Answer to Review #1, https://doi.org/10.5194/gmd-2022-152-RC1

We thank the reviewers for the thoughtful review. Detailed point by point responses to the major and minor comments are given below, with reviewers´ comments in black and answers of the authors in blue.

Goris et al., Gulf Stream and interior western boundary volume transport as key regions to constrain the future North Atlantic Carbon Uptake

This study aimed for regional optimization of the emergent constraints for projecting future North Atlantic carbon uptake. A previous study (Goris et al., 2018) identified two indicators, i.e., seasonal pCO_2^{sea} anomaly in middle-to-high latitude and fraction of anthropogenic carbon inventory below 1000m, for future carbon uptake projection in the North Atlantic. The authors apply a genetic algorithm to further find out which spatial area and depth ranges are crucial for emergent relationships. This study is scientifically interesting to constrain the projections of the North Atlantic Ocean carbon uptake, and also practically provide guidance for monitoring and observational strategies. However, this manuscript needs some further work and clarification to be published.

We thank the reviewer for the encouraging and constructive comments.

Major comments:

-Inconsistency of the season for pCO_2^{sea} anomaly: it is winter time pCO_2^{sea} in this study, but the cited paper (Goris et al., 2018) used summer time pCO_2^{sea}. The correlations should be reversed but are the same in both manuscripts.

Answer 1: In Goris et al. (2018), the negative mean summer pCO_2^{sea}-anomaly is utilised in parts of the manuscript so that positive correlations can be visualised (correlations with the summer time pCO_2^{sea}-anomaly are negative). As Goris et al. (2018) define the mean summer pCO_2^{sea}-anomaly to be the averaged May–October pCO_2^{sea}-value minus the annual pCO_2^{sea}-value of the same year, the negative mean summer pCO_2^{sea}-anomaly equals the mean winter pCO_2^{sea} -anomaly (November-April). We regret not having expanded on this in the original manuscript and have added an explanation about the relation between mean winter pCO_2^{sea} -anomaly and negative mean summer pCO_2^{sea}-anomaly as used in Goris et al. (2018) to our revised manuscript.

-The constrained relationship of winter pCO_2^{sea} anomaly is relative small (r=0.79), maybe it is because the definition of winter months (November to April) in this study. The variations in different months should be quite different, especially in the transit seasons, i.e., spring and autumn. Definition of the focus season with less months, e.g. December to February, or January to March, might end up with clear relationship and higher correlation.

Answer 2: We thank the reviewer for this suggestion. It is the goal of our manuscript to show how a genetic algorithm can be utilised to regionally constrain already existing emergent constraints. As a showcase, we use the already existing emergent constraints from Goris et al. (2018). Here, it is not our goal to redefine these existing emergent constraints and we note that even correlations weaker than r=0.79 are commonly applied in the context of emergent constraints (e.g., Qu et al. 2018, Selten et al., 2020, Mystakidis et al., 2017, Tokarska et al., 2020). We have added a similar explanation to our revised manuscript.

We would like to expand that we did check other definitions of seasonal pCO_2^{sea} anomalies when preparing the manuscript of Goris et al. (2018) and found that less (or a different selection of) months do not provide higher correlations. This is because the seasonal pCO_2^{sea} anomaly is chosen as a measure to capture the difference between models whose pCO_2^{sea} seasonality is driven by variations in dissolved inorganic carbon (driven by mixed layer depth and biological production) and models whose pCO_2^{sea} seasonality is driven by variations in sea surface temperature. As the here considered models have different timings for their peak in biological production (ranging from May to July) and as seasonal warming and biological production is not in phase (the peak in seasonal warming occurs in August for the here considered models), it is necessary to at least cover the months from May to August to capture the different seasonal drivers at play. However, further investigation revealed that seasonal warming is a dominant driver until the month of October. We have added a similar explanation in our revised manuscript.

-This study presented several predictors including the two from Goris et al. (2018). As shown in Fig. 8, each predictor provides a different estimate of the constrained range of future North Atlantic carbon uptake. Which estimate is more plausible?

