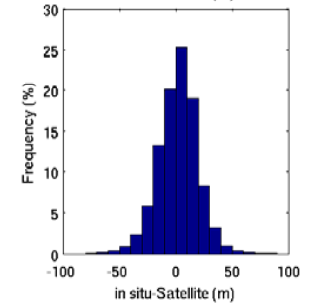
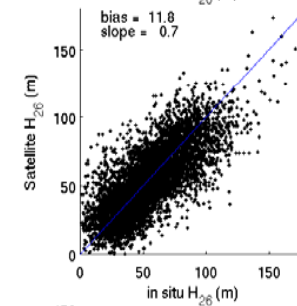
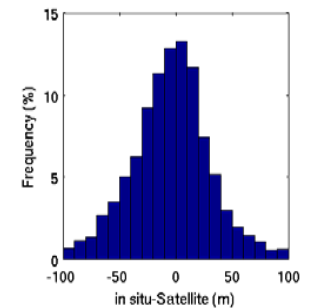
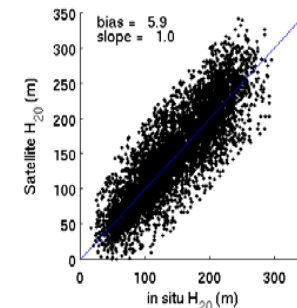
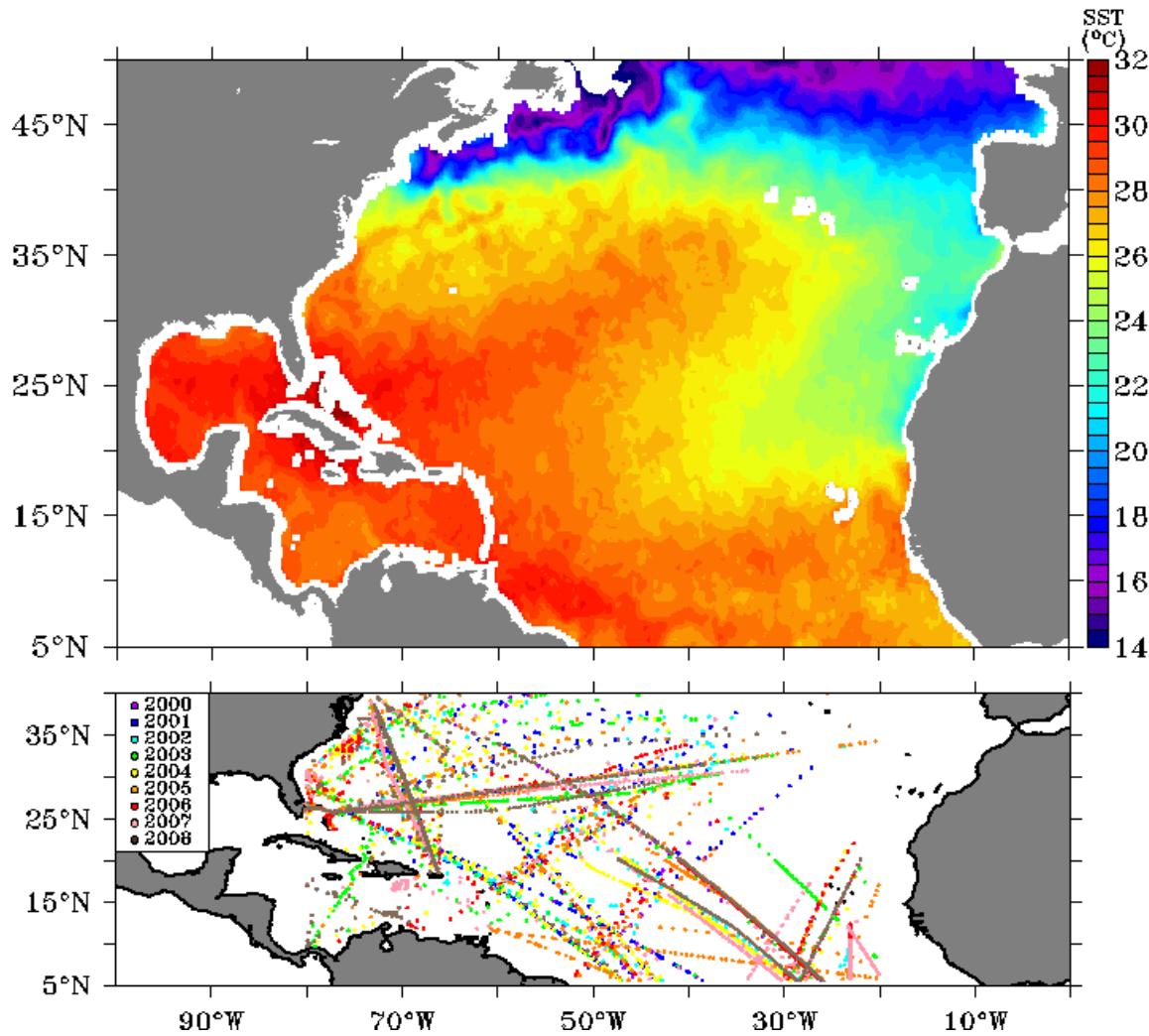
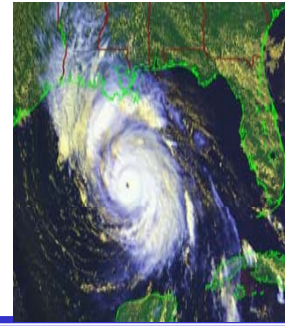


