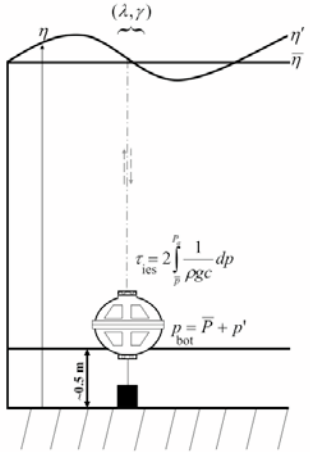
Satellite Altimetry Sea Surface Height Variability and In Situ Observations Along An Eddy Corridor

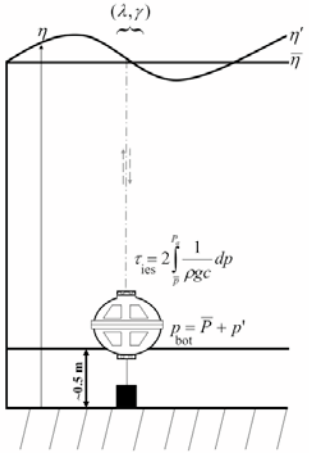
Dr. Sheekela Baker-Yeboah

[1]NOAA/NESDIS/National Center for Environmental Information,
[2]University of Maryland Earth System Science Interdisciplinary Center
Cooperative Institute for Climate and Satellites



Overview

Part 1 **Observational background: SSH from Altimeter & PIES**



Part 2 **Decomposing the SSH signal**

- **Baroclinic**
- **Barotropic**

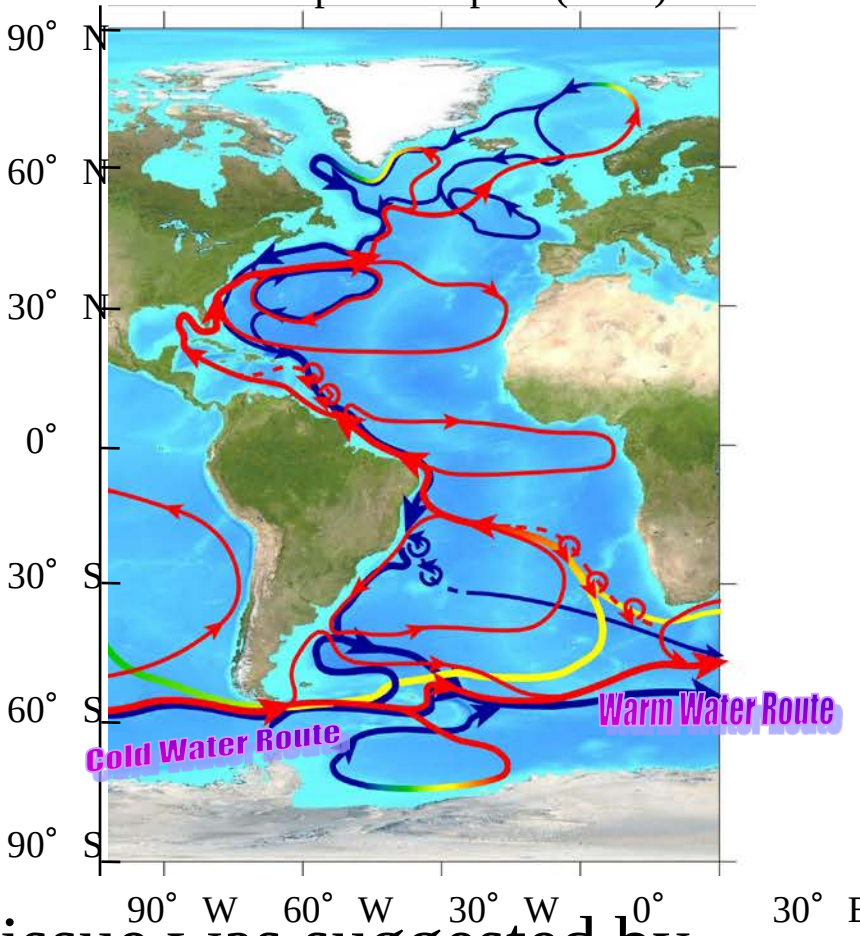
Part 3 **Summary**

Eddies in the AMOC;

➢The exchange of waters from the Indian to the Southeast Atlantic has been postulated as a key link in the meridional overturning circulation of the ocean.

➢Role of the warm-water route (Gordon 1986, 1987) versus the cold-water route (Rintoul,1988) of the MOC in the SA remains under debate.

From Lumpkin & Speer (2007)



- A potentially significant climate issue was suggested by Arnold Gordon (1986,1987):

Eddies in the AMOC;

➢Role of the warm-water route:

"Might the Atlantic become warmer and saltier during periods when the Agulhas route is favored, versus colder and fresher when the Drake Passage route is favored?"

"Might this have important feedback to the production rate of NADW?"

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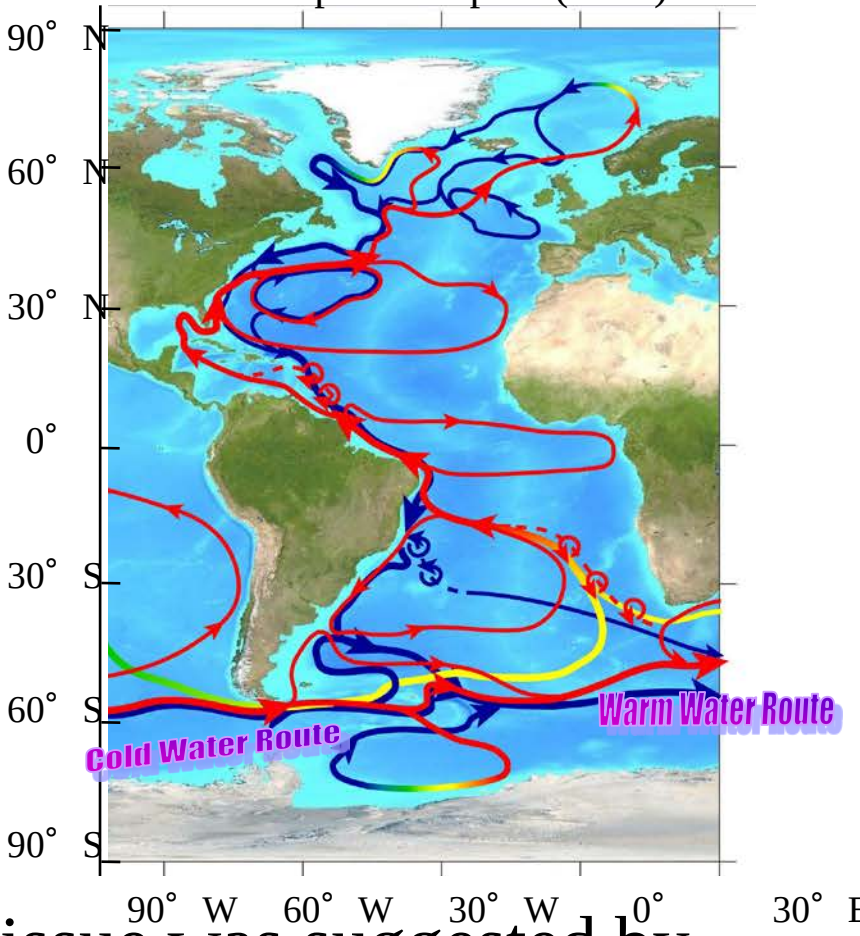

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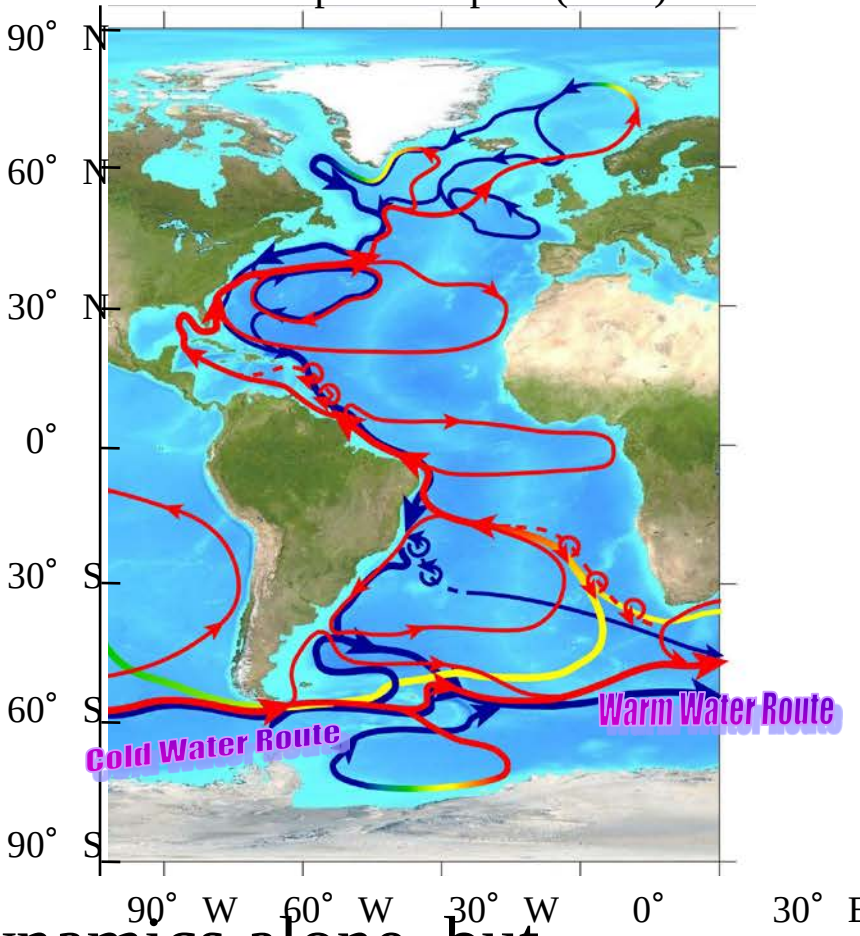


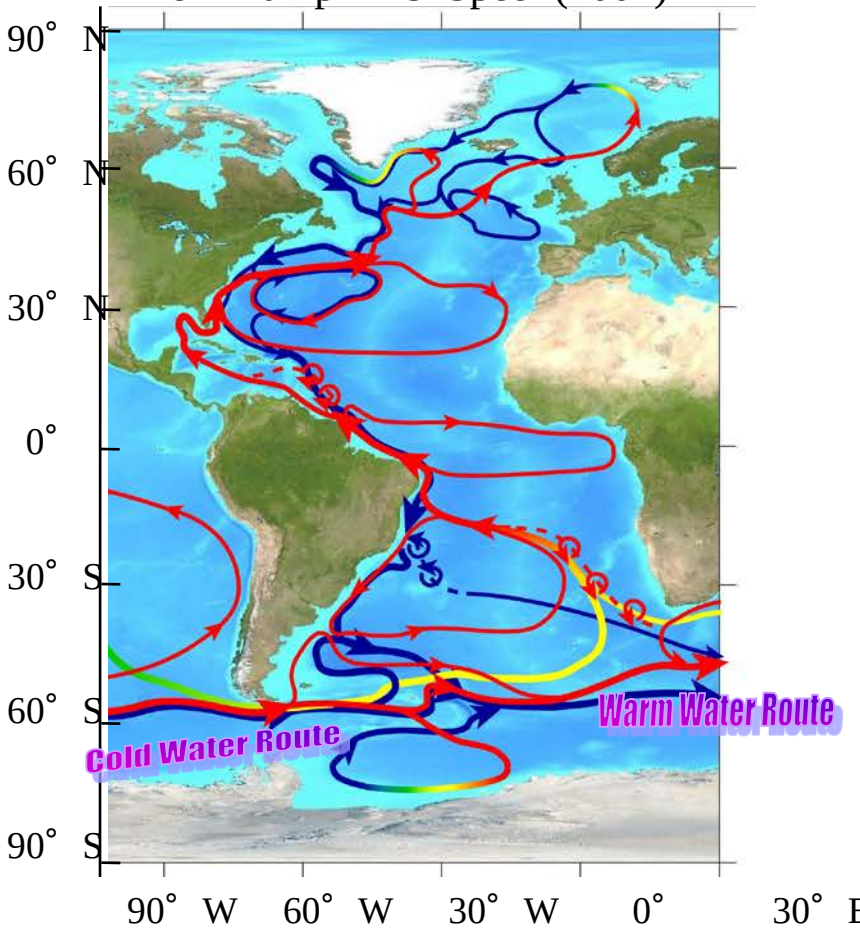
- Not determined by large-scale dynamics alone, but significantly influenced by the regional, mesoscale dynamics.

