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1 **Decadal freshening of the Antarctic Bottom Water exported from**  
2 **the Weddell Sea**

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## ABSTRACT

9 Recent decadal changes in Southern Hemisphere climate have driven strong responses from  
10 the cryosphere. Concurrently, there has been a marked freshening of the shelf and bottom  
11 waters across a wide sector of the Southern Ocean, hypothesised to be caused by accelerated  
12 glacial melt in response to a greater flux of warm waters from the Antarctic Circumpolar  
13 Current onto the shelves of West Antarctica. However, the circumpolar pattern of changes  
14 has been incomplete: no decadal freshening in the deep layers of the Atlantic sector had been  
15 observed. In this study, we document a significant freshening of the Antarctic Bottom Water  
16 exported from the Weddell Sea, which is the source for the abyssal layer of the Atlantic  
17 overturning circulation, and we trace its possible origin to atmospheric-forced changes in  
18 the ice shelves and sea ice on the eastern flank of the Antarctic Peninsula that include an  
19 anthropogenic component. These findings suggest that the expansive and relatively cool  
20 Weddell gyre does not insulate the bottom water formation regions in the Atlantic sector  
21 from the ongoing changes in climatic forcing over the Antarctic region.

## 22 1. Introduction

23 Antarctic Bottom Water (AABW), filling the deepest layer of the World’s oceans, plays  
24 a critical role in the lower limb of the global oceanic overturning circulation, and contributes  
25 to the regulation of Earth’s climate by storing heat, freshwater and biogeochemical tracers in  
26 the abyssal ocean (Orsi et al. 1999). Changes in the properties of AABW or in the strength  
27 of its circulation have the potential to impact significantly on the global ocean’s energy  
28 budget, sea level and the deep ocean ecosystem (Purkey and Johnson 2010; Church et al.  
29 2011; Sutherland et al. 2012).

30 The properties of AABW are set by interactions between the ocean, the atmosphere and  
31 the cryosphere in the margins of Antarctica, and are very sensitive to the drastic and rapid  
32 climate changes occurring in the region (Foster and Carmack 1976; Gill 1973; Orsi et al. 1999;  
33 Jacobs 2004; Nicholls et al. 2009). Near the continental slope, Warm Deep Water (WDW)  
34 originating in the Antarctic Circumpolar Current (ACC) penetrates onto the shelf in certain  
35 locations, often in modified form. This mixes with cold shelf waters that are made saline by  
36 brine rejection during sea ice formation, creating dense products that spill off the shelf and  
37 entrain further mid-layer waters as they descend in plumes (Killworth 1974; Carmack and  
38 Foster 1975; Foldvik et al. 2004; Wilchinsky and Feltham 2009). Interaction of shelf waters  
39 with the underside of floating ice shelves is also important in setting the properties of some  
40 of the shelf waters, with temperatures below the surface freezing point made possible by the  
41 pressure at which the interaction occurs (Nicholls et al. 2009).

42 In the Weddell Sea, the locally-formed variety of AABW is comprised of two water masses,  
43 namely Weddell Sea Bottom Water (WSBW) and Weddell Sea Deep Water (WSDW).  
44 WSBW, formed primarily in the southern Weddell Sea near Filchner-Ronne Ice shelf (Nicholls  
45 et al. 2009), is the coldest and densest of AABW varieties ( $\Theta < -0.7^\circ\text{C}$ ,  $\gamma_n > 28.31 \text{ kg m}^{-3}$ ).  
46 WSBW is too dense to overflow the topographic barriers isolating the Weddell Sea from the  
47 lower latitude Southern Ocean to the north (Fig 1a). The lighter WSDW ( $28.26 < \gamma_n < 28.31$   
48  $\text{kg m}^{-3}$ ,  $0^\circ > \Theta > -0.7^\circ\text{C}$ ) is either produced directly by mixing between dense shelf waters

49 and WDW (Foldvik et al. 2004; Nicholls et al. 2009), or indirectly by slow diapycnal up-  
50 welling of WSBW within the Weddell gyre. The WSDW formed near the Larsen ice shelves  
51 (LIS) in the western Weddell Sea (Fig 1b) is generally lighter and fresher than the AABW  
52 formed further south (Fahrbach et al. 1995; Gordon et al. 2001; Huhn et al. 2008; Gordon  
53 et al. 2010) and is preferentially exported toward the Scotia Sea through several deep gaps  
54 in the South Scotia Ridge (Naveira Garabato et al. 2002b).

55 The occurrence of extensive decadal-scale changes in the bottom layer of the ocean has  
56 been reported recently. The abyssal layer of the Southern Hemisphere oceans warmed signif-  
57 icantly between the 1980s and the 2000s (Johnson and Doney 2006; Johnson et al. 2008a,b;  
58 Purkey and Johnson 2010). Purkey and Johnson (2012) argued that this warming was po-  
59 tentially an indication of a slowdown of the lower limb of the MOC. In the Indian and Pacific  
60 sectors of the Southern Ocean, AABW and its precursor shelf waters have been freshening  
61 since the 1960s. In the Ross Sea, the shelf and bottom waters have freshened at rates of 0.03  
62 decade<sup>-1</sup> and 0.01 decade<sup>-1</sup>, respectively, since 1958 (Jacobs and Giulivi 2010). Off Adélie  
63 Land, Aoki et al. (2005) and Rintoul (2007) reported an AABW freshening of 0.03 between  
64 the 1990s and the mid-2000s. The origin of the freshening trend in the Indo-Pacific sector of  
65 the Southern Ocean has been attributed to an accelerated melting of the ice shelves of West  
66 Antarctica (Shepherd et al. 2004; Rintoul 2007; Jacobs et al. 2002; Jacobs and Giulivi 2010),  
67 where the proximity of the ACC to the continent allows warm water to flood the coastal  
68 areas (Thoma et al. 2008; Jacobs et al. 2011).

69 In the Weddell Sea, however, no evidence of a freshening of the AABW has thus far  
70 been found (Fahrbach et al. 2011). Using 8 hydrographic sections along the Greenwich  
71 meridian between 1984 and 2008, Fahrbach et al. (2011) suggested that the WSDW and  
72 WSBW in the central Weddell Sea were dominated by multi-annual cycles. This lack of  
73 a clear freshening trend has led to the perception of this sector as being largely resilient  
74 to the ongoing changes in Southern Hemisphere climate, most likely due to the region's  
75 ice shelves being sheltered from the influence of the ACC by the cyclonic Weddell gyre.

76 Recently, however, model simulations have raised the prospect of potentially rapid changes  
77 in the southern Weddell Sea ice shelves in response to atmospheric-driven perturbations in  
78 the ocean circulation caused in part by receding sea ice (Hellmer et al. 2012). The realism  
79 of the climatic sensitivities of AABW properties apparent in these model results is unclear,  
80 but it does call for further detailed understanding of the response of the ocean-ice system in  
81 the Atlantic sector to climatic changes in forcing, underpinned by observations.

82 Here we provide direct evidence that the AABW exported from the Weddell gyre to the  
83 lower limb of the Atlantic Meridional Overturning Circulation has been freshening over the  
84 last decade, and trace the most likely origin of this freshening to atmospheric-forced ice shelf  
85 collapse, deglaciation and sea ice changes on the eastern side of the Antarctic Peninsula.  
86 These findings complete the pattern of circumpolar freshening of dense waters of Antarctic  
87 origin, but also suggest that the processes driving the freshening in the Atlantic sector are  
88 distinct from those in the Indo-Pacific sector.

## 89 **2. Data**

### 90 *a. The SR1b repeat hydrographic section*

91 Detection and attribution of decadal change in ocean circulation and climate is a fore-  
92 most problem in global environmental sciences. In the upper ocean, the advent of an array  
93 of profiling floats has revolutionised the ability to quantify and understand such changes  
94 (Roemmich et al. 2009), but achieving the same in the deep ocean remains a significant  
95 challenge. Nowhere is this more true than in the data-sparse Southern Ocean. In this con-  
96 text, the SR1b repeat hydrographic section in Drake Passage (between South America and  
97 the tip of the Antarctic Peninsula; Fig.1a) represents a unique data set. It is one of the most  
98 frequently occupied continent-to-continent oceanographic transects in the world, with 18 oc-  
99 cupations since 1993. There have been only two Antarctic summer seasons (1995/1996 and  
100 1998/1999) in which the SR1b transect could not be conducted due to logistical constraints.

101 During the 2008/2009 season, there were two occupations of the section within 3 months,  
102 the common November-December occupation, and another in February 2009 (Table 1).

103 The Drake Passage hydrographic programme is a joint effort between the National  
104 Oceanography Centre in Southampton and the British Antarctic Survey in Cambridge, U.K.  
105 Most section occupations were conducted using the RRS *James Clark Ross*. Each occupation  
106 typically consists of 30 full-depth conductivity-temperature-depth (CTD) stations between  
107 Burdwood Bank and Elephant Island in the eastern Drake Passage, with a typical horizontal  
108 resolution of 30 nautical miles. In early cruises, the data were collected using a Neil Brown  
109 Instrument MkIIIc CTD, whereas the later cruises were undertaken using a SeaBird 911  
110 plus CTD. A description of the CTD calibration and measurement errors is given in the  
111 Appendix. Characteristic distributions of potential temperature and salinity are shown in  
112 Fig. 2b,c. AABW, defined for this work as the water denser than  $\gamma_n = 28.26 \text{ kg m}^{-3}$ , fills  
113 the abyssal layer of the southern end of the section, its northward extent being delineated  
114 by the Polar Front (Fig. 2).

