

Decadal Variability of Thermocline and Intermediate Waters at 24°S in the South Atlantic

GERARD MCCARTHY, ELAINE McDONAGH, AND BRIAN KING

National Oceanography Centre, Southampton, United Kingdom

(Manuscript received 11 March 2010, in final form 11 June 2010)

ABSTRACT

New data are presented from 24°S in the South Atlantic in an investigation of the decadal variability of the intermediate and thermocline water masses at this latitude. Variation of salinity on neutral density surfaces is investigated with three transatlantic, full-depth hydrographic sections from 1958, 1983, and 2009. The thermocline is seen to freshen by 0.05 between 1983 and 2009. The freshening is coherent, basinwide, and of a larger magnitude than any errors associated with the datasets. This freshening reverses a basinwide, coherent increase in salinity of 0.03 in the thermocline between 1958 and 1983. Changes in apparent oxygen utilization (AOU) are investigated to support the salinity changes. In the thermocline of the eastern basin, a correlated relationship exists between local AOU and salinity anomalies, which is consistent with the influence of Indian Ocean Water. This correlated relationship is utilized to estimate the magnitude of Indian Ocean influence on the salinity changes in the thermocline. Indian Ocean influence explains half of the salinity changes in the eastern thermocline from 1958 to 1983 but less of the salinity change in the eastern thermocline from 1983 to 2009. Antarctic Intermediate Water properties significantly warm from 1958 through 1983 to 2009. A significant salinification and increase in AOU is evident from 1958 to 1983. Changes in the salinity of AAIW are shown to be linked with Indian Ocean influence rather than changes in the hydrological cycle. Upper Circumpolar Deep Water is seen to be progressively more saline from 1958 through 1983 to 2009. Increased Agulhas leakage and the intensification of the hydrological cycle are conflicting influences on the salinity of thermocline and intermediate waters in the South Atlantic as the former acts to increase the salinity of these water masses and the latter acts to decrease the salinity of these water masses. The results presented here offer an interpretation of the salinity changes, which considers both of these conflicting influences.

1. Introduction

The intermediate and thermocline water masses of the South Atlantic have been changing over the past 50 yr. The thermocline and Antarctic Intermediate Water (AAIW) have been freshening in the south western basin (Curry et al. 2003). Upper Circumpolar Deep Water (UCDW) from 1000 to 2000 m has been warming and becoming more saline on isobars at 24°S from the late 1950s to the mid 1980s (Arbic and Owens 2001). The variability of these water masses is important for a number of reasons.

First, the thermocline and intermediate waters are the water masses that constitute the return branch of the meridional overturning circulation (MOC; Donners and Drijfhout 2004; Gordon 1986). Thermocline and

intermediate waters enter the South Atlantic from the Indian Ocean primarily via the transfer of Agulhas rings (Lutjeharms 1996; de Ruijter et al. 1999). The exchange of this warmer, more saline, lower oxygen Indian Ocean Thermocline and Intermediate Water with the South Atlantic has been shown to have a vital role in the strength of the MOC in paleoceanographic (Peeters et al. 2004) and modeling studies (Weijer et al. 2001; Marsh et al. 2007; Biastoch et al. 2008). Biastoch et al. (2009) also showed an increase in Agulhas leakage is likely to have occurred because of the poleward shifting of Southern Hemisphere westerlies. This would bring increased salt and heat into the South Atlantic, which should be visible in the water masses there.

Second, the formation of the intermediate and thermocline water masses in the South Atlantic can be linked back to atmospheric forcing in the formation regions of the water masses. With climate change, the hydrological cycle is expected to intensify (Bindoff et al. 2007), leading to water masses that outcrop in precipitation (evaporation) dominated regions becoming fresher (more saline).

Corresponding author address: Gerard McCarthy, National Oceanography Centre, University of Southampton Waterfront Campus, European Way, Southampton SO14 3ZH, United Kingdom.
E-mail: gerard.mccarthy@noc.soton.ac.uk

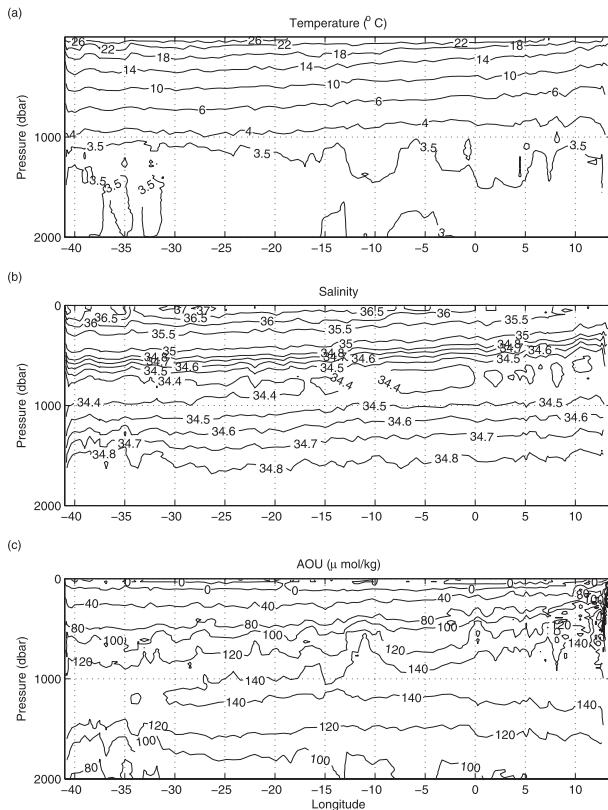


FIG. 1. Sections of properties from the 2009 cruise: (a) temperature, (b) salinity, and (c) AOU. All CTD data linearly interpolated onto a regular grid with no smoothing applied.

