Edits in "Track Changes.

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

Wenjun Yao1 , Jiuxin Shi1

1Key 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-scale freshening of Antarctic Intermediate Water (AAIW) is reported to have dominated occurred in the South Atlantic Ocean during the period from 2005 to 2014, as shown by the gridded monthly means Argo (Array for Real-time Geostrophic Oceanography) data. The relevant investigation This phenomenon was also revealed by two transatlantic occupations of repeated transects along a section along at 30° S, from performed during the World Ocean Circulation Experiment Hydrographic Program. Freshening of the AAIW was compensated by the opposinga salinity increase of thermocline water, indicating the contemporarya hydrological cycle intensification. This was illustrated supported by the precipitation less evaporation change in the Southern Hemisphere from 2000 to 2014., with fFreshwater input from atmosphere to ocean surface increasing increased in the subpolar, high-precipitation region and *vice versa* in the subtropical high-evaporation region. Against the background of hydrological cycle augmentchanges, the decreased a decrease in the transport of Agulhas Leakage (AL) was proposed to be one of thea contributors for to the associated freshening of AAIW. This indirectly estimated

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variability of AL, reflected by thewas inferred from a weakening of wind stress over the South Indian Ocean since the beginning of the 2000s, which would facilitates the freshwater input from the source region and partly contributes to the observed freshened freshening of AAIW. Both of ourThe mechanical analysis analyses used in this study areis qualitative, but thisit is contended that this study 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 onpart in global overturning circulation by ventilating the subtropical gyres in different parts of the world oceans [Sloyan and Rintoul, 2001]. ~~Meanwhile t~~They also constitute the northern limb of the Southern Hemisphere supergyre [Ridgway and Dunn, 2007; Speich et al., 2002]. ~~Many~~ Previous studies have ~~focused on~~addressed the variability of intermediate water. Wong et al. [2001] ~~pointed out~~found that the intermediate water had freshened ~~from~~ between the 1960s ~~to~~ and the period 1985-94 in the Pacific Ocean.~~,~~ Bindoff and McDougall [2000] reported that there had been a 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~~showed a salinity reduction on the isopycnal surface of intermediate water for the period 1950s -1990s in the western Atlantic. ~~All of the~~The freshening variability can be traced back to the signature of water in the formation regions [Church et al., 1991]. The freshening examples given above are in agreement with ~~the worldwide augment of~~changes in the 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~~ over the last 50 years [Held and Soden, 2006; Skliris et al., 2014].

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Antarctic Intermediate Water (AAIW) is characterized by a salinity minimum (core of AAIW) and concentrated at a depth 600 -1000 m (Fig. 1), which lies within a potential density (reference to sea surface) of s0 = 27.1 -27.3 kg/m3 [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~~continues. ~~The first popular one is the controversially~~For example, there is the circumpolar formation theory of AAIW along the SAF, through mixing with Antarctic Surface Water (AASW) along an isopycnal [Fetter et al., 2010; Sverdrup et al., 1942]~~. And the other~~Alternatively, it has been proposed that there is a ~~the~~ local formation ~~perspective~~ of AAIW in specific regions, as a 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, the South Atlantic is fed by two different sources of AAIW [Sun and Watts, 2002]. The first is ~~the~~ younger, fresher and has a lower apparent oxygen utilization (AOU) ~~AAIW originated~~and originates 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~~ T~~t~~hese ~~origin~~ source regions of AAIW ~~is~~ are mostly 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 which 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 a transition ~~for~~ of 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~~substantial [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 the period from 1950s to the early 2~~1~~000s [Durgadoo et al., 2013; Lübbecke et al., 2015], but ~~no one has focused on~~there have been no studies addressing ~~discussing~~ the influence of AL on the AAIW in South Atlantic since 2000~~, especially for the last decade~~.

With the ~~development~~ instigation of the Argo (Array for Real-time Geostrophic Oceanography) program, *in-situ* hydrographic observations have~~s~~ ~~tremendously~~ greatly 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~~ addresses the freshening of AAIW in the South Atlantic ~~for the recent~~over the preceding decade (2005 -2014). Against the background of an enhanced hydrological cycle, decreased

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transport of AL contributes to such ~~a variation~~freshening and may be driven~~, suggested~~ by ~~the~~ a weakening of wind stress in the South Indian Ocean during the same period.

2. Data and Methods

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 depth intervals ~~vertically~~ using a 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~~ their 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 profiles is rapidly increasing year by year, and part of ~~its~~ their distribution hasd been outlined in ~~some~~ previous studies, *inter alia* [Hosoda et al., 2008; Roemmich et al., 2015].

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

To reduce the effect of dynamic processes in the ocean interior (i.e. mesoscale eddies and internal waves), the investigation of halocline variation ~~would~~ should be along neutral density surfaces [G McCarthy et al., 2011; McDougall, 1987]. The layer of AAIW is defined using neutral density (.n, unit: kg/m3) [Jackett and McDougall, 1997] instead of potential density, with the upper and lower boundaries ~~of~~ being 27.1.n and 27.6.n [Goes et al., 2014], respectively.

