Review 1:

General

We thank the reviewer for taking the time to review our paper and for constructive and helpful feedback. We have considered each comment carefully and reply to them below.

This is an interesting work with significance for research communities interested and working on similar topics. It shows the importance of in-situ observations and the synergies between different platforms to better understand the spatio-temporal dynamics of biogeochemical parameters coupled to physical phenomena. The hypothesis on what is driving the CO2 sink anomaly is sound (i.e. dissolved iron), however the results from this study only make an indirect connection and do not provide a way to quantify this.

We agree with the reviewer. And our hypothesis that dissolved iron is responsible for a bloom near sea ice edge, as suggested by some studies (Fitch and Moore, 2007), is not at all demonstrated by our study. Iron released during ice melt (Lancelot et al., 2009, Lannuzel et al., 2016, Person et al., 2021) probably contributed to the development of the phytoplankton bloom at the ice edge in spring 2021, but other factors as well, such as stratification due to fresher waters released during melting, light availability, grazing pressure and phytoplankton community composition (Smith and Comiso, 2008, Briggs et al., 2018, Mc Clish and Bushinsky., 2023) should also be considered. We have therefore modified this statement, accordingly, putting emphasis on the early sea ice retreat (of spring 2021, as referred in Wang and al., 2022) instead of the dissolved iron only.

The arguments and references in the discussion section provide a justification but not strong enough to have an explicit statement as the one mentioned in the abstract (line 24).

Yes, the reviewer is right, we have removed that statement. (See the comment above.)

The methodological approach and the subsequent analysis are robust to constrain air – sea CO2 fluxes, considering the inherent limitations that in situ- technology and the deployment area impose. The use of satellite data is coherent and complements well that in-situ observations. One surprising point is that SOCAT, GLODAP, BGC ARGO/SOCCOM data (exception: the Briggs et al., 2018 paper) are not used or explored to identify whether they can increase the data density and/or comparisons with previous years. If such data are not relevant due to spatio-temporal differences, it will be useful to mention it. To an extent this might strengthen the relevance of the dataset and work as the dataset will be even more valuable.

We chose to show comparisons to the year 2019, as this was the year in which the most data were available at the same position and same dates as the CARIOCA. We used the waveglider data (Nicholson et al., 2022) and did a comparison with data from Ogundare (Fig. D1) (Ogundare et al., 2021).

However, the reviewer is right, it would be useful to increase the comparisons using individual SOCAT datasets. We have replaced section 3.4 of the paper, by a comparison between the CARIOCA and the previous SOCAT campaigns. We have added a histogram of the $dfCO_2$, around 0 °E, 54 °S in summer, for the previous years, using all the available SOCAT data from 2000 to 2022. Section 3.4, showing the comparison between summers 2022 and 2019, has been moved to the appendix. (See the answer to the comment below, on section 3.4 of the results, to get a detailed description.)

Concerning GLODAP, there were no data in summer 2022 around 0 °E, 54 °S. However, the climatology profiles (GLODAP mapped climatologies v2 2016b) of DIC and O_2 are coherent with the hypothesis of DIC increase and O_2 decrease, during the mixing events identified in February and March 2022. (See the reply to the comment at line 223, in the results section below).

There were very few BGC ARGO floats around the CARIOCA during its whole trajectory and most of them were too far away to be of any relevance. In summer 2022, there was only one float spatially and temporally close to the CARIOCA, on the 23rd of January 2022. This BGC ARGO float only measured T, S and fluorescence, and didn't bring any additional information to our study as we already had vertical profiles from the glider dataset, which are even more accurate since the glider followed the CARIOCA and stayed very close to the buoy for one month and a half. Moreover, the only BGC ARGO floats with pH measurements (which would have enabled us to approximate the pCO_2) around the CARIOCA's path, didn't sample the same water masses (different SST), as they were farther away. There was however one BGC ARGO float with oxygen measurements, close to the CARIOCA and which sampled the same water mass (same SST and SSS), on the 23 October 2022 (see the comment in the methods section below).

On that note the relevance and impact of this work is evident, especially if one considers that it's in a severely under-sampled areas and with a large contribution to earth's climate.