Eddies in the AMOC;

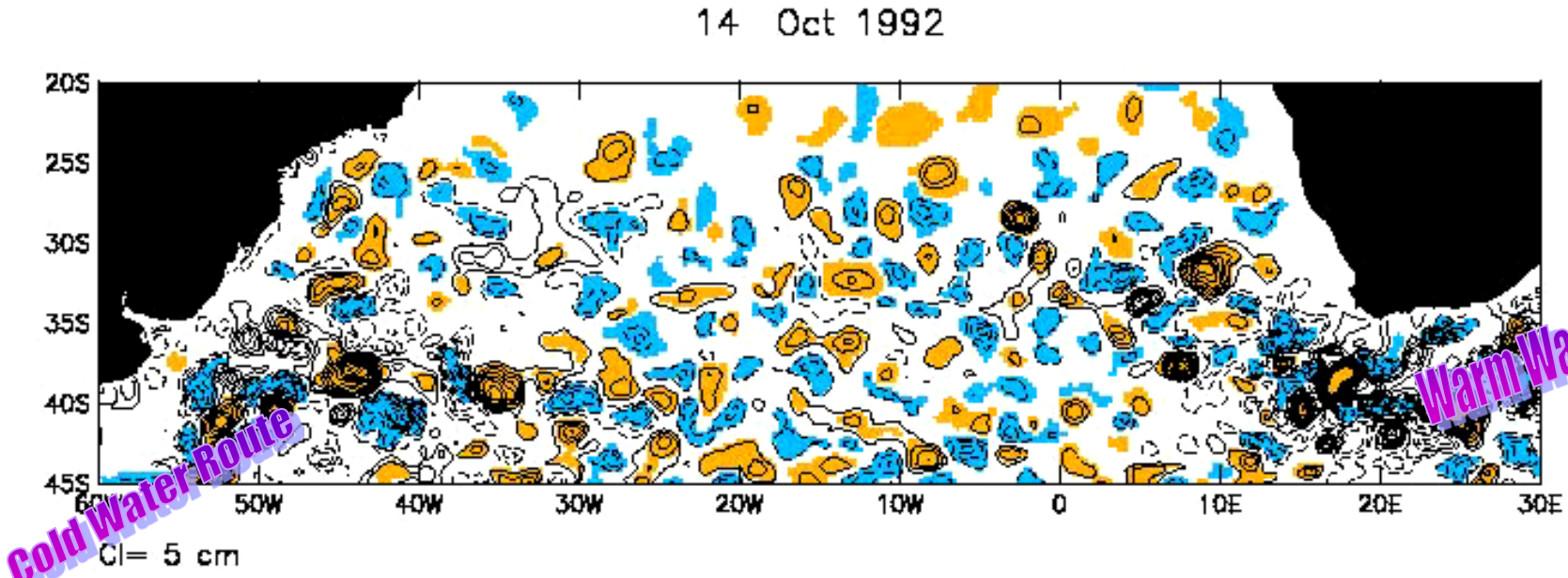
➢Role of the warm-water route

•The dynamics of mesoscale ocean physics are key to understanding the transfer of ocean properties relevant to the larger scale flow, such as the MOC), and thereby to climate.

From Lumpkin & Speer (2007)



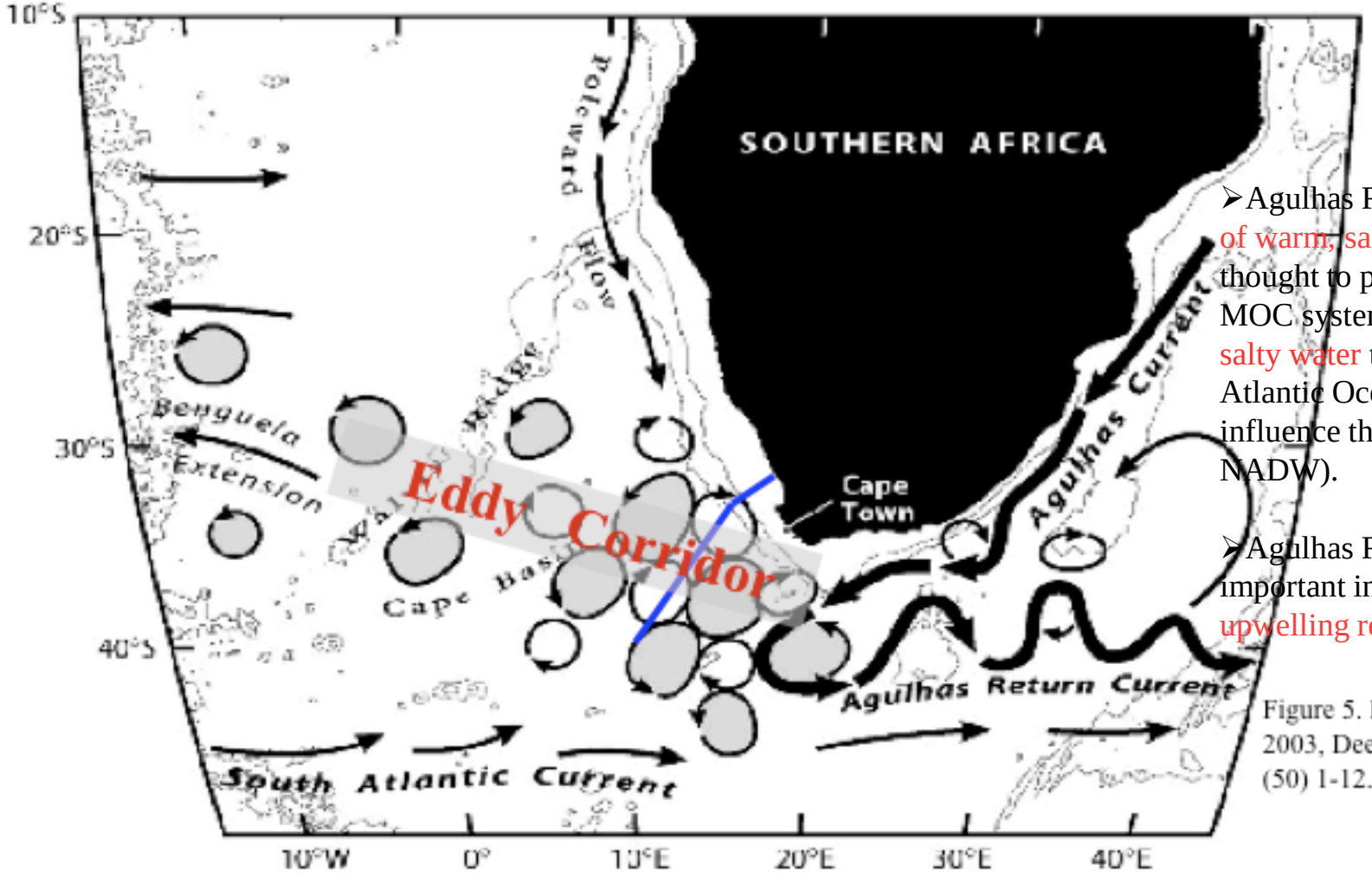
Mesoscale Eddy Enhanced Ocean Circulation?



Movie by Dudley Chelton

On the Structure of Agulhas Eddies

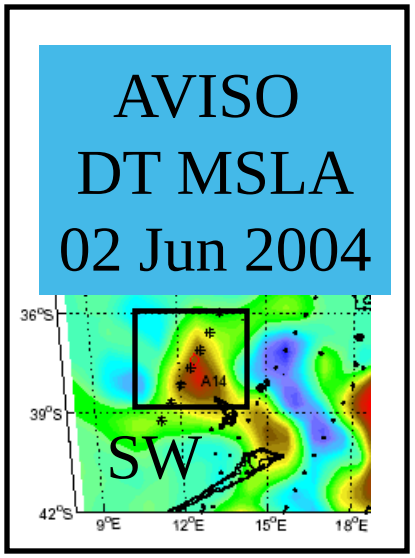
Satellite and in situ observations spanned an "eddy corridor" where Agulhas rings pass, carrying cores of Indian Ocean water into the South Atlantic.



- Agulhas Rings carry cores of warm, salty water and are thought to play a role in the MOC system by supplying salty water through the Atlantic Ocean (salt link influence the formation of NADW).
- Agulhas Rings are also important in the Benguela upwelling regime.

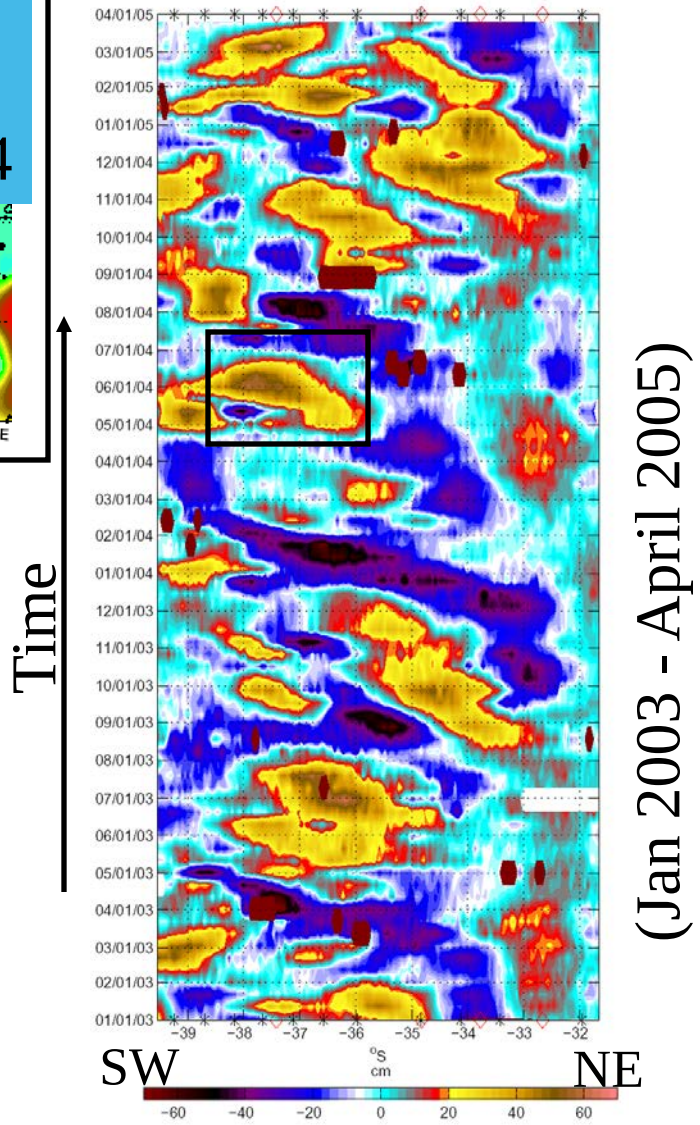
Figure 5. Richardson et. al. 2003, Deep-Sea Research II (50) 1-12.

