General Comments

The main objective of this article is to report a freshening of the Antarctic Intermediate Waters (AAIW) in the South Atlantic in the past decade. The authors showed this change using a monthly climatological field based on Argo data. Two WOCE hydrographic section were used for validation. The changes in the AAIW were associated to a decrease in the Agulhas Leakage transport which in turn was related a weakening in the wind stress over the Indian Ocean. The authors did not perform any any direct calculation of freshwater transport to back up their claim. The associations between signals and trends are done just looking at simple statistics such as mean. The findings are interesting and maybe even important if a more careful study is carried out. For instance, show that the transport of the Agulhas Current is really changing in terms of freshwater flux. A qualitative study is not enough to be provided as evidence for the freshening.

The manuscript needs improvements in terms of clarifying some ideas but also with the written part. I find very noble that one of the reviewers is helping them to accomplish that. I have some suggestions which I included as specific suggestions below but I did not spend much time in correcting their English. As I stated earlier, I think that as a scientific paper the manuscript needs a huge improvement specifically about their hypothesis which is that the freshening is controlled by the Agulhas Currents. They need to think more about that and include some concluding evidences.

I strongly suggest that they include more work, maybe try to follow some of their own suggestions of quantifying the different contributions to the changes. It is my opinion that the manuscript in the present form should be rejected.

Below are some more specific comments.

Specific Comments

• line 33: Ocean. Bindoff ... (period instead of comma)

Answer: Thanks and revised.

• line 34: Indian Ocean. Curry et al...

Answer: Thanks and revised.

• line 35: "showed a" instead of "discovered the"

Answer: Thanks and revised.

• Line 42: " is centered at the depths of 600 m and 1000 m

Answer: Thanks and revised.

• Line 49: "The first popular one" is very informal.

Answer: Replaced by 'For example, there is the …'

• Lines 49–54 : Please, explain better what are the concepts involved in each one of the arguments.

Answer: Adding 'The first standpoint states that the AAIW are primarily derived from entire subpolar sources, meanwhile the second one emphasizes the role that air-sea interaction plays in the oceans south of South America.'

• line 68: "greatly large" by "dominant".

Answer: Replaced 'greatly large' by 'substantial'.

• line 71: 21s?

Answer: Replaced by '2000s'.

• line 71: The acronym is not used any more.

Answer: The 21s? Revised as above.

• line 77: the uncertainty for the research has decreased or the uncertainty of the estimates? Just decadal variability? What about the other scales?

Answer: Revised by 'This decreases the uncertainty of estimates for the research on both seasonal and decadal variations of subsurface and intermediate waters.'

• lines 79: Replace "discovers" by "reports".

Answer: Thanks and Revised.

• line 99: Replace "occupations" by "cruises". Replace elsewhere.

Answer: Thanks and Revised.

• Line 144: Explain why warming of surface waters lead to colder trends of AAIW.

Answer: '*Church et al.* [1991] and *Bindoff and Mcdougall* [1994] has researched the counterintuitive cooling of AAIW temperature induced by warming of surface water. They showed that a warming parcel at mixed layer would subduct further equatorward, which would lead the *S-θ* curve to become cooler and fresher at a given density.'

• Line 149: "mixing with more saline surrounding waters cannot give rise to a salt loss in the salinity minimum region"

Answer: Thanks and Revised.

• line 152: The diagrams from JAMSTEC data is not very clear. Expand the lines in the little square.

Answer: Thanks and Revised. See figure below.
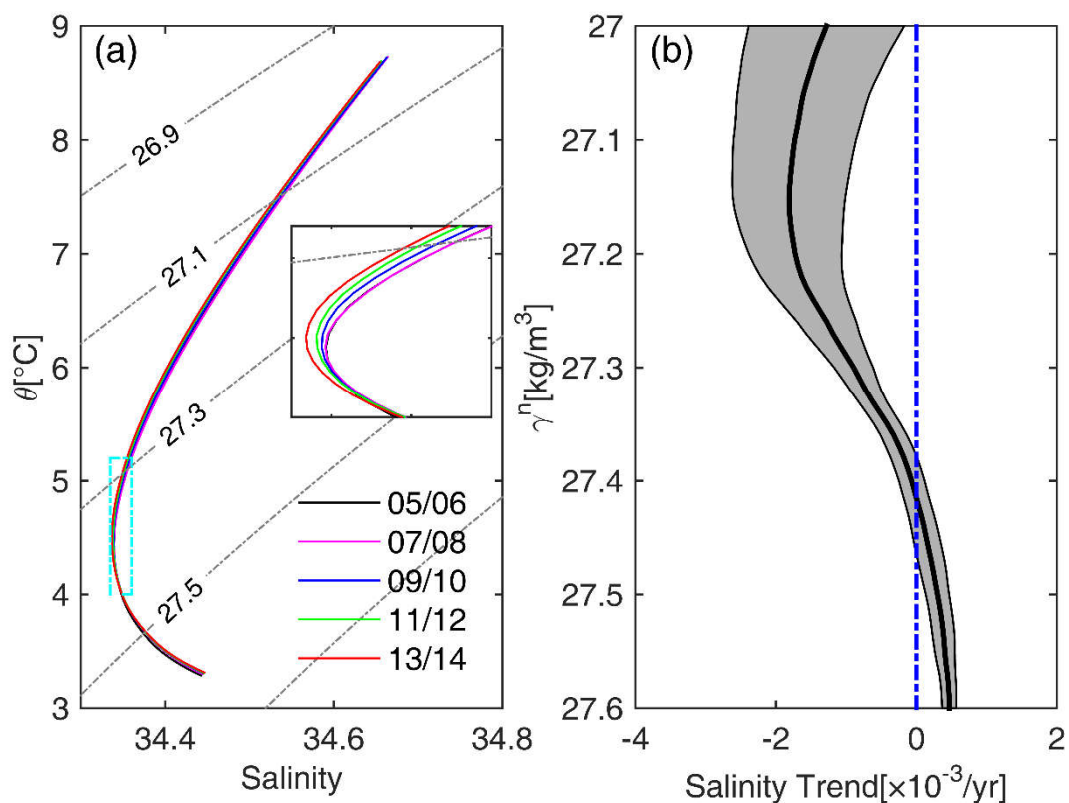
Supplementary 1

• line 164: "P minus E"

Answer: Thanks and Revised.

• line 177: Replace "Here we further" by "Additionally we "

Answer: Replaced by 'Here two …'

• Line 185: A transatlantic cruise is not exactly a "snapshot". Remove "snapshot".

Answer: Thanks and Revised.

• line 192: Replace "little lesser" by "smaller".

Answer: Thanks and Revised.

