Progress Report
Quarterly Reports on the Meridional Heat Transport in the Atlantic Ocean

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1. Project Summary

Goal/Rationale: To contribute to the assessment of the state of the ocean by providing quarterly products of the meridional transports in the North and South Atlantic oceans that can be used as indicators. The heat and fresh water transports are directly related to the role that this basin plays in the meridional overturning circulation (MOC) and is an important benchmark for integrated air-sea fluxes and numerical model performance. Models indicate that the variability on the MOC has important consequences for the global climate. This project directly addresses the goal of the ocean observing system for climate to better understand the extent to which the ocean sequesters heat; to identify where heat enters the ocean and where it emerges to interact with the atmosphere; and to identify changes in thermohaline circulation and monitor for indications of possible abrupt climate change.

Project Output: "State of the ocean" quarterly estimates of meridional oceanic heat transport in the center of the subtropical gyres in the North and South Atlantic. This project supports the development of a methodology to estimate heat transport variability using data collected along two High Density Expendable Bathythermograph (XBT) transects operated by NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML), satellite data (altimeter and scatterometer), wind products from the National Center for Environmental Prediction (NCEP) reanalysis and products from general circulation models. Quarterly reports are posted on the AOML web site.

General Overview: The Atlantic Ocean is the major ocean basin involved in large-scale northward transports of heat typically associated with the MOC where warm upper layer water

flows northwards, and is compensated for by southward flowing North Atlantic Deep Water. This large-scale circulation is responsible for the northward heat flux through the entire Atlantic Ocean. Historical estimates of the net northward heat flux in the vicinity of its maximum, which occurs in the North Atlantic roughly at the latitude of the center of the subtropical gyre, range from 0.9 PW[1] to 1.6 PW, while estimate in the 30°S to 35°S band are even more uncertain, ranging from negative to more than 1 PW. While much of this variability may be a consequence of the different methods used to estimate the heat transport, natural variability cannot be ruled out. The importance of this heat transport to the world climate together with the possibility of monitoring its variability motivates this project.

Scope: AOML collects XBT data on two transects spanning the subtropical oceans: in the North Atlantic since 1995 (quarterly repeats) along AX7 running between Spain and Miami, Florida, and in the South Atlantic since 2002 (twice per year until 2004 and quarterly thereafter) along AX18 between Cape Town, South Africa, and Buenos Aires, Argentina. These data capture the upper limb of the MOC transport. In the North Atlantic much of the northward transport is confined to a strong boundary current through the Florida Straits, where XBT data is augmented with other data from the NOAA/CPO funded Western Boundary Time Series program. In the South Atlantic, the SAM moored array provides the much needed estimates of the deep western boundary current at these latitudes. This program currently funds the analysis of the heat transport across these two sections, culminating in values published within three months of the completion of each XBT realization on the AOML web site (and other journal articles as appropriate). During the past year, in addition to the estimates obtained from the XBT data, other observations (Argo profilers, Altimeter) as well as model products had been analyzed to provide scientific insight to the products. The study is complemented by including estimates of salt fluxes (fresh water transports) as an additional indicator of the state of the ocean and the climate.

2. Scientific and Observing System Accomplishments

Products Delivered: Quarterly Reports on the Meridional Heat Transport in the Atlantic Ocean

From data collected along two high density XBT transects in the Atlantic, AOML continues to provide quarterly reports of the estimated heat transport in the North and South Atlantic (Figures 1 and 2). Results are posted quarterly on AOML's state of the ocean web site at http://www.aoml.noaa.gov/phod/soto/mht/index.php. Each figure shows: the position of the most recent XBT transect (red) and the position of the all the transects completed to date (blue) (Top left panel); the temperature section corresponding to the last section (top right panel); the time series of the obtained values for the different components of the heat transport (bottom left) and the annual cycle of the heat transport components (bottom right).

[1] PW is PetaWatt or 10^{15} Watts, a unit of power commonly used for ocean heat transports.

