Anthropogenic Impact on Agulhas Leakage

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/grl.50243

Abstract

Recent work suggests that changes of the Southern Hemisphere (SH) winds led to an increase in Agulhas leakage and a corresponding salinification of the Atlantic. Climate model projections for the 21st century predict a progressive southward migration and intensification of the SH westerlies. The potential effects on the ocean circulation of such an anthropogenic trend in wind stress are studied here with a high-resolution ocean model forced by a step-function change in SH wind stress that involves a 7% increase in westerlies strength and a 2°-shift in the zero wind stress curl. The model simulation suggests a rapid dynamic adjustment of Agulhas leakage by 4.5 Sv, about a third of its original value, after a few years. The change in leakage is reflected in a concomitant change in the transport of the South Atlantic subtropical gyre, but leads only to a small increase in the Atlantic Meridional Overturning Circulation (AMOC) of O(1 Sv) after three decades. A main effect of the increasing inflow of Indian Ocean waters with potential long-term ramifications for the AMOC is the salinification and densification of upper-thermocline waters in the South Atlantic, which extends into the North Atlantic within the first 3 decades.

1. Introduction

Inflow of thermocline and intermediate waters into the South Atlantic serves to replace the export of North Atlantic Deep Water (NADW) generated in the subarctic North Atlantic. This return flow mainly follows the ‘warm water route’ via the Agulhas regime south of Africa [*Donners and Drijfhout*, 2004]. It is characterized by a complicated interplay between a strong western boundary current, the Agulhas Current [*Lutjeharms*, 2006], that partly retroflects back into the Indian Ocean, and vigorous eddy dynamics governing the transport of warm and salty Indian Ocean water towards the South Atlantic, the 'Agulhas leakage' [*Beal et al.*, 2011]. As a consequence of leakage dynamics, the 'supergyre' [*Speich et al.*, 2007] that connects the SH subtropical gyres is not constant in time but varies on all timescales [*Biastoch et al.*, 2009a]. Part of the Agulhas leakage eventually leaves the horizontal gyre circulation and is advected to the North Atlantic [*Van Sebille et al.*, 2011]; there it can affect NADW production on decadal and longer timescales [*Weijer et al.*, 2002].

Due to strong nonlinear interactions in the Cape Basin [*Boebel et al.*, 2003] Agulhas leakage is difficult to quantify. The latest assessment, considering a decade of Lagrangian observations, estimated 15 Sv (1 Sv = 1 × 10^6 m^3s^{-1}) [*Richardson*, 2007] or 20% of the Agulhas transport [*Bryden et al.*, 2005]. Only a part of this amount forms the flow towards the north representing the upper limb of the AMOC [*Speich et al.*, 2007]. Recent model integrations suggest that, superimposed by strong interannual variability, Agulhas leakage included a significant trend towards higher values in the last decades due to changes in the Southern Hemisphere (SH) wind fields [*Biastoch et al.*, 2009a; *Rouault et al.*, 2009]. A key element in the evolution of Agulhas leakage seems to be its response to the SH westerlies [*Biastoch et al.*, 2009a]. Its intensification in the past decades is (in combination with a southward migration) predicted to continue by CMIP3 and CMIP5 experiments under global warming [*Swart and Fyfe*, 2012].

There is evidence that the increase of Agulhas leakage led to additional salt import to the South Atlantic: both model hindcasts [*Biastoch et al.*, 2009a; *McCarthy et al.*, 2012] and analyses of historic hydrographic sections [*McCarthy et al.*, 2011] report a salinification of the upper thermocline and Antarctic Intermediate Water (AAIW) at 24°S.

How will Agulhas leakage evolve under climate-changing conditions in the 21st century? In this study we begin to address these questions with a high-resolution ocean model, simulating the response of the Agulhas system to projected trends in SH wind stress.

2. Model experiments

The model used here was specifically set up to capture the mesoscale processes that are of particular importance in the Agulhas system [*Biastoch et al.*, 2009b]. Based on the NEMO code (v2.3) [*Madec*, 2008] and developed within the DRAKKAR collaboration [*The DRAKKAR Group*, 2007] the model consists of a 1/10° regional grid around South Africa (20°W-70°E, 47-7°S). Using a two-way nesting scheme [*Debreu et al.*, 2008] it is embedded in a global model at coarser (1/2°) resolution. A number of studies demonstrate the fidelity in simulating observed features of the Agulhas Current [*Biastoch et al.*, 2009b], Agulhas leakage [*Biastoch et al.*, 2008b], and its large-scale response [*Biastoch et al.*, 2008a, 2009a]. The atmospheric forcing is based on the CORE reanalysis product [*Large and Yeager*, 2004], with wind stress and thermohaline fluxes computed from bulk formulae at 6-hourly to daily resolution. Instead of using the interannually varying data, the control experiment (AG01-C) is based on the CORE 'normal-year' forcing, featuring a repeated, climatological seasonal cycle.