Jason-10 d
GFO- 17 d
Envisat- 35 d



— LAT[D=gfo2005_250_265_30.trk]
— LAT[D=ja12005_253_263_30.trk]
— LAT[D=env2005_241_275_30.trk]

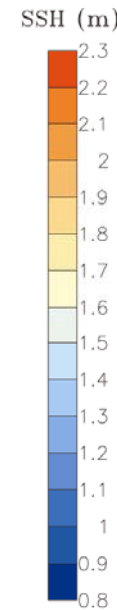
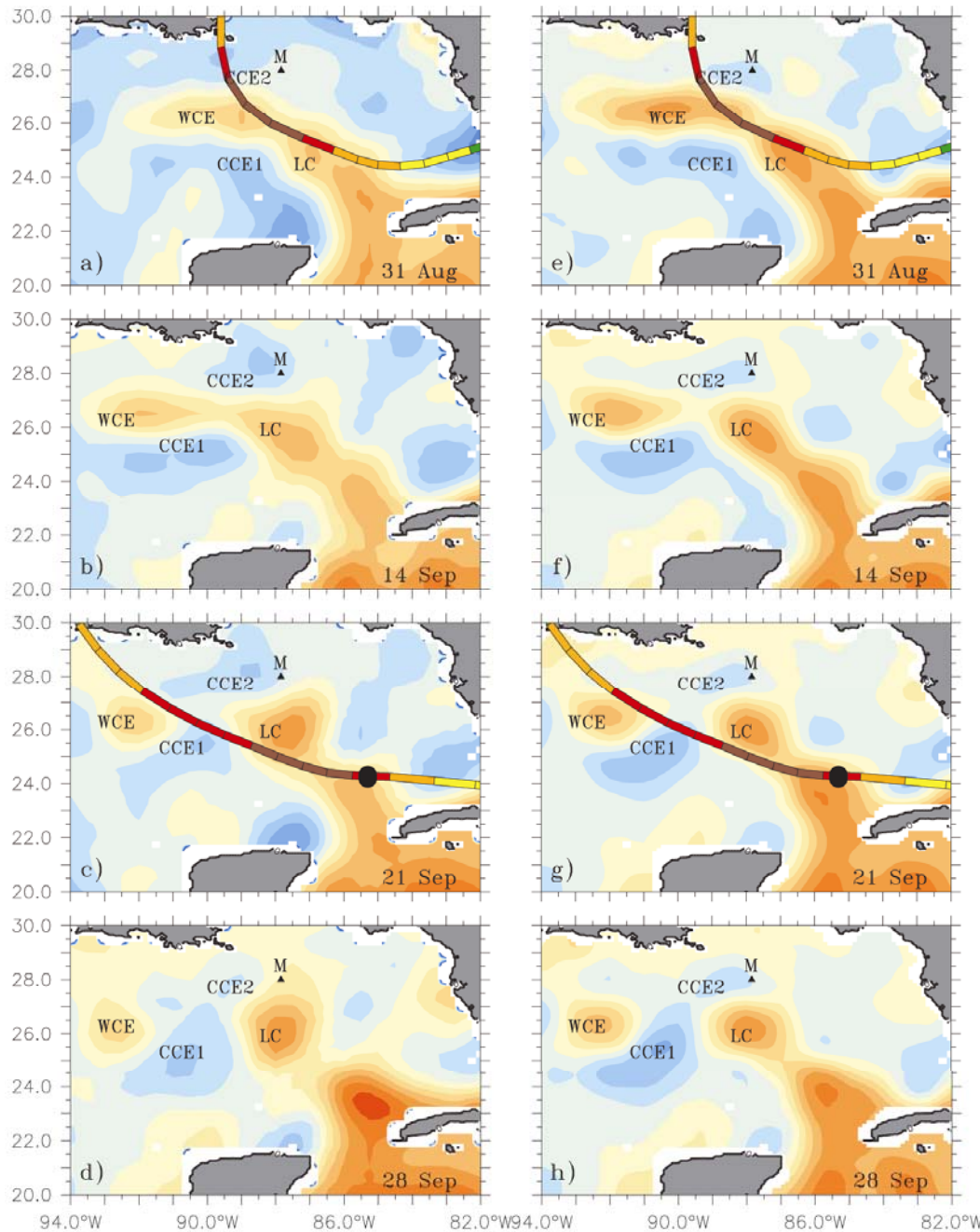
Atlantic Ocean 00-08 XBT Transect Comparisons