SSH Variability



Satellite

AVISO times-space plot of total SSH (delayed-time data).



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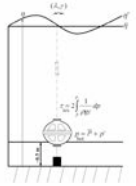
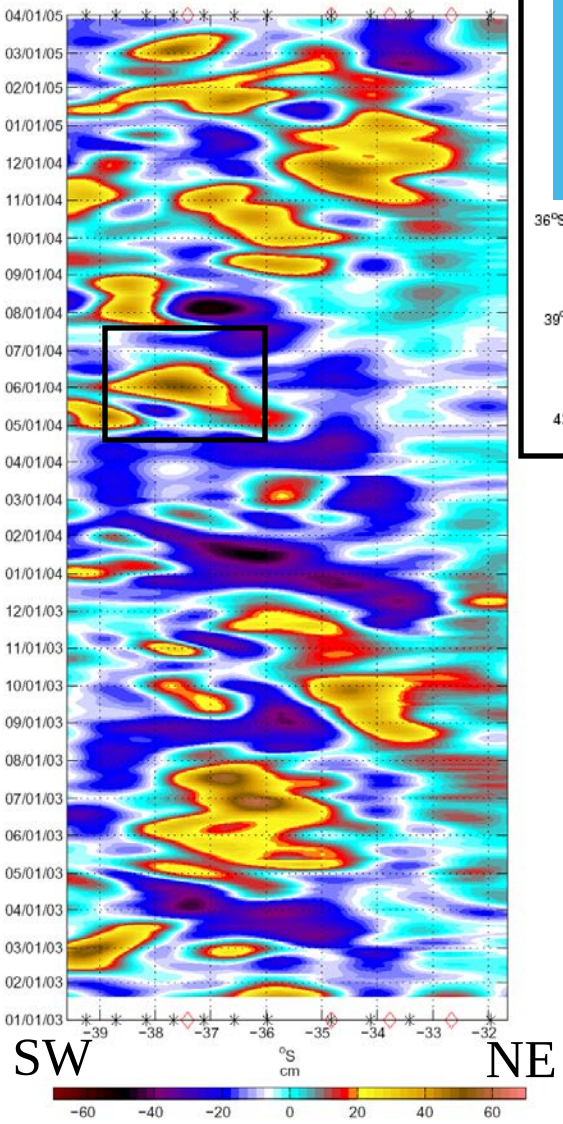
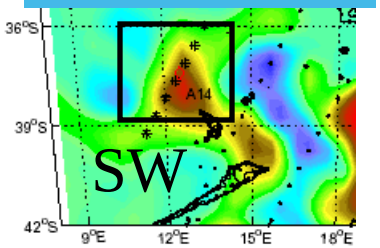


PIES



AVISO
DT MSLA
02 Jun 2004



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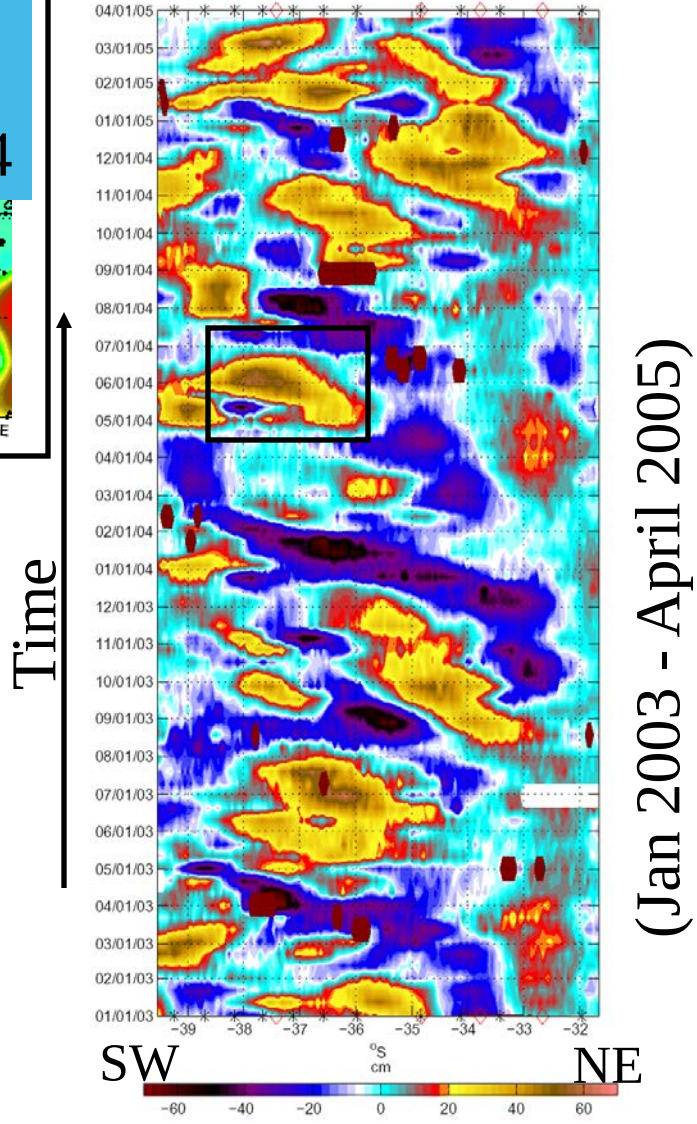
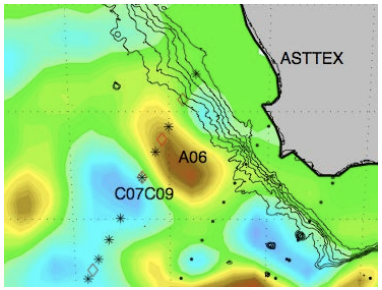


(Jan 2003 - April 2005)

PIES Sea surface height from PIES instruments

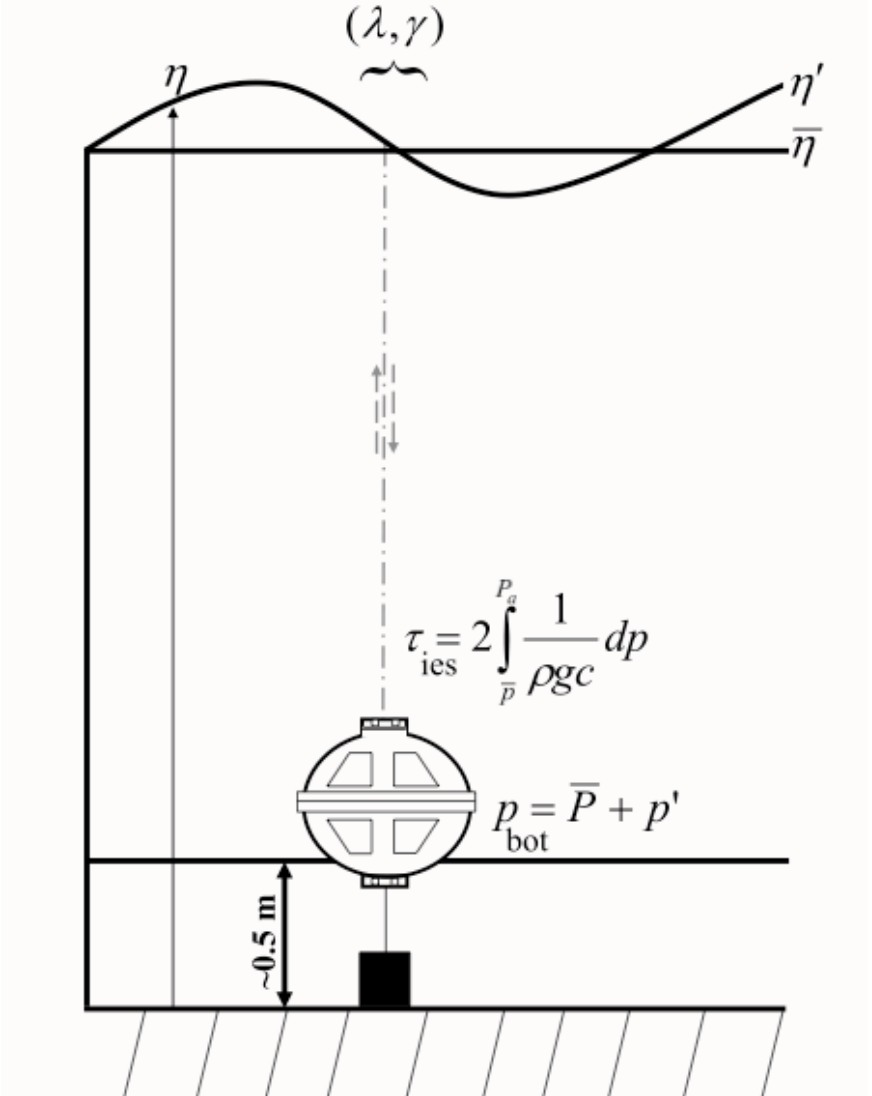


Pressure-sensor equipped Inverted Echo Sounder

- Bottom moored instrument
- Measures
  - bottom pressure and
  - round trip acoustic travel time

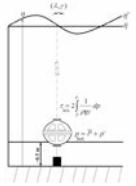
- Provide two components of sea surface height (SSH):
  - bottom pressure gives variable mass loading
  - travel time gives variable volume expansion (steric)

- Ping frequency of 12 kHz

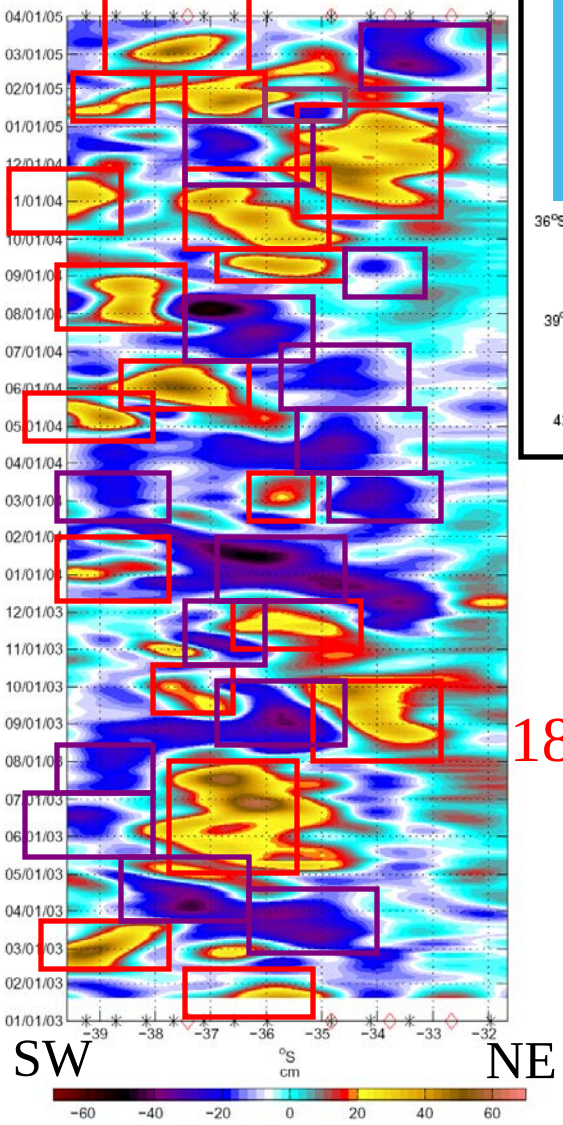


(Baker-Yeboah,Watts, & Byrne, 2010)

