Southwest Atlantic MOC ("SAM")

Christopher S. Meinen[1], Silvia L. Garzoli[2,1], Renellys C. Perez[2,1], and Shenfu Dong[2,1]
[1]NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida
[2]Univ. of Miami – Cooperative Institute for Marine and Atmospheric Studies, Miami, Florida

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1. Project Summary

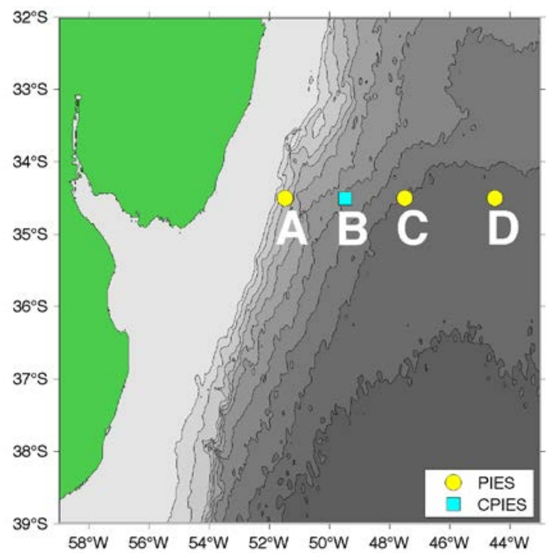

Figure 1: Locations of the four pressure-equipped inverted echo sounders (PIES) and current-and-pressure-equipped inverted echo sounders (CPIES) deployed as part of the NOAA funded SAM project. Note in July 2011 the CPIES at Site B was replaced with a PIES.

Variations in the Atlantic Meridional Overturning Circulation (MOC) have been shown to have connections to changes in precipitation patterns, air temperatures and extreme weather (e.g. hurricanes) conditions over large segments of the globe. The 2007 US interagency Ocean Research Priorities Plan designated the study of the MOC as a key near-term priority, and the US AMOC implementation panel has identified improving the observations of the MOC in the South Atlantic as one of the critical needs to better understand MOC variability. In the subtropical South Atlantic the MOC cell has a number of characteristics that distinguish it from the MOC circulation in the subtropical North Atlantic. Unlike in the north, where the MOC consists primarily of two western boundary components, in the South Atlantic the MOC circulation is more widely spread across the basin. Near 34-35°S the warm northward flowing upper limb is carried in the basin interior (via Agulhas Rings) and along the eastern boundary (via the Benguela Current), while the cold southward limb flows in the Deep Western Boundary Current (DWBC), which is primarily located under the southward flowing Brazil Current, although it is thought that another component of the deep southward limb may flow southward along the west coast of Africa. This longitudinal spread is indicative of the role that the South Atlantic plays as both a 'gateway' and a 'mixing pot' of waters exchanged simultaneously with the Indian and Pacific Oceans. Deep waters that are formed in the northern North Atlantic must pass through the South Atlantic on their way to the Southern Ocean, where they are spread throughout the global ocean. Warm waters returning to the northern North Atlantic from the Indian and Pacific must pass through the South Atlantic where those waters are mixed on their way northward towards the equator. The NOAA Southwest Atlantic MOC (‘SAM’) project began in March 2009 as a collaboration between the US, Argentina and Brazil; the goal is to observe key MOC flows near the western boundary of the ocean in the South Atlantic. A parallel effort underway in the Southeast Atlantic is operated by France and South Africa. Locations of the four NOAA-funded moored instruments deployed as part of SAM are shown in Figure 1.

The SAM project is designed to parallel and complement NOAA’s ongoing efforts to monitor the MOC in the North Atlantic through the Western Boundary Time Series (WBTS) project. In the same way that the WBTS project has formed the cornerstone for an international trans-basin MOC measurement array at 26.5°N, the SAM project represents the first step to initiate a similar international array at 34.5°S. Initially, the SAM project was based on a moored array consisting of two different types of moored instruments (Figure 1): inverted echo sounders equipped with pressure sensors (PIES), and inverted echo sounders equipped with both a pressure sensor and a single-depth acoustic current meter (CPIES). Now, the NOAA array is comprised solely of PIES moorings. Work in the WBTS project has demonstrated that an array of PIES and/or CPIES is capable of quantifying the upper and deep layer transports.

