Temperature and Salinity trends in the South Atlantic

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Abstract. Recent studies indicate that the Agulhas leakage increased in the last decades due to the poleward shift of westerlies, what contributed to the observed warming of the Agulhas Current system and salinification of the South Atlantic thermocline waters. In this work we show that there is an unequal increasing in temperature and salinity in different areas of the South Atlantic, but there is no doubt that it getting warm and salty. A fraction of the warm and salty waters injected into the South Atlantic by the Agulhas leakage remains in the South Atlantic while the rest of it is transmitted to the North Atlantic as part of the thermocline return flow of the AMOC.

Keywords: South Atlantic, Agulhas leakage, salinification, temperature, thermocline.

1. Introduction

The transport of warm salty Indian Ocean waters into the South Atlantic is called Agulhas leakage. Recent observations (Richardson, 2007; Ridgway et al., 2007; Speich et al., 2007) confirm that Agulhas system and Indian Ocean subtropical gyre are embedded into the Southern Hemisphere supergyre that connects Atlantic, Indian, and Pacific Oceans. So, a fraction of the Agulhas leakage remains in the South Atlantic subtropical gyre feeding the Atlantic Meridional Overturning Circulation (AMOC), while the rest of it circulates back to the Indian Ocean through the return flow of the supergyre, the South Atlantic Current. As a main source of heat and salt for the surface branch of the AMOC (Gordon, 1986) the Agulhas leakage variability may impact global climate. Recent studies (Biastoch et al., 2009; Rouault et al., 2009, Beal et al., 2011) show that the transport of Indian Ocean waters into South Atlantic through Agulhas leakage increased in the last decades due to the poleward shift of westerlies, what contributed to the observed warming of the Agulhas Current system and salinification of the South Atlantic thermocline waters (Curry and Mauritzen, 2005).

The objective of present work is to use multiple datasets to inverstigate regional trends of temperature and salinity in the South Atlantic and suggest possible implications.

2. Data and methods

2.1 Data

In this study we use two datasets described below.

Reynold optimally interpolated sea surface temperature

The high resolution Optimally Interpolated Sea Surface Temperature (OISST) (version 2) dataset has a spatial grid resolution of 0.25 deg. and temporal resolution of 1 day. It uses Advanced Very High Resolution Radiometer (AVHRR) infrared satellite Sea Surface Temperature (SST) data and *in situ* data from ships and buoys and include a large-scale adjustment of satellite biases with respect to the *in situ* data. A description of the OISST can be found in Reynolds (1994, 2007). The dataset is distributed by NCDC - National Climatic Data Center (NCDC) – NOAA.

Subsurface temperature and salinity analysis by Ishii

This dataset consists of monthly objectively analyzed subsurface temperature and salinity with spatial grid resolution of 1 deg. at 16 levels in the upper 700 m from 1945 to 2012 (Ishii et al., 2005, 2006). The analysis is based on the World Ocean Database/Atlas 2005 WOD05/WOA05, the Global temperature-salinitiy in the tropical pacific from IRD (L'institut de recherche pour le developement, France), and the Centennial *in situ* Observation Based Estimates (COBE) sea surface temperature. ARGO profiling buoy data have also been used in the final several years. The XBT depth bias correction is applied in the current version (ishii ans Kimoto, 2009).

2.2 Methods

In order to study the spatial variations in temperature and salinity trends, we consider the four regions displayed at Fig. 1: Agulhas region, gyre region, Brazil-Malvinas Confluence (BMC) region, and North Brazil Current (NBC) region For each region, temperature and salinity will be averaged such that we will end up with time series of these variables during the time span of each dataset.

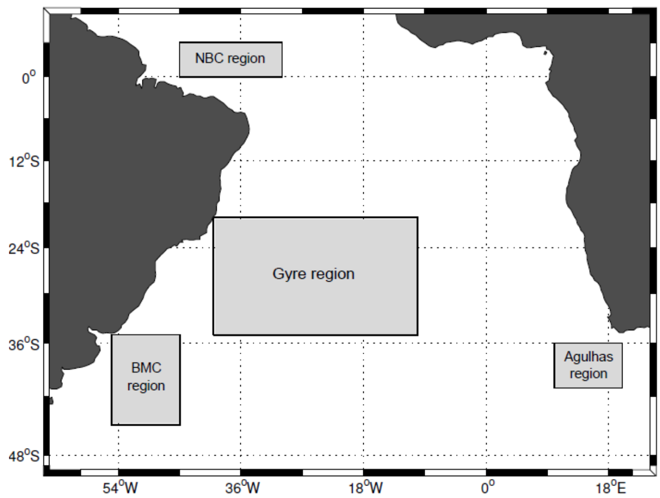

Figure 1. Schematic figure indicating the four regions of interest: Agulhas region, Gyre region, NBC region, and BMC region.