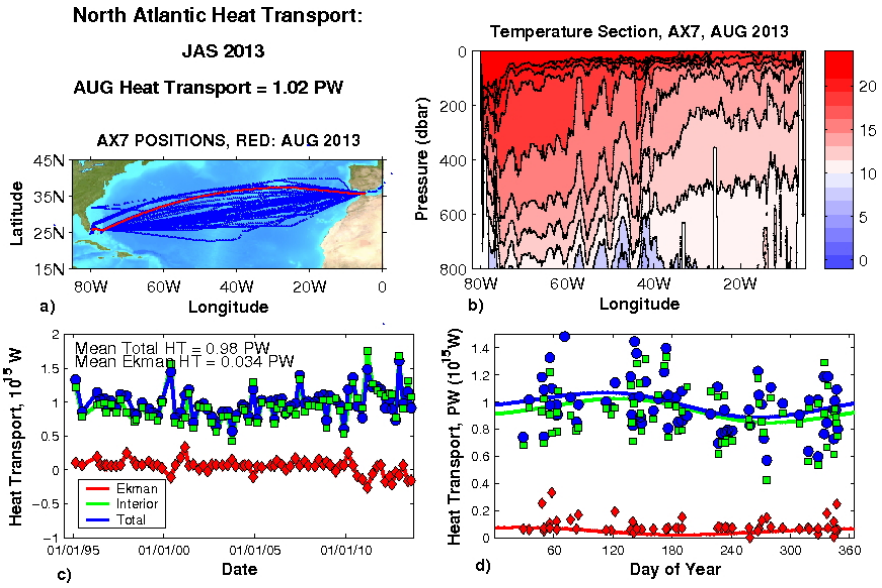

Figure 1: *Report for the July-August-September quarter of 2013 for North Atlantic Meridional Heat transport along the AX7 high density XBT transect. Transport results based on September 2012 XBT section (positions shown in top left, temperature section shown in top right). Heat transport estimates were decomposed into the geostrophic (interior) and Ekman components and their total (lower left).*

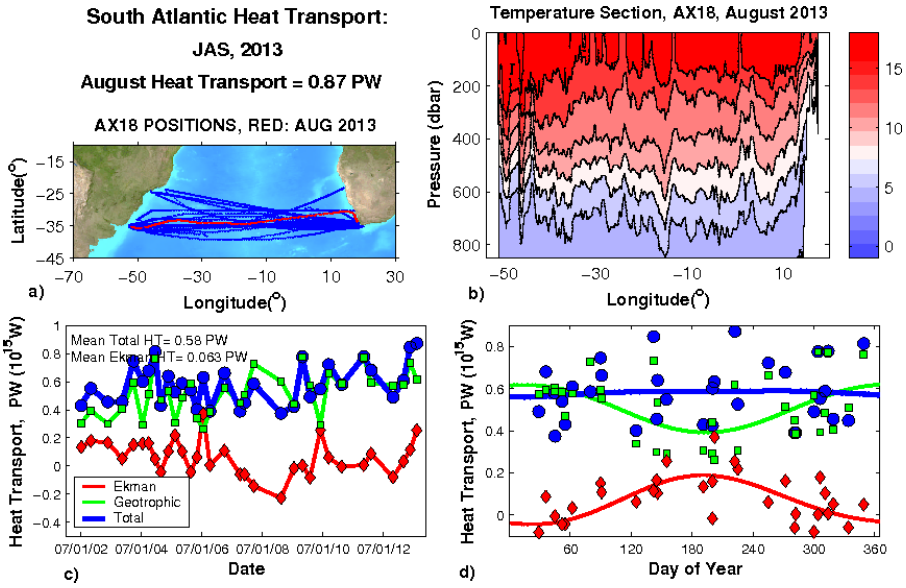

Figure 2: *Report for the July-August-September quarter of 2013 for South Atlantic Meridional Heat transport along the AX18 high density XBT transect. Transport results based on September 2013 AX18 XBT section (positions shown in top left, temperature section shown in top right). Heat transports were estimated using a shallow (green squares) and deep (red diamonds) reference level (lower left). Total heat transports demonstrate no*

significant seasonal signal because the seasonal signal in the Ekman layer is directly out of phase with the geostrophic signal (lower right).

Values of heat transport are given in PW (1 PW = 10^{15}W). One PW is equivalent to the amount of electricity produced by *one million* of the largest nuclear power plants in existence today (the largest nuclear plants produce about 1 gigawatt of electrical power).

This analysis quantifies the transport of heat in the North and South Atlantic. During the previous year, no abrupt climate change signals were observed, directly addressing the ocean observing systems program requirement to evaluate the heat transports within the oceans and assess abrupt climate change and variability. Papers highlighting the improved understanding of the climate system are described below.

