Ocean Sci. Discuss., doi:10.5194/os-2016-54, 2016
Manuscript under review for journal Ocean Sci.
Published: 1 August 2016

Freshening of Antarctic Intermediate Water in the South Atlantic Ocean in 2005 - 2014

Wenjun Yao[1] , Jiuxin Shi[1]

[1]Key Lab of Physical Oceanography (Ocean University of China), Ministry of Education, Qingdao 266100, Shandong, China

Correspondence to: E-mail address: wjimyao@gmail.com (Wenjun Yao)

Abstract

Basin-scaled freshening of Antarctic Intermediate Water (AAIW) is reported to have dominated South Atlantic Ocean during period from 2005 to 2014, as shown by the gridded monthly means Argo (Array for Real-time Geostrophic Oceanography) data. The relevant investigation was also revealed by two transatlantic occupations of repeated section along 30° S, from World Ocean Circulation Experiment Hydrographic Program. Freshening of the AAIW was compensated by the opposing salinity increase of thermocline water, indicating the contemporaneous hydrological cycle intensification. This was illustrated by the precipitation less evaporation change in the Southern Hemisphere from 2000 to 2014, with freshwater input from atmosphere to ocean surface increasing in the subpolar high-precipitation region and vice versa in the subtropical high-evaporation region. Against the background of hydrological cycle augment, the decreased transport of Agulhas Leakage (AL) was proposed to be one of the contributors for the associated freshening of AAIW. This indirectly estimated variability of AL, reflected by the weakening of wind stress over the South Indian Ocean since the beginning of 2000s, facilitates the freshwater input from source region and partly contributes to the observed freshened AAIW. Both of our mechanical analysis is qualitative, but this work would be helpful to validate and test predictably coupled sea-air model simulations.

Keywords: Freshening; Antarctic Intermediate Water; South Atlantic; Agulhas Leakage; Wind Stress

1. Introduction

Thermocline and intermediate waters play an important role on global overturning circulation by ventilating the subtropical gyres in different parts of the world oceans [*Sloyan* *and Rintoul*, 2001]. Meanwhile they also constitute the northern limb of the Southern Hemisphere supergyre [*Ridgway and Dunn*, 2007; *Speich et al.*, 2002].

Many studies have focused on the variability of intermediate water. *Wong et al.* [2001] pointed out that the intermediate water had freshened from 1960s to 1985-94 in the Pacific Ocean, *Bindoff and McDougall* [2000] reported that there had been freshening of water between 500 and 1500 db from 1962 to 1987 along 32 °S in the Indian Ocean, and *Curry et al.* [2003] discovered the salinity reduction on the isopycnal surface of intermediate water for the period 1950s - 1990s in the western Atlantic. All of the freshening variability can be traced back to the signature of water in the formation regions [*Church et al.*, 1991]. The freshening above are in agreement with the worldwide augment of hydrological cycle, in which context the wet (precipitation > evaporation, $P>E$ dominance) subpolar regions have been getting wetter and vice versa for the dry ($P<E$ dominance) subtropical regions since the last 50 years [*Held and Soden*, 2006; *Skliris et al.*, 2014].

Antarctic Intermediate Water (AAIW) is characterized by salinity minimum (core of AAIW) and concentrated at depth 600 - 1000 m (Fig. 1), lies within potential density (reference to sea surface) σ_0 = 27.1 - 27.3 kg/m^3 [*Piola and Georgi*, 1982]. The AAIW is found from just north of the Subantarctic Front (SAF) [*Orsi et al.*, 1995] in the Southern Ocean and can be traced into as far as 20 °N [*Talley*, 1996]. It is generally accepted that the variability of AAIW is largely controlled by air-sea-ice interaction [*Close et al.*, 2013; *Naveira Garabato et al.*, 2009; *Santoso and England*, 2004], but the argument about its origin and formation process is still going on. The first popular one is the controversially circumpolar formation theory of AAIW along SAF, through mixing with Antarctic Surface Water (AASW) along isopycnal [*Fetter et al.*, 2010; *Sverdrup et al.*, 1942]. And the other is the local formation perspective of AAIW in specific regions, as bi-product of Subantarctic Mode Water (SAMW) relating to deep convection [*McCartney*, 1982; *Piola and Georgi*, 1982].

In the South Atlantic, AAIW constitutes the return branch of the Meridional Overturning Circulation (MOC) [*Donners and Drijfhout*, 2004; *Speich et al.*, 2007; *Talley*, 2013]. As an open ocean basin, South Atlantic is fed by two different AAIW [*Sun and Watts*, 2002]. The first is the younger, fresher and lower apparent oxygen utilization (AOU) AAIW originated from the Southeast Pacific [*McCartney*, 1977; *Talley*, 1996] and the winter waters west of Antarctic Peninsula [*Naveira Garabato et al.*, 2009; *Santoso and England*, 2004]. Almost all these origin regions of AAIW is dominated by the net surface freshwater flux from atmosphere to ocean (P>E), which facilitates the freshening of AAIW with time. The second is the older, saltier and higher AOU AAIW comes from Indian Ocean, transported by Agulhas Leakage (AL) as Agulhas rings (Fig. 2). The mixture of the above two types of AAIW can lead to transition for hydrographic properties across the subtropical South Atlantic [*Boebel et al.*, 1997].

The influence of AL on variability of AAIW in the South Atlantic has been demonstrated to be greatly large [*Hummels et al.*, 2015; *Schmidtko and Johnson*, 2012], as 50 - 60% of the Atlantic AAIW originates from the Indian Ocean [*Gordon et al.*, 1992; *G D McCarthy et al.*, 2012], with increased (decreased) transport of AL relating to salinification (freshening) of AAIW. AL has apparently increased during period from 1950s to the early 21s [*Durgadoo et al.*, 2013; *Lübbecke et al.*, 2015], but no one has focused on discussing the influence of AL on the AAIW in South Atlantic since 2000, especially for the last decade.