Answer 3: We thank the reviewer for this very interesting question. We would like to first point out that our preprint states that "all newly constrained values for the future North Atlantic C_{ant*} uptake are consistent which each other, i.e. the uncertainties around the constrained mean values are large enough for the solutions to not contradict each other" (lines 410ff). Accordingly, all estimates can be true at the same time. When it comes to the mechanisms that we are using to constrain the future North Atlantic C_{ant*} uptake, it is our understanding that both emerging mechanisms are not completely independent in determining the C_{ant*}-uptake strength in the North Atlantic and they should not be viewed as two separate constraints. That is (i) the AMOC strength in the upper 500m drives the cold waters and the productivity levels in the high latitude North Atlantic; concurrently, (ii) the strength of the lower limb AMOC, which relates to the strength of upper limb AMOC, drives the effectiveness of surface-to-deep C_{ant*} transport. For both upper ocean and deep ocean constraints, the AMOC-observations come with lower observational uncertainty, yet they represent a purely physical constraint such that we consider the biogeochemical constraints as more closely related to the North Atlantic C_{ant*} uptake and hence more plausible. This is reflected in the fact that they also offer higher correlations with the North Atlantic C_{ant*} uptake when compared to the AMOC-constraints in the same ocean depth-range. A lower observational uncertainty in the biogeochemical constraints would hence be of high value. We have added a similar explanation to our revised manuscript.

-How are the uncertainty range of the predictand C_{ant*}-uptake in Fig. 1, 8 and Table 1 calculated? I suppose they should be determined by the cross points of the linear regression line and the vertical lines of the observational uncertainty, but apparently it is not the case as shown in Fig. 1(c and e) and Fig. 8.

Answer 4: Indeed, this is not the case. We had noted in lines 401ff that "For details of the method that we utilise to calculate the unconstrained and observationally constrained estimates of the future North Atlantic C_{ant*} uptake, the reader is referred to Bourgeois et al. (2022)." However, we understand that this statement is appearing too late in the manuscript and that a short introduction of the method would be helpful to the reader. Our method of estimating the constrained estimate follows the original approach of Cox et al. (2013). Here, the unconstrained estimate is given by the model mean and its uncertainty by the multi-model standard deviation. Assuming that all models are equally likely to simulate the true future

North Atlantic C_{ant*} uptake and are sampled from a Gaussian distribution, a probability density function (PDF) can be calculated for the unconstrained estimate using model mean and standard deviation. Similarly, a PDF of the observational estimate and of the linear regression between predictor and predicant is established. For the observationally constrained future North Atlantic C_{ant*} uptake, a conditional PDF is calculated by integrating over the product of the PDF of the observational estimate and the PDF of the linear regression. The observationally constrained estimate equals the expected value of the conditional PDF and the uncertainty of the estimate is given by its standard deviation. We have added a similar short introduction of the method to our revised manuscript, and, within the revised manuscript, we refer to this short introduction in the captions of Figures 1 and 6 as well as Table 1.

- It is not very clear how to interpret Fig. 5 and Fig. 7. The results in the two figures seem to contradict each other, both upper ocean (Fig. 5) and deeper ocean (Fig. 7) have high correlations. How to combine the information? In addition, L467-469: "…the deep ocean southward volume transport between 700m-4700m at 26N." Is this statement based on Fig. 7? This figure shows the 700m-5300m and 21N has reached the largest correlations.

Answer 5: We refer to Answer 3 and add that the strength of the northward mass transport with the AMOC (i.e., its upper cell or upper limb) is highly related to the strength of the southward mass transport with the AMOC (i.e., its lower cell or lower limb). Specifically, the upper branch of the AMOC transports warm waters from the low latitude to the high latitude North Atlantic, thereby releasing heat to the atmosphere (e.g., Rhein et al., 2011). Upon losing its heat, the water becomes denser and sinks. This densification links the warm, surface limb with the cold, deep return limb at regions of deep convection in the Nordic and Labrador Seas. For the Atlantic north of 26°N, volume conservation dictates that, for constant sea level, the net northward flow of upper waters balances the southward flow of deeper waters with a tolerance of 1Sv (McCarthy et al., 2015) such that there is a direct link between upper and lower cell of the AMOC. Though we are not considering the exact boundaries of the upper and lower limb, we have made an additional Figure (Figure R1, below) showing that the tight connection between upper and lower limb also holds for the here considered depth ranges. We have added a similar explanation to our revised manuscript.