Specific comments on sections

Introduction

This section is concise and comprehensive. The reference coverage is ok but some additional references like, Sutton, A. et al., 2021 (https://doi.org/10.1029/2020GL091748), Landschützer, P. et al., 2015 (https://doi.org/10.1126/science.aab2620), Sarmiento, J. et al., (https://doi.org/10.1016/j.pocean.2023.103130) seem relevant.

The reviewer is totally right, we have added a few lines to the introduction, citing these references.

Line 52: For additional simplicity it might be useful. The references are adequate, but it will be helpful for the reader if values for interdecadal and interannual variability are mentioned.

We have added the following text to Line 55: Present-day sampling by fCO_2 products may overestimate the decadal variability of the Southern Ocean carbon sink by 50 %–130 % due to data sparsity (Hauck et al., 2023). When derived from the pCO_2 product, mean decadal amplitude is 6.31 Tmol yr^{-1} and mean interannual amplitude is 1.68 Tmol yr^{-1}. On the other hand, when derived from the GOBMs, both mean decadal amplitude and mean interannual amplitude is 2.1 Tmol yr^{-1} (Mayot et al., 2023).

Line 74 – 75: Please add some references

Here are the references: Ardyna et al, 2019, Boyd et al., 2007; Blain et al., 2008.

According to Merlivat et al., 2015, in introduction section, at p. 2: « In high-nutrient, low-chlorophyll (HNLC) regions, including the Southern Ocean, more than 2 decades of intense research have confirmed that increasing iron supply stimulates primary production (Boyd et al., 2007; Blain et al., 2008). »

Line 77: The point is not visible in Fig 1.

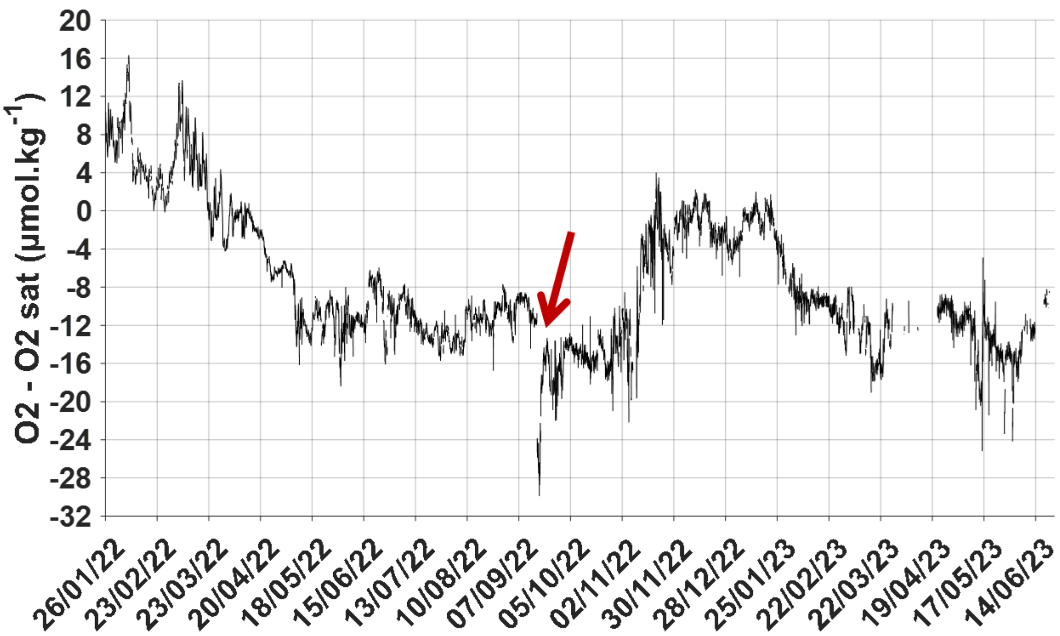
We have modified this figure accordingly.

Methods

Overall, the section is well presented. The lack of calibrations procedures for the optode is a short-fall. The authors do explain how this is addressed but there's no assessment of whether this assumption is adequate for this work. The 8 uM correction is high and there is a question whether this is drifting with time. The fact that O2 is used as a diagnostic and showcasing trends, makes this shortfall less important, however there might be an impact on the O2-O2sat calculation.

