Southwest Atlantic MOC – SAM

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1. Project Summary

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 northern hemisphere. 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 (in 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’) observing project began in March 2009 as a collaboration between the US, Argentina and Brazil; the goal is to measure key MOC flows near the western boundary of the ocean in the South Atlantic. A parallel effort is underway in the Southeast Atlantic 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 well-established project monitoring the MOC in the North Atlantic, the Western Boundary Time Series (WBTS) project. 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 array at 34.5°S. The SAM array is based on two different types of moored instruments: 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). Work in the WBTS project has demonstrated that this combination of instruments is capable of quantifying the upper and deep layer transports. The initial SAM pilot array involving four PIES/CPIES represents a test of the array locations and the start of a long-term monitoring project for the MOC in the South Atlantic.

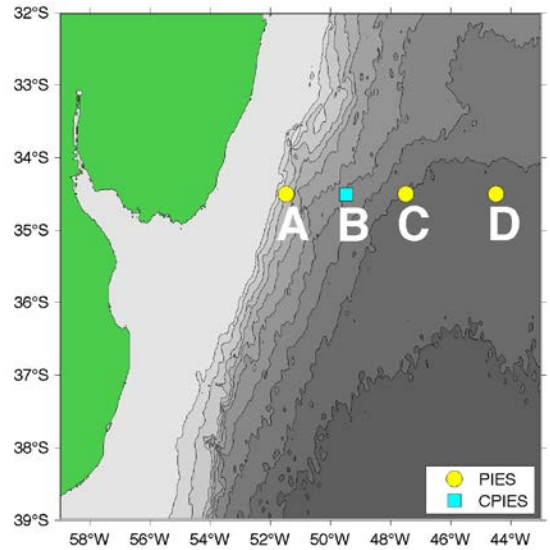

Figure 1: Locations of the four pressure-equipped inverted echo sounders (PIES) and current-and-pressure-equipped inverted echo sounders (CPIES) deployed as part of the NOAA funded SAM project. Note in July 2011 the CPIES at Site B was replaced with a PIES.

The time series observations in SAM 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 35°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. WBTS at 26.5°N, MOVE at 16°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 the NOAA climate goals by providing long-term, integrated, measures of the global thermohaline (overturning) circulation. This project is designed to deliver 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 web at: www.aoml.noaa.gov/phod/research/moc/samoc/sam/ .

2. Scientific and Observing System Accomplishments

Exciting results are coming from the first few years of the SAM project, despite a series of fiscal years with financial difficulties. The project has had a chronic funding shortfall since the beginning due to unfortunate budgetary timing. SAM was initially funded very modestly in FY09 because the sole task that year was to complete the initial deployment cruise (i.e. no data were scheduled to be downloaded and processed in year one). Unfortunately, the arrival of the flat budget regime after that year has resulted in the project never maturing and having sufficient funding to hire programming support for data processing and quality control when data began being downloaded during cruises in FY10 and beyond. It has been a significant challenge to fully process and subject the data to the best quality control because of these funding shortfalls, however a basic clean up and processing of the data has been done (primarily by the lead PI under AOML base funding) so that preliminary scientific analyses could be completed and so that we could satisfy our commitments to our international partners. Despite all of these challenges, important results are coming from the project – as will be discussed 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. Please see the progress reports from previous years for more information. During FY13, in December 2012 the three PIES at Sites A, C and D that were reaching the end of their ~4-year battery life were recovered on a cruise onboard the Brazilian research vessel N. Oc. Alpha-Crucis and the raw hourly data were downloaded. The instruments were then fitted with fresh batteries and redeployed. The data from the PIES at Site B – which had been turned over the previous year – were also acoustically downloaded during this cruise. Charter funds were not available for the planned July 2013 cruise on the Argentine research vessel SHN Puerto Deseado, so that cruise was not conducted.

In terms of deliverables, because charter funds were not available for the July 2013 cruise, during FY13 the SAM array data are only available up through the time of the December 2012 cruise. The remainder of the FY13 data will be acoustically downloaded during the first FY14 cruise, scheduled for December 2013. The acoustic travel time and bottom pressure

measurements can be combined with historical hydrographic data from the region (CTD and Argo) to produce estimates of the full water column velocity profile orthogonal to the array. These data thereby yield data on the key ocean transports in this important region. For the period where FY13 data are available, the SAM array returned 83% of the daily estimates of acoustic travel time (missing data is mainly due to noise during acoustic download at Site B) and 97% of the daily estimates of bottom pressure up through December 2012. Since March 2009, the SAM array has returned 87% 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.