2.1. Contribution to Climate Program Deliverables

The Meridional Heat Transport (MHT) project, through its analysis of temperature and salinity profile data and ocean circulation observations, contributes to the following NOAA/Climate Observation Division Program Deliverables (in rough order of impact and relevance):

- ***Ocean Heat Content and Transport***, to better understand the extent to which the ocean sequesters heat; to identify where heat enters the ocean and where it emerges to interact with the atmosphere; and to identify changes in thermohaline circulation and monitor for indications of possible abrupt climate change.

  The MHT project specifically addresses this NOAA climate goal by providing long-term integrated indicators of the global thermohaline (overturning) circulation and heat transport that directly addresses the program deliverable on "***ocean heat content and transport***". This project is designed to deliver quarterly estimates of the state of the thermohaline circulation and heat transport.
- ***Sea Surface Temperature and Surface Currents***, to identify significant patterns of climate variability and change.

  The MHT analysis provides an integrated estimate of the strength of the Brazil Current, and the currents associated with the net meridional overturning circulation.
- **Air-Sea Exchanges of Heat, Momentum, and Fresh Water**, to identify changes in forcing functions driving ocean conditions and atmospheric conditions; and to elucidate oceanic influences on the global water cycle

  The MHT analysis provides an *in situ* ocean heat and mass transport time series that can be used as a constraint on air-sea flux estimates and numerical model validation. This type of direct oceanic-transport-based flux estimate helps to reduce errors in surface products and assess numerical models.
- ***Sea Level***, to identify changes resulting from trends and variability in climate

  The MHT analysis provides indirect indicators that can influence sea-level variability through estimates of the Meridional Overturning Circulation and heat transport. Changes in heat content (e.g. induced by changes in the divergence of heat transports) and the meridional overturning circulation can affect sea level.

- ***Ocean Carbon Uptake and Content***, to better understand the extent to which the ocean sequesters CO2 and how cycling among ocean-land-atmosphere carbon reservoirs varies on seasonal-to-decadal time scales

  As noted above, the transport of boundary currents and the overturning circulation are central to determining Carbon uptake, but without direct carbon estimates these can only provide context with mean and variability of currents. The MHT analysis provides a boundary current estimate of the Florida Current, Brazil Current, Benguela Current and MOC that can be used to place Carbon flux estimates in context (e.g. at 24N Macdonald et al, 2003; Hansell et al, 2004).

2.2. Contribution to Societal Challenges

NOAA's Climate Goal is focusing on an initial set of societal challenges:

- Reduce vulnerability to extreme weather (extremes);
- Prepare for drought and water resource challenges (drought);
- Manage risks to coastlines and coastal infrastructure (coastal inundation); and
- Sustainably manage marine ecosystems (marine ecosystems)

The MHT analysis provides only a modest indirect contribution to these societal challenges. The program provides direct estimates of the boundary current transports that could kinematically affect coastal sea level. Similarly, changes in the net meridional overturning circulation can influence long-term sea-level. Extreme weather (e.g. hurricanes) and drought (e.g. rainfall) have been linked to the strength of the meridional overturning circulation. Continued analysis of boundary currents and the meridional overturning circulation and heat transport may improve forecasts of coastal inundation, seasonal forecasts of hurricanes, etc.

2.3. Scientific Accomplishments

In a recent publication (Garzoli et al., 2013) the properties of the meridional overturning circulation (MOC) and associated meridional heat transport (MHT) and salt fluxes are analyzed in the South Atlantic. The oceanographic data used for the study consist of Expendable bathythermograph (XBT) data collected along 27 sections at nominally 35°S for the period of time 2002 to 2011, and Argo profile data collected in the region. Previous estimates obtained with a shorter record are improved and extended, using new oceanographic sections and wind fields. Different wind products are analyzed to determine the uncertainty in the Ekman 33 component of the MHT derived from their use. Results of the analysis provide a nine-year time series of MHT, and volume transport in the upper layer of the MOC.

Analysis of the data shows that the South Atlantic is responsible for a northward MHT with a mean value of 0.54 ± 0.14 PW. The MHT exhibits no significant trend from 2002 to 2011. The MOC varies from 14.4 to 22.7 Sv with a mean value of 18.1 ± 2.3 Sv and the maximum overturning transport is found at a mean depth of 1250 m. Statistical analysis suggests that an increase of 1 Sv in the MOC leads to an increase of the MHT of 0.04 ± 0.02 PW.