The effect of projected 21st century trends is then simulated in a sensitivity experiment (AG01-W) in a strategy similar to *Spence et al.* [2010], for which the wind stress of the control case was perturbed by the wind stress anomalies obtained from an anthropogenic climate change scenario with the 'Kiel Climate Model' (KCM) [*Park et al.*, 2009]. KCM has been run in an ensemble of seven 100-yr long climate change integrations (with an annual increase of 1% in CO_2 and stabilization after doubling the initial value after 70 years) started from different states of a control simulation at present-day greenhouse gases; the ensemble mean wind stress of the last 30 years was then compared against the control simulation (Fig. 1a). Broadly consistent with recent CMIP3 and CMIP5 models [*Swart and Fyfe*, 2012] the zero line of wind stress curl in this climate change scenario shifts southward by ~2° latitude. In combination with an intensification of the maximum of the westerlies (by ~7%), the simulation involves a poleward migration of the SH westerlies. The zonal-mean difference functions for both wind stress components (Fig. 1a shows only the dominant zonal component) were then used in AG01-W to perturb the reference wind stresses. By applying the wind anomalies to the momentum fluxes only, the present study concentrates on the dynamical response of ocean circulation and neglects any thermohaline forcing effects.

3. Changes in Agulhas leakage

For the quantification of Agulhas leakage we follow the Lagrangian strategy used in former analyses [*Biastoch et al.*, 2008b, 2009a; *Van Sebille et al.*, 2009] by tracing a large number of virtual floats seeded in the Agulhas Current at 32°S every five days. The floats are assigned with a transport of 0.1 Sv [*Blanke et al.*, 1999] and advected with the time-varying three-dimensional velocity field. We define an annual-mean Agulhas leakage (Fig. 1b) as the total transport carried by the floats that crossed the GoodHope section (dashed line in Fig. 2a) [*Swart et al.*, 2008] within three years after release. With a mean transport of 15.1 Sv (std. dev. of ± 1.8 Sv) the reference case is close to 15 Sv obtained from observational estimates [*Richardson*, 2007], but features strong year-to-year variations related to the intermittent ring shedding (even though the atmospheric forcing does not vary from year to year). Application of the changed wind stress conditions in AG01-W results in an increased Agulhas leakage within few years of integration, reaching a new level of 19.6 ± 1.6 Sv over the last 20 years.

Van Sebille et al. [2009] related Agulhas leakage to the inertia of the Agulhas Current. This mechanism seems to principally apply here: Changes in the transition between trades and westerlies are associated with a 10% reduced wind stress curl at 32°S in AG01-W, reflected in a reduction of the Agulhas Current transport of 6 Sv. Using the linear inverse relation derived from the same model under interannually-varying forcing [*Van Sebille et al.*, 2009] would result in an Agulhas leakage increase of 4.4 Sv, a value very close to the change seen here. However, this relation does not conclusively explain cause and effect; Agulhas Current transport and Agulhas leakage could follow a similar response to the vorticity input by the atmospheric anomaly. A more comprehensive quantification and separation into the individual effects of shifts vs. strengthening [*Nof et al.*, 2011] is beyond this study and under investigation with dedicated sensitivity experiments.

4. Impact on the large-scale circulation

How does the large-scale circulation react to the change in the wind field? The difference in the horizontal gyre circulation (Fig. 2) shows a southward expansion of the subtropical supergyre (the zero line of the streamfunction shifts south by ~1.8° latitude) combined with a weakening north of ~37°S. While regional transport increases can be larger in the individual basins, the 5-Sv contour line in the difference streamfunction connects the Indian Ocean and the South Atlantic, implying that the bulk of the Agulhas leakage increase corresponds to changes in the horizontal gyre circulation.

