

1 Comments Referee 1

2 General comments: This manuscript deals with temporal variations of anthropogenic CO₂ in bottom
3 waters in the Southern Ocean. The Southern Ocean is said to take up 40% of anthropogenic CO₂
4 absorbed by the ocean. Thus, investigations of temporal variability of anthropogenic CO₂ are very
5 important to evaluate ocean's capacity of absorbing atmospheric CO₂, information of which is
6 indispensable for the projection of global warming. In terms of oceanic observation, the Southern
7 Ocean is one of the regions, where the number of measurements, especially for chemical and biological
8 properties, is scarce. In this point also, it is worth of being published in the journal. The manuscript is
9 well organized, and is easy to read. The approaches used in the study are not new, but traditional ones.
10 It is not a problem. It would be necessary to adopt an approach, which has been demonstrated to be
11 useful for the detection of small signals of anthropogenic CO₂ variations. The authors attempt also to
12 relate the variations to those of AABW formation, although not clearly found. As a whole, it seems that
13 the manuscript is worthy of publication in the journal, but after a moderate revision. A few major
14 comments are stated in the followings, and the minor ones are stated in the specific comments.

15 **Response: we are thankful for the quick answer provided by the reviewer. The concerns of the**
16 **reviewer have been answered here after and have been valuable help to upgrade the manuscript.**

17 In this paper, temporal variability of anthropogenic CO₂ is examined using historical data collected at
18 OISO. The data have been quality controlled by some data synthesis activities such as GLODAP.
19 Nevertheless, I have a question on this point; the data syntheses have been done with a purpose of
20 obtaining data consistency of a basin-scale. By contrast, the authors examine temporal variability of a
21 local scale. In addition, data consistency is usually confirmed by data in deep layers of > 2000 m. This
22 paper deals with data in deep layers. From these points, it is necessary to show that results obtained
23 in the present study is not influenced by the data synthesis. Furthermore, for the recent data, quality
24 control is made independently. Is there any possibility that the C_{ant} stability is caused by the quality
25 control? I recommend the authors to conduct quality-control on OISO data independently.

26 **Response: The reviewer is correct. For most of the ocean basins, data consistency is generally based**
27 **on data in deep layers (> 1500 or 2000 m). However, because in the Southern Ocean anthropogenic**
28 **CO₂ is also found at depth (> 3000 m), comparison is investigated in "old" deep waters, say around**
29 **2000-3000m (LCDW) where C_{ant} (and DIC) should be relatively stable from one year to the next**
30 **(within error of measurements, 1-3 $\mu\text{mol}\cdot\text{kg}^{-1}$). Following the reviewer's recommendation, we**
31 **propose to add a figure in Supplement Material (Fig. S1) showing the consistency of our dataset at**
32 **the two OISO stations where samples were collected down to the bottom, the OISO-ST11 presented**
33 **in the manuscript and the OISO-ST17 sampled in the Subtropical Zone (30° S-66° E). This figure shows**
34 **a limited number of measurements that are out of the range of tolerance, but one has to keep in**
35 **mind that interannual (or multiannual) variations may occur and this calls for great care before**
36 **applying an adjustment.**

37 Since 1987 (when the cruise INDIGO3 was performed), a shift in A_T is suggested at high latitudes by
38 the comparisons of INDIGO3 data (unadjusted, following the GLODAPv1 and CARINA
39 recommendations) with other cruises data (adjusted, following the GLODAPv2 recommendations).
40 This comparison shows differences that range between -4 $\mu\text{mol}\cdot\text{kg}^{-1}$ and +10 $\mu\text{mol}\cdot\text{kg}^{-1}$ (Fig. S2). Most
41 of the crossovers that suggest a positive offset for INDIGO3 data (between +6 $\mu\text{mol}\cdot\text{kg}^{-1}$ and +10
42 $\mu\text{mol}\cdot\text{kg}^{-1}$) are found south of 60°S, suggesting that A_T may have decreased in deep waters at high
43 latitudes since 1987. This is why we first decided for no adjustment in the submitted manuscript (as
44 in the GLODAPv1 and CARINA data products, whereas the INDIGO3 data in GLODAPv2 were

45 corrected by $-8 \mu\text{mol}.\text{kg}^{-1}$). However, at the OISO-ST11, A_T data from the INDIGO3 cruise are also
46 about $8 \mu\text{mol}.\text{kg}^{-1}$ higher than the mean value in deep waters (2000-3000m), in good agreement with
47 the other crossovers at high latitudes. In order to reduce the potential bias that could result from
48 either over-adjusting the data (GLODAPv2 recommendation) or not adjusting the data (GLODAPv1
49 and CARINA recommendations), and because most of the crossovers at mid-latitudes suggest a small
50 positive offset, we propose to apply an intermediate adjustment of $-4 \mu\text{mol}.\text{kg}^{-1}$ in the revised
51 manuscript (the impact on C_{ant} is $+2 \mu\text{mol}.\text{kg}^{-1}$). The uncertainty regarding this adjustment will be
52 discussed in Supplement Material. Fig. 3 (before Fig. 4) presenting the interannual variability of
53 LAABW properties and Table 2 presenting the calculated trends will be adjusted correspondingly.

54 Figure S1 also shows that the low A_T values between late 1998 and 2004 are found both in the
55 Antarctic zone and the Subtropical zone. This is surprising, but there are no reason to believe that
56 the data are biased since CMRs were used for all OISO cruises, and the instrument and data
57 processing were the same during the first OISO cruise in January/February 1998 (showing A_T values
58 close to the mean in Fig. S1) and the following cruises.

59 In discussion, the authors attempt to relate variations of anthropogenic CO₂ in AABW to changes in
60 AABW formation region. It is well discussed, but information of water mass age of AABW is lacking. It
61 is necessary to show that linkages between variations of AABW formation region and observed AABW
62 signals at OISO are appropriate in terms of water mass age. O₂ and AOU are used simultaneously. I
63 think, it is enough for one of which, probably AOU.

64 **Response:** we are sorry that there is no measurement related to water mass age in the available
65 data (i.e. no CFCs measured during OISO cruises), other than O₂ which is too sensitive to biological
66 activity to be used as a water mass age tracer. We agree that the mention of both O₂ and AOU is
67 unnecessary. This is a point also noticed by Reviewer 2. Because we are most discussing the O₂
68 concentration in the manuscript, we suggest to only present O₂ in Figure 3.

69 Specific comments:

70 Line 18 (here around 460): "from about $+7 \mu\text{mol} \text{ kg}^{-1}$ ", increase from what?

71 **Response:** We guess that what confused the two referees is the positive sign. We will delete the
72 positive sign and rephrase as follows: 'from the average concentration of $7 \mu\text{mol}.\text{kg}^{-1}$ calculated for
73 the period 1978-1987 to the averaged concentration of $13 \mu\text{mol}.\text{kg}^{-1}$ in the period 2010-2018.'

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75 Line 20 (here around 463): "CT", this is the first appearance in the abstract. Write it in full.

76 **Response: this will be added.**

77

78 Line 23 (here around 467): " θ , S", they are the first appearance in the abstract. Write them in full.

79 **Response: this will be added.**

80

81 Lines 90-91 (here around 535-536): "station 430", depth?

82 **Response: the depth (4710 m) will be added.**

83 Line 91 (here around 535): "405 km and 465 km", away from where?

84 **Response: These are the distance away from the OISO-ST11 sampling site. This will be rephrased as**
85 **"located near the OISO-ST11 sampling site (405 km and 465 km away from it, respectively)"**

86

87 Line 109 (here around 556): "the PET sector", is it usually used? I do not understand where it is.

88 **Response: A short sentence will be added to the text, as well as the references mentioned here after**
89 **to clarify the use of this name. The PET, Princess Elizabeth Though, is also referred as the Balleny**
90 **Though in Orsi et al. (1999), even if more currently mentioned as PET. It corresponds to the ocean**
91 **section separating the Kerguelen Plateau from the Antarctic continent. Its deepest point is 3750 m,**
92 **deep enough to allow AABWs to flow between the Australian Antarctic Basin and the Enderby Basin**
93 **(Heywood et al., 1999). The work of Heywood et al. (1999; Fig. 1) revealed that in the northern part**
94 **of the PET the AABW flow from west to east, while in the southern part the flow is from east to west.**

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96 Line 150 (here around 612): "AT", Probably this is the first appearance. Spell out here.

97 **Response: this will be added.**

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99 Line 160 (here around 628): " θ and S", spell out here. '

100 **Response: this will be added.**

101
102 Lines 163-165 (here around 633-635): according the description, it seems that the figures are not
103 accuracy but repeatability.

104 **Response: The referee is correct. The accuracy is given by the analysis of CRMs. This will be corrected.**

105
106 Line 236 (here around 714): "January", which year. In this paper, all the data are analyzed assuming
107 that seasonal variations in deep waters are negligible (lines 154-156). It is not appropriate to refer to
108 months.

109 **Response: the authors agree with the reviewer. This will be adjusted by mentioning the early and**
110 **late 1998 sampling.**

111 Line 276 (here around 762): "underlying", do you mean a water mass below AABW?

112 **Response: this is a mistake, we meant overlying the AABW (referring to LCDW). This will be corrected**
113 **by using 'LCDW' instead.**

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126 **Comments Referee 2**

127 General comments

128 The study presents results from a time series in the Indian sector of the Southern Ocean, which
129 together with historical relevant data span a 40-year period. Using this time series, the authors
130 evaluate the evolution of anthropogenic CO₂ (Cant) in the Antarctic Bottom Waters (AABW). It is an
131 interesting and generally well written work, and generally good figures and tables. There are some
132 need for clarity in some parts and there is some concern of the treatment of data gaps, but most of
133 this should be rather easily dealt with, and I recommend publication after minor revision. A detailed
134 list of comments follows below.

135 **The authors are thankful for the fast answer and the positive interest given to the manuscript, as
136 well as for the numerous valuable comments.**

137 My main comments are related to the definition and subsequent presentation of AABW, and, the data
138 gap between 1987 and 1998 and how this is handled and presented. To start with the definition of
139 AABW, this is not an issue in itself, since the denser definition has been used before, and also, since
140 almost any definition can be accepted as long as it is clearly presented. The latter is the problem here,
141 at least for someone not as familiar with the area and these water masses (I usually work in the high-
142 northern latitudes). The definition and choice is clearly described in 2.3, but, then the reader is referred
143 to Fig. 3, where AABW is noted in the layer above the focus of this study, while the data evaluated is
144 in the layer annotated "Considered data". When then the results of the property evolution of AABW
145 are further presented in Fig. 4, at least I got somewhat confused. Whether this is only me or not, this
146 may call for some added clarity. I would suggest to annotate your AABW layer (hence at neutral density
147 >28.35) as AABW (or AABW* or similar), to make this clear, and then make a distinction with the more
148 common AABW.

149 **Response: the authors understand the concern of the reviewer. To solve this potential confusion,
150 we suggest labelling the AABW as define in our manuscript (neutral density >28.35 kg.m⁻³) Lower
151 Antarctic Bottom Water (LAABW).**

152 Nevertheless, this mostly refers to Fig. 3, and I have several concerns with this figure, as detailed below.
153 Hovmöller plot is a wonderful thing, and can be very illustrative. However, it can also be deceiving,
154 especially when there are gaps in the data, and the gridding is allowed to interpolate over these gaps,
155 which often can create features that give a false picture of actual evolution. Fig. 3 suffers from this
156 when plotting the older data (1978–1987) together with the OISO time-series data starting from 1998.
157 There are several peculiar features in Fig. 3, especially for Cant and AT. The fact that most of the other
158 plotted parameters show overall stable layer properties, over the full period, may seem to reduce this
159 concern, but I am not convinced. In addition, I'm not fully convinced about the benefit of showing
160 depths from 1500 m, when almost all results and discussion are concerned with the layer below 4000
161 m. Even more so when the upper layers seems to show most of the strange features, for example the
162 minimum in Cant in the older data (which may in part show the issue with the TrOCA method, with
163 even negative concentrations, which are not realistic, in the most upper part of the deep waters).

164 **Response: The authors agree that the figure needs to be upgraded, clarified and simplified. The
165 suggestions of the referee have been taken into account by redrawing the Fig. 3 (now Fig. 2) using
166 only the OISO data (from 1998 to 2018). The extrapolations were very misleading indeed, so the
167 figure is now drawn with weighted-average gridding (and limited extrapolation around the data
168 point). The aim of this figure is to show the differences in AABW and LCDW characteristics before**

169 focusing on the variability and trends observed in the bottom layer (it also shows that the neutral
170 density 28.35 is a better definition for a more homogeneous bottom layer that we now define as
171 LAABW). In addition, the control quality of the data is performed in the old deep waters (well
172 characterized in the figure by the maximum in C_T). Following the recommendation from the other
173 Referee, we propose to add a figure in Supplement Material (Fig. S1) showing the consistency of our
174 dataset at the two OISO stations where samples were collected down to the bottom, the OISO-ST11
175 presented in the manuscript and the OISO-ST17 sampled in the Subtropical Zone (30° S-66° E). This
176 figure shows a limited number of measurements that are out of the range of tolerance, but one has
177 to keep in mind that interannual (or multiannual) variations may occur and this calls for great care
178 before applying an adjustment.

179 Since 1987 (when the cruise INDIGO3 was performed), a shift in A_T is suggested at high latitudes by
180 the comparisons of INDIGO3 data (unadjusted, following the GLODAPv1 and CARINA
181 recommendations) with other cruises data (adjusted, following the GLODAPv2 recommendations).
182 This comparison shows differences that range between $-4 \mu\text{mol}.\text{kg}^{-1}$ and $+10 \mu\text{mol}.\text{kg}^{-1}$ (Fig. S2). Most
183 of the crossovers that suggest a positive offset for INDIGO3 data (between $+6 \mu\text{mol}.\text{kg}^{-1}$ and $+10$
184 $\mu\text{mol}.\text{kg}^{-1}$) are found south of 60°S, suggesting that A_T may have decreased in deep waters at high
185 latitudes since 1987. This is why we first decided for no adjustment in the submitted manuscript (as
186 in the GLODAPv1 and CARINA data products, whereas the INDIGO3 data in GLODAPv2 were
187 corrected by $-8 \mu\text{mol}.\text{kg}^{-1}$). However, at the OISO-ST11, A_T data from the INDIGO3 cruise are also
188 about $8 \mu\text{mol}.\text{kg}^{-1}$ higher than the mean value in deep waters (2000-3000m), in good agreement with
189 the other crossovers at high latitudes. In order to reduce the potential bias that could result from
190 either over-adjusting the data (GLODAPv2 recommendation) or not adjusting the data (GLODAPv1
191 and CARINA recommendation), and because most of the crossovers at mid-latitudes suggest a small
192 positive offset, we propose to apply an intermediate adjustment of $-4 \mu\text{mol}.\text{kg}^{-1}$ in the revised
193 manuscript (the impact on C_T is $+2 \mu\text{mol}.\text{kg}^{-1}$). The Fig. 3 (before Fig. 4) presenting the interannual
194 variability of the LAABW properties and the Table 2 presenting the calculated trends will be adjusted
195 correspondingly. Fig. S2 will be completed by the list of the cruises presented.

