REPORT of the
CLIVAR/OOPC/IAI WORKSHOP

ON THE SOUTH ATLANTIC CLIMATE OBSERVING SYSTEM
(SACOS)

FEBRUARY 6 – 8, 2003
Hotel Portogalo, Angra dos Reis - Brazil

Sponsors:
CLIVAR, OOPC, IAI
ONRIFO, WCRP, US-CLIVAR, IOC, INPE/CPTEC, IOUSP, MCT-BR, BCLME

CLIVAR is a component of the World Climate Research Programme (WCRP). WCRP is sponsored by the World Meterorological Organisation, the International Council for Science and the Intergovernmental Oceanographic Commission of UNESCO. The scientific planning and development of CLIVAR is under the guidance of the JSC Scientific Steering Group for CLIVAR assisted by the CLIVAR International Project Office. The Joint Scientific Committee (JSC) is the main body of WMO-ICSU-IOC formulating overall WCRP scientific concepts.

Bibliographic Citation: International CLIVAR Project Office, 2007: Report of the CLIVAR/OOPC/IAI Workshop on the South Atlantic Climate Observing System (SACOS). June. International CLIVAR Project Office, CLIVAR Publication Series No. 114. (not peer reviewed).

Executive Summary

Recommendations for the implementation of a South Atlantic Climate Observing System (SACOS) were discussed at a workshop convened by the WCRP/GOOS Ocean Observing Panel for Climate (OOPC), CLIVAR, and the Inter-American Institute for Global Change Research (IAI). The workshop, hosted by Dr. E. Campos (Univ. of Sao Paulo, Brazil), was held in Angra dos Reis, Brazil, from February 6 to 8 of 2003. The discussions were structured around a series of invited white papers. The workshop opened with a series of oral presentations, followed by deliberations in focus groups and plenary sessions. The two general topics of discussion were the influence of the South Atlantic circulation on the meridional overturning circulation (MOC), and on the regional climate.

The South Atlantic's influence on the MOC: The influence of the South Atlantic circulation on the MOC was discussed in invited talks on interocean exchange, thermohaline circulation, and water mass transformation. Working group deliberations focused on the uncertainties in the determination of the South Atlantic meridional heat flux, the role of the interocean exchanges, and the relative importance of water mass transformations on climate variability. The highlights of these deliberations are as follows:

- *Meridional heat flux:* It is well known that heat transport anomalies associated with the South Atlantic MOC can have important impacts on the climate system. There are, however, large uncertainties in our knowledge of the mean meridional heat transport, estimates of which vary between –0.6 PW and 0.65 PW. In order to advance our understanding of the climate system, it is necessary to reduce the uncertainties in the mean value and variance of the South Atlantic meridional heat flux, and to identify the dynamic and thermodynamic processes responsible for its variations. To address these necessities this panel recommends the implementation of a feasibility study to monitor the meridional heat flux at or near 30°S.
- *Interocean exchanges:* The net buoyancy flux from the South Atlantic to the North Atlantic depends on the ratio of the water mass contributions driven from the South Indian Ocean and from the South Pacific Ocean. There are, however, large uncertainties in the estimates of these interocean exchanges. To advance our understanding of these matters, this panel recommends the creation of new observational programs aimed at monitoring the magnitude of the oceanic exchanges south of the Cape Horn and Cape of Good Hope. During the course of the workshop it was noted that existing monitoring programs suffer from dissimilar observational protocols that impair the quantitative assessment of the interocean exchanges. To address these shortcomings this panel also recommends the future coordination of international observational programs.
- *Water-mass transformations:* Observations and models indicate that, rather than being just a passive conduit for the passage of remotely formed water masses, the South Atlantic actively influences the water masses through dynamic and thermodynamic processes occurring within the South Atlantic basin. The magnitude of these transformations and the nature of the dynamic processes that are responsible for them are largely unknown. Since there is evidence that the most active water mass transformations occur in localized regions within the southwestern Atlantic and the Cape Basin, this panel recommend further research in those areas. In addition to enhanced observations, we also recommend the implementation of coordinated modeling programs to investigate the mechanisms by which interocean exchanges and water-mass transformation interact to impact the MOC.

The SA influence on the regional climate: Recent observational and modelling studies show statistically significant correlations between sea surface temperature (SST) and wind anomalies over the South Atlantic, and also precipitation over parts of South America and southern Africa. There is also a growing body of evidence that links the oceanic variability of the subtropics to climatic variability in the tropics. Several studies suggest that the leading mode of coupled variability over the South Atlantic has a decadal time-scale and involves modulation of the strengths of the South Atlantic anticyclone and the subtropical gyre. Owing to the sparse data coverage, however, the temporal and spatial structures of all of the identified modes of oceanic and atmospheric variability over the South Atlantic are still controversial. The lack of data has also hindered the efforts to separate the portion of climate variability that can be associated with regional air/sea interactions from the portion attributable to remote forcing by global scale phenomena (e.g., ENSO, the Antarctic Circumpolar Wave, and the Southern Hemisphere Annular Mode). The influence of these global-scale phenomena on the regional climate remains undetermined.

The focus groups concurred that our understanding of the coupled ocean-atmosphere-land system in the South Atlantic region is at an early stage. It was noted, for example, that even up-to-date coupled models fail to describe correctly the time-mean state or seasonal cycle in the tropical Atlantic. Particularly challenging areas for coupled models are the cold tongue in the eastern equatorial Atlantic and the marine stratocumulus region west of Angola and Namibia. Some of these issues may be addressed further in planned experiments and monitoring programs such as the AMMA and EGEE experiments for the West African monsoon and Gulf of Guinea, the Tropical Atlantic Climate Experiment (TACE) and work done under the auspices of the Benguela Current Large Marine Ecosystem (BCLME). During the discussions it was noted that most of these planned efforts are focused on the equatorial regions or in the coastal peripheries of the South Atlantic, and that the subtropics have not received sufficient attention. Since the amplitudes of much interannual and decadal variability are largest in the subtropics, this panel recommends that efforts be made to improve the monitoring of air/sea fluxes, SST and the upper ocean variability in this region.

Table of Contents

1. Scientific Background

The South Atlantic Ocean connects three major ocean basins: the Pacific, the North Atlantic and the Indian oceans. The meridional gaps between its continental landmasses and Antarctica allow a free exchange of mass and energy. Although these exchanges are thought to be a critical component of the global thermohaline circulation, the dynamical mechanisms that control their magnitudes and variability are poorly understood. Because of the intrinsic importance of the South Atlantic circulation to climate, during the last few decades there have been several attempts to estimate the magnitude of the South Atlantic interocean fluxes and their links to the basin-scale circulation. Lack of data, the extent of the boundary regions, and the high variability of the flow has hindered most of these efforts. These difficulties have been compounded by the fact that the South Atlantic is not a passive conduit for the transit of remotely forced water masses, but actively influences them through air-sea interactions, mixing, subduction and advection processes. It is not sufficient, for example, to know the magnitude of the inflows south of Cape Horn and the Cape Agulhas to determine the South Atlantic export of thermocline waters to the North Atlantic Ocean because the characteristics of the northward fluxes depend on time and spatial scales set by the South Atlantic circulation.

The mean meridional circulation of the South Atlantic Ocean involves a deep, southward flow of cold and salty North Atlantic Deep Water along the eastern coast of South America, and a compensating northward flow of a mixture of warm and salty surface waters, and cooler and fresher Antarctic Intermediate Waters in the interior. These circulation patterns in which warm waters flow towards the equator and cold water towards the pole results in an equatorward heat flux. Although this anomalous heat flux was recognized by the middle of the last century, the sources for the upper return flow that make it possible are still in dispute. Observations indicate that a portion of the South Atlantic upper waters are produced locally but most of the upper waters are thought to originate in the Pacific and Indian oceans. Although the relative contributions of the Pacific and Indian ocean to the South Atlantic upper ocean budget is still controversial, observations indicate that the main gateway for the entrainment of these waters into the subtropical gyre are the boundary regions located at the opposite margins of the basin, i.e., the Brazil/Malvinas Confluence (BMC) and the Agulhas Retroflection Region (ARR). Observations also indicate that the main region for the detrainment of these waters is located off northwestern Brazil, where the South Equatorial Current bifurcates to feed the cross-equatorial flow of the North Brazil Current. Given that the thermohaline circulation is usually thought as a sluggish, planetary scale phenomenon, it is remarkable that its upper return flow appears to be more associated with mesoscale turbulence than with the mean circulation. In fact, two of the main gateways for the South Atlantic interocean exchange, the BMC and the ARR are also among the most energetic regions of the world ocean. Not surprisingly, the connections between these regions and the large-scale circulation are mostly unknown and, therefore, should be determined if we wish to improve our understanding of the global thermohaline circulation.

There is strong evidence that intense ocean-atmosphere interaction involving the Atlantic Ocean play a major role in determining the variability of the American monsoons on several time scales, particularly the interannual. For example, the variability of the South Atlantic

Convergence Zone (SACZ) has been linked to sea surface temperature anomalies in the tropical Atlantic, and in the southern subtropics of this ocean. However, the way in which interannual SST anomalies in Atlantic and coupled ocean-atmosphere interactions influence the South American climate is a matter of current debate. Long records of research quality surface heat flux estimates are very limited over the tropical and south Atlantic oceans and must be augmented to support improvement and validation of boundary layer parameterizations in ocean-atmosphere climate models.

There is also evidence that South Atlantic SST anomalies influence rainfall patterns in Southern Africa – midlatitude SST anomalies have been linked to winter rainfall in southwestern South Africa, while SST in the Tropical SE Atlantic appears to influence summer rainfall in parts of Namibia, Angola and neighboring countries. The latter suggests that another important monitoring region may be upstream of the Angola/Benguela frontal zone. This zone is also important for regional fisheries.

2. Motivation

The SACOS workshop was motivated by the belief that the South Atlantic circulation influences, directly or indirectly, the variability of the regional and global climate. In spite of the high-density surveys carried out as part of the World Ocean Circulation Experiment, the South Atlantic remains one of the more poorly sampled portions of the World Ocean. It is also believed that in order to address the challenges posed by the lack of data it is essential to foster the participation of the South Atlantic countries in the formulation of a research strategy. Considering their strategic locations, these countries could greatly contribute to the development of an observing system, which will not only augment the observational data bases but will also build scientific and operational partnerships to train their technicians and to reduce the operational costs.

2.1 Workshop Goals

- To provide an overview of the scientific understanding of the influence of the South Atlantic Ocean on the regional and global climate.
- To discuss existing and identify new elements for a South Atlantic observing system required for a more complete understanding of the climate system in regional and global scales.
- To integrate the region's diagnostic, modeling and observational communities and to develop joint actions and principles for a long-term observing strategy.
- To identify potential funding sources and associated operational partners.

The scientific and operational goals of this workshop also include:

- Social and economic regional impacts of climate change and climate prediction.
- National commitments and plans for research and operational observations
- Data management activities, including historical data
- Development of multinational action-plans

3. Structure of the Workshop

The Workshop was structured around a series of discussion and review presentations, interspersed with discussion-sessions to develop crosscutting ideas and consensus. The main presentations were based on short review papers, prepared by a group of invited authors. Poster Sessions were organized for allowing more contributions to the presentations. Four working groups were formed on the last day of the workshop for further discussion on specific topics and to formulate the recommendations for future scientific plans in South Atlantic.

3.1 The Discussion Papers

Review presentations were prepared by a group of specialists selected by each lead author. Lead authors and collaborators are given below. Voluntary contributors were accepted in form of posters. Each lead-author were requested to make a 30-minutes presentation. It was also requested each lead-author to spend no less than the last 5 minutes of their time to propose a set of observations as part of a multi-year monitoring program.

1. Review of South Atlantic intraseasonal to interdecadal variability. (**C.Vera**, W. Hazeleger, I. Wainer, J. Servain)
2. The South Atlantic role on the global thermohaline circulation (**A.Piola,** A. Gordon, E. Campos)
3. Interocean Exchanges (**W. de Ruijter**, S. Cunningham, A. Gordon, J. Lutjeharms, R. Matano and A. R. Piola)
4. South Atlantic links and impacts to regional and global climate (**A. Grimm**, A. Robertson, Chris Reason)
5. The South Atlantic Observing System (**S. Garzoli**, M. Johnson, A. Piola, C. Provost)
6. The Mesoscale Circulation of the South Atlantic Ocean: Does it Matters to Climate? (**R. Matano**, B. Barnier, E. Campos, A. Coward, J. McLean, E. Palma, T.Penduff, M.Schouten, A-M. Treguier, I. Wainer and D. Webb)
7. The role of the South Atlantic in the variability of the ITCZ (**Y. Kushnir,** A. Lazar, M. Barreiro, P. Rizzoli)

Each presentation addressed the following issues:

a) What do we already know about climate in the South Atlantic Ocean from TOGA, WOCE, CLIVAR and other sources?
b) What are the burning scientific questions now?
c) Where and in what aspects are we most likely to develop useful climate predictions?
d) What and where are sustained observations needed to observe climatic variability and develop applications?

3.2 The Working Groups

1. **WG1**: Links between the upper South Atlantic, the deeper ocean and the other basins (leader *Alberto Piola*)

2. **WG2**: The South Atlantic links and impacts to regional and global climate (leader *Alice Grimm*)
3. **WG3**: Modelling the Coupled Ocean-Atmosphere System (leader *Ricardo Matano*)
4. **WG4**: South Atlantic Observing System and Operational Forecasts System (leader *Silvia Garzoli*)

4. The Working Groups Reports

4.1 Working Group 1: Links between the upper South Atlantic, the deeper ocean and the other ocean basins (*Alberto R. Piola – Chair and Christine Provost - Rapporteur*)

The working group discussed several research topics related to interocean exchanges between the South Atlantic and the South Indian and South Pacific Oceans as well as water mass transformations within the basin. The group recognized that large discrepancies exist between estimates of the Atlantic meridional heat flux through 30°S. In the South Atlantic the meridional heat flux is uncertain, estimates vary between -0.6 and +0.65 PW. Estimates derived from oceanic observations, e.g. inverse models, strongly depend on whether the export of North Atlantic Deep Water is compensated by thermocline waters from the Indian Ocean, Intermediate waters derived from the Indian Ocean or from the Pacific. Thus, the meridional heat flux is strongly related to the interocean exchanges and their possible variability. Since the meridional heat flux in the ocean is a key element of the climate system, the group concludes that to better understand the global ocean thermohaline circulation and its impact on climate it is necessary to reduce the heat flux uncertainty in the South Atlantic

Our working hypothesis is that the meridional heat flux in the South Atlantic is determined by the export of cold NADW to other ocean basins and import of relatively warm thermocline and intermediate waters in the upper layers. Consequently the heat flux through the South Atlantic is equatorward.

Scientific issues that need to be addressed are:
- What is the meridional heat flux through the South Atlantic?
- What factors determine and can induce variability in the South Atlantic meridional heat flux?

The WG recommends the following tasks to be carried out:
- Compile all available estimates of the meridional heat flux through the South Atlantic from direct and indirect methods and from numerical models.
- Evaluate the feasibility of carrying out an experiment to observe the meridional heat flux at or near 30°S.

What factors determine and can induce variability in the meridional heat flux?
- Variations in the contribution of Pacific (via Drake Passage) and Indian Oceans (via Agulhas leakage) to the upper layer return flow
- Variations in the thermohaline characteristics of the above waters
- Water mass conversions within the South Atlantic Basin

The WG did not specifically address the South Atlantic sea-air CO_2 exchanges. However, regions of winter convection, primarily near the Subtropical Front in the western Argentine Basin, CO_2 sinks along the Subtropical Front/South Atlantic Current, and along the edges of the Subtropical gyre are likely to play a role in the CO_2 transfer from surface water to subthermocline levels.

The group recommended the following observations: the regions of high eddy energy in the South Atlantic are located in the western Argentine Basin and in the eastern Cape Basin.

These are regions of enhanced mixing and water mass conversion. Subantarctic and subtropical mode waters which subduct under the subtropical thermocline, are formed or altered by sea-air interaction in the western South Atlantic. Thermocline and intermediate waters from the Indian Ocean penetrate into the South Atlantic as part of Agulhas eddies. Therefore, it is suggested that these regions are of special interest to monitor the water mass properties and their time variability. In addition, the western boundary near 15°S is suggested for monitoring the upper layer flow into the tropical Atlantic. These monitoring lines are shown in red in Figure 1. Additional regions potentially important in water mass transformation are along the edges of the subtropical gyre. The working group notes the lack of observations along the South Atlantic Current.

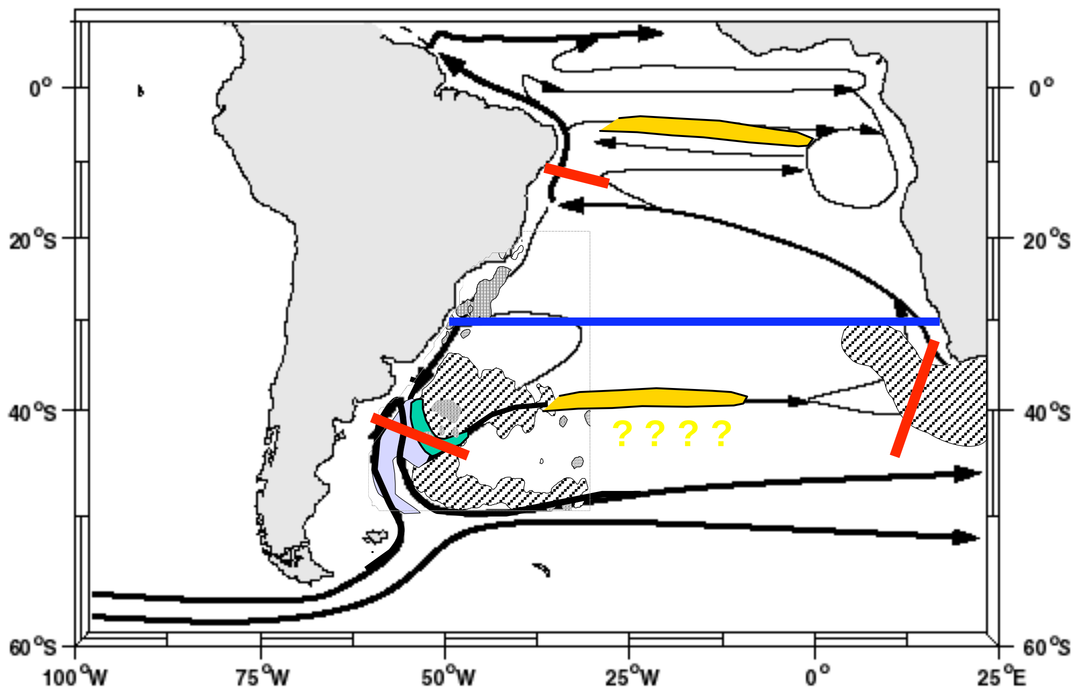


Figure 1: Proposed observations in the South Atlantic. The hatched regions mark the areas of high eddy energy in the basin. The red lines indicate regions for monitoring the flow and water mass properties at the entry points of the upper layer return flow into the South Atlantic. The yellow areas mark regions of potential interest for water mass subduction under the subtropical thermocline. The blue line at 30°S indicates schematically the heat flux study region.

4.2 Working group 2: Climate variability in the South Atlantic and impacts on regional climate (*Alice Grimm – Chair and Carolina Vera - Rapporteur*)

Introduction. The South Atlantic is characterized by substantial variability on intraseasonal, interannual, interdecadal and longer time scales and there are significant impacts on neighboring South America and southern Africa, as well as further afield. The mechanisms associated with this variability remain poorly understood. However, modulations of the South Atlantic anticyclone and the subtropical gyre seem to play a central role. It is important to establish what proportion of these modulations is related to external forcing (e.g., ENSO, the

Southern Annular Mode, Antarctic Circumpolar Wave) and what arises internally via ocean-atmosphere interactions within the South Atlantic itself.

Recommendation. Important Atlantic modes, such as the Atlantic ENSO, Benguela Niño and Niña, the Atlantic gradient mode, as well as variations in the South Atlantic Convergence Zone, the central South Atlantic and the Brazil / Malvinas confluence, appear to involve modulations of the South Atlantic anticyclone. An overarching recommendation of WG2 is to design an observing system to better monitor the annual cycle of the South Atlantic anticyclone and the subtropical gyre as well as its intraseasonal, interannual and interdecadal variability.
To improve understanding of the variability of the South Atlantic and its impacts on South America and Africa, WG2 posed a set of general and specific questions as follows.

General questions:
- What are the physical mechanisms associated with the ocean-atmosphere variability modes on intraseasonal, interannual and interdecadal timescales in the South Atlantic?
- What are the relative roles of remote versus local processes? To what extent are they predictable?
- What are the most important impacts of South Atlantic climate modes?

Some specific issues:
- What triggers the equatorial zonal mode and related strength of the warm and cold events in the SE Atlantic? What is the role of changes in the subtropical high? What is the impact on regional rainfall?
- What are the mechanisms driving ENSO signals in the South Atlantic and how do they impact on South America and Africa? How do the subseasonal variations of circulation and SST in southwestern subtropical Atlantic, associated with ENSO, interact with each other?
- The meridional SST gradient between the tropical North and South Atlantic seems to strongly influence the West African monsoon and also tropical Brazilian rainfall. Is it linked to rainfall variability in subtropical South America and southern Africa and, if so, how?
- Do changes in the Brazil-Malvinas confluence have an impact on South American and southern African climate? Are the decadal-multidecadal signals seen in the South Atlantic a regional mode, or part of a near-global signal and how do they impact on South American and African climate?

4.3 Working Group 3: Modeling the coupled ocean-atmosphere system (*Wilco Hazeleger, Ricardo Matano – Chairs and Alban Lazar – Rapporteur*)

Climate research strives to understand the behavior of the land/ocean/atmosphere coupled system and numerical simulations are one of the most important tools in the pursuit of this goal. Numerical studies are particularly well suited to investigate the effects of climate-related processes that are otherwise difficult to observe (e.g., the sensitivity of the ocean thermohaline circulation to the atmospheric forcing), or to establish the dynamical relationships between regional and global climate variability patterns. During this group deliberation it was acknowledged that, in spite of their relative importance, there are relatively few numerical studies of the South Atlantic climate system and that this deficiency reflects in a lack of understanding and predictability of its variability. It is well known, for example, that even in the tropical Atlantic, the most studied and best surveyed of the South Atlantic's regions, coupled ocean/atmosphere models fail to reproduce the seasonal cycle. In order to improve our understanding of the South Atlantic climate system this group identified and discussed the topics deemed to be most relevant to the regional climate, posed the research questions that should lead to their further understanding, and considered the hypotheses that might address some of those questions. To facilitate the debate the discussion was divided in two distinct time-scales: seasonal to decadal, and interdecadal and longer. Although somehow arbitrary, this division reflects the increased importance of the thermohaline circulation in the coupled climate system, which is expected to be more important on decadal and longer time scales. At the end of the workshop it was acknowledged that the scientific hypotheses formulated by other working groups are also relevant to modeling studies and it was recommended that common hypotheses should be pursued, particularly with the WKG 1 (Links to Deeper Oceans and Other Basins) and WKG 2 (Impacts and predictability).

Seasonal-to-decadal time scales. Due to the relatively small size of the South Atlantic basin its climate variability from seasonal to decadal time scales is likely to be influenced by land processes and land-ocean temperature contrasts. The paucity of South Atlantic's focused studies, however, has hindered the determination of the contribution of different processes (e.g., ocean/atmosphere interactions), to the climate variability in this time range. There are, nevertheless, indications that ocean and land processes influence the atmospheric circulation. It is, for example, recognized that SST patterns in the South Atlantic affect rainfall of certain regions of South America and Africa, and that the low frequency variability of the tropical region can be influenced by subtropical SST patterns. Although the South Atlantic's influences on the climate variability of other basins is still not established, there is evidence that the South Atlantic itself is affected, to varying degrees, by global phenomena such as ENSO, the Antarctic Circumpolar Wave, or the Southern Hemisphere Annular Mode. The working group discussion, however, concluded that the existing observational and modeling studies cannot answer the following fundamental questions:

- How robust are the South Atlantic's coupled modes of interannual variability?
- Do decadal variations of SST anomalies in the subtropical region influence the SACZ variability and African rainfall?
- What are the mechanisms by which global climate modes (e.g., ENSAO, PSA, NAO, and ACW) influence the South Atlantic's climate and viceversa?
- What are the mechanisms by which the South Atlantic's variability influences the ITCZ variability?
- What is the impact of oceanic mesoscale variability (e.g., in the southwestern or southeastern Atlantic) on regional climate?

The working group discussion concluded that answers to these questions from existing modeling studies are severely handicapped by: 1) deficiencies in the parameterization of planetary boundary layer processes in AGCM, 2) low resolution in AGCM which generate uncertainties in the surface fluxes (a particularly important issue for the study of the influence of the oceanic mesoscale variability on regional climate), 3) uncertainties in the sensitivity of entrainment and upwelling at the base of the oceanic mixed layer to the parameterization of turbulent processes. In the overall balance it was concluded that it is important to foster the implementation of new numerical simulations on the South Atlantic's climate variability. The panel recommends that coupled ocean/atmosphere modeling studies prioritize the improvement of the existing forecasts of the South Atlantic's annual cycle.

Decadal and longer time scales. It is generally acknowledged that the sluggish, but far reaching, meridional overturning circulation sets the characteristics of the climate system at decadal and longer time scales. The South Atlantic is the only basin that it is in direct contact with all the other major oceans and therefore in a rather unique position to influence their inter-basin exchanges. In order to understand climate variability, therefore, the focus group concluded that it is important to determine the dynamical processes that control the South Atlantic's inter-ocean exchange and the water-mass transformation occurring within its domain. The panel discussions on these matters were framed by the following questions:

- Are there significant water masses transformations in the South Atlantic? where do they occur, and how do they affect the upper limb of the MOC and its variability?
- What are the relative contributions of the *warm* and *cold* paths to the South Atlantic's northward export of thermocline water?
- What is the impact of South Atlantic's circulation on the low-frequency variability of the coupled climate system and on the stability of the MOC?

Numerical simulations indicate the existence of significant water mass transformations in the Brazil/Malvinas Confluence and the Cape Basin regions. These transformations appear to be driven by ocean/atmosphere interactions and diapycnal mixing stirred by the mesoscale variability of these highly energetic regions. During the panel discussions, however, it was noted that water mass transformations simulated by the models are likely to be influenced by the particulars of the model architecture (i.e., resolution, mixing parameterization, vertical coordinate, surface fluxes, etc). The panel therefore, recommends further studies on the South Atlantic's water mass transformations and the sensitivity of the model's estimates to the model's characteristics. As a first step in that direction the panel recommends the design and execution of comparative studies using isopycnal, z-level, and sigma-level coordinates models at varying resolutions.

The panel also discussed the dynamical mechanisms by which the South Atlantic's circulation might regulate the interocean fluxes through the Drake Passage and the Cape Agulhas. Numerical simulations and paleoceanographic data indicates that variations in the magnitude of the South Atlantic's interocean exchanges might influence the stability of the meridional overturning circulation. In this regards the panel recommends the encouragement of new modeling studies to investigate the dynamical mechanisms that regulate the warm and cold path's contributions to the South Atlantic's buoyancy flux. In particular the implementation of studies on the circulation in the southwestern Atlantic, the Cape Basin region, and the region where the South Equatorial Current bifurcates into the Brazil and the North Brazil Current. The ultimate goal of those studies should be to increase our understanding of the mechanisms that link the stability of the meridional overturning circulation to the low-frequency variability of the South Atlantic circulation.

Finally, the panel noted that since model results are likely to be hindered by the shortcomings of the existing data bases and intrinsic deficiencies in model's architectures it recommends that efforts be made to a) improve the data on surface fluxes (which might otherwise lead to large uncertainties in the South Atlantic's heat transport), b) to conduct inter-model comparisons to establish the robustness of model results to mixing parameterizations, advection schemes, etc.

4.4 Working Group 4: South Atlantic Observing Systems and Operational Forecast Systems (Silvia L. Garzoli - Chair and Deirdre Byrne - Rapporteur)

The discussions in WG 4 started with the formulation of hypotheses on the role of the South Atlantic in climate that should be tested experimentally. This was followed by a discussion on what types of observations are needed to test these hypotheses, which was done in the framework of the already existing sustained observations and existing international programs. Finally, recommendations on sustained observations were made.

To clarify the discussions, the following qualification of observations was made according to their operational time scales:

- Process studies: observational and modeling studies to test specific hypotheses and to improve model parameterizations. The duration of these is typically two to three years.
- Sustained observations: Long-term observations, based on long-term funding. These are carried out by research institutions. The evolution of their design and instrumentation is dictated by science.
- Operational programs: These are already proven observational programs that will be maintained in the same modus operandum by operational agencies.

Scientific hypotheses

Hypothesis 1: The decadal signal observed in sea surface temperature (SST) in the subtropical gyre of the South Atlantic Ocean is due to variability in the coupled air-sea mode which involves the SST field of the South Atlantic subtropical gyre and the wind stress curl.
Test: Verifying this hypothesis requires monitoring the variability of the subtropical gyre. If the phenomenon is similar to the one modeled in the North Atlantic, the memory is in the ocean stored in the form of planetary waves. Testing will require good coverage of long-term SST data (to resolve the 14-year peak in the SST spectrum) and of the 3-dimensional structure of the gyre. Wind data are also required.
Observations required:

- SST: satellites and surface drifters can provide SST. An increase in the resolution of surface drifter coverage is necessary. We recommend the implementation of the full resolution of the drifter array as planned at 5°x5° was recommended.
- Structure of the gyre: The subsurface structure of the gyre can be provided by a combination of altimetry, profiling floats, and high-density XBT lines. (Note: A high-resolution XBT section from Rio de Janeiro to Isla de Trindade every two months would be particularly helpful)
- Profiling floats: In order to determine if the current ARGO resolution is sufficient to study the structure of the gyre, the 3°x3° resolution should be tested in models.
- Wind stress: These data can be provided by scatterometer and SSMI.
- Surface fluxes: These can be supplied by surface moorings and satellite measurements. Surface moorings should measure momentum and air-sea fluxes. At least one mooring is needed at the northern edge of the subtropical gyre (20°S, 10°W) as well as at 20°S, 30°W and 20°S, 0°E. Typically 5 W/m^2 resolution is needed; this should be checked with model data. IMET observations along AX08 and AX18 will also provide ground truth for satellite calibrations.

Hypothesis 2*:* Sea Surface Tempeature (SST) variability in the southeastern (southwestern) South Atlantic has a direct impact on precipitation in Africa (South America).
Test: To test this hypothesis it is necesary to measure the heat storage in the upper water column and the air-sea fluxes in these regions.

Observations required: (Note: This was the subject of the PIRATA-9 workshop. Information is provided in the PIRATA web site)

- Surface moorings: The PIRATA extensions (1 in the southeast and 2 in the southwest) are at this time the most appropriate way to measure upper ocean heat storage. Problems with piracy in the eastern basin, requires that new technologies be used to collect observations in the Gulf of Guinea.
- Profiling floats: ARGO profiling floats can be used to provide information on the surface and subsurface structure. If the resolution achieved by Argo is not sufficient to test the hypothesis, the surface moorings may be equipped with subsurface measurements of temperature, salinity and currents (or subsurface moorings may be deployed at a nearby location).
- Satellites: These will provide surface and momentum fluxes.
- Measurements of precipitation: In addition to the surface moorings and the satellites, subsurface measurements of rain may be collected using passive acoustic technology.

Hypothesis 3*:* Variability in inter-ocean and interhemispheric fluxes in combination with regional surface fluxes and water mass transformations determine SSS, SST, and upper layer heat, salt and mass fluxes, thus affecting the climate on seasonal to decadal time scales.
Test: It is recommend the collection of sustained observations to document the inter-ocean and inter-hemispheric exchanges and to relate those changes to variability in surface and subsurface properties and fluxes in the South Atlantic. This includes better documentation of the heat and salt anomalies entering the South Atlantic from other basins, and combining these with an index of the NADW production and export rates, which might be done through modeling and/or appropriate long time series such as one derived from the Florida Straits cable. There is also a need to better understand and constrain the attenuation rates of heat and salt anomalies in areas of intense mixing and air-sea fluxes, such as the Cape Cauldron and the Brazil-Malvinas Confluence. To understand the interhemispheric exchanges, it is necessary to determine the variability of the structure of the South Equatorial Current (SEC) and the heat and mass transported by its branches, in particular the branch of the SEC that feeds the tropical Atlantic current system. Also, it is necessary to determine how seasonal and mesoscale variability impact the upper-layer interhemispheric transport.
Observations required:

- Thermohaline flux variability at the South Atlantic chokepoints should be monitored on a sustained basis at mesoscale resolution in space, and better than monthly resolution in time. Air-sea fluxes in these regions should be better monitored. Models will provide an important tool for helping to calculate attenuation rates of the heat and salt anomalies from observations and indicate likely routes for the propagation and eventual distribution of thermohaline/density anomalies.
- Sustained observations are required for the following: the Pacific-Atlantic exchanges (Drake Passage and Malvinas Current), the inter-hemispheric exchanges of the upper limb of the MOC (Southern Hemisphere to Northern Hemisphere), and the Indian-Atlantic exchanges (the Benguela-Agulhas systems).
- The Pacific-Atlantic: (i.e., Drake Passage & Malvinas). Currently there are three existing programs: An array of current meters positioned across the Malvinas Current along a Jason groundtrack to re-evaluate the mean flow and enable examination of the interannual variability of the transport. Those current meters are not permanent. ARGAU**,** a 10-year monitoring program of physical, biological and chemical conditions in the western South

Atlantic and Atlantic Sector of the Southern Ocean. The main goal of ARGAU is to establish the relation between the near-surface oceanic conditions and the ocean-atmosphere CO_2 fluxes. The volume transport through Drake Passage should be monitored using a combination of altimetry and current meters. For this effort, a current meter array deployed along a Jason groundtrack spanning the Passage is needed. In the same way as for the Malvinas Current, it is recommended that these observations become sustained.

- The interhemispheric exchanges: We recommend monitoring the bifurcation of the South Equatorial Current (SEC) into the North Brazil and the Brazil Currents. This could be done with ARGO floats and surface drifters, the already existing AX08 high density XBT line, and the proposed Brazilian XBT line between Rio de Janeiro and Isla de Trindade. Moored instrumentation for long-term monitoring of the Brazil Current and the North Brazil Current are needed.
- The Indian-Atlantic: The GoodHope and ASTTEX projects, directed, respectively, at measuring the entire Indian-Atlantic chokepoint periodically, and the Agulhas Leakage at high resolution, are efforts now in place although not at present planned as sustained experiments. We recommend maintaining sustained observations based on the results of these experiments.

In addition to the sustained observations described above it is necessary to collect the following data basin-wide to help characterize the state of the South Atlantic as a whole:

- Sea Surface Height: altimetry, tide gauges
- Sea Surface Temperature: satellite, surface drifters, profiling floats, VOS
- Sea Surface Salinity: thermosalinigraphs, satellite, profiling floats, VOS
- Air-sea fluxes: satellites (wind stress, latent and sensible heat fluxes)

Existing sustained observations:

This part of the discussion dealt with existing sustained observations and recommendations to those programs in order to fulfill the requirements of an observing system for the South Atlantic.

- Argo: This program has just begun. Coverage is aimed at 3°x3° resolution of the global ocean. It may be necessary to increase the resolution in those areas where a closer array of observations is needed. Funds should be provided to collect extra observations in these cases.
- VOS: These platforms provide partial coverage of SST. The VOS measurement of SST has bias and must be improved. We recommend increasing the number of VOS ships equipped with thermosalinigraphs.
- Drifters: We need to increase both coverage and density to achieve the 5°x5° design. Funds should be made available for deployment in specific areas not covered by VOS.
- High-density XBT lines: AX8 and AX18 are already in place. We recommend converting AX15 to a high-density XBT line. The possibility was discussed of building on AX18 using Argentinean vessels to add other measurements such as surface pCO_2, surface meteorological data (using IMET), surface temperature and salinity (measured by thermosalinigraph), etc.
- Tide Gauges: The tide gauge network around the South Atlantic is not particularly well-developed (maintained). More locations and improved equipment may be needed.
- Satellites: more calibration/validation data are needed in the subtropical gyre. The main parameters that will be retrieved from satellite measurements are:

    - Remotely Sensed Parameters: Wind vector; wind stress; Curl, Divergence; Sea state; SST; Latent heat flux; Sensible heat flux; SSI; DLI; SSS; Air temperature (profile); water vapor.
    - Satellites operational from 1991-present : ERS-1/2; DMSP (SSM/I); NOAA (AVHRR); METEOSAT; GOES: QuikScat; TOPEX/Poseidon; GFO, Jason-1; TRIM; ADEOS-2; WindSat; SAC-C, GRACE.
    - Future missions: MSG (2003); METOP (2005); Jason-2 (2005),AQUARUS/SAC-D (2007), OSTM (2005)
- Meteorological observations over the ocean: There are not at present sufficient direct measurements of meteorological parameters being made in the ocean basins. The limitations of current technologies (for example, for accurately measuring evaporation and precipitation over the ocean) suggest that the development and implementation of improved methods should be encouraged.

5. The White Papers

5.1 Climate Variability In The South Atlantic Ocean

Vera, C.S.[1], W. Hazeleger [2], I. Wainer [3] and J. Servain [4]

[1] *CIMA/Department of Atmos. and Ocean Sci. University of Buenos Aires-CONICET, Argentina*
[2] *Royal Netherlands Meteorological Institute (KNMI), De Bilt, Netherlands*
[3] *Department of Physical Oceanography, University of Sao Paulo, Sao Paulo, Brazil*
[4] *Fundação Cearense de Meteorologia (FUNCEME), Brazil*

5.1.1. Introduction

The variability of the South Atlantic Ocean circulation and sea surface temperature (SST) are not as well understood yet as in the North Atlantic. This in part is due to the fact that the data coverage in the South Atlantic is rather poor, especially south of 35°S (Fig. 1). Variations of the South Atlantic Ocean circulation patterns and SST can occur over time scales ranging from sub-seasonal to the seasonal, interannual and interdecadal. The most dramatic contrasts in SST of the entire South Atlantic occurs at its western boundary when the warm and salty waters of the southward flowing Brazil Current meet the colder and fresh waters of the northward flowing Malvinas Current, where temperature gradients are as high as 1°C/100m. The confluence zone between these two currents migrates up and down the continental margin at seasonal and possibly longer time scales, which in turn impacts on the atmosphere, with likely effects on cyclogenesis and regional rainfall distribution.

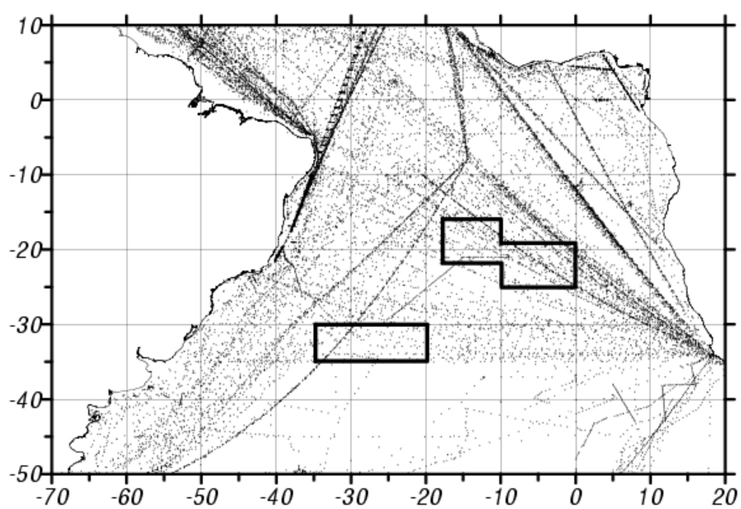


Fig. 1: In situ SST observations available in the South Atlantic for the period 1990-2000. Boxes encompass main centers of South Atlantic dipole (From Palastanga et al. 2002)

Because the South Atlantic plays a key role in the energy transport towards the North Atlantic and influences the climate over South America, a better understanding of the basin-scale SST variability is required. Several studies (Paegle and Mo 2002, and references therein) have diagnosed strong links between rainfall variability over South America and SST conditions in the South Atlantic. Recently, Robertson et al. (2002) examined the atmospheric response to oceanic anomalies in the tropics and subtropics of the South Atlantic based on AGCM simulations and found strong, statistically significant signals on the atmospheric low-level circulation and precipitation on interannual time scales.

5.1.2. Available data for the South Atlantic Ocean study

Several datasets are currently available for the study of the South Atlantic SST variability. However it must be taken in consideration that because they are based on different interpolation methods and observation sets, they provide results somewhat different.

Among the datasets which combine in situ observations with satellite data, two of the most used by the scientific community are the Global Sea Ice and Sea Surface Temperature dataset (GISST), based on the Poisson equation technique (Rayner et al. 1996) and the Reynolds dataset, based on the optimum interpolation analysis (Reynolds and Smith 1994). The SST fields from the NCEP-NCAR reanalysis dataset (Kalnay et al. 1996) includes the 2.3b version of the GISST dataset prior to 1982 while after that time, SSTs correspond to the Reynolds dataset. Comparisons between GISST and Reynolds datasets showed that the 2.3b version GISST data exhibit spurious variability at mid and high latitudes of the South Atlantic (Palastanga 2002), probably due to the poor performance of the GISST interpolation method on very sparse data regions (Hurrel and Trenberth 1999). New versions of GISST data are recently available however, at least to our knowledge, there are no evaluations of their quality over the South Atlantic.

Other datasets like the Comprehensive Ocean-Atmosphere Data Set (COADS) which only includes in situ observations are also strongly affected by the lack of information south of 35°S (Fig. 1).

5.1.3. Seasonal cycle of the South Atlantic Ocean

The annual cycle of the SST and circulation in the South Atlantic Ocean has not been discussed in detail on basin scales. Although the seasonal variations of the Southwestern Atlantic and in particular in the Brazil-Malvinas confluence region have been subject of more interest (Wainer et al., 2000, and references therein).

Palastanga (2002) recently explored the seasonal cycle of SST and SLP from NCEP reanalyses and showed that while at the South Atlantic tropical regions maximum mean temperatures occur between March and April, at extratropical regions maximize between February and March. On the other hand, coldest mean temperatures occur between August and September, almost simultaneously over the whole basin. Moreover, a strong relationship between the seasonal changes of the SST and SLP is observed at tropical and subtropical latitudes which is characterized by a strengthening (weakening) of the anticyclonic gyre and a warming (cooling) of the surface ocean.

Wainer et al. (2000) show that the dominant feature of the South Atlantic annual mean surface currents as simulated by the coupled, global general circulation ocean-atmosphere-land and sea ice NCAR/Climate System model (CSM) is the broad subtropical gyre (Fig. 2a). Within this gyre, the westward South Equatorial Current in the north, the southward Brazil Current to the west, the eastward South Atlantic Current to the south and the northward

Benguela current can be observed in agreement with the wind-driven schematic representation of the currents by Peterson and Stramma (1991). The mean annual SSTs from both the CSM (averaged over 200 years, Fig. 2b) and COADS (averaged over the 1950-1979 period, Fig. 2c) show a weak southwest-northeast gradient north of 35°S, whereas, the isotherms are predominantly zonal further south. Also, the overall broad gyre wind circulation patterns are very similar, although the wind stress derived from the model is stronger.

a) b) c)

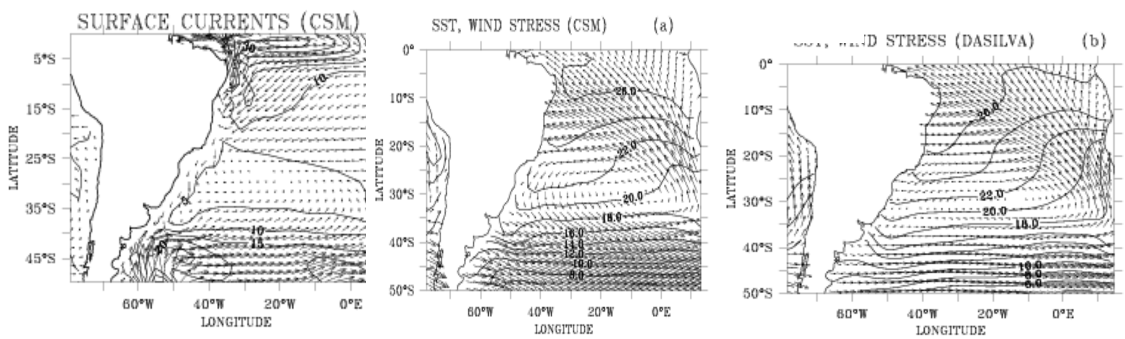


Figure 2: (a) Annual mean surface currents from the NCAR/CSM model. Maximum vector length is 35 cm s^{-1}; velocity magnitude contour interval is 5 cm s^{-1}. Annual mean wind stress and SST contours from (b) the CSM and (c) DALSILVA et al. (1994). Maximum vector is 0.15 N m^{-2}, and contour interval is 2°C. (From Wainer et al. 2000)

Wainer et al. (2000) pointed out that the main features of the annual cycles of wind stress and SSTs can be reproduced by the CSM. However, the differences between the CSM results and several observed climatologies are comparable to the differences between the climatological products themselves, discernible in wind stress (Fig. 3) as well as in heat flux fields (not shown).

5.1.4. Large scale patterns of SST variability

Climate variability in the South Atlantic region seems to be prominent in several time scales, which may have significant impact on the coupled ocean-atmosphere interaction and predictability. However, the sparse data available in the South Atlantic might be limiting the possibilities to make robust conclusions on time scales (and even variability patterns).

A number of studies report on a time scale of variability around 14-16 years. The analysis of the SST anomaly time-series in the two regions identified by boxes in Fig. 1 show maximum variability at around 14 years being particularly dominant in the extratropical South Atlantic region (Palastanga et al. 2002). Venegas et al. (1997) identified those time scales in the large-scale SST-SLP co-variability. Interdecadal variability is also found in the la Plata Basin river discharges as well as in the variability of the South Atlantic Convergence zone (Robertson and Mechoso, 1998, 2000).

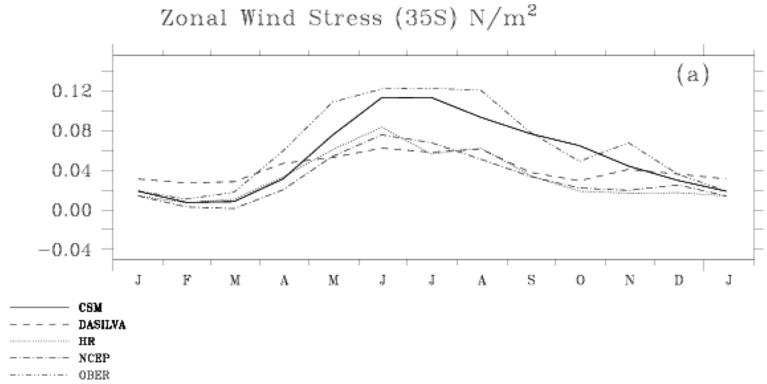


Figure 3: Zonal component of wind stress, zonally averaged between 65°W and 15°E, at 35°S (N m^{-2}) from the CSM, DASILVA, Hellerman and Rosestein (1983) (HR), NCEP, and Oberhuber (1988) (OBER) climatologies (From Wainer et al. 2000)

Despite the sparse data coverage in the South Atlantic Ocean some studies have been already published which describe the leading patterns of SST variability and their relation to atmospheric variability. (Venegas et al. 1997 and 1998; Sterl and Hazeleger 2002; Robertson et al. 2002; Palastanga et al. 2002, among others). However, the structure and variability of the leading modes are still controversial. The disagreements might be explained by differences in the datasets, filtering techniques as well in the methods of climate pattern detection.

Some papers have identified as the main mode of SST low-frequency variability (from EOF analyses) a monopole pattern characterized by a maximum along the path of the South Equatorial Current (SEC) (Venegas et al 1997, Sterl and Hazeleger 2002). It was hypothesized that this monopole pattern was associated with the shift of the strong temperature gradient associated with the SEC. However, recently Palastanga et al. (2002) questioned the stability of that monopole pattern as it seems to be influenced by the inhomogeneous distribution of in-situ observations in the South Atlantic (Fig. 1) and by the technique used for its identification. They showed that the monopole is only discernible as the leading SST mode of variability if the considered data period largely extends prior to 1982 (when satellite data were not available) and the EOF analysis is performed in the spatial domain (S-EOF). In contrast, the uneven data configuration does not appear to significantly affect the results of the EOF analysis when it is performed in time domain (T-EOF).

The first three dominant SST anomaly patterns derived from the T-EOF analysis (Palastanga et al. 2002) are displayed in Fig. 4. SST anomalies were defined as the difference between monthly means and the corresponding climatological means without applying any further filtering to isolate the low frequency variability. T-EOF1 displays the typical north-south oriented dipole with dominant variability on interdecadal time scales. T-EOF2 is characterized by a strong center at around 20°W, 30°S and two centers of opposite-sign located south of Africa and along the South American coast, respectively. This is the only leading mode exhibiting a significant spectral peak on subannual time scales. These high-frequency SST variability centers are located over the most energetic regions of oceanic meso-scale variability in the South Atlantic, the Brazil-Malvinas confluence and the Agulhas retroflection (Chelton et al, 1990). T-EOF3 exhibits an east-west dipole pattern at mid latitudes with significant variability at interannual time scales. This mode presents a large correlation with

ENSO (Sterl and Hazeleger, 2002), being highest when the ENSO index leads T-EOF3 by 6 months (Palastanga et al. 2002). The mechanism for this connection with ENSO is not understood yet.

