THE SOUTH ATLANTIC AND THE CLIMATE

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Abstract: *As a contribution to the OCEANOBS99 objectives, we give a brief description of the present knowledge of the South Atlantic and identify some key processes and areas which need to be monitored in order to understand the role of that part of the ocean in the global climate. Included are suggestions of strategies for a first approximation towards an ocean climate monitoring system in the South Atlantic.*

1 - INTRODUCTION

Throughout the duration of the WOCE and TOGA programs, ocean-atmosphere interactions over the Atlantic Ocean received considerably less attention than the Pacific Ocean. Programmatically, there was not a great deal of coordination between these two WCRP programs oriented towards studying the links between the tropical and mid-latitude oceans. However, near the end of WOCE and TOGA and going into CLIVAR, climate variability across the entire Atlantic Ocean basin on interannual to decadal time scales has emerged as an active area of research given its important social and economic ramifications. Many fundamental questions are arising regarding the role of the Atlantic Ocean circulation and sea surface temperature (SST) in determining or influencing low-frequency changes in the coupled climate system for the region.

It is in Walker's (1924) work that the Southern Oscillation (SO) was first described. In his search for Indian monsoon forecasting tools, Walker discovered a significant see-sawing between atmospheric pressure in Buenos Aires, Argentina and Sydney, Australia. This first description of the atmospheric SO cycle clearly ties climate conditions in the region to events in the Pacific. Presently the mechanisms underlying these modes of variability are not fully understood. Regional precipitation and ocean surface anomalies have been fairly well documented. There are significant correlations between SO and rain anomalies over the drainage basin that feed the Rio de la Plata estuary and the Patos-Mirim complex in southern Brazil that is fed from the eastern side of the highlands (Ropelewski and Halpert, 1987; Pisciotanno et al., 1994). These rainfall anomalies are also associated with large positive sea surface temperature (SST) anomalies in the southern Argentine basin. These anomalies are set up late in El Nino years and are apparently reinforced by ENSO-correlated perturbations in SST that translate around the Antarctic Circumpolar Current (White and Peterson, 1996).

The connections of the three major oceans are in the South Atlantic. 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 receives considerable inflows from the Pacific, through the Drake Passage, and from the Indian Ocean by means of the rings shed from the Agulhas Current retroflection. The South Atlantic is a peculiar ocean because it is the only basin wherein the net meridional heat flux is equatorward in subtropical regions, resulting in a cross-equatorial export of heat towards the northern hemisphere. This interhemispheric heat transport requires a northward cross-equatorial mass flux in the upper layers, in order to compensate for the North Atlantic Deep Water (NADW) transported southward in the lower layers. It is by now well established the existence of this north-south trade of water. Nonetheless, some intriguing questions still remain on how much heat is transported into the North Atlantic, and from where come the water masses crossing the equator and what are the main routes followed by them. While the regions of formation of the NADW are relatively well known, there are still large uncertainties regarding the origins of the waters exported into the North Atlantic.

Variations of the South Atlantic ocean circulation patterns and SST can occur over time scales ranging from subseasonal to the seasonal and interannual. It is thought that these variations are strongly influenced by interactions between the opposing flows of the Brazil Current and the Malvinas Current, which in turn are affected by the basin scale wind field and other atmospheric features, such as, for instance, the South Atlantic Convergence Zone (SACZ). The SACZ is formed in the austral summer by the high frequency transient synoptic systems, by remote forcing from the Pacific and by the intense convective activity in the Amazon region. The SACZ extends southeastward from the core of the South American continent to the South Atlantic. The region over the continent depends on the moisture supply from the Amazon region, but the region over the ocean is strongly dependent on the low level meridional moisture flux convergence (Kodama, 1993; Tanajura, 1998). There is a high correlation between the 850 mb meridional wind in the western edge of the Atlantic subtropical high and precipitation in the SACZ. It is observed that this low level wind passes over a region in the Atlantic in which evaporation attains its maxima in the South Atlantic basin. Therefore, this region supplies moisture to the maintenance of the SACZ. Reanalyzed data and model experiments show that the contribution of the meridional moisture convergence to the SACZ is often much greater than local evaporation. This indicates that this convergence zone, in opposition to the ITCZ, is not necessarily formed over the local warmest waters.

Given the South Atlantic ocean phenomena outlined above, and their impact on global and regional scale climate, it becomes important that variables such as SST, currents, fluxes, etc. be monitored on a continuous basis if one wishes to determine and predict the relationship between oceanic variability in the south Atlantic and global/regional climate. We understand that efforts should be concentrated in the study of the air-sea-land interactions leading to sea surface temperature variability, and the processes associated with the interhemispheric exchange of mass and heat by the Atlantic Merididional Overturning Cell.

In the context of the first of these two issues, the dynamics of the atmospheric convergence zones, both the ITCZ and the SACZ, their dependence on land and ocean surface processes (i.e., soil moisture, SST, etc.), and how the upper ocean responds to the atmospheric circulation, are important targets. The knowledge of these mechanisms in the subtropical South Atlantic would serve as an important integrator of equatorial-to-extratropical processes, both in the ocean and the atmosphere. It would also have enormous practical significance for seasonal climate forecasting affecting economically important areas of South America and Africa.

The knowledge of long term variations of the Atlantic thermohaline circulation and how these variations lead to changes in SST and oceanic heat transports are key issues to be addressed. The thermohaline circulation is a global-scale phenomenon. However, its dynamics and variability are controlled by rather small-scale processes associated with the formation and spreading of the different water masses. In the South Atlantic, there are some key locations where very important of such processes occur, and need to be monitored. These are the Brazil/Malvinas Confluence, the Agulhas Retroflection, the Benguela Current and the Bifurcation of the South Equatorial Current.

In this paper we discuss some of the undertakings needed to advance the understanding of the role of the South Atlantic in the climate, from regional to global scales. The envisioned efforts are a consistent combination of observational and modeling programs. In this context, the most important issues to be addressed are identified as the following:

- The large-scale oceanic and atmospheric circulation in the South Atlantic, considering mean state and variabilities;
- The dynamics and variabilities in the Brazil-Malvinas Confluence and their connection to local and global climate;
- The role of the Drake Passage as an ``entry point'' of subantarctic water masses and the impact of variabilities of the transport through the passage on the cold water component of the upper layer return route to the North Atlantic;
- The retroflection of the Agulhas Current, and the contribution of the Benguela Current and the Agulhas rings to the mass and heat transport into the subtropical and Equatorial South Atlantic;
- The links between wind stress curl in the SA and variabilities in the SEC bifurcation;
- The land-air-sea interactions; the genesis and maintainance of the ITCZ-SACZ, their variability and impact on SST;
- The envisioned ways of improving our understanding (and forecasting capability) of seasonal to interannual variability of SSTA over the South Atlantic;

2 - THE SOUTH ATLANTIC CIRCULATION

Compared to the North Atlantic, the oceanic circulation in the South Atlantic is poorly understood. The large scale mean circulation near the surface can be represented schematically as in Fig. 1 (Peterson, per. comm.), which is based on the works of Peterson and Stramma (1991) and Stramma and England (1999). In this representation, the circulation near the surface is dominated by a wind-driven, anticyclonic subtropical gyre. This gyre is formed by the Benguela Current, the southernmost branch of the South Equatorial Current, the Brazil Current and the South Atlantic Current. The southern limit of the gyre is referred in the literature as the South Atlantic Subtropical Front (or Convergence). To the south of the Subtropical Convergence, along the western side of the basin, the Malvinas Current flows equatorward carrying water from the Antarctic Circumpolar

Current. At approximately 36-38 S, the Malvinas Current encounters the Brazil Current, forming the Brazil-Malvinas Confluence. On the eastern side, the Agulhas current contributes with Indian Ocean water through the rings shed from its retroflection.