With the development of Argo (Array for Real-time Geostrophic Oceanography) program, in-situ hydrographic observation has tremendously expanded since 2003 [*Roemmich et al.*, 2015], particularly in the Southern Ocean (SO) where historical data are sparse and intermittent. This decreases the uncertainty for the research on decadal variation of subsurface and intermediate waters.

The present work discovers the freshening of AAIW in the South Atlantic for the recent decade (2005 - 2014). Against the background of enhanced hydrological cycle, decreased transport of AL contributes to such a variation, suggested by the weakening of wind stress in the South Indian Ocean during the same period.

2. Data and Method

Based on individual temperature (T) and salinity (S) profiles from Argo, International Pacific Research Centre (IPRC) gridded monthly means data for period 2005 - 2014 are produced using variational interpolation. The IPRC data have 27 levels from 0 to 2000 m depth vertically, nominal 1°×1° grid globally and monthly temporal resolution. (http://apdrc.soest.hawaii.edu/projects/Argo/data/gridded/On_standard_levels/index-1.html). To reduce the error from low vertical resolution of data when computing the hydrographic values on isopycnal surface, here *T* and *S* profiles are first interpolated onto 1 m interval vertically using spline instead of linear method. Because the IPRC data are interpolated from randomly distributed Argo profiles, it is necessary to demonstrate the robust nature of its signals, by comparing with the other Argo gridded products. As a result, the Japan Agency of Marine-Earth Science and Technology (JAMSTEC, [*Hosoda et al.*, 2008]) *T* and *S* data from 2005 to 2014 with 1° longitude and 1° latitude resolution are also collected for comparison and verification. The number of Argo profile is rapidly increasing year by year, and part of its distribution had been outlined in some previous studies [*Hosoda et al.*, 2008; *Roemmich et al.*, 2015].

Two hydrographic occupations of repeated transect along 30°S are collected in the World Ocean Circulation Experiment (WOCE) Hydrographic Program (http://www.nodc.noaa.gov/woce/wdiu/diu_summaries/whp/index.htm). Their positions are presented in Fig. 2. The first occupation was collected with 72 stations in 2003 by the R/V Mirai (Japan, [*Kawano et al.*, 2004]), the other was in 2011 with 81 stations by the Ronald H. Brown (United States, [*Feely et al.*, 2011]) (http://www.nodc.noaa.gov/woce/wdiu/diu_summaries/whp/index.htm). These two sections are not only measured in almost the repeated positions in the subtropical South Atlantic, but also performed in the same season (Nov and Oct). Furthermore, the investigation time interval between the two synoptic sections from Nov 2003 to Oct 2011 are nearly the same as the IPRC data (Jan 2005 - Dec 2014), which can be used to confirm the result of IPRC data.

To reduce the effect of dynamic process in ocean interior (i.e. mesoscale eddies and internal waves), the investigation of halocline variation would be along neutral density surface [*G McCarthy et al.*, 2011; *McDougall*, 1987]. The layer of AAIW is defined using neutral density (γ^n, unit: kg/m^3) [*Jackett and McDougall*, 1997] instead of potential density, with the upper and lower boundaries of 27.1γ^n and 27.6γ^n [*Goes et al.*, 2014], respectively.

Monthly 10m wind fields between years 1980 and 2014 from ERA-interim archive at European Centre for Medium Range Weather Forecasts (ECMWF) (http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/) are used to display the decadal variability of wind stress (WS) over the South Indian Ocean. Another reanalysis wind product of NCEP2 (National Centers for Environmental Prediction-Department of Energy Atmospheric Model Intercomparison Project reanalysis 2, NCEP-DOE AMIP Reanalysis-2, http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html) for period 1980-2014, meanwhile the satellite-derived wind products of QuikSCAT for 2000-2007 and ASCAT for 2008-2014 (Quick Scatterometer and Advanced Scatterometer, both in ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/MWF/L3/) are further collected to compare and verify the decadal variability of WS revealed by ERA-interim wind product. The WS in this work over open ocean is calculated from 10 m wind field data using equation adopted in *Trenberth et al.* [1989].

Reanalysis data including precipitation (*P*) and evaporation (*E*) from ERA-interim are used to reveal the freshwater input from atmosphere to ocean surface in the recent decade.

3. Freshening of Antarctic Intermediate Water

3.1 Freshening observed from Argo gridded products

The Argo gridded products provide global distributed and continuous time series of *T* and *S* profiles down to 2000 m ocean depth. The present work would focus on the AAIW in South Atlantic Basin (Fig. 2, Region A), which encompasses most of the subtropical gyre and a part of the tropical regimes [*Boebel et al.*, 1997; *Talley*, 1996]. By the Argo gridded data of IPRC, the biennial mean of θ-S diagram (Fig. 3a) clearly exhibits that the AAIW has experienced a process of progressively basin-scale freshening during the period from Jan 2005 to Dec 2014. The linear trend of salinity (Fig. 3b) further reveals that the freshening takes up most of the AAIW layer but with a little salinification in the lower part of it. Except around the 27.42γ^n neutral density surface, the AAIW variation is significant at 95% confidence level, using the *F*-test criteria. In comparison with Fig. 3a, we found that the cut-off point of transformation from salinity decrease to increase is near the salinity minimum. Above salinity minimum, the shift of θ-S curves towards cooler and fresher values along

Ocean Sci. Discuss., doi:10.5194/os-2016-54, 2016
Manuscript under review for journal Ocean Sci.
Published: 1 August 2016

density surface responses to the warming and freshening of surface waters where AAIW ventilates. Such thermohaline change had also been found in the Pacific and Indian oceans over a different time period [*Wong et al.*, 1999], and had been explained by *Bindoff and Mcdougall* [1994], especially for the counterintuitive cooling of AAIW temperature. For the salinity decline of core of AAIW, it indicates that such change can only be induced by freshwater input from the source region, as mixing with surrounding more saline waters cannot give rise to salt loss in salinity minimum.

