Responses to reviewer 2
;;;;;;;;;;;;;;;;;;;;;;;;;;;;; Review 2, 5/9/2025

Metzl et al. compile observations and observation-based reconstructed surface ocean carbonate parameters to assess historical and future trends in ocean acidification in Mozambique Channel. They find an acceleration of acidification since the 1990s and predict the timing of the crossing of critical thresholds for coral reefs. Given the scarcity of observations in this region, and the Indian Ocean in general, as well as the existence of nearby coral reef ecosystems, this is an important contribution to the scientific literature. However, there are several issues that should be addressed in order to clarify the methodology, reporting, and implications of the results.

AR-01: We thank the reviewer for her/his positive and clear report. Our responses are in blue.

Seasonality of the observations and reconstructions:

Given the significant seasonality of surface ocean carbonate chemistry in this region (Figures 3 and 4) and the desire to report trends without adequate observational coverage in all seasons, it would be useful to better align trend comparisons in the same month(s). In section 3.3.2, trends from historical observations from April-May should be compared to trends from the FFNN product from April-May rather than only April. Figure 3 shows there are significant differences in the climatology between April and May. In addition, it is unclear why August is used for the future predictions (Line 636) when the comparison is being made to July observations (639). It would be better to align those FFNN months with the available observing months or report seasonal FFNN results that encompass the observations (Jan-Mar, Apr-Jun, Jul-Sep).

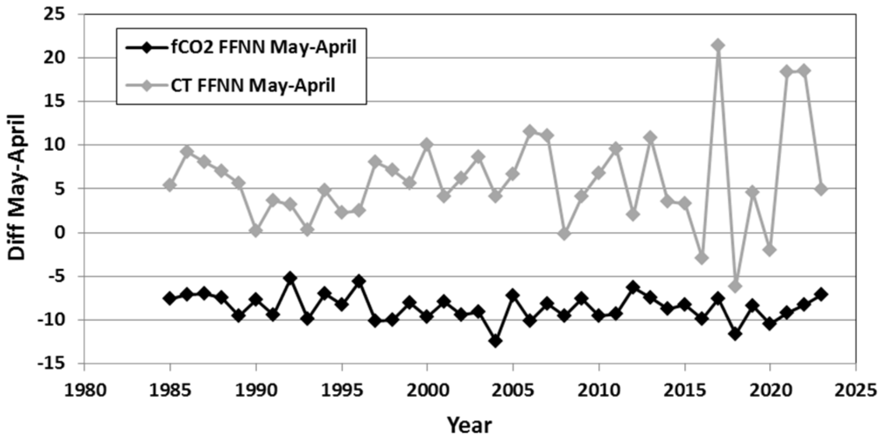
AR-02: We understand the question regarding the selection of months for the trend analysis. The reviewer is correct; we first described the seasonality in order to select data for the trends described in section 3.3.2 and for the observations we select cruises in April-May. We have calculated the trends in April and May separately and found the same results. This is confirmed when exploring the trend of the differences (Figure R1). We suggest add the results for May in Table 2 to show that the same trends are obtained for both months.

Table R1: Same as Table 4 after adding results from FFNN in May.

Trends of properties in the southern Mozambique Channel derived from observations and the FFNN model. For observations, the trends are evaluated for April-May season only. For FFNN, trends are estimated for all seasons or only for January, April, May and July. Standard-deviations are in bracket.

Method	Period	fCO_2 µatm.yr^{-1}	C_T µmol.kg.yr^{-1}	A_T	pH TS.yr^{-1}
Obs April-May	1963-1995	1.11	0.91	0.52	-0.0012
Obs April-May	1963-2022	1.84 (0.21)	0.69 (0.20)	0.08 (0.13)	-0.0020 (0.0002)
Obs April-May	1995-2022	2.57 (0.30)	0.49 (0.52)	-0.34 (0.22)	-0.0027 (0.0003)
FFNN April	1985-2023	1.74 (0.03)	1.01 (0.07)	0.03 (0.07)	-0.0017 (0.0000)
FFNN May	1985-2023	1.71 (0.03)	1.07 (0.05)	0.07 (0.05)	-0.00167 (0.00003)

Figure R1: Time-series of the difference between May and April for oceanic fCO_2 and C_T concentrations from the FFNN-LSCE model over 1985-2023. There is no trend in these differences. Consequently the fCO_2 and C_T trends for April or May are the same (Table R1).



