Meridional Heat Transport Variability 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 reports on the meridional heat transport in the North and South Atlantic oceans. This heat transport is 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

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

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. This program 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).

2. Scientific and Observing System Accomplishments

Products Delivered: State of the 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).

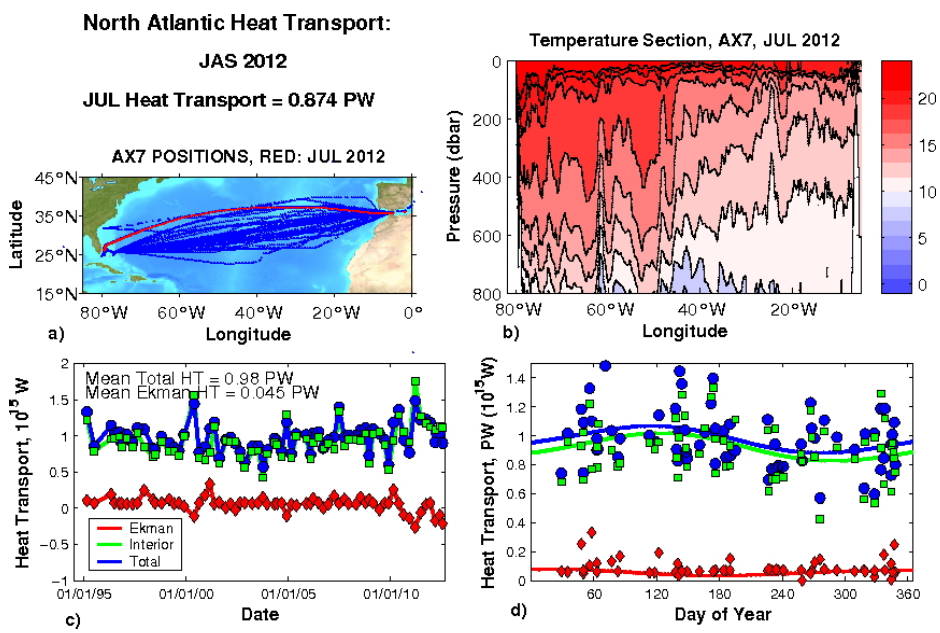


Figure 1: *Report for the July-August-September quarter of 2012 for North Atlantic Meridional Heat transport along the AX7 high density XBT transect. Transport results based on September 2012 XBT section (positions shown in top left, temperature section shown in top right). Heat transport estimates were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