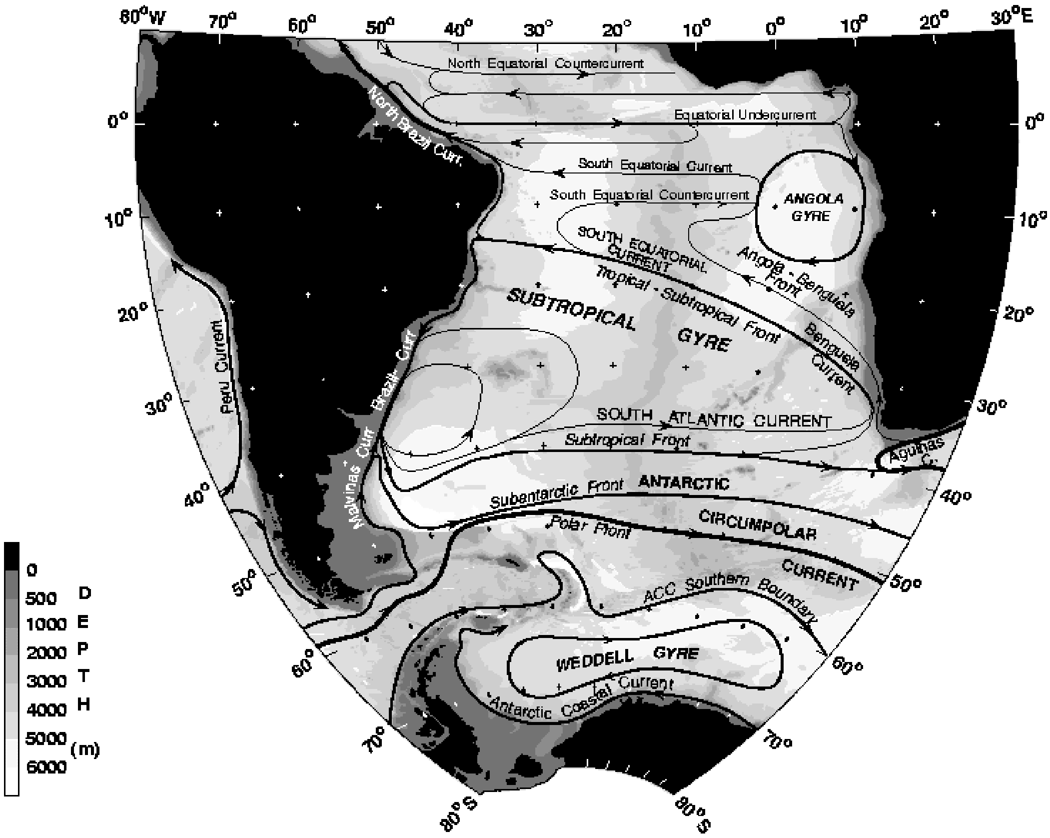

Figure 1. Schematic representation of the circulation in the upper levels of the South Atlantic (Peterson, per. comm., based on Peterson and Stramma, 1991 and Stramma and England, 1999).

2.1 - The Thermohaline Circulation

The Atlantic thermohaline circulation is one of the research areas identified as scientifically relevant to climate. According to Gordon (1986) and to Schmitz (1995), the thermohaline circulation may be equal or even more important to the global circulation system than the wind driven circulation as it couples the full volume of global ocean to the atmosphere forming a global circulation network of mass and heat transports. 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 exchanges cold deep water for warm upper water coming from the South Atlantic. The 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. As a result, the Atlantic is a peculiar ocean because it is the only one that transfers heat northward across the equator.

In spite of this knowledge, some intriguing questions still remain. For instance: how much heat is transported into the North Atlantic? From where do the different water masses involved come and what are the main routes followed by them? How is supplied the upper limb of the ``conveyor belt'' circulation? How much is warm and salty upper layer water entering the region from the Indian Ocean and how much is colder and fresher water originating out of the Drake Passage? What are the main routes of these passages and what are the mechanisms that control the transfers?

There are two main possible sources of water for the northward flow. One is the leakage from the Agulhas Current, which contributes with warmer and more saline Indian Ocean waters (Gordon, 1986; Gordon et al., 1987). The other is Antarctic Intermediate Water (AAIW), represented by the northern branches of the Antarctic Circumpolar Current (AACP).

2.2 - The Agulhas Retroflection and the Benguela Current

A regions that requires special attention because of its role in the thermohaline circulation, lies near the southern tip of South Africa where the Indian to Atlantic inter-ocean exchange takes place. One of the key questions still to be answered is how much heat and salt is transferred from the Indian to the Atlantic Ocean and what are the processes involved in this exchange. The inter ocean exchange is mostly due to the process of ring detachment and associated entrainment at the Agulhas retroflection. Energetic rings enters the Atlantic Ocean transporting salt and warm water into the Atlantic Ocean (e.g. Gordon, 1985; Lutjeharms and van Ballegoyen, 1988; Duncombe Rae et al, 1996). Several studies have been conducted in the region to determine the processes associated with the ring generation and evolution, and to study their properties (e.g. i.e., Olson and Evans, 1986; Gordon and Haxby, 1990; Duncombe Rae, 1991; van Ballegoyen et al, 1994; Duncombe Rae et al, 1996; Goni et al, 1997; Arhan et al. (1999); Garzoli et al, 1999). Estimates of the volume and heat transported by these rings from the Indian Ocean to the Atlantic Ocean have been summarized and comprehensively discussed by de Ruijter et al. (1999). Based on single realizations of hydrographic data, Gordon (1985) and Gordon et al. (1987) have suggested a net transfer between 5 to 15 Sverdrups (1 Sv = 106 m3/s) per year.

The main conduit for entraining the Indian Ocean water into the Atlantic are the Benguela Current and its extension. Across 30 S, the Benguela Current is confined between the African continental shelf and the Walvis Ridge located between 2 S 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, what changes are the sources from where the Benguela Current gains its water (Garzoli and Gordon, 1996, Garzoli et al, 1997). In the mean, the barotropic northward Benguela transport ranges between 12 and 15 Sv, with fluctuations up to 25 Sv due to the high velocities associated with the ring's shear. The main contribution to the Benguela transport comes from the South Atlantic (approximately 44 \%), the contribution from the Indian Ocean is approximately 28 \%, and the rest is a mix of Indian Ocean water that enters the region in the form of filaments and tropical Atlantic water that flows south along the coast of Africa. In a study of the first 5 years of TOPEX/POSEIDON information, Garzoli and Goni (1999) have corroborated these results but also and showed substantial interannual variability.

