

Review of “The evolution of anthropogenic carbon accumulation in the North Atlantic Ocean: the influence of physical and chemical drivers over the last three decades” by Wimart-Rousseau et al. for Biogeosciences

In this response, the “original manuscript” refers to the first submitted manuscript that has been evaluated by the reviewer; and the “revised manuscript” refers to the manuscript that has been modified according to the reviewer’s comments. Comments from the reviewer are pasted below in black font; our point-by-point responses immediately follow in blue font. Blue italic sentences are those that have been modified/added in the revised manuscript. When indicated, line numbers refer to the new version of the manuscript (Pdf version). We have also submitted a document with the “track changes” function activated, which should help the reviewer in figuring out the changes.

Paper synopsis

This paper is based on a 30 years dataset and aims to quantify the variability of anthropogenic carbon (Canth) on a spatio-temporal scale over the whole North Atlantic. In addition, the paper aims to identify the drivers of Canth variability. The drivers are the North Atlantic Oscillation (NAO), the Atlantic Meridional Overturning Circulation (AMOC), water mass volume changes and Canth concentration. All these drivers act on Canth variability but at different temporal and spatial scales.

The paper is well written, figures are clear and the main text is comprehensive. I particularly appreciate the comparison between NAO-influence and AMOC influence on Canth variability. However I have two concerns:

- (1) The manuscript is long, and there are a lot of analyses. Without changing the subregional division and the density layers division, I think the authors should summarize some of their findings. It would help the reader to follow the manuscript. Sometimes I felt a bit loss and had to go back several pages to check the figure or read the main text again.

We appreciate the reviewer’s kind comments about the quality of the manuscript and appreciate their remarks regarding length and detail. Unfortunately, due to the nature of the subject matter (full North Atlantic assessment of individual water masses and their carbon accumulation), this necessitates a thorough examination. The length of our submission (10 figures, 5 supplementary figures) compares similarly with other studies covering similar content (e.g., Steinfeldt et al., 2024, 12 figures, 4 supplementary figures; Liu & Tanhua, 2026, 18 figures, 0 supplementary). However, we agree with the referee that the reader would be helped by adapting the text, so we have shortened sentences where possible and added summaries at the end of each section to highlight the main findings and “take-home” messages.

“Overall, the mean C_{Anth} distribution in the NA reflects the combined control of surface-driven uptake, thermocline structure, and overturning circulation. Elevated concentrations at low latitudes are tightly linked to thermal stratification, while high-latitude provinces exhibit broader vertical distributions driven by deep convection and water-mass transformation. Subpolar provinces stand out as the most efficient C_{Anth} storage regions per unit area — approximately 25% more efficient than the basin mean — while subtropical and tropical provinces dominate total basin inventories due to their larger spatial extent and water volumes, thus highlighting a clear regional contrast between storage efficiency and total storage capacity.” (L. 311-316)

“Taken together, these results show that interannual C_{Anth} variability across the NA is primarily governed by water-mass volume changes rather than C_{Anth} concentration anomalies, and that this variability is spatially structured according to the dominant physical regime. In subpolar and Nordic provinces, coherent multi-layer anomalies reflect convection-driven water-mass renewal, with the NAO emerging as the primary atmospheric driver. In contrast, subtropical and tropical provinces exhibit more episodic variability, largely confined to surface and intermediate layers, where volume anomalies do not systematically translate into C_{Anth} concentration changes. Critically, these interannual fluctuations modulate not only short-term C_{Anth} anomalies but also the regional partitioning of long-term storage, underscoring that the NA carbon sink cannot be fully characterised by a single linear trend and motivating a quantitative assessment of the role of the NAO and AMOC in driving this variability.” (L.501-509)

“In summary, accumulated AMOC variability thus acts through two complementary pathways: modifying water-mass volumes and enriching tracers at the formation site (captured by OSNAP) and redistributing that signal downstream via the return limb (captured by RAPID). When viewed alongside the NAO (Fig. 7), the largely inverted spatial patterns confirm that the two indices reflect fundamentally different aspects of C_{Anth} variability — the NAO driving rapid atmospheric responses, the accumulated AMOC integrating these into a slow, basin-scale oceanic signal — together spanning the full range of timescales over which North Atlantic C_{Anth} storage evolves.” (L. 697-702)

“Together, these results confirm that NAO variability is the primary driver of short-term (annual-to-decadal) C_{Anth} modulation in the subpolar gyre, acting through its control on winter convection depth and water-mass renewal. In both basins, C_{Anth} saturation ratios confirm that sustained positive NAO periods drive storage progressively closer to the atmospheric signal. Taken with Section 3.4.2, these findings emphasise a temporal hierarchy of controls: the NAO dominates interannual-to-decadal C_{Anth} fluctuations through direct atmospheric forcing, while accumulated AMOC anomalies integrate and propagate these signals over longer timescales and across broader latitudinal ranges.” (L. 766-772)

- (2) In my opinion, the “Methods” section can be improved. For instance, the authors could detail how they computed the C_{Anth} inventories and the area-normalized

Canth inventories. How is the surface of each subregion computed? Canth saturation is only introduced at the end of the manuscript. How was it computed? This explanation should be added in the “Methods” section. In the main text, the authors describe how accumulated AMOC anomalies are computed and they justify their choice. However, it comes within the “Results” section, and this should be moved to the “Methods” section.

