USE OF ARGO FLOATS TO STUDY THE OCEAN DYNAMICS SOUTH OF AFRICA: WHAT WE HAVE LEARNED FROM THE GOODHOPE PROJECT AND WHAT WE PLAN WITHIN THE SAMOC INTERNATIONAL PROGRAMME.

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Introduction

South of Africa, the Southern Ocean provides the export channel for NADW to the global ocean and the passage for heat and salt from the Indian and Pacific oceans (Figure 1). This region is influenced by the largest turbulence observed in the ocean. The eastward flowing ACC, the South Atlantic Current and NADW meet with the westward flow of Indian waters carried by the Agulhas Current, leading to water masses exchanges through jets, meanders, vortices, and filaments interactions. These local mesoscale and submesoscale interactions and the derived meridional fluxes might constitute the major link between the Southern Ocean and the global meridional overturning circulation (MOC). At the same time, mixing and air-sea interactions are responsible for significant water masses properties modifications. Mounting evidence from palaeoceanographic and modelling studies suggest that interocean exchanges south of Africa are drivers of global climate change. For example, through their southern influence on the Atlantic portion of the OC, changes in the flux of warm, salty waters from the Indian Ocean may have triggered the end of ice ages, as well as effecting shorter-term climate variability. Yet, owing to the relative isolation of the region from the US and Europe, few modern observations time series existed in this sector of the global ocean before 2004. This was the main reason to foster an international cooperation to monitor regularly this oceanic sector.

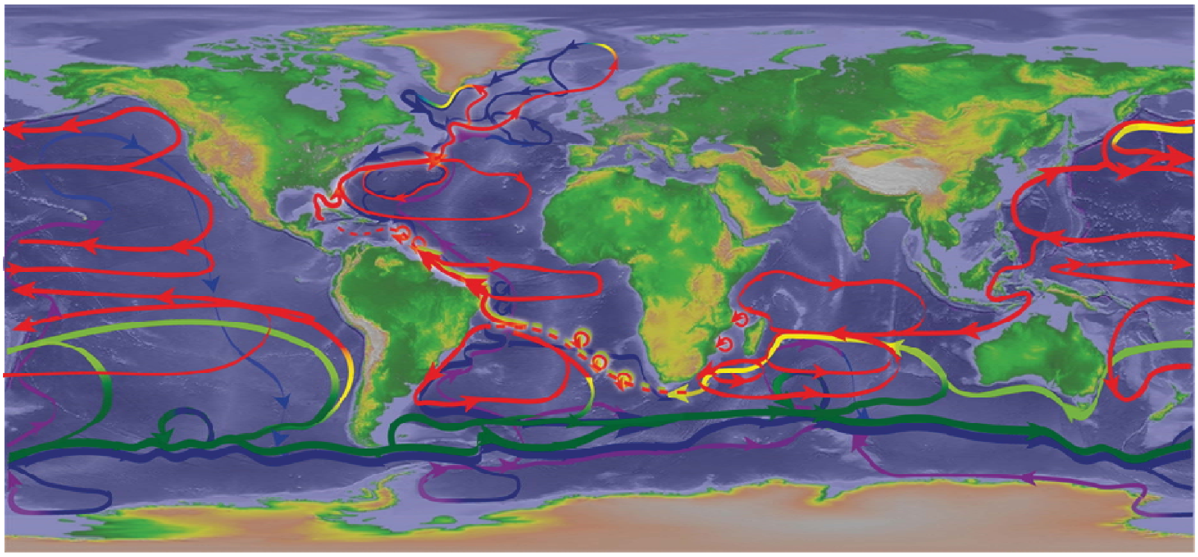


Figure 1. Schematic of the world ocean overturning circulation. Red is surface flows, blue and purple are deep flows, and yellows and greens represent transitions between depths. Base map derived by S. Speich, adapted from R. Lumpkin. This map is based on Speich et al., 2007, Blanke et al. 2001, and Lumpkin and Speer, 2007.

The project has been named GoodHope (GH hereafter) by the Cape of Good Hope. The international partnership is gathering together means (in terms of human, observing platforms, ship time and general financial support) from 11 different institutions and six countries (France, South Africa, United States, Germany, Russia and Spain). The project is coordinated by the *Laboratoire de Physique des Océans,* Brest, France. It has been approved in 2003 by the International CLIVAR panel and endorsed by SCAR and CliC.