196 The Figure S1 also shows that the low A_T values between late 1998 and 2004 are found both in the
197 Antarctic zone and the Subtropical zone. This is surprising, but there are no reason to believe that
198 the data are biased since CMRs were used for all OISO cruises, and the instrument and data
199 processing were the same during the first OISO cruise in January/February 1998 (showing A_T values
200 close to the mean in Fig. S1) and the following cruises.

201 The interpolation of this minimum patch leads to unfortunate wordings in the results, such as on line
202 236, with “a sudden increase. . . between January and December 1998” seems to refer to the low
203 values calculated for the 1987 data and the clearly higher concentrations calculated for the OISO data.
204 (I also don’t really understand the “between Jan and Dec 1998” part, since the first OISO data were
205 sampled in Feb 1998, and the next in Dec the same year.) Apparently there are some need for
206 clarifications here, but also to be cautious when interpreting interpolated values over large gaps. One
207 way to solve this is of course to exclude the older data from the Hovmöller plots. These can still be
208 used in the comparison/evaluation, and included in Fig. 4.

209 **Response: the reviewer is right about the issue for the 1998 samplings mentioned (same as Reviewer
210 1). This is because the first OISO cruise started in January 1998, but the station 11 was actually
211 sampled in the beginning of February as mentioned in Table 1. This will be corrected. We also agree
212 that extrapolation can be misleading and we thank the Reviewer for pointing this issue. Having
213 removed the GEOSECS and INDIGO data from the Hovmöller plots (Fig 2., before was Fig. 3), the
214 extrapolation is no more an issue for interpreting the signal observed for the first OISO cruises, but**

215 the increase in **Cant** between February 1998 and December 1998 remains (from < 6 $\mu\text{mol}.\text{kg}^{-1}$ to
216 about 10 $\mu\text{mol}.\text{kg}^{-1}$).

217
218 To continue on this figure (Fig. 3), for the bottom layer, the fact that it is stretched below the deepest
219 samples seems to create at least the distinct maximum in mid-2000s. Perhaps this will be reduced if
220 the maximum depth/pressure is set to the deepest sample, to exclude extrapolations below that
221 depth.

222
223 **Response: Having removed the INDIGO1 data from the Hovmöller plots, this no more an issue**
224 **because the deepest sample is collected at the same depth for all cruises**

225
226
227 Specific comments

228 L18 (here around 460): Do the changes here (+7 and +13, respectively) refer to the whole period?
229 Please clarify.

230 **Response: these are not changes, but Cant concentrations. The following rephrasing is suggested:**
231 **'from the average concentration of 7 $\mu\text{mol}.\text{kg}^{-1}$ calculated for the period 1978-1987 to the average**
232 **concentration of 13 $\mu\text{mol}.\text{kg}^{-1}$ for the period 2010-2018.'**

233
234 L23 (here around 467): A rather tiny remark, but the use of "pluriannual" may be grammatically correct
235 (I'm not a native English speaker), but consider using "multiannual" (or multi-annual), which are more
236 common (I believe). The same is used on L360.

237 **Response: We agree that this is maybe not the best word to use. It will be replaced by 'multi-annual'.**

238 L59 (here around 502): I'm expecting a reference in the end of this sentence. This may be refer to the
239 reference in the previous line, but you may consider moving this to the end.

240 **Response: We agree that the reference is misplaced. It will be moved to the end of the sentence.**

241 L95 (here around 541): I can't find a definition of "AAC" anywhere. Please write out and define the first
242 time.

243 **Response: We agree that the definition of ACC is missing (Antarctic Circumpolar Current). That will**
244 **be corrected.**

245 L96-97 (here around 542-543): Unclear sentence. Need some rephrasing/re-writing. Suggestion: "...
246 .Weddell Sea, where deep and bottom waters are produced...".

247 **Response: The sentence will be rephrased as suggested.**

248 L98-100 (here around 544-546): In the same sentence, there are several instances where the full water
249 mass name is not spelled out, for example "the Ross Sea (RSBW; ...". This may be intuitive, but I don't
250 think the full names of some of these are written out at any place in the manuscript so would suggest
251 to consider doing that at some place.

252 **Response: The full names will be added explicitly.**

253 L100 (here around 546): Rephrase: In the Prytz Bay, AABW formation has also. . . This sentence is
254 overall quite unclear, especially the last part, so please consider rewriting for clarification.

255 **Response: It is indeed quite unclear. We propose the following rewriting : 'AABW formation has also**
256 **been observed in the Prydz Bay (Rodehacke et al., 2007; Yabuki et al., 2006). There, three polynyas**

257 and two ice shelves have been identified as Prydz Bay Bottom Water (PBBW) production hotspots
258 from seal tagging data (Williams et al., 2016). This PPBW flows out the Prydz Bay through the Prydz
259 Channel and get mixed with the CDBW.'

260
261 L105 (here around 552): The "Warm Deep Water" is not described, so not easy to follow without a
262 previous knowledge of the area and the present water masses. Please clarify.

263 **Response: we agree that it may be difficult to follow. The Warm Deep Water is slightly modified**
264 **Circumpolar Deep Water (by mixing with surface waters when it enters the Weddell Basin). For**
265 **simplification, we suggest rewriting as follows: The exported WSDW originates from the**
266 **Circumpolar Deep Water (CDW) that enters the Weddell basin and mixes with WSBW and High**
267 **Salinity Surface Water (HSSW) (see Fig.2 in van Heuven et al., 2011).**

268
269 Section 2.4: Part of this section, and in particular from L133, deals with results of Cant from the
270 methods not yet described. I would suggest to move this to the Result section, at least the Cant parts,
271 or maybe part of the Discussion.

272 **Response: the authors agree that this section does not fit in the material and method part of the**
273 **manuscript, but rather in the discussion section as suggested.**

274
275 L152 (here around 614): Since the "P" in GLODAP refers to "Project", the "project" after should be
276 avoided (I think). You could rephrase this into something like:not yet qualified (or included in) the
277 most recent GLODAPv2 product.

278 **Response: the mention of GLODAP will be rephrased as suggested.**

279
280 L161 (here around 629): The stated accuracy for temperature and salinity seems too low. The standard
281 CTD accuracy, for example found at the GO-SHIP home page (Hydro-manual) is 0.002 for both. Please
282 check.

283 **Response: the authors agree and will correct the accuracy for temperature (0.002°C) and salinity**
284 **(0.005 for measurements using a salinometer).**

285
286 L161 (here around 629): As far as I can see, this is the first time "AT" is mentioned, but not defined.
287 Please add this.

288 L166 (here around 636): Same for "O2" as for AT above. Please define first time.

289 **Response: AT and O2 will be defined here.**

290
291 L170 (here around 641): You mean "onshore"?

292 **Response: the reviewer is right about this mistake.**

293
294 L184 (here around 656): Clarify which "Redfield ratio". You mean the C:O ratio? Please add this.

295 **Response: Initially, only C/O₂ and N/O₂ ratios were involved in the definition of the parameter 'a'**
296 **(Touratier and Goyet, 2004b; Lo Monaco et al., 2005b). In the latest definition of the method**
297 **Touratier et al. (2007) presents an upgraded definition of this parameter by combining the Redfield**
298 **equation coefficients for CO₂, O₂, HPO₄²⁻ and H⁺ and the same rules of construction as Broecker (1974)**
299 **did for tracers NO or PO. Because we want to keep the explanation simple in the manuscript, we**
300 **suggest to rephrase L184 as follows : 'where a is defined in Touratier et al. (2007) as combination of**

301 the Redfield equation coefficients for CO₂, O₂, HPO₄²⁻ and H⁺. For more details about the definition
302 and the calibration of this parameter, please refer to Touratier et al. (2007).'

303 L217 (here around 691): Either remove "after", so it reads "... and only impacted by...", or if more
304 correct, add "subduction", so it reads "and after subduction only impacted by...".

305 **Response: the word 'subduction' will be added as suggested.**

306
307 L233: "LCBW" is here mentioned for the first time, without definition or any description anywhere in
308 the manuscript, as far as I can see. Please add this.

309 **Response: LCDW refers to the Lower Circumpolar Deep Water laying above AABW in the entire**
310 **Southern Ocean. Details about this water mass will be added in Section 2.2 where it is first**
311 **mentioned.**

312
313 L235-236: This is what was commented on in the general comments above, with the "sudden
314 increase". Please revise and clarify. It is more likely that there was a more gradual evolution, and none
315 of the other parameters calls for any sudden changes. Also, the data quality and methods between the
316 older data and the OISO data may differ, so extra caution is taken when comparing them.

317 **Response: we removed the older data form the Hovmoller plot, but the change in C_{ant} in LCDW**
318 **remains (from <6 µmol.kg⁻¹ in Feb 1998 (similar as for the older data) to about 10 µmol.kg⁻¹ for the**
319 **following cruises).**

320
321 L240 (here around 719): The maximum in C_{ant} in 2004 is one occasion, and followed by five (almost
322 six) years without any data. I would be cautious to over interpret this. However, it co-incides with a
323 maximum in oxygen, which could indicate a ventilation event.

324 **Response: we agree with the referee about being cautious with the measurements in 2004. Indeed**
325 **the maximum in C_{ant} is due to the maximum in O₂ (not associated with a maximum in C_T).**

326
327 L256-260 (here around 739-743): The lower concentrations of AT in the years around 2000 at all depths
328 below (at least) 1500 m (have you checked the whole water column?) seems a bit odd. Especially when
329 this is not seen in any of the other parameters. Also, when comparing two years in the 1980s with data
330 more than a decade later, one should be extra cautious in the interpretation, not the least when the
331 two years/occasions in 1985/87 show the highest concentrations seen over the evaluated period.
332 Certainly the years after 2000 show much lower concentrations, which may be a phase due to a change
333 in different forcing, but to suggest reduced calcification from only a few years/occupations of data is
334 very speculative, and clearly something that change a few years later.

335 **Response: As mentioned in the general comments, the low A_T values between late 1998 and 2004**
336 **are found both in the Antarctic zone and the Subtropical zone (Figure S1), but they are not observed**
337 **in the surface layer (this will be added in the revised manuscript). The hypothesis about reduced**
338 **calcification could explain this contrast between the surface waters and the deep ocean.**

339 L259-260 (here around 742-743): Is it realistic that the increase in CT is lower than the accumulation
340 of C_{ant}?

341 **Response: The small increase in C_T over the period 1987-2004 could be caused by a reduction in C_{T,nat}**
342 **around the year 2000 (associated with the low A_T values). This said, we also have to keep in mind**
343 **the uncertainty on the C_{ant} calculations. This will be clarified in the results and in the discussion.**

344 L261 (here around 744): While there is a rather clear trend in oxygen during this period – although I
345 would be careful in talking about trends over such short periods, especially when comparing to a year
346 with a maximum (2004) – there is no trend in C_{ant} . Instead the latter shows some clear interannual
347 variability. Also, the “trend” in temperature is indeed very small, and even if not significant, the change,
348 or better, variability, in salinity is rather large. Consider these points when revising this part. Your
349 statement on L267-268 highlights this issue.

350 **Response: we agree with the reviewer that there is no clear trend in C_{ant} over 2004-2018. We will**
351 **change “decrease in C_{ant} ” for “no increase in C_{ant} ”. The same is true for temperature and salinity.**

352 L270-271 (here around 755): There is also a maximum in temperature in 1985, so this could indicate
353 more mixing with WSDW, which are both fresher and warmer.

354 **Response: we agree with the reviewer that more mixing with WSDW (or CDBW) could also explain**
355 **the higher C_{ant} concentrations and lower S in 1985 (the signal in temperature is not well marked due**
356 **to the large error bars). This will be added in the text.**

357
358 L275-278 (here around 761-764): This is a very long sentence. I suggest to divide it, with period after
359 “...the underlying deep waters.” Then remove “and”, and start on “Since”, or change the start of the
360 sentence. For the last part of this sentence (L277-278), the suggestion of increased contribution from
361 the Ross Sea is not clear to me since the oxygen decrease, while the salinity goes up and down. Or are
362 you only referring to the one occupation in 2012? (If this is the case, it seems to detailed to explain a
363 single year taken out of a long time series.)

364 **Response: the suggestion made by the reviewer to shorten the sentence will be used. Our aim is to**
365 **discuss the variability in C_{ant} concentrations that could reflect variations in the contribution of**
366 **different types of AABWs. We suggest that the lower C_{ant} concentrations observed in 2011, 2012**
367 **and 2013 may be due to an increased contribution of older types of AABW. We agree that pointing**
368 **to RSBW as a possible candidate because salinity was higher in 2012 is too speculative. This will be**
369 **removed.**

370
371 L280 (here around 767): The stated freshening of 0.01, for which period is that observed? Please clarify.

372 **Response: The sentence will be corrected as follows: ‘The freshening in S of -0.006 decade⁻¹ between**
373 **2004 and 2018 that we observed on the Western side of the Kerguelen Plateau was also observed**
374 **on the Eastern side of the Plateau by Menezes et al. (2017) over a similar period.’**

375 L312-313 (here around 823): “... (15 umol kg⁻¹) due to mixing with older CDW.”

376 **Response: the sentence will be corrected.**

377 L317 (here around 827): “that contain very high amounts of C_{ant} ...”

378 **Response: the sentence will be correct as suggested.**

379 L318-320 (here around 829-830): The last sentence of this paragraph basically repeats what have been
380 said above. Consider to remove.