Without any correction (i.e. considering only the factory calibration of the optode), we observed that O_2-O_2sat was negative during some periods in summer 2022 while the CARIOCA buoy and the glider were detecting Chl-a and biological activity (as shown by measured fluorescence and by diurnal cycles of O_2-O_2 sat and DIC in opposition phase on the 5-7 February 2022). Unfortunately, we were not able to correct for the optode calibration using other measurements because there were no oxygen CTD measurements corresponding to CARIOCA measurements, and the glider's oxygen data was also uncorrected and could not be used as reference. Moreover, there were no BGC ARGO float with oxygen measurements near the CARIOCA, in summer 2022. We chose an arbitrary correction of + 8 µmol kg^{-1} to ensure positivity of O_2-O_2sat in summer 2022. This correction has no impact on the trend of O_2-O_2 sat, it only brings the values +8 µmol kg^{-1} higher. Without any way to correct the data, the correction of + 8 µmol kg^{-1} was therefore most logical choice for the period shown in our paper (26 January to the 27 June 2022). Since we are looking at the trend, this does not change the interpretation of our results.

On the 23 October 2022, there was a BGC ARGO float with oxygen measurements, close to the CARIOCA, and which sampled the same water mass (same SST and SSS). This BGC ARGO measured oxygen values of 342 µmol kg^{-1}, at 78.1 °E, 53 °S, while the CARIOCA measured a mean oxygen value of 321.2 µmol kg^{-1} on the same date, at around 77.6 °E, 54.4 °S. Considering this, an even higher correction, of + 20.8 µmol kg^{-1} (instead of +8 µmol kg^{-1}) should be applied to the CARIOCA oxygen measurements as from the 23 October 2022. However, we cannot exclude that the correction evolved between beginning 2022 and spring 2022. In particular, we observe a negative jump of approximately 10 µmol kg^{-1} in O_2-O_2sat on the 17/09/2022. Adding this jump to the correction of 8 µmol kg^{-1} at the beginning of the time series would make it close to the BGC ARGO float observation.



(This figure is shown here for reference but has not been added to the paper.)

We kept a correction of + 8 µmol kg^{-1} for the whole time series and specified in the legend of figure S2 that there might be an underestimation of about 10 µmol kg^{-1} for O_2-O_{2sat}, as from the 17/09/2022 (Cf. our response to reviewer 2: we have added a figure similar to figure 2 of the paper but with the CARIOCA whole time series, to the supplementary material).

We have also modified line 93: According to the manufacturer, the accuracy of the O_2 measurements is ~ 16 µmol kg^{-1} (5 %).

Why is the oxygen flux (FO2) mentioned (see comment in results as well) since it's not used later in the results or analysis?

FO_2 is used when estimating the NCP_{O_2}, following the same methodology as in Merlivat et al., 2015 (we used the same methodology as in Merlivat et al., 2015, but we used the mixing layer depth to estimate the NCP, as in Merlivat et al., 2022). We have added this to the line 125 of the paper, explaining how the FO_2 is used.

Line 91-92: Please mention the model, type of sensors and how good they performed.

-The seawater dissolved pCO_2 sensor is a spectrophotometer (manufactured by NKE-France), using thymol blue dye and doing measurements at three wavelengths (810, 434 and 596 nm), with an accuracy of ± 3 µatm (Copin-Montégut et al., 2004, Boutin et al., 2008).

-Conductivity (accuracy: ± 0.003 mS cm^{-1}) via SBE37 SI probe, from which SSS was derived (Sea-Bird salinometer, model Microcat SBE 37 SI).

-Seabird SST sensor (Accuracy: ± 0.002°C for temperatures between -5 and 35°C).

- Dissolved Oxygen via (Aanderaa) Optode 4835, with an accuracy of 16 µmol kg^{-1} (5%).

-Fluorescence (Chlorophyll) via Wetlabs fluorometer

Also, refer to Copin-Montégut et al., 2004 and to Boutin et al., 2008, for a more detailed description of how CARIOCA sensors generally work. A small table summarizing this has been added to the supplementary material.