The GH experiment includes conductivity– temperature–depth (CTD) measurements (five realizations performed by the Shirshov Institute of Moscow, and a French multidisciplinary one, BONUS-GoodHope, achieved in early 2008 in the framework of the International Polar Year), geochemical tracer samplings, and expendable bathythermograph (XBT) measurements on the same and separate cruises. A large portion of the GH section was designed to follow a groundtrack of the JASON satellite, with the aim of joining hydrographic and altimetric data analyses

(Figure 2). ARGO floats launched during these cruises furthermore provide year-round hydrographic information on the region. A first description of water masses and full depth transport observations along the GH transect in late 2004 can be found in Gladyshev et al. (2008). Since it starts, GH has been one of the major projects in improving the data coverage of the Southern Ocean in terms of number of available monthly profiles.

With the relatively important number of full-depth hydrographic cruises, of high resolution XBT sampling, of deployed profiling floats and satellite altimetry in complement with numerical simulation analyses we have been able to improve quantitatively the knowledge on regional dynamics and water properties exchanged south of Africa. In particular the increased number of vertical profiles obtained by the repeat deployment of Argo floats along the GH line allowed us to make important progresses on the understanding and quantifying particular aspects of the regional dynamics. They include the estimate of the ACC variability for the upper 2500 m (Swart et al. 2010; Swart and Speich 2010; the regional mixing layer heat budget (Faure et al. 2010); aspects of the regional mesoscale dynamics (Gladyshev et al. 2008; Dencausse et al. 2011; Arhan et al. 2011); the Indo-Atlantic Antarctic Intermediate Water (AAIW) exchanges (Rusciano et al. 2012); global estimates of halothermosteric variability in connection with sea-level changes (von Schukman et al. 2012).

Hereafter we describe some of the results we obtained that are based, at least partially, on analyses of Argo data within the GH project.

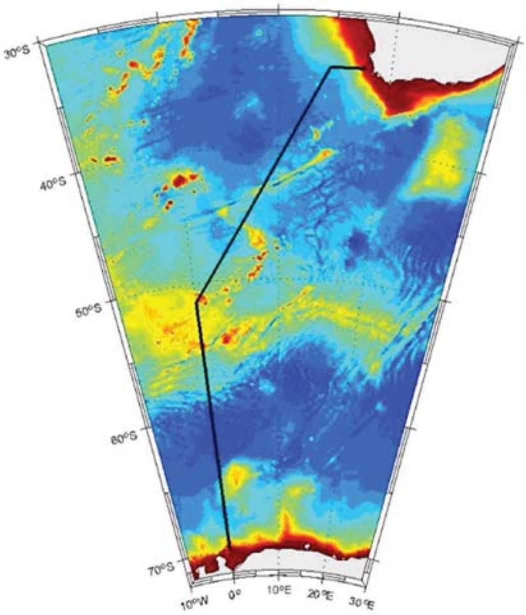


Figure 2. Locations of the GoodHope CTD and XBT sections.

Antarctic Circumpolar Current Variability

By using the entire *in situ* GH data set (full-depth hydrography and Argo data) we developed a proxy method based on the technique originally developed by Sun and Watts (2001 and 2002) and Watts et al. (2001) for the SO to project hydrographic sections onto a baroclinic stream function coordinate Γ(π,ϕ) (in this case dynamic height at the sea surface, referenced to a common pressure, ϕ2500) in order to give us insight into the subsurface thermohaline structure of the ACC. This projection is called the gravest empirical mode (GEM). In particular, we combined the GEM with satellite altimetry SSH data and demonstrated the ability of this method to recreate in situ observations (Swart et al. 2010; Swart and Speich, 2010). This method provides us with a valuable 16 year time series (weekly intervals) of temperature and salinity fields at the GH line, which can be used to improve our understanding of the ocean dynamics in this least understood ‘‘choke point’’ of the ACC. Altimetry GEM (AGEM) is the name we assigned to this product. For the first time, the AGEM is able to provide information on the subsurface baroclinic structure of the ocean at eddy resolving spatial and temporal scales.