Following both referee’s comments and suggestions regarding the needed improvement of the Data and Methods section, substantial changes and modifications have been implemented in the revised manuscript. Please find them listed below:

About the C_{Anth} inventories, area-normalisation and saturation computations, a new section has been added in the revised manuscript:

“2.2 C_{Anth} data processing

C_{Anth} column inventories for each province and density layer were computed by multiplying the annually averaged C_{Anth} calculated values (in $\mu\text{mol kg}^{-1}$) by the mean seawater density (in kg m^{-3}) and the corresponding water mass volume derived from ARMOR3D (in m^3 , see Section 2.3) for each year, layer and region considered, yielding absolute C_{Anth} inventories expressed in moles. These values were converted to petagrams of carbon (PgC) by using the molar mass of carbon (12.01 g mol^{-1}). To allow inter-province comparison while removing the impact of regional spatial extent, C_{Anth} inventories were also normalised by the surface area of each province (in mol m^{-2}). The spatial boundaries of all defined provinces (see Section 2.5) were extracted from the respective shapefiles, and their areas (in m^2) were calculated from geographic coordinates (latitude and longitude) using the WGS84 ellipsoid as the reference. To assess how closely calculated C_{Anth} concentrations approach the theoretical maximum set by atmospheric CO_2 forcing, a C_{Anth} saturation ratio, defined as the ratio between actual C_{Anth} concentration and $C_{Anth, 0}$ has been computed following Fröb et al. (2016), where $C_{Anth, 0}$ is defined as:

$$C_{Anth, 0}(t) = C_{eq}(T, S, TA^0, p\text{CO}_2(t)) - C_{eq}(T, S, TA^0, p\text{CO}_2 = 280\text{ppm}) \quad (2)$$

Here, C_{eq} represents the total inorganic carbon at air-sea equilibrium with respect to the atmospheric CO_2 concentration at time t , computed using CO2SYS van Heuven et al. (2011) with preformed TA and $p\text{CO}_2$ as input variables. Annual mean of atmospheric $p\text{CO}_2$ concentrations from the Mauna Loa record for each year t were used. The preformed TA used here is derived directly from the ϕC_0^T method (see Section 2.1) to ensure internal consistency with the C_{Anth} estimates. For each province and year, T , S , and TA^0 were averaged across all GLODAP data points located above the annual maximum Mixed Layer Depth (MLD), defined as the maximum monthly-mean MLD within each province and year. When no data were available for a given province-year combination, values were estimated from linear trends fitted to the available time series. Values of saturation lower than 100% indicate that the water mass has not yet equilibrated with the accumulated anthropogenic CO_2 forcing since the pre-industrial era.

To perform the calculations, the carbonic acid dissociation constants K_1 and K_2 from Mehrbach et al. (1973) as refitted by Dickson and Millero (1987) and the dissociation constant for HSO_4^- from Dickson (1990) were used. Uppström (1974) was used to calculate the ratio of total boron to salinity and Dickson and Riley (1979) to calculate the hydrogen fluoride constant.” (L. 131-156)

About the accumulated AMOC anomalies: “In this study, rather than raw transport signals, 12-month running means of AMOC strength were used to reduce short-term and seasonal variability (Jackson et al., 2019) and facilitate comparison with model outputs. Following Bryden et al. (2014), these values were then used to derive the accumulated AMOC anomalies by integrating AMOC deviations at both sites from a 10-year moving baseline, providing a physically consistent measure of the cumulative circulation anomaly that integrates persistence and magnitude over multi-year timescales (see Supp. Fig. A1). This avoids spurious correlations with short-term variability and better reflects the long-term redistribution of heat, freshwater, and carbon by the overturning circulation. Hence, the 12-month running mean values characterise the temporal evolution of AMOC transport while the accumulated anomaly captures the integrated, multi-year influence of overturning variability on carbon storage.” (L. 188-195)

The rest of my comments are listed below.

We thank the reviewer for his constructive and helpful comments about our paper, his positive opinion concerning the manuscript and its aim to disentangle the drivers of the observed change. We have followed his advice to reduce the manuscript’s length to enhance clarity and readability. Comments and suggestions made by the referee on text and/or figure/table edits are discussed below and addressed in the revised version of our manuscript.

Major comments

Abstract

In the abstract, I would add one sentence to detail how you compute C_{Anth} . Say that you use the ϕC_0^T back-calculation method.

Following the referee’s recommendation, the information in the revised manuscript: “Using GLODAP data, C_{Anth} estimates were derived for the period 1993-2021 using a back-calculation ϕC_0^T method, with the aim to assess the drivers of observed changes and evaluate the role of key oceanic processes, such as circulation and ventilation.” (L. 9-11).

Carbon data

If I understand correctly, to obtain your C_{Anth} data, you use the GLODAPv2.2023 variables (DIC, TA, O2...) as inputs for the ϕC_0^T back-calculation method. Did you

compare your results with the GLODAPv2 Canth database (Lauvset et al., 2016)? This database uses the TTD method to compute Canth and I would be curious to see if there are differences between your estimates and Lauvset et al. (2016) estimates.

Concerning the uncertainty, it is true that the original uncertainty for the ϕC_0^T backcalculation method is $\pm 5.2 \mu\text{mol kg}^{-1}$. However, concerning the $\pm 5.9 \mu\text{mol kg}^{-1}$ and $\pm 3.9 \mu\text{mol kg}^{-1}$ values that we found with Monte Carlo simulations, they represent the uncertainty of our whole methodology chain (Argo T/S/O2 data + Neural networks nutrients and TA/DIC + ϕC_0^T back-calculation method). So, these values are not uncertainties for the ϕC_0^T back-calculation method but uncertainties resulting from our whole methodology.

The referee is correct: C_{Anth} values were derived using the ϕC_0^T back-calculation method. Following his suggestion, a comparison with the GLODAPv2 C_{Anth} database has been performed (Figs. 1 & 2 below, not included in the revised manuscript). However, this product is normalised to the year 2002 and does not directly provide density information. To enable a physically meaningful comparison on a neutral density axis, we computed the neutral density γ for each GLODAPv2 grid cell from the accompanying temperature and salinity climatologies (GLODAPv2.2016b.temperature.nc and GLODAPv2.2016b.salinity.nc), similarly to what has been done in the manuscript.