Monthly 10m wind fields between years 1980 and 2014 from the ERA-interim archive at the 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) is used for the period 1980-2014.~~,~~ ~~meanwhile~~ Additionally, 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~~used to compare and verify the decadal variability of WS revealed by the ERA-interim wind product. The WS in this work over open ocean is calculated from 10 m wind field data using the 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 the atmosphere to ocean surface in the ~~recent~~ preceding decade.

3. Freshening of Antarctic Intermediate Water

3.1 Freshening observed from Argo gridded products

The Argo gridded products provide a globally distributed and continuous time series of T and S profiles down to 2000 m ocean depth. The present work ~~would~~ focus~~s~~es on the AAIW in the 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~~The Argo gridded data of IPRC, the biennial mean of .-S diagram (Fig. 3a) clearly ~~exhibits~~ shows that the AAIW has experienced a process of progresse~~ively~~ 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~~ deeper part of it. Except around the 27.42.n neutral density surface, the AAIW variation is significant at the 95% confidence level, using the F-test criteria. In comparison with Fig. 3a, ~~we~~ it was found that the cut-off point of transformation from salinity decrease to increase is near the salinity minimum. Above the salinity minimum, the shift of .-S ~~curves~~ tends towards cooler and fresher values along

~~5~~ five

density surfaces and may be a response~~s~~ to the warming and freshening of surface waters where AAIW ventilates. Such thermohaline change has~~d~~ also been found in the Pacific and Indian oceans over a different time period [Wong et al., 1999], and has~~d~~ been ~~explained~~ researched by Bindoff and Mcdougall [1994], especially for the counterintuitive cooling of AAIW temperature. ~~For the~~The salinity ~~decline~~ decrease 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 the 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 surfaces in the AAIW layer were found, but also ~~for the~~a freshening of the salinity minimum. Both the isoneutral salinity increases of IPRC and JAMSTEC data below the salinity minimum are quite small. The ~~most distinct~~main discrepancy between them is that the ~~amplitude~~ degree of freshening ~~revealed by~~ in the JAMSTEC data is somewhat less than IPRC and at ~~larger~~ a higher 95% confidence level. The freshwater gain for the basin-scale salinity decrease of AAIW (mean salinity difference of 0.012 between 27.1.n and 27.6.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 26.6.n and 27.6.n) is ~~in turn~~ 0.0014;~~,~~ ~~as~~ since a salinity increase of thermocline water balances the ~~entirely~~ observed freshening of AAIW. This salinity budget implies contemporary 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~~ these cases, the thermocline (intermediate) water that ventilates in the high-evaporation (precipitation) subtropical (subpolar) regions gets more saline (freshened), as shown by the hydrographic observations (Fig.

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3b).

Against the background of hydrological cycle augmentation, the annually freshwater input in the AAIW ventilation region during the freshened freshening period increased by 0.02 mm day-1, about 17% of the P-E in 2005 (Fig. 4b). ActuallyIt is considered that, the increase of P-E began in 1992, but there was a significant increase around 2003 (Fig. 4b, 5-yr running mean line), which means the observed freshened

AAIW could be traced back to 2003. Though ~~we could not~~it was not possible to compute the direct freshwater input to the South Atlantic Basin ~~here~~in this study, 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 were used to explore the decadal ~~freshened~~ freshening signal identified in the above subsection. Similarly to Fig. 3a, the sectional mean .-S diagram (Fig. 5a) displays thea same shift of thermohaline values, including ~~the~~ freshening of the salinity minimum, ~~the~~ salinity reduction in the upper AAIW layer and *vice versa* in the lower layer. ~~Comparing~~ Compared to the .-S curves of IPRC data (Fig. 3a), the curves of WOCE (Fig. 5a) seem to be, in general, ~~with~~ cooler . and fresher S. ~~in general,~~It is suggested that this is because the IPRC mean ~~has more weight of~~is weighted towards the 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 snapshot sections ~~of snapshot~~ in the WOCE observations. Instead of calculating the linear trend of salinity (as was done with the IPRC data) ~~done~~, the difference of salinity observed in 2003 and 2011 ~~is~~ was estimated (Fig. 5b). The light ~~gray~~ grey shading denotes the 95% confidence interval~~s~~ using simple t-test criteria~~, after considering~~and having considered 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 27.2.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 less~~er~~ than IPRC (Fig. 3b). Below the salinity minimum, the salinity increase shown in the WOCE data is relatively large ~~revealed by WOCE data~~ (Fig.

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3d). This is thought to be because the salinity rise reached ~~to~~ its maximum around 2011~~,~~. This is shown in the time series of basinwide averaged salinity on 27.45.n and 27.55.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 26.6-26.7.n (Fig. 5b). ~~But~~ It is contended that this would not affect the ~~result that~~ salinity budget over the water column (Fig. 5b), ~~with~~ given that the salt gain of thermocline water ~~balancing~~ would balance the observed freshened AAIW. In conclusion, the general trend and ~~detailed~~ consistency of the detail therein of the salinity change ~~signal~~ over the last ten year time period revealed by

IPRC and WOCE data ~~makes sure that our reported~~leads us to state that the freshening of AAIW is a robust finding and valid~~ated~~.