3. Results and Discussion

In Figs. 2-5 upper panels, we plot time series of OISST (red lines) from 1982 to 2012, and Ishii temperature at surface (black lines) from 1960 to 2012. Both time series where filtered with a 12 month running mean to eliminate oscillations with periods smaller than a year. The straight lines are the best linear fits (using least squares, so called ls-lines) for each time series. The dotted black straight line is the ls-line for the Ishii SST for the period 1960-2012, the solid black straight line is the ls-line for the Ishii SST for the period 1982-2012, and the solid red straight line is the ls-line for the OISST for the period 1982-2012.

In all plots, we can observe that SST from both datasets agree very well in the period 1982-2012, except in the BMC region, where the OISST is about 2^{O}C colder than Ishii SST. The temperature trends at surface (Figs. 2-5 upper panels) are summarized in Table 1. We also included in Table 1 the temperature trends in the 0-500m layer derived from Ishii dataset.

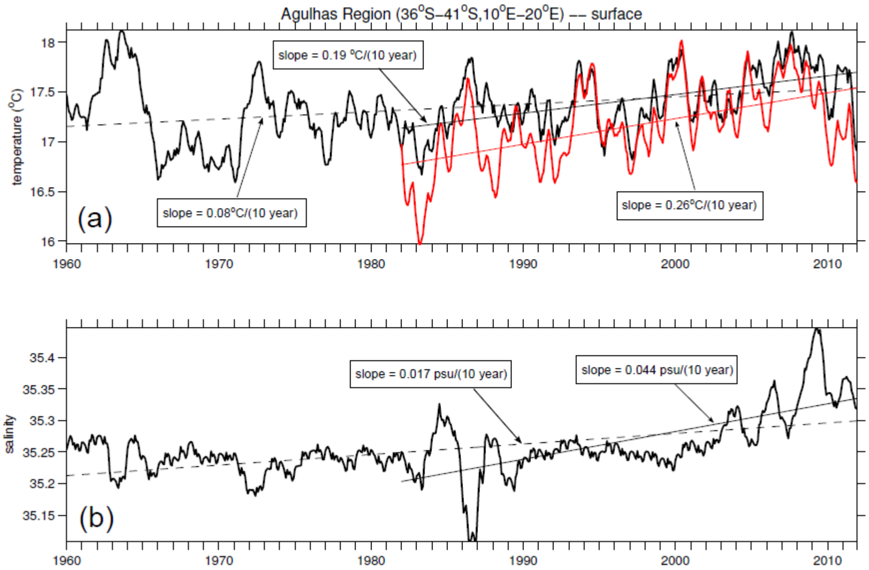

Figure 2. (a) SST time series derived from Ishii et al. (solid line), and from Reynolds et al (red solid line). (b) Salinity time series at surface derived from Ishii et al. The straight lines are the best linear fits for the periods 1960-2012 and 1982-2012. The line colors match the respective time series colors. The time series where calculated averaging monthly SST and Salinity in the Agulhas region (Fig. 1). All time series where filtered with a 12 month running mean.

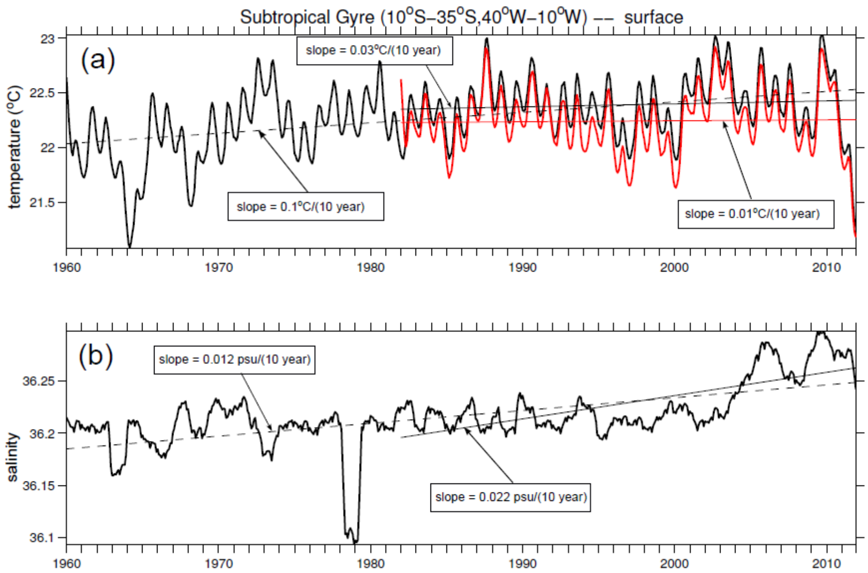

Figure 3. Same as Fig. 2 for the Gyre region (Fig. 1).