For each of the 13 biogeochemical provinces, Fig. 1 shows the mean $C_{\text{Anth}} \pm$ inter-annual range from this study (black error bars, one per neutral density layer) alongside the mean $\pm$ standard deviation of the GLODAPv2 climatological C_{Anth} binned into the same density layers (blue error bars). Across all provinces/regions, the two datasets show consistent vertical structure with C_{Anth} decreasing systematically with increasing neutral density (i.e., with depth), and the GLODAPv2 profile falling within or close to the inter-annual variability range of our estimates in most layers. A modest positive offset in our estimates relative to GLODAPv2 (typically lower than $5 \mu\text{mol kg}^{-1}$) was expected and is observed. This shift can be explained by the different temporal coverage of the two datasets. As C_{Anth} has increased progressively with the rise in atmospheric CO_2 and anthropogenic carbon inputs, our dataset, which extends to 2021, naturally captures higher C_{Anth} concentrations than the GLODAPv2 climatology, which is based on measurements collected from 1972-2013 and centered in the year 2002. Additionally, methodological differences may contribute to the observed (rather small) differences, as the TTD method used to derive GLODAPv2 C_{Anth} data relies on CFC distributions as ventilation tracers, which have been shown to be decoupled from C_{Anth} transport in the subpolar North Atlantic (Álvarez & Gourcuff, 2010; 10.1016/j.jdsr.2010.03.0069).

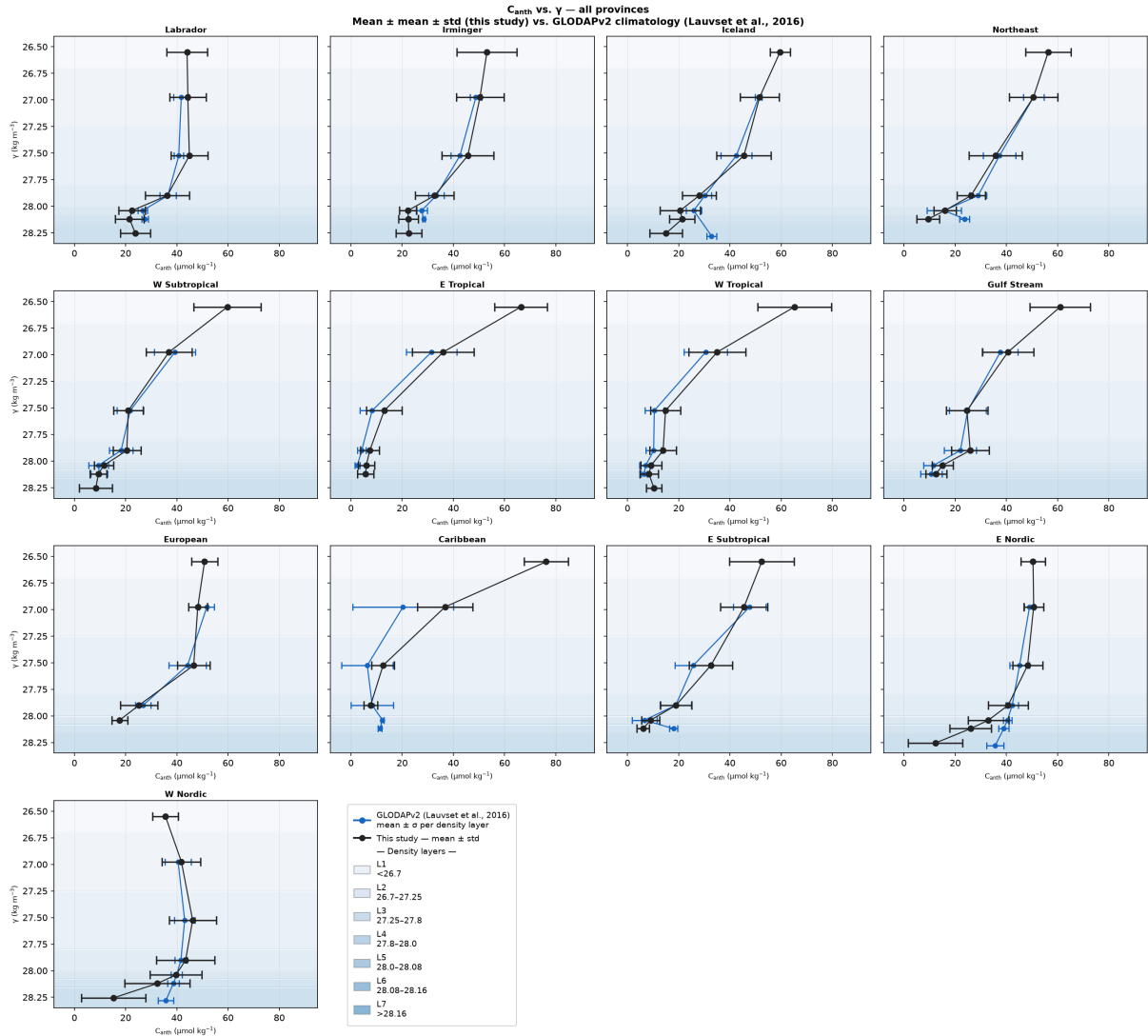


Figure 1 (not included in the revised manuscript). Comparison of C_{Anth} estimates between this study (C_{Anth} derived using the ϕC_0^T back-calculation method; black dots) and the GLODAPv2 C_{Anth} mapped climatology from Lauvet et al., 2016 (derived using the TTD back-calculation method; blue dots) for the 13 modified Longhurst provinces considered in this study. Values were binned into the same density layers, with neutral density computed from the GLODAPv2 temperature and salinity climatologies. Coloured bands indicate the seven neutral densities used in this study. Please note that all derived C_{Anth} estimates were used in this analysis, including those that were subsequently rejected by the secondary quality control. As a result, the estimated trends may be subject to a larger bias in comparison with the dataset used in the study.

As a complementary check, we plotted a point-by-point scatter of our ϕC_0^T estimates against the GLODAPv2 TTD climatology, matched by geographic location and depth for each GLODAP profile (Fig. 2). Across all 13 provinces, our estimates show a strong correlation with GLODAPv2 ($r^2 = 0.65\text{--}0.90$ in most regions), indicating overall consistency between the two back-calculation methods and the resulting C_{Anth} estimates. However, substantial differences are observed in some provinces (i.e., the Caribbean, tropical provinces, and Labrador Sea), where the temporal trend in C_{Anth} is strongest, while scatter increases at shallow depths, consistent with stronger seasonal and interannual variability that is not captured by a time-averaged climatology. In addition, the European and Caribbean regions show a poorer relationship with the climatology, likely reflecting both the large biogeochemical variability of

these regions and the substantially smaller number of data points compared with the other provinces. Overall, the agreement is strongest at depth (>1500 dbar), where deep-water C_{Anth} is both methodologically better constrained and less temporally variable. Hence, these comparisons indicate that our derived C_{Anth} values are broadly consistent with the literature and provide a reliable representation of previously reported values.

