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 1 (anonymous):

We thank reviewer 1 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.

Summary

"The authors present a detailed analysis of multi-decadal summer trends in fCO2 and pH in the Indian sector of the Southern Ocean. They present a clear, detailed comparison with past works to discuss trends and investigate the drivers behind the changes reported within. This work is valuable to the ocean carbon community, especially given the in depth analysis for a less-observed region such as the Indian Ocean. While I found the results stimulating and well-written, the section explaining the set up of the analysis left me often confused and could use some attention to clarify for the reader."

Response: We agree with the reviewer. The section explaining the set up of the analysis will be rewritten to improve the understanding. This was also emphasized by reviewer 2.

Overarching comments

"You are only evaluating summer trends in this work, which is valuable of course, but still limited in the interpretation of your findings. Your title does not indicate that these are specifically results only for the summer season. You state clearly on Pg 3, Line 11-13 that the pH trend in the Drake Passage varies greatly in the region and by season so the fact that the results discussed and analyzed within are only inferred from summer observations is an important fact to include in the title."

Response: We also agree with the reviewer on this point. In the main part of the manuscript, we use only data collected during summer. The new title could be: "Summer trends and drivers of sea surface fCO_2 and pH changes observed in the Southern Indian Ocean over the last two decades (1998-2019)".

We however also use "winter layer" water data (from stations) to discuss anthropogenic carbon changes.

"While the results of this analysis are valuable and clearly discussed (Section 4), the leadup (Section 2 specifically) left me lost as to understanding what data was being used, where the comparisons were being made, over what regions (how many?), etc. Table 1 (as I mention below) is overwhelming and needs to be split into multiple tables to truly allow the reader to follow along (scattering these throughout Section 4 so that you can see the trends right there when discussing the comparisons would be helpful)."

Response: We understand your difficulty to understand each of the datasets used. We are rewriting Section 2 and cut Table 1 in several sub-tables which will be successively commented upon in Section 3 (Results). This seems a better place for these tables than in Section 4 (Discussion). We will comment in more detail these new tables in the section on technical comments for Table 1.

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 Tables 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).

For the two underway datasets, 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 section 2 will be revised as:

2 Material and methods

2.1 Study area

[…]

Figure 1.

“To investigate the long-term fCO2 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). Results for each station in the mixed layer will be then compared to those obtained in the corresponding boxes and regions.”

Technical comments

Pg 1, Ln 34: Awkward, consider rewording: "…since the start of the industrialization."

Response: The sentence will be revised as: "CO_2 emissions into the atmosphere have been steadily increasing since the beginning of the industrial age."

Pg 2, Line 6-7: Are the decadal changes in response to climate change (as stated in the sentence) or because of climatic shifts/transitions such as the SAM index (which is mentioned later in the sentence). I do not consider these things the same thing.

Response: We are aware that climate change and climatic shifts/transitions (such as the SAM index) are not exactly similar. Transitions of the SAM index can be either natural or climate change related (but the reverse is not true). We can certainly modify our sentence (see below) but we will not investigate it further, as this is beyond the scope of this study.

"It is now well recognized that the Southern Ocean experienced changes in the carbon uptake at decadal scale in response to natural or climate-induced variability (notably the Southern Annual Mode): a weakening of CO_2 uptake in the 1990s in connection with increasing winds (e.g. Le Quéré et al., 2007; Metzl, 2009; Lenton et al., 2009), followed by a reversal of this trend until the early 2010s (Landschützer et al., 2015), and since 2011 a decrease in the CO_2 sink is detected (Keppler and Landschützer, 2019)."

Pg 2, Line 25-26: consider saying, "…the model-specific/dependent evolution of the Southern Ocean carbon sink."

Response: Thank-you. This will be included.

Pg 2, Ln 29-30: Consider comparing to (or at least referencing) the Ocean-SODA product: Gregor, Luke; Gruber, Nicolas (2020). OceanSODA-ETHZ: A global gridded dataset of the surface ocean carbonate system for seasonal to decadal studies of ocean acidification (v2021) (NCEI Accession 0220059). NOAA National Centers for Environmental Information. Dataset. https://doi.org/10.25921/m5wx-ja34. Version 2021. NOAA National Centers for Environmental Information Dataset. (https://www.ncei.noaa.gov/access/oceancarbon-data-system/oceans/ndp_103/ndp103.html)

Response: Thank you for reminding us of this reference. We choose to cite the corresponding paper (rather than the database): Gregor, L. and Gruber, N.: OceanSODA-ETHZ: a global gridded data set of the surface ocean carbonate system for seasonal to decadal studies of ocean acidification, Earth Syst. Sci. Data, 13, 777–808, https://doi.org/10.5194/essd-13-777-2021, 2021.

The sentence will be revised as: "The long-term decrease in sea surface pH has been revealed from direct observations at regional scale (notably at time-series stations, e.g. Bates et al., 2014) or at global scale using reconstructed pH fields (e.g. Lauvset et al., 2015; Jiang et al., 2019; Chau et al., 2020; Gregor and Gruber, 2021; Iida et al., 2021)."

Pg 2, Line 42: The stated trends here (+1.0 uatm/yr and +4.0 uatm/yr)- are they from literature or from this work? It's unclear since it's the same range stated in the abstract. If it's from other work (which would be more appropriate given that it is in the Introduction) please reference which papers that provide these specific trends.