115 In the ACC, averaging properties over a fixed latitudinal band and pressure range can  
116 introduce biases due to isopycnal heave and frontal displacement. On the other hand, the  
117 contrary, the use of neutral density ( $\gamma^n$ ; Jackett and McDougall (1997)) as a vertical axis  
118 isolates property changes on isopycnals from those associated with heave, whilst dynamic  
119 height ( $\phi$ ) as a horizontal axis provides an accurate proxy for the cross-stream positioning  
120 of observations within the ACC. The along-section gradient in  $\phi$  has been shown to agree  
121 well with the thermohaline definition of the ACC fronts given in Orsi et al. (1995) (see  
122 Naveira Garabato et al. (2009) for more details). Therefore, to prevent ACC frontal mean-  
123 dering and isopycnal heave from affecting our record of AABW properties, the data from  
124 each of the 18 repeat sections are here gridded in  $\gamma^n - \phi$  space. For this study, we use  $\phi$  at  
125 400 dbar relative to 2000 dbar (Figure 2a) so as to exclude the influence of high-frequency  
126 upper-ocean water mass variability and of changes in the bottom layer under scrutiny here.  
127 An assessment of the propagation of the CTD measurement errors through the gridding

128 procedure is given in the Appendix.

129 *b. Sea ice concentration*

130 Monthly means of sea ice concentration from the Nimbus-7 SMMR and DMSP SSM/I-  
131 SSMIS Passive Microwave sea ice concentration measurements between October 1978 and  
132 December 2010 (Cavalieri et al. 1996) were obtained from the National Snow and Ice Data  
133 Center in Boulder, USA (<http://nsidc.org/>). Since 1 January 2011, the daily mean sea ice  
134 concentration based solely on DMSP SSM/I-SSMIS data (Maslanik 1999) were obtained  
135 from the same data centre, and the monthly means calculated subsequently.

### 136 **3. Freshening of AABW**

137 The SR1b repeat hydrographic section is optimally located to study changes in the  
138 AABW outflow from the Weddell Sea. It lies directly downstream of the Orkney Pas-  
139 sage, the main gap in the South Scotia Ridge through which AABW flows into the Scotia  
140 Sea (Naveira Garabato et al. 2002b; Nowlin Jr and Zenk 1988), and a sufficient distance  
141 downstream of the AABW source regions for the substantial seasonal signal in outflow speed  
142 and properties (Gordon et al. 2010) to be largely eroded. AABW is always present at the  
143 southern end of the section, typically occupying the bottom 500-1000m of the water column  
144 south of the Polar Front (Fig. 2).

145 The deep  $\Theta$ -S properties, gridded in dynamic height and neutral density, south of the  
146 Polar Front are shown in Figure 3. For clarity, the mean  $\Theta$ -S profile for each section is shown.  
147 The two deep water masses exhibit different types of variability. The Lower Circumpolar  
148 Deep Water (LCDW), characterized by a temperature and salinity maximum, does not  
149 exhibit a long-term change in its thermohaline properties as the most recent sections (light  
150 colors) are superimposed on top of the earliest sections (Fig. 3, left panel). On the contrary,  
151 the AABW has experienced a steady decrease in salinity (and a simultaneous temperature



152 decrease along isopycnals) since occupation of the section commenced, as manifested in the  
153 progressive displacement of the entire deep  $\Theta$  - salinity profile below  $28.26 \text{ kg m}^{-3}$  toward  
154 lower salinity values (Fig. 3, right panel).

155 For each section occupation, the salinity is averaged between  $\gamma^n = 28.26 \text{ kg m}^{-3}$  (the  
156 upper bound of AABW in Drake Passage) and  $\gamma^n = 28.31 \text{ kg m}^{-3}$  (the densest AABW class  
157 that is present in all section occupations), and the thickness of the layer bounded by the  
158 two density surfaces is calculated. This procedure excludes the component of interannual  
159 variability in AABW properties introduced by the intermittent presence of denser AABW  
160 classes, which has been shown to reflect wind-driven changes in the flow of AABW over the  
161 South Scotia Ridge (Fig. 1) rather than perturbations to AABW properties at formation  
162 (Jullion et al. 2010; Meredith et al. 2011).

163 The resulting time series (Fig. 4a) shows a statistically significant (at the 99% level of  
164 confidence) freshening tendency of  $0.004 \text{ decade}^{-1}$ , totalling  $0.007$  (std =  $0.0033$ ) between  
165 1993 and 2011. A 2 point regression model did not find any statistically significant point of  
166 inflection in the trend, suggesting that it is not possible to determine precisely the starting  
167 time of the trend based on the available data. All the data used were collected during the  
168 same Antarctic late spring / summer season, thus reducing the possibility of any seasonal  
169 aliasing of the trend. Moreover, the two occupations in the 2008/2009 season exhibit little  
170 difference in the AABW salinity despite having been conducted three months apart (Fig.  
171 4a), suggesting negligible intra-seasonal variability in the AABW properties. No systematic  
172 change is observed in the thickness of the AABW layer examined (Fig. 4b), indicating that  
173 there is no evidence here for a significant alteration in the rate of AABW export from the  
174 Weddell gyre.

175 The same analysis was done for the LCDW salinity maximum ( $\gamma_n = 28.00 - 28.11 \text{ kg}$   
176  $\text{m}^{-3}$  - Fig. 4c,d) in order to investigate any inter-cruise biases. The calculated freshening  
177 trend is not statistically significant at the 90% significance level ( $p = 0.14$ ). The LCDW time  
178 series is dominated by a multi annual fluctuation, with a period of no salinity change between

179 1993 and 2002 followed by an abrupt salinity decrease between 2003 and 2007 and a recovery  
180 between 2008 and 2012. The inter annual variability of LCDW, large compared to the AABW  
181 time series, is consistent with Provost et al. (2011) who observed large (0.01 in salinity) high  
182 frequency (3 weeks) along stream changes in the LCDW density range during two occupations  
183 of a section across Drake Passage. Moreover, there is no statistically significant correlation  
184 between the two time series ( $r = 0.36$ ,  $p=0.13$ ) confirming that the AABW trend is not  
185 dominated by inter-cruises biases. The magnitude of the AABW trend (0.007 between 1993  
186 and 2012) is larger than the uncertainties associated with the propagation of measurement  
187 errors through the gridding procedure ( $O(0.0005)$ , see error bars on Figure 4 and Appendix  
188 for details). Overall, the absence of correlation between the AABW and LCDW salinity time  
189 series and the small errors compared with the trend suggest that the trend observed is not  
190 contaminated by inter-cruise biases or by measurement errors.

191 This freshening trend is approximately a factor of 2 smaller than the equivalent freshening  
192 trends reported for AABW in the Indo-Pacific sector (Jacobs and Giulivi 2010; Aoki et al.  
193 2005; Rintoul 2007). The extent to which the factor-of-two difference in the rate of freshening  
194 is influenced by proximity to the source region (which was substantially less in the studies  
195 concerned with Indo-Pacific AABW) is unknown, though it is worth noting that intense  
196 diapycnal mixing processes in the Orkney Passage and the Scotia Sea (Naveira Garabato  
197 et al. 2004) are likely to dampen any signals of source water mass change emanating from  
198 the Weddell Sea.

199 The freshening of the AABW in Drake Passage may be conceivably caused by several  
200 processes. First, a change in the balance of the rates of AABW export through the different  
201 deep passages in the South Scotia Ridge, where thermohaline characteristics differ on isopy-  
202 cnals (Naveira Garabato et al. 2002a), could result in modified AABW properties north of  
203 the ridge. In the absence of sustained observations across all the passages, assessing varia-  
204 tions in export routes is difficult. Nonetheless, the analysis of a recent repeat of a section of  
205 hydrographic and velocity measurements along the South Scotia Ridge in 2010 (Jullion et

206 al, in prep) shows no evidence of significant change relative to a section occupation in 1999  
207 (Naveira Garabato et al. 2002b). Perturbations in wind forcing are also thought to influence  
208 the export of AABW over the Scotia Ridge (Jullion et al. 2010) on interannual and longer  
209 time scales. A decadal-scale weakening of the wind stress over the northern Weddell Sea  
210 could potentially explain the freshening by allowing colder, fresher AABW to flow through  
211 the Orkney Passage (Meredith et al. 2008). However, the decrease in wind stress that would  
212 be required for this is not supported by observations (Marshall et al. 2004). Further, such a  
213 decrease in the wind stress would also result in a reduction in the temperature and speed of  
214 the AABW outflow (Meredith et al. 2011), thereby leading to a decrease in the volume of  
215 AABW in the Scotia Sea for which there is no evidence in our observations (Fig. 4a).