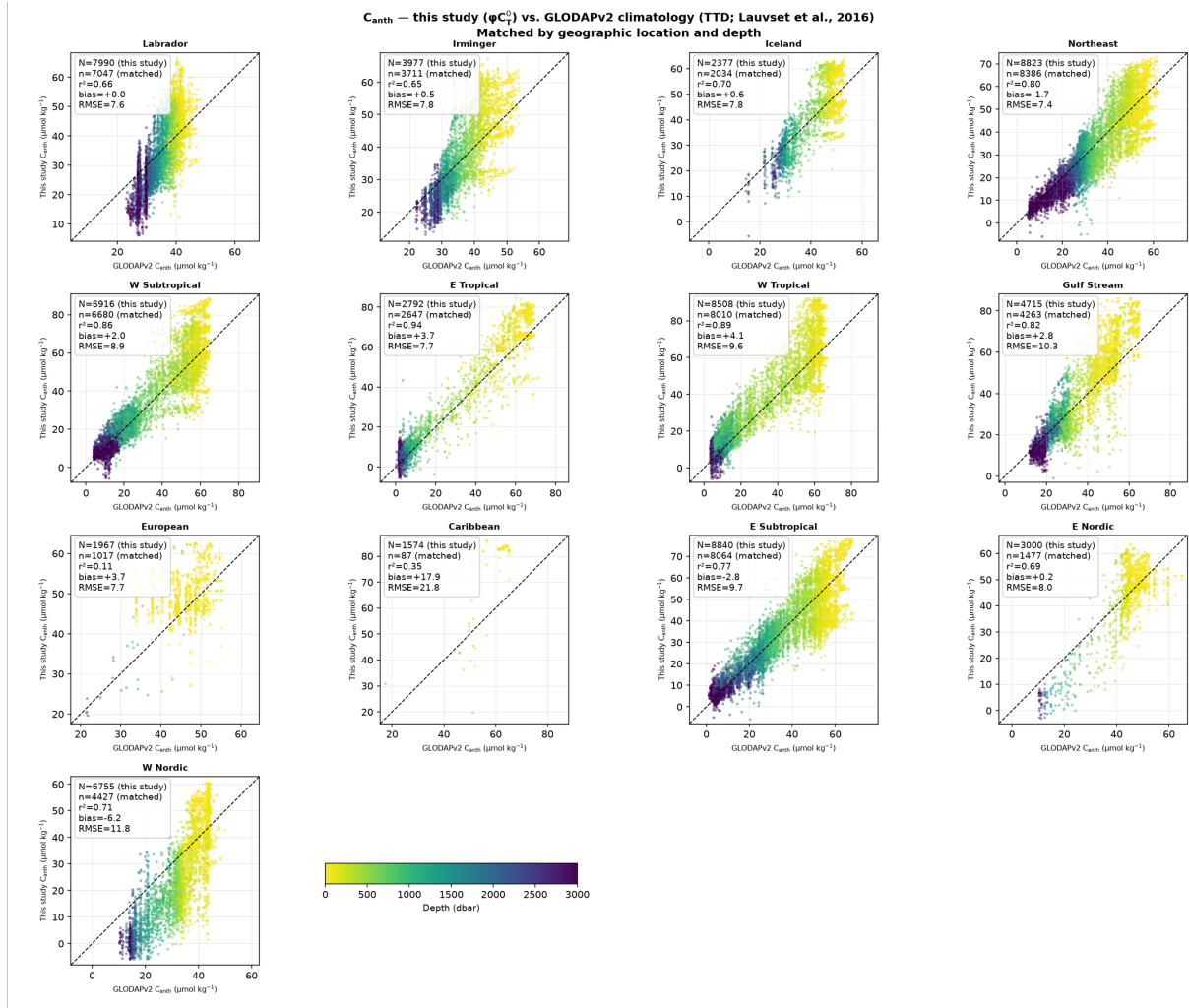


Figure 2 (not included in the revised manuscript). Scatter plots comparing the C_{Anth} values presented in this study (derived using the ϕC_0^T back-calculation method; y-axis) with the GLODAPv2 C_{Anth} database (derived using the TTD back-calculation method; x-axis) for the 13 modified Longhurst provinces considered in this study. Colours indicate depth (dbar). The inset reports the statistics for each sub-region, including the coefficient of determination (r^2), the number of C_{Anth} data points available in this study (N), and the number of data points matched with GLODAPv2 (n). Please note that all derived C_{Anth} estimates were used in this analysis, including those that were subsequently rejected by the secondary quality control. As a result, the estimated trends may be subject to a larger bias in comparison with the dataset used in the study.

Taken together, we believe that these comparisons provide strong evidence that our C_{Anth} estimates are consistent with the GLODAPv2 TTD climatology and that the two methods agree to within the expected temporal drift of the oceanic C_{Anth} signal.

Additionally, we would like to point out that, in the manuscript, comparisons with the literature have been performed and showed consistent values (see Section 3.2), notably with the estimates of Steinfeldt et al., 2024 (<https://doi.org/10.5194/bg-21-3839-2024>), which is a TTD-based estimate of the temporal changes in anthropogenic carbon in the North Atlantic.

About the uncertainty: We thank the referee for spotting this mistake. In the revised manuscript, the uncertainty associated with the C_{Anth} determination method has been modified accordingly.

Water mass volumes and mixed layer depth

I agree with the authors that the density threshold approach to compute MLD is better than the temperature-based criterion. However, I would like to point out that the threshold of 0.03 kg m^{-3} overestimates MLD values in the Irminger and Labrador by up to several hundred meters (Piron et al., 2016 ; <http://dx.doi.org/10.1016/j.dsr.2015.12.012>). For these basins, the recommended threshold value is 0.01 kg m^{-3} . On Figure 10 you show the MLD for the Irminger and Labrador basin so it would be more appropriate to use the 0.01 kg m^{-3} value.

