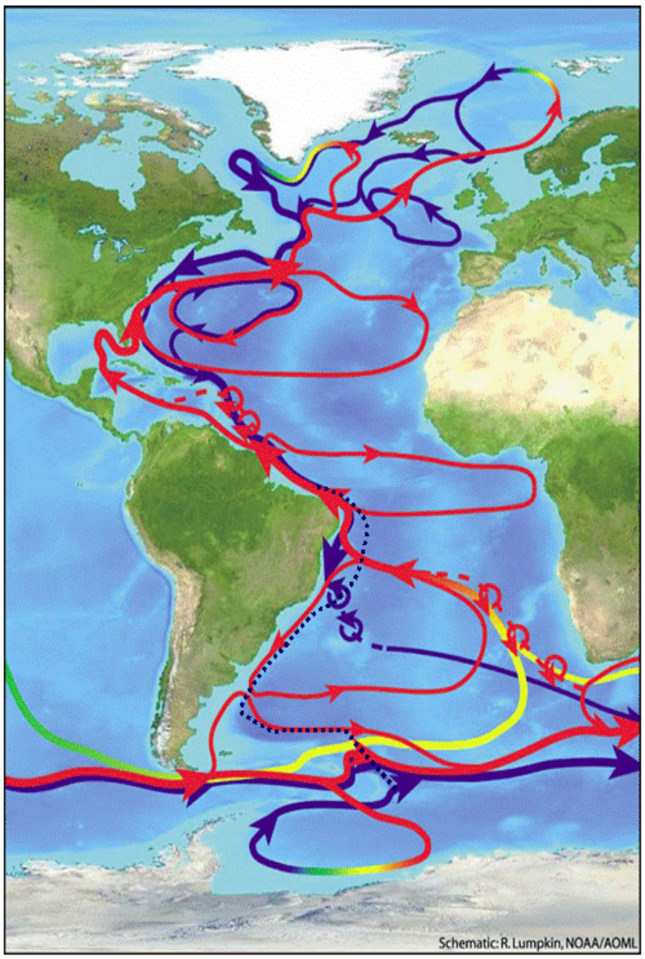
Workshop Report

A monitoring system for heat and mass transports in the South Atlantic as a component of the Meridional Overturning Circulation

Estancia San Ceferino, Buenos Aires, Argentina

May 8, 9, and 10, 2007



Prepared by Silvia L. Garzoli, Alberto Piola, Sabina Speich, Molly Baringer, Gustavo Goni, Kathy Donohue, Chris Meinen, Ricardo Matano and with valuable comments from all participants.

Summary

This workshop gathered scientists from Argentina, Brazil, France, Germany, Italy, Russia, Uruguay, United Kingdom, and the United States (Appendix I) 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 (*SA*MOC). The workshop was financially supported by the NOAA Climate Program Office and US CLIVAR. After reviewing and discussing existing modeling and observational efforts in the South Atlantic Ocean it was concluded that they are inadequate to monitor the MOC and ensuing discussions were focused on the design of an observational array that was adequate for this purpose. Plans were established to coordinate modeling efforts, and existing and future observations in the Drake Passage, in the region between South Africa and Antarctica, and on a zonal transect nominally across 30˚S.

The main recommendations from the workshop can be summarized as follows:

1. Modeling results indicate the need to increase observations not only in the choke points but also in the interior of the South Atlantic, where water mass transformations occur and large discrepancies exist between different models and between models and observations. Therefore, it is imperative to sustain and expand the existing basin wide observations (i.e. Argo, surface drifters, high density XBT programs) and satellite altimetric missions with sufficient spatial and temporal resolution to resolve mesoscale features. The group also endorsed collaboration with the Aquarius-SAC D and Soil Moisture and Ocean Salinity (SMOS) programs that will provide remote observations of salinity on a basin wide scale.

2. The Drake Passage and the region south of South Africa are key chokepoints for the Antarctic Circumpolar Current (ACC). Heat, salt, mass, freshwater, nutrients and other oceanic properties are transported between the Atlantic, Pacific and Indian Oceans, with consequences for global climate. A better understanding and quantification of the ACC variability and the Agulhas leakage on a range of timescales, and on how these changes impact lower latitudes, is sorely needed. In particular this knowledge will help to design a monitoring system that might be capable of measuring heat and salt fluxes. These properties are transported equatorward in the South Atlantic and they impact on the characteristics of the waters contributing to the upper limb of the MOC in the North Atlantic. Therefore, there is also a need to routinely measure meridional

mass, heat and fresh water transports in the South Atlantic. Present and planned observations in the two key chokepoints mentioned above and along a basin-wide zonal line in the South Atlantic, should be sustained and further enhanced.

3. Monitoring systems should be able to transmit data in time scales of about 3 to 6 months (equivalent to ‘real-time’ for climate-scale signals) for climate model assimilations and should be able to collect full water column measurements. Therefore, it was recommended to develop new cost effective technology to allow near real-time observations over the full depth of the ocean.

4. A strong recommendation was made to collaboratively analyze the different data sets and model products presently available and soon to be obtained, as well as to conduct process modeling studies and Observing System Simulation Experiments (OSSEs) to determine the most adequate and cost effective monitoring system for the MOC in the South Atlantic for climate time-scales.

Introduction

The South Atlantic Ocean (SAO) is unique in its role as a nexus for water masses formed elsewhere and in-route to remote regions of the World Ocean. Its mean meridional circulation involves a deep, southward, flow of cold and salty North Atlantic Deep Water (NADW) along the eastern coast of South America and, in the interior of the basin, a compensating northward flow that is a mixture of warm and salty surface waters and cooler and fresher Antarctic Intermediate Waters (AAIW) (Fig. 1). This circulation pattern, in which warm waters flow towards the equator and cold water towards the pole results in an equatorward heat flux. In fact, the South Atlantic is the only major ocean basin that transports heat from the poles towards the equator. Although this anomalous heat flux was recognized by the middle of the last century (Model, 1950), the sources for the upper return flow that make this heat flux possible are still in dispute (Gordon, 1986; Rintoul, 1991). Understanding of the roles of these sources is made more difficult due to the water mass changes that occur within the SAO; relatively cold and fresh bottom waters derived from the Southern Ocean mix and upwell into the NADW layer and therefore also contribute to the vertical exchanges in the Atlantic MOC. Observations indicate that a portion of the SAO upper waters are produced locally (e.g., Stramma and England, 1999 and references therein), but most of the SAO upper waters are thought to originate in the Pacific and Indian oceans. The relative importance of each of these sources as well as the mechanisms of entrainment are still under debate.

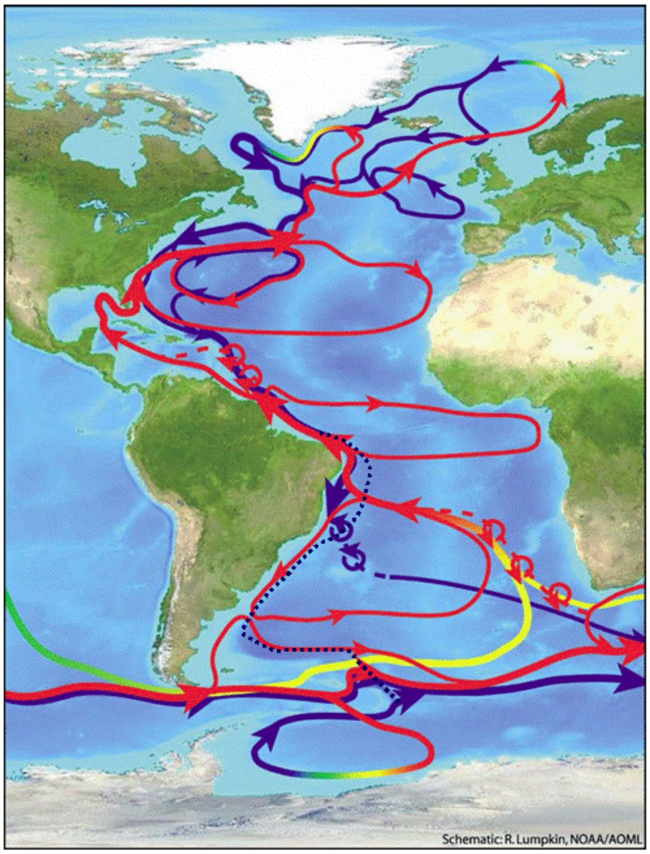


Figure 1*:* *Pathways of the overturning circulation in the Atlantic Ocean that represents the large-scale conversion of surface waters (red arrows) to deep waters (blue arrows in the Southern Ocean; dashed blue line arrows North Atlantic Deep Water) that have global impacts. The Atlantic overturning circulation has many complex and interacting parts (e.g. rings, inter-basin and inter-ocean exchanges) but the most important aspect is the large heat it carries and its apparent sensitivity to the hydrological cycle and climate change (adapted from "Charting the course of the Ocean Science in the United States for the next decade", 2007, to include Antarctic Bottom Water). Graphics: R. Lumpkin, NOAA/AOML.*

The Drake Passage and the Agulhas Retroflection Region are the main gateways for the entrainment of surface waters from the Indian and Pacific basins into the South Atlantic's surface waters (Stramma and England, 1999; Boebel *et al*., 1999; De Ruijter *et al*., 1999). These waters are first funneled into the South Atlantic's subtropical gyre and then are diverted to the northern basin by strong mean currents and highly energetic eddies. The South Atlantic subtropical gyre salinity would be lower if its Sverdrup transport were closed by the relatively fresh South Atlantic Current rather than the salty subtropical waters entrained from the Indian Ocean via the Agulhas leakage (Gordon, 1986). Within the South Atlantic these water masses are significantly altered by local air-sea interactions and diapycnal fluxes, particularly in regions of intense mesoscale variability such as the Argentine Basin and the Cape Basin (Stramma and England, 1999; Sloyan and Rintoul, 2000). Thus, the South Atlantic circulation not only transports remotely formed water masses but also modifies them. The importance of these contributions to the MOC has been highlighted by paleoclimate studies linking changes in the South Atlantic interocean exchanges to abrupt climate changes (Duplessy and Shackleton, 1985; Weijer *et al.*, 2002; Peteers *et al.*, 2004). Furthermore, MOC variability can be linked to the equatorward heat transport in mid latitudes that operates over longer time scales than surface fluxes, and hence could provide some predictability for climate. In the South Atlantic, changes in the heat transport across 30S are first noticed in the circulation of the eastern boundary. It has been shown by multiple experiments that a freshening in the North Atlantic induces a surface warming in the Benguela upwelling region (e.g. Stouffer, 2006). This can be understood by the deepening of the local thermocline due to a decreased equator-to-subtropics surface density gradient that affects the surface wind-driven circulation (Fedorov *et al* 2007, Barreiro *et al* 2008). The coastal upwelling region may thus be key for the indirect monitoring of the changes in the Atlantic Ocean heat transport.