Response: You are right, this is so confusing. We were talking about all the previous references in the Southern Ocean (fCO_2 data). Indeed, the range of variation of fCO2 trends is not precisely reported in the draft. If you look at Table S1 and the previous references, the range is actually between +0.9 to +4.2 µatm yr^{-1} (Metzl, 2009; Takahashi et al., 2009, 2012; Lourantou and Metzl, 2011; Lenton et al., 2012; Fay and McKinley, 2014; Tjiputra et al., 2014; Lauvset et al., 2015). To clarify this, we will rephrase the sentence as:

"In other regions of the Southern Ocean, the trends of fCO_2 were evaluated from the synthesis of fCO_2 data and vary between +0.9 µatm yr^{-1} and +4.2 µatm yr^{-1} (Metzl, 2009; Takahashi et al., 2009, 2012; Lourantou and Metzl, 2011; Lenton et al., 2012; Fay and McKinley, 2014; Tjiputra et al., 2014; Lauvset et al., 2015). This range corresponds to different regions and periods, but most values in the open ocean are close to the increase in the atmosphere (around +2.0 µatm yr^{-1})."

Pg 3, Ln 4: In the Brown et al. 2019 reference, the analysis is 1993-2017 but then the explanation later in that sentence says it is analysis done "using few years of data". I wouldn't call 24 years "a few".

Response: We fully agree with the reviewer; this sentence is very contradictory. In fact, we wanted to point to Lenton et al. (2012) which uses 8 years of data (2001-2008). We will review this part such as:

"A few results present negative fCO2 trends in summer, but these are not significant, for example -0.8 (±1.0) µatm yr-1 in the Western Antarctic Peninsula over 1993-2017 (Brown et al., 2019) or -0.9 (± 2.5) µatm yr-1 in the Atlantic sector over 2001-2008 (Lenton et al., 2012), highlighting the difficulty to evaluate the trends in summer when using few years of data."

Pg 3, Ln 5: Disconnected transition between these two paragraphs. Consider adding a sentence to guide the reader on this transition.

Response: This will be added.

"Like for fCO_2, the pH trends previously estimated in the Southern Ocean present large range (Table S1). This is not surprising as the observed pH trends in this region were generally deduced from fCO_2 data, i.e. not from direct pH measurements."

Figure 1: I wouldn't say this region is the "South-Western Indian Ocean" but more so the Indian Ocean sector of the Southern Ocean.

Response: We fully agree with the reviewer. The new title of Figure 1 will be: "Map of the Indian sector of the Southern Ocean […]".

Pg 4, Line 11: You say these observations are from the OISO cruises but then in Figure 2 caption (and elsewhere) you state that the fCO2 is from SOCATv2020. I understand that you used the fCO2 values from the cruises that the SOCAT program calculated (as opposed to the measured pCO2 values on the cruise) but perhaps consistency would help to clarify this. Are the observations in Figure 2 from all observations available in SOCATv2020 in this region? Or just from the OISO cruises? Perhaps these are indeed the only obs available in SOCAT for this region but I just find it confusing when you don't mention SOCAT at all in first paragraph of Section 2.2.

Response: Actually, we use all the fCO_2 data available for this region during summer in the SOCAT database. But as you mention, these are mostly data from the OISO cruises. Indeed, we only used one supplementary cruise (expocode 74E320041213 in SOCAT.v2020). This ambiguity will be corrected, and we will also mention it in Section 2.2.

"The surface underway fCO_2, A_T and C_T data (and metadata) are available at the NCEID/OCADS database (www.ncei.noaa.gov/access/ocean-carbon-data-system/oceans/VOS_Program/OISO.html). The oceanic fCO_2 data are also available in the SOCAT data product (Bakker et al., 2016). Note that all the data used come from fCO_2 measurements from OISO cruises, except one in 2004/2005 near Crozet Island (expocode 74E320041213 in SOCAT). Note also, that when added to SOCAT, original fCO_2 data are recomputed (Pfeil et al., 2013) using temperature correction from Takahashi et al. (1993). Given the small difference between sea surface temperature (SST) and equilibrium temperature, the fCO2 data from our cruises are identical (within 1.0 µatm) in SOCAT and NCEI/OCADS. Here we used fCO_2 values as provided by SOCAT."

Figure 2: This is a very confusing figure. First, I don't feel that the black dots marking the cruise lines/fCO2 observations are needed. I do not understand the point of the yellow boxes (labeled in caption as "yellow squares" even though they are not squares and it is unclear their purpose of being labeled on the map. Could you just say that the data within +/- latitude bounds were averaged monthly for trend analysis? The red "squares" (again, not squares and very difficult to identify the boundaries) are used the identify the 6 areas used for trend analysis. But in the abstract you say you do analysis over "three domains". Why such jagged and somewhat random region definition? Why not just N/S of the frontal zones and then define an area around the islands based on the chl bloom or simple lat/lon range? Overall, as a reader, just from figures 1 and 2 im confused and overwhelmed. Is it 3 regions or 6? Is it based on the fronts or not (many red and yellow-defined regions in Fig 2 cross the frontal boundary). Even a statement about why it's so important to have these strange boundary regions would at least allow the reader to understand the need for something as confusing as this.