To demonstrate the robustness of AAIW variations revealed by IPRC data, re-plots of Fig. 3a-b using another Argo gridded product, the JAMSTEC, are also shown for comparison (see Supplementary 1, only AAIW layer shown). Not only the same variation along density surface in the AAIW layer found, but also for the freshening of salinity minimum. Both the isoneutral salinity increases of IPRC and JAMSTEC below salinity minimum are quite small. The most distinct discrepancy between them is that the amplitude of freshening revealed by JAMSTEC is somewhat less than IPRC and at larger 95% confidence level.

The freshwater gain for the basin-scale salinity decrease of AAIW (mean salinity difference of 0.012 between 27.1γ^n and 27.6γ^n over a mean water mass thickness of 500 m) is estimated at 15mm yr^{-1} in its source region. However, the depth-integrated salinity change over the water column (between 26.6γ^n and 27.6γ^n) is in turn 0.0014, as salinity increase of thermocline water balances the entirely observed freshening of AAIW. This salinity budget implies contemporaneous hydrological cycle intensification in the southern hemisphere, which is illustrated by the *P* less *E* change from 2000 to 2014, with *P-E* increasing in the subpolar region and vice versa in the subtropical region (Fig. 4a). In this case the thermocline (intermediate) water that ventilates in the high-evaporation (precipitation) subtropical (subpolar) regions gets saline (freshened), as shown by the hydrographic observations (Fig. 3b).

Against the background of hydrological cycle augment, the annually freshwater input in AAIW ventilation region during the freshened period increased by 0.02 mm day^{-1}, about 17% of the *P-E* in 2005 (Fig. 4b). Actually, the increase of *P-E* began in 1992, but significant increase around 2003 (Fig. 4b, 5-yr running mean line), which means the observed freshened

Ocean Sci. Discuss., doi:10.5194/os-2016-54, 2016
Manuscript under review for journal Ocean Sci.
Published: 1 August 2016

AAIW could be traced back to 2003. Though we could not compute the direct freshwater input to the South Atlantic Basin here, the Argo era freshening of AAIW is qualitatively consistent with the freshwater gain in its source region.

3.2 Freshening in the quasi-synchronous WOCE CTD observations

Here we further used two synoptic transatlantic sections from WOCE hydrographic program to explore the decadal freshened signal in the above subsection. Similar to Fig. 3a, sectional mean θ-S diagram (Fig. 5a) displays a same shift of thermohaline values, including the freshening of salinity minimum, the salinity reduction in upper AAIW layer and vice versa in lower layer. Comparing to the θ-S curves of IPRC data (Fig. 3a), the curves of WOCE (Fig. 5a) seem to be with cooler θ and fresher S in general, this is because the IPRC mean has more weight of warmer and saltier waters in the north.

Unlike the Argo gridded product which has continuous time series of T and S data, there are only two sections of snapshot in the WOCE observations. Instead of calculating the linear trend of salinity as the IPRC data done, difference of salinity observed in 2003 and 2011 is estimated (Fig. 5b). The light gray shading denotes the 95% confidence intervals using simple t-test criteria, after considering the number of degrees of freedom. Above the salinity minimum, the freshening of AAIW revealed by IPRC and WOCE data are quite similar, with the maximum appearing near 27.2γ^n. Because the last WOCE observation terminated in 2011 and the salinity reduction would continue at least up to 2014 as displayed in Fig. 3a, the magnitude of the freshening in WOCE (Fig. 5b) is a little lesser than IPRC (Fig. 3b). Below the salinity minimum, the salinity increase is relatively large revealed by WOCE data (Fig. 3d). This is because the salinity rise reached to its maximum around 2011, shown in the time series of basinwide averaged salinity on 27.45γ^n and 27.55γ^n density surfaces (see Supplementary 2).

For the salinification of thermocline water, there is a large discrepancy between IPRC and WOCE data, on neutral density surfaces 26.6-26.7γ^n (Fig. 5b). But this would not affect the result that salinity budget over the water column (Fig. 5b), with the salt gain of thermocline water balancing the observed freshened AAIW. In conclusion, the general and detailed consistency of salinity change signal over the last ten year time period revealed by

IPRC and WOCE data makes sure that our reported freshening of AAIW is robust and validated.

4. Decrease of Agulhas Leakage transport

AAIW in the South Atlantic is largely influenced by AL through the intermittent pinching off of Agulhas rings (Fig. 2) [*Beal et al.*, 2011], transferring salty thermocline and intermediate water from Indian Ocean to the South Atlantic [*De Ruijter et al.*, 1999]. The above discussion suggests that the freshening of AAIW is induced by input of freshwater from the source region. As a result, if the transport of more saline water from Indian Ocean decreased, it would promote the effect of this freshwater supplement. In this part of paper, the decrease of AL transport would be demonstrated by using an indirect indicator as below. And at last, thorough discussion with respect to other works is displayed.

4.1 Weakening of the westerlies in the South Indian Ocean

There have never been continuous measurements of the AL transport until now. The earlier study suggested that an increased AL transport correlates well with poleward shift of westerlies [*Beal et al.*, 2011]. However, after using reanalyss and climate models, *Swart and Fyfe* [2012] argued that strengthening of Southern Hemisphere surface westerlies has occurred without robust trend in its latitudinal position over the period from 1979-2010, during which period the AL has largely increased [*Biastoch et al.*, 2009]. A more recent study of *Durgadoo et al.* [2013] even showed that the increase of AL is concomitant with equatorward rather than poleward shift of westerlies in their simulation cases. And they concluded that the intensity of westerlies is predominantly responsible in controlling this Indian-Atlantic transport. Many relevant studies agreed on this relationship that the enhancement of westerlies intensity relating to the increase of AL [*Goes et al.*, 2014; *Lee et al.*, 2011; *Loveday et al.*, 2015].