Line 93: Is the unit umol l^{-1} or umol Kg^{-1}?

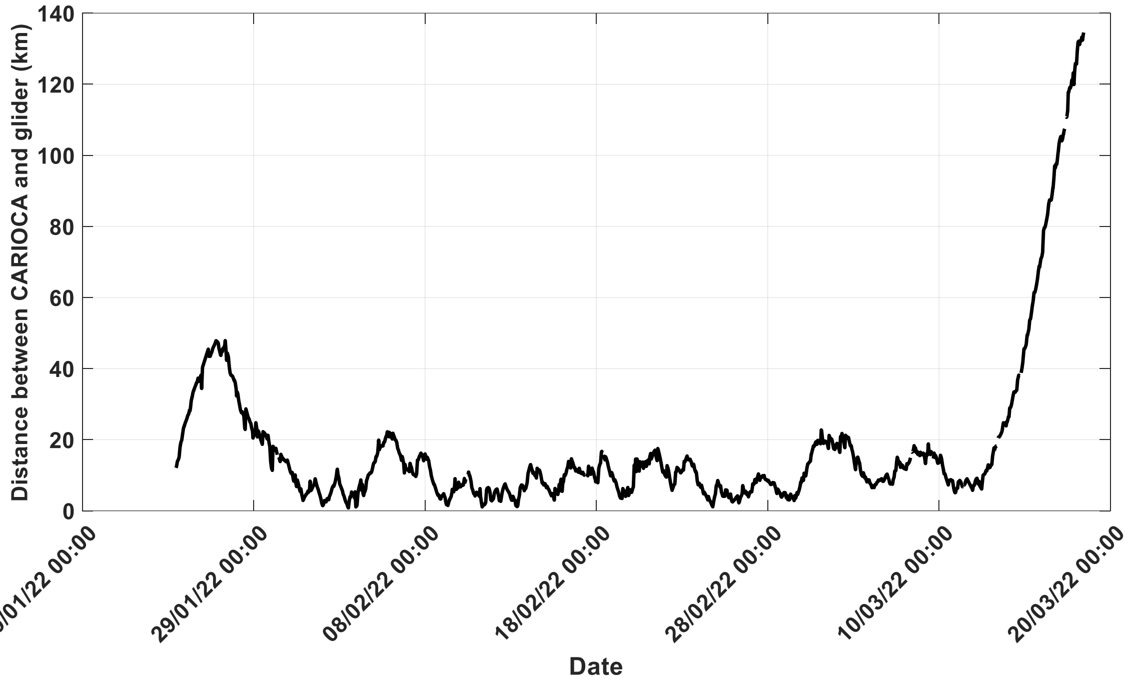
The optode measurement for oxygen is in µmol L^{-1}, then I converted it to µmol kg^{-1}, for consistency throughout the paper.

Line 127: typo

Thank you, we have corrected this.

Line 133: How close is "nearest"? Not clear whether this is 20 km or less.

It is 20 km or less, between the 31st of January and the 10th of March 2022. We have added this to the paper at line 133. Below is the graph showing the distance between the CARIOCA and glider. We will not add this figure to the paper, but we show it here for reference.



Results

Surprised that flux data for both CO2 and O2 are not presented at all (even in the appendix). The authors do make a valid point of the use of DIC and NCP fluxes, however it's a bit confusing to mention sinks and fluxes in the title, explain how they are calculated and mention them throughout the manuscript and don't include a single graph.

The reviewer is right, we have included the CO_2 flux in the figure 2 (a).