The continuous time series of thermohaline fields are, for example, exploited to understand the dynamic nature of the ACC fronts in the region. In particular, we derived weekly estimates of heat content (HC) and salt content (SC) for the ACC along GH (Figure 3). These estimates compare favorably to observed data. The resulting 16-year time series of HC and SC estimates are used to explain the subsurface thermoha-

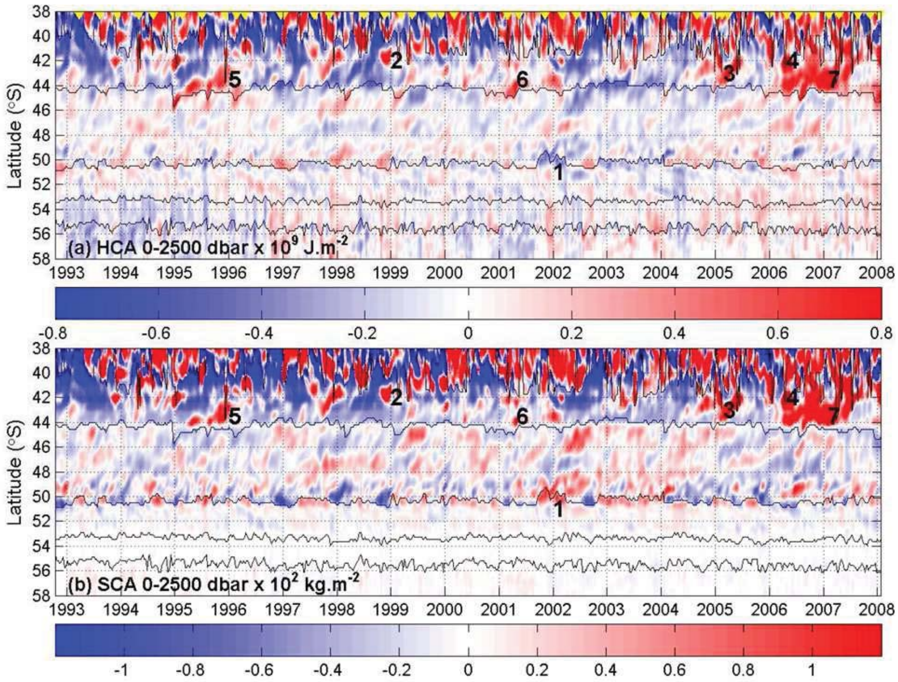


Figure 3. A Hovmöller representation of the (a) HCA and (b) SCA between the surface and 2500 dbar, along the GH line, from 1992-2008. The latitudinal positions of the ACC fronts (thin black lines) are from north to south: STF, SAF, APF, SACCF, SBdy. Adapted from Swart and Speich (2010).

line variability at each ACC front and frontal zone. The variability at the Subantarctic Zone (SAZ) is principally driven by the presence of Agulhas Rings, which occur in this region approximately 2.7 times per annum and are responsible for the longest and highest scales of observed variability.

The variability of the SAZ is responsible for over 50% and 60% of the total ACC HC and SC variability, respectively. Poleward of the SAZ, the variability is largely determined by the influence of the local topography on the fronts of the region and can be explained by the conservation of potential vorticity. Wavelet analysis is conducted on the time series of meridionally integrated HC and SC in each ACC front and frontal zone, revealing a consistent seasonal mode that becomes more dominant towards the south of the ACC. The lower frequency signals are compared with two dominant modes of variability in the Southern Ocean. The Southern Annular Mode correlates well with the HC and SC anomaly estimates at the Antarctic Polar Front, while the Southern Oscillation Index appears to have connections to the variability found in the very southern domains of the ACC.

Mixing Layer Heat Budget

While the oceanic region located south of South Africa has been studied extensively for its dynamical processes contributing to the transfer of Indian Ocean Central Water to the South Atlantic, other issues related to air-sea fluxes and water mass conversion, though also influencing the inter-oceanic exchanges, have been comparatively less examined in this area than at other longitudes of the Southern Ocean. A reason for this certainly resides in the fact that no Subantarctic Mode Water (SAMW) is formed in the SAZ south of Africa, unlike in the Indian Ocean and Pacific Ocean (McCartney, 1977; Sallée et al., 2008).