Another important phenomenon related to the Agulhas Current is the Natal Pulse, a solitary meander on its trajectory (Lutjeharms, 1981; Lutjeharms and Roberts, 1988; Grundlingh, 1992). The path of the northern Agulhas Current is very stable, mostly because of the narrow and steep continental shelf that stabilizes the current and minimizes the meandering (de Ruijter et al, 1999). This stability is interrupted by the passage of the Natal Pulse that alters the path of the flow, with a direct effect on the interbasin exchange of water south of South Africa. It has namely been demonstrated that each arrival of a Natal Pulse at the Agulhas Retroflection triggers the shedding of a ring (van Leewen et al., 1999). The Natal Pulses are themselves triggered by disturbances that come from the Mozambique Channel and the Region east of Madagascar. These sources of variability are the focus of some international Research projects. In a study of the influence of the Agulhas Current on the adjacent coastal ocean, Lutjeharms and de Ruijter (1996) have theorized that a change in the wind stress over the souther Indian Ocean will lead to a higher occurrence frequency of the Natal Pulse. The reduced amount of Agulhas water that enters the Atlantic Ocean will then conceivably slow down the thermohaline overturning rate. According to Lutjeharms and de Ruijter (1996), this phenomenon may have a disruptive effect on pelagic fish recruitment along the southeastern coast of South Africa and cause a significant reduction of rainfall along this shoreline.

It has been hypothesized that since some Agulhas rings can cross the full width of the South Atlantic Ocean relatively intact they will eventually reach the Brazil Current, interact with it and modify its subsequent behavior. With real-time altimetric monitoring it should not be too difficult to deploy a vessel to intercept such an Agulhas ring and to observe its interaction with the Brazil Current. Disturbances of this kind to the trajectory of the Agulhas Current have been shown to have major consequences farther downstream (Lutjeharms, 1996) and thus will indirectly affect climate. It is not inconceivable that the same may be true in the very analogous case of the Brazil Current.

2.3 - The SEC Bifurcation

As it approaches the easternmost tip of South America, the South Equatorial Current (SEC), carrying about 30~Sv in boreal winter, bifurcates giving origin to two important western boundary currents: the Brazil Current (BC), initially carrying about 4~Sv to the south, and the North Brazil Current (NBC), carrying the remainder northwestward along the northern coastline of Brazil. Eventually the NBC crosses the equator, carrying approximately 12 Sv into the northern hemisphere---comparable to the 15 Sv of the North Atlantic Deep Water Source (Stramma and Peterson, 1990; Stramma and England, 1999). The region surrounding the SEC bifurcation in the South Atlantic Ocean is one of the least well researched regions of the oceans. Yet it is a region of considerable importance. Being in the zone of the Southeast Trades, the SEC bifurcation variability may play a significant role in local climate fluctuations of Northeast Brazil, a region afflicted recently with a severe drought. It may also have important climatic effects in remote regions, through its probable effects on both the Atlantic Meridional Overturning Cell (MOC) and the Brazil-Malvinas Current Confluence.

In order to understand the role of SEC bifurcation in the regional and global climate, it is first necessary to improve our knowledge of that oceanic feature itself. At the present time, there is substantial observational evidence of the bifurcation. Knowledge of the bifurcation has existed for 230 years: it can be surmised from surface current observations made by Captain James Cook on the Endeavor in October 1768 (Beaglehole, 1955). But, in spite of this knowledge, and the importance of the phenomenon, there have been remarkably few studies of the region and there are still several unanswered questions regarding the location, and spatio-temporal variabilities of the bifurcation, and even which of the SEC's three branches feeds the NBC and BC flows.

Conditions at the bifurcation besides influencing climate will also affect downstream meso-scale processes in the ocean. For example, in the region south of Cabo Frio (22 S), the BC presents a very energetic pattern, with frequent formation of strong cyclonic and anticyclonic meanders, which sometimes detach from the main flow as well-developed rings. The cyclones, which occur on the inshore side of the current, play an important role in pumping nutrient-rich South Atlantic Central Water (SACW) from the slope region onto the continental shelf (Campos et al., 1995). The frequency and intensity of these meso-scale processes are very likely related to the behavior of the circulation at the SEC bifurcation. Although the probable effects of SEC variability are important, to date there have been no studies aimed at understanding any of these tropic-extratropic connections.

2.4 - The Brazil-Malvinas Confluence

The Brazil Current meets the Malvinas Current around 38 S, a region that has been called the Confluence region (Gordon and Greengrove, 1986). At the Confluence, a strong thermohaline front originates. The position of this front varies considerably (Olson et al., 1988; Garzoli and Garraffo, 1989). As a result there is strong variability in the northward penetration of the cold, fresh water that characterizes the Malvinas Current. This in turn affects several processes associated with the climate over South America. Olson et al. (1988) suggested that variations in the latitude of the Brazil-Malvinas Confluence might be driven by changes in the Malvinas transport, which in turn are forced by variations in the Antarctic Circumpolar Current (ACC).

Large variations in the latitude of the frontal zone, or Confluence, separating the warm Brazil Current from the cold Malvinas Current have been obvious since at least the Meteor Expedition in the 1920s (Defant, 1941). The large amplitude meanders extending offshore create large SST anomalies. The location of the separation of the currents from the continental shelf edge also varies up to 930km along the coast (Legeckis and Gordon, 1982; Olson et al., 1988). The major question is the nature of the dynamics behind these variations and how they are related to the nature of the two currents and the factors that force them. These variabilities lead to large SST variations both on a seasonal and interannual time scales. Podesta et al (1991) and Provost et al (1992) found that the annual signal in SST weakens to the south. The frequency of major oscillations is tied to the relative strengths of the annual cycle in the Brazil Current forced by winds in the subtropics, as compared to the semi-annual forcing over the subantarctic sector. The annual signal in the Brazil Current involves southward shifts in the separation latitude and an extension of warm waters into the first meander crest offshore around the first of the year (Olson et al., 1988) that corresponds to altimetric sea surface height signals over the region (Matano et al., 1993).

Results of observational and modeling studies clearly implicate that wind forcing and non-linear instabilities are sources for variabilities in the Confluence (Olson et al, 1988; Campos and Olson, 1991; Provost and Le Traon, 1993). Additionally, there are several other factors that can modify the annual and semiannual signals to produce interannual variability. Variations of the offshore boundary currents, local winds, and freshwater inputs from the continent dominate the circulation over the broad southeastern South American continental shelf, which produces SST anomalies that are nearly as strong as those produced offshore. A recent work (Campos et al., 1999) based on the analysis of satellite AVHRR data suggested that interannual variability of the SST along the eastern South American Continental Shelf could be related to ENSO. According to this work and other studies (Campos, Piola and Matano, 1999; Piola et al., 1999), the possible connections would be through precipitation over the continent and the discharge of Rio de la Plata.

