We would like to thank the reviewer for the time spending in reading the manuscript and for the valuable comments. Our replies are marked in blue.
Our replies to the minor comments can be found as comments in the annotated pdf-file.

Review of bg-2023-113

Decadal changes of anthropogenic carbon in the Atlantic 1990–2010

By Steinfeld et al.

Reviewer: Jens Daniel Müller

Conflict of interest statement: Reiner Steinfeldt and Jens Daniel Müller are both active contributors to GLODAP, and have jointly co-authored previous release papers of GLODAP (Lauvset et al., 2022)

Short summary

The authors provide a reconstruction of the total anthropogenic carbon storage in the Atlantic Ocean for 1990, 2000 and 2010. These estimates are obtained with a modified version of the previously developed TTD method applied to transient tracers such as CFCs and SF6. Decadal changes in the anthropogenic carbon storage are obtained by subtracting estimates from the three reference years. In addition, decadal anomalies in the accumulation rates of Cant are determined by comparing the Cant accumulation directly obtained from observations centred around the years 2000 and 2010, to those predicted from the transient tracer data of the previous decade. The anomalous Cant accumulation is interpreted comprehensively in the context of ocean circulation studies and previous Cant reconstructions.

General assessment

The study appears overall carefully executed and described mostly in sufficient detail. The method appears appropriate, but a major clarification (or revision) of the use of a dilution factor is required. The focus of the study on decadal anomalies in the Cant accumulation yields a high scientific significance, which could even be enhanced if the authors revised their decision to deliberately neglect tracer observations since 2014. As a consequence of this decision, the study cannot contribute to the ongoing debate about the recent evolution of the ocean carbon sink. References to previous literature are generally comprehensive and the results of this study are well contextualised with previous knowledge on ocean circulation and its variability. However, a few key references are missing and I noted an imbalance to emphasise the assumptions and shortcomings of other methods a bit stronger than those associated with the TTD method. The presentation quality is overall high, although some edits could help to improve the figures. Likewise, the structure and sequence of the text could be revised to increase the emphasis on the most relevant findings, while the use of English language is appropriate and of high quality.

Main comments

A **dilution factor** is introduced and described to account for the admixture of old waters free of anthropogenic tracers. However, the magnitude of this dilution factor is determined such that it reduces decadal anomalies in the accumulation of Cant that are obtained without the dilution factor. Hence, the definition of the dilution factor seems not to reflect the physical process of water mass mixing and - more importantly - it builds on the a priori assumption that the accumulation of Cant in water masses older than 100 years occurs steadily and without decadal variability. I found only a vague explanation addressing why the anomalous Cant accumulation is detected without a dilution factor ("an artefact of the TTD parameterization in the form of a single inverse Gaussian function"). Furthermore, it appears contradictory that the dilution factor reduces the Cant accumulation in the AABW, which is at the same time highlighted as a water mass with considerable amounts of CFCs. Therefore, I deem it important that the general application of this dilution factor, but at least its description as a representation of water mass mixing, is reassessed critically.

The idea to use those TTD parameters that minimize deviations between observed and TTD-derived tracer values over a lobner time period is not new, but has already been used e.g. in Klatt et al. (2002) and Steinfeldt and Rhein (2004). There is no contradiction in the low Cant accumulation and the considerable amounts of Cfc in this water mass. All TTD parameters used in this study reproduce the observed tracer values according to Eq.1. The AABW has a relatively small Cant increase compared to the actual Cant concentration. This has already been shown in previous studies (van Heuven et al., 2011, and Huhn et al., 2013). This implies that AABW gets older with time. The amount of this aging, however, depends on the choice of the TTDparameters. The reason for that is, that the shape of the TTD determines the ‚expected‘ increase in anthropogenic tracers. From a tracer observation at time t1 (C(t1)) different TTDs with different parameterization can be derived. These TTDs can be used to ‚predict‘ the tracer concentration at time t2 (C(t2)), but the exact value C(t2) depends on the TTD parameters (the shape of the TTDs). If the observed tracer concentration at time t2 is smaller than the predicted value from the TTD, the water has become older. As the TTD prediction C(t2) depends on the shape of the TTD, also the amount of ‚aging‘ is related with the TTD parameterization (Delta/Gamma ratio and dilution factor in our case).