AR-02: Concerning the month selected for prediction (August), we select August as this is the month with the lowest Ωar. Unfortunately, in austral winter there are observations only in July and we think is was useful to add this data point on the figure. Note that Reviewer 1 asked for detail comparison between reconstruction and FFNN results and our response is copied below:

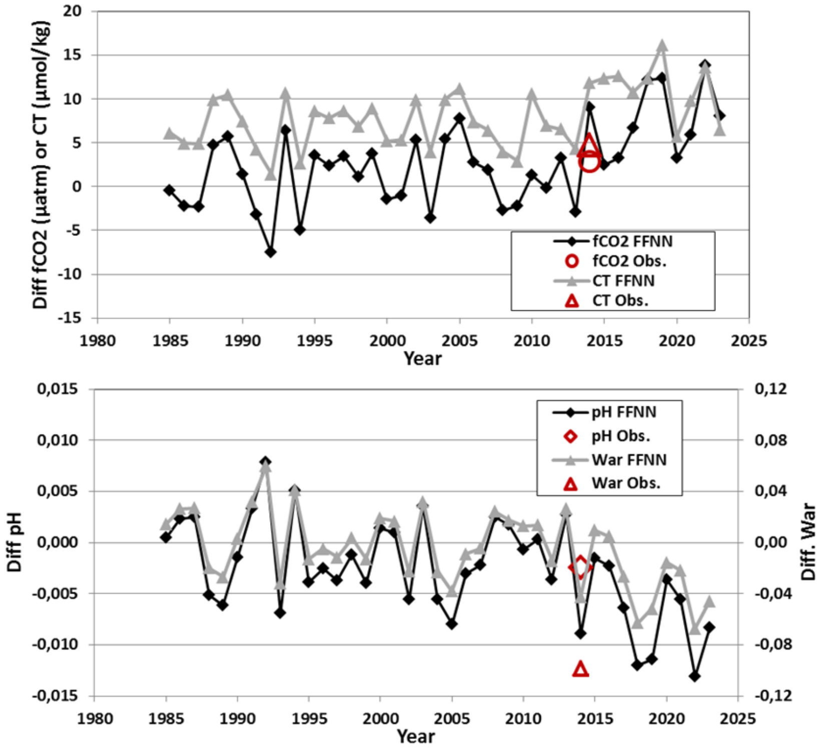
Line 639: "The reconstructed CT, fCO2, pH and Ωar for August compared well with the observations (in July) and with the FFNN model in August (Figure 8) indicating that the simulation captured the decadal evolution of the properties".

We agree that "compared well" as visualized in Figure 8 need more detail.
We have reported the differences corresponding to the results in Figure 8 (Table R1 and Figure R4) and suggest add the table R1 and Figure R4 in Supp Mat.

Table R1: Mean difference between simulation and FFNN for August 1985-2022 and with observation in July 2014. SD in brackets.

Method	Year	fCO2 µatm	CT µmol/kg	pH TS	War nu
Sim-FFNN	1985-2022	2.6 (4.9)	7.9 (3.4)	-0.003 (0.005)	-0.005 (0.029)
Sim.-Obs.	2014	2.8	4.8	-0.002	-0.099

Figure R4: Time-series of the difference of (top) oceanic fCO2 and CT concentrations and (bottom) pH and Ωar between the reconstruction using SSP85 scenario and the FFNN-LSCE model over 1985-2023 in August or with observations (July 2014, red). The differences are calculated from data presented in Figure 8.