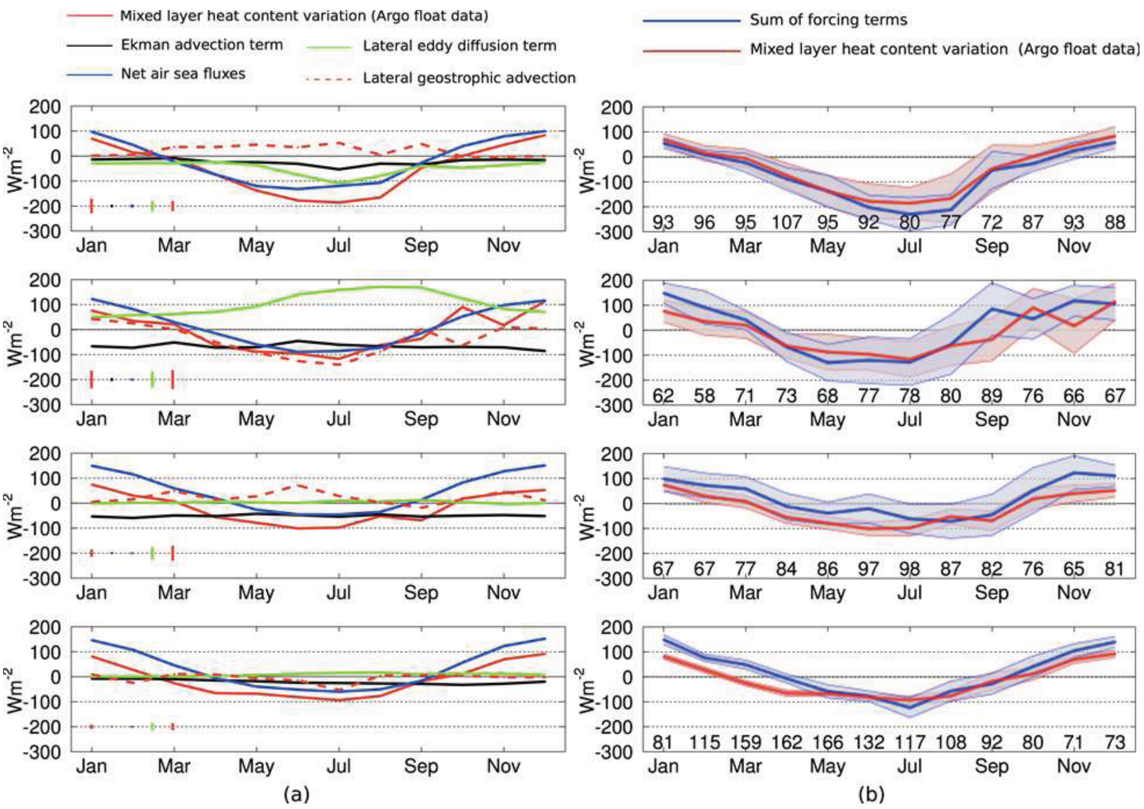


Figure 4. Seasonal variations of the SML heat budget terms of equation (1), averaged over the period 2004-2008. (a) The SML heat rate of change (left hand side of equation (1)) is shown along with each forcing term. (b) The heat rate of change is shown along with the sum of the forcing terms. Uncertainties were computed assuming that the number of independent individual heat budget estimates was one fifth of the number of ARGO profiles each month. Adapted from Faure et al. 2011.

In this study we used ARGO hydrographic profiles, two hydrographic GH transects, and satellite measurements of air-sea exchange parameters to characterize the properties and seasonal heat budget variations of the Surface Mixed Layer (SML) south of Africa (Faure et al. 2011). Two recent studies using ARGO floats, though not focused on the region south of Africa, provide information on the SML heat balance in this sector of the Southern Ocean. Sallée et al. (2006), while studying the formation of SAMW in the southeastern Indian Ocean, found that upstream (west) of this formation area heating by eddy diffusion related to the nearby South Indian western boundary current system (the Agulhas Current and Agulhas Return Current) counterbalances the cooling due to air-sea fluxes and Ekman transport. Dong et al. (2007), in a circumpolar study of the Southern Ocean SML heat budget, underlined the role of air-sea fluxes at the seasonal time scale, and the relative weakness of the geostrophic advection term, in contrast with western boundary current regions.