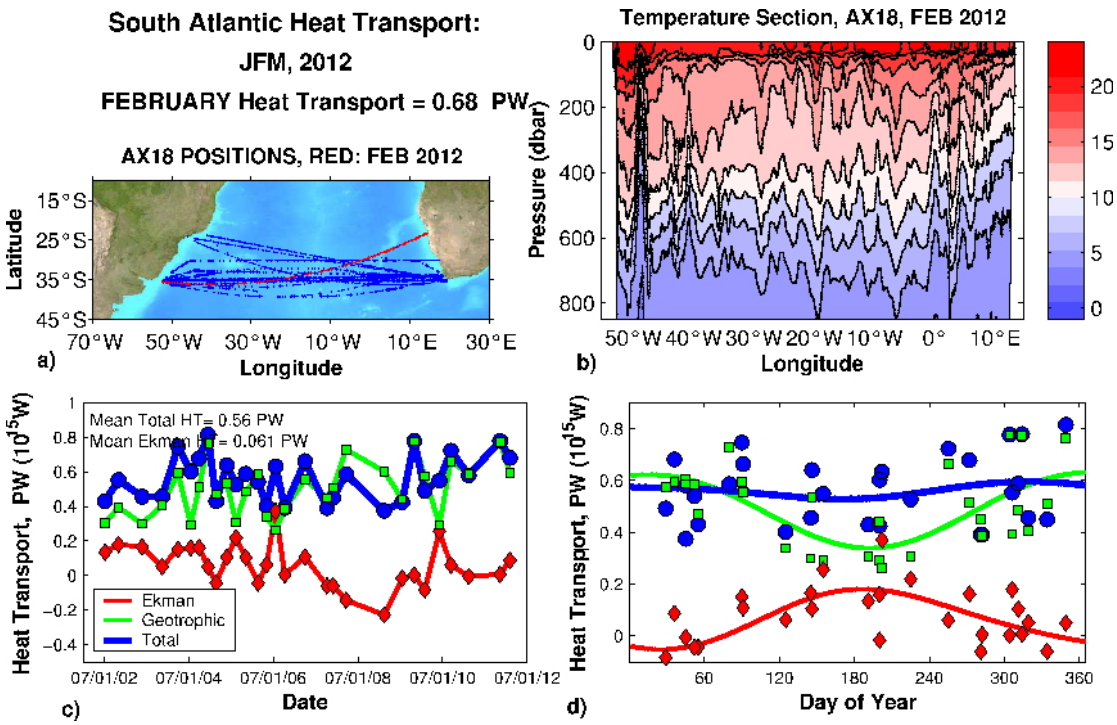


Figure 2: *Report for the January-February-March quarter of 2011 for South Atlantic Meridional Heat transport along the AX18 high density XBT transect. Transport results based on February 2011 AX18 XBT section (positions shown in top left, temperature section shown in top right). Heat transports were 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.

Scientific Findings:

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.

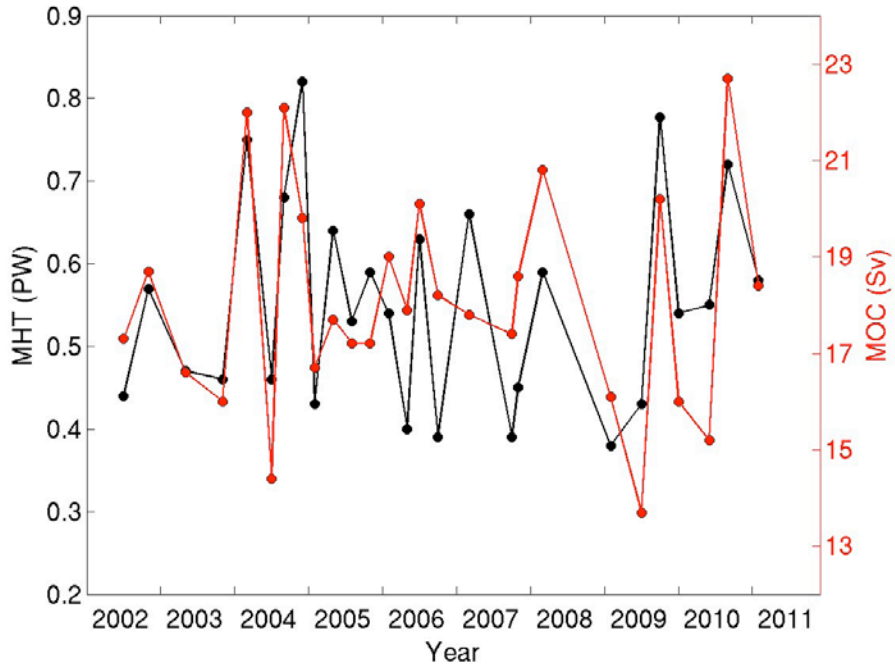


Figure 3: *Time series of the MHT (black) and the AMOC (red) along nominally 35°S for the time period 2002 to 2011 (from Garzoli et al., 2012).*

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.

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.

