Leseurre, C., Lo Monaco, C., Reverdin, G., Metzl, N., Fin, J., Mignon, C., and Benito, L.: Trends and drivers of sea surface fCO_2 and pH changes observed in the Southern Indian Ocean over the last two decades (1998–2019), Biogeosciences Discuss. [preprint], https://doi.org/10.5194/bg-2022-22, in review, 2022.

Review 2 (anonymous):

Leseurre et al. use a 20-year observational data set to interrogate trends in seawater fCO2 and pH in three zones of the Southern Indian Ocean. They find a range of rates of change due to different processes in each of the zones. This study offers a unique data analysis in a data-poor region important to ocean CO2 uptake. Given the variety of observations made, this study also allows for valuable comparisons of different approaches to estimating carbon chemistry and Cant.

We thank reviewer 2 for her/his review, comments and questions that will be considered when revising the manuscript. Below we list our responses before preparing a revised manuscript.

Major comment:

Data grouping and analysis methodology – The methods of determining and applying data groupings need to be explained in more detail. How were the size/shape of the boxes in Figure 2 determined? It's not clear whether this was a practical decision based on the density of data or whether the boxes map to the science questions for each of the three domains. What is the difference between the red and yellow boxes/lines? Do the boxes only refer to data grouping for the surface underway data, or are underway data also grouped with surface measurements from the discrete data at stations O6-O12 and A3? Are the trends presented in Table 2 for stations O6-O12 and A3 just trends for the near surface measurements, or do those trends also include subsurface water column data? Or all measurements in the mixed layer as alluded to in the results? If so, what are average summer mixed layer depths in these domains? All this needs to be clarified in the methods.

Response: Thank you for pointing out these problems (as did reviewer 1). We understand your difficulty to understand each of the data used and grouped. To resume:

Our study area is separated into 2 regions: south of the polar front, in the permanent open ocean zone (POOZ), and north of the polar front in the polar front zone (PFZ). In each region we distinguish high nutrient and low chlorophyll waters (HNLC) from fertilized waters (bloom). As our initial work was centered on stations (because of information on winter layer), we were interested to find how representative the stations were of the surrounding area. To do this, we again divided our study areas:

- PFZ HNLC (Station O7, O8, O9)
- PFZ bloom Crozet (Station O6)

- PFZ bloom Kerguelen (Station O12)
- POOZ bloom Kerguelen (Station A3)
- POOZ north HNLC (Station O10)
- POOZ south HNLC (Station O11)

We chose to separate the HNLC part of the POOZ in two parts because theses 2 stations are very distant. In addition, station O10 (bottom 1650m) was occupied more often than station O11 in open ocean (bottom 4850m).

Thus, we end up with six areas which characteristics are listed in Table 1 and 2. This is also what is illustrated by the red "boxes" in Figure 2 (we will come back to this figure in more details for the technical comments).

Altogether, we used three different datasets:

- Data in the mixed layer for the 8 stations (OISO only),
- Data from underway AT and CT measurements (OISO only),
- Data from underway fCO2 measurements (from SOCAT, mostly OISO).

For the last two, we grouped and averaged data in small homogeneous boxes (for physical and biogeochemical parameters) which are presented in Figure 4. These small boxes correspond to the yellow "boxes" on Figure 2 (you are right, this was very confusing…).

The yellow boxes (represented by yellow borders) are supposed to represent each grouping by latitude and longitude done to construct Figure 4. We agree with the reviewer, that on Figure 2 this is not at all clear. What was done is that initially we constructed boxes of 1° of latitude and 2° of longitude (where T, S, A_T, C_T, or fCO_2 are homogeneous). Secondly, we enlarged these boxes when the stations were in a corner of the boxes, or when the longitudinal surrounding boxes were homogeneous between them, to form one large box. You can see on Figure RC2-1 what the yellow boxes are supposed to be (without the red boxes on top).

The red boxes correspond to the six areas presented above and to estimate the underway trends presented in Table 1. Again, we agree that this is not legible in Figure 2. You can see on Figure RC2-2 what the red boxes are supposed to be (without the yellow borders).