• line 190–192: The salinity difference is estimated between the two WOCE sections which occurred in an interval of 8 years. To compare the results from fig 3b and 5b, maybe it is a good idea to show the salinity difference divided by 8 years, so that we can have a better comparison. In any case, the difference between these two sections seems to be similar as the one calculated as salinity trend.

Answer: WOCE sections were observed in 2003 and 2011, while the IPRC data are from 2005 to 2014, is it proper to compare the exact salinity difference between two different periods, even though the intervals are the same.

• line 192–193: What is "Bellow the salinity minimum"? Refer to the neutral density values in Fig. 5b to make the discussion clearer. The comparison between Fig 3b and 5b induces to a faulty conclusion. If you show a salinity difference over a period of 8 years, then you will have 0.0013 S/year. When you compare to the trend in Fig3b, this values are not that large.

Answer: 'In the water layer below the salinity minimum (around $27.41\gamma^n$), the salinity increase shown in the WOCE data is relatively large (错误!未找到引用源。b).' Is it OK?

We were to show that the salinity below the salinity minimum increased for the study period, and the magnitude displayed by the WOCE was larger than that by the IPRC. Is there any contradiction ?

• line 194: Shouldn't be Fig. 5b?

Answer: Yes and Revised.

• line 209: It is not very clear what do you call "source region". Be specific.

Answer: 'The above discussion suggests that the freshening of AAIW is induced by the input of freshwater from the source regions, which are consisted of the southeast Pacific Ocean and the circumpolarly subpolar oceans (see introduction).'

• line 201: Replace "supplement" by "increase".

Answer: line210? Thanks and Revised.

• Line 216: reanalysis

Answer: Thanks and Revised.

• line 337: Fig. 6a: Interim

Answer: Thanks and Revised.

• Line 240: Remove "in the years 00-04

Answer: Replaced by 'reached a peak in the years 2000-2004'.

• line 243–244: Replace "concomitant with" by "in corroboration with"

Answer: Thanks and Revised.

• line 249–250: I don't see in the present study a concrete evidence that the AL transport has a decadal variation. The authors showed evidence for wind stress changes averaged over the Indian Ocean. How much of these changes will effectively affect the transport of water in to the South Atlantic?

• line 263–264: The evidences for such decadal changes in the South Atlantic salinity should come from strong quantitative arguments. There is no causal relation between the Atlantic and the Indian Ocean changes in the salinity. You have not actually estimated the freshwater fluxes changes from the Agulhas Current and that is the weakest point of the study. Indirect evidences are not enough.

Answer: It remains a great challenge to quantify the leakage transport, this is why we choose to qualify it in the present work.

We have added a new subsection of 4.1, and hope it can satisfy the referee's requirement.

'In the study of modeling, it is widely acceptable to quantify the leakage follows a Lagrangian approach [*Biastoch et al.*, 2009; *van Sebille et al.*, 2009]. Here a simplified strategy was employed to compute the leakage by integrating the velocity within AAIW layer (approximately between 610 and 1150m, according to 错误!未找到引用源。), which was demonstrated to result to a similar quantification to the Lagrangian one [*Le Bars et al.*, 2014]. The depth integration is along the Goodhope section (green line in 错误!未找到引用源。), using the cross-component velocity. Note that the leakage calculation is from the continent to the zero line of barotropic streamfunction, which is the separation of the Agulhas regime and the Antarctic Circumpolar Current [*Biastoch et al.*, 2015].

Before showing the transport computed from the SODA velocity data, it is necessary to verify that the SODA hydrographic data could reveal the same freshening of AAIW as the other dataset done. And in consequence, the AAIW in the South Atlantic was also shown to have freshened during period 2005-2014, though with relatively small magnitude (Supplementary 3). Yearly leakage computation within AAIW layer was employed for the period 2000-2015 (错误!未找到引用源。). It shows that the leakage in the early 2010s is smaller than that in the middle and post 2000s, forming a decreased trend in a nearly ten-year period. This estimation of leakage seems to be consistent with the below indirect estimation of AL transport.'
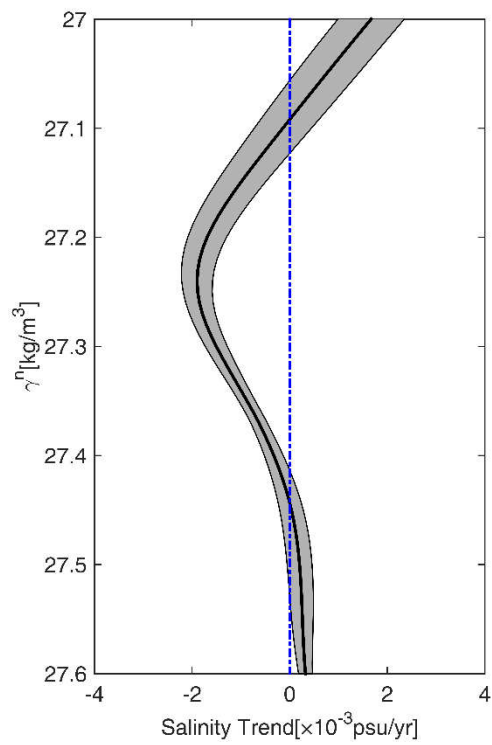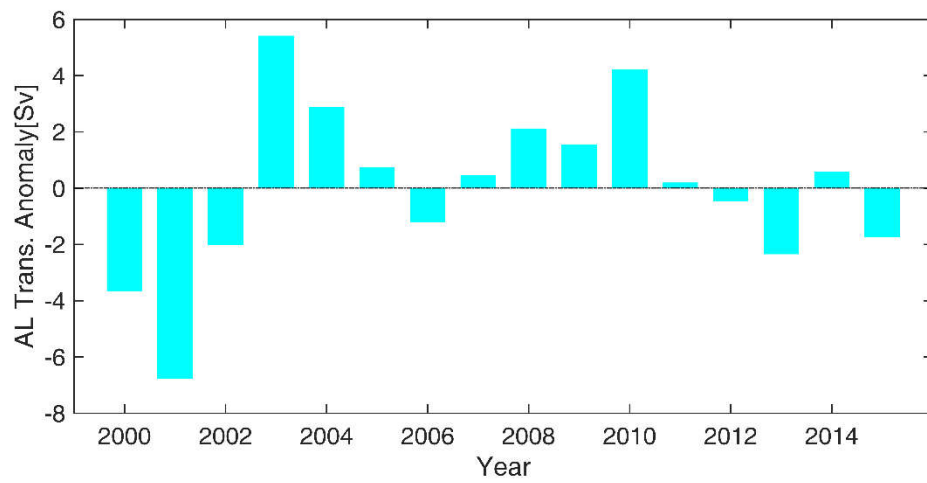
Supplementary 1

Fig. 6

More information please see the manuscript.

It seems that the new manuscript still has many problems, but this is the all we can do up till now.