daily η

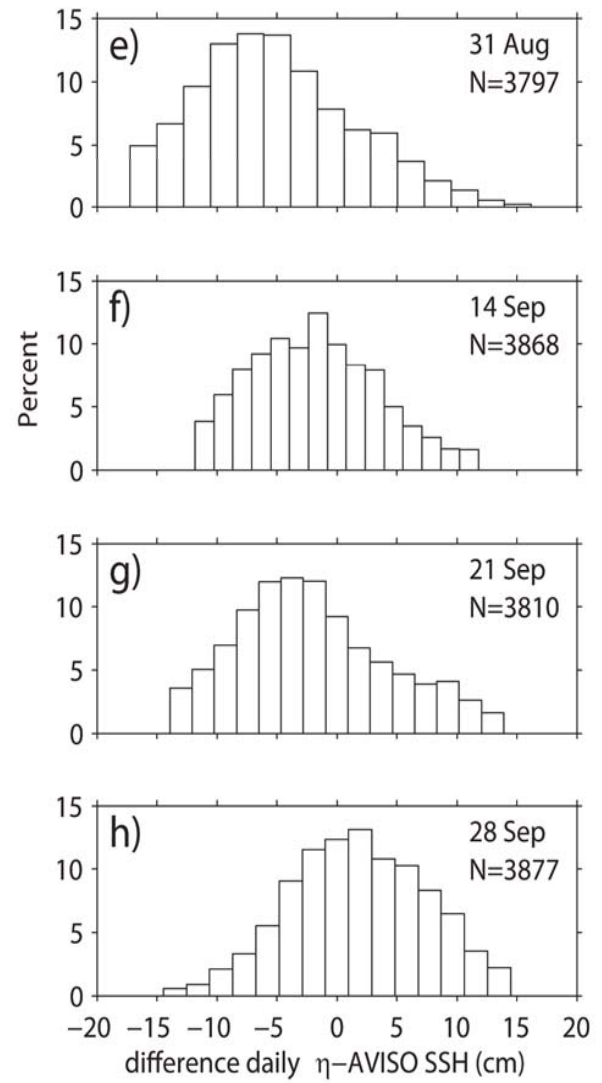
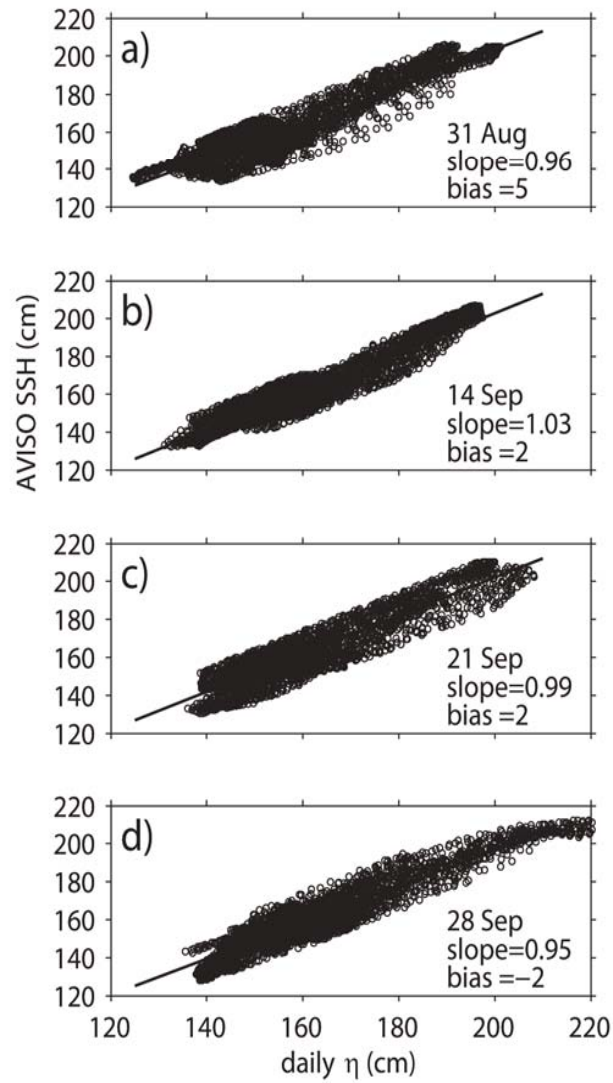
7-day AVISO SSH