We tried to separate the yellow and red boxes in Figure 2 in order to show in which boxes the different trends were estimated (for Figure 4 or Table 1). But we agree that this is not clear and adds confusion. Instead, we decided for the new Figure 2 to present the Figure RC2-2.

The trends presented in Table 2 concern only the station dataset. A comparison is made between trends from summer mixed layer data (Table 1, called ML in Table 2) and trends from data just below mixed layer (called BML in Table 2); and this for each of the eight stations studied. To evaluate the depth of the mixed-layer we carefully looked at profiles for each station and each period and identified the layer where properties are homogenous (including O_2, nutrients, A_T and C_T). For this analysis we prefer this "geochemical view" rather than a purely physical (temperature or density criteria derived from CTD-1db profiles) which is sometimes difficult to interpret in the Southern Ocean (e.g. Park et al, 1998). We agree with you to add a paragraph on the average depth of the summer mixed layer for each of these stations.

The section 2 will be revised as:

2 Material and methods

2.1 Study area

[…]

Figure 1.

"To investigate the long-term fCO_2 and pH trends we thus separate the domain in 6 main sectors (Fig. 2): (i) HNLC waters in the Polar Front Zone (PFZ) between the SAF and the PF, (ii) part north and (iii) part south of HNLC waters south of the PF in the Permanent Open Ocean Zone (POOZ), and the phytoplanktonic bloom regions associated with (iv) the Crozet shelf, (v) the north and (vi) the south of Kerguelen shelf."

"The HNLC waters in the POOZ have been divided into northern and southern parts because the two stations in this region are very distant (O10: 50.6°S and O11: 56.6°S; Fig. 1). Station O10 is at the edge of the continental shelf of Kerguelen (bottom 1650m) and was occupied more often than station O11 in the open ocean (bottom 4850m)."

2.3 Data selection

[…]

Figure 3.

"In order to estimate the trends from underway datasets, gridded values for each cruise were averaged in boxes of 1° of latitude and 2° of longitude. Some boxes were enlarged if the surrounding boxes were homogeneous both for physical and biogeochemical parameters. Then trends were estimated provides some conditions are fulfilled (as on Figure 4): the box must contain at least 8 cruises (years) and must have been visited at the beginning of the period, in at least one of the years 1998, 1999, 2000, as well at the end of the period, in at least, one of the years 2017, 2018, 2019. Finally, the boxes were grouped into six large regions (Figure 2). As we are interested in separating the anthropogenic signal from natural variability for both fCO_2 and pH trends, and because anthropogenic CO_2 concentrations are not well evaluated in surface waters, we also estimated the trends at each station selecting the data just below the summer mixed layer (a layer referred to as BML). South of the PF, this subsurface layer corresponds to the Winter Water well identified by a subsurface temperature minimum observed in summer at 150-200m (Fig. 3; Metzl et al., 2006; Mackay and Watson, 2021)."

"From the station dataset, the mixed layer was defined for each station and each year. To evaluate the depth of the mixed layer we carefully looked at profiles for each station and each period and identified the layer where properties are homogenous (including O_2, nutrients, A_T and C_T). On average the summer mixed layer depth over the period 1998-2019 is between 50m and 75m for the PFZ region (station O6, O7, O8, O9, O12) and between 75m and 100m for the POOZ region (station A3, O10, O11)."

Other comments:

Page 6 lines 18-19 – Please describe the typical frequency of the summer cruises.

Response: The program OISO carried out one summer cruise per year (usually between the beginning of January and the end of February; but sometimes the cruises starts in December or end in March, depending on the availability of the Marion Dufresne ship). We will go into more detail in the text:

"To investigate the fCO_2 and pH trends and their drivers over the period 1998-2019 we used the observations regularly conducted during summer cruises (one summer cruise per year, between December and beginning of March)".

In the supplementary material (Figure S1) you can see all sampled years. Tables RC2-1-2-3 show each of the years used (and month) to estimate the trends (for the 3 datasets).