216 Second, a change in the relative contributions of the different source waters that mix  
217 to form AABW could be responsible for the observed freshening. AABW is formed as a  
218 mixture of two main precursor water masses: the WDW ( $S \sim 34.5$ ,  $\Theta \sim -0.5^\circ\text{C}$ ) imported  
219 to the Weddell gyre from the ACC, and the high-salinity shelf waters formed during brine  
220 rejection ( $S \sim 34.7$ ,  $\Theta \sim -1.9^\circ\text{C}$ ). Any modification in the proportion in which these two  
221 primary component water masses mix could result in changes in the properties of AABW.  
222 Tracer-based studies suggest that the AABW in the northern Weddell Sea is made up of  
223  $\sim 25\%$  of shelf water. A 5% change in the source water mixing ratio would thus be enough  
224 to account for the measured freshening. However, such an increase in the proportion of  
225 WDW contributing to AABW production would also drive a warming of the AABW (by  
226  $\sim 0.07^\circ\text{C}$ ), which is not consistent with our observations. We conclude therefore that a  
227 change in the mixing ratio of AABW source waters does not provide a plausible explanation  
228 for the observed freshening. Such a change would result in a translation along the existing  $\Theta$ -  
229  $S$  relationship, rather than the measured shift to a different  $\Theta$ - $S$  profile with lower salinities  
230 observed here.

231 Finally, a source water mass property change could give rise to the freshening of AABW  
232 in Drake Passage. Extensive observations of WDW and the overlying Winter Water in the

233 Weddell Gyre have yielded no indication of a freshening of those water masses over the  
234 period of interest (Fahrbach et al. 2011; Behrendt et al. 2011). Therefore, we deduce that  
235 the AABW freshening reported here is likely to originate from the second major precursor  
236 water mass: the dense shelf waters formed on the continental shelves of the southern or  
237 western Weddell Sea.

238 According to the existing literature, the AABW overflowing the South Scotia Ridge  
239 is mostly ventilated by relatively fresh shelf waters from the northeastern margin of the  
240 Antarctic Peninsula (Gordon et al. 2001), specifically from the continental shelf area off  
241 the LIS (Fahrbach et al. 1995; Huhn et al. 2008). That the vicinity of LIS is key to the  
242 formation of the AABW of interest here is also indicated by the correlation between winter  
243 sea ice concentration and AABW salinity in Drake Passage (Fig.5). The correlation is  
244 significant, reflecting the role of sea ice production in raising the salinity of the shelf waters  
245 sufficiently for them to participate in AABW formation. The lag at peak correlation (15-  
246 18 months) is consistent with an estimated transit time from the Orkney Passage to the  
247 SR1b section area of about 5 months (Meredith et al. 2011), and with an estimated transit  
248 time from the LIS region to the Orkney Passage of about 7 months (assuming a distance  
249 of 1800 km between the sill of the Orkney Passage and the tip of the Antarctic Peninsula,  
250 and a mean deep boundary current speed of  $10 \text{ cm s}^{-1}$  (Gordon et al. 2010)). The modest  
251 level of significance of the correlation ( $\sim 80\%$ ) may be explained by a variety of factors,  
252 most notably the unavoidable simplicity of the assumed local linear relationship between  
253 sea ice concentration (the measured parameter) and production (the variable of relevance  
254 to shelf water salinity) and the relatively low number of degrees of freedom in our time  
255 series of measurements. The freshening tendency in Drake Passage is not observed within  
256 the AABW formed further south near the Filchner-Ronne Ice Shelf (Fahrbach et al. 2011),  
257 which indicates that the freshening originates downstream (to the north) of that region.

258 A further indication that a change in shelf water properties may be the main driver of the  
259 measured AABW freshening stems from the recent observation of a significant freshening of

260 the shelf waters ( $\sim 0.09$ ) in the western Weddell Sea between 1989 and 2006 by Hellmer  
 261 et al. (2011), although we caution that this result was based on observations from only three  
 262 years in that period. Since the AABW in the Weddell gyre contains around one quarter  
 263 shelf waters (Meredith et al. 2000), the observed AABW freshening of  $\sim 0.007$  requires the  
 264 shelf waters off the LIS to have freshened by  $\Delta S \sim -0.03$ , broadly in line with the previous  
 265 measurement of a shelf water freshening in the area (Hellmer et al. 2011). In the following,  
 266 we seek to determine the causes of the shelf water freshening off the LIS.

## 267 4. Discussion

### 268 a. A freshwater budget of the LIS region

269 We construct a simplified freshwater budget of the continental shelf region off the LIS  
 270 to estimate the additional (relative to the pre-freshening era) freshwater volume,  $V_{fw}$ , that  
 271 is required to have entered the area to explain the observed AABW freshening. It is worth  
 272 noting that any attempt to calculate an accurate estimate of  $V_{fw}$  and to precisely determine  
 273 the driving mechanism are subject to significant uncertainty, given the sparse data available  
 274 in the region. Therefore, we restrict our analyses to order-of-magnitude calculations, so as  
 275 to identify the processes most likely to play a primary role in the freshening of the AABW.

276 Salt and mass conservation respectively dictate that

$$S_0 V_0 \rho_0 = S_f V_f \rho_f, \quad (1)$$

$$V_f \rho_f = V_0 \rho_0 + V_{fw} \rho_{fw}, \quad (2)$$

277 where  $\rho_0$ ,  $S_0$  and  $V_0$  are the initial *in situ* density, salinity and volume of the shelf waters,  
 278 and  $\rho_f$  and  $S_f$  are the *in situ* density and salinity of the shelf waters after modification by  
 279 the input of an additional freshwater volume,  $V_{fw}$ , of density  $\rho_{fw}$ . Combining these two

280 equations, we obtain

$$V_{fw} = \frac{-V_0\rho_0}{S_f\rho_{fw}}(S_f - S_0). \quad (3)$$

281 We set  $\rho_0 = 1027 \text{ kg m}^{-3}$  and  $\rho_{fw} = 1000 \text{ kg m}^{-3}$ . We define  $V_0$  as the volume of the  
282 continental shelf adjacent to the LIS where shelf water salinity has been observed to exceed  
283 the threshold value for AABW ventilation (Gill 1973). Using available *in situ* data on the  
284 continental shelf (Fig. 1b), the latitudinal extent of the shelf area where the bottom salinity  
285 of the shelf waters was greater than Gill's (1973) threshold is approximated ( $64^\circ - 70^\circ\text{S}$ ).  
286 The longitudinal extent of the control volume is defined by the coast and the 1000m isobath  
287 based on the GEBCO One Minute bathymetry (<http://www.gebco.net/>), and the average  
288 depth of the shelf is estimated to be approximately 500 m. This yields  $V_0 \sim 9.10^{13} \text{ m}^3$ . To  
289 estimate  $S_f$ , we refer to the most recent stations in the control area, occupied in 2004 (Fig.  
290 1b), which reveal that  $S_f \sim 34.6$ . Thus, we find that  $V_{fw} \approx 8 \times 10^{10} \text{ m}^3$ .

### 291 *b. Origin of the freshening*

292 This excess freshwater supply to the control area may have been associated with three  
293 mechanisms: an increase in net precipitation; a reduction in sea ice production; or an increase  
294 in freshwater runoff from the LIS and tributary glaciers. The plausibility of each of these  
295 mechanisms contributing significantly to the observed shelf water freshening is examined  
296 next.

#### 297 1) PRECIPITATION

298 In order for the excess freshwater  $V_{fw}$  to have been supplied by an increase in net pre-  
299 cipitation in the continental shelf region off the LIS, an additional  $\sim 40 \text{ cm}$  of freshwater  
300 is required to have precipitated there between 1993 and 2011, relative to the pre-freshening  
301 era. Estimates of net precipitation in the oceanic region adjacent to the LIS are on the order  
302 of  $50 \text{ cm yr}^{-1}$  (Bromwich et al. 2011; Munneke et al. 2012), so that a modest percentage

303 increase in the annual-mean value would have been sufficient to account for the observed  
 304 freshening signal. A recent intercomparison of several atmospheric reanalyses revealed no  
 305 detectable decadal-scale tendency in net precipitation in our control region (Bromwich et al.  
 306 2011). Thus, whilst the uncertainties in the reanalyses do not allow us to rule it out, the  
 307 scenario of a major contribution to  $V_{fw}$  from an increase in net precipitation is not supported  
 308 by an existing evidence.

## 309 2) SEA ICE

310 Sea ice production in winter is a key process in the formation of AABW, as the resulting  
 311 brine rejection makes shelf waters dense enough to cascade down the continental slope.  
 312 Thus, sea ice production acts as the main transmitter of any climatic signal imprinted in  
 313 shelf waters (regardless of the signal's origin) to the AABW layer, and one can expect a  
 314 relationship between variability in sea ice concentration near the LIS and AABW salinity in  
 315 Drake Passage. The existence of such a relationship is suggested by the substantial degree  
 316 of positive correlation that occurs between interannual-scale fluctuations in AABW salinity  
 317 in the SR1b section and sea ice concentration anomalies off the LIS (Fig.5a). The pattern of  
 318 the correlation and its lag (15-18 months), described in the previous section, suggest that a  
 319 reduction in sea ice production cannot be excluded as a contributor to the observed AABW  
 320 freshening trend.