We thank the referee for this relevant suggestion regarding the threshold used to determine the mixed layer depth, as proposed by Piron et al. (2016). In the revised manuscript, this recommendation has been implemented, and the MLD criterion has been modified accordingly. The results presented in the manuscript, and notably those shown in the revised Figure 10, have therefore been recalculated using the updated criterion.

In addition, following a comment from the second referee, we carefully inspected the exceptionally large MLD value ($>3000 \text{ m}$) identified in the Labrador Sea in November 1996. After examining the corresponding temperature, salinity, and density profiles, we concluded that this value was not representative of the mixed-layer depth and decided not to retain it in the analysis. This specific case and the procedure used to assess such anomalous values have now been clarified in the revised Materials and Methods section (L. 171-176): “*However, since this method can overestimate the MLD during periods of intense winter deep convection, we conducted a visual inspection of the temperature, salinity, and density profiles associated with exceptionally deep MLD values. This additional inspection was used to assess the physical consistency of the automatically derived MLD values. When a value identified by the threshold method was found to be inconsistent with the corresponding vertical profiles, the MLD was excluded from the analysis. In particular, exceptionally large values were carefully examined to avoid retaining spurious estimates associated with anomalous or poorly resolved profiles.*”

Biogeochemical provinces and density layers

The authors evaluate the C_{Anth} concentration, inventories, etc. along seven neutral densities. In my opinion, they should introduce here which water masses these neutral densities represent. Especially because it is introduced in the results section while, in

my opinion, it should be introduced in the methods section. For instance, line 226 the North Atlantic Deep Water is defined ($\gamma_n > 28.16 \text{ kg m}^{-3}$) while it should be done before. The reader could then directly understand why the authors selected these seven neutral densities.

As requested by both referees, the density intervals' meanings have been clarified in the revised manuscript: “From the surface to the bottom, the seven selected density intervals tend to represent: the surface waters ($\gamma_n < 26.7 \text{ kg m}^{-3}$), the North Atlantic Central Waters ($26.7 < \gamma_n < 27.25 \text{ kg m}^{-3}$), the Antarctic Intermediate Waters ($27.25 < \gamma_n < 27.8 \text{ kg m}^{-3}$), the Labrador Sea Waters ($27.8 < \gamma_n < 28.0 \text{ kg m}^{-3}$), the upper North Atlantic Deep Waters ($28.0 < \gamma_n < 28.08 \text{ kg m}^{-3}$), the lower North Atlantic Deep Waters component with the Iceland-Scotland Overflow Waters ($28.08 < \gamma_n < 28.16 \text{ kg m}^{-3}$), and the lower North Atlantic Deep Waters component with the Denmark Strait Overflow Waters ($\gamma_n > 28.16 \text{ kg m}^{-3}$).” (L. 214-219).

Regional distribution and average states of *Canth* in the North Atlantic Ocean

I like Figure 2 because it clearly shows that warm waters contain high *Canth* concentrations. However, to help the reader, I would add a linear regression fit on each panel and maybe its R^2 value to illustrate this result. Adding the R^2 value could, for instance, show the noisier relationship in the subpolar regions compared to the subtropical/tropical regions. It is just a suggestion and, doing so, could overload the Figure.

We thank the referee for this pertinent suggestion, which has been implemented in the revised manuscript (see Fig. 3 below, added in the revised manuscript). In the main text, the strength of the relationships is now discussed too, based on the updated Fig.2.

“Indeed, these regions show tight $\theta - C_{Anth}$ correlations ($R^2 = 0.79-0.91$), consistent with a well-stratified water column where C_{Anth} concentrations are strongly linked to temperature. In contrast, the shallow European Shelf-Sea region (mean depth 107 m) exhibits a narrower C_{Anth} concentration range, largely due to limited recent data that precludes firm conclusions, despite enclosed seas typically being more strongly influenced by anthropogenic carbon inputs (e.g., Borges et al., 2006). Intermediate patterns occur in regions such as the Gulf Stream and Northeast, which bridge subtropical clarity and subpolar complexity, reflecting combined effects of advection, mixing, and surface exchange. By contrast, Nordic and subpolar regions (e.g., Nordic-W/E, Labrador; Irminger; Iceland) display broader ranges and noisier relationships, where interannual variability, deep convection, and overturning obscure clearer C_{Anth} -temperature structures. In these regions, lower R^2 values (0.11-0.74) have been derived, reflecting not an absence of the $\theta - C_{Anth}$ relationship, but rather the smaller thermal range of these processes such as deep convection, which introduces waters of similar temperature but contrasting C_{Anth} content, adding variability beyond what temperature alone can capture.” (L. 235-245).

Line 212-215: I agree that Canth concentration is higher in the Irminger and Iceland basins compared to the Labrador basin within the density range $27.25\text{--}27.8\text{ kg m}^{-3}$ whereas the opposite pattern is observed for the density range $27.8\text{--}28\text{ kg m}^{-3}$. However, the evidence for an east-west enrichment within the $27.8\text{--}28\text{ kg m}^{-3}$ layer is less convincing because it falls within the uncertainty of the method. Using the values the authors give in the main text, Canth concentration increases from $31\pm 5.2\text{ }\mu\text{mol kg}^{-1}$ in Iceland basin to $36\pm 5.2\text{ }\mu\text{mol kg}^{-1}$ in Labrador basin, a difference that is not statistically significant.

We agree with the reviewer that the $5.2\text{ }\mu\text{mol kg}^{-1}$ difference between the Iceland and Labrador basins within the $27.8\text{--}28\text{ kg m}^{-3}$ -layer falls within the method uncertainty. The text has been revised to describe this as suggested rather than an established pattern, with an explicit caveat regarding the method uncertainty.

“Within the $27.8 < \gamma_n < 28\text{ kg m}^{-3}$ layer, an east-west enrichment is suggested ($31\text{ }\mu\text{mol kg}^{-1}$ in Iceland to $36\text{ }\mu\text{mol kg}^{-1}$ in Labrador; though this difference approaches the method uncertainty of $5.2\text{ }\mu\text{mol kg}^{-1}$ and should be interpreted with caution), while the overlying [...].” (L. 263-266)

Interannual variability in the Canth storage

Line 423: I do not agree with “basin-wide inventory increases steadily”. Figure 4 and several papers (Gruber et al., 2019; Müller et al., 2023; Steinfeld et al., 2024) show that this increase is not steady over time. I think, what really bothers me is the word “steadily”.