The analysis distinguishes the Subtropical domain (STZ), and the SAZ, Polar Frontal Zone (PFZ) and Antarctic Zone (AZ) of the ACC. While no Subantarctic Mode Water forms in that region, occurrences of deep SML (up to ~450 m) are observed in the SAZ in anticyclones detached from the Agulhas Current retroflection or Agulhas Return Current. These are present latitudinally throughout the SAZ, but preferentially at longitudes 10°E-20°E where, according to Dencausse et al. 2011, the S-STF is interrupted. Likely owing to this exchange window and to transfers at the SAF also enhanced by the anticyclones, the SAZ shows a wide range of properties largely encroaching upon those of the neighbouring domains (Fig. 4).

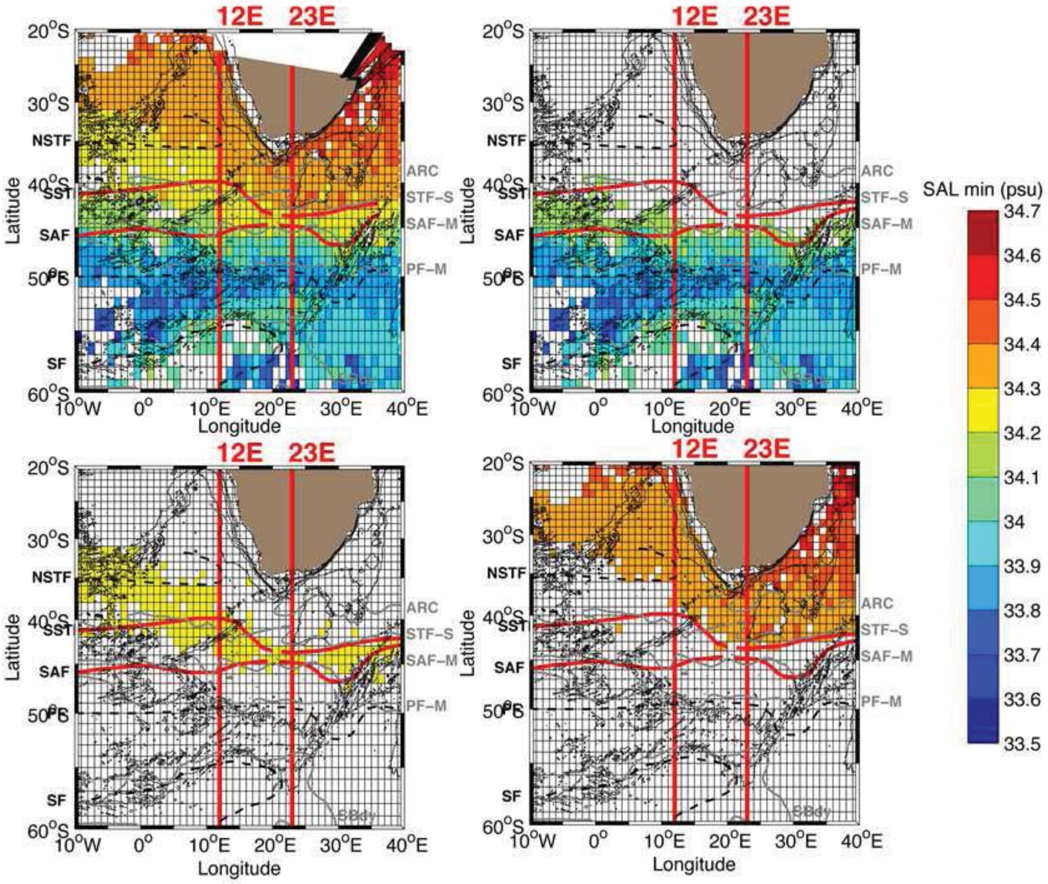
Heat budget computations in each zone reveal significant meridional changes of regime. While air-sea heat fluxes dictate the heat budget seasonal variability everywhere, heat is mostly brought through lateral geostrophic advection by the Agulhas Current in the STZ, through lateral diffusion in the SAZ, and through air-sea fluxes in the PFZ and AZ. The cooling contributions are by Ekman advection everywhere, lateral diffusion in the STZ (also favoured by the ~10-degree breach in the Subtropical Front), and by geostrophic advection in the SAZ. The latter likely reflects eastward draining of water warmed through mixing of the subtropical eddies.