In addition, it is not always clear what time period is being referred to. For example, is the FFNN trend referred to in Lines 501-502 FFFN annual or FFNN April?

AR-03: Thank you. We have specified the periods more clearly when appropriate: Lines 501-502 revised as follows:

"In contrast, the neural network suggested smaller pH trends. However, as in the observations, the annual pH change from the model was faster in recent decades (-0.0018 yr^{-1} over 1995-2022 against -0.0011 yr^{-1} over 1985-1995, Table 4)."

Coral reef implications:

How close in space are the historical sampling locations and the coverage of the FFNN reconstructions to the coral reefs in the Mozambique Channel? It is not obvious whether surface ocean carbonate chemistry presented here overlaps at all with nearshore subsurface coral reefs. More evidence is needed to conclude that the current and projected low aragonite saturation state conditions presented here are likely to be the same conditions occurring near coral reefs in this region. In Figure 1, it would be useful to include the extent of coverage used from the FFNN products as well as locations of coral reef ecosystems. The shading in Figure 1 needs to be described in the caption, and if they represent bathymetry, a scale for that should also be included.

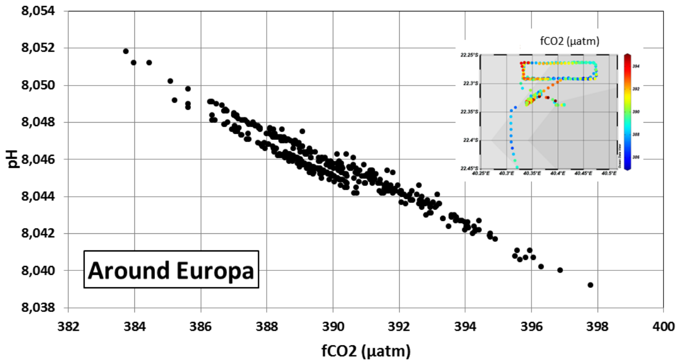
AR-04: This is an important point. In our present analysis, we explored the ocean acidification in the open ocean waters from available data in the Mozambique Channel. During few cruises, CLIM-EPARSES 2019 and RESILIENCE 2022 observations were also conducted very close or within the coral reefs (Europa at 22.5°S-40.5°E, Bassas de India at 22°S-39.5°E). With only two cruises, these data could not support the trend analysis. They are available in SOCAT and Seanoe (as listed in the Data availability section) and might be used for future investigation with new observations conducted in the same region.

As shown in Figure 2, in April 2019 the properties north of a front at 23°S and around 22.5°S were highly variable. This corresponds to observations conducted around Europa. Detailed information is shown in Figure R2. Around Europa, we observed a large spatial and diurnal variability making it challenging to detect a long-term trend in these complex domains. In 4 days (8-11 April) the fCO_2 ranged between 384 and 398 µatm and pH ranged between 8.040 and 8.052, i.e. 0.012. This is a large signal compared to the mean difference observed over 3 years in the band 23-26°S (Table 2 of the manuscript, +7.9 µatm for fCO_2 and -0.005 for pH). This is why we select the region south of 23°S for the trends.

In addition, although we used the 0.25x0.25 degree resolution version of the FFNN model, the model is still not adapted for meso or small scales reconstructions (work in progress for coastal zones). Further analysis is needed to explore the distribution in corals reefs areas in detail; this will be prepared in other studies along with reconstructions from coral cores sampled in the reefs (e.g. Alaguarda et al, 2025; Alaguarda et al, accepted,)