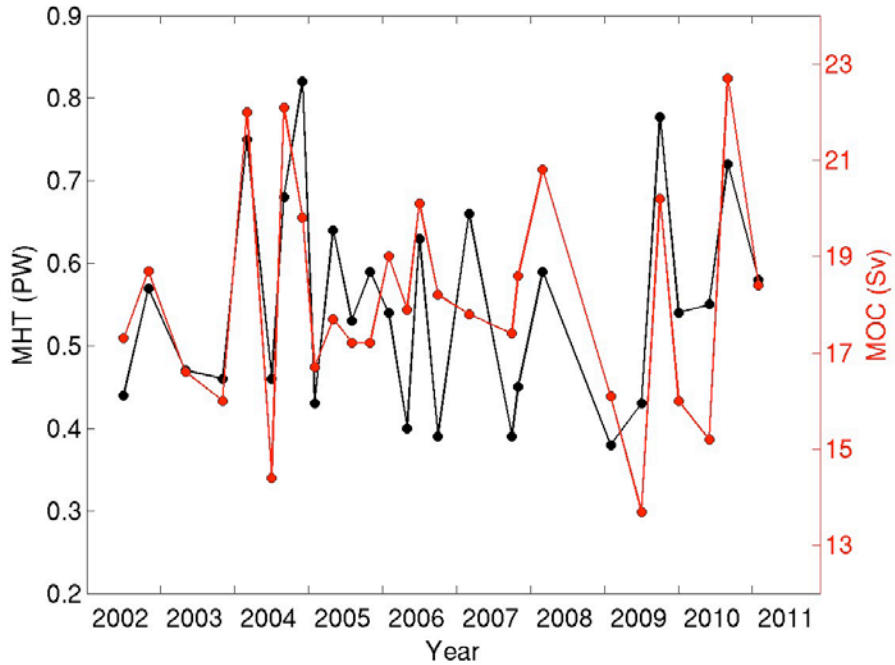

Figure 3: Time series of the MHT (black) and the AMOC (red) along nominally 35°S for the time period 2002 to 2011 (from Garzoli et al., 2013).

Salt fluxes at 35°S are estimated using a parameter introduced by numerical studies, the M_{ov} that represents the salt flux and helps determine the basin scale salt feedback associated with the MOC. Volume and heat transport by the western and eastern boundary currents are estimated, and their covariablity is examined. Estimates of the M_{ov} from data collected from three different kinds of observations, contrary to those obtained from models, feature a positive salt advection feedback ($M_{ov} < 0$) suggesting that freshwater perturbations will be amplified and that the MOC is bistable. In other words, the MOC might collapse with a large enough freshwater perturbation. Observations indicate that the mean value of the Brazil Current is -8.6 ± 4.1 Sv at 24°S and -19.4 ± 4.3 Sv at 35°S, increasing towards the south.

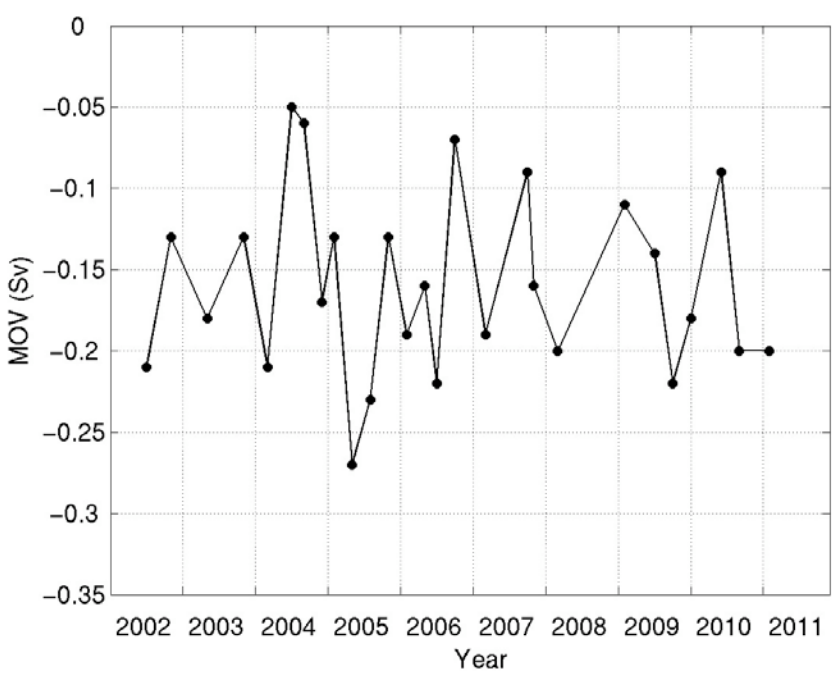

Figure 4: Time series of the M_{ov} nominally across 35°S for the time period 2002. Values are negative contrary to model results indicating that the MOC is bistable (from Garzoli et al., 2013).