Figure 3 – This figure includes winter data, but only summer data collection is described in the methods. Please explain.

Response: You are correct, only summer cruises are used for the trend analysis. OISO winter cruises were only conducted in 1998 and 2000 (and also in October 2005, 2011 and 2016) but as the pCO_2 and C_T seasonality is large they are not used in the trends analysis. Here the winter cruises are first used to validate the calculation of C_{ant} in the "winter layer" as presented in Figure 3. For a preliminary estimate of fCO_2 and pH change in winter, we also used the winter fCO_2 data in 2000 to compare with data from a Saildrone in 2019 to have a flavor of the changes observed over 19 years in the POOZ-HNLC region. From only 2 datasets it is not clear to derive a trend. This is why this part is only presented in the appendix. Finally, in October, we have only 3 cruises to estimate the change between 2005 and 2016 (as discussed for station A3, Section 4.2.2). Therefore, only summer trends are presented and discussed in detail in this paper.

Equation 1 – It may be useful to provide the r squared value to show the correlation between measured and estimated alkalinity.

Response: The r squared value is 0.41. This value is explained by the quite small variations of A_T and S in this region (Figure RC2-3).

Captions of Tables 1 and 2 – Student "t-"test?

Response: Yes, we did perform the Student's t-test. Legends of Tables will be modified.

Figure 4c – What is the reason alkalinity trends are so different between the underway and O7 and O8 data sets? I see later in the discussion the interpretation that this is due to biologically-driven changes in alkalinity not captured by the underway data. Could there also be changes in alkalinity deeper in the water column that vary from the surface?

Response: This is an important point. We have no clear explanation at present for this and we decided to show the results derived from the 3 datasets in Figure 4. The results for each station were presented in Figure S1. For station O7 and O8 the A_T concentrations derived from station data (mean in ML, orange symbols) were often lower than underway A_T (black symbols) as well as when A_T is reconstructed from salinity (grey symbols) especially in years 1998-2001. Notice that we do not always have the data for the same periods in the different datasets which could also lead to different trends (as noted on Page 18 lines 20-23). For example, in 2004, only fCO_2 data were available around station O8 in this region. The relatively low A_T concentrations at the start of the time series leaded to a positive trend for A_T of +0.4 (+/- 0.2) µmol kg^{-1} yr^{-1} for both stations O7 and O8, i.e. higher than deduced in the PZF from underway datasets but not significantly -0.1 (+/- 0.2) µmol kg^{-1} yr^{-1} (as listed in Table 1). We also explored the change in deep layers (around 1000m) and we detected an increase in A_T but not in C_T at stations O7 and O8. We have no explanation for the A_T increase in both surface and at depth; as recalled by the reviewer we suggest that this might be linked to biological processes (Page 18 lines 31-35) but we have no biological data to confirm and investigate this in more detail.

Page 14 line 32 – Are the results not shown from chlorophyll data collected as part of this study, or from another analysis of satellite ocean color?

Response: The results not shown from chlorophyll data (after 2012) are from another analysis of satellite ocean color and chlorophyll measurements during the OISO cruises (these studies were carried out during master internships in our laboratory). We have chosen not to show these (preliminary) results because it is not the purpose of this paper and they need further discussion. This will be the subject of a future study and paper.

Page 14 line 33 – How would interannual variability of biological processes bias the trends? Do you mean cause increased uncertainty (via noise) in the trends?

Response: Indeed, we can have large biological anomalies and these can have a large impact on the trends when it occurs at the beginning or the end of the time series (at it is discussed for station O12).

Page 14 line 35 – Given the strong decadal variability in the Southern Ocean as pointed out in the introduction, is calling a 10-20 year trend a long-term trend accurate? It may be more accurate to call them decadal trends.

Response: This will be modified throughout all the manuscript.

Page 15 line 23 – Do you mean no significant "deviation in CO2 uptake from equilibration with the atmosphere" during the summer?