Of particular interest for the connection with the North Atlantic Ocean is the response of the overturning circulation. Two aspects may be distinguished here: the response of the velocity field and modifications of the water masses invading the South Atlantic from the Indian Ocean. The AMOC response is inspected in Fig. 3. The main signal over multi-decadal time scales is a gradually increasing northward transport between ~200-1000 m depth (note that the near surface transport anomaly is governed by a southward response in Ekman transport due to the local wind stress change), implying a strengthening of the upper branch of the AMOC (Figs. 3a, b). The evolution of the upper ocean is characterized by a gradual increase to O(1 Sv) in the subtropical South Atlantic, partly extending across the equator and fading out in the North Atlantic (Supplementary Fig. 1). This trend is superimposed by interannual to decadal fluctuations, reminiscent of the variability signal induced by the dynamics of the Agulhas regime [*Biastoch et al.*, 2008a] and communicated to the north by Rossby and Kelvin waves [*Van Sebille and Van Leeuwen*, 2007]. The strengthening in mean northward transport is qualitatively consistent with, but stronger compared to earlier results from coarse-resolution ocean-only [*Oke and England*, 2004] and coupled ocean-atmosphere [*Sijp and England*, 2009] model experiments under similar perturbation forcing. In the tropical Atlantic, the increase in the AMOC transport is concentrated along the western boundary: the time-mean transport of the North Brazil Current at 6°S increases by 0.9 Sv, similar to the trend in the upper branch of the AMOC, confirming the potential of this boundary current as an indicator for large-scale interhemispheric changes [*Zhang et al.*, 2011].

The present model suggests that the trend in upper-layer meridional transport cannot be interpreted in terms of a simple strengthening of the mean AMOC pattern: while the transport signal in the upper 1000 m implies a strengthening of the upper branch of the AMOC, the vertical structure of the trend at deeper levels (Fig. 3b) differs from the mean transport profile (Fig. 3a). The response of the AMOC is probably a complex superposition of effects due to changes in Agulhas leakage, local Ekman dynamics and Southern Ocean overturning (Fig. 3c, d). Unraveling the individual causes of the deep transport changes is beyond the model setup; we note, however, that the vertical structure of the change below 1500 m simulated here is consistent with a spinup of the Deacon Cell in the Southern Ocean (Supplementary Fig. 2).

A signal that is potentially more important for the long-term evolution of the AMOC than the weak dynamic effect seen in Fig. 3, is the progressive change in the South Atlantic water mass properties induced by the rapid increase of the leakage transport. In the control experiment 69% of Subantarctic Mode Water (SAMW) and 47% of AAIW at the GoodHope section have their origin in the Agulhas Current (Supplementary Tabs. 1, 2). Modifications of the T/S properties conveyed by changes in Agulhas leakage have been found to be linked to the evolution of northern hemisphere climate on centennial time scales [*Banks et al.*, 2007]. In the wind change experiment salinification and warming trends (Fig. 4) are seen in the upper AAIW and in the overlying SAMW. More specifically, the stronger leakage leads to an increase of 2.8 Sv (48%) for SAMW and 1.3 Sv (45%) for AAIW.

The net density impacts of AAIW and SAMW in the South Atlantic remain limited due to the opposing effects of temperature and salinity (Supplementary Fig. 3b) and due to the slow propagation of these signals along the deep isopycnals. In contrast, thermocline water is much faster advected to the north by more vigorous near-surface currents. Accordingly, the upper South Atlantic experiences a salinity increase by more than 0.1 during the first decade, with anomalies spreading along the northwesterly pathway in the subtropical gyre (not shown). After 2-3 decades a significant amount enters the North Atlantic through the tropical circulation regime (Fig. 4a). Changes in the upper-ocean water mass signatures are mainly restricted to salinity, since temperature anomalies are effectively damped by the surface heat fluxes (Fig. 4b). As a result of the increased Agulhas leakage, there is a net gain of density in the upper layer of the South Atlantic on the order of 0.1 sigma units within the first 3 decades (Supplementary Fig. 3c).

5. Conclusions

An increase in Agulhas leakage due to projected 21st century changes in the SH wind stress has consequences not only for the regional circulation around South Africa but also the basin-wide circulation in the Atlantic Ocean with potential ramifications for global climate. One of the key findings is the rapid adjustment of Agulhas leakage to the SH wind stress changes: in the present case, the transport increases by about one third of its original value within very few years. This wind-induced change in leakage is manifested in the South Atlantic subtropical gyre circulation, reflected in a southward expansion of the subtropical supergyre. The dynamic response of the AMOC is comparatively small, with a gradual increase of the interhemispheric, northward flow in the surface branch by less than 1 Sv after three decades of adjustment.