The time series observations generated from the SAM project are seen as serving three main purposes for climate variability studies:

- Monitoring, in conjunction with hydrography collected by our Argentine and Brazilian partners, the DWBC transport and water mass signatures related to changes in the strengths and formation regions of high latitude water masses in the North Atlantic for the ultimate purpose of assessing rapid climate change.
- Serving as a western boundary endpoint of a nascent international MOC monitoring system (“SAMBA”) designed to measure the basin-wide meridional flows across the South Atlantic Ocean near 34.5°S.
- Quantifying how variations in the MOC propagate meridionally between the North and South Atlantic through comparison with MOC estimates at other latitudes (e.g. RACE/SACUS at 11°S, MOVE at 16°N, RAPID/MOCHA/WBTS at 26.5°N).

The SAM project is a component of the NOAA “Ocean Reference Station” system in the Atlantic Ocean, and is one of the few time series observing sites in the Global Ocean Observing System (GOOS). SAM seeks to specifically address NOAA climate goals by providing long-term, integrated, measures of the global thermohaline (overturning) circulation. This project is designed to provide data useful for delivering yearly estimates of the state of the thermohaline circulation, i.e. its intensity, properties, and heat transport. Heat and carbon generally are released to the atmosphere in regions of the ocean far distant from where they enter. Monitoring the transport within the ocean is a central element of documenting the overturning of fresh water, heat and the uptake and release of carbon. Long-term monitoring of key locations will provide a measurement of the primary routes of ocean heat, carbon, and fresh water transport and hence include the key components of the MOC. Measurements from the SAM project provide critical records for use in validation and evaluation of the ocean general circulation models and coupled climate models that are and will be used in the future for informing governments and agencies on the ocean's role in climate change and planning to address societal challenges. Data from the SAM instruments are publically available after semi-annual or annual data-download cruises via the SAM website at: www.aoml.noaa.gov/phod/research/moc/samoc/sam/.

2. Scientific and Observing System Accomplishments

The SAM array has become the western boundary cornerstone of a developing international monitoring array near 34.5°S for continuous basin-wide studies of the South Atlantic MOC. Despite funding challenges and infrastructure problems in its early years, the SAM project has been collecting highly valuable observations of the western boundary components of the MOC in the South Atlantic since 2009. Beginning in FY13, a new agreement with our Brazilian partners resulted in a joint cruise that was fully funded by our Brazilian partners. As part of that December 2012 joint cruise, our Brazilian partners essentially doubled the existing western boundary array by adding three new CPIES moorings. During a September 2013 cruise, our French partners deployed an array of eight CPIES and two bottom-mounted ADCPs near the eastern boundary. Additionally, late in 2013 our Brazilian partners deployed two instruments on the western shelf (a bottom pressure gauge and a bottom-mounted acoustic Doppler current profiler). Finally, our South African partners will deploy 10-12 new moorings on the eastern boundary in late 2014. Furthermore, in addition to the international array expansion, the additional funding provided by CPO for the SAM project in FY14 has allowed for significant improvements to the data processing and quality control of the SAM data and has resulted in new publically available data products, as will be described below.