381 **Response: the authors agree with the reviewer and will remove this sentence.**

382 L325 (here around 835): Here you write out “Southern Ocean” after having used the abbreviation
383 throughout the manuscript, even the sentence before. Consider to revise.

384 **Response: “Southern Ocean” will be changed to SO.**

385 L340 (here around 845): "evaluated" should here instead be "estimated", or "calculated", or "found"
386 (I think).

387 **Response: "evaluated" will be replaced by "calculated".**

388 L386 (here around 898): Consider rewording "...vary in a very large range. . .". Suggestion: "show a
389 very large variability", or maybe, "vary over a very large range".

390 **Response: the rewording 'vary over a very large range' will be used.**

391 L387-388 (here around 901): "(-221 mmol C m⁻² d⁻¹; Roden et al., 2016).

392 **Response: we will correct this according to the reviewer suggestion.**

393 L416 (here around 928): Both these water masses (RSBW and ALBW) have higher salinity, and while
394 oxygen show a reduced trend the salinity goes up and down, so this explanation does not hold for all
395 years during this period.

396 **Response: we understand the concern of the reviewer. The mention of the WSDW will be added, as
397 for the response of the comment L275-278.**

398 L424 (here around 937): "explains most, but not all, of the observed. . ."

399 **Response: the sentence will be corrected.**

400 L463 (here around 977): GLODAPv2 version are written as "GLODAPv2.2021 (.2020 is soon to be
401 released). You do mean 2021 and not 2020?"

402 **Response: the data will not be included in GLODAP in the 2020 version, but in the following one.**

403

404 L851-853 (here around 1353-1354): Table 2 (and in general): You may want to consider if you want to
405 keep AOU as parameter, when you mostly refer to oxygen. The trends are almost exactly the same (but
406 opposite of course), and gives the same message.

407 **Response: we agree with the reviewer. AOU will be removed from Table 2 and from Figure 2 (and
408 from the corresponding parts in the text).**

409

410 Technical comments

411 L22: This is, however, modulated. . .

412 **Response: the commas will be added.**

413 L35: The references should, typically, be chronologically ordered. Please check throughout the
414 manuscript. (There are more examples of this, but I won't comment on this more.)

415 **Response: we agree with the referee. We will check for other occurrences.**

416 L71: This is, however, not the. . .

417 **Response: the commas will be added.**

418 L91: "...(405 and 465 km, respectively)."

419 **Response: the coma will be added.**

420 L107-113: Examplified with “. . .East of the Kerguelen. . .”, this section has many of these
421 “directions/locations” (east/west/. . .) spelled with a large letter, even not part of a name. I think this
422 is not correct, and if so, please change.

423 **Response: this will be corrected.**

424 L118-119: . . .28.27-bottom, respectively. . .

425 **Response: the coma will be added.**

426 L172-173: Change font; the part of the sentence from “for deep samples. . .” are in a different font
427 (maybe “Cambria”).

428 **Response: the font will be changed.**

429 L220: Change font for “value for”.

430 **Response: the font will be changed.**

431 L306: Add a comma: “2018 (Fig 3a), probably . . .”

432 **Response: the coma will be added.**

433 L340: Add a “.”: Pardo et al. (2017)

434 **Response: the dot will be added.**

435 L347: For consistency, change “South-Western” to “South-western” (similar as on L325).

436 **Response: this will be corrected.**

437 L449: Remove “.” for consistency: (e.g. Frölicher et al., 2014).

438 **Response: the coma will be deleted.**

439 L451: References in chronological order.

440 **Response: we agree with the referee. This will be corrected.**

441

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448 **Answer to the Topic Editor comments:**

449 Comments to the Author:

450 Dear Dr. Mahieu and co-authors,

451 Thank you for the revised submission. I am generally satisfied with the changes you made following
452 the comments by the referees. Going through the manuscript myself, I have listed my comments
453 below. Please prepare the final version of your manuscript taking into account these comments.

454 **Response: Dear Dr. Hoppema, we are thankful for your comments. Please find hereafter our
455 responses.**

456 In the title: Antarctic Bottom Water (without -s) as this study measured only one type at one
457 location.

458 **Response: we wanted to insist on the mix of AABW from different sources by writing it this way.
459 This will be corrected as suggested.**

460 Section 2.1 is clearly part of the methods and should thus be moved to Section 3.

461 **Response: this section will be moved as suggested.**

462 I suggest to call the water mass defined here as Lower AABW, not as Low AABW. Just like other well-
463 known water masses like Lower CDW, etc.

464 **Response: this will be corrected as suggested.**

465 Please place all 2 in CO₂ in subscript.

466 **Response: this will be corrected in the title and the references.**

467 Please check the references because many are incomplete.

468 **Response: this will be done. DOIs will be updated and page numbers checked. The last references
469 without page numbers do not mention any online.**

470 As to the data used in this study, there are several more OISO cruises (as also in the GLODAP tables).
471 Please provide the arguments for including the cruises that the authors did, while excluding others.

472 **Response: the missing OISO cruises in this study correspond to the cruises when this station was
473 not re-occupied. To clarify this, the following sentence will be added to section AABW sampling: 'In
474 our analysis, we included all the data available for the OISO-ST11 location (which has not been
475 sampled during each cruise for logistical reasons).'**

476 As to the supplement Table S1 (and discussion in the main text) with the adjustments from the
477 different quality control efforts, it is shown that AT at the OISO cruises did not receive any
478 adjustments. However, this is not the complete story. The GLODAP table says that there is not
479 sufficient data for comparison in this region, upon which the OISO data did not get an adjustment
480 because this could not be argued safely. This is actually the same as getting no quality control. This
481 should be made clear in the manuscript.

482 **Response: we agree and will clarify this point as follows:**

483 '... this calls for great care before applying an adjustment. This is the case for A_T data that did not
484 get an adjustment in GLODAP because this could not be argued safely due to the limited number of
485 data in this region.'

486 L5 Shouldn't the University of Liverpool be mentioned?

487 **Response: this is missing indeed and will be added.**

488 L9 Antarctic bottom water (AABW) is known ...

489 **Response: this will be corrected.**

490 L9 ... but the sink is hardly quantified ...

491 **Response: this will be added.**

492 L13 in the framework of ...

493 **Response: this will be corrected.**

494 L16 At this location, the main sources of AABW are the low-saline ... (fresh is not the word here,
495 because this is a saline water mass; I suggest to skip "younger" because: younger against what?)

496 **Response: we understand your concern and will correct this sentence as suggested.**

497 L20 SO has not been defined before

498 **Response: this will be added.**

499 L24 hydrographic (not: hydrological)

500 **Response: this will be corrected.**

501 L27 AABW

502 **Response: this will be corrected.**

503 L27-28 This sentence is trivial, and if not followed by which of these processes are important or how
504 they function, not necessary/useful.

505 **Response: we agree and will remove this sentence.**

506 L43 3% is more like the maximum. Mostly C_{NT} is much less. I suggest to write here: less than 3%

507 **Response: we agree and will correct this.**

508 L53-55 "Thus, there is a need to better explore the CT and C_{NT} temporal variability in the deep
509 ocean, especially in the SO where observations are relatively sparse." I cannot understand the
510 connection of this concluding sentence with the previous text in this paragraph. Please modify.

511 **Response: we agree that the sentence has no clear link with the previous statements. We suggest
512 to remove it.**

513 L56 AABW (without \rightarrow) Please change this throughout the manuscript.

514 **Response: this will be corrected.**

515 L58 ... by covering a major part of the world ocean floor ...

516 **Response: this will be corrected.**

517 L84 Study area

518 **Response: this will be corrected.**

519 L86 framework

520 **Response: this will be corrected.**

521 L98 is dominated by (instead of: is mainly governed)

522 **Response: this will be corrected.**

523 L111 ... Lower Circumpolar ...

524 **Response: this will be corrected.**

525 L112 I think HSSW is generally the abbreviation for High Salinity Shelf Water

526 **Response: this is correct, the abbreviation will be removed.**

527 L116-117 The PE deepest point of the PET is 3750 m, ...

528 **Response: this will be corrected as 'The deepest point of the PET is 3750 m...'**

529 L158-160 "The accuracy of CT and AT measurements was ensured by daily analyses of Certified

530 Reference Materials (CRMs) provided by A.G. Dickson laboratory (Scripps Institute of

531 Oceanography)." This is indeed important to warrant the accuracy. For the interpretation it is also

532 important to know the accuracy. Please give the accuracy here.

533 **Response: A single accuracy value for all cruises is difficult to specify. Although we used the same**

534 **technic (and data processing) accuracy range between around 1.5 and 3 $\mu\text{mol/kg}$ for both AT and**

535 **CT depending on the cruise. A complete list of CRMS batch number used during OISO cruise is**

536 **available at NCEI/OCADS with information on duplicates for each cruise**

537 **(https://www.nodc.noaa.gov/ocads/oceans/VOS_Program/OISO.html).** As this information is

538 **available at NCEI/OCADS (and the link recall in the section "Data Availability"), we think it was not**

539 **appropriate to list all CRM batch values for each cruise in the manuscript. We suggest to correct as**

540 **follows: 'The accuracy of C_T and A_T measurements (always better than $\pm 3 \mu\text{mol}\cdot\text{kg}^{-1}$ for all cruises**

541 **since 1998) was ensured...'**

542 L164 silicate (no capital)

543 **Response: this will be corrected.**

544 L171 using (instead of: considering)

545 **Response: this will be corrected.**

546 L171 I do not understand why the value of 33 $\mu\text{mol/kg}$ was used, as the mean value from GLODAPv2

547 is 32.4 $\mu\text{mol/kg}$. Even if the error because of this is small, it does increase it for no good reason.

548 **Response: this is correct. The value has been changed to 32.4 $\mu\text{mol}\cdot\text{kg}^{-1}$. The change on the C_{ant}**

549 **values calculated with C° is $-0.3 \mu\text{mol}\cdot\text{kg}^{-1}$.**

550 L187-188 from deep waters free of anthropogenic CO₂ ...

551 **Response: this will be corrected.**

552 L245-246 “the theoretical C_T trend at the AABW formation sites would be of the order of +8
553 $\mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{decade}^{-1}$.” How was this calculated? Only part of the AABW, when it is formed, contains
554 water that has been at the surface. Only that part could follow the atmospheric increase on CO₂.
555 What percentage of surface water was assumed as contributing to AABW?

556 **Response:** This value was listed to give a taste of the theoretical C_T increase in Antarctic surface
557 waters assuming that ocean fCO₂ follows the atmospheric CO₂ increase. In the Prydz Bay region
558 Roden et al (2016) concluded that “surface waters in the seasonal ice zone track the atmospheric
559 increase in fCO₂”. For our calculation we used the mean properties in Antarctic surface waters
560 observed in the Prydz Bay by Roden et al. (2016): SST=-1°C, SSS= 34.2, A_T=2291 $\mu\text{mol}/\text{kg}$ and fCO₂=
561 376 μatm in 2006. Assuming that oceanic fCO₂ increased at a rate of 1.8 μatm we calculated C_T and
562 we derived a trend in C_T of +8 $\mu\text{mol}/\text{kg}/\text{decade}$ in the Antarctic surface water (assuming no change
563 in temperature, salinity and alkalinity). Note that this value is close to the theoretical trend in C_T
564 calculated by Van Heuven et al. (2014) in the Weddell Sea (about +0.8 $\mu\text{mol}/\text{kg}/\text{yr}$, the red circle in
565 Figure 4a in Van Heuven et al., 2014). We suggest to revise following: “Due to the mixing of AABW
566 with old CDW (Cant free), these trends are lower than the theoretical trend expected from the
567 increase in atmospheric CO₂. Indeed, assuming that the surface ocean fCO₂ follows the
568 atmospheric growth rate (+1.8 $\mu\text{atm}\cdot\text{year}^{-1}$ over 1978-2018) in the seasonal ice zone (Roden et al.,
569 2016), the theoretical C_{ant} trend at the AABW formation sites would be of the order of +8 $\mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{decade}^{-1}$ in the Antarctic surface water. This is close to the theoretical C_T trend estimated for
570 freezing shelf water in the Weddell Sea (Van Heuven et al 2014).”
571

572 L288 experiences

573 **Response: this will be corrected.**

574 L310 and ends ... (instead of: and lasts)

575 **Response: this will be corrected.**

576 L315 ... in the 1980s in the Indian sector of the Southern Ocean ...

577 **Response: this will be corrected.**

578 L316 quality control (instead of: qualification)

579 **Response: this will be corrected.**

580 L427 “recognized freshening of AABWs over the last decades (Rintoul, 2007).” With a reference from
581 2007, this is not about the last decades. Please change wording or give a different reference.

582 **Response: we agree that there is a lack of consistency between the sentence and reference. We**
583 **suggest to change the sentence as follow: ‘recognized freshening of the AABW (Rintoul, 2007;**
584 **Anilkumar et al., 2015).’**

585 L484 change to: GLODAPv2.2021

586 **Response: this will be corrected.**

587 L504 Please add info on what kind of this reference is and possibly where it can be found online.

588 **Response: we suggest to replace the current reference by the following:**
589 **Coverly, S. C., Aminot, A., and R. Kérout, 2009. Nutrients in Seawater Using Segmented Flow**
590 **Analysis, In Practical Guidelines for the Analysis of Seawater, Ed. Oliver Wurl, CRC Press, June 2009,**
591 **doi: 10.1201/9781420073072.ch8.**

592 L506 Cycles (also in other cases where this journal is concerned)

593 **Response: this will be corrected.**

594 L538 pages: 205-206

595 **Response: this will be corrected.**

596 L551 pCO₂

597 **Response: this will be corrected.**

598 L602 should be cited as: 18, GB1042, doi:10.1029/2002GB002017

599 L606 should be cited differently, similar as above

600 L624 pages: 346-349

601 L636 pages: 1221-1224

602 In many cases the references are incomplete, for example missing page numbers. Please go through the references and correct them.