The statement in L467-469 is based on two considerations: (1) While Figure 7 indicates that the southward transport between 700m-5300m reaches the highest correlations with the future North Atlantic C_{ant*} uptake, the amount of C_{ant*} that can be transported below 4700m is negligible. (2) We considered 26N instead of 21N as an observational constraint is available at 26N, while this is not the case at 21N. While we had denoted both considerations at different places in the preprint, we failed to summarise this more prominently. We have added a more prominent summary in our revised manuscript.

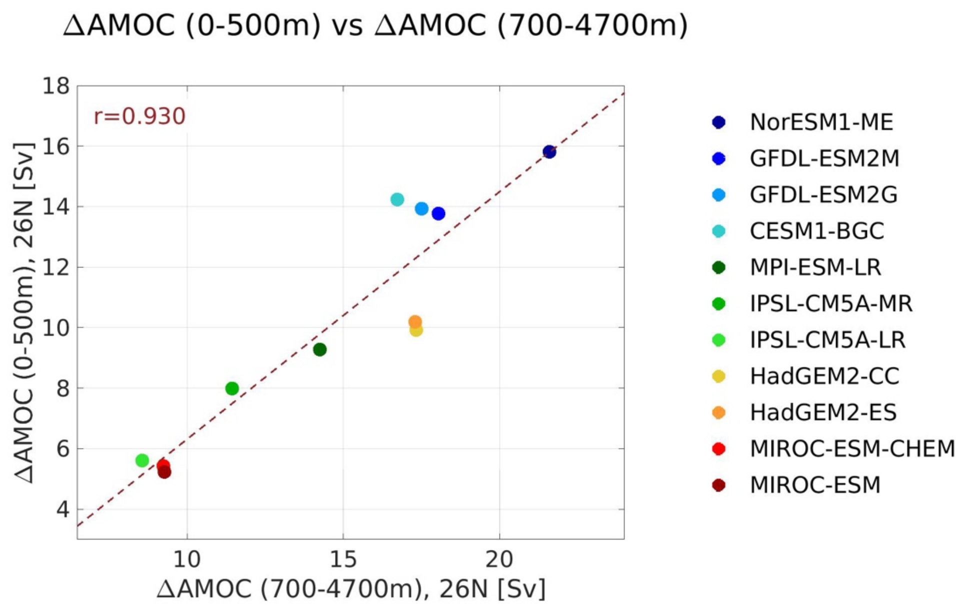

Figure R1: *Scatter plot of simulated mass transport at 26N in the upper 500m versus simulated mass transport at 26N between 700 and 4700m. The associated correlation coefficient is indicated in the upper left, the considered models and their color-coding is denoted in the legend.*

Minor comments:

-The information of figures are incomplete. I would suggest the authors to ensure all the figures are more or less self-explainable.

Answer 6: We thank the reviewer for pointing this out. As answer to this comment, we have re-done Figure 3 (see Answer 7), added units and expanded the captions for Figures 4 and 6 (see Answer 8) and presented the models in colours in Figure 8 (see Answer 9).

Fig. 3: the titles of x-axis and y-axis are missing, the y-axis' title is relative easy to guess, but the x-axis is not so straightforward. The readers need to check back and forth of the context to figure out that it should be number of iterations.

Answer 7: We apologize for overlooking this and thank the reviewer for pointing this out. Considering the previous comment of the reviewer, we decided to re-do Fig. 3 (depicted below) so that it hopefully is now self-explanatory and easier to understand.