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 the Indian Ocean to the South Atlantic [De Ruijter et al., 1999]. The above discussion suggests that the freshening of AAIW is induced by the input of freshwater from the source region. As a result, if the transport of more saline water from the Indian Ocean decreased, it would promote the effect of this freshwater supplement. In this ~~part of paper~~section, the decrease of AL transport ~~would be~~is 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

Continuous measurements of the AL transport are now possible. ~~There have never been continuous measurements of the AL transport until now.~~ The study mentioned above ~~earlier study~~ suggested that an increased AL transport correlates well with a poleward shift of westerlies [Beal et al., 2011]. However, after using re-analysis and climate models, Swart and Fyfe [2012] argued that strengthening of Southern Hemisphere surface westerlies has occurred without ~~robust trend~~major transgressions 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~~They also 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~~ is related 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~~ 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 period since 1980 (Fig. 6a and d). ~~As the same results as~~Previous ~~many other~~ studies [Lee et al., 2011; Loveday et al., 2015], have found that the WS has considerably increased from 1980s to the beginning of 2000s (Fig. 6d), consistent with the contemporary increase of AL transport. Though there are oscillations during 1990s, the WS reached ~~to~~ its peak around the years 2000-2004 (Fig. 6d)~~. And~~ then ~~the WS~~ began to decline. ~~Thus it shows that~~It can be concluded that the WS has weakened for period 2000 – 2014 (Fig. 6d), ~~suggesting the~~which is concurrent with a 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~~The three zonally averaged WS datasets agree ~~on~~ that during the period 2000-2014, the westerlies reached ~~to its~~a peak in the years 2000-2004, and then progressively subsided through 2005-2009 to 2010-2014. The process of gradual decline of WS is most ~~distinctly illustrated~~pronounced in the NCEP2 data. ~~And what is important, we also note~~It is noteworthy that ~~neither~~ none of the three products show a significant meridional shift of the latitude of maximum WS from 2000 to 2014, ~~concomitant~~ agreeing 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~~ show the decadal variation of AL present. ~~here.~~ In their result (Figure 8 in Le Bars et al. [2014]), the anomalies of AL from satellite altimetry~~er~~ reached ~~to the~~a peak around 2003 (annual average), and then began to subside, ~~though in the middle of 2011 it appeared to increase again~~apart from a mid-2011 increase. 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 was reduced during the 2000s in contrast to the 1990s. ~~There is another work done~~ Another study by Biastoch et al. [2015] ~~which could~~may be of help in the present discussion.~~support the discussion here.~~ Though the time series of AL obtained from models did n~~’~~ot show a distinct decline of AL transport in the last decade, which may be 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

(Figure 5 in Biastoch et al. [2015]). ~~These~~ This peak and subsequent decline of salt transport ~~are~~ is consistent with the freshening of AAIW over the similar time period ~~observed~~ considered here. Thus, in addition to the freshwater input that gives rise to the salt loss of the AAIW in the South Atlantic Ocean, ~~less~~ reduced transport of AL or salt will further ~~facilitate~~ enhance this signal. ~~But~~ ~~U~~Unfortunately, ~~both~~ the analysis of the contribution from both the source region and AL ~~are~~ is qualitative.~~ly~~ ~~instead of quantitatively, only by using the traditionally hydrographic and atmospheric 265 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~~This freshening in the intermediate water layer is ~~illustrated~~ thought to be compensated by increased salinity in shallower thermocline water, indicating ~~the~~ a contemporary intensification of the hydrological cycle (Fig. 3b and Fig. 5b). In this case the freshwater input from atmosphere to ocean surface increased in the 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~~associated with a ~~the~~ weakening of westerlies over the South Indian Ocean. It shows that the WS over the South Indian

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Ocean reached to its peak around 2000-2004 and began to subside through 2005-2009 to 2010-2014 (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 itother studies covering over thea similar period [Biastoch et al., 2015; Le Bars et al., 2014]. As the AAIW carried by AL is more 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~~ reduced transport in the AL reported here are qualitative but not quantitative. The purpose of this work is to reveal the decadal freshening of AAIW in the South Atlantic Ocean over the last ten year time period, and ~~its corresponding~~suggest a contributing mechanism. Future work should be focused on the quantification of these two contributors, ~~meanwhile~~ ~~revealing~~ and ~~its~~ the influence it has 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

Fig. 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 .n surfaces ranging from 26.9 to 27.5 kg/m3, with 0.2 kg/m3 interval.

Fig. 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.

Fig. 3 (a) Biennial mean .-S diagram averaged over Region A for IPRC data with .n surfaces superimposed (gre~~a~~y solid-dotted lines). The inserted figure is the magnification of the area delineated by cyan solid-dotted box. The corresponding time for each .-S curve in is listed in their bottom-right corner (i.e. 05/06 for 2005-2006). (b) Salinity trend along .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 gre~~a~~y shadings, calculated from IPRC data.

Fig. 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).

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

Fig. 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.