321 The plausibility of this contribution may be assessed by considering, once again, a simple  
 322 freshwater budget. Salt and mass conservation dictate that

$$\rho_0 V_0 S_0 = \rho_f V_f S_f + \rho_{si} V_{si} S_{si}, \quad (4)$$

$$\rho_0 V_0 = \rho_f V_f + \rho_{si} V_{si}, \quad (5)$$

323 where  $\rho_{si} = 920 \text{ kg m}^{-3}$  and  $S_{si} = 6$  are the characteristic density and salinity of sea ice,  
 324 respectively (Eicken 1997), and  $V_{si}$  is a change in sea ice volume. From these expressions,  
 325 we estimate the reduction in sea ice production required to explain the observed freshening

$$V_{si} = -\frac{\rho_0 V_0}{\rho_{si}(S_f - S_{si})}(S_f - S_0), \quad (6)$$

327 and obtain  $V_{si} \approx 1.1 \times 10^{11} \text{ m}^3$  by substituting the appropriate values quoted above. As-  
 328 suming a full sea ice cover over the control area ( $\sim 2 \times 10^{11} \text{ m}^2$ ) in winter (Stammerjohn  
 329 et al. 2008) and a characteristic sea ice thickness of 2 m (Zwally et al. 2008), this value  
 330 of  $V_{si}$  implies that a reduction of  $\sim 25\%$  of the total sea ice production between 1993 and  
 331 2011 (or a  $\sim 1\%$  decrease in the net annual sea ice production averaged between 1993 and  
 332 2011) is required to account for the observed freshening signal. In the absence of reliable  
 333 estimates of sea ice production near the LIS, assessing the extent to which a reduction in sea  
 334 ice production may explain the observed AABW freshening is difficult. Tamura et al. (2008)  
 335 used sea ice concentration data from satellite and air-sea reanalysis products to estimate  
 336 the sea ice production in several polynyas around Antarctica (but not near the LIS) and  
 337 reported a 30% decrease in the production of sea ice in Weddell Sea polynyas between 1992  
 338 and 2001. Whilst this result suggests that trends of the correct sign and order of magnitude  
 339 are at least plausible in the region, the lack of appropriate sea ice production estimates for  
 340 the LIS area prevents us from making a definitive statement on the importance of reduced  
 341 sea ice production in the observed AABW freshening.

### 342 3) INCREASED GLACIAL LOSS

343 The glaciers and ice shelves of the eastern Antarctic Peninsula have undergone consider-  
 344 able changes over the last 15 years. The break up of major ice shelves (Larsen A in 1995 (Rott  
 345 et al. 1996) and Larsen B in 2002, (Scambos et al. 2003)) and the subsequent acceleration of  
 346 their tributary glaciers due to the removal of the ice shelves' buttressing effect (Rignot et al.  
 347 2004; Shuman et al. 2011) has resulted in a large volume of ice being discharged to the ocean  
 348 in the control area of our freshwater budget. We estimate the net excess freshwater loss by



349 the ice shelves and their tributary glaciers by collating the findings of a range of glaciological  
350 studies (Table 2), and conclude that the volume of freshwater added to the continental shelf  
351 off the LIS between 1993 and 2011 was  $V_{gi} \sim 3.2 \times 10^{12} \text{ m}^3$ . The bulk of  $V_{gi}$  ( $\sim 3 \times 10^{12} \text{ m}^3$ )  
352 is contributed by the disintegration of the ice shelves themselves, whereas the contribution  
353 of accelerated tributary glaciers is an order of magnitude smaller ( $\sim 2 \times 10^{11} \text{ m}^3$ ).

354 Whilst  $V_{gi}$  dwarfs our estimate of the volume of excess freshwater required to explain the  
355 observed freshening signal by two orders of magnitude, the fraction of  $V_{gi}$  that enters the  
356 continental shelf in liquid form and thereby effects a freshening of the local shelf waters is  
357 uncertain, as it depends on the poorly constrained trajectories and melt rates of the numer-  
358 ous small icebergs into which the Larsen A and B ice shelves fragmented (Scambos et al.  
359 2003; MacAyeal et al. 2003). In the western Weddell Sea, icebergs have been observed to  
360 drift at rates on the order of  $400 \text{ m h}^{-1}$  (Rack and Rott 2004; Schodlok et al. 2006). The area  
361 loss during the collapse of the Larsen A and B ice shelves has been estimated to be around  
362  $1.1 \times 10^{10} \text{ m}^2$  (Rack and Rott 2004). Given the characteristic iceberg drift rate and the width  
363 of the continental shelf in front of the LIS ( $\sim 300 \text{ km}$ ), the residence time of the icebergs  
364 generated by the Larsen A and B ice shelf disintegration events may be crudely estimated at  
365 around 1 month. The melting rates of icebergs are uncertain and depend upon iceberg size,  
366 geometry and adjacent meteorological (air temperature) and oceanographic (water temper-  
367 ature) conditions. Observed and modelled melt rates vary by one order of magnitude ( $0.2\text{-}2$   
368  $\text{ m month}^{-1}$  Schodlok et al. (2006); Jansen et al. (2007)). Taking these rates to be represen-  
369 tative, the volume lost on the continental shelf off the LIS by the icebergs resulting from  
370 the ice shelf collapses may then be estimated as  $0.2 - 2 \times 10^{10} \text{ m}^3$ , which is substantially  
371 less than  $V_{fw}$ . Whilst the uncertainty surrounding several steps of this calculation again  
372 prevents us from being categorical, the estimate suggests that the icebergs deriving from the  
373 disintegration of the A and B sectors of the LIS probably played a temporary or minor role  
374 in freshening the local shelf waters.

375 The mass loss resulting from the Larsen A and B tributary glaciers after the ice shelf break

376 ups is likely to provide a more significant and persistent source of freshwater to the coastal  
377 region off the LIS over the study period than the disintegration of the ice shelves themselves.  
378 Silva et al. (2006) reported a modelled total iceberg melt rate of  $0.5 \text{ m m}^{-2} \text{ y}^{-1}$  for the  
379 western Weddell Sea and showed that only 3 % of small icebergs (such as those generated  
380 by the acceleration of LIS tributary glaciers) reach north of  $63^\circ\text{S}$ , suggesting a significant  
381 melting of small icebergs in the coastal region to the east of the Antarctic Peninsula. Since  
382 the accelerated LIS thinning and retreat rate is still one order of magnitude larger than  $V_{fw}$   
383 ( $\sim 2 \times 10^{11} \text{ m}^3$ ; Table 2), a melting of only 25% of the resulting small icebergs within the LIS  
384 region would be sufficient to explain the observed AABW freshening. This scenario appears  
385 plausible in light of the preceding argument, leading us to conclude that increased glacial  
386 loss from the LIS is likely to be a significant player in the freshening.

## 387 5. Conclusion

388 A time series of AABW salinity in Drake Passage has been constructed using 18 repeats of  
389 the SR1b hydrographic section between 1993 and 2010. A significant freshening of the bottom  
390 water ( $0.004 \text{ decade}^{-1}$ ) has been reported with no significant decrease in the thickness of the  
391 AABW layer. We deduce that increased glacial loss from the Antarctic Peninsula following  
392 the break up of the Larsen A and B ice shelves is likely to have contributed significantly to  
393 the observed AABW freshening. The implication of reduced sea ice production or increased  
394 precipitation off the LIS in the freshening cannot be ruled out with the available data, but  
395 the sheer size of the glacial contribution suggests that it may be the dominant driver.

396 There is evidence that the AABW freshening in the Indo-Pacific sector of the Southern  
397 Ocean is primarily forced by deglaciation in areas of West Antarctica, where an ocean-  
398 induced enhancement of basal melting has been observed in recent decades (Jacobs et al.  
399 2002; Rintoul 2007; Jacobs and Giulivi 2010; Pritchard et al. 2012). In contrast, the changes  
400 in glacial runoff in the western Weddell Sea that primarily underpin the freshening of the

401 region's AABW outflow are argued here to result from atmospheric forcing. The collapse  
402 of the Larsen A and B ice shelves and the subsequent acceleration in glacial runoff have  
403 been linked to the summertime intensification of the circumpolar westerly winds over the  
404 Southern Ocean in recent decades (Scambos et al. 2003; van den Broeke 2005), which has  
405 been attributed in part to anthropogenic processes including ozone depletion (Thompson and  
406 Solomon 2002). The intensification of the westerlies has been shown to lead to a weakening  
407 of the blocking effect of the Antarctic Peninsula orography, with the associated promotion of  
408 advection of relatively warm maritime air onto the eastern side of the Peninsula (Orr et al.  
409 2004; Marshall et al. 2006) raising regional summer temperatures by 2°C over the last four  
410 decades (King et al. 2004). This summer warming has been highlighted as pivotal in the  
411 enhanced surface melting of the LIS that heralded the collapse of large sectors of the ice shelf  
412 around the turn of the century (Scambos et al. 2003; van den Broeke 2005). Consequently,  
413 to the extent that the AABW freshening observed here can be attributed to the collapse  
414 of parts of the LIS and acceleration of its tributary glaciers, the same freshening can also  
415 be attributed to the strengthening atmospheric circulation over this part of the Southern  
416 Ocean, with a previously argued anthropogenic cause.

417 A continuation of the AABW freshening tendency over the coming decades may be  
418 expected on the basis of our present glaciological knowledge of the LIS region. For example,  
419 the acceleration of glacial runoff in the Larsen B area observed over the last 15 years is  
420 expected to persist into the years to come (Shuman et al. 2011). Further, the intact Larsen  
421 C Ice Shelf contains a volume of freshwater that is greater than that in the collapsed Larsen  
422 A and B sectors by an order of magnitude, and buttresses a much larger glacial catchment.  
423 Larsen C is already thinning in response to variations in climatic forcing (Shepherd et al.  
424 2003; Fricker and Padman 2012), and its snow-pack is showing signs of meltwater influence  
425 (Holland et al. 2011). These changes seemingly herald a progression towards the point at  
426 which further atmospheric melting may drive crevassing and ice-shelf failure, following which  
427 a large volume of freshwater is expected to enter the continental shelf region off the LIS from

428 which the AABW outflow from the Weddell Sea is ventilated.