The location of the SAO, at the crossroad of the MOC, has motivated several efforts to estimate the interocean exchanges, but the lack of data, the extent of the boundary region, and the variability of the flow has hindered most of these efforts (e.g., de Ruijter *et al*., 1999). The uncertainty about the South Atlantic interocean exchanges is particularly evidenced by the range of disparate estimates of its northward heat flux, which vary from a maximum of 0.88 PW to a minimum of -0.23 PW (Fu, 1981; de las Heras and Schlitzer, 1999; Garzoli and Barringer, 2007). Such a broad spread not only reflects a lack of data but also the deficiencies in the methods of calculation. Bennett (1978) pointed out that since hydrographic cross-sections cannot resolve mesoscale structures, the sections underestimate the total heat flux due both to their neglect of the eddy component (both barotropic and baroclinic) and due to their misrepresentation of the structure of boundary currents. These limitations are particularly relevant to the South Atlantic because of its high eddy activity and the presence of strong boundary currents on both sides of the basin (e.g., Gordon and Haxby, 1990; Garzoli and Gordon, 1996; Richardson and Garzoli, 2003; Matano and Beier, 2003; Fu, 2006). The coupling between the South Atlantic and contiguous basins and its contribution to the climate variability over South America and Africa at climatically important time scales can also be addressed based on analysis of numerical simulations. Global and regional models with increasing resolution and large coverage have been developed and analyzed (e.g., Stammer *et al*., 2006; Tokmakian and Challenor, 1999; Speich *et al*. 2007) and are useful for studying the present and past circulation in the South Atlantic, and its connection to the MOC and global climate, and also to predict its future evolution. However, the limitations imposed by lack of observations is compounded by the deficiencies of *state-of-the-art* simulations to reproduce the path of the Agulhas eddies or the formation of the Zapiola Anticylone, which are thought to contribute significantly to the South Atlantic's interocean exchanges and its water masses transformations.

In spite of its climatic importance, there is no observational system in place to monitor the South Atlantic's interocean exchanges in a sustained mode. There are, however, individual efforts to document the circulation in portions of its natural chokepoints (Drake Passage, Cape Basin). None of these efforts have previously been coordinated, nor were these systems designed for long-term monitoring purposes. Based on these considerations the participants of the SAMOC workshop agreed on the need to improve our assessments of the South Atlantic's interocean exchanges. Discussions were directed towards the design of a monitoring system for the Atlantic MOC of the South Atlantic. Plans were established to coordinate existing and future observations in the Drake Passage, in the region between South Africa and Antarctica, and on a zonal line at nominally 30˚-35˚S. The group also noted the need to increase observations in the interior of the basin to document the processes responsible for the known water mass transformations. As a step in this direction the group strongly endorsed the continuation of the Argo Program, which is the only global source of subsurface data in the open ocean and away from the tropics. The group also strongly endorsed the continuation of satellite altimetric mission and considered important the success of, and collaboration with, the Aquarius-SAC D and Soil Moisture and Ocean Salinity (SMOS) programs. Also stressed was the need to collect data in poorly sampled regions of the South Atlantic to allow the assessment of the strengths and weaknesses of numerical models to improve the next generation of numerical simulations. Two areas of particular concern are the Argentine Basin and the region just to the west of the Walvis Ridge. The study of the former should bring a deeper understanding of the contributions of the Brazil/Malvinas Confluence and the Zapiola Anticyclone to the local water mass conversions. The study of the region just west of the Walvis Ridge should help us to understand the structure of the Agulhas eddies after they leave the Cape Basin and their potential impact on northward heat and mass fluxes in the South Atlantic.

The group recommendations are described in detail in the following three sections which reflect the organizational structure of the SAMOC workshop, namely: a) Pacific-Atlantic interocean exchanges, b) Indian-Atlantic interocean exchanges, and c) tropical-subtropical interocean exchanges. During the breakout group sessions a recompilation of all current and proposed observations was made (Figure 2). Deployment locations were adjusted to optimize the efforts through collaborations that derived from the workshop discussions. Appendix I includes a list of participants. Appendix II contains a summary of the reports from the breakout groups. Copies of the individual presentations are available at the workshop web page: http://www.aoml.noaa.gov/phod/SAMOC/.

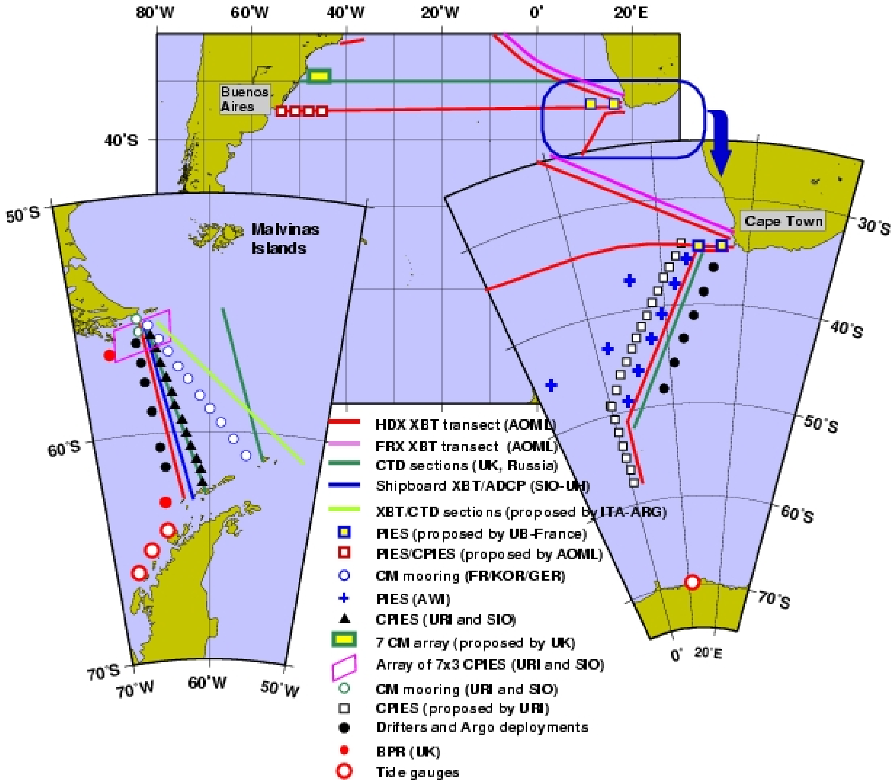


Figure 2. *Map of the South Atlantic and Southern Ocean, including the two principal choke point regions, the Drake Passage and south of South Africa, with the current and proposed locations of instrument deployments and the institutes leading the corresponding associated projects.*

Session 2.1: Inter-ocean exchanges: Pacific/Atlantic

Reporter: Kathy Donohue

The Antarctic Circumpolar Current (ACC), the world's largest current, carries large quantities of mass, heat, and salt around the Southern Ocean. Within each ocean basin, the ACC interacts with lower-latitude circulation and therefore it moves water properties between the Atlantic, Pacific, and Indian Oceans. The nature of this interaction has consequences for local, regional, and global ecosystems and climate. The property divergence within any particular ocean basin, a measure of the ACC-basin exchange, requires knowledge of the chokepoint transports. Drake Passage is the Pacific-Atlantic chokepoint. The present observational effort in Drake Passage is diverse, both spatially and scientifically (Table I and Figure 2, lower left panel). Here we briefly review Drake Passage programs in the context of future sustained monitoring and organize the measurements in terms of sampling strategy: irregular (< 2 weeks sampling interval), continuous, and remote surface sampling from satellites. We assess the present effort in Drake Passage as adequate for mass-transport monitoring on time scales up to interannual. In the future, efforts in Drake Passage must evolve from process-oriented experiments to a sustained observation system.

Synoptic hydrographic surveys provide snapshot estimates of heat, freshwater and nutrient fluxes. A distinct benefit of these surveys is the typically high-horizontal resolution with full-depth sampling of a suite of observations. Several hydrographic lines have been repeated annually or biennially across the Drake Passage. Lead by UK scientists, the SR1b line has been occupied annually since November 1993. In 2008, the A21 line will be occupied in lieu of a SR1b section (http://www.noc.soton.ac.uk/JRD/HYDRO/drake/index.php). Additionally, the Russian Artic and Antarctic Research Institute (AARI) participate in biennial repeat Drake Passage sections in odd-numbered years. The US/UK Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES) program will conduct Drake Passage sections in 2010 and 2011 (http://dimes.ucsd.edu/). It is important to note that Drake Passage transport exhibits variability on the order of tens of Sverdrups on weekly, seasonal, and interannual time scales; as a result synoptic sections will not provide reliable annual or interannual transport estimates (Meredith and Hughes 2005, see also the Meredith abstract from this workshop). Thus, hydrographic surveys are not sufficient for a stand-alone monitoring effort.

Irregular sampling

Autonomous
Profiling floats (Argo)
Lagrangian floats (DIMES)
Animal-borne profiling (Southern Elephant Seals as Oceanographic Samplers (SEaOS) and other regional efforts)
Shipboard
Annual synoptic hydrographic surveys (Russia, DIMES, UK)
Repeat Expendable Bathythermograph (XBT), Acoustic Doppler Current Profilers (ADCP), $_pCO_2$ (US R/V Gould programs)
Continuous Monitoring
In situ
Bottom pressure recorders (UK)
Tide gauges (UK)
Current meter moorings (French)
Inverted echo sounder with pressure gauges and current meters (US)
Global Monitoring from satellite missions:
Sea height
Gravity
Sea Surface Temperature
Sea Surface Salinity
Surface Winds

Table I: *Summary of observational efforts in Drake Passage. A summary of current and proposed observations are shown in Figure 2 and Figure AII-1.*

Autonomous monitoring has been proven over the past few years to dramatically increase spatial and temporal data distribution. For example, Argo profiling floats access remote regions with little or no seasonal bias. In Drake Passage, 4 to 5 Argo floats are being released quarterly. In December 2007, approximately 30 ice-capable iridium Argo floats will be released in the Bellinghausen Sea and they are expected to flow though the southern portion of Drake Passage. The US NSF-funded DIMES program also has an extensive float program. The tracer release area will be seeded with floats in both 2009 and 2010. Also 75 isopycnal RAFOS floats will be deployed in 2009 and again 2010 and ~5 EM-APEX floats. RAFOS floats will be launched in triplets to measure horizontal dispersion. Floats will have 2-year missions and will map out flow in the Scotia Sea. Over the next few years there will also be animal-borne CTD profiles, for example the SEaOS program, http://biology.st-andrews.ac.uk/seaos/index.html, utilizing elephant seals as oceanographic samplers.