Interocean Exchanges of Antarctic Intermediate Water

Here again we combined the ARGO hydrographic profiles collected between 2004-2009 in the South Atlantic south of Africa in combination with the a GH hydrographic transect to describe the characteristic and the flow of the Antarctic Intermediate Water (AAIW).

We reorganized the ARGO raw data in a 1° x 1° grid in an area extending from 10°W to 40°E and from 20°S to 60°S. The AAIW characteristics and dynamics are compared in nine (9) different regions defined on the base of the regional SO front that are relevant to the AAIW dynamics: the S-STF, and the SAF. Following Faure et al. (2010), the fronts location we used is the mean position of fronts defined as function of their surface dynamic height value and computed from the ARGO floats. We present here estimates of the relative importance of the different regional varieties of AAIW and their origins: south-west Atlantic (A-AAIW), characterized by salinities lower than 34.2, Indian (I-AAIW), with salinities exceeding 34.3, and a new intermediate water found north of the S-STF between 10°W and 12°E and south of the S-STF between 12°E and 40°E with salinities comprised between 34.2 and 34.3. We defined this water as Indo-Atlantic AAIW (IA-AAIW).

Figure 5. Salinity vertical minimum maps from Argo floats data. The subplots show S_{min} (top-left panel); $S \leq 34.2$ (top-right panel); $34.2 < S < 34.3$ (bottom-left panel); $S \geq 34.3$ (bottom right panel). Adapted from Rusciano et al. 2012.



The collected Argo profiles show a quasi-zonal distribution of the salinity minimum values computed within AAIW on the isoneutral surfaces (γ^n = 27.3) on a grid 1°×1°. The zonal AAIW matches fairly well the SO fronts location. The Indian and Atlantic varieties of AAIW are separated by the S-STF in the western part of the domain; the area to the north of the S-STF is largely dominated by I-AAIW with area-normalized volume values of about $5,14*10^2$ m^3/m^2, west of 23°E. The A-AAIW volume, abundant between the S-STF and SAF, decrease very importantly eastward of 12°E certainly due to the mixing between Indian and Atlantic varieties because of the spawning of eddies in the Cape Basin that induces a strong mixing. This mixing has been measured in the SAZ south of Africa during the Bonus-GoodHope cruise. In the core of an anticyclone, the salinity minimum related with AAIW is 34.25, slightly above the values of the neighbouring stations. This salinity minimum is typical of the new water mass with intermediate characteristics between A-AAIW and I-AAIW.

Making use of the recently developed ANDRO velocity dataset (Ollitrault and Rannou, 2011) we estimates for the regional AAIW absolute geostrophic velocity and transport within the isoneutral layer. The AAIW has speed between 0.1 - 0.3 m/s in the Agulhas Current and 0.1 - 0.23 m/s in the Agulhas Return Current. AAIW flows in the subtropical region have a speed approximately of 0.03 m/s. A net increase of the eastward transport is evident from 40°S to 60°S, in particular at the S-STF and PF location. The transport across the latitudinal lines shows an evident variability between 12°E – 23°E, which represents the frontal “window” characterized by high mesoscale and submesoscale activity due to eddies and rings detected from in-situ observations and satellite altimetry.

Toward a South Atlantic observing network for the MOC (SAMOC)

The South Atlantic Ocean is not merely a passive conduit for remotely formed water masses, rather, within the South Atlantic Ocean, these water masses are significantly altered by local air-sea interactions and diapycnal fluxes, particularly in regions of intense mesoscale activity (Stramma and England, 1999; Sloyan and Rintoul, 2000). The importance of these contributions to the MOC has been highlighted by paleoclimate studies linking changes in the basin exchanges to abrupt climate changes (Duplessy and Shackleton, 1985; Weijer *et al.*, 2002; Peeters *et al.*, 2004; Rickaby and Bard, 2009).