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 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 successful with each country, and it represents a very significant cost savings to NOAA versus requiring ship time on a NOAA vessel in the South Atlantic and funding for a complete hydrographic team.

Research highlights

The data collected in the first year of the SAM project have provided a first look at the absolute transport variability of the Deep Western Boundary Current at 34.5°S (see Figure 2). The transport observations demonstrate significant variations at a range of time scales, with 40+ Sv changes occurring in just a few days and 20-30 Sv anomalies lasting a month or more. The hydrographic data collected by our international partners during the joint cruises has also proven crucial for water mass identification, providing solid evidence that the SAM array is robustly capturing the Deep Western Boundary Current. This work has therefore provided

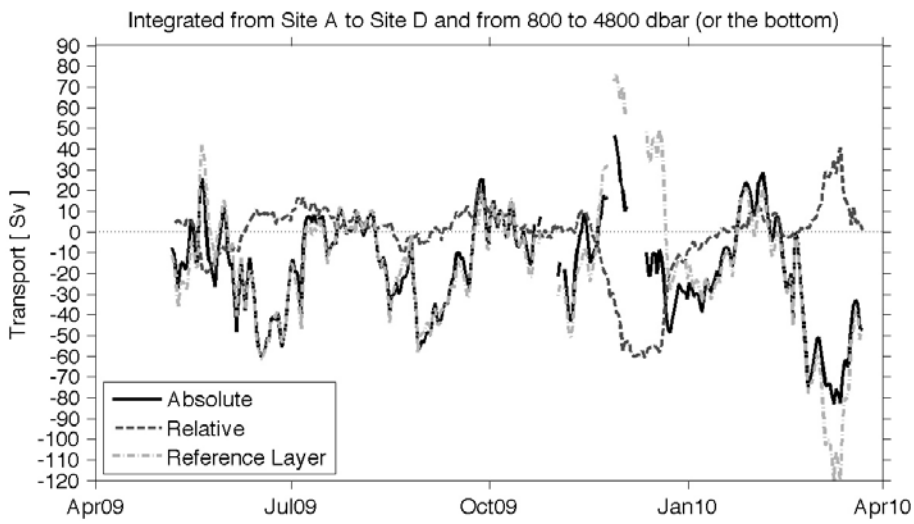

Figure 2: Time series of absolute geostrophic transport determined using data collected by pressure-equipped inverted echo sounders in the SAM array together with CTD and Argo data from the region. The absolute, baroclinic (relative to an assumed level of no motion at 800 dbar) and the barotropic (reference layer) transports are all shown. Modified from Meinen et al., (2012).

crucial information that will be useful for validating model estimates of the lower limb of the MOC in the South Atlantic, and it has led in FY13 to the first published paper based primarily on data collected in SAM (Meinen et al., 2012).

The first ~20 months of data at SAM Site A also was used together with concurrent data from a French CPIES on the South African coast as well as wind and hydrographic observations in the region to produce the first daily time series estimates of the basin-wide MOC variability at 34.5°S. This estimate was fairly crude/preliminary, and the methods used to calculate it will improve as the international trans-basin array at 34.5°S becomes more fully implemented later in 2013, however even this early estimate has demonstrated that the MOC upper limb in the South Atlantic at 34.5°S is at least as variable as has been observed at 26.5°N in the North Atlantic. Furthermore, these MOC estimates have clearly demonstrated both the necessity for monitoring on both the western and eastern boundaries and the importance of continuous time series observations. A manuscript on these results has recently been revised and resubmitted after receiving very positive, minor comments during the initial peer review (Meinen et al., 2013).

Perhaps one of the most exciting highlights for FY13 is the international growth of the trans-basin MOC array at 34.5°S. Our Brazilian colleague, Dr. Edmo Campos of the Univ. of São Paulo, has greatly improved the horizontal resolution of the SAM array by deploying three new CPIES at the approximate midpoints horizontally between the existing SAM sites. Dr. Campos' new instruments were deployed in December 2012, and they are funded to continue for at least three years (and hopefully much longer). In December 2013, Dr. Campos will also be adding an additional moored bottom pressure gauge and a bottom-mounted Acoustic Doppler Current Profiler (ADCP) on the continental shelf/slope inshore of our SAM Site A location in order to help us better characterize the flow in the relatively shallow wedge inshore of the SAM array. And on the eastern side of the basin our French (Dr. Sabrina Speich, Univ. of Brest) and South African (Dr. Mike Roberts, Oceans and Coasts, and Dr. Isabelle Ansorge, Univ. of Cape Town) colleagues have just deployed an extensive array of CPIES in late 2013 and will deploy short and tall moorings in the earlier part of 2014. With these newly deployed additions to the trans-basin array, we will be able to do much more detailed studies of the MOC at 34.5°S than have been possible in the past.