Dedicated programs coordinated along repeat ship tracks yield systematic and sustained *in situ* observational programs. Three programs exist using the R/V Gould. The R/V Gould is a major research platform for ocean and climate studies, and it is also the principal supply vessel for the U. S. Antarctic Program research station at Palmer Station, Antarctica. The R/V Gould routinely travels from Punta Arenas, Chile to the Antarctic Peninsula region, crossing the Drake Passage 2 to 4 times per month. A six-time-a-year XBT/XCTD survey has been in operation since 1996 (PI Janet Sprintall). A shipboard acoustic Doppler current profiler measures upper-ocean current on each Drake Passage crossing on the R/V Gould twenty times per year (1999-2004 upper 300 m vertical range; 2004-2009 upper 1000 m vertical range) (PI Chereskin/Firing). Surface $_{p}CO_2$ has also been measured 2002-2008 on each crossing (PI Sweeney). Another repeat section program, CANOPO (Southern Hemisphere Constellation, project name: The Role of the Atlantic Sector of the Southern Ocean in CO2 Sequestration), is a collaboration between Italy, Argentina, and France consisting of repeat XBT/XCTD 2004-2007 aboard the Argentine icebreaker M/V Irizar (http://clima.casaccia.enea.it/canopo/index.php?lang=en), . These measurements extend beyond Drake Passage and into the undersampled area of the Weddell Sea to reveal the importance of both vertical heat fluxes and the interaction between fronts and biology in the Weddell Sea

Bottom pressure recorders and tide gauges provide a useful way to monitor Drake Passage transport, in particular because they do not alias high-frequency signals. The UK Acclaim program (http://www.pol.ac.uk/psmsl/programmes/acclaim.info.html) has brought together these measurements with modelling and satellite altimeter research. Drake Passage transport varies on a range of timescales: subseasonal (forced by the Southern Annual Mode and remotely forced continental shelf waves), seasonal, and interannual. Changes in transport are mainly barotropic for the subseasonal and seasonal time scales whilst interannual variability is reflected in the baroclinic (steric) transport. Two bottom pressure recorders, ND2 and SD2 were first deployed during WOCE at the northern and southern sides of Drake Passage, respectively. Nearly 20 years of data exist with funding for another 5 years secured. A new tide gauge as part of GLOSS at South Georgia Island will come on line shortly.

Some in situ time series can be referenced to altimetry-derived sea surface height, thereby extending the time series back to 1992. This has been done in the Malvinas Current (PI C. Provost) and in the Brazil Current (PI G. Goni). Additionally as part of a collaborative effort between LOCEAN (PI C. Provost), KORDI (PI J-H. Lee), and AWI (PI E. Farhbach) ten tall current meter moorings have been deployed along Jason track #106 at 9 cross-over points with an additional mooring in the Yanghan Basin. The full 10-mooring array has been in the water since February 2006 and will be recovered in April 2008. Five to six moorings will be redeployed in the Yaghan Basin and recovered in September 2009.

An array of C-PIES (Current and Pressure recording Inverted Echo Sounders) will be deployed in November 2007 for a period of four years to quantify the transport and dynamics of the Antarctic Circumpolar Current in the Drake Passage. Two short current meter moorings will also be deployed for one year along the northern continental shelf to help evaluate the vertical and temporal structure associated with continental shelf waves. The C-PIES array consists of a transport line and a local dynamics array. The transport line has resolution of 45-65 km and it will be used to determine the seasonal and annual transport, the lateral and vertical transport partitioning and to recommend a minimal long-term monitoring array design for the future (PIs Chereskin, Donohue and Watts).

Topics for discussion in the working group included:

- How do we move from process studies to sustained and effective monitoring?
- What are the observational gaps? (For example, how do we measure transport and water properties (T, S) with same resolution? Do we need to a better understanding of continental shelf wave propagation?)
- What are the models telling us? (variability *vs* mean)
- How will we use models (process or prediction)?

- What model validation needs to be done?
- Is there a role for models to synthesize data?

Session 2.2: Interocean Exchange: Indian-Atlantic Ocean

Reporter: Gustavo Goni

In this session results were presented from observations, numerical models and theoretical studies on water exchange between the Indian and the Atlantic oceans. A particular focus was given to the most dynamical active regions with regards to these exchanges, the Cape Basin and the Southern Ocean south off Africa. It was agreed that any one single measure cannot resolve the intricate processes that occur in the Cape Basin, nor monitor the complex oceanic fronts south of Africa. It was argued that the key element when designing the observing system in this region of the South Atlantic is to better understand the time and space scales of measurements and the type of observations that need to be done. Present and future observations should be used to assess model capability to represent the observed dynamics. The physics behind the processes is also critical to understand the models and to justify and design future observations.

South of Africa, the Agulhas leakage is the main conduit of inter-ocean exchange. It occurs mainly by means of Agulhas rings and a small contribution from a mean flow leakage. These rings carry large amounts of salt and heat. Altimetry observations reveal that there is a strong year-to-year variability in the shedding of rings, which on average transport from 0.5 Sv to 1.5 Sv in each ring, with 1 to 6 rings shed per year (Goni *et al*., 1997) (Figure 3).

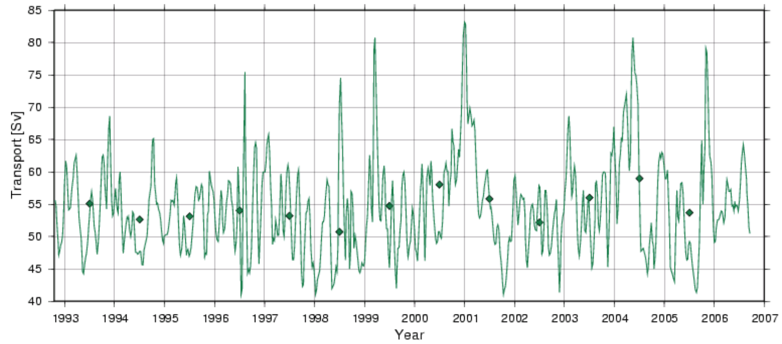


Figure 3. *Altimeter-derived geostrophic transport of the Agulhas Current. The peaks in the transport values are usually associated with the shedding of an Agulhas ring.*

The potential of altimetry fields should be exploited by blending these data with those from observations from other platforms. For example, statistical analysis between sea height anomaly fields and the depths of the isotherms in the south Atlantic indicates that the Agulhas Current vertical thermal structure below the mixed layer depth may be investigated using altimetry observations, where correlations coefficients above 0.7 over most places exist between the variability of the sea height anomalies and that of isotherm depths within the thermocline waters (Figure 4, left panel). Likewise, the correlation between along-track sea height anomaly gradients and across-track drifter-derived geostrophic currents suggests that altimetry fields can be used to estimate the geostrophic velocity and transports of the Brazil and Agulhas Currents (Figure 4, right panel). Statistical analysis using altimetry observations, although not accurate as actual observations, are shown to be practical and to provide helpful spatial information to monitor the variability of certain parameters and to carry out model validations.

The development of regional high-resolution numerical simulations has allowed the scientific community to investigate dynamical processes suspected to play a key role on the Agulhas Current retroflection, Agulhas rings shedding and Indo-Atlantic interocean exchange. Numerical sensitivity experiments show that smoothing of the bathymetry produces larger leakage of Indian Ocean waters into the South Atlantic. Also, the leakage appears to be very sensitive to the open boundaries mean field applied. (Figure 5; from Speich *et al.* 2006, 2007).

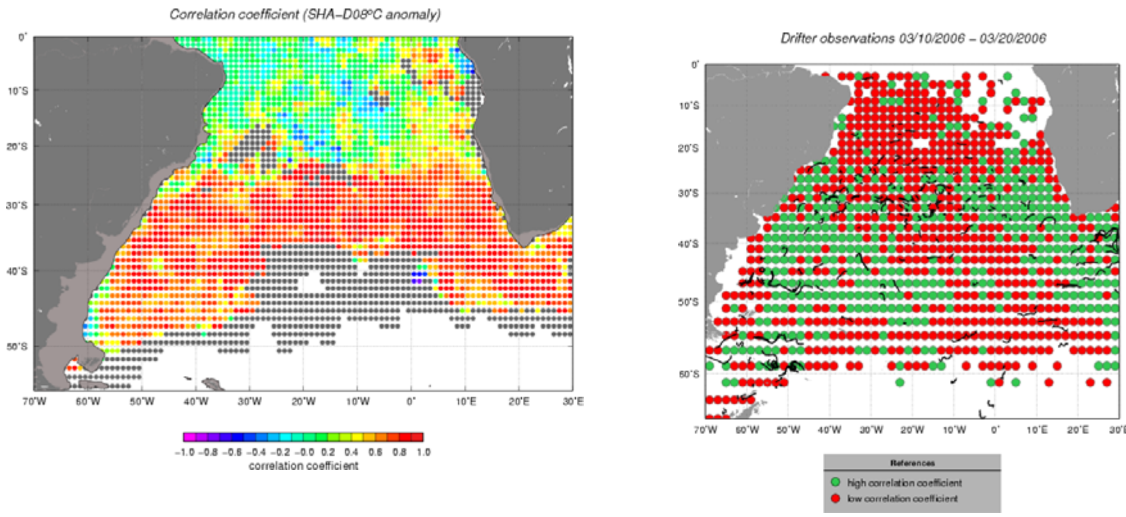


Figure 4. *(left) Correlation coefficient between altimeter-derived sea height anomalies and the depth of the 8ºC isotherm obtained from XBT and profiling float observations between 1993 and 2006. (right) Correlation coefficient between sea height anomaly gradients and drifter derived (Ekman removed) surface velocities between 1993 and 2006. Superimposed are the trajectories of drifters during a 10-day period in March 2006. Areas of high correlation coefficient can be used to estimate surface velocities from altimetry where there are no surface drifter observations.*

These numerical studies suggest that the separation of the Agulhas Current from the continent occurs because of the radius of curvature of the slope du to the high current inertia. The amount of Indian Ocean water that flows into the South Atlantic is sensitive to the latitude of the eddy shedding, the boundary conditions, beta effect, as well as the existence of topography features such as the Agulhas Plateau. Interocean transport values may range between 4 Sv (beta=0) and 56 Sv when the Agulhas Plateau is removed. Mean values ranging between 25 and 15 Sv occur for a realistic configuration, the Indo-Atlantic leakage depending now on model resolution and open boundaries thermodynamical fields.