The thermocline is identifiable by the large vertical gradients in temperature and salinity above 800 dbar (Figs. 1a,b). If the thermocline at 24°S is viewed as being ventilated through the subduction of local surface waters, then changes of the properties in the thermocline can be related to forcing at the surface. Curry et al. (2003) linked the strong freshening of up to 0.2 on density surfaces from the 1950s–1960s to the 1980s–1990s in the thermocline to an intensification in the hydrological cycle as the changes occurred in a region where precipitation dominates over evaporation ($P > E$). The freshening is consistent with trends throughout the Southern Hemisphere seen in a 2004–08 average of Argo data with respect to *World Ocean Atlas 2001* climatology (Roemmich and Gilson 2009) and with other ocean basins at 17°S in the Pacific Ocean between 1967 and 1994 and also at 32°S in the Indian Ocean between 1962 and 1987 (Bindoff and McDougall 2000; Wong et al. 1999). However, when the 32°S section in the Indian Ocean was revisited in 2002, the freshening of the upper thermocline water previously reported from 1967 to 1987 had reversed (Bryden et al. 2003; McDonagh et al. 2005), the spatial and temporal coherence of which was confirmed by King and

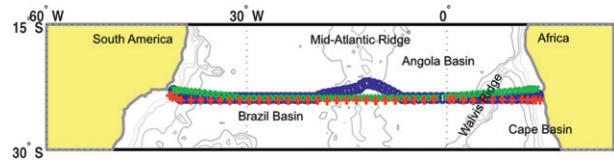


FIG. 2. Station locations of the three repeats of the 24°S section. Red pluses are the 1958 data (Fuglister 1960), green crosses are the 1983 data (McCartney and Woodgate-Jones 1991), and blue circles are the 2009 data. The major oceanic basins the Brazil, Angola, and Cape basins, and the major topographic features the Mid-Atlantic Ridge and the Walvis Ridge are shown.

McDonagh (2005) using Argo data. This highlights that oscillations in thermocline salinity are possible among any trends.

AAIW and UCDW are the main intermediate water masses of the South Atlantic. AAIW is identified by a salinity minimum in vertical profiles (Wüst 1935; Talley 1996) with salinity less than 34.4 around 800 dbar (Fig. 1b). It is believed to be formed either in the southeast Pacific Ocean (McCartney 1977; Talley 1996) or in the winter waters of the Bellinghousen Sea (Santoso and England 2004; Naviera Garabato et al. 2009). These are both in regions where $P > E$; hence, this water mass is expected to become fresher with an intensification of the hydrological cycle. Freshening of AAIW has been seen in all three basins of the Southern Hemisphere: the Pacific, the Indian, and the South Atlantic (Wong et al. 1999; Bindoff and McDougall 2000; Curry et al. 2003). The situation of AAIW in the South Atlantic is different from other ocean basins. In the South Atlantic, there is a combination of younger [higher oxygen and hence lower apparent oxygen utilization (AOU)], fresher AAIW from Drake Passage and older (lower oxygen, higher AOU), saltier AAIW from the Indian Ocean. This mixture leads to variations of 0.05 in salinity on the AAIW salinity minimum across the subtropical South Atlantic (Boebel et al. 1997). UCDW is the upper branch of Circumpolar Deep Water, a water mass of the Southern Ocean that arises from the mixing of upwelled NADW with water circulating in the Antarctic Circumpolar Current. Because it is a mixed and old water mass, it is difficult to isolate distinct forcing mechanisms for its variability. It is located at pressures between 1000 and 2000 dbar and identified by high AOU ($>120 \mu\text{mol kg}^{-1}$) because of its old age (Fig. 1c).

New data from RRS *James Cook* cruise 32 (JC 32), in March–April 2009, are presented here to extend the record of the decadal variability in the South Atlantic at 24°S. Salinities from three cruises from 1958, 1983, and 2009 (Fig. 2) are compared on neutral density surfaces. Practical salinity is used rather than absolute salinity for ease of comparison with previous studies. Thermocline

waters will be shown to have increased in salinity from 1958 to 1983 and freshened from 1983 to 2009. The influence of inflow from the Indian Ocean is estimated by linking high salt, high AOU anomalies with Indian Ocean Water masses. AAIW will be shown to be more saline in the 1983 and 2009 datasets than it was in 1958. Using the fact that salinity and AOU are highly correlated on the salinity minimum in the South Atlantic, this increase in salinity is again linked with Indian Ocean influence.

2. Data and sources of errors

There have been three full-basin hydrographic occupations of 24°S in the South Atlantic each separated by about a quarter of a century: the first occupation was in 1958 by the *Crawford* as part of the International Geophysical Year (Fuglister 1960), the second was in 1983 by the *Oceanus* (McCartney and Woodgate-Jones 1991), and the most recent was in 2009 by the *James Cook* (King 2009). The station locations are shown in Fig. 2. CTD data at 2-dbar resolution are available for both the 1983 and 2009 data. Discrete bottle data of up to 24 samples in the vertical are available for the 1958 data.

Measurement errors vary depending on the era of the measurement. The CTD measurements for the 1983 data and the 2009 data were acquired using a Neil Brown and a SeaBird 9/11 + CTD, respectively. All CTD measurements are calibrated against laboratory measured bottle salinities; although the CTD provides precise measurements, the accuracy of these data is dependent on the bottle samples against which these measurements are calibrated. Bottle salinity from all three cruises were obtained using conductivity measurements. The 1958 salinity data were acquired using a Woods Hole mark 2 salinometer; the 1983 and 2009 data used a Guideline Autosal. Measurement errors are assigned in accordance with Mantyla (1994) for the data from the 1950s and 1980s and extended here to the latest data from 2009 in accordance with the increasing accuracy of the measurements. The salinity data from 1958 are assigned a measurement uncertainty of 0.01. For salinities from 1983 and 2009, measurement uncertainties of 0.003 and 0.002 are assigned, respectively. Temperature measurement errors are assigned as 0.01°C for the 1953 data, 0.003°C for the 1983 data, and 0.002°C for the 2009 data.

To reduce the impact of seasonal variations, data from pressures less than 300 dbar were excluded from all subsequent analysis. It was particularly important to exclude the impact of seasonal variations from the 1958 data. The 1983 and 2009 data were gathered in February–March and March–April, respectively, whereas the 1958 data were gathered in October–November. The impact of this seasonal difference was considered by examining

the surface data of each cruise. The surface salinities (temperatures) were similar in the 1983 and 2009 data ranging from 37 (28°C) in the west to 35.5 (20°C) in the east. This is expected, given the similar season. The 1958 surface data were cooler by up to 6°C and fresher by up to 0.3 in salinity.