At surface all regions are warming in the period 1960-2012. The Agulhas, gyre, and NBC regions have trends with the same order of magnitude, whereas the BMC has a three times bigger trend. From 1983 on the all regions present an SST trend with the same order of magnitude except the gyre region. Note that in both data sets the Agulhas and NBC regions have a warming trend of about 0.2 ^{O}C/(10 year). In the BMC region the datasets disagree, since the warming trend from OISST is half of the warming in the Ishii-SST, but there is no doubt that the BMC regions has a significant warming as well. When wee look at the 0-500m layer, the Agulhas region present the most vigorous warming in the period 1982-2012, indicating inflow of Indian Ocean warm waters into the South Atlantic, through Agulhas leakeage, happens from surface up to intermediate depths. The NBC region warming trend at

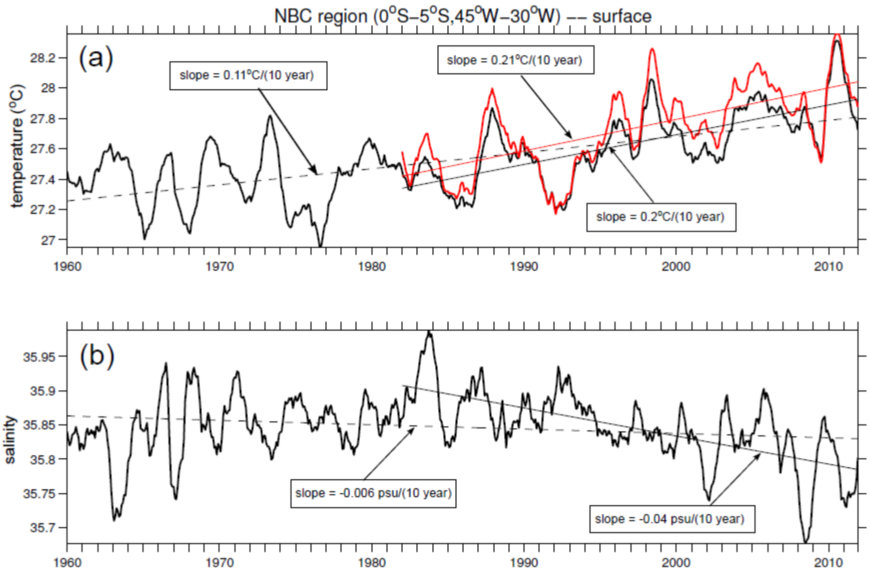

Figure 4. Same as Fig. 2 for the NBC region (Fig. 1).

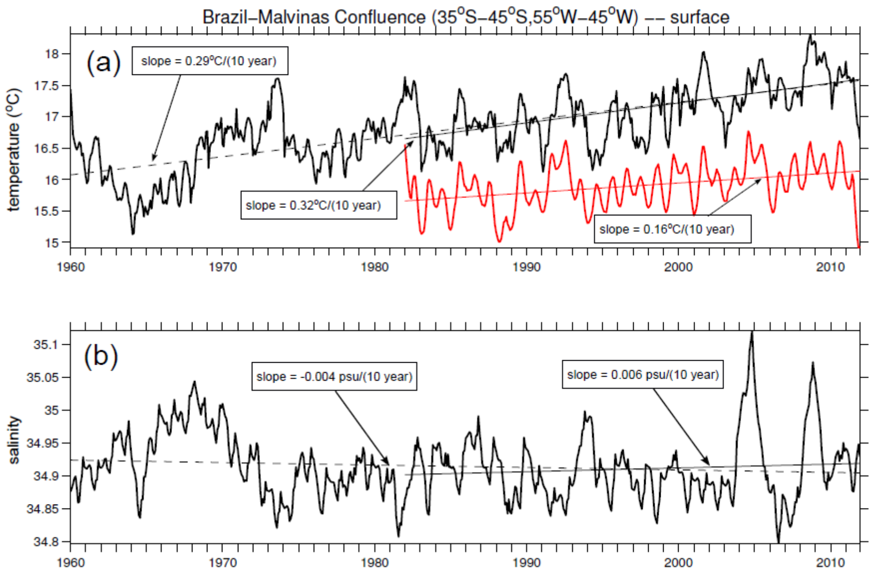

Figure 5. Same as Fig. 2 for the BMC region (Fig. 1).