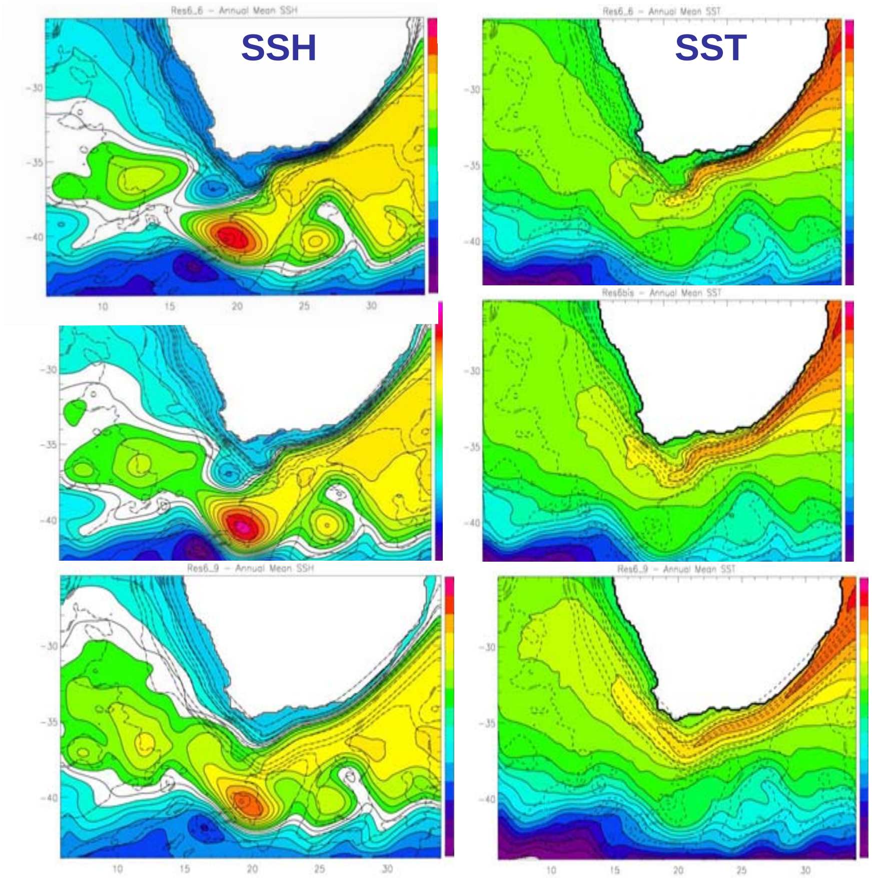


Figure 5. *The Agulhas retroflection and rings in several sensitivity runs within a ROMS. The smoother bathymetry produced a larger leakage of Indian Ocean waters into the South Atlantic, as reproduced by sea surface height (SSH) and sea surface temperature (SST) fields.*

Additionally, the variable leakage produced by the Agulhas rings was suggested to be strongly influenced by the coastal slant within a nonlinear analytical model. It was also hypothesized that the shift to the north in the zero wind stress curl position alone could not be sufficient to block the leakage, as rings would still exist. It is therefore suggested that the particular shape of the African coastline is responsible for the varying leakage, high in the present day situation and low during periods of glaciation (Figure 6).

The regional study also suggests that nonlinear interactions in the Cape Basin are very important in the convergence and mixing of water masses of different origins, and therefore they influence the properties of water finally injected into the South Atlantic. The relative vorticity appears to be the most appropriate variable for the method to isolate the structure of eddies (Figure 7). This way it is possible to determine the water masses composition and evolution of such features.

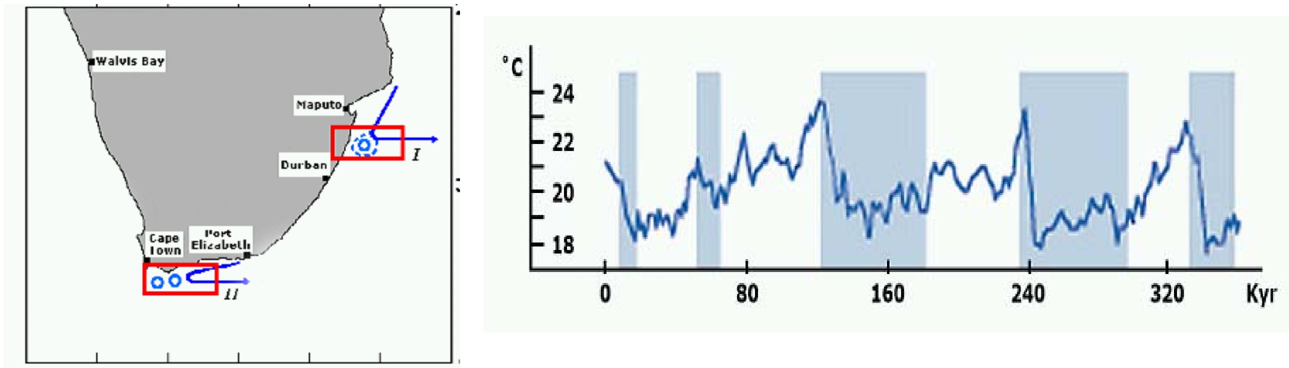


Figure 6. *(left) Diagram of the Agulhas Current and its retroflection. It is hypothesized that, due to a northward shift in the position of the vanishing wind stress curl, the retroflection during the glaciation periods occurred in a lower latitude where the orientation of the coast line is close to meridional (situation I). During the presentday, the retroflection occurs farther to the south, where the coastline inclination is almost zero (Situation II). It is also hypothesized that almost no ring detachment would occur in situation I. However, many rings would detach in situation II. (right) Southeast Atlantic sea surface temperature (in ºC) at the Cape Basin Region core situated at 35ºS and 18ºE, for the past 36,000 years as determined by Pale Oceanographic proxies (adapted from Peeters, 2004). Note the dramatic increase in temperature in the end of each glaciation period (vertical shaded blue). These increases are attributed to an increase in ring production, which induces a transfer of warm and salty Indian Ocean water to the colder South Atlantic (Peeters et al, 2004).*

Preliminary results show that local processes are very important to modify Agulhas rings properties. Water masses from the Southern Ocean, the South Atlantic and from the African continental slope mix with Indian waters. The next step is to precisely evaluate the mixing together with the involved processes. This will allow the determination of the water masses that are eventually advected from the Cape Basin cauldron into the South Atlantic. Results will be validated against altimetry initially, and possibly with historical hydrology, biogeochemical data, and using results from possible future experimental process studies.

Results from ASTTEX, a recently completed experiment, were presented at the meeting as well. During this experiment 12 PIES and 3 CMM were deployed for an 800 day period from January 2003 until April 2005 (Figure 8). These instruments measured over 90% of the rings present in the Cape Basin and ASTTEX provided an important yardstick for future MOC monitoring design.

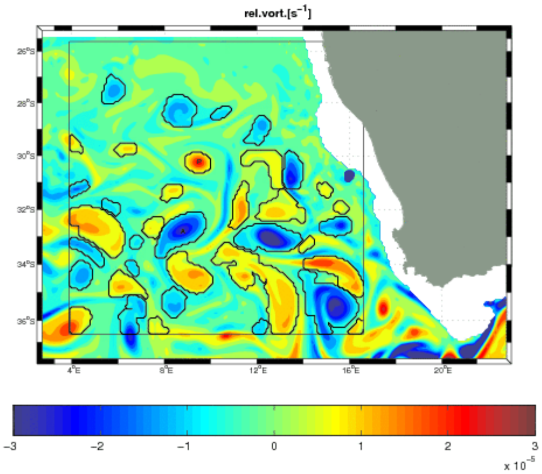


Figure 7. *In order to identify mesoscale structures, horizontal slices of relative vorticity are decomposed with the wavelet technique following the classical approach utilized in image processing.*

A model-based pilot study using the 0.1-degree global POP model indicates that the spatial and temporal sampling resolution used in ASTTEX is adequate to resolve the mass and anomaly heat and salt transports to within 25% of the true transports. A test calculation performed on the actual moored data indicated that doubling the mooring spacing to ~150 km introduced significant aliasing, about 50% of the measured signal.

ASTTEX provided integrated measures, such as travel time from IES and PIES, which were blended with steric height values obtained from synthetic travel time and steric height data calculated from historic T-S profile data. Work is underway to improve point estimates of steric height from altimetry, including tidal corrections and barotropic component of sea height, and use of new orbits and sea state bias corrections. Thus although the salinity anomaly (and thus probably the baroclinic transport) will be underestimated, at present the ASTTEX mooring data are being interpreted using only travel time to make estimates of S(z) and T(z), and corresponding baroclinic transports. Plans for present and future observations were presented and discussed.

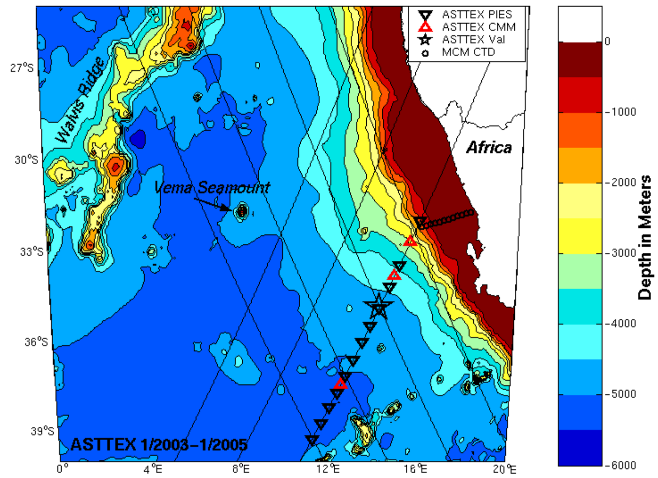


Figure 8. *Location of the ASTTEX moorings.*

The availability of altimetry data from future missions was addressed. It was argued that capturing the mesoscale features as provided, for example, by a Jason-1-like and Envisat-like constellation of satellites, were critical to investigate and monitor processes such as the Agulhas Current retroflection and the shedding of rings. It was proposed that future deployments (PIES, C-PIES, IES, CMs, etc) when possible, be made along Jason altimeter ground tracks from South Africa to Antarctica to measure the variability of the frontal regions and of the mass, salt and heat transport. A large international effort began in September 1996 to monitor the upper ocean thermal structure from XBT transects across the Drake Passage (see Section 2.1). In comparison, similar efforts between South Africa and Antarctica are relatively new as they started in February 2004 with two to three transects carried out per year along the AX25 XBT transect (Figure 9). This transect is a collaborative effort between the University of Cape Town, NOAA/AOML, University of Brest, and the Shirshov Institute of Oceanology. At the time of the workshop, 8 transects had been completed. The objective of this line is in support of the GoodHope project to investigate the Indo-Atlantic water exchanges and their impact on the global thermohaline circulation, to study the variability of the frontal regions and their transports between South Africa and Antarctica, and to support other environmental and meteorological observations carried out during each transect.

During the session efforts to coordinate measurements between different programs in the Drake were discussed.A Drake Passage transport array involving 17 CPIES (Chereskin, Donohue and

Watts) is scheduled for deployment in late 2007 with recovery 4 years later (see Section 2.1). This array will measure the flow between the South Pacific and South Atlantic Oceans. It would be especially valuable to have simultaneous measurements of the flow between the Indian and South Atlantic Oceans. A cost-effective means for measuring long-time-series sections of velocity, temperature and salinity is a 1-d line of C-PIES instruments. Data from such an array would complement data from the Drake Passage array and supplement data from the GoodHope transect (Speich *et al*. 2003). PIES deployments are already planned for the region south and west of South Africa by Boebel/Macrander and Speich.