Rings shed from both sides of this Confluence may have a decisive effect on the formation of water masses, on the ventilation of the local thermocline and on the distribution of heat and salt over a wide expanse of the South Atlantic Ocean. All these factors are of substantial climatological importance. The rings shed from the Brazil Current are thought to travel in an easterly direction after spawning. Altimetric information from satellites suggest that they dissipate rather rapidly, but no substantive study has as yet been made of this aspect of their life history. It has even been claimed that Brazil rings drift all the way to the Agulhas retroflection and have been observed there (Smythe-Wright et al., 1996). This result has recently been challenged by McDonagh and Heywood (1999) who showed that this particular ring was of Agulhas Current and not Brazil Current origin. Nonetheless, all the questions pertaining to the Agulhas rings, namely: where do they move, how fast do they spin down, where do they lose their salt and heat to ambient water masses, what effect do they have on the circulation as a whole, are all equally applicable to Brazil rings. The heat and salt fluxes brought about by these meso-scale features are essential elements of the wider circulation in the South Atlantic. Many aspects of these rings can be studied with remote sensing, but detailed hydrographic measurements at sea are essential to validate such results from remote sensing and to establish heat and salt fluxes. All that has been said here pertaining to Brazil rings holds equally for cold rings detached at the Confluence from the Malvinas Current. Both warm and cold vortex features deserve increased research attention because of their influence on wider climatic conditions of the ocean, but also for their possible impact an the climate variability of the adjacent land masses.

A potential impact of BMC variability on the thermohaline circulation would be related to the fate of western South Atlantic AAIW rather than its formation: southward fluctuations of BMC (and the Subtropical Front, STF) may lead to a larger export of AAIW to the Indian Ocean by way of the northward edge of the ACC and the Agulhas return current. In contrast, northward displacements of the BMC may lead to a further northward penetration of AAIW into the western South Atlantic, a larger northward flow of AAIW along the eastern branch of the South Atlantic subtropical gyre and a lesser export to the Indian Ocean. The significance of this northward penetration of the AAIW is in the heat and salt balances of the upper limb of the MOC: larger proportions of AAIW will reduce the temperature and salinity of the upper limb. In addition to the BMC-STF, there is also the question as to what amount of thermocline water and AAIW recirculate southward after reaching the South America by re-joining the Brazil Current and what amount of each component cross the equator and flow/mix further north into the northern North Atlantic. Important questions here are: Are these flows real? If they are, can we find evidence that their mixtures vary with time in connection to changes observed in the subtropical South Atlantic? Do these variations affect the properties or even the amount of NADW?

2.5 - The Subtropical Front

The Subtropical Front forms the generic border between the Subtropical water masses and the Subantarctic water masses, at least in the upper levels. Over long time averages it is a zone of convergence, with the subduction of Subantarctic Surface Water, although on the short term it may be considerably more complex. furthermore, specific water masses such as Subantarctic Mode Water may be formed at certain specific parts of the Subtropical Front during certain parts of the year. This is therefore a very important feature of this ocean and knowledge of the processes that occur here may be crucial to a better understanding of the climatically important workings of the ocean in general. How much is know about the Subtropical Front in the South Atlantic Ocean? Regrettably, not enough by far.

Some attention has been given to the Subtropical Front in the south-eastern corner of the South Atlantic (Lutjeharms, 1985), mostly in connection with studies of the Agulhas Current and the Agulhas Return Current (Lutjeharms and Ansorge, 1999). It has been demonstrated that the Subtropical Front, when enhanced by the outflow from the Agulhas Current is highly variable, with many meanders and eddy shedding (Lutjeharms and Valentine, 1988). This type of mesoscale turbulence is characteristic for the Subtropical Front wherever it lies adjacent to a western boundary current. It also holds true for the Brazil Current termination. Since these regions are relatively close to land they have in general been hydrographically surveyed. This is not the case for the Subtropical Front farther away from the basin borders.

Very little is known about the nature of the Subtropical Front in the central parts of the South Atlantic. Meridional sections (e.g. Whitworth and Nowlin, 1987) have shown it to be sharp and to extend to at least intermediate water depths. Studies with satellite thermal infrared products and with regular XBT sections (Lutjeharms et al., 1993) have suggested that it has a seasonal characteristic, but that its surface expression may be ephemeral here. Subsequent investigations that have included a number of high-quality hydrographic sections (Smythe-Wright et al., 1998) have indicated that on occasion the Subtropical Front may be thought of as consisting of multiple fronts, forming the borders of the South Atlantic Current (Stramma and Peterson, 1990). These studies have all added to our knowledge of the region, but have more than ever high-lighted our ignorance. Are eddies formed at the Subtropical Front away from the basin borders and where do these eddies move? Is water subducted at the front continuously or spasmodically? Is there a seasonal component to this behavior? What is the hydrographic structure of the Subtropical Front across the width of the South Atlantic? The answers to all these questions have considerable consequences for a better understanding of climate.

3 - THE AIR-LAND-SEA AND THE TROPIC-EXTRATROPIC INTERACTIONS

3.1 - Air-Land-Sea Interactions and the Regional Climate

The role that the South Atlantic plays in the climate variability of the adjacent continents should be significant. On the eastern side of the basin, studies of teleconnections between sea surface temperatures in the South Atlantic and rainfall over the southern African subcontinent (Walker, 1990) have in fact demonstrated that this statistical relationship is substantial and quantifiable. It has even been demonstrated by numerical modeling (Crimp et al., 1998) that a small increase in the surface temperature in the Agulhas retroflection region will bring about a measurable change in the patterns of atmospheric circulation over southern Africa. Jury (1995) and Mason (1995) have recently summarized the solid body of results on such relationships that has been gathered since the first work by Walker. This research is continuing, but remains hamstrung by a lack of knowledge on how this statistical coupling is achieved physically.

A number of preliminary studies have been carried out in this regard in the southern Agulhas Current and the Agulhas retroflection. The aim has been to establish the effect of this warm current on the overlying atmosphere. It has thus been demonstrated (Walker and Mey, 1988) that there are large, year-long fluxes of heat and moisture from the southern Agulhas Current to the atmosphere. These fluxes have a very important and vertically extensive influence on the overlying atmosphere (Lee-Thorp et al., 1999). Heat fluxes from Agulhas rings south of the Subtropical Front (Rouault and Lutjeharms, 1999) to the atmosphere have been shown to go as high as 800 W/m2. All these studies have been carried out close to land and over very specific components of the southern Agulhas Current system. It is unlikely that these would be representative of larger regions of the South Atlantic Ocean. Such observations should therefore be extended over a greater part of this ocean.

On the western side of the basin, the subtropical to temperate end of South America represents a unique climatic zone. It is bound on the north by the greatest expanse of tropical rain forest on earth, the Amazon. To the west, the atmospheric flow is strongly perturbed by the presence of the Andes, leading to desert conditions extending from Patagonia, in the south, up the eastern edge of the mountains. The intermediate region is characterized by wet and dry savannas, and one of the world's greatest river drainages, the Parana-Paraguay basins. Separated from these basins by coastal mountains is the highly populated Atlantic seaboard, dominated by coastal lagoons from the Patos-Mirim system, in the southern Brazil and Uruguay, to the Guanabara Bay at Rio de Janeiro. The region is home to a population of nearly 200 million people, most of whom are concentrated in the great commercial/industrial centers of Rio de Janeiro, Sao Paulo, Porto Alegre, Montevideo and Buenos Aires. Much of the remaining region is dominated by agricultural activities. During the last few decades, climatic variations have had an important economic and social impact on the region. Drought periods have produced changes in cattle population, drained the water supplies of Buenos Aires and Montevideo, and caused shortages of hydroelectrical power. In the 1970s, there was a significant expansion of farming in the Argentine Pampas, apparently as a response to a westward shift in precipitation for some unknown reason. While the existence of these sorts of climate fluctuation over this region have been appreciated for at least 80 years, the mechanisms behind them are still unclear.