Because the temperature difference dominates, the 1983 and 2009 data have lighter surface density; if the salinity on density surfaces of these datasets is compared with the salinity on density surfaces in the 1958 surface ocean, an apparent freshening is seen. This freshening is abrupt and dissimilar from salinity changes throughout the rest of the water column. It is found that this apparently abrupt change in salinity is removed by excluding data at pressures less than 300 dbar. Hence, this was chosen as the cutoff for excluding seasonality from the results.

Systematic differences between datasets can arise because of cruise tracks not overlying each other. The 1958 cruise is primarily along 24.2°S; the 1983 cruise departs from 24°S at 0° and 30°W to reach east and west coast boundaries, respectively, at 23°S; the 2009 cruise deflected to the north over the Mid-Atlantic Ridge to achieve the deepest transit through the ridge. Any station that was more than 1° of latitude from 24°S was excluded from the comparison. This led to eight stations being excluded from the 2009 dataset, which deviated as far as 22.2°S.

The meridional gradients of salinity on density surfaces are investigated to assess the error associated with the track offset between cruises. Delayed mode Argo salinity data from 2003 to 2009 were linearly interpolated onto density surfaces. A second-order, least squares polynomial fit was applied to this with respect to latitude. Throughout most of the water column, apart from in waters less dense than $\sigma_0 = 26.7$, salinity increases on density surfaces going northward around 24°S. The maximum salinity gradient is 0.01 salinity increase per degree of latitude, which occurs at a density of $\sigma_0 = 27.1$, which corresponds to the salinity minimum of the AAIW.

AOU is the difference between saturated and observed concentrations of dissolved oxygen. Assuming that biological consumption is constant, AOU can be a proxy for the age of the water mass and hence informs of changes in circulation and renewal of water masses. AOU is used in preference to oxygen concentration as, in calculating the oxygen saturation, account is taken of the effect that the temperature of the water mass has on the saturated oxygen concentration. Oxygen and AOU are inversely related: AOU approaches 0 at the surface where oxygen concentration is large. Hence, water masses that have a low oxygen signal—such as those entering the South Atlantic from the Indian Ocean—have a high AOU.

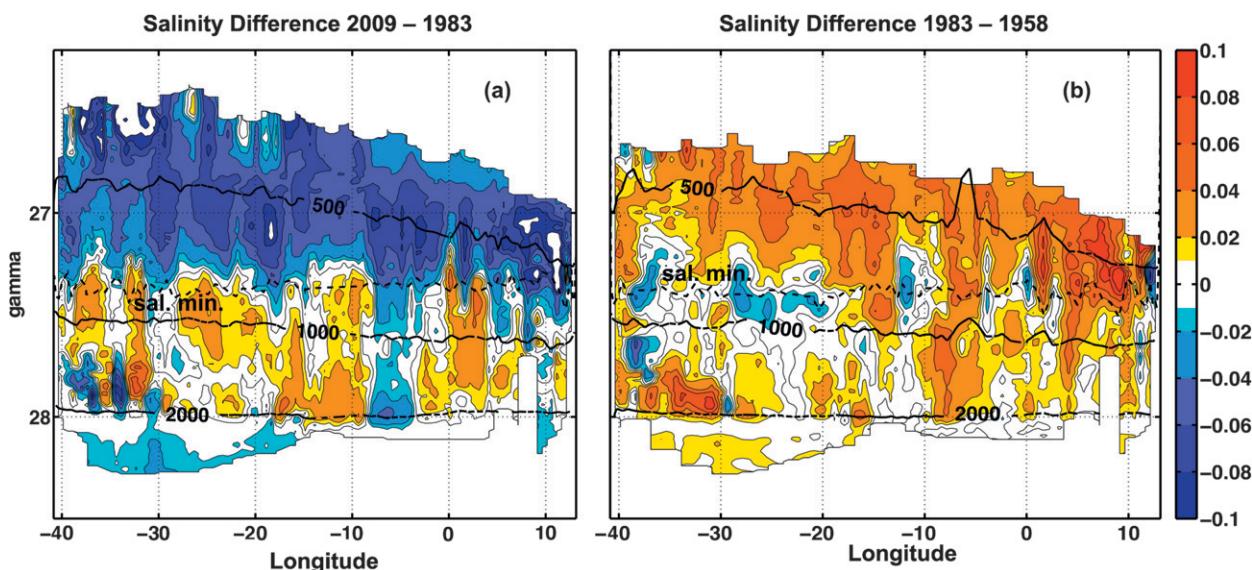


FIG. 3. Salinity data gridded on a 0.01 kg m^{-3} neutral density γ and 0.5° longitude grid with a 0.02 kg m^{-3} vertical running average of the data and excluding data at pressures <300 dbar; the older dataset is subtracted from the newer. (a) The changes from 1983 to 2009 and (b) the changes from 1958 to 1983. The 1983–2009 comparison shows a strong, coherent freshening through the thermocline to the salinity minimum, whereas the 1958–1983 comparison shows a strong, coherent salinification through the thermocline. The UCDW salinifies in both comparisons, although this salinification is less coherent than the variations seen in the thermocline. Pressure contours of 500, 1000, and 2000 dbar and a contour of the salinity minimum—all from the newer dataset—are indicated. The abrupt jump in the pressure contours near 6°W is explained by the presence of an Agulhas ring in the data.

High-quality CTD oxygen data calibrated against discrete bottle samples are available for the 2009 cruise. Bottle oxygen data are available from the 1983 and 1958 data. These are converted from ml l^{-1} to $\mu\text{mol kg}^{-1}$. The density conversion requires knowledge of the temperature at which the sample is fixed. Fixing temperature data are unavailable for the 1983 and 1958 data, so a relation between in situ temperature and fixing temperature is derived from these data from the 2009 cruise. This is then applied to 1983 and 1958 data to perform the density conversion. Discrete bottle data are then fitted to a 20-dbar grid using an Akima spline.