603

604 **Response: all the references will be checked and updated. The DOIs will be updated, and the page numbers checked. The last references without page numbers do not mention any online.**

605

606 Figure 1 Please add that these are very rough transport paths. The dashed line for the ACC gives the position, says the caption. What position? The ACC is wide; please explain. The path of the AABW in

607 the Weddell Sea is not correct. Neither is the path of the AABW from Prydz Bay and Cape Darnley,

608 which flows along the coast to the west and enters the Weddell circulation.

609

610 **Response: the mention will be added and the figure updated.**

611 Figure 2 The term is Hovmöller diagram.

612 **Response: this will be corrected.**

613 Thank you and best wishes

614 Mario Hoppema

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622 **Variability and stability of anthropogenic CO₂ in Antarctic**
623 **Bottom Waters observed in the Indian sector of the Southern**
624 **Ocean, 1978-2018**

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631 **Abstract**

632 Antarctic bottom waters (AABW_s) ~~are-is~~ known as a long term sink for anthropogenic CO₂ (C_{ant}) but ~~the sink~~ is
633 hardly quantified because of the scarcity of the observations, specifically at an interannual scale. We present in
634 this manuscript an original dataset combining 40 years of carbonate system observations in the Indian sector of
635 the Southern Ocean (Enderby Basin) to evaluate and interpret the interannual variability of C_{ant} in the AABW.
636 This investigation is based on regular observations collected at the same location (63° E-56.5° S) in the ~~frame~~
637 ~~work~~ of the French observatory OISO from 1998 to 2018 extended by GEOSECS and INDIGO observations (1978,
638 1985 and 1987).

639 At this location the main sources of AABW sampled is the ~~fresh-and-younger-low-saline~~ Cape Darnley Bottom
640 Water (CDBW) and the Weddell Sea Deep Water (WSDW). Our calculations reveal that C_{ant} concentrations
641 increased significantly in the AABW, from the average concentration of 7 μmol.kg⁻¹ calculated for the period
642 1978-1987 to the average concentration of 13 μmol.kg⁻¹ for the period 2010-2018. This is comparable to previous
643 estimates in other ~~Southern Ocean (SO)~~ basins, with the exception of bottom waters close to their formation sites
644 where C_{ant} concentrations are about twice as large. Our analysis shows that total carbon (C_T) and C_{ant} increasing
645 rates in the AABW are about the same over the period 1978-2018, and we conclude that the long-term change in
646 C_T is mainly due to the uptake of C_{ant} in the different formation regions. This is, however, modulated by significant
647 interannual to multi-annual variability associated with variations in hydro~~graphic~~
648 ~~logical~~ (potential temperature (Θ), salinity (S)) and biogeochemical (C_T, total alkalinity (A_T), dissolved oxygen (O₂)) properties. A surprising
649 result is the apparent stability of C_{ant} concentrations in recent years despite the increase in C_T and the gradual
650 acceleration of atmospheric CO₂. ~~The C_{ant} sequestration by AABW_s is more variable than expected and depends~~
651 ~~on-a-complex-combination-of-physical-chemical-and-biological-processes-at-the-formation-sites-and-during-the~~
652 ~~transit-of-the-different-AABW_s~~. The interannual variability at play in AABW_s needs to be carefully considered on
653 the extrapolated estimation of C_{ant} sequestration based on sparse observations over several years.

654

655 **1 Introduction**

656 Carbon dioxide (CO₂) atmospheric concentration has been increasing since the start of the industrialization
657 (Keeling and Whorf, 2000). This increase leads to an ocean uptake of about a quarter of C_{ant} emissions (Le Quéré
658 et al., 2018; Gruber et al., 2019a). It is widely acknowledged that the Southern Ocean (SO) is responsible for 40

659 % of the C_{ant} ocean sequestration (Mata, 2001; Orr et al., 2001; McNeil et al., 2003; Gruber et al., 2009;
660 Khatiwala et al., 2009). Ocean C_{ant} uptake and sequestration have the benefit to limit the atmospheric CO_2 increase
661 but also result in a gradual decrease of the ocean pH (Gattuso and Hansson, 2011; Jiang et al., 2019). Understanding
662 the oceanic C_{ant} sequestration and its variability is of major importance to predict future atmospheric CO_2
663 concentrations, impact on the climate and impact of the pH change on marine ecosystems (de Baar, 1992; Orr et
664 al., 2005; Ridgwell and Zeebe, 2005).

665 C_{ant} in seawater cannot be measured directly and the evaluation of the relatively small C_{ant} signal from the total
666 inorganic dissolved carbon (C_T ; ~~around less than~~ 3 %; Pardo et al., 2014) is still a challenge to overcome. Different
667 approaches have been developed in the last 40 years to quantify C_{ant} concentrations in the oceans. The 'historical'
668 back calculation method based on C_T measurement and preformed inorganic carbon estimate (C^0) was
669 independently published by Brewer (1978) and Chen and Millero (1979). This method has been often applied at
670 regional and basin scale (Chen, 1982; Poisson and Chen, 1987; Chen, 1992; Goyet et al., 1998; Körtzinger et al.,
671 1998, 1999; Lo Monaco et al., 2005a). More recently the TrOCA method (Tracer combining Oxygen, dissolved
672 Carbon and total Alkalinity) has been developed (Touratier and Goyet, 2004a, b; Touratier et al., 2007) and applied
673 in various regions including the SO (e.g. Lo Monaco et al., 2005b; Sandrini et al., 2007; Van Heuven et al., 2011;
674 Pardo et al., 2014; Shadwick et al., 2014; Roden et al., 2016; Kerr et al., 2018). Comparisons with other data-based
675 methods show significant differences in C_{ant} concentrations, especially at high latitudes and more particularly in
676 deep and bottom waters (Lo Monaco et al., 2005b; Vázquez-Rodríguez et al., 2009; Pardo et al., 2014). ~~Thus, there~~
677 ~~is a need to better explore the C_T and C_{ant} temporal variability in the deep ocean, especially in the SO where~~
678 ~~observations are relatively sparse.~~

679 Antarctic bottom waters (AABW~~s~~) are of specific interest for the atmospheric CO_2 and heat regulation as they
680 play a major role in the meridional overturning circulation (Johnson et al., 2008; Marshall and Speer, 2012).
681 AABW~~s~~ represent a large volume of water by covering ~~the majority of the bottom~~ ~~a major part of the~~ world ocean
682 ~~floor~~ (Mantyla and Reid, 1995), and their spreading in the interior ocean through circulation and water mixing is
683 a key mechanism for the long-term sequestration of C_{ant} and climate regulation (Siegenthaler and Sarmiento, 1993).
684 The AABW formation is a specific process occurring in few locations around the Antarctic continent (Orsi et al.,
685 1999). In short, the AABW formation occurs when the Antarctic surface waters flows down along the continental
686 shelf. The Antarctic surface waters density required for this process to happen is reached by the increase in salinity
687 (S) due to brine release from the ice formation and by a decrease in temperature due to heat loss to either the ice-
688 shelf or the atmosphere. Importantly, AABW formation process is enhanced by katabatic winds that open areas
689 free of ice called polynyas (Williams et al., 2007). Indeed, katabatic winds are responsible for an intense cooling
690 that enhance the formation of ice constantly pushed away by the wind, leading to cold and salty surface waters in
691 contact with the atmosphere. The variable conditions of wind, ice production, surface water cooling and continental
692 slope shape encountered around the Antarctic continent lead to different types of AABW, hence the AABW
693 characteristics can be used to identify their formation sites.

694 The ability of AABW to accumulate C_{ant} has been controversial since one can believe that the ice coverage limits
695 the invasion of C_{ant} in Antarctic surface waters (e.g. Poisson and Chen, 1987). This is, however, not the case in
696 polynyas, and several studies have reported significant C_{ant} signals in AABW formation regions, likely due to the
697 uptake of CO_2 induced by high primary production (Sandrini et al., 2007; van Heuven et al., 2011, 2014; Shadwick
698 et al., 2014; Roden et al., 2016). However, little is known about the variability and evolution of the CO_2 fluxes in

699 AABW formation regions, and since biological and physical processes are strongly impacted by seasonal and
700 interannual climatic variations (Fukamachi et al., 2000; Gordon et al., 2010, McKee et al., 2011; Gordon et al.,
701 2015; Gruber et al., 2019b), the amount of C_{ant} stored in the AABW~~s~~ may be very variable, which could bias the
702 estimates of C_{ant} trends derived from data sets collected several years apart (e.g. Williams et al., 2015; Pardo et al.,
703 2017; Murata et al., 2019).
704 In this context of potentially high variability in C_{ant} uptake at AABW formation sites, as well as in AABW export,
705 circulation and mixing, we used repeated observations collected in the Indian sector of the Southern Ocean to
706 explore the variability in C_{ant} and C_T in the AABW and evaluate their evolution over the last 40 years.

707 **2 Studied area**

708 **2.1 AABW sampling during the last 40 years**

709 Most of the data used in this study were obtained in the frame of the long-term observational project OISO (Ocean
710 Indien Service d'Observations) conducted since 1998 onboard the R.S.V. Marion Dufresne (IPEV/TAAF). During
711 these cruises, several stations are visited, but only one station is sampled down to the bottom (4800 m) south of
712 the Polar Front at 63.0° E and 56.5° S (hereafter noted OISO-ST11). This station is located in the Enderby Basin
713 on the Western side of the Kerguelen Plateau (Fig. 1) and coincides with the station 75 of the INDIGO-3 cruise
714 (1987). In our analysis, we also included data from the station 14 (deepest sample taken at 5109 m) of the INDIGO-
715 1 cruise (1985) and the station 430 (deepest sample taken at 4710 m) of the GEOSECS cruise (1978) located near
716 OISO-ST11 sampling site (405 km and 465 km away from it, respectively; Fig. 1). All the re-occupations used in
717 this analysis are listed in Table 1. Since seasonal variations are only observed in the surface mixed layer (Metz et
718 al., 2006), we used the observations available for all seasons (Table 1).

719 **Table 1**

720 **2.12 AABW~~s~~ circulation in the Atlantic and Indian sectors of the Southern Ocean**

721 The circulation in the SO is ~~mainly governed dominated~~ by the Antarctic Circumpolar Current (ACC) that flows
722 eastward, while the Coastal Antarctic Current (CAC) flows westward (Fig. 1) (Carter et al., 2008). The ACC and
723 the CAC influence the circulation of the entire water column; ~~including the AABW~~s~~ and generate gyres, crucial~~
724 ~~drivers of SO circulation (Carter et al., 2008). The most important gyres encountered around the Antarctic~~
725 ~~continent correspond to major AABW formation sites (Fig. 1).~~ The main AABW formation sites are the Weddell
726 Sea, where Weddell Sea Deep Water and Weddell Sea Bottom Water are produced (WSDW and WSBW,
727 respectively; Gordon, 2001; Gordon et al., 2010), the Ross Sea for the Ross Sea Bottom Water (RSBW; Gordon
728 et al., 2009, 2015), the Adelie Land coast for the Adelie Land Bottom Water (ALBW; Williams et al., 2008, 2010)
729 and the Cape Darnley Polynya for the Cape Darnley Bottom Water (CDBW; Ohshima et al., 2013). AABW
730 formation has also been observed in the Prydz Bay (Yabuki et al., 2006; Rodehacke et al., 2007). There, three
731 polynyas and two ice shelves have been identified as Prydz Bay Bottom Water (PBBW) production hotspots from
732 seal tagging and mooring data (Williams et al., 2016). This PBBW flows out the Prydz Bay through the Prydz
733 Channel and get mixed with the CDBW. The mix of CDBW and PBBW (hereafter called CDBW) represents a
734 significant AABW export (13 % of all AABW~~s~~ exports; Ohshima et al., 2013).

735 The largest bottom water source of the global ocean is the Weddell Sea (Gordon et al., 2001). The exported WSDW
736 is a mixture of the WSBW and Warm Deep Water (WDW). The WDW is a slightly modified Lower Circumpolar
737 Deep Water (LCDW) by mixing with ~~h~~High ~~s~~Salinity ~~s~~Surface ~~w~~Water (~~HSSW~~) when the LCDW enters the
738 Weddell basin (see Fig. 2 in van Heuven et al., 2011). The WSDW mixes with the LCDW during its transit ~~from~~
739 ~~the Weddell basin~~. A part of the WSDW deflecting southward with the ACC in the Enderby Basin reaches the
740 north-western part of the Princess Elizabeth Trough (PET) region (area separating the Kerguelen Plateau from the
741 Antarctic continent), where it mixes with other types of AABW~~s~~ (Heywood et al., 1999; Orsi et al., 1999). The
742 PET deepest point ~~of the PET~~ is 3750 m, deep enough to allow AABW~~s~~ to flow between the Australian Antarctic
743 Basin and the Enderby Basin (Heywood et al., 1999).

744 At the east of the PET, the CAC transports a mixture of RSBW and ALBW and accelerates northward along the
745 eastern side of the Kerguelen Plateau (Mantyla and Reid, 1995; Fukamachi et al., 2010) ~~following the Australian-~~
746 ~~Antarctic gyre, also called Kerguelen gyre (Vernet et al. 2019)~~. Part of the ALBW-RSBW mixture ~~also~~ reaches
747 the western side of the Kerguelen Plateau by the southern part of the PET (Heywood et al., 1999; Orsi et al., 1999;
748 Van Wijk and Rintoul, 2014) and mixes with the CDBW. The mixture of CDBW and ALBW-RSBW ~~either~~ flows
749 westward with the CAC and dilutes with the LCDW (Meijers et al., 2010) ~~or~~ ~~flows northward (Ohshima et al.,~~
750 ~~2013) and mixes with the WSDW before reaching the location of our time series station in the eastern Enderby~~
751 ~~Basin until it reaches the Weddell gyre (Carter et al., 2008)~~.

752 Figure 1

753 **2.3-2 AABW definition**

754 The distinction of water masses is usually performed according to neutral density (γ^n) layers. In the SO, LCDW
755 and AABW properties are generally well defined in the range 28.15-28.27 kg.m⁻³ and 28.27-bottom, respectively
756 (Orsi et al., 1999; Murata et al 2019). However, to interpret the long-term variability of the properties in the AABW
757 core at our location, we prefer to adjust the AABW definition to a narrow (more homogeneous) layer that we call
758 Lower Antarctic Bottom Water (LAABW), characterised by $\gamma^n > 28.35$ kg.m⁻³ (roughly ranging from 4200m to
759 4800m, see Fig. 3). This definition corresponds to the AABW characteristics observed at higher latitudes in the
760 Indian SO sector (Roden et al., 2016). The layer above the LAABW is hereafter called Upper Antarctic Bottom
761 Water (UAABW).