Several studies point out the importance of Atlantic ocean SST in modulating rainfall over South America (Wainer and Soares, 1997; Sperber and Hameed, 1993; Kalnay et al., 1986; Hastenrath and Heller, 1977). Wainer and Soares, 1997 discuss from a statistical point of view the relationship not only between rainfall changes in Northeast Brazil and the position of the ITCZ but also with respect to rainfall variability in the Sahel region. By looking at patterns of correlation coefficient between monthly meridional wind stress anomalies, averaged for February, March and April and the Hastenrath index for precipitation anomalies, for the period 1964-1984 they show an out of phase relationship between these two regions, that is a function of the position of the ITCZ.

Kalnay et al. (1986) diagnosed and modeled a strong SACZ event and they found that low-level cyclonic vorticity values were associated with negative SST anomalies. This correlation therefore would indicate that the atmospheric anomalies were causing the SST anomalies, which in turn provide a negative feedback to the atmosphere. However, there are some indications that warm SST anomalies may have a role in the onset of the convection over tropical South America. Therefore the possible influence on intraseasonal time scales, of WSA SST anomalies on SACZ and convection onset should be further explored. Furthermore, Vera and Mechoso, 1998 point out the results of Diaz et al. (1998) who show significant relationships between rainfall anomalies over southeastern South America and SST in the Pacific and Atlantic oceans. The links between SST anomalies in the southwestern Atlantic ocean and rainfall anomalies in the entire region are more pronounced during October-December and April-July (Diaz et al, 1998). The fact that the years which show positive peaks in these links do not necessarily coincide with those obtained for the Pacific ocean, indicate that the SST anomalies in the Atlantic, may contribute on their own to rainfall anomalies over Uruguay and southern Brazil.

Observations of SST anomalies over the Subtropical South Atlantic off the coast of Brazil have indicated that short lived variability in the range of one to two months may play a crucial role in determining intraseasonal rainfall variability over parts of South America. It appears that for some periods, e.g. January-February 1998, warm anomalies in excess of 2 C off the coast of Brazil which lasted for 6 weeks may have caused the South Atlantic Convergence Zone to remain quasi-stationary and to lie over the warm waters. That caused a particular pattern of high rainfall over land. That pattern was not correctly predicted by GCM's which used persisted anomalies from December to predict seasonal climate (January-March). The mechanisms for genesis and decay of such pattern of anomalies are not established as yet.Although there is significant evidence showing the importance of monitoring South Atlantic SST anomalies for regional climate and weather prediction in southern South America, much work is still needed in order to understand the details of how these SST anomalies (sometimes short-lived) affect rainfall regimes, weather patterns and how (or if) these in turn will modify the SST distribution.

Sea surface temperature anomalies (SSTA's) in the tropical Atlantic are weaker than those associated with the Pacific El Nino. Nonetheless, they can cause disastrous climate hazards over the Americas and Africa. The well-known droughts of Northeast Brazil and the Sahel in Africa, for example, have been shown to be closely related to tropical Atlantic SST variability. Of particular importance is a much debated form of variability seemingly unique to the Atlantic Ocean, often referred to as the Atlantic SST dipole (Moura and Shukla, 1981). This feature involves a low-frequency oscillation of the SST gradient across the equator, which has spatially coherent SST patterns in the tropics/subtropics of either hemisphere. Empirical studies based on 100-year observations suggest that the dipole-like SST variability has a pronounced spectral peak at a period of approximately 12-13 years and accounts for about 20 \% of the total yearly-averaged SST variance in the tropical Atlantic Ocean (Mehta, 1998). However, this work has cast serious questions on the existence of the so-called dipole as a physical mode of the coupled system, since a majority of the coherent decadal variance in the cross-equatorial SST gradient is due to large-scale coherent SST fluctuations from the South Atlantic Ocean. Yet, at the present time we do not have a good understanding of the mechanisms that give rise to such SST variability that spans the tropics and subtropics.

3.2 - The Tropic-Extratropic Interactions

Possible links between the tropics, subtropics, and mid-latitude oceans have received greater emphasis in the Pacific Ocean because of the prospects for decadal modulations of El Nino. Theoretical studies of the interaction between the tropics and subtropics have been stimulated by the Pedlosky's (1987) paper that extended the ventilated thermocline theory from the subtropics to the equator. Potential vorticity arguments were invoked to link subducted fluid parcels from the subtropics with the Equatorial Undercurrent. Subsequent modifications to the theory took into account the initial specification of the undercurrent transport by the western boundary current, the downstream decrease in transport along the equator due to entrainment of eastward momentum up into the mixed layer (Pedlosky, 1988; Pedlosky and Samuelson, 1989; Pedlosky and Robinson, 1991), and the modification of the subduction structure by an overlying mixed layer (Pedlosky and Robinson, 1991). A corresponding series of idealized numerical modeling studies (McCreary and Lu, 1991; Liu, 1994; Liu et al., 1994, Liu and Philander, 1995) have served to isolate the relative influence of the equatorial Pacific zonal wind stress versus the wind stress curl over the subtropical gyres with respect to the subduction of water feeding the Equatorial Undercurrent along the equator, into the western boundary currents, or recirculating within the subtropical gyre. Rothstein et al. (1998) used realistic forcing to simulate the annual mean water pathways connecting the tropical and subtropical Pacific Ocean. Potential vorticity dynamics were used to explain the path taken by subtropical thermocline water as it flowed into the tropics. The existence of vigorous zonal currents made this exchange much more complicated than a conceptual meridional circulation cell. Gu and Philander (1997) hypothesized that exchange between subtropical and tropical water masses through thermocline ventilation could cause decadal changes in the depth of the thermocline at the equator and, as a result, could modify the nature of ocean-atmosphere coupling and lead to decadal SST variability. Zhang et al. (1998) analyzed subsurface temperature observations and tracked the evolution large-scale anomalies in the subsurface thermal field beginning in the subtropical Pacific and terminating in the tropics.

The possibility of such interactions in the Atlantic Ocean is not new, but is beginning to receive more scrutiny. In contrast to the Pacific Ocean, the zonally averaged circulation in the tropical Atlantic is characterized by a net northward transport of mass and heat. For example, Bjerknes (1964) recognized the possible importance of advection in determining regional SST patterns. He described the path of an SST anomaly originating in the South Atlantic, subsequently being advected into the subtropics of the North Atlantic (i.e., cross equatorial and cross gyre exchanges), and the associated atmospheric response. More recently, Hansen and Bezdek (1996) presented observational evidence of anomalous SST variability on decadal and interdecadal time scales extending into the tropical Atlantic from the North Atlantic. For the South Atlantic, Venegas et al (1998) have shown the existence of SST anomalies propagating anticyclonically around the subtropical gyre with a period of twenty years. Together with associated changes in sea level pressure, horizontal advection by the upper ocean circulation and local changes in the air-sea heat fluxes were proposed as a possible coupled mechanism. However, the largest interannual scale anomalies dominating the South Atlantic are derived from the Drake Passage and appear to be coupled to ENSO and the Antarctic Circumpolar Wave (White and Peterson, 1996).