Operational highlights

The PIES/CPIES instruments used in SAM can be deployed for up to 4 years on a single set of batteries. Real-time data collection from the subsurface PIES/CPIES moorings is not yet technologically possible, however a key feature of these instruments is that it is possible to acoustically collect the most recent 6-12+ months of daily average data from the moorings using a nearby research vessel without needing to recover, download, and redeploy the instruments during each visit. The goal of the project has been to acoustically download data every six months via cruises on either Argentine or Brazilian research vessels. However charter fund shortfalls and ship problems have resulted in the cancellation of several cruises, including the July 2013 cruise, which was canceled due to lack of charter funds. Please see the progress reports from previous years for more information. During FY14, two cruises were originally scheduled – December 2013 on a Brazilian research vessel and September 2014 on an Argentine research vessel. Due to the breakdown of the Brazilian vessel, the December 2013 cruise was first postponed, and then ultimately canceled. The September 2014 cruise on the Argentine vessel was delayed slightly, but was completed during October 4-16. During the October 2014 cruise the data from all four NOAA PIES were acoustically downloaded, providing data since the last visit in December 2012 (i.e. nearly two years of data).

In terms of deliverables, the raw SAM array data are available up through the beginning of October 2014. During FY14 the quality control and data processing code were significantly improved (due to additional funding from CPO), and this code is presently being applied to the data collected during the October 2014 cruise. The acoustic travel time and bottom pressure measurements will be combined with historical hydrographic data from the region (CTD and Argo) to produce daily estimates of the full water column temperature and salinity at each PIES site. These observations will also be combined with the measured bottom pressures to yield daily profiles of absolute geostrophic velocity between each pair of PIES. These data thereby provide data on the key ocean transports in this important region. For the period of FY14, the SAM array returned 76% of the daily estimates of acoustic travel time (missing data is mainly due to noise during acoustic download) and 84% of the daily estimates of bottom pressure. Much of the missing data should be retrieved later either during future acoustic downloads or when the instruments are recovered. Since March 2009, the SAM array has returned 85% of the daily estimates of acoustic travel time and 87% of the daily estimates of bottom pressure, with the bulk of the missing data being due to the malfunctioning and subsequently lost CPIES from Site B in 2010-2011. Based on the newly developed quality control and processing code, daily time series of full-water-column profiles of temperature and salinity are being served from the SAM project web page, and the quality control and processing is underway to process the nearly two years of data collected during the October 2014 research cruise.

Another significant strength of the SAM project is that these joint research cruises aboard the Brazilian and Argentine research vessels are primarily funded by their home governments; NOAA covers only part of the cost of the fuel and funds for a single participant for these short cruises when on the Argentine vessel, and only the cost for 1-2 participants when on the Brazilian vessel. Partnering scientists from the University of Buenos Aires, the Argentine Hydrographic Service, the University of São Paulo and/or the Federal University of Rio Grande collect hydrographic, chemical, and velocity data along the mooring line from the coast to the furthest deployed instrument. These data not only provide the necessary calibration data for the PIES/CPIES measurements but also allows for the study of the continental shelf and deep water masses and their interactions in the region. This aspect of the project has been beneficial for each country, and it represents a very significant cost savings to NOAA as the alternative would require ship time on a NOAA vessel to transit to/from the South Atlantic and funding for a complete hydrographic team.

Research highlights

The PIES data collected in the first two years of the SAM project have been combined with data from a parallel French project ("GoodHope") involving CPIES moorings on the eastern boundary to provide a first look at the daily variability of the MOC at 34.5°S (see Figure 2). The daily

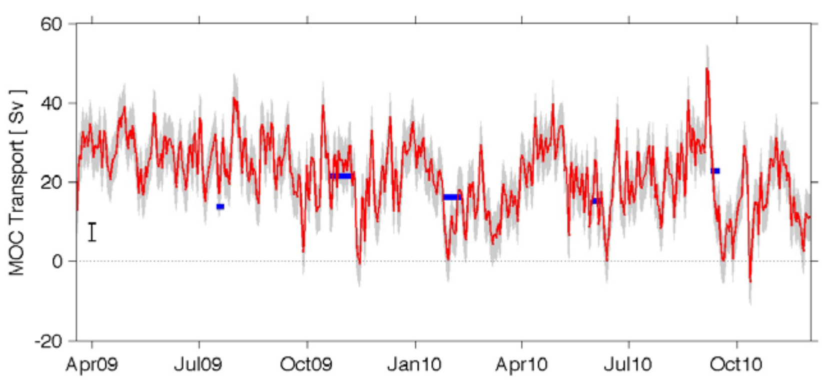

Figure 2: Daily time series of meridional overturning circulation (MOC) volume transport (red line) determined using data collected by pressure-equipped inverted echo sounders in the SAM array together with parallel data from the French GoodHope moorings on the eastern boundary as well as CTD and Argo data from the region. Gray shading indicates estimated error bars on the measured MOC transports, while blue lines indicate MOC estimates from concurrent expendable bathythermograph (XBT) sections.