Despite considerable effort and expenditure being deployed in the South Atlantic Ocean (see Figure 6 for a summary of ongoing/planned observations), the current range of observations being made are not capable of monitoring the OC, nor do they constitute a sustained observing system capable of monitoring large-scale interbasin fluxes of heat, freshwater, mass and other climate-relevant quantities.

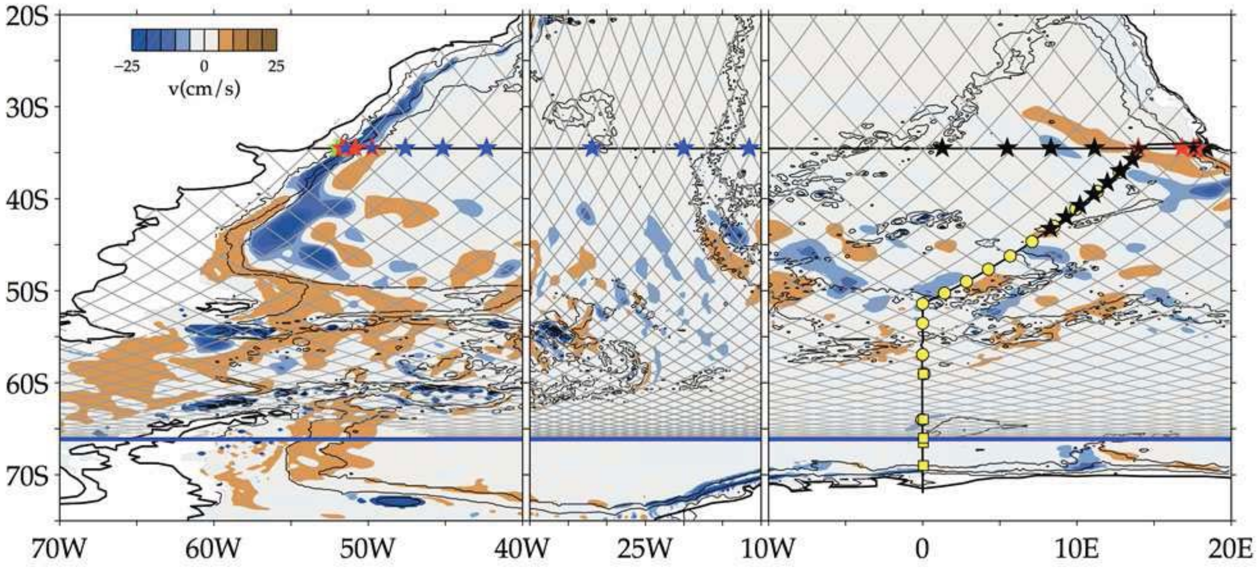


Figure 6. Schematic of the proposed trans-basin array along 34.5°S and the oblique GoodHope transect. Note the x-axis scale is stretched over western and eastern boundaries. Stars indicate the different components of the array that have been (or will be) submitted to respective funding agencies: eastern boundary PIES/CPIES by France-ANR (black stars), and western boundary bottom pressure gauges, CPIES and ADCP by Brazil-/FAPESP/FACEPE (green stars) dynamic height moorings to USA-NSF (red stars), western boundary PIES/CPIES and interior PIES-DP to USA-NOAA (blue stars). Colour contours are of 27-year mean OGCM For the Earth Simulator (OFES) meridional velocity at 200 m depth. JASON ground-tracks are overlaid as light gray lines.

Individual efforts to document the circulation in portions of its natural chokepoints (Drake Passage and South of Africa) are ongoing. Nonetheless, no proper quantitative monitoring system is in place, nor were these systems designed for long-term monitoring purposes. These are the reasons that brought a group of scientists to create a working group to foster collaborations and to discuss the design and implementation of an observational system to monitor the South Atlantic’s branch of the Meridional Overturning Circulation (SAMOC).

In the last five years, four workshops have been organized to achieve this objective. Copies of the presentations that were made at the workshops and complete workshops reports were published in Clivar Exchanges and are available on the NOAA-AOML web site at www.aoml.noaa.gov/phod/SAMOC/.