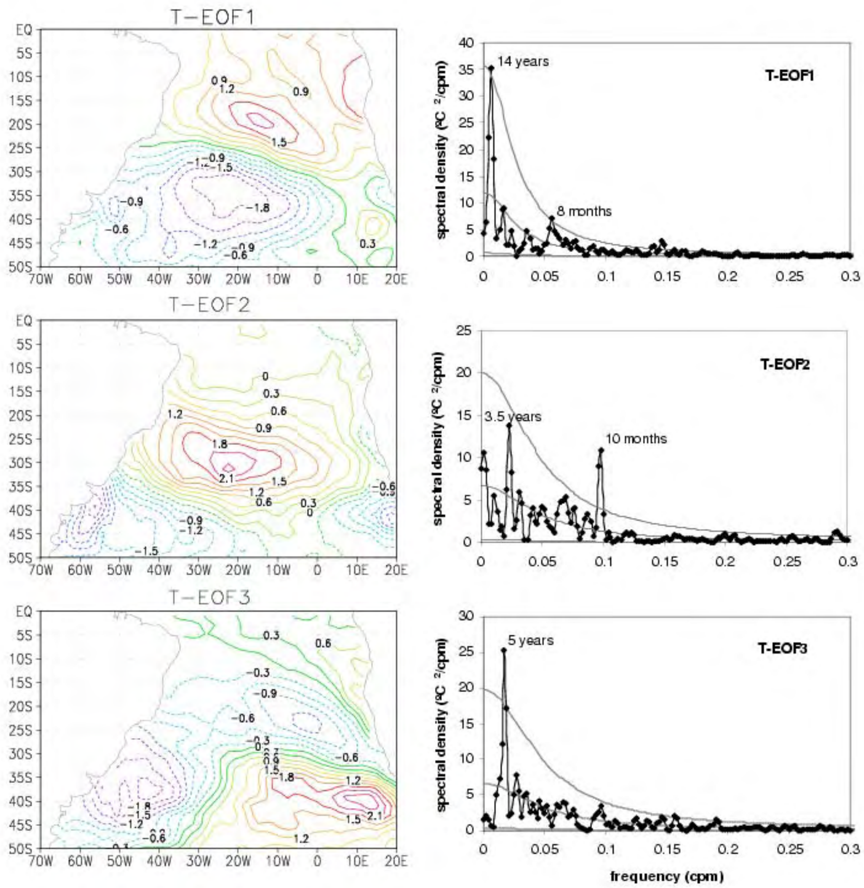


Figure 4: (Left panels) principal components of the first three modes of the T-EOF analysis for the period 1972-2000. Contour interval is 0.3°C. (Right panels) spectra of the first three T-EOFs including expected red noise spectra and 95% confident bands. (From Palastanga et al. 2002).

To better assess the ocean-atmosphere relationship in the South Atlantic, singular value decomposition (SVD) has been also performed on the cross-covariance matrix between SST and SLP (Venegas et al., 1997, Sterl and Hazeleger, 2002). The first mode exhibits a strong and highly significant coupling between SST and SLP and it is associated with a monopole in atmospheric pressure variability representing a weakening (strengthening) and a northward (southward) displacement of the subtropical high. The SST expression of this coupled mode corresponds with the leading dipole SST pattern (Fig. 4a).

The second mode of coupled ocean-atmosphere variability in Sterl and Hazeleger (2002) is related to the third leading SST pattern displayed in Fig. 4 and, in agreement with Palastanga et al. (2002), this mode of coupled variability is connected to ENSO variability.

5.1.5. The leading mode of SST variability

The dipolar structure that characterizes the leading mode of SST variability in the South Atlantic (Fig. 4a) seems to be a very robust pattern. In contrast to what was found for the tropical cross-hemispheric Atlantic dipole (Dommenget and Latif, 2000 and references therein), the South Atlantic dipole remains as the leading variability mode even after the EOF rotation method is applied (Palastanga et al. 2002). Also, significant correlation between the SST anomalies of the two main dipole centers is observed on interdecadal timescales (Sterl and Hazeleger, 2002). The dipole seasonal variation seems to be very minor although it appears stronger during austral winter (Robertson et al., 2002). Moreover, in a model study Robertson et al. (2000) has shown that SST anomalies in the South Atlantic may have an impact on the North Atlantic Oscillation. The dipole pattern seems to depict an atmosphere-to-ocean forcing, in which the ocean response to the atmospheric changes appears with an intraseasonal time lag (Venegas et al. (1997). However, the mechanisms, maintaining the South Atlantic dipole are not clear yet and some of them are discussed in the next section.

It is noticeable that the tropical action center of the South Atlantic dipole covers the southern region of the called tropical Atlantic dipole (Dommenget and Latif 2000 and references therein). Although, Mestas-Nuñez and Enfield (1999) and Dommenget and Latif (2000), among others, have questioned the existence of the tropical SST dipole and concluded that the centers of action across the equator present almost independent variability. The SST variability over the tropical Atlantic has been related to the cross-equatorial temperature gradient, which in turn affects the trade wind system in the tropics (e.g. Servain 1991, Chang et al 1997, Enfield and Mayer 1997) with significant impact on northeast Brazil precipitation (Nobre and Shukla, 1996).

5.1.6. Mechanisms of SST low-frequency variability

Ocean and atmospheric variability on interannual to decadal and multi-decadal time scales in the South Atlantic is not well understood. Some progress has been made both in terms of our understanding of the South Atlantic and our ability to observe it but much remains to be uncovered, in particular with respect to the sensitivity of the South Atlantic to climate change scenarios. So far, only a few studies have addressed the question of mechanisms of interannual to decadal variability in the South Atlantic. From lag-regression analysis of the NCEP/Reanalysis data, Sterl and Hazeleger (2002) found that SST anomalies are created by anomalous latent heat fluxes, which are created by anomalous winds, and anomalous entrainment induced by wind stress variations. The latent heat fluxes also damp the dominant mode of SST variability, consistently with the stochastic climate model of Frankignoul and Hasselmann (1977). The role of the latent heat fluxes and wind-induced mixing has been confirmed by Haarsma et al (2002) in a hierarchy of models. Wainer and Venegas (2002) also suggest the atmospheric forcing of low-frequency variability through the analysis of simulated SST variability by the CSM. However, they suggest a role of oceanic transport in generating SST anomalies in the Brazil-Malvinas confluence. This region has been found to contain strong small-scale variability that may also be forced by internal ocean dynamics (Olson et al. 1988). The interaction between localized oceanic variability and basin wide oceanic variability is also visible in sea level height variability (Witter and Gordon, 1994). The SST variability in the tropical South Atlantic also seems to be forced by the atmosphere that creates the variability by anomalous latent heat fluxes wind-generated (e.g. Chang et al. 1997). The heat transports in the upper ocean basically damp the SST anomalies (Seager et al. 2001). Much is still unknown concerning mechanisms of variability. If there is a decadal signal in SST anomalies and the atmosphere creates the variability, a mechanism lacks for explaining the variability. Recently Haarsma et al. (2002) using an atmosphere model of intermediate complexity (SPEEDY, Molteni, 2002) coupled to a hierarchy of ocean models, explored the physical mechanisms responsible for the dominant patterns of coupled SLP and SST variability.

The coupled modes of simulated SLP and SST anomalies (Fig. 5) strongly resemble those identified from reanalysis datasets (Fig. 4). The authors found that the patterns are due to a combined effect of turbulent surface heat fluxes, Ekman transport and wind mixing while they suggest that another potential mechanism for generating SST variability in the South Atlantic might be the advection by (anomalous) geostrophic currents.

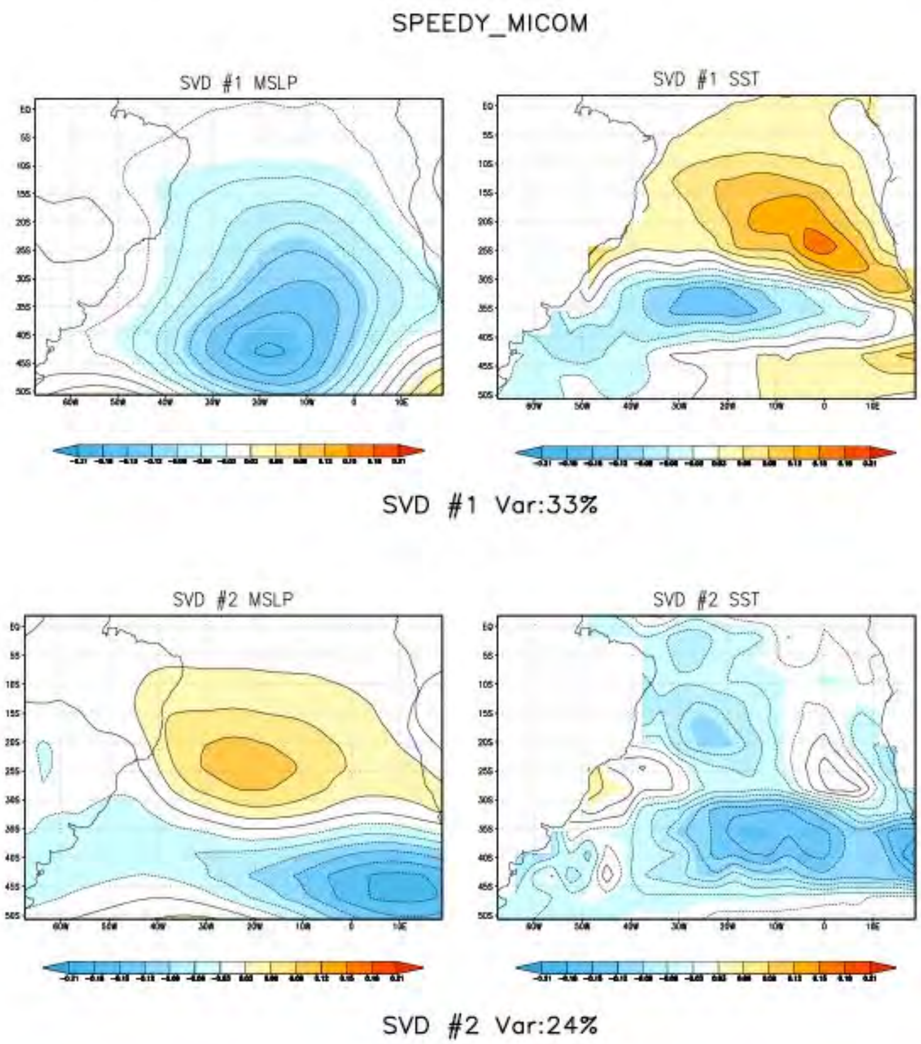


Figure 5: Fist two leading modes of a combined SVD analysis of SLP and SST anomalies simulated by the SPEEDY-MICOM model. (From Haarsma et al. 2002)

Another intriguing mechanism is the interaction with the basin wide meridional overturning circulation, as the South Atlantic is an active part of this circulation. Water masses enter the South Atlantic either through Drake Passage or by Agulhas leakage. Subtropical Cells are an active part of the upper branch of the meridional overturning and may play a role in the variability themselves. Especially the South Atlantic feeds the equatorial thermocline by these cells (e.g. Hazeleger et al. 2003, Zhang and McPhaden 2003). On long time scales variability in Subtropical Cells are likely to affect the tropical thermocline, on decadal or shorter time scales such a connection for SST anomalies is not likely. Also, interaction with circumpolar variability might be a candidate for generating the decadal time scale. Variations associated with variability in Interbasin exchange are discussed elsewhere (white paper of de Ruyter et al.).

5.1.7. Scientific issues about the South Atlantic variability

Many fundamental questions remain unanswered regarding the climate variability in the South Atlantic Ocean:

- How uncertain is the current diagnosis of the SST variability in the South Atlantic because of the lack of a reasonably dense data coverage? How reliable are heat fluxes computed from reanalisis dataset?

- What are the physical mechanisms that cause the SST variability on interdecadal, interannual and intraseasonal timescales in the South Atlantic? What are the feedbacks among surface heat fluxes, winds, heat content and SST that contribute to low-frequency SST variability?

- What is the ocean's role in creating these SST anomalies? What is the relative importance between western boundary current transports and interior Ekman transports? What is the relation between SST and thermocline variability? How does the Subtropical Cell in the South Atlantic vary and does it play a role in determining the tropical thermocline and SST variability? Do oceanic waves play an important role in determining SST fluctuations in the South Atlantic Ocean?

- How important are remote influences versus local air-sea interactions in the genesis and evolution of the South Atlantic SST anomalies? If remote influences are important, where are their origins and through what physical processes do they exert their influences on the South Atlantic?
- Does the South Atlantic influence remote regions? What is the atmospheric response to South Atlantic SST variations (remote response to extratropical SST anomalies is suggested by Robertson et al 2002 and to tropical SST anomalies by Chang et al 1997 in the tropics)?

- What is impact of the South Atlantic on the basin-wide Atlantic meridional overturning circulation? What is the role of interbasin exchange (see white paper of de Ruyter et al), interior mixing in the South Atlantic basin and the interaction with the Subtropical Cell?

5.1.8. Special observing needs

The ARGO program plans to spread by 2004 in the world ocean 3,000 autonomous floats which will provide real time information on the thermo-haline structure in the top 2,000 meters of the water column. In this context, about 600 autonomous floats will need to be spread by 2004 in the Atlantic Ocean, half of them in the South Atlantic. Autonomous floats have an expected lifetime of 3 years at least. Ships of opportunity constitute a privileged means for floats deployment. It is at least the basic hypothesis that has been retained at international level by the Argo project. This is true for vast portions of the world oceans, but not warranted of course in all the world oceanic zones. This is particularly the case for the south Atlantic Ocean where the routes of merchant ships are very scattered and leave an enormous hole between South America and South Africa (Fig. 1). In that sense, a proposal was recently made (Servain et al., 2001; Marchand and Servain, 2002) to the physical ocean science community. The purpose is to facilitate and to optimize field activities of operational oceanography (OP/OC) in the tropical and South Atlantic Ocean. To be sure to get an adequate ARGO sampling in the South Atlantic, it will be necessary to drop floats from specially dedicated platforms. The NOR-50 (named “NOR-50” for “Navire Océanographique Rapide de 50 m”) can be used as an answer to this question of floats dropping on difficult ARGO grid locations in the Southern Ocean. Maintenance of the ARGO network in the totality of the zone described in Fig. 5 is insured with three missions during three years (1 mission/year, Table 1). Every mission breaks into four east-west trans-oceanic crossings spaced out by about 9° of latitude. Distance crossed for every annual mission is about 16,000 miles, and about 50 days in duration (Natal-Natal), with four intermediate stopovers. The number of ARGO floats dispatched every year will be around sixty, for a total number covering this region of 190.

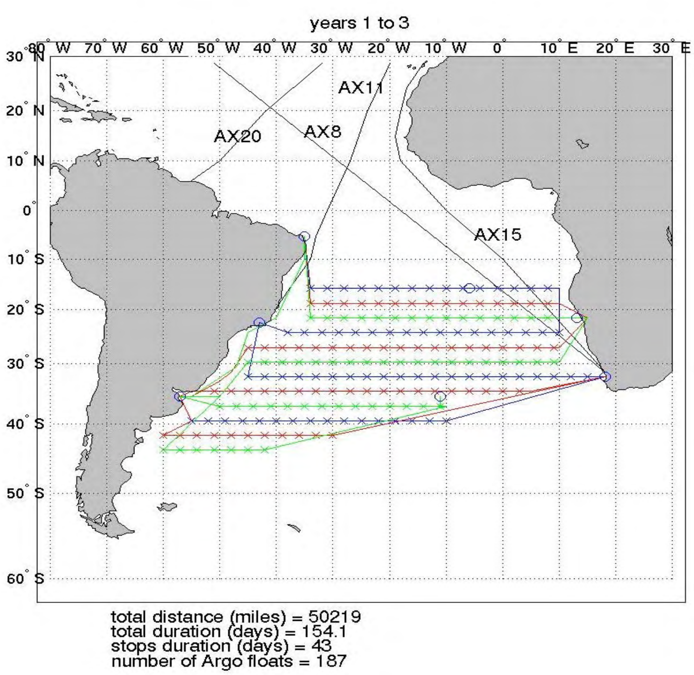


Figure 5: Argo Deployment in the South Atlantic

In addition, moorings in the western boundary current regions are necessary for studying the ocean's role in the decadal variability. At present there is a reasonable coverage in the tropical South Atlantic, but they need to be maintained to be able to study variations in the ocean heat transport.

Table 1: Argo Deployment (3-year coverage)

Year	Total Cruise Distance Natal-Natal (miles)	Total Cruise Duration Natal-Natal (days)	Number Argo Floats	Stop Places (days)
1	16400	50.3	65	Natal/Sta Helena(2)/Rio de Janeiro(3)/Cape Town(3)/Mar del Plata(3)/Natal(3) (Total = 14 days)
2	17868	54.4	63	Natal/Swakopmund(3)/Mar de Plata(3)/Cape Town(3)/Mar del Plata(3)/Natal(3) (Total = 15 days)
3	15951	49.4	59	Natal/Swakopmund(3)/Mar del Plata(3)/Tristan da Cunha(2)/Mar del Plata(3)/Natal(3) (Total = 14 days)
3-Year TOTAL	**50219 miles**	**154.1 days**	**187**	43 days

5.1.9 Modeling needs

A hierarchy of ocean-atmosphere models is presently used to study South Atlantic variability. This line should be continued to address the main issues mentioned above. Key regions in interbasin and interhemispheric exchange show large internal mesoscale oceanic variability that affects the large-scale circulation and variability. For oceanic questions regarding South Atlantic climate variability this variability must be properly taken into account, so high-resolution ocean models are needed with resolutions higher than the deformation radius. Ensembles of coupled ocean-atmosphere models can be used to study predictability of South Atlantic climate. Specifically designed experiments (akin GOGA, TOGA, MOGA runs) should be carried out to investigate the role of South Atlantic SST variability in global climate.

5.1.10 References

Chang, P., L. Ji, and H. Li, 1997: A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air-sea interactions. *Nature*, 385, 516-518.

Chelton, D. B., M. G. Schlax, D. L. Witter, and J. G. Richman, 1990: Geosat altimeter observations of the surface circulation of the southern ocean, *J. Geophys. Res.,* 95, 17,877-17,903.

Da Silva, A., A. Young, and S. Levitus, 1994: *Algorithms and Procedures.* Vol. 1 *Atlas of Surface Marine Data 1994,* NOAA Atlas NESDIS 6.

Dommenget, D., and M. Latif, 2000: Interannual to decadal variability in the Tropical Atlantic. *J. Climate.,* 13, 777-792.

Enfield, D.B., and D.A. Mayer, 1997: Tropical Atlantic SST variability and its relation to El Nino Southern Oscillation. *J. Geoph. Res.*, 102, 929-945.

Frankignoul, C. and K. Hasselmann, 1977: Stochastic climate models. II Application to sea surface temperature variability and thermocline variability. *Tellus*, 29, 284-305.
Haarsma, R. J., E. J.D. Campos, R. A. F. de Almeida, A. R. Piola, W. Hazeleger, and F. Molteni, 2002: Mechanisms generating the dominant modes of variability in the South Atlantic Ocean: A study with a hierarchy of ocean-atmosphere models. *(manuscript in preparation)*
Hazeleger, W., P. de Vries, and Y. Friocourt, 2003: Sources of the Equatorial Undercurrent in the Atlantic in a high-resolution ocean model. *J. Phys. Oceanogr*. In press.
Hurrell, J. W.,and K. E.Trenberth, 1999: Global sea surface temperature analyses: Multiple problems and their implications for Climate Analysis, Modeling and Reanalysis. *Bull. Amer. Meteor. Soc*, 80, 2661-2678.
Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40 Year Reanalysis Project. *Bull. Amer. Meteor. Soc*., 77, 437-471.
Marchand P. and Servain J. : The NOR-50: A Tool for Operational Oceanography. *Sea Technology*, 43, N° 6, June 2002, pp 49-54.
Mestas-Nuñez and A.M., D.B. Enfield, 1999: Rotated global modes of non-ENSO sea surface temperature variability. *J. Climate,* 12, 2734-2746.
Molteni, F., 2002: Atmospheric simulations using a GCM with simplified physical parametrizations. I: Model climatology and variability in multi-decadal experiments. *Clim. Dynamics.* In press.
Nobre, P., and J. Shukla, 1996: Variations of sea surface temperatures, wind stress, and rainfall over the tropical Atlantic and South America. *J. Climate*, 9, 2464-2479.
Olson, D.B., G.P. Podesta, R.H. Evans, and O.B. Brown, 1988: Temporal variations in the separation of Brazil and Malvinas currents. *Deep Sea Res.*, Part A, 35, 1971-1990.
Palastanga, V., 2002: About the variability of the sea surface temperature in the South Atlantic Ocean. Master thesis, University of Buenos Aires, Argentina 109 pp. (in spanish).[Available from Departamento de Cs. de la Atm., 2do. piso, Pab. II, Ciudad Universitaria, 1428 Buenos Aires, Argentina.
Palastanga, V., C. S. Vera and A. R. Piola, 2002: On the leading modes of sea surface temperature variability in the South Atlantic Ocean. *CLIVAR Exchanges,* 25.
Paegle, Julia N., Kingtse C. Mo, 2002: Linkages between Summer Rainfall Variability over South America and Sea Surface Temperature Anomalies. *J. Climate*: Vol. 15, 12, 1389–1407.
Peterson, R. G. and L. Stramma, 1991: Upper-level circulation in the South Atlantic. *Prog. Oceanogr.*, 26, 1-73.
Rayner, N.A., and Coauthors, 1996: Version 2.2 of the Global Sea- Ice and Sea Surface Temperature data set, 1903-1994. *Climate Research Technical Note* 74, 21 pp. plus figures.
Reynolds, R.W., and T. M. Smith, 1994: Improved global sea surface temperature analysis using optimum interpolation. *J. Climate*, 7, 929-948.
Robertson, A.W., and C.R. Mechoso, 1998: Interannual and decadal cycles in river flows of southeastern South America. *J. Climate*, 11, 2570-2581.
________, and C.R. Mechoso, 2000: Interannual to decadal variability of the South Atlantic Convergence Zone. *Mon. Wea. Rev.*, 2947-2957.
________, J. D. Farrara and C. R. Mechoso, 2002: Simulations of the atmospheric response to South Atlantic sea surface temperature anomalies. Submitted to *J. Climate*
Seager, R., Y. Kushnir, P. Chang, N. Naik, J. Miller and W. Hazeleger, 2001: Looking for the role of the ocean in tropical Atlantic decadal climate variability. *J. Climate*, 14, 638-655.
Servain, J., 1991: Simple climate indices for the tropical Atlantic Ocean and some applications. *J. Geophys. Res*., 96, 15137-15146.
_______, Marchand P. and Zaharia R. : The NOR-50, A Tool for Operational Oceanography. *Publication IRD-Brest, juillet 2001.*
Sterl, A., and W. Hazeleger, 2002: Patterns and mechanisms of air-sea interaction in the South Atlantic Ocean. Submitted to *Climate Dyn.*
Venegas, S.A., L.A. Mysak, and D.N.Straub, 1997: Atmosphere-ocean coupled variability in the South Atlantic. *J. Climate*, 10, 2904-2920.
Venegas, S.A., L.A. Mysak, and D.N.Straub, 1998: An interdecadal climate cycle in the South Atlantic and its links to other basins. *J. Geophys. Res.*, 103, C11, 24,723-24,736.
Wainer, I., P. Gent, and, G. Goni, 2000: The annual cycle of the Brazil-Malvinas confluence region in the National Center for Atmospheric Research Climate System Model. *J. Geophys. Res.*, 105, 26, 176-26 178.
______, and S. A. Venegas, 2002: South Atlantic Multidecadal variability in the Climate System Model. *J. Climate*, 15, 1408-1420.

Witter, D.L., and A.L. Gordon, 1999: Interannual variability of South Atlantic circulation from 4 years of TOPEX/POSEIDON satellite altimeter observations. *J. Geoph. Res.*, 104, 20927-20948.
Zhang, D., and M. McPhaden, 2003: Observational evidence for flow between the subtropical and tropical Atlantic: the Atlantic Subtropical Cells. *J. Phys. Oceanogr*. Submitted.

5.2 The South Atlantic contribution to the global thermohaline circulation

Alberto R. Piola [1], Edmo J.D. Campos [2], John Donners[3], Arnold L. Gordon [4] and Doron Nof [5]

[1] *Departamento Oceanografia, Servicio de Hidrografia Naval, and Departamento de Ciencias de la Atmosfera y los Oceanos, FCEN, UBA, Buenos Aires, Argentina*
[2] *Instituto Oceanografico, Universidad de Sao Paulo, Sao Paulo, Brazil*
[3] *Royal Netherlands Meteorological Institute, De Bilt, The Netherlands*
[4] *Lamont Doherty Earth Observatory, Columbia University, Palisades, New York, USA*
[5] *Florida State University, Tallahassee, Florida, USA*

5.2.1. Introduction

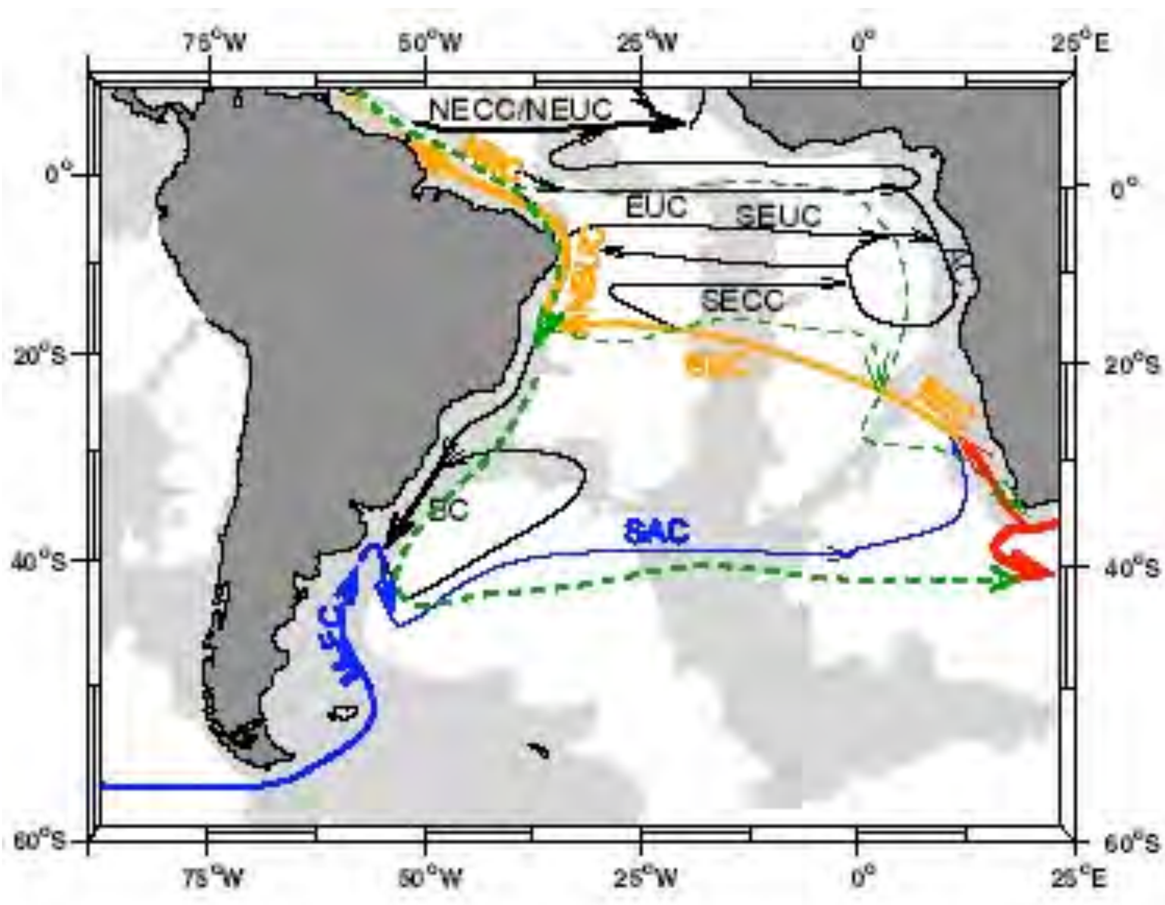


Figure 1: Schematic diagram of the meridional circulation elements in the South Atlantic. North Atlantic Deep Water (in green) flows southward primarily along the western boundary and also on the eastern basins and is exported to the Indian Ocean south of Africa. This flow is compensated by northward flows within the

thermocline and intermediate layers from Drake Passage (in blue) and as part of the Agulhas leakage (red), following the subtropical gyre and the North Brazil Current. Adapted from Peterson and Stramma (1991) and Stramma and England (1999).

The export of about 15 to 20 Sv (1 Sv = $1x10^6$ m^3 s^{-1}) of North Atlantic Deep Water through the South Atlantic to other ocean basins requires a compensating net northward flow through the South Atlantic and across the equator at other levels. Compensating northward flow is possible within the surface, intermediate and bottom water layers (Figure 1). Modifications of the water masses participating in the return flow within the South Atlantic can potentially lead to alterations of the thermohaline circulation and the associated meridional heat and freshwater fluxes. Diapycnal advection and mixing may be effective shortcircuits of the thermohaline circulation (THC). Similarly changes in the circulation may alter the meridional heat fluxes and impact the THC. An increased share of warm upper layer waters to the northward return flow would lead to increased net northward heat flux through the South Atlantic. The purpose of this note is to review the present knowledge on the meridional fluxes within the South Atlantic, to evaluate mechanisms within the South Atlantic that may impact on the THC.

5.2.2. Circulation and transports

South Atlantic and Indian Ocean thermocline water subducted at the southern edge of the subtropical gyres of the South Atlantic and South Indian Oceans are major contributors to the thermocline waters in the southwestern North Atlantic (Poole and Tomczak, 1999). Therefore, these water masses effectively participate in the net cross equatorward upper layer flow that balances the southward flux of NADW.

Denser waters contributing to the upper branch of the thermohaline circulation enter the Atlantic through Drake Passage and the Malvinas/Falkland Current (referred to as the cold water route) and the Agulhas Current and its retroflection (the warm water route). Based on a coarse resolution, just under 2°, numerical model England and Garçon (1994) estimated that the northward return flow was composed of 6.5 Sv from Drake Passage, 2.5 Sv of Indian Ocean thermocline water and 1.6 Sv of recirculated Indian Ocean Intermediate water. Recent analysis of water mass characteristics and volume transports suggests that Antarctic Intermediate Water (AAIW) is the major contributor to the upper layer return flow to the North Atlantic (de las Heras and Schlitzer, 1999; You, 2002). In contrast other studies suggest that warm surface and thermocline waters, presumably derived from the warm water route, are responsible for the cross-equatorial mass flux (eg. Macdonald and Wunsch, 1996; Holfort and Siedler, 2001; Donners and Drijfhout, 2003).

Within the South Atlantic various regions of enhanced mixing and modification of AAIW have been identified. Such enhanced property transfers are generally associated with small-scale mixing (Bianchi et al., 1993, 2002) and meso-scale eddies (Boebel et al., 1999a,b). Exchange between relatively cold-fresh AAIW derived from Drake Passage and AAIW recirculated within the South Atlantic subtropical gyre occurs in Brazil Malvinas Confluence (Piola and Gordon, 1989). Enhanced meridional exchange has also been associated with the Zapiola eddy in the southern Argentine Basin (Boebel et al., 1999a). AAIW from the Indian Ocean penetrates into the Atlantic from the Agulhas Current region and flows northwestward within the eastern limb of the Subtropical Gyre (Gordon, et al., 1992; Suga and Talley, 1995).

Water mass modification by vertical (diapycnal) mixing is significant throughout the South Atlantic (Sloyan and Rinotul, 2000) and there is evidence of intense mixing of the different varieties of AAIW in the subequatorial gyre (Suga and Talley, 1995).

Estimates of the relative contribution of each AAIW component and the meridional transports differ widely. You (2001) estimates a northward transport of AAIW across 10°S of about 4.3 Sv, with 2.7Sv entering the South Atlantic through Drake Passage and 1.6 Sv from the Indian Ocean. This transport is in good agreement with estimates based on lagrangian observations (eg. Boebel et al., 1999a). A recent analysis suggests that of 3.1 Sv of AAIW flowing northward across 25°S in the Atlantic 1.9 Sv are derived from Drake Passage, with and the remaining is derived from the Indian Ocean, Red Sea and the Indonesian Seas (You et al., 2003). However, some inverse calculations (de las Heras and Schlitzer, 1999) and numerical simulations (Marchisiello et al., 1998) lead to much larger net trans-equatorial flow of AAIW of 9 to 10.1 Sv. In the inversion the intermediate water flow is mostly derived from Drake Passage or locally formed within the South Atlantic basin. Other inverse solutions suggest that both the cold and warm water routes are important source waters for deep water formation in the north (Macdonald and Wunsch, 1996). This observation is in agreement with the findings of Poole and Tomczak (1999) who, based on water mass analysis, concluded that about half the thermocline waters in the Caribbean Sea are supplied from warm waters formed in the South Atlantic and Indian Oceans.

Based on inverse solutions for the global circulation, the transport of NADW across the equator is around 12 to 15 Sv. The net northward upper layer flow derived from hydrographic data being only slightly higher (18Sv, Wienders et al., 2000). Inversions also suggest that, as it flows southward through the South Atlantic, NADW transport is increased by about 50% by contributions of AAIW from above and "Antarctic Bottom Water" (γ^n > 28.11 kg m^{-3}) from below (Ganachaud and Wunsch, 2000). These South Atlantic dianeutral transfers are significant short-circuits in the global meridional overturning that require further investigation. Global thermohaline and Chlorofluorocarbon analyses also suggest that south of 30°S about 10 Sv of abyssal water upwell through the γ^n = 28.11 kg m^{-3} neutral surface (Orsi et. al., 1999). A substantial part of this transfer in the Atlantic sector occurs within the Argentine Basin. This study also shows that a branch of water less dense than σ_θ = 28.28 kg m^{-3} flows northward into the Brazil Basin, thus contributing to balance the flow of NADW across 30°S. There is also evidence of strong mixing between NADW and Circumpolar Deep Water (CDW) in the Argentine Basin (Georgi, 1981). In addition, eddy stirring may play a key role in the meridional exchange of NADW-CDW across the ACC within the western Gerogia Basin (Arhan et al. 2002). Estimates of the abyssal contribution to the northward flow across 30°S in the Atlantic range between 6 Sv (γ^n > 28.11 kg m^{-3}, Ganachaud and Wunsch, 2000) and 3 Sv (de las Heras and Schlitzer, 1999).

A Lagrangian analysis based on the output of the OCCAM circulation model provides new insight on the role of the warm water route in the upper limb of the thermohaline circulation in the South Atlantic (Donners and Drijfhout, 2003). The technique quantifies the contribution of different water mass pathways. This study suggests that most of the Atlantic upper layer cross-equatorial flow (15.5 Sv) originates in the Indian Ocean, within the upper 1200m of the Agulhas leakage (Figure 2). The Lagrangian analysis is not incompatible with previous section integrated inverse solutions, which suggest a major contribution from the cold water route (eg. Sloyan and Rintoul, 2001). The apparent inconsistency is mostly due to relatively large recirculations, which are not properly resolved in the section integrated fluxes. However, the inferred sources of South Atlantic upper layer return flow are important since they strongly impact on the estimated meridional heat flux.

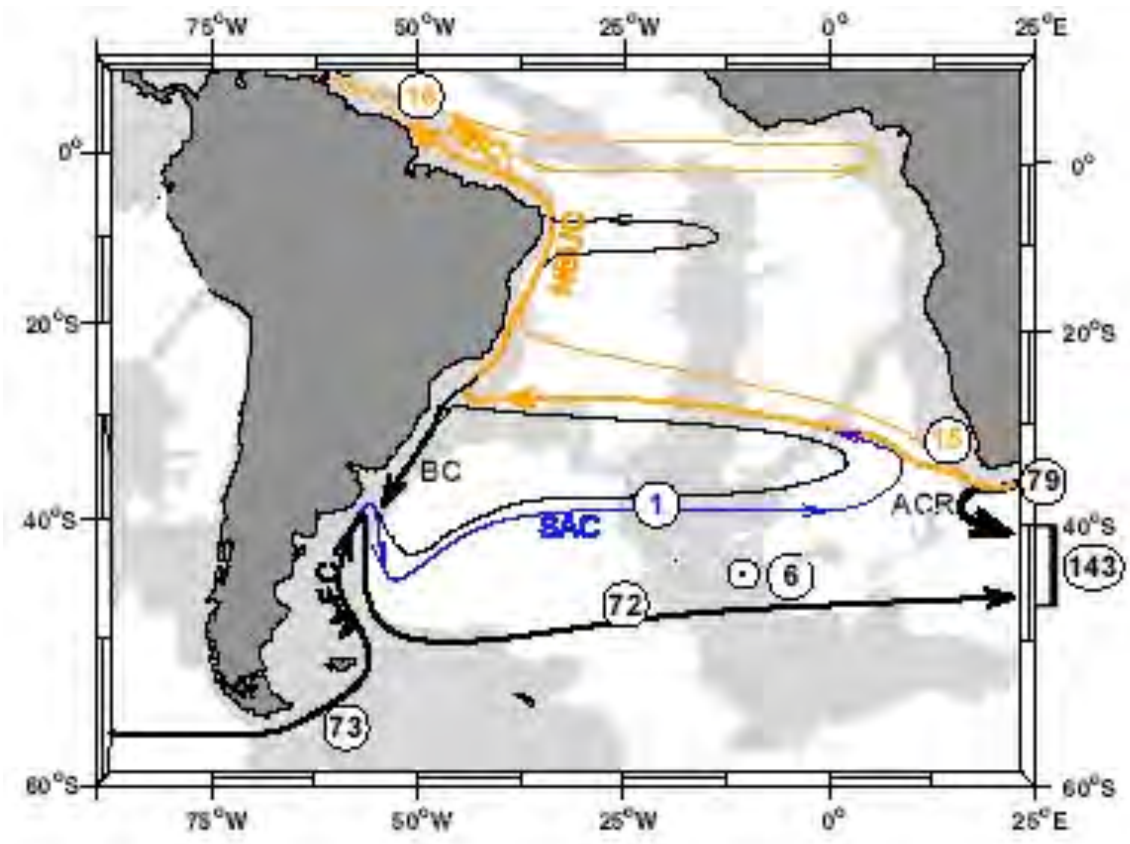


Figure 2: Schematic diagram of the upper layer limb of the Atlantic meridional circulation derived from the lagrangian analysis of Donners and Drijfhout (2003). The blue line represents the flow from the Pacific Ocean and the orange line the Agulhas leakage. The black arrows represent other parts of the upper layer circulation. Numbers within circles are volume transports (Sv). The symbol ⊙ represents upwelling from through the base of the intermediate waters. The shaded areas are shallower than 4000m.

5.2.3. The meridional heat flux

The thermohaline properties of the water masses contributing to the northward return flow in the Atlantic, together with NADW characteristics, determine the ocean's meridional heat and freshwater fluxes. Variations of the thermohaline properties, which are directly related to the different pathways and water masses, must lead to variability of the meridional fluxes. Since variations in the thermohaline properties of NADW are relatively small, we expect that meridional flux variability will be dominated by changes in the composition of the water masses within the upper limb of the THC. For instance, an increased share of warm upper layer waters derived from the Indian Ocean to the northward return must lead to increased net northward heat flux through the South Atlantic. Estimates of the South Atlantic meridional heat flux near 30°S are given in Table 1. To some extent the wide range in these estimates arise from misrepresentations of the eddy heat fluxes (eg Bennett, 1978). In Bennett's direct estimates the large range is due to different parameterizations of the width of the western boundary current. In fact, a realistic width (~100 km) leads to the lower heat flux estimates of order 0.2 PW.

Table 1. Estimates of South Atlantic meridional heat flux near 30°S

Latitude (°S)	*Heat Flux (PW)*	*Method / Source*
32	0.66-0.88	Inverse / Fu (1981)
30	0.69	Sea-air fluxes / Hastenrath (1982)
32	0.16-0.68	Direct / Bennett (1978)
32.5	0.63	Numerical model (OCCAM) / Donners
32	0.4	Direct / Bryan (1962)
30	0.39	Sea-air fluxes / Bunker (1980)
30	0.38	Sea-air fluxes / Hsiung (1985)
30	0.3	Inverse / Macdonald & Wunsch (1996) and Ganachaud & Wunsch (2000)
30	0.29	Numerical model / Marchesiello et al. (1998)
30	0.26	Numerical model / Matano (personal comm., 2003)
32	0.24	Inverse / Rintoul (1991)
30	0.22	Direct / McDonogh and King (2002)
30	0.19	Numerical model / Matano & Philander (1993)
30	- 0.23	Inverse / de las Heras & Schlitzer (1999)

The analysis of de las Heras and Schlitzer (1999) suggests that the southward flow of NADW is balanced primarily by Atlantic AAIW, but their standard solution exhibits poleward heat flux at 30°S. In agreement with Gordon (1986), their inversions show that increased Agulhas leakage, mostly of Indian Ocean AAIW, results when the solution is forced to achieve positive heat fluxes in the South Atlantic. When forced to produce the largest meridional heat fluxes estimated for the Atlantic across 30°S (e.g. ~ 0.69 PW, Hastenrath, 1982), the northward flux is composed of 5.5 Sv of warm waters and 9.9 Sv of AAIW. This latter solution produces mass and heat fluxes similar to OCCAM´s (Donners and Drijfhout, 2003), but, compared to observations, also leads to an unrealistic upper layer temperature drift over large areas of the subtropical South Atlantic.

5.2.4. Variability - Winds

The above studies are not suitable to shed light on the possible effects of the wind over the South Atlantic on the thermohaline circulation. However, a basin scale numerical model (eg Marchisiello et al., 1998) produces a variable, wind dependent, northward flow across the South Atlantic at intermediate levels. In the model, the contributions of upper layer waters and AAIW to the northward flow vary in response to seasonal variations of the mid-latitude wind. Contributions of each flow component are 6 and 7.5 Sv in winter to 4.5 and 9.6 Sv in summer, respectively. The model derived seasonal flow variability leads to an increased basin-wide meridional heat flux in summer. Variability of the mid-latitude winds over the

South Atlantic must produce variations in the strength of the subtropical gyre circulation and possibly impacts on the trans-equatorial transfer of upper layer water into the North Atlantic. The region of interest is the bifurcation of the South Equatorial Current near South America, and whether changes in the gyre strength may impact the transport and water mass properties of the North Brazil Current. Because the strongest northward flows appear to be associated to the highly variable North Brazil Current, direct evidence of these changes is not available. Moreover, substantial discrepancies in the surface wind produced by different sources (eg. NCEP, ECMWF) may lead to large uncertainties in the associated upper layer flow patterns and fluxes derived from numerical models (see Oke et al., 2003).

Numerical simulations have shown that variations in the heat and freshwater fluxes associated with the Indian to Atlantic transfer can induce relatively large changes in the strength of the meridional circulation (Weijer et al., 2002). In the model, heat and freshwater anomalies produce changes in the zonally averaged meridional pressure gradient and the circulation changes primarily occur along the western boundaries.

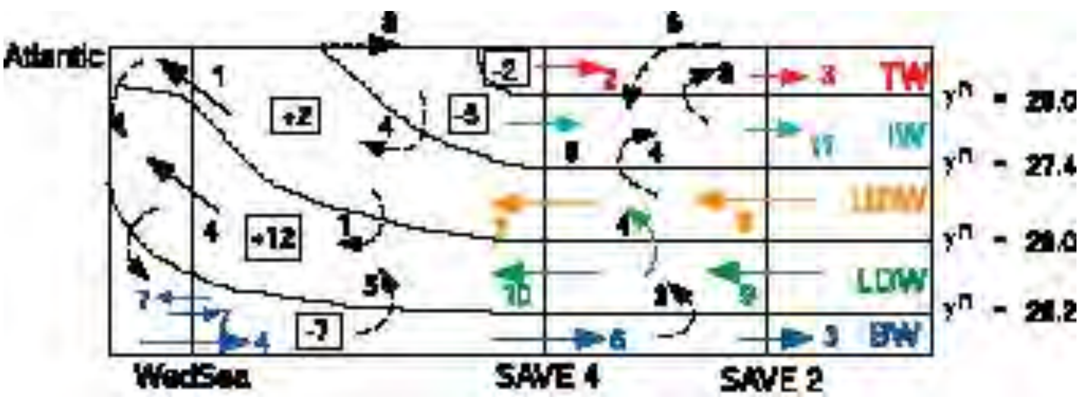


Figure 3: Schematic representation of the South Atlantic meridional circulation (Sv) in selected neutral surface intervals (TW: Tropical Water, IW: Intermediate Water, UDW; Upper Deep Water, LDW: Lower Deep Water, and BW: Bottom Water). Epineutral fluxes are represented by solid arrows, dianeutral fluxes by dashed arrows. The near surface dotted arrows from UDW to IW at the outcrop of γ^n = 27.4 and from TW to IW, represent dianeutral fluxes due to sea-air interaction. Adapted from Sloyan and Rintoul (2001).

Numerical and theoretical studies suggest that if eddy fluxes are neglected, the thermohaline circulation is a function of the strong southern winds (i.e., the winds along the section connecting the tip of South America with the tip of South Africa, Nof, in preparation). Furthermore, even though this transport is determined by the wind, it is not the Ekman transport itself that ends in the North Atlantic as NADW. Rather, it is a broad flow of surface and intermediate water along the eastern part of the basin, which flows northward, crosses the equator and then become NADW. Previous studies have suggested a strong dependence of NADW formation to zonal Southern Hemisphere winds (e.g. Toggweiler and Samuels, 1993, 1995). However, model studies show that thermohaline forcing in the northern North Atlantic alone can generate about 75% of NADW.

5.2.5. Water mass conversions within the Subtropical South Atlantic

Sinking of North Atlantic Deep Water in the northern North Atlantic must be balanced by upwelling in other regions of the World Ocean. Because direct observation of vertical velocities is not possible, in the past uniform upwelling has sometimes been assumed (e.g. Stommel and Arons, 1960). Estimates of vertical or cross-isopycnal fluxes can be derived indirectly from observations or from numerical simulations. Inverse box models have been used to estimate the area averaged cross isopycnal or dianeutral fluxes. Sloyan and Rintoul (2000) explicitly included the diapycnal fluxes of mass, heat and salt in the set of unknowns of their inversion for the Southern Ocean. Their results indicate significant water mass transformations within the subtropical South Atlantic. These fluxes would explain the changes in the thermohaline characteristics of each water mass within the basin. However, the effects of isopycnal mixing can also lead to similar water mass transformations.

In the region bounded by the Save 2 and Save 4 hydrographic sections the inversion of Sloyan and Rintoul leads to an upward (towards less dense water) mass flux of NADW/CDW of about 6 Sv, into the densest intermediate water layer. The heat and salt fluxes through this interface are also upward. The upward (up-gradient) heat flux is a result of advective heat fluxes being larger than the (downward) diffusive heat flux. A small upward mass flux and downward heat and salt fluxes are estimated through the intermediate water - thermocline interface, mostly dominated by downward diffusion. The layers most affected by these diapycnal fluxes correspond to Subantarctic Mode Water (e.g. the less dense intermediate water). Sloyan and Rintoul speculate that the diapycnal fluxes most likely occur in regions of intense mixing and eddy variability, such as the Brazil/Malvinas Confluence in the western South Atlantic. As a result of the heat and salt fluxes, downstream modifications of the thermohaline properties of the water mass cores are observed.

Ongoing analysis of eddy permitting global numerical simulations based on POCM (Matano et al., 2003) suggest that in the southwest Atlantic there is a conversion of NADW and surface water to intermediate water. This result is qualitatively in agreement with the increased northward transport (3 Sv) of intermediate waters derived by the inversion of Sloyan and Rintoul (2000, 2001). The inversion also suggest that about 6 Sv of warm-salty upper layer water are converted to intermediate water by sea-air exchange and suggest that these modifications most likely occur in the Argentine Basin (Sloyan and Rintoul, 2001).

The POCM analysis also shows that surface (sigma-theta < 26.2) and intermediate waters (sigma theta > 26.7) are converted to subsurface waters within the Cape Basin, while further north, in the subtropical gyre, the conversion is mostly from subsurface water to surface waters (sigma theta < 26). The model suggests that the regions of largest water mass conversions are the Cape Basin and the western South Atlantic, which are those of highest mesoscale variability within the South Atlantic Ocean.

5.2.6 References

Arhan, M., A.C. Naveira Garabato, K.J. Heywood and D.P. Stevens, 2002, The Antarctic Circumpolar Current between the Falkland Islands and South Gerogia, *J. Phys.Oceanogr*., 32, 1914-1931.

Bennett, A.F., Poleward heat flux in southern hemisphere oceans, *J. Phys.Oceanogr*., 8, 785-796.

Bianchi, A.A., C.F. Giulivi and A.R. Piola, 1993, Mixing in the Brazil/Malvinas Confluence, *Deep-Sea. Res*. I, 40, 1345-1348.

Boebel, O., C. Schmid, G. Podestá and W. Zenk, 1999b, Intermediate water in the Brazil-Mlavinas Confluence Zone: A Lagrangian view, *J. Geophys. Res*., 104, 21063-21082.

Boebel, O., R.E.Davis, M. Ollitrault, R.G. Peterson, P.L.Richardson, C. Schmid and W. Zenk, 1999a, The intermediate depth circulation of the western South Atlantic, *Geophys. Res. Lett*., 26, 3329-3332.

Bryan, K, 1962, Measurements of meridional heat transports by ocean currents, *J. Geophys. Res*., 67, 3403-3414.

de las Heras, M.M. and R. Schlitzer, 1999, On the importance of intermediate water flows for the global ocean overturning, *J. Geophys. Res*., 104, 15515-15536.

Donners, J. and S.S. Drijfhout, 2003, The lagrangian view of South Atlantic interbasin exchange compared with inverse model results, *J. Phys. Oceanogr*., in press.

England, M.H. and V.C. Garçon, 1994, South Atlantic circulation in a general circulation model. *Ann. Geophys.*, 12, 812-825.

Ganachaud, A. and C. Wunsch, 2000, Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data, *Nature*, 408, 453-457.

Gordon, A.L., R.F. Weiss, W.M. Smethie, Jr. and M.J. Warner, 1992, Thermocline and Intermediate Water communication between the South Atlantic and Indian Oceans, *J. Geophys. Res*., 97, 7223-7240.

Hastenrath, S., 1982, On the meridional heat fluxes in the World Ocean, *J.Phys.Oceanogr*., 12, 922-927.

Holfort, J. and G. Siedler, 2001, The meridional overturning oceanic transports of heat and nutrients in the South Atlantic, *J.Phys.Oceanogr*., 31, 5-29.

Macdonald, A. and C. Wunsch, 1996, An estimate of global ocean circulation and heat fluxes, *Nature*, 382, 436-439.