transports range from a maximum of nearly 50 Sv down to essentially zero; after smoothing with a 10-day low-pass filter the range of observed transports is 3-39 Sv. The transport observations demonstrate significant variations at a range of time scales, with 40-50 Sv changes occurring in 5-7 days and 20+ Sv anomalies lasting a month or more. This work has led in FY14 to a published paper on MOC variability at 34.5°S (Meinen et al., 2013) that was highlighted both by the journal (the Journal of Geophysical Research) and the American Geophysical Union newsletter/newspaper, EOS. This paper also illustrated the importance of measuring ocean variability on both sides of the basin, demonstrating that density variations on either side of the basin play roughly equivalent roles in the observed MOC variability out to the longest time scales available in the ~20 month records.

A second study has been conducted to determine the pathways of North Atlantic Deep Water (NADW) that constitute the lower limb of the MOC in the South Atlantic (Garzoli et al., 2014). The study is of particular interest because it establishes what portion of the lower limb of the MOC is captured by the SAM array. Knowledge of the pathways of the MOC in the South Atlantic is a first order prerequisite for understanding the fluxes of climatically important properties. In the study, historical and new observations, including hydrographic sections, Argo and SAM data, and chlorofluorocarbon measurements, are examined together with two different analyses of the Ocean General Circulation Model for the Earth Simulator (OFES) to trace the pathway of the Deep Western Boundary Current (DWBC) through the South Atlantic. Together, observations and model outputs indicate that after crossing the equator, the DWBC flows with the characteristics of NADW and a total volume transport of approximately 14 Sv (1 Sv = 10^6 m^3/sec). It crosses 5°S mostly along the western boundary and breaks up into rings near 8-11°S. When this very energetic eddying flow reaches the Vitória-Trindade ridge (~20°S), the flow branches due to conservation of potential vorticity. The main portion of the flow continues along the continental shelf of South America in the form of a strong reformed DWBC, while a smaller portion, about 20%, is advected towards the interior of the basin. It is hypothesized that this eastward motion results from eddy thickness flux divergence due to overlying Agulhas Ring decay and enhanced mixing caused by the energetic eddy field at the Vitória-Trindade ridge.

A third study was conducted to diagnose the possible causes for the model-data difference in the seasonal variations of the MOC at 34.5°S. The results indicate that model biases in both the geostrophic and Ekman transports contribute to this difference. Compared to the hydrographic observations, the models show stronger seasonal cycles in the Ekman transport and weaker seasonal cycles in the geostrophic transport. The difference in geostrophic transports between the observations and the coupled models explains much of the disparity in the AMOC seasonal cycles between models and the real world. The net geostrophic transport in the upper ocean across a trans-basin section is related to the density difference between the eastern and western boundaries. The observed east-west density difference is largely controlled by the western boundary, whereas in the coupled models the eastern boundary dominates. The observed seasonal cycle of the density at the western boundary is controlled by the strength of the Malvinas Current, which induces a considerable northward excursion of the coastal isotherms during winter when it is strong. In the models, however, the Malvinas Current plays a minimal role in the density changes at the western boundary because it separates from the coast further south, allowing the eastern boundary to dominate. The other factor behind the strong seasonal cycle in the geostrophic transport from the observations is associated with the vertical coherence in the velocity signals below the mixed layer. The models lack this vertical coherence, showing strong artificial baroclinicity below the surface mixed layer, yielding out-of-phase variations that sum to a very weak annual cycle in the geostrophic transports in the models. Evaluating the vertical density gradients in both the data and the models suggests that the structure in the models below the mixed layer is likely due to erroneously strong vertical density shear, which prevents the models from correctly moving information down from the mixed layer to the deeper layers.