Following these meetings, and in particular the last one (the Fourth SAMOC Meeting, Simmon’s Town, South Africa, 27-30 September 2011), a coordination effort has been designed to implement the SAMOC observing network together with modelling and theoretical studies. International agreements for the use of resources from countries at the margins, or cruising the South Atlantic were made during the Infrastructure session. In particular, ships from Argentina, Brazil, Russia and South Africa are made tentatively available for the program.

Data from existing observational systems are crucial for the SAMOC field program. These include ARGO float deployment and the high-density XBT transects along 34.5°S (AX18), across Drake Passage (AX22) and south of South Africa (AX25). In particular, for the integrated observing platform we are building within SAMOC, it is really capital to maintain the homogeneity of the ocean sampling distribution in the region south of Africa as it is for today (this sampling has been obtained essentially *via* the ARGO float GoodHope programme : Figure 7). Others global observing systems, as the global drifter array, along with satellite observations of sea height, sea-surface temperature, sea-surface salinity (SMOS, and Aquarius) and surface wind will provide horizontal context for the SAMOC field program, as well as, information about the surface forcing. The SAMOC consortium constitutes an unprecedented opportunity to coordinate ship time with additional float deployments in the Southern Atlantic sector.

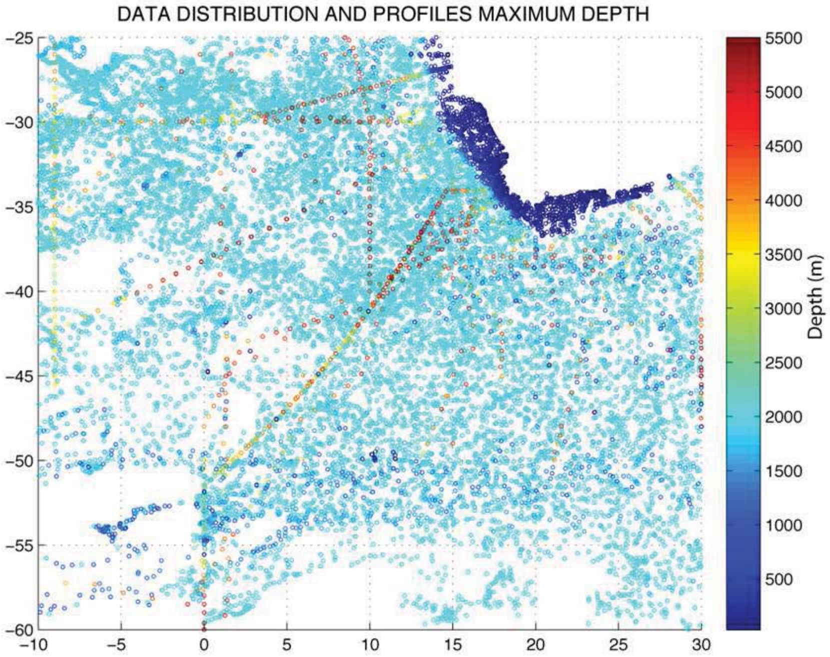


Figure 7. Distribution of hydrological observations in the region around south Africa and the Goodhope transect. Dots represent individual profiles from CTD casts and ARGO floats. Colours represent the maximum depth reached by each profile. From the figure it appears clearly that the sampling of ARGO floats (light blue dots) has completely changed, by improving it, the spatial coverage of hydrologic data in the region that was mainly based on deep hydrological transects (orange dots because they reach depths down to 5000 m).

Conclusions

The scientific interest of the ARGO network in the Southern Ocean is now accepted as evidence. Since the first deployment of profiling floats in this region in late 2003/early 2004, the GoodHope project effort has contributed significantly to SO unfolding. With the establishment of this network we have now access to the surface and subsurface structure of the ocean and their seasonal to interannual variations. This has enabled us to progress in a very fast and quantitative way on the knowledge of the specific ocean dynamics of the SO.

Aknowledments

The IPY/BONUS-GoodHope and CLIVAR/GoodHope projects received support, in France, from the Institut National des Sciences de l'Univers (INSU), the CNRS, the IFREMER program "Circulation Océanique", and the Agence Nationale de la Recherche (ANR). the Groupe Mission Mercator Coriolis. The SAMOC project is funded in France by the ANR, Ifremer, UBO-IUEM.

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