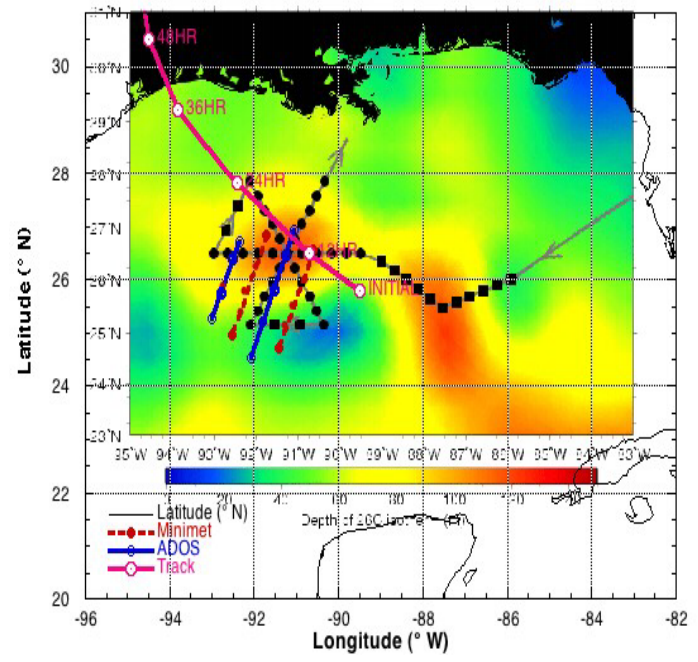
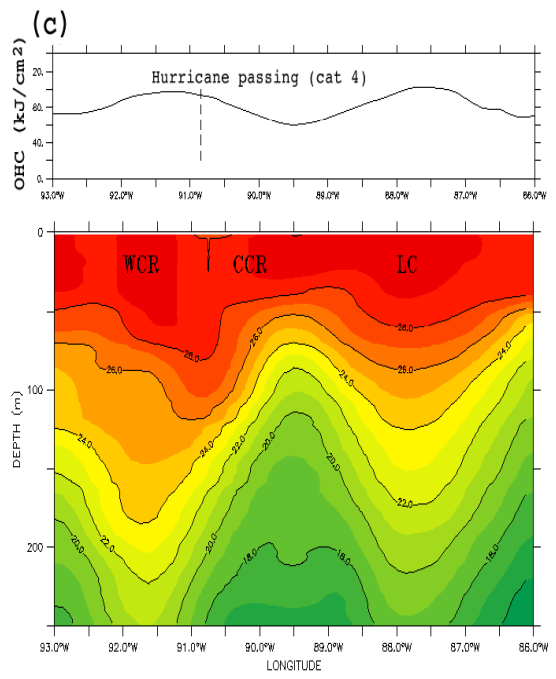
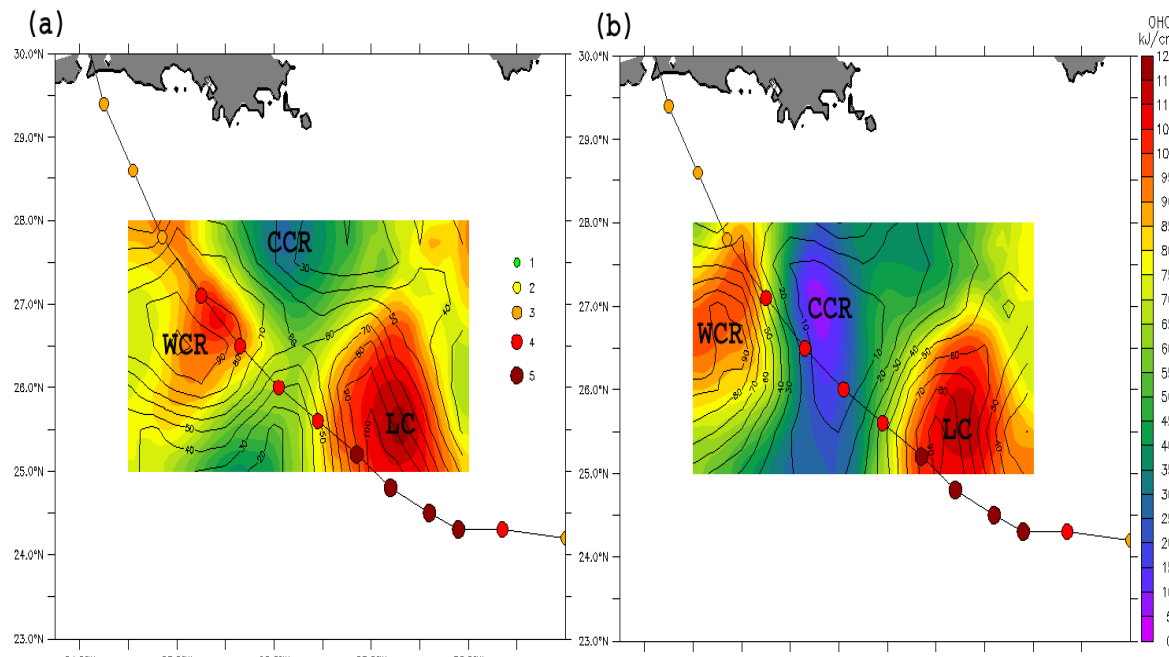
Daily η and 7-day merged AVISO SSH are absolute dynamic topography.

Daily η is from the sum of daily SSHA (Mainelli et al. 2008) and the Rio05 Combined Mean Dynamic Topography (Rio and Hernandez, JGR, 2004).

7-day merged AVISO SSH also considers the Rio05 mean (Jaimes and Shay, MWR, In Press, 2009)