We thank the referee for picking this up: the word ‘steadily’ has been replaced with “significantly” in the revised manuscript.

Interaction between the NAO and the Canth evolution

I would be careful with Figure 7 and its analysis. If I understand correctly, the numbers over the while labels are the coefficient of determination (R^2). For the Nordic NA provinces, the maximum R^2 value is 0.4, which is reported in the main text. However, most of the R^2 values range from 0.0 to 0.1 for these regions. This result indicate that NAO variability is poorly correlated with Canth concentration residuals, Canth inventory residuals and water mass volume anomalies. By consequence, NAO variability explains only a small part (~10%) of the interannual variance of Canth concentration/inventory residuals and water mass volume anomalies in most of the Nordis NA provinces and over most of the density layers. I think it should be mentioned somewhere.

Same applies to Figure 8 where most of the R^2 values range from 0.0 to 0.1.

We thank the reviewer for this careful and important observation. The referee is correct: colors in Figures 7 and 8 indicate the regression slopes between the considered variables (accumulated AMOC or NAO) and the residuals (of either water mass volumes, C_{Anth} concentrations, or C_{Anth} inventories), the white labels show the R^2 , and cells have been crossed when the p-value found was lower than 0.5.

Furthermore, we fully agree that low R^2 values characterise most region-density interval combinations in Figures 7 and 8, and that this limitation deserves explicit acknowledgement in the manuscript. However, it should be noted that Figs. 7 & 8 have been redrawn in the revised manuscript with the residuals now computed exclusively from years with direct observational coverage. For years without direct observations, no anomaly was computed and those years do not contribute to the regression. The overall spatial patterns and regression slopes in Figs. 7 and 8 are unchanged in comparison with the original Figures 7 and 8, confirming the robustness of the results, though the R^2 values are slightly modified as expected given the reduced number of data points entering the regression. In the revised manuscript, this point has been addressed directly at both relevant locations. For Fig. 7 (NAO), the following has been added: *“In these areas, while the R^2 values are typically low (0-0.2 across most regions and layers), the regression slopes (sensitivities) indicate that positive NAO phases are mostly associated with enhanced C_{Anth} content and storage. Hence, NAO variability can explain up to 80 % of the interannual variance in specific cases, particularly for the C_{Anth} concentration residuals, though these high values in data-sparse cells should be interpreted with caution given the limited degrees of freedom when only measured years are retained.”* (L. 521-525). For Fig. 8 (AMOC), the following has been added: *“Although the coefficients of determination (R^2) are generally modest (0.0-0.5), this is expected given the complexity of regional variability. In association with the limitation of the observational timescale, multiple processes add noise to the signal and reduce the proportion of variance explained by AMOC alone. In addition, high R^2 values in data-sparse cells should be interpreted with caution given the limited degrees of freedom when only measured years are retained (i.e., in the Caribbean region). Nonetheless, the emergence of consistent spatial clusters across density layers strengthens confidence in the robustness of these relationships.”* (L. 716-721). Finally, we would like to highlight that the low individual R^2 values are also partly a consequence of the very low effective degrees of freedom in this dataset: both the accumulated AMOC anomaly index and the C_{Anth} anomaly time series exhibit strong temporal autocorrelation, reducing the effective sample size well below the 30-year record. Under these conditions, the spatial coherence of regression patterns across adjacent regions and density layers, rather than the magnitude of any individual R^2 , is the primary basis for our physical interpretations.

NAO and AMOC: relationships and controls on the C_{Anth} content

Line 619-623: Here the authors justify the choice of accumulated AMOC anomalies and how it is computed. I think this justification much come before, when the accumulated AMOC is first introduced or even in the “Methods” section.

We agree with the referee that the rationale for using accumulated AMOC anomalies rather than the raw transport signal was not sufficiently clear in the Methods section of the original manuscript, and that the corresponding explanation appeared too late in the text. In the revised manuscript, we have clarified this point by modifying the Methods section as follows: “*In this study, rather than raw transport signals, 12-month running means of AMOC strength were used to reduce short-term and seasonal variability (Jackson et al., 2019) and facilitate comparison with model outputs. Following Bryden et al. (2014), these values were then used to derive the accumulated AMOC anomalies by integrating AMOC deviations at both sites from a 10-year moving baseline, providing a physically consistent measure of the cumulative circulation anomaly that integrates persistence and magnitude over multi-year timescales (see Supp. Fig. A1). This avoids spurious correlations with short-term variability and better reflects the long-term redistribution of heat, freshwater, and carbon by the overturning circulation. Hence, the 12-month running mean values characterise the temporal evolution of AMOC transport while the accumulated anomaly captures the integrated, multi-year influence of overturning variability on carbon storage.*” (L. 188-195)

In addition, we would like to point out that the accumulated AMOC anomaly time series for both sites (OSNAP and RAPID) have been added to Fig. S1 to further clarify the approach and facilitate interpretation.