Response: Thank you for pointing out these problems (as did reviewer 2). We will respond to your comments:

The black dots correspond to all the data used. This figure was originally made to show the amount of observations and secondly the boxes (but that became 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 larger box. You can see on Figure RC1-1 what the yellow boxes are supposed to be (without the red boxes on top).

Your suggestion to simply say that the data has been averaged into x° latitude and x° longitude boxes for each cruise, seems a much simpler solution, than to show it on a figure, which is too heavy.

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 RC1-2 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 RC1-2.

You are right that our definition of regions is not expressed in the same way throughout the article. Finally, our study area was separated from N/S of PF and then 3 areas near the islands (station O6, A3, O12) based on the chl-a bloom. We cannot lump together these 3 stations located in 3 different blooms which present different results associated with rather different bloom characteristics. But we can certainly group together what we call the POOZ north and POOZ south which present similar tendencies. However, by keeping these two regions separate, we show that even a station close to the Kerguelen plateau (O10) is representative of the POOZ.

Concerning the PFZ HNLC region (Figure RC1.2): yes, this box crosses the frontal boundary. But we represent an average position of the PF which can be very variable west of Kerguelen (Pauthenet et al., 2018).

Pg 5: After reading through your discussion of the observation methods and related uncertainties I think it would be very valuable to have a table (or add it on to another table) where you include these uncertainties due to measurement along with the trends you are seeing. The uncertainty calculation you explain on Pg 8, Ln 32 is outside of the uncertainty in obtaining the measurements themselves so this would be a worthwhile comparison to allow for in a table.

Response: Thank-you for this comment. A table could be interesting. On the other hand, Figure 6 provides already an estimate of what are the uncertainties on each contribution to the trend (see error bars for each contribution). Thus, a table would be redundant with this information.

For each calculated data, an uncertainty related to the calculation is associated (with CO2SYS). But then we make an average of several data in a box. Thus, the uncertainty associated with the average in the box is much higher than the error related to the measurement.

Pg 6, Ln 19-22: Here is where you explain the “three datasets” you will evaluate trends for. This needs to be more prominent, but also it is confusing because it is more than just 3 datasets as it is shown in Table 1. I understand the 3 to be 1 using underway fCO2, 1 using underway At and Ct, and the last using mixed layer values at stations. Perhaps acronyms or abbreviations for these would be helpful to define/assign because Table 1 is absolutely overwhelming in its current format. Which leads me to…

Response: Yes, that's right, there are three datasets as you can see in Figure 4 and in each of the regions in Table 1:

- Data in the mixed layer for the 8 stations (OISO only),
- Data from underway A_T and C_T measurements (OISO only),
- Data from underway fCO_2 measurements (from SOCAT, mostly OISO).

The dataset using the mixed layer values at station, includes 8 stations (which are taken separately). We understand that Table 1 is too crowded for you, but the different data used are well specified in this table each time in the second column. We will divide table 1 into sub-tables, which we hope will make the results clearer (as you suggest below).

Table 1: There is too much text here in one table and it is too small. Perhaps putting the stations in a separate table? Or at least the bottom 3 that are looking at the island bloom regions. Also, why 6 regions when everywhere else in the manuscript you say you are looking at "3 domains"? How do we now suddenly have 6? Why are we breaking it into "north HNLC" and "south HNLC"? no justification was provided for that. Also, in your Table 1 caption it repeats "the HNLC part of the north POOZ and the HNLC part of the south POOZ" which just adds to the confusion. Why present trends with different start/end years and call them comparable? Why not just truncate all time-series to a common trend? Do you consider if the significant trends are also significant with +/- one year of observations? I.e are they dependent on the specific start/end year or are the trends persistent for the long-term (20-ish) year time period overall?

Response: We will respond to your comments in order (for the ones for which we have not already answered earlier on):

We do not think it wise to put the station trends in a separate table. Indeed, the goal is to show that for the 3 datasets, we have similar trends in each region. But we agree with you to divide this table into 3 smaller tables: the results in the 1) PFZ HNLC region, 2) POOZ HNLC region, 3) blooms regions.

Concerning the 6 regions, we have already answered above and this will be clarified.

We are aware that not all periods used to estimate trends are the same. For example, stations O7 and O8 were not sampled in 2018 and 2019. But station O9 was and we also have underway data. We made the choice to use as much available data as possible to highlight the need to continue these sampling cruises. Here is an example for station O9 if we cut the trends to 2017:

T °C yr^{-1}	S yr^{-1}	A_T µmol kg^{-1}	C_T yr^{-1}	fCO_2 µatm yr^{-1}	pH yr^{-1}	periods
0.02 (0.04)	-0.001 (0.002)	0.0 (0.1)	0.5 (0.4)*	**1.5 (0.8)**	**-0.0016 (0.0008)**	(1998-2017)
0.03 (0.03)	-0.001 (0.002)	0.1 (0.1)	**0.6 (0.3)**	**1.6 (0.6)**	**-0.0016 (0.0008)**	(1998-2019)

As the reviewer mentioned, we did not explain why we separated the POOZ into north and south part. A sentence has been added (see the revised section 2.1, above).

Pg 6, Line 32: Please include your chosen definition of the mixed layer here.

Response: 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) that is sometimes difficult to interpret in the Southern Ocean (e.g. Park et al, 1998). Sentences have been added in section 2.3 (see above).