SSH Variability



PIES



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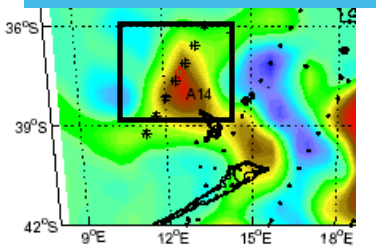
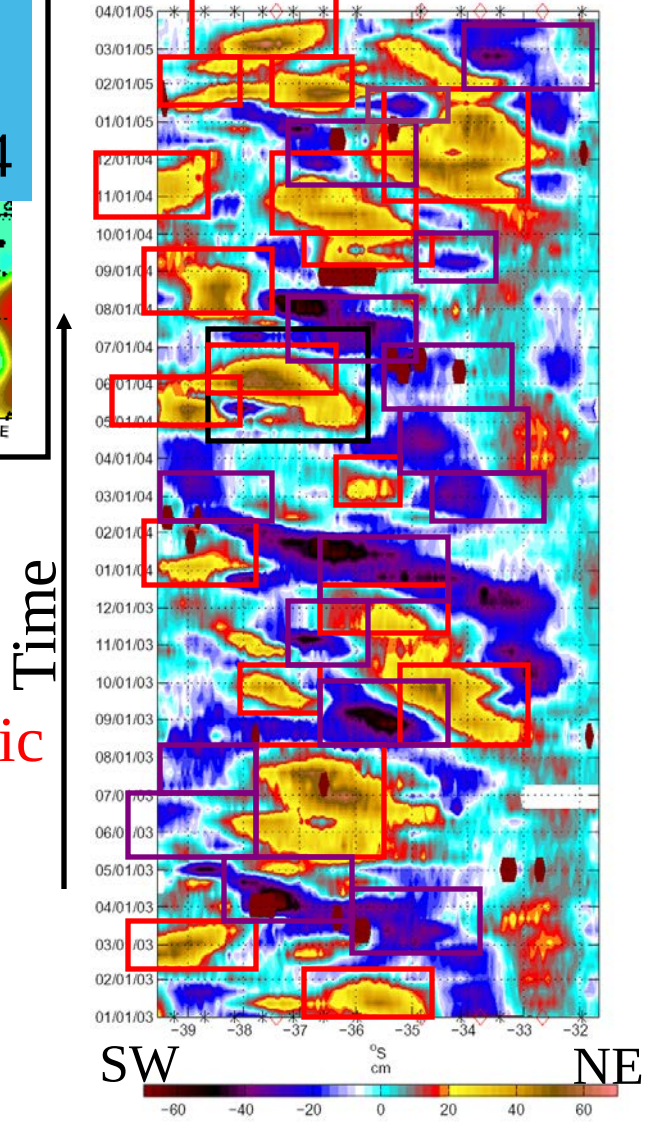


18 Anticyclonic
17 Cyclonic
eddies

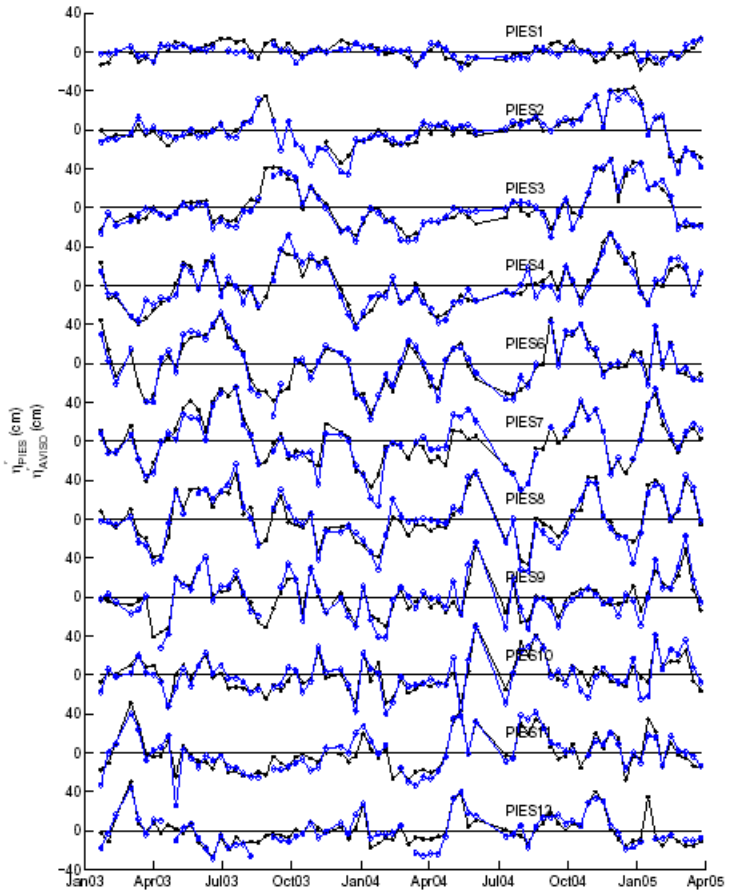
Satellite

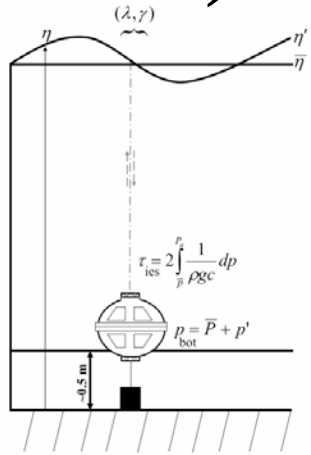


How well correlated?

$R = 0.93$

- PIES & Altimeter (AVISO)





- The *rms* difference for AVISO-and-PIES was 7.3 cm
- Satellite and PIES data compare well in the region of study.

Overview

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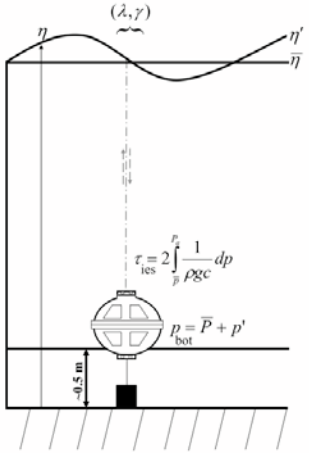

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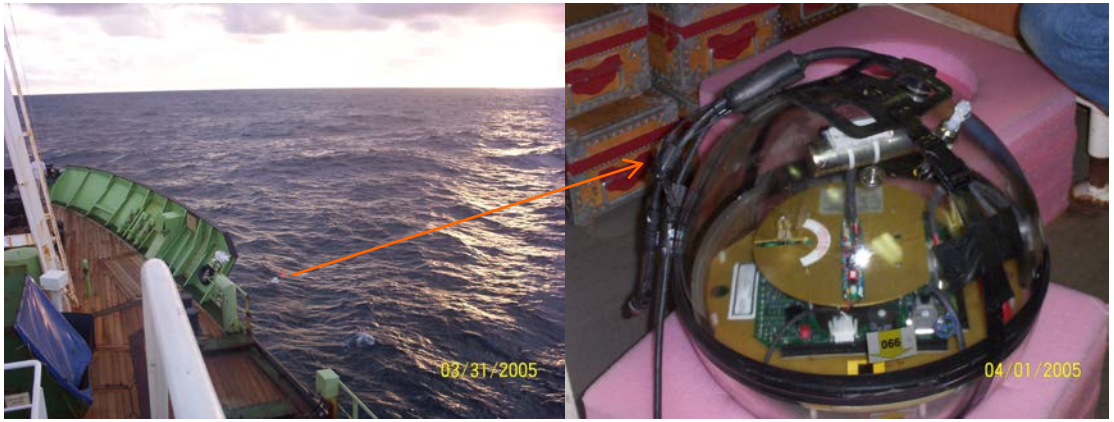
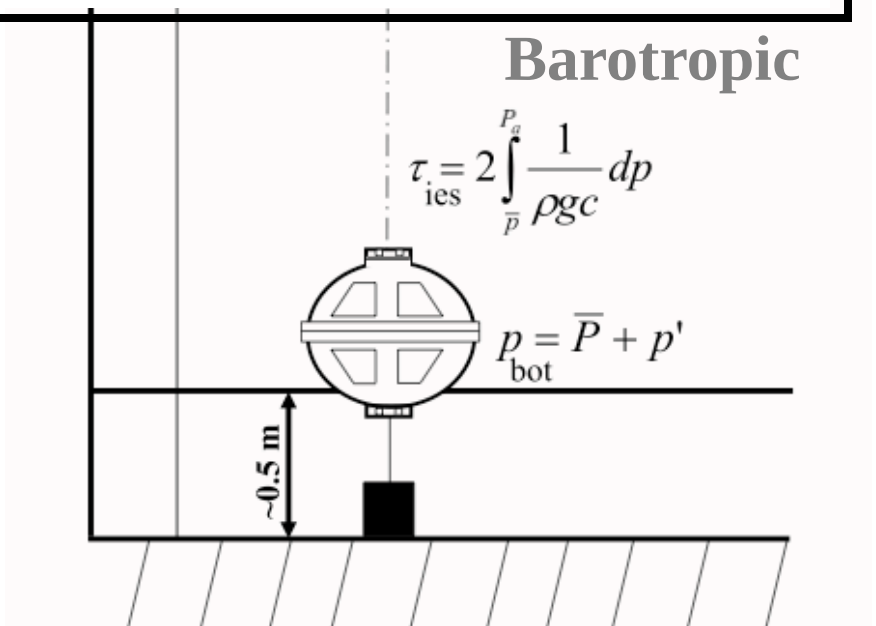


PIES Sea surface height from PIES

$$\eta' - \eta_{IB} + H = \int_{\overline{P}_a}^{\overline{P}} \frac{1}{\rho g}\, dp + \int_{\overline{P}}^{p_{bot}} \frac{1}{\rho g}\, dp,$$