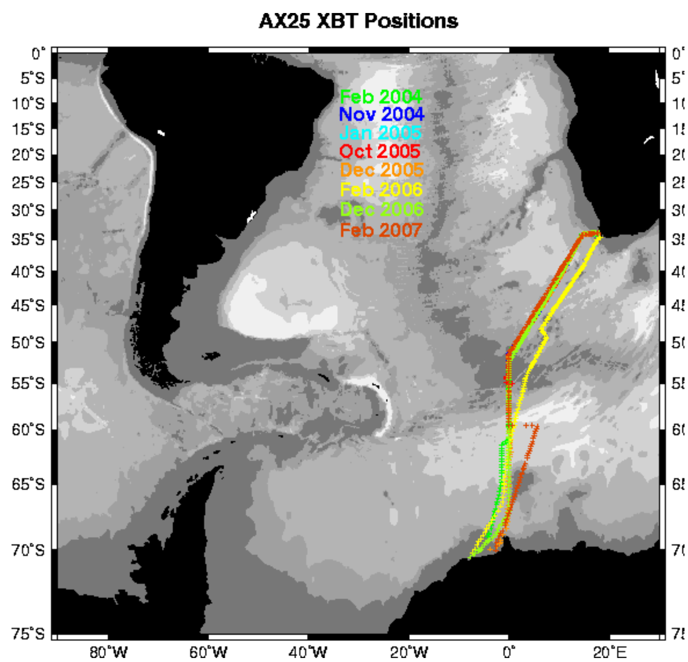


Figure 9. *Location of the first eight XBT transects carried along AX25.*

A "straw-man" plan was proposed: 23 C-PIESs along the GoodHope line (due west from Cape Town to Jason-1 Track #133, southwestward on this track to the Zero Meridian, and due south from there) to 60ºS (see red dots in Figure 10). The deployment would be in 2008-09 and the recovery would be in 2011-12. Scientists from AWI-Bremerhaven (PI Boebel/Macrander) have already deployed 6 PIESs at Jason-1 crossover points on the GoodHope section of Track #133: and 3 additional PIESs further to the north for GRACE comparisons. Additional instrumentation will be deployed in the area: The GoodHope project (PI Speich) will deploy 2 C-PIESs; URI (PI

Wimbush) proposed contributing with approximately 20 CPIESs; University of Maine (PI Byrne) will make available 12; and NOAA-AOML (PI Garzoli) will supply 4 PIES and 1 C-PIES.

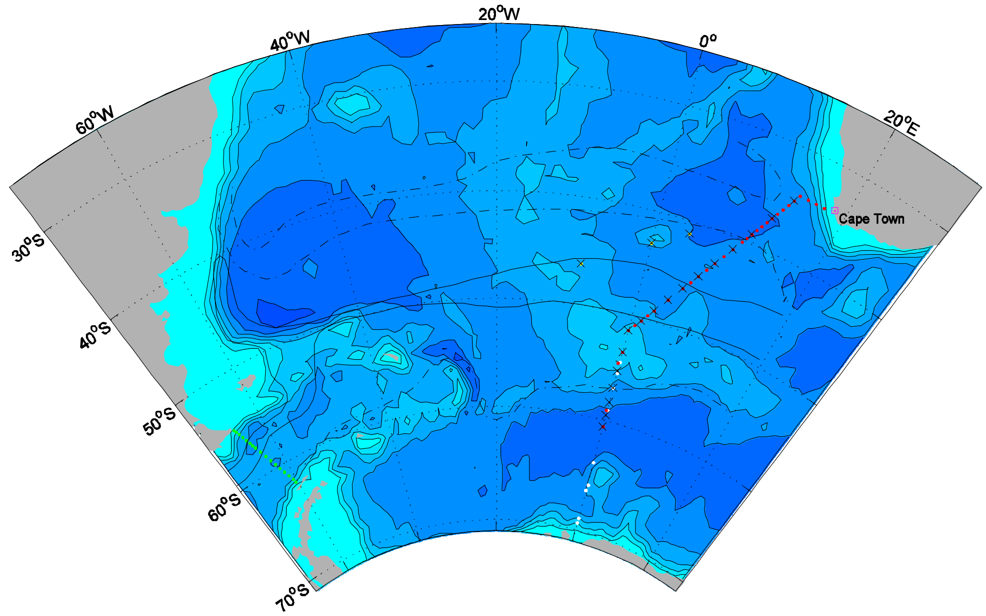


Figure10: *The proposed SR2/GoodHope-line array of C-PIES/PIES instruments (red dots) and tall moorings (white dots). Jason-1 crossover points are marked "×". [To the north, at 41-46°S, 3 additional PIES instruments (magenta dots) are deployed by AWI for validation of the GRACE satellite gravimeter.] The Drake Passage transport array of C-PIES instruments is also shown (green dots). Frontal locations from Belkin (1993) are shown. From north to south they are NSTF, SSTF, SAF, PF, SF (the first two and the last, dash-dot lines; the other two, solid black lines). Depth contours are at 1000 m intervals.*

During the session it was agreed that the following issues need to be further discussed as part of the planning for this "straw-man":

1. C-PIES/PIES spacing in high-energy/frontal regions (e.g., Agulhas rings, SAF, PF)
2. Evaluation if 60˚S is an appropriate southern end point for the array, and if the northern limit of the array should be north of 42˚S,
3. Integration of the C-PIES array with PIESs from different groups (Boebel, Speich, Byrne, Garzoli),
4. Number of C-PIES instruments needed,
5. Identify ships to perform the deployment and recovery of instruments,
6. Evaluate possibility of performing CTD casts at the C-PIES/PIES sites,
7. Explore the possibility of acoustically telemetering the data to a ship,

8. Implementation of GEM fields to interpret data, and
9. Evaluate if the arrays will allow measuring heat and salt fluxes in addition to mass fluxes.

To maximize the outcome of these efforts discussions already started among the different groups to coordinate several ongoing projects and plans. It was also agreed that efforts should be made for data collection and transmission in near real time, if possible within periods no longer than 3 to 6 months.

Session 2.3: Meridional inter-hemispheric fluxes

Reporter: Molly Baringer

This session began with a description of some modeling work that emphasizes the importance of the South Atlantic thermohaline circulation in setting decadal variations in tropical SSTs. The Atlantic basin imports heat across 33°S, uptakes heat mainly in the equatorial cold tongue region and loses it in the high northern latitudes. Both the meridional overturning circulation and the subtropical cells participate in the meridional transport of heat. Calculations with numerical models of different complexity show that under perturbations that alter the heat input the ocean adjusts its heat budget in different ways. For highly diffusive models such as those used in IPCC assessments, the decrease in heat loss due to a freshening of the northern Atlantic is balanced by a reduction of the input of heat across 33ºS through a weakening of the meridional overturning circulation (Figure 11, left). Meanwhile, there is minimal change in equatorial sea-surface temperature. In high-resolution models, instead, there is a large warming along the equator and in coastal-upwelling regions that signals a decrease in the heat uptake that helps balance the decrease in heat loss (Figure 11, right). This equatorial decrease is achieved mainly by changes in the subtropical cells as a consequence of a decrease in the meridional density gradient. Computation of the heat budget in the freshening experiment shows that the flux of heat out of the surface reaches a new equilibrium within a decade, but the adjustment of the meridional overturning circulation, and of the transport of heat across 33°S, takes far longer. The total budget is close to a new balance after about 60 years (not shown). While the circulation continues to adjust, the flux of heat into the ocean across its surface hardly changes because the increase in heat uptake in the northern region is balanced by reduced heat uptake in the equatorial region. Further correlation analysis show that the heat-transport across 33ºS co-varies with sea-surface temperature along the coastal upwelling regions on interdecadal time scales (not shown). Thus, it was concluded that the region near 33°S is a good location to monitor changes in the Atlantic heat budget, in part due the differing responses in model products that need to be resolved, but also due to its high correlation with equatorial sea-surface temperature and hence the tropical climate system.

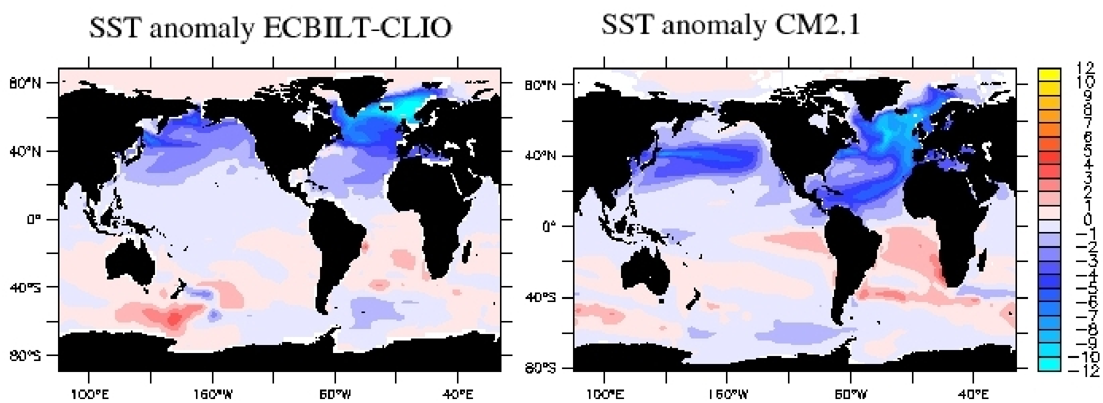


Figure 11: *Comparison of sea-surface temperature anomalies induced in freshening experiments using a low-resolution model (left) and high resolution model (right).*

This session included presentations from our hosts in Argentina outlining the already existing international collaborations involving Argo floats, drifting buoys and XBT deployments in the region through the International South Atlantic Buoy Program and the South Atlantic Argo Regional Center (Figure 12, right). One such program includes outreach to local high school students with the Argentine Naval Hydrographic Center. Also, the Argentine National Fishery Research and Development Institute (INIDEP) offers ships of opportunity to support to a meridional overturning circulation observing system or related activities (Figure 12, left). Through coordination with INIDEP, ships could be obtained for mooring deployments and servicing of CPIES/PIES or current meters arrays. These sea-going platforms can provide mid range (2500m) rosette/CTD casts. Additionally, the Fundacao Universidade do Rio Grande (FURG) in Brazil, plans to continue collaborations with NOAA/AOML in the MOVAR project, the high resolution XBT line measuring the Brazil Current variability between the coast of Brazil and Trinedad Island, and confirms that the line is funded for riders and will receive shiptime from the Brazilian Navy until 2009 (Figure 13, right). So far 8 repeats have taken place with most of the probes being supplied by NOAA/AOML.