A potentially stronger effect on the AMOC could arise from salinity changes in the water masses advected northward in the upper thermocline. Thermocline anomalies from increased Agulhas leakage reach the western boundary of the tropical South Atlantic within the first decades. While the additional heat is largely released to the atmosphere, the excessive salt signal remains in the ocean, therefore causing a net gain in density. Although the present study suggests this increase may be smaller than the lowering in density of due to projected warming and freshening of the subpolar North Atlantic under global warming [*Capotondi et al.*, 2012; *Weaver et al.*, 2012], the potential impact on the future evolution of the overturning circulation warrants a more comprehensive examination of the Agulhas effect in global climate models. A realistic simulation (i.e., with sufficient resolution) of the regional dynamics remains a difficult task, however, considering the excessive overestimation of Agulhas leakage even in modern CMIP5 climate models [*Weijer et al.*, 2012].

Acknowledgments.

The integration of the experiments has been performed at the Höchstleistungsrechenzentrum Stuttgart (HLRS). We thank Wonsun Park for providing KCM output. The analysis was performed in the BMBF framework project "Nordatlantik 2" (03F0605).

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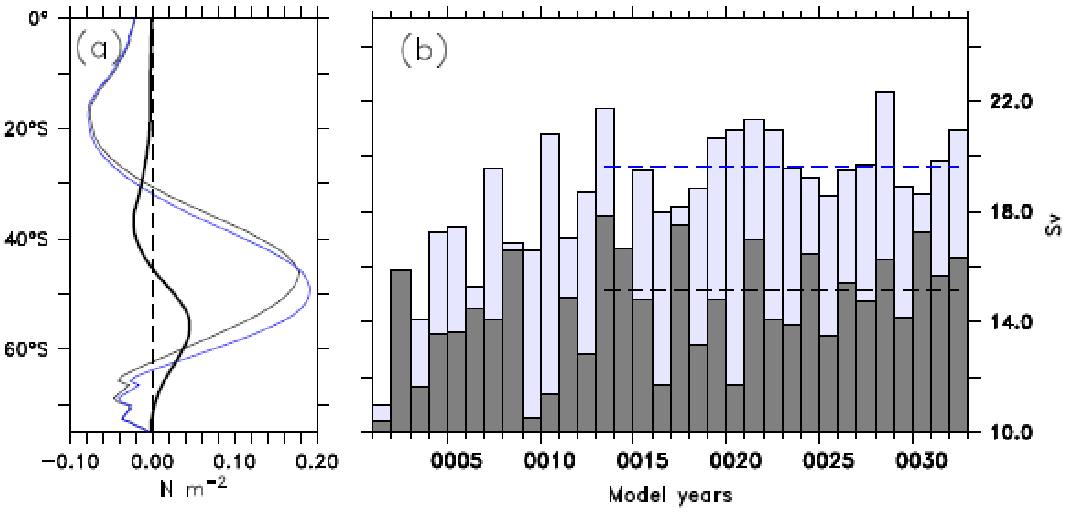

Figure 1. Wind shift and Agulhas leakage response. (a) Ensemble mean of zonally averaged wind stress (zonal component only) in the KCM climate model under present-day (black line) and global warming (blue) conditions. The difference function (thick) was applied to the ocean model experiments AG01-W. (b) Annual Agulhas leakage for AG01-C (dark bars) and AG01-W (light bars) experiments. Dashed lines represent the mean value of Agulhas leakage over the last 20 years of integration.