East of 3°E, the northward flowing Benguela Current and Agulhas rings have a net northward transport of 22.5 ± 4.7 Sv. No significant correlation is observed between the MOC and the Brazil Current transport, and most of the compensation derives from the eastern boundary and interior transports.

An on going research based on data collected along AX18 is examining the causes for model-data differences in the seasonal variations of the MOC and MHT in the South Atlantic. Temperature and salinity climatology from the high density data collected along the AX18 line and Argo profiling floats are used together with products from GFDL models to estimate the MOC/MHT at 34S. The MOC derived from model T/S fields show strong transport in the ocean interior region compared to the MOC from Argo T/S fields. The geostrophic component of the MOC from T/S data shows a seasonal variation with the maximum value in January and minimum value in August. However, the seasonal variations of the geostrophic contributions from model T/S fields is very weak. Differences are seen in all three regions: western boundary, interior region, and eastern boundary, with the largest difference in the eastern boundary. Examination of the density field suggests that the difference in the eastern boundary is related to the vertical coherent density variations in observations, which is not shown in the model field. Wind stress curl from models and observations show strong differences in the eastern boundary, which could explain why the models are unable to reproduce the seasonal variations in geostrophic component of the MOC.

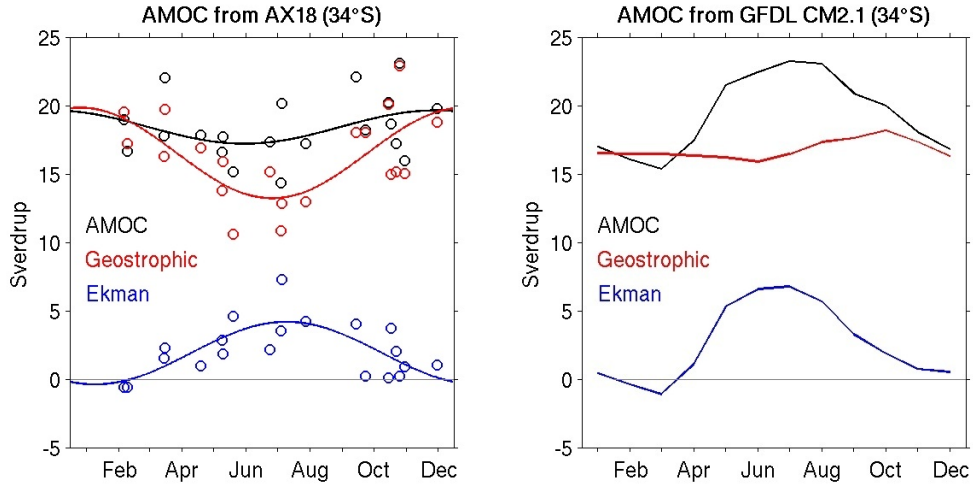

Figure 5: Seasonal variations of the MOC (black) and contributions from geostrophic (red) and Ekman (blue) components at 34°S derived from (left) high-density XBT transects AX18 and (right) GFDL CM2.1 model (Dong, personal communication)

Another important line of research, based on the high density XBT lines, is the one that combines the data with altimetry and other hydrographic data in the region to expand the MHT estimates to the basin. Monthly temperature profiles along 20°S, 25°S, 30°S, and 35°S were estimated using historical sea height anomaly – depth of isotherm relationships obtained from

XBT/CTD/Argo temperature profiles in the South Atlantic Ocean (Figure 6). For most isotherms, the correlation between T and SHA is higher than 0.6 south of 20°S. When correlations are low, the depth of an isotherm tends to the climatological value. Errors in temperature estimates for individual section are, in general, larger (~0.5°C) at the depth of the main thermocline (Figure 6). Salinity profiles were also obtained using historical T-S relationships (Thacker, 2008).

