A GO-SHIP recommendation regarding South Atlantic zonal section A10
February 2019

Pre-amble
The South Atlantic zonal sections (25–35˚S) have received increasing attention with interest in constraining heat and mass transport of the South Atlantic component of the meridional overturning circulation (SAMOC). Three hydrographic sections in relatively close proximity have been occupied over the past 30 years: A9.5 along nominally along 24˚S, A10 along 30˚S, and A10.5 along 34.5˚S. To date A10 has been the designated reference section but at times all three sections have been referred to as A10 (Table 1). There are sound scientific and logistical reasons to consider making one of the other sections the reference section in the future. One of the charges of the GO-SHIP executive committee is to assess which sections should be designated as core reference sections that should be repeated to full GO-SHIP specifications.

Recommendations
All three zonal sections are of importance for determining trends, variability and divergence of the SAMOC, and its associated properties. The lines are important for quantifying transport and inventories of climate and ecosystem variables (anthropogenic carbon, oxygen, nutrients, inorganic carbon (DIC), and transient tracers). Section A10 (30 ˚S) has been the primary GO-SHIP section that has been occupied to GO-SHIP reference specifications since WOCE. Based on occupations performed to date analyses should be performed on differences and uncertainties of transport for the lines particularly between A9.5 and A10. These analyses will be greatly aided by the quality datasets available for the A10 occupations with datasets from 1992, 2003, 2011 (and planned in 2021/22) with A9.5 occupied in 2009 and 2018. Any decision to move the reference section should incorporate climate observation principles applied to changing methodologies (Karl et al., 1996; Trenberth et al. 2002). A full analysis of differences must include transport of anthropogenic CO_2 and biogeochemical parameters to avoid biasing observed trends over time. It is recommended to retain all designated naming conventions, that is A9.5, A10 and A10.5 to avoid confusion and misinterpretation of results. The A10.5 cruise, that was a one-off occupation of the section along 34.5 ˚S, is an important GO-SHIP associated cruise that supports the mooring array but it does not have the support, or historical biogeochemical data, to be a GO-SHIP reference section.

The next occupation of A10 is scheduled for 2021/2022 under the auspices of USA/NOAA. If the cruise follows the designated track along 30˚S, the cruise should include a short extension (an extra ≈3 days at sea (DAS)) to include station occupations across the Vema Channel, a deep trough at 31.3°S, 39.4°W in the Rio Grande Rise that is a critical deep water choke point for transport estimates.

Discussion

The recommendation and discussion are based on input from several experts of the oceanography of the South Atlantic, and leaders of the cruises along the sections. They include (along with their primary section of interest in parenthesis). Alison Macdonald (A10), and Johannes Karstensen (A10.5), Elaine McDonagh, (A9.5); Brian King (A9.5); and Sabrina Speich (A10.5). Abridged copies of their responses to the inquiry are attached as appendices. Furthermore, the discussions benefitted from an impromptu exchange between Brian King, Greg Johnson, Molly Baringer and Rik Wanninkhof at the Argo Science Meeting in Tokyo Oct. 23, 2018.

A map of the nominal locations of the sections superimposed on a map of major deep currents and bathymetric features is provided in Figure 1. The locations of the zonal sections are of importance not only for transport calculations of heat and properties, but also for inventory estimates. There are strong gradients due to interleaving of watermasses originating from the North and from the South.

An overview of the canonical view of South Atlantic circulation can be found in Stramma and England (1999) that illustrates the prevailing water masses and currents at different depths, and the complexities due to interaction between the currents and bathymetry. This dynamic area and differing objectives for the (re)occupations make strong recommendations on the reference section challenging. Full basin meridional transports calculated for the A10 section are more uncertain because topography around the Rio Grande Rise affects the measured current structure. The transport estimates will be more robust for the A9.5 section. A10 on the other hand, repeats sampling in a longstanding timeseries of changing abyssal properties in Hunter Channel and in Rio Grande Gap entryway to the Vema Channel, the most direct northward routes for Antarctic Bottom Water. However, A10 is not well suited for measuring transport in the narrow Rio Grande Gap and Vema Channel.