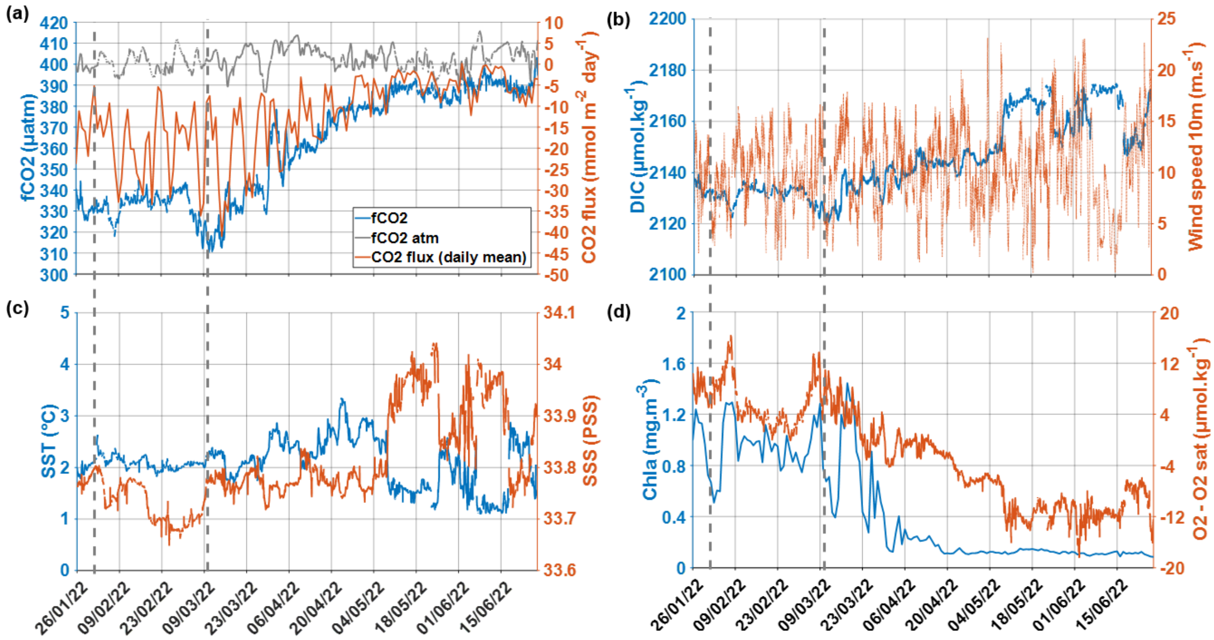


Figure 2: CARIOCA time series from the 26 January 2022 to the 27 June 2022: (a) Atmospheric and surface ocean fCO_2 (fCO_{2atm} and fCO_2), and daily mean of CO_2 flux, (b) DIC and wind speed, (c) SST and SSS, (d) Chl-a and O_2-O_{2sat}, with the period during which the glider followed the buoy (31 January to 10 March 2022) indicated by dotted lines.

Line 223: "…probably entraining waters rich in DIC…". Can GLODAP provide more quantitative information on this and enhance the XLD analysis?

There were no GLODAP data in summer 2022 around 0 °E, 54 °S. However, we can make an estimation using GLODAP climatological profiles of DIC and O_2 (using mapped climatologies v2 2016b, Lauvset et al., 2016). For instance, we plotted vertical profiles of DIC and O_2 using climatological GLODAP data at 0.5 °E, 54.5 °S, corresponding approximately to the location of the CARIOCA between the 7th and 9th of February and at 4.5 °E, 53.5 °S, corresponding to the event between the 14th and 17th of March.

In the paper, at lines 222-223, we mention a mixing event (after the 15th of March) during which DIC was likely brought to the surface from the subsurface layer. The GLODAP climatological profile (mentioned above) reinforces this hypothesis, with DIC increasing sharply from 50 m depth. For the mixing event between the 7th and 9th of February, using GLODAP climatology profiles at 0.5 °E, 54.5 °S, for an XLD deepening from 40 m to 80 m, the GLODAP climatological profiles show a DIC increase of about 10 µmol kg^{-1} and O_2 decrease of about 7.5 µmol kg^{-1}, which is relatively coherent with the changes observed by the CARIOCA (Cf. figure (a) below and figure 4 of the paper).

These profiles also show that DIC varies more rapidly than O_2 at depth, explaining the lower diminution of O_2 compared to the DIC increase, during the mixing event in March. According to the figure (b) below, a DIC increase of about 15 µmol kg^{-1}, and an O_2 decrease of < 5 µmol kg^{-1}, can be expected due to an XLD deepening from 60 m to 90 m, which is relatively coherent with the DIC increase and O_2 decrease measured by the CARIOCA, between the 14th and 17th of March (Cf. Figure 4 of the paper).