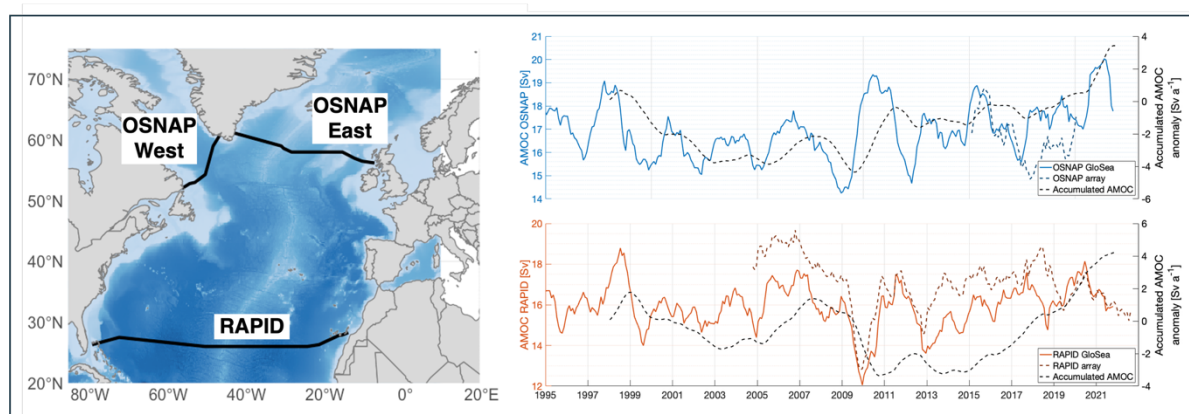


Figure A1 – Supplementary Material (included in the revised manuscript). Time-series of the 12-month running mean AMOC values acquired across the OSNAP array in the subpolar North Atlantic (top panel) and the RAPID array at 26°N (bottom panel). On both plots, two datasets are shown: OSNAP or RAPID array observational data (dashed colored lines) and GloSea5 global ocean reanalysis data (full colored lines). Dashed black lines on both panels represent the accumulated AMOC anomaly time series, derived following Bryden et al. (2014) using a 10-year moving baseline. The inset map shows the locations of the two arrays.

Local processes and events: the peculiar subpolar regions

I wonder why the authors chose to show only the density layers 27.25-27.8 and 27.8-28 kg m⁻³.

These two layers were selected because they represent the SPMW/LSW dipole, i.e., the pair of density classes showing the most contrasting and pronounced response to NAO-driven convection variability in the Labrador and Irminger Seas. In the revised manuscript, a short justification has been added as follows: *“We focus on the two density layers of the SPMW/LSW dipole ($27.25 < \gamma_n < 27.8$ and $27.8 < \gamma_n < 28 \text{ kg m}^{-3}$), identified in Section 3.4.2 as the pair most directly and contrastingly influenced by deep convection variability in the subpolar gyre.”* (L. 727-729)

Looking at Figure 10, I wonder what happened in the Labrador Sea, for C_{Anth} saturation between 1998 and 2001. That’s the only moment where the yellow line passes below the purple one. It indicates a higher saturation for the denser layer comparable to the lighter layer, right? Do the authors have an hypothesis for this particular period?

The apparent crossing of the two density layers in the Labrador Sea around 1999-2001 is based on extremely sparse observations (only one cruise, data sampled in the south-eastern part of the province; see Fig.3 below, not included in the revised manuscript). Indeed, the year 1999, the only year with direct measurements during this period, contains just 2 profiles in the $27.25\text{-}27.8 \text{ kg m}^{-3}$ layer (yellow line, SPMW) and 8 profiles in the $27.8\text{-}28 \text{ kg m}^{-3}$ layer (purple line, LSW), all from a single station at 51°N , 43°W , well outside the main deep convection zone ($\sim 55\text{-}60^\circ\text{N}$). It can also be noted that the surrounding years (1998, 2000, 2001) contain no direct observations in this region and layer and are fully reconstructed by interpolation, which can also explain why the crossing appears smooth and extended in the figure despite being anchored to a single anomalous data point.

As hypotheses, we propose two contributing mechanisms: (1) the intense NAO+ convection of the mid-1990s likely eroded the SPMW layer through densification into LSW, leaving a poorly ventilated SPMW with anomalously low C_{Anth} in 1999 and/or (2) the southern station location may be influenced by lateral advection of older, C_{Anth} -depleted water masses from the subpolar gyre, unrepresentative of the Labrador interior. However, it can be noted that this feature does not alter the interpretation of the broader NAO-driven dynamics discussed in the paper. In the revised manuscript, Figure 10’s caption has been amended to highlight this data sparsity in 1999 specifically: *“Note: the apparent inversion between density layers in the Labrador Sea around 1999 is based on two observations from a single station at the southern basin margin (51°N , 43°W); adjacent years are reconstructed (no direct observations) and should be interpreted with caution.”* (Page 32)

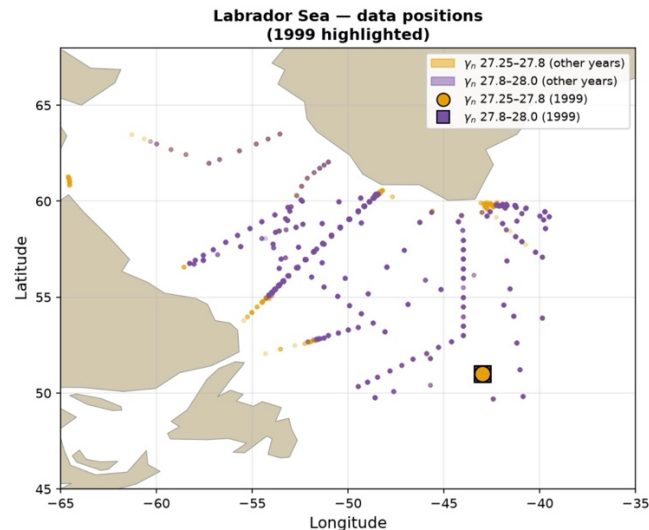


Figure 3 (not included in the revised manuscript). Geographic distribution of the inferred C_{Anth} values in the Labrador Sea province, with specific markers for the year 1999. Only data for the 27.25-27.8 kg m^{-3} (yellow line) and 27.8-28 kg m^{-3} (purple line) density intervals are shown to enhance clarity.

Minor comments

Line 60: remove parenthesis around C_{Anth} .

The bracket has been deleted.

Line 72-73: “The key behaviour... processes” please rephrase, I feel there is a verb missing.

The sentence has been modified as requested: “*The key behaviour of this region with respect to C_{Anth} uptake and storage is governed by two dominant processes: (1) the northward advection of C_{Anth} -rich subtropical waters, and (2) deep winter convection, particularly in the Labrador and Irminger Seas, which facilitates the subduction of C_{Anth} -enriched surface waters into the interior ocean (Körtzinger et al., 1999; Pérez et al., 2008; Pérez et al., 2013; Gruber et al., 2019; Ridge and McKinley, 2020).*” (L. 69-73)

Line 84: replace “anthropogenic CO2” by “ C_{Anth} ”.