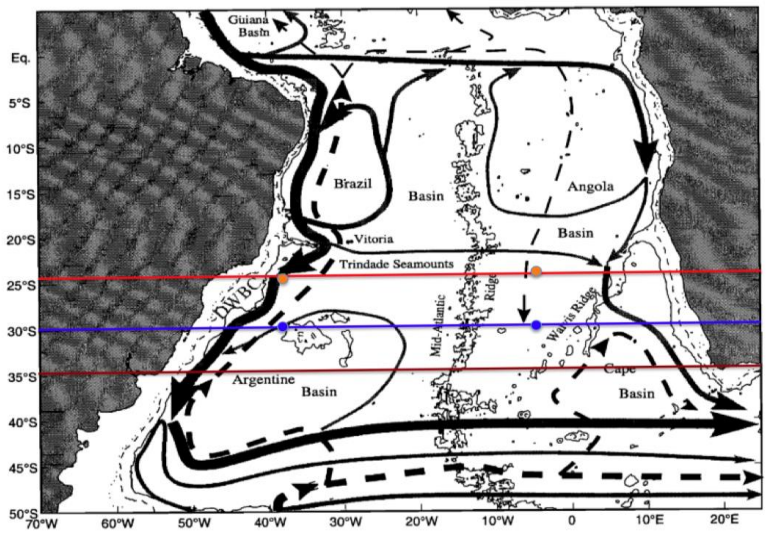

Figure 1. Schematic deep water flows along with locations of the section (Figure 5 from Stramma and England, 1999). The blue and red circles are the locations of the depth profiles shown in figures 2 and 3.

Section A10.5
A10.5, nominally along 34.5 ˚S, was occupied in 2017 using vessel *Maria S Merian*, MSM60. There are no other full occupations of this section. A cruise along A11, nominally along 45˚S for the western section up to 15 ˚W and diagonally toward the terminus at 10˚S, 32˚S, was occupied in 1992 as a WOCE section but without inorganic carbon measurements. The A10.5 section shows less topographic interference, but transport is heavily influenced by the Agulhas and Benguela currents along the Eastern part of the section. It also is in the area of westward moving Agulhas rings that can alias transport estimates. The same issue, albeit to a lesser extent, holds for A10.

The major advantageous attribute of the A10.5 section is that lies along the SAMBA and SAMOC current arrays maintained by a multi-national group of South African, US, Argentinian, Brazilian, French and German scientists. It is therefore frequently occupied by research ships for servicing the array that often perform CTD stations. The co-location of a comprehensive mooring array for continuous coverage with a hydrographic section has merit. The eastern and western parts of the array are maintained separately but a cruise with most GO-SHIP level 1 measurements was completed in 2017 with the of goal linking the observations between the eastern and western components. Hydrographic measurements made on the array servicing cruises often meet the criteria to be associated GO-SHIP cruises. However, anticipated resources, the energetic flow regime, and lack of "champions" advocating for a repeat does not make this section a likely candidate as a replacement for the A10 reference section.

Details of the SAMBA array are as follows: "The SAMBA array has moorings on both the western and eastern sides of the basin, with moored instruments extending from near the shelf break on either side out to several degrees of longitude offshore of the continental slope. The western component of the SAMBA array consists of four pressure-equipped inverted echo sounders (PIES), and three current-and-pressure-equipped inverted echo sounders (CPIES). In addition to the moored instruments, routine CTD sections (some including lowered-ADCP) are conducted both along the SAMBA-west mooring line and up onto the shallow continental shelf. The Eastern part of the section has moorings SAMBA east The eastern side of the SAMBA array consists of seven CPIES and two bottom moored ADCP that are deployed from the top of the continental slope offshore to near the Walvis Ridge, as well as four tall dynamic height and current meter moorings, maintained by South Africa".[1]

Section A9.5
Section A9.5, along nominally 24˚S, has strong merits from a transport perspective as it lies north of the Rio Grande Rise, and covers the Brazil Basin exclusively, compared to A10 that covers the northern end of Argentine Basin in the west and Brazil Basin to the

[1] This paragraph is from:
http://www.aoml.noaa.gov/phod/SAMOC_international/documents/2016_SAMOC_VI_WorkshopReport.pdf]

east. Section A9.5 lies to the north of the prevailing corridor of Agulhas Rings. It was occupied to GO-SHIP reference section specifications in 2009 and 2018.