The High Latitude Oceanography Group from FURG will be funded by Brazilian PROANTAR (Antarctic Survey) in the framework of the International Polar Year. There will be intense activities near the tip of Antarctic Peninsula in summer 2008/9 on the topic of the Weddell Sea outflow and shelf-slope interactions (Figure 13, left). Argentina and Brazil also continue to cooperate with the US Argo, drifter and high density XBT programs that have substantially increased the data coverage in the South Atlantic in the past five years. These data are critical for estimating circulation pathways in the previously data sparse South Atlantic.

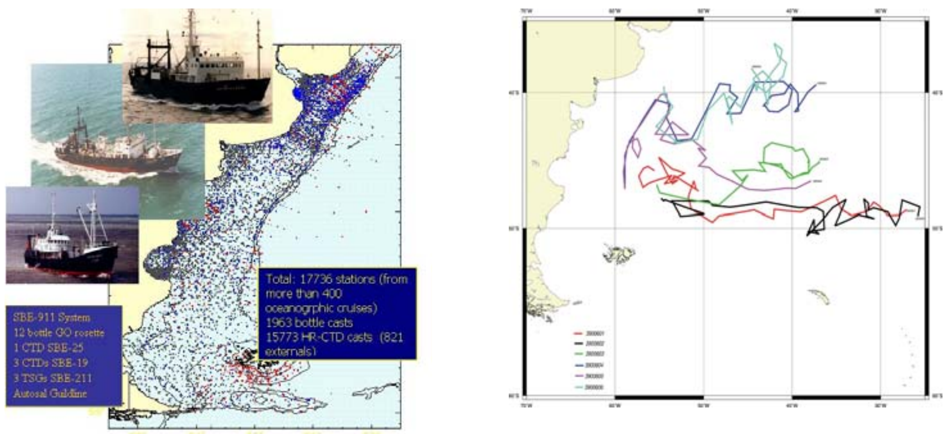


Figure 12: *Two examples of international collaboration opportunities with the Argentinean National Fishery Research Institute and the Argentine Naval Hydrographic Center. (left) deployment platform opportunities and extensive existing historical data collection. (right) examples of trajectories from ARGO floats deployed through the international ARGO Program.*

A presentation pointed out at the availability of Lagrangian observations in the South Atlantic. Two data sets are available in real time: Surface velocities from the Global data Surface Drifters program, and velocity vectors at nominally 1000 or 2000 m from the Argo program. Examples of these data sets are shown in Figures 14.

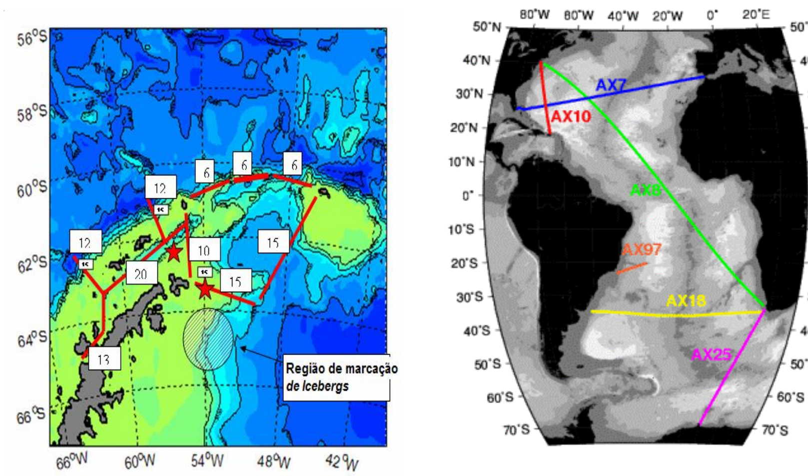


Figure 13: *(left) Synoptic Antarctic Shelf-Slope Interactions (SASSI) initiative for the International Polar Year (IPY) includes a component from the Brazilian Antarctic Survey. (right) Expendable Bathythermograph (XBT) programs currently f*unded including international collaborations between the United States, Brazil, Argentina and South Africa.

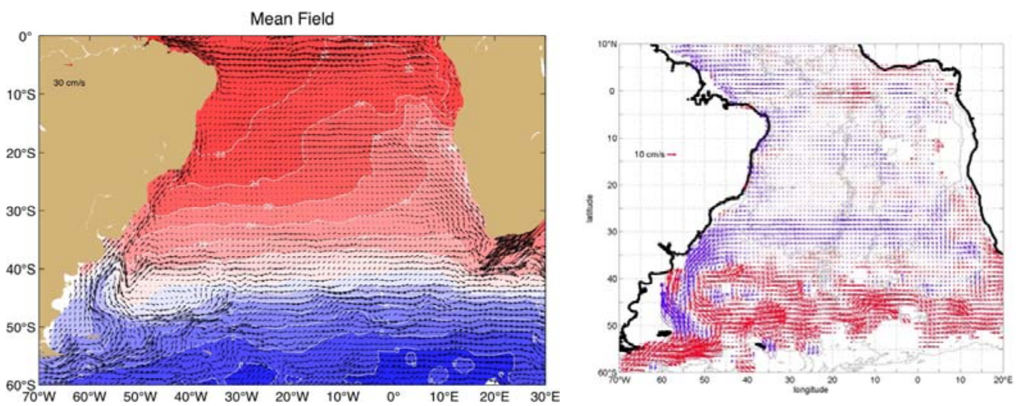


Figure 14: *Left: Mean surface velocity field derived from surface drifters' observations superimposed on sea surface temperature. The figure shows the thermal front originated at the Brazil Malvinas confluence in the South Western Atlantic, the Agulhas retroflection and the Benguela current in the South Eastern Atlantic. Right: Velocity fields after objective analysis of the observed velocities. Color coded by the direction of the zonal velocity (red towards the east).) The objective analysis is essentially a least squares fit to the data. Input parameters to the objective analysis are a zonal and meridional correlation length scales as well as rms errors for the observations and the climatology. This figure shows the gyre at intermediate depth (800-1100 dbar) east to west along 30S and west to east in two branches north and south of the Zapiola gyre and one branch along 45S farther east (east of 20W). (Source AOML)*

A summary of the heat transport estimates obtained from the high-density XBT line AX18 was presented (Figure 13, right). Fourteen temperature sections collected between July 2002 and May 2006 are analyzed to obtain estimates of the meridional heat transport variability of the South Atlantic Ocean (Figure 15, left). The results from the analysis indicate a mean meridional heat transport of 0.54 PW (PW = 10^{15} Watts) with a standard deviation of 0.11 PW. The geostrophic component of the heat flux has a marked annual cycle following the variability of the Brazil Malvinas Confluence Front, and the geostrophic annual cycle is 180° out of phase with the annual cycle observed in the Ekman fluxes (Figure 15, right). As a result, the total heat flux shows significant interannual variability with only a small annual cycle. These results emphasized the importance of continuous time series measurements of the circulation including properly accounting for annual cycle variations so as not to alias interannual changes.

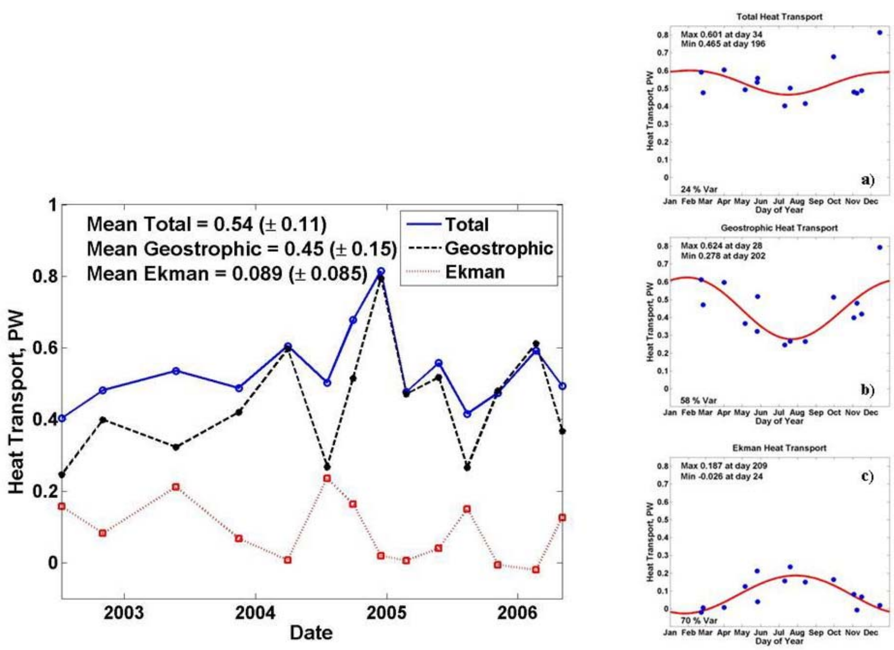


Figure 15: *Heat transport estimated for the XBT line AX18 near 34ºS (left). (right) annual cycle of various components in the heat transport estimate (from Garzoli and Baringer, 2007).*

The presentations included discussions of the importance of measuring the western boundary current regime, e.g. with both traditional current meter observations (Figure 2) and new instrument development systems like inverted echo sounders coupled with an expendable data retrieval system (Figure 16). The proposed Current meter array coincident with the 30ºS repeat hydrographic line and the proposed PIES/C-PIES deployment along 35ºS near the western boundary of the Atlantic basin was discussed. These mooring arrays would provide absolute velocity estimates in an area of the Brazil Current, for use with the repeat hydrographic line and the high density XBT work currently underway on the AX18 line (Figure 13, right). The data pod system for the PIES/C-PIES could provide a unique real-time data transmission technology that would allow for data access in near real-time in remote regions and this system could be expanded to other areas and other types of mooring deployments.

In summary the presentations pointed to

- Meridional overturning circulation variability can be linked to 30ºS/33ºS heat transport but over longer time scales than surface fluxes
- Discernable changes in sea-surface temperature appear linked to the eastern boundary circulation
- Western Boundary Currents are critical to observe accurately either the meridional overturning circulation or heat transport
- Very little is currently in place or even proposed that will capture all the meridional overturning circulation as a sustained observing system

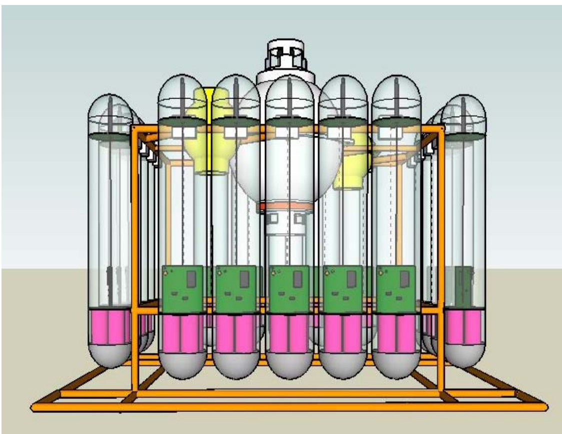


***Figure 16**: Data pod expendable data retrieval system coupled to an inverted echo sounder (IES). This system is being proposed by investigators in the United States to be deployed in the 30-35ºS region along the western boundary (see Figure 2 for locations, red squares).*

References

Barreiro M, A. Fedorov, R. Pacanowski, G. Philander, 2008. Abrupt climate changes: How freshening of the northern Atlantic affects the thermohaline and wind-driven oceanic irculations, In Press, Rev. Earth. Planet Sci.