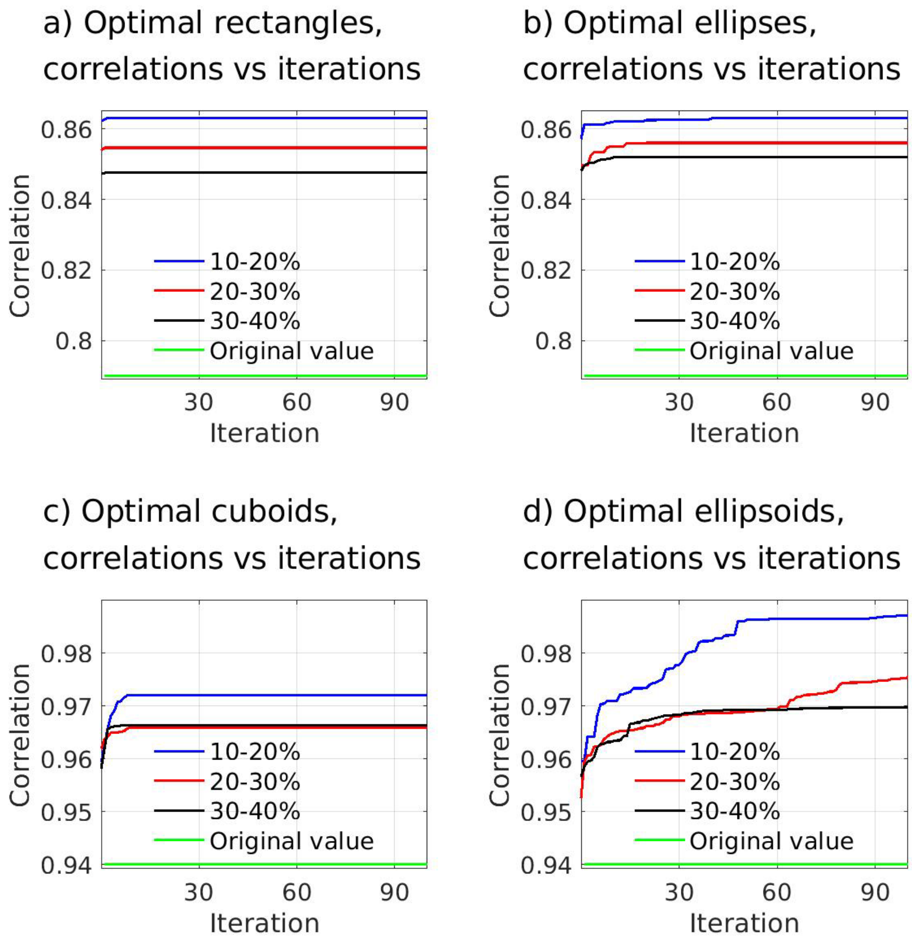

Figure 3: *Iteration (population) versus cross-correlations for our application of the genetic algorithm. The correlation coefficients are calculated between contemporary values of the predictor within the best-performing regions identified by the genetic algorithm (per iteration) and future values of the predictand. For each shape (rectangle, ellipse, cuboid, and ellipsoid), three different applications of the genetic algorithm have been carried out based on different area or volume constraint (marked in blue, red and black). The green lines illustrate the cross-correlation without regional optimisation of the predictor.*

Fig. 4: the unit of the presented variable is missing on both plots and in the figure caption. Why are the color shadings much lighter in Fig. 4c-d than in the Fig. 4b, as they are presenting the same quantity? The same question is also for Fig. 6c-f.

Answer 8: We have added the units of the presented variables to our revised Figures 4 and 6. Colour shading in Fig. 4c-d as well as in Fig. 6c-d appear lighter than in Fig. 4b und Fig. 6b, respectively, as we had added a transparency of 70% such that the optimal regions are easier to identify. In our revised Figures 4 and 6, we have added the same transparency to all panels such that the colour shadings look the same in all sub-figures and do not lead to confusion.

Fig. 8: as specific model like CESM1-BGC is mentioned to perform well in L413-414, and more information and comparison can be made if the authors present the models with colors as in Fig. 1.

Answer 9: We followed the suggestion of the reviewer and revised Figure 8 to present the models in the same colours as in Figure 1.

-Abstract L3: "A previous study…" needs to add the reference paper citation so that the readers get the context. From reading the main text, I guess this study refers to Goris et al. (2018).

Answer 10: We thank the reviewer for pointing this out. The guidance for abstracts from GMD reads that "Reference citations should not be included in this section, unless urgently required". We interpret the reviewer's comments such that the reference is urgently needed and have added it to our revised manuscript.

-Abstract L5: "…winter pCO_2^{sea} – anomaly…", but the previous paper (Goris et al., 2018) suggested the pCO_2^{sea} anomaly in summer (May to October) NOT winter (November to April). As the winter and summer are taken actually half a year in this study, respectively, I guess the counterpart season should be with the same magnitude of correlation but a reversed sign. So I am quite confused that this study based on winter months and the previous study based on summer months get exactly the same correlations as shown in Fig. 1c.