762 **3 Material and methods**

763 **3.2.1 AABW sampling during the last 40 years**

764 Most of the data used in this study were obtained in the framework of the long-term observational project OISO
765 (Ocean Indien Service d'Observations) conducted since 1998 onboard the R.S.V. Marion-Dufresne (IPEV/TAAF).
766 During these cruises, several stations are visited, but only one station is sampled down to the bottom (4800 m)
767 south of the Polar Front, at 63.0° E and 56.5° S (hereafter noted OISO-ST11). This station is located in the Enderby
768 Basin on the Western side of the Kerguelen Plateau (Fig. 1) and coincides with the station 75 of the INDIGO-3
769 cruise (1987). In our analysis, we included all the data available for the OISO-ST11 location (which has not been
770 sampled during each cruise for logistic reasons). We also included data from the station 14 (deepest sample taken
771 at 5109 m) of the INDIGO-1 cruise (1985) and the station 430 (deepest sample taken at 4710 m) of the GEOSECS

772 cruise (1978) located near OISO-ST11 sampling site (405 km and 465 km away from it, respectively; Fig. 1). All
773 the re-occupations used in this analysis are listed in Table 1. Since seasonal variations are only observed in the
774 surface mixed layer (Metzl et al., 2006), we used the observations available for all seasons (Table 1).
775 Table 1

776 **3.21 Validation of the data**

777 For 1998-2004, the OISO data were quality controlled in CARINA (Lo Monaco et al., 2010) and for 2005 and
778 2009-2011 in GLODAPv2 (Key et al., 2015; Olsen et al., 2016, 2019). The 3 additional datasets from GEOSECS,
779 INDIGO-1 and INDIGO-3 were first qualified in GLODAPv1 (Key et al., 2004) and used for the first C_{ant} estimates
780 in the Indian Ocean (Sabine et al., 1999). The adjustments recommended for these historical datasets have been
781 revisited in CARINA and GLODAPv2. In this paper we used the revised adjustments applied to the GLODAPv2
782 data product, with one exception for the total alkalinity (A_T) data from INDIGO-3 for which we applied an
783 intermediate adjustment between the recommendation from GLODAPv1 (confirmed in CARINA) for no
784 adjustment (in reason of the lack of available observations in this region for robust comparison) and the adjustment
785 by $-8 \mu\text{mol.kg}^{-1}$ applied to the GLODAPv2 data product (justification in Supp. Mat.).
786 For the recent OISO cruises conducted in 2012-2018 not yet included in the most recent GLODAPv2 product, we
787 have proceeded to a data quality control in deep waters where C_{ant} concentrations are low and subject to very small
788 changes from year to year (see Supp. Mat.).

789 **3.22 Biogeochemical measurements**

790 Measurement methods during OISO cruises were previously described (Jabaud-Jan et al., 2004; Metzl et al., 2006).
791 In short, measurements were obtained using Conductivity-Temperature-Depth (CTD) casts fixed on a 24 bottles
792 rosette equipped with 12 L General Oceanics Niskin bottles. Potential temperature (Θ) and salinity (S)
793 measurements have an accuracy of 0.002 °C and 0.005 respectively. A_T and C_T were sampled in 500 mL glass
794 bottles and poisoned with 100 μL of mercuric chloride saturated solution to halt biological activity. Discrete C_T
795 and A_T samples were analyzed onboard by potentiometric titration derived from the method developed by Edmond
796 (1970) using a closed cell. The repeatability for C_T and A_T varies from 1 to $3.5 \mu\text{mol.kg}^{-1}$ (depending on the cruise)
797 and is determined by sample duplicates (in surface, at 1000 m and in bottom waters). The accuracy of C_T and A_T
798 measurements (always better than $\pm 3 \mu\text{mol.kg}^{-1}$ for all cruises since 1998) was ensured by daily analyses of
799 Certified Reference Materials (CRMs) provided by A.G. Dickson laboratory (Scripps Institute of Oceanography).
800 Dissolved oxygen (O_2) concentration was determined by an oxygen sensor fixed on the rosette. These values were
801 adjusted using measurements obtained by Winkler titrations using a potentiometric titration system (at least 12
802 measurements for each profile). The thiosulphate solution used for the Winkler titration was calibrated using iodate
803 standard solution (provided by Ocean Scientific International Limited) to ensure the standard O_2 accuracy of 2
804 $\mu\text{mol.kg}^{-1}$. Nitrate (NO_3) and Si concentrations were measured onboard or onshore with an automatic
805 colorimetric Technicon analyser following the methods described by Trégouët and Le Corre (1975) until 2008, and
806 the revised protocol described by Aminot and Kérouel (2007)Coverly et al. (2009) since 2009. Based on replicate
807 measurements for deep samples we estimate an error of about 0.3 % for both nutrients. NO_3 data are not available
808 for all the cruises used in this analysis. The mean NO_3 concentrations in the LAABW at OISO-ST11 is 32.8 ± 1.2
809 $\mu\text{mol.kg}^{-1}$ while the average value derived from the GLODAP-v2 database in bottom waters south of 50°S in the

810 South Indian Ocean is $32.4 \pm 0.6 \mu\text{mol} \cdot \text{kg}^{-1}$. The lack of NO_3 data for few cruises has been palliated by [considering](#)
 811 [using](#) a climatological value of [32.43](#) $\mu\text{mol} \cdot \text{kg}^{-1}$ with a limited impact on C_{ant} determined by the C° method (<2
 812 $\mu\text{mol} \cdot \text{kg}^{-1}$ on estimates based on the differences observed between NO_3 measurements and the climatological
 813 value).

814 **3.43 C_{ant} calculation using the TrOCA method**

815 The TrOCA method was first presented by Touratier and Goyet (2004a, b) and revised by Touratier et al. (2007).
 816 Following the concept of the quasi-conservative tracer NO (Broecker, 1974), TrOCA is a tracer defined as a
 817 combination of O_2 , C_T and A_T , following:

$$818 \quad \text{TrOCA} = \text{O}_2 + a \left(\text{C}_T - \frac{1}{2} \text{A}_T \right), \quad (1)$$

819 where a is defined in Touratier et al. (2007) as combination of the Redfield equation coefficients for CO_2 , O_2 ,
 820 HPO_4^{2-} and H^+ . For more details about the definition and the calibration of this parameter, please refer to Touratier
 821 et al. (2007). The temporal change in TrOCA is independent of biological processes and can be attributed to
 822 anthropogenic carbon (Touratier and Goyet, 2004a). Therefore, C_{ant} can be directly calculated from the difference
 823 between TrOCA and its pre-industrial value TrOCA° :

$$824 \quad \text{C}_{\text{ant}} = \frac{\text{TrOCA} - \text{TrOCA}^\circ}{a}, \quad (2)$$

825 where TrOCA° is evaluated as a function of θ and A_T (Eq. 3):

$$826 \quad \text{TrOCA}^\circ = e^{\left[b - (c) \cdot \theta - \frac{d}{\text{A}_T^2} \right]}, \quad (3)$$

827 In these expressions, coefficients a , b , c and d were adjusted by Touratier et al. (2007) from [deep waters](#) free [of](#)
 828 anthropogenic CO_2 [deep waters](#) using the tracers $\Delta^{14}\text{C}$ and CFC-11 from the GLODAPv1 database (Key et al.,
 829 2004). The final expression used to calculate C_{ant} is:

$$830 \quad \text{C}_{\text{ant}} = \frac{\text{O}_2 + 1.279 \left(\text{C}_T - \frac{1}{2} \text{A}_T \right) - e^{\left[7.511 - (1.087 \cdot 10^{-2}) \cdot \theta - \frac{7.811 \cdot 10^5}{\text{A}_T^2} \right]}}{1.279}, \quad (4)$$

831
 832 The consideration of the errors on the different parameters involved in the TrOCA method results in an uncertainty
 833 of $\pm 6.25 \mu\text{mol} \cdot \text{kg}^{-1}$ (mostly due to the parameter a , leading to $\pm 3.31 \mu\text{mol} \cdot \text{kg}^{-1}$). As this error is relatively large
 834 compared to the expected C_{ant} concentrations in deep and bottom SO waters (Pardo et al., 2014) we will compare
 835 the TrOCA results using another indirect method to interpret C_{ant} changes over 40 years.

836 **3.54 C_{ant} calculation using the preformed inorganic carbon (C^0) method**

837 To support the C_{ant} trend determined with the TrOCA method, C_{ant} was also estimated using a back-calculation
 838 approach noted C^0 (Brewer, 1978; Chen and Millero, 1979), previously adapted for C_{ant} estimates along the
 839 WOCE-I6 section between South Africa and Antarctica (Lo Monaco et al., 2005a). This method consists in the
 840 correction of the measured C_T for the biological contribution (C_{bio}) and the preindustrial preformed C_T (C^0_{pi}):

$$841 \quad \text{C}_{\text{ant}} = \text{C}_T - \text{C}_{\text{bio}} - \text{C}^0_{\text{pi}}, \quad (5)$$

842 C_{bio} (Eq. 6) depends on carbonate dissolution and organic matter remineralization, taking account of the corrected
 843 C/O_2 ratio from Kortzinger et al. (2001):

$$844 \quad \text{C}_{\text{bio}} = 0.5 \Delta \text{A}_T - (\text{C}/\text{O}_2 + 0.5 \text{N}/\text{O}_2) \Delta \text{O}_2, \quad (6)$$

845 Where $C/O_2 = 106/138$ and $N/O_2 = 16/138$. ΔA_T and ΔO_2 are the difference between the measured values (A_T and
846 O_2) and the preformed values (A_T^0 and O_2^0). A_T^0 (Eq. 7) has been computed by Lo Monaco et al. (2005a) as a
847 function of Θ , S and the conservative tracer PO :

$$848 A_T^0 = 0.0685PO + 59.79S - 1.45\theta + 217.1, \quad (7)$$

849 PO (Eq. 8) has been defined by Broecker (1974) and depends on the equilibrium of O_2 with phosphate (PO_4). When
850 PO_4 data are not available, nitrate (NO_3) can be used instead as follows (the N/P ratio of 16 is from Anderson and
851 Sarmiento, 1994):

$$852 PO = O_2 + 170PO_4 = O_2 + (170/16)NO_3, \quad (8)$$

853 To determine O_2^0 , it is assumed that the surface water is in full equilibrium with the atmosphere ($O_2^0 = O_{2,sat}$; Benson
854 and Krause, 1980) and that after subduction O_2 in a given water mass is only impacted by the biological activity
855 (Weiss, 1970). A correction of O_2^0 has been proposed by Lo Monaco et al. (2005a) to take account of the
856 undersaturation of O_2 due to sea-ice cover at high latitudes. O_2^0 is, therefore, corrected by assuming a mean mixing
857 ratio of the ice-covered surface waters $k=50\%$ (Lo Monaco et al., 2005a), and a mean value for O_2 undersaturation
858 in ice-covered surface waters $\alpha = 12\%$ (Anderson et al., 1991) according to Eq. 9:

$$859 \Delta O_2 = (1 - \alpha k)O_{2,sat} - O_2 = AOU, \quad (9)$$

860 C^0_{PI} in equation 5 is a function of the current preformed C_T (C^0_{obs}) and a reference water term (Eq. 10):

$$861 C^0_{PI} = C^0_{obs} + [C_T - C_{bio} - C^0_{obs}]_{REF}, \quad (10)$$

862 $C_{0,obs}$ has been computed similarly as A_T^0 (Eq. 11):

$$863 C^0_{obs} = -0.0439PO + 42.79S - 12.02\theta + 739.8, \quad (11)$$

864 Where the reference water term is a constant for a given time of observation, corresponding to the time when C^0_{obs}
865 is parameterized. In this paper, we used the parameterization given by Lo Monaco et al., (2005a) and their
866 estimated value for the reference term of $51 \mu\text{mol}.\text{kg}^{-1}$. This number has been computed using an optimum
867 multiparametric (OMP) model to estimate the mixing ratio of the North Atlantic deep water in the SO (used as
868 reference water, i.e. old water mass where $C_{ant} = 0$). For more details about the C^0 method, which has a final error
869 of $\pm 6 \mu\text{mol}.\text{kg}^{-1}$, please see Lo Monaco et al. (2005a).

870 4 Results

871 The vertical distribution of hydrological and biogeochemical properties observed in deep and bottom waters and
872 their evolution over the last 40 years are displayed in Fig 2. The LCDW layer ($\gamma^n = 28.15\text{--}28.27 \text{ kg}.\text{m}^{-3}$) is
873 characterized by minimum O_2 concentrations (Fig. 2c), higher C_T (Fig. 2b) and lower C_{ant} concentrations than in
874 the AABW (Fig. 2a). C_{ant} concentrations were not significant in the LCDW until the end of the 1990s ($< 6 \mu\text{mol}.\text{kg}^{-1}$),
875 then our data show an increase in C_{ant} between the two 1998 reoccupations, followed by relatively constant C_{ant}
876 concentrations ($10 \pm 3 \mu\text{mol}.\text{kg}^{-1}$). In the LAABW ($\gamma^n > 28.35 \text{ kg}.\text{m}^{-3}$), well identified by low Θ , low S and high O_2 ,
877 C_{ant} concentrations are higher than in the overlying UAABW and LCDW (Fig. 2a). The evolutions of the mean
878 properties in the LAABW over 40 years are shown in Fig. 3. In this layer, C_{ant} concentrations increased from 5 ± 4
879 $\mu\text{mol}.\text{kg}^{-1}$ in 1978 and $7 \pm 4 \mu\text{mol}.\text{kg}^{-1}$ in the mid-1980s to $13 \pm 2 \mu\text{mol}.\text{kg}^{-1}$ at the end of the 1990s and up to 19 ± 2
880 $\mu\text{mol}.\text{kg}^{-1}$ in 2004 (Fig. 3a). Figure 3a also shows a very good agreement between the TrOCA method and the C^0
881 method for both the magnitude and variability of C_{ant} in the LAABW. Our results show a mean C_{ant} trend in the
882 LAABW of $+1.4 \mu\text{mol}.\text{kg}^{-1}.\text{decade}^{-1}$ over the full period and a maximum trend of the order of $+5.2 \mu\text{mol}.\text{kg}^{-1}$

883 $^1\text{.decade}^{-1}$ over 1987-2004 (Table 2). Due to the mixing of AABW with old CDW (C_{ant} free), these trends are lower
884 than the theoretical trend expected from the increase in atmospheric CO_2 . Indeed, assuming that the surface ocean
885 fCO_2 follows the atmospheric growth rate ($+1.8 \mu\text{atm}\text{.year}^{-1}$ over 1978-2018) in the seasonal ice zone (Roden et
886 al., 2016), the theoretical C_{ant} trend at the AABW formation sites would be of the order of $+8 \mu\text{mol}\text{.kg}^{-1}\text{.decade}^{-1}$
887 in the Antarctic surface water. This is close to the theoretical C_T trend estimated for freezing shelf water in the
888 Weddell Sea (van Heuven et al 2014). These trends are lower than the theoretical trend expected from the increase
889 in atmospheric CO_2 . Indeed, assuming that the surface ocean fCO_2 follows the atmospheric growth rate ($+1.8$
890 $\mu\text{atm}\text{.year}^{-1}$ over 1978-2018), the theoretical C_{ant} trend at the AABW formation sites would be of the order of $+8$
891 $\mu\text{mol}\text{.kg}^{-1}\text{.decade}^{-1}$. The observed slow C_{ant} trends can be partly explained by the transit time for AABW to reach
892 our study site and the mixing of AABWs with older LCDW that contain less C_{ant} over their transit (Fig. 2a).