Correlation coefficients were between 0.92 and 0.94



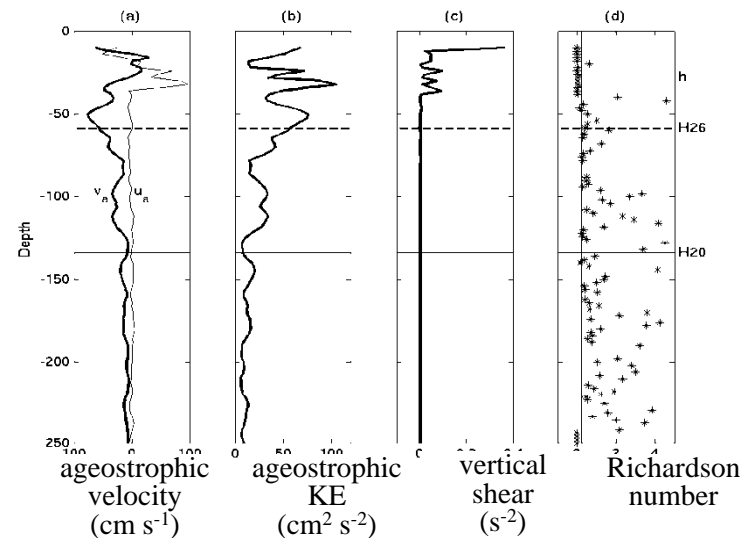
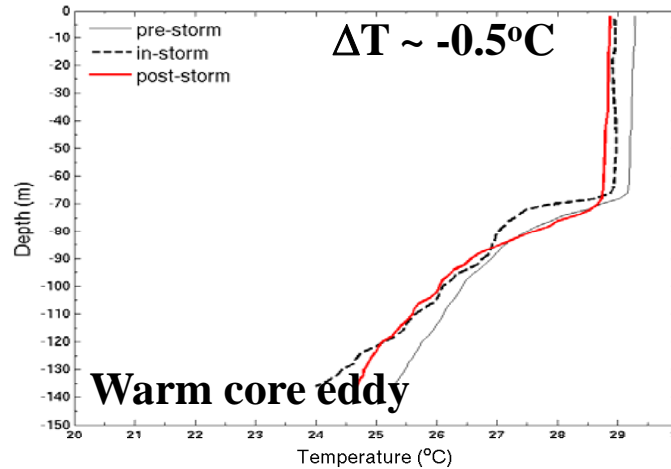
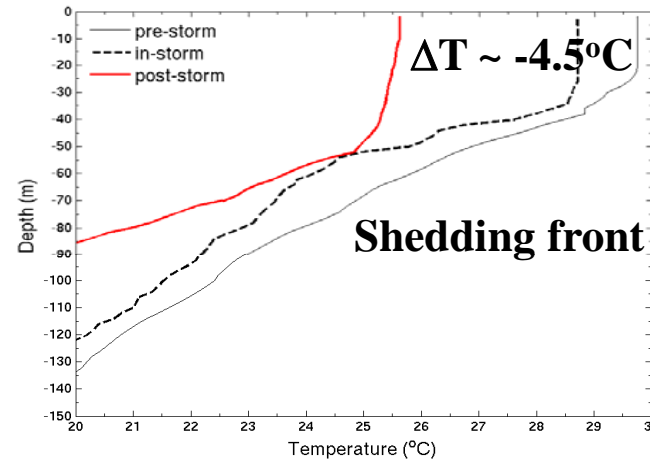
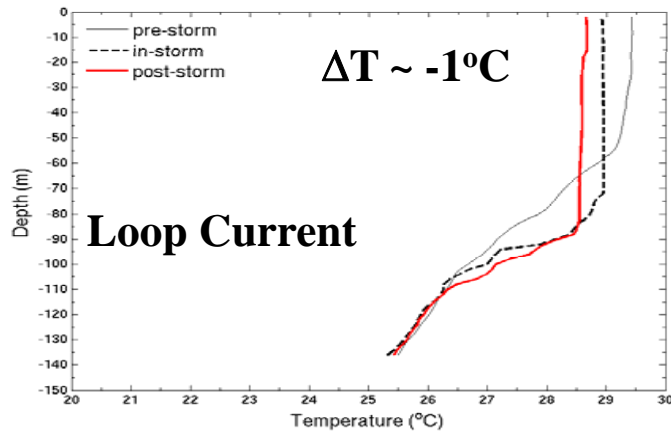
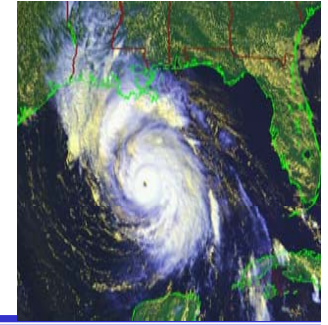
Sampling Pattern: AXCTDs and Drifters relative to OHC and Rita's track.

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

Vertical structure of the thermal layers from AXCTDs.

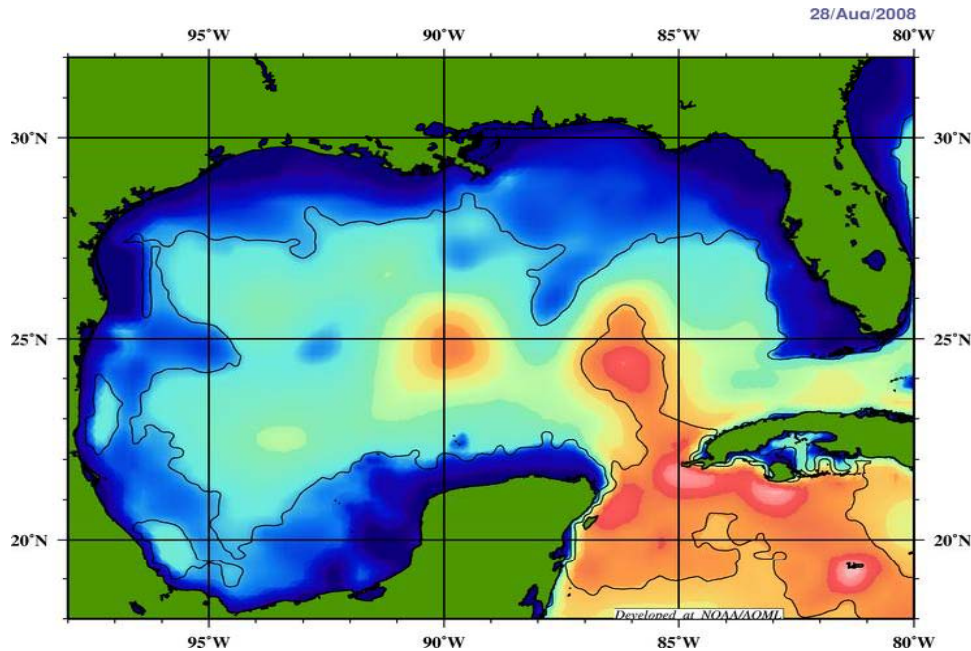
(Jaimes and Shay, MWR, *In Press*, 2009a)