While it is relatively close (6 degrees latitude ≈600 km) to the A10 section there are marked differences is the chemical properties in deep and intermediate waters reflecting the different water mass and biogeochemical properties. Figure 2 compares stations on A9.5 and A10 in the eastern Brazil Basin. Figure 3 shows select properties for stations in western basin, where the A10 section sampled to the south of the Vema Channel, with the deep outflow from the Argentine basin, and A9.5 the western Brazil Basin. The low salinity, low oxygen, high DIC Antarctic Intermediate water (≈1200 m) is at shallower depth for A9.5 than A10, in large part due to shoaling of isopycnal surfaces to the north. The AAIW shows a stronger contribution towards the west. The NADW signal (2200-3600 m) with higher salinity and oxygen and lower DIC is also more prevalent to the west, but interestingly also to the south. The maximum of the NADW signature is significantly shallower at A9.5 compared to A10 indicating the influence of circulation (and mixing) in the deep basin (See Figure 1).

There is strong interest by the UK GO-SHIP community to continue this section as a reference section. A synopsis of the merits of this section can be found in the input from Elaine McDonagh appended below.

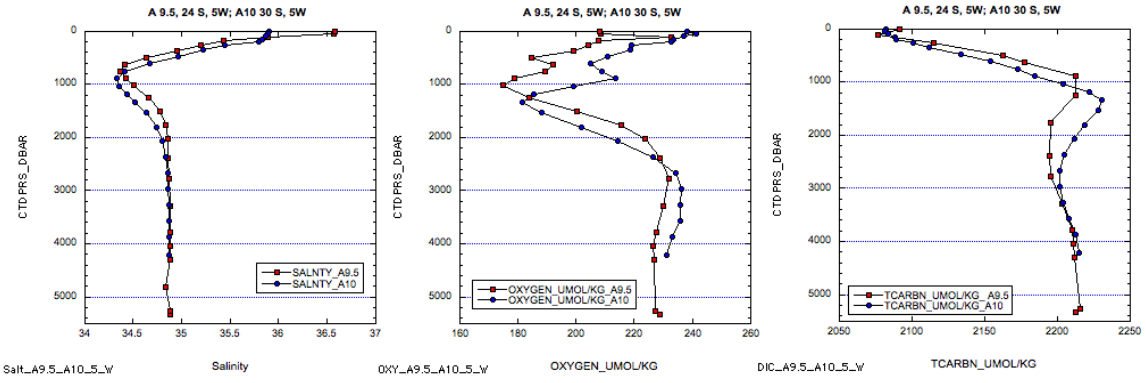

Figure 2. Profiles of salinity, oxygen, and DIC for a station on A9.5, 24˚S(red), and A10, 30˚S (blue) in the Eastern Basin (5˚W). Appreciable displacement of isopycnals for the AAIW waters cause the minimum in salinity and oxygen, and maximum in DIC to be shallower for the A9.5 section. Also of note, is the lower O_2 for the NADW for the A9.5 suggesting a deep re-circulation. These differences are of significant for basin inventory determinations, including anthropogenic CO_2.

Section A10

Section A10, along nominally 30˚S, has the longest record of quality observations of physics and biogeochemistry (Table 1); with GO-SHIP quality measurements and most level 1 observations since the early 1990's. Transport calculations along the A10 section are challenged by topography, notably the Rio Grande Rise and associated boundary currents on the western side of the basin (Figure 1). In particular, intermediate water flow is disrupted upstream of the Rio Grande Rise. In the east large changes in transport can occur, along with aliasing, by variations in the Benguela Current and the Agulhas Rings.

The Western part of A10 samples both waters in the Argentine basin and the Brazil Basin. The stations between the continental margin of Brazil and the Rio Grand Rise sample AABW in Argentine Basin and its export northward into the Vema Channel. The Southern Ocean endmember is more prevalent than for the stations north of the rise along A9.5. Figure 3 shows the large differences in biogeochemical properties, and will impact the determination of the decadal changes in biogeochemical inventories and anthropogenic CO_2 estimates. A clear illustration of the southern and northern component waters can be observed with silica with high silica concentrations in the southern component (Fig. 3d). The differences in temperature, salinity, silica and DIC profiles along A10 (Argentine Basin and northern part of the Vema Channel) and A9.5 for sampling the Brazil Basin is shown in Figure 3.