Also exciting for FY14 is the continued growth of the international trans-basin MOC array at 34.5°S. New and existing components of the array were described in an article for the American Geophysical Union journal EOS (Ansorge et al., 2014) and in a manuscript submitted to the Marine Technology Society Journal about NOAA's portfolio of MOC measurements (Perez et al., 2015). In addition to the new instruments deployed by our Brazilian and French colleagues in FY13, our South African collaborators have begun deploying tall 'dynamic height moorings' on the eastern boundary, and the final moorings are planned to be in the water by December 2014. These new moorings will provide invaluable information on temperature and salinity variability throughout the water column with a higher level of accuracy than is available from PIES/CPIES moorings.

As noted in FY13, the travel time and bottom pressure data collected in SAM are also being used to improve ocean state estimations with assimilating models – with the data being assimilated into the Southern Ocean State Estimate (SOSE) being run by Drs. Matthew Mazloff and Teri Chereskin at Scripps Institute of Oceanography. Dr. Chereskin characterized the importance of the SAM data for their endeavor by stating that the SAM instruments "would provide critical information" in a region of high variability where there are not a lot of other observations to guide their model.

The raw data from the moored PIES/CPIES instruments is presently maintained at NOAA-AOML; the additional funding provided by CPO in FY14 will soon lead to high quality data being submitted to NODC. Until that point, the basic "raw" travel time and bottom pressure data is provided via the project web page and is already being used (e.g. the SOSE assimilation study). Without appropriate funding it will be possible to continue collecting data but it will be very difficult to consistently maintain the processing of the raw data at the highest quality needed for good estimates of ocean transport, particularly if there is a return to the environment of Climate Program Office flat or cut budgets and overall OAR reductions in AOML base funds.

Information about the SAM project can be found at:

www.aoml.noaa.gov/phod/research/moc/samoc/sam/

<u>Answers for data collection questions:</u>

a. Are your data distributed in real time on the Global Telecommunications System?

Like many/most subsurface moored instruments/moorings, the PIES/CPIES data collected in this project are internally recorded in the moored subsurface instruments *and can only be obtained via visits with research vessels (either via acoustic download or through recovery of the instruments from the ocean bottom). As such it is not possible for these data to be distributed in real time.*

b. Where do your real time data reside? Are the data available online?

   Real-time data are not available for the reasons mentioned above.

c. Where do your delayed mode data reside? Are the data available online?

   Daily mean data collected by the moored instruments in this project reside on computers at AOML, and they are available to users as ASCII data files up through December 2012. We are presently processing the data collected in October 2014 (the most recent visit to the mooring sites) and this data should be available online shortly. SAM data can be found via the project web page: www.aoml.noaa.gov/phod/research/moc/samoc/sam/

d. When did you make your most recent data publicly available?

   The raw data (travel time & bottom pressure) up through December 2012 were made available online within a few months after the December 2012 cruise. New data products created from the moored data through December 2012 were made available online in September 2014 (based on additional support from CPO in FY14).

e. Where are your data archived and with what frequency?

   Archives of the raw and processed data are maintained at AOML and are updated after each 6-12 month cruise. We are presently working on procedures to archive the final data at NODC as well.

f. What is the web site where the data for your program can be accessed? If you haven't updated your web site recently, please do so now.

   The raw data are available (generally within 3-4 months after each data download cruise) from the project web page: www.aoml.noaa.gov/phod/research/moc/samoc/sam/

g. Have you successfully retrieved your program's data from the website or Data Assembly Center where your data reside, just to ensure the accessibility of the data? If not, please do this now and address any problems with data access.

   The data have been successfully downloaded from the project web page – as noted above archiving at NODC has not yet been implemented, but will be in the near future.

h. Do you have a publications supported through COD funding? We encourage your bibliographies to be posted online.