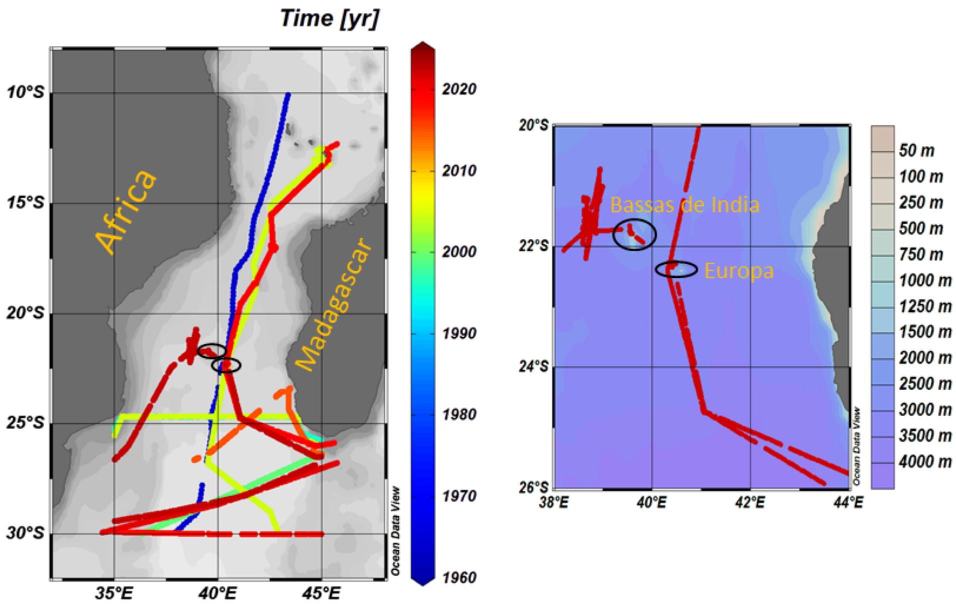
On this issue, we have added in the results (section 3.1):
"Given the variability observed around Europa Island and the front identified at 22.5°S in April 2019 (Figure 2) the data were averaged in the band 23°-26°S."

Figure R2: pH versus fCO_2 observed in April 2019 around Europa (location of data in the insert map, and color code is for fCO_2). In 4 days (8-11 April) the pH ranged between 8.040 and 8.052, i.e. a change of 0.012 being more than twice compared to the difference between 2019 and 2022 (-0.005 for pH).



AR-05: As suggested, the color code for the time of cruises has been changed and locations of coral reef named in the manuscript also added in Figure 1 (circles for Bassas de India and Europa). We also added a map to show in detail the 2 locations with the bathymetry scale as suggested.

Figure 1 revised: Left: Tracks of cruises in the Mozambique Channel in the SOCAT data-base, version v2024 (Bakker et al., 2016; 2024). This includes recent OISO-31 and RESILIENCE cruises in 2021 and 2022. Color code is for Year. Black circles identified the coral reefs locations. Right: Tracks of cruises near the coral reefs area. Figures produced with ODV (Schlitzer, 2018).



Other comments:

Line 18: I assume "TS" refers to pH in total scale? If yes, define that acronym at first instance in the main text (line 49) and just say in the abstract "ranging from a pH change of -0.012 decade -1" in the abstract. It wasn't until I got to Figure 2 that I figured out what TS was.

AR-06: Yes thank you, TS refer to total scale. We have changed pH to pH_T in the manuscript and tables, and units corrected.

Line 25: How do you define "low"? Should this be "lowest"?

AR-07: Thank you, changed by "the lowest" on line 25.

Line 27: Briefly describe the two emission scenarios here.

AR-08: Line 27 revised (in short for the abstract): "A projection of the C_T concentrations based on observed anthropogenic CO_2 in subsurface water and future anthropogenic CO_2 emissions scenario, suggests that a risky level for corals ($\Omega ar < 3$) could be reached as soon as year 2034."

Line 160: Even though this alkalinity proxy is described in another contribution, the uncertainty in the alkalinity proxy should be provided here.