PIES BC

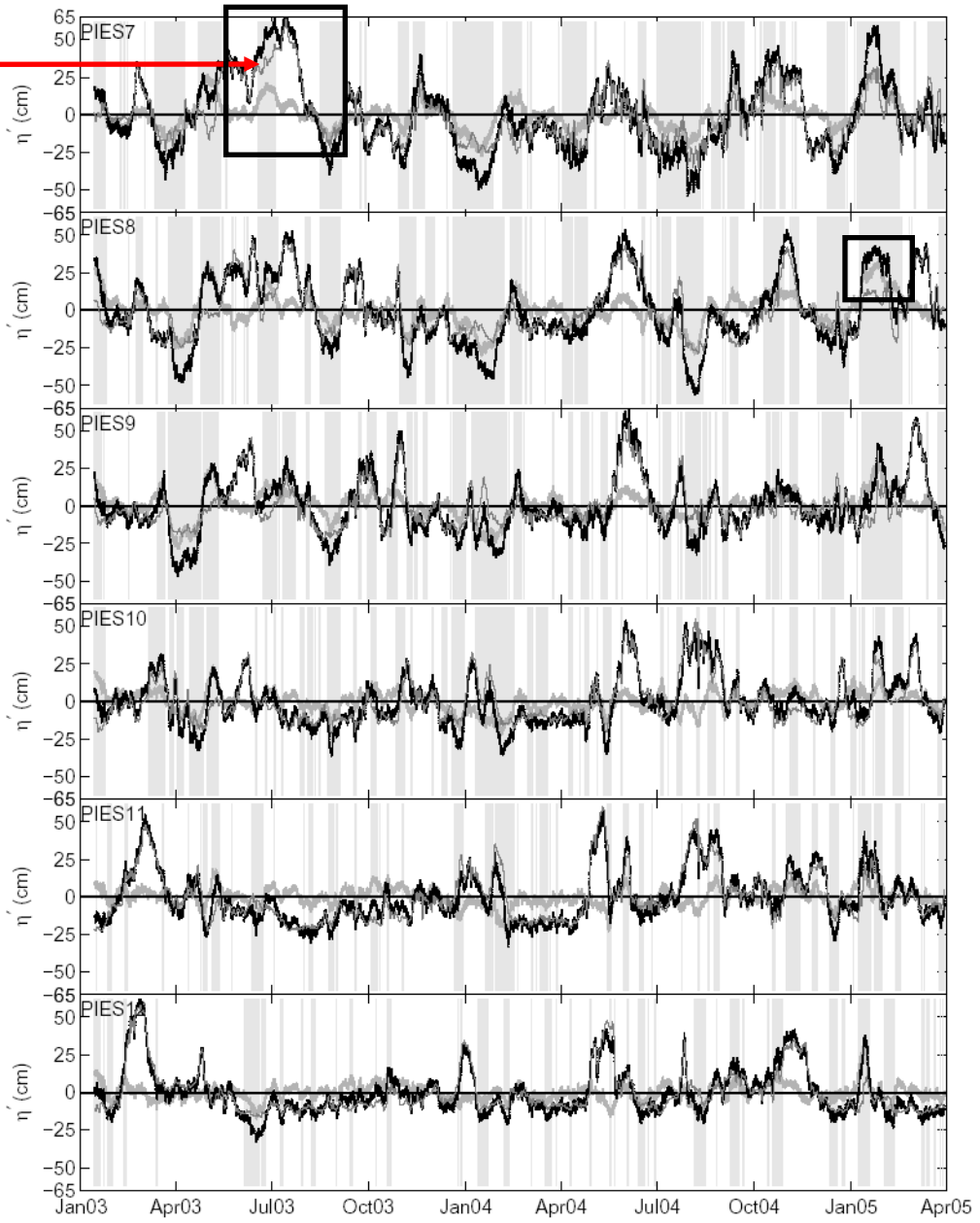


(Baker-Yeboah,Watts, & Byrne, 2010)

- SSH variability from PIES data

$$\eta'_{bc} = \frac{\phi'_{4500}}{g}$$

Part 2



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- SSH variability from PIES data

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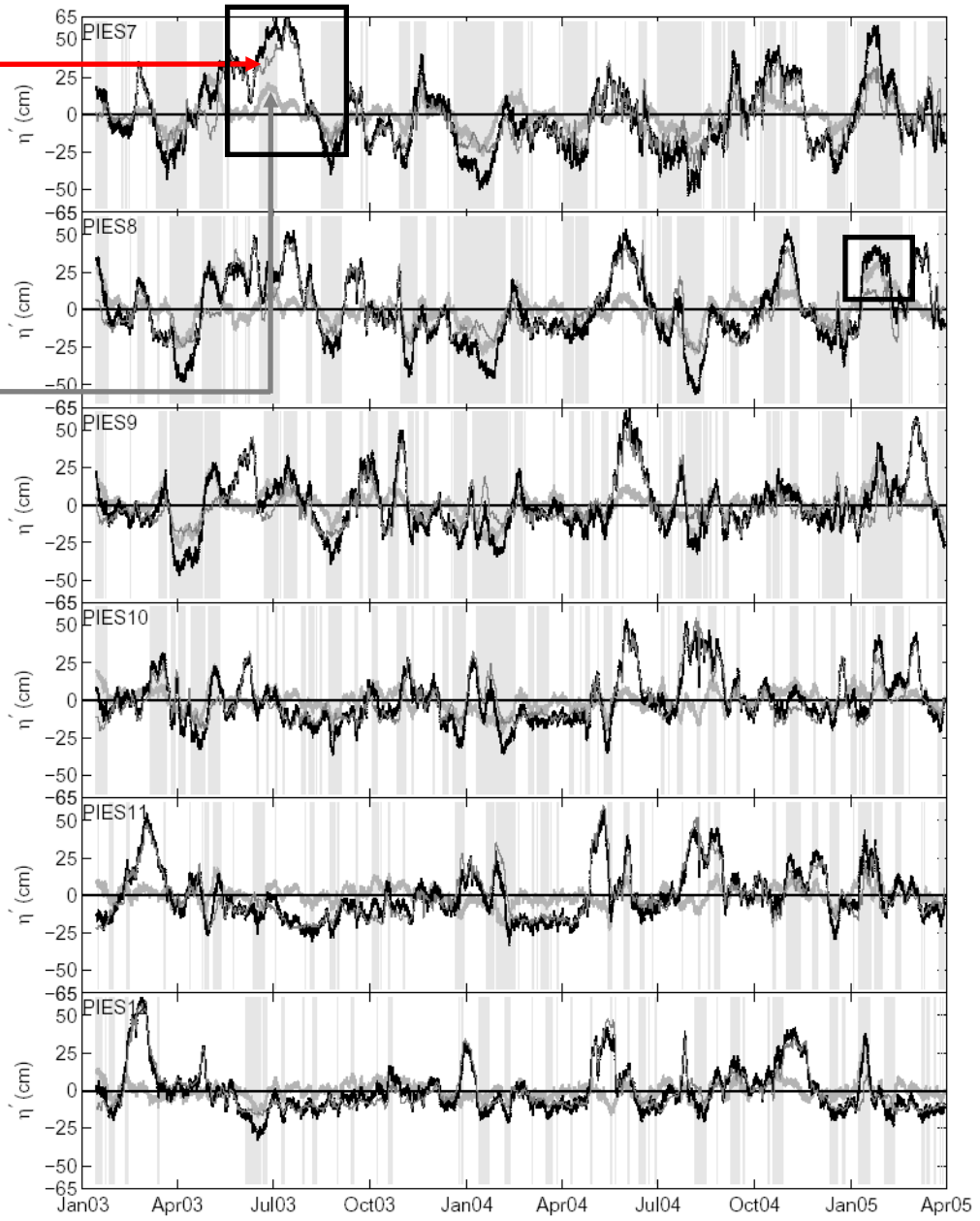
$$\eta'_{bc} = \frac{\phi'_{4500}}{g}$$

$$\eta'_{bt} = \frac{p'}{\rho_b g}$$



(Baker-Yeboah,Watts, & Byrne, 2010)

- SSH variability from PIES data

$$\eta'_{PIES} = \eta' - \eta_{IB} = \eta'_{bt} + \eta'_{bc}$$

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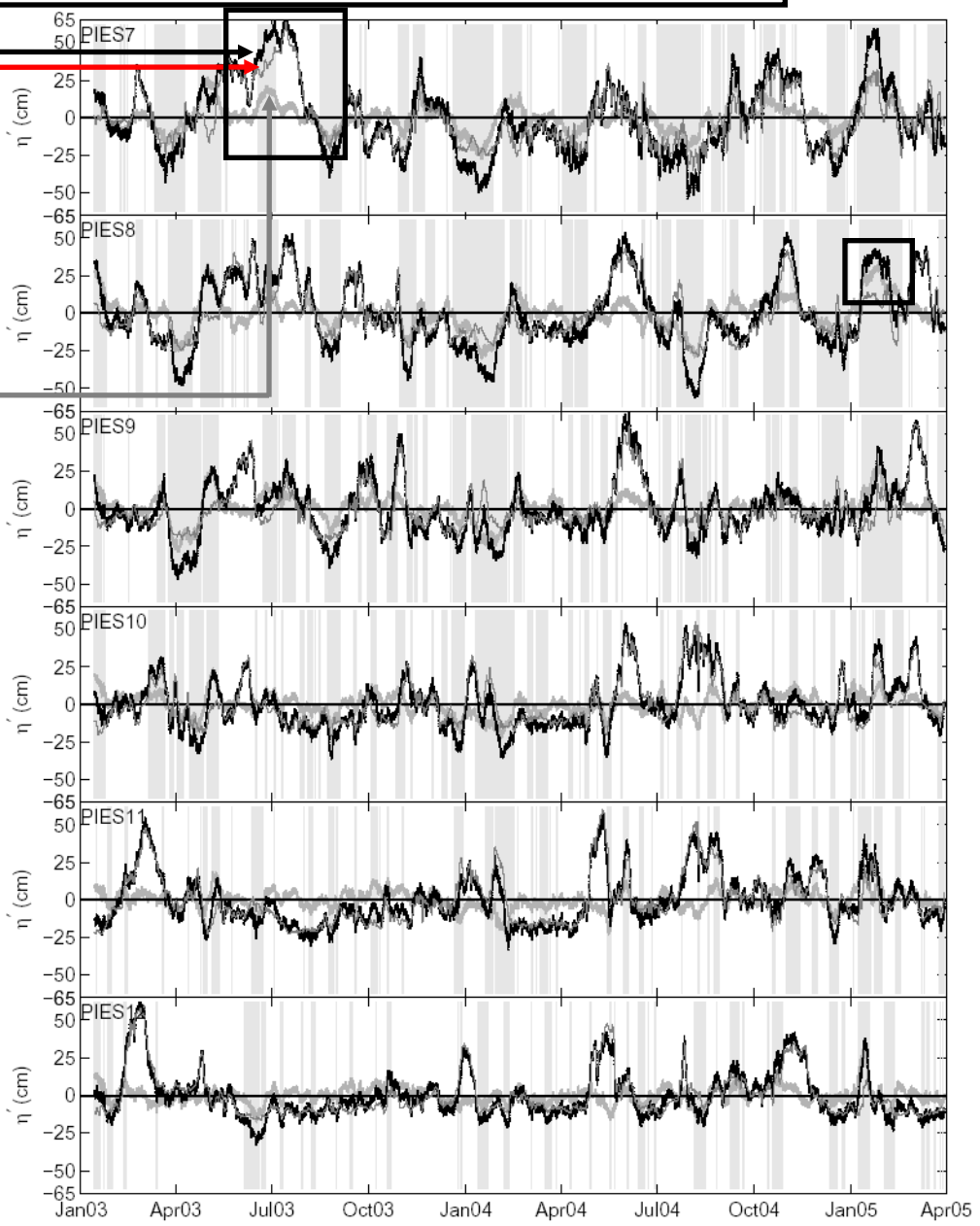