Pg 6: How does the standard deviation and or n (number of observations) in underway compare to the values at the stations (given the monthly means you calculate here). Such a comparison would help to provide proof that the box is represented by the station.

Response: We select the underway data in a box around each station (yellow boxes). There is thus only 1 average value in the ML per station/year and for underway this depends on the track of the cruise and time when the ship was operating the casts. On average there is between 30-100 underway fCO_2 data and around 10-30 A_T and C_T underway data in each yellow box per year. The comparisons for each station/period are clearly identified in Figure S1 for the 3 datasets.

Pg 7, Ln 14: How often was At not available? Also, did you compare this to the LIAR algorithm of Carter et al? Carter et al., Limnol. Oceanogr.: Methods 16, 2018, 119–131

Response: There was no A_T data at stations during OISO-4 (Jan-2000) because we found large bias and noisy A_T data (not in C_T) probably due to bottles used for the sampling. This is the only explanation we have for this cruise and we prefer to remove A_T data in the file (including for the CARINA or GLODAP data products for this cruise). We used new bottles in July 2000 and there was no more pb for A_T data after 2000.

On the other hand, we are aware of the LIAR method developed by Carter et al (2016) based on T, S, AOU, Si and N data to reconstruct A_T vertical profiles (e.g. for Bio-ARGO). Here we want to reconstruct surface A_T in order to calculate C_T and pH from fCO_2 underway data. For this we used the A_T/S relationship based on Equation 1 (we have no underway AOU, N and Si data needed to apply the LIAR method). Note that other relationships (e.g. Millero et al, 1998; Jabaud-Jan et al 2004; Lee et al, 2006) might be used, but this did not change the trend analysis and we thus used the relationship based on semi-continuous A_T data as explained in the MS.

Figure 5: I like the display of information here (and color designation for the HNLC/bloom stations) but perhaps include a small map of where these stations are located as a subplot to this figure. It would help with the interpretation immensely.

Response: Good point, thank you. Will we include a small map (as Figure 1) on Figure 5 and Figure 6 (see further down).

Pg 15, Line 21: Does the idea that the summer observed trend is close to the trend in the atmosphere imply that "there is no significant change in the CO2 uptake in the summer"? That seems like a confusing way to state it. It means that the ocean is tracking the atmosphere for these decades for summertime ocean carbon uptake. But to say "no significant change"? Change from what? Change caused by biological uptake in summer months as compared to annual trend? In the following sentences, when comparing to the stronger trend reported by Metzl 2009, that is a fair comparison to make but the word choice in that first sentence is inappropriate.

Response: Thank you for pointing out this confusion. 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."

Pg 22, Ln 21-30: The paragraph discussing GOBMs, while valuable and definitely important, seems out of place here. Could you connect it to the work in the introduction to provide some motivation for this work instead of here in the conclusions?

Response: This will be moved in the introduction just after the 3rd paragraph.

" […]. This however depends on both the anthropogenic CO_2 emission scenario (Bopp et al., 2013; Sasse et al., 2015; Jiang et al., 2019; Kwiatkowski et al., 2020) and the way the Southern Ocean carbon sink will evolve in the future.

Global Ocean Biogeochemical Models (GOBM) attempt to reproduce the ocean CO_2 sink over several decades, since the 1960s and in the future, are generally consistent with data-based methods at global scale, but at regional scale discrepancies are pronounced, especially in the Southern Ocean (Hauck et al., 2020). Comparison of fCO_2 (and air-sea fluxes) in the Southern Ocean between models and observations also shows discrepancies at seasonal scale due to incorrect or missing biophysical processes in models (e.g. Lenton et al., 2013; Kessler 25 and Tjiputra, 2016; Mongwe et al., 2018) leading to large bias in timing and amplitude of the C_T and/or SST cycles (a value of simulated annual ocean CO_2 sink might be correct but for the wrong reasons). This is a problem when using current Earth

System Models (ESM) to project future changes of the ocean CO_2 sink (Kessler and Tjiputra, 2016) or ocean acidification in the Southern Ocean (Sasse et al., 2015). For these reasons, it is important to maintain the continue and understand the observations of carbon cycle to feed the models.

The long-term decrease in sea surface pH has been revealed from direct observations at regional scale (notably at time-series stations, e.g. Bates et al., 2014) or at global scale using reconstructed pH fields (e.g. Lauvset et al., 2015; Jiang et al., 2019; Chau et al., 2020; Iida et al., 2021). […].”

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.