Marchisiello, P, B. Barnier, and A.P. de Miranda, 1998, A sigma-coordinate primitive equation model for studying the circulation in the South Atlantic. Part II: Meridional transports and seasonal variability, *Deep-Sea Res*. I, 45, 573-608.

Matano, R., B.Barnier, E.Campos, A.Coward, J.McLean, E.Palma, T.Penduff, M.Schouten, A-M.Treguier, I.Wainer, D.Webb, 2003, The Mesoscale Circulation of the South Atlantic Ocean: Does it Matter to Climate? 'White paper' for the CLIVAR/OOPC/IAI Workshop on the South Atlantic Climate Observing System, February 6 – 8, 2003, Angra dos Reis – Brazil.

Matano, R.P. and S.G.H. Philander, 1993, Heat and mass balances of the South Atlantic Ocean calculated from from a numerical model, *J. Geophys. Res.,* 98, 977-984.

Oke, P.R., M.H. England and C.J.C. Reason, 2003, On the sensitivity of a coarse resolution world ocean model to different wind stress climatologies, submitted to *J. Phys.Oceanogr.*

Orsi, A.H., G.C. Johnson and J.L. Bullister, 1999, Circulation, mixing and production of Antarctic Bottom Water, *Progr. Oceanogr*., 43, 55-109.

Peterson, R.G. and L. Stramma, Upper level circulation in the South Atlantic Ocean. *Progr. Oceanogr*., 26, 1-73.

Piola, A.R. and A.L. Gordon, 1989, Intermediate waters in the southwest South Atlantic, *Deep-Sea Res*. A, 36, 1-16.

Poole, R. And and M. Tomczak, 1999, Optimum multiparameter analysis of the water mass structure in the Atlantic Ocean thermocline, *Deep-Sea Res*. I, 46, 1895-1921.

Rahmstorf, S. and M. H. England, 1997. Influence of Southern Hemisphere winds on North Atlantic Deep Water flow. *J. Phys. Oceanogr.*, 27, 2040-2054.

Sloyan, B.M and S.R. Rintoul, 2000, Estimates of area-averaged dyapicnal fluxes from basin-scale budgets, *J. Phys. Oceanog*., 30, 2320-2349.

Sloyan, B.M and S.R. Rintoul, 2001, Circulation, renewal, and modification of Antarctic Mode and Intermediate Water, *J. Phys. Oceanog*., 31, 1005-1030.

Stommel, H.M. and A.B. Arons, 1960. On the abyssal circulation of the world ocean. I. Stationary planetary flow patterns on a sphere. *Deep-Sea Res., 6*, 140-154.

Stramma, L. and M. England, 1999, On the water masses and mean circulation of the South Atlantic Ocean, *J. Geophys. Res*., 104, 20,863-20883.

Suga, T. And L.D. Talley, 1995, Antarctic Intermediate Water circulation in the tropical and subtropical South Atlantic, *J. Geophys. Res*., 100, 13441-13453.

Toggweiler, J. R. and B. Samuels, 1993. Is the magnitude of the deep outflow from the Atlantic Ocean actually governed by Southern Hemisphere winds? The Global Carbon Cycle, M Heimann, Ed., Springer, 303-331.

Toggweiler, J. R. and B. Samuels, 1995. Effect of Drake Passage on the global thermohaline circulation. *Deep-Sea Res.*, 42, 477-500.
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.
Wienders, N., M. Arhan and H. Mercier, 2000, Circulation at the western boundary of the South and Equatorial Atlantic: Exchanges with the ocean interior, *J. Mar. Res*., 58, 1007-1039.
You, Y., 2002, Quantitative estimate of Antarctic Intermediate Water contributions from Drake Passage and the southwest Indian Ocean to the South Atlantic*, J. Geophys. Res*., 107, 10.1029-6.
You, Y., J.R.E. Lutjeharms, O. Boebel, W.P.M. de Ruijter, 2003, Quantification of interocean exchange of intermediate water masses around southern Africa, *Deep-Sea Res. II*, 50, 197-228.

5.3 South Atlantic Inter-Ocean Exchanges

Wilhelmus P.M. de Ruijter [1], Stuart A. Cunningham [2], Arnold L. Gordon [3], Johann R.E. Lutjeharms [4], Ricardo P. Matano [5] and Alberto R. Piola [6].

[1] *Institute for Marine and Atmospheric Research, Utrecht University, Princetonplein 5, 3584 CC Utrecht, Netherlands;*
[2] *Southampton Oceanography Centre, Southampton, UK.*
[3] *Lamont Doherty Earth Observatory of Columbia University, Palisades NY, USA*.
[4] *Department of Physical Oceanography, University of Cape Town, South Africa.*
[5] *College of Oceanic and Atmospheric Sciences, Oregon State University, USA.*
[6] *University of Buenos Aires, Argentina*

5.3.1 Introduction

The exchanges of the South Atlantic with the Indian and Pacific Oceans are of critical importance for the global thermohaline circulation and its variability. The South Atlantic is the gateway by which the Atlantic meridional overturning circulation (MOC) communicates with the global ocean, exchanging properties and mass with the Indian and Pacific via the Southern Ocean and around South Africa. These inter-ocean links make possible the unique global reach of North Atlantic Deep Water (NADW) and of the compensating return flow within the ocean upper layers. The latitude of the passages connecting the South Atlantic to the Pacific and Indian Oceans as well as the sharply different nature of southeastern Pacific and southwestern Indian Ocean water masses, allow South Atlantic access of very different water types. As a result the South Atlantic involves nearly all the major climatically important water masses of the World Ocean (Antarctic Intermediate Water, Antarctic Bottom Water, NADW and Mode and thermocline waters). Cool, low salinity waters are introduced through the Drake Passage; warm, saline subtropical Indian Ocean waters enter at the Agulhas Retroflection (the cold and warm water routes, respectively). The resultant heat, freshwater and buoyancy budget of the South Atlantic is expected to be sensitive to the ratio of these two return flows. Which of the South Atlantic's neighbors dominates the inter-ocean exchange may to a large measure determine the meridional fluxes of the South Atlantic (Gordon, 1986, 2001; Weijer et al., 1999). Temporal variations in the ratio may be associated with climate variability as well as variations in the overturning circulation of the Atlantic Ocean. This explains why inter-ocean exchanges have been subject to much attention in recent years. Several review papers on the subject have appeared recently (Gordon, 2001; De Ruijter et al., 1999) and the reader is referred to those reviews for detailed descriptions of regional and global aspects of the topic. In this paper emphasis will be on recent results concerning exchanges between the subtropical South Atlantic and the Southern Ocean, the Pacific link via the Drake Passage and the subsequent transformations at the Brazil/Malvinas Confluence, and the Indian-Atlantic Ocean connection at the Agulhas Retroflection.

5.3.2 Exchanges between the South Atlantic and the Southern Ocean.

The real ocean conveyor flows around Antarctica, where the Antarctic Circumpolar Current (ACC) provides the major connection between the three oceans. Meridional fluxes of heat and freshwater, necessary to balance the air-sea buoyancy fluxes south of the ACC, are largely provided by mesoscale eddies (DeSzoeke and Levine, Bryden and Cunningham, 2001, Karsten and Marshall, 2001). Fresh water evaporating from the subtropical South Atlantic increases the surface salinity of the subtropical water. It is carried southward by the atmosphere and was observed to lead to a freshening of the surface layer of the ACC on its way eastward across the South Atlantic (Gordon and Piola, 1983). This fresh water is subsequently carried into the Pacific by the ACC and eventually has to return to the Atlantic via the Drake Passage and/or the Bering Strait.

Table 1: Solution fluxes from McDonagh and King (2002) on the sections corrected to zero net mass flux except the net freshwater flux that is calculated relative to a Bering Strait throughflow of 0.8 Sv at an average salinity of 32.5.

	A10 (30°S)	A11 (45°S)
Layer transports (Sv)		
Surface	7.1	9.7
Intermediate	7.3	6.0
Deep	-19.9	-21.0
Bottom	5.5	5.3
Heat (PW)		
Ekman	-0.03	0.21
Overturning	0.55	0.17
Gyre	-0.31	0.05
total heat	0.22±0.08	0.43±0.08
total salt (Sv psu)	-9.7	-2.9
Section average		
potential temperature (°C)	4.35	2.58
salinity	34.81	34.65
Net freshwater flux (Sv)	-0.5	-0.7

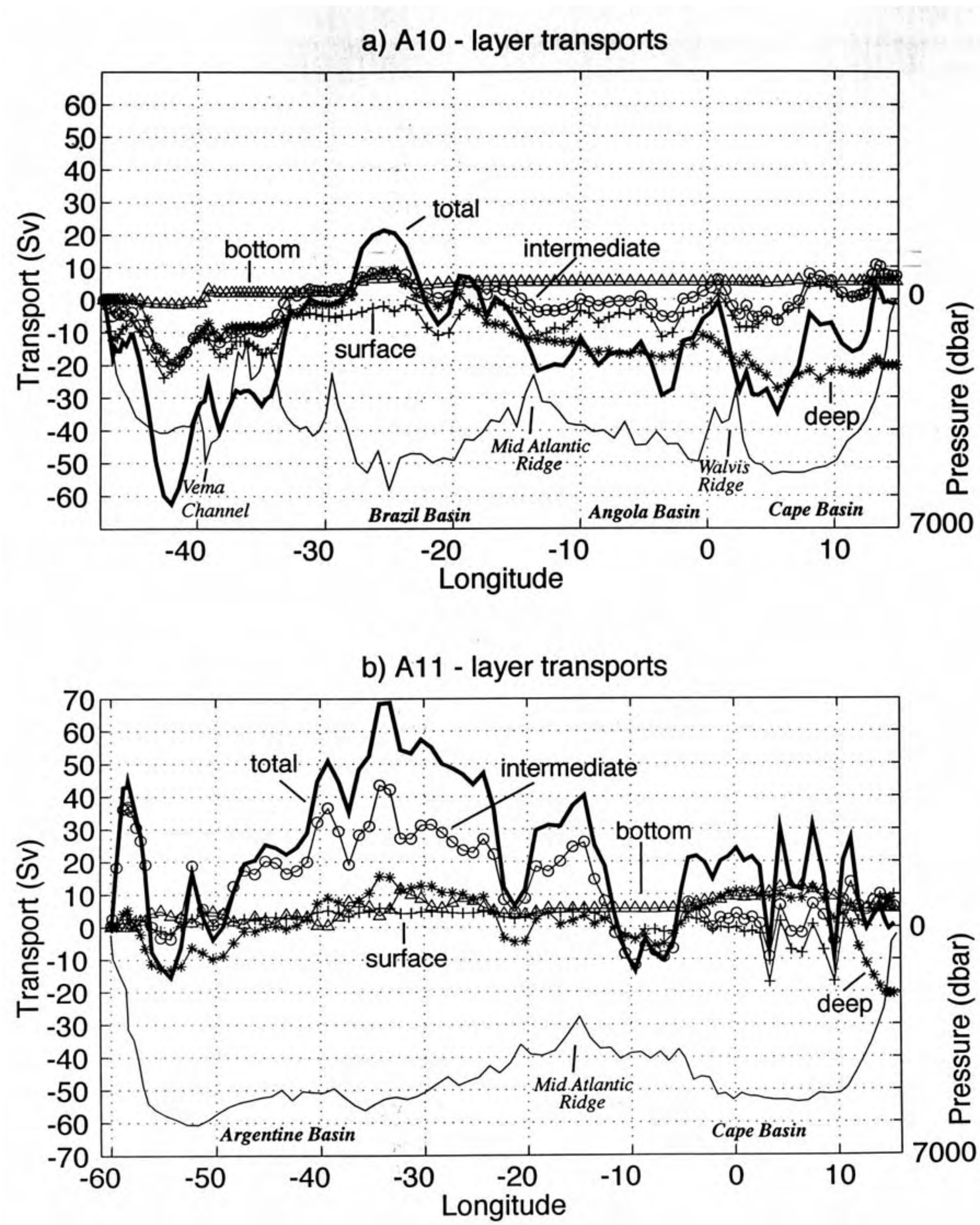


Figure 1: Transport in Sv (positive northwards) cumulated from the western end of the section for a) WOCE section A 10 and b) A 11. Transports of surface (+), intermediate (o), deep (∗) and bottom (Δ) water are shown as well as the total transport in bold. The thin line shows the pressure of the bathymetry in each plot. (From McDonagh and King, 2002).

Several studies have concluded that the cold water route contributes significantly to the cross equatorial flow into the North Atlantic. England and Garçon (1994) estimated that about 6.5

Sv of these waters flow into the North Atlantic. Similar or larger cold water route contributions, based on inverse methods, water mass studies and models have also been estimated (eg. de las Heras and Schlitzer, 1999; Marchisiello et al., 1999; Sloyan and Rintoul, 2001b; You, 2002).

During WOCE (the World Ocean Circulation Experiment) two transatlantic hydrographic sections were occupied almost simultaneously: section A10 at 30°S and A11 eastward from South America to about 15°W at a nominal 45°S and from there closing on to South Africa. McDonagh and King (2002) analyzed these sections using an inverse model (constraining western boundary current transports and other elements of the circulation), providing the most recent estimate of the circulation and fluxes in this region. Their results confirm the, well known, fact that the South Atlantic carries heat equatorward (in contrast to the Pacific and Indian Oceans where it is poleward). At the A11 section the estimated northward heat flux is 0.43±0.08 PW while at 30°S it has decreased to 0.22±0.08 PW (1PW=1×10^{15}W). This implies a flux of heat from the ocean to the atmosphere in this latitude band of the South Atlantic of about 0.21 PW. Uncertainties in these heat flux estimates are dominated by uncertainty in the location and temperature of the flow near the surface (McDonagh and King, 2002).

The equatorward heat transport appears to be primarily a function of the large-scale meridional overturning circulation (Table 1); in the horizontal plane the wind-driven subtropical gyre transports heat poleward. Northward flows of warm surface, intermediate and bottom waters were balanced by 20 Sv of southward flowing North Atlantic Deep Water during the occupation of these WOCE-lines. Surface and intermediate waters (Figure 1 & Table 1) were returned to the South Atlantic at the A11 section from the Pacific via the Drake Passage and from the Indian Ocean via the Agulhas Retroflection.

The estimated net northward flux of intermediate water during this period is 6.0 Sv and comes entirely from the western part of the Atlantic subtropical gyre, i.e. west of 12°W (Fig. 1). East of 12°W the net flux of intermediate water was slightly negative (Fig. 1), suggesting that the intermediate water that is exported from the South Atlantic south of the Agulhas retroflection as part of the subtropical 'supergyre' (Gordon et al., 1992; De Ruijter, 1982) is partly transformed to surface water while looping through the western Indian Ocean. So, this result does not preclude a flux of intermediate water from the Indian to the Atlantic Ocean, as observed earlier (Gordon et al., 1992; Mc.Donagh et al., 1999) but it indicates that the Antarctic intermediate water residing within the Argentine Basin provides the primary balance at intermediate depths for Atlantic export of NADW. In addition there is northward flux of surface water is estimated at 9.7 Sv, returning to the Atlantic from the Indian Ocean.

Based on an analysis of data from a December 1988-January 1989 SAVE (South Atlantic Ventilation Experiment) cruise Gordon et al. (1992) concluded that during that period 15 Sv of the 25 Sv geostrophic transport of the Benguela Current was derived from the Indian Ocean and that 9 Sv (2 Sv warmer than 9°C and 7 Sv of lower thermocline and Intermediate Water) of that Indian Ocean water crossed the equator within the North Brazil Current.

The Atlantic freshwater flux remains controversial. Wijffels et al., 1992 estimated 0.8 Sv flow through the Bering Strait and 0.7 Sv of net evaporation between there and 35°S in the

Atlantic. However, the recent inverse analyses at 45°S (McDonagh and King, 2002, Saunders and King, 1995 and Holfort and Siedler, 2001) consistently estimate that the freshwater flux southward through section A11 is between 0.55 Sv and 0.75 Sv, implying no net evaporation over the Atlantic north of that section.

5.3.3 Where and how to monitor the basin scale overturning fluxes?

There are a number of reasons for choosing the latitude of 30°S rather than 45°S (i.e. A11) for observing the net effect of the interocean exchanges between the South Atlantic and the Southern Ocean on the overturning fluxes: 1. 30°S crosses the subtropical gyre without excursion into the Southern Ocean; 2. the western boundary current at 30°S is clear of the confluence region of the Brazil and Malvinas/Falkland currents where transport estimates are difficult; 3. the flux of Antarctic Bottom Water across 30°S is constrained in the Vema and Hunter Channels and can be monitored; 4. to close onto the African continent a section at 45°S has to cut through the Cape Basin, where Agulhas Rings are injected into the South Atlantic (see below); in fact, to avoid intersection with the Agulhas Ring 'corridor' (evidenced also in Fig 1b) one would have to take an even more northerly section at about 26°S; 5. at 30°S transatlantic sections are zonal; 6. at 45°S there is significant zonal depth averaged temperature gradient which means that heat flux estimates are sensitive to small shifts in the horizontal gyre scale circulation.

In the inverse modelling studies mentioned earlier the detailed circulation patterns and hence the basin scale budgets are dominated by the a priori constraints on the solution, the most significant of these being the strength and properties of the western boundary currents such as the Brazil and Malvinas/Falklands Currents and Deep Western Boundary Current. Other constraints are also important, such as wind stress, air-sea buoyancy fluxes, Antarctic Bottom Water flux and the eastern boundary currents such as the Benguela. (For example in the inverse solutions of McDonagh and King (2002) the eastern side of the subtropical gyre circulations at A11 had a significantly different circulation from an earlier inverse solution of these data (Saunders and King, 1995). The depth-averaged differences in the Cape Basin circulation were greater than 40 Sv and accounted for the reduced equatorward heat flux estimates in the later section study. Improved observations of all these quantities will help to describe and quantify the basin scale exchanges. The large-scale baroclinic structure set up by the properties and distribution of the various water masses also contributes to uncertainty in the net fluxes. Making sufficient realizations of a transatlantic section at 30°S to reduce this error is probably impractical though monitoring the basin wide thermal shear by boundary density measurements (as demonstrated in a modelling study by Hirschi et al. (2002) for 26.5°N in the Atlantic) could be a practical option.

In the North Atlantic Jayne and Marotzke (2001) showed that the meridional overturning heat transport fluctuations were dominated by fluctuations in the velocity field. Continuous observations of the horizontal circulation and properties would likely constrain the estimates of the overturning and heat flux variability: profiling floats would partly provide such information, in particular in combination with well designed monitoring arrays across the western boundary current and across the Cape Basin (the latter to monitor the portion of the Agulhas leakage that takes part in the MOC).

5.3.4 The Pacific link with the Southwest Atlantic.

Volume transport through the Drake Passage.

The cold water flow from the Pacific Ocean into the South Atlantic is associated with the Antarctic Circumpolar Current (ACC) as it deflects northward downstream of Drake Passage. Since 1993 the UK has completed seven occupations of WOCE Southern Repeat section 1 across Drake Passage from Burdwood Bank to Elephant Island. Cunningham et al. (2001) analyzed these data to determine the transport and variability of the Antarctic Circumpolar Current in Drake Passage. The net through passage baroclinic transport relative to the deepest common level is 136.7±7.8 Sv and is carried principally by the two main jets of the ACC: the Subantarctic Front 53±10 Sv and the Polar Front 57±5.7 Sv. From the ISOS current meters, hydrography and bottom pressure measurements Whitworth III and Peterson (1985) determined the average total net transport through Drake Passage to be 134±11.2 Sv. Comparing the net and baroclinic transports suggests that the baroclinic field contains most of the net ACC transport through Drake Passage. This was shown in the work of Bryden and Pillsbury (1977), where the net transport contribution due to the velocity field at 2700 m was small, though variable. Rintoul et al. (2001) and Cunningham et al. (2001) reinterpreted the results of Whitworth III and Peterson (1985) to conclude that above 2500 m barotropic variability (±9.9 Sv) of the ACC is of the same order as the baroclinic variability (5.5 Sv): there is no reason to suppose that this variability would not be transferred to the Malvinas/Falkland Current. This has the important implication that monitoring of variability cannot be done purely by measuring pressure differences but must also include measurements of water mass variability.

Heat transport and divergence.

Transport or divergence of heat is a useful concept only where there is a net balance of volume. However, the volume-transport-weighted mean temperature across a boundary can be used to give an indication of the way a property is changing in some region.

Georgi and Toole, (1982) reported the volume-transport-weighted mean temperature for their analysis of two Drake Passage sections. This quantity is the total property transport divided by the total volume transport, and in the Georgi and Toole analysis has the value 2.52°C. They used the difference between this value and the equivalent value south of Africa (1.82 °C) to infer the heat lost by this sector of the ACC: essentially 0.7°C times 127 Sv (0.36 PW). The transport-weighted mean temperatures in °C for the six WOCE sections (Cunningham et al. (2001) ranged between 2.10 and 2.50. High values were for cruises, conducted in late Austral Spring, and the lower values were for early spring observations. In other words, the seasonal cycle, through heating of the surface layer where the velocities are greatest, introduces considerable changes in the heat transported through Drake Passage with a range of 0.4x137 Sv°C, or 0.22 PW. A study of heat gained or lost along the track of the ACC using mean temperatures at the choke points must therefore make very careful consideration of the seasonal signals in all the data used.

5.3.5 The Brazil-Malvinas confluence.

The Subantarctic Front, located near 56-57°S at Drake Passage, loops northward reaching 38°S in the western Argentine Basin to form the Malvinas/Falkland Current (MFC). Estimates of the volume transport of the MFC range between 40 and 70Sv, the barotropic component accounting for about 75 to 85% of the transport (eg. Saunders and King, 1995a; Peterson et al., 1996; Vivier and Provost, 1999, see also Fig.1b). MFC variations have been found to be associated to anomalies in the wind stress curl north of 60°S and to baroclinic waves propagating along the shelf break of South America (Vivier et al., 2001, see also Garzoli and Giuliv, 1994). In contrast with transport variations at the eastern boundary of the South Atlantic, it has been suggested that even large fluctuations of MFC transport have a moderate effect on the meridional heat flux across 40°S (Saunders and King, 1995b). However this conclusion does not consider possible temperature changes within the core of the western boundary current (see also the above discussion on the a priori constraints imposed on inverse models).

Near 38°S the MFC collides with the southward flowing Brazil Current forming the Brazil/Malvinas Confluence (BMC). That region is characterized by high mesoscale eddy energy and thermohaline finestructure activity. The BMC undergoes large meridional fluctuations (Olson et al., 1988), presumably caused by wind induced transport fluctuations of the Brazil Current (Matano et al., 1993) and wind fluctuations further south (Garzoli and Giulivi, 1994). A substantial, not yet quantified, amount of MFC water describes a sharp cyclonic loop, returning southward to about 50°S, near the Falkland Escarpment.

In the upper layers the MFC carries the densest variety of Subantarctic Mode Waters (SAMW, sigma theta < 27.15) from the southeast Pacific, and the denser Antarctic Intermediate Water (AAIW, sigma theta > 27.25). These waters are responsible for the remarkably low salinity water observed in the western South Atlantic (generally referred to as AAIW). The lighter variety (SAMW) is exposed to the winter atmosphere within the MFC and its southward return, therefore local modifications by sea-air interactions are possible (Piola and Gordon, 1989; Talley, 1996; Stramma and England, 1999; Sloyan and Rintoul, 2001b). The region between the MFC and its return is frequently occupied by waters found south of the Subantarctic Front in the ACC, but there is no evidence of interaction with waters from the Subtropical domain.

The inverse calculations suggests that within the Atlantic sector of the Southern Ocean about 8 Sv of Antarctic Surface Water are converted into lower SAMW by sea-air interaction (Sloyan and Rintoul, 2001b). Most of this conversion takes place in the SW Atlantic. The same study concludes that an additional 6 Sv of warm-salty thermocline water is converted to upper SAMW by sea-air interaction between the Argentine Basin and the mid ocean ridge at 20°W.

At the BMC and its seaward extension there is evidence of subduction and intense mixing of the cold fresh varieties of Drake Passage intermediate waters with the AAIW recirculated in the South Atlantic subtropical gyre, which enters the region as part of the Brazil Current (see also Fig 1a). There is also evidence of subduction of relatively fresh intermediate waters along the South Atlantic Current. A substantial amount (50%) of South Atlantic water is estimated to contribute to the northward flowing Benguela Current in the eastern South Atlantic (Garzoli and Gordon, 1996). This appears to be the main path of northward flow of Atlantic waters at subtropical latitudes (Sloyan and Rintoul, 2001b).

The above results suggest that the inflow of SAMW and AAIW and the modifications of these water masses within the southwest Atlantic are key elements of the thermohaline circulation. The possible effects of the large variations of the mass transport of the MFC as well as variability in the wind stress and sea-air heat and freshwater fluxes within the western South Atlantic are unknown. However, these changes are likely to impact on the thermohaline characteristics of the SAMW/AAIW layers and ultimately on the properties of the northward flux of these waters further downstream in the Subtropical and Tropical South Atlantic.

Further down in the water column the MFC carries varieties of Circumpolar Deep Water (CDW) and Antarctic Bottom Water (AABW). The northward flow of deep waters (~40 Sv) occurs in a narrow band along the western boundary and most of these waters appear to return southward with the Malvinas Return Current (Sloyan and Rintoul, 2001a). The thermohaline characteristics of the deep water within the Malvinas Return Current show clear penetrations of NADW well south of the Brazil/Malvinas Confluence. Arhan et al., (2002) have detected diluted NADW flowing over the Falkland Plareau. There is evidence of intense lateral (isopycnal) mixing between varieties of CDW and NADW within the Argentine Basin, notably along the western boundary current (Georgi, 1981), and associated to energetic eddies in the Georgia Basin (Arhan et al., 2002). Further east the core of NADW becomes progressively less salty due to vertical mixing. Thus, the Southwest Atlantic is the region of intense mixing, where NADW first comes in contact with the deep waters from the ACC.

Clearly, an intelligent monitoring system has to be designed for this highly variable region of intense exchange and mixing. A long term monitoring array should also be maintained across the Drake Passage to observe the varying Pacific to Atlantic fluxes.

5.3.6 The exchanges between the Indian and South Atlantic Oceans.

The South Atlantic, South Indian and Southern Ocean waters intermingle in the Cape Basin region, one of the most turbulent spots of the world ocean. In the canonical description of the global conveyor belt the South Atlantic's subtropical gyre draws heat and salt from this region and exports them to the tropics. Although this entrainment in the upper layers is largely ascribed to the shedding of large rings and eddies from the Agulhas Current, the major western boundary current of the South Indian Ocean, it is unclear how these mesoscale, transient fluxes are ultimately integrated into the global thermohaline circulation. The exchanges in the opposite direction, taking place in the lower layers, are largely inferred from water type dilutions (e.g. You et al., 2003; Van Aken et al., 2003) and modelling (e.g. Matano and Beier, 2003).

Modelling of the Atlantic meridional overturning circulation has demonstrated (Weijer et al., 2001, 2003) that the insertion of the warm and salty waters from the South Indian Ocean has a stimulating and stabilizing impact on the thermohaline overturning cycle of the Atlantic as a whole. Furthermore, ocean modelling simulations of the southern hemisphere suggest

(Speich et al., 2002) that the wind-driven circulation is connected in a subtropical super-gyre that results in an efficient conveyer of upper layer waters between all three oceans, north of the ACC. This implies that monitoring the exchanges around South Africa will have far wider implications than the local circulation only.

The Agulhas Retroflection.

The major and most studied part of the interocean exchange south of Africa is the shedding of rings at the Agulhas retroflection (De Ruijter et al., 1999). A secondary, but much smaller, source is the leakage due to Agulhas filaments (Lutjeharms and Cooper, 1996). Direct leakage of Agulhas water at different levels is probably also a component of the interocean exchange, but this part is very poorly quantified due to the dominance of the rings in the region. There is evidence that variations of the Benguela Current transport are due to a variable Agulhas leakage (Garzoli et al., 1996).

At its westward termination the Agulhas Current carries out an abrupt retroflection with the majority of its water subsequently flowing eastward as the Agulhas Return Current (Gordon et al., 1987; Lutjeharms and Ansorge, 2002). To what extent the Aguhas Return Current is an extension of the South Atlantic Current (Stramma and Peterson, 1990) is not known, but water that recirculates as part of the above-mentioned subtropical super-gyre will pass into the Indian Ocean directly south of the retroflection (De Ruijter, 1982; Gordon et al.,1992). The retroflection loop lies between 10° and 21° E and regularly occludes (Lutjeharms and Gordon, 1987), forming an Agulhas ring that subsequently moves off into the South Atlantic. This process of ring shedding is controlled from upstream through the downstream movement of large, solitary meanders, Natal Pulses (Van Leeuwen et al., 2000). These, in turn, seem to be related to inherent circulation variability of the larger Indian Ocean as described below.

On occasion the Agulhas Current may undergo an early retroflection and the throughflow to the retroflection may cease for a number of months (De Ruijter et al., 2003; Lutjeharms et al., in preparation).

Heat flux and dissipation of Agulhas rings.

Agulhas rings may have diameters of up to 500 km, but the more general, average diameter for these features is 320 km. They extend to the ocean floor and have azimuthal speeds between 0.3 and 1.5 m/s (e.g. Van Aken et al., 2003). On having been shed, they move off into the South Atlantic at rates of about 4-8 km/day. Rings have been tracked across the greater part of the South Atlantic Ocean subtropical gyre (Byrne et al., 1995; Schouten et al., 2000). In a recent review Boebel et al. (2003) estimated that only half of the Agulhas eddies that populate the Cape Basin cross the Walvis Ridge and propagate to the west. Although revealing, this value is likely to underestimate the anisotropic distribution of the eddy variability in the southeastern Atlantic as satellite altimeter data indicate differences of eddy variability across the Walvis Ridge of approximately an order of magnitude (Fig. 2). Altimeter based descriptions (Schouten et al., 2000) have also indicated that, on average, Agulhas rings loose at least 50% of their energy in the Cape Basin within the first half year after their shedding, i.e. between their point of origin and the Walvis Ridge (Fig. 3). A large part seems to dissipate - to an extent that they are no longer identifiable as entities in the altimeter signal- in the same region. This implies that most of the energy, excessive salt and heat carried by Agulhas rings is not evenly distributed across the South Atlantic gyre, but is inserted into the water masses in this far-south-western corner of the ocean basin. It may subsequently be advected northwestward within the Benguela Current, the South Equatorial Current and across the equator. This makes monitoring of the evolution of these features as closely as possible to their point of origin essential.

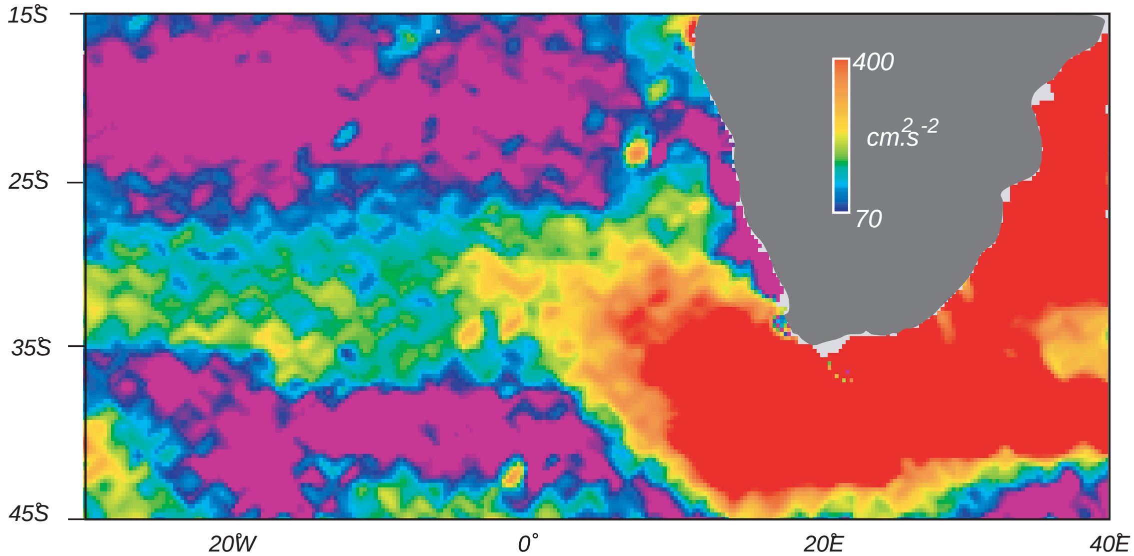


Figure 2: RMS variability of sea surface height in the southeastern Atlantic computed from 10 years of T/P altimeter data, clearly revealing the main paths of Agulhas Rings and the sharp decay of eddy variability away from the Cape Basin.

One of the reasons for the sharp decay of eddy variability away from the Cape Basin seems to be related to the dynamical structure of the rings and eddies and their interactions with each other, the mean circulation and the bottom topography. The most recent analyses of the Cape Basin variability show the co-existence of cyclonic and anticyclonic vortices. While the existence of anticyclones has been known for quite some time (e.g., De Ruijter et al., 1999 and references therein) the cyclonic structures have been largely ignored until quite recently. One of the reasons is that the surface signature of cyclones, in the region where most of the observations have been taken, is substantially smaller than that of the anticyclones. Cyclones, however, seem to outnumber anticyclones by a 3 to 2 ratio (Boebel et al., 2003). The analysis of numerical model simulations indicate that anticyclones and cyclones tend to form dipole-like structures that resemble the Heton model of Hogg and Stommel (1985), with an anticyclone intensified at the surface and a cyclone intensified at the bottom (Matano and Beier, 2003). In the simulations the propagation of both cyclones and anticyclones is strongly affected by the bottom topography. The Walvis Ridge and the Vema Seamount block the passage of bottom-intensified cyclones and changes the trajectories of the upper-intensified anticyclones. From the anticyclones that are able to escape the basin the deep compensation generated by the ridge generates substantial losses of energy.

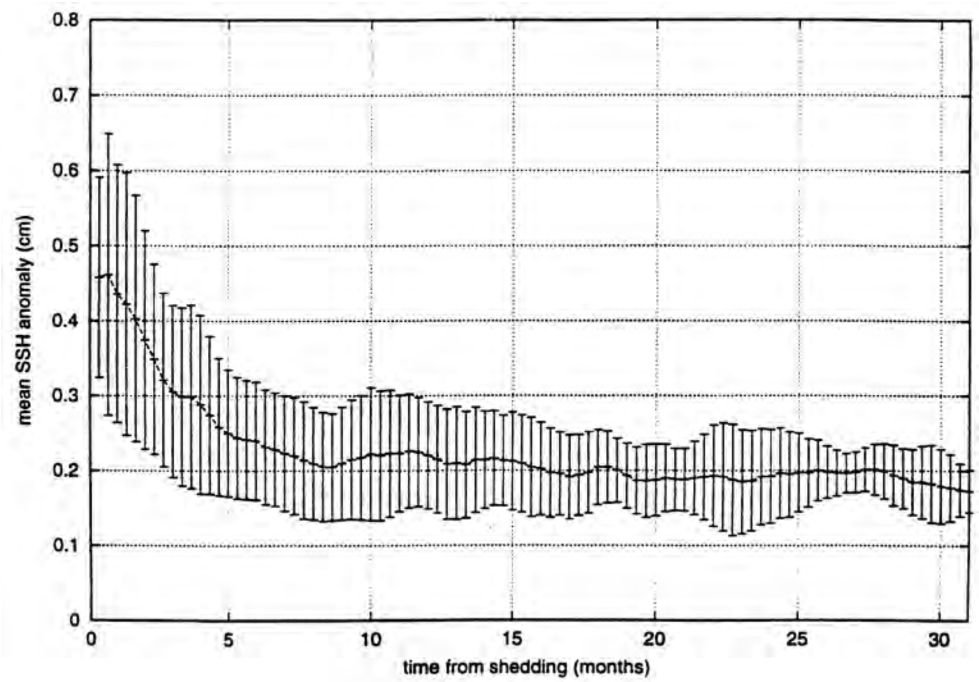


Figure 3: Mean sea surface height variability (and bars of 1 standard deviation) of an ensemble of 11 Agulhas Rings as a function of their age, showing very strong decay in the Cape Basin in the first 5 months of their lifetime.

Rings and eddies that do cross the Walvis Ridge follow a mostly westward path towards the western boundary and although their ultimate fate is unknown it seems reasonable to surmise that mixing processes within the subtropical gyre can transfer a portion of their properties to the global conveyor belt.

A number of other factors also play an important role in the modifications of Agulhas rings once shed. The anomalous surface temperatures of fresh Agulhas rings and the reigning atmospheric conditions in the general region lead to enormous heat and fresh water losses from these features (Walker and Mey, 1988) of up to 1000 W/m^2 on occasion (Rouault and Lutjeharms, 2000). This leads to substantial mixing and convective overturning in the upper layers of these features (Olson et al., 1992) and thus to changes to their water mass characteristics. Recent studies have demonstrated that Agulhas rings may spend substantial periods in the south-western corner of the Cape Basin (Schouten et al., 2000), with water being exchanged between them at intermediate depths (Boebel et al., 2003a) and between them and recently discovered Agulhas cyclones (Lutjeharms et al., 2003). Clearly, this *Cape Cauldron* is a region of intense mesoscale turbulence and mixing which complicates considerably the estimation and monitoring of the exchange between the South Indian and the South Atlantic Ocean.

The anomalous heat flux brought about by a newly spawned Agulhas ring relative to its new South Atlantic environment was estimated to be 7.5×10^{-3} PW and the salt flux due to one ring about 4×10^5 kg/s (Van Ballegooyen et al., 1994). However, the ranges of these variables as estimated from different research projects are very large, sometimes because authors use different reference temperatures (De Ruijter et al., 1999; Gordon, 2001). McDonagh and King

(2002) analysed the impact of two Agulhas rings that were sampled in the Cape Basin on the A11 hydrographic section. They estimated that together the two eddies contributed 0.08±0.14 PW northward heat flux. This recent estimate of northward heat flux due to Agulhas rings is much larger than that estimated by Van Ballegooyen et al. (1994). Using the work of Byrne et al. (1995) McDonagh and King (2002) estimate that half of the Agulhas rings crossing A11 remain intact north of that section, and each ring injects about 0.025 PW of heat into this region. Clearly, these are huge quantities for mesoscale eddies in the ocean, both facilitating and hindering their accurate monitoring.

The heat flux from the Indian to the Atlantic Ocean for an Agulhas leakage of 15 SV if balanced by water that leaves the Atlantic within the upper 1500m (i.e. via the supergyre) is 0.3 PW. If balance is made with the colder NADW then the flux will be 0.8 PW (Gordon, 2001). The estimated total injection of Indian Ocean water into the Atlantic by the rings is from 5 to 10 Sv.

5.3.7 Upstream control from the Indian Ocean

It has been demonstrated recently from satellite altimeter data that the shedding of Agulhas rings is a much more regular process then previously thought, at a frequency of 4 to 5 cycles per year (Schouten et al., 2002a). Eddies from the Mozambique Channel (De Ruijter et al., 2002) and from the East Madagascar Current (De Ruijter et al., 2003) reach the retroflection at that frequency and trigger the shedding of the Rings. The intermittency found in ring shedding statistics in earlier studies is probably related to processes such as instabilities and ring splitting occurring between the actual pinching off and the first unambiguous observation of a separate ring from the altimeter signal.

From altimeter data Schouten et al. (2002b) have presented evidence for an oceanic teleconnection between wind variations over the equatorial Indian Ocean and the regular shedding of Agulhas Rings at a lag of about two years. The equatorial signal seems to be carried across the Indian Ocean by a succession of Kelvin and Rossby waves that eventually seem to control the timing and frequency of the eddy formation around Madagascar and subsequent Agulhas Ring formation. Two observed ‘gaps’ in ring formation over the past decade, one in 1996 (Goni et al., 1997) the other one between January and September 2000 (Quartly and Srokosz, 2002), could be traced back to the equatorial anomalies asociated with the 1994 and 1997/1998 Indian Ocean Dipole/El Niño events, respectively. So, interannual and longer time scale variations in the interocean exchange around South Africa may be linked to the strength and variability of the equatorial climate modes of the Indian Ocean.

5.3.8 Monitoring.

A number of possibilities exist for the monitoring of the oceanic exchanges that take place south of Africa. The first is to observe and identify Agulhas ring shedding from satellite remote sensing. If the surface thermal expressions of Agulhas rings can be directly related to the average heat and salt content of such features (Lutjeharms and Van Ballegooyen, 1988), observations from satellite of the thermal signature of rings would give a first order estimate of the heat and salt flux brought about by these features. However, these features rapidly loose their distinctive surface temperatures due to exchanges with the atmosphere thus making them indistinguishable from the general background environment. The use of satellite altimetry overcomes this liability. Agulhas rings have one of the strongest sea surface height signals in the world. This makes them eminently observable with altimetry. It has been shown that the sea surface height and the dynamical signal of rings based on hydrographic observations are closely related (Goñi et al., 1997). However, altimetry signals of smaller rings may be lost between suborbital tracks and it has been shown that rings may break up and dissipate (Schouten et al., 2000) or subsequently coalesce (Boebel et al., 2003a). This makes the tracking of rings to monitor the heat and salt flux they represent difficult. The best current option would be to monitor Agulhas rings with altimetry while making simultaneous current or hydrographic observations. This has been achieved (Garzoli and Goni, 2000; Van Aken et al., 2003) with a high degree of success. Two monitoring projects using this combination of observations are currently planned.

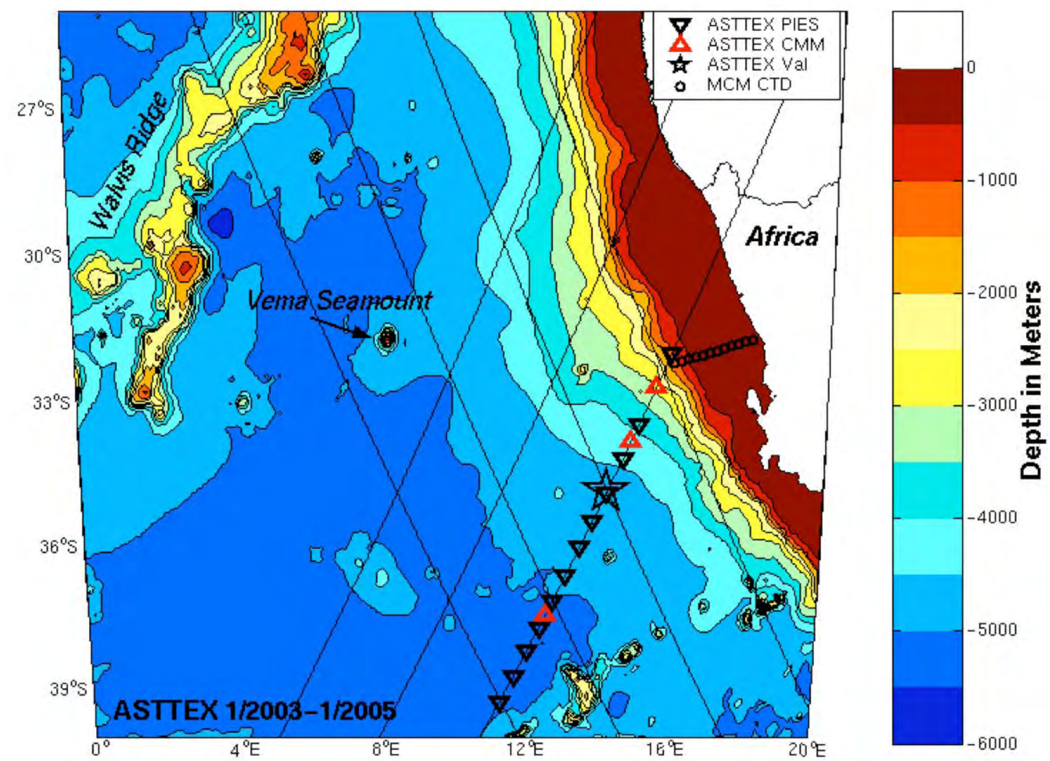


Figure 4: The ASTTEX array southwest of Africa (from the web site: http://www.gyre.umeoce.maine.edu/ASTTEX).

The first, ASTTEX (see http://www.gyre.umeoce.maine.edu/ASTTEX), will place a line of inverted echosounders on a TOPEX/Poseidon suborbital track to the southwest of Africa (Fig. 4). By all estimates this will effectively monitor Agulhas leakage and the movement of rings into the South Atlantic for the years 2003 - 2005. A further, international proposal, GoodHope will attempt to cover this line with hydrographic observations at least twice a year. The line will then extend along the SR2 line of WOCE to the Antarctic continent to monitor changes in the Antarctic Circumpolar Current south of Africa. It therefore seems that for the immediate future, this part of the interocean exchange will be monitored sufficiently, but for a time period limited to only a few years. Other components of the system will not be covered in the same way.

The inflow and variability of the South Atlantic Current (Stramma and Peterson, 1990) to the region south of Africa is poorly known. Exactly how much of this water is absorbed into the equatorward drift of the Benguela Current and how much continues on to join the Agulhas Return Current (Boebel et al., 2003b) carrying water into the South Indian should be established. Considering the temporal variability of the currents in this region, it is relatively safe to assume that the flux carried by the South Atlantic Current would be highly variable. To date there are no plans to monitor this.

It may be crucial to an understanding of the thermohaline circulation of the Atlantic Ocean to establish how much heat and salt are injected by Agulhas rings in the Cape Basin and how much is carried into the subtropical gyre of the South Atlantic. It might be considerably more difficult to design a monitoring array to establish these fluxes unequivocally. A pilot project, MARE (Mixing of Agulhas Rings Experiment), to try to establish the amount of heat and salt injected into the Benguela by an Agulhas Ring has recently finished its observational phase (e.g. Van Aken et al., 2003). One ring has been surveyed three times at half-yearly intervals, but the analysis appears to be severely hampered by the mesoscale turbulence features mentioned above. Combining these in situ observations with satellite altimetry data into a data-assimilation system is presently underway and this ‘tuned’ system will then be used to design a long term monitoring system for the interocean exchanges in this highly variable region of the South Atlantic.

5.3.9 Discussion.

Both the Brazil-Malvinas confluence in the southwest Atlantic and the Cape Basin in the southeast Atlantic are hot spots of variability and mesoscale turbulence of the World Ocean. This is to an important degree controlled by the varying inter-ocean fluxes through the Drake Passage and around South Africa, respectively, together with fluctuations of the South Atlantic subtropical gyre (Gordon, 2003). Waters of Pacific, Indian, Atlantic and Southern Ocean origin collide and blend in these regions. Moreover, very large buoyancy fluxes across the ocean-atmosphere interface lead to intense vertical mixing, convection and subduction in these regions. Eventually, the transformed water masses feed the Benguela Current and subsequently the upper equatorward limb of the meridional overturning circulation of the Atlantic. Their temperature and salinity characteristics, in particular also their vertical profiles, are controls on the buoyancy budget and overturning of the Atlantic. Variability in these characteristics results from both the varying ratio between the input of cool and relatively fresh Pacific waters around South America and that of warm and salty Indian Ocean waters around South Africa and from the varying intensity of the water mass transformation processes in the southwest Atlantic and the Cape Basin. Modelling studies have shown that Agulhas leakage tends to stimulate and stabilize the northern sinking mode of the Atlantic overturning circulation (Weijer et al.,2002, 2003). Bering Strait (or other northern) fresh water fluxes oppose and destabilize it. In the present day situation the stabilizing southern ocean fluxes dominate, but with reduced (or no) Indian Ocean input the northern overturning is expected to be much closer to a switch to a different mode, with associated climate fluctuations.

A monitoring program for the South Atlantic should therefore involve measurements of these varying interocean fluxes as well as the air-sea fluxes and estimates of the mixing and modifications in the two major blending regions of the South Atlantic. To monitor the net effect of the varying interocean exchanges and subsequent mixing and water mass modifications on the vertical buoyancy characteristics of the South Atlantic and the basin-scale overturning fluxes a zonal section is proposed across the South Atlantic at about 30° S, i.e. north of the Brazil Malvinas Confluence and the Agulhas Ring 'corridor'.

As described earlier, observational programmes around South Africa have been funded for the coming few years and will provide very valuable new and improved estimates of the interocean exchages. However, the observational periods are too short to obtain estimates of the variability of the fluxes at the important time scales of the interannual climate modes. As far as we know, no new monitoring programmes have been funded recently for the southwest Atlantic.