Thanks for your comments again.

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

2 Wenjun Yao[a,*], Jiuxin Shi[a], Xiaolong Zhao[a]

3 [1]Key Lab of Physical Oceanography (Ocean University of China), Ministry of Education,

4 Qingdao 266100, Shandong, China

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

6 **Abstract**

7 Basin-scale freshening of Antarctic Intermediate Water (AAIW) is reported to have

8 ~~dominated~~ occurred in the South Atlantic Ocean during the period from 2005 to 2014, as

9 shown by the gridded monthly means Argo (Array for Real-time Geostrophic Oceanography)

10 data. ~~The relevant investigation~~ This phenomenon was also revealed by two ~~transatlantic~~

11 ~~occupations of~~ repeated ~~section~~ transects along a section at ~~along~~ 30° S, ~~from~~ performed

12 during the World Ocean Circulation Experiment Hydrographic Program. Freshening of the

13 AAIW was compensated by ~~the opposing~~ a salinity increase of thermocline water, indicating

14 ~~the contemporaneous~~ a hydrological cycle intensification. This was ~~illustrated~~ supported by

15 the precipitation less evaporation change in the Southern Hemisphere from 2000 to 2014~~,~~

16 ~~with~~. ~~freshwater~~ Freshwater input from atmosphere to ocean surface ~~increasing~~ increased in

17 the subpolar high-precipitation region and *vice versa* in the subtropical high-evaporation

18 region. Against the background of hydrological cycle ~~augment~~ changes, ~~the decreased~~ a

19 decrease in the transport of Agulhas Leakage (AL) which was revealed by the simulated

20 velocity field, was proposed to be ~~one of the~~ a contributor~~s~~ ~~for~~ to the associated freshening of

21 AAIW. This ~~indirectly~~ estimated variability of AL~~, reflected by the~~ was inferred from a

22 weakening of wind stress over the South Indian Ocean since the beginning of the 2000s,

23 which would facilitate~~s~~ ~~the~~ freshwater input from the source region and partly contribute~~s~~ to

24 the observed ~~freshened~~ freshening of AAIW. ~~Both of our~~ The mechanical ~~analysis~~ analyses

25 used in this study are ~~is~~ qualitative, but ~~this work~~ it is contended that this study would be

26 helpful to validate and test predictably coupled sea-air model simulations.

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

∗ Corresponding author at: Key Lab of Physical Oceanography (Ocean University of China), Ministry of Education, 238 Shongling Road, Laoshan District, Qingdao 266100, Shandong, China. Mob: +86 151 5421 9251. E-mail address: wjimyao@gmail.com (Wenjun Yao)

1 Introduction

Thermocline and intermediate waters play an important ~~role on~~ part 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 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 t~~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].

Antarctic Intermediate Water (AAIW) is characterized by a salinity minimum (core of AAIW) and ~~concentrated~~ is centered at the depths of 600 m ~~—~~and 1000 m (Fig. 1~~Fig. 1~~), which 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~~ 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 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]. The first standpoint states that the AAIW are primarily derived from entire subpolar sources, meanwhile the second one emphasizes the role that air-sea interaction plays in the oceans south of South America.

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) and AAIW originated 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 these origin These source regions of AAIW are mostly 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 which comes from Indian Ocean, transported by Agulhas Leakage (AL) as Agulhas rings (Fig. 2Fig. 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 21s 2000s [*Durgadoo et al.*, 2013; *Lübbecke et al.*, 2015], but there have been no studies addressing no one has focused on discussing the influence of AL on the AAIW in South Atlantic since 2000, especially for the last decade.

82   With the instigation ~~development~~ of the Argo (Array for Real-time Geostrophic

83   Oceanography) program, *in-situ* hydrographic observation has tremendously expanded since

84   2003 [*Roemmich et al.*, 2015], particularly in the Southern Ocean (SO) where historical data

85   are sparse and intermittent. This decreases the uncertainty of estimates for the research on

86   both seasonal and decadal variations of subsurface and intermediate waters.

87   The present work ~~discovers~~ reports the freshening of AAIW in the South Atlantic ~~for the~~

88   ~~recent~~ over the preceding decade (2005 - 2014). Against the background of an enhanced

89   hydrological cycle, decreased transport of AL contributes to such ~~a variation~~ freshening,

90   ~~suggested by the~~ and may be driven by a weakening of wind stress in the South Indian Ocean

91   during the same period.

92   **2   Data and Methods**

93   Based on individual temperature (*T*) and salinity (*S*) profiles from Argo, International

94   Pacific Research Centre (IPRC) gridded monthly means data for period 2005 - 2014 are

95   produced using variational interpolation. The IPRC data have 27 levels from 0 to 2000 m

96   depth vertically, nominal 1°×1° grid globally and monthly temporal resolution.

97   (http://apdrc.soest.hawaii.edu/projects/Argo/data/gridded/On_standard_levels/index-1.html).

98   To reduce the error from low vertical resolution of data when computing the hydrographic

99   values on isopycnal surface, ~~here~~ *T* and *S* profiles are first interpolated onto 1 m depth

100   intervals vertically using a spline instead of linear method. Because the IPRC data are

101   interpolated from randomly distributed Argo profiles, it is necessary to demonstrate the robust

102   nature of ~~its~~ their signals~~,~~ by comparing with the other Argo gridded products. As a result, the

103   Japan Agency of Marine-Earth Science and Technology (JAMSTEC, [*Hosoda et al.*, 2008]) *T*

104   and *S* data from 2005 to 2014 with 1° longitude and 1° latitude resolution are also collected

105   for comparison and verification. The number of Argo profiles is rapidly increasing year by

106   year, and part of ~~its~~ their distribution ~~had~~ has been outlined in ~~some~~ previous studies, *inter*

107   *alia Hosoda et al.* [2008] and *Roemmich et al.* [2015].

108   Two hydrographic ~~occupations~~ cruises of repeated transect~~s~~ along 30° S ~~are~~

109 ~~collected~~were conducted in the World Ocean Circulation Experiment (WOCE) Hydrographic

110 Program (http://www.nodc.noaa.gov/woce/wdiu/diu_summaries/whp/index.htm). Their

111 ~~positions~~ locations are presented in Fig. 2~~Fig. 2~~. The first ~~occupation was collected~~

112 ~~with~~transect consisted of 72 stations in 2003 by the R/V Mirai (Japan, [*Kawano et al.*, 2004]),

113 the ~~other~~ second was in 2011 with 81 stations ~~by~~ sampled from the Ronald H. Brown (United

114 States, [*Feely et al.*, 2011])

115 (http://www.nodc.noaa.gov/woce/wdiu/diu_summaries/whp/index.htm). These two ~~sections~~

116 ~~are~~transects were not only ~~measured~~ performed in almost ~~the~~ repeated positions in the

117 subtropical South Atlantic, but also ~~performed~~ conducted in the same season (Nov and Oct

118 respectively). Furthermore, the investigation time interval between the two ~~synoptic~~

119 sections from Nov 2003 to Oct 2011 ~~are nearly the same as~~is very similar to the IPRC data

120 (Jan 2005 - Dec 2014)~~, which~~ and can therefore be used to confirm ~~the result of IPRC~~

121 ~~data~~those results.