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



**Cluster-averaged
temperature profiles**

TCHP-Pre Gustav

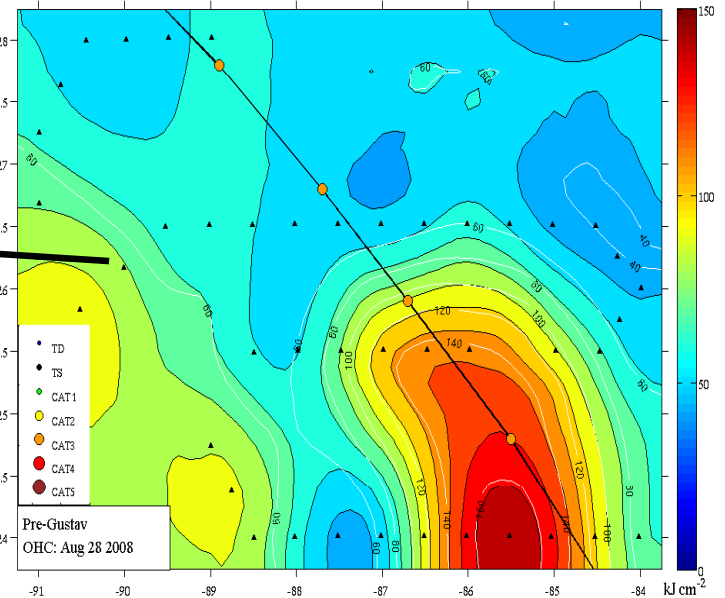
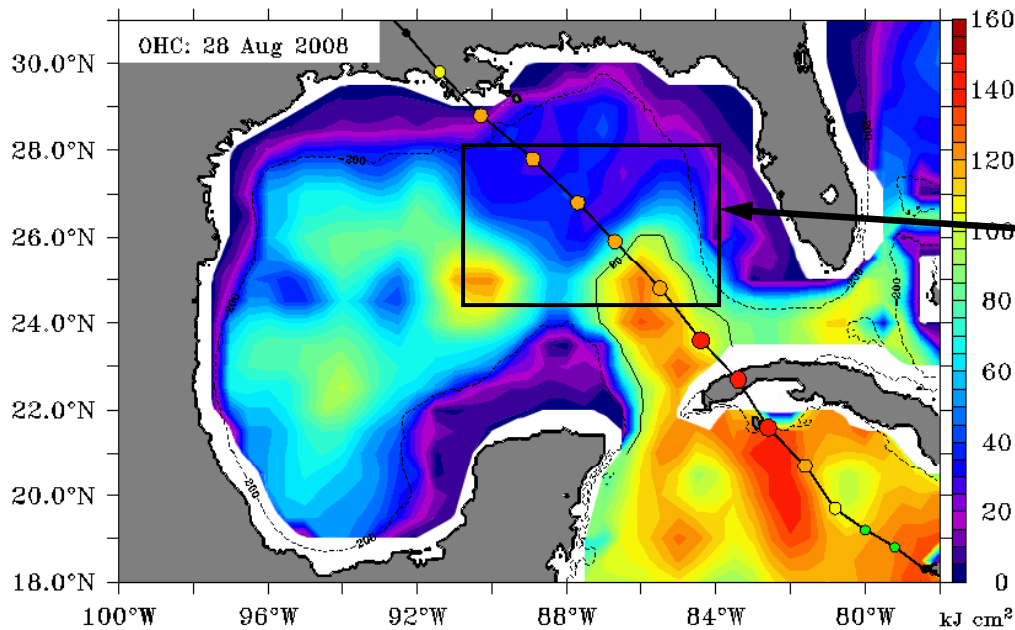


Comparison of AOML TCHP (upper) and TPC/RSMAS OHC Images (lower left) on 28 Aug 2008-Pre Gustav.

OHC and D26 (contours) from AXBTs Deployed in the LC.

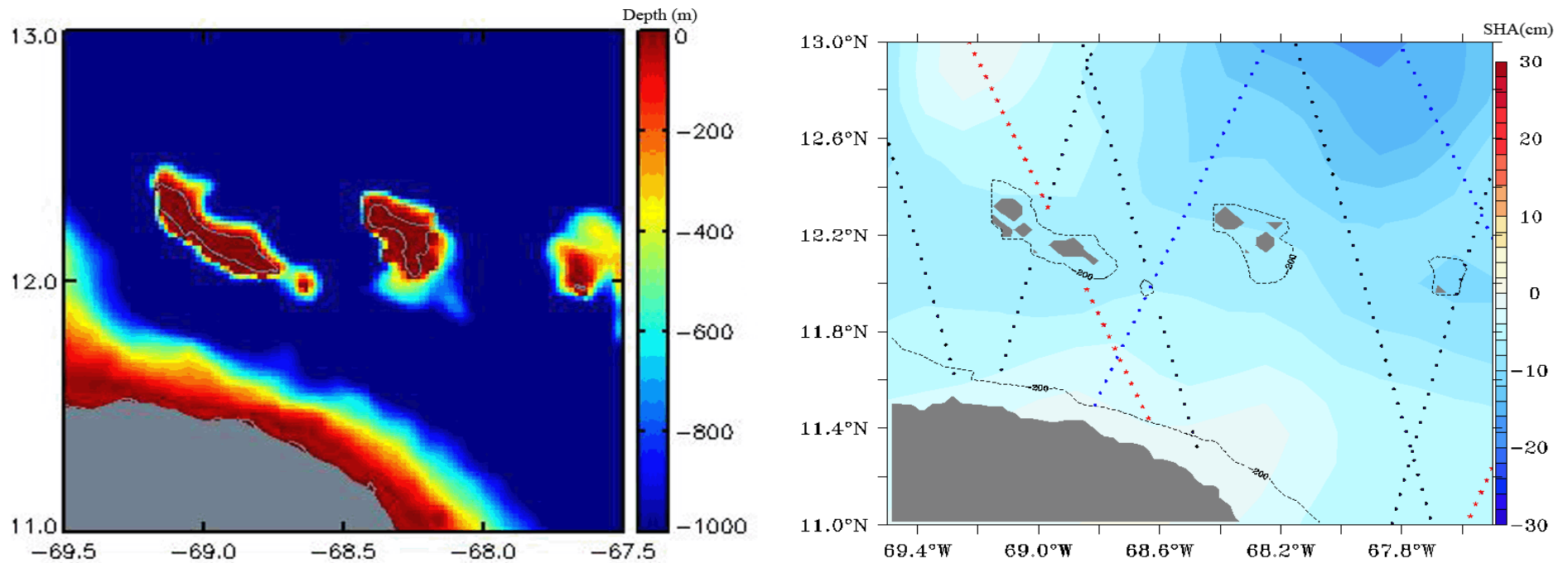
Differences in magnitude and structure of $\sim 20 \text{ kJ cm}^{-2}$. Eddy is detached.....