Response: Yes, you have understood our proposal. We will change the sentence as:

"The averaged fCO_2 trend that we estimated over 1998-2019 in the POOZ (+2.1 ± 0.3 μatm yr^{-1}) is close to the trend in the atmosphere, suggesting that there is no significant deviation in CO_2 uptake from equilibration with the atmosphere in summer."

Page 16 lines 15-18 – Isn't this partially explained by what's presented in Figure 6?

Response: We wanted to point out that after 2010, the increase in C_T is smaller, but we do not know for which reason. Figure 6 considers the overall period (1998-2019).

Page 17 lines 10-11 – Aren't there caveats to this? Some but not all properties? Biogeochemical processes are happening in the subsurface over that previous year while the water is not in contact with the atmosphere.

Response: You are right. We will rephrase this.

"At station A3, the data collected below the mixed layer (in the Winter Water) could partially reflect the properties of the surface 10 layer during the preceding winter."

Figure S1 – Since the discussion in section 4.4 relies completely on data presented in the supplemental, it may be worth moving the saturation state data from this figure to the main portion of the manuscript.

Response: You are right. We have chosen to add to the manuscript a table assembling the trends of the saturation state of Aragonite and Calcite, from the data in the mixed later, as well as the estimated years of the transition to saturation state = 1 (see Table RC2-4). Note that these years of undersaturation are dependent on the value of saturation state in the region and also on the trends.

References.

Park, Y., Charriaud, E., Ruiz-Pino, D., Jeandel, C., 1998. Seasonal and interannual variability of the mixed-layer properties and steric height at station KERFIX, southwest off Kerguelen. J. Mar. Syst. 17, 571–586.

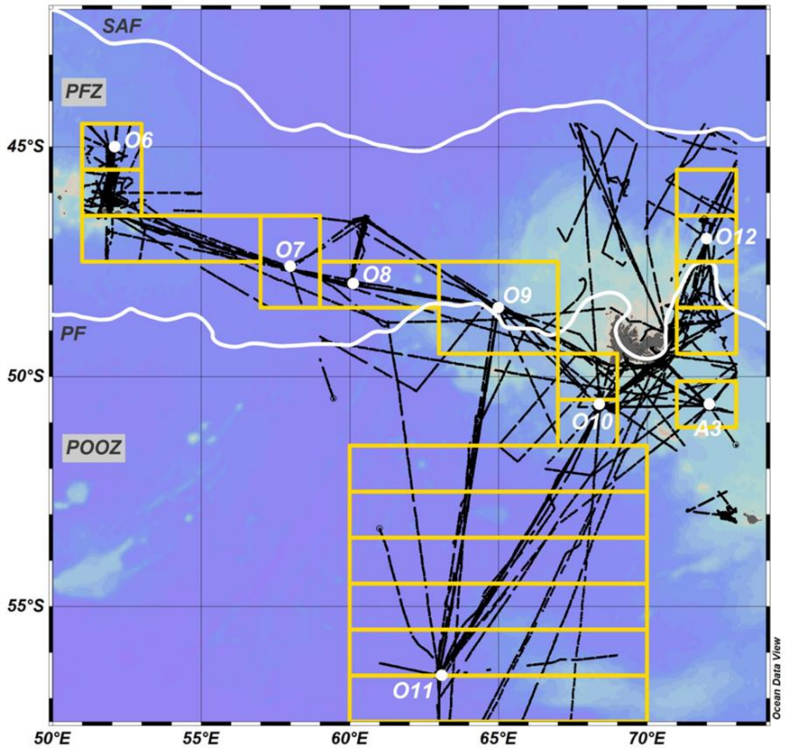

Figure RC2-1. The yellow boxes represent the grouping by latitude and longitude in order to construct Figure 4.