122   To reduce the effect of dynamic processes in the ocean interior (i.e. mesoscale eddies

123 and internal waves), the investigation of halocline variation ~~would~~ should be along neutral

124 density surfaces [*G McCarthy et al.*, 2011; *McDougall*, 1987]. The layer of AAIW is defined

125 using neutral density (γ^n, unit: kg/m^3) [*Jackett and McDougall*, 1997] instead of potential

126 density, with the upper and lower boundaries ~~of~~being 27.1γ^n and 27.6γ^n [*Goes et al.*, 2014],

127 respectively.

128   Monthly 10m wind fields between years 1980 and 2014 from the ERA-~~interim~~Interim

129 archive at the European Centre for Medium Range Weather Forecasts (ECMWF)

130 (http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/) are used to display the

131 decadal variability of wind stress (WS) over the South Indian Ocean. Another reanalysis wind

132 product of NCEP2 (National Centers for Environmental Prediction-Department of Energy

133 Atmospheric Model Intercomparison Project reanalysis 2, NCEP-DOE AMIP Reanalysis-2,

134 http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html) is also used for the

135 period 1980-2014~~,~~. ~~meanwhile~~Additionally, the satellite-derived wind products of

136 QuikSCAT for 2000-2007 and ASCAT for 2008-2014 (Quick Scatterometer and Advanced

137   Scatterometer, both in ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/MWF/L3/) are

138   ~~further collected~~used to compare and verify the decadal variability of WS revealed by the

139   ERA-~~interim~~Interim wind product. In this work, ~~T~~the WS ~~in this work~~ over open ocean is

140   calculated from 10 m wind field data using the equation adopted in *Trenberth et al.* [1989].

141   Reanalysis data including precipitation (*P*) and evaporation (*E*) from ERA-~~interim~~

142   Interim are used to reveal the freshwater input from the atmosphere to ocean surface in the

143   ~~recent~~preceding decade.

144   The   up-to-date   SODA3.3.1   (Simple   Ocean   Data   Assimilation,

145   http://www.atmos.umd.edu/~ocean/), which is forced by MERRA2 (The Modern-Era

146   Retrospective analysis for Research and Applications, Version 2), spans the 36-year period

147   1980-2015 ([*Carton et al.*, 2016]). The global simulated velocity field at specified depths

148   make it available to evaluate the transport of AL.

3   Freshening of Antarctic Intermediate Water

3.1   Freshening observed from Argo gridded products

151   The Argo gridded products provide a globally distributed and continuous time series of *T*

152   and *S* profiles down to 2000 m ocean depth. The present work ~~would~~ focuses on the AAIW in

153   the South Atlantic Basin (Fig. 2~~Fig. 2~~, Region A), which encompasses most of the subtropical

154   gyre and a part of the tropical regimes [*Boebel et al.*, 1997; *Talley*, 1996]. ~~By~~Computed from

155   the Argo gridded data of IPRC, the biennial mean of θ-S diagram (Fig. 3~~Fig. 3~~a) clearly

156   ~~exhibits~~shows that the AAIW has experienced a process of ~~progressively~~progress of

157   basin-scale freshening during the period from Jan 2005 to Dec 2014. The linear trend of

158   salinity (Fig. 3~~Fig. 3~~b) further reveals that the freshening takes up most of the AAIW layer

159   but with a little salinification in the ~~lower~~deeper part of it. Except around the $27.42\gamma^{n}$ neutral

160   density surface, the AAIW variation is significant at 95% confidence level, using the *F*-test

161   criteria. In comparison with Fig. 3~~Fig. 3~~a, ~~we~~it was found that the cut-off point of

162   transformation from salinity decrease to increase is near the salinity minimum. Above the

6

salinity minimum, the shift of *θ-S* ~~curves~~ trends towards cooler and fresher values along density surface and seem to be a response~~s~~ to the warming and freshening of surface waters where AAIW ventilates. Such thermohaline change ~~had~~ has also been found in the Pacific and Indian oceans over a different time period [*Wong et al.*, 1999]. *Church et al.* [1991] and *Bindoff and Mcdougall* [1994] has researched the counterintuitive cooling of AAIW temperature induced by warming of surface water. They showed that a warming parcel at mixed layer would subduct further equatorward, which would lead the *S-θ* curve to become cooler and fresher at a given density. ~~, and had been explained 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 more saline surrounding ~~more saline~~ waters cannot give rise to a salt loss in the salinity minimum layer.

To demonstrate the robustness of AAIW variations revealed by IPRC data, re-plots of Fig. 3~~Fig. 3~~a-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~~s~~ in the AAIW layer 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 $27.1\gamma^n$ and $27.6\gamma^n$ 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 $26.6\gamma^n$ and $27.6\gamma^n$) 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~~minus *E* change from 2000 to 2014, with *P-E* increasing in the subpolar region and *vice versa* in the subtropical region (Fig. 4~~Fig. 4~~a). In ~~this~~these cases, the thermocline (intermediate) water that ventilates in the high-evaporation

192 (precipitation) subtropical (subpolar) regions gets more saline (freshened), as shown by the

193 hydrographic observations (Fig. 3~~Fig. 3~~b).

194   Against the background of hydrological cycle augmentation, the annual~~ly~~ freshwater

195 input in AAIW ventilation region during the ~~freshened~~ freshening period increased by 0.~~0~~2

196 mm day^{-1}, about 17% of the P-E in 2005 (Fig. 4~~Fig. 4~~b). ~~Actually~~It is considered that, the

197 increase of P-E began in 1992, but there was a significant increase around 2003 (Fig. 4~~Fig. 4~~b,

198 5-yr running mean line), which means the observed freshened AAIW could be traced back to

199 2003. Though ~~we could not~~it was not possible to compute the direct freshwater input to the

200 South Atlantic Basin ~~here~~in this study, the Argo era freshening of AAIW is qualitatively

201 consistent with the freshwater gain in its source region.