3. Method

CTD salinity data were linearly interpolated onto a regular neutral density grid at intervals of 0.01 and longitude grid of 0.5° with care taken not to interpolate across intervening topography. Neutral density γ (Jackett and McDougall 1997) is chosen as the density coordinate. There are density inversions in potential density in deeper waters; for this reason, γ is the preferred density variable. Discrete bottle salinities were fitted to a regular 20-dbar pressure grid using an Akima spline (Akima 1970) before being similarly gridded in density and longitude space. Using a spline is preferable to linear interpolation of sparse bottle data as the curvature of

the γ - S curve leads to biases in a linear interpolation. For example, at the salinity minimum, linear interpolation of sparse bottle data tends toward an overestimate of the salinity. The magnitude of errors associated with this is investigated by comparing the minimum salinity in the raw bottle data and the minimum salinity from bottle data, which had been interpolated using a spline against high resolution CTD data. This showed that the data fitted to a spline, although still overestimating the salinity of the salinity minimum, reduces the error from up to 0.01 to below 0.002.

Changes are investigated on a density grid as these surfaces are less affected by dynamic variations in the water column caused by mesoscale eddies and internal waves. Temperature and salinity variations on density surfaces are not independent of each other. A freshening (salinification) will correspond to a cooling (warming) and for this reason only the salinity changes will be discussed here.

4. Decadal variability at 24°S

a. Changes on neutral density

The differences between the gridded salinity data from each cruise are shown in Fig. 3. In each case, the older salinity values were subtracted from the newer. Figure 3a shows the comparison between the 2009 and 1983 datasets.

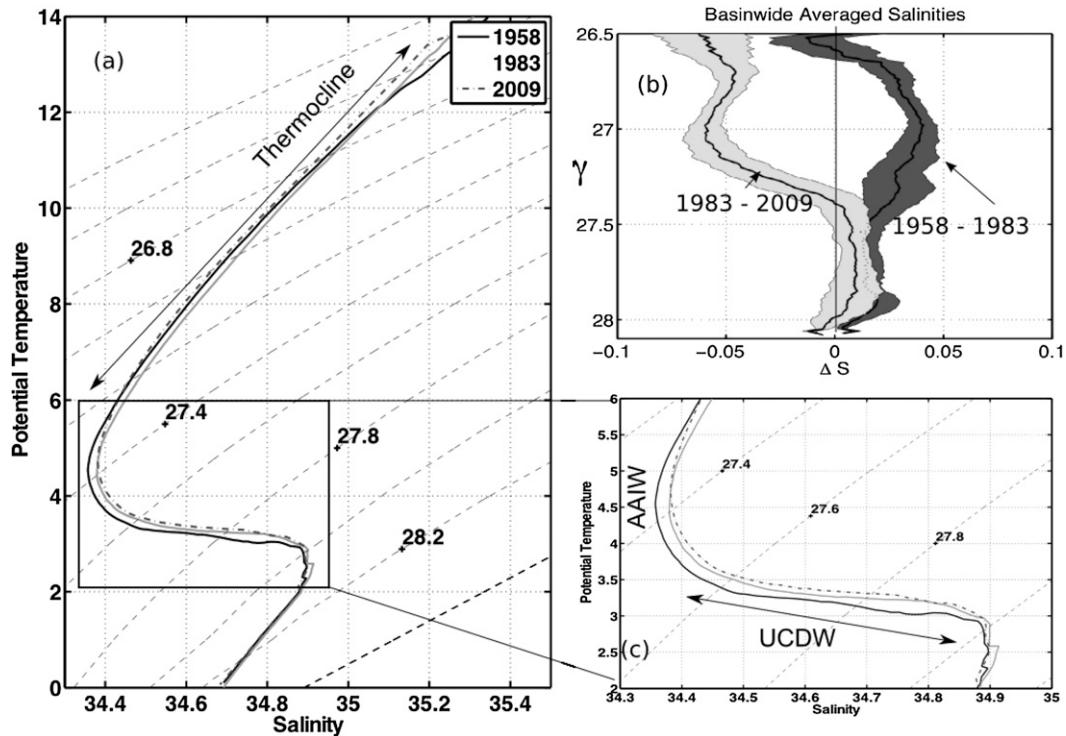


FIG. 4. The θ - S curves for the 3 cruises, focusing on the (a) thermocline and (c) intermediate water masses. To produce an averaged θ - S diagram, potential temperature and salinity were gridded on neutral density and longitude before averaging. (b) The basinwide average anomaly between the three cruises. Mean averaged differences are shown with black lines. Uncertainties of 1 standard deviation from 1983 to 2009 are in light gray; uncertainties of 1 standard deviation from 1958 to 1983 are in dark gray. Error bars of length 1 standard deviation are shown. This figure is an average of the data presented in Fig. 3.

A basinwide, coherent freshening signal throughout the thermocline above the salinity minimum is the most striking feature. The freshening from 1983 to 2009 has a magnitude of 0.05 in the density range $26.5 < \gamma < 27.4$ (Fig. 3a). In contrast, Fig. 3b shows the comparison between the 1983 and 1958 data. In this case, a basinwide, coherent increase in salinity is evident in the thermocline. This salinification from 1958 to 1983 has a magnitude of 0.03 in the density range $26.5 < \gamma < 27.4$ (Fig. 4b). Both changes are similar in that they occur across the whole ocean basin with a similar magnitude.

Between 1000 and 2000 dbar, in the density range $27.4 < \gamma < 28$, the UCDW has become more saline from 1958 through 1983 to 2009 (Figs. 3a,b). This water mass is 0.02 more saline on density surfaces in 2009 than it was in 1958.

The changes on density surfaces are also evident in θ - S space. Figure 4a highlights the basin-averaged oscillation in salinity shown in θ - S space. Figure 4c highlights the coherent changes in θ - S properties of the UCDW. These changes are consistent with an increase in salinity seen on density surfaces but do not exclude a rise in temperature being the cause of the apparent salinity changes.

b. Thermocline salinity and AOU relationship

Thermocline salinity in the subtropical South Atlantic is intermittently influenced by the more saline water from the Indian Ocean introduced via the shedding of Agulhas Rings. This high salinity water has a high AOU signal relative to the native waters of the South Atlantic (Gordon et al. 1992). Signals in the AOU are investigated for correlation with salinity, which would indicate the influence of Indian Ocean Water.