We will try to explain that also in the manuscript.

Klatt, O., W. Roether, M. Hoppema, K. Bulsiewicz, U. Fleischmann, C. Rodehacke, E. Fahrbach, R. F. Weiss, and J. L. Bullister (2002) Repeated CFC sections at the Greenwich Meridian in the Weddell Sea. *J. Geophys. Res.*, 107(C4), doi:10.1029/2000JC000731.

Steinfeldt, R., and M. Rhein (2004), Spreading velocities and dilution of North Atlantic Deep Water in the tropical Atlantic based on CFC time series. *J. Geophys. Res.*, 109(C3), C03046, doi:10.1029/2003JC002050.

Observations obtained past 2014 are neglected to avoid "mixing data from years of extremely deep versus years with shallower convection when calculating the mean value of the last decade." However, it remains unclear whether data from 2014 to 2022 could not be included and assessed separately to provide the Cant reconstruction for another decade, that is, for the reference year 2010. If this was achieved, it would drastically increase the significance of the study.

We will use the newest GLODAP version (v2.2023), which contains tracer data until 2020, to provide Cant estimations for the period 2014-2020 with reference year 2020. However, the data gaps for this period are much larger than for the previous decades.

The observational data provided through GLODAP undergo a rigorous quality control and are eventually adjusted to increase their overall consistency. In this study, the authors included additional data from 11 cruises. However, the **consistency of the additional data** with those provided through GLODAP has not been assessed, or at least this is not described in the manuscript. To my impression, it would increase the overall trust in the results if the data consistency could be addressed.

We will address the data consistency. Moreover, some of the ‚additional' cruises have been incorporated in the more recent GLODAP data set without any cjanges in the transient tracer data.

The total Cant for each reference year is calculated as "the difference between the carbon concentration at time tref and the preindustrial time (year 1780)". This **choice of the preindustrial time** is relevant for the definition of Cant (Bronselaer et al., 2017). An earlier starting date of the industrial time usually leads to a higher Cant in each reference year, as it goes along with a lower preindustrial pCO2 and longer time period for Cant to accumulate in the ocean. As a consequence, the choice of the starting date is directly relevant for the comparison of Cant estimates obtained from models and various observation-based approaches (Terhaar et al., 2022). Given the relevance of this decision, it would be great if the authors could provide a justification for their definition of the starting date and assess the sensitivity of their Cant estimates to variations in the starting date.

We will perform calculations to evaluate the sensitivity of the C_{ant} estimates on the starting date of the industrial period.

The authors provide an extensive, carefully executed and mostly complete comparison to previous estimates of the oceanic Cant accumulation. However, it is very hard for readers to digest this comparison as the **differences to previous estimates are not visualised**. Hence, I would encourage the authors to reproduce section plots from previous studies, as well as the differences to the results obtained in this study.

We will try to get the data form Khatiwala et al. (2013) and Sabine et al. (2004) to visualize the differences.

The interpretation of decadal anomalies and their comparison to previous estimates is mostly presented without **consideration of uncertainties**. For example, Fig. 10 in this study and Fig. 5 in Clement and Gruber (2018) display uncertainties for the zonal mean sections of Cant, an information that could be considered when comparing the anomalous changes in Cant. Furthermore, it would be informative if the quantitative uncertainty estimates of the TTD method could be visualised as maps and zonal sections. This would enable an understanding of the spatial distribution of uncertainties, which cannot be obtained solely from the stippling that is currently shown on maps and sections.

Fig. 10 does not display uncertainties, the uncertainties are only indicated by stippling in the same way as in the other figures. Also Fig. 5 in Clement and Gruber (2018) does not show ‚uncertainties‘, but the difference between reconstructed Cant increas by the eMLR(*C) method and directly calculated C_{ant} increase in the model. This, of course, is only possible for a study based on model data, not on real data, where the ‚real‘ C_{ant} values are unknown.