202 **3.2   Freshening in the quasi-synchronous WOCE CTD observations**

203   Here ~~we further used~~ two synoptic transatlantic sections from WOCE hydrographic

204 program were used to explore the decadal ~~freshened~~ freshening signal identified in the above

205 subsection. Similar to Fig. 3~~Fig. 3~~a, sectional mean θ-S diagram (Fig. 5~~Fig. 5~~a) displays ~~a~~the

206 same shift of thermohaline values, including ~~the~~ freshening of the salinity minimum, ~~the~~

207 salinity reduction in the upper AAIW layer and *vice versa* in the lower layer. ~~Comparing~~

208 Compared to the θ-S curves of IPRC data (Fig. 3~~Fig. 3~~a), the curves of WOCE (Fig. 5~~Fig. 5~~a)

209 seem to be, in general, ~~with~~ cooler θ and fresher S. ~~in general,~~It is suggested that this is

210 because the IPRC mean ~~has more weight of~~is weighted towards the warmer and saltier waters

211 in the north.

212   Unlike the Argo gridded product which has continuous time series of T and S data, there

213 are only two sections ~~of snapshot~~ in the WOCE observations. Instead of calculating the linear

214 trend of salinity (as was done with the IPRC data)~~ done~~, the difference of salinity observed in

215 2003 and 2011 is estimated (Fig. 5~~Fig. 5~~b). The light ~~gray~~ grey shading denotes the 95%

216 confidence interval~~s~~ using simple t-test criteria~~, after considering~~ and having consider the

217 number of degrees of freedom. Above the salinity minimum, the freshening of AAIW

218 revealed by IPRC and WOCE data are quite similar, with the maximum appearing near $27.2\gamma^{n}$.

219 Because the last WOCE observation terminated in 2011 and the salinity reduction would

continue at least up to 2014 as displayed in Fig. 3~~Fig. 3~~a, the magnitude of the freshening in WOCE (Fig. 5~~Fig. 5~~b) is ~~a little lesser~~smaller than IPRC (Fig. 3~~Fig. 3~~b). In the water layer ~~Below~~below the salinity minimum (around $27.41\gamma^n$), the salinity increase shown in the WOCE data is relatively large ~~revealed by WOCE data~~ (~~Fig. 3d~~Fig. 5~~Fig. 5~~b). This is thought to be because the salinity rise reached ~~to~~its maximum around 2011, ~~shown~~which is shown in the time series of basinwide averaged salinity on $27.45\gamma^n$ and $27.55\gamma^n$ 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 $26.6\text{-}26.7\gamma^n$ (Fig. 5~~Fig. 5~~b). ~~But~~It is considered that this would not affect ~~the result that~~the salinity budget over the water column (Fig. 5~~Fig. 5~~b), ~~with~~giver 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~~leads us to state that ~~our reported~~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~~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 regions, which are consisted of the southeast Pacific Ocean and the circumpolarly subpolar oceans (see introduction). As a result, if the transport of more saline water from the Indian Ocean decreased, it would promote the effect of this freshwater ~~supplement~~increase. In this ~~part of paper~~section, the decrease of AL transport ~~would be~~was evaluated by depth integration of velocity field and further demonstrated by using an indirect indicator ~~as below. And at last, thorough discussion with respect to other works is displayed~~.

4.1 Evaluation from SODA velocity

In the study of modeling, it is widely acceptable to quantify the leakage follows a Lagrangian approach [*Biastoch et al.*, 2009; *van Sebille et al.*, 2009]. Here a simplified strategy was employed to compute the leakage by integrating the velocity within AAIW layer (approximately between 610 and 1150m, according to Fig. 1~~Fig. 1~~), which was demonstrated to result to a similar quantification to the Lagrangian one [*Le Bars et al.*, 2014]. The depth integration is along the Goodhope section (green line in Fig. 2~~Fig. 2~~), using the cross-component velocity. Note that the leakage calculation is from the continent to the zero line of barotropic streamfunction, which is the separation of the Agulhas regime and the Antarctic Circumpolar Current [*Biastoch et al.*, 2015].

Before showing the transport computed from the SODA velocity data, it is necessary to verify that the SODA hydrographic data could reveal the same freshening of AAIW as the other dataset done. And in consequence, the AAIW in the South Atlantic was also shown to have freshened during period 2005-2014, though with relatively small magnitude (Supplementary 3). Yearly leakage computation within AAIW layer was employed for the period 2000-2015 (Fig. 6~~6~~). It shows that the leakage in the early 2010s is smaller than that in the middle and post 2000s, forming a decreased trend in a nearly ten-year period. This estimation of leakage seems to be consistent with the below indirect estimation of AL transport.

4.2 Weakening of the westerlies in the South Indian Ocean

Continuous measurements of the AL transport have never been realized so far~~There have never been continuous measurements of the AL transport until now~~. The earlier study suggested that an increased AL transport correlates well with a poleward shift of westerlies [*Beal et al.*, 2011]. However, after using reanalysis 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

10

273 of *Durgadoo et al.* [2013] ~~even~~ showed that the increase of AL is concomitant with

274 equatorward rather than poleward shift of westerlies in their simulation cases. ~~And t~~They also

275 concluded that the intensity of westerlies is predominantly responsible in controlling this

276 Indian-Atlantic transport. Many relevant studies agreed on this relationship, that the

277 enhancement of westerlies intensity ~~relating~~ is related to the increase of AL [*Goes et al.*, 2014;

278 *Lee et al.*, 2011; *Loveday et al.*, 2015].

279 The AL corresponds most significantly to westerlies strength averaged over the Indian

280 Ocean in contrast to that averaged circumpolarly or locally [*Durgadoo et al.*, 2013]. ~~And~~

281 ~~a~~According to the work of *Durgadoo et al.* [2013], zonally averaged WS was calculated from

282 the wind product of ERA-~~interim~~Interim over the Indian Ocean (20-110° E) for every 5-yr

283 period since 1980 (Fig. 7~~Fig. 7~~a and d). ~~As the same results as many other~~Previous studies

284 [*Lee et al.*, 2011; *Loveday et al.*, 2015]~~,~~ have found that the WS has considerably increased

285 from 1980s to the beginning of 2000s (Fig. 7~~Fig. 7~~d), consistent with the contemporary

286 increase of AL transport. Though there are oscillations during 1990s, the WS reached ~~to~~its

287 peak around the years 2000-2004 (Fig. 7~~Fig. 7~~d). ~~And~~ then ~~the WS~~ began to decline. ~~Thus it~~

288 ~~shows~~It can be concluded that the WS has weakened for period 2000 – 2014 (Fig. 7~~Fig. 7~~d),

289 ~~suggesting the~~which implies a concurrent decrease of AL transport.