The AL corresponds most significantly to westerlies strength averaged over the Indian Ocean in contrast to that averaged circumpolarly or locally [*Durgadoo et al.*, 2013]. And according to the work of *Durgadoo et al.* [2013], zonally averaged WS was calculated from the wind product of ERA-interim over the Indian Ocean (20-110° E) for every 5-yr since 1980 (Fig. 6a and d). As the same results as many other studies [*Lee et al.*, 2011; *Loveday et*

Ocean Sci. Discuss., doi:10.5194/os-2016-54, 2016
Manuscript under review for journal Ocean Sci.
Published: 1 August 2016

al., 2015], the WS has considerably increased from 1980s to the beginning of 2000s (Fig. 6d), consistent with the contemporaneous increase of AL transport. Though there are oscillations during 1990s, the WS reached to its peak around the years 00-04 (Fig. 6d). And then the WS began to decline. Thus it shows that the WS has weakened for period 2000 – 2014 (Fig. 6d), suggesting the concurrent decrease of AL transport.

In addition to the ERA-interim wind data, we have further checked the zonally averaged WS over the Indian Ocean (20-110 °E), using another reanalysis product of NCEP2 (Fig. 6b and e) and the combined QuikSCAT-ASCAT (Fig. 6c and f) satellite-derived wind products. All of the three zonally averaged WS agree on that during the period 2000-2014, the westerlies reached to its peak in the years 00-04, and then progressively subsided through 05-09 to 10-14. The process of gradual decline of WS is most distinctly illustrated in the NCEP2 data. And what is important, we also note that neither of the three products show a significant meridional shift of the latitude of maximum WS from 2000 to 2014, concomitant with the conclusion of *Swart and Fyfe* [2012].

4.2 Evidence from other works

Many efforts have been made to estimate AL transport, especially using model simulations [*Lübbecke et al.*, 2015; *Loveday et al.*, 2015]. In recent years, *Le Bars et al.* [2014] provided the time series of AL transport over the satellite altimeter era, computed from absolute dynamic topography data, which can manifest the decadal variation of AL present here. In their result (Figure 8 in *Le Bars et al.* [2014]), the anomalies of AL from satellite altimeter reached to the peak around 2003 (annual average), and then began to subside, though in the middle of 2011 it appeared to increase again. In addition, their negative trend of AL (Figure 9 in *Le Bars et al.* [2014]) over the period from Oct 1992 to Dec 2012 indicates that the transport reduced during the 2000s in contrast to the 1990s. There is another work done by *Biastoch et al.* [2015] which could support the discussion here. Though the time series of AL obtained from models didn't show a distinct decline of AL transport in the last decade, partly due to the data filter applied and the end of time series in 2010 (Figure 4 in *Biastoch et al.* [2015]), it apparently displays a maximum of salt transport around 2000

Ocean Sci. Discuss., doi:10.5194/os-2016-54, 2016
Manuscript under review for journal Ocean Sci.
Published: 1 August 2016

(Figure 5 in *Biastoch et al.* [2015]). These peak and subsequent decline of salt transport are consistent with the freshening of AAIW over the similar time period observed here.

Thus, in addition to the freshwater input that gives rise to the salt loss of the AAIW in South Atlantic Ocean, less transport of AL or salt further facilitate this signal. But unfortunately, both the analysis of contribution from source region and AL are qualitatively instead of quantitatively, only by using the traditionally hydrographic and atmospheric reanalysis data. Future work should be focused on quantification of each factor based on model simulations.

5. Conclusions

The analysis of IPRC gridded data shows that AAIW in the South Atlantic has experienced basin-scale freshening for the period from Jan 2005 to Dec 2014 (Fig. 3a and b), with freshwater input estimated at 15 mm yr^{-1} in its source region. Two synoptic transects of WOCE hydrographic program observed in 2003 and 2011 also reveal the above well-marked variation of AAIW in the last decade (Fig. 3c and d).

Such freshened signal in the intermediate water layer is illustrated to be compensated by increased salinity in shallower thermocline water, indicating the contemporaneous intensification of hydrological cycle (Fig. 3b and Fig. 5b). In this case the freshwater input from atmosphere to ocean surface increased in subpolar high-evaporation region and vice versa in the subtropical high-precipitation region (Fig. 4a). Over the last ten year time period, significant freshwater gain began around 2003 (Fig. 4b), suggesting the observed freshened AAIW could be traced back to this time.

Against the background of hydrological intensification, the decrease of AL transport is proposed to contribute to the freshening of AAIW in the South Atlantic, reflected by the weakening of westerlies over South Indian Ocean. It shows that the WS over South Indian Ocean reached to its peak around 00-04 and began to subside through 05-09 to 10-14 (Fig. 6), reversing its increasing phase from 1950s to the beginning of 2000s, during which period the AL had concomitantly increased [*Durgadoo et al.*, 2013; *Lübbecke et al.*, 2015]. This indirectly estimated variability of AL, is consistent with the discussion of it over the similar period [*Biastoch et al.*, 2015; *Le Bars et al.*, 2014]. As the AAIW carried by AL is more

Ocean Sci. Discuss., doi:10.5194/os-2016-54, 2016
Manuscript under review for journal Ocean Sci.
Published: 1 August 2016

saline relative to its counterpart in the South Atlantic Ocean, its decrease would promote the effect of freshwater input from the source region, contributing to the observed freshening.

Both the analysis of freshwater input and less transport of AL reported here are qualitative but not quantitative. The purpose of this work is to reveal the decadal freshening of AAIW in South Atlantic Ocean over the last ten year time period, and its corresponding mechanism. Future work should be focused on the quantification of these two contributors, meanwhile revealing its influence on the world ocean circulation.

Acknowledgements

This study is supported by the Chinese Polar Environment Comprehensive Investigation and Assessment Programs (Grant nos. CHINARE-04-04, CHINARE-04-01).