this layer is about half of the surface's, what is consistent with a shallower thermocline in the equatorial regions. If we consider that the upper cell of AMOC is an intra thermocline flow, the warming into the Agulhas region would result into a warming into the NBC region. The gyre presents a very uniform low warming trend in all depth ranges indicating that there is no accumulation of heat due to increase in the Agulhas leakage. In the BMC region the subsurface trends are smaller than its surface counterparts. In order to investigate this phenomenon, we calculated the mean latitude of the 34.4 isohaline at surface between 55^{O}W and 45^{O}W (not shown) that characterizes the BMC front at surface. Its latitudinal displacements indicate the displacements of the BMC front. We found that the BMC front shifted southward at a rate of 0.03 deg lat/(10 year) from 1982-2012, and accelerated to 0.43 deg lat/(10 year) starting at 2000. So, the warm waters from BC are penetrating southward in shallow depths, what may cause a northward penetration of cold MC waters in intermediate depths. This may explain why the temperature trend is higher at surface than in the upper 500m depth in the BMC region.

Table 1. Temperature trends.

Region	Temperature trends [^{O}C/(10 years)]				
	Ishii SST 1960-2012	Ishii SST 1982-2012	OISST 1982-2012	Ishii 0-500 1960-2012	Ishii 0-500 1982-2012
Agulhas	0.08	0.19	0.26	0.07	0.25
Gyre	0.10	0.03	0.01	0.03	0.01
NBC	0.11	0.21	0.20	0.10	0.12
BMC	0.29	0.32	0.16	0.17	0.07

In Table 2, we list the salinity trends derived from Ishii data set at surface and in the 0-500m layer for our regions of study (Fig. 1). The Agulhas region shows a very consistent salinity trend. The salinization of this regions accelerated in the more recent period (1982-2012). Also, the salinity trends in the 0-500m layer are roughly half of the trends at surface, indicating the penetration of warmer/salty waters from Indian Ocean. In the gyre region the salinization decelerated during 1982-2012 in the 0-500m layet, but accelerated at surface. The change in the wind pattern (causing the increase the Agulhas leakage) as well as increase in sea temperature may increase the evaporation rate implying a more saline surface layer. In the NBC region there is a decrease in surface salinity in both periods, but with a much higher drop rate from 1982 on. When we look at the deeper layer (0-500m) the change has an opposite sign, and salinity increases in both periods. Comparing with results from Biastoch et al. (2009) [their Fig 5. inlet] for a region to the south of ours, there is a trend of approximately 0.03 psu/(10 year) in the period 1960-2012, and 0.002 psu/(10 year) in the period between 1990-2010.. So, there is also an strong decreasing in salinity trend in the last decade. In the BMC region there is also and increase in salinity from 1982-2012.

Considering that at surface the salinity has a big influence of surface fluxes we think that the 0-500m layer is more representative for the salinity distribution in the South Atlantic, from Table 2 we conclude that there is an increased salt accumulation in the Agulhas region and in the BMC region. Although there is a salinity trend in the NBC region it seems that it does not accumulate salt, since this is a region of connection between South and North Atlantic, and probably most of the salt crosses this region and goes Northward. The gyre also accumulates salt, but at rate smaller than in the period 1960-2012

Table 2. Salinity trends.

Region	Salinity trends [psu/(10 years)]			
	Ishii surface 1960-2012	Ishii surface 1982-2012	Ishii 0-500 1960-2012	Ishii 0-500 1982-2012
Agulhas	0.017	0.044	0.008	0.020
Gyre	0.012	0.022	0.030	0.010
NBC	-0.006	-0.040	0.006	0.002
BMC	-0.004	0.006	0.005	0.013

4. Conclusions

Recent studies (Biastoch et al., 2009; Roualult et al., 2009; Beal et al., 2011) indicate that the Agulhas leakage increased in the last decades due to the poleward shift of westerlies, what contributed to the observed warming of the Agulhas Current system and salinification of the South Atlantic thermocline waters (Curry and Mauritzen, 2005). In this work we show that there is an unequal increasing in temperature and salinity in different areas of the South Atlantic, but there is no doubt that it getting warm and salty. A fraction of the warm and salty waters injected into the South Atlantic by the Agulhas leakage remains in the South Atlantic while the rest of it is transmitted to the North Atlantic as part of the thermocline return flow of the AMOC.

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