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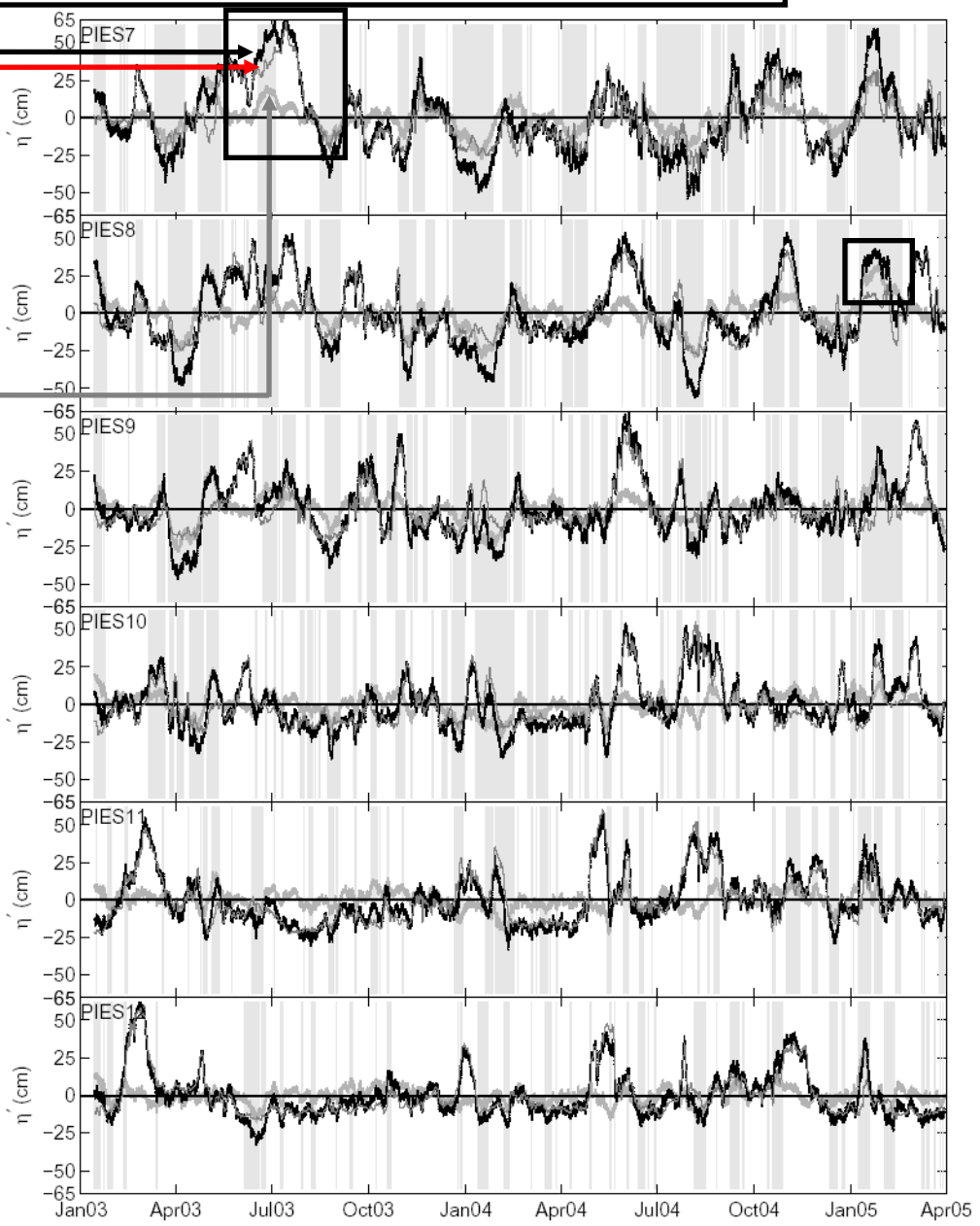


- Shaded region

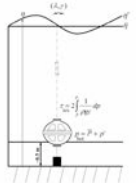
$$^{\dagger}R_{bt} = \frac{|\eta'_{bt}|}{|\eta'_{bc}| + |\eta'_{bt}|}$$

$$|\eta'_{PIES}| \geq 15 \text{ cm}$$

(Baker-Yeboah,Watts, & Byrne, 2010)

SSH Variability

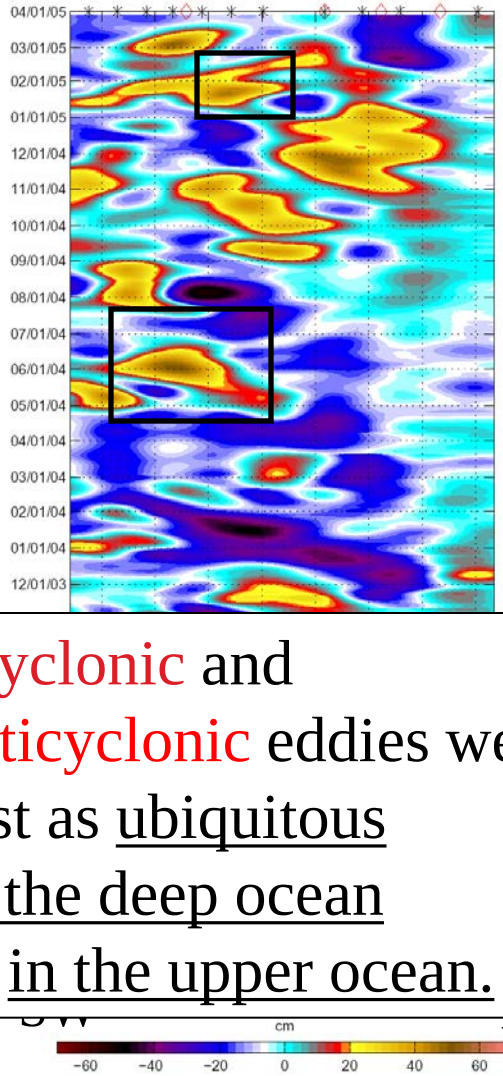
Part 2

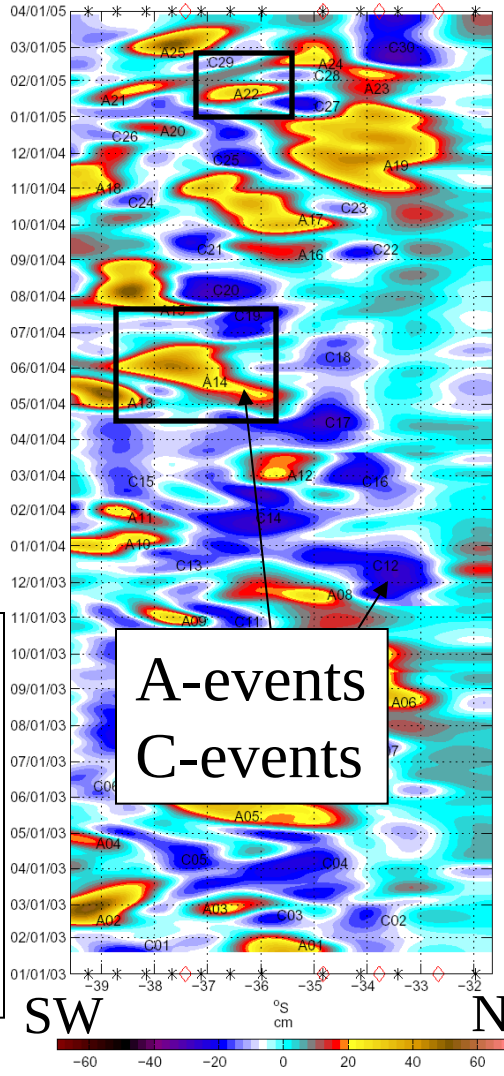


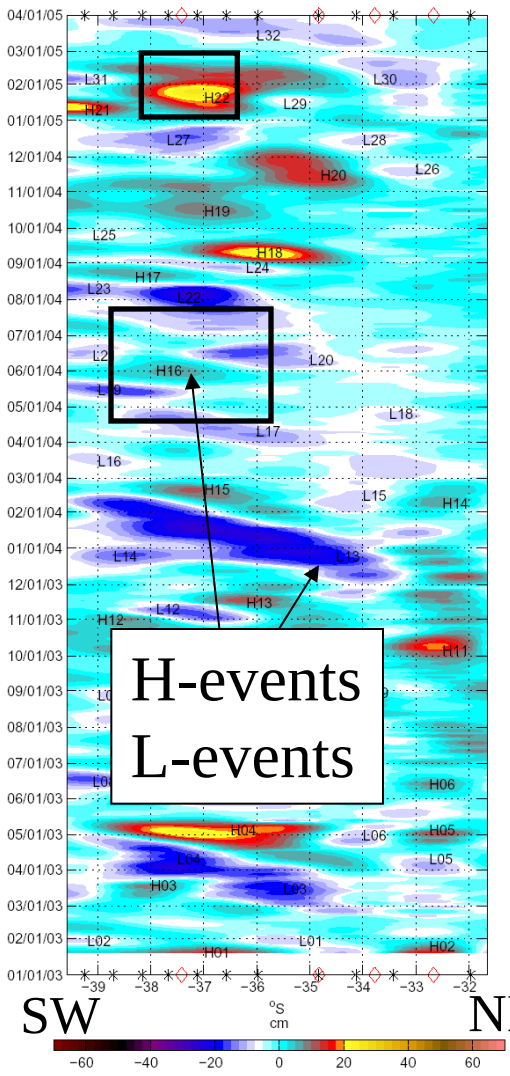
PIES Tot

PIES BC

PIES BT



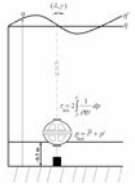




Cyclonic and anticyclonic eddies were just as ubiquitous in the deep ocean as in the upper ocean.