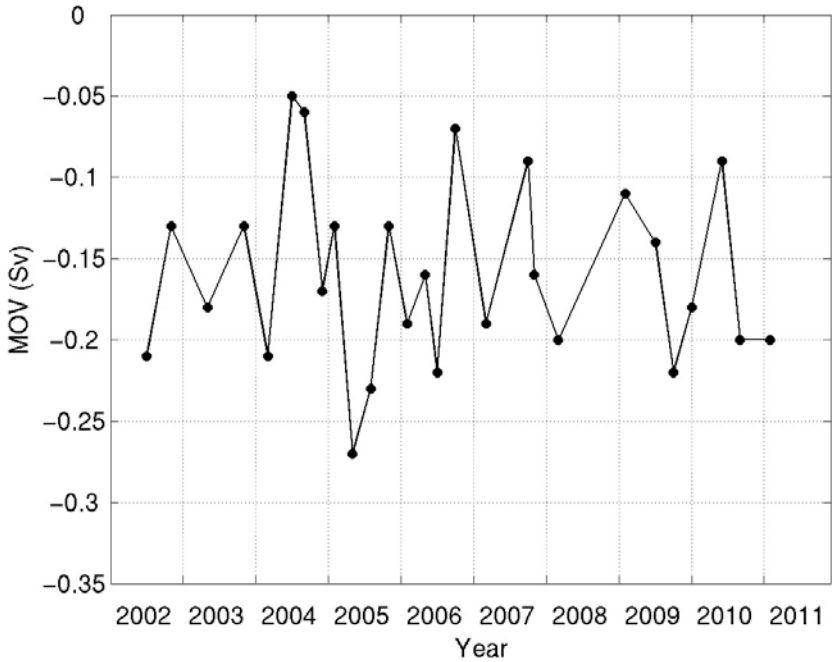


Figure 4: *Time series of the M_{ov} nominally across 35°S for the time period 2002. Values are negative contrary to model results indicating that the MOC is bistable (from Garzoli et al., 2012).*

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.

Also based on data collected along AX18 to examine 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.

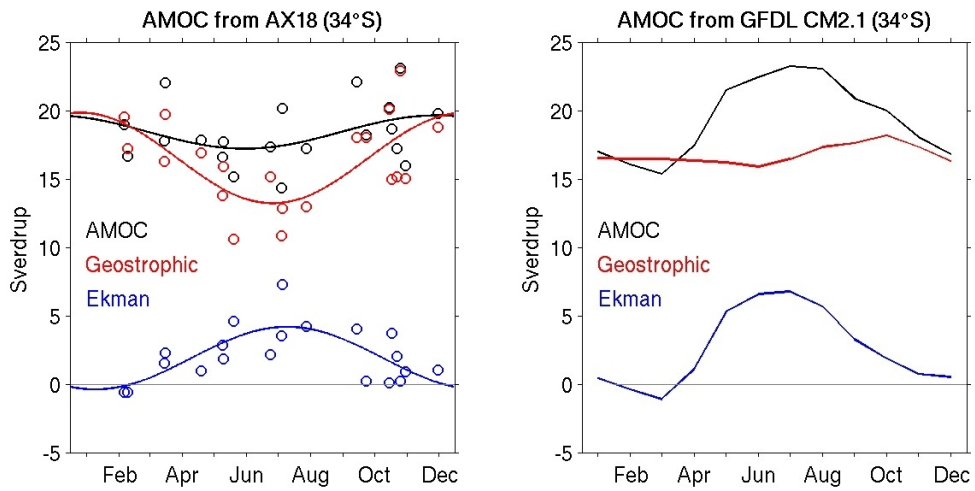


Figure 5: *Seasonal variations of the MOC (black) and contributions from geostrophic (red) and Ekman (blue) components at 34°S derived from (left) high-density XBT transects AX18 and (right) GFDL CM2.1 model (Dong, 2012.*

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).