Publications supported by the project are listed on the project web page: www.aoml.noaa.gov/phod/research/moc/samoc/sam/

i. How are you tracking uptake and use of the data and products produced by your project? Some have found it helpful to establish a standard and recognizable name (e.g.. Argo, OceanSITES)? We encourage this approach to improve the recognition, discoverability, and visibility of your project.

   At present we are tracking use of our data on a case-by-case basis (e.g. the SOSE example mentioned in the text).

j. How do you direct users of your data to acknowledge its use? Do web pages that provide data and products from COD support acknowledge CPO/COD support?

   We ask data users to provide a citation to the SAM project and NOAA/CPO in their acknowledgements. This request is posted on the web page where the data are made available.

3. Outreach and Education

Postdoctoral fellows, undergraduate and graduate students from several universities in Argentina and Brazil are participating in each of the SAM research cruises. Our lead Argentine collaborator, Dr. Alberto Piola, has a Ph.D. student, Mr. Daniel Valla, who is working on data collected as part of the SAM project for his doctoral research topic, and one of the SAM PIs (Meinen) will serve as a PhD committee member for Dr. Piola's student. One of the SAM PIs gave a seminar and worked with students at the University of Sao Paulo, Brazil, during a visit. Two articles relating to the December 2013 JGR paper and the October 2014 SAM cruise were prepared for the AOML Keynotes publication by the PIs. One of the PIs (Meinen) was interviewed by a researcher working to develop a new climate program at North Carolina State University. One PI (Meinen) participated in a television interview with the Irish public broadcaster RTE to discuss several issues associated with the MOC. All of the SAM PIs participated in a news article describing the advances of the international transbasin MOC array at 34.5°S for the American Geophysical Union journal EOS (Ansorge et al., 2014) and a submitted manuscript about NOAA's portfolio of MOC measurements (Perez et al., 2015). One of the PIs (Perez) has been maintaining a webpage describing advances for the broad South Atlantic MOC initiative on behalf of all of the national and international partners (www.aoml.noaa.gov/phod/SAMOC_international/). Several of the PIs also participated in public education activities in Miami, such as participating in a panel discussions on regional sea level rise, and speaking at science and career day events hosted by local K-12 schools, NOAA/AOML, or the University of Miami. And several of the PIs (Garzoli, Perez, Dong) are working with women scientists to increase retention in the field (MPOWIR). Several of the PIs are participating in national and international science advisory bodies, including the US CLIVAR Phenomenon, Observations, and Synthesis panel (Perez), the USAMOC Executive Committee (Meinen), and the IAPSO Executive Council (Meinen). Finally, several SAM related presentations were given by the PIs at national and international science conferences including the 2014 US AMOC meeting and the 2014 Ocean Sciences meeting.

One additional outreach activity that should be highlighted took place in very early FY15. Silvia Garzoli participated in the US-Argentina Joint Commission Meeting (JCM) on Science and Technology, organized by and held at the US State Department, on October 22-23. The US delegation was led by Catherine Novelli, the US undersecretary for Economic Growth, Energy, and Environment, and included representatives of ONR, NSF, State Department, Smithsonian Institution, and several US universities. The Argentine counterparts were led by their Minister of Science, Technology and Innovation, and included the Ministry Director of International Relationships, and representatives of the Argentine Hydrographic Office, Argentine Coast Guard, of several Argentine universities, as well as the Ambassador of Argentina. Silvia Garzoli presented the status and plans of work related to the South Atlantic Meridional Overturning Circulation (SAMOC) Project with emphasis on the SAM array. After the discussions an Action Plan was drafted. This Action Plan recommendations included continuing support of current partnership efforts to maintain the global ocean observing system in the Southwest Atlantic Ocean (including SAM surface drifters, Argo floats, and XBT operations), maintaining and enhancing the observational and research efforts related to the SAMOC moorings at 34.5°S, and increasing capacity building in the areas of technological innovation, data stewardship, scientific exchanges, and research on regional impacts in ecosystems and the environment related to climate variability. JCMs such as this one, present an excellent opportunity to discuss current US research work and plans with scientists and high-level government officials.