SSH Variability

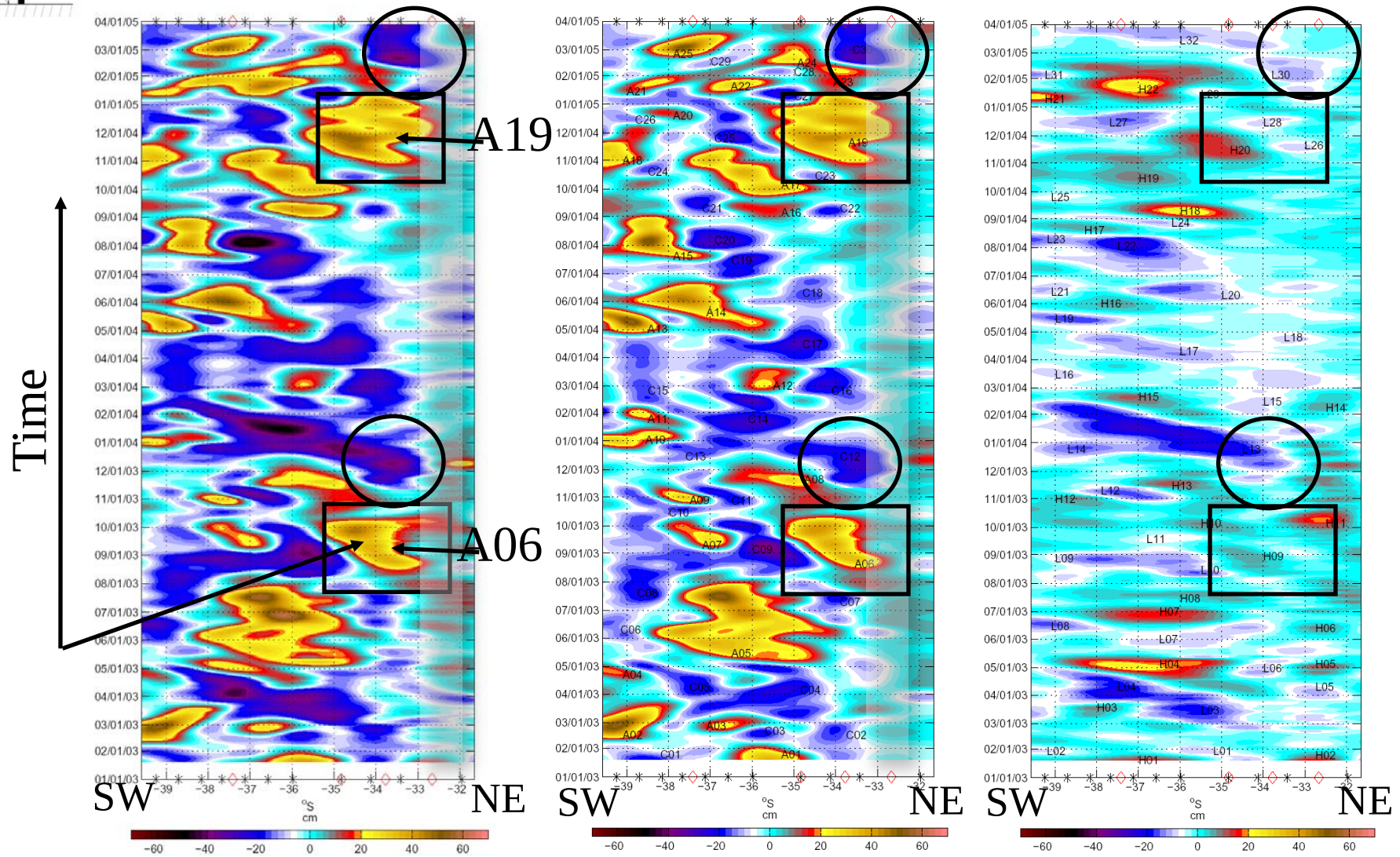
Part 2



PIES Tot

PIES BC

PIES BT



(Baker-Yeboah, Byrne, & Watts 2008)

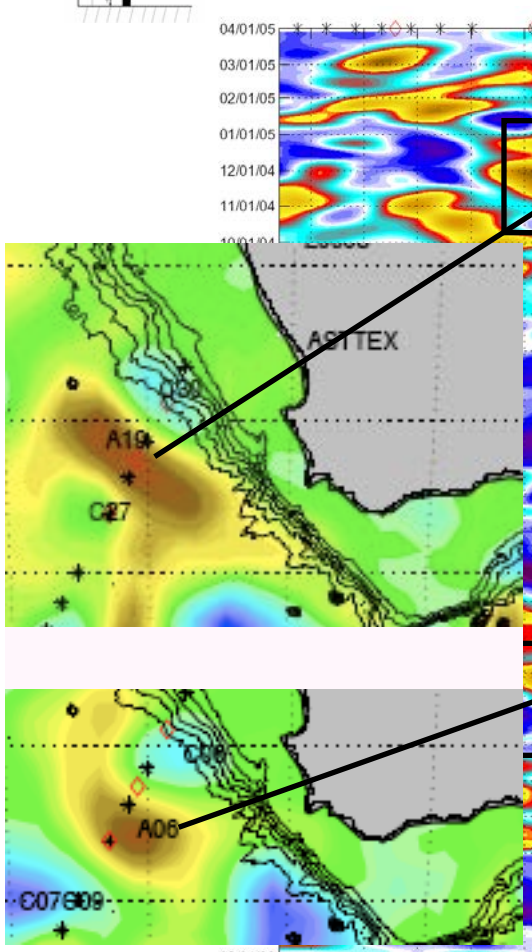
SSH Variability

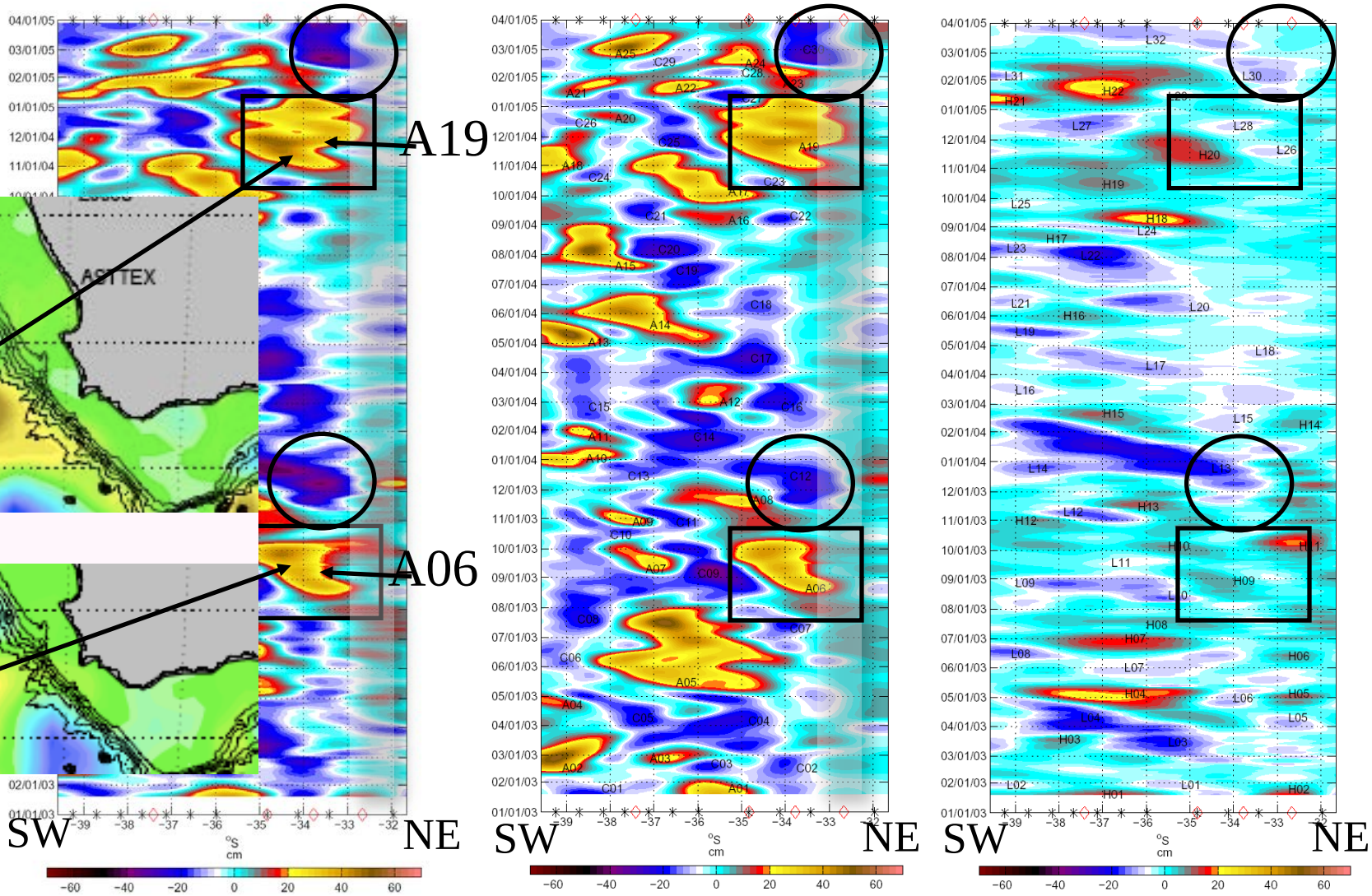
Part 2

PIES Tot

PIES BC

PIES BT





(Baker-Yeboah, Byrne, & Watts 2008)

- SSH variability from PIES data

$$\eta'_{PIES} = \eta' - \eta_{IB} = \eta'_{bt} + \eta'_{bc}$$

Part 2

$$\eta'_{bt} = \frac{p'}{\rho_b g}$$

- **The BT component contributes**
  - an average of 47% of the total SSH for SSH anomaly > 15 cm;
  - 20% of the overall SSH variance

- Shaded region

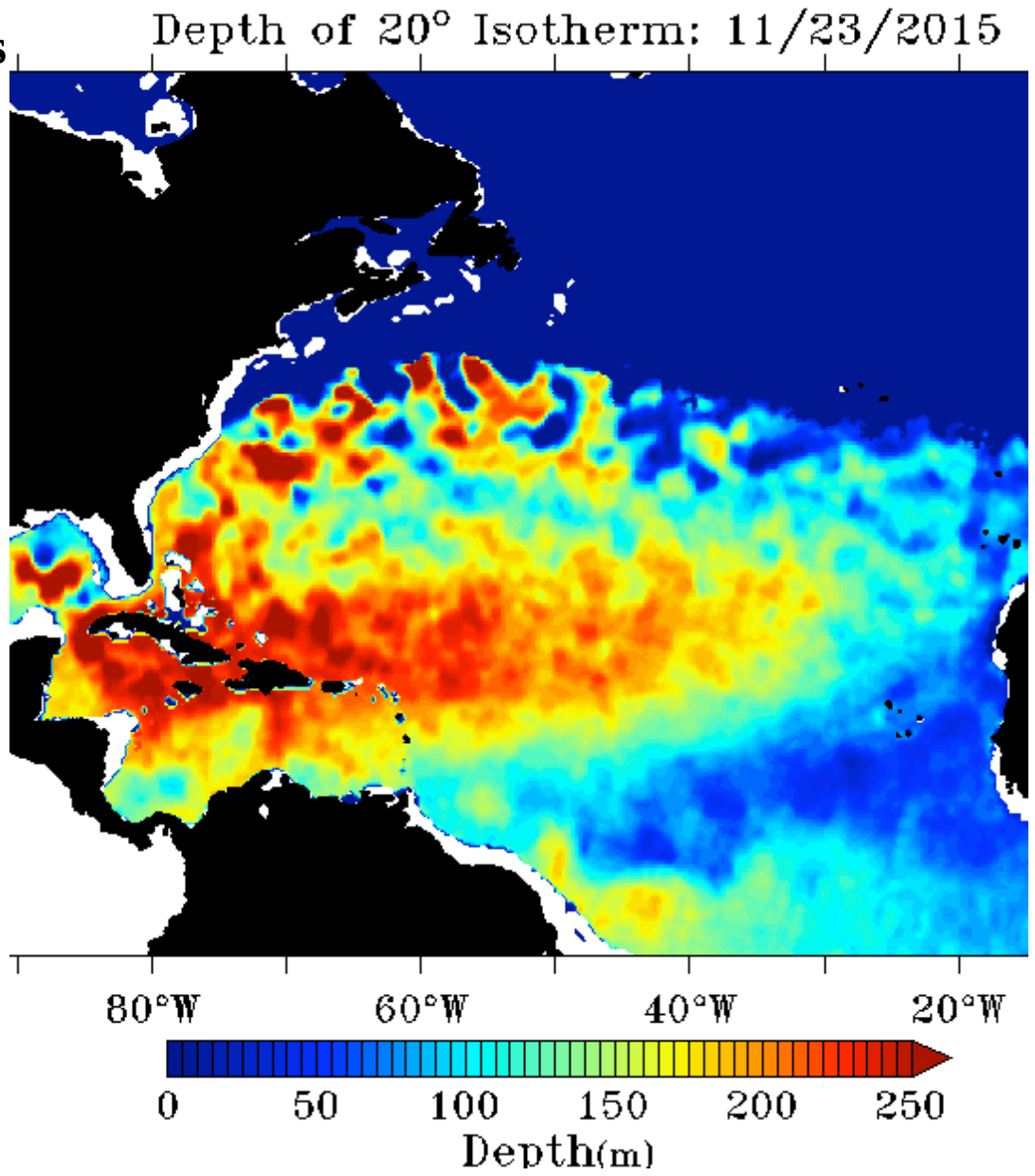
$$^{\dagger} R_{bt} = \frac{|\eta'_{bt}|}{|\eta'_{bc}| + |\eta'_{bt}|}$$

$$|\eta'_{PIES}| \geq 15 \text{ cm}$$

(Baker-Yeboah,Watts, & Byrne, 2010)

Improved understanding of altimeter SSH ocean signals provided a gateway into extracting the OHC.
→NOAA Product

- Recent White Paper (Baker-Yeboah, et. al., 2015) highlight the work by Shay and Brewster (2010) and Meyers et al. (2014) in which they developed a revised algorithm that estimates the depth of the 20^{0}C and 26^{0}C isotherms as well as mixed layer depth (MLD) from satellite altimetry and *in situ* profiles (Argo, XBT) and mooring data.
- Combined with SST from satellite, one can calculate ocean heat content. This is the basis for a NOAA operational product that calculates OHC daily (Figures 2-3, http://www.ospo.noaa.gov/Products/ocean/ ocean_heat.html).