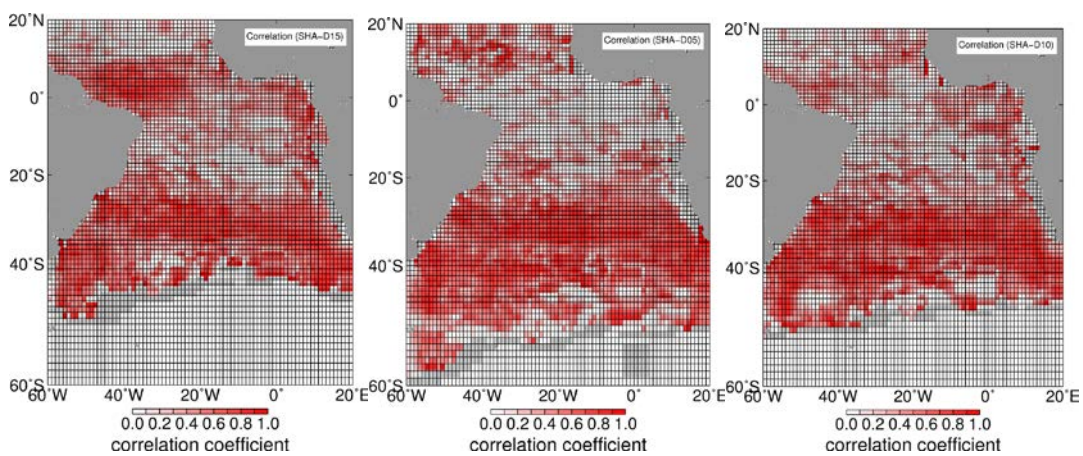


Figure 6. *Correlation coefficients between sea height anomaly and the depth of the (starting on left) 5°C 10°C and 15°C isotherms in the South Atlantic*

Using the synthetic temperature and salinity profiles, and following the same methodology used to compute the MHT from XBT observations (Baringer and Garzoli, 2007), the MHT was estimated at the same times and locations of the XBT High Density realizations of the AX18 transect. The correlation coefficient between both estimates is slightly above 0.5 (Figure 7).

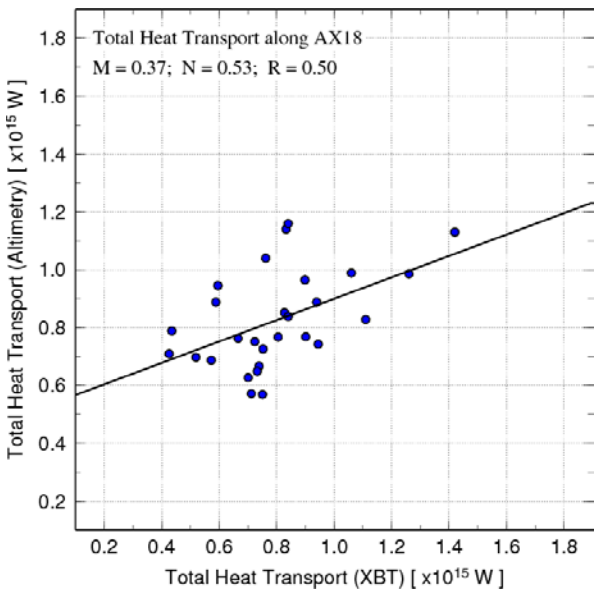
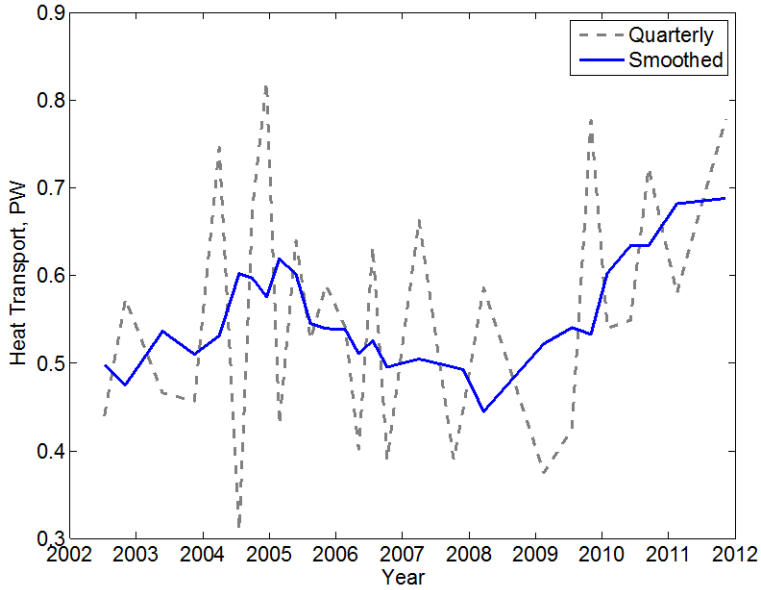


Figure 7: *Correlation between meridional heat transport obtained from the BT data and the same quantity obtained from the altimeter derived synthetic profiles.*

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).*



Risks:
Heat transport analysis requires the underlying data to sustain time series information. During FY2011, the high-density transect AX18 was occupied twice during the year due to shipping route changes. Recruitment efforts have resulted in finding new ships that will provide the necessary coverage.