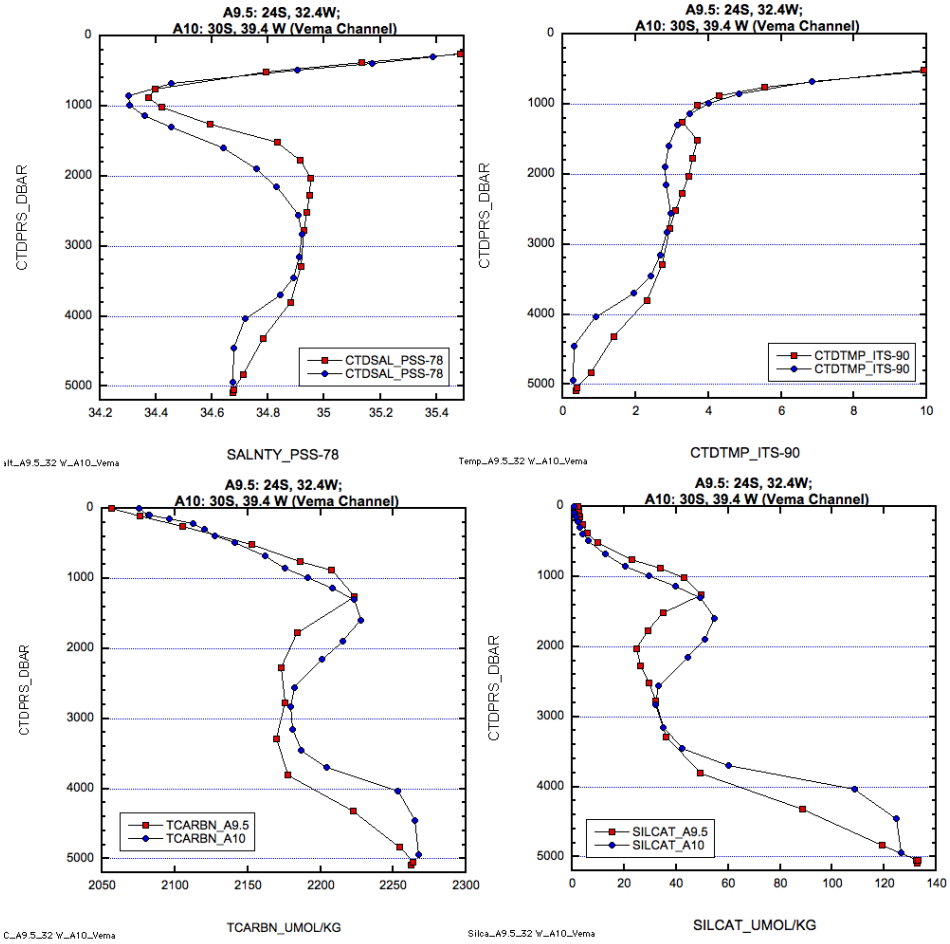

Figure 3. Comparison of salinity, temperature, DIC, and silica for station 44 (24 ˚S, 32.42 ˚W) on the 2009, A9.5 cruise, and Station 97 (39.4 ˚W, 30 ˚S; Northern end of the Vema Channel) on the 2011, A10 cruise.

The 30˚S line has been the demarcation of the Southern Ocean and used in several analyses to constrain heat and mass fluxes into the Indian, Pacific and Atlantic Basins. JAMSTEC carried out the research cruise along WOCE/WHP sections along 30 ˚S in its entirety the southern hemisphere with oceanographic research vessel MIRAI from August

2003 to February 2004 providing a unique near-synoptic snapshot of the section. Future opportunities and value to re-occupy the entire section in the same timeframe should be taken into consideration.