We could, if desired, show sections and maps with undertainties, but that would almost double the number of figures in this paper. Also other data based studies on C_{ant} hardly present maps or sections with the uncertainty.

In addition to the two previous general comments, I permit myself to point the authors to a study recently published by colleagues and myself (Müller et al., 2023), in which we reconstruct **decadal trends in the oceanic Cant accumulation with the eMLR(C*) method**. This new study extends the results of Gruber et al. (2019) by reconstructing Cant for two decades and providing a more rigorous uncertainty assessment that is directly bound to the results. This update is thus more suitable to be used for comparison to the results obtained in this study.

We will refer to this new publication in the discussion.

My overall impression is that the authors tend to be **overly confident in the results obtained with the TTD method**, while other methods are more critically evaluated. For example, the assumptions of other methods used to quantify the accumulation of Cant from observations are mentioned in the introduction, which is not the case for the TTD method. In this regard, a key citation that deals with the assumptions of the surface equilibrium of Cant and variable ratios of the TTD parameters (width and mean age) should be referenced and reflected in this study (Raimondi et al., 2021).

We will also include the findings from Raimondi et al., 2021, in our discussion. Note however, that the idea of C_{ant} and tracer ‚saturations‘ in that paper disagrees with our idea. We assume that the surface saturations are those from the surface waters directly before the convection period. These surface waters are then densified and transferred into the density range of the deep water. However, measurements diuring the deep convection period are sparse. In Raimondi et al. (2021) the tracer and C_{ant} values from the deep water in the ocean interior measured after the convection period are used. In our view, this deep water is a mixture consisting of the newly formed deep water and older waters that have been in the area of water mass formation prior to convection. As these older waters have a lower concentration of transient tracers, the ‚apparent saturation‘ of the mixture of newly formed and older waters used in Raimondi et al. (2021) does not depend only on the saturation of the newly formed water, but also on the age of the older waters and the degree of mixing.

In the abstract and conclusion section, the authors state that “the total Cant inventory increases … almost in unison with the rising CO2 in the atmosphere” and that “only a reduction of the Atlantic ventilation over several decades would severely change this relationship”. However, the second conclusion is not directly supported by the results of this study. **It remains unclear why ventilation changes need to be effective for several decades in order to impact the sensitivity of the oceanic sink for anthropogenic carbon**. Wouldn’t a hypothetical collapse of the AMOC over the course of a single decade already drastically change the accumulation of Cant? I suggest removing this statement or argue more carefully and comprehensively.

We will remove that statement.

The overall **quality of the figures** is high, but a few edits could help to improve the interpretability:

1. Avoid rainbow colour scale for sequential data and use one of the plenty appropriate alternatives, such as the Viridis, Brewer or Scientific colour scales

   We will use the Brewer colour scales instead.

2. Avoid unevenly spaced breaks in colour scales

   We think that unevenly spaced colour scales are sometimes necessary, especially for salinity. Using an even spaced colour map for salimity would lead to either a very large number of intervals, or the contrast in the deep waters is completely missing (all deep waters have the same colour). For Cant, the error is (partially) proportional to the concentration, so small intervals at high concentrations would be much smaller than the error, whereas at low concentrations small intervals are reasonble and show significant differences.

3. Use the fine grid onto which Cant was interpolated instead of corse boxes to produce maps

   We will ty that approach, but if the maps look too scattered, we will stick to the coarser boxes. Another reason for preferring the coarser boxes is that it shows the mean cant storage rate for a larger area, which might be more important than small scale differences. On the fine scale, it is not easy or even impossible to identify the mean storage rate for a larger region.

The **text** is generally well structured. However, I would suggest moving the somewhat lengthy description of water masses from the methods to the appendix, and restructure the results section such that you start with the most important findings, which to my understanding are the decadal anomalies in the Cant accumulation. In contrast, the general patterns in Cant are well known and have been described and attributed extensively in previous studies. Hence, this part of the results could be compressed.

We will follow the suggestions of the reviewer by moving the description of water masses to the appendix and change the order in the results section.

Minor comments

Please refer to the annotations in the attached pdf file for additional minor comments, and consider them as an integral component of this review.

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