Bennett, A. F., 1978. Poleward heat fluxes in the Southern Hemisphere oceans. J. Phys. Oceanogr., 8, 785–798.

Boebel, Olaf, Schmid, Claudia, Zenk, Walter, 1999. Kinematic elements of Antarctic Intermediate Water in the western South Atlantic. Deep-Sea Research-II. 46, 355-392.

Boebel, Olaf, Schmid, Claudia, Podesta Guillermo, Zenk, Walter, 1999. Intermediate water in the Brazil-Malvinas Confluence Zone: a Lagrangian view. Journal of Geophysical Research, 104(C9), 21063-21082.

Belkin, I. M., 1993. Front structure of the South Atlantic, in Pelagicheskie Ekosistemy Yuzhnogo Okeana (Pelagic Ecosystems of the Southern Ocean), (in Russian), edited by N. M. Voronina, pp. 40–53, Nauka, Moscow, 1993.

de las Heras, M. M. and R. Schlitzer, 1999. On the importance of intermediate water flows for the global ocean overturning. Journal of Geophysical Research, 104, 15515-15536.

de Ruijter, W. P. M., A. Biastoch, S. S. Drijfhout, J. R. E. Lutjeharms, R. P. Matano, T. Pichevin, P. J. van Leeuwen, and W. Weijer, 1999. Indian-Atlantic interocean exchange: Dynamics, estimation and impact. J. Geophys. Res., 104, 20885-20910.

Doglioli, A., M. Veneziani, B. Blanke, S. Speich, A. Griffa, 2006. A Lagrangian analysis of the Indian-Atlantic interocean exchange in a regional model, Geophys. Res. Lett., Vol. 33, No. 14, L14611 10.1029/2006GL02649825 July 2006.

Doglioli, A. M., B. Blanke, S. Speich, and G. Lapeyre, 2007. Tracking coherent structures in a regional ocean model with wavelet analysis: Application to Cape Basin eddies, J. Geophys. Res., 112, C05043, doi:10.1029/2006JC003952.

Duplessy, J.-C. & Shackleton, N.J., 1985. Response of global deep-water circulation to the Earth's climatic change 135,000-107,000 years ago. Nature, 316, 500-507.

Fedorov A, M. Barreiro, G. Boccaletti, R. Pacanowski, G. Philander, 2007. The freshening of surface waters in high latitudes: Effects on the themrohaline and wind-driven circulations. JPO 37, 896-907.

Fu, L. L., 1981. The General Circulation and Meridional Heat Transport of the Subtropical South Atlantic Determined by Inverse Methods. Journal of Physical Oceanography, 11, 1171-1193.

Fu, L-L, 2006: Pathways of eddies in the South Atlantic revealed from satellite altimeter observations. *Geoph. Res. Lett.*, 33, L14610, doi:10.1029/2006GL026245.

Garzoli S. and Baringer O. M., 2007. Meridional heat transport determined with expandable bathythermographs –Part II: South Atlantic transport. Deep Sea Reasearch Part I. 54 1402-1420.

Garzoli, S.L., Gordon, A.L., 1996. Origins and variability of the Benguela current. Journal of Geophysical Research 101, 897–906.

Goni, G., S. Garzoli, A. Roubicek, D. Olson and O. Brown, 1997. Agulhas Rings Dynamics from TOPEX/POSEIDON Satellite Altimeter Data, J. Mar. Res., 55, 861-883.

Gordon, A. L., 1986. Interocean exchange of thermocline water. *Journal of Geophysical Research*, **91**, 5037-5046.

Gordon, A. L. and W. F. Haxby, 1990. Agulhas eddies invade the South Atlantic: Evidence from GEOSAT altimeter and shipboard conductivity-temperature-depth survey. *J. Geophys. Res. 95*(C3), 3117-3125.

Legeais, J.-F., S. Speich, M. Arhan, I. Ansorge, E. Fahrbach, S.L. Garzoli, and A. Klepikov, 2005. The baroclinic transport of the Antarctic Circumpolar Current south of Africa. Geophysical Research Letters, 32(24):L24602, doi:10.1029/2005GL023271.

Matano, R.P., and E.J. Beier, 2003. A kynematic analysis of the Indian/Atlantic interocean exchange, *DeepSea Res. II, 50*, 229249.

Meredith, M. P., and **C.** W. Hughes, 2005. On the sampling timescale required to reliably monitor interannual variability in the Antarctic circumpolar transport. Geophys. Res. Lett., 31, L09609, doi: 10.1029/2004GL022086.

Model, F., 1950. Warmwasserheizung Europas. Ber. Deut. Wetterdienstes, 12, 51-60.

Orsi, A. H. and Whitworth III, T. and Nowlin Jr., W. D., 1995 On the meridional extent and fronts of the Antarctic Circumpolar Current. *Deep Sea Res., Part I*, 42,641-673.

Peeters FJC, Acheson R, Brummer G-J, deRuijter WPM, Schneider RR, Ganssen GM, Ufkes E, Kroon D, 2004. Vigorous exchange between Indian and Atlantic ocean at the end of the past five glacial periods. Nature 430, 661-665.

Richardson, P.L. and S.L. Garzoli, 2003. Characteristics of intermediate water flow in the Benguela current as measured with RAFOS floats. Deep Sea Research II, 50(1): 87-118.

Rintoul S. R., 1991. South Atlantic interbasin exchange. J. Geophys. Res, 96, 2675–2692.

Sloyan B. M., and S. R. Rintoul, 2000: Estimates of area-averaged diapycnal fluxes from basin-scale budgets. J. Phys. Oceanogr, 30, 2320–2341.

Speich et the GoodHope team, 2003:http://www.clivar.org/organization/southern/process.htm.

Speich, S., P. Penven, B. Blanke, et J. Lutjeharms, 2006. The Indo-Atlantic exchange : dynamics of a regime transition from a western boundary current to an eastern boundary system. Geophys. Res. Lett., VOL. 33, L23611, doi:10.1029/2006GL027157.

Speich, S., B. Blanke, and W. Cai, 2007. The Atlantic Meridional Overturning Circulation and the Southern Hemisphere Supergyre. Geophys. Res. Lett. Subjudice.

Stramma L., and M. England, 1999. On the water masses and mean circulation of the South Atlantic Ocean. J. Geophys. Res, 104, 863–883.

Stammer, D., C. Wunsch and K. Ueyoshi, 2006. Temporal Changes in Ocean Eddy Transports. J. Phys. Oceanogr., 36(3), pp. 543-550, doi:10.1175/JPO2858.1.

Stouffer, R. J., 2006. Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes, J. Clim. 19, 1365-1387.

Tokmakian, R. T. and P. G. Challenor, 1999. On the joint estimation of model and satellite sea surface height anomalies. Ocean Modelling, 1, 39-52.

Weijer, W., W. P. M. De Ruijter, A. Sterl and S. S. Drijfhout, 2002. Response of the Atlantic overturning circulation to South Atlantic sources of buoyancy. Global and Planetary Change, 34, 293-311.

Appendix I: List of Participants

Name	Country	Institution
Baringer, Molly	USA	NOAA/AOML
Barreiro, Marcelo	Uruguay	Univ. De LA Republica/Uruguay
Byrne, Deirdre	USA	Univ. of Maine
Campos, Edmo	Brazil	IOUSP/Brazil
Chereskin, Teri	USA	SIO/.UCSD USA
Donohue, Kathleen	USA	URI
*Garzoli, Silvia	USA	NOAA/AOML
Gladyshev, Sergey	Russia	SIO, Moscow
Goni, Gustavo	USA	NOAA/AOML
Guerrero, Raúl	Argentina	INIDEP
Lagerloef, Gary (only day 1)	USA	ESR
Lindstrom, Eric (only day 1)	USA	NASA/HQ
Macrander, Andreas	Germany	AWI, Bremerhaven
Mata, Mauricio M.	Brazil	FURG/Brazil
Matano, Ricardo P.	USA	OSU
McDonagh, Elaine	England	NOC, Southampton
Meinen, Christopher	USA	NOAA/AOML
Meredith, Mike	England	British Antarctic Survey
Nof, Doron	USA	Florida State Univ.
Owens, Breck	USA	WHOI
*Piola, Alberto	Argentina	SHN/UBA
Piotrowicz, Steve	USA	NOAA/OAR
Provost, Christine	France	CNRS/LOCEAN
Rupolo, Volfango	Italy	ENEA
Sokov, Alexey	Russia	SIO, Moscow
*Speich, Sabrina	France	LPO, Univ. of Brest
Troisi, Ariel Hernan	Argentina	SHN
Watts, Randy	USA	Univ. Rhode Island
Wimbush, Mark	USA	GSO, Univ. of R.I.

* The Organizing Committee

Appendix II

Reports from the breaking groups

Pacific-Atlantic Working Group Discussion

Attendees: Mike Meredith, Randy Watts, Teri Chereskin, Breck Owens, Sergei Gladyshev, Elaine McDonagh, Alberto Piola, Christine Provost, Volfango Ruppolo and Kathy Donohue

Reporter: Kathy Donohue

Working Group Discussion

A key companion to monitoring is an ever increasing knowledge of the system. Since measurements will contain spatial and temporal errors it is essential that we understand the processes and the sampling rates in which they need to be sampled. We need to understand the observed changes for two reasons: first for predictive ability and second because the understanding of these changes provides assurance that we know what we have measured.

As mentioned previously, the present observational array is probably adequate for mass transport on time scales up to interannual time scales. In the longer term we can’t neglect Drake Passage. Do we know the answer to a very fundamental question: Why is the ACC transport what it is? If a numerical model gets the number right, how assured are we that the physical processes are well represented in the model? Is it possible to get the number right for the wrong reason? There are gaps both spatial and temporal. For example, we lack understanding of the continental shelf waves which propagate around the northern Drake Passage from the Pacific to the Atlantic. We currently have no strategy in place that would allow us to evaluate decadal change. If there is a change in transport, what are the implications? For example, we know winds are getting stronger and contracting towards to pole. Will the ACC change position? How will this impact the interaction of ACC with subtropics and polar areas? Perhaps the most serious gap is the lack of sustained and frequent property measurements. How do we go beyond mass transport and monitor heat and freshwater fluxes? A change in eddy heat flux would have direct implications for the meridional overturning cell.