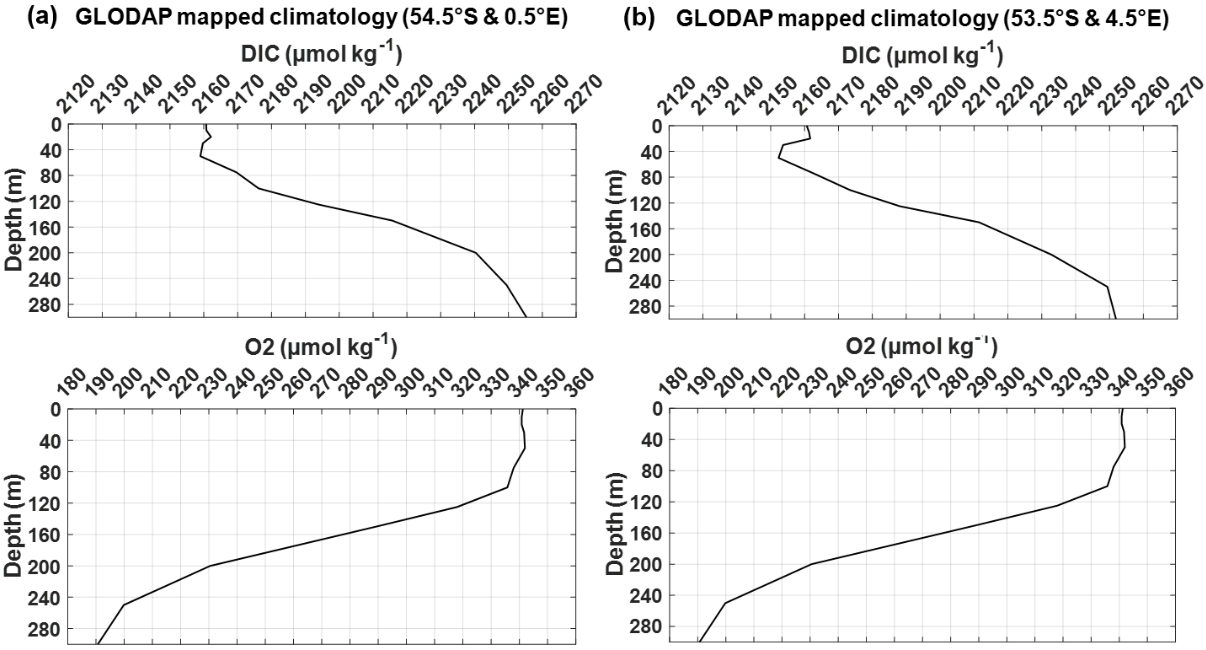


Figure: Vertical profiles of DIC and oxygen (using GLODAP mapped climatologies v2 2016b) at (a) 0.5 °E et 54.5 °S corresponding to CARIOCA's location between the7th and 9th of February 2022 and at (b) 4.5 °E et 53.5 °S, corresponding to CARIOCA's location between the 14th and 17th of March 2022.

In the paper we have added that the DIC and O_2 changes we observe are consistent with the orders of magnitude that could be derived using GLODAP climatological DIC and O_2 profiles, considering the change in XLD.

Section 3.4: The comparison is valid, yet difficult to provide strong conclusions considering that it's a comparison against only one season 2 years before. Maybe SOCAT data can provide a bit more coverage.

We chose to go into detail about the comparison of the CARIOCA data with the waveglider (Nicholson et al, 2019), because both instruments were around 0 °E, 54 °S, at the same dates, enabling us to do a comparison of T, S, fCO_2, MLD and DIC between summers 2022 and 2019. We feel that this provides an ideal case study to illustrate the high-frequency processes that lead to interannual variability of variables that are difficult to obtain. We also mentioned Ogundare (2019) dataset, showing the DIC variations north and south of the SACCF in 2019, and Takahashi's climatology, for more consistency. Nonetheless, the reviewer is right, we have added to the paper a histogram comparing $dfCO_2$ for all SOCAT data available in January and February, between 2000 and 2022, near 0 °E, 54 °S.