5.3.10 References

Boebel, O., J. Lutjeharms, C. Schmid, W. Zenk, T. Rossby, C. Barron - The Cape Cauldron: a regime of turbulent inter-ocean exchange - *Deep-Sea Research II* **50** (1), 57-86 (2003a)

Boebel, O., T. Rossby, J. Lutjeharms, W. Zenk, C. Barron - Path and variability of the Agulhas Return Current - *Deep-Sea Research II* **50** (1), 35-56 (2003b)

Byrne, D.A., A.L. Gordon, W.F. Haxby - Agulhas Eddies: a synoptic view using Geosat ERM data - *Journal of Physical Oceanography* **25** (5), 902-917 (1995)

De Ruijter, W. P. M. - *Asymptotic* analysis of the Agulhas and Brazil Current systems - *Journal of Physical.Ocenography* **12**, 361-373 (1982)

De Ruijter, W. P. M., A. Biastoch, S. S. Drijfhout, J. R. E. Lutjeharms, R. P. Matano, T. Pichevin, P. J. van Leeuwen, W. Weijer - Indian-Atlantic inter-ocean exchange: dynamics, estimation and impact - *Journal of Geophysical Research* **104** (C9), 20.885-20.911 (1999)

De Ruijter, W.P.M., H. Ridderinkhof, J.R.E. Lutjeharms, M. Schouten C.W. Veth - Observations of the flow in the Mozambique Channel - *Geophysical Research Letters*, DOI 10.1029/2001GL013714 (2002)

De Ruijter, W.P.M., H.M .van Aken, E.J. Beier, J.R.E.Lutjeharms, R.P.Matano, M.W. Schouten - Eddies and dipoles around South Madagascar: formation, pathways and large-scale impact - *Deep-Sea Research*, submitted. (2003)

Garzoli, S.L., A.L. Gordon - Origins and variability of the Benguela Current - *Journal of Geophysical Research* **101**, 897-906 (1996)

Garzoli, S.L., A.L. Gordon, V. Kamenkovich, D. Pillsbury, C. Duncombe Rae - Variability and sources of the southeastern Atlantic circulation - *Journal of Marine Research* **54,** 1039-1071 (1996)

Garzoli, S.L., G.J. Goñi - Combining altimeter observations and oceanographic data for ocean circulation and climate studies - In Satellites, Oceanography and Society, editor D. Halpern, Elsevier, Amsterdam, pp. 79- 97 (2000)

Goñi, G.J., S.L. Garzoli, A.J. Roubicek, D.B. Olson, O.B. Brown - Agulhas ring dynamics from TOPEX/POSEIDON satellite altimeter data - *Journal of Marine Research* **55**, 861-883 (1997)

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

Gordon, A.L. Interocean Exchange Chapter 4.7 In: Ocean Circulation and Climate, G. Siedler, J. Church, J. Gould (Eds.), Academic Press 303-314 (2001)

Gordon, A.L., J.R.E. Lutjeharms, M.L. Gründlingh - Stratification and circulation at the Agulhas Retroflection - *Deep-Sea Research* **34**, 565-599 (1987)

Gordon, A.L., A.R. Piola - Atlantic ocean upper layer salinity budget - *Journal of Physical Oceanography* **13**, 1293-1300 (1983)

Gordon, A.L., R.F. Weiss, W.M. Smethie Jr., M.J. Warner - Thermocline and intermediate water communication between the South Atlantic and Indian Oceans - *Journal of Geophysical Research* **97**, 7223-7240 (1992)
Hirschi, J., J. Baehr, S.A. Cunningham - A monitoring design for the Atlantic meridional overturning circulation - *Geophysical Research Letters*, submitted (2002)
Hogg, N.G., H.M. Stommel – The heton, an elementary interaction between discrete baroclinic geostrophic vortices and its implications concerning heat flow. *Proc. R. Soc. London.* **A 397**, 1-20 (1985)
Holfort, J., G. Siedler - The meridional oceanic transports of heat and nutrients in the South Atlantic - *Journal of Physical Oceanography* **31**, 5-29 (2001)
Jayne, S.R., J. Marotzke - The dynamics of ocean heat transport variability - *Reviews of Geophysics* **39** (3), 385-411 (2001)
Lutjeharms, J.R.E., I. Ansorge - The Agulhas Return Current - *Journal of Marine Systems* **30** (1/2), 115-138 (2001)
Lutjeharms, J.R.E., O. Boebel, T. Rossby - Agulhas cyclones - *Deep-Sea Research II* **50** (1), 13-34 (2003)
Lutjeharms, J.R.E., J. Cooper - Interbasin leakage through Agulhas Current filaments - *Deep-Sea Research* **43** (2), 213-238 (1996)
Lutjeharms, J.R.E., A.L. Gordon - Shedding of an Agulhas Ring observed at sea - *Nature* **325** (7000), 138-140 (1987)
Lutjeharms, J.R.E., R.C. van Ballegooyen - The retroflection of the Agulhas Current - *Journal of Physical Oceanography* **18** (11), 1570-1583 (1998)
Lutjeharms, J.R.E., C. Whittle, W.P.M. de Ruijter, H. van Aken - Temporary cessation of interocean exhange south of Africa - *Nature*, in preparation (2002)
Matano, R.P., E.J.Beier - A kinematic analysis of the Indian/Atlantic interocean exchange - *Deep-Sea Research II* **50** (1), 229-249 (2003)
McDonagh, E.L., K.J.Heywood, M.P.Meredith – On the structure, paths and fluxes associated with Agulhas Rings – *Journal of Geophysical Research*, **104** (C9), 21007-21020 (1999)
McDonagh, E.L., B.A. King - Oceanic fluxes in the South Atlantic - *Journal of Physical Oceanography* submitted, (2002)
Olson, D.B., R.A. Fine, A.L. Gordon - Convective modifications of water masses in the Agulhas - *Deep-Sea Research* **39** (Supplement 1), s163-s181 (1992)
Quartly, G.D., M.A. Srokosz - SST observations of the Agulhas and East Madagascar Retroflections by the TRMM Microwave Imager - *Journal of Physical Oceanography* **32**, 1585-1592 (2002)
Rouault, M., J.R.E. Lutjeharms - Air-sea exchange over an Agulhas eddy at the Subtropical Convergence - *The Global Atmosphere and Ocean System* **7** (2), 125-150 (2000)
Saunders, P.M., B.A. King - Oceanic fluxes on the WOCE A11 section - *Journal of Physical Oceanography* **25** (9), 1942-1958 (1995)
Schouten, M.W., W.P.M. de Ruijter, P.J. van Leeuwen – Upstream control of Agulhas Ring shedding – *Journal of Geophysical Research*, DOI 10.1029/2001JC000804 (2002a)
Schouten, M. W., W.P.M. de Ruijter, P.J. van Leeuwen, H.A. Dijkstra - An oceanic teleconnection between the equatorial and southern Indian Ocean - *Geophysical Research Letters*, DOI 10.1029/2001GL014542 (2002b)
Schouten, M.W., W.P.M. de Ruijter, P.J. van Leeuwen, J.R.E. Lutjeharms - Translation, decay and splitting of Agulhas rings in the south-eastern Atlantic ocean - *Journal of Geophysical Research* **105** (C9) 21.913-21.925 (2000)
Speich, S., B. Blanke, P. de Vries, K. Döös, S. Drijfhout, A. Ganachaud, R. Marsh - Tasman leakage: A new route for the global conveyer belt - *Geophysical Research Letters* **29**, 10-13 (2002)
Stramma, L., R.G. Peterson - The South Atlantic Current - *Journal of Physical Oceanography* **20** (6), 846-859 (1990)
Van Aken, H.M., H. Ridderinkhof, W.P.M. de Ruijter - Spreading of North Atlantic Deep Water in the Southwest Indian Ocean - Submitted to *Deep Sea Research* (2003)
Van Aken, H.M., A.K. van Veldhoven, C. Veth, W.P.M. de Ruijter, P.J. van Leeuwen, S.S. Drijfhout, C.P. Whittle, M. Rouault - Observations of a young Agulhas Ring, Astrid, during MARE, the Mixing of Agulhas Rings Experiment – *Deep-Sea Research II* **50**, 167-195 (2002)
Van Ballegooyen, R.C., M.L. Gründlingh, J.R.E. Lutjeharms - Eddy fluxes of heat and salt from the southwest Indian Ocean into the southeast Atlantic Ocean: a case study - *Journal of Geophysical Research* **99** (C7), 14.053-14.070 (1994)
Van Leeuwen, P.J., W.P.M. de Ruijter, J.R.E. Lutjeharms - Natal Pulses and the formation of Agulhas rings - *Journal of Geophysical Research* **105** (C3), 6425-6436 (2000)

Walker, N.D., R.D. Mey - Ocean/atmosphere heat fluxes within the Agulhas Retroflection region - *Journal of Geophysical Research* **93** (C12), 15.473-15.483 (1988)
Weijer, W., W.P.M. de Ruijter, H.A. Dijkstra, P.J. van Leeuwen - Impact of interbasin exchange on the Atlantic overturning circulation - *Journal of Physical Oceanogr*aphy **29**, 2266-2284 (1999)
Weijer, W., W.P.M. de Ruijter, H.A. Dijkstra - Stability of the Atlantic overturning circulation: competition between Bering Strait freshwater flux and Agulhas heat and salt sources - *Journal of Physical Oceanography* **31**, 2385-2402 (2001)
Weijer, W., W.P.M.de Ruijter, A.Sterl and S.S.Drijfhout - Response of the Atlantic overturning circulation to South Atlantic sources of buoyancy, *Global and Planetary Change,* **34***,* 293-311. (2002).
Wijffels, S.E., R.W. Schmitt, H.L. Bryden, A. Stigebrandt - Transport of freshwater by the Oceans - *Journal of Physical Oceanography* **22** (2), 155-162 (1992)
You, Y., J.R.E. Lutjeharms, O. Boebel, W.P.M. de Ruijter - Interocean exchange of intermediate water masses south of Africa - *Deep-Sea Research II* **50** (1), 197-228 (2003)

5.4 South Atlantic links and impacts to regional and global climate

Alice M. Grimm [1], Andrew W. Robertson [2], and Chris Reason [3]

[1] *Department of Physics, Federal University of Paraná, Brazil*
[2] *International Research Institute for Climate Prediction, USA*
[3] *EGS & Oceanography Depts., University of Cape Town, South Africa*

5.4.1 Links between Atlantic variability and South American climate

a. Tropical SST variability

Variability of SSTs over the tropical South Atlantic contribute to the fluctuation of the meridional gradient of SST across the equator (Chang et al. 2000) as well as the zonal gradient of SST along the equator (Zebiak 1993). Thus, SST variability over the South Atlantic is intimately linked to the tropics.

The influence of tropical Atlantic SSTs on rainfall over the northern part of Northeast (NE) Brazil has been extensively studied (e.g., Hastenrath and Heller 1977; Moura and Shukla 1981; Mechoso et al. 1990; Nobre and Shukla 1996; Uvo et al. 1998). The rainy season in the region (austral autumn, Fig. 1) is associated with the southward seasonal migration of the Atlantic Intertropical Convergence Zone (ITCZ) to its southernmost position. Droughts occur when the ITCZ is shifted northward because of changes in the meridional SST gradient across the equator, due either to warm SST anomalies over the tropical North Atlantic (TNA) or to cold SST anomalies over the tropical South Atlantic (TSA).

The precipitation anomalies affecting the northern NE Brazil during March–May (MAM) due to changes in the SST meridional gradient are part of a larger scale variability pattern: they also affect eastern Amazon and there are also associated weaker precipitation anomalies of opposite sign in the northernmost part of South America (Nobre and Shukla 1996; Paegle and Mo 2002) (Fig. 2).

During the pre-rainy season (DJF) there is also a pattern of anomalous rain over NE Brazil associated with the meridional SST gradient. In this season, the anomalies over northern NE Brazil are weaker and displaced to the north, and there are strong opposite anomalies over southern NE Brazil (Nobre and Shukla 1996) (Fig. 2). Thus the rainfall anomalies over the southern part during DJF have the opposite sign to those over the northern NE and eastern Amazon during MAM. Since DJF (MAM) is part of the rainy season in southern (northern) NE, drought years over the northern NE are commonly preceded by wet years over the southern NE. Thus, considering that droughts predominate in northern NE in MAM during El Niño events, excess rainfall would be expected in southern NE in DJF of these events, which is consistent with the results of Grimm (2003a).

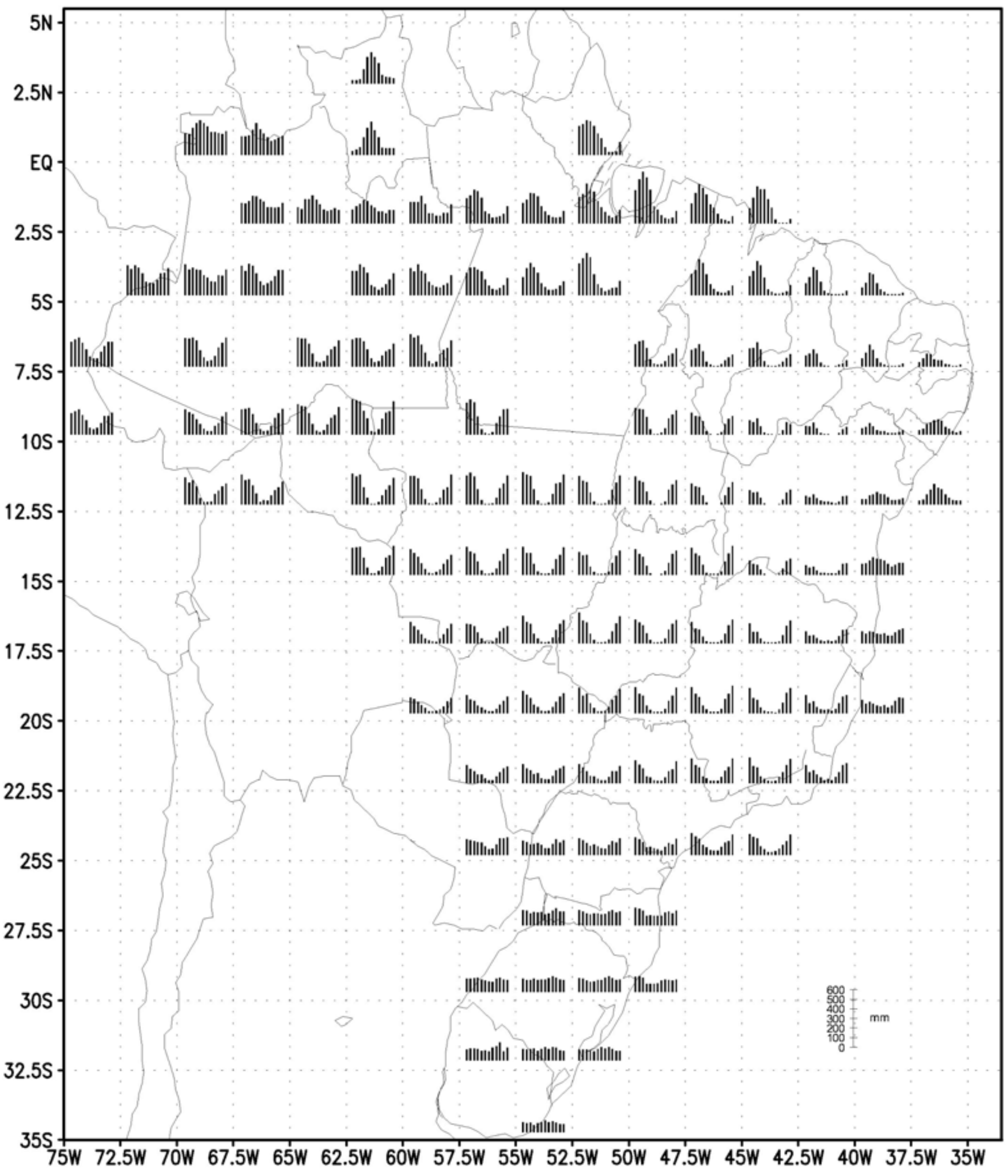


Fig. 1. Annual cycles of precipitation over Brazil, averaged over 2.5°×2.5° boxes, for the period 1956-1992. (Grimm 2003a)

ENSO can influence rainfall over NE Brazil during the rainy season directly through the Walker circulation, and indirectly through the SST anomalies over the tropical Atlantic. Giannini et al. (2003) have proposed that pre-existing anomalies in TNA and TSA act as a preconditioner of the predictability of NE rainfall during ENSO events.

March–May rainfall over the northern NE Brazil is better correlated with TSA anomalies than with TNA anomalies in the preceding seasons (SON and DJF) (Paegle and Mo 2002). The TSA anomalies appear also to be more predictable than those of over TNA (Giannini et al. 2003), which are disrupted by the direct influence of the NAO. Thus, the tropical South Atlantic may be key to improved rainfall predictability over the NE Brazil.

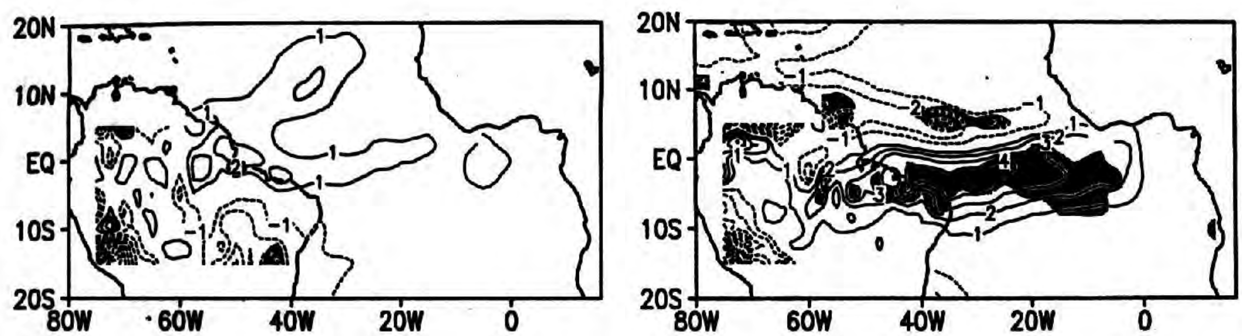


Fig. 2. Difference between the composite rainfall for years in which SSTs were colder than the mean in the TNA and warmer in the TSA and the composite rainfall for years in which the SST anomalies were reversed (COLD-WARM), for (left) DJF and (right) MAM. Contour interval is 1mm day^{-1}. (Nobre and Shukla 1996).

The summer monsoon regime in South America is responsible for the rainy season in most of Brazil (Grimm 2003) (Fig. 1) and in several neighboring countries. In austral summer, as the major heating zone migrates to the subtropics, a thermal low pressure system develops over central South America, while pressure increases in the subtropical north Africa. The resulting anomalous southwest-northwest pressure gradient enhances the northeasterly trade winds over the tropical Atlantic, and consequently the moisture flux into the continent. Low level wind and moisture convergence associated with the interaction between the trade winds, the continental low, the South Atlantic high, and the Andes orography enhance precipitation over most of South America, as in west, central and Southeast Brazil (where the South Atlantic Convergence Zone (SACZ) is at its most active stage), as well as in large regions of neighboring countries.

The influence of tropical Atlantic SSTs on the South American Monsoon System (SAMS) is much less clear than for NE Brazil rainfall. Robertson and Mechoso (1998) suggest that anomalies over TNA influence the Paraná riverflow. Paegle and Mo (2002) indicate that while rainfall over the upper La Plata River basin is linked to TNA anomalies, TSA anomalies may be linked to rainfall over the lower La Plata River basin. In Natori (2003) the canonical modes of SST-precipitation joint variability for which the TNA is colder and/or the TSA is warmer than normal tend to have precipitation below normal over southern NE Brazil (consistently with Nobre and Shukla 1996), and above normal in a region a little south of the SACZ, centered on the southern part of Central-West Brazil, which covers most of the upper La Plata basin. This is consistent with the composite of the difference between vertical velocities for extreme opposite phases of the meridional mode by Wang (2002).

It is difficult to separate the effect of the meridional SST gradient in the tropical Atlantic on the summer monsoon rainfall in subtropical South America from the effect of ENSO and the NAO that alter this gradient and which themselves have direct effects on rainfall over South

America. For example, Robertson and Mechoso (1998) found a significant cycle at about 8 years in the Paraná river flow record at Corrientes (Argentina) whose period and phase closely match the near decadal cycle in the NAO. Most of the Paraná and Paraguay basins, which are part of the upper La Plata basin, are under the summer monsoon precipitation regime. Both cycles are strongly reflected in SST anomalies over the TNA, but this response may be purely passive.

b. Subtropical SST variability

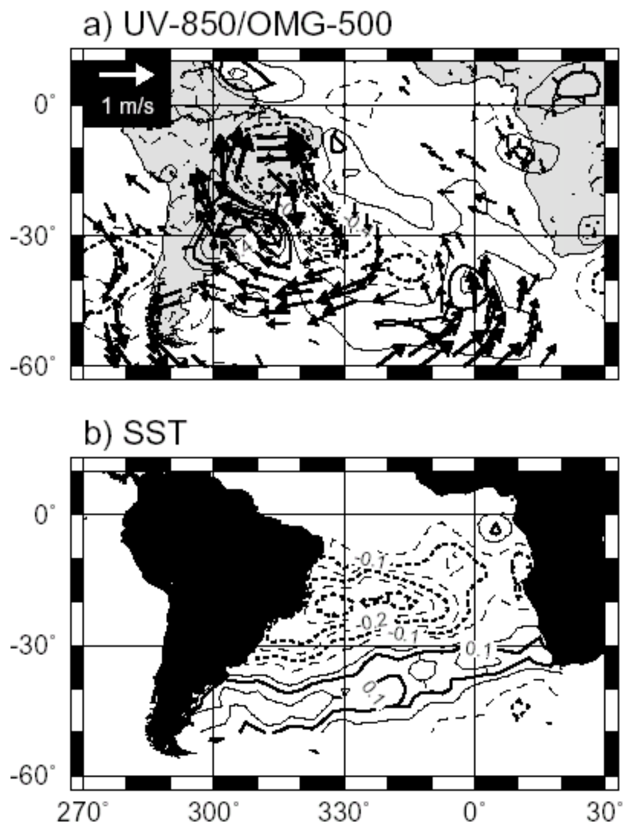


Fig. 3. Regression maps of the leading PC of 200 hPa JFM-averaged winds 1958-97 over southern South America. Top: 850-hPa winds and 500-hPa omega. Bottom: GISST SST. Contour intervals are 0.2×10^{-2} Pa s^{-1}, and 0.05 K, respectively, with zero contours omitted. (Robertson et al. 2003).

The SACZ forms the subtropical extension of the monsoon system. The subtropical convergence zones including the SACZ are intimately related to the adjacent subtropical anticyclones (Kodama 1992, 1993). The southeastward extension of the SACZ is partially a result of broad-scale southeastward advection of high moist static energy around the Atlantic subtropical High. In turn, the latter forms a subsiding branch of the monsoonal circulation. SST anomalies over the subtropical Atlantic are thus expected to be linked to SAMS, and the SACZ in particular.

The observed interannual SACZ variations over the continent are reflected by the leading mode of circulation variability over South America in JFM (SACZ mode) (Robertson and

Mechoso 2000). This mode is associated with a dipole in the vertical motion field with centers of opposite signs in the SACZ and in the southern plains. It is correlated with dipolar SST anomalies over the South Atlantic, such that cold SST anomalies are observed to underlie an intensified SACZ (Fig. 3). Barros et al. (2000) reported the same relationship between SACZ variations and SST. It is also described in the second joint variability mode for rainfall in southeastern South America and Atlantic SSTs found by Natori (2003).

Studies of observed interannual covariability between the subtropical high and underlying SST anomalies indicate that the subtropical Atlantic is largely a passive basin, with SST anomalies tending to result through the surface fluxes associated with changes in the strength and position of the subtropical high (Venegas et al. 1997, Sterl and Hazeleger 2003).

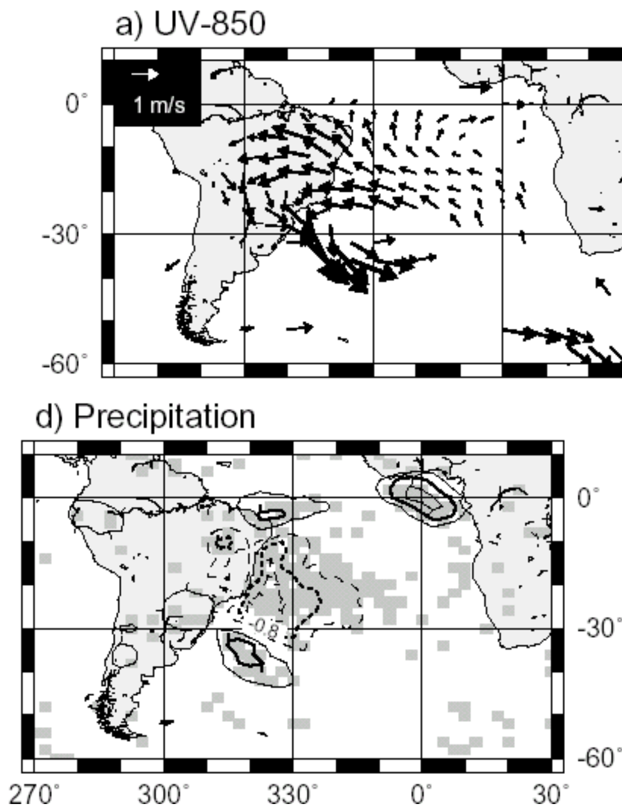


Fig. 4. GCM response (JFM averaged) to the SST anomaly pattern in Fig. 3, with the latter scaled by a factor of three. Top: 850-hPa winds. Bottom: precipitation. Shading indicates the 95% significance level, and only significant vectors are plotted. Contour intervals are 0.4 mm day^{-1} with zero contours omitted. (Robertson et al. 2003).

Our knowledge of the atmosphere's response to South Atlantic SST anomalies is derived primarily from GCM experiments. Nobre et al. (2002) showed that the CPTEC/COLA GCM response to prescribed warm (cold) SST anomalies over the SW Atlantic, in the SACZ region, enhances (weakens) the SACZ, in contrast with the observed cold SST anomalies that underlie an enhanced SACZ. Robertson et al. (2003) studied the response of the UCLA GCM to prescribed fixed SST anomalies typical of (a) observed interannual SACZ variations (Fig. 3) and (b) the leading interannual EOF of SST in South Atlantic, which is a dipolar pattern, with nodal line near 30°S, and maximum SST anomalies shifted eastward in relation to the first case. In the first case, the results agree with those of Nobre et al. (2002). They show the same broad circulation anomaly pattern of the SACZ mode, but of opposite polarity to the observed one (Fig. 4). The GCM response is baroclinic, while the observed circulation pattern is barotropic. Thus, the observed precipitation and vertical velocity anomalies associated with the SACZ variations are not those expected to be forced by the subtropical SST anomalies accompanying them, which are predominantly atmospherically forced.

In the second case, the dipolar SST anomalies in the subtropics with warm anomalies north of 30°S cause a decrease in the strength of the low-level circulation around the subtropical high, especially over the western part of the basin (Fig. 5). There is evidence of positive feedback in the surface heat fluxes in the TSA region. The results are similar to those of Barreiro et al. (2002), who have studied the response of the atmosphere during austral summer to subtropical south Atlantic SST anomalies associated with interannual variations in the SACZ and subtropical high. In an ensemble of multidecadal simulations of the NCAR CCM3, Barreiro et al. (2002) found a localized atmospheric response within the South Atlantic Ocean with almost no signal over land. The associated SST anomaly is dipolar with the nodal line near 25°S, and resembles the leading EOF of SST during austral summer. The response consists of a dipole-like structure in precipitation close to the coast of South America with positive anomalous rainfall and a clockwise anomalous circulation of surface winds associated with warm SST anomalies north of 25°S. The upper-level response is anticyclonic, centered at the same location, indicating a Gill-type baroclinic response. Both studies indicate that the marine portion of the SACZ can be influenced by subtropical SST anomalies over the South Atlantic.

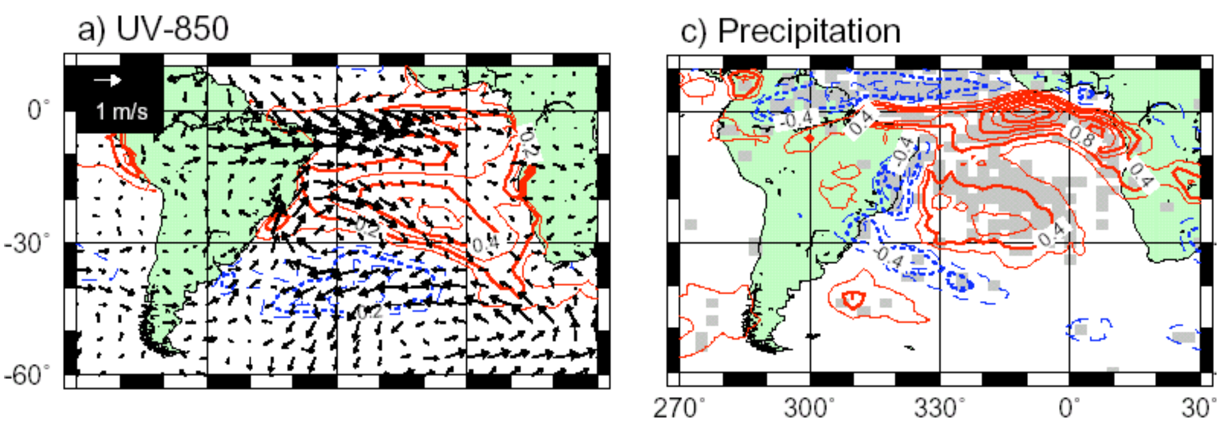


Fig. 5. The January–March response of the UCLA GCM to a prescribed South Atlantic SST anomaly pattern. Leftt: 850 hPa winds and prescribed SST anomaly (contours). Right: precipitation. The response is defined as the difference between an ensemble of 10 anomaly simulations and 10 control simulations. Shading indicates the 95% significance level, computed from a two-sided Student *t*-test with 18 degrees of freedom. Contour intervals on right are 0.2 mm day^{-1}. Zero contours are omitted. (Robertson et al. 2003)

The agreement between the GCM simulations and observed ocean-atmosphere covariability is much greater further eastward in the region of the subtropical high. The picture that emerges from these GCM studies is that the atmospheric circulation is sensitive to SST anomalies during austral summer over the subtropics of the South Atlantic, and shows a deep baroclinic response that modulates the subtropical high. The intense intrinsic variability of the SACZ, however, tends to mask this effect locally.

Chaves and Nobre (2003) did a number of AMIP-type AGCM and OGCM experiments and concluded that a predominantly negative feedback process exist between the atmosphere and the ocean, with warm SSTA favoring the formation and/or the intensification of the SACZ, which in turn reduces the incoming short wave solar radiation due to increased cloudiness. This negative feedback mechanism represents the most important modulating effect of SSTA locally. Other mechanisms affecting SSTA were also investigated, but their effect is one order of magnitude smaller (sensible, evaporative, long wave cooling, as well as upwelling).

The observational results of Grimm (2003), with monthly resolution, indicate that SST anomalies in the subtropical Southwest Atlantic off the southeastern coast of Brazil during spring and summer fluctuate on the same intraseasonal time scale as the circulation and precipitation anomalies (Fig. 6). Enhanced summer precipitation in eastern Brazil is associated with cooler SSTs off the southeastern coast of Brazil and is preceded by less than normal spring precipitation accompanied by warmer SSTs in the same region. These results, although indicating that the ocean responds to atmospheric forcing, do not discard the influence of SST anomalies in spring in setting up the circulation anomalies that lead to the positive precipitation anomalies in January. These anomalies, though intense, are relatively short lasting (but they tend to dominate the seasonal precipitation mean). They could produce cooling of the SST (and also of the surface temperature over land) that tends to weaken the atmospheric anomalies. This effect would be detectable only in an ocean-atmosphere coupled model (and with interactive land-surface processes).

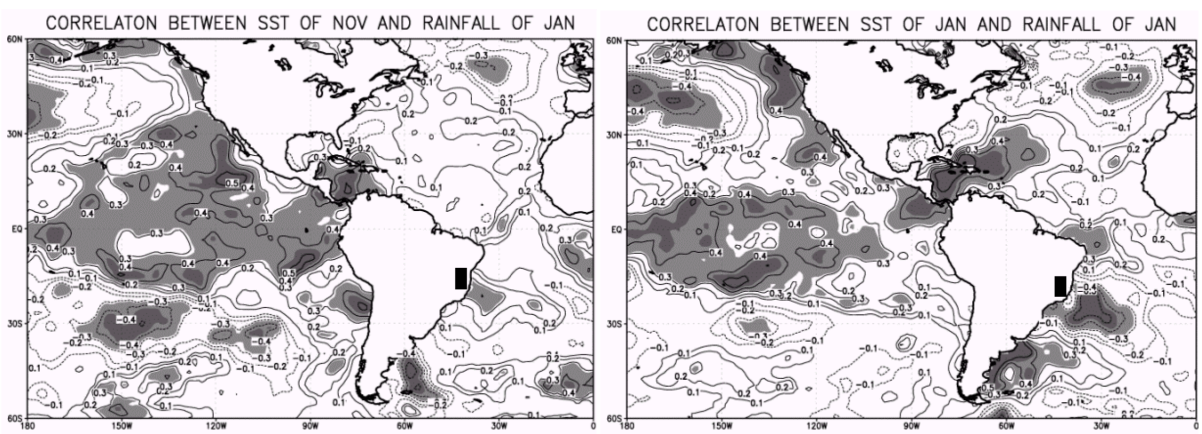


Fig. 6. Correlation coefficients between January precipitation in the region marked in eastern Brazil and SST in November (left) and in January (right). The correlation in the SACZ is positive in November and negative in January. Shadowed areas have correlation coefficients significant over 95% confidence level. (Grimm 2003a)

Therefore, probably the atmospheric predictability when using persisted SST anomalies over the subtropical South Atlantic is low, although one could not say that rainfall anomalies are insensitive to South Atlantic SST anomalies.
Surface temperature anomalies in South America might be related to SST anomalies in the South Atlantic, but the mechanism of the relationship is not very clear. There is a component of local influence near the coast, but in the inland regions other mechanisms prevail, like the

enhancement (weakening) of the northerly advection of warm temperatures (Barros et al. 2002). Rusticucci et al. (2003) found that an increased number of warm days in central/eastern Argentina and a decreased number of cold days in central/northern Argentina are associated with warm SST near the coasts of Argentina south of 30ºS in both ocean basins. The relationship is stronger in winter. Cardoso and Silva Dias (2000) found significant correlations between the winter temperatures in São Paulo and SST anomalies in South Atlantic and the Niño 3 region. In both cases the SST anomalies in South Atlantic corresponding to warmer temperature depict a dipole-like pattern with warmer temperatures in the southern part. This is consistent with the strengthening of the subtropical anticiclone near South America (Venegas et al. 1997). This strengthening may be associated with the production of the dipole-like SST anomalies and with an enhancement of the northerly advection of temperature.

Figure 7 shows a schematic of some of the Atlantic-South American relationships discussed. Rainfall associated with the SAMS is depicted in green. The regions of tropical SST that are maximally correlated with Nordeste rainfall (Feb–Apr) are shown in red & blue. Over the subtropics, the mean position of the subtropical anticyclone is shown (Jan–Mar), along with the centers of the leading interannual EOF of SST variability (Jan–Mar, shaded).

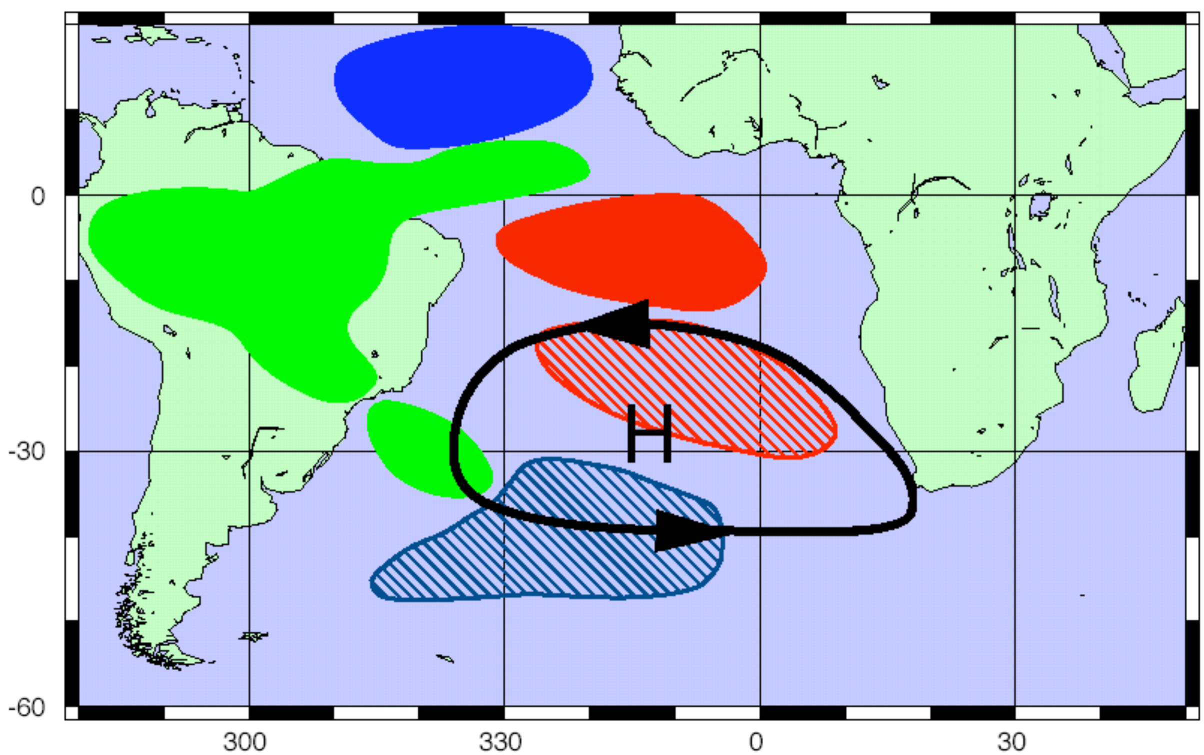


Fig. 7. Schematic picture of some of the Atlantic-South American relationships discussed. Rainfall associated with the SAMS is depicted in green. The regions of tropical SST that are maximally correlated with Nordeste rainfall (Feb–Apr) are shown in red & blue. Over the subtropics, the mean position of the subtropical anticyclone is shown (Jan–Mar), along with the centers of the leading interannual EOF of SST variability (Jan–Mar, shaded).

5.4.2. Links between Atlantic variability and African climate

a. *Southern Africa*

Southern Africa is characterized by mainly summer rainfall (convective) with a winter rainfall region (frontal) in the southwest and along the south coast of South Africa. Recent work (Reason *et al.*, 2002) suggests that winter rainfall in southwestern South Africa may be linked to midlatitude SST anomalies in the South Atlantic (Fig. 8) as well as to sea-ice extent in the Atlantic sector of the Southern Ocean. Experiments with the HadAM3 GCM forced with these SST anomalies suggests that the mechanism involves northward shifts in the midlatitude storm tracks and increased moisture flux from the tropical SW Atlantic during wet winters.

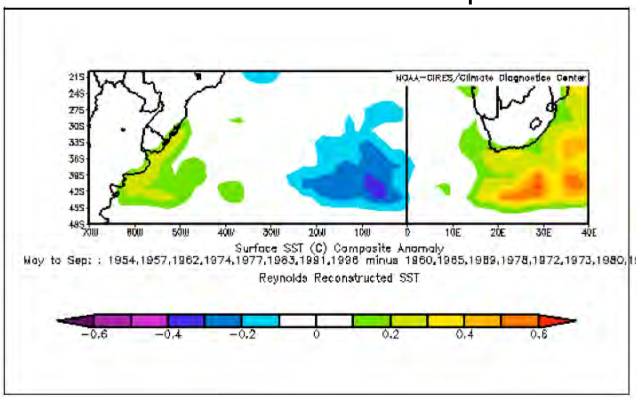


Fig. 8. SST anomalies (0.1°C contour interval) derived for wet – dry southwest South African winters 1950-2001 (Reason *et al.,* 2002).

The potential influence of tropical SE Atlantic SSTs on Angolan and Namibian rainfall has been studied by Hirst and Hastenrath (1983) and Nicholson and Entekhabi (1987). More recently, Rouault *et al.* (2002) have drawn attention to the influence of SE Atlantic warm events on not just the coastal rainfall of tropical southwestern Africa but also, on occasion, over a much larger region of southern Africa (Fig. 9). Coastal fisheries also appear to be substantially impacted (Binet *et al.,* 2001). It appears that large scale circulation anomalies help determine the relative influence of moisture transport from the tropical SW Indian and SE Atlantic Oceans and hence whether the rainfall anomaly is confined to the Angolan / Namibian region (1984, 1995) or extends over a much larger area in southern Africa (1986, 2001). Analyses with an ocean GCM forced by NCEP winds and heat fluxes (Florenchie *et al.*, 2002) suggest that warm (cold) events in the tropical SE Atlantic are related to weakening (strengthening) of the trade winds and originate as an equatorial Kelvin wave in the western equatorial Atlantic. Since this phenomenon may, in principle, be predictable and because its impacts on regional fisheries and rainfall are substantial, designing an observing system to better monitor this region (e.g., a PIRATA extension) could lead to significant economic and societal benefits.

On decadal – multidecadal scales, there is strong evidence of a roughly bi-decadal signal in summer rainfall over much of South Africa and neighbouring countries (e.g. Tyson *et al.*, 1975) and also in winter rainfall over southwestern South Africa. Reason and Rouault (2002) present evidence that these signals are related to the regional manifestation (including South Atlantic SST) of ENSO-like decadal patterns. Various studies (e.g., Venegas *et al.* 1997; Reason, 2000; Wainer and Venegas, 2002) have found decadal – multidecadal signals in SST, MSLP and winds over the South Atlantic but whether these are basin-only modes or part of a near-global mode remains to be clarified. As yet, it is unclear as to whether these modes significantly influence southern African rainfall although the modulations of the South Atlantic anticyclone that is part of these modes suggests that there could well be a link.

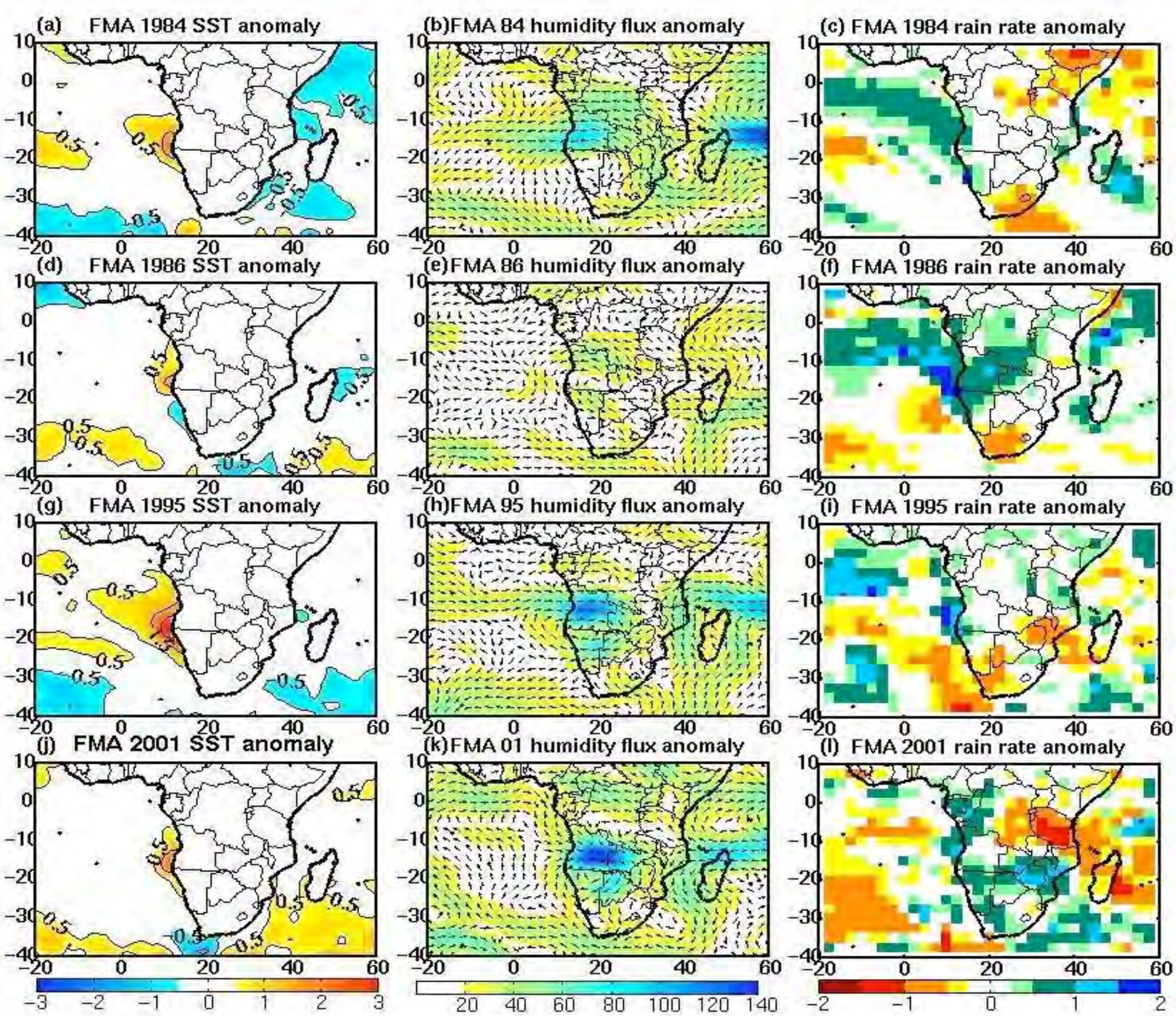


Fig. 9. SST, moisture flux and rainfall anomalies during SE Atlantic warm events (Rouault *et al.*, 2002)

b. West Africa

A number of studies have investigated links between Sahelian rainfall (boreal summer) and tropical Atlantic SST (e.g., Lamb, 1978; Lough, 1986; Wagner, 1996). In particular, the meridional SST gradient between the tropical North and South Atlantic (which appears to show substantial decadal variability – e.g., Melice and Servain, 2002) is important for influencing the location of the ITCZ and hence the West African monsoon. ENSO leads to significant variability in tropical Atlantic SST (e.g. Enfield and Meyer, 1997) and there is also evidence of ENSO-related impacts on Sahelian rainfall (e.g. Janicot *et al.*, 2001). The mechanisms associated with West African monsoon variability are complex, and not only involve SSTs but also land-surface conditions and other factors. An intensive observational and modelling experiment (AMMA) is currently underway to investigate the dynamics, regional water cycle, atmospheric chemistry, and surface conditions of the West African monsoon and its variability (see AMMA website - http://medias.obs-mip.fr:8000/amma/english/index_en.html).

5.4.3. Other links and impacts on the global climate

a. The influence of ENSO on the South Atlantic

The influence of ENSO on the South Atlantic is weak compared to its influence on the tropical North Atlantic (Enfield and Mayer 1997), and is less understood. Correlations between the Southern Oscillation Index and annual-mean Atlantic SSTs are strongest near 25°S off the coast of Brazil; they are very small at the equator (e.g. Venegas et al. 1997) (Fig. 10).

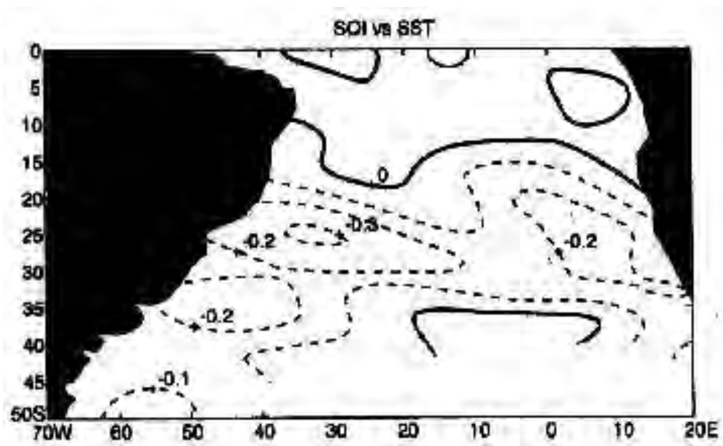


Fig. 10. Correlation map between the SOI and gridpoint SST anomalies. (From Venegas et al. 1997)

Proposed paths of influence on the South Atlantic include (1) ENSO-induced Walker circulation anomalies acting on SST in the Gulf of Guinea (Latif and Barnett 1995; Latif and Grötzner 2000), (2) anomalies in the strength of the SE Trades in response to ENSO-induced SST anomalies over the TNA (Enfield and Mayer 1997), acting on the TSA SSTs (Häkkinen and Mo 2002), and (3) a Pacific-South American extratropical Rossby wavetrain producing SSTAs in South Atlantic (Mo and Häkkinen 2001). Mo and Häkkinen (2001) find that quasi-biennial component of ENSO dominates over the tropical South Atlantic, and that the linkage is strongest in the austral spring. On the other hand, Venegas et al. (1997) find a 4-5 year time scale in their third SST mode, with highest correlations near 25°S off the coast of Brazil.

The subtropical location of the strongest ENSO-related SST anomalies coincides with the region of the SACZ, suggesting that ENSO may influence the South Atlantic through the SACZ. Some observational studies of interannual SACZ variability (e. g., Robertson and Mechoso 2000) find the influence of ENSO on the SACZ to be small during January–March, while warm ENSO events tend to be associated with a weakening of the SACZ during October–December. Grimm (2003a, b) indicates that this apparent independence between the SACZ variability and ENSO during summer is due to strong subseasonal variations of the ENSO impact on summer climate in Brazil that are smoothed out in a seasonal average (Fig. 11). During spring (specially in November) of ENSO events rainfall anomalies in the SACZ are significantly negative and the SST anomalies off the southeastern coast of Brazil are positive. In January there is an abrupt change in the sign of the anomalies, the precipitation in SACZ is above normal (Fig. 11) and the SST anomalies are negative. In February the precipitation anomalies turn negative again (Fig. 11). The circulation anomalies undergo similar strong intraseasonal variations in the SACZ region (Fig. 12). The impact of ENSO on the SACZ is also confirmed by the modeling results of Barreiro et al. (2002).