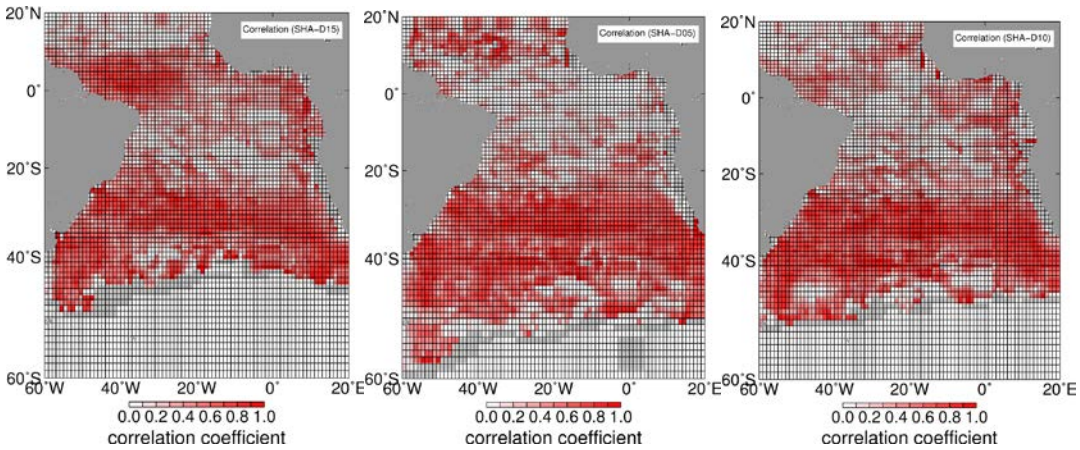

Figure 6. Correlation coefficients between sea height anomaly and the depth of the (starting on left) 5°C 10°C and 15°C isotherms in the South Atlantic

Using the synthetic temperature and salinity profiles, and following the same methodology used to compute the MOC and MHT from XBT observations (Baringer and Garzoli, 2007; Dong et al., 2009), the MOC and MHT was estimated at the same times and locations of the XBT High Density realizations of the AX18 transect. The correlation coefficient between estimates from XBTs and altimetry is 0.78 for MOC and 0.83 for MHT, well above 95% significance level of 0.4 (Figure 7). This methodology allows us to extend the MOC/MHT estimates the entire altimetry period, i.e., back to 1993 (Figure 7).

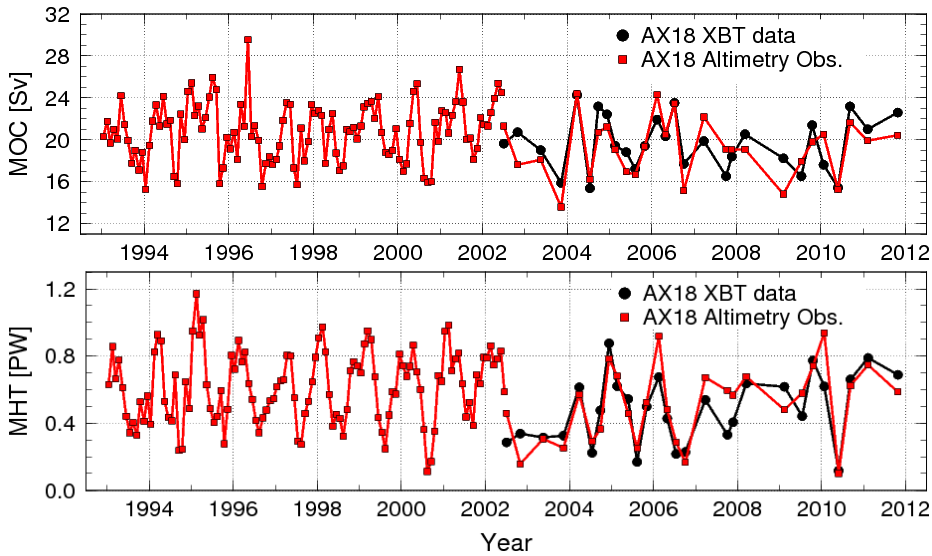

Figure 7: Time series of the MOC (top) and MHT (bottom) at 34.5°S in the South Atlantic obtained from the XBT data (black) and those obtained from the altimeter derived synthetic profiles (red).

The heat transport derived from XBT observations was presented for the first time in the Bulletin of Meteorological Society's State of the Climate Report. Figure 8 shows the meridional heat transport as shown in the paper. Following an increase in heat transport since 2008, the year 2011 had a substantial increase in the mean annual transport value (0.68 PW), the highest recorded annual mean (however, still within one standard error of the mean). In addition, a new paper was submitted for the WOCE Encyclopedia describing heat transport in the Atlantic. This includes estimates from the XBT observations.