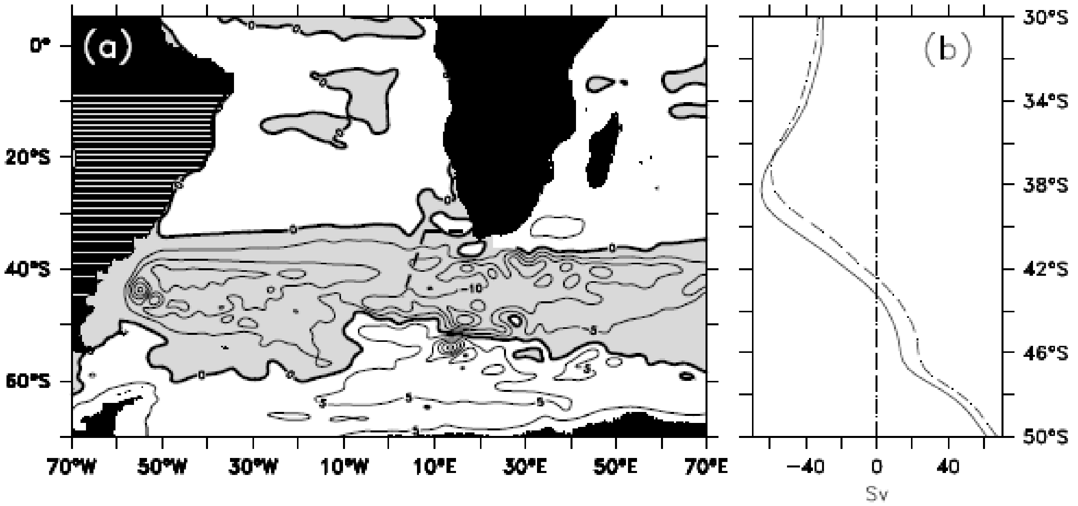

Figure 2. Horizontal gyre response to wind shift. Barotropic streamfunction change (a) from AG01-C to AG01-W (last 20 years; negative values are indicated by gray shading). The dashed line marks the GoodHope section. (b) Zonally averaged (20° - 60° E) streamfunction for AG01-C (dashed) and AG01-W (thick) averages.