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

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#

2.1. Outreach and Education

M. Baringer is 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. She co-authored a paper published in FY2012 with postdoctoral fellow Eric van Sebille looking at the propagation pathways of Labrador Sea Water in the North Atlantic (the postdoctoral fellow was support under the MOCHA/Rapid/WBTS program funded by NSF). This year M. Baringer hosted two Teachers at Sea on the February 2012 Western Boundary Time Series Ronald H. Brown cruise (including funding one of their participation through the Western Boundary Time Series project).

3. Publications and Reports

3.1. Publications by Principal Investigators

Published if FY2012 (electronic versions of published articles are available via hyperlink):

Baringer, M. O., S. A. Cunningham, C. S. Meinen, S. Garzoli1, J. Willis, M. Lankhorst, A. Macdonald, U. Send, W. R. Hobbs, E. Frajka-Williams, T. O. Kanzow, D. Rayner, W. E. Johns, and J. Marotzke, 2012. [Global Oceans] Meridional Overturning Circulation and Heat Transport Observations in the Atlantic Ocean [in "State of the Climate in 2011"], Bull. Am. Met. Soc., 93 (7), S78-81.

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

van Sebille, Erik, Molly O. Baringer, William E. Johns, Christopher S. Meinen, Lisa M. Beal, M. Femke de Jong, and Hendrik M. van Aken, 2011. Propagation pathways of classical Labrador Sea Water from its source region to 26deg N, Journal of Geophysical Research Oceans, 116, C12027, doi:10.1029/2011JC007171.

Mata, Mauricio M., Mauro Cirano, Mathias R. van Caspel, Caio S. Fonteles, Gustavo Goni and Molly Baringer, 2012. Observations of Brazil Current baroclinic transport near 22˚S: variability from the AX97 XBT transect. Clivar Exchanges, 58, 17, 1, 5-10.

Published in FY2013 (in press as the end of FY2012)

Meinen, C. S., William E. Johns, Silvia L. Garzoli, Erik van Sebille, Darren Rayner, Torsten Kanzow, and Molly O. Baringer, 2011. 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

Garzoli, S.L., M.O. Baringer, S. Dong, R.C. Perez, and Q. Yao (2012). South Atlantic meridional fluxes. *Deep-Sea Res. II*, doi:10.1016/j.dsr.2012.09.003

McCarthy, G., E. Frajka-Williams, W. E. Johns, M. O. Baringer, C. S. Meinen, H. L. Bryden, D. Rayner, A. Duchez, C. Roberts, and S. A. Cunningham, 2012. Observed Interannual Variability of the Atlantic Meridional Overturning Circulation at 26.5°N. *Geophysical Research Letters*, 39, L19609, 12 October 2012, doi:10.1029/2012GL052933, 2012.

In Revision

Macdonald, A., and M. Baringer 2012. 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), submitted.

Submitted

Goni, G., J. Sprintall, D. Roemmich, M. Baringer, and A. Gronell Thresher, 2012. The Global XBT Network. IOOS Summit Proceedings, Community White Papers, submitted.

Lumpkin, R. K. Dohan, M. Baringer, L. Centurioni, M. Cronin, G. Goni, G. Lagerloef, D. Lee and N. Maximenko, 2012. Observing the global ocean surface Circulation. IOOS Summit Proceedings, Community White Papers, submitted.

Baringer, M., S. A. Cunningham, W. Johns, J. Toole, S. Østerhus, J. Fischer, A. Piola, E. McDonagah, S. Lozier, U. Send, T. Kanzow, J. Marotzke, M. Rhein, S. Garzoli, S. Rintoul, Bernadette Sloyan, S. Speich, S. Wijffels, S. Talley, J. Baehr, C. Meinen, A-M. Treguier and P. Lhernminier, A. Macdonald, R. Lumpkin, G. Goni, 2012. The Atlantic meridional overturning circulation and heat transport. , IOOS Summit Proceedings, Community White Papers, submitted.

Abstracts

Silvia L. Garzoli1, Molly O. Baringer, Shenfu Dong, Renellys C. Perez and Qi Yao, 2012. South Atlantic Meridional Fluxes. (2012 AMOC Annual PI Meeting, August 15-17, 2012).