893 Figure 2

894 Over the full period, C_T increased by $2.0 \pm 0.5 \mu\text{mol}\text{.kg}^{-1}\text{.decade}^{-1}$, mostly due to the accumulation of C_{ant} (Table
895 2). Our data also show a significant decrease in O_2 concentrations by $0.8 \pm 0.4 \mu\text{mol}\text{.kg}^{-1}\text{.decade}^{-1}$ over the 40-years
896 period (Fig. 3c, Table 2) that could be caused by reduced ventilation, as suggested by Schmidtko et al. (2017) who
897 observed significant O_2 loss in the global ocean. In the deep Indian SO sector, these authors found a trend
898 approaching $-1 \mu\text{mol}\text{.kg}^{-1}\text{.decade}^{-1}$ over 50 years (1960-2010), which is consistent with our data. We did not detect
899 any significant trend in A_T , Θ and S over the full period, but on shorter periods our data show a significant decrease
900 in A_T . The low A_T values observed over 2000-2004 (Fig. 3d) could suggest reduced calcification in the upper
901 ocean leading to less sinking of calcium carbonate tests and a decrease in A_T in deep and bottom waters over this
902 period (Fig. 2d). For this period the increase in C_T was lower than the accumulation of C_{ant} , but such feature is
903 disputable in view of the uncertainty on the C_{ant} calculation. This event is followed by an increase in the 'natural'
904 component of C_T (C_{nat} , calculated as the difference between C_T and C_{ant}) since 2004 associated to a decrease in O_2
905 and no increase in C_{ant} (Table 2). These trends were not associated with a significant trend in Θ or S (Fig. 3e,f,
906 Table 2). The increase in C_{nat} is thus unlikely originating from increased mixing with LCDW during bottom waters
907 transport, confirming that our LAABW definition exclude mixing with the LCDW. Enhanced organic matter
908 remineralization is also unlikely since NO_3 did not show any significant trend (Table 2).

909 Table 2

910 Figure 3

911 Importantly, our data show substantial interannual variations in LAABW properties, which could significantly
912 impact the trends estimated from limited reoccupations (e.g. Williams et al., 2015; Pardo et al., 2017; Murata et
913 al., 2019). For example, we found relatively higher C_{ant} concentrations in 1985 ($10 \mu\text{mol}\text{.kg}^{-1}$) compared to 1978
914 ($5 \mu\text{mol}\text{.kg}^{-1}$) and 1987 ($7 \mu\text{mol}\text{.kg}^{-1}$). This is linked to a signal of low S in 1985 (Fig. 3f) that could be due to a
915 larger contribution of fresher waters such as the WSDW or CDBW. This could also be related to the different
916 sampling locations. Over the last decade (2009-2018), our data show large and rapid changes in S that are partly
917 reflected on C_T and O_2 , and that could explain the relatively low C_{ant} concentrations observed over this period.
918 Indeed, the S maximum observed in 2012 (correlated to higher Θ) is associated with a marked C_T minimum
919 (surprisingly almost as low as in 1987), as well as low A_T (hence low C_{nat}), and low NO_3 concentrations. Since
920 these anomalies were associated with a decrease in C_{ant} concentrations, one may argue for an increased contribution
921 of bottom waters ventilated far away from our study site. A few years later our data show a S minimum (correlated
922 to lower Θ), associated with a rapid increase in C_T and a rapid decrease in O_2 between 2013 and 2016, suggesting

923 the contribution of a closer AABW type such as the CDBW. The freshening of $-0.006 \text{ decade}^{-1}$ in S between 2004
924 and 2018 that we observed on the western side of the Kerguelen Plateau was also observed on the eastern side of
925 the Plateau by Menezes et al. (2017) over a similar period. In this region, Menezes et al. (2017) evaluated a change
926 in S by about $-0.008 \text{ decade}^{-1}$ from 2007 to 2016 (against $-0.002 \text{ decade}^{-1}$ between 1994 and 2007), suggesting an
927 acceleration of the AABW freshening in recent years. However, they also reported a warming by $+0.06 \text{ }^{\circ}\text{C} \cdot \text{decade}^{-1}$,
928 while we observed cooler temperature in 2016-2018. This suggests that we sampled a different mixture of
929 AABW.
930

Figure 4

931 **5 Discussion**

932 **5.1 LAABW composition at OISO-ST11**

933 At each formation site, AABW~~s~~ experience~~sd~~ significant temporal property changes, mostly recognized at decadal
934 scale (e.g. freshening in the South Indian Ocean, Menezes et al., 2017) with potential impact on carbon uptake and
935 C_{ant} concentrations during AABW formation (Shadwick et al., 2013). The Θ-S diagram constructed from yearly
936 averaged data in bottom waters (Fig. 4) shows that the LAABW at OISO-ST11 is a complex mixture of WSDW,
937 CDBW, RSBW and ALBW. The coldest type of LAABW was observed at the GEOSECS station at 60° S (-0.56
938 °C), while the warmer type of LAABW observed at the INDIGO-1 station at 53° S (-0.44 °C). These extreme Θ
939 values could be a natural feature or may be related to specific sampling. For the other cruises, Θ in LAABW ranges
940 from -0.51 to -0.45 °C with no clear indication on the specific AABW origin. The S range observed in the bottom
941 waters at OISO-ST11 (34.65-34.67) illustrates either changes in mixing with various AABW sources or temporal
942 variations at the formation site. Given the knowledge of deep and bottom waters circulation and characteristics
943 (Fig. 1 and 4) and the significant C_{ant} concentrations that we calculated in the LAABW (Fig. 3a), the main
944 contribution at our location is likely the younger and colder CDBW for which relatively high C_{ant} concentrations
945 have been recently documented (Roden et al., 2016). From its formation region, the CDBW can either flow
946 westward with the CAC or flow northward in the Enderby Basin (Ohshima et al., 2013, Fig. 1). In the CAC branch,
947 the CDBW mixes with the LCDW along the Antarctic shelf and the continental slope between 80° E and 30° E
948 (Meijers et al., 2010; Roden et al., 2016). On the western side of the Kerguelen Plateau, CDBW also mixes with
949 RSBW and ALBW (Orsi et al., 1999; Van Wijk and Rintoul, 2014). In this context, the C_{ant} concentrations
950 observed in the bottom layer at OISO-ST11 are probably not linked to one single AABW source, but are likely a
951 complex interplay of AABW~~s~~ from different sources with different biogeochemical properties.

952 **5.2 C_{ant} concentrations**

953 In order to compare our C_{ant} estimates with other studies, we separated the 40-years time-series into 3 periods: the
954 first period (1978-1987) corresponds to historical data when C_{ant} is expected to be low; the second period (1998-
955 2004) starts when the first OISO cruise was conducted (and using CRMs for A_T and C_T measurements) and ~~lasts~~
956 ~~ends~~ when C_{ant} concentrations in the LAABW are maximum (Fig. 3a); the third period consists in the observations
957 performed in late 2009 to 2018 when the observed variations are relatively large for S and small for C_{ant}. The mean
958 C_{ant} concentrations for each period are 7, 14 and 13 $\mu\text{mol} \cdot \text{kg}^{-1}$, respectively, which is consistent with the results
959 from other studies (Table 3). The C_{ant} values for 1978-1987 can hardly be compared to other studies because very

960 few observations were conducted in the 1980s in the SO Indian sector of the SO (Sabine et al., 1999) and because
961 of potential biases for historical data despite their careful qualification-quality control in GLODAP and CARINA
962 (Key et al., 2004; Lo Monaco et al., 2010; Olsen et al., 2016). In addition, the different methods used to estimate
963 C_{ant} can lead to different results, especially in deep and bottom waters of the SO (Vázquez-Rodríguez et al., 2009).
964 Overall, Table 3 confirms that C_{ant} concentrations were low in the 1970s and 1980s, and reached values of the
965 order of $10 \mu\text{mol}.\text{kg}^{-1}$ in the 1990s, a signal not clearly captured in global data-based estimates (Gruber, 1998;
966 Sabine et al., 2004; Waugh et al., 2006; Khatiwala et al., 2013).
967 The observations presented in this analysis, although regional, offer a complement to recent estimates of C_{ant}
968 changes evaluated between 1994 and 2007 in the top 3000 m for the global ocean (Gruber et al., 2019a). In the
969 Enderby Basin at the horizon 2000-3000 m, the accumulation of C_{ant} from 1994 to 2007 is not uniform and ranges
970 between 0 and $8 \mu\text{mol}.\text{kg}^{-1}$ (Gruber et al., 2019a). At our station, in the LCDW (2000-3000_m) the C_{ant}
971 concentrations were not significant in 1978-1987 (-2 to $5 \mu\text{mol}.\text{kg}^{-1}$) but increase to an average of $9 \pm 3 \mu\text{mol}.\text{kg}^{-1}$
972 in 1998-2018 (Fig. 2a), probably due to mixing with AABW~~s~~ that contain more C_{ant} . Interestingly, this value is
973 close but in the high range of the C_{ant} accumulation estimated from 1994 to 2007 in deep waters of the south Indian
974 Ocean (Gruber et al., 2019a).
975 Not surprisingly, high C_{ant} concentrations are detected in the AABW formation regions (Table 3). The highest C_{ant}
976 concentrations in bottom waters (up to $30 \mu\text{mol}.\text{kg}^{-1}$) were observed in the ventilated shelf waters in the Ross Sea
977 (Sandrini et al., 2007). In the Adélie and Mertz Polynya regions, Shadwick et al. (2014) observed high C_{ant}
978 concentrations in the subsurface shelf waters (40 - $44 \mu\text{mol}.\text{kg}^{-1}$) but lower values in the ALBW ($15 \mu\text{mol}.\text{kg}^{-1}$) due
979 to mixing with older LCDW. In WSBW, all C_{ant} concentrations estimated from observations between 1996 and
980 2005 and with the TrOCA method (Table 3) lead to about the same values ranging between 13 and $16 \mu\text{mol}.\text{kg}^{-1}$
981 (Lo Monaco et al., 2005b; van Heuven et al., 2011). In bottom waters formed near the Cape Darnley (CDBW),
982 Roden et al. (2016) estimated high C_{ant} concentrations in bottom waters ($25 \mu\text{mol}.\text{kg}^{-1}$) resulting from the shelf
983 waters that contain very high amounts of C_{ant} ($50 \mu\text{mol}.\text{kg}^{-1}$). The comparison with other studies confirms that far
984 from the AABW formation sites, contemporary C_{ant} concentrations are not exceeding $16 \mu\text{mol}.\text{kg}^{-1}$ on average.
985 Table 3.