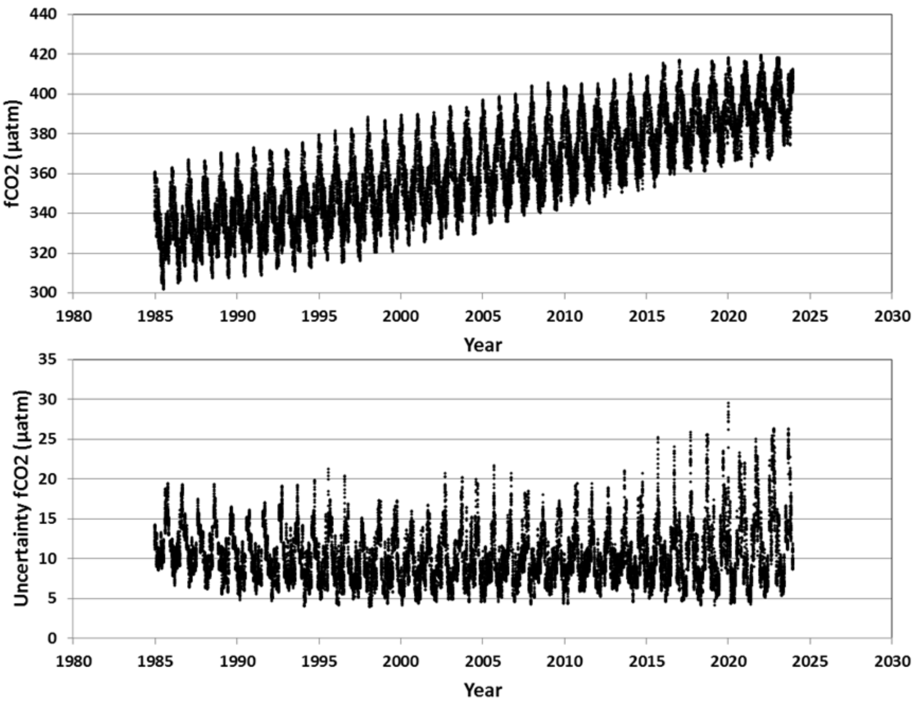
AR-09: The same comment by Reviewer 1. Error and R2 added in Eq1:
A_T (µmol.kg^{-1}) = 73.841 (± 1.15) * SSS – 291.02 (± 40.4) (n= 548, r^2= 0.88) (Eq. 1)

Line 172: Similarly, a brief overview of the estimated uncertainty of reconstructed fCO2 should be provided here. Given one season has no data for training the neural network, are there any assessments of predicted uncertainty during that season?

AR-10: Recall Line 172: "A full description of the model is presented in Chau et al (2024)."
Each data point in the FFNN model is associated to an uncertainty value (in the CMEMS files) based on an ensemble of 100 reconstructions. For example, in the region investigated here, the mean error and standard-deviation of fCO_2 is 10.2 ±3.5 µatm for 24336 data points in 1985-2023 (see Figure R3). Here, we referred to the original publication and the reader can find the detail of the model, their constraints and uncertainties evaluated in specific regions and at global scale.

Line 172 has been revised as follows: "A full description of the model is presented in Chau et al (2024) and the datasets including uncertainties are available under the DOI https://doi.org/10.48670/moi-00047

Figure R3: Time-series of the of oceanic fCO_2 (top) and fCO_2 uncertainties (bottom) in the region 17-30°S around 40°E from the FFNN model.



Line 174: This section seems to be both Results and Discussion?

AR-11: This is correct, thank you. Title section revised: "Results and Discussion"

Lines 322-325: Given the rapid warming in this region, have the authors considered assessing the thermal and non-thermal components of the fCO2 trend? Later in the results, values are presented that correct for the SST warming, but the method used for doing this is not presented.

AR-12: The effect of warming was tested in a previous study (Lo Monaco et al, 2021). Here we discussed the effect of warming on pH changes between 1963 and 1995 (line 500). Note that based on reviewer 1 comment, we added a figure of the SST anomalies and lines 322-325 revised as follows:"Specifically, in the southern Mozambique Channel the SST has increased by +0.11 ± 0.009 °C per decade since the 1960s (Figure S4), a signal that should be taken into account when interpreting the decadal trends of carbonate properties and CO2 fluxes. In January 2025 the SST anomaly reached +1.6°C at 25°S in the Channel."