Summary

The outyear schedule of the US GO-SHIP includes re-occupation of A10 in 2021/2022 timeframe and, contingent on the results of the intercomparison between A9.5 and A10, it is anticipated that this cruise be completed along 30˚S as planned. The results of the currently funded effort (Macdonald, WHOI, PI) of a comprehensive analysis of heat and mass transport using the previous cruises along the A9.5 and A10 sections is needed to determine the impacts of changing the location of the GO-SHIP reference section. Other comparisons of data from A9.5 and A10 should include an assessment how moving the section would impact both the magnitude and uncertainties in mass and heat transport calculations, including transport of anthropogenic carbon, natural carbon, oxygen and other parameters of biogeochemical interest into/out of Atlantic sector of the Southern Ocean. The magnitude and uncertainties in changes biogeochemical inventory over time using either A9.5 or A10 in the South Atlantic should be determined as well.

Table 1. Cruises along A9.5 (first two cruises) and A10 that are currently in the CCHDO holdings with GO-SHIP level 1 measurements (from: https://cchdo.ucsd.edu). Note the recent A10.5 cruise (2107) has not been posted yet.

Expocode	Line(s)	Ship	Country	Start Date	End Date	PI
740H20180228	• A9.5 • A10 • A095 • A09.5 • A09	JAMES COOK	UK	2018-02-28	2018-04-10	• Brian King
740H20090307	• A09 • A09.5 • A095 • A10 • A9.5 • AO95	JAMES COOK	GB	2009-03-07	2009-04-21	• Brian A. King
06MT22_5	• A10	METEOR	DE	1992-12-27	1993-01-31	• Thomas J. Mueller
49NZ20031106	• A10	MIRAI	JP	2003-11-06	2003-12-05	• Yasushi Yoshikawa
33RO20110926	• A10	RONALD H. BROWN	US	2011-09-26	2011-10-31	• Alison Macdonald • Molly O. Baringer

References

Stramma, L., and M. England (1999), On the water masses and mean circulation of the South Atlantic Ocean, *Journal of Geophysical Research: Oceans*, *104*(C9), 20863-20883, doi:10.1029/1999JC900139.

Karl, T. R., V. E. Derr, D. R. Easterling, C. K. Folland, D. J. Hoffman, S. Levitus, N. Nicholls, D. E. Parker, and G. W. Withee (1996), Critical Issues for Long-Term Climate Monitoring, in *Long Term Climate Monitoring by the Global Climate Observing System*, edited by T. R. Karl, pp. 55-92, Kluwer Publishing.

McDonagh, E. L., and B. A. King (2005), Oceanic Fluxes in the South Atlantic, *J. Phys. Oceanogr.*, *35*, 109-122, doi:10.1175/JPO-2666.1

Trenberth, K. E., T. R. Karl, and T. W. Spence (2002), The need for a systems approach to climate observations, *Bull. Amer. Meteor. Soc.*, *83*, 1593-1602.

Supplementary Material
Abridged input from South Atlantic experts, in response to the inquiry listed first

On 27/08/18 Rik Wanninkhof & Bernadette Sloyan, co-chairs GO-SHIP wrote:

In recent years we have occupied A9.5, A10, and A10.5, and now is a good time to consider which of these sections may be considered a full GO-SHIP reference section in future decadal surveys. The rationalization of selection has, of course, scientific, logistical, and financial implications. It is unlikely that more than one line in that area could be a GO-SHIP reference line, but we need to discuss merits - pros and cons. We recognize that each line has its benefits (such as A9.5 being the better line for "closure/transport"; A10.5 having a mooring array; and A10 having the historical record). The questions we hope you could address are:
-The benefits of the location of your favorite line
- Plans for re-occupation of the line including the estimated year
-Plans for re-occupation as a GO-SHIP reference line (following the established sampling density and level 1 measurements).

On 9/18/1 Sabrina Speich wrote:
A GO-SHIP line on 10.5 should be mandatory because of the mooring design that measures the AMOC from (essentially) PIES bottom mooring. Yet, there is not in the SAMOC community a strategy to achieve a repeat line. The potential is there (S. African and Brazilian new ships), but the economy in those countries are not going very well. During AtlantOS it has been possible to organize a first cruise (thanks to Johannes). At the moment it is all what we have. I go back today to the SAMOC executive committee to have their final word on this matter.