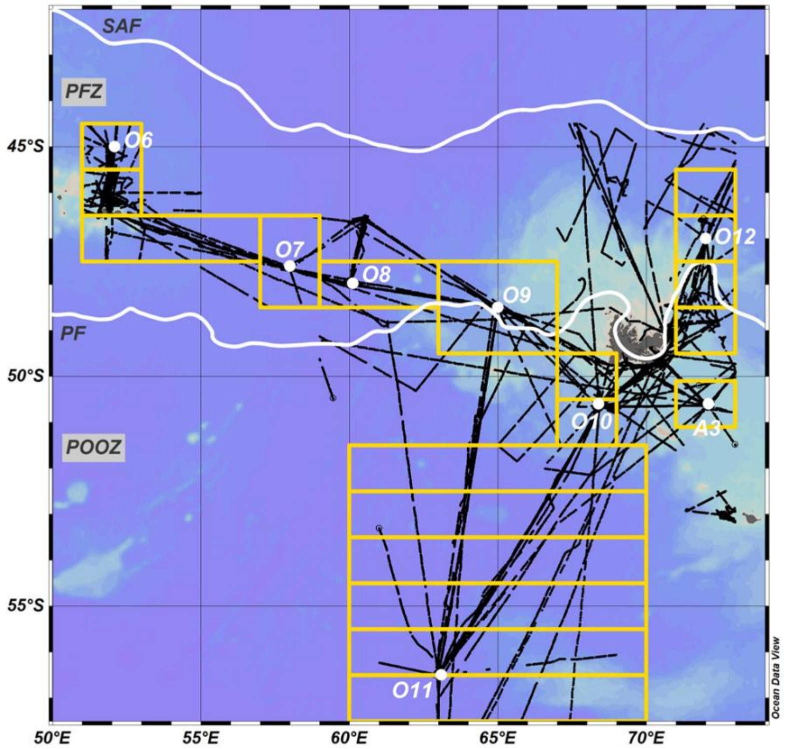

Figure RC1-1. The yellow boxes represent the grouping by latitude and longitude in order to construct Figure 4.

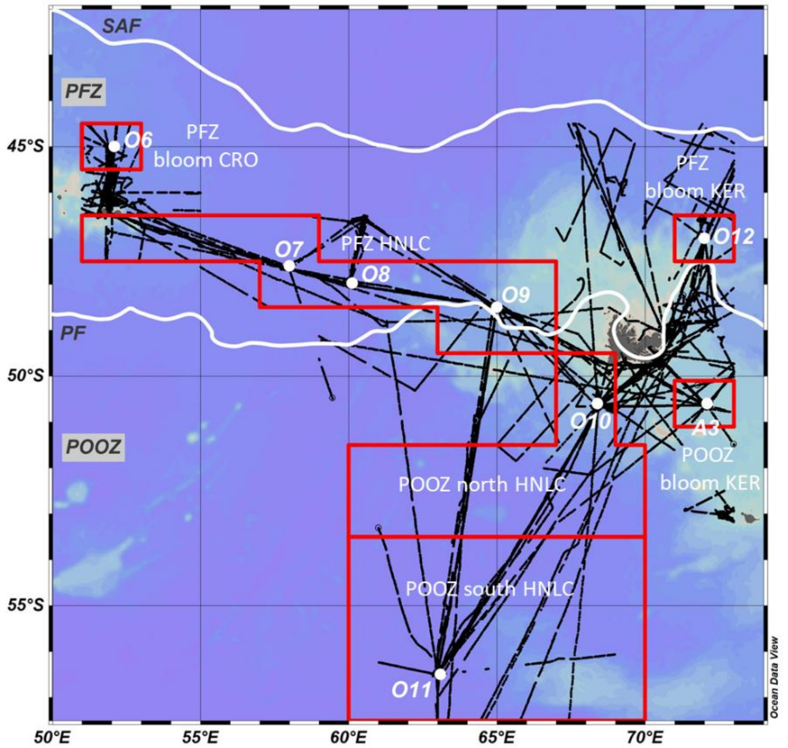

Figure RC1-2. The red boxes correspond to the large regions identified for underway trends presented in Table 1.

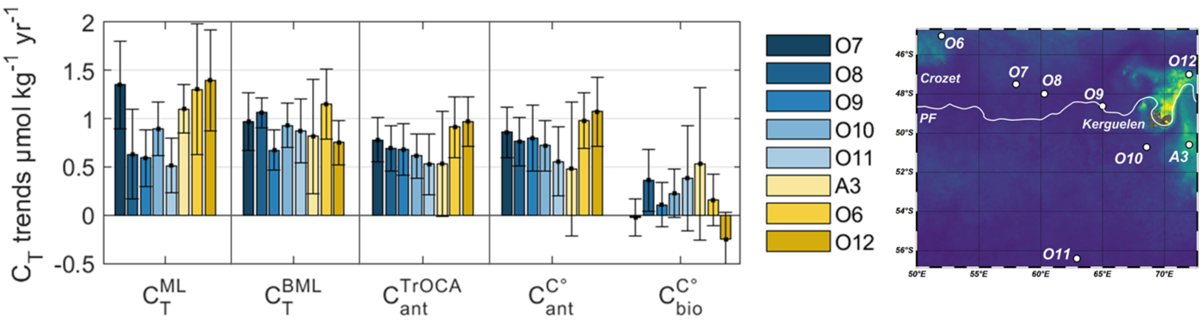

Figure 5. CT trends in mixed layer (ML) and below mixed layer (BML). Decomposition of C_T^{BML} in C_{ant} (TrOCA and C^0 methods) and C_{bio} from C^0 method. The three phytoplanktonic bloom stations are shown in yellow (last) and are separated of the HNLC stations (first five, shown in blue). To help the interpretation, a map with localization of these station is included.