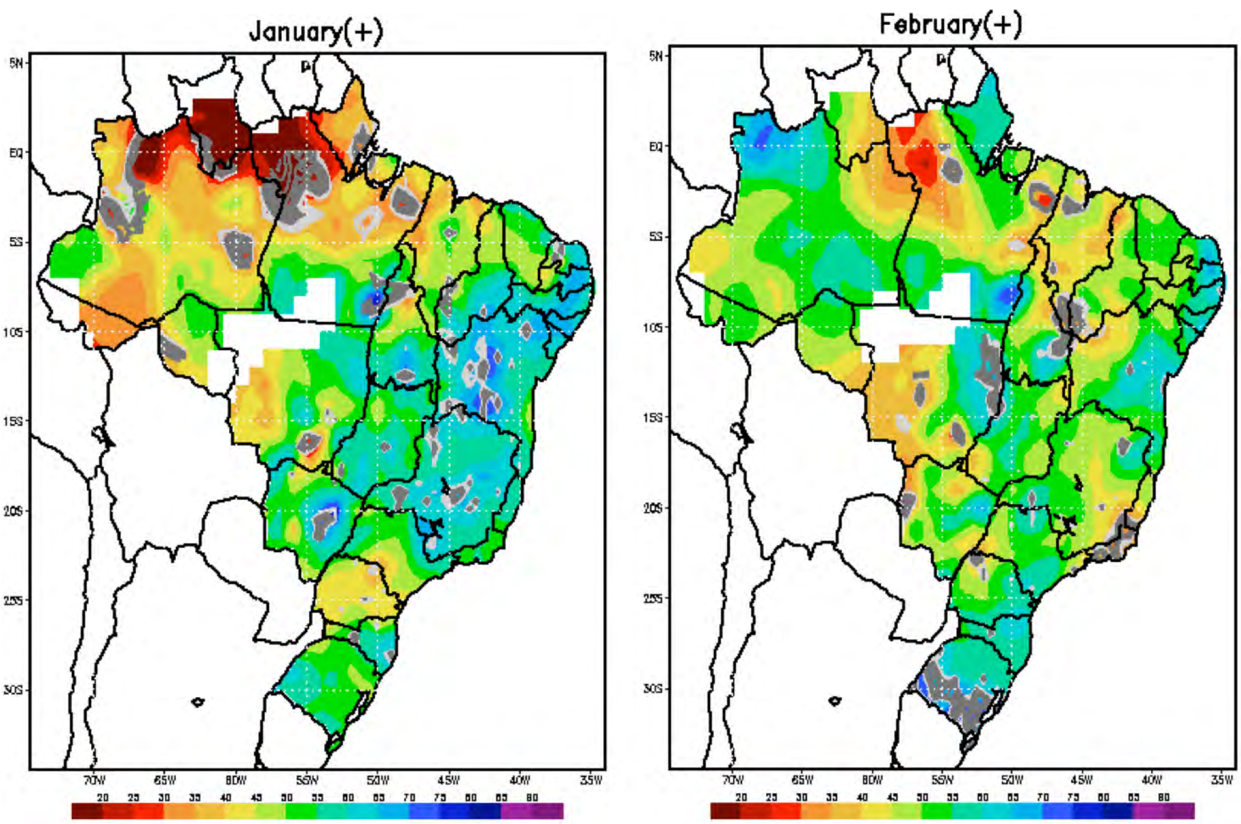


Fig. 11. Intraseasonal variations in the ENSO impact on SACZ: precipitation percentiles expected for January (left), and February (right). Shadowed areas have precipitation anomalies consistent over 90% confidence level. (Grimm 2003a)

The correlation between January precipitation in eastern Brazil and SST (Fig. 6) shows that while the main patterns of correlation remain the same in the Pacific and North Atlantic, the correlations in the South Atlantic, off the southeast coast of Brazil fluctuate on a time-scale comparable to that of the atmospheric circulation and precipitation. Grimm (2003a) suggested that the warmer SSTs in spring (along with the higher temperature over land) may help trigger the enhanced convection in the region in January. These higher SSTs may be due to an increased solar flux into the ocean and smaller than normal heat fluxes associated with weaker than normal winds. On the other hand, the cooling of SST in January might be related to the enhanced convection and excess rainfall during this month. It is, however, not clear how the ENSO-related intraseasonal variations of atmospheric circulation and SST anomalies in South Atlantic interact with each other.

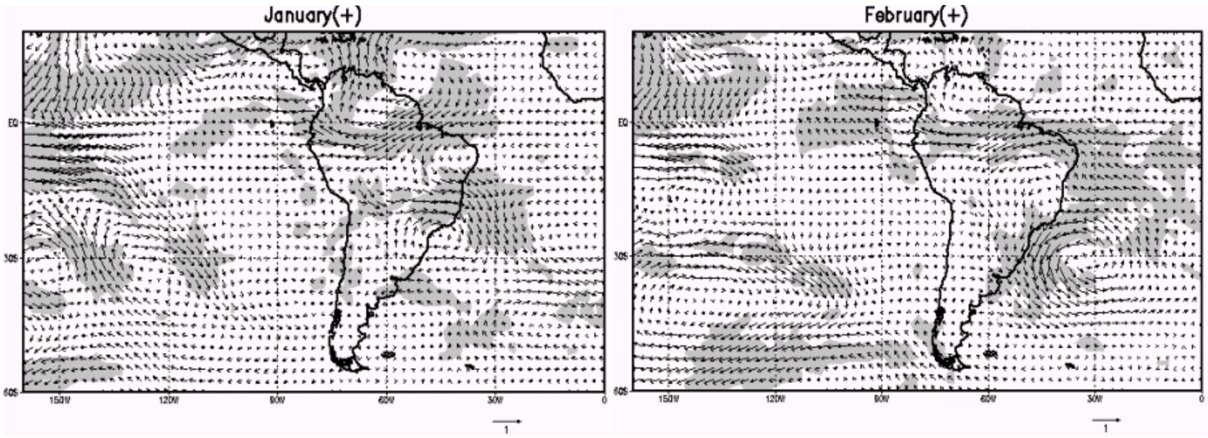


Fig. 12. Intraseasonal variations in the ENSO impact on SACZ: composite of vertically integrated moisture flux for January (left) and February (right). The shaded areas indicate consistency over 90% confidence level. (Grimm 2003a)

ENSO exerts a substantial influence on South America as well as on southern African rainfall, with the main impact in different regions occurring in different seasons (e. g., Grimm 2003a, b). However, the influence on South American and African climate of the coherent signals in SST and winds over the South Atlantic associated with El Niño and La Niña events (e.g., Reason *et al.,* 2000), is not clear. Modeling studies indicate that in spring of El Niño years the influence from the Pacific is stronger and able to explain the main impacts on South America (Grimm et al., 2002).

b. Other links to the global climate

According to Häkkinen and Mo (2002) the forcing of tropical Atlantic SST anomalies is tied to NAO, although these anomalies may cause an atmospheric response that is felt in the Northern Hemisphere. The meridional SST gradient is related to both, ENSO and NAO, since they impact on the tropical Atlantic variability, not only on TNA (Wang 2002) but also on TSA (Häkkinen and Mo 2002). Thus, rainfall anomalies associated with these modes may appear in composites for TNA and TSA anomalies. The impacts of ENSO and NAO may enhance each other or ENSO may suppress the influence of NAO, depending on their relative phase. The modes found by Natori (2003) for both the Atlantic Ocean and for Atlantic + Pacific Ocean that are most correlated with NAO and ENSO, have the same sign of rainfall anomalies in the upper La Plata basin for positive NAO and positive SOI, although not always significant.

Robertson et al. (2003) also investigated the atmospheric response to the seasonal evolution of the leading monthly EOF of South Atlantic SST, as it evolves from a predominantly subtropical pattern in austral summer, to a largely equatorial one by the boreal summer. The GCM response is found to be dominated by the equatorial component of the SST anomalies.

During boreal summer these give rise to a statistically-significant upper-tropospheric wavetrain that extends northward into Europe and southward into southern South America.

Rajagopalan et al. (1998) and Robertson et al. (2000) suggested that SST anomalies over the tropical South Atlantic may even influence the NAO during boreal winter, but other modeling and observational studies have not found this teleconnection (Sutton et al. 2000; Paegle and Mo 2002; Wang 2002).

5.4.4. Some scientific questions that a South Atlantic observing system might address

i. What determines the strength of warm and cold events in the SE Atlantic, how do they impact on regional rainfall, and is there any predictability?

ii. What are the mechanisms driving ENSO signals in the South Atlantic and how do they impact on South America and Africa? How do the intraseasonal variations of circulation and SST anomalies in South Atlantic, associated with ENSO, interact with each other?

iii. What relationships exist between South American and African rainfall and are they seasonally dependent? Are these relationships driven by South Atlantic SST variability?

iv. The meridional SST gradient between the tropical North and South Atlantic seems to strongly influence the West African monsoon and also Brazilian rainfall. Does this gradient also influence southern Africa and, if so, how?

v. The TSA anomalies seem potentially more predictable than those in the TNA. Since atmospheric GCMs are highly sensitive to SST gradients in the equatorial Atlantic, seasonal forecasts in the tropical Atlantic sector stand to be improved if TSA anomalies can be predicted to some extent. What are their origins? Is ENSO involved in causing them? What is the role of the ocean, and of coupling with the atmosphere?

vi. Are the decadal-multidecadal signals seen in the South Atlantic a regional mode, or part of a near-global signal and how do they impact on South American and African climate?

vii. How do interannual SST anomalies in Atlantic and coupled ocean-atmosphere interactions influence the South American climate?

5.4.5 Some considerations about sustained observations

Extensive sustained ocean observations are needed, firstly to answer these questions, and secondly for assimilation into coupled forecast models that can predict SST several seasons in advance. Particularly important parameters are surface thermodynamic and momentum fluxes, and ocean mixed-layer depth.

Extension of the existing PIRATA array both to the SW (0-10 S off the NE region of Brazil) and to the SE (0-10 S, 5 W - 10 E) would help with better monitoring and potential prediction of the Benguela Niño type warm and cold events in the tropical SE Atlantic. The proposed locations of ATLAS buoys in the tropical SE Atlantic still needs to be resolved; there are competing proposals depending on whether the main application is for fisheries (in which case monitoring the Angola / Benguela front and the upwelling zone are seen as most important) or for climate prediction (in which case deployment further offshore in the Angola dome region is desirable). ATLAS buoys provide surface flux and sub-surface temperature and pressure.

Contribution to the Argo float program to increase the density of these floats in the subtropical and midlatitude South Atlantic is desirable. Argo floats can be thought of as an oceanographic "radiosonde" and are very useful for monitoring sub-surface ocean variability on intraseasonal to interannual and longer time scales and for validating ocean models. They will be essential for developing ocean state estimation models and climate predictions.

As of January 2003, there are about 620 active Argo floats globally with very few in the South Atlantic. Currently, there are no floats in the SW Atlantic or tropical SE Atlantic (see www.argo.ucsd.edu). So far, no South Atlantic rim countries seem to have committed to purchase floats although some may be assisting with deployment. Floats are relatively easy to deploy; thus, ships of opportunity (e.g. container shipping lines) could be used.

Contributions towards the extension in time of already funded intensive field programs in certain sensitive areas of the South Atlantic could be another valuable exercise. Piggybacking on such experiments to deploy Argo floats, surface drifters, XBTs etc during the research cruises of these programs is an effective way of reducing costs and building up local capacity in the region. Efforts are underway at Cape Town to make use of the Southern Ocean cruises of the Polarstern and supply cruises of the SA Agulhas to Gough (SE Atlantic) and Marion (SW Indian) Islands and SANAE (Antartica). XBTs and Argo floats (on some SA Agulhas cruises) will help with monitoring in the mid- to high latitude South Atlantic. An example in the subtropical SE Atlantic could be the ASTTEX program aimed at monitoring Agulhas rings (important for both regional and global climate via their influence on the MOC) in the SE Atlantic during the January 2003-05 period. The CLIVAR Southern Ocean and Atlantic Panels web sites provide links to planned and ongoing cruises in the region.

5.4.6 References

Barreiro, M., P. Chang, and R. Saravanan, 2002: Variability of the South Atlantic Convergence zone simulated by an atmospheric general circulation model. *J. Climate,* **15,** 745-763.

Barros, V. R., M. Gonzalez, B. Liebmann, and I. Camilloni, 2000: Influence of the South Atlantic convergence zone and South Atlantic sea surface temperature on interannual summer rainfall variability in southeastern South America. *Theor. Appl. Climatol*., **67**, 123-271.

Barros, V. R., A. M. Grimm, and M. E. Doyle: Relationships between temperature and circulation in southeastern South America and its influence from El Niño and La Niña events*. J. Meteor. Soc. Japan*, 80, 21-32.

Binet, D, Gobert B. and L. Maloueki, 2001: El Niño-like warm events in the Eastern Atlantic (6°N, 20°S) and fish availability from Congo to Angola (1964-1999). *Aquat. Living Resour.* **14**, 99–113.

Cardoso, A. O., and P. L. Silva Dias, 2000: A influência da temperatura da superfície do mar no clima de inverno na cidade de São Paulo. Proceedings of the 11th Brazilian Meteorological Congress. Brazilian Meteorological Society.

Chang, P., R. Saravanan, L. Ji, and G. C. Hegerl, 2000: The effect of local sea-surface temperatures on atmospheric circulation over the tropical Atlantic sector. *J. Climate*, **13**, 2195-2216.

Chao, Y., M. Ghil, and J. C. McWilliams, 2000: Pacific interdecadal variability in this century's sea surface temperatures, *Geophys. Res. Lett*., **27**, 2261–2264.

Chaves, R. R., and P. Nobre, 2003: Interactions between the South Atlantic Ocean and the atmospheric circulation over South America. (Extracted from the first author's PhD. thesis, *to be submitted to GRL*).

Enfield, D.B., and D.A. Mayer, 1997: Tropical Atlantic sea surface temperature variability and its relation to El Niño-Southern Oscillation. *J. Geophys. Res*., **102**, 929-945.

Florenchie, P., C.J.C. Reason, J.R.E. Lutjeharms and S. Masson, 2002: Evolution of south east Atlantic warm events. *Submitted to J. Phys. Oceanogr.*.

Giannini, A., R. Saravanan, and P. Chang, 2003: The preconditioning role of Tropical Atlantic variability in the prediction of Nordeste rainfall during ENSO events. *Submitted to J. Climate*.

Grimm, A. M., I. F. A. Cavalcanti e C. A. C. Castro, 2002: Importância relativa das anomalias de temperatura da superfície do mar na produção das anomalias de circulação e precipitação no Brasil num evento El Niño. Proceedings of the 12th Brazilian Meteorological Congress. (in CD, CT-2: Variabilidade e Mudanças do Clima), Foz do Iguaçu, August 2002, Brazilian Meteorological Society.

Grimm, A. M., 2003a: The El Niño impact on the summer monsoon in Brazil: regional processes versus remote influences. *Journal of Climate*, **16**, 263-280.

Grimm, A. M., 2003b: How do La Niña events disturb the summer monsoon system in Brazil? *Submitted to Clim. Dyn*.

Hastenrath, S., and L. Heller, 1977: Dynamics of climate hazards in Northeast Brazil. *Quart. J. Roy. Meteor. Soc.*, **103**, 77-92.

Häkkinen, S., and K. Mo, 2002: The Low-Frequency variability of the tropical Atlantic Ocean. *J. Climate*, **15**, 237-250.

Hirst, A.C. and S. Hastenrath, 1983: Atmosphere-ocean mechanisms of climate anomalies in the Angola–Tropical Atlantic sector, *J. Phys. Oceanog.,* **13**, 1146–1157.

Kodama, Y.-M., 1992: Large-scale common features of subtropical precipitation zones (the Baiu frontal zone, the SPCZ, the SACZ) Part I: Characteristics of subtropical frontal zones. *J. Meteor. Soc. Japan*, **70**, 813-835.

Kodama, Y.-M., 1993: Large-scale common features of subtropical precipitation zones (the Baiu frontal zone, the SPCZ, the SACZ) Part II: Conditions of the circulations for generating the STCZs. *J. Meteor. Soc. Japan*, **71**, 581-610.

Lamb, P.J., 1978: Large-scale tropical Atlantic surface circulation anomalies associated with sub-Saharan weather anomalies. *Tellus,* **30**, 240-251.

Lough, J.A., 1986: Tropical Atlantic sea surface temperature and rainfall variations in sub-Saharan Africa. *Mon. Wea. Rev.*, **114**, 561-570.

Mechoso, C. R., S. W. Lyons, and J. A. Spahr, 1990: The impacts of sea surface temperature anomalies on the rainfall over northeast Brazil. *J. Climate*, **3**, 422-826.

Melice, J-L. and J. Servain, 2002: The tropical Atlantic meridional SST gradient index and its relationships with the SOI, NAO and Southern Ocean. *Clim. Dyn.*, in press.

Mo, K. C., and S. Häkkinen, 2001: Interannual variability in the tropical Atlantic and linkages to the Pacific. *J. Climate*, **14**, 2740-2762.

Moura, A. D., and J. Shukla, 1981: On the dynamics of droughts in Northeast Brazil: observations, theory and numerical experiments with a general circulation model. *J. Atmos. Sci*., **38**, 2653-2675.

Natori, A. A., 2003: Relação entre precipitação no sudeste da América do Sul e temperatura da superfície do mar nos oceanos Pacífico e Atlântico. M.Sc. Dissertation. Department of Atmospheric Sciences, University of São Paulo.

Nicholson, S.E. and D. Entekhabi, 1987: The nature of rainfall variability in equatorial and southern Africa: Relationships with SST along the southwestern coast of Africa. *J. Clim. Applied Meteorol.,* **26**, 561–578.

Nobre, P., and J. Shukla, 1996: Variations of sea surface temperature, wind stress, and rainfall over the tropical Atlantic and South America. *J. Climate*, **9**, 2464-2479.

Nobre, P., M. Malagutti, R. R. Chaves, and M. B. Sanches, 2002: Modulações da ZCAS pelas temperaturas da superfície do mar no Atlântico Sudoeste. *XII Congresso Brasileiro de Meteorologia*, SBMet, Foz do Iguaçu.

Nogués-Paegle, J., K. C. Mo, 2002: Linkages between summer rainfall variability over South America and sea surface temperature anomalies. *J. Climate*, **15**, 1389-1407.

Rajagopalan, B., Y. Kushnir, and Y. M. Tourre, 1998: Observed midlatitudes and tropical Atlantic climate variability. *Geophys. Res. Lett.,* **25,** 3967–3970.
Reason, C.J.C., 2000: Multidecadal climate variability in the subtropics / midlatitudes of the Southern Hemisphere. *Tellus*, **52A**, 203-223.
Reason, C.J.C., R.J. Allan, J.A. Lindesay and T.J. Ansell, 2000: ENSO and climatic signals across the Indian Ocean basin in the global context: Part I, Interannual composite patterns, *Int. J. Climatol.,* **20**, 1285-1327.
Reason, C.J.C., and M. Rouault, 2002: ENSO-like decadal variability and South African rainfall. *Geophys. Res. Lett.,* **29**, 16-1 – 16-4.
Reason, C.J.C., M. Rouault, J.-L. Melice and D. Jagadeesha, 2002: Interannual winter rainfall variability in SW South Africa and large scale ocean-atmosphere interactions. *Met. Atmos. Phys.,* Special Issue on *Atmosphere-surface interactions*, **80 (1-4)**, 19-29.
Robertson, A. W., and C. R. Mechoso, 1998: Interannual and decadal cycles in river flows of southeastern South America. *J. Climate*, **11**, 2570-2581.
Robertson, A. W., and C. R. Mechoso, 2000: Interannual and interdecadal variability of the South Atlantic convergence zone. *Mon. Wea. Rev.*, **128**, 2947-2957.
Robertson, A. W., C. R. Mechoso, and Y.-J. Kim, 2000: The influence of Atlantic Sea Surface Temperature Anomalies on the North Atlantic Oscillation. *J. Climate*, 13, 122-138.
Robertson, A. W., J. D. Farrara, and C. R. Mechoso, 2003: Simulations of the atmospheric response to South Atlantic sea surface temperature anomalies. *Submitted to J. Climate*.
Rouault, M., P. Florenchie, N. Faucherau and C.J.C. Reason, 2002: South east tropical Atlantic warm events and southern African rainfall. *Geophys. Res. Lett.,* in press.
Sterl, A., and W. Hazeleger, 2003: Coupled variability and air-sea interaction in the South Atlantic Ocean. *Submitted to Climate Dynamics*.
Sutton, R. T., S. P. Jewson, and D. P. Rowell, 2000: The elements of climate variability in the tropical Atlantic region. *J. Climate*, **13**, 3261-3284.
Tyson, P.D., T.G.J. Dyer and M.N. Mametse, 1975: Secular changes in South African Rainfall: 1880-1972. *Quart. J. Roy. Meteor. Soc.*, **101**, 817-833.
Uvo, C., A. A. Repelli, S. E. Zebiak, and Y. Kushnir, 1998: the relationships between tropical Pacific and Atlantic SST and northeast Brazil monthly precipitation. *J. Climate*, **11**, 551-562.
Venegas, S.A., L.A. Mysak, and D.N. Straub, 1997: Atmosphere-ocean coupled variability in the South Atlantic. *J. Climate,* **10**, 2904-2920.
Wagner, R.G., 1996: Decadal-scale trends in mechanisms controlling meridional sea surface temperature gradients in the tropical Atlantic. *J. Geophys. Res.*, **101**, 16683-16694.
Wainer, I. And S.A. Venegas, 2002: South Atlantic multidecadal variability in the climate system model. *J. Clim.*, **15**, 1408-1420.
Wang, C., 2002: Atlantic climate variability and its associated atmospheric circulation cells. *J. Climate*, **15**, 1516-1536.
Zebiak, S. E., 1993: Air-sea interaction in the equatorial Atlantic region. *J. Climate*, **6**, 1567-1586.

5.5 South Atlantic Ocean Observing System for Climate

Silvia L. Garzoli[1], Mike Johnson[1], Alberto Piola[2], Christine Provost[3], and Gustavo Goni[1].

[1] *National Oceanic and Atmospheric Administration, US*
[2] *Servicio de Hidrografia Naval, Argentina*
[3] *Laboratoire d'Oceanographie Dynamique et de Climatologie, France*

5.5.1. Scientific background

The South Atlantic Ocean connects the three major ocean basins: The Pacific Ocean, the Atlantic Ocean and the Indian Ocean. The meridional gaps between the continents of the Southern Hemisphere and Antarctica allow for a free exchange of water among the basins. The South Atlantic is a peculiar ocean because it is the only basin, in which the net meridional heat flow is equatorward, resulting in a cross equatorial export of heat towards the Northern Hemisphere. Despite its small size, the Atlantic Ocean is responsible for over half of the heat transport carried by the global ocean. Meridional heat flux in the ocean is a key element of the climate system because of the role that the ocean plays in determining the Earth's climate through its interaction with the atmosphere. Therefore, in order to understand and predict variability, it is crucial to understand the mechanisms and the pathways of mass and heat transport in the global ocean. The ability to understand and quantify this northward flow is crucial to properly model and forecast the Northern Hemisphere weather and climate. Compared to the North Atlantic and the Pacific, the oceanic circulation in the South Atlantic, and therefore how this heat is transported to the north, is poorly understood. It was not until very recently that the concept of observing the World Ocean to understand climate changes and improve weather forecasts for northern hemispheric countries was embraced. The South Atlantic has been historically one of the less sampled basins. The spatial and temporal gaps in the observations result in poor climate forecasts. The proposed observations should be considered as a way to fill these crucial gaps.

This ocean meridional heat flux is due to a worldwide vigorous circulation that connects all the oceans, the Atlantic thermohaline circulation, which is one of the research topics identified as scientifically relevant to CLIVAR. The importance of the role that the South Atlantic plays in this circulation is indisputable. The classical picture of the conveyor belt (Broecker, 1991) indicates that the North Atlantic trades cold deep water for warm upper water coming from the South Atlantic. This thermohaline overturning cell is composed of northward transports of warm surface- and intermediate-layer waters in the upper 1000m, southward transport of North Atlantic Deep Water (NADW), and at the bottom northward flowing Antarctic Bottom Water.

Most of these exchanges take place via the boundary currents, which are the major distributors of mass and heat across basins and oceans, and the rings shed at their retroflections. However, some intriguing and unanswered questions are: How much heat is transported into the North Atlantic and from where? How the upper limb of the "conveyor belt" circulation is supplied? How much of it is warm and salty upper layer water entering the region from the Indian Ocean? How much of it is colder and fresher water originating out of the Drake Passage? What are the main routes of these passages and the mechanisms that originate the transfers? Moreover, there have been indications of recent warming which might be related to variability of deep convection and water mass transformation in the Weddell Sea. Hence, monitoring the various in- and outflows through the southern entrance of the South Atlantic is important for understanding decadal variability and has to be a prime objective of an ocean program in CLIVAR.

One of the key questions when dealing with the thermohaline circulation in the South Atlantic is how much heat and salt is transferred from the Indian and from the Pacific oceans to the Atlantic Ocean. The profound disagreements between volume estimates (Rintoul, 1991; Gordon et al., 1992; Gordon, 1996; Schmitz, 1996; You, 1999; You 2001) suggest significant variations. The time scales of those variations and their impact are unknown. This inter-ocean exchange between the Indian and the Atlantic oceans takes place through the Benguela /Agulhas system, south of South Africa. The Agulhas Current, at its retroflection, sheds energetic rings that carry salt and warm water into the South Atlantic. Approximately 3 to 7 rings per year are shed at the retroflection and in average, each one of the rings transports 1 Sv of water. The Benguela Current, and its extension, are the main conduits of Indian Ocean water into the Atlantic. Across 30°S, the Benguela Current is confined between the African continental shelf and the Walvis Ridge located between 2° and 4°E (Reid, 1989). In the early 90's an experiment called Benguela Sources and Transports (BEST), took place in the region. One of the main results of the BEST experiment was that while the mean transport of the Benguela Current remains approximately constant every year, there is a marked variability of the water masses from where the Benguela Current drain its sources (Garzoli and Gordon, 1996 and Garzoli *et al*, 1997). Further studies based on the BEST and altimeter data, indicated that in addition to this variability, during the years when the Agulhas Current was stronger, most of the contribution to the Benguela Current was not from the Indian Ocean but from the South Atlantic (Garzoli and Goni, 1999). These results posed the question of why, when the Agulhas transport is higher than usual, less Indian Ocean water contributes to the Benguela Current? Modeling studies (Matano, personal communication) indicate that a stronger Agulhas Current increases the inertia and a larger portion of the current is forced to flow over the shallower depths of the Agulhas plateau. The current gets trapped in the topography and as a result, fewer and larger rings are shed at the retroflection. Matano's theoretical results are in total agreement with the observations and provide a theoretical explanation to the results. These results have a direct implication on the thermohaline circulation. Further studies are needed to determine the causes of this variability and its impact in the conveyor belt.

On the southwest region of the South Atlantic basin, the Malvinas Current (MC) is the main conduit of Pacific water into the Atlantic. The first current meter measurements were gathered between December 1993 and June 1995 in the MC near its merger with the Brazil Current. These showed the mean flow to be equivalent barotropic in form (Killworth, 1992), whereas the variability is dominated by a surface intensified barotropic-like empirical mode, the structure of which is suggestive of mode coupling caused by steep topography (Vivier and Provost, 1999a). Transport variability was found to be about 12 Sv root mean squared, a significant part of which is due to mesoscale activity, reducing to about half this for time-scales beyond two months. The ability of TOPEX/Poseidon (T/P) data from ground track 26 to monitor the MC transport was tested against in situ measurements (Vivier and Provost, 1999b). Transport estimates were extended to 5 years using TOPEX/Poseidon (T/P) data (Vivier et al., 2001), and showed substantial energy near 70 and 180 days, and by contrast a weak annual harmonic. The 70 day peak (coherent with bottom pressure to the northern edge of Drake Passage) is identified as a baroclinic shelf wave trapped along the edge of the Patagonian Plateau. These propagate from Drake Passage, and may originate from equatorial waves in the Pacific. The second broad spectral peak in the MC transport near the semi-annual periods appears to reflect a barotropic adjustment to changes in the wind stress curl (ECMWF) north of 50S mostly in the Pacific sector (20 day lag). It is suggested that the Antarctic Circumpolar Current and the Malvinas Current respond differently to the wind forcing, and that these two modes cohabit at Drake Passage (the ACC responds to the zonally averaged wind stress along its path whereas the Malvinas is sensitive to the wind stress curl north of 50°S). Further observations and studies are needed to examine interannual fluctuations.

It is also unclear to how much subantarctic water enters the subtropical gyre in the eastern South Atlantic, and thus may eventually contribute to the upper layer cross equatorial flow required to balance the southward flow of NADW. Subantarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW) ventilate the subtropical thermocline of the Southern Hemisphere oceans on gyre circulation time scales. Understanding the formation rates, evolution, and penetration of SAMW and AAIW is relevant to climate variability studies for several reasons. The range of densities of SAMW/AAIW spans the main thermocline, and changes in its formation rate or characteristics could change the shape and heat content of the southern subtropical gyres. The SAMW renews itself, at least partially each winter, and provides a useful way to measure climate change over longer time periods. In the Pacific Ocean, the densest subducting layer is also the densest of the global SAMWs, and is identical there to AAIW. AAIW is formed in the southeastern Pacific, just west of southern Chile, from where it spreads to the entire southern hemisphere and tropics throughout the globe (Talley, 1999). The Pacific AAIW salinity minimum originates from this single source region, through northward subduction. The AAIW found in the Atlantic and Indian originates primarily from this source as well, as a portion of the new AAIW flows eastward through Drake Passage, north of the Subantarctic Front. Some modification of the AAIW takes place during this passage and then it spreads into the South Atlantic's subtropical gyre through eddy shedding and mixing out of the Malvinas Current loop. (This is not a wind-driven subduction process.) Based on oxygen, potential vorticity and salinity in the Atlantic and Indian Oceans, there is no source of AAIW in these oceans other than the southwestern Atlantic. A monitoring of the water mass transformation in the Argentine will therefore be an important component of the observing system.

Another topic of relevance to CLIVAR is the distribution of sea surface temperature (SST). The knowledge of the distribution of SST anomalies in the South Atlantic is important at the global scale for modeling and prediction. SST distribution is also important, because their anomalies in the southwestern Atlantic affect the climate, and therefore living conditions, of the most densely populated region of the southern hemisphere: the seaward corridor between northern Brazil and southern Argentina. It has been shown that during the last few decades climatic variations have had an important economic and social impact on the region (SACS Document, 1996). Drought periods have produced changes in cattle population, drained the water supplies of large cities and caused shortages of hydroelectric power. A westward shift in precipitation patterns, which occurred during the ‘70s, has been related to a significant expansion of farming in the south of Argentina, Uruguay and southern Brazil. While the mechanisms behind these climatic fluctuations remain unclear the few existing observations point to relations between climate variability and the large SST changes observed in the open ocean.

5.5.2. The Climate Observing System in the South Atlantic

The international scientific community, together with their local policy makers, established the need for a global ocean observing system. The observing system should be directed to monitor and observe as well as understand and describe climatic phenomena with the objective of improving climate predictions in all time scales. It is well accepted today that documenting and forecasting climate will require continuous measurement from space along with the instrumenting of the global ocean.

In order to succeed, a Climate Observing system should have the following characteristics:
1) Long term and sustained observations,
2) Sustained funding, and
3) Research based.

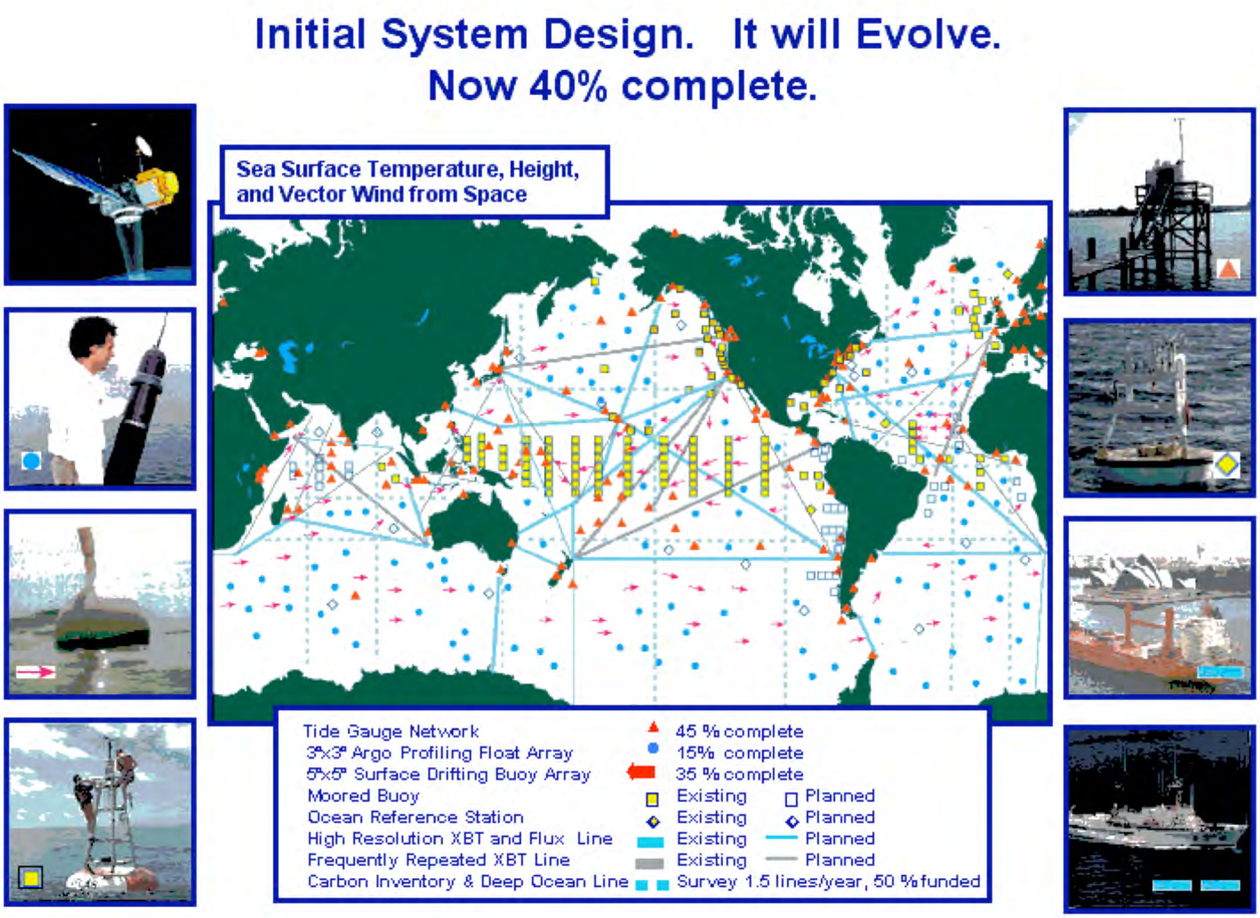


Figure 1: Initial Global Observing System design.

The Observing System will also need to incorporate a capability for producing global and regional analysis of products for the atmosphere, ocean, and land based. It is important to recognize that a climate observing system is a complex system and that in addition to the ocean/atmospheric component it also has biological and chemical components.

The currently existing components of the international effort comprise *in situ*, space based, data and assimilation subsystems: 1) Global Tide gauge Network; 2) Global Surface drifting Buoy Array; 3) Global Ships of Opportunity Network; 4) Tropical Moored Buoy Network; 5) ARGO profiling float array; 6) Ocean reference Stations; 7) Coastal Moorings; 8) Ocean carbon Monitoring Network; 9) Dedicated Ship Operations; 10) Satellites for Sea Surface Temperature, Sea Surface height, and Surface Vectors Winds; 11) Data and Assimilation Systems (GODAE). The initial system design is shown in Figure 1.

In what follows the components of this system relevant to the South Atlantic, will be presented. For the purpose of this white paper, we will consider the region comprising the tropical Atlantic and the South Atlantic (20°N to 60°S). Web sites referring to the places where all information can be obtained are given below the subtitles when available. Some of the figures or text included in this white paper were obtained from those sites.

5.5.3. Sustained Observations

1) Global Tide Gauge Network

http://badc.nerc.ac.uk/data/gloss/

http://lwf.ncdc.noaa.gov/oa/climate/research/slp/index.html

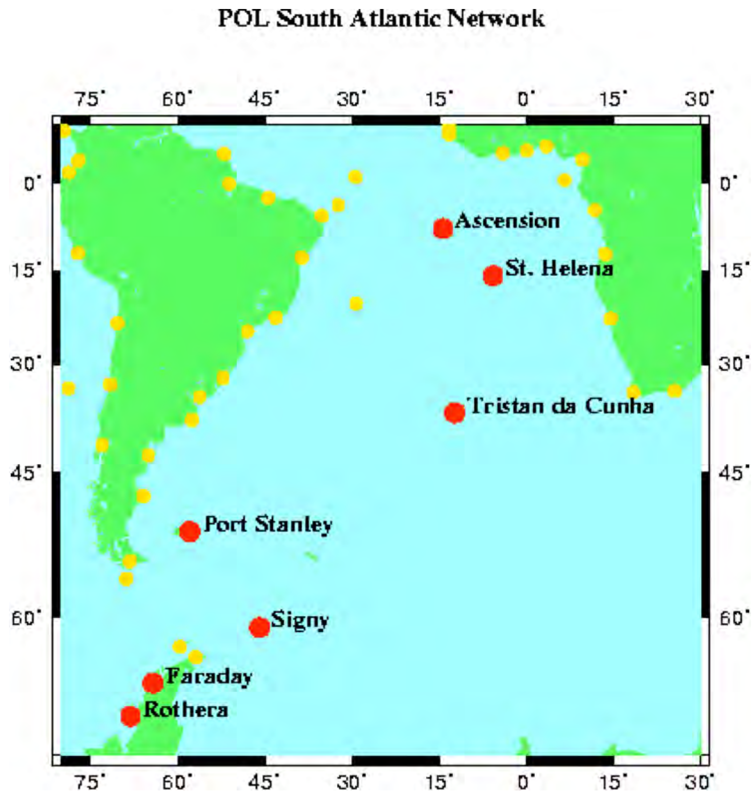


Figure 2: Red dots indicate sites the South Atlantic coastal tide gauge network (ACCLAIM), while the yellow dots show gauges (not necessarily operational) committed to the GLOSS program by countries in the region.

The tide gauge data from the international program Global Sea Level Observing System (GLOSS) aims at the establishment of high quality global and regional sea level networks, including the South and tropical Atlantic Ocean, in an evenly distributed spatial sampling. The NODC and the University of Hawaii provide access to the sea level data through the Join Archive for Sea Level (JASL).   These data, primarily since 1980, are hourly, daily and monthly from stations in tropical and subtropical areas of all ocean basins, including the South and tropical Atlantic. However current data are measured with different standards and has a Northern

Hemisphere bias. Most data belong to tide gauges although some are derived from bottom-mounted pressure gauges. The observations obtained from them are used to conduct research activities that include interannual and decadal sea level fluctuations and tropical ocean dynamics. Within this context, the archive of long-term data records, as provided by NODC, is key to complement observations by altimetry that began in 1985 with the launch of the GEOSAT mission, to estimate long-term modulation of events, to determine the temporal characteristics of the record covered by altimetry, and to monitor ocean circulation. Moreover, these tide gauge data records are needed to calibrate altimeters, to provide information where altimetry has data gaps in time and space, to provide long-term records on coastal and in high latitude regions. In the South Atlantic, the ACCLAIM (Antarctic Circumpolar Current Levels by Altimetry and Island Measurements) program added measurements from coastal tide gauges and bottom pressure stations, together with an ongoing research program in satellite altimetry. The network of GLOSS and ACCLAIM stations is shown in Figure 2.

2) Global Surface Drifting Buoys Array.

http://www.aoml.noaa.gov/phod/dac

The primary goal of this project is to assemble and provide uniform quality control of sea surface temperature (SST) and surface velocity measurements. These measurements are obtained as part of an international program designed to make this data available in an effort to improve climate prediction. Climate prediction models require accurate estimates of SST to initialize their ocean component. Drifting buoys provide essential ground truth SST data. The Global Drifter Center is located at AOML in Miami, Florida. The center manages the deployment of drifting buoys around the world. Using research ships, Volunteer Observation Ships (VOS), and U.S. Navy aircraft, Global Lagrangian Drifters (GLD) are placed in areas of interest. Once verified operational, they are reported to AOML's Data Assembly Center (DAC). Incoming data from the drifters are then placed on the Global Telecommunications System (GTS) for distribution to meteorological services everywhere.

A joint effort between SIO and the AOML started in 1997, to deploy and maintain an array of SVP drifting buoys in the tropical Atlantic, within 20 degrees of latitude of the equator, for the purpose of observing a basin-wide scale tropical current and SST fields on time scales of the inter-annual variations of tropical Atlantic SST. Additionally, to support hurricane predictions, ten wind drifters (WOTAN) were purchased per year. Some of the drifters will be air deployed in front of developing hurricanes to provide observations of the ocean response. Since the program started approximately 360 drifters were deployed in the region. The drastic change in data coverage can be seen in figure 3.

In FY03, a new component of this program started to partially solve the problem of data scarcity in the south tropical Atlantic (20°S to 40°S). A good coverage of SST data is needed to resolve the meridional modes of variability of the tropical Atlantic. Funds were provided to deploy 20 additional floats/year in the region. During 2003 14 SVP Drifters were deployed in the Extra - Tropical Atlantic (20°S- 40°S) and 30 SVP-B Drifters in the South Atlantic (40°S – 60°S). The upgrade of SVP drifters with Barometers was funded by the South African Weather Service and NOAA/SIO.

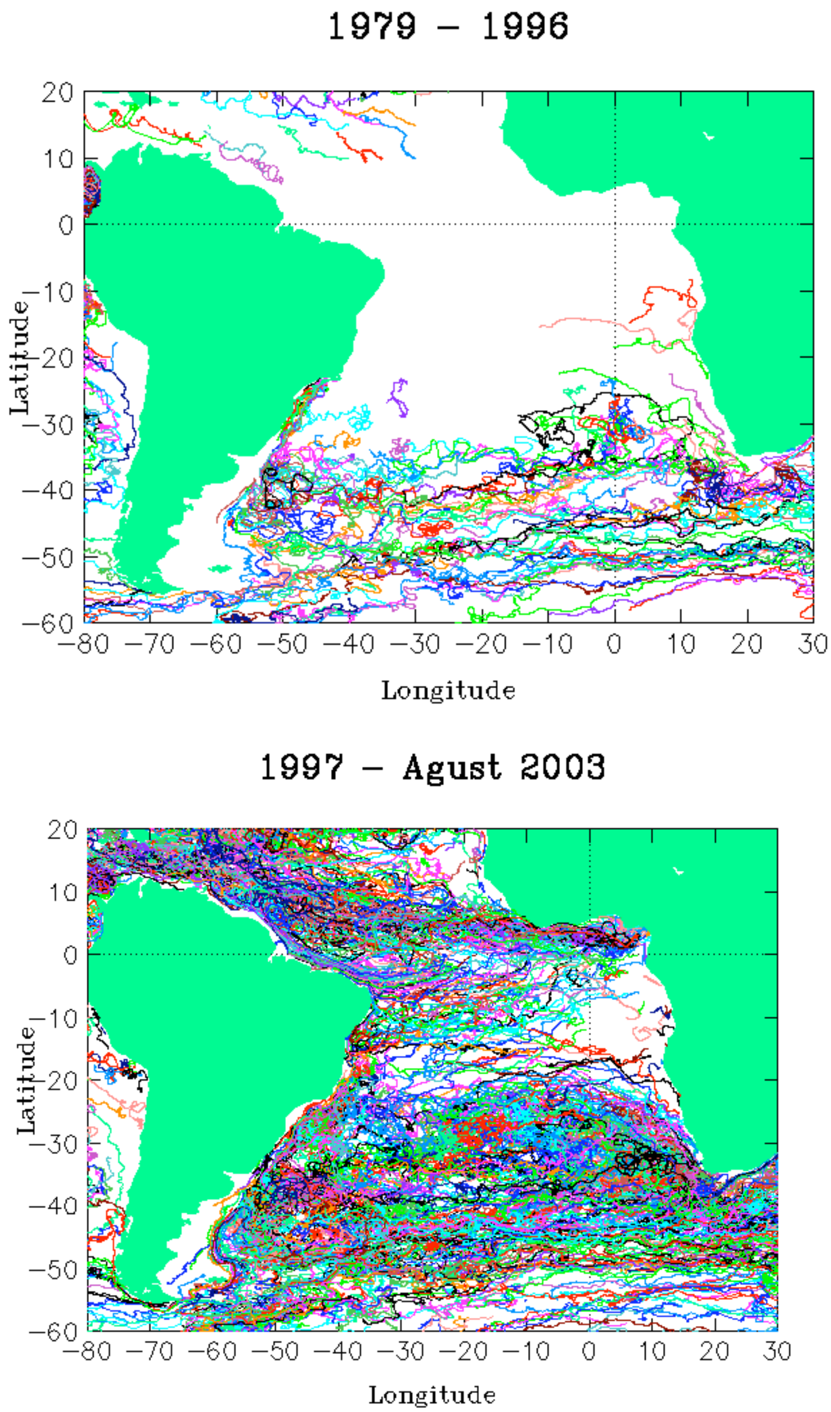


Figure 3: Evolution of the Atlantic surface drifter's array. Top: trajectories of drifters deployed in or entering the region from 1979 trough 1997 (18 years); Bottom: trajectories of drifters deployed in or entering the region, from 1978 to the present.

3) Global Ships of Opportunity Network

http://www.brest.ird.fr/soopip/

The Ship-of-Opportunity Program (SOOP) is an international effort directed primarily towards the continued operational maintenance and co-ordination of the XBT ship of opportunity network but other types of measurements are being made (e.g. TSG, XCTD, CTD, ADCP, pCO2, phytoplankton concentration).

In conjunction with SOOP, a program developed by National Oceanic and Atmospheric Administration (NOAA) SEAS (http://seas.amverseas.noaa.gov/seas/) was created to provide accurate meteorological and oceanographic data in real time from ships at sea through the use of satellite data transmission techniques. The system transmits data through either the GOES or INMARSAT C satellites to NOAA for use in weather, climatological and ocean models such as in the Fleet Numerical Oceanography and Meteorology Center (FNMOC) OTIS SST analysis above. Its goal on the World Wide Web is to provide information on the past and current activities of the NOAA SEAS XBT program. An example of the present SOOP network is shown in Figure 4.

The XBT sampling is performed at three different resolutions.

1)Low-resolution sampling, targeted the large-scale, low frequency modes of climate variability and making no attempt to resolve the energetic, mesoscale eddies that are prevalent in much of the ocean. The low-resolution lines are maintained through an international consortium with oversight by the SOOP Implementation Panel and data are frequently available in real-time for operational climate forecasts and analyses.

Figure 4: Example of the international XBT lines conducted for the period January-2002 to December 2002. Full lines correspond to high density lines and point lines correspond to low density sampling.

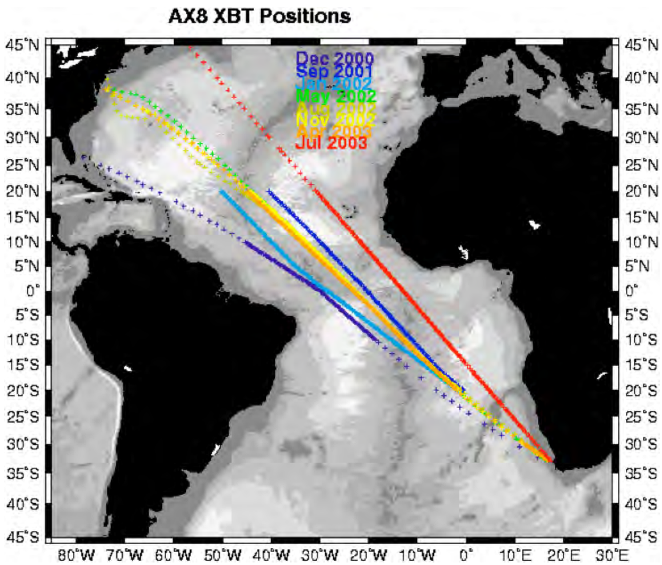
2)Frequently repeated XBT (FRX) lines are mostly located in tropical regions to monitor strong seasonal to inter-annual thermal variability in the presence of intra-seasonal oscillations and other small scale geophysical noise. They are intended to capture the large-scale thermal

response to changes in equatorial and extra-equatorial winds. The lines are (ideally) covered 18 times per year with an XBT drop every 100 to 150 km.
3)High resolution XBT (HRX) lines are those whose sampling criteria require boundary-to-boundary profiling, with closely spaced XBTs to resolve the spatial structure of mesoscale eddies, fronts and boundary currents. The repetition frequency is about four times per year.

Of particular interest for SACOS are two lines operated by NOAA: AX08 that runs from Cape Town to North America and AX18, from Cape Town to South America. Information and data collected along those lines can be found at:
http://www.aoml.noaa.gov/phod/hdenxbt/

4) Tropical Moored Buoy Network

http://www.pmel.noaa.gov/pirata/



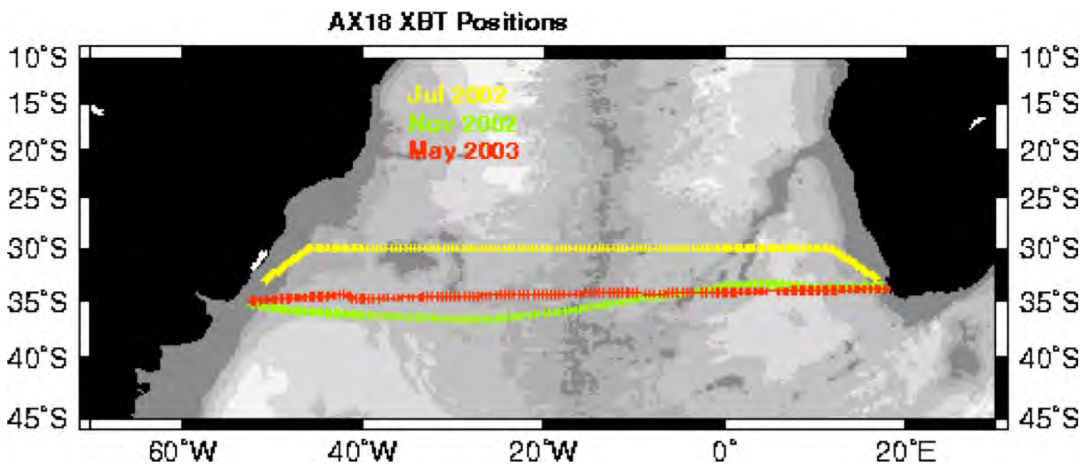


Fig 5: Track of the high density HBT lines in the South Atlantic. Top AX08. Bottom AX18.

PIRATA (Pilot Research Moored Array in the Tropical Atlantic) is a project designed by a group of scientists involved in CLIVAR, and is implemented by the group through multi-national cooperation. The purpose of PIRATA is to study ocean-atmosphere interactions in the tropical Atlantic that are relevant to regional climate variability on seasonal, interannual and longer time scales.