The role and importance of subducted water masses in the South Atlantic is relatively unknown. By analogy, we know that in the North Pacific Ocean before water subducts into the thermocline from the subtropics, it first circulates around the perimeter of the subtropical gyre, and then flows westward across the basin as part of the North Equatorial Current. At the western boundary, the current bifurcates near the Philippine coast feeding the Kuroshio to the north and the Mindanao Current to the south. The work of Qiu and Lukas (1996) has shown that the interannual changes in the wind stress curl to the east govern the incoming transport, and the meridional migration of the zero wind stress curl line has a major influence on the latitude of the bifurcation. However, in the South Atlantic little is known of the mechanisms governing the location of the bifurcation and the variability of the SEC. This is not an esoteric question restricted to the ocean circulation, as Diaz et al (1998) have shown that anomalous SST variability in the western Atlantic from 20 S - 30 S, i.e., in the vicinity of the bifurcation, may exert an important local influence on interannual precipitation over Uruguay and Southern Brazil.

Thus, it is recognized that anomalous changes in the communication between the tropics and subtropics may exist. What is less well known are the pathways for mass and heat exchange between the subtropical and tropical Atlantic Ocean, what induces decadal scale anomalies of the subsurface thermal field, and whether there is a link between this variability in the subtropics and interannual to decadal scale variability of SST?

4 - THE PROPOSED STRATEGIES

An important point that arises from the introductory description of the South Atlantic is that we ought to decide for a few control points and key processes, and propose an observational/modeling program for studying them in next decade. For instance, while it seems clear that the variabilities in the Brazil-Malvinas Confluence are important to regional climate, their connection to the global system is not as straightforward and need to be further investigated. There are speculations that the spatial variability of the BMC location could interplay with the AAIW and, thus, have some impact on the thermohaline circulation. Other processes of fundamental interest are the retroflection of the Agulhas Current, the Benguela Current, the SEC bifurcation and the formation of the AAIW south of the Subtropical Front.

The envisioned observational program should include the measurement of the current systems in the control points, and the interactions of these currents with the larger-scale oceanic circulation, the river discharges, and shelf processes be understood. The ecology of key planktonic species in this region should be identified and described in order to predict the impact of global climate changes on the regions ecosystem's. Besides their intrinsic value as diagnostic tools, these measurements could provide the basic information for a monitoring scheme, on decadal time scales, and the development of prognostic model simulations. The proposed techniques should be a combination of ship-based hydrographic samplings, moored arrays of currentmeters and other profiling instruments, ARGO-based moorings and drifters, XBT lines and Acoustic measurements, surface flux measurements and remote sensing. Contribution of the South American oceanographic community would be of great interest in the monitoring of the BMC and SEC bifurcation regions. Cooperation with Africans would be desirable for the surveys in the Agulhas retroflection.

The connection between the South Atlantic Ocean and the global circulation can be made through the collection and analysis of atmospheric and oceanic observations and numerical simulations. Meteorological data bases of particular interest to the envisioned research program are: (1) global analyses produced by major forecast centers (e.g., ECMWF,NCEP); (2) observations at station locations (e.g, precipitation, river discharge); and (3) satellite estimates of surface winds, SST and sea surface height (SSH). Since global analyses provide only a coarse description of regional quantities, a hierarchy of embedded atmospheric models of increasing resolution should be developed to provide high resolution data on the regional scale. These database would in turn be used by high resolution ocean models.

In addition to the possible reoccupation of WOCE lines in the South Atlantic, it is proposed that hydrographic surveys be repeated at convenient intervals, in the key locations identified here as control points: the Brazil/Malvinas Confluence, the SEC Bifurcation and the Agulhas Retroflection.

These hydrographic measurements would provide valuable information about heat and volume transports, as well as about the water mass formation and evolution in time. As extensively discussed in this document, it is necessary to understand circulation on the control points and the interactions with the adjacent oceans, in order to predict the effects of climate change in the South Atlantic. Conversely, the gained knowledge could also be used to understand the role of the South Atlantic in the variations of the global climate. Thus, the observations at the basin scale should be directed to understand the interaction with the Pacific and Indian Oceans. In consequence, measurements should monitor the Antarctic Circumpolar Current transport at the Drake Passage to determine its effect on the Confluence Dynamics.

The observational program should include CTD/tracer (chlorofluorcarbon,CFC) measurements. The objective of these measurements is to monitor changes in the partitioning of the air-sea fluxes as they affect the properties of the Mode and AAIW waters. The importance of these changes in the meridional overturning circulation on long time scales could be evaluated through model simulations and related to long term variations in SST such as ENSO and the Atlantic Oscillation.

Although the ultimate goal is the understanding of the climate as a whole, for an effective contribution of the local communities the regional aspects of climate change should be taken in consideration. This requires that part of the observational and modeling effort be dedicated to the shelf and shelf break regions. In particular, the oceanographic research on continental shelves of eastern South America should be directed to understand the mechanism which control heat and fresh water fluxes on the shelf, and their relationship to global change. This region between the estuaries along the coast and the western boundary currents at the shelf break is the dynamical interface between the terrestrial oceanic systems. Processes in those areas affect and are affected by atmospheric dynamics through both direct and indirect couplings. Mesoscale processes on the continental shelf such as wind-driven upwelling (e.g., at Cabo Frio) and meander-induced upwelling (e.g., along the southern Brazil and northern Argentine shelf-breaks), and density-driven currents (e.g. the cold low salinity Rio de la Plata coastal plume) transport significant quantities of heat, salt and nutrients which are key to controlling biological and physical dynamics in the region. Changes in the winds, surface heat fluxes, and riverine discharges can substantially alter the strength of these transport mechanisms. These can modify fluxes to the atmosphere and, therefore, potentially, result in a feedback to the continental shelf dynamics.

In combination with the proposed observational program, a hierarchy of numerical and analytical models should be used to investigate the circulation in the South Atlantic, and to evaluate its sensitivity to climate change scenarios. The sensitivity to various climate change scenarios in the atmosphere (uncoupled model) should be first investigated in a global model. The focus would be on how the modeled South Atlantic connections to the rest of the world oceans are modified under these various scenarios. In particular, the property changes in water masses and associated impact on the thermohaline circulation (strength, pathways) should be documented. Coupled runs with an atmospheric model should them be performed and the results compared to the uncoupled runs with the ultimate goal of identifying the mechanisms behind any climate change in the South Atlantic. At the basin scale the objective will be to determine the impact of local and remote forcings (winds, ACC transport, Agulhas transfer) on the heat and mass balances of the South Atlantic. Regions such as the Agulhas retroflection, SEC bifurcation and the BMC should receive special attention.

5 - CONCLUDING REMARKS

We would like to close this document calling the attention to a few, very important, facts: the South Atlantic Ocean is, definitively, a fundamental piece in the global climate puzzle; Togheter, the adjacent portions of the continents are home for hundreds of million of human beings; due to the clear political importance of the ability to understand and predict impacts of climate changes on local economies, the South Atlantic countries are certainly willing to contribute with international efforts aimed at this problem. As a matter of fact, there are underway several significant contributions by the local scientific communities, most of them in productive collaboration with international partners.

Finally, it should be kept in mind that the present knowledge of the South Atlantic circulation, climate, atmosphere-ocean interaction and variability is very limited compared to those of the North Atlantic, equatorial Pacific and North Pacific. Thus, the proposed observation efforts should be regarded only as a first approximation to an ocean climate monitoring system.