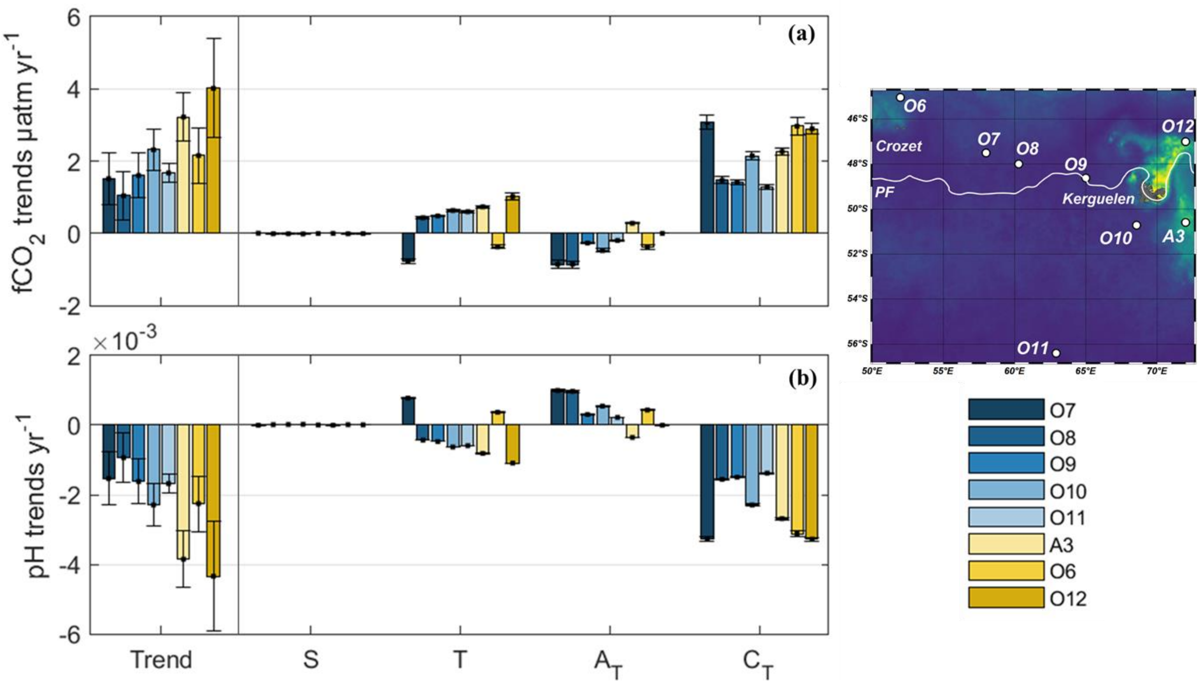

Figure 6. Trends and decomposition of fCO_2 (a) and pH (b) trends in mixed layer, according to Eq. 9. The effect of change in salinity (S), temperature (T), total alkalinity (A_T) and carbon (C_T) is shown. The three phytoplanktonic bloom stations are shown in yellow (last) and are separated of the HNLC stations (first five, shown in blue). To help the interpretation, a map with localization of these station is included.

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)."

<u>Other comments</u>:

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

<u>Response</u>: 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. <u>Tables RC2-1-2-3</u> 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.

<u>Response</u>: 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.

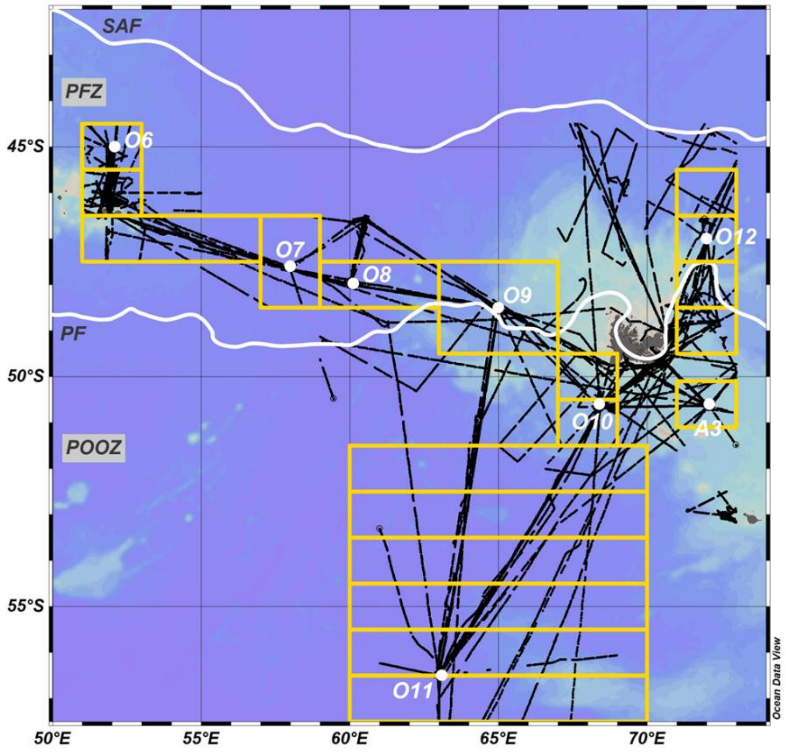

Figure RC2-1. The yellow boxes represent the grouping by latitude and longitude in order to construct Figure 4.