Figures 2 and 3: Should FFNN-2010 be presented as gray to match the observations from the same time period like FFNN-2022?

AR-13: Thank you, this is probably for Figures 3 and 4. FFNN-2010 line revised in grey.

Figure 3: Is FFNN-2022 missing?

AR-14: Thank you, this is probably for Figure 4. This figure aimed at showing the link between C_T and MLD to explain the C_T increased when MLD was deeper and highlight presence of anomalies. The results from FFNN model for 2022 added (Figure 4 revised below). This shows the C_T increase between 2010 and 2022 and highlight anomalies observed in April 2018 and 2022, i.e. challenging to detect the C_T seasonality from observations only.

Figure 4 revised:
"Figure 4: Seasonal cycle of C_T (µmol kg^{-1}) in the southern Mozambique Channel (24-30°S). Average observations are presented for each cruise (colored circles). The full seasonal cycles are shown based on the monthly climatology for a reference year 2010 (Fay et al, 2024) and the FFNN-LSCE model for year 2010 (Chau et al, 2024). The mixed-layer depth (MLD in m, blue line) is averaged in this region (from multi-year reprocessed monthly data, ARMOR3D L4, https://doi.org/10.48670/moi-00052, last access 20/4/2025)."

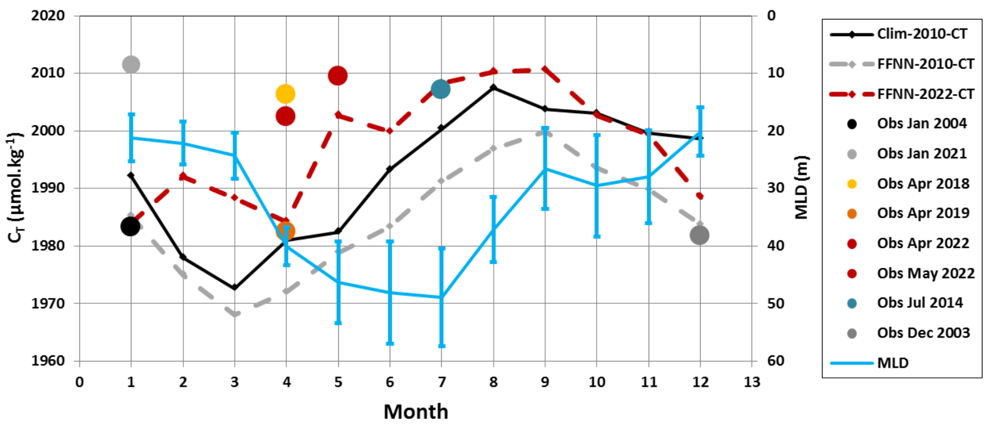


Figure 3: Include an interpretation of what may be causing the anomalous observations in April 2018-2022. Is this due to the variability from the 2021 eddies described in Lines 424-425?

AR-15: Thank you, this is probably Figure 4. Figure 4 aimed at describing the C_T seasonality derived from climatology and its link with the MLD. We added averaged observed data on this figure to show that, in this region, the full seasonal cycles cannot be derived from observations.