Captions of Figures

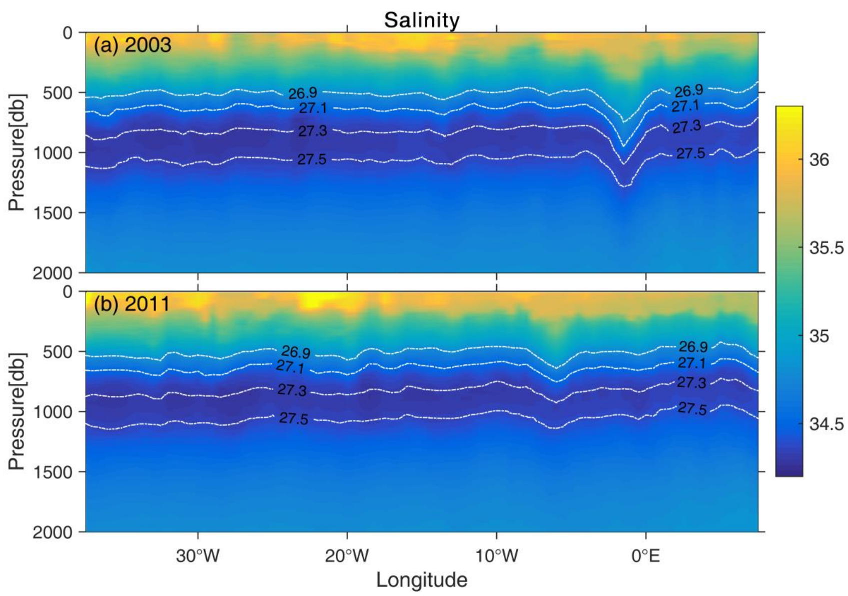

Figure 1. WOCE salinity sections along 30 °S in the South Atlantic Ocean (positions shown in Fig. 2) observed in (a) 2003 and (b) 2011. Overlaid white solid-dotted lines are γ^n surfaces ranging from 26.9 to 27.5 kg/m^3, with 0.2 kg/m^3 interval.

Ocean Sci. Discuss., doi:10.5194/os-2016-54, 2016
Manuscript under review for journal Ocean Sci.
Published: 1 August 2016

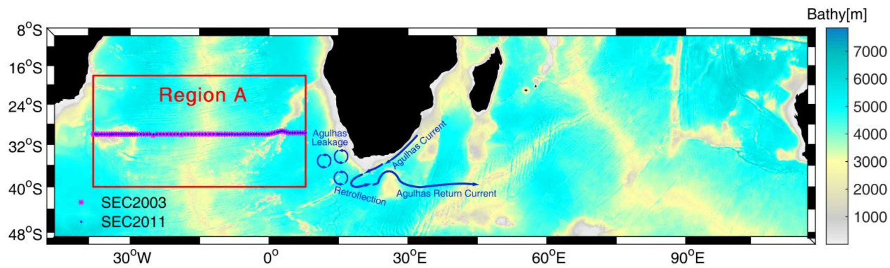

Figure 2. Bathymetry of the South Indian-Atlantic oceans. Color shading is ocean depth. Red box delineates the area for the basinwide average of gridded data (hereafter refers to Region A). Magenta stars represent transatlantic CTD stations measured in 2003, meanwhile blue dots in 2011. The Agulhas Current, Retroflection, Agulhas Return Current and Agulhas Leakage (as eddies) are also shown and ticked.

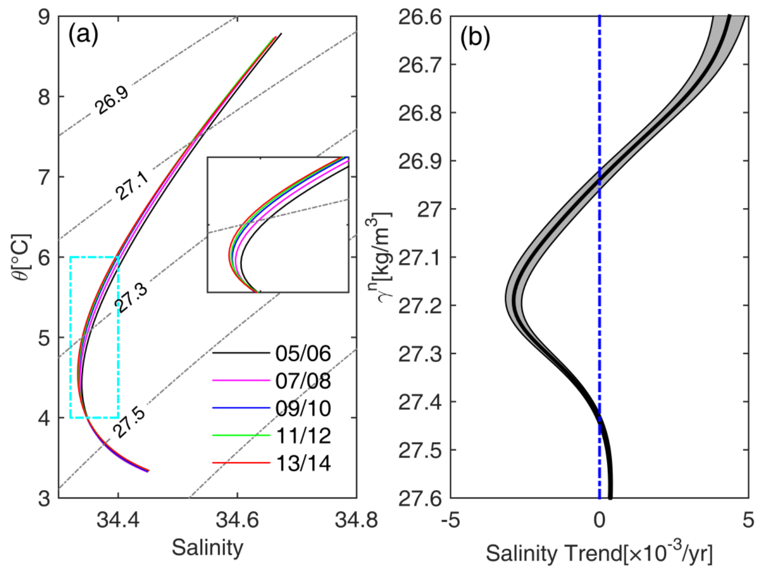

Figure 3. (a) Biennial mean θ-S diagram averaged over Region A for IPRC data with γ^n surfaces superimposed (gray solid-dotted lines). The inserted figure is the magnification of the area delineated by cyan solid-dotted box. The corresponding time for each θ-S curve in is listed in their bottom-right corner (i.e. 05/06 for 2005-2006). (b) Salinity trend along γ^n surfaces for period Jan 2005 – Dec 2014 is displayed by the thick black line, and the 95% confidence intervals (F-test) are represented by the light gray shadings, calculated from IPRC data.