429 The freshening of Atlantic-sourced AABW reported here completes a circumpolar-wide  
430 pattern of AABW freshening, albeit with different mechanisms being important in different  
431 sectors. As much of the AABW exported through the Orkney Passage ultimately escapes  
432 the Scotia Sea into the wider South Atlantic (Naveira Garabato et al. 2002a), our results  
433 suggest that the AABW feeding the lower limb of the Atlantic Overturning Circulation is  
434 freshening. Relating this freshening to the strength of the lower limb of the Atlantic MOC  
435 is not straightforward: it is possible that horizontal density gradients may be modified, with  
436 impacts on abyssal current speeds. However, the broad-scale finding of an AABW freshening  
437 in Drake Passage with no attendant decrease in layer thickness argues that the formation rate  
438 has not changed discernibly, and that it is formation properties that are being climatically  
439 altered. We have argued that dense water production in the Weddell Sea is sensitive to the  
440 impact of regional and large-scale decadal climatic change, and that the Weddell gyre does  
441 not insulate the bottom water formation regions from such change.

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455

## CTD calibration, data accuracy and errors

456 To detect water mass changes in the deep ocean, it is necessary to quantitatively assess  
 457 the data quality, as the signals of change are small and can potentially be affected by mea-  
 458 surement error and inter-cruise biases. Here we investigate CTD measurement errors and  
 459 the propagation of these errors through the procedure of gridding in density and dynamic  
 460 height coordinates. Salinity errors are particularly important here, because the reported sig-  
 461 nal is a freshening, and because salinity is the dominant factor in density changes at low  
 462 temperature.

### 463 *a. CTD measurement error*

464 We conduct an error analysis similar to that of Naveira Garabato et al. (2009) and  
 465 Williams et al. (2006) who used the same data set to investigate the variability of other  
 466 water masses. Starting with the measurement error, we define the error on the CTD data  
 467 as the quadratic sum of 2 terms:

$$\sigma_{ctd} = \sqrt{\sigma_{sy}^2 + \sigma_{sb}^2} \quad (\text{A1})$$

468 where  $\sigma_{sy}^2$  is the systematic error representing the accuracy of the measurement of a tracer  
 469 and  $\sigma_{sb}$  is the sampling error both in the vertical and the horizontal directions. Sampling  
 470 error is particularly important for bottle data because of their coarse vertical resolution.  
 471 CTD data have a much higher vertical resolution (1 or 2 dbar when averaged) but still suffer  
 472 from a limited horizontal resolution (the station spacing) and might be affected by small scale  
 473 structures. The sampling error is estimated by horizontally subsampling the 1997 section

474 (which had 50 stations instead of the usual 32) and regridding the subsampled section to  
475 calculate the mean salinity and temperature of the AABW. The sampling error is found to  
476 be 0.002 in salinity and 0.002°C in temperature.

477 The systematic error represents the accuracy of the measurement of a tracer. A detailed  
478 account of the data processing can be found in the individual cruise reports (<http://www.noc.soton.ac.uk/ooc/TRANSPORTS/DrakePassage.php>). For each cruise, the CTD data  
479 were carefully analyzed in order to identify and correct for potential issues with the data.  
480 Concerning the pressure and temperature measurements, cruise reports show that the data  
481 accuracy is  $\sigma_{ctdT} = 1$  db in pressure and  $\sigma_{ctdT} = 1 \times 10^{-3}$  °C in temperature.  
482

483 CTD conductivity sensors, particularly in the early cruises, were subject to drift and  
484 imprecisions in the measurements, requiring that the CTD data are calibrated against con-  
485 ductivity measured in water samples collected at different depths during station occupations.  
486 Twelve water samples covering the whole water column were typically taken at each station.  
487 Conductivity/salinity was measured for each water sample using a Guildline Autosal 8400B  
488 salinometer. The salinometer was standardized using IAPSO Standard Seawater - SSW (Ta-  
489 ble 1 for details on the different batch used). The differences between the CTD salinity and  
490 bottle data were calculated and, if necessary, offsets were applied to minimize the residuals  
491 between the CTD and bottle conductivities (In 94/95, due to issue with the conductivity cell,  
492 extra care was taken and the CTD-bottle differences were examined on a station by station  
493 basis so that the mean difference between the bottle and CTD salinities is  $-1 \times 10^{-4}$ ). Several  
494 duplicates were taken during each cruise to monitor the performance of the salinometer and  
495 the differences between duplicates were found to be of the order  $1 \times 10^{-4}$ . Furthermore, the  
496 quality of the CTD salinity increased with improvements in the CTD sensors and few/small  
497 corrections were needed in the most recent cruises.

498 The accuracy and reliability of the SSW has been investigated by several independent  
499 groups (Mantyla 1980, 1987, 1994; Kawano et al. 2006; Bacon et al. 2000, 2007). The  
500 accuracy and consistency of the different batch of SSW is important as they are used to

501 calibrate the salinometer and thus help calibrate both the bottle and CTD salinity. Kawano  
502 et al. (2006), found that the batch to batch differences improved significantly since the  
503 1980s and the standard deviation of is  $0.3 \times 10^{-3}$ . Their proposed correction for the SSW  
504 batch used during the different SR1b cruises is of the order  $1 \times 10^{-3}$ . Moreover, Bacon  
505 et al. (2007) performed a detailed analysis of the uncertainties and stability of the SSW  
506 manufacturing process. They demonstrated that there was no significant change in the label  
507 conductivity ratio for SSW batches P130 to P144 outside the uncertainty of the conductivity  
508 ratio. Gouretski and Jancke (2000) analyzed a large hydrographic data set and found that  
509 difference in SSW batch did not seem to be the main cause of inter-cruise biases. The  
510 systematic error resulting from the CTD calibration and SSW batch differences is therefore  
511 small ( $2 \times 10^{-3}$ ).

512 *b. Error propagation*

513 These errors on the CTD salinity data propagate through our salinity field gridded in  
514  $\gamma_n - \Phi$  1) by affecting the values of salinity used to calculate the mean and 2) by biasing  
515 the coordinate system as both density and dynamic height are a function of salinity. Errors  
516 in temperature and pressure measurement also impact on the calculation of density and  
517 dynamic height. Isolating the relative contribution of the two on the mean salinity of the  
518 AABW is difficult and instead we investigate their combined effect. To estimate the influence  
519 of these errors, we introduce in each temperature, salinity and pressure field an error:

$$S = S + \sigma_{ctdS}$$

$$T = T + \sigma_{ctdT}$$

$$P = P + \sigma_{ctdP}$$

520 where  $\sigma_{ctdS}$ ,  $\sigma_{ctdT}$  and  $\sigma_{ctdP}$  are normally-distributed random errors with mean equal to  
521 zero and standard deviation equal to  $2.8 \times 10^{-3}$ ,  $2.2 \times 10^{-3}^\circ\text{C}$  and 1 db respectively. The

522 same gridding procedure is then applied using the biased fields and the mean AABW salinity  
 523 and thickness are then calculated and compared with our time series. The mean regridding  
 524 errors calculated are  $\sigma_{rgS} = 6 \times 10^{-4}$  (std =  $6 \times 10^{-4}$ ) and  $\sigma_{rgTh} = 30.7m$  (std 37.5 m) for  
 525 the mean AABW salinity and thickness respectively.

526 The final error to consider is the standard error of the mean salinity,  $\sigma_{se}$ , defined as:

$$\sigma_e = \frac{s}{\sqrt{n}} \quad (\text{A2})$$

527 where  $s$  is the standard deviation of the salinity mean for a given cruise and  $n$  is the  
 528 number of samples (the number of grid points used to calculate the mean). The mean  
 529 standard error found here is  $\sigma_{eS} = 4 \times 10^{-4}$  for salinity and  $\sigma_{eTh} = 32.4$  m for the thickness.

530 The total error on salinity is  $\sigma_S = \sqrt{\sigma_{eS}^2 + \sigma_{rgS}^2}$  and on thickness is  $\sigma_{Th} = \sqrt{\sigma_{eTh}^2 + \sigma_{rgTh}^2}$ .  
 531 The errors are plotted as error bar on Figure 4. The error analysis reveals that the observed  
 532 salinity trend is larger than the potential errors coming from CTD measurement errors and  
 533 their subsequent propagation through the derived quantities presented in this study.