Answer 11: This related to the fact that Goris et al. (2018) show the negative mean summer pCO_2^{sea}-anomaly in their Fig. 10 in order to be able to depict positive correlations. Here, the negative mean summer pCO_2^{sea}-anomaly equals the mean winter pCO_2^{sea} -anomaly (see Answer 2). We regret not having expanded on this in the manuscript and have added an explanation about the relation between negative mean summer pCO_2^{sea}-anomaly and mean winter pCO_2^{sea} -anomaly to our revised manuscript to avoid confusion. As this explanation is not fitting for the abstract, we have changed the wording in the abstract to "seasonal pCO_2^{sea} anomaly" to avoid confusion.

-Some relevant details need to be described in this paper, so that the readers don't need to refer to Goris et al. (2018) all the time. For instance: how is the pCO_2^{sea} anomaly defined, is it relative to the annual mean or long-term specific season mean? Which time periods are 1990s, 1997s, and 2090s?

Answer 12: Here, the 1990s are defined as an average over the years 1990-1999, the 2090s as an average over the years 2090-2090s and the 1997s as an average over the years 1997-2007. The last time-frame has been chosen as one of the utilised observation-based products is normalized to the year 2002. The mean winter pCO_2^{sea}-anomaly is defined to be the averaged November to April pCO_2^{sea}-values relative to the mean annual pCO_2^{sea} -values.

We have added explanations about the terms in question to our revised manuscript to avoid confusion.

-L350, 354, 363, Figs. S01, Figs. S03 and S04 are inconsistent with the figure numbering in the supplementary.

Answer 13: We have corrected this in our revised manuscript.

-L411: "…consistent which…" -> "…consistent with…"

Answer 14: We have corrected this in our revised manuscript.

-L487: "…averaged aver…" -> "…averaged over…"

Answer 15: We have corrected this in our revised manuscript.

References:

Cox, P., Pearson, D., Booth, B., Friedlingstein, P., Huntingford, C., Jones, C. D. and Luke, C. M.: Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability. *Nature* 494, 341–344, https://doi.org/10.1038/nature11882, 2013.

McCarthy, G. D., Smeed, D. A., Johns, W. E.,Frajka-Williams, E., Moat, B.I., Rayner, D., Baringer, M.O., Meinen, C.S., Collins, J., Bryden, H.L.: Measuring the Atlantic Meridional Overturning Circulation at 26°N, Progress in Oceanography, Volume 130, 2015, 91-111, https://doi.org/10.1016/j.pocean.2014.10.006., 2015.

Mystakidis, S., Seneviratne, S. I., Gruber, N., and Davin, E. L.: Hydrological and biogeochemical constraints on terrestrial carbon cycle feedbacks, Environmental Research Letters, 12, 014 009, https://doi.org/10.1088/1748-9326/12/1/014009, 2017.

Qu, X., Hall, A., DeAngelis, A. M., Zelinka, M. D., Klein, S. A., Su, H., Tian, B., and Zhai, C.: On the Emergent Constraints of Climate Sensitivity, Journal of Climate, 31, 863 – 875, https://doi.org/10.1175/JCLI-D-17-0482.1, 2018.

Rhein, M., Kieke, D., Hüttl-Kabus, S., Roessler, A., Mertens, C., Meissner, R., Klein, B., Böning, C. W., and Yashayaev, I.: Deep water formation, the subpolar gyre, and the meridional overturning circulation in the subpolar North Atlantic, Deep Sea Research Part II: Topical Studies in Oceanography, 58, 1819–1832, https://doi.org/https://doi.org/10.1016/j.dsr2.2010.10.061, 2011.

Selten, F. M., Bintanja, R., Vautard, R., and van den Hurk, B. J. J. M.: Future continental summer warming constrained by the present-day seasonal cycle of surface hydrology, Scientific Reports, 10, https://doi.org/10.1038/s41598-020-61721-9, 2020.

Tokarska, K. B., Stolpe, M. B., Sippel, S., Fischer, E. M., Smith, C. J., Lehner, F., and Knutti, R.: Past warming trend constrains future warming in CMIP6 models, Science Advances, 6, eaaz9549, https://doi.org/10.1126/sciadv.aaz9549, 2020.