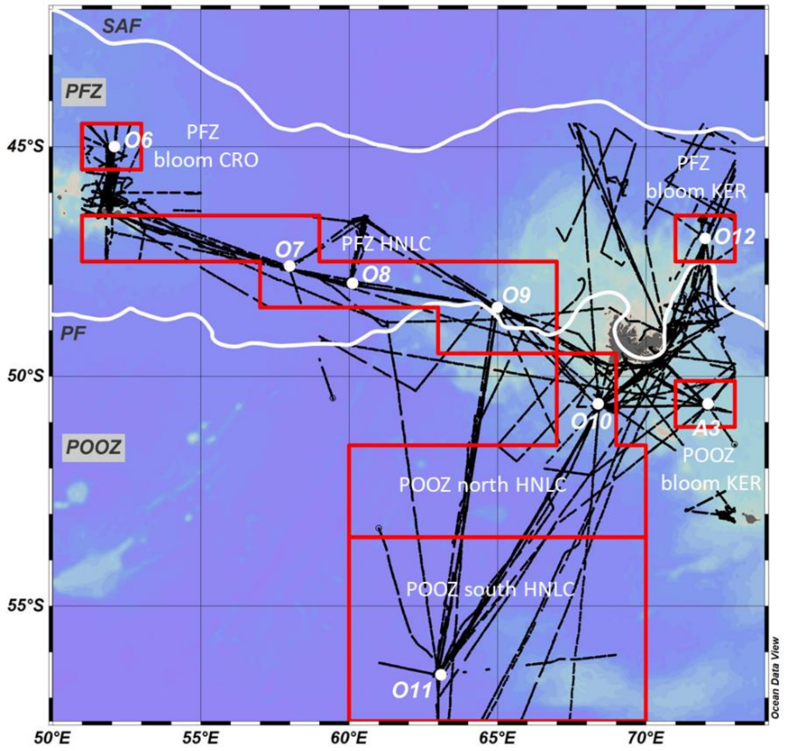

Figure RC2-2. The red boxes correspond to the large regions identified for underway trends presented in Table 1.

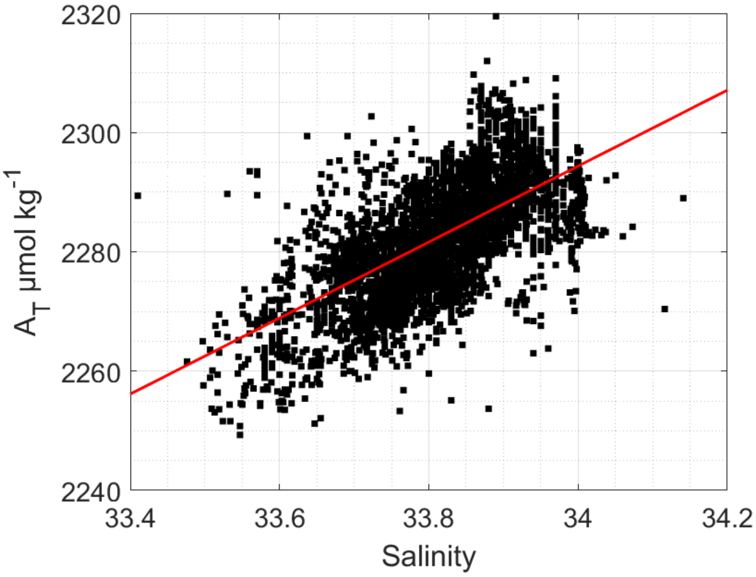

Figure RC2-3. Dispersion of underway A_T and salinity in the study area (shown in Figure 2). $A_T = 64.341 * S + 106.764$ ($R^2 = 0.41$, rmse = 7.485 µmol kg^{-1}, n = 4775).

Table RC2-1. fCO_2 underway dataset used. Each column correspond to an individual yellow box in Figure RC2-1.