The scientific goals of the PIRATA array are: to provide a description of the seasonal-to-interannual variability in the upper ocean and at the air-sea interface in the Tropical Atlantic; to improve our understanding of the relative contributions of the different components of the surface heat flux and ocean dynamics to the seasonal to interannual variability of SST within the tropical Atlantic basin; and to provide a data set that can be used to develop and improve predictive models of the coupled Atlantic climate system. (PIRATA Science and Implementation Plan, 1996). To achieve the objectives PIRATA designed, deployed and maintain a pilot array of ATLAS moored oceanic buoys that measure a set of oceanic and atmospheric parameters. Data is collected and transmitted in real time via satellite and posted in a web page. The location of the PIRATA moorings is given in Figure 6

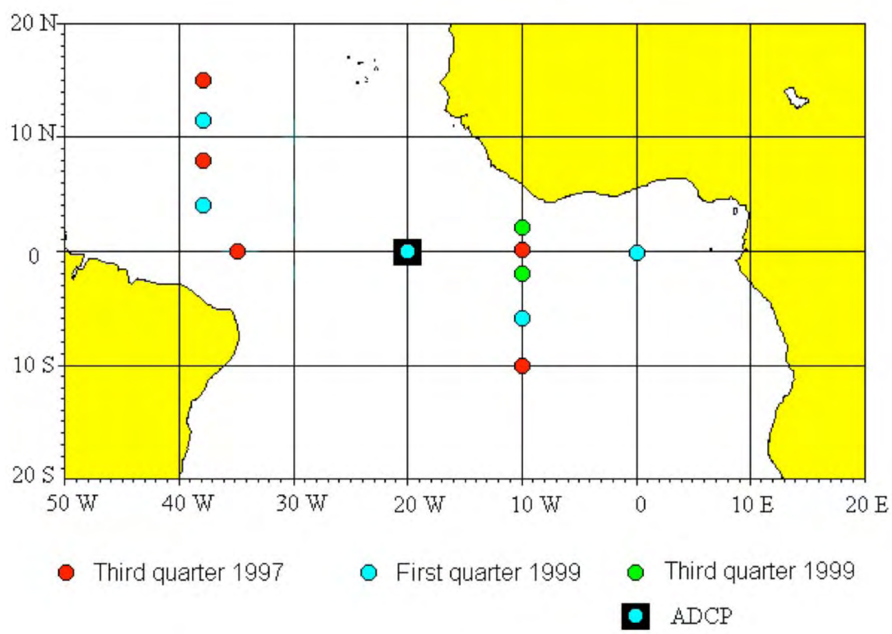


Figure 6: Location of the PIRATA moorings.

5) ARGO profiling float array

http://argo.jcommops.org/argomain.html

ARGO is an international program that calls for the deployment of 3,000 free drifting profiling floats, distributed over the global oceans, which will measure the temperature and salinity in the upper 2,000 m of the ocean providing 100,000 T/S profiles and reference velocity measurements per year. This will allow continuous monitoring of the climate state of the ocean, with all data being relayed and made publicly available within hours after collection. Floats are deployed at a pre-fixed depth and drift with the currents for 10 days. After 10 days the float rises to the surface while collecting temperature and conductivity data. Once at the surface the float transmits the data via satellite. After a period from 4 to 12 hrs, it sinks again to the pre-fixed depth and the cycle continues for a life time from 2 to 4 years. Examples of the data collected with the ARGO profilers in the South Atlantic are given in Figures 7 and 8.

6) Ocean reference Stations

http://uop.whoi.edu/geo/Sites.html

The Global Ocean Timeseries Observatory System is a Pilot experiment for global Eulerian observatory systems that will be multidisciplinary in nature, providing physical, meteorological, biological, chemical and geophysical time series observations (Figure 9).

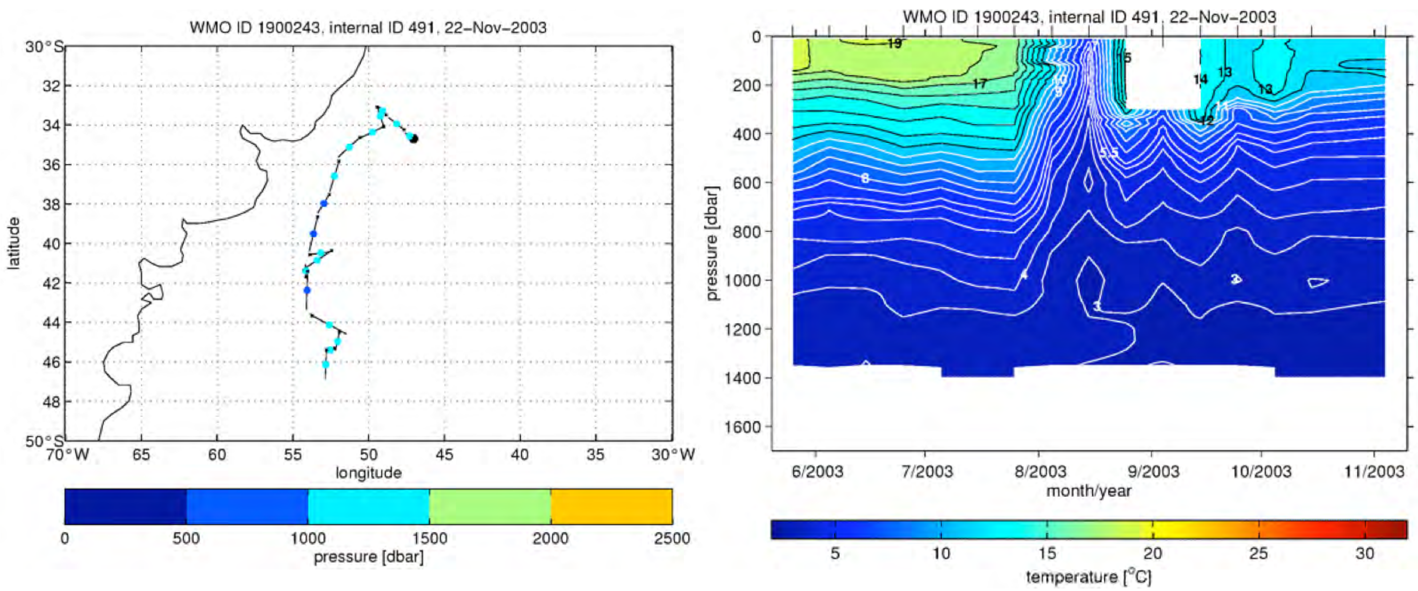


Figure 7: Trajectory and vertical temperature profiles collected by ARGO float 491 deployed May 30 2003 at 34° 41.7'S 47° 01.92'W. Left: trajectory. Right: Temperature.

The definition of an ocean time series site in the global system is that it has the following characteristics (Weller, 2003):

- *in-situ* observations of ocean/climate related quantities at a fixed geographic location/region
- sustained and continuous, contributing to a long-term record at the site
- autonomous moored sampling should be pursued to resolve high- frequency variability, to achieve high vertical resolution, and to obtain coincident multi- disciplinary sampling
- as an alternate to a mooring, shipboard observations from regular occupation of a site as at Ocean Weather Stations, historical sites or sites where moorings have not been established provide an alternate method
- site selection is determined by the value of the site as representative of one, and where possible more, meteorological, physical, or chemical area of interest.

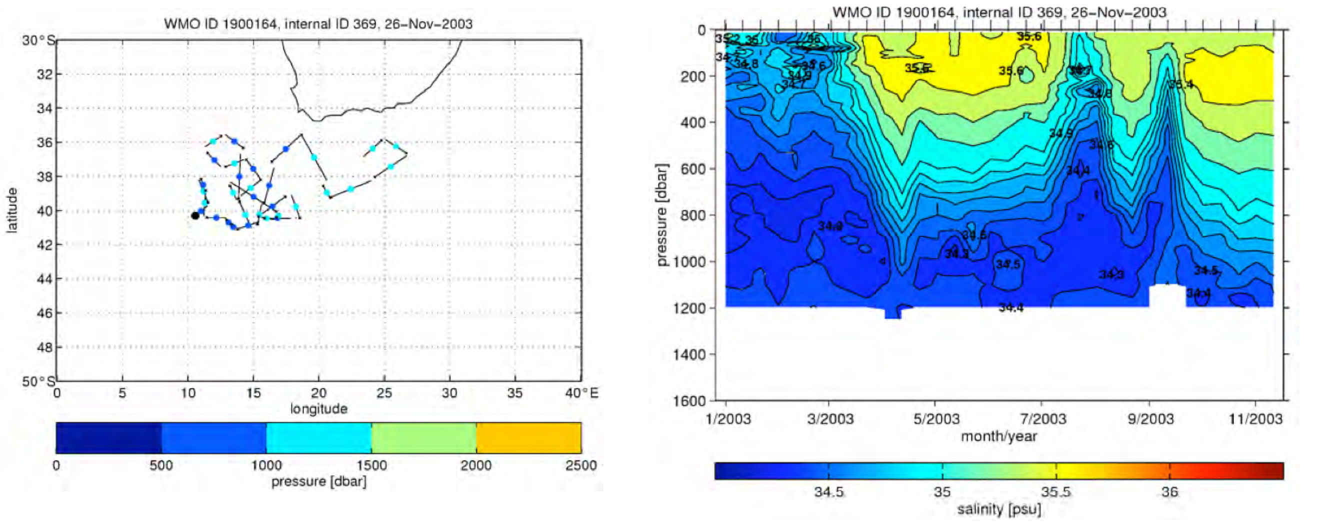


Figure 8: Trajectory and vertical salinity profiles collected by ARGO float 369 deployed on January 4, 2003 at 40° 18.9'S 10° 33.06'E. Left: trajectory. Right: Salinity

In the South Atlantic there are up to date only recommended sites. The only operating observatories are in the Southern Ocean located at 55°S 0°E, 66°S 0°W and 73.5°S 35°W operated by Norway, and at 63°S 42.5°W operated by the US.

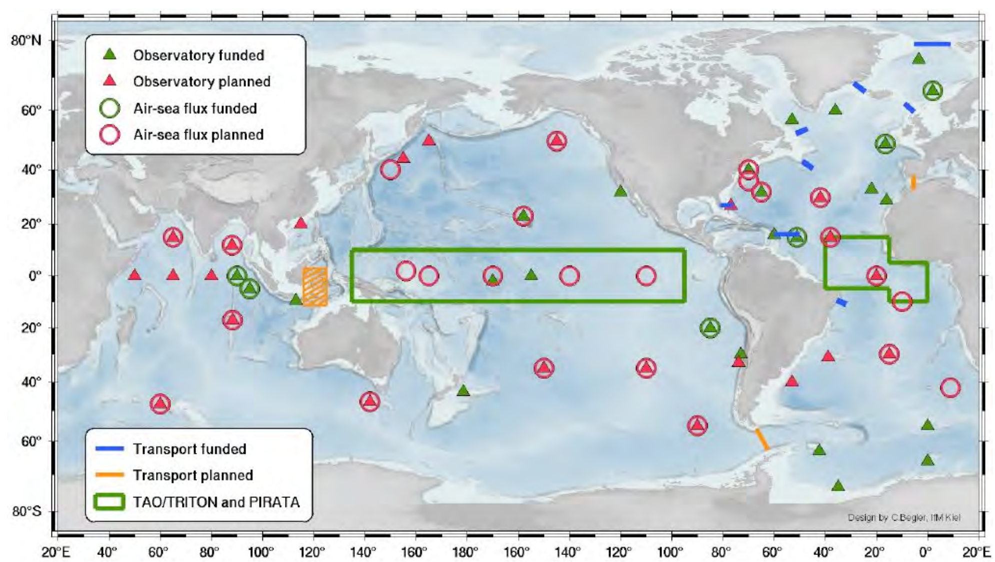


Figure 9: Location of the funded and proposed time series observatories

7) Ocean Carbon Monitoring Network

www.ioccp.org

Two major international efforts are in place to establish a monitoring carbon network: the repeat hydrography program, and the ocean CO_2 flux program. International coordination for ocean carbon efforts is facilitated through the International Ocean Carbon Cycle Project (IOCCP), which is part of IOC/UNESCO.

The major objectives of the repeat hydrography program are to monitor the anthropogenic CO_2 inventory in the ocean on decadal time-scales and determine oceanic sources and sinks (flux maps) on seasonal time-scales, relying heavily on a systematic and sustained observing strategy. Changes in anthropogenic CO_2 inventory in the ocean, which quantifies the natural sequestration capability of the ocean, will be accomplished by measuring total inorganic carbon content, nutrients and transient tracers on the joint NSF/NOAA CO_2 CLIVAR repeat hydrography lines. The repeat hydrography program, which follows the initial global CO_2 survey in the 1990's performed in conjunction with WOCE, commenced in 2003 with 3 meridional transects in the North Atlantic. This will be followed with transects in 2004 in the South Atlantic, Subtropical Pacific and South Pacific with cruises as indicated in Figure 10. Detailed objectives of the program can be found at: http://ushydro.ucsd.edu/cruises.html.

In the South Atlantic, the first realization took place in 2003. Plans for the future are shown in Figure 10.

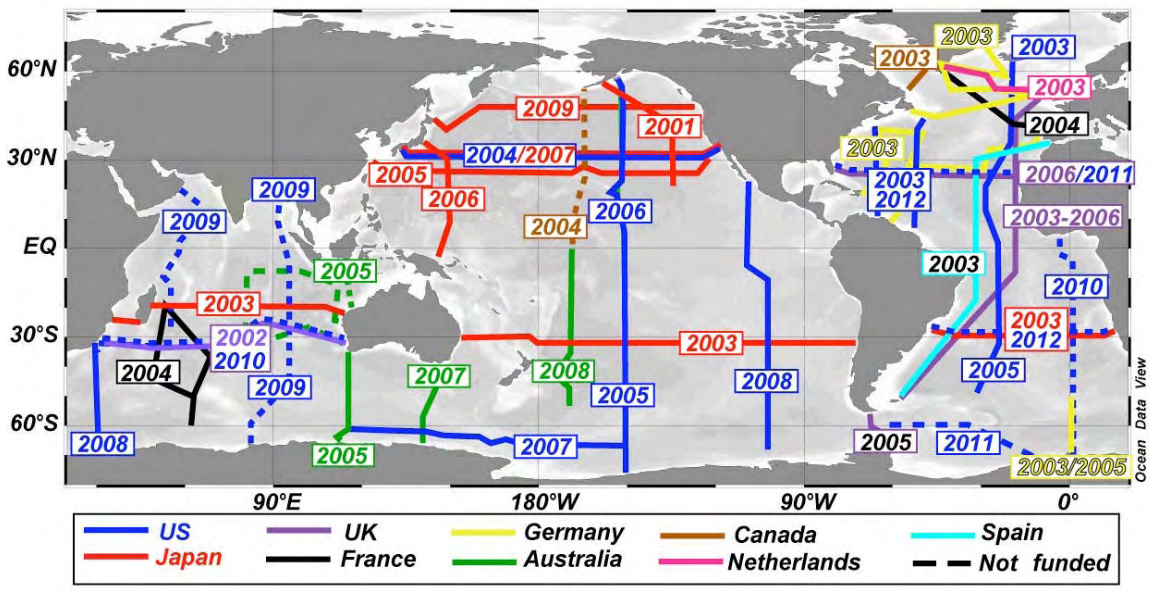


Figure 10: International CLIVAR/ CO_2 lines repeated every 10 years

The ocean CO_2 flux program to develop seasonal maps of sources and sinks of CO_2 in the ocean will occur primarily on volunteer observing ships and buoys. The ships are part of the GOOS XBT program to take advantage of the ancillary measurements that are used to interpret and extrapolate the pCO_2 data. Based on de-correlation length scale analyses, measurements are needed on a monthly basis with spacing of lines approximately 10 degrees apart to constrain regional fluxes. The initial focus of the program is in the North Atlantic, North Pacific and Equatorial Pacific in support of the interagency North American Carbon Program (NACP). The second phase (2006 onward) will expand the study area to the Southern Hemisphere (Figure 11). An Argentine-French program (ARGAU) is collecting underway surface data including pCO_2 and nutrients in the western South Atlantic during the Austral summer since 2000 (see IV.2 below).

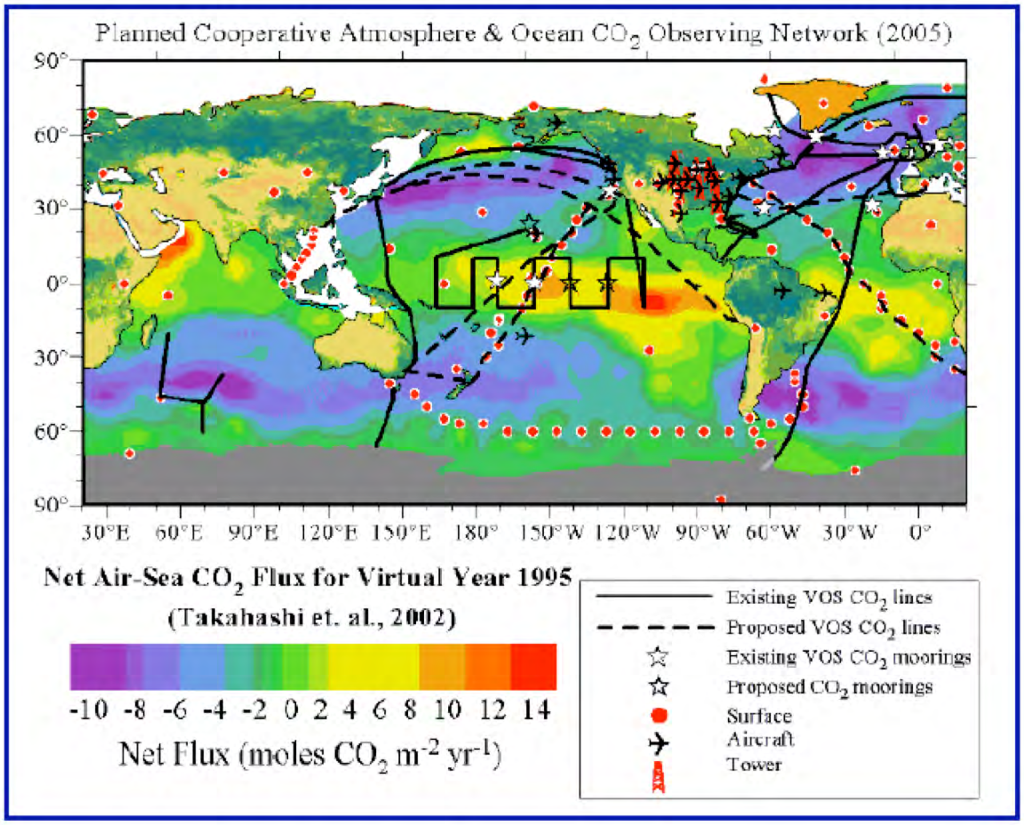


Figure 11: current observing pCO_2 lines and mooring locations

8) Satellites

Remote observations obtained from diverse constellations of satellites are used to investigate the variability in oceanic circulation, atmospheric forcing and surface fluxes.

The sea surface temperature can be obtained from several products at different spatial and temporal resolutions. The NOAA/NASA Pathfinder Advanced Very High Resolution Radiometer (AVHHR) provides a high quality data set derived from NOAA polar-orbiting satellites at daily, 8-day and monthly averages, and 9km, 18km and 54km. NOAA-16 and NOAA-17 are the two current operational satellites that provide AVHRR observations. Other satellites currently providing sea surface temperature observations are GOES (Geostationary Operational Environmental Satellites) at a 6km spatial resolution and the TRMM Microwave Imager (TMI) that provides measurements capable of accurately determine the SST through clouds.

The altimetric fields provide estimates of sea surface height to within 2 or 3 cm uncertainty on a monthly time scale. Blended data from several altimeters are produced by NAVOCEANO and distributed in near-real time. The more accurate altimeter fields obtained from these data will improve our knowledge of the upper ocean general circulation (Figure 12) and its role in climate.

These fields currently have a spatial resolution that is highly dependent on the available altimeters. The altimeter fields are also supported and validated by tide gauges, and are used to help interpret temperature profiles from low and high density XBT observations, help investigate the ageostrophic component when compared with surface drifter observations and are used in data assimilation for the development of operational oceanography. Current satellite altimetry missions include Jason-1, TOPEX/Poseidon, GFO (Geosat Follow-On), Envisat, and ERS-2. Future satellite missions include OSTM (Ocean Surface Topography Mission), which is a follow on to Jason-1.

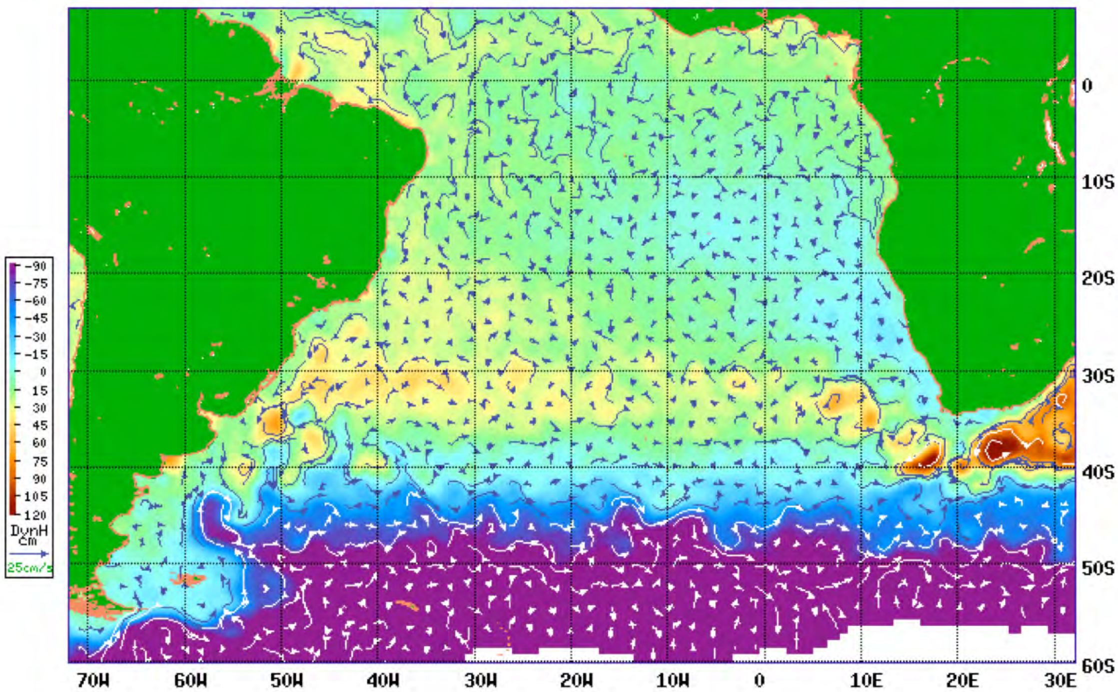


Figure 12: Near-real time monitoring of surface and geostrophic currents from blended altimeter fields corresponding to December 1, 2002; superimposed to the altimetry-derived dynamic height field (colors). From www.cwcaribbean.aoml.noaa.gov

While the instruments placed on buoys and in ships of the VOS provide measurements of the surface wind vectors, their coverage is insufficient to provide a complete coverage in the tropical Atlantic basin. Satellite-based active (radar) and passive (radiometer) sensors supply excellent measurements capable of determining ocean surface wind speed and wind direction, and outstanding coverage in time and space. Wind measurements are critical for computations of sensible and latent heat fluxes through bulk formulae. Satellite wind estimates may be also used to estimate the Ekman component of currents. The most important instruments measuring ocean vector winds are the SeaWinds instruments (microwave radar scatterometers) on board of the ADEOS-II and the QuickSCAT satellites. Other instruments also providing wind fields include the ERS-2 scatterometer, the SSMI/I radiometers, TMI, and ERS-1microwave sensor.

5.5.4. Long term observations:

Monitoring the Malvinas Current

An array of current meters is in place across the Malvinas Current below a Jason track (26) to reevaluate the mean and enable examining interannual variability of the transport (deployed in December 2001- and recovered in November 2003). Those current meters are not permanent. However, they will be needed on a time basis to be defined to examine whether the mean flow fluctuates and check the validity of the transfer function between altimetry and transport.

The Yoyo profiler was deployed to provide a profile of temperature salinity and nitrates every other day over the first 1000 m of the upper column with The YOYO mooring equipped with CTD and nitrate analyzer is meant to document processes and variations of SAMW / AAIW in the argentine basin. The location on the current meter and YOYO moorings are shown in Figure 13.

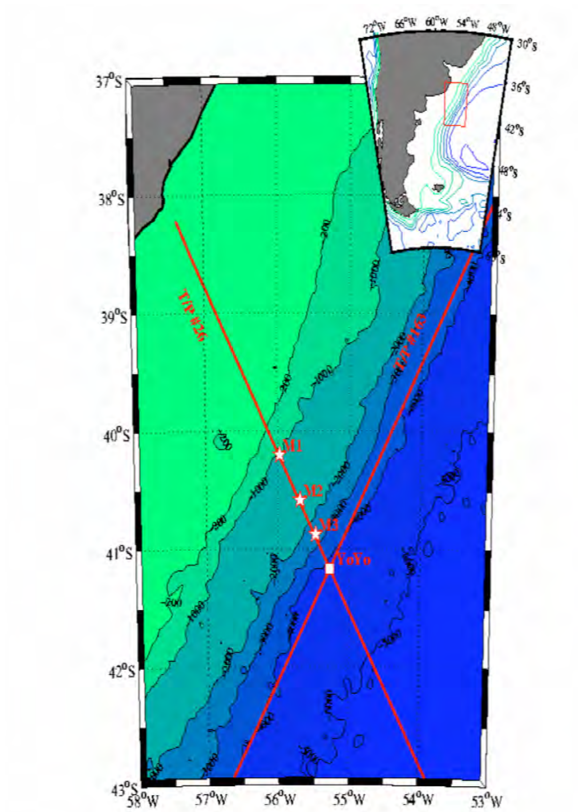


Figure 13: location of the current meter and YOYO CTD-nutrient moorings deployed across the Malvinas Current.

ARGAU

ARGAU is a 10 year monitoring program to study the physical biological and chemical conditions in the western South Atlantic and Atlantic Sector of the Southern Ocean. The main goal of the program is to establish the relation between the near surface oceanic conditions and the ocean atmosphere CO2 fluxes. Underway measurements are conducted between the South American and Antarctic continents (Figure 14). The first line (red of Figure 13) was conducted from March 24 through May 12, 2000.

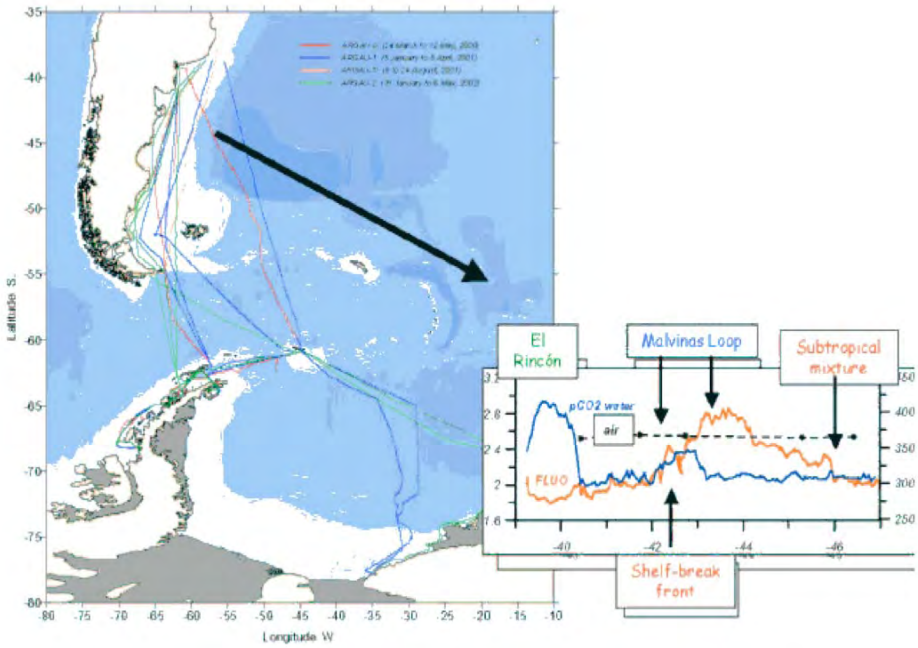


Figure 14: Location of the ARGAU lines. The insert shows preliminary transports results.

Drake passage

A current meter array across Drake Passage will be deployed by LODYC to monitor the volume transport of water (Figure 15). The array will be placed below a Jason satellite track will to serve as a ground truth to allow future observations of volume transport with altimetry. As for the array deployed in the Malvinas Current, this array will need to be maintained on a "regular basis" (from 5 to 10 years) to be defined based on the data analysis from the first deployments.

ASTTEX , Cape of Good Hope and WECCON Experiments

http://gyre.umeoce.maine.edu/ASTTEX/index.html

http://www.ifremer.fr/lpo/speich/GOODHOPE/goodhope.htm

www.awi-bremerhaven.de/Research/IntCoop/Oce/weccon.html

ASTTEX examines the fluxes of heat, salt and mass entering the South Atlantic Ocean via the Agulhas Retroflection. The goal of the experiment is to provide a quantitative, multi-year Eulerian measurement of the strength and characteristic scales of Agulhas-South Atlantic mass and thermohaline fluxes, which contain a strong mesoscale component, resolving those fluxes on density horizons.

The core of the ASTTEX field component is a 24-month deployment of sixteen moorings that monitor the transports of Indian Ocean water into the South Atlantic via the Agulhas Current at eddy-resolving resolution (70 - 80 km). The moored array consists of twelve pressure sensor-equipped inverted echo sounders (PIES) three near-bottom current meters (CM), and one validation mooring with six recording conductivity-temperature (CT) sensors. All of the moorings are deployed along a Topex-Poseidon/Jason satellite altimeter groundtrack. The mooring deployment was completed on January 16, 2003. The location of the moored instruments is given in Fig 16.

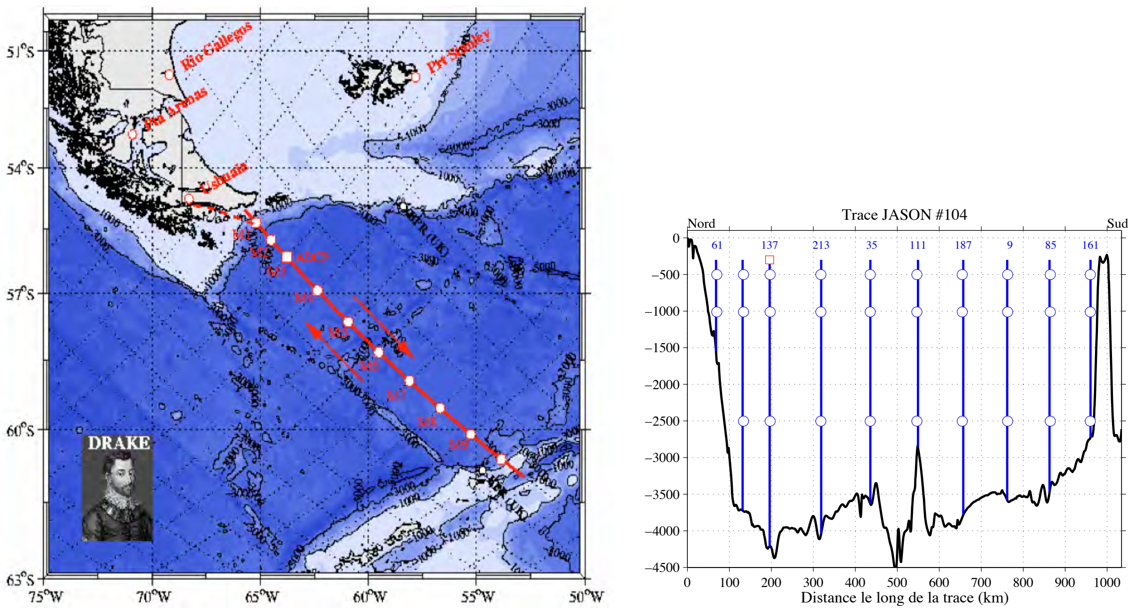


Figure 15: Distribution of the moorings across Drake Passage. Under Jason track 104: red circle current meter mooring , red square: upward looking ADCP. Black stars correspond to tide gauge operated by the Proudman Oceanographic Laboratory.

Good-Hope is an international cooperative project whose main objective is to establish a program of regular and appropriate observations across a line connecting the African and Antarctic contents. In particular, the Goo Hope project aims to quantify and monitor:

- The nature and variability of Indo-Atlantic water exchanges
- The Indian Ocean water masses involved in the closure of the global circulation;
- The Indo-Atlantic interbasin component of the Atlantic

The proposed survey follows the WOCE SR2 transect between cape Town and the Greenwich meridian (Figure 15). Advantages of monitoring this transect are that it follows the Jason-1 ground-track along a significant portion of its length and complement both the ASTEX and the WECCON projects.

The Antarctic ocean contributes through atmosphere-ice-ocean interaction processes to the variability of the climate system. A major contribution of the formation of deep and bottom water of the world ocean occurs in the Weddell Sea. WECCON, Weddell Sea Convection Control, is a German program to study the large scale processes and long-term variations of convection in the Weddell Sea.
The program has two main foci

- To investigate processes which occur in the Weddell Sea to form deep and bottom water

- To study the influence of variations of the inflow from the Antarctic Circumpolar Current into the Weddell Sea.

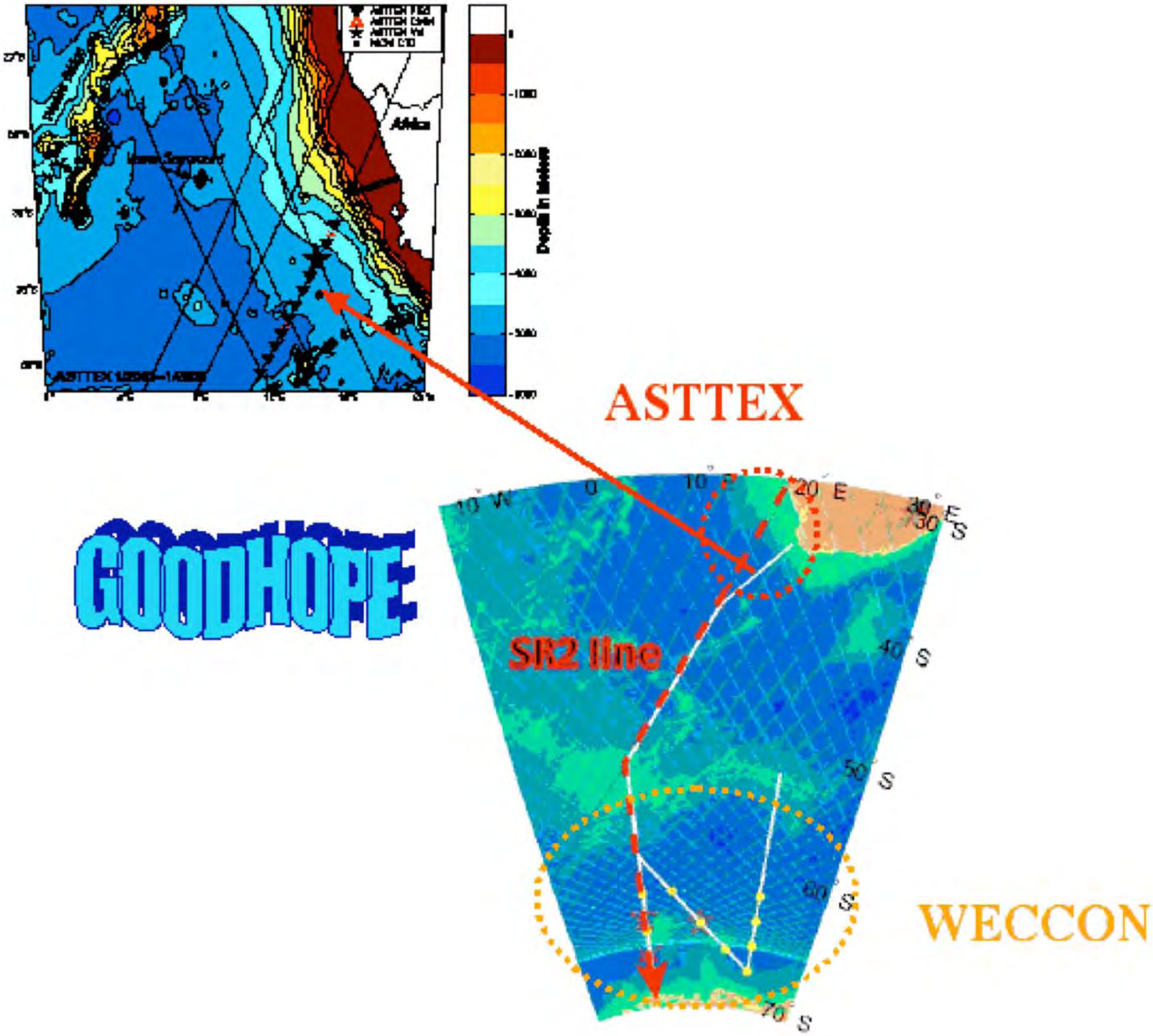


Figure 16: Location of the GOODHOPE, ASTEX and WECCON arrays.

5.3.5 Summary

This white paper presents a summary of (to the best of our knowledge) up to date sustained and long-term observations in the South Atlantic. These observations are shown schematically in the figure shown in the cover page. During the course of the SACOS workshop, deficiencies in the observing system were discussed. Results of the discussions are given in the SACOS report.

5.3.6 References

Broecker, W.S., 1991. The great ocean conveyor. Oceanography, 4, 79-89.

Garzoli, S.L., and A.L. Gordon, 1996. Origins and variability of the Benguela Current. J. Geophys. Res., 101(C6):987-906.
Garzoli, S.L., and G. Goni, 2000. Combining Altimeter Observations and Oceanographic Data for Ocean Circulation and Climate Studies. *Satellites, Oceanography and Society* D. Halpern, editor. Elsevier Science B. V. p 79 to 97.
Garzoli, S.L., G. Goñi, A. Mariano, and D. Olson, 1997. Monitoring South Eastern Atlantic Transports using altimeter data. Jour. Mar. Res, 55, 453-481, 1997.
Gordon, AL. 1996. Communication between oceans. Nature, vol. 382, no. 6590, pp. 399-400.
Gordon, AL; Weiss, RF; Smethie, WM Jr; Warner, MJ., 1992. Thermocline and intermediate water communication between the South Atlantic and Indian Oceans., J. GEOPHYS. RES., vol. 97, no. C5, pp. 7223-7240.
Killworth, P. D., 1992. An equivalent-barotropic mode in the Fine Resolution Antarctic Model. Journal of Physical Oceanography, 22, 1379-1387.
Rintoul, SR , 1991. South Atlantic interbasin exchange. Journal of Geophysical Research. C. Oceans [J. GEOPHYS. RES. (C OCEANS).], vol. 96, no. C2, pp. 2675-2692.
SACC Document, 1996. South Atlantic Climate Change, NOAA/AOML/PhOD Report, October 1996. Web site: www.oce.orst.edu/po/research/matano2/sacc.
Schmitz, W.J., Jr., 1995. On the interbasin-scale thermohaline circulation. *Rev. Geophys*., 33, 151-173.
Vivier F. and C. Provost, 1999a. Direct velocity measurements in the Malvinas Current. J. Geophys. Res., 104, 21083-21104.
Vivier F. and C. Provost, 1999b. Volume Transport of the Malvinas Current: Can the flow be monitored by TOPEX/Poseidon? J. Geophys. Res., 104, 21105-21122.
Vivier F., C. Provost and M. P. Meredith, 2001. Remote and local wind forcing in the Brazil/Malvinas Region. J. Phys. Oceanogr., 31, 892-913.
You, Yushu, 1999. Dianeutral mixing, transformation and transport of Antarctic Intermediate Water in the South Atlantic Ocean. Deep-Sea Research (Part II, Topical Studies in Oceanography) [Deep-Sea Res. (II Top. Stud. Oceanogr.)]. Vol. 46, no. 1-2, pp. 393-435.

5.6 The Mesoscale Circulation of the South Atlantic Ocean: Does it Matters to Climate?

R. Matano[1], E. Campos[2], A. Coward[3], J. McLean[4], E. Palma[5], T. Penduff[6], M. Schouten[1]

[1] *College of Oceanic & Atmospheric Sciences, Oregon State University, USA.*
[2] *Instituto Oceanografico de Universidad de San Pablo, San Pablo, Brazil.*
[3] *Southampton Oceanographic Center, Southampton, UK.*
[4] *Naval Postgraduate School, Monterey, USA.*
[5] *Universidad Nacional del Sur, Bahia Blanca, Argentina.*
[6] *Laboratoire des Ecoulements Geophysiqes et Industriels, Grenoble, France*

5.6.1. Introduction

Unlike the North Atlantic, the central Pacific, or the Southern Ocean, the South Atlantic does not have a well-defined, indigenous climate phenomenon such as El Niño, the North Atlantic Oscillation, or the Antarctic Circumpolar Wave. This does not necessarily means that the South Atlantic is irrelevant to climate because its importance might not be tied to what happens above its surface but below it. The North Atlantic Oscillation or the Antarctic Circumpolar Wave, for example, are not the only reason of why their host regions are climatically important. In fact, it can be argued that the North Atlantic or the Southern Oceans are more relevant to climate for their participation in the global thermohaline circulation than for harboring these local phenomena. In these regards there is no doubt that the South Atlantic is an important nexus of the global thermohaline circulation. The question, however, is whether the SA is just a passive conduit for the transit of remotely formed water masses or whether it is an active participant in the global water-mass transformation process. The distinction is important because if, on the one hand, the South Atlantic were a mostly passive conduit then it could be argued that the details of its interior circulation would be largely unimportant and for advancing our understanding of the global thermohaline, it would suffice to know the inflows and outflows at strategically located choke points (e.g., the Cape Horn or the Cape of Good Hope). If, on the other hand, the South Atlantic were to influence the characteristics of the participating water masses, or to regulate the fluxes between its neighboring basins, then it is evident that advances in our understanding of the South Atlantic circulation would also benefit our understanding of the global circulation and, hence, climate.

In this article we use the results of numerical simulations to discuss the impact of mesoscale processes, occurring within the South Atlantic basin, on the global thermohaline circulation. The following section focuses on the results of global, eddy-permitting, simulations, which indicate that there are significant water mass conversions within this basin, and that those conversions are largely concentrated in regions of intense mesoscale variability. This is followed by a discussion of the connections between the mesoscale variability and the large-scale circulation.

5.6.2. Water mass conversions

The mean meridional circulation in the South Atlantic involves the deep southward flow of cold and salty North Atlantic Deep Water (NADW) along the eastern coast of South America, and a compensating northward flow of a mixture of warm and salty surface waters, and cooler and fresher Antarctic Intermediate Waters (AAIW) in the interior of the basin. The relevance of the South Atlantic to the global thermohaline circulation depends on whether the water masses associated with this global conveyor belt are significantly affected by their passage through the basin. The articles of Piola et al. and De Ruijter et al. examined this issue using the results of long-term hydrographic observations. In this section we discuss the influence of mesoscale processes in the global thermohaline circulation using the results of the Parallel Ocean Climate Model (POCM-4C); a global, eddy permitting, simulation derived from a primitive equation z-level model (Tokmakian and Challenor, 1998). To quantify the South Atlantic water mass conversions we computed volume divergences in 4˚x4˚ horizontal boxes bounded in the vertical by sigma levels. These boxes were grouped in seven distinct regions that represent dynamically distinct portions of the SA circulation (Fig. 1). Sections I and VI, for example, are regions dominated by the influence of the Malvinas and the Brazil Current. Section IV encompasses the Brazil/Malvinas Confluence (BMC) and its offshore extension, the South Atlantic Current. Sections II and V include the open ocean regions of the subpolar and subtropical basins. Section III represents the Cape Basin (CB), a region dominated by the inflow from Agulhas Current. Finally, Section VII, includes the equatorial band and its region of influence along the African coast.

The most conspicuous characteristic of the water mass balances is that the most important transformations occur in regions of intense mesoscale variability. There is a conversion from surface and deep waters into intermediate waters in the BMC, and from intermediate into surface waters in the CB (Fig. 1). Near the tropics, there is a net conversion of intermediate into surface waters. A heat balance of the model reveals that the passage of these water masses at 30˚S generates a northward heat flux of 0.25 PW, a value close to the 0.21 PW estimated by McDonogh and King (e.g. De Ruijter et al.).

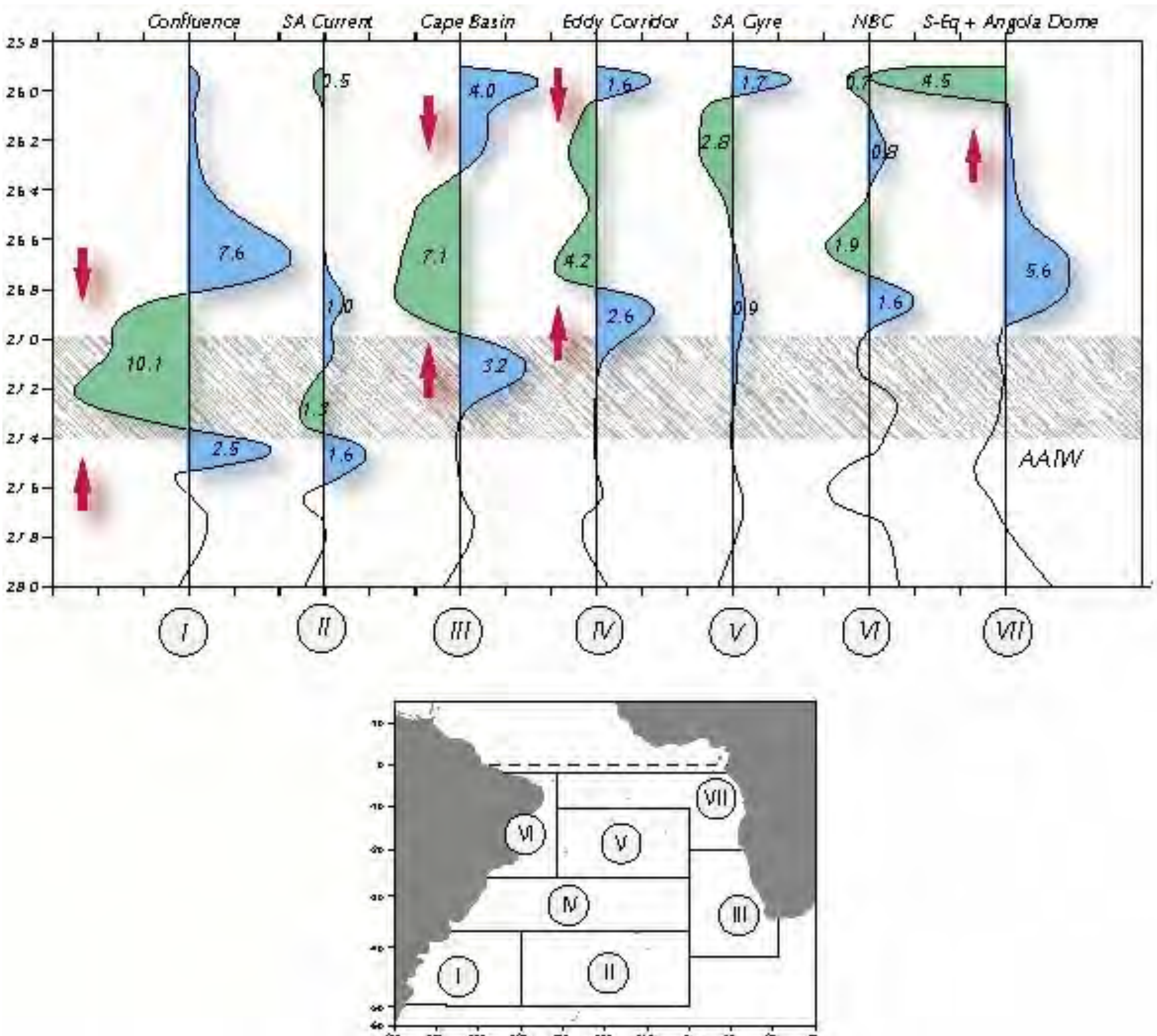


Figure 1: Water mass transformation in the Parallel Ocean Climate Model (experiment 4-C). The upper panel shows the volume divergences and the lower panel shows the locations of the different boxes. The arrows indicate the direction of the water mass fluxes.

The signs and magnitudes of the water mass conversions indicated by the model are in general agreement with the values suggested by the observations (Sloyan and Rintoul, 2001; Piola et al.). It is no well determined the nature of the dynamical processes that lead to the observed water mass transformation. It has been observed that subduction of surface waters in the BMC can lead to the formation of new intermediate waters. Air-sea interactions in the CBR can partly account for the observed conversion of intermediate and relatively light surface waters into a denser variety of surface waters. The correlation between water mass transformations and mesoscale variability, however, is symptomatic of cross-isopycnal mixing processes. The dynamical processes responsible that lead to those cross-isopycnal fluxes remain largely undetermined. It seems, therefore, that in order to advance our understanding of the water mass transformation in the South Atlantic Ocean it is necessary to encourage further observational programs on the BMC and the CBR. These studies should be complemented with modeling studies aimed to understand the nature of the dynamical processes responsible for the water mass conversions and the adequacy of their representation (e.g., mixing) in state-of-the-art numerical simulations.

5.6.3. On the variability of the BMC and the CB

Since the previous analysis indicates that the variability of the South Atlantic's western boundary regions might play an important role in the water mass transformations it is of general interest to establish the linkages between these regions and the large-scale circulation. Little is known, however, about these matters. It remains largely undetermined, for example, whether the BMC variability is influenced by changes in the transport of the Antarctic Circumpolar Current (ACC), or if the shedding of Agulhas rings is modulated by the low frequency variability of the South Indian Ocean. Such topics, however, are not only relevant to our understanding of the local water-mass conversion processes, but also to our understanding of the mechanisms that regulate the South Atlantic's choke points.

The Southwestern Atlantic:

- **The BMC:** Since the seminal study of Olson et al. (1988), investigators have wondered whether changes in the ACC transport are reflected in the Malvinas Current and hence might influence the BMC variability. Although earlier model studies (e.g., Agra and Nof, 1993; Matano, 1993; Matano et al., 1993; Smith et al., 1994; Gan et al., 1998; Wainer et al., 2000) noted that changes of the ACC transport should lead to corresponding changes in the Malvinas transport, these results have not been corroborated by long-term observations. In fact, recent studies on the subject (Vivier and Provost, 1999a, 1999b) reported that the Malvinas Current transport has a seasonal cycle that peaks during the austral winter although it appears to be uncorrelated with seasonal variations of the ACC transport. Since the ACC is the main source for the Malvinas transport, this lack of correlation is intriguing. Fetter-Filho et al. (2004, manuscript in preparation) analyzed the results of POCM and reported that although, and in agreement with the results of Vivier and Provost, the model shows no significant correlation between the variations of the ACC and Malvinas transport at the annual time scale there is a statistically significant correlation between these two transports at interannual time scales. The model results indicate that the after leaving the Drake Passage the ACC branches along the Burwood Bank. Farther north these branches reunite over the continental slope of Argentina to form the Malvinas Current. The time series of the transports of these two branches have a relatively high negative correlation; the strengthening of one leads to a weakening of the other. Fetter-filho argued that due to this negative correlation variations of the ACC transport at the Drake Passage might not necessarily lead to a corresponding variation of the Malvinas Current transport because, sometimes, the ACC variability is diverted towards the subpolar front instead of the subtropics.