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6 - REFERENCES:

Arhan, M, H. Mercier and J. R. E. Lutjeharms (1999): The disparate evolution of three Agulhas rings in the South Atlantic Ocean. Journal of Geophysical Research, in press.

Bjerknes (1964): J. Atlantic air-sea interaction, In Advances in Geophysics, H.E. Landsberg and J.V. Mieghemeds, Academic Press, pp. 1-82.

Beaglehole, J.C. (1955): The Journals of Captain James Cook on his Voyages of Discovery. Vol. 1. The Voyage of the Endeavour 1768--1771. Cambridge University Press (Hakluyt Society Extra Series No. 34).

Broecker, W.W. (1991): The great ocean conveyor belt, Oceanography, 4, 79-89, 1991.

Campos, Edmo J. D. and D. B. Olson (1991): Stationary Rossby Waves in Western Boundary Current Extensions. J. Phys. Oceanogr. 21(8), 1202-122.4

Campos, E. J. D., J. E. Goncalves and Y. Ikeda (1995): Water Mass Structure and Geostrophic Circulation in the South Brazil Bight -- Summer of 1991. J. Geophys. Res., Vol. 100, No. C9, 18,537-18,550;

Campos, E.J.D., C.A. Lentini, J.L. Miller and A.R. Piola (1999): Interannual variability of the sea surface temperature in the South Brazil Bight, Geophys. Res. Letters, Vol. 26, No. 14 pp. 2061-2064.

Campos, E.J.D., A.R Piola and R.P Matano (1999): The Western South Atlantic and Climatic Variations over South America. IAI NewsLetter, Issue 19, 13-18.

Crimp, S. J., J. R. E. Lutjeharms and S. J. Mason (1998): Sensitivity of a tropical-temperate trough to sea-surface temperature anomalies in the Agulhas retroflection region. Water SA, 24(2): 93-101.

Defant (1941): A., Die Absolute Topographic das phys. Meeresniveaus un der Druckflachen, sowie die Wasserbewegungen im Atl. Ozean. Meteor Werk. 6(2). 5., 191-250.

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

Diaz, A.F., C. D. Studzinski, and C. R. Mechoso (1998): Relationships between precipitation anomalies in Uruguay and Southern Brazil and sea surface temperature in the Pacific and Atlantic Oceans, J. Clim., 251-271, 11.

Duncombe Rae, C.M. (1991): Agulhas Retroflection rings in the South Atlantic Ocean: An overview. S. Afr. J. Mar. Sci., 11:327-344.

Duncombe Rae, C.M., S.L. Garzoli, and A.L. Gordon (1996): The eddy field of the southeast Atlantic Ocean: A statistical census from the Benguela Sources and Transports Project. J. Geophys. Res., 101(C5):11,949-11,964.

Garzoli, S.L., and Z. Garraffo (1989): Transports, frontal motions and eddies at the Brazil-Malvinas currents Confluence. Deep-Sea Research, 36, 681--703.

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., G. Goni, A. Mariano, and D. Olson (1997): Monitoring South Eastern Atlantic Transports using altimeter data. Jour. Mar. Res, 55, 453-481, 1997.

Garzoli, S.L., and G. Goni (1999): Combining Altimeter Observations and Oceanographic Data for Ocean Circulation and Climate Studies. To be published in the ICSOS Book.

Garzoli, S.L., P.L. Richardson, C.M. Duncombe Rae, D.M. Fratantoni, G.J. Goni and A.J. Roubucek (1999): Three Agulhas Rings Observed During the Benguela Current Experiment. In press.

Goni, G. J., S.L. Garzoli, A.J. Roubicek, D.B. Olson, and O.B. Brown (1997): Agulhas ring dynamics from TOPEX/POSEIDON satellite altimeter data. J. Mar. Res., 55(5):861-883.

Gordon, A.L. (1985): Indian-Atlantic transfer of thermocline water at the Agulhas Retroflection. Sciences, N.Y., 227(4690):1030-1033.

Gordon, A.L. and C. Greengrove (1986): Geostrophic circulation of the Brazil-Falkland Confluence. Deep Sea Res., 33, 573-585.

Gordon, A.L. (1986): Interocean exchange of thermocline water. J. Geophys. Res., 91, 5037-5046.

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

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

Grundlingh, M. L. (1992): Agulhas Current meanders: review and a case study. S. Afr. Geogr. J., 74(1): 19-28.

Gu, D. and S.G.H Philander (1997):, A theory for interdecadal Climate fluctuations, Science, 275, 805-807.

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

Hastenrath, S., and L. Heller (1977): Dynamics of climatic hazards in north-east Brazil. Quart. J. R. Meteor. Soc., 110, 411-425.

Jury, M. R. (1995): A review of research on ocean-atmosphere interactions and South African climate variability. South African Journal of Science, 91(6): 289-294.

Kalnay, E., K.C. Mo and J. Paegle (1986): Large amplitude, short-scale stationary Rossby waves in the Southern Hemisphere: Observations and mechanistic experiments to determine their origin. J. Atmos. Sci., 43, 252-275.

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

Lee-Thorp, A. M., M. Rouault and J. R. E. Lutjeharms (1999): Moisture uptake in the boundary layer above the Agulhas Current; a case study. Journal of Geophysical Research, 104(C1): 1423-1430.

Legeckis, R. and A. L. Gordon (1982): Satellite observations of the Brazil and Falkland Currents, 1975 to 1976 and 1978. Deep Sea Res., 29(3A), 375-401.

Liu, Z. (1994): A simple model of the mass exchange between the subtropical and tropical ocean, J. Phys. Oceanogr., 24, 1153-1165.

Liu, Z., S.G.H. Philander and R.C. Pacanowski (1994): A GCM study of subtropical-tropical upper-ocean water exchange, J. Phys. Oceanogr., 24, 2606-2623.

Liu, Z. and SGH. Philander (1995): How different wind stress patterns affect the tropical-subtropical circulations of the upper ocean, J. Phys. Oceanogr., 25, 449-462.

Lutjeharms, J.R.E. (1981): Features of the southern Agulhas Current circulation from satellite remote sensing. S. Afr. J. Sci., 77, 231-236.

Lutjeharms, J.R.E., and R.C. van Ballegoyen (1988): The retroflection of the Agulhas Current. J. Phys. Oceanogr., 18:1570-1583.

Lutjeharms, J.R.E., and H.R. Roberts (1998): Eddies at the Sub-Tropical Convergence south of Africa, J. Phys. Oceanogr., 18, 761-774

Lutjeharms, J.R.E., and W.P. de Ruijter (1996): The influence of the Agulhas Current on the adjacent coastal ocean: possible impacts of climate change, J. Marine System, 7, 321-336.

Lutjeharms, J. R. E. (1985): Location of frontal systems between Africa and Antarctica: some preliminary results. Deep-Sea Research, 32(12):1499-1509.

Lutjeharms, J. R. E. and H. R. Valentine (1988): Eddies at the Sub-Tropical Convergence south of Africa. Journal of Physical Oceanography, 18(5): 761-783.

Lutjeharms, J. R. E., H. R. Valentine and R. C. van Ballegoyen (1993): The Subtropical Convergence in the South Atlantic Ocean. South African Journal of Science, 89(11/12): 552-559.

Lutjeharms, J. R. E. (1996): The exchange of water between the South Indian and the South Atlantic. In "The South Atlantic: Present and Past Circulations", editors G. Wefer, W. H. Berger, G. Siedler and D. Webb, Springer-Verlag, Berlin, pp. 125-162.