On another note, 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; to date it has not been provided to the data centers (e.g. NODC), because proper quality control and data processing has been quite limited under the tight budget scenario as mentioned earlier. Nevertheless, 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 in 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/

Answers for data collection questions:

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

   The PIES/CPIES data collected in this project are internally recorded in subsurface moored 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? What is the date of the most recent data available publicly?

   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 (the most recent visit via ship to the mooring sites). These data are available via the project web page: www.aoml.noaa.gov/phod/research/moc/samoc/sam/

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

   Because the data collected in this project have not been fully quality controlled or processed (due to funding limitations), the final data are not yet being archived at the national centers (e.g. NODC). However, archives of the raw and preliminarily processed data are maintained at AOML and are updated after each 6-12 month cruise.

e. 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/

f. 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 due to funding limitations, and the resultant limited quality control of the data, the data are not being archived at a Data Assembly Center.

g. Do you have a data management plan for the data collected as part of your project? If so, list the url where the data management plan can be found.

Because the project does not have funding for quality control or processing, no formal data management plan has been formulated.

3. Outreach and Education

Even though the SAM project is still at a relatively early stage, significant efforts at outreach and education are already underway. Numerous postdoctoral fellows and graduate students from Argentina and Brazil are participating in each of the SAM research cruises, and this will continue. Our lead Argentine collaborator, Dr. Alberto Piola, has a Ph.D. student 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 (Meinen) also served as an external examiner for a Masters candidate working on a related project with one of our South African colleagues, Dr. Isabelle Ansorge. Two of the SAM PIs (Meinen & Garzoli) were interviewed on MOC topics related to SAM for an article that was being prepared for the climate.gov web site. One SAM PI (Garzoli) was also interviewed for a news article in Nature. An article relating to the December 2012 SAM cruise was prepared for the AOML Keynotes publication by the PIs. 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 SAM related 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

4.1. Publications by Principal Investigators

<u>Published:</u>

Meinen, C. S., A. R. Piola, R. C. Perez, and S. L. Garzoli, 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, 2012.

Garzoli, S. L., M. O. Baringer, S. Dong, R. C. Perez, and Q. Yao, South Atlantic meridional fluxes, Deep Sea Res. I, 71, 21-32, doi:10.1016/j.dsr.2012.09.003, 2013.

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. Heimbach, E. Frajka-Williams, A. Macdonald, S. Dong, and J. Marotzke, Global oceans: Meridional overturning circulation and heat transport observations in the Atlantic Ocean, *in* State of the Climate in 2012, J. Blunden and D.S. Arndt (eds.). Bull. Am. Met. Soc., 94 (8), S65-S68, 2013.

Submitted:
Meinen, C. S., S. Speich, R. C. Perez, S. Dong, A. R. Piola, S. L. Garzoli, M. O. Baringer, S. Gladyshev, and E. J. D. Campos, Temporal variability of the Meridional Overturning Circulation at 34.5°S: Results from two pilot boundary arrays in the South Atlantic, J. Geophys. Res., (submitted), 2013.

4.2. Other Relevant Publications

Funding for quality control and processing of the SAM data has not yet been available, and as such the data are only being used in a limited way in research by outside groups for publications. Listed here are several North Atlantic MOC related publications by the project PIs are also relevant to the broader goals of SAM:

Other relevant publications by project PIs

Meinen, C. S., W. E. Johns, S. L. Garzoli, E. van Sebille, D. Rayner, T. Kanzow, and M. O. Baringer, Variability of the Deep Western Boundary Current at 26.5°N during 2004-2009, Deep Sea Res. II, 85, 154-168, doi:10.1016/j.dsr2.2012.07.036, 2013.

Frajka-Williams, E., W. E. Johns, C. S. Meinen, L. M. Beal, and S. A. Cunningham, Eddy impacts on the Florida Current, Geophys. Res. Lett., 40 (2), 349-353, 2013.

Szuts, Z. B., and C. Meinen, Salinity transport in the Florida Straits, J. Atmos. Oceanogr. Tech., 30, 971-983, doi:10.1175/JTECH-D-12-00133.1, 2013.

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

Beron-Vera, F., Y. Wang, M. Olascoaga, G. Goni, and G. Haller, Objective detection of oceanic eddies and the Agulhas leakage. J. Phys. Oceanogr. ,43, 1426-1438, doi:10.1175/JPO-D-12-0171.1, 2013.