On 8/28/18 Johannes Karstensen wrote:
I can give you my perspective being the chief scientist for the A10.5 in 2017 (Maria S Merian MSM60).
The cruise was done because it was just a great opportunity (ship available) - however, the financing was only for the cruise and the analysis is lacking. It difficult to answer your questions - before a thorough analysis (of the individual cruises as well as an inter-comparisons) no decision can be made on priorities for future re-occupations.

From my experience in 2017 - I confirm you the incentive a cruise "along the array" has for all SAMOC players - a fact that should not be neglected in the decision making process for future cruises.

I do not plan to repeat the 34.5°S cruise in the next five or so years.

On 8/27/2018 Alison Macdonald wrote:
a) I agree with each of the pros you list for the various sections.

b) A10 has the additional interesting pro, I think, though some might see it as a con - that it covers multiple basins and therefore multiple routes and pathways, particularly (but not only) for bottom waters.

c) The combination of A10 and A9.5 is interesting in and of itself because of the change from multiple basins to an east/west geography.

d) A10.5 has moorings (and an XBT line) but I have no sense for how stable those observations are and the lack of historical record means …
It is hard for me to see A10.5 becoming the "reference", but then I know that line the least so my opinion is biased. With the project I am working at the moment that understanding some of the differences between A10 and A9.5 might allow either one of them to be the reference line without necessarily losing the historical record or the transport closure.

As models improve and the historical record from Argo lengthens, I wonder whether the question of "observed" transport from a hydrographic transport is as important as it was 20 or even 10 years ago….at least for mass and heat. For carbon and biochemical transports I imagine the moorings are of less use and hydrographic line is of paramount importance.

On 9/19/1, Elaine McDonagh wrote:

- Brian King's and I have written the following view of the latitude for choosing the GO-SHIP sections in the South Atlantic is based on the ability to calculate transports and budgets from them as well as property changes. The South Atlantic connects and controls the exchange between the North Atlantic and Southern Ocean. The South Atlantic is unusual it transports heat equatorwards, contributes to the northward transport of upper ocean saline water that supports the AMOC. And also plays a role in the accumulation of anthropogenic carbon in the North Atlantic. Pre-WOCE there was a hydrographic section at 24 S in the Atlantic, that had been occupied by the Meteor Expedition in 1926 (Wust, 1935), and also in 1958 (Fuglister, 1960), and 1983 (McCartney and Woodgate-Jones, 1991). During WOCE the subtropical southern hemisphere sections were located at 30S so that global analyses could analyze transports across and convergence and divergence of properties north and south of a single latitude. The WOCE 30S/A10 section was occupied in 1993, 2003 and 2011. Brian and I were involved in the analyses of the WOCE A10 and A11 South Atlantic sections (Saunders and King, 1995 McDonagh and King 2005). One difficulty with the full section inverse analyses of A10 relates to the topography near the western end of the section. The topography across the Rio Grande Rise, Vema Channel and Rio Grande Plateau causes issues related to variability in column average properties that adds considerable uncertainty into the calculation. In addition the important and complicated flow through Vema Channel is not well resolved by the standard open-ocean GO-SHIP sampling (McDonagh et al 2002). Finally the contribution of Agulhas Rings (part of the warm/salty return path of thermohaline circulation) has to be separately accounted for as they are not in the background flow but are in discrete mesoscale features. As well as simpler topography at 24S occupying the section further north reduces the uncertainty in the transport estimate associated with the

mesoscale variability of the Brazil-Malvinas confluence and Agulhas Rings that both add noise to the calculation. In addition the contribution of Agulhas Rings (the warm/salty path of the thermohaline circulation) is better represented by the background/thermocline flow observed by a hydrographic section. When we had the opportunity to propose a UK section in the late 2000[1]s our priority was to optimally determine the South Atlantic transports and we concluded that this was best done at 24S. The UK has occupied 24S (A9.5) in 2009 and earlier this year in 2018. A repeat of this section is on our roadmap of activity on a decadal repeat but our horizon of confirmed funding does not yet reach to the next occupation. The system in the UK requires us to find funding for GO-SHIP cruises on a section by section or regional basis. Although we do not get funding for a whole repeat hydrography program our system does recognize the value GO-SHIP hydrography and having A9.5 as one of the reference sections will (in my view), increase the likelihood of support improve the security of a UK contribution to the GO-SHIP network in the subtropical south Atlantic.