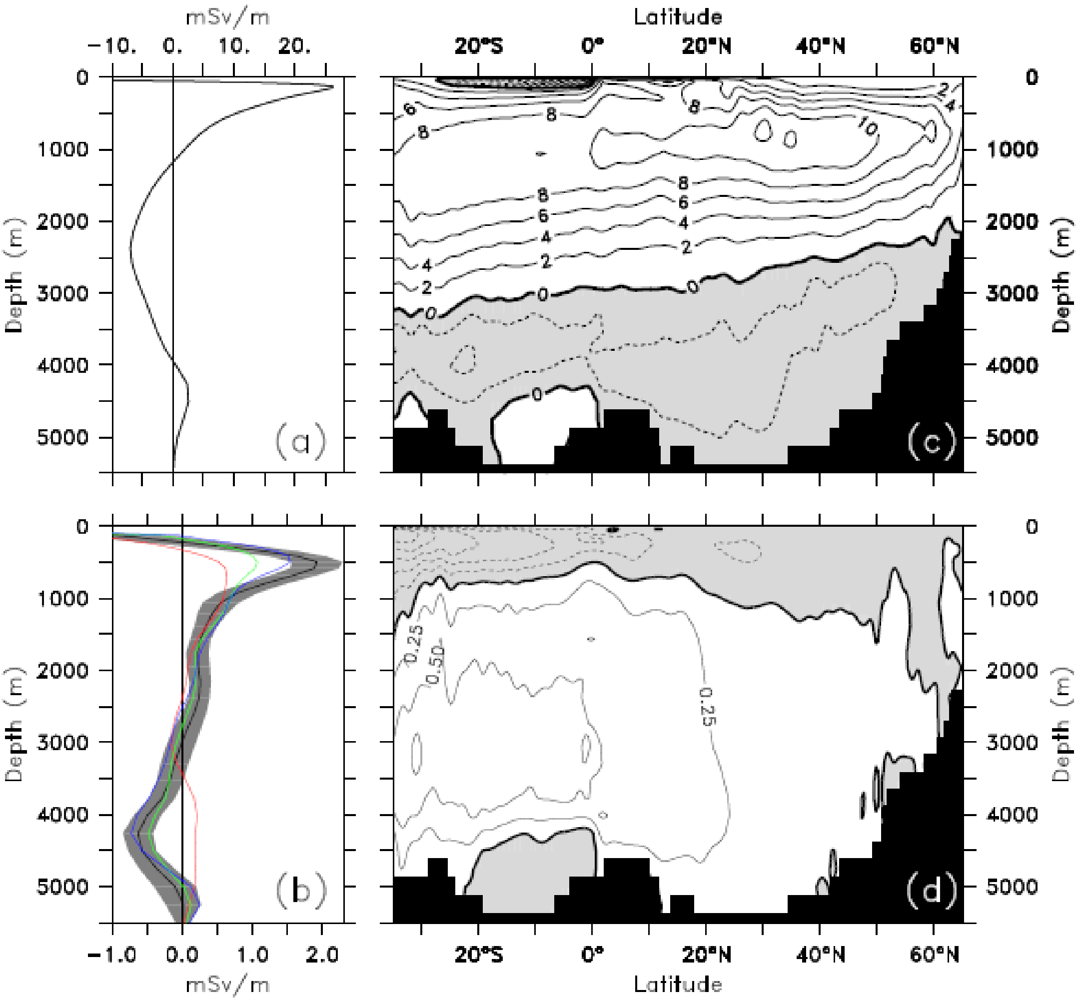

Figure 3. AMOC response to wind shift. (a) Northward transport per unit depth in AG01-C (25°-20°S, last 20 years) and (b) change between AG01-C and AG01-W: last 20 years (thick black curve) and interannual s.t.d. (shading), years 3-7 (red), 8-12 (green), and 12-16 (blue) years after wind application. (c) AMOC structure in AG01-C and (d) change between AG01-C and AG01-W (last 20 years).

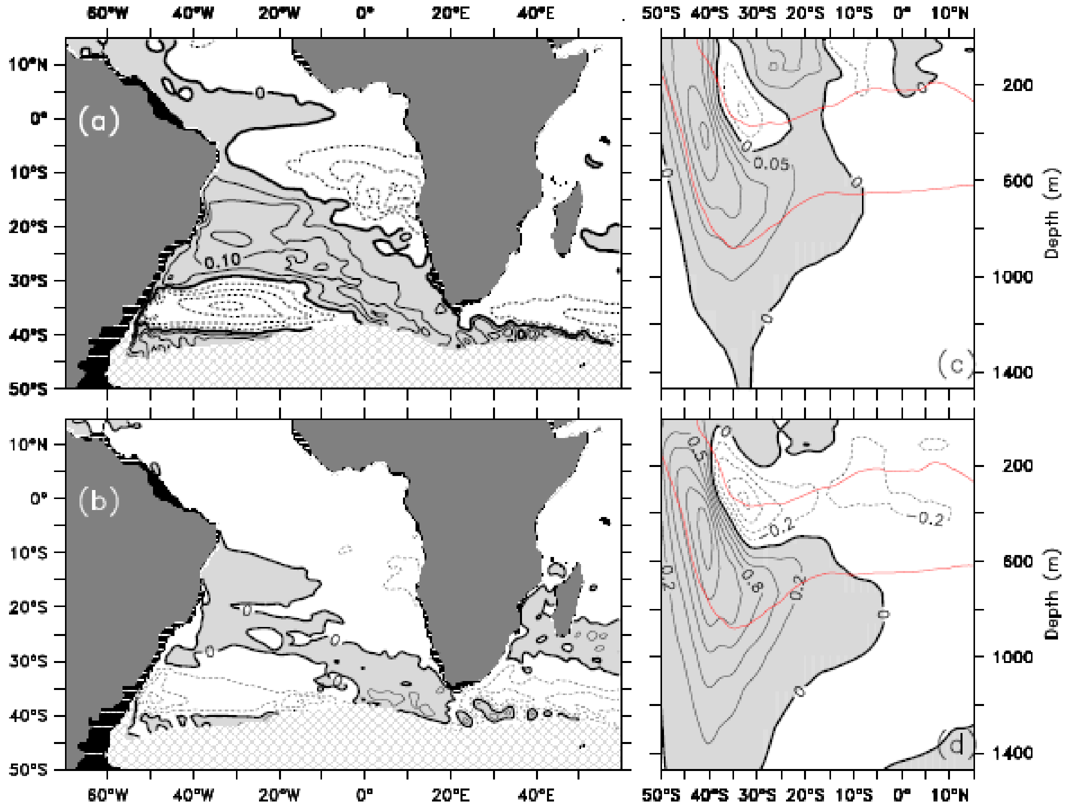

Figure 4. Water mass changes in the Atlantic due to the wind shift. (a) Salinity and (b) temperature changes in the upper thermocline from AG01-C to AG01-W (last 5 years), averaged over the top 300 m and limited to S > 35 to exclude AAIW (Regions with SSS < 35 are cross-hatched). Atlantic zonally averaged changes of (c) salinity and (d) temperature. The red isolines represent the SAMW range ($\sigma_0 = 26.5$ and 27.2) in AG01-C. (For the changes in density see Supplementary Fig. 3)