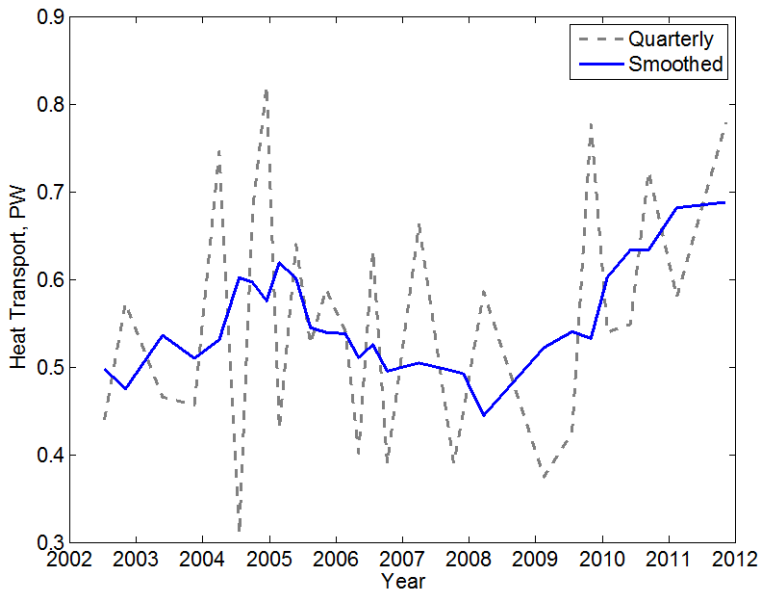

Figure 8. Heat transport in the South Atlantic near 35ºS derived from quarterly transects along the high-density line AX18 (grey dashed line) and smoothed values of heat transport (using a five-point running mean; blue solid line).

2.4. Issues

Heat transport analysis requires the underlying data to sustain time series information. For example during FY2011, the high-density transect AX18 was occupied only twice during the year due to shipping route changes. Fortunately, recruitment efforts have resulted in finding new ships to provide the necessary coverage and during FY13, four realizations of AX18 were conducted.

2.5. Miscellaneous Information

1. The analysis project funded here can be accessed here: http://www.aoml.noaa.gov/phod/soto/mht/index.php

2. The high-density XBT data that are relied upon for this analysis can be found here: http://www.aoml.noaa.gov/phod/hdenxbt/index.php#

3. Outreach and Education

M. Baringer served as a contributing author for Chapter 3: Observations: Oceans for Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Intergovernmental Panel on Climate Change Fifth Assessment Report.

The following is a link to a news story reported in FY2013 regarding on various publications co authored by principle investigators of this project

Abraham, John (28 August 2013). Global warming and oceans: what are the known unknowns?. *Climate Consensus - the 97%, hosted by The Guardian*.

S. Garzoli was interviewed on MOC topics for an article that was being prepared for the climate.gov web site. S. Garzoli was also interviewed for a news article in Nature. An article relating to the December 2012 "Southwest Atlantic MOC – SAM" project cruise was prepared for the AOML Keynotes publication by S. Garzoli. Several of the PIs also participated in public education activities in Miami, including discussions with school children and the public during the AOML Open House in May 2013, and working with women scientists to increase retention in the field (MPOWIR). Finally, several presentations were given by the PIs at national and international science conferences including the US AMOC/RAPID meeting and the IAHS-IAPSO-IASPEI joint assembly.

4. Publications and Reports

Publications by Principal Investigators

Published in FY2013

Baringer, M. O., W. E. Johns, G. McCarthy, J. Willis, S. Garzoli, M. Lankhorst, C. S. Meinen, U. Send, W. R. Hobbs, S. A. Cunningham, D. Rayner, D. A. Smeed, T. O. Kanzow, P. Heimback, E. Frajka-Williams, A. Macdonald, S. Dong, and J. Marotzke, 2013: Global oceans: Meridional overturning circulation and heat transport observations in the Atlantic, in State of the Climate in 2012, J. Blunden and D.S. Arndt (eds.), Bull. Amer. Meteor. Soc., 94, S65-S68.

Goes, M., G.J. Goni, V. Hormann, and R.C. Perez, 2013: Variability of eastward currents in the equatorial Atlantic during 1993-2010. *J. Geophys. Res.*, doi:10.1002/jgrc.20186, 118, 1-20.