OHC-Pre Gustav (TPC/RSMAS)



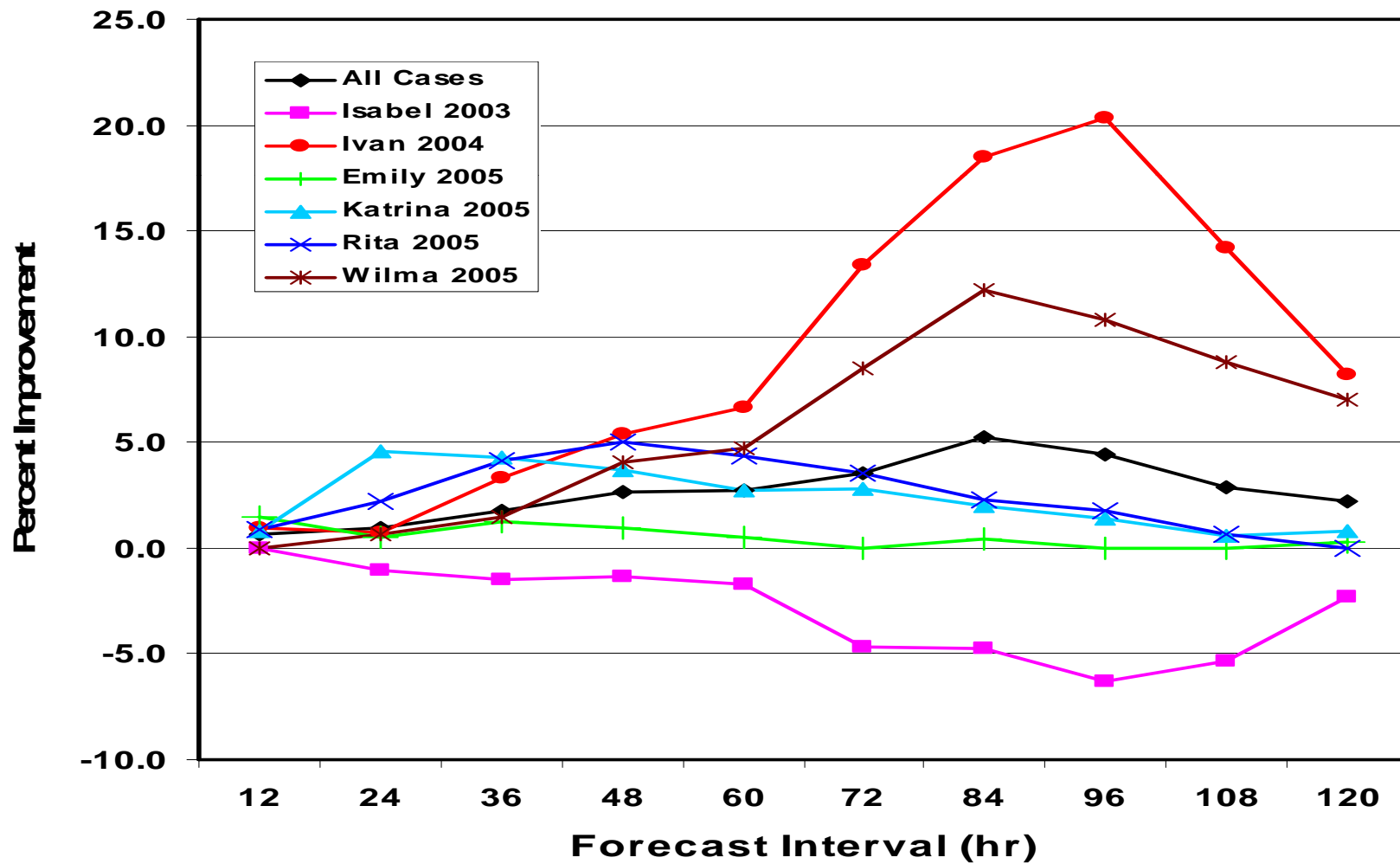
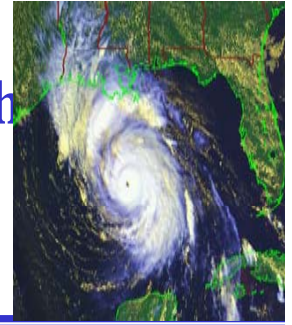
OHC/D26 From AXBTs

Bonaire National Marine Park (S. Heron NOAA Coral Reef Group)



- 100 km (60 miles) off Venezuela
- Fringing reefs from the shoreline to 300-m offshore in some areas
- Drop-off at 30-60° inclination, steeper at north to 100-m depth
- Existing temperature profile measurements since early 2007 at depths of 5-m, 12-m and 20-m, at 13 locations around the island (Ramon de Leon, Manager BNMP)
- OA'ed SHA 9 June 09 (black circles –Envisat; Red stars -Jason -1; Blue circles - Jason-2).