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## 759 List of Tables

- 760 1 Drake Passage (SR1b) section details. Cruise numbers starting with JR were  
761 made on board RRS James Clark Ross and those starting with JC were made  
762 on board RRS James Cook. The batch number of the Standard Sea Water  
763 used for salinity calibration are given when available. SB: SeaBird, NBI: Neil  
764 Brown Instrument 35
- 765 2 Total ice loss by the LIS (top rows) and tributary glaciers (lower rows) based  
766 on published data (assuming density of ice is  $900 \text{ kg m}^{-3}$ ). Ice shelf volume  
767 losses are estimated from the total volume losses for each ice shelf (Shepherd  
768 et al. 2010) distributed in time according to the ice-area losses (Scambos et al.  
769 2003). 36

TABLE 1. Drake Passage (SR1b) section details. Cruise numbers starting with JR were made on board RRS James Clark Ross and those starting with JC were made on board RRS James Cook. The batch number of the Standard Sea Water used for salinity calibration are given when available. SB: SeaBird, NBI: Neil Brown Instrument

| Season  | Start Date<br>(yyyy/mo/dd) | Start Date<br>(yyyy/mo/dd) | Ship/Cruise | CTD type    | Thermometer | SSW batch         |
|---------|----------------------------|----------------------------|-------------|-------------|-------------|-------------------|
| 1993/94 | 1993/11/21                 | 1993/11/26                 | JR0a        | NBI MkIIIc  | Reversing   | P120, 123         |
| 1994/95 | 1994/11/15                 | 1994/11/21                 | JR0b        | NBI MkIIIc  | Reversing   | P123              |
| 1995/96 | No cruise                  | -                          | -           | -           | -           | -                 |
| 1996/97 | 1996/11/15                 | 1996/11/20                 | JR 16       | NBI MkIIIc  | Reversing   | Unknown           |
| 1997/98 | 1997/12/29                 | 1998/01/07                 | JR 27       | NBI MkIIIc  | Reversing   | P132              |
| 1998/99 | No cruise                  | -                          | -           | -           | -           | -                 |
| 1999/00 | 2000/02/12                 | 2000/02/17                 | JR 47       | SB 911 plus | SBE35       | P132              |
| 2000/01 | 2000/11/22                 | 2000/11/28                 | JR 55       | NBI MkIIIc  | Reversing   | P136, 138         |
| 2001/02 | 2001/11/20                 | 2001/11/26                 | JR 67       | SB 911 plus | SBE35       | P137, 139,<br>140 |
| 2002/03 | 2002/12/27                 | 2003/01/01                 | JR 81       | SB 911 plus | SBE35       | P140              |
| 2003/04 | 2003/12/11                 | 2003/12/15                 | JR 94       | SB 911 plus | SBE35       | P143              |
| 2004/05 | 2004/12/02                 | 2004/12/08                 | JR115       | SB 911 plus | SBE35       | P143, 144         |
| 2005/06 | 2005/12/07                 | 2005/12/12                 | JR139       | SB 911 plus | SBE35       | P144, 146         |
| 2006/07 | 2006/12/08                 | 2006/12/12                 | JR163       | SB 911 plus | SBE35       | P144, 146         |
| 2007/08 | 2007/11/30                 | 2007/12/05                 | JR193       | SB 911 plus | No          | P147              |
| 2008/09 | 2008/12/13                 | 2008/12/18                 | JR194       | SB 911 plus | SBE35       | Unknown           |
| 2008/09 | 2009/02/20                 | 2009/02/26                 | JC031       | SB 911 plus | SBE35       | P150              |
| 2009/10 | 2009/11/19                 | 2009/11/26                 | JR195       | SB 911 plus | SBE35       | P150              |
| 2010/11 | 2010/11/19                 | 2010/11/26                 | JR242       | SB 911 plus | SBE35       | Unknown           |
| 2010/11 | 2011/03/01                 | 2011/03/07                 | JR276       | SB 911 plus | SBE35       | Unknown           |
| 2011/12 | 2011/11/28                 | 2011/12/05                 | JR265       | SB 911 plus | SBE35       | Unknown           |

TABLE 2. Total ice loss by the LIS (top rows) and tributary glaciers (lower rows) based on published data (assuming density of ice is  $900 \text{ kg m}^{-3}$ ). Ice shelf volume losses are estimated from the total volume losses for each ice shelf (Shepherd et al. 2010) distributed in time according to the ice-area losses (Scambos et al. 2003).

| Period    | Location                        | Total Ice loss ( $\text{km}^3$ )   |
|-----------|---------------------------------|------------------------------------|
| 1993      | Gustav; LAIS                    | $190 \pm 40$                       |
| 1995      | Gustav; LAIS; LBIS              | $950 \pm 200$                      |
| 1998-2000 | LBIS                            | $740 \pm 150$                      |
| 2002      | LBIS                            | $1000 \pm 200$                     |
| 2001-2006 | LBIS (Crane–Drygalski glaciers) | $62 \pm 14$ (Shuman et al. 2011)   |
| 2006-2011 | LBIS (Pequod–Hektoria)          | $50 \pm 12$ (Berthier et al. 2012) |
| 2003      | LBIS (Leppard–Drygalski)        | $27 \pm 9$ (Rignot et al. 2004)    |
| 2005      | LBIS (Leppard–Drygalski)        | $34 \pm 10$ (Rignot 2006)          |
| 2008      | LBIS (Pequod–Hektoria)          | $4 \pm 2$ (Rott et al. 2011)       |

## 770 List of Figures

771 1 a) Map of Drake Passage and SR1b station positions (in red). Schematic views  
772 of the Weddell Gyre (black) and AABW circulation (blue) are shown by the ar-  
773 rows. The southern boundary of the ACC (Orsi et al. 1995) is marked in green.  
774 The black box delineates the area of the map shown in Fig. 1b. SSR: South  
775 Scotia Ridge. b) MODIS Mosaic of Antarctica Image Map of the Antarctic  
776 Peninsula (corresponding to the black box in Fig. 1a) downloaded from the  
777 National Snow and Ice Data Center (<http://nsidc.org/data/moa/index.html>).  
778 The near-bottom salinity of hydrographic stations in the vicinity of the LIS  
779 is shown by the coloured circles. CTD data were obtained from the Pangaea  
780 web site (<http://www.pangaea.de/>) and include stations from the Ice Station  
781 Weddell, Winter Weddell Gyre Study, Ice Station Polarstern and ANT\_X.7  
782 cruises. The thin white line is the 1000m isobath and the thick white line  
783 delimits the shelf region where shelf waters are saline enough (Gill 1973) to  
784 contribute to AABW formation. 39

785 2 (a) Dynamic height at 400 db relative to 2000 db. The positions of the main  
786 fronts of the Antarctic Circumpolar Current are indicated. SB: Southern  
787 Boundary; PF: Polar Front; SAF: Sub-Antarctic Front. Illustrative (b) po-  
788 tential temperature and (c) salinity distributions from the 2011/2012 SR1b  
789 section occupation. The neutral density ( $\gamma_n$ ) limits of the main water masses  
790 are shown in black and the upper boundary of AABW ( $\gamma_n = 28.26 \text{ kg m}^{-3}$ )  
791 is shown in white. SAMW: Sub-Antarctic Mode Water; AAIW: Antarctic In-  
792 termediate Water; UCDW: Upper Circumpolar Deep Water; LCDW: Lower  
793 Circumpolar Deep Water; AABW: Antarctic Bottom Water. 40

- 794 3 Time series of the 18  $\Theta$ -salinity mean profiles of the AABW on the SR1b  
795 section gridded into dynamic height / neutral density space (see section 2).  
796 The profiles are color-coded as a function of year. The upper neutral density  
797 ( $\gamma_n$ ) limit of AABW ( $\gamma_n = 28.26 \text{ kg m}^{-3}$ ) is shown. AABW is only present in  
798 the southernmost part of the SR1b section south of the Polar Front (Figure 2). 41
- 799 4 Time series of a) salinity and b) layer thickness of the Antarctic Bottom  
800 Water ( $\gamma_n = 28.26 - 28.31 \text{ kg m}^{-3}$ ) on the SR1b sections. Time series of c)  
801 salinity and d) layer thickness of the Lower Circumpolar Deep Water ( $\gamma_n =$   
802  $28.00 - 28.26 \text{ kg m}^{-3}$ ) on the SR1b sections. Linear trends of the salinity  
803 time series are shown by the dashed lines. Error bar on the mean salinity and  
804 thickness are shown as vertical bars (See Appendix for details on the error  
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807 sea ice concentration 18 months before in the western Weddell Sea. The black  
808 rectangle shows the location of the statistically significant correlation (at the  
809 80% confidence level) off the LIS. 43



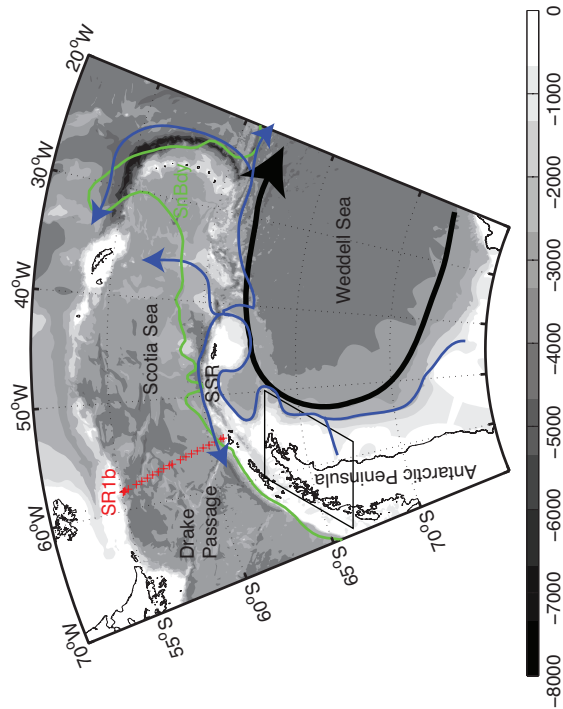
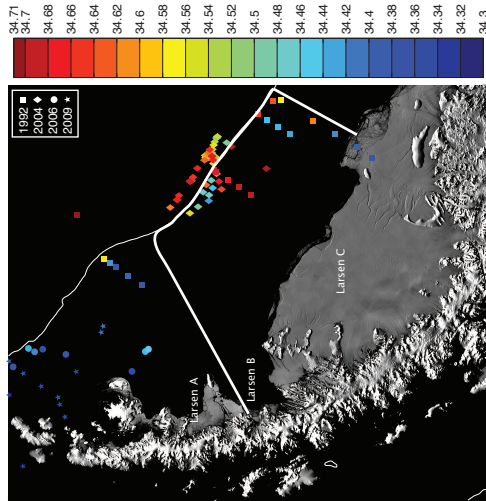