Shenfu Dong, Molly Baringer, Gustavo Goni, and Silvia Garzoli, 2012. Causes for model-data differences in seasonal variations of the South Atlantic Meridional Overturning Circulation. (2012 AMOC Annual PI Meeting, August 15-17, 2012).

William Johns, Stuart Cunningham, Molly Baringer, Eleanor Frajka-Williams, Harry Bryden and Jian Zhao, 2012. Interannual Variability of the AMOC and Ocean Heat Transport at 26.5°N observed by the RAPID-MOCHA Array. (2012 AMOC Annual PI Meeting, August 15-17, 2012).

Wanninkov, R., M. Baringer, J. Bulister, A. Dickson, R. Feely, G. Johnson, C. Langdon, F. Millero, C. Mordy, C. Sabine, J-K. Zhong, 2011. Observations for Climate: The NOAA

component of the CLIVAR CO2/Tracer Repeat Hydrography Program. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)
Baringer, M., S. Dong, S. Garzoli, G. Goni, S-k. Lee, R. Lumpkin, C. Meinen, R. Perez, 2011. Sustained Observations that contribute to understanding the Meridional Overturning Circulation. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)
Dong, S., M. Baringer, S. Garzoli, G. Goni, 2012. Observations for Climate: The contribution of the XBT network to climate studies. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)
Lumpkin, R., M. Baringer, S. Garzoli, G. Goni, C. Schmid, 2011. Observations for Climate: Evaluating the Global Ocean Observing System. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)
Szuts, Z., M. Baringer and C. Meinen, 2011. Atlantic Meridional Overturning Circulation: Salinity and water mass transports in the Florida Straits. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)
Johns, W., M. Baring, L. Beal, H. Bryden, S. Cunningham, R. Curry, J. Hirschi, T. Kanzow, J. Marotzke, C. Meinen, 2011. Atlantic Meridional Overturning Circulation: New estimates of Atlantic Ocean Heat Transport at 26.5°N from the RAPID-MOCHA Array. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)
Van Sebille, E., M. Baringer, L. Beal, F. de Jong, W. Johns, C. Meinen, H. van Aken, 2011. Atlantic meridional overturning circulation: Propagation pathways of classical Labrador Sea Water from its source region to 26N. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)
Frajka-Williams, E., M. Baringer, H. Bryden, S. Cunningham, J. Hirschi, W. Johns, C. Meinen, D. Rayner, 2011. Atlantic Meridional Overturning Circulation: Towards a decade-long time series of observations at RAPID-MOCHA 26N. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

Conference Presentations:

Baringer, M, 2012. Meridional overturning and heat transport from expendable bathythermograph data (2012 AMOC Annual PI Meeting, August 15-17, 2012).
Goni, G., Shenfu Dong, Molly Baringer, Silvia Garzoli, Francis Bringas, 2012. Variability of the MOC in the South Atlantic since 1993. (2012 AMOC Annual PI Meeting, August 15-17, 2012).

3.2. Other Relevant Publications

Arndt, D. S., and Coauthors, 2012: STATE OF THE CLIMATE IN 2011 Special Supplement to the Bulletin of the American Meteorological Society Vol. 93, No. 7, July 2012 INTRODUCTION. *Bulletin of the American Meteorological Society*, **93**.
Backeberg, B. C., P. Penven, and M. Rouault, 2012: Impact of intensified Indian Ocean winds on mesoscale variability in the Agulhas system. *Nature Climate Change*, **2**.
Levitus, S., and Coauthors, 2012: World ocean heat content and thermosteric sea level change (0-2000 m), 1955-2010. *Geophysical Research Letters*, **39**.
Perez, R. C., S. L. Garzoli, C. S. Meinen, and R. P. Matano, 2011: Geostrophic Velocity

Measurement Techniques for the Meridional Overturning Circulation and Meridional Heat Transport in the South Atlantic. *Journal of Atmospheric and Oceanic Technology*, **28**.
Weijer, W., and Coauthors, 2012: The Southern Ocean and Its Climate in CCSM4. *Journal of Climate*, **25**.