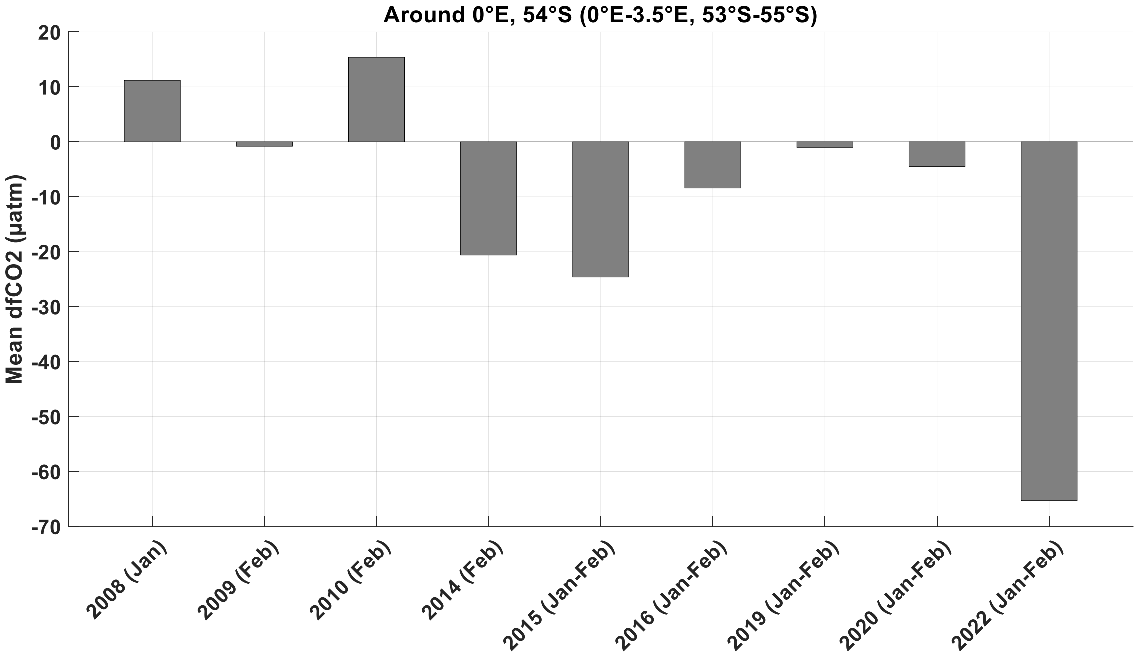


Figure: Histogram of $dfCO_2$ in January and February, estimated using all SOCAT data available between 0 °E – 3.5 °E and 53 °S – 55 °S, from 2000 to 2022. The summer 2019 data is from the waveglider (Nicholson et al., 2022).

The SOCAT measured only act to corroborate our findings. There was outgassing in summers 2008 and 2010 and in 2019 the fCO_2 of the ocean was close to equilibrium with the atmosphere. This was observed in Nicholson et al. (2019). During these years, there was no local bloom, with backward trajectories demonstrating that the waters reaching 0 °E, 54 °S did not come from a spring bloom near the ice edge either. On the other hand, in 2014, 2015 and 2020, a small sink was observed in summer (Jan - Feb) even though there was no local bloom. The waters reaching the region these years, as identified from backward trajectories, came from a bloom near sea ice edge in November (except in February 2014, when the waters came from a bloom occurring in December). Similarly, in 2016, the waters might have come from a November bloom near the ice edge, but due to missing data (on CCI Chl-a maps), we cannot be sure. However, these spring blooms were less intense than the one in 2021 (our study case). (Refer to Figure 9 of the paper, comparing the intensity of Chl-a at both ends of the backward trajectories, in February and November, for all the years.) In 2009, when the fCO_2 of the ocean was close to equilibrium with the atmosphere, there was no local bloom, but the waters reaching the region came from a November bloom. However, it was a less intense bloom and there might have been mixing the following months, explaining the smaller $dfCO_2$ compared to the other years. Summer 2022 was the first summer with such a large negative $dfCO_2$ around 0 °E, 54 °S and demonstrates the importance of sea ice and freshwater advection for carbon variability in the Southern Ocean.