FIG. 1. a) Map of Drake Passage and SR1b station positions (in red). Schematic views of the Weddell Gyre (black) and AABW circulation (blue) are shown by the arrows. The southern boundary of the ACC (Orsi et al. 1995) is marked in green. The black box delineates the area of the map shown in Fig. 1b. SSR: South Scotia Ridge. b) MODIS Mosaic of Antarctica Image Map of the Antarctic Peninsula (corresponding to the black box in Fig. 1a) downloaded from the National Snow and Ice Data Center (<http://nsidc.org/data/moa/index.html>). The near-bottom salinity of hydrographic stations in the vicinity of the LIS is shown by the coloured circles. CTD data were obtained from the Pangaea web site (<http://www.pangaea.de/>) and include stations from the Ice Station Weddell, Winter Weddell Gyre Study, Ice Station Polarstern and ANT\_X\_7 cruises. The thin white line is the 1000m isobath and the thick white line delimits the shelf region where shelf waters are saline enough (Gill 1973) to contribute to AABW formation.

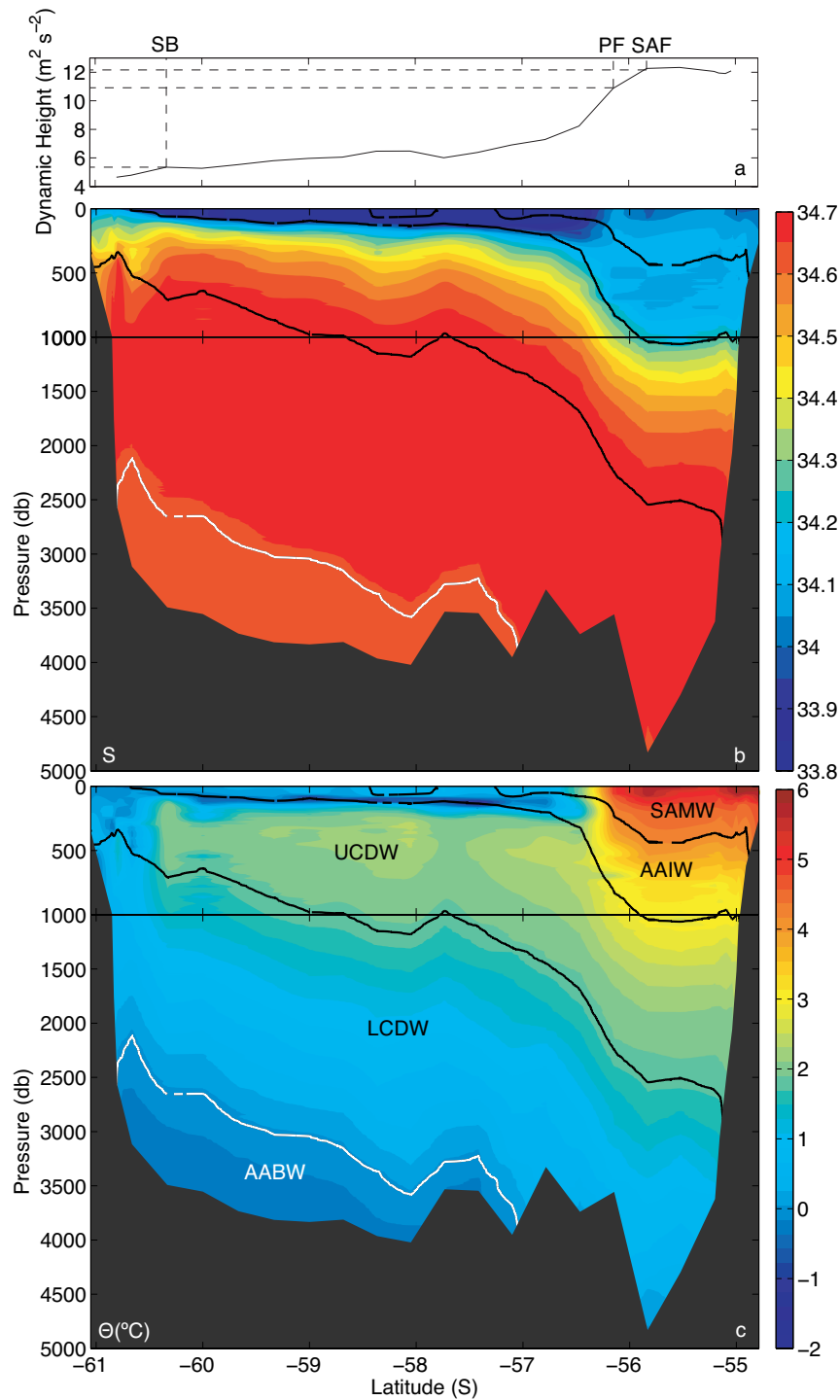


FIG. 2. (a) Dynamic height at 400 db relative to 2000 db. The positions of the main fronts of the Antarctic Circumpolar Current are indicated. SB: Southern Boundary; PF: Polar Front; SAF: Sub-Antarctic Front. Illustrative (b) potential temperature and (c) salinity distributions from the 2011/2012 SR1b section occupation. The neutral density ( $\gamma_n$ ) limits of the main water masses are shown in black and the upper boundary of AABW ( $\gamma_n = 28.26 \text{ kg m}^{-3}$ ) is shown in white. SAMW: Sub-Antarctic Mode Water; AAIW: Antarctic Intermediate Water; UCDW: Upper Circumpolar Deep Water; LCDW: Lower Circumpolar Deep Water; AABW: Antarctic Bottom Water.

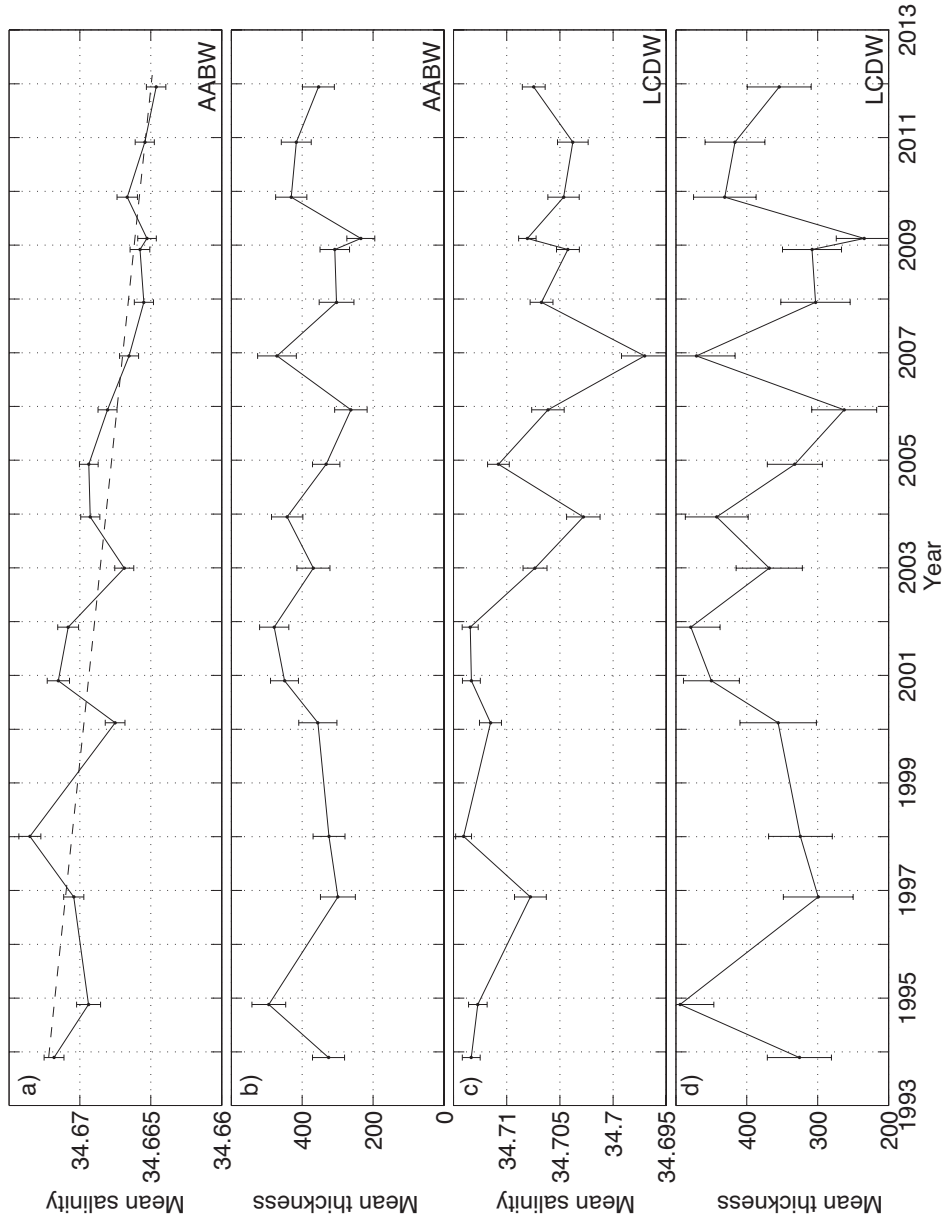


FIG. 3. Time series of the 18  $\Theta$ -salinity mean profiles of the AABW on the SR1b section gridded into dynamic height / neutral density space (see section 2). The profiles are color-coded as a function of year. The upper neutral density ( $\gamma_n$ ) limit of AABW ( $\gamma_n = 28.26 \text{ kg m}^{-3}$ ) is shown. AABW is only present in the southernmost part of the SR1b section south of the Polar Front (Figure 2).