As noted in the figure captions the average observations were evaluated in the band 24-30°S. However, in April 2018 the data were available mostly at 30°S, whereas in April 2019 and 2022 at 24°-27°S. This explains in part that C_T in 2018 was higher (orange circles in Figure 4). In addition, Figure 4 also shows that in March-April-May the MLD deepens; therefore, a small change of MLD from year to year could impact the surface properties leading to significant variability of C_T. The result of the FFNN model also shows that in 2022 the increase of C_T from April to May could be as high as +18.4 µmol/kg, much larger than in 2010 (+6.8 µmol/kg). Figure R4 below (not in the manuscript) shows that the variations from April to May could be higher than 15 µmol/kg (in 2017, 2021 and 2022). Given these results, i.e. observations available for few years and the inter-annual variability, we have selected specific season for the trend analysis, the main aim of the study. Finally, we note that the data from the BGC-Argo float also indicate large variability of C_T; specifically we observed that C_T increase when MLD is deeper (Figure R5). The analysis of the inter-annual variability as depicted in figure R4 should be further studied using more observations, satellite data, MLD derived from model at small-scale, and extend the FFNN results to year 2025 (period of the BGC-Argo float).

Figure R4: Time-series of the difference between May and April for oceanic fCO_2 and C_T concentrations from the FFNN-LSCE model over 1985-2023. This highlights the variability in 2017, 2021 and 2022.

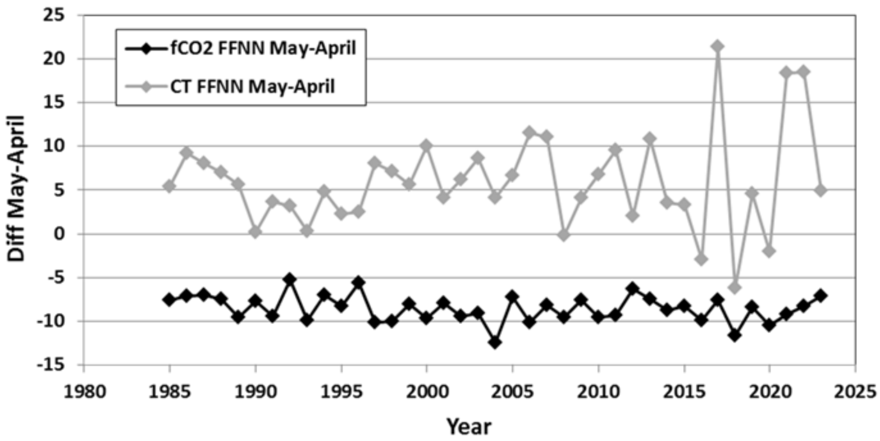
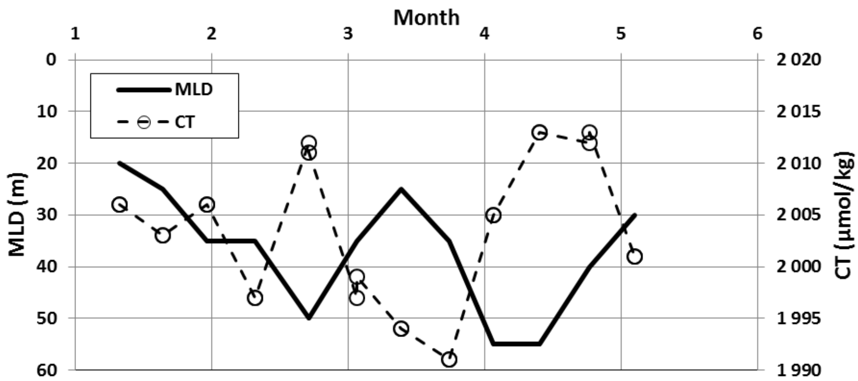


Figure R5: Time-series of MLD and surface C_T in the southern Mozambique Channel based on BGC-Argo data (WMO7902123) in January to May 2025. The large C_T increase (> 15 µmol/kg) in February or from late March to late April occurred when the MLD was deeper (> 50m).



Lines 418-419: Measurement and calculated parameter errors should be stated somewhere. Are these errors a part of the standard deviations in Table 3?

AR-16: Standard deviations in Table 3 correspond to those of the mean values estimated for each cruise along the track (27-29°S/40-43°E). For the errors on parameters we suggest to add 2 lines in Table 3 to compare the differences in regard to the errors of measurement or calculations (noted as * in the table).