Ocean Sci. Discuss., doi:10.5194/os-2016-54, 2016
Manuscript under review for journal Ocean Sci.
Published: 1 August 2016

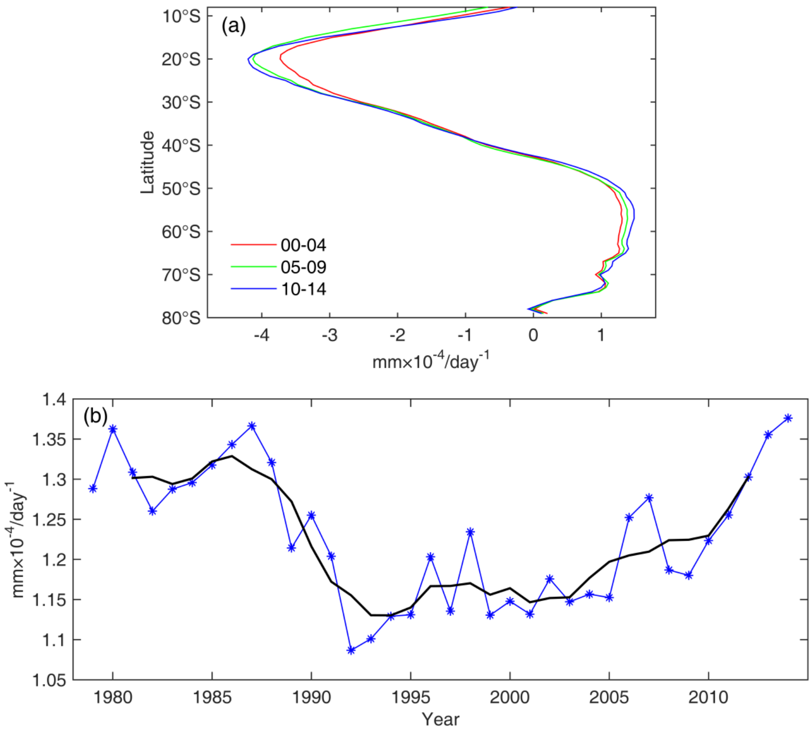

Figure 4. Calculated from ERA-interim precipitation and evaporation data: (a) Zonally mean (ocean areas only) of annually *P-E* (freshwater input, mm day^{-1}), each line represents a 5-yr averaged result. The corresponding time period (i.e. 00-04 for 2000-2004) is listed in the bottom-left corner. (b) Time series of annually *P-E* averaged over the oceans in 45-65 ° S, 0-360 °E band from 1979 to 2014 (blue star), and its 5-yr running mean (black).

Ocean Sci. Discuss., doi:10.5194/os-2016-54, 2016
Manuscript under review for journal Ocean Sci.
Published: 1 August 2016

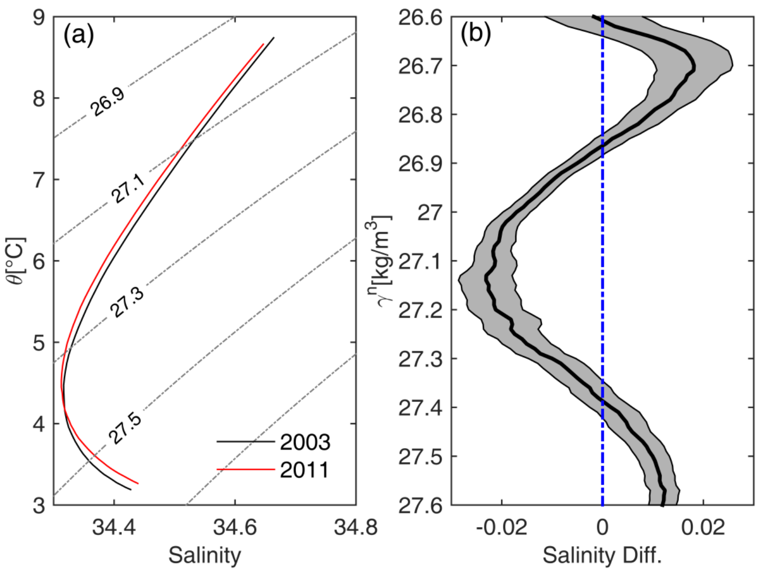

Figure 5. (a) The same as Fig. 3a but for sectional mean of WOCE hydrographic casts. The corresponding year for each θ-S curve in is listed in their bottom-right corner. (b) Sectional mean differences (thick black line) of WOCE hydrographic data along γ^n and their 95% confidence intervals (gray shadings, *t*-test).

Ocean Sci. Discuss., doi:10.5194/os-2016-54, 2016
Manuscript under review for journal Ocean Sci.
Published: 1 August 2016