- **The Zapiola eddy**. The circulation in the southwestern Atlantic contains a unique example of eddy driven flow, the Zapiola Anticyclone, a stationary eddy with a diameter of approximately 1000 km and a transport of the same order of magnitude than the ACC (above 100 Sv). This feature was discovered during the WOCE era by independent developments in theory

(Dewar, 1998), observations (hydrography, floats, satellite altimetry) (Weatherly, 1993; Fu, 2001), and models (Miranda et al., 1999). Theory supported by numerical model experiments argues that the anticyclone is driven by ocean turbulence along topographically controlled pathways. The Zapiola Anticyclone appears to play a major role in the separation of the subtropical and sub Antarctic fronts in the western South Atlantic. It may also affect the regional climate. SST observations from ATSR identify the Zapiola Anticyclone as a region of minimum temperature gradients, and NCEP/NCAR reanalysis indicate a minimum turbulent heat exchanges that in this case would act to reduce cyclogenesis. Since the Zapiola Anticyclone is close to the BMC it seems likely that it has the potential to enhance the vertical and horizontal mixing that determine the water mass structure of the upper limb of the global thermohaline circulation.

- **The Cape Basin***:* South Atlantic, South Indian and Southern Ocean waters intermingle in the intensely turbulent Cape Basin. In the classical description of the global conveyor belt, the South Atlantic's subtropical gyre draws heat and salt from this region and exports them to the tropics. Although this entrainment is largely ascribed to the shedding of large rings and eddies, it is unclear how these transient, mesoscale fluxes are ultimately integrated into the global thermohaline circulation. There are no recorded observations of any of these eddies beyond the limits of the subtropical gyre. Altimeter-based descriptions indicate that only a portion of the Agulhas rings are able to propagate beyond the Walvis Ridge and, therefore, the bulk of the transfer of properties from the meso- to the large-scale circulation occurs within the Cape Basin. Boebel et al., (2003) estimated that only half of the Agulhas eddies that populate this region travel beyond the Walvis Ridge. Treguier et al. (2003) and Matano and Beier (2003) speculated that the sharp decay of eddy variability away from the Cape Basin is likely to be related to the dynamical structure of the rings and to their interaction with the bottom topography. These authors also noted that the main effect of the Agulhas eddies in the South Atlantic is indirect (except very close to their source). Eddies modify the time-mean currents, thereby affecting the transports of heat and freshwater by the mean flow, rather than generating eddy transports through turbulent fluxes of heat and salt. This makes the eddy effect more difficult to diagnose in models and questions the emphasis put on heat, salt and thickness fluxes in parameterizations theories. Because of their sheer size, the mass and energy input of the Agulhas eddies are likely to influence not only the SA variability but also its mean circulation. The foremost example for the possible influence of Agulhas eddies is Gordon's (1986) warm-path hypothesis. Although the simplicity of Gordon's hypothesis is appealing, there is no evidence to prove that the Agulhas eddies directly participate in the interbasin exchange between the South and the North Atlantic basins. In fact, according to the available observations, most eddies seem to travel to the west (not to the northwest) after leaving the Cape Basin, and usually disappear before reaching the western boundary (Byrne and Gordon, 1995). Even if an Agulhas eddy reached the coast of South America it would more likely be advected to the south by the poleward flow of the Brazil Current than to the north. Ray Peterson (personal communication) noted that according to the scant evidence available, it seems reasonable to suggest that the Agulhas eddies would not only contribute to a northward heat flux, as originally envisioned by Gordon, but also to *poleward* mass and heat flux. He hypothesized that the entrainment of an Agulhas eddy in the Brazil Current should lead to an increase of the variability in the BMC and therefore to a poleward heat flux. If that were to be the case, then it could be argued that the variabilities of the Brazil and the

Agulhas Currents would be (at least weakly) coupled. This seems to be an interesting possibility for the only subtropical basin that hosts two western boundary systems.

- **The bifurcation region.** An interesting feature of the South Atlantic's subtropical gyre is the recirculation cell observed south of the bifurcation of the South Equatorial Current (Siedler et al., 1996). After reaching the coast of South America, the South Equatorial Current splits into a northward branch that carries intermediate waters to the tropical latitudes, and a southward branch that feeds the Brazil Current. Boebel et al. (1999) noted that the southerly branch has an unexpectedly higher transport than the northerly branch. Schmid (1998) estimated that, at its bifurcation, the South Equatorical Current diverts approximately 9 Sv to the south and only 3 SV to the north. The recirculation created by the South Equatorial Current cell is important because it can influence both the amount of upper water that is diverted to the north, and which component of these waters (i.e., AAIW or South Indian) can effectively flow out of the basin. The driving force that creates this re-circulation cell is not known. From a dynamical point of view, the two most likely candidates are the wind stress (external forcing) and the eddy fluxes (internal forcing). Simple considerations of the wind curl magnitude over this region indicate that although regional winds can contribute to the maintenance of the recirculation cell, they are unlikely to be the only source of energy. The second potential mechanism for driving the recirculation cell in a western boundary region is the divergence of the eddy potential vorticity (PV) fluxes. Spall (1996) showed that eddy fluxes of PV anomalies resulting from unstable western boundary currents can create plateaus of homogenized PV upon which strong inertial recirculation gyres can develop. Keffer (1985) presented evidence that such regions exist in the SA. Although eddy fluxes have been considered the cause of the observed recirculation cells in the North Atlantic and North Pacific, the SA differs in that these eddy fluxes may arise not only from instabilities of the Brazil Current, but also from the propagation of Agulhas eddies into this region. In fact, since Agulhas eddies are substantially larger than the eddies generated in the upstream portion of the Brazil Current, they may be the main driving mechanism for the PV homogenization of the western SA, and an important source of energy for the recirculation cell.

5.6.4 Summary

Since Gordon's (1986) influential article on the workings of the global thermohaline circulation, numerical and observational studies have attempted to estimate the magnitude of the heat and salt fluxes in the South Atlantic. Most of these studies have not considered explicitly the role of mesoscale processes in the determination of the pathways and variability of the global thermohaline cell. Neglect of mesoscale process has no scientific justification. Rather it has resulted from the lack of both data and the computing power required to resolve the short period, mesoscale processes responsible for the upper portion of the global thermohaline circulation, and the long period, large-scale processes responsible for the deeper branches. Modern simulations however, indicate that the most important water mass conversions occur in regions of intense mesoscale variability such as the BMC and the CB regions. The relative contribution of different dynamical processes to these water mass conversions need to be better understood through the development of new programs focused in the acquisition of new observations and the improvement of existing models. Herein, we argue that in order to understand the South Atlantic contribution to the global thermohaline circulation it is also necessary to establish the linkages between the large-scale circulation and the mesoscale variability in the southwestern Atlantic, the CB, and the region where the South Equatorial Current bifurcates into the Brazil and North Brazil Current. The rationale being that it is not sufficient to establish the magnitude of the inflows south of Cape Horn and the Cape of Good Hope to determine the South Atlantic buoyancy's fluxes to the North Atlantic because the characteristics of these depend on time and spatial scales set by the South Atlantic circulation.

5.6.5 References

Agra, C., and D. Nof, 1993: Collision and separation of boundary currents. *Deep-Sea Research,* 40, 2259-2282.

Boebel, O., J. Lutjeharms, C. Schmid, W. Zenk, T. Rossby, and C. Barron, 2003: The Cape Cauldron: a regime of turbulent iner-ocean exchange. *Deep-Sea Research,* II, 50, 57-86.

Boebel, O., R. E. Davis, M. Ollitraut, R. G. Peterson, P. L. Richardson, C. Schmid, and W. Zenk, 1999: The intermediate depth circulation of the western South Atlantic. *Geophysical Research Letters.* 26, 3,329-3,332.

Byrne, D. A., A. L. Gordon, and W. F.Haxby, 1995: Agulhas eddies. A synoptic view using Geosat ERM data. *Journal of Physical Oceanography.* 25, 902-917.

Dewar, W. K., 1998: Topography and barotropic transport control by bottom friction. *Journal of Marine Research.* 56, 295-328.

Fu, L. L., B. Cheng, and B. Qiu, 2001: 25-day period large-scale oscillations in the Argentine basin revealed by the TOPEX/POSEIDON altimeter. *Journal of Physical Oceanography*. 31, 506-517.

Gan, J., L. Mysak, and D. Straub, 1998: Simulation of the South Atlantic circulation and its seasonal variability. *Journal of Geophysical Research.* 103, 10,241-10,251.

Gordon, A. L., 1986: Interocean exchange of thermocline water. *Journal of Geophysical Research.* 91, 5,037-5,046.

Keffer, T., 1985: The ventilation of the world's ocean: maps of the potential vorticity field. *J. Phys. Oceanogr.,* 15**,** 509-523.

Matano, R. P., 1993: On the separation of the Brazil Current from the coast. *Journal of Physical Oceanography*. 23, 79-90.

Matano, R. P., M. G. Schlax, and D. B. Chelton, 1993: Seasonal variability in the southwestern Atlantic. *Journal of Geophysical Research.* 98, 18,027-18,035.

Matano, R. P. and E. J. Beier, 2003: A kinemati analysis of the Indian/Atlantic interocean exchange. *Deep-Sea Research*. 50, 229-249.

Miranda, A., B. Barnier, and W. K. Dewar, 1999: On the dynamics of the Zapiola Anticyclone. *Journal of Geophysical Research.* 57, 213-244.

Schmid, C., 1998: *Zirkulation des Antarktischen* Zwischenwassers *im Südatlantik*. Ph.D. thesis. University of Kiel, Germany.

Spall, M. A., 1996: Dynamics of the Gulf Stream deep western boundary current crossover. 1. Entrainment and recirculation. *Journal of Physical Oceanography.* 26, 2,152-2,168.

Sloyan, B. M., and S. R. Rintoul, 2001: The Southern Ocean limb of the global deep overturning circulation. *Journal of Physical Oceanography.* 31, 143-173.

Smith, L. T., E. P. Chassignet, and D. B. Olson, 1994: Wind forced variations in the Brazil/Malvinas confluence region as simulated in a coarse resolution numerical model of the South Atlantic. *Journal of Geophysical Research.* 99, 5,095-5,117.

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

Treguier, A. M., O. Boebel, B. Barnier, and G. Madec, 2003: Agulhas eddy fluxes in a 1/6˚ Atlantic model. *Deep-Sea Research*. Part II, 50, 251-280.

Vivier, F., and C. Provost, 1999a: Direct velocity measurements in the Malvinas Current. *Journal of Geophysical Research,* 104, 12,083-12,096.

Vivier, F., and C. Provost, 1999b: Volume transport of the Malvinas Current: Can the flow be monitored by TOPEX/POSEIDON? *Journal of Geophysical Research.* 104, 21,105-21,122.

Wainer, I., P. Gent, and G. Goñi, 2000: Annual cycle of the Brazil-Malvinas confluence region in the NCAR Climate System Model. *Journal of Geophysical Research.* 105, 26,167-26,177.
Weatherly, G. L., 1993: On deep current and hydrographic observations from a mudwave region and elsewhere in the Argentine basin. *Deep-Sea Research,* 40, 851-858.

5.7 The Role of the South Atlantic in the Variability of the ITCZ

Y. Kushnir[1], M. Barreiro[2] , P. Chang[3] , J. Chiang[4], A. Lazar[5] , and P. Malanotte-Rizzoli[6]

[1] *Lamont-Doherty Earth Observatory of Columbia University, New York, USA*
[2] *Princeton University, Princeton, New Jersey, USA*
[3] *Texas A&M University, Texas, USA*
[4] *University of California, Berkeley, California, USA*
[5] *LODYC, Université Paris, France*
[6] Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

In the tropical Atlantic region, the ITCZ and its associated atmosphere and ocean elements are the most outstanding climatic feature. The ITCZ controls rainfall and other climatic impacts (e.g., storms and dust transport) in regions with high population density. Its annual migration north and south and the significant interannual variability thereof have direct impact on society. The ITCZ in the Atlantic is extremely sensitive to small changes in regional surface temperature gradients and external atmospheric influences. Much smaller SST anomalies than those associated with ENSO have significant impact on rainfall in NE Brazil and West Africa. There is modeling evidence of strong coupling between SST and convection variability near the equator that allows for external influences to create significant impacts. This setting implies that anomalies in the South Atlantic atmosphere and ocean can set off an interaction that is as effective in modulating ITCZ variability as the well documented effects of ENSO and the North Atlantic Oscillation. This paper reviews the pattern and impact of ITCZ variability in the tropical Atlantic region to set the stage for understanding how the South Atlantic can impact this sensitive system. Evidence from recent research is presented that the South Atlantic does indeed play a role in ITCZ variability and issues for future research are discussed.

5.7.1. Introduction

The climate, mean and variability, of the South Atlantic (hereafter SA) and of other parts of the vastly water covered Southern Hemisphere, are less well undestood than their Northern Hemisphere counterparts. This is primarily because of the paucity of in-situ data, which have been collected mainly along narrow ship tracks (see *Figure 1*). Moreover, even along the relatively better sampled ship tracks there is a lack of important information such as rainfall and upper-air data. This situation has been somewhat alleviated by the introduction of data from remote sensing satellite instruments since the early 1980s (although such data need to be continually calibrated against in-situ observations to allow the removal of instrumental drifts and biases) and by the ongoing global dissemination of ARGO profiling floats that provide in-situ hydrographic data. Any attempt to better understand the global climate system and its response to natural and anthropogenic forcing should recognize as a goal the improvement of our understanding of the Southern Ocean Basins.

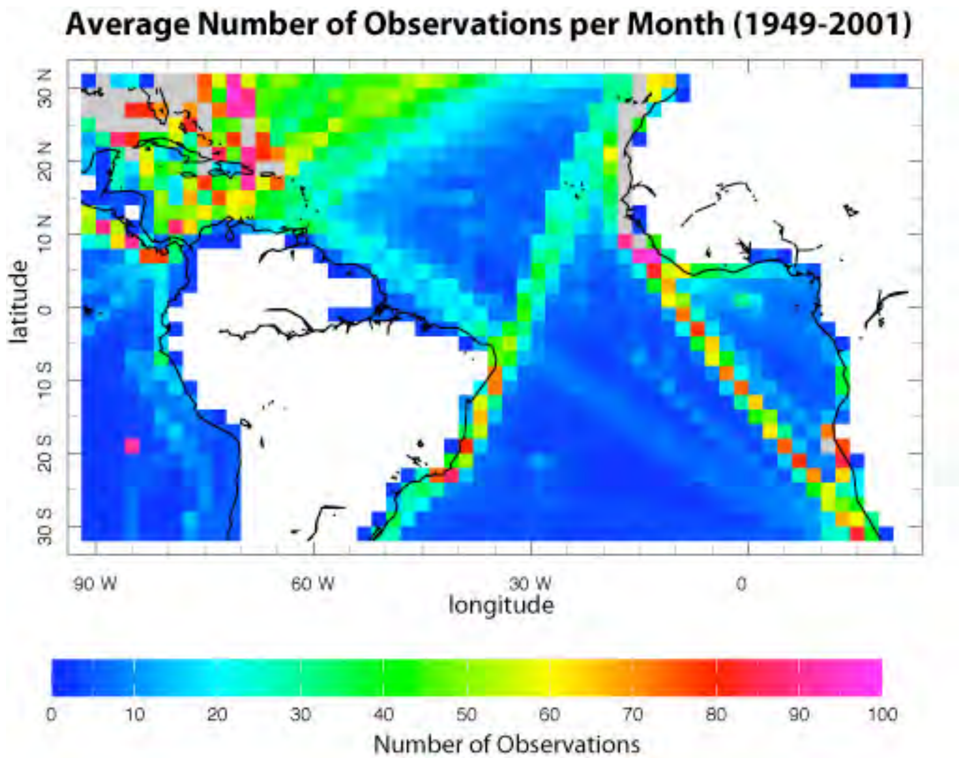


Figure 1: The year-round average number of ship meteorological observations per months (COADS data) for the years 1949-2001. The regions of relatively large numbers of observations denote the ship tracks.

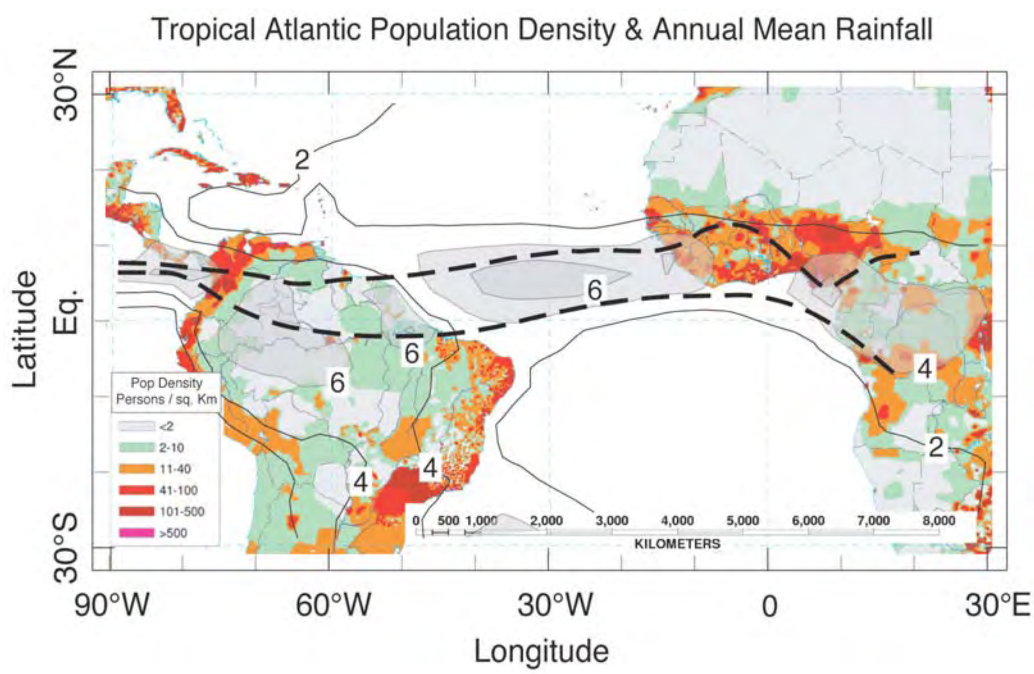


Figure 2: A map of population density in persons/km^2 (colors, see inserted legend), overlaid by contours of annual mean rainfall (in mm/day) with values > 4 mm/day (~150 cm/yr) shaded in transparent gray to indicate the mean position of the ITCZ. The north (July-August) and south (March-April) limits of the ITCZ climatological annual migration are indicated by thick dashed lines. Population density data for 1994 are from Tobler et al., 1995 also available at: http://www.nrcs.usda.gov/technical/worldsoils/mapindx/popden.html. Precipitation data are from NASA/GPCP (Huffman et al., 1997) available from: http://precip.gsfc.nasa.gov/index.html.

In the Atlantic, the climatic variability of the marine ITCZ and the tropical ocean-atmosphere system associated with it is of major consequence to society (Hastenrath and Heller, 1977). The annual migration of the ITCZ related rainfall and its interannual variability have direct impact on the health and livelihood of millions of people living in equatorial West Africa and northeastern South America (see *Figure 2*). Within this domain, the semi-arid region of Northeast Brazil and sub-Saharan Africa are particularly sensitive to interannual fluctuations in the intensity and position of the ITCZ (*Figure 3*), as it is only during the part of the year that it extends far enough from its annual mean position that these regions receive their rain (*Figures 2, 3* and *4*).

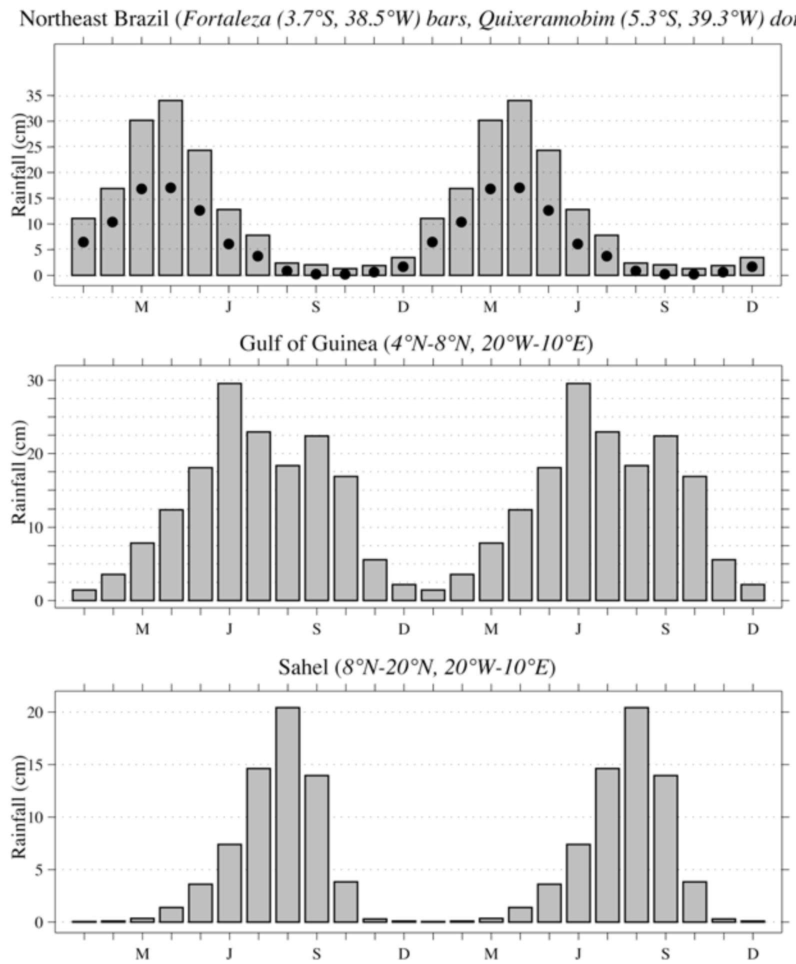


Figure 3: The annual cycle of precipitation in regions affected by the interannual variability in Atlantic ITCZ position and intensity. Adopted from JISAO website graphics calculated and plotted by T. P. Mitchell (http://tao.atmos.washington.edu/data_sets/).

The topic of SA and tropical Atlantic (hereafter TA) inter-relationship has been the subject of a handful of studies in the recent few decades. These studies include data and modeling investigations to look at atmosphere-ocean patterns and mechanisms in a domain including the tropics and the extratropical Southern Hemisphere, as well as the entire Atlantic Ocean. Of related importance are studies that investigated the effect of ENSO on both TA and SA regions. The purpose of this white paper is to review the available information on this topic, assess the degree of influence exerted by the SA on the TA, evaluate the importance of this influence to the state of the Atlantic ITCZ, and point at outstanding issues or questions regarding this relationship.

The paper is organized as follows: Section 2 reviews our current understanding of mechanisms of interannual ITCZ variability. It compares the role of various interactions internal to the Atlantic (in contrast to ENSO influences) and points at the ways SA influences can be communicated to the TA region. Section 3 examines the known patterns of atmosphere-ocean variability in the SA regions and our current understanding regarding their dynamics, in order to evaluate their effect on the TA. Section 3 also discusses the role of ocean dynamics in the SA that can affect TA SST variability and by inference the ITCZ. Section 4 offers in conclusion an evaluation of outstanding issues and problems related to the SA effect on the TA region and the ITCZ.

5.7.2. Tropical Atlantic ITCZ variability

Annual cycle

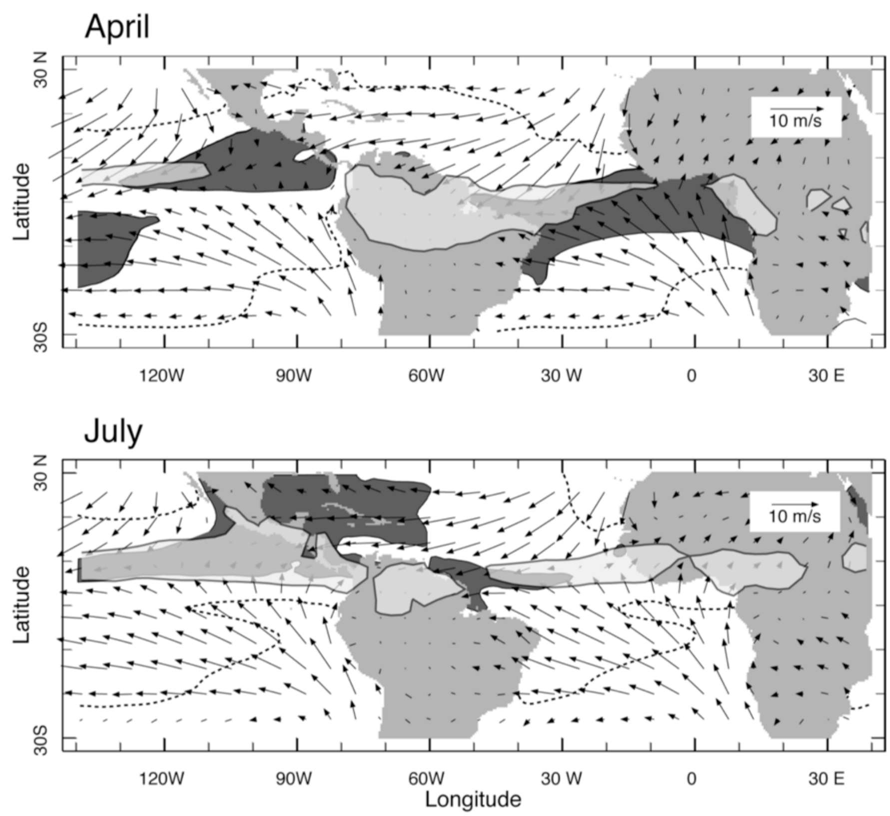


Figure 4: April and July climatologies of the tropical Atlantic and eastern Pacific. Dark shaded areas are regions with SST ≥28°C. Light, semi-transparent areas are regions with rainfall ≥6 mm/day (the ITCZ). The arrows depict the surface (10 m) wind vectors with scale indicated in the figure. The dotted contour is the 24°C isotherm demarcating the regions of relatively cold water and the eastern ocean cold tongues. SST and wind data are from NCEP/NCAR CDAS-1 (Reanalysis) and rainfall from GPCP.

In a narrow sense, the Atlantic marine ITCZ (AMI) is the region within the TA Ocean Basin, close to the equator, where the mean rainfall associated with average effect of transient convective systems reaches a maximum. In a broader context the ITCZ represents a complex of phenomena, which include the equatorial low-pressure trough, the trade wind convergence zone, and the regional maximum in SST values. The AMI complex stretches across the TA basin in a nearly perfect, east-west orientation (*Figures 2 and 4*) and migrates north and south with the season, reaching furthest south in the boreal spring (March-April) and furthest north in the boreal summer (July-August) as illustrated in *Figures 1 and 4* (see also Mitchell and Wallace, 1992).

Patterns of interannual variability

Interannual variability of AMI location and intensity is closely linked with interannual SST variability within the broader TA region (Moura and Shukla, 1981; Hastenrath and Greischar, 1993; Nobre and Shukla, 1996; Fontaine and Janicot, 1996; Servain et al., 1999; Chiang et al., 2002). Thus most studies of the AMI variability focused on identifying and studying the patterns anomalies in SST, surface winds, and convection/rainfall and their inter-relationships.

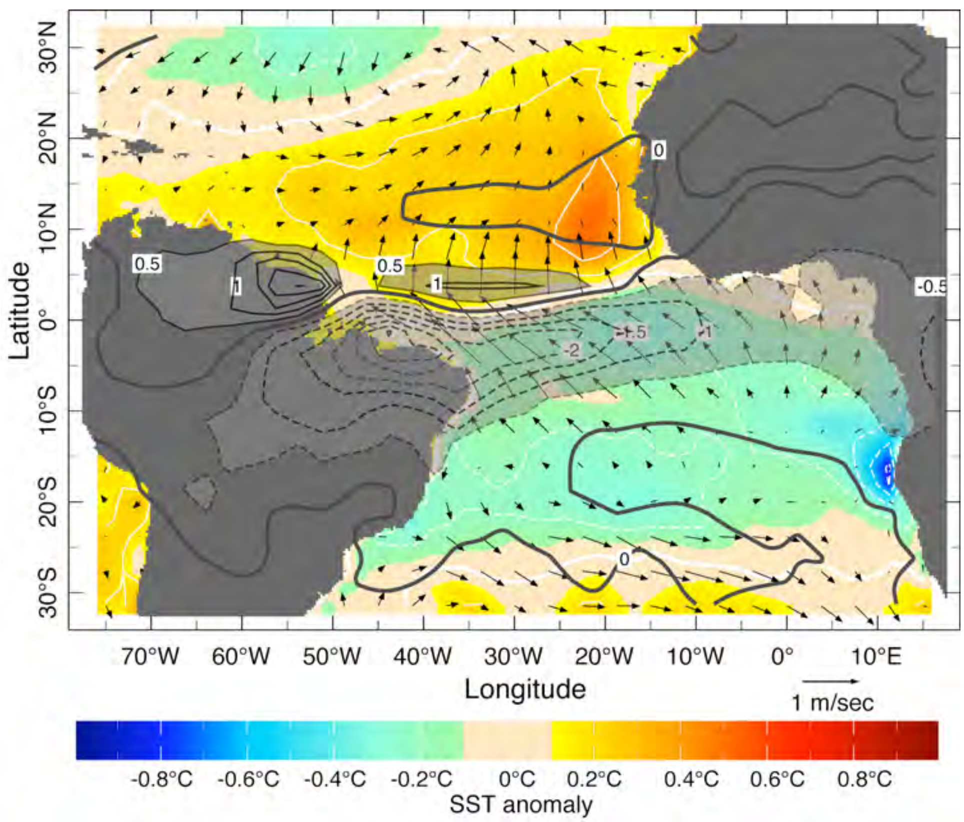


Figure 5: The dominant pattern of surface ocean-atmosphere variability in the tropical Atlantic region during boreal spring. The black contours depict the first EOF of the regional March-April rainfall anomaly (from GPCP data, 1979-2001) in units of mm/day. This EOF explains 33% of the seasonal variance. The colored field is the March-April SST anomaly regressed on the principal component time series of the rainfall EOF (units are °C, see scale below; white contours every 0.2° are added for further clarity). Arrows depict the seasonal surface wind vector anomaly in m/sec, regressed on the same time series (see arrow scale below frame).

The association between ocean and atmosphere variability depends on the season. During its furthest excursion southward, in the boreal spring, the AMI is diverted from its climatological position towards the anomalously warmer hemisphere. This is manifested in a well-documented pattern (e.g., Nobre and Shukla, 1996; Ruiz-Barradas et al., 1999, Dommenget and Latif, 2000). Here the pattern is derived from a principal component analysis of the March-April averaged rainfall anomaly in the TA Basin (*Figure 5*). The pattern depicts an anomalous (stronger than normal) northward SST gradient in the TA region, i.e., warmer than normal SST in the north TA (NTA) and somewhat colder than normal SST in the south TA (STA). This SST anomaly pattern is associated with a northward cross equatorial surface wind anomaly, with weaker than normal trades in the NTA and stronger than normal trades in the STA. In rainfall this SST-wind pattern is associated with weaker than normal rainfall over the southern flank of the climatological ITCZ position (compare *Figures 5* and *4* during April) and somewhat stronger than normal rainfall to the north. This implies a weakening in the ITCZ strength together with a northward shift in its position towards the warmer hemisphere (see also Chiang et al., 2002). Because the SST variability in this pattern exhibits a north-south contrast, it is often dubbed as the TA "meridional mode" of variability (Servain et al., 1999).

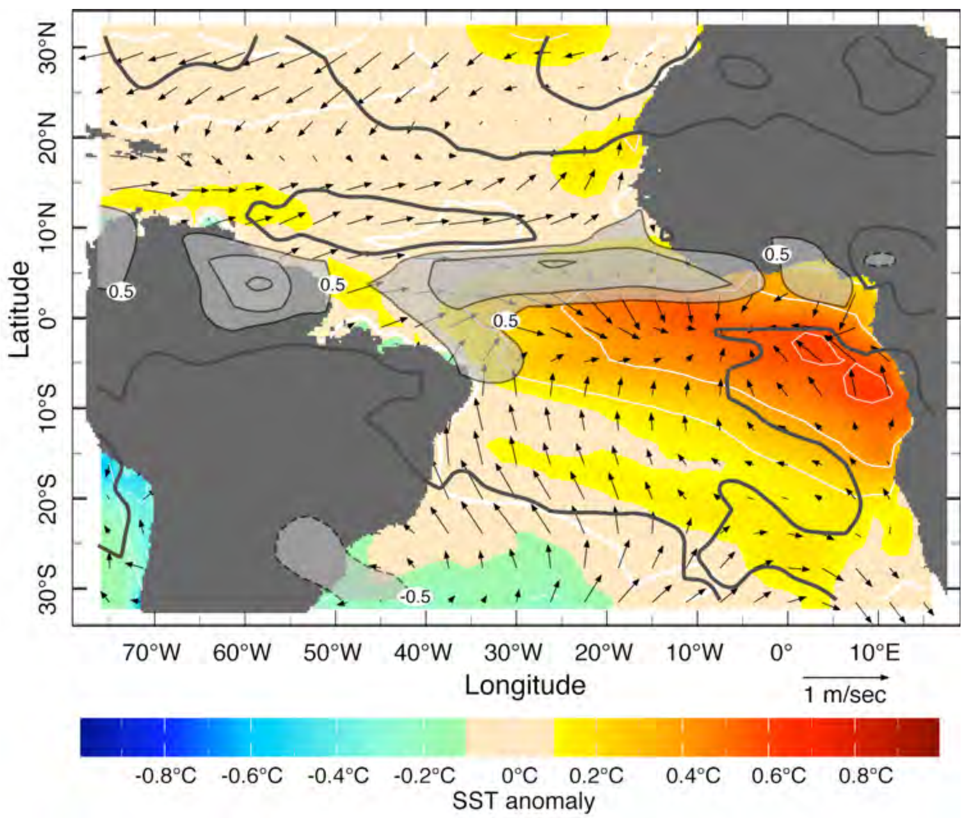


Figure 6: As in Figure 5 but for the boreal summer season (June-August). The rainfall EOF of this season explains 23% of the variance.

In the boreal summer season, when the ITCZ moves to its furthest position in the NTA, SST variability peaks just north of the so-called Atlantic cold tongue region, in the equatorial east Atlantic. This is the time when SST reaches its coldest annual state there (see Mitchell and Wallace, 1992) but also the time when it is most prone to the appearance of warm anomalies thought to be similar to El Niño (see Zebiak, 1993 and Carton and Huang, 1994). Unlike their equatorial Pacific counterpart, the warm events in the Atlantic cold tongue persist no longer than a season or two (Carton and Huang, 1994). The pattern in Figure 6 is derived from a principal component analysis of TA rainfall during the summer (June-August, GPCP data1979-2001 is used) and is not entirely identical to an analysis based on the TA cold tongue index (e.g., as in Zebiak, 1993). However, it depicts the phenomenon in a consistent manner: an appearance of a warm anomaly along the equator, on the eastern side of the basin and a convergence of the surface winds towards the warmest region (*Figure 6*, see also Zebiak, 1993). The effect on the ITCZ entails a southward shift and intensification in convection and rainfall (*Figure 6*, see also Carton and Huang, 1994). The associated pattern of SST (and subsurface ocean) variability is also referred to as the TA "zonal mode" of variability (Servain et al., 1999).

Mechanisms

The close diagnostic link between SST in the ITCZ location and intensity does not, of course, reveal the cause and effect or the dynamical processes that are at work. In fact, there are serious gaps in our understanding of processes in the TA region. Yet recent diagnostic and modeling studies reveal that there are several key climatic processes that lead to the formation of the variability.

As indicated above, there is some evidence from observations and models that the *boreal summer*, eastern equatorial Atlantic variability involves a Bjerknes mechanism akin to that acting in ENSO; that is, a coupled interaction between the strength in equatorial upwelling and related SST values on one hand, and the atmospheric circulation, most prominently overlying surface winds stress anomalies on the other hand (Houghton, 1991; Zebiak, 1993; Carton and Huang, 1994; Sutton et al., 2000; Chang et al., 2000). There are questions regarding the degree of the subsurface ocean involvement in this variability, particularly the response of the thermocline to the wind forcing. What also seems to be in question is the ability of such variability to self-generate and self-sustaine as ENSO. Influences from the Pacific ENSO (see more below) and the boreal spring mode of TA variability have been implicated in its forcing (Zebiak, 1993; Servain et al., 1999; Murtugudde et al., 2001). As far as the ITCZ is concerned, there are gaps in our understanding of the relationship between this 'zonal mode' and the meridional propagation of the ITCZ and its intensity.

The *boreal spring* variability associated with the meridional SST contrast has received considerable attention since it was first clearly identified (Hastenrath, 1978; 1984; Servain, 1991). While it has become relatively well established that the meridional ITCZ displacement involves a strong mutual interaction between convection, cross-equatorial surface winds, and the meridional SST gradient across the mean latitude of the ITCZ (Hastenrath and Greischar, 1993; Chang et al., 2000, Chiang et al., 2002), how the gradient is initially formed and maintained is still not fully understood. Early investigations suggested that it is associated with heat flux exchange between ocean and atmosphere (Curtis and Hastenrath, 1995; Carton et al., 1996); that is, the SST anomaly centers in the subtropics, particularly in the NTA (*Figure 5*), is generated primarily by surface heat flux forcing due to changes in windspeed (see also Seager et al., 2000; Seager et al., 2001; Kushnir et al., 2002). Such interaction however, can be due entirely to external forcing such as that resulting from ENSO or the North Atlantic oscillation (NAO) as has been indeed suggested based on compelling observational and modeling evidence (e.g., Enfield and Mayer, 1997; Hastenrath et al., 1987; Dommenget and Latif, 2000; Saravanan and Chang, 2000; Chiang et al., 2002; Sutton et al., 2000; Czaja et al., 2002). This is because both these phenomena affect trade wind intensity and hence ocean-atmosphere heat exchange in the NTA.

Evidence that “coupled” air-sea interaction within the near-equatorial region, affects the temporal characteristics of the ‘meridional mode’ of TA variability is increasing (Chang et al., 1997; Chang et al., 2000; Chang et al., 2001; Chiang et al., 2002; Kushnir et al., 2002; Tanimoto and Xie, 2002). This atmosphere-ocean coupling mechanism relies on the effect that a change in the inter-hemispheric, meridional SST gradient during boreal spring has on the position of the ITCZ (convection and surface wind pattern included). In that season, the climatological SST gradient is at its weakest state (Chiang et al., 2002) and the trade wind system is almost symmetric around the equator. In such state, even small SST anomalies north or south of the equator can tilt the slope of the large-scale inter-hemispheric pressure gradient and affect the ITCZ such that it is displaced towards the anomalously warmer hemisphere (see Hastenrath and Greischar, 1993; Hastenrath, 2000a; Chiang et al., 2002). This, in turn, reinforces the strength of the trades, weakening them further in the anomalously warm hemisphere and strengthening them in the cold one. This effect enhances the heat flux anomaly that lead to the SST formation, particularly in the near-equatorial region, yielding a positive wind-SST-evaporation (WES) feedback (Xie, 1999, see also *Figure 5*). The debate is still on however, whether or not such mechanism can give rise to self-sustained, long-term variability (Xie, 1999; Chang et al., 2000; Kushnir et al., 2002; Okajima et al., 2003).

The role of external influences in TA climate variability, including the effect on the AMI, cannot be overstated. Czaja et al. (2002) ascribe the majority of the strong NTA SST anomalies in the recent half-century to the forcing from ENSO and the NAO. The discussion of the mechanisms associated with the two patterns of variability introduced much of this issue, particularly its role in the meridional mode of the variability due to the effects of ENSO and the NAO on the TA SST. The impact of ENSO in particular is pervasive and thought to come through several “atmospheric bridge” pathways. The impact on the NTA is thought to come through the ENSO impact on the Pacific-North American Pattern (Horel and Wallace, 1981; Hastenrath, 2000b). The ENSO impact on the South Tropical Atlantic is less well established. Mo and Hakinen (2001) have argued for a teleconnection through the Pacific-South American pattern, but acting only the quasi-biennial component of ENSO. A recent coupled model study of the 97-98 ENSO event, also identifies an ENSO impact on south tropical Atlantic SST (Elliott et al., 2001)

ENSO also has a direct effect on the AMI through its influence on the circulation and vertical stability of the tropical atmosphere. It causes a shift in the Walker circulation (and thus enhanced subsidence over the TA) and a warming (and stabilization) of the entire tropical atmosphere surrounding the equatorial Pacific region. These two effects lead to a marked suppression of AMI intensity during the entire ENSO cycle, but particularly during the boreal winter and spring (Hastenrath et al., 1987; Chiang et al., 2002; Chiang and Sobel, 2002). Recently, Giannini et al. (2003) found that for rainfall anomalies in NE Brazil (and the ITCZ location) during boreal spring, the interplay between ENSO influence and the underlying state of the Atlantic interhemispheric SST gradient present at the time of ENSO influence is important. When the gradient is “pre-conditioned” such that the NTA region is warmer than normal before the teleconnection from the equatorial Pacific affect the region, the impact of ENSO is stronger than normal and *vice versa*. The importance of the overall sensitivity of TA climate variability is that it opens the door for influences from the South Atlantic region as well. This topic is discussed in the following section.

5.7.3. Role of the south Atlantic

From the nature of TA variability discussed above it is plausible that remote effects from the SA invoke interannual variations in AMI. It is noteworthy however, that most of the research on TA climate variability has focused on the interactions along the equator and to the north and work on the role of the SA is just beginning. One obvious way for the SA to affect the TA region and the ITCZ is through changes in the SA trade wind intensity, and through that SST in the STA region that influences the ITCZ (see section 2 above). This is then a similar mechanism to that acting in the northern trades, which are affected by such Northern Hemisphere phenomena as the NAO. Other ways by which the SA can be important is through a more active ocean role such as related to changes in the ocean transport of heat, whether at the surface or in the thermocline level. The goal of this section is to examine the processes by which the SA Ocean can affect the TA and the ITCZ. We do not discuss here the general issue of SA ocean-atmosphere variability, a subject deserving separate attention.

The influence of the SA atmosphere on the TA

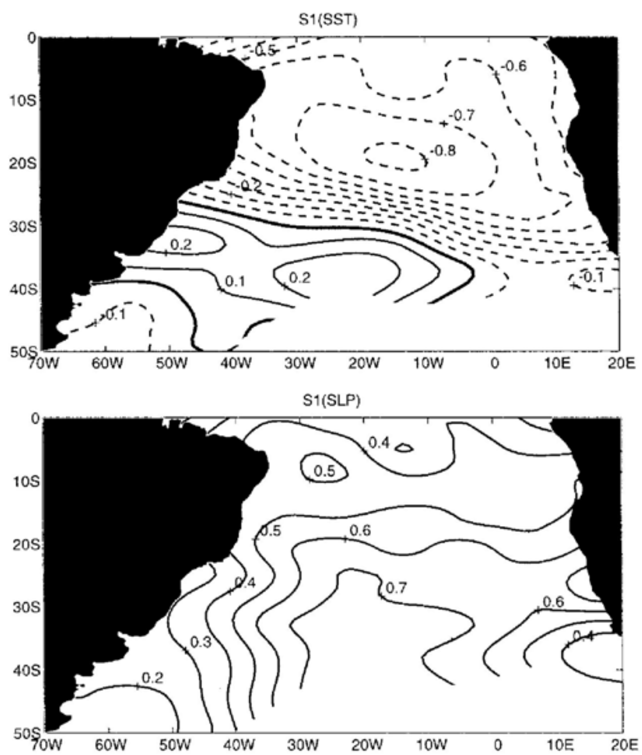


Figure 7: The first joint mode of sea level pressure and SST in the South Atlantic from Venegas et al. (1997) based on monthly anomalies from spatially interpolated COADS data, 1953-1992, that were processes with an SVD analysis.

A detailed analysis of the patterns of ocean-atmosphere variability in the SA was offered by Venegas and collaborators in a few consecutive studies (Venegas et al., 1996; 1997; 1998).

Their work is based on analyses of in-situ data (COADS observations), which are prone to sampling errors (see Introduction and *Figure 1*). However, the analysis results, particularly in term of the leading pattern of joint sea level pressure (SLP) and SST variability is consistent with more recent analyses based on the NCAR/NCEP Reanalysis (e.g., Sterl and Hazeleger, 2002; Barreiro et al., in preparation, see below).

The leading SA pattern (*Figure 7*) depicts an association between the strengthening of the SA subtropical high (see Venegas et al., 1997 for a figure of the climatological mean state) and a trade wind region SST anomaly north of 30°S. According to Sterl and Hazeleger this pattern explains almost 40% of the combined SST and SLP variance. The relationship between the centers of action in the SLP and SST fields and a lag correlation analysis of the SST and SLP associated time series, where SLP is leading SST by 1-2 months, indicate that fluctuations in the surface atmospheric circulation force the SST variability. This is confirmed by diagnosing the terms in the SST tendency equation in the Sterl and Hazeleger study.

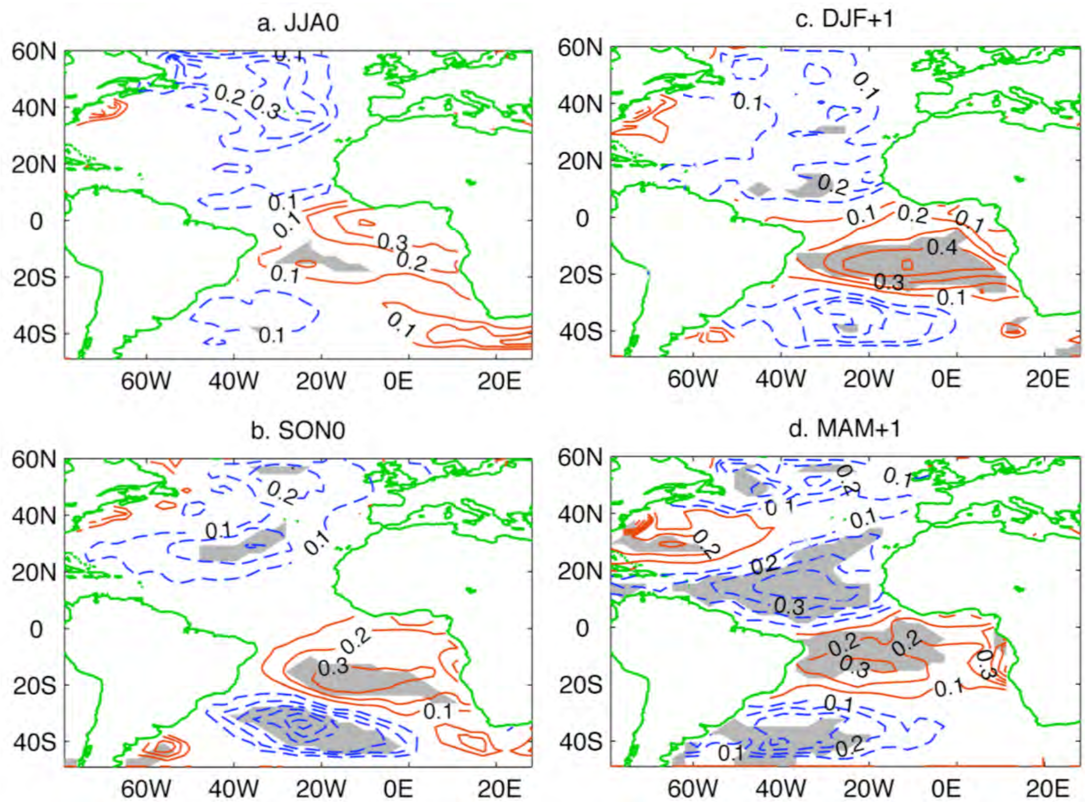


Figure 8: Composite of observed SST constructed as the difference between negative and positive years of the boreal spring, tropical Atlantic cross-equatorial SST gradient for (top to bottom): the states in the preceding summer, preceding fall, preceding winter, and the concomitant spring. Contour interval is 0.1°C with zero contour omitted and negative (positive) contours in blue (red). Shading denotes statistical significance at the 95% confidence level. From Barreiro et al. (in preparation).

Barreiro et al. (in preparation) examine the evolution of SA SST and atmospheric circulation associated with the formation of an inter-hemispheric SST gradient during the boreal spring. They begin with selecting all the years in the Reanalysis period where a strong gradient was observed in the absence of an El Niño. Using four years with a strong negative gradient (NTA colder than STA) and four with a strong positive gradient, they form a composite of their difference during boreal spring (March-May) in the entire Atlantic basin. They denote this state MAM+1. They then use the same years to create the composite SST pattern form the previous winter (December of the previous year to January of the same year), previous fall (September-November of the previous year), and previous summer (June-August of the previous year), denoting them DJF+1, SON0, and JJA0, respectively.

The results, shown in *Figure 8*, exhibit an evolution from a weak austral winter (JJA0) SST dipole in the SA, to a strong SST dipole flanking the equator in the following boreal spring. An analysis of the SLP field (not shown) indicates that the process begins by the presence of a strong SH SLP dipole akin to the one discerned by Venegas et al. (1997), forcing the ocean during the austral winter. The SA SST dipole development lags that of the SLP, reaching maximum in the Austral spring (SON0). The southern pole of the SA dipole disappears in the boreal winter. However, the northern pole of this pattern persists and in the boreal spring an SST anomaly of the opposite sign appears in the NTA. Barreiro et al. demonstrate the robustness of this evolution using a large ensemble of coupled GCM integrations (*Figure 9*) where a slab ocean is freely interacting with the atmosphere over the entire global ocean accept the equatorial Pacific, where observed SST from 1950 to 1994 were prescribed. In this model the SA-TA interaction is a coherent "free-mode" of the coupled climate system in the Atlantic, that is, variability that is independent of ENSO. The GCM results (*Figure 9*) show that SA SST dipole forms in response to internal atmospheric variability exerting an anomalous surface heat exchange with the ocean (note that in the GCM composite, unlike the observed one, years with strong NAO anomalies were also excluded). The STA pole of the SA SST anomaly invokes a southward shift of the ITCZ and a surface wind response as early as the boreal winter (DJF+1), consistent with the mechanism explained in Section 2.2 (see also *Figure 5*). This wind response forces an equatorial SST dipole, which persists throughout the boreal spring (MAM+1). Thus there appears to be clear evidence that atmospheric variability in the SA is affects the TA and the ITCZ through the mediation of the more slowly evolving and more persisting upper ocean heat content anomaly.