Correlation does exist between AOU and salinity on anomaly scales in the eastern thermocline at 24°S . AOU and salinity, gridded on density surfaces, east of 0° , in the density range $26.5 < \gamma < 27.4$ was averaged to form a mean profile for each of the three cruises. Anomalies of AOU (ΔAOU) and salinity (ΔS) for each cruise were calculated relative to these means. The correlation between ΔS and ΔAOU for each cruise is shown in Fig. 5. The correlation is strong: 0.94, 0.76, and 0.80 for the 1958, 1983, and 2009 data. Even if a conservative estimate of the number of degrees of freedom as being greater than the number of stations (order 25) times the number of independent observations per station (>2) is made, then

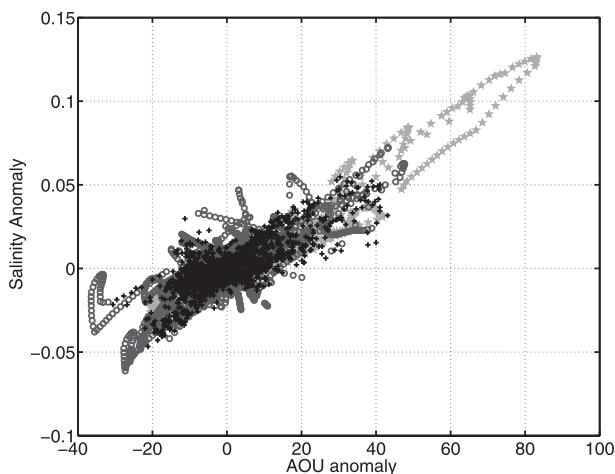


FIG. 5. The AOU vs salinity anomaly for the 1958 (stars), 1983 (open circles), and 2009 (pluses) data from the thermocline ($26.5 < \gamma < 27.4$) east of 0° to the African coast. Mean salinity and AOU profiles are calculated for each cruise by simple averaging of thermocline salinity and AOU gridded in longitude and density. Salinity and AOU anomalies are calculated relative to these average profiles and plotted against one another. This results in high correlation between the local salinity and AOU anomalies.

the P value for these correlations is less than 0.0001. The relationship between ΔAOU and ΔS is the same for all three cruises. Higher local salinity anomalies are related to higher ΔAOU , and this implicates the Indian Ocean.

The $\Delta\text{AOU}-\Delta S$ relationship, shown in Fig. 5, can be used to investigate how much of the large-scale changes (Fig. 3) are due to Indian Ocean influence. A single $\Delta\text{AOU}-\Delta S$ relationship is defined by fitting a linear regression to the data in Fig. 5. The salinity data were then adjusted to remove the effect of the slope of this line [$S' = S - (\text{slope} \times \text{AOU})$]. The averaged salinity anomalies are investigated as before, and the results are shown in Fig. 6. Before any trend is removed, the average salinity difference in the eastern thermocline, $26.5 < \gamma < 27.4$, is a 0.04 salinity increase from 1958 to 1983 and a 0.05 freshening from 1983 to 2009. When the trend with $\Delta\text{AOU}-\Delta S$ is removed, the differences become 0.02 salinity increase from 1958 to 1983. There is a smaller change in the average freshening 1983–2009 over this density range: the freshening reduces from 0.05 to 0.04 when the Indian Ocean influence is removed.

c. Core properties of AAIW

The properties of the water in the salinity minimum core of the AAIW are shown in Fig. 7 with the basin averages and standard deviations in Table 1. Here, the data are taken from the level corresponding to the salinity minimum rather than from a density level. Hence, independent changes in temperature and salinity are

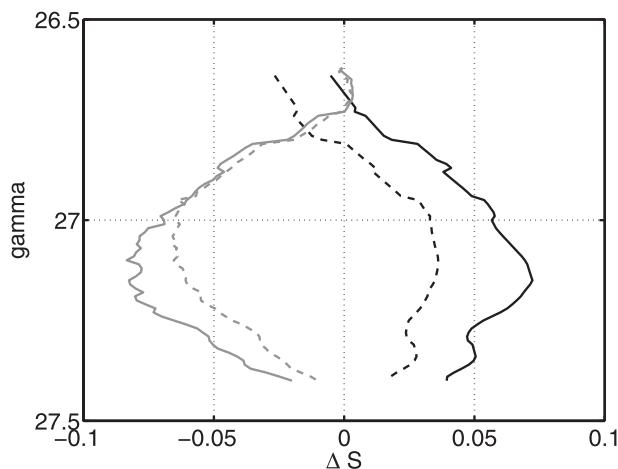


FIG. 6. The averaged salinity differences between the 3 cruises east of 0° with and without the influence of the high salinity, high AOU Indian Ocean Water. The black lines refer to the difference between the 1958 and the 1983 cruises; the gray lines refer to the difference between the 1983 and the 2009 cruises. Solid lines refer to the unadjusted salinity differences, and dashed lines refer to salinity adjusted to remove the influence of Indian Ocean Water.

possible. From 1958 to 1983, there was a significant salinity increase (oxygen decrease) of 0.027 ($11 \mu\text{mol kg}^{-1}$), whereas no significant change in salinity (oxygen) occurred from 1983 to 2009. This has been accompanied by significant increases in temperature of 0.15°C from 1958 to 1983 and a further 0.08°C from 1983 to 2009. Significant changes in oxygen correspond inversely to significant changes in AOU; hence, the oxygen decrease from 1958 to 1983 has a correspondent increase in AOU. This warming with no corresponding increase in salinity from 1983 to 2009 leads to a significant decrease in density at the core of the AAIW of 0.01 kg m^{-3} . There are no significant changes in pressure of the salinity minimum.

Figure 8 shows the salinities and AOU for 1958 and 2009 on the salinity minimum core of the AAIW. There is a high and significant correlation between salinity and AOU of $r > 0.9$. Although not shown, this relationship also holds for the 1983 data. This shows the close relationship between the salinity and age of AAIW represented by the AOU. This relationship is of a different nature than that seen in the thermocline. In the thermocline, it is the local salinity anomaly that is correlated with the local AOU anomaly. At the salinity minimum, it is the raw salinity and AOU that are correlated. This is a relationship that holds for all AAIW in the South Atlantic.