4. Publications and Reports

4.1. Publications by Principal Investigators

<u>Published:</u>

Ansorge, I. J., M. O. Baringer, E. J. D. Campos, S. Dong, R. A. Fine, S. L. Garzoli, C. S. Meinen, R. C. Perez, A. R. Piola, M. J. Roberts, S. Speich, J. Sprintall, T. Terre, M. A. Van de Berg, 2014: Basin-Wide Oceanographic Array Bridges the South Atlantic. *EOS*, 95, 53-54.

Baringer, M. O., G. McCarthy, J. Willis, M. Lankhorst, D. A. Smeed, U. Send, D. Rayner, W. E. Johns, C. S. Meinen, S. A. Cunningham, T. O. Kanzow, E. Frajka-Williams, and J. Marotzke, 2014: [Global Oceans] Meridional overturning circulation observations in the North Atlantic Ocean [in “State of the Climate in 2013”]. Bull. Amer. Meteor. Soc., 95(7), 67 -69.

Baringer, M. O., W. E. Johns , S. Garzoli, S. Dong, D. Volkov, W. R. Hobbs, J. Willis, 2014: [Global Oceans] Meridional Oceanic Heat Transport in the Atlantic Ocean [in “State of the Climate in 2013”]. Bull. Amer. Meteor. Soc., 95(7), 69

Domingues, R., G. J. Goni, S. Swart, and S. Dong, 2014: Wind forced forced variability of the Antarctic Circumpolar Current south of Africa between 1993 - 2010, J. Geophys. Res. 119 , 1123-1145, Doi: 10.1016/j.csr.2013.12.009.

Dong, S., M. O. Baringer , G. J. Goni , C. S. Meinen , and S. L. Garzoli, 2014: Seasonal variations in the South Atlantic Meridional Overturning Circulation from observations and numerical models , Geophys. Res. Lett., 41 , 4611 - 4618 , doi: 10.1002/2014GL060428.

Garcia, R. F., and C. S. Meinen, 2014: Accuracy of Florida Current volume transport measurements at 27°N using multiple observational techniques, J. Atmos. Ocean. Tech., 31 (5), 1169-1180, 10.1175/JTECH-D-13-00148.1.

Meinen, C. S., S. Speich, R. C. Perez, S. Dong, A. R. Piola, S. L. Garzoli, M. Baringer, S. Gladyshev, and E. Campos, 2013: Temporal variability of the meridional overturning circulation at 34.5S: Preliminary results from two boundary arrays in the South Atlantic. *J. Geophys. Res.*, 118, 1-18, doi:10.1002/2013JC009228.

Meinen C. S., and S. L. Garzoli, 2014: Attribution of Deep Western Boundary Current variability at 26.5°N. paper in Deep-Sea Res.I,, 90, 81-90, doi:10.1016/j.dsr.2014.04.016, 2014.

Smeed, D. A., McCarthy, G. D., 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., 2014: Observed decline of the Atlantic meridional overturning circulation 2004-2012, Ocean Sci., 10, 29-38, doi:10.5194/os-10-29-2014.

In press:

Johns, E. M., B. A. Muhling, R. C. Perez, F. E. Muller-Karger, N. Melo, R. H. Smith, J. T. Lamkin, T. L. Gerard, and E. Malca, 2014: Amazon River water in the northeastern Caribbean Sea and its effect on larval reef fish assemblages during April 2009., Fisheries Oceanogr., in press.

McCarthy, G.D., D.A. Smeed, W.E. Johns, E. Frajka-Williams, B.I. Moat, D. Rayner, M.O. Baringer, C.S. Meinen, J. Collins, and H.L. Bryden. Measuring the Atlantic Meridional Overturning Circulation at 26°N. Progress in Oceanography, doi:10.1016/j.pocean.2014.10.006, in press.