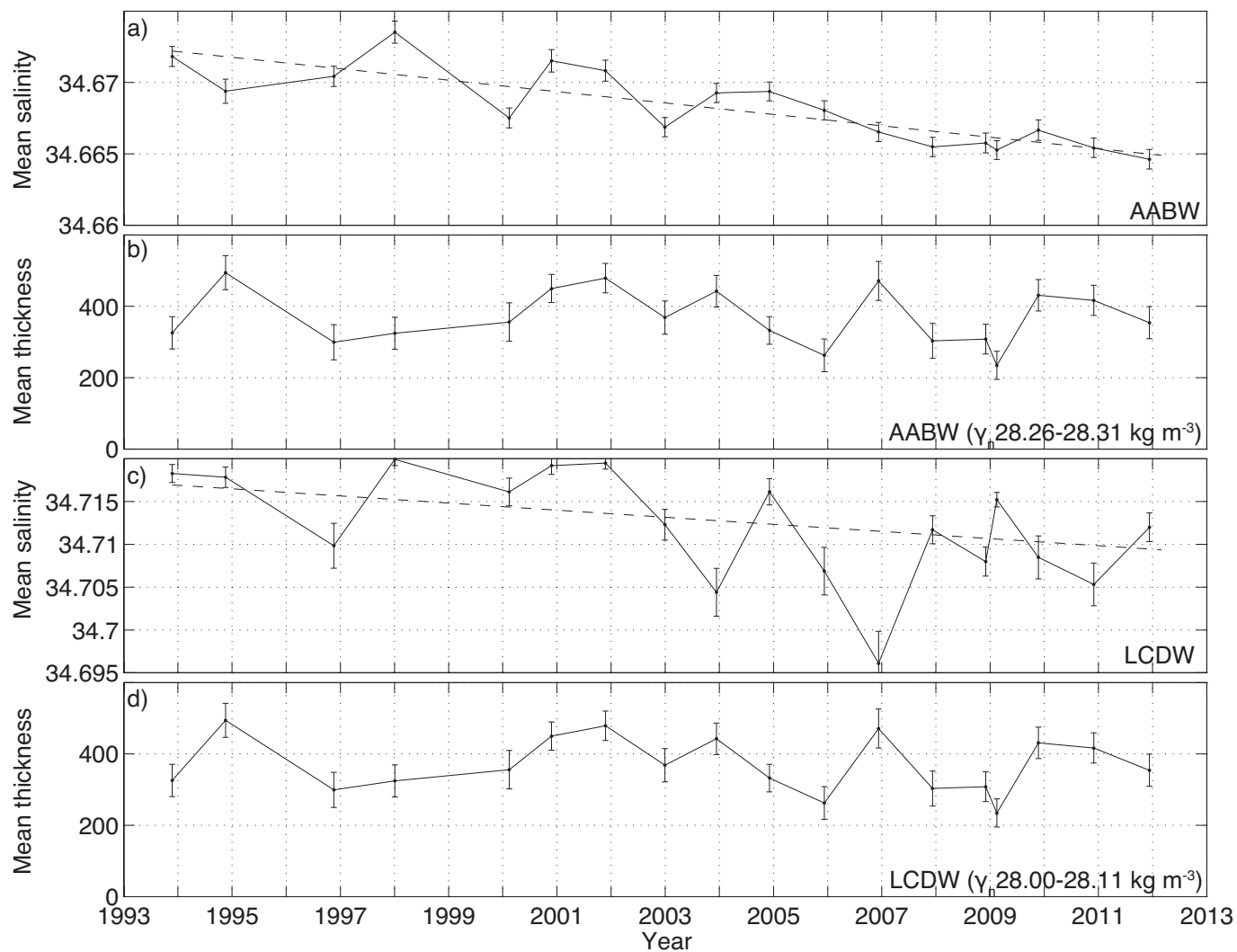


FIG. 4. Time series of a) salinity and b) layer thickness of the Antarctic Bottom Water ( $\gamma_n = 28.26 - 28.31 \text{ kg m}^{-3}$ ) on the SR1b sections. Time series of c) salinity and d) layer thickness of the Lower Circumpolar Deep Water ( $\gamma_n = 28.00 - 28.26 \text{ kg m}^{-3}$ ) on the SR1b sections. Linear trends of the salinity time series are shown by the dashed lines. Error bar on the mean salinity and thickness are shown as vertical bars (See Appendix for details on the error calculation).

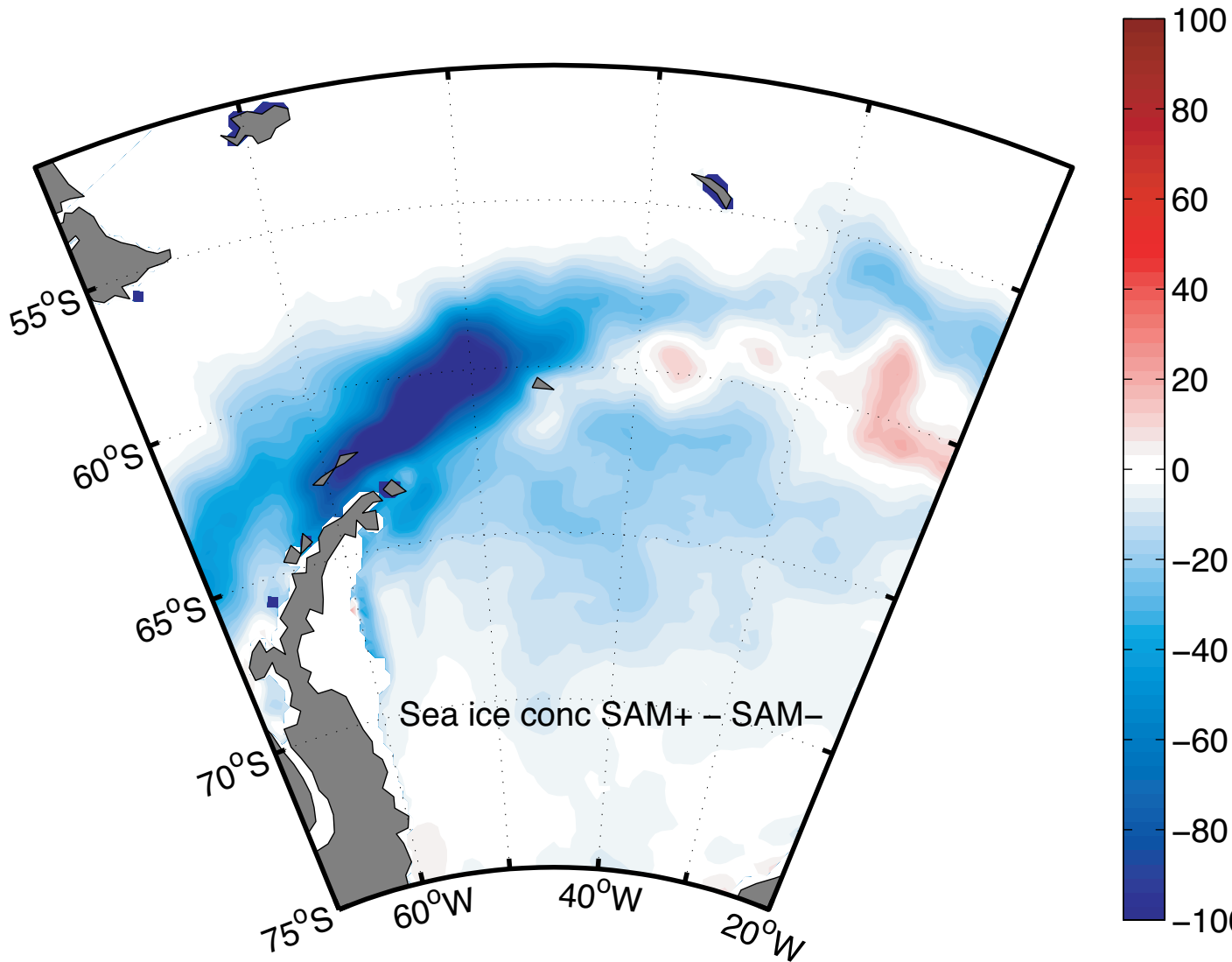


FIG. 5. Map of the correlation between the SR1b AABW salinity and the winter (JJA) sea ice concentration 18 months before in the western Weddell Sea. The black rectangle shows the location of the statistically significant correlation (at the 80% confidence level) off the LIS.