The word has been replaced as suggested.

Line 88: replace “anthropogenic carbon” by “ C_{Anth} ”.

The suggestion has been implemented.

Line 127: you excluded 37 C_{Anth} data points but which percentage of your database does it represent? I guess a tiny fraction, looking at Figure 1

We thank the referee for suggesting that we report the percentage of the dataset removed during the filtering process. This information has been added to the revised manuscript (i.e., 3.1% of the dataset was removed after filtering, L.123).

Line 146: “spanning Labrador Sea”?

The sentence has been modified and clarified: “*The OSNAP (Overturning in the Subpolar North Atlantic Program) array, extending from the Labrador continental shelf to Scotland across the subpolar North Atlantic, provides AMOC records for 2014-2022 (Fu et al., 2025), while RAPID (RAPID-Meridional Overturning Circulation and Heatflux Array-Western Boundary Time Series) at 26°N has delivered continuous transport estimates since 2004 (Moat et al., 2024)*” (L. 178-182)

Line 162-165: “In this study... area (Fig.1)” this sentence is quite long and difficult to follow. Please separate it into two sentences.

The sentence has been split as requested: “*In this study, the North Atlantic Ocean was spatially clustered into distinct regions. The regionalisation broadly follows the approach presented in Steinfeldt et al. (2024), with a slight modification of the widely used Longhurst (2007) biogeochemical provinces, resulting in 13 provinces across the study area (Fig. 1).*” (L. 205-210)

Line 169: remove the parenthesis at the end of the line.

The bracket has been deleted.

Line 175: there is a parenthesis and a comma directly after. And then there is no closing parenthesis.

We thank the referee for spotting this mistake. The sentence has been corrected in the revised manuscript.

Line 210: “Notably... buffering capacity” I guess this sentence refers to the density layer $<26.7 \text{ kg m}^{-3}$? Please add this information.

It has been clarified in the revised manuscript: “*Notably, in the lightest density layer ($\gamma_n < 26.7 \text{ kg m}^{-3}$) Nordic-E/W, Labrador, Irminger, and Iceland provinces show mean concentrations [...]*” (L. 261)

Line 213: “27.26-27.8” units are missing.

The unit (i.e., kg m^{-3}) has been added

Line 273: “panel b” of Figure 5, right?

We are referring to panels b of Fig. 4 & 5. It has been clarified in the revised manuscript.

Line 290-292: Please rephrase, I don't understand this sentence

The sentence has been rephrased: “*While the strongest trends are observed in the European Shelf province ($\gamma_n = 27.25\text{-}28 \text{ kg m}^{-3}$), reaching $1.3 \mu\text{mol kg}^{-1} \text{ a}^{-1}$, respectively, in the open ocean, the upper layer ($\gamma_n < 27.25 \text{ kg m}^{-3}$) consistently exhibits increases of at least $0.4 \mu\text{mol kg}^{-1} \text{ a}^{-1}$.*” (L. 366-368)

Line 299: “Over the considered time period”, please indicate specifically which time period (1993-2021, right)?

Yes, it has been clarified in the revised manuscript: “*Over the considered 1993-2021 period [...]*” (L. 374)

Line 426: I don’t get the “and deviations from linear trends” at the end of the sentence.

“*and deviations from linear trends*” was inadvertently retained from an earlier draft. This part of the sentence has been removed in the revised manuscript

Line 439: What are the “intermediate density layers”?

The intermediate density layers considered here have been specified (intermediate density layers (i.e., 27.25-27.8 & 27.8-28.0 kg m⁻³)

Line 442: The reference should not be between parentheses. In addition, Raimondi et al. (2021) only focuses on the Labrador Sea. I would suggest finding a reference for the Irminger Sea as well.

The parentheses have been removed, and a reference to Fröb et al. (2018) has been added. (Fröb, F., Olsen, A., Pérez, F. F., García-Ibáñez, M. I., Jeansson, E., Omar, A., and Lauvset, S. K. (2018). Inorganic carbon and water masses in the Irminger Sea since 1991. *Biogeosciences*, 15, 51-72)

Line 465: Replace “upt” by “up”. Thanks, the correction has been made.

Figure 7: For the colorbar label, wouldn’t it be “Regression slope” rather than “Regression coefficient”?

We thank the referee for pointing this out. We agree that Regression slope is a more accurate and consistent label than Regression coefficient. The colorbar label has been revised accordingly in the updated figure.

Line 523: I think the authors should add a reference to Fig. A1 so the reader could see where OSNAP and RAPID lines are located.

The reference has been added.

Figure 8: Panels (d), (e) and (f) are missing.

We thank the referee for identifying this labelling error. Panels d-f correspond to the AMOC-RAPID heatmaps, which were incorrectly labelled as panels a-c in the original manuscript. To avoid confusion with the AMOC-OSNAP heatmaps, the panel labels have been clarified in the revised manuscript: panels a–c now refer to the AMOC-OSNAP heatmaps, and panels d-f refer to the AMOC-RAPID heatmaps (see pages 26-27).

Figure 9: Colorbars on the upper panels cannot be read. Please change “four panels” to “six panels”. The figure caption says that there are “four main regions” but I think there are more regions displayed.

We thank the referee for these helpful comments. We have revised the figure caption accordingly (page 30). The reference to “four panels” was indeed an error and has been corrected to “six panels.” In addition, the colorbars have been enlarged to improve readability, and, for greater clarity, the figure has been reformatted in landscape orientation. We also agree that the schematic displays more than four sub-regions. However, the caption refers to the four major regions defined in the manuscript (Section 2.4), namely the Nordic, Subpolar, Subtropical, and Tropical regions, each of which comprises several sub-regions. We have revised the caption to make this distinction clearer and avoid any ambiguity.

Line 649: There is an issue with the parentheses between the references and the figure reference.

The parentheses have been removed.

I wish you all the best for the resubmission,

We would like to sincerely thank the referee again for his positive, constructive, and detailed feedback, which has helped us improve the manuscript throughout.

Rémy Asselot