The AOU–salinity relationship has not changed, but there is lower AOU and salinity in the 1958 data than in the 2009 data. This indicates that the salinity change is due to higher AOU (older), more saline AAIW in the

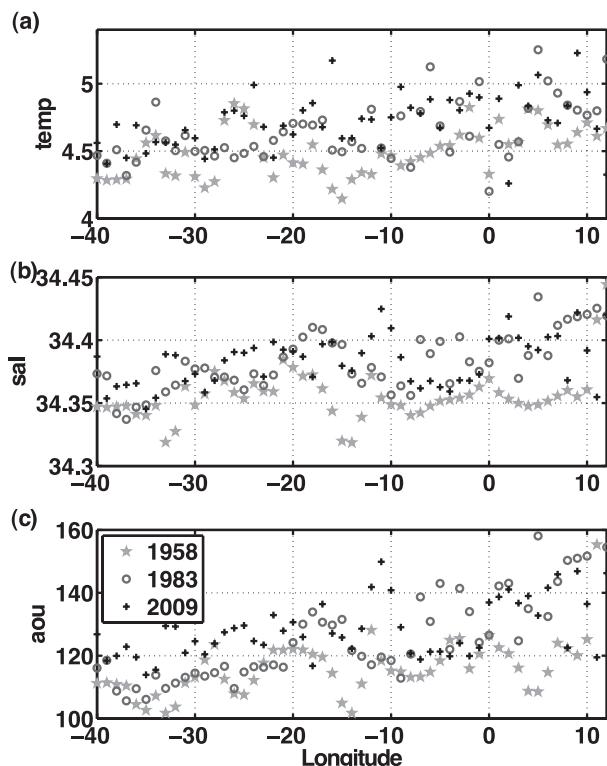


FIG. 7. (a) Temperature, (b) salinity, and (c) AOU from the core of the AAIW on the salinity minimum at 24°S. All data were interpolated onto a regular longitude grid. Stars, open circles, and pluses refer to data from 1958, 1983, and 2009, respectively.

2009 data. This, together with the fact that the low salinity (low AOU) in the 1958 data is concentrated in the east of the basin (Figs. 7a,b), indicates that there is more AAIW from the Indian Ocean in the 2009 and 1983 data than in the 1958 data. This increase in the fraction of AAIW is the driver of the increase in salinity. If the salinity had increased because of a change in freshwater balance at its formation region, then there would be no reason to expect a correlated increase in AOU.

5. Discussion

The variations of salinity throughout the thermocline with a basinwide-averaged value of 0.03 from 1958 to 1983 and -0.05 from 1983 to 2009 are of a larger magnitude than could be attributed to any measurement or track offset errors. Indeed, Mantyla (1994) suggests that salinity data from the 1950s are systematically too high by 0.005. This adjustment was not applied to the data here; however, if this was the case, the salinification from 1958 to 1983 would be larger.

The decadal changes discussed here are revealed by synoptic hydrographic sections separated by tens of years:

TABLE 1. Mean salinities, temperatures, neutral densities γ , and dissolved oxygen with standard deviations in parentheses on the salinity minimum from the 3 cruises.

	Salinity (psu)	Temperature (°C)	Density (kg m^{-3})	Oxygen ($\mu\text{mol kg}^{-1}$)
1958	34.356 (0.020)	4.49 (0.18)	27.383 (0.023)	196 (12)
1983	34.383 (0.023)	4.64 (0.19)	27.386 (0.021)	185 (16)
2009	34.383 (0.019)	4.72 (0.20)	27.376 (0.027)	183 (9)

just three sections in 50 yr makes this one of the best sampled sections in the subtropical South Atlantic. It is natural to ask whether the variability reported on these sections is in fact a much higher frequency variability aliased by the available sampling. This can be addressed to some extent using Argo data; however, although the section at 30°S was well seeded with floats in 2003, the 24°S section has been only sparsely covered during the Argo era. In 2009, 16 new floats were deployed on JC 32, so that in another 2–3 yr it will be possible to quantify the interannual variability with greater certainty. Analysis of the float data that are available at present does not show basinwide coherent variability comparable to the section differences reported here.

High salinity, high AOU anomalies in the thermocline of the eastern basin are detectable in the datasets (Fig. 5), suggesting the influence from the Indian Ocean. When the AOU–salinity trend shown in Fig. 5 is removed from the salinity data, the magnitude of the Indian Ocean influence can be separated from the underlying salinity differences. The increase in salinity in the eastern

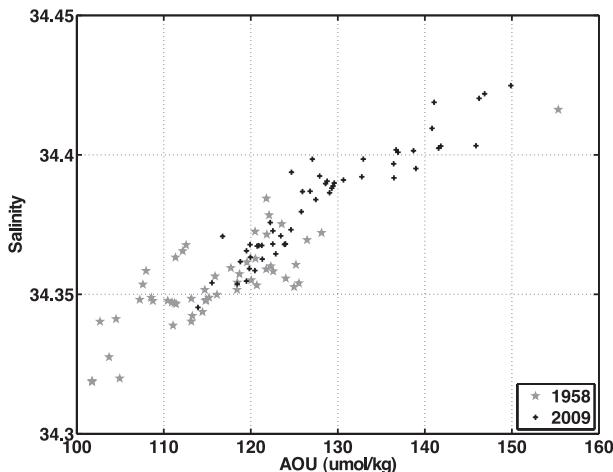


FIG. 8. The AOU is plotted against the salinity of the AAIW. Stars and pluses represent the 1958 and 2009 data, respectively (the 1983 data are excluded for clarity). The higher salinity and AOU in 2009 than 1958 indicates that a higher fraction of older, more saline AAIW is present across 24°S. This relationship also holds for the 1983 data.

thermocline from 1958 to 1983 reduces from 0.04 to 0.02, explaining half of the observed trend, whereas the freshening in the eastern thermocline from 1983 to 2009 is reduced from 0.05 to 0.04 when the Indian Ocean influence is removed. This influence is not of a large enough magnitude or coherent enough across the basin to drive the underlying salinity differences seen.