Improvement in Intensity Forecasting From SHIPS with OHC: (Mainelli et al. , MWR, 2008)



NOAA WP-3D profiling over MMS Moorings (In collaboration with AOML HRD, AOC, TPC, NCEP)

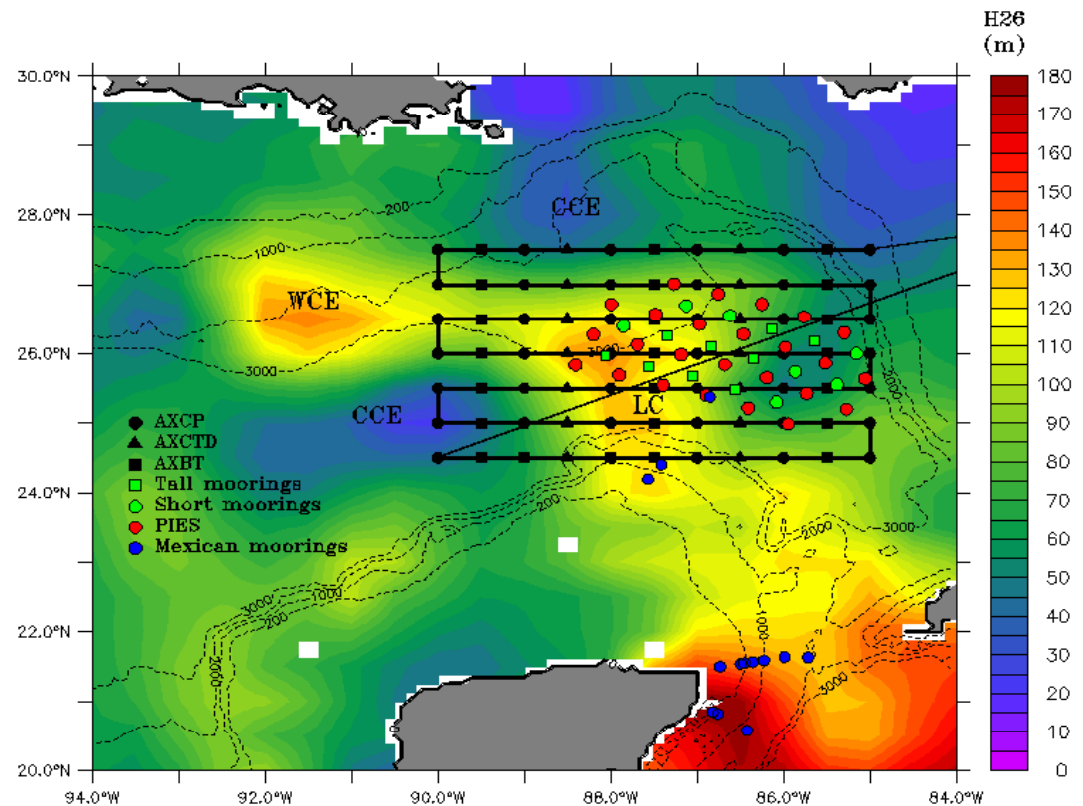


Deliverables include:

V, T, S profiles to 1000 m @
2-m resolution.

Surface winds (SFMR, GPS)
provided by HRD.

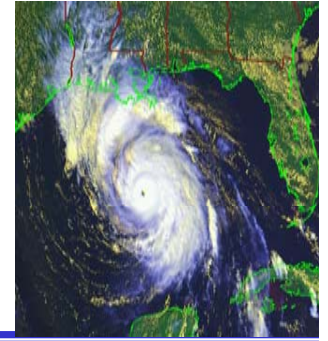
Atmospheric profiles of V, T
and RH @ 5-m resolution.



Goal: To observe and improve our understanding of the LC response to the near-surface wind structure during TC passages. Specific objectives are:

1. Determine the oceanic response of the LC to TC forcing; and,
2. Influence of the LC response on the TC's boundary layer and intensity.

Summary



No perfect climatology or modeling approach. OHC is within 10 to 15% of in situ profiles and approach is sensitive to surface boundary conditions (e.g., SSTs).

Updated Mainelli (2000) approach in the Atlantic Ocean Basin to 0.25 degree resolution and are evaluating using XBTs, moorings, floats, drifters, and AXBTs.

Agreement with HYCOM model from the pre-Ivan and pre-Isidore/Lili states-Katrina and Rita-JHT project with NCEP (Halliwell et al. , MWR, 2008; 2009).

Extending the East Pacific to Western Pacific Ocean - requires a careful examination of satellite derived values and the climatology.

Aircraft measurements provide synoptic snapshots (e.g., Gustav, Ike) to examine the spatial variability of the thermal and salinity structure is important in Subtropical water (Nowlin 1972; Shay et al. 1992; 1998).

Extension of approach to shallow water coral reef structures represents a basic research challenge.