290 In addition to the ERA-~~interim~~Interim wind data, we have further checked the zonally

291 averaged WS over the Indian Ocean (20-110° E), using another reanalysis product of NCEP2

292 (Fig. 7~~Fig. 7~~b and e) and the combined QuikSCAT-ASCAT (Fig. 7~~Fig. 7~~c and f)

293 satellite-derived wind products. ~~All of t~~The three zonally averaged WS agree ~~on~~that during

294 the period 2000-2014, the westerlies reached ~~to its~~a peak in the years 2000-2004, and then

295 progressively subsided through 2005-2009 to 2010-2014. The process of gradual decline of

296 WS is most ~~distinctly illustrated~~pronounced in the NCEP2 data. ~~And what is important, we~~

297 ~~also note~~It is noteworthy that ~~neither~~none of the three products show a significant meridional

298 shift of the latitude of maximum WS from 2000 to 2014, ~~concomitant with~~ in corroboration

299 with the conclusion of *Swart and Fyfe* [2012].

4.24.3 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 ~~altimeter~~ altimetry 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~~ should be of help in the present discussion. ~~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, which seems 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 the subsequent decline of salt transport are 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 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. 3~~Fig. 3~~a 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. 3~~Fig. 3~~c 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 hydrological cycle (Fig. 3~~Fig. 3~~b and Fig. 5~~Fig. 5~~b). In this case the freshwater input from atmosphere to ocean surface increased in the subpolar high-precipitation region and *vice versa* in the subtropical high-evaporation region (Fig. 4~~Fig. 4~~a). Over the last ten year time period, significant freshwater gain began around 2003 (Fig. 4~~Fig. 4~~b), suggesting the observed freshened AAIW could be traced back to this time.

Against the background of hydrological cycle intensification, the decrease of AL transport is proposed to contribute to the freshening of AAIW in the South Atlantic, ~~reflected by the~~ associated with a weakening of westerlies over the South Indian Ocean. This decrease was revealed by the leakage evaluation along the GoodHope section. ~~It~~ The mechanical analysis shows that the WS over the South Indian Ocean reached ~~to~~ its peak around 2000-2004 and began to subside through 2005-2009 to 2010-2014 (Fig. 7~~Fig. 7~~), 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~~ other studies covering a 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.

351   Both the ~~analysis~~ analyses of freshwater input and ~~less~~ reduced transport in the AL

352   reported here are qualitative but not quantitative. The purpose of this work is to reveal the

353   decadal freshening of AAIW in the South Atlantic Ocean over the last ten year time period,

354   and ~~its corresponding~~ suggest a contributing mechanism. Future work should be focused on

355   the quantification of these two contributors, ~~meanwhile revealing its~~ and the influence they

356   have on the world ocean circulation.

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362   Captions of Figures

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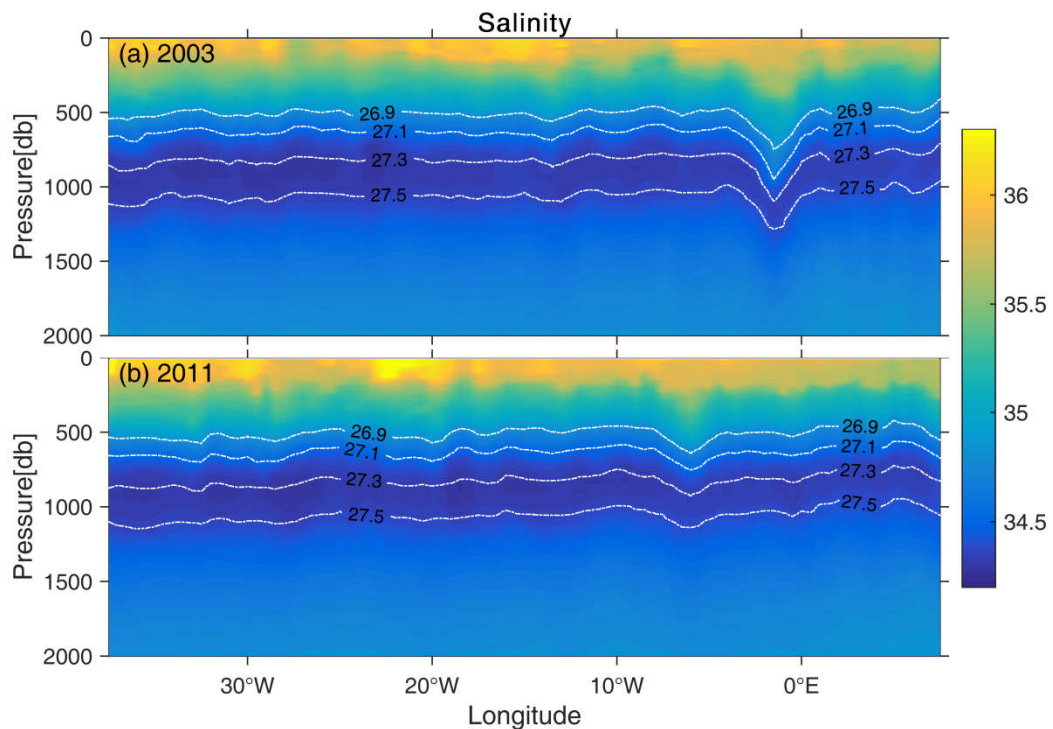
364   Fig. 1 WOCE salinity sections along 30° S in the South Atlantic Ocean (positions shown in

365   Fig. 2~~Fig. 2~~) observed in (a) 2003 and (b) 2011. Overlaid white solid-dotted lines are γ^n

366   surfaces ranging from 26.9 to 27.5 kg/m^3, with 0.2 kg/m^3 interval.

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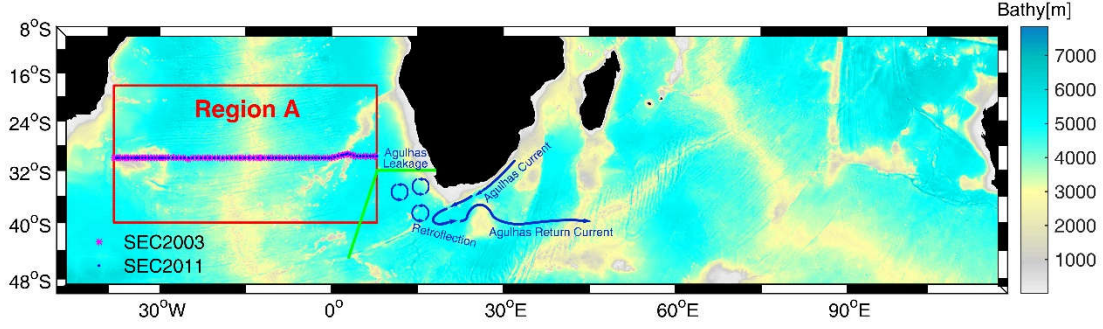
369 Fig. 2 Bathymetry of the South Indian-Atlantic oceans. Color shading is ocean depth. Red box
370 delineates the area for the basinwide average of gridded data (hereafter refers to Region A).
371 The green line shows the GoodHope section which is used to calculate the leakage transport
372 to the South Atlantic. Magenta stars represent transatlantic CTD stations measured in 2003,
373 meanwhile blue dots in 2011. The Agulhas Current, Retroflection, Agulhas Return Current
374 and Agulhas Leakage (as eddies) are also shown and ticked.