Cruise Method Period	Nb	SST °C	SSS -	A_T µmol.kg^{-1}	C_T	fCO_2 µatm	pH TS	Atm. xCO_2 ppm
Difference 2021-2004								
Underway fCO2		0.532	0.225	16.7	28.3	37.8	-0.032	37.4
Underway AT-CT		0.400	0.267	11.5	29.4	45.7	-0.040	
Error using fCO2		0.01	0.01	4	7.3 *	2	0.014*	
Error using AT-CT		0.01	0.01	4	4	13.9*	0.007*	

Figure 6: Everything in the figure legend needs to be defined in the caption. Unclear what fCO2 and AT-CT are? Measured or calculated?

AR-17: In this plot we show results derived from underway fCO2 measurements or underway A_T C_T measurements.

Captions revised as follows: Figure 6: Distribution of measured or calculated C_T (a, µmol kg^{-1}), AT (b, µmol kg^{-1}), fCO_2 (c, µatm) and pH (d, TS) along the same track in January 2004 (black symbols) and January 2021 (grey symbols). Values derived from fCO_2 measurements are in filled symbols/lines, those from the A_T C_T measurements in open symbols/dashed lines. In (c) the red lines represent the atmospheric CO_2 in 2004 and 2021. Average values and their differences are presented in Table 3.

Line 564: Unclear what is meant by “ambient conditions” here.

AR-18: Line 563-564: “Note that there are reefs know to thrive at Ωar < 3.25 but that their species composition and coral cover is different than at ambient conditions (e.g. Strahl et al. 2015 in Papua New Guinea; see also review by Camp et al. 2018).”

Than you, we clarified for “ambient conditions” as follows:
« Note that there are reefs know to thrive at Ωar <3.0 like at volcanic CO2 seeps in Papua New Guinea (Ωar = 2.41, Strahl et al. 2015; see also review by Camp et al. 2018) but that their species composition and coral cover are different than at ambient conditions (i.e. Ωar > 3.3 considering Hoegh-Gulberg et al. 2007). However, Strahl et al. (2015) showed that calcification rate seems to vary among coral species, suggesting take conclusions of Hoegh-Gulberg et al (2007) with caution".

Line 636: How is “low” defined? Is “lowest” meant here?

AR-19: Thank you. Line 636 revised: “To explore the change of the aragonite saturation state, we applied this model (Eq. 2) for August when Ωar is the lowest.”

Line 696-697: Reference the methodology for deriving fCO2 from pH.

AR-20: Reference added: New line: “The fCO_2 and Ωar from the pH float data were calculated using CO2sys as for the shipboard data (section 2.3).”

Figure 9b: Define “War” in legend.

AR-20: “War” is Ωar

Figure 744: Is it a permanent sink given the observations from 2025? What are the potential implications of increasing marine heatwaves in this region to the CO2 sink?

AR-20: Interesting question. The effect of the MHW on the CO_2 sink in this region would be analyzed in further studies, including estimates of the annual integrated CO_2 flux over the full domain (Mozambique Channel and SW Indian Ocean). We think this could be achieved using the FFNN model extended to year 2025 as that was tested recently at global scale for the year 2023 (Müller et al, 2025).

;;;;;;;;; Reference in the review not listed in the manuscript:

Alaguarda, D, Chevalier N, Klein N, Massé A, Tribollet A (accepted) Lipid biomarkers of microboring communities in living massive corals: an interesting tool for understanding their composition and abundance. Coral Reefs.

Alaguarda, D, Brajard J, Lguensat R, Tribollet A (2025) Machine learning approach to study microboring assemblage dynamics in two genera of massive corals. Limnology & Oceanography Methods. https://doi.org/10.1002/lom3.10714

Müller, J.D., Gruber, N., Schneuwly, A. et al. Unexpected decline in the ocean carbon sink under record-high sea surface temperatures in 2023. Nat. Clim. Chang. 15, 978–985 (2025). https://doi.org/10.1038/s41558-025-02380-4

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