986 5.3 C_{ant} trends and variability

987 Comparison of long-term C_{ant} trends in deep and bottom waters of the SO is limited to very few regions where
988 repeated observations are available. To our knowledge, only 3 other studies evaluated the long-term C_{ant} trends in
989 the SO based on more than 5 reoccupations: in the South-western Atlantic (Rios et al., 2012) and in the Weddell
990 Gyre along the Prime meridian section (van Heuven et al., 2011, 2014). Temporal changes of C_T and C_{ant} have
991 also been investigated in other SO regions, but limited to 2 to 4 reoccupations (Williams et al., 2015; Pardo et al.,
992 2017; Murata et al., 2019). Given the C_{ant} variability depicted at our location (Fig. 3a), different trends can be
993 deduced from limited reoccupations. As an example, Murata et al., (2019) evaluated the change in C_{ant} from data
994 collected 17 years apart (1994–1996 and 2012–2013) along a transect around 62° S and found a small increase at
995 our location ($< 5 \mu\text{mol}.\text{kg}^{-1}$ around 60° E). This result appears very sensitive to the time of the observation given
996 that we found a minimum in C_{ant} concentrations between 2011 and 2014 (Fig. 3a) associated with a marked C_T
997 minimum (Fig. 3b). In addition, our results show that the detection of C_{ant} trends appears very sensitive to the time
998 period considered (Table 2). As an extreme case, the C_{ant} trend calculated for the period 1987-2004 is $+5.2 \mu\text{mol}.\text{kg}^{-1}$

999 decade^{-1} (relatively close to the theoretical C_{ant} trend of $+8 \mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$), but it reverses to $-3.5 \mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$ for the period 2004-2018.
1000
1001 The long-term C_T trend that we estimated in the LAABW in the eastern Enderby Basin ($2.0 \pm 0.5 \mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$) is slightly faster than the C_T trends estimated in the WSBW in the Weddell Gyre: $+1.2 \pm 0.5 \mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$ over the period 1973-2011 and $+1.6 \pm 1.4 \mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$ when restricted to 1996-2011 (van Heuven et al., 2014). Along the SR03 line (south of Tasmania) reoccupied in 1995, 2001, 2008 and 2011, Pardo et al. (2017) calculated a C_T trend of $+2.4 \pm 0.2 \mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$ in the AABW, composed of ALBW and RSBW in this sector. This is higher than the C_T trends found at our location and in the Weddell Gyre, but surprisingly, this was not associated with a significant increase in C_{ant} . The C_T trend in AABW along the SR03 section was likely due to the intrusion of old and C_T -rich waters also revealed by an increase in Si concentrations during 1995-2011 (Pardo et al., 2017). This is a clear example of decoupling between C_T and C_{ant} trends in deep and bottom waters as observed at our location in the last decade (Table 2). For C_{ant} , our 40-years trend estimate ($1.4 \pm 0.5 \mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$) appears close to the trend reported by Rios et al. (2012) in the south-western Atlantic AABW from 6 reoccupations between 1972 and 2003 ($+1.5 \mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$). However, if we limit our result to the period 1978-2002 or 1978-2004 (about the same period as in Rios et al., 2012), our trend is much larger ($+3-4 \mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$).
1010 At our location, the C_{ant} trend over 40 years ($+1.4 \pm 0.5 \mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$) explains most of the observed C_T increase ($+2.0 \pm 0.5 \mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$). The residual of $+0.4 \mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$ reflects changes in natural processes affecting the carbon content (different AABW sources, ventilation, mixing with deep waters, remineralization or carbonates dissolution). Although this is a weak signal, the natural C_T change (C_{nat}) mirrors the observed decrease in O_2 by $-0.8 \pm 0.4 \mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$. This O_2 decrease detected in the Enderby Basin appears to be a real feature that was documented at large scale for 1960-2010 in deep SO basins (Schmidtko et al., 2017), suggesting that the changes observed at 56.5°S/63°E/56.5°S are related to large-scale processes, possibly due to a decrease in AABW formation (Purkey and Johnson, 2012).
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1022 5.4 Recent C_{ant} stability

1023 Although most studies suggest a gradual accumulation of C_{ant} in the AABW, our time-series highlights significant
1024 multi-annual changes, in particular over the last decade when C_{ant} concentrations were as low as around the year
1025 2000 (Fig. 3a) and decoupled from the increase in C_T (Fig. 3b). This result is difficult to interpret because at our
1026 location, away from AABW sources (Fig. 1), the temporal variability observed in the LAABW layer can result
1027 from many remote processes occurring at the AABW formation sites (such as wind forcing, ventilation, sea-ice
1028 melting, thermodynamic, biological activity and air-sea exchanges). Additionally, internal processes during the
1029 transport of AABW~~s~~ (such as organic matter remineralization, carbonate dissolution and mixing with surrounding
1030 waters) must also be taken into account. The apparent steady C_{ant} feature suggests that AABW~~s~~ found at our
1031 location has stored less C_{ant} in recent years. This might be linked to reduced CO_2 uptake in the AABW formation
1032 regions, as recognized at large-scale in the SO from the late 1980s to 2001 (Le Quéré et al., 2007; Metzl, 2009;
1033 Lenton et al., 2012; Landschützer et al., 2015). This large-scale response in the SO during a positive trend in the
1034 Southern Annular Mode (SAM) is mainly associated to stronger winds driven by accelerating greenhouse gas
1035 emissions and stratospheric ozone depletion, leading to warming and freshening in the SO (Swart et al., 2018),
1036 change in the ventilation of the C_T -rich deep waters and reduced CO_2 uptake (Lenton et al., 2009). The
1037 reconstructed pCO_2 fields by Landschützer et al. (2015) suggest that the reduced CO_2 sink in the 1990s is identified

1038 at high latitudes in the SO (see Fig. 2a and S9 in Landschützer et al., 2015). However, as opposed to the circumpolar
1039 open ocean zone (e.g. Metzl, 2009; Takahashi et al., 2009, 2012; Munro et al., 2015; Fay et al., 2018), the long-
1040 term trend of surface $f\text{CO}_2$ and carbon uptake deduced from direct observations are not clearly identified in the
1041 seasonal ice zone (SIZ) and shelves around Antarctica, and thus in the AABW formation regions of interest to
1042 interpret our results (Laruelle et al., 2018). There, surface $f\text{CO}_2$ data are sparse, especially before 1990, and cruises
1043 were mainly conducted in austral summer when the spatio-temporal $f\text{CO}_2$ variability is very large and driven by
1044 multiple processes at regional or small scales, such as primary production, sea-ice formation and retreat, and water
1045 circulation and mixing. This leads to various estimates of the air-sea CO_2 fluxes around Antarctica depending on
1046 the region and period and large uncertainty when attempting to detect long-term trends (Gregor et al., 2018).
1047 In particular, in polynyas and AABW formation regions where $f\text{CO}_2$ is low and where katabatic winds prevail,
1048 very strong instantaneous CO_2 sink can occur at the local scale (up to $-250 \text{ mmol C.m}^{-2}.\text{d}^{-1}$ in Terra Nova Bay in
1049 the Ross Sea according to De Jong and Dunbar, 2017). In the Prydz Bay region where CDBW is formed, recent
1050 studies show that surface $f\text{CO}_2$ in austral summer vary over a very large range ($150\text{--}450 \mu\text{atm}$), with the lowest
1051 $f\text{CO}_2$ observed in the shelf region generating very strong local CO_2 sink ($-221 \text{ mmol C.m}^{-2}.\text{d}^{-1}$; Roden et al. 2016).
1052 The carbon uptake was particularly enhanced near Cape Darnley and coincided with the highest C_{ant} concentrations
1053 that Roden et al. (2016) estimated in the dense shelf waters that subduct to form AABW. In the Prydz Bay coastal
1054 region, surface $f\text{CO}_2$ values in 1993–1995 were as low as $100 \mu\text{atm}$ (Gibson and Trull, 1999) leading to a strong
1055 local CO_2 uptake of $-30 \text{ mmol C.m}^{-2}.\text{d}^{-1}$ in summer. In addition, Roden et al. (2013) found a large C_T increase over
1056 16 years ($+34 \mu\text{mol.kg}^{-1}$) in the Prydz Bay, which is much higher than the anthropogenic signal alone ($+12$
1057 $\mu\text{mol.kg}^{-1}$) and likely explained by changes in primary production that would have been stronger in 1994. To our
1058 knowledge, this is the only direct observation of decadal C_T change in surface waters in a region of AABW
1059 formation (here the Prydz Bay) and it highlights the difficulty not only to evaluate the C_T and C_{ant} long-term trends
1060 in these regions but also to separate natural and anthropogenic signals when this water reaches the deep ocean. We
1061 attempted to detect long-term changes in CO_2 uptake in this region using the qualified $f\text{CO}_2$ data available in the
1062 SOCAT database (Bakker et al., 2016), but our estimates (not shown) were highly uncertain due to very large
1063 spatial and temporal variability. To conclude, all previous studies conducted near or in AABW formation sites
1064 clearly reveal that these regions are potentially strong carbon sinks, but how the sink changed over the last decades
1065 is not yet evaluated, and thus we are not able to certify that the recent C_{ant} stability that we observed in the LAABW
1066 at our location is directly linked to the weakening of the carbon sink that was recognized at large-scale in the SO
1067 from the 1980s to mid-2000s (Le Quéré et al., 2007; Landschützer et al., 2015).
1068 Changes in the accumulation of C_{ant} in AABW could also be directly related to changes in physical processes
1069 occurring in AABW formation regions. Decadal decreasing of sea-ice production and melting of sea-ice have been
1070 documented in several regions including Cape Darnley polynyas (Tamura et al., 2016; Williams et al., 2016). The
1071 consequent changes in Antarctic surface waters properties are transmitted into the deep ocean, notably the well-
1072 recognized freshening of [the AABW over the last decades](#) (Rintoul, 2007; Rintoul, 2007; Anilkumar et al., 2015).
1073 The warming of bottom waters was also documented in the Enderby basin (Couldey et al., 2013) as well as at a
1074 larger scale in all deep SO basins (Purkey and Johnson, 2010; Desbruyères et al., 2016). Associated to a decrease
1075 in AABW formation in the 1990s (Purkey and Johnson, 2012), these physical changes could explain the recent
1076 stability of C_{ant} concentrations in AABW observed at our location. As AABW from different sources spread and
1077 mix with C_T -rich deep waters before reaching our location (Fig. 1), less AABW formation and export would result

1078 in an increase in C_T (increase in C_{nat}) not associated with an increase in C_{ant} , and a decrease in O_2 (as observed in
1079 recent years in Fig. 3a,b,c). Finally, it is also possible that the LAABW observed in recent years at our location is
1080 the result of a larger contribution of older RSBW, ALBW or even WSBW that have lower C_{ant} and O_2
1081 concentrations compared to CDBW formed at Cape Darnley and Prydz Bay.

1082 **6 Conclusion**

1083 The distribution and evolution of C_{ant} in the bottom layer of the SO are related to complex interactions between
1084 climatic forcing, air-sea CO_2 exchange at formation sites, as well as biological and physical processes during
1085 AABW_s circulation. The dataset that we collected regularly in the Enderby basin over the last 20 years (1998-
1086 2018) in the frame of the OISO project, together with historical observations obtained in 1978, 1985 and 1987
1087 (GEOSECS and INDIGO cruises), allows the investigation of C_{ant} changes in AABW over 40 years in this region.
1088 The focus on the AABW variability is made by defining a Lower_{er} Antarctic Bottom Water (LAABW) as described
1089 in the Section 2.3. Our results suggest that the accumulation of C_{ant} explains most, but not all, of the observed
1090 increase in C_T . We also detected a decrease in O_2 that is consistent with the large-scale signal reported by
1091 Schmidtko et al. (2017), possibly due to a decrease in AABW_s formation (Purkey and Johnson, 2012). Our data
1092 further indicate rapid anomalies in some periods suggesting that for decadal to long-term estimates care have to
1093 be taken when analyzing the change in C_{ant} from data sets collected 10 or 20 years apart (e.g. Williams et al., 2015;
1094 Murata et al., 2019). Our results also show different C_{ant} trends on short periods, with a maximum increase of 6.5
1095 $\mu\text{mol}\cdot\text{kg}^{-1}\cdot\text{decade}^{-1}$ between 1987 and 2004 and an apparent stability in the last 20 years (despite an increase in
1096 C_T). This suggests that AABW_s have stored less C_{ant} in the last decade, but our understanding of the processes that
1097 explain this signal is not clear. This might be the result of the reduced CO_2 uptake in the SO in the 1990s (Le Quéré
1098 et al., 2007; Landschützer et al., 2015), but this is not yet verified from direct C_T or fCO_2 observations in AABW
1099 formation regions due to the lack of winter data and very large variability during summer. This calls for more data
1100 collection and investigations in these regions. The apparent stability of C_{ant} in the LAABW since 1998 could also
1101 be directly linked to a decrease in AABW_s formation in the 1990s (Purkey and Johnson, 2012) or a change in the
1102 contributions of AABW_s from different sources, especially in the Prydz Bay region (Williams et al., 2016). In
1103 these scenarios, an increased contribution of C_T -rich and O_2 -poor older LCDW along AABW_s transit would also
1104 explain the decoupling between C_{ant} and C_T (increase in C_{nat}) and decrease in O_2 concentrations observed in recent
1105 years, even if we tried to isolate this specific feature in our data selection. The decoupling between C_{ant} and C_T is
1106 not a unique feature, as it was also reported along the SR03 section between Tasmania and Antarctica, most
1107 probably due to advection of C_T -rich waters (Pardo et al., 2017). This highlights the importance of the ocean
1108 circulation in influencing the temporal C_T and C_{ant} inventories changes (De Vries et al., 2017) and the need to
1109 better separate anthropogenic and natural variability based on time-series observations.
1110 The evaluation and understanding of decadal C_{ant} changes in deep and bottom ocean waters are still challenging,
1111 as the C_{ant} concentrations remain low compared to C_T measurements accuracy (at best $\pm 2 \mu\text{mol}\cdot\text{kg}^{-1}$, Bockmon and
1112 Dickson, 2015) and uncertainties of data-based methods ($\pm 6 \mu\text{mol}\cdot\text{kg}^{-1}$). Long-term repeated and qualified
1113 observations (at least 30 years) are needed to accurately detect and separate the anthropogenic signal from the
1114 internal ocean variability; we thus only start to document these trends that should now help to identify
1115 shortcomings in models regarding the carbon storage in the deep SO (e.g. Frölicher et al., 2014). As changes in

1116 the SO (including warming, freshening, oxygenation/deoxygenation, CO₂ and acidification) are expected to
1117 accelerate in the future in response to anthropogenic forcing and climate change (e.g. Heuzé et al., 2014; Hauck et
1118 al., 2015; Ito et al., 2015, Yamamoto et al., 2015), it is important to maintain time-series observations to
1119 complement the GO-SHIP strategy, and to occupy more regularly other sectors of the SO (Rintoul et al., 2012). In
1120 this context, we hope to maintain our observations in the Southern Indian Ocean in the next decade, and with
1121 ongoing synthetic products activities such as GLODAPv2 (Olsen et al., 2016, 2019), SOCAT (Bakker et al., 2016)
1122 and more recently the SOCCOM project (Williams et al., 2018), to offer a solid database to validate ocean
1123 biogeochemical models and coupled climate/carbon models (Russell et al. 2018), and ultimately reduce
1124 uncertainties in future climate projections.

1125 **Data availability**

1126 GEOSECS, INDIGO and OISO 1998-2011 data are publicly available at the Ocean Carbon Data System (OCADS;
1127 https://www.nodc.noaa.gov/ocads/oceans/GLODAPv2_2019). OISO original data are available at:
1128 https://www.nodc.noaa.gov/ocads/oceans/RepeatSections/clivar_oso.html. OISO 2012-2018 will be available in
1129 GLODAPv2-2021.

1130 **Author contributions**

1131 LM, CLM, NM, JF and CM performed the sampling and carried out the measurements of the OISO data. LM
1132 prepared the manuscript with contributions from CLM and NM.

1133 **Competing interests**

1134 The authors declare that they have no conflict of interest.

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Table 1. List of the cruises used in this study.