The salinification (warming) trend in the UCDW between 1000 and 2000 dbar reported by Arbic and Owens (2001) from 1958 to 1983 has continued to 2009 leaving this water mass 0.02 more saline now than in 1958. Linking this observation with possible forcing mechanisms is difficult because of the modified nature of this water mass.

That a salinification of 0.03 from 1958 to 1983 has occurred in the AAIW is different from other ocean basins where there has been a freshening (Wong et al. 1999; Bindoff and McDougall 2000; Naviera Garabato et al. 2009). This salinity change was associated with an increase in AOU. There was no change in the salinity–AOU relationship between the 1958 data and either the 1983 or the 2009 data. Also, the low salinities of the 1958 data are located in the east of the basin. This evidence supports the hypothesis that the higher salinities in 1983 and 2009 are driven by more of the older, more saline AAIW entering from the Indian Ocean.

Because water is primarily transferred between the Indian and South Atlantic Oceans via Agulhas rings, it is possible to calculate how much salt would need to be put into the South Atlantic around 24°S by Agulhas rings to bring the low salinities of the 1958 data up to the modern values of the 1983 and 2009 cruises. McDonagh et al. (1999) provides figures for available salt anomaly (ASA) for an Agulhas ring in the South Atlantic. If the layer associated with the AAIW is defined as between 4° and 5°C, then the ASA for the AAIW of an Agulhas ring can be assigned as 0.5×10^{12} kg (McDonagh et al. 1999, Fig. 6). Using these isotherms as upper and lower limits of a box representing the AAIW gives an average layer thickness from the 1958 and 2009 cruises of 160 m. The low salinities of AAIW in 1958 are highly visible east of 0° to the coast at around 13°E; this is chosen as the zonal extent considered for this box. Here, 30°S is chosen as a southern boundary for Agulhas Rings entering the subtropical South Atlantic (Byrne 1995). The meridional extent chosen is irrelevant if the transports of salt into this box through 30°S is considered. McDonagh and King (2005) estimate the northward transport of AAIW through 30°S as 7.3 Sv ($1 \text{ Sv} \equiv 10^6 \text{ m}^3 \text{ s}^{-1}$) northward transport of AAIW in the layer $26.8 < \sigma_0$, $\sigma_1 < 32.26$. This layer is on average 875 m thick and spread across the entire width of the section at 30°S—a width of 6000 km—giving an area of $5.2 \times 10^9 \text{ m}^2$. The

south face of the box in consideration here has an area of $0.2 \times 10^9 \text{ m}^2$, leading to a scaling factor of 26 between the two areas. This results in an estimate of the transport across the southern face of the box of 0.3 Sv or $10^{13} \text{ m}^3 \text{ yr}^{-1}$ to the nearest significant figure.

The number of extra rings per year that needs to enter this region around 24°S can be calculated by considering the number of rings needed to make up the salinity difference as mass of AAIW \times (salinity difference/ASA) per ring divided by a flushing time given by volume–transport, which reduces to give the number of extra rings per year as density of AAIW (10^3 kg) \times salinity difference (0.03×10^{-3}) \times transport ($10^{13} \text{ m}^3 \text{ yr}^{-1}$)/ASA per ring ($0.5 \times 10^{12} \text{ kg}$ per ring). This shows that 0.6 extra rings per year would add sufficient salt at AAIW levels around 24°S. This implies that a gradual change with about an extra ring being shed about every 2 yr between 1958 and 1983 would make up the salt difference. Because Agulhas ring shedding is a variable and aperiodic process (de Ruijter et al. 1999), this amount of extra rings being shed is conceivable within the bounds of natural variability.

The results presented here tie together two conflicting views on how the salinity of water masses of the South Atlantic should vary. On one hand, the thermocline and intermediate waters should freshen because of the intensification of the hydrological cycle. On the other hand, increased Agulhas leakage due to the poleward shift of the westerlies in the Southern Hemisphere should bring more saline water into the South Atlantic. The freshening of the thermocline at 24°S from 1983 to 2009 is consistent with trends of freshening throughout the Southern Hemisphere and with an intensification of the hydrological cycle. In the face of this expected freshening, the salinification in the thermocline from 1958 to 2009 could be seen as evidence of natural oscillations in the hydrological cycle. However, half of that salinification can be attributed to a higher proportion of Indian Ocean Water in the 1983 and 2009 data than in the 1958 data. This change in proportion of Indian Ocean Water is further supported by the changes in AAIW. Although no major increase in the proportion of Indian Ocean Water is evident in the 2009 data in comparison with the 1983 data, no decrease is evident either. Hence, both a freshening due to the intensification in the hydrological cycle and an increase in salinity due to increased Agulhas leakage are supported by these results.

Acknowledgments. GM is supported by the University of Southampton and the Ocean Observing and Climate Group at the National Oceanography Centre, Southampton. *James Cook* cruise 32 was funded as part of NERC Oceans 2025 program. It is a pleasure to acknowledge the master, officers, and crew of RRS *James*

Cook cruise 32, whose efforts enabled the collection of the dataset. We also acknowledge the contribution of the other members of the scientific party. The dissolved oxygen data were collected by a team led by Dr. Sinhue Torres Valdes.