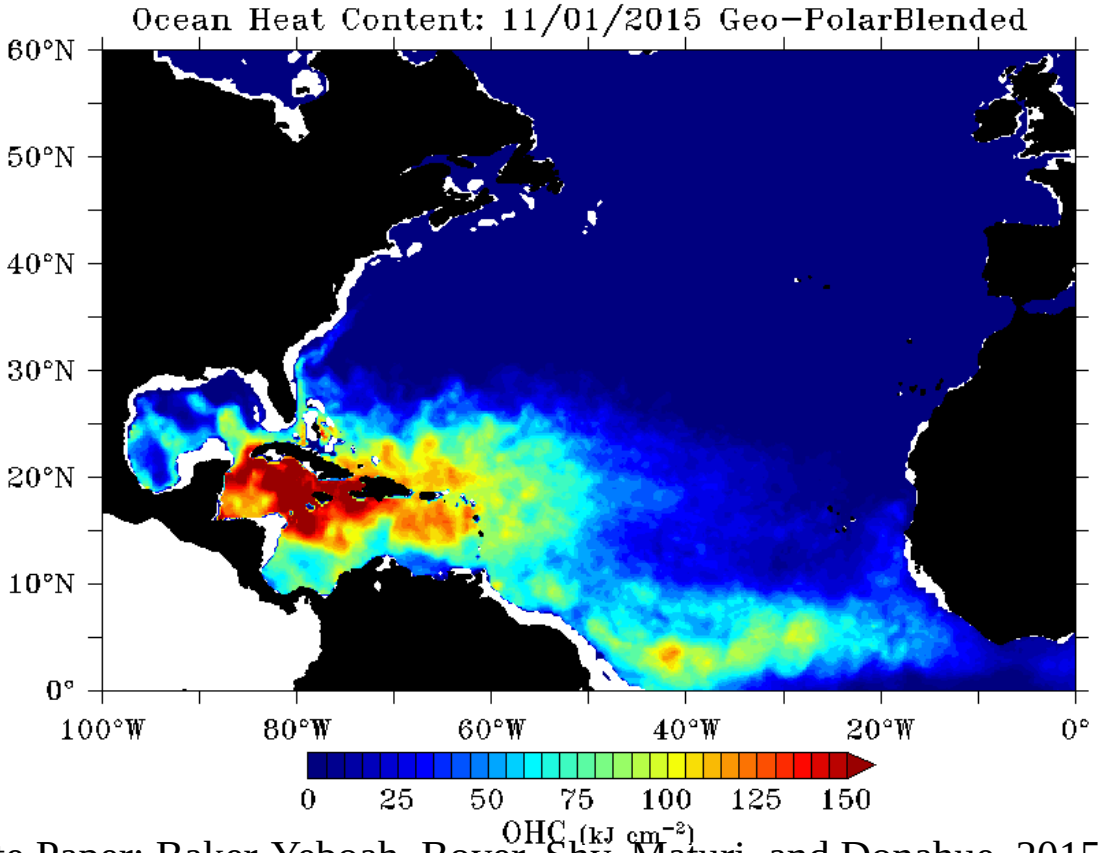


(White Paper: Baker-Yeboah, Boyer, Shy, Maturi, and Donahue, 2015)

Improved understanding of altimeter SSH ocean signals provided a gateway into extracting the OHC.
→NOAA Product

- The World Ocean absorbs, transports, and releases a vast amount of heat that feeds climate and weather systems. Ocean Heat Content (OHC) can be estimated using surface and subsurface measures of temperature.
- Space-based Sea Surface Height (SSH) altimeter data can also be used to estimate OH.
- A key challenge is to provide a consistent decadal climate data record of satellite altimeter data, which can then be used to generate an operational decadal satellite based OHC product.

- Altimeter and *in situ* derived ocean heat content: a NOAA operational product as described in Shay et al. (2015).



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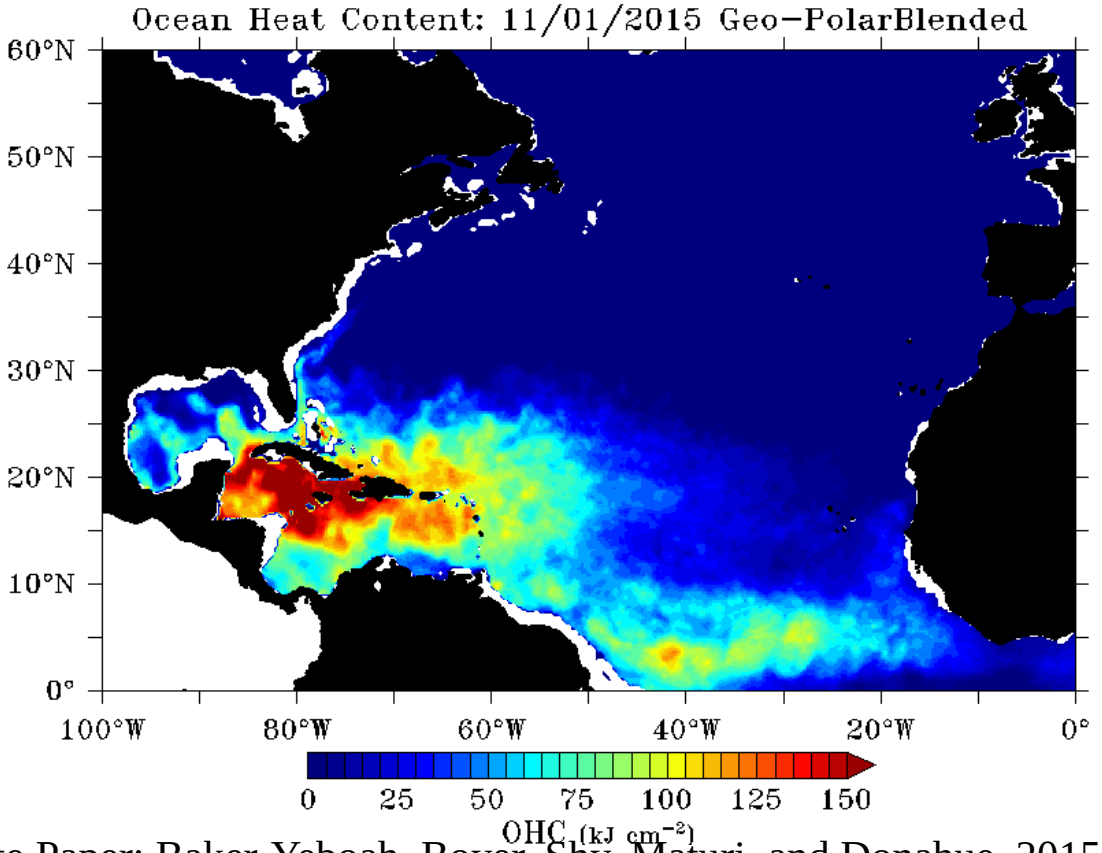
Improved understanding of altimeter SSH ocean signals provided a gateway into extracting the OHC.
→NOAA Product

- With the upcoming launch plans for Jason 3 this January 2016 (U.S. and international programs) to aid the continuity of space borne time records of SSH altimeter data and the concerted effort of the NOAA Climate Data Record Program (see Privette, Zhao, and Kearns, 2015, companion white paper) to support operational Reference Environmental Data Records (REDRs), this is a timely effort, especially with respect to operational readiness.
- Space-based observations from altimeters and AVHRR sensors provide decadal records of high-resolution data that can be used to provide continuous assessments of ocean dynamics and OHC to improve our understanding of how climate and weather is changing.

- Altimeter and *in situ* derived ocean heat content: a NOAA operational product as described in Shay et al. (2015).



(White Paper: Baker-Yeboah, Boyer, Shy, Maturi, and Donahue, 2015)

Summary

Observational of SSH from Altimeter & PIES

- spanning an "eddy corridor" where Agulhas rings pass, carrying cores of Indian Ocean water into the South Atlantic revealed the barotropic component contributes substantially to the total sea surface height (SSH) anomaly: an average of 47% of the total SSH during periods when the SSH anomaly exceeds 15 cm, and 20% of the overall SSH variance.

Summary

- Interestingly the barotropic timeseries data have about twice the spatial correlation scale of the baroclinic timeseries data: 200 km compared to 110 km.
- Cases of strong barotropic cyclonic eddies are almost always vertically aligned with baroclinic eddies.
- Moreover, most baroclinic anticyclonic eddies were laterally coupled to a mixed baroclinic-barotropic cyclonic eddy before or during transit across the observation array.

Summary

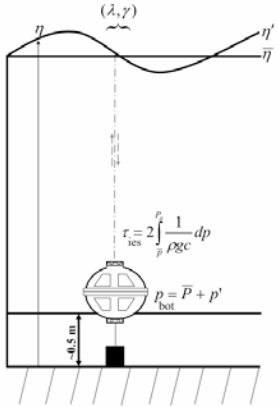
Decomposing the SSH signal

- *In situ* measurements can be used to **decompose** SSH into barotropic and baroclinic components and when combined, show complete agreement with altimeter SSH measurements.
- Space-based SSH altimeter data can also be used to estimate OHC. Further investigations are underway to explore ocean heat content based on a NOAA operational product that calculates OHC daily.

Acknowledgments

Coauthors
G. R. Flierl (MIT), G.G. Sutyrin (URI), Y. Zhang (MIT), D. A. Byrne (South Africa),D. R.Watts (URI)

T. Boyer (NOAA/NESDIS/NCEI), L.K. Shay (RSMAS), E.M. Maturi (NOAA/NESDIS/STAR), D. Donahue (NOAA/NESDIS/OSPO)



PIES Error Budget	**Measurement Error**	**Height Error**
Atmospheric Pressure IB effect in p_{bot}	NA	
Atmospheric Pressure IB effect in τ	0.13 ms	0.3 cm
Geophysical: Sea State Scatter		
One Ping	2.00 ms	
Twenty-Four Pings	0.40 ms	
Daily Lowpass Filtered	0.08 ms	0.3 cm
Spline-Curve Look Up Error (ASTTEX Region)	0.056 m^2/s^2	5.6 cm
Tides: Ocean		0.1 cm
Instrumental: Pressure Sensor Drift	10 mbar	
Pressure Drift Residual	1 mbar	1.0 cm
Instrumental: Mooring Motion		0.2 cm
Total		5.7