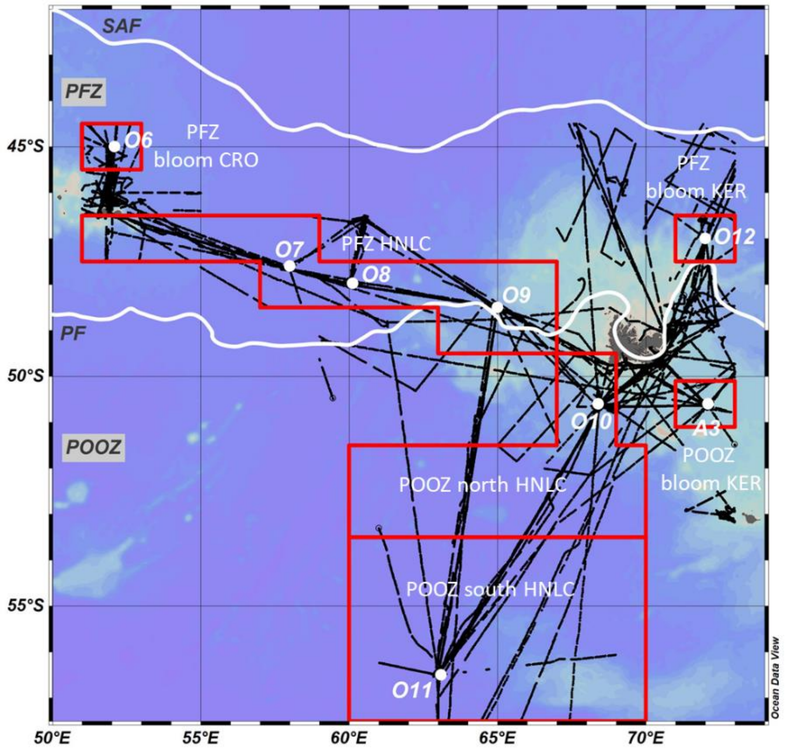

Figure RC2-2. The red boxes correspond to the large regions identified for underway trends presented in Table 1.

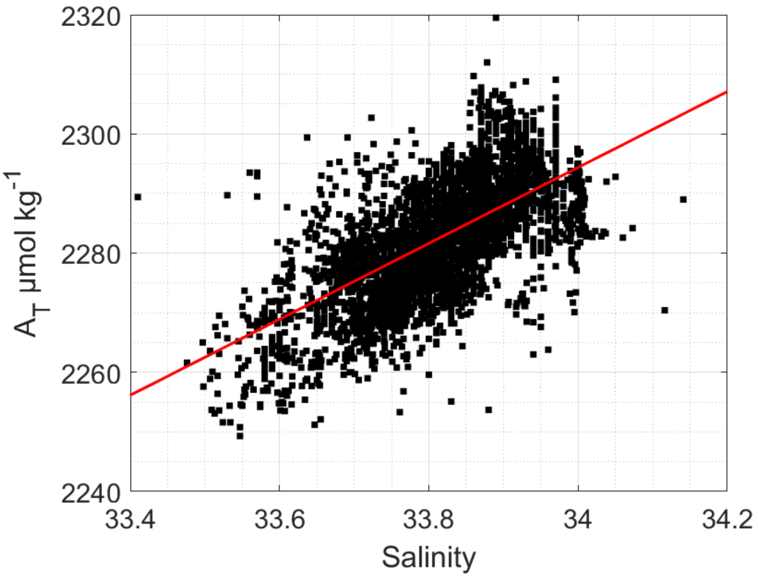

Figure RC2-3. Dispersion of underway A_T and salinity in the study area (shown in Figure 2). A_T = 64.341 * S + 106.764 (R^2 = 0.41, rmse = 7.485 µmol kg^{-1}, n = 4775).

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

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.

Associate Editor (Jack Middelburg):

I would like to point out a technical issue that requires attention before eventual publication. Your manuscript uses the rainbow color palette and mixes green and red colors in figures. This is suboptimal for readers with color vision deficiencies. I therefore recommend you consult the guidelines in more details for advice on this matter.

Response: We want to thank Jack Middelburg for highlighting this technical issue. Here are the revised figures with new colors. The text will be changed accordingly when we refer to the colors of these figures (color bars in Figure 5 and 6, for example).