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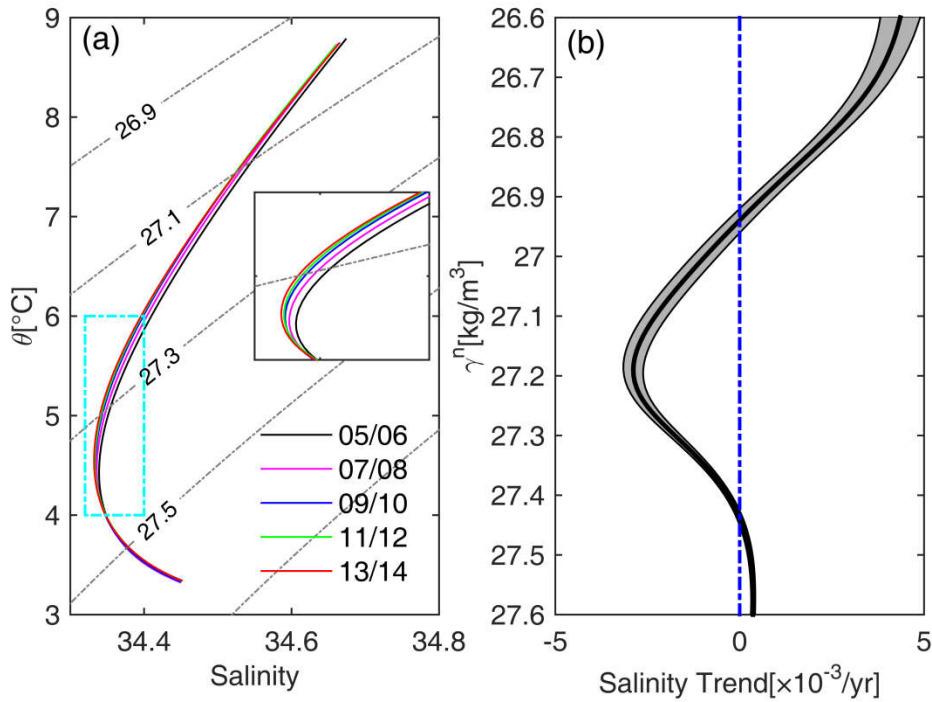
377 Fig. 3 (a) Biennial mean θ-S diagram averaged over Region A for IPRC data with γ^n surfaces
378 superimposed (gray grey solid-dotted lines). The inserted figure is the magnification of the
379 area delineated by cyan solid-dotted box. The corresponding time for each θ-S curve is listed
380 in their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