Cruise	Station	Location	Year	Month
GEOSECS	430	61.0°E / 60.0°S	1978	February
INDIGO-1	14	58.9°E / 53.0°S	1985	March
INDIGO-3	75	63.2°E / 56.5°S	1987	January
OISO-01	11	63.0°E / 56.5°S	1998	February
OISO-03	11	63.0°E / 56.5°S	1998	December
OISO-05	11	63.0°E / 56.5°S	2000	August
OISO-06	11	63.0°E / 56.5°S	2001	January
OISO-08	11	63.0°E / 56.5°S	2002	January
OISO-11	11	63.0°E / 56.5°S	2004	January
OISO-18	11	63.0°E / 56.5°S	2009	December
OISO-19	11	63.0°E / 56.5°S	2011	January
OISO-21	11	63.0°E / 56.5°S	2012	February
OISO-23	11	63.0°E / 56.5°S	2014	January
OISO-26	11	63.0°E / 56.5°S	2016	October
OISO-27	11	63.0°E / 56.5°S	2017	January
OISO-28	11	63.0°E / 56.5°S	2018	January

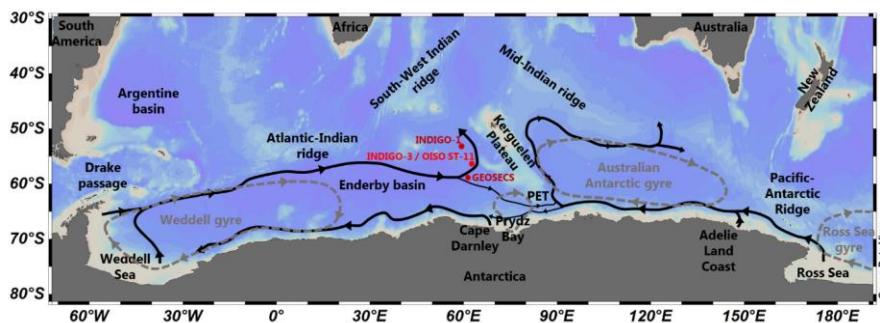
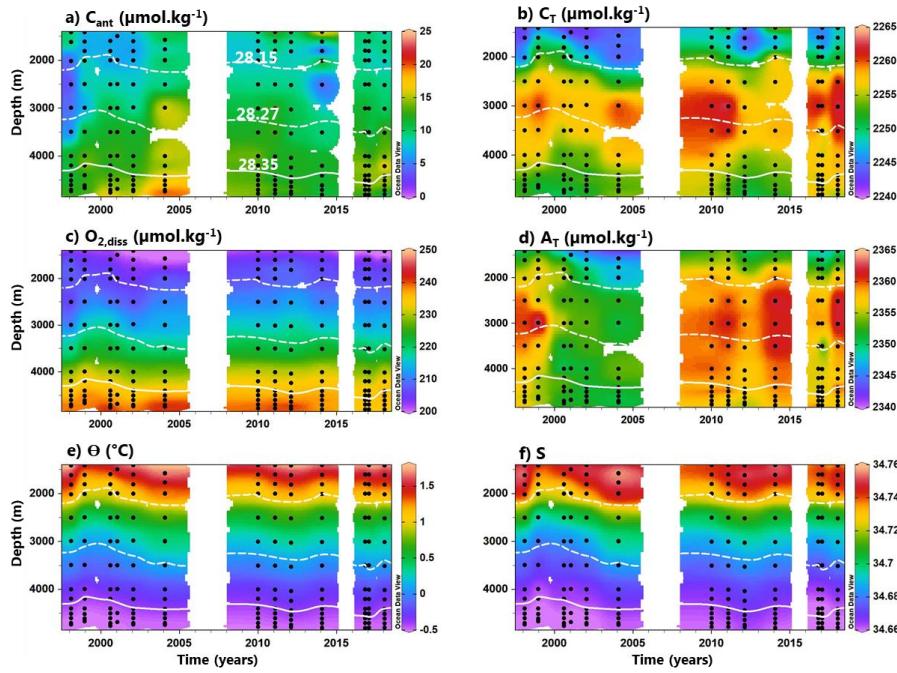


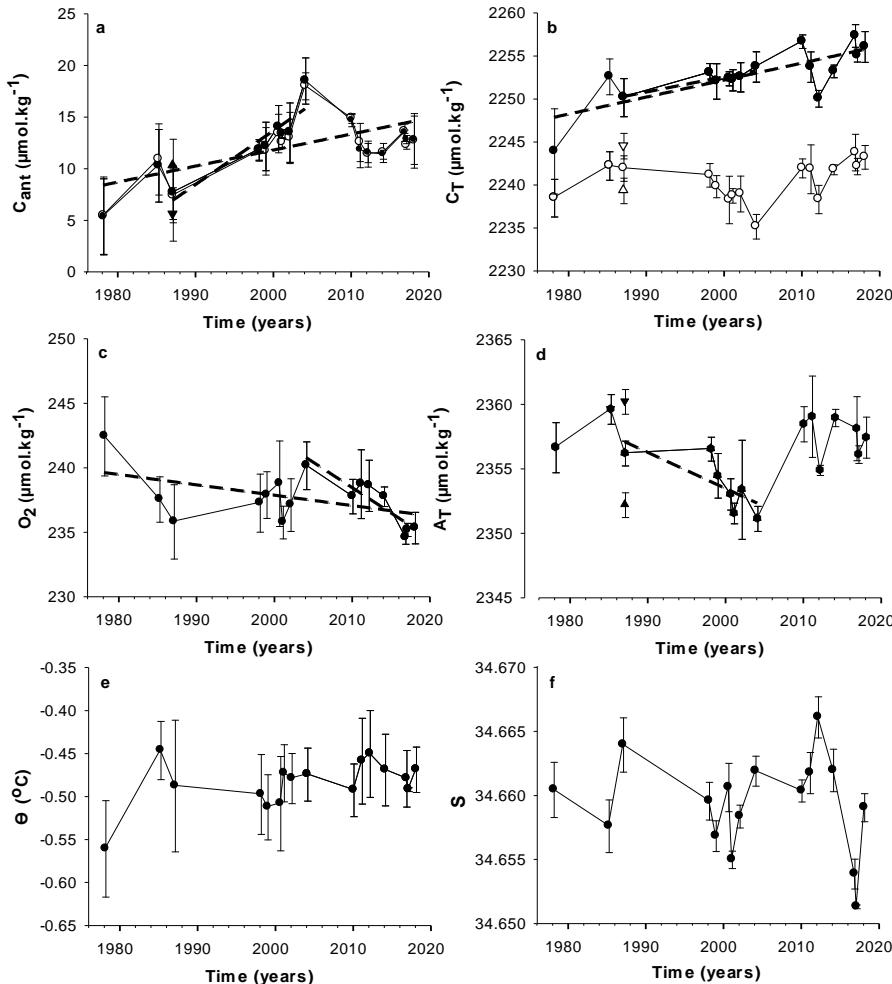
Figure 1. The AABWs circulation **rough transport paths** from the literature (Fukamachi et al., 2010; Orsi et al., 1999; Carter et al., 2008; Fukamachi et al., 2010; Williams et al., 2010; Vernet et al., 2019) and this study, with geographic indications (black text), **main SO currents-gyres** (blue-dark yellow text and dash lines for the approximative **boundaries****locations**) and stations considered in this study (red text and dots). PET: Princess Elizabeth Trough. Figure produced with ODV (Schlitzer et al., 2019).



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Figure 2. Hovmöller [section-diagram](#) of (a) C_{ant} via TrOCA, (b) C_T , (c) O_2 , (d) A_T , (e) θ and (f) S based on the OISO data presented in Table 1. Data points are represented by black dots. The white isolines represent the water masses separation by γ^n (from the bottom: LAABW, UAABW and LCDW). Figure produced with ODV (Schlitzer et al., 2019).

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Figure 3. Interannual variability (dash lines lines) and significant trends (at 95 %, see Table 2; dotted lines) for the 40
years of observation of the OISO-ST11 LAABW properties, including (a) C_{ant} by the TrOCA (black circles and
triangles) and the C^0 (open circles) method, (b) C_T (black circles) and C_{nat} (open circles), (c) O_2 , (d) A_T , (e) Θ and (f) S .
For (a) C_{ant} , (b) C_{nat} and (d) A_T , the triangles pointing down and up correspond to INDIGO-3 value without and with
- 8 $\mu\text{mol.kg}^{-1}$ of correction on the A_T , respectively (see Supp. Mat. for more details).

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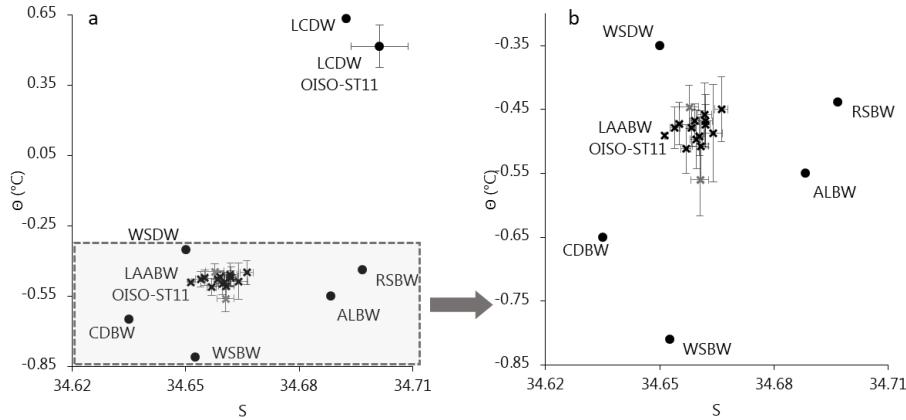
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1559 **Table 2: Trends (per decade) of observed and calculated properties in the LAABW estimated over different periods (in
1560 bold: significant trends at 95 % confidence level).**

Period	S	Θ °C	Si $\mu\text{mol.kg}^{-1}$	NO_3 $\mu\text{mol.kg}^{-1}$	O_2 $\mu\text{mol.kg}^{-1}$	At $\mu\text{mol.kg}^{-1}$	C_tr $\mu\text{mol.kg}^{-1}$	C_am TrOCA $\mu\text{mol.kg}^{-1}$
1978-2018	-0.001 \pm 0.001	0.01 \pm 0.01	-1.2 \pm 0.9	0.2 \pm 0.2	-0.8 \pm 0.4	-0.1 \pm 0.1	2.0 \pm 0.5	1.4 \pm 0.5
1987-2018	-0.001 \pm 0.001	0.01 \pm 0.01	-1.9 \pm 1.4	0.3 \pm 0.4	-0.3 \pm 0.5	0.6 \pm 0.1	1.6 \pm 0.5	1.1 \pm 0.8
1987-2004	-0.003 \pm 0.002	0.01 \pm 0.01	-6.5 \pm 1.8	0.9 \pm 0.9	1.7 \pm 1.0	-1.9 \pm 1.1	1.8 \pm 0.4	5.2 \pm 1.1
2004-2018	-0.006 \pm 0.003	0.01 \pm 0.01	-1.8 \pm 4.5	-0.5 \pm 1.0	-3.9 \pm 0.7	3.4 \pm 0.2	1.7 \pm 1.9	-3.5 \pm 1.5

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1563 **Figure 4. (a) Full Θ -S diagram of studied water masses and (b) zoomed on bottom waters. Values are from literature
1564 for the WSBW (Fukamachi et al., 2010; van Heuven, 2013; Pardo et al., 2014; Robertson et al., 2002), the WSDW
1565 (Carmack and Foster, 1975; Fahrbach et al., 1994; van Heuven, 2013; Robertson et al., 2002), the RSBW (Fukamachi
1566 et al., 2010; Gordon et al., 2015; Johnson, 2008; Pardo et al., 2014), the ALBW (Fukamachi et al., 2010; Johnson, 2008;
1567 Pardo et al., 2014), the CDBW (Ohshima et al., 2013) and the LCDW (Lo Monaco et al., 2005a; Pardo et al., 2014; Smith
1568 and Treguer, 1994), and from the OISO-ST11 dataset for the OISO-ST11 LAABW and OISO-ST11 LCDW. Error bars
1569 are calculated from the individual annual averaged values for the OISO-ST11 LAABW and from all data for the OISO-
1570 ST11 LCDW. For the OISO-ST11 LAABW, the grey cross are the GEOSECS (lowest Θ) and INDIGO-1 (highest Θ)
1571 values.**

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Table 3. Compilation of C_{ant} sequestration investigations in the AABW_s ($\gamma^n \geq 28.25 \text{ kg.m}^{-3}$) using the TrOCA method. The C_{ant} estimation of Pardo et al. (2014) is calculated using theoretical AABW mean composition (with 3% of ALBW) and the carbon data from the GLODAPv1 and CARINA databases. Sandrin et al. (2007) values has been measured at the bottom in the Ross Sea and correspond to recently sink high salinity shelfface water (**HSSW**). The mean values published by Roden et al. (2016) for the AABW_s present WSDW characteristics but can be a mix of CDBW and LCDW.

Source	Location	Water masses considered	Year	C _{ant} μmol.kg ⁻¹
Pardo et al. (2014) Fig. 5	Averaged AABW composition	WSBW-RSBW-ALBW	1994	12
Lo Monaco et al. (2005b) Fig. 4b	WOCE line 16 (30° E; 50°-70° S)	WSBW CDBW	1996	15 20
Sandrini et al. (2007) Fig. 4a	Ross Sea	HSSW (previous RSBW)	2002/2003	Max. of 30
Shadwick et al. (2014) Table 2	Mertz polynya and Adelie depression	ALBW	2007/2008	15
Roden et al. (2016) Table 2	South Indian ocean (30°-80° E; 60°-69° S)	WSDW-LCDW- CDBW	2006	25
van Heuven et al. (2011) Fig.13	Weddell gyre (0° E; 55°-71°S)	WSBW	2005	16
				1978-1987
				8 ± 3
				1987-1998
				10 ± 4
This study	Enderby basin (56.5° S/63° E)	<u>LAABW</u> <u>(mix of</u> WSDW- CDBW-RSBW- <u>ALBW</u>)	1987-2004	13 ± 4
			1998-2004	14 ± 2
			2010-2018	13 ± 1
			1978-2018	12 ± 3

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