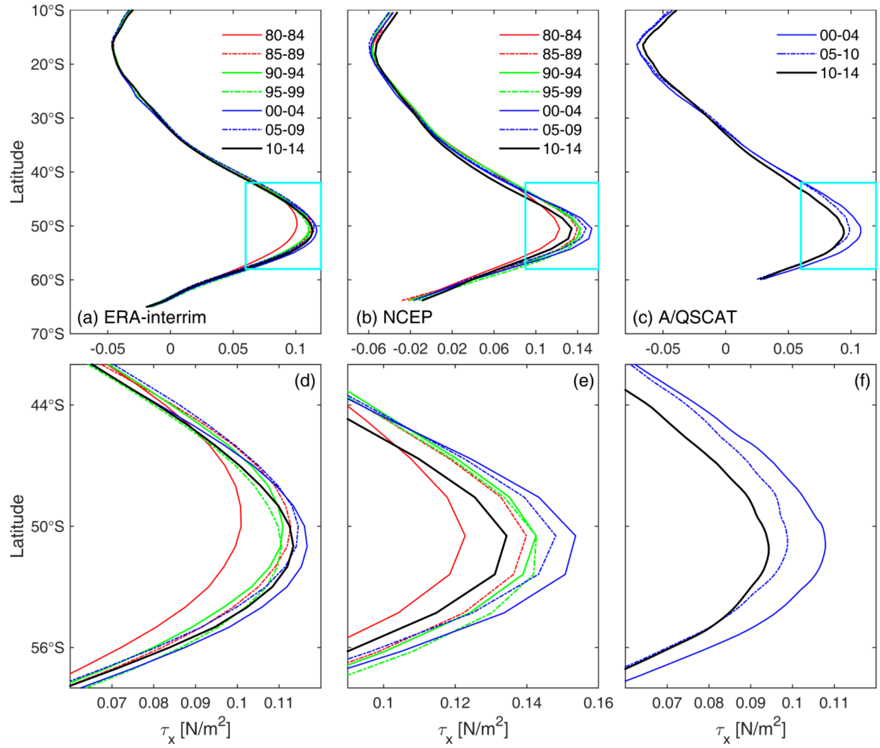

Figure 6. Zonally averaged wind stress calculated from the wind product of (a) ERA-interim, (b) NCEP2 and (c) ASCAT/QSCAT over the Indian Ocean (20 ° E-110 ° E) for different periods (i.e. 80-84 for Jan 1980 - Dec 1984; 00-04 for Jan 2000 - Dec 2004) listed in the top-right corners. (d), (e) and (f) are the magnification of cyan boxes in (a), (b) and (c), respectively.

REFERENCES

Beal, L. M., W. P. De Ruijter, A. Biastoch, and R. Zahn (2011), On the role of the Agulhas system in ocean circulation and climate, *Nature.*, *472*(7344), 429-436.

Biastoch, A., C. W. Böning, F. U. Schwarzkopf, and J. Lutjeharms (2009), Increase in Agulhas leakage due to poleward shift of Southern Hemisphere westerlies, *Nature.*, *462*(7272), 495-498.

Biastoch, A., J. V. Durgadoo, A. K. Morrison, E. van Sebille, W. Weijer, and S. M. Griffies (2015), Atlantic multi-decadal oscillation covaries with Agulhas leakage, *Nature communications*, *6*.

Bindoff, N. L., and T. J. Mcdougall (1994), Diagnosing climate change and ocean ventilation using hydrographic data, *J. Phys. Oceanogr.*, *24*(6), 1137-1152.

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*(6), 1207-1222.

Ocean Sci. Discuss., doi:10.5194/os-2016-54, 2016
Manuscript under review for journal Ocean Sci.
Published: 1 August 2016

Boebel, O., C. Schmid, and W. Zenk (1997), Flow and recirculation of Antarctic intermediate water across the Rio Grande rise, *J. Geophys. Res. Oceans (1978–2012)*, *102*(C9), 20967-20986.

Church, J. A., J. S. Godfrey, D. R. Jackett, and T. J. McDougall (1991), A model of sea level rise caused by ocean thermal expansion, *J. Climate.*, *4*(4), 438-456.

Close, S. E., A. C. Naveira Garabato, E. L. McDonagh, B. A. King, M. Biuw, and L. Boehme (2013), Control of mode and intermediate water mass properties in Drake Passage by the Amundsen Sea Low, *J. Climate.*, *26*(14), 5102-5123.

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*(6968), 826-829.

De Ruijter, W., A. Biastoch, S. Drijfhout, J. Lutjeharms, R. Matano, T. Pichevin, P. Van Leeuwen, and W. Weiger (1999), Indian-Atlantic interocean exchange: Dynamics, estimation and impact, *J. Geophys. Res.*, *104*(C9), 20885-20910.

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*(5), 1019-1035.

Durgadoo, J. V., B. R. Loveday, C. J. C. Reason, P. Penven, and A. Biastoch (2013), Agulhas Leakage Predominantly Responds to the Southern Hemisphere Westerlies, *J. Phys. Oceanogr.*, *43*(10), 2113-2131.

Feely, R. A., R. Wanninkhof, S. Alin, M. Baringer, and J. Bullister (2011), Global Repeat Hydrographic/CO2/Tracer surveys in Support of CLIVAR and Global Cycle objectives: Carbon Inventories and Fluxes.

Fetter, A., M. Schodlok, and V. Zlotnicki (2010), Antarctic Intermediate Water Formation in a High-Resolution OGCM, paper presented at EGU General Assembly Conference Abstracts.

Goes, M., I. Wainer, and N. Signorelli (2014), Investigation of the causes of historical changes in the subsurface salinity minimum of the South Atlantic, *J. Geophys. Res. Oceans*, *119*(9), 5654-5675.

Gordon, A. L., R. Weiss, W. M. Smethie Jr, and M. J. Warner (1992), Thermociine and Intermediate Water Communication, *J. Geophys. Res.*, *97*(C5), 7223-7240.

Held, I. M., and B. J. Soden (2006), Robust responses of the hydrological cycle to global warming, *J. Climate.*, *19*(21), 5686-5699.

Hosoda, S., T. Ohira, and T. Nakamura (2008), A monthly mean dataset of global oceanic temperature and salinity derived from Argo float observations, *JAMSTEC Rep. Res. Dev.*, *8*, 47-59.

Hummels, R., P. Brandt, M. Dengler, J. Fischer, M. Araujo, D. Veleda, and J. V. Durgadoo (2015), Interannual to decadal changes in the western boundary circulation in the Atlantic at 11 °S, *Geophys. Res. Lett.*, *42*(18), 7615-7622.

Jackett, D. R., and T. J. McDougall (1997), A neutral density variable for the world's oceans, *J. Phys. Oceanogr.*, *27*(2), 237-263.

Kawano, T., H. Uchida, W. Schneider, Y. Kumamoto, A. Nishina, M. Aoyama, A. Murata, K. Sasaki, Y. Yoshikawa, and S. Watanabe (2004), Cruise Summary of WHP P6, A10, I3 and I4 Revisits in 2003, paper presented at AGU Fall Meeting Abstracts.

Lübbecke, J. F., J. V. Durgadoo, and A. Biastoch (2015), Contribution of increased Agulhas

Ocean Sci. Discuss., doi:10.5194/os-2016-54, 2016
Manuscript under review for journal Ocean Sci.
Published: 1 August 2016

leakage to tropical Atlantic warming, *J. Climate.*, *28*(24), 9697-9706.