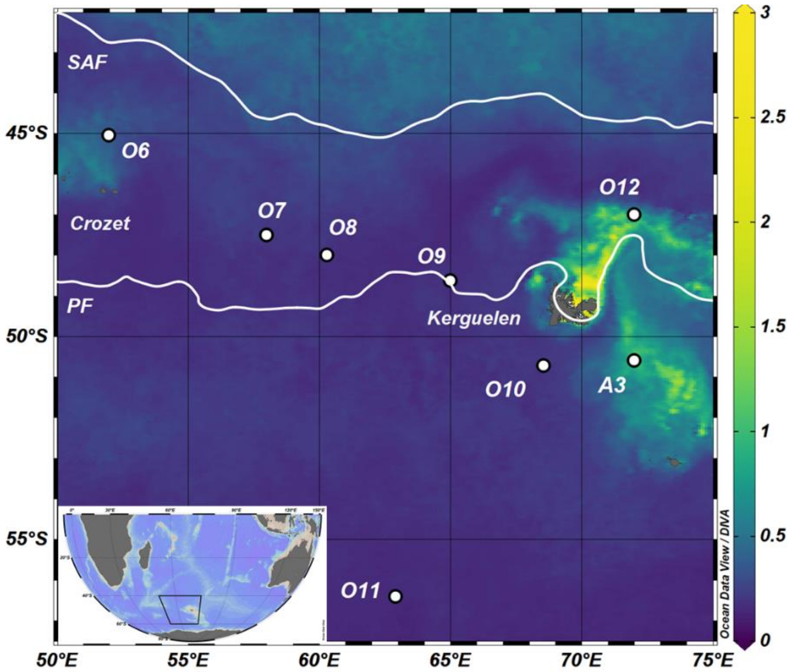

Figure 1. Map of the Indian sector of the Southern Ocean. The eight stations reoccupied are identified by white circles. The two major fronts are represented with white lines: the sub-Antarctic (SAF, 12°C isotherm) and the polar (PF, 5.2°C isotherm) fronts. The background corresponds to the summer climatological surface waters chlorophyll-a concentration (mg m^{-3}) (Aqua Modis data generated by Nasa's Ocean Color https://oceancolor.gsfc.nasa.gov/ (last access: 15 June 2017); January 2002-2017 composite with a spatial resolution of 4 km). Figure produced with ODV (Schlitzer, 2021).

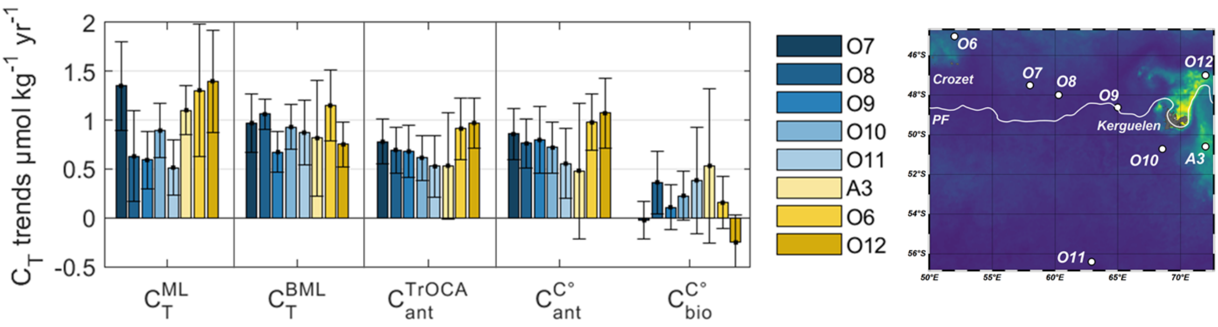

Figure 5. C_T trends in mixed layer (ML) and below mixed layer (BML). Decomposition of CT^{BML} in C_{ant} (TrOCA and C^0 methods) and C_{bio} from C^0 method. The three phytoplanktonic bloom stations are shown in yellow (last) and are separated of the HNLC stations (first five, shown in blue). To help the interpretation, a map with localization of these station is included.

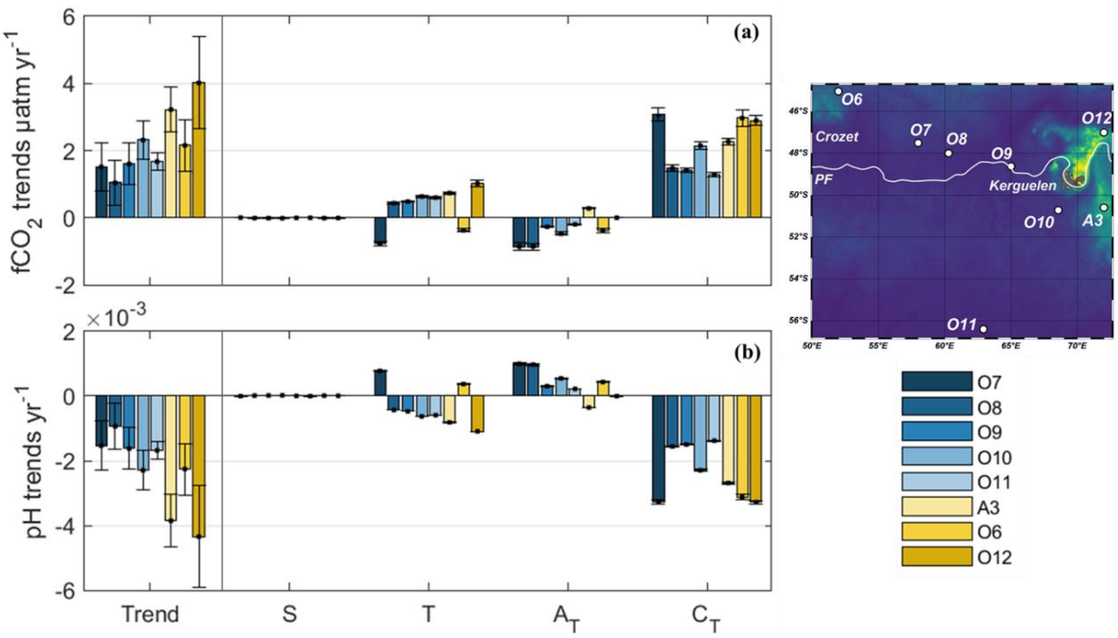

Figure 6. Trends and decomposition of fCO_2 (a) and pH (b) trends in mixed layer, according to Eq. 9. The effect of change in salinity (S), temperature (T), total alkalinity (A_T) and carbon (C_T) is shown. The three phytoplanktonic bloom stations are shown in yellow (last) and are separated of the HNLC stations (first five, shown in blue). To help the interpretation, a map with localization of these station is included.