Goes, M., G.J. Goni, and K. Keller, 2013: Reducing Biases in XBT Measurements by Including Discrete Information from Pressure Switches. *J. Atmos. Ocean. Techn.*, 30(4), pp.810-824, 10.1175/JTECH-D-12-00126.1.

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Lindo-Atichati, D., F. Bringas, and G. Goni, 2013: Loop Current excursions and ring detachments during 1993 - 2009. *Int. J. Rem. Sens*., 34(14):5042-5053, doi:10.1080/01431161.2013.787504.

Lumpkin R**.**, G. Goni and K. Dohan, 2013: Surface Currents. [in "State of the Climate in 2012"]. *Bull. Amer. Meteor. Soc.*, 94 (8) S62-65.

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Meinen, C. S., William E. Johns, Silvia L. Garzoli, Erik van Sebille, Darren Rayner, Torsten Kanzow, and Molly O. Baringer, 2012: Variability of the Deep Western Boundary Current at 26.5°N during 2004-2009. *Deep-Sea Res. II*, 10.1016/j.dsr2.2012.07.036.

Meinen, C. S., A. R. Piola, R. C. Perez, and S. L. Garzoli, 2012: Deep Western Boundary Current transport variability in the South Atlantic: Preliminary results from a pilot array at 34.5°S, Ocean Science, 8 (6), 1041-1054, doi:10.5194/os-8-1041-2012.

Srokosz, M., M. Baringer, H. Bryden, S. Cunningham, T. Delworth, S. Lozier, J. Marotzke and R. Sutton, 2012: Past, present and future change in the Atlantic meridional overturning circulation. Bull. Amer. Meteo. Soc., doi: 10.1175/BAMS-D-11-00151.1, Nov 2012.

In Press

Abraham, J.P., M. Baringer, N.L. Bindoff, T. Boyer, L.J. Cheng, J.A. Church, J.L. Conroy, C.M. Domingues, J.T. Fasullo, J. Gilson, G. Goni, S.A. Good, J. M. Gorman, V. Gouretski, M. Ishii, G.C. Johnson, S. Kizu, J.M. Lyman, A. M. Macdonald, W.J. Minkowycz, S.E. Moffitt, M.D. Palmer, A.R. Piola, F. Reseghetti, K. Schuckmann,K.E. Trenberth, I. Velicogna, J.K. Willis, 2013: A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change, *Rev. Geophys.*, **51**, 450–483, doi: 10.1002/rog.20022.

Beron-Vera, F.J., Y. Wang, M.J. Olascoaga, G.J. Goni, G. Haller, 2013: Objective detection of oceanic eddies and the Agulhas leakage. *J. Phys. Oceanog.*, doi:10.1175/JPO-D-12-0171.1, in press.

Goni, G ., J. Sprintall, D. Roemmich, A. Gronell Thresher, R. Couley, and M. Baringer**,** 2013: The global network of XBT temperature sections in support of Oceanographic and climate studies. Chapter 5: Oceans and Society: Blue Planet, ed. Samuel Djavidnie, Cambridge Scholars Publishing, in press.

Macdonald, A., and M. Baringer, 2013: Observed Ocean Transport of Heat. Chapter 6.3 of "Ocean Circulation and Climate (Second edition)", ed. G. Siedler, J. Church, J. Gould and S. Griffies, Academic Press (Elsevier), in press.

Smeed, D. A., McCarthy, G., Cunningham, S. A., Frajka-Williams, E., Rayner, D., Johns, W. E., Meinen, C. S., Baringer, M. O., Moat, B. I., Duchez, A., and Bryden, H. L.: Observed decline of the Atlantic Meridional Overturning Circulation 2004 to 2012, 2013: Ocean Sci. Discuss, 10, 1619-1645, doi:10.5194/osd-10-1619-2013.

Data Reports

Hooper, J.A., and M.O. Baringer, 2013: Hydrographic measurements collected aboard the NOAA Ship *Ronald H. Brown*, 15 February-5 March 2012: Western boundary time series cruise RB-12-01 (AB1202). NOAA Data Report, OAR-AOML-43, 267 pp.

Hooper, J.A., W.E. Johns, and M.O. Baringer. Hydrographic measurements collected aboard the UNOLS Ship R/V *Endeavor*, 24 September-10 October 2012: Western boundary time series cruise EN-517 (AB1209). NOAA Data Report, OAR-AOML-44.