Le Bars, D., J. V. Durgadoo, H. A. Dijkstra, A. Biastoch, and W. P. M. De Ruijter (2014), An observed 20-year time series of Agulhas leakage, *Ocean Sci.*, *10*(4), 601-609.

Lee, S. K., W. Park, E. van Sebille, M. O. Baringer, C. Wang, D. B. Enfield, S. G. Yeager, and B. P. Kirtman (2011), What caused the significant increase in Atlantic Ocean heat content since the mid‐20th century?, *Geophys. Res. Lett.*, *38*(17).

Loveday, B., P. Penven, and C. Reason (2015), Southern Annular Mode and westerly‐wind‐driven changes in Indian‐Atlantic exchange mechanisms, *Geophys. Res. Lett.*, *42*(12), 4912-4921.

McCarthy, G., E. McDonagh, and B. King (2011), Decadal variability of thermocline and intermediate waters at 24 S in the South Atlantic, *J. Phys. Oceanogr.*, *41*(1), 157-165.

McCarthy, G. D., B. A. King, P. Cipollini, E. L. McDonagh, J. R. Blundell, and A. Biastoch (2012), On the sub-decadal variability of South Atlantic Antarctic Intermediate Water, *Geophys. Res. Lett.*, *39*, L10605.

McCartney, M. S. (1977), Subantarctic Mode Water, in *Angel, M.V. (Ed.), A Voyage of Discovery: George Deacon 70th Anniversary Volume (Suppl. To Deep-Sea Res.). Pergamon*, edited, pp. 103-119, Woods Hole Oceanographic Institution.

McCartney, M. S. (1982), The subtropical recirculation of mode waters, *J. Mar. Res.*, *40*, 427-464.

McDougall, T. J. (1987), Neutral surfaces, *J. Phys. Oceanogr.*, *17*(11), 1950-1964.

Naveira Garabato, A. C., L. Jullion, D. P. Stevens, K. J. Heywood, and B. A. King (2009), Variability of Subantarctic Mode Water and Antarctic Intermediate Water in the Drake Passage during the Late-Twentieth and Early-Twenty-First Centuries, *J. Climate.*, *22*(13), 3661-3688.

Orsi, A. H., T. Whitworth Iii, and W. D. Nowlin Jr (1995), On the meridional extent and fronts of the Antarctic Circumpolar Current, *Deep-Sea Res. I.*, *42*(5), 641-673.

Piola, A. R., and D. T. Georgi (1982), Circumpolar properties of Antarctic intermediate water and Subantarctic Mode Water, *Deep-Sea Res. A.*, *29*(6), 687-711.

Ridgway, K. R., and J. R. Dunn (2007), Observational evidence for a Southern Hemisphere oceanic supergyre, *Geophys. Res. Lett.*, *34*, L13612.

Roemmich, D., J. Church, J. Gilson, D. Monselesan, P. Sutton, and S. Wijffels (2015), Unabated planetary warming and its ocean structure since 2006, *Nature Clim. Change*, *5*(3), 240-245.

Santoso, A., and M. H. England (2004), Antarctic Intermediate Water circulation and variability in a coupled climate model, *J. Phys. Oceanogr.*, *34*(10), 2160-2179.

Schmidtko, S., and G. C. Johnson (2012), Multidecadal Warming and Shoaling of Antarctic Intermediate Water*, *J. Climate.*, *25*(1), 207-221.

Skliris, N., R. Marsh, S. A. Josey, S. A. Good, C. Liu, and R. P. Allan (2014), Salinity changes in the World Ocean since 1950 in relation to changing surface freshwater fluxes, *Climate dynamics*, *43*(3-4), 709-736.

Sloyan, B. M., and S. R. Rintoul (2001), Circulation, Renewal, and Modification of Antarctic Mode and Intermediate Water*, *J. Phys. Oceanogr.*, *31*(4), 1005-1030.

Speich, S., B. Blanke, and W. Cai (2007), Atlantic meridional overturning circulation and the

Southern Hemisphere supergyre, *Geophys. Res. Lett.*, *34*, L23614.

Speich, S., B. Blanke, P. de Vries, S. Drijfhout, K. Döös, A. Ganachaud, and R. Marsh (2002), Tasman leakage: A new route in the global ocean conveyor belt, *Geophys. Res. Lett.*, *29*(10), 1416.

Sun, C., and D. R. Watts (2002), A view of ACC fronts in streamfunction space, *Deep-Sea Res. I.*, *49*(7), 1141-1164.

Sverdrup, H. U., M. W. Johnson, and R. H. Fleming (1942), *The Oceans: Their physics, chemistry, and general biology*, Prentice-Hall New York.

Swart, N., and J. Fyfe (2012), Observed and simulated changes in the Southern Hemisphere surface westerly wind - stress, *Geophys. Res. Lett.*, *39*(L16711).

Talley, L. D. (1996), Antarctic intermediate water in the South Atlantic, in *The South Atlantic*, edited, pp. 219-238, Springer.

Talley, L. D. (2013), Closure of the global overturning circulation through the Indian, Pacific, and Southern Oceans: Schematics and transports, *Oceanography*, *26*(1), 80-97.

Trenberth, K. E., W. G. Large, and J. G. Olson (1989), The effective drag coefficient for evaluating wind stress over the oceans, *J. Climate.*, *2*(12), 1507-1516.

Wong, A. P., N. L. Bindoff, and J. A. Church (1999), Large-scale freshening of intermediate waters in the Pacific and Indian Oceans, *Nature.*, *400*(6743), 440-443.

Wong, A. P., N. L. Bindoff, and J. A. Church (2001), Freshwater and heat changes in the North and South Pacific Oceans between the 1960s and 1985-94, *J. Climate.*, *14*(7), 1613-1633.