REFERENCES

- Akima, H., 1970: A new method of interpolation and smooth curve fitting based on local procedures. *J. Comput. Math.*, **17**, 589–602.
- Arbic, B. K., and W. B. Owens, 2001: Climatic warming of Atlantic Intermediate Waters. *J. Climate*, **14**, 4091–4107.
- Biastoch, A., C. W. Boning, and J. R. E. Lutjeharms, 2008: Agulhas leakage dynamics affects decadal variability in Atlantic overturning circulation. *Nature*, **456**, 489–492.
- , —, F. U. Schwarzkopf, and J. R. E. Lutjeharms, 2009: Increase in Agulhas leakage due to poleward shift of Southern Hemisphere westerlies. *Nature*, **462**, 495–499.
- Bindoff, N. L., and T. J. McDougall, 2000: Decadal changes along an Indian Ocean section at 32°S and their interpretation. *J. Phys. Oceanogr.*, **30**, 1207–1222.
- , and Coauthors, 2007: Observations: Oceanic climate change and sea level. *Climate Change 2007: The Physical Science Basis*, S. Solomon et al., Eds., Cambridge University Press, 385–432.
- Boebel, O., C. Schmid, and W. Zenk, 1997: Flow and recirculation of Antarctic Intermediate Water across the Rio Grande Rise. *J. Geophys. Res.*, **102** (C9), 20 967–20 986.
- Bryden, H. L., E. L. McDonagh, and B. A. King, 2003: Changes in ocean water mass properties: Oscillations or trends? *Science*, **300**, 2086–2088.
- Byrne, D. A., 1995: Agulhas eddies: A synoptic view using Geosat ERM data. *J. Phys. Oceanogr.*, **25**, 902–917.
- Curry, R., B. Dickson, and I. Yashayaev, 2003: A change in the freshwater balance of the Atlantic Ocean over the past four decades. *Nature*, **426**, 826–829.
- de Ruijter, W. P. M., A. Biastoch, S. S. Drijfhout, J. R. E. Lutjeharms, R. P. Matano, T. Pichevin, P. J. van Leeuwen, and W. Weijer, 1999: Indian-Atlantic interocean exchange: Dynamics, estimation and impact. *J. Geophys. Res.*, **104** (C9), 20 885–20 910.
- Donners, J., and S. S. Drijfhout, 2004: The Lagrangian view of South Atlantic interocean exchange in a global ocean model compared with inverse model results. *J. Phys. Oceanogr.*, **34**, 1019–1035.
- Fuglister, F. C., 1960: *Atlantic Ocean Atlas*. Vol. 1, Wood Hole Oceanographic Institution, 209 pp.
- Gordon, A. L., 1986: Interocean exchange of thermocline water. *J. Geophys. Res.*, **91** (C4), 5037–5046.
- , R. F. Weiss, J. W. M. Smethie, and M. Warner, 1992: Thermocline and intermediate water communication between the South Atlantic and Indian Oceans. *J. Geophys. Res.*, **97**, 7223–7240.
- Jackett, D. R., and T. J. McDougall, 1997: A neutral density variable for the world's oceans. *J. Phys. Oceanogr.*, **27**, 237–263.
- King, B. A., 2009: Cruise report from James Cook Cruise 32. National Oceanography Centre Tech. Rep., 173 pp.
- , and E. L. McDonagh, 2005: Decadal changes in ocean properties revealed by ARGO floats. *Geophys. Res. Lett.*, **32**, L15601, doi:10.1029/2005GL023145.
- Lutjeharms, J. R. E., 1996: The Exchange of Water between the South Indian and the South Atlantic Oceans. *The South Atlantic: Present and Past Circulation*, G. Wefer, Ed., Springer, 125–162.
- Mantyla, A. W., 1994: The treatment of inconsistencies in Atlantic deep water salinity data. *Deep-Sea Res. J.*, **41**, 1387–1405.
- Marsh, R., W. Hazeleger, A. Yool, and E. J. Rohling, 2007: Stability of the thermohaline circulation under millennial CO₂ forcing and two alternative controls on Atlantic salinity. *Geophys. Res. Lett.*, **34**, L03605, doi:10.1029/2006GL027815.
- McCartney, M. S., 1977: Subantarctic mode water. *Deep-Sea Res.*, **14** (Suppl.), 103–119.
- , and M. E. Woodgate-Jones, 1991: A deep reaching anticyclonic eddy in the subtropical gyre of the eastern South Atlantic. *Deep-Sea Res.*, **38**, S411–S443.
- McDonagh, E. L., and B. A. King, 2005: Oceanic fluxes in the South Atlantic. *J. Phys. Oceanogr.*, **35**, 109–122.
- , K. J. Heywood, and M. P. Meredith, 1999: On the structure, paths and fluxes associated with Agulhas rings. *J. Geophys. Res.*, **104** (C9), 21 007–21 020.
- , H. L. Bryden, B. A. King, R. J. Sanders, S. A. Cunningham, and R. Marsh, 2005: Decadal changes in the South Indian Ocean thermocline. *J. Climate*, **18**, 1575–1590.
- Naviera Garabato, A. C., L. Jullion, D. P. Stephens, K. J. Heywood, and B. A. King, 2009: Variability of Subantarctic Mode Water and Antarctic Intermediate Water in Drake Passage during the late-twentieth and early-twenty-first centuries. *J. Climate*, **13**, 3661–3688.
- Peeters, F. J. C., R. Acheson, G.-J. A. Brummer, W. P. M. de Ruijter, R. R. Schneider, G. M. Ganssen, E. Ufkes, and D. Kroon, 2004: Vigorous exchange between the Indian and Atlantic Oceans at the end of the past five glacial periods. *Nature*, **430**, 661–665.
- Roemmich, D., and J. Gilson, 2009: The 2004–2008 mean and annual cycle of temperature, salinity and steric height in the global ocean from the Argo program. *Prog. Oceanogr.*, **82**, 81–100.
- Santoso, A., and M. England, 2004: Antarctic Intermediate Water circulation and variability using a coupled climate model. *J. Phys. Oceanogr.*, **34**, 2160–2179.
- Talley, L. D., 1996: Antarctic Intermediate Water in the South Atlantic. *The South Atlantic: Present and Past Circulation*, Springer, 219–238.
- Weijer, W., W. P. M. de Ruijter, A. Sterl, and S. S. Drijfhout, 2001: Response of the Atlantic overturning circulation to South Atlantic sources of buoyancy. *Global Planet. Change*, **34**, 293–311.
- Wong, A. P. S., N. L. Bindoff, and J. A. Church, 1999: Large-scale freshening of intermediate waters in the Pacific and Indian Oceans. *Nature*, **400**, 440–443.
- Wüst, G., 1935: *Schichtung und Zirkulation des Atlantischen Ozeans. Die Stratosphäre. Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition auf dem Forschungs- und Vermessungsschiff "Meteor" 1925–1927*. Berlin, 288 pp.