Looking at the GCM ensemble, Barreiro et al also find that the SA-TA interaction does not influence the Northern Hemisphere beyond the NTA region and vice versa, variability in the Northern Hemisphere does not invoke variability in the SA. This is in contrast to previous studies that found that SST in the STA region is associated with or can invoke Northern Hemisphere variability in the form of the NAO (Rajagopalan et al., 1998; Xie and Tanimoto, 1998; Tanimoto and Xie, 1999; Robertson et al., 2000). The latter studies however, emphasized longer timescale phenomena while Berreiro et al. Focused on interannual variability. In addition the present analysis excluded an examination of the interhemispheric impacts by eliminating *a-priori* years with strong NAO variability.

Robertson and collaborators (Robertson et al., 2003) offer a somewhat different, albeit consistent, view on the influence of SA anomalies in the TA regions. They force an atmospheric GCM with SA SST anomaly patterns derived from observations and examined the response during the boreal winter and fall seasons (January through June). Of particular interest is their response to an SST pattern similar to that of Venegas et al. (1997), which displays an evolution from a lattitudinally broad pattern (similar to *Figure 7*) during January-March to a more equatorially confined pattern during May and June (as in *Figure 6*). The model TA atmosphere responds strongly to this SST pattern by creating an anomalous westerly low-level flow when the SSTs south of the equator are warmer than normal. The response is strongest in boreal spring with a strong enhancement of rainfall over the Atlantic cold tongue region and a southward shift of the ITCZ.

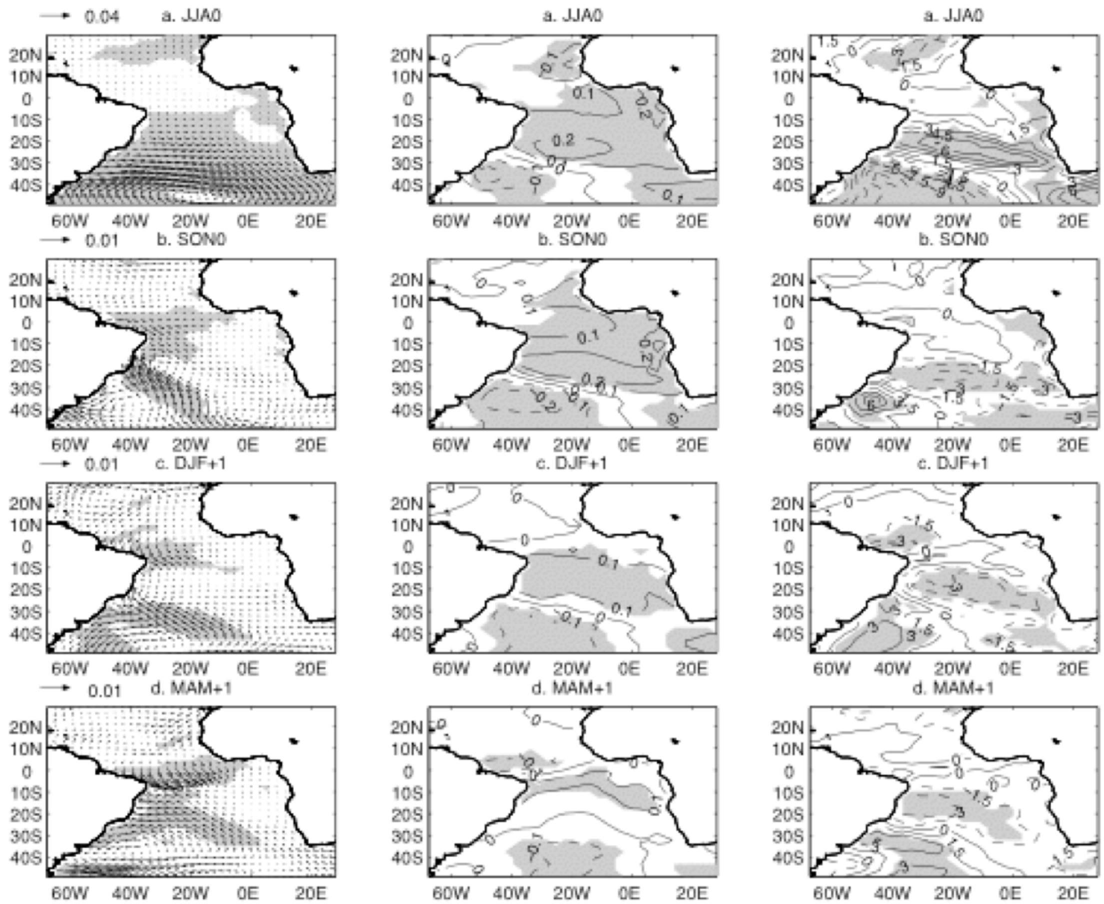


Figure 9: Composite evolution of wind stress (left panels, in Nm^{-2}), SST (middle panels, in °C) and net surface heat flux (right panels, in Wm^{-2}) anomalies constructed as the difference between positive and negative years of SA winters with large cyclonic anomaly at 50°S and 20°W in a large ensemble of a atmospheric GCM coupled to a slab ocean (see text above). ENSO years and years with strong NAO forcing were excluded from the analysis. Shading denotes statistically significant regions. From Barreiro et al. (in preparation).

Overall, as Sterl and Hazeleger (2002) find in a careful budget analysis of the SST tendency, SST anomalies in the SA are mainly generated through heat flux and momentum exchange between the ocean and atmosphere. The former creates thermal anomalies in the mixed layer while the latter creates vertical stirring and horizontal Ekman transport which act on the mean temperature gradient (vertical and horizontal). It is only along the Angolan coast and in the equatorial cold tongue region that they find evidence that ocean dynamics (i.e., transports by ocean geostrophic currents) are important. These ocean mechanisms are discussed in the next sub-section.

The influence of the SA Ocean

The ocean circulation can impact the climate by affecting SST through lateral advection or/and propagation of anomalies within the mixed layer or the thermocline. Formally there are at least three types of mechanisms through which this can be achieved:

- The transport of temperature or/and salinity (active tracers) anomalies by the mean circulation or a $\overline{V}$ T' mechanism (e.g.; Gu and Philander, 1997; Schneider et al., 1999).
- The transport of the mean temperature gradient by circulation anomalies or a **V**'$\overline{T}$ mechanism (e.g., Kleeman et al., 1999).
- The coupling of circulation and active tracer anomalies, or a **V**'T' mechanism, in particular, the propagations of subsurface wave signals (Rossby or Kelvin) within the interior ocean or along coastlines (e.g.; Liu, 1999; Huang and Pedlosky, 1999; Schneider, 2000; Lazar et al., 2001).

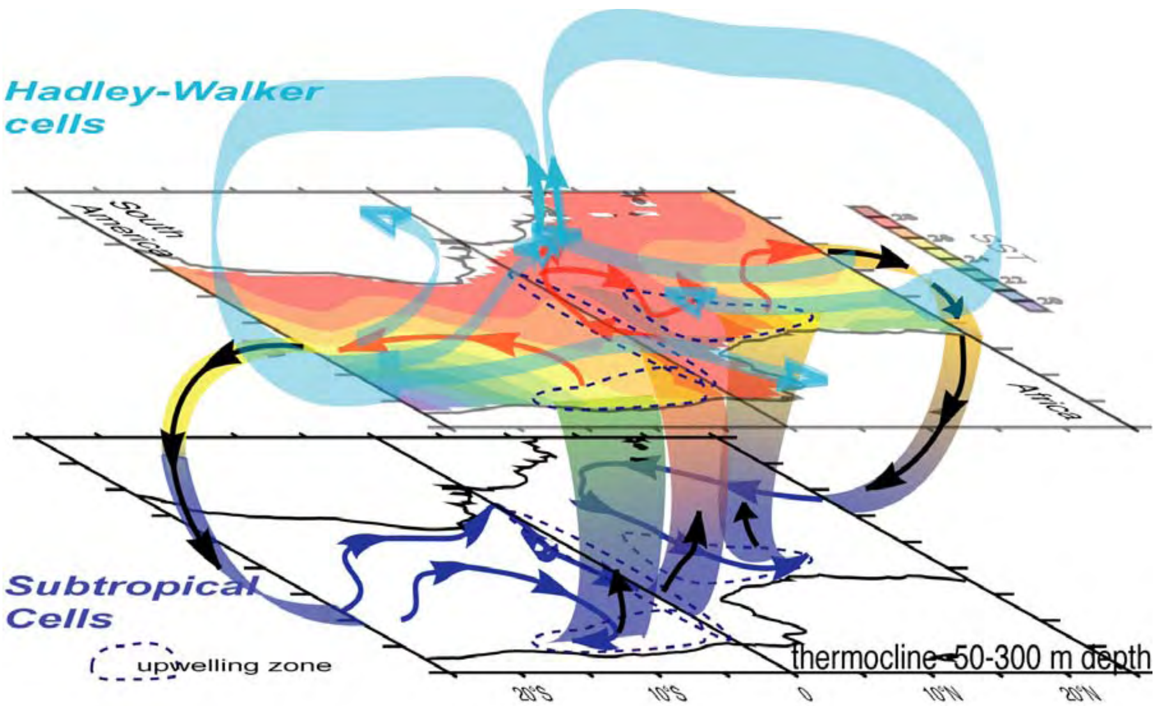


Figure 10: A schematic 3-dimenstional drawing of the Atlantic Subtropical Cells (STCs, in purple arrows) and the overlying atmospheric, large-scale circulation (in light blue arrows). The climatological SST field is shown in colors on the interfacing surface where the regions of upwelling are also demarcated by blue dashed lines.

Observations hint that such advective mechanisms are acting in the North and South Atlantic and are manifested in propagation of SST anomalies (Hansen and Bezdek, 1996; Sutton and Allen, 1997; Venegas et al., 1997; Mehta, 1998). Numerical modelling studies with forced ocean GCMs, show that in the trade wind regions, advection by ocean currents within the ocean mixed layer acts to damp thermal anomalies that are forced by surface fluxes (Seager et al., 2001).

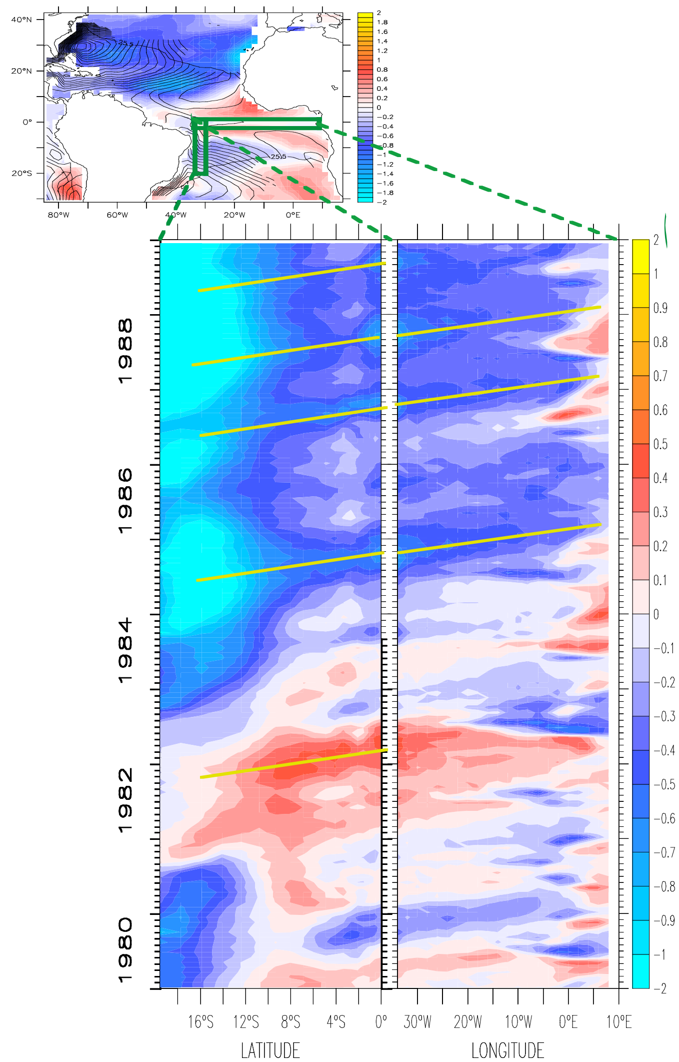


Figure 11: Propagation of salinity compensated temperature anomalies on isopycnal 25.5, within the thermocline along the Brazilian coast and then within the equatorial undercurrent (EUC) as seen in an ocean GCM forced at the surface by NCEP-NCAR Reanalysis data (see Lazar et al., 2001).

In the SA however, there is evidence that the geostrophic, wind driven circulation is important in generating the SST anomalies (Hakkinen and Mo, 2002). Other numerical modelling studies suggest that the Atlantic thermocline could be influenced by horizontal advection mechanisms (Huang and Pedlosky, 1999). Less attention has been given to the vertical and turbulent aspect of the problem, that is, how anomalous signals of mass flow or active tracer are passed into or out of the mixed layer with the exception of the present diagnostic study of Sterl and Hazeleger (2002). This aspect is strongly dominated by upwelling and diapycnal turbulent mixing.

The upwelling region along the equator, acts as the main termination area for the subsurface limb of the southern (and northern) Subtropical Cells (STCs, sometimes referred to as the Shallow Subtropical/Tropical Cells, see *Figure 10*) and therefore is the first area where anomalous subsurface signals coming from the SA have the potential to reach the surface and affect the local ocean-atmosphere interaction. It is here where the slow ocean dynamics have the potential to affect the atmosphere by creating surface signals that the ITCZ is sensitive to. Furthermore, due to the role of atmospheric heating and convection in the ITCZ in creating global teleconnections, this part of the atmosphere may be able to transmit anomalous oceanic signals to other regions of the globe (e.g., Xie and Tanimoto, 1998; Robertson et al., 2000).

Several recent model studies looking at particle trajectories or the role of the MOC in the tropical Atlantic through a $\mathbf{V}'\bar{T}$ mechanism (Blanke et al., 1999; Fratantoni et al., 2000; Malanotte-Rizzoli et al., 2000, Inui et al., 2002) underscored that in agreement with estimates from observations (Stramma and Schott, 1999) the Southern Atlantic is the main source of water for the equatorial thermocline and the surface. Within the Pacific, MacPhaden and Zhang (2002) identified a clear control of the equatorial upwelling rate by the tropical and subtropical winds through the STC overturning. A similar and perhaps even stronger role can be played by South Atlantic winds, but attempts to detect that effect have been unsuccessful (McPhaden, personal communication) maybe due to the extreme paucity of data in the region. In addition to these mass sources and their variations, an Atlantic ocean GCM forced with NCEP-NCAR Reanalysis data indicates that there exists a subsurface advective bridge of heat or salt anomalies from the southern subtropics to the equator (a $\bar{V}$ T' mechanism, see Lazar et al., 2001). Zhang et al. (personal communication) found evidence for this mechanism in observations.

This said it is however still unknown if a subsurface heat anomaly can surface at the equator with a significant intensity, especially after its passage through intense mixing region within the North Brazil Current. Nonetheless, a recent model study by Lazar et al. suggests that the spiciness (the temperature and salinity characteristics of an isopycnal layer) of the equatorial undercurrent can be inferred from tropical SST and sea surface salinity (SSS) a few years earlier, thanks to the long-term propagation of salinity compensated heat anomalies (see *Figure 11)*.

As discussed above in Section 2, in the tropical Atlantic it is the inter-hemispheric SST gradient that is the most influential factor determining ITCZ variability, only to be seconded by SST anomalies in the equatorial upwelling region (Xie et al. 1998; Sutton et al., 2000). Recent studies (e.g., Lazar et al. 2001) identify two large upwelling/obduction regions in the tropics, which terminate the subsurface limbs of the STCs and therefore are areas where anomalous subsurface signals coming from the subtropics can interact with the surface, through mixing (see *Figures 10 and 12*). These regions coincide in latitude with the two African *coastal upwelling* regions (the Guinea and Angola Domes) commonly invoked for eastern tropical sources of thermocline water, but extend beyond them. In particular, these two large upwelling areas appear to coincide with the Northern and Southern Hemisphere centres of action associated with the variability of the inter-hemispheric SST gradient and thus can influence the ITCZ (compare the extension of the warm SST regions in *Figure 5* and *6* with the upwelling extension *Figure 12*).

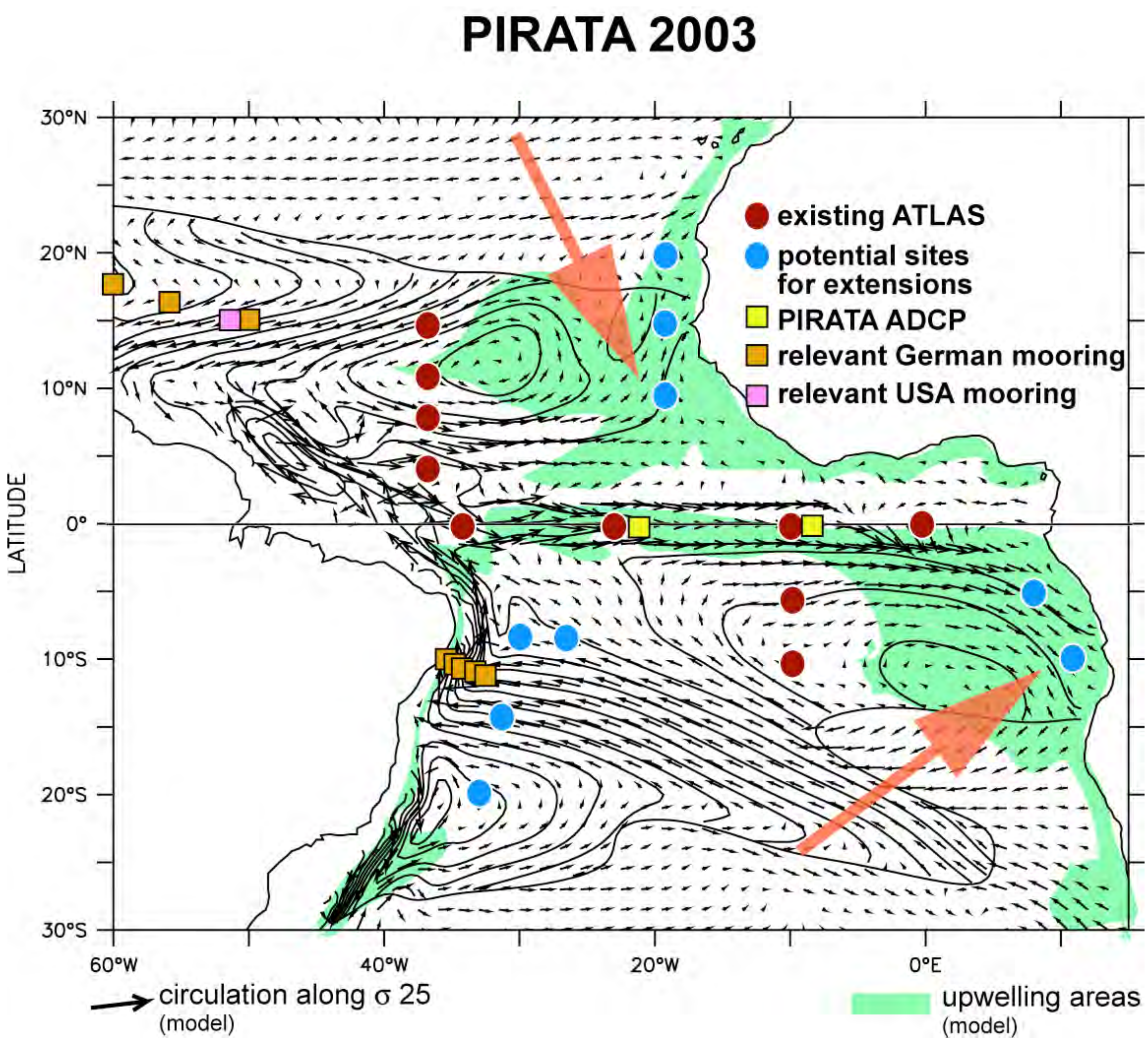


Figure 12: A schematic representation of the returning limb of the tropical Atlantic STCs and the regions of surface upwelling. Orange arrows point at the center of two broad off-equatorial upwelling regions: the Guinea and Angola Domes (after Lazar et al., 2002).

Even though the strong equatorial upwelling is also providing water to these two regions, their subsurface properties are likely to be intensely modified during the mixed layer transit from the equator and can transmit directly and efficiently the subsurface anomalous signals to the eastern tropical mixed layer. We hypothesize therefore that the STCs, through their influence on SST in the subtropical upwelling areas, provide yet another way by which *slow ocean processes* modulate the meridional gradient of tropical SST, particularly on long (decadal) time scales.

Other potential remote influences of the SA ocean are the *Agulhas Rings*, which arrive at the western equator from the southern tip of Africa and could modify the SST and the Air-sea interactions in the western basin and the *meridional overturning circulation (MOC)* that changes in intensity and could produce effects in a comparable way in its western tropical Atlantic surface limb.

5.7.4. Summary and FUTURE WORK

In the TA the ITCZ is highly sensitive to changes in SST gradients, particularly in the meridional direction and during the boreal spring, but also in summer when the zonal gradient along the equator is strong. There is now sufficient evidence to imply that the SA plays a role in shaping these gradients through surface ocean atmosphere interactions and subsurface, oceanic pathways.

Two aspects of ocean-atmosphere interaction in the South Atlantic Basin can lead to climate anomalies in the ITCZ region. On seasonal to interannual time scales, large-scale, extratropical atmospheric perturbations akin to the NAO can create basin wide SST anomalies, which through their persistence precondition the tropical coupled system for a positive feedback interaction two to three seasons later. On longer time scales, ocean-atmosphere interactions can lead to changes in the oceanic transports of temperature and salinity to the tropics, which can affect the properties of upwelling water in the tropical regions off western Africa and the equatorial cold tongue. Thus, South Atlantic climate interactions are evidently set to affect the variability of the AMI on interannual to decadal time scales and should be considered in addition to the more familiar effects of the NAO and ENSO.

The study of SA influences on the ITCZ is in its early stages and more work needs to be done to understand and quantify the processes described above. Fore example, the link between the chaotic extratropical SA atmosphere and the ITCZ provides potential predictability because of the long delay between the phenomenon's inception in the austral winter and its impact on the ITCZ in the austral fall (boreal spring). Can this potential be materialized? Can the precursors be identified in a robust manner to allow a long-lead prediction? How does this phenomenon interact with other external influences on the ITCZ? How does it interact with the apparently large austral summer variability?

The role of the ocean circulation in affecting longer-term variability needs to be better understood. The importance of the STCs in setting up the mean properties of the upper ocean is unequivocal, but the impact on variability is not quantified. It is obviously difficult to detect such effects when they underlie the impact of the direct and highly variable surface interactions. Long-term observations need to be available to allow such analysis. The issues that need to be addressed are the effects of the SA STC on upwelling in the eastern part of the basin off Angola and to what extent this intervenes with the strong surface forcing by the atmosphere there and influences the inter-hemispheric SST gradient. Another important influence occurs in the tropical thermocline and the effect on SST and the formation of Atlantic warm events should be studied.

There are ongoing long-term observation efforts in planning for the SA. It is important to coordinate them with existing efforts in the TA to achieve maximum benefit with addressing the causes of ITCZ variability.

5.7.5 References

Barreiro, M., A. Giannini, P. Chang, and R. Saravanan, in preparation: The pre-conditioning role of the Southern Hemisphere atmospheric circulation in tropical Atlantic variability. *N/A*.

Blanke, B., M. Arhan, G. Madec, and S. Roche, 1999: Warm water paths in the equatorial Atlantic as diagnosed with a general circulation model. *J. Phys. Oceanogr.*, **29,** 2753-2768.

Carton, J. A. and B. H. Huang, 1994: Warm events in the tropical Atlantic. *J. Phys. Oceanogr.*, **24,** 888-903.

Carton, J. A., X. H. Cao, B. S. Giese, and A. M. daSilva, 1996: Decadal and interannual SST variability in the tropical Atlantic Ocean. *J. Phys. Oceanogr.*, **26,** 1165-1175.

Chang, P., L. Ji, and H. Li, 1997: A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air-sea interactions. *Nature*, **385,** 516-518.

Chang, P., L. Ji, and R. Saravanan, 2001: A hybrid coupled model study of tropical Atlantic variability. *J. Climate*, **14,** 361-390.

Chang, P., R. Saravanan, L. Ji, and G. C. Hegerl, 2000: The effect of local sea surface temperatures on the atmospheric circulation over the tropical Atlantic sector. *J. Climate*, **13,** 2195–2216.

Chiang, J. C. H. and A. H. Sobel, 2002: Tropical tropospheric temperature variations caused by ENSO and their influence on the remote tropical climate. *J. Climate*, **15,** 2616-2631.

Chiang, J. C. H., Y. Kushnir, and A. Giannini, 2002: Deconstructing Atlantic ITCZ variability: Influence of the local cross-equatorial SST gradient, and remote forcing from the eastern equatorial Pacific. *J. Geophys. Res.*, **107,** 10.1029/2000JD000307.

Curtis, S. and S. Hastenrath, 1995: Forcing of anomalous sea-surface temperature evolution in the tropical Atlantic during Pacific warm events. *J. Geophys. Res.-Oceans*, **100,** 15835-15847.

Czaja, A., P. van der Vaart, and J. Marshall, 2002: A diagnostic study of the role of remote forcing in tropical Atlantic variability. *J. Climate*, **15,** 3280-3290.

Dommenget, D. and M. Latif, 2000: Interannual to decadal variability in the tropical Atlantic. *J. Climate*, **13,** 777-792.

Elliott, J. R., S. P. Jewson, and R. T. Sutton, 2001: The impact of the 1997/98 El Nino event on the Atlantic Ocean. *J. Climate*, **14,** 1069-1077.

Enfield, D. B. and D. A. Mayer, 1997: Tropical Atlantic sea surface temperature variability and its relation to El Nino Southern Oscillation. *J. Geophys. Res.-Oceans*, **102,** 929-945.

Fontaine, B. and S. Janicot, 1996: Sea surface temperature fields associated with West African rainfall anomaly types. *J. Climate*, **9,** 2935-2940.

Fratantoni, D. M., W. E. Johns, T. L. Townsend, and H. E. Hurlburt, 2000: Low-latitude circulation and mass transport pathways in a model of the tropical Atlantic ocean. *J. Phys. Oceanogr.*, **30,** 1944-1966.

Giannini, A., R. Saravanan, and P. Chang, 2003: How predictable is Nordeste rainfall during ENSO events? The preconditioning role of tropical Atlantic variability. *J. Climate***,** submitted.

Gu, D. F. and S. G. H. Philander, 1997: Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics. *Science*, **275,** 805-807.

Hakkinen, S. and K. C. Mo, 2002: The low-frequency variability of the tropical Atlantic Ocean. *J. Climate*, **15,** 237-250.

Hansen, D. V. and H. F. Bezdek, 1996: On the nature of decadal anomalies in the North Atlantic sea surface. *J. Geophys. Res.*, **101,** 8749-8758.

Hastenrath, S., 1978: On modes of tropical circulation and climate anomalies. *J. Atmos. Sci.*, **35,** 2222-2231.

Hastenrath, S., 1984: Interannual variability and annual cycle - mechanisms of circulation and climate in the tropical Atlantic sector. *Mon. Wea. Rev.*, **112,** 1097-1107.

Hastenrath, S., 2000a: Interannual and longer-term variability of upper air circulation in the Northeast Brazil-tropical Atlantic sector. *J. Geophys. Res.-Atmos.*, **105,** 7327-7335.

Hastenrath, S., 2000b: Upper air mechanisms of the Southern Oscillation in the tropical Atlantic sector. *J. Geophys. Res.-Atmos.*, **105,** 14997-15009.

Hastenrath, S. and L. Heller, 1977: Dynamics of climatic hazards in Northeast Brazil. *Quart. J. Roy. Meteor. Soc.*, **103,** 77-92.

Hastenrath, S. and L. Greischar, 1993: Circulation mechanisms related to Northeast Brazil rainfall anomalies. *J. Geophys. Res.-Atmos.*, **98,** 5093-5102.

Hastenrath, S., L. C. Castro, and P. Acietuno, 1987: The Southern Oscillation in the tropical Atlantic Sector. *Contrib. Atmos. Phys.*, **60,** 447-463.

Horel, J. D. and J. M. Wallace, 1981: Planetary-Scale Atmospheric Phenomena Associated with the Southern Oscillation. *Mon. Wea. Rev.*, **109,** 813-829.

Houghton, R. W., 1991: The relationship of sea-surface temperature to thermocline depth at annual and interannual time scales in the tropical Atlantic-Ocean. *J. Geophys. Res.-Oceans*, **96,** 15173-15185.
Huang, R. X. and J. Pedlosky, 1999: Climate variability inferred from a layered model of the ventilated thermocline. *J. Phys. Oceanogr.*, **29,** 779-790.
Huffman, G. J., R. F. Adler, P. A. Arkin, A. Chang, R. Ferraro, A. Gruber, J. E. Janowiak, A. McNab, B. Rudolf, and U. Schneider, 1997: The Global Precipitation Climatology Project (GPCP) combined precipitation data set. *Bull. Amer. Meteorol. Soc.*, **78,** 5-20.
Inui, T., A. Lazar, P. Malanotte-Rizzoli, and A. Busalacchi, 2002: Wind stress effects on subsurface pathways from the subtropical to tropical Atlantic. *J. Phys. Oceanogr.*, **32,** 2257-2276.
Kleeman, R., J. P. McCreary, and B. A. Klinger, 1999: A mechanism for generating ENSO decadal variability. *Geophys. Res. Lett.*, **26,** 1743-1746.
Kushnir, Y., R. Seager, J. Miller, and J. C. H. Chiang, 2002: A simple coupled model of tropical Atlantic decadal climate variability. *Geophys. Res. Lett.*, **29,** 2133, doi:10.1029/2002GL015874.
Lazar, A., R. Murtugudde, and A. J. Busalacchi, 2001: A model study of temperature anomaly propagation from the subtropics to tropics within the South Atlantic thermocline. *Geophys. Res. Lett.*, **28,** 1271-1274.
Lazar, A., T. Inui, P. Malanotte-Rizzoli, A. J. Busalacchi, L. P. Wang, and R. Murtugudde, 2002: Seasonality of the ventilation of the tropical Atlantic thermocline in an ocean general circulation model. *J. Geophys. Res.-Oceans*, **107,** art. no.-3104.
Liu, Z. Y., 1999: Planetary wave modes in the thermocline: Non-Doppler-shift mode, advective mode and Green mode. *Quart. J. Roy. Meteor. Soc.*, **125,** 1315-1339.
Malanotte-Rizzoli, P., K. Hedstrom, H. Arango, and D. B. Haidvogel, 2000: Water mass pathways between the subtropical and tropical ocean in a climatological simulation of the North Atlantic ocean circulation. *Dyn. Atmos. Ocea.*, **32,** 331-371.
McPhaden, M. J. and D. X. Zhang, 2002: Slowdown of the meridional overturning circulation in the upper Pacific Ocean. *Nature*, **415,** 603-608.
Mehta, V. M., 1998: Variability of the tropical ocean surface temperatures at decadal-multidecadal timescales. Part I: The Atlantic Ocean. *J. Climate*, **11,** 2351-2375.
Mitchell, T. P. and J. M. Wallace, 1992: The Annual Cycle in Equatorial Convection and Sea-Surface Temperature. *J. Climate*, **5,** 1140-1156.
Mo, K. C. and S. Hakkinen, 2001: Interannual variability in the tropical Atlantic and linkages to the Pacific. *J. Climate*, **14,** 2740-2762.
Moura, A. D. and J. Shukla, 1981: On the dynamics of droughts in Northeast Brazil - observations, theory and numerical experiments with a general-circulation model. *J. Atmos. Sci.*, **38,** 2653-2675.
Murtugudde, R. G., J. Ballabrera-Poy, J. Beauchamp, and A. J. Busalacchi, 2001: Relationship between zonal and meridional modes in the tropical Atlantic. *Geophys. Res. Lett.*, **28,** 4463-4466.
Nobre, P. and J. Shukla, 1996: Variations of sea surface temperature, wind stress, and rainfall over the tropical Atlantic and South America. *J. Climate*, **9,** 2464-2479.
Okajima, H., S. P. Xie, and A. Numaguti, 2003: Interhemispheric coherence of tropical cliamte variability: Effect of the climatological ITCZ. *J. Met. Soc. Japan*, sumbitted.
Rajagopalan, B., Y. Kushnir, and Y. M. Tourre, 1998: Observed decadal midlatitude and tropical Atlantic climate variability. *Geophys. Res. Lett.*, **25,** 3967-3970.
Robertson, A. W., C. R. Mechoso, and Y. J. Kim, 2000: The influence of Atlantic sea surface temperature anomalies on the north Atlantic oscillation. *J. Climate*, **13,** 122-138.
Robertson, A. W., J. D. Farrara, and C. R. Mechoso, 2003: Simulation of the atmospheric response to South Atlantic sea surface temperature anomalies. *J. Climate*, in press.
Ruiz-Barradas, A., J. A. Carton, and S. Nigam, 1999: Structure of interannual-to-decadal climate variability in the tropical Atlantic sector. *J. Climate*, **12,** 1-43.
Saravanan, R. and P. Chang, 2000: Interactions between tropical Atlantic variability and El Nino-southern Oscillation. *J. Climate*, **13,** 2177-2194.
Schneider, N., 2000: A decadal spiciness mode in the tropics. *Geophys. Res. Lett.*, **27,** 257-260.
Schneider, N., A. J. Miller, M. A. Alexander, and C. Deser, 1999: Subduction of decadal North Pacific temperature anomalies: Observations and dynamics. *J. Phys. Oceanogr.*, **29,** 1056-1070.
Seager, R., Y. Kushnir, P. Chang, N. H. Naik, J. Miller, and W. Hazeleger, 2001: Looking for the role of the ocean in tropical Atlantic decadal climate variability. *J. Climate*, **14,** 638-655.
Seager, R., Y. Kushnir, M. Visbeck, N. Naik, J. Miller, G. Krahmann, and H. Cullen, 2000: Causes of Atlantic Ocean climate variability between 1958 and 1998. *J. Climate*, **13,** 2845-2862.

Servain, J., 1991: Simple climatic indices for the tropical Atlantic Ocean and some applications. *J. Geophys. Res.*, **96,** 15,137-15,146.

Servain, J., I. Wainer, J. P. McCreary, and A. Dessier, 1999: Relationship between the equatorial and meridional modes of climatic variability in the tropical Atlantic. *Geophys. Res. Lett.*, **26,** 485-488.

Sterl, A. and W. Hazeleger, 2002: Coupled variability and air-sea interaction in the South Atlantic Ocean. *Clim. Dyn.*, submitted.

Stramma, L. and F. Schott, 1999: The mean flow field of the tropical Atlantic Ocean. *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, **46,** 279-303.

Sutton, R. T. and M. R. Allen, 1997: Decadal predictability of North Atlantic sea surface temperature and climate. *Nature*, **388,** 563-567.

Sutton, R. T., S. P. Jewson, and D. P. Rowell, 2000: The elements of climate variability in the tropical Atlantic region. *J. Climate*, **13,** 3261-3284.

Tanimoto, Y. and S. P. Xie, 1999: Ocean-atmosphere variability over the Pan-Atlantic basin. *J. Met. Soc. Japan*, **77,** 31-46.

Tanimoto, Y. and S. P. Xie, 2002: Inter-Hemisphere Decadal Variations in SST, surface wind, heat flux and cloud cover over the Atlantic basin. *J. Met. Soc. Japan*, **80,** 1199-1219.

Tobler, W., V. Deichmann, J. Gottsegen, and K. Maloy, 1995: The global demography project. Technical Report TR-95-6, National Center for Geographic Information analysis, Univ. Santa Barbara, CA., 75 pp.

Venegas, S. A., L. A. Mysak, and D. N. Straub, 1996: Evidence for interannual and interdecadal climate variability in the South Atlantic. *Geophys. Res. Lett.*, **23,** 2673-2676.

Venegas, S. A., L. A. Mysak, and D. N. Straub, 1997: Atmosphere-ocean coupled variability in the South Atlantic. *J. Climate*, **10,** 2904-2920.

Venegas, S. A., L. A. Mysak, and D. N. Straub, 1998: An interdecadal climate cycle in the South Atlantic and its links to other ocean basins. *J. Geophys. Res.-Oceans*, **103,** 24723-24736.

Xie, S.-P., 1999: A dynamic ocean-atmosphere model of the tropical Atalantic decadal variability. *J. Climate*, **12,** 64-70.

Xie, S. P. and Y. Tanimoto, 1998: A pan-Atlantic decadal climate oscillation. *Geophys. Res. Lett.*, **25,** 2185-2188.

Zebiak, S. E., 1993: Air-Sea Interaction in the Equatorial Atlantic Region. *J. Climate*, **6,** 1567-1568.

APPENDIX A

Organizing Committee:

Edmo Campos	IOUSP (Chair)
Gisleine Cunha	INPE/CPTEC (secretary)
Roberta Boscolo	WCRP/CLIVAR
Gerhard Breulmann	IAI Directorate
Eduardo Banus	IAI Directorate
Carlos Ereño	WCRP/CLIVAR
Mike Johnson	NOAA/OGP
Carlos Nobre	INPE/CPTEC
Janice Trotte	DHN-IOC/GOOS

Scientific Committee:

Edmo Campos	Brazil (chair)
Stuart Cunningham	UK
Silvia Garzoli	USA
Wilco Hazeleger	Holland
Johann Lutjeharms	South Africa
Ricardo Matano	USA
Paulo Nobre	Brazil
Alice Grimm	Brazil
Alberto Piola	Argentina (co-chair)
Chris Reason	South África
Steve Rintoul	Australia
Andrew Robertson	USA
Carolina Vera	Argentina
Ilana Wainer	Brazil
Walter Zenk	Germany
Will de Ruijter	Holland

APPENDIX B

AGENDA

DAY 1 - Thursday, February 6

08:00 – 08:15 Registration
08:15 – 08:30 Opening Remarks – Edmo Campos

08:30 – 09:30 Few words from the sponsors:
CLIVAR - Tony Busalacchi
CLIVAR Atlantic - Martin Visbeck
IOC/UNESCO and Rio de Janeiro GOOS Project Office - Janice Trotte
IAI Directorate - Eduardo Banus
ONR International Field Office - Jerry Miller
WCRP - Roberta Boscolo

Morning Session (Tony Busalacchi – Chair and Bob Molinari – Rapporteur)
09:30 – 10:10 Review of South Atlantic intraseasonal to interdecadal variability - Carolina Vera
Coffee break
10:30 – 11:10 The South Atlantic role on the global thermohaline circulation - Alberto Piola
11:10 – 11:50 Interocean exchanges - Johann Lutjeharms
11:50 – 12:30 South Atlantic links and impacts to regional and global climate - Alice Grimm
Lunch break

Afternoon Session (Alberto Piola – Chair and Carolina Vera – Rapporteur)
14:00 – 14:40 The South Atlantic Observing System - Silvia Garzoli
14:40 – 15:20 The Mesoscale Circulation of the South Atlantic Ocean: Does it Matter to Climate? - Ricardo Matano
15:20 – 16:00 The role of the South Atlantic in the ITCZ Variability – Alban Lazar
Coffee break
16:20 – 16:40 The VAMOS concerns relevant to the South Atlantic - Roberto Mechoso
16:40 – 17:00 ARGO in the South Atlantic: Field program, data management and program management - Robert Molinari

17:00 – 19:00 Poster Session I - Carlos Lentini (Chair/Rapporteur)

19:00 Reception

DAY 2 – Friday, February 7

08:30 – 10:45 Plenary Discussions and Poster Session II - Wilco Hazeleger (Chair/Rapporteur)
Coffee break
10:45 – 12:00 Formation of the Working Groups

- WG1: Links between the upper South Atlantic, the deeper ocean and the other basins (Leader: Alberto Piola)
- WG2: The South Atlantic links and impacts to regional and global climate (Leader: Alice Grimm)
- WG3: Modeling the Coupled Ocean/Atmosphere System (Leader: Ricardo Matano)
- WG4: South Atlantic Observing System and Operational Forecast System (leader: Silvia Garzoli)

Lunch break

14:00 -18:00 Working groups continue

DAY 3 – Saturday, February 8

08:30 - 12:00 Plenary presentations of the Working Groups leaders, followed by discussions, recommendations, etc.
12:00 Adjourn

APPENDIX C: List of Participants

NAME	FIRST NAME	INSTITUTION	EMAIL
Adedoyin	Akintayo	Un. of Botswana - Botswana	adedoyin@mopipi.ub.bw
Almeida	Roberto Antonio Ferreira de	IO/USP - Brazil	roberto@oceanografia.org
Arruda	Wilton Zumpichiatti	UFRJ - Brazil	wilton@im.ufrj.br
Banús	Eduardo M.	IAI - Brazil	banus@dir.iai.int
Beaverson	Christopher	NOAA - USA	chris.beaverson@noaa.gov
Bentamy	Abderrahim	IFREMER - France	abderrahim.bentamy@ifremer.fr
Bicalho	Andréa de Castro	MCT - Brazil	andreac@mct.gov.br
Blanco	Cintia Maria Rodrigues	MCT - Brazil	cmblanco@mct.gov.br
Boscolo	Roberta	CLIVAR - Spain	rbos@iim.csic.es
Boulegue	Jacques	IRD - France	dme@paris.ird.fr
Bourles	Bernard	IRD - France	bourles@ird.fr
Bunge	Lucia Gabriela	LODYC - France	lbulod@lodyc.jussieu.fr
Busalachi	Antonio	ESSIC/UM - USA	tonyb@essic.umd.edu
Byrne	Dierdre	University of Maine - USA	dbyrne@umeoce.maine.edu
Calado	Leandro	IO/USP - Brazil	leandro@ceres.io.usp.br
Campos	Edmo	IO/USP - Brazil	edmo@usp.br
Campos	José Nilson Bezerra	FUNCEME - Brazil	nilson@funceme.br
Caniaux	Guy	MeteoFrance - France	caniaux@meteo.fr
Castelão	Guilherme Pimenta	IO/USP - Brazil	guilherme@castelao.net
Cirano	Mauro	UFBA - Brazil	mauro@cpgg.ufba.br
Clauzet	Gabriel	IO/USP - Brazil	gclauzet@usp.br
Colomb	Raul	CONAE - Argentina	rcolomb@conae.org.ar
Costa	Fernando Alberto Gomes	DHN - Brazil	
Cunningham	Stuart Andrew	SOC - UK	scu@soc.soton.ac.uk
Dereczynski	Claudine Pereira	UFRJ - Brazil	claudine@acd.ufrj.br
Diaz	Álvaro Fidel	IMFIA - Uruguay	adiaz@fing.edu.uy
Diongue	Aida	Dir de la Meteo Nation - Senegal	aida@env.leeds.ac.uk
Durand	Bruno Jacques	FUNCEME - Brazil	bruno@funceme.br
Eldin	Gerard	LEGOS/GRGS - France	Gerard.Eldin@cnes.fr
Ereño	Carlos Eduardo	VAMOS/CLIVAR - Argentina	ereno@at.fcen.uba.ar
Fidel	Quilanda	Institute Investigation Marinha, Namibe	aasafaris@netangola.com
Florenchie	Pierre	Un. Cape Town - South Africa	pierre@ocean.uct.ac.za
Francisco	Cayo	IO/USP - Brazil	cayoprado@ceres.io.usp.br
Fuller	Geoffrey	NOAA - USA	geoffrey.fuller@noaa.gov
Garzoli	Silvia L.	NOAA/AOML - USA	silvia.garzoli@noaa.gov
Giarolla	Emanuel	CPTEC / INPE - Brazil	emanuel@cptec.inpe.br

Goes	Marlos	IO/USP - Brazil	marlos@usp.br
Goni	Gustavo Jorge	NOAA/AOML - USA	gustavo.goni@noaa.gov
Granero	Marco	IO/USP - Brazil	marcogranero@ceres.io.usp.br
Grimm	Alice Marlene	UFPR - Brazil	grimm@fisica.ufpr.br
Haarsma	Reindert Julius	KNMI - The Netherlands	haarsma@knmi.nl
Hazeleger	Wilco	KNMI - The Netherlands	hazelege@knmi.nl
Hong	Sherry	US State Department / US Embassy Brasília	HongCS@state.gov
Huaring	Enrique	IO/USP - Brazil	huaringa@usp.br
Iita	Aina Tuyakula	National Marine - Namibia	aiita@mfmr.gov.na
Janino	Marco Antonio Dutra	DHN - Brazil	
Jochum	Markus	MIT - USA	markus@ocean.mit.edu
Johnson	Michael	NOAA - USA	mike.johnson@noaa.gov
Kroeger	Juergen	ESSIC/UM - USA	kroeger@essic.umd.edu
Krusche	Nisia	DGEO/FURG - Brazil	dgenisia@furg.br
Lartigue	Maria Eugênia	SECYT - Argentina	melarti@correo.secyt.gov.ar
Lazar	Alban	LODYC - France	alban.lazar@lodyc.jussieu.fr
Leite	Jose Roberto	IO/USP - Brazil	zerodelta@ceres.io.usp.br
Lentini	Carlos	IO/USP - Brazil	lentini@yemanja.io.usp.br
Lorenzzetti	João Antonio	INPE - Brazil	loren@ltid.inpe.br
Lutjeharms	Johann R. E.	Un. Cape Town - South Africa	johann@ocean.uct.ac.za
Machado	Maria Cordélia Soares	MCT - Brazil	mmachado@mct.gov.br
Malagutti	Marta	CPTEC / INPE - Brazil	marta@cptec.inpe.br
Martinez Lopez	Carlos Manuel	Un. de La Republica - Uruguay	carmar@glaucus.fcien.edu.uy
Matano	Ricardo P.	Oregon State Un. - USA	rmatano@coas.oregonstate.edu
McPhaden	Michael J.	NOAA - USA	mcphaden@pmel.noaa.gov
Mechoso	Carlos Roberto	UCLA - USA	mechoso@atmos.ucla.edu
Melice	Jean-Luc	IRD - France	jlmelice@lodyc.jussieu.fr
Miller	Jerry L.	ONR - UK	jmiller@onrifo.navy.mil
Miranda	Sérgio da Silveira	DHN - Brazil	
Molinari	Robert Lucian	NOAA/AOML - USA	bob.molinari@noaa.gov.br
Moller	Osmar	FURG - Brazil	dfsomj@furg.br
Nobre	Paulo	CPTEC / INPE - Brazil	pnobre@cptec.inpe.br
Nobre	Carlos	CPTEC / INPE - Brazil	nobre@cptec.inpe.br
Nuñez	Mario Nestor	CIMA/CONICET/UBA - Argentina	mario.nunez@fibertel.com.ar
Nuñez Riboni	Ismael Diego	Alfred Wegener Institute - Germany	inunez@awi-bremerhaven.de
Oliveira	Luis Augusto de	CHM / DHN - Brazil	14@chm.mar.mil.br
Paiva	Afonso de Moraes	COPPE/UFRJ - Brasil	mpaiva@peno.coppe.ufrj.br
Palma	Elbio Daniel	Un. del Sur - Argentina	uspalma@criba.edu.ar
Paula	Ana Claudia	IO/USP - Brazil	anadepaula@ceres.io.usp.br

Penduff	Thierry	LEGI / CNRS - France	thierry.penduff@hmg.inpg.fr
Pereira	Janini	IO/USP - Brazil	janini@usp.br
Piola	Alberto R.	Servicio de Hidrog. Naval - AR	apiola@hidro.gov.ar
Provost	Chistine	LODYC - France	Christine.Provost@lodyc.jussieu.fr
Reason	Chris	Un. Cape Town - South Africa	cjr@egs.uct.ac.za
Robertson	Andrew William	IRI - USA	awr@iri.columbia.edu
Rouault	Mathieu	Un. Cape Town - South Africa	rouault@physci.uct.ac.za
Rusticucci	Matilde Mónica	UBA - Argentina	mati@at.fcen.uba.ar
Sabaté	Pierre	IRD - France	secret.ird@apis.com.br
Sanchez	Ramiro Pedro	INIDEP - Argentina	rsanchez@inidep.edu.ar
Schmidt	Andre	IO/USP - Brazil	schmidt@ceres.io.usp.br
Servain	Jacques	FUNCEME - Brazil	servain@funceme.br
Silveira	Ilson Carlos Almeida da	IO/USP - Brazil	ilson@ipanema.io.usp.br
Soares	Ivan	FURG - Brazil	dfsivan@furg.br
Speich	Sabrina	Labor. de Phys des Oceans - FR	sabrina.speich@univ-brest.fr
Stevens	David Philip	UEA - UK	d.stevens@uea.ac.uk
Tanajura	Clemente Augusto de Souza	LNCC - Brazil	cast@lncc.br
Taschetto	Andrea	IO/USP - Brazil	andreast@usp.br
Todd	James Forrest	NOAA - USA	james.todd@noaa.gov
Trotte	Janice Romaguera	DHN - Brazil	j.trotte@openlink.com.br
Urbano Neto	Domingos	IO/USP - Brazil	dfurbano@ceres.io.usp.br
Valladares	Javier Armando	Servicio de Hidrog. Naval - Argentina	valladar@hidro.gov.ar
Vauclair	Fabrice Martin	IO/USP - Brazil	fabrice@ceres.io.usp.br
Vera	Carolina	UBA - Argentina	carolina@at.fcen.uba.ar
Visbeck	Martin	LDEO - USA	visbeck@ldeo.columbia.edu