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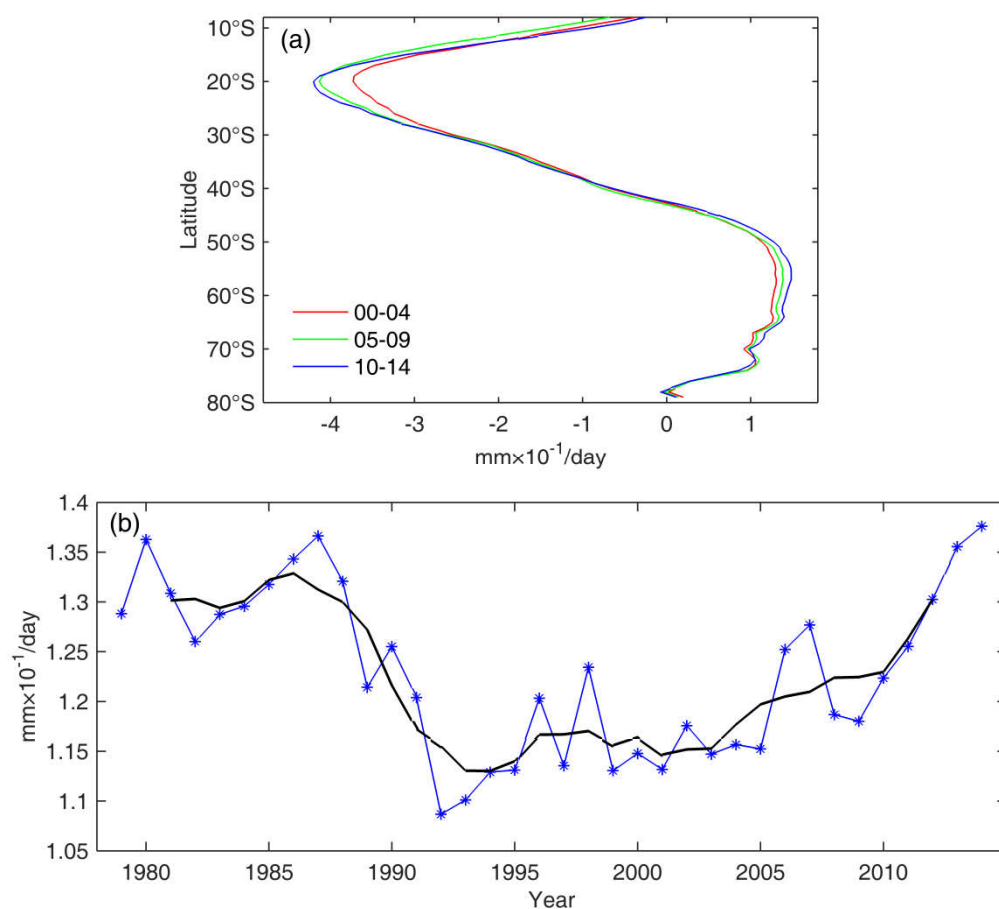
Fig. 4 Calculated from ERA-~~interim~~ Interim precipitation and evaporation data: (a) Zonally
mean (ocean areas only) of annually *P-E* (freshwater input, mm day^{-1}), each line represents a
5-yr averaged result. The corresponding time period (i.e. 00-04 for 2000-2004) is listed in the
bottom-left 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).
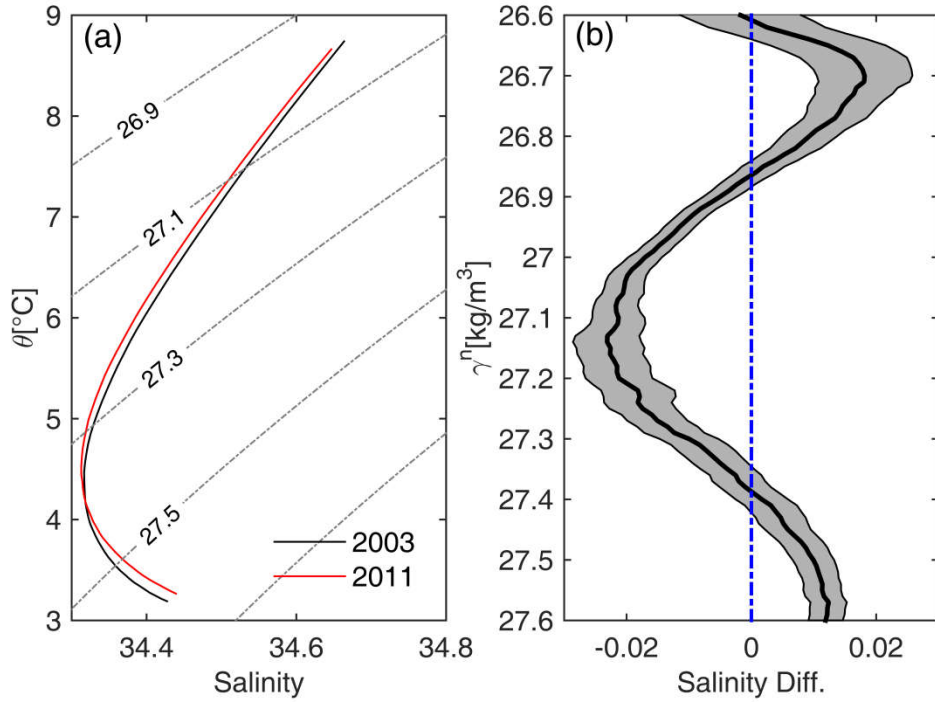
Fig. 5 (a) The same as Fig. 3Fig. 3a but for sectional mean of WOCE hydrographic casts. The corresponding year for each θ-S curve is listed in their bottom-right corner. (b) Sectional mean differences (thick black line) of WOCE hydrographic data along γ^n and their 95% confidence intervals (gray grey shadings, t-test).
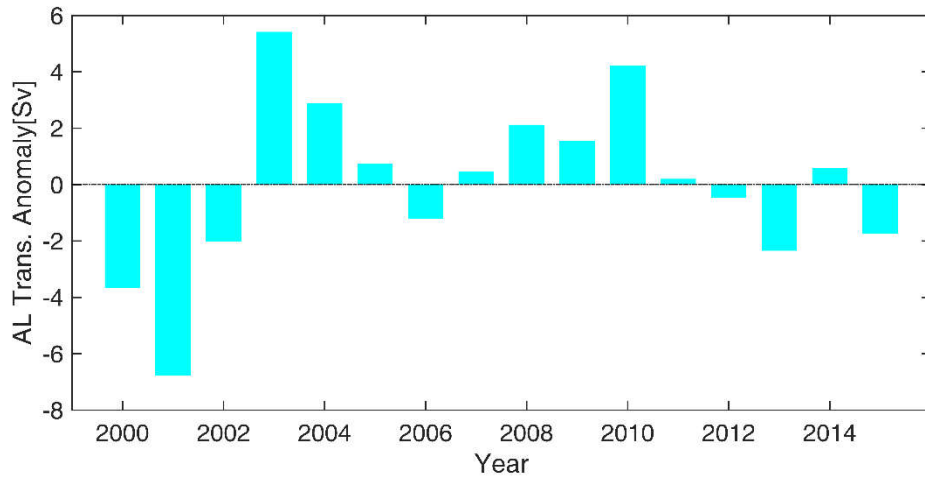
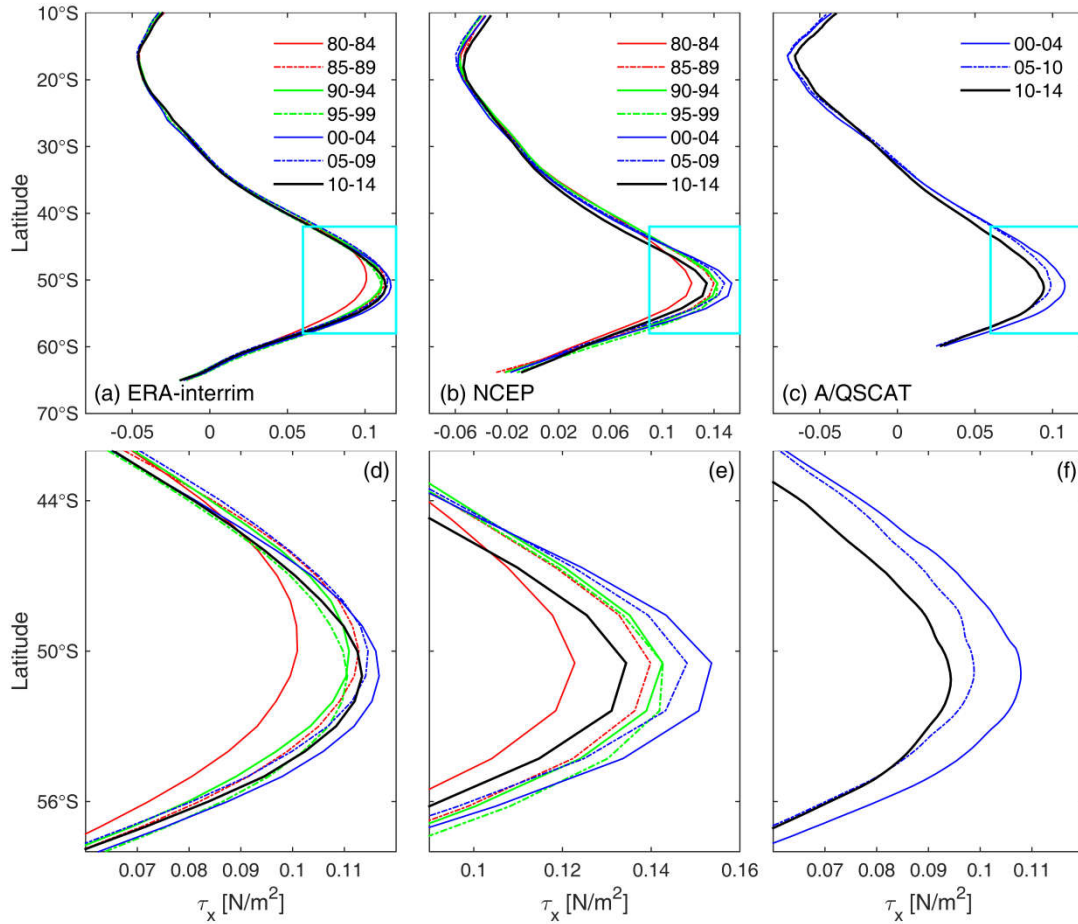Fig. 6 Computation of Agulhas Leakage transport anomaly from the SODA velocity field along the Goodhoop Line. Note that the depth integration is only for the AAIW layer.

Fig. 7 Zonally averaged wind stress calculated from the wind product of (a) ERA-interimInterim, (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.

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