We have replaced section 3.4 of the paper with the figure above (histogram of SOCAT $dfCO_2$) and added a detailed description of the comparison between the CARIOCA and the previous SOCAT campaigns. Section 3.4 in the original manuscript – showing the comparison between summers 2022 and 2019 – has been moved to the appendix.

Discussion

Line 316: What's the definition of "massive"? Also related to the general comment in the results section, is the fact that there's no value with the term "unusually large CO2 sink".

Thank you, this was an oversight on our part. The CARIOCA $dfCO_2$ is on average about – 60 µatm from January to March 2022, with $dfCO_2$ reaching values as high as – 90 µatm, during periods of high local biological activity.

These values are close to the ones usually observed around Kerguelen (which is an area known for high biological activity) in summer and spring. We did a comparison (not shown in the paper) to the KEOPS2 (Kerguelen Ocean and Plateau compared Study expedition) campaign in November 2011, during which a CARIOCA drifter had been deployed east of Kerguelen Island (Merlivat et al, 2015). In spring 2011, $dfCO_2$ as low as -70 µatm were measured east of Kerguelen. We also found that NCP values estimated in summer 2022 east of Bouvet were, although smaller, close to the ones measured east of Kerguelen in spring 2011. Similarly, in November 2016, during the SOCLIM project (Pellichero et al., 2020) a CARIOCA sensor was used at a fixed mooring near Kerguelen and measured $dfCO_2$ as low as -90 µatm.

Moreover, when comparing to pCO_2 climatologies (Takahashi et al, 2012), the region observed by the CARIOCA in summer 2022 is usually in equilibrium with the atmosphere or is a much smaller sink. Also refer to the histogram in Section 3.4 above, showing the $dfCO_2$ values for every SOCAT data available in that region in summer, compared to CARIOCA $dfCO_2$.

Line 322: Again what's the definition of "more massive"?

We have replaced the term 'massive' by orders of magnitudes in the paper.

When we used the term massive, we were referring to values of Chl-a larger than 1 mg m^{-3}. From January to March 2022, the CARIOCA measured Chl-a concentrations between 0.8 and 1.2 mg m^{-3}, with values reaching as high as 1.4 mg m^{-3} in March. In comparison to previous years, Chl-a concentrations in that area usually do not exceed 0.6 mg m^{-3}, even with the synergy of iron from Bouvet Island and from hydrothermal vents of seamounts (Sergi et al, 2020).

4.2. Interannual variation: It would have been useful to elaborate more on air-sea co2 fluxes variability.

We have added a reference to the figure 2 (b) - (d), of Gruber et al., 2019, which shows that climatologies of yearly air-sea CO_2 fluxes are close to 0 mol m^{-2} in the region sampled by the CARIOCA (around 54 °S, east of 0° E). The CARIOCA CO_2 flux integrated over the studied period (26/01/2022 – 27/06/2022) is -1.88 mol m^{-2}, which, assuming negligible flux the rest of the year, is considerably greater than the climatological values in that region.

We have added a few lines describing the CARIOCA CO_2 flux in comparison to the ones shown in Gruber et al., 2019 to section 4.2 of the paper.

Moreover, as stated above (Cf. our reply to the comment on section 3.4), among all SOCAT campaigns, the CARIOCA in summer 2022 observes the largest negative $dfCO_2$.

1. Wondering whether it will be informative to show and attempt connections with sea ice retreat anomalies. The paper from Morioka, Y., et al., 2024 https://doi.org/10.1038/s43247-024-01783-z is very recent and wouldn't have been possible to include it but might be a source of inspiration(?)

Thank you very much for this valuable suggestion. We agree that there is a considerable interest in sea ice retreat anomalies, particularly since the notable decline in sea ice concentration since 2016 and what impact this might have on CO_2 fluxes in the Southern Ocean. While we do not include this in the current manuscript, this will be of interest for future work.