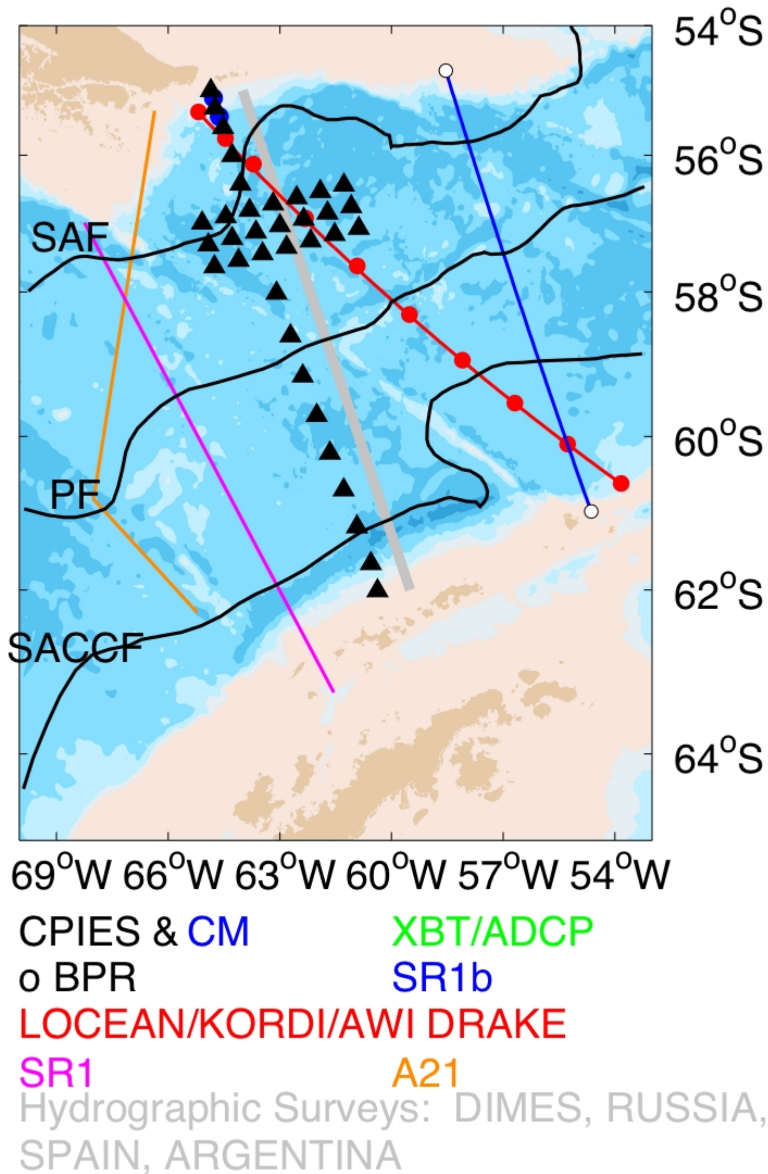


Figure Appendix II 1. *Present or planned observations in Drake Passage. Tide gauge network is not shown. Topography from Smith and Sandwell 1997 contoured every 1000 m depth. Antarctic Circumpolar Current fronts from Orsi et al. 1995.*

Indian Ocean-Atlantic Ocean Group

Attendees: Silvia Garzoli, Mark Wimbush, Doron Nof, Sabrina Speich, Gustavo Goni, Andreas Macrander, Sergey Gladyshev, Marcelo Barreiro, and Alexey Sokov.

Reporter: Gustavo Goni

The group agreed on that the critical objective would be to investigate the sources of the MOC in the South Atlantic.

The Agulhas leakage is the export of Indian Ocean waters into the South Atlantic, importing into this region one of the major interbasin volume transports of water masses, salt and heat away from the ACC. Any array to measure this leakage should consist in closing a box (Drake Passage – 30/35°S – South Africa to Antarctica) to compute the volume balance in the SA. This array will need to be coordinated with current efforts in the Drake Passage monitoring system and the current/proposed 30/35°S monitoring transects. To accomplish this, and based on past and current observations that proved to be successful, the group proposed to carry observation in: 1) Agulhas leakage and rings, 2) ACC fronts, and in the Benguela upwelling region.

The water leakage is also critical to compute the meridional heat transports in the South Atlantic. For this reason, the HD line AX18 at 35S is recommended to be kept and to install two or more C-PIES (to be provided by Speich) at the eastern edge of AX18. This will allow providing a reference level when computing transports. A detailed map of altimeter based trajectory of rings could help to determine the best location for the C-PIES.

Besides HD AX18, it is recommended to continue the HD lines: AX08, AX25.

The monitoring of Agulhas Current rings, the leakage of Indian Ocean waters into the Atlantic and ACC transport are proposed to be maintained using:

- Current German and 4 year array recommend by Mark Wimbush
- Good Hope - AX25 line. It was pointed out that the sampling on AX25 is biased towards the summer months. To correct this, Gladyshev volunteered to provide fall month XBT/CTD sections, if funded. Other XBT observations, including those obtained from

the Akademik Vavilov, will be provided by Gladyshev to AOML and also placed into the GTS by the NOAA/AOML SEAS group.

- Additionally, both AX08 and AX18 capture the upper 700m of the thermal structure of most of the rings shed by the Agulhas Current.

The array proposed by this group would consist of:

2 C-PIES, provided by Good-Hope (Speich)

21 PIES provided by URI (Wimbush)

1 CPIES and 8 PIES provided by AWI (Boebel/Macrander)

3 additional PIES to be provided by AWI (Boebel/Macrander: funding already in place)

The southernmost location for this array is proposed to be at 60S that is south of the Southern Boundary of the ACC at this latitude (Legeais *et al.* 2005). South of this latitude the AWI is committed to continue the deployment and monitoring of the Weddel Gyre through classical mooring, every 2 year CTD hydrology and deployment of Argo floats specifically developed for seasonal sea-ice covered regions (AWI WECCON program).

Spacing would be variable and the mean spacing would be about 150km, and denser in the Agulhas Current region and around the Polar Front, at approximately 50S.

The group agreed that the ideal would be to have pop-up transmission systems in the moorings, which have already been successfully tested by AWI. The data would be transmitted into the GTS with the aid of NOAA/AOML SEAS group. The group also recommended that the sites that were occupied in previous moorings should be continued.

All these instruments will be placed along one Jason-1 like altimeter groundtrack, except for 3 German PIES that will be used for validation of the Grace satellite mission. Sea height anomalies provided by altimetry complements the data provided by the moorings. Therefore, current and future altimetry missions with Jason-1-like groundtracks are strongly supported by this group. One Jason-1-like and one Envisat-like altimeter mission are strongly supported by this group, as it would be the only way to obtain surface maps of mesoscale features and circulation in support of the moorings.

The group recommended maintaining the current rate of deployment, with the same spatial resolution, of drifters and floats.

The group recommended analyzing products of process studies of IPCC models and looking for sources of MOC in the SA and variability and determining what parameters need to be measured. We should start with global models that are not eddy-resolving and continue with regional models to investigate more specific processes.

The group discussed the use of satellite-derived sea surface salinity from the upcoming SMOS and Aquarius missions. It was agreed that salinity obtained from purely statistical methods, such as GEM, could greatly benefit from this type of mission since larger error from this type of methods are usually found at the surface.

The group discussed the possibility of deploying gliders to resolve finer structures, such as filaments, in regions where this type of resolution is needed.

Additionally, the upper ocean structure in the Benguela upwelling region was discussed, as changes in this region are sensitive and connected to variability of meridional ocean heat transport. Additionally, this region has been shown to vary significantly in past climate. Surface observations could be obtained from microwave, altimetry, and Argo. Moorings close to the coast where other observations are not possible/available would be preferred. The group recommended contacting the PIRATA Program to discuss this further.

Meridional inter-hemispheric Fluxes

Attendees: S. Garzoli, M. Baringer, D. Byrne, R. Guerrero, M. Mata, R. Matano, E. McDonagh, C. Meinen, A. Troisi, and R. Watts

Reporter: Christopher Meinen

Discussions in the breakout group focusing on the 30/35ºS line centered around where observations should be made and what instruments should be used. The two trans-basin observational programs that are already underway are the quarterly high-density XBT line that is run along 35ºS and the infrequent but sustained hydrographic sections that are obtained roughly every few years along 30ºS. Much of the debate in this breakout group centered on the positives and negatives of these two latitudes as locations for future observations. The 35ºS latitude used for the high-density XBT line (AX18) is dictated by the availability of the volunteer observing ships for use by the program, and it was agreed that changing this would be difficult or perhaps impossible for pragmatic reasons. The 30ºS latitude chosen for the repeat hydrographic section is similarly firm as the program depends on the ability to compare future observations made to those that have been taken in the same location in the past. Although many positives and negatives were discussed, such as the weakness of the 35ºS latitude because of the migration of the Brazil-Malvinas confluence near the western end of the line and the impact of the Walvis Ridge and the Rio Grande Rise on the circulation at both 30ºS and 35ºS, there was general agreement that the two lines were likely to remain where they are presently.

The future observations that are planned, including the western boundary observations being proposed for 30ºS using current meter moorings (PI McDonagh), the western boundary observations proposed for 35ºS using PIES and C-PIES, (PIs Garzoli, Meinen, and Baringer), and the eastern boundary observations under discussion for either 35ºS or 30ºS using PIES and C-PIES (PIs Speich and Byrne), were all discussed in the context of how they could best connect with the trans-basin observations. The question arose about whether the time series of the MOC in the South Atlantic could be made by simply measuring the variability on the western and eastern boundaries and allowing Argo and the AX18 repeat XBT line to provide information on the variability in the center of the basin. This led to a question about what the horizontal spatial scales of temperature and salinity were in this region. From the observations from the ASTTEX experiment, it was posited that roughly 75% of the salt and heat fluxes in the eastern boundary portion of the basin are in “large” blobs in the main thermocline while the other 25% is in heavily interleaved intermediate water. The role of the Aghulas rings in carrying heat and salt across the interior of these lines was brought up, and while the meridional heat transported within the rings was thought to be only around 0.05 PW, none of the participants had made estimates of the salt carried by these rings. Finally, another key point that was raised was the importance of barotropic observations across the section given the often smaller-horizontal-scale nature of the barotropic signals. It was agreed that the barotropic contributions were likely to be very important, which might increase the number of moorings needed, particularly in the presence of significant topography changes, such as the Mid-Atlantic Ridge. It was acknowledged that additional work was needed, possibly utilizing high-resolution models of the South Atlantic, to answer most of these questions. Work along these lines is already underway (Johanna Baehr, MIT). Most of the participants thought, however, that the place to start was by attempting to begin a MOC monitoring program at either 30ºS or 35ºS that might be adjusted in the future as we learn more about the circulation in the region. For pragmatic reasons of ship availability and piggy-backing on programs that already exist, it was thought that we should move forward by trying to measure the mass transport between the surface and a depth of 4000 meters using moored instruments and ship sections, probably at 35ºS.