Lutjeharms, J. R. E. and I. J. Ansorge (1999): The Agulhas Return Current. Journal of Physical Oceanography, submitted.

Mason, S. J. (1995): Sea-surface temperature - South African rainfall associations, 1910-1989. International Journal of Climatology, 15( ): 119-135.

Matano, R.P., M.G. Schalx,and D.B.Chelton (1993): Seasonal variability in the southwestern Atlantic. J.Geophys. Res., 98, 18,027-18,035.

McDonagh, E. L. and K. J. Heywood (1999): The origin of an anomalous ring in the Southeast Atlantic. Journal of Physical Oceanography, 29( ): 2025-2064.

McCreary, J.P. and P. Lu (1994): Interaction between the subtropical and equatorial ocean circulations: the subtropical cell, J. Phys. Oceanogr., 24, 466-497.

Mehta, V. M. (1998): Variability of the tropical ocean surface temperatures at decadal-multidecadal timescales. Part I: The Atlantic Ocean, J. Clim., 11, 2351-2375.

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.

Olson, D.B., and R.H. Evans (1986): Rings of the Agulhas Current. Deep-Sea Res., 33:27-42.

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 Research, 35, 1971--1990.

Pedlosky, J. (1987): An inertial theory of the equatorial undercurrent, J. Phys. Oceanogr., 17, 1978-1985.

Pedlosky, J. (1988): Entrainment and the termination of the equatorial undercurrent, J. Phys. Oceanogr., 18, 880-886.

Pedlosky, J. and Robinson (1991): The link between western boundary current and equatorial undercurrent, J. Phys. Oceanogr., 21, 1553-1558.

Pedlosky, J. and R.M. Samuelson (1989): Wind forcing and the zonal structure of the Equatorial Undercurrent, J. Phys. Oceanogr., 19, 1244-1254.

Peterson, R.G and L. Stramma (1991): Upper-level circulation in the South Atlantic Ocean. Progress in Oceanogr, 26, 1-73.

Piola, A.R., E.J.D. Campos, O.O. Moller Jr., M. Charo and C. Martinez (1999): The Subtropical Shelf Front off eastern South America. Jour. Geophys. Res., in press.

Pisciotanno, G., A. Diaz, G. Cazes and C.R. Mechoso (1994): El Nino-Southern Oscillation impact on rainfall in Uruguay. J. Climate 7(8), 1286-1302.

Podesta, G.P., O.B. Brown, and R.H. Evans (1991): The annual cycle of satellite-derived sea surface temperature in the southwestern Atlantic Ocean. J. Climate, 4, 457-467.

Provost, C., O. Garcia and V. Garcon (1992): Analysis of satellite sea surface temperature time series in the Brazil-Malvinas Currents Confluence region: Dominance of the annuyal and semiannual periods. J. Geophys. Res., 97, 17,841-17,858.

Provost, C. and P. Le Traon (1993): Spatial and temporal scales in altimetric variability in the Brazil-Malvinas Current Confluence region: Dominance of the semiannual period and large spatial scales. J. Geophys. Res., 98, 18,037-18,052.

Reid, J. (1989): On the total geostrophic circulation of the South Atlantic Ocean: flow patterns, tracers and transport, Progress in Oceanography. Pergamon Press, 23, 149-244.

Ropelewski, C.F. and M.S. Halpert (1987): Global and regional scale precipitation patterns associated with the El Nino/Southern Oscillation. Mon. wea. Rev., 115, 1606-1626.

Rothstein, L.W., R-H. Zhang, A.J. Busalacchi, and D. Chen (1998): A numerical simulation of the mean water pathways in the subtropical and tropical Pacific Ocean, J. Phys. Oceanogr., 28, 322-343.

Rouault, M. and J. R. E. Lutjeharms (1999): Air-sea exchange over an Agulhas eddy at the Subtropical Convergence. The Global Atmosphere and Ocean System, accepted.

Schmitz, WJ (1995): On the interbasin-scale thermohaline circulation. Reviews in Geophysics 33(2): 151-173.

Smythe-Wright, D., A. L. Gordon, P. Chapman and M. S. Jones (1996): CFC-113 shows Brazil eddy crossing the South Atlantic to the Agulhas retroflection region. Journal of Geophysical Research, 101(C1): 885-895.

Smythe-Wright, D., P. Chapman, C. Duncombe Rae, L. V. Shannon and S. M. Boswell (1998): Characteristics of the south Atlantic subtropical frontal zone between 15W and 5E. Deep-Sea Research, 45(1): 167-192.

Sperber, K and S. Hameed (1993): Phase Locking of Nordeste Precipitation with sea surface temperatures. Geophysical Research Let. 20, no 2, 113-116.

Stramma, L. and R. G. Peterson (1990): The South Atlantic Current. Journal of Physical Oceanography, 20(6): 846-859.

Stramma, L. and M. England (1999): On the water masses and mean circulation of the South Atlantic Ocean. Jour. Geophys. Research, in press.

Tanajura, C. A. S. (1998): A Seasonal Simulation of the SACZ with the Eta Model and the COLA GCM. CD-Rom X Brazilian Conference on Meteorology, Brazilian Meteorological Society, October 26 to 31, 1998, Brasilia, DF, Brazil.

Van Ballegoyen, R.C., M.L. Grundlingh, and J.R.E Lutjeharms (1994): Eddy fluxes of heat and salt from the southwest Indian Ocean into the southeast Atlantic Ocean: A case study. J. Geophys. Res., 99(C7), 14,053-14,070.

van Leeuwen, P. J., W. P. M. de Ruijter and J. R. E. Lutjeharms (1999): Natal Pulses and the formation of Agulhas rings. Journal of Geophysical Researech, in press.

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., 103, 24,723-24,736.

Vera, C. and R. Mechoso (1998): The Atlantic ocean impact on Climate Variability over South America. Report of the VAMOS Working Group on the South American Monsoon System (SAMS). October 1998, Miami, Florida

Wainer, I., and J. Soares (1997): North Northeast Brazil Rainfall and its Decadal Scale Relationship to Wind Stress and Sea Surface Temperature. Geophys. Res. Letters. 24,277-280.

Walker, G. (1924): Correlations in seasonal variations of weather, IX. India Meteor. Dept. Memoirs (9).

Walker, N. D. (1990): Links between South African summer rainfall and temperature variability of the Agulhas and Benguela Current Systems. Journal of Geophysical Research, 95(C3): 3297-3319.

Walker, N. D. and R. D. Mey (1988): Ocean/atmosphere heat fluxes within the Agulhas retroflection region. Journal of Geophysical Research, 93(C12): 15473-15483.

White W.B. and R.G. Peterson (1996): Ant Antarctic Circumpolar wave in surface pressure, wind, temperature, and sea ice extent. Nature, 380, 699-702.

Whitworth, T. and W. D. Nowlin (1987): Water masses and currents of the Southern Ocean at the Greenwich meridian. Journal of Geophysical Research, 92(C6): 642-6476.

Zhang, R.L., L. M. Rothstein, and A. J. Busalacchi (1998): Origen of upper-ocean warming and El Nino change on decadal scales in the tropical Pacific Ocean. Nature, 391, 879-883.