Latitude	**-45**	**-46**	**-46**	**-47**	**-47**	**-47.4**	**-48**	**-48**	**-48.3**	**-49**	**-50**	**-50.6**	**-51**	**-52**	**-53**	**-54**	**-55**	**-56**	**-57**
Longitude	**52**	**52**	**72**	**54**	**72**	**58**	**61**	**72**	**65**	**72**	**68**	**72**	**68**	**65**	**65**	**65**	**65**	**65**	**65**
Nb Cruises	18	18	15	14	15	15	14	15	18	17	18	11	18	16	14	14	15	15	14
1998	Jan, Dec	Jan, Dec	Feb, Dec	Jan, Dec	Feb, Dec	Jan, Dec	Jan, Dec	Feb, Dec	Feb, Dec	Feb, Dec	Feb, Dec		Feb, Dec	Feb, Dec	Feb, Dec	Feb, Dec	Feb, Dec	Feb, Dec	Feb, Dec
1999																			
2000	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan		Jan	Jan	Jan	Jan	Jan	Jan	Jan
2001	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan		Jan	Jan	Jan	Jan	Jan	Jan	Jan
2002	Jan	Jan	Jan	Jan		Jan	Jan	Jan	Jan	Jan	Jan		Jan	Jan	Jan	Jan	Jan	Jan	Jan
2003																			
2004	Jan, Dec	Jan, Dec		Jan		Jan	Jan		Jan	Jan	Jan, Feb	Jan	Jan, Feb	Jan	Jan	Jan	Jan	Jan	Jan
2005	Jan, Feb	Jan, Feb		Jan, Feb		Feb			Feb		Feb	Jan, Feb	Feb						
2006	Jan	Jan		Jan		Jan	Jan		Jan		Jan	Jan							
2007											Jan	Jan							
2008		Jan	Jan	Jan	Jan			Jan	Jan	Jan	Jan	Jan	Jan	Jan					
2009	Dec	Dec															Dec	Dec	Dec
2010			Jan		Jan			Jan		Jan	Jan		Jan						
2011	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan, Feb	Jan		Jan	Jan	Jan	Jan	Jan	Jan	Jan
2012	Jan	Jan, Feb	Feb	Feb	Feb	Feb	Feb	Feb	Feb	Feb	Feb		Feb	Feb	Feb	Feb	Feb	Feb	Feb
2013	Feb	Feb			Feb				Feb	Feb	Feb		Feb	Feb	Feb	Feb	Feb	Feb	
2014	Jan	Jan	Feb	Jan	Jan	Jan	Jan	Jan, Feb	Jan	Jan, Feb	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan
2015	Jan		Jan		Jan	Jan	Jan	Jan	Jan	Jan		Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan
2016	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan		Jan	Jan	Jan					
2017	Jan	Jan	Jan		Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan
2018	Jan	Jan	Jan		Jan			Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan
2019	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan

Table RC2-2. A_T and C_T underway dataset used. Each column correspond to an individual yellow box in Figure RC2-1.

Latitude	**-45**	**-46**	**-46**	**-47**	**-47**	**-47.4**	**-48**	**-48**	**-48.3**	**-49**	**-50**	**-50.6**	**-51**	**-52**	**-53**	**-54**	**-55**	**-56**	**-57**
Longitude	**52**	**52**	**72**	**54**	**72**	**58**	**61**	**72**	**65**	**72**	**68**	**72**	**68**	**65**	**65**	**65**	**65**	**65**	**65**
Nb Cruises	14	16	15	11	15	11	9	15	15	16	17	11	17	15	13	13	13	13	11
1998	Jan, Dec	Jan, Dec	Feb, Dec	Jan, Dec	Feb, Dec	Jan, Dec	Jan, Dec	Feb, Dec	Feb, Dec	Feb, Dec	Feb, Dec		Feb, Dec	Feb, Dec	Feb, Dec	Feb, Dec	Feb, Dec	Feb, Dec	Feb, Dec
1999																			
2000	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan		Jan	Jan	Jan	Jan	Jan	Jan	Jan
2001	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan		Jan	Jan	Jan	Jan	Jan	Jan	Jan
2002	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan		Jan	Jan	Jan	Jan	Jan	Jan	Jan
2003																			
2004	Jan, Dec	Jan, Dec		Jan		Jan			Jan	Jan	Jan, Feb	Jan	Jan, Feb	Jan	Jan	Jan	Jan	Jan	Jan
2005	Jan, Feb	Jan, Feb		Jan, Feb		Feb			Feb		Feb	Jan, Feb	Feb						
2006	Jan	Jan		Jan		Jan	Jan		Jan		Jan	Jan							
2007											Jan	Jan							
2008		Jan	Jan	Jan	Jan			Jan	Jan	Jan	Jan	Jan	Jan	Jan					
2009	Dec	Dec				Dec	Dec		Dec					Dec	Dec	Dec	Dec	Dec	Dec
2010			Jan		Jan			Jan		Jan	Jan		Jan						
2011			Jan		Jan			Jan		Jan, Feb	Jan		Jan	Jan	Jan	Jan	Jan	Jan	Jan
2012			Feb		Feb			Feb	Feb	Feb	Feb		Feb						
2013		Feb	Feb		Feb			Feb	Feb	Feb	Feb	Feb	Feb	Feb	Feb	Feb	Feb	Feb	Feb
2014																			
2015	Jan	Jan	Jan		Jan			Jan		Jan		Jan	Jan	Jan	Jan	Jan	Jan	Jan	
2016	Jan	Jan	Jan	Jan	Jan			Jan		Jan		Jan	Jan	Jan					
2017	Jan	Jan	Jan		Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	
2018	Jan	Jan	Jan		Jan			Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan
2019	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan

Table RC2-3. A_T and C_T water column dataset used. This includes the 8 stations identified on Figure 1.

Station	O6	O7	O8	O9	O11	O10	A3	O12
Latitude	**-45**	**-48**	**-48**	**-48.5**	**-56.5**	**-50.6**	**-50.6**	**-47**
Longitude	**52**	**58**	**60**	**65**	**63.1**	**68.4**	**72.1**	**72**
Nb Cruises	14	14	12	14	15	17	9	14
1998		Jan, Dec	Jan, Dec	Feb, Dec	Feb, Dec	Feb, Dec		Feb, Dec
1999								
2000	Jan	Jan	Jan	Jan	Jan	Jan		Jan
2001	Jan	Jan		Jan	Jan	Jan		Jan
2002	Jan	Jan	Jan	Jan	Jan	Jan		Jan
2003								
2004	Jan	Jan			Jan	Jan		
2005	Feb	Feb	Feb	Feb		Feb	Feb	
2006							Jan	
2007							Jan	
2008								
2009	Dec	Dec	Dec	Dec	Dec			
2010						Jan		Jan
2011	Jan	Jan	Jan	Jan	Jan	Jan		Jan
2012	Jan	Feb	Feb	Feb	Feb	Feb		Feb
2013					Feb	Feb	Feb	
2014	Jan	Jan	Jan	Jan	Jan	Jan		Feb
2015	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan
2016	Jan	Jan	Jan			Jan	Jan	Jan
2017	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan
2018	Jan			Jan	Jan	Jan	Jan	Jan
2019	Jan			Jan	Jan	Jan	Jan	Jan

Table RC2-4. Trends (per year) of Ω Aragonite and Ω Calcite, evaluated from the A_T and C_T data in the summer mixed layer (ML) at each station between the same years as in Table 1. The significant trends (Student's t-test) are represented in bold (at 95%). Years of transition to Ω = 1 are also estimated when the trends are significant.

		Ω Aragonite		Ω Calcite	
		trend (yr^{-1})	estimated year Ω = 1	trend (yr^{-1})	estimated year Ω = 1
PFZ HNLC	O7	**-0.008 ± 0.004**	2210	**-0.013 ± 0.006**	2160
	O8	-0.001 ± 0.004		-0.002 ± 0.006	
	O9	-0.004 ± 0.003		-0.006 ± 0.004	
POOZ north HNLC	O10	**-0.005 ± 0.002**	2160	**-0.008 ± 0.004**	2230
POOZ south HNLC	O11	-0.003 ± 0.002		-0.005 ± 0.003	
POOZ bloom Kerguelen	A3	**-0.011 ± 0.004**	2090	**-0.018 ± 0.006**	2080
PFZ bloom Crozet	O6	**-0.010 ± 0.008**	2130	**-0.016 ± 0.008**	2120
PFZ bloom Kerguelen	O12	**-0.012 ± 0.006**	2070	**-0.019 ± 0.009**	2120