Answer to Review #2, https://doi.org/10.5194/gmd-2022-152-RC2

We thank the reviewer 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.

Review #2:

I'm surprised to see this paper in review for GMD as it does not obviously meet any of the journal's manuscript types. It seems like the direct utility of this work is thinking about how to guide observational strategies to constrain N. Atlantic carbon uptake. This is however a call for the editor.

Answer 1: We would like to thank the reviewer for his/her very constructive review which has been very insightful for us. Though this is indeed a call for the editor, we would like to explain our reasoning behind choosing GMD to also assist the editor: It is our opinion that our paper meets the manuscript type "Methods for assessment of models" as it describes a "novel way of comparing model results with observational data". Specifically, our application of the genetic algorithm to regionally optimise emergent constraint had a twofold goal:

(1) To isolate key processes driving the multi-model spread, thereby enhancing our understanding of these processes, and identifying potential dynamical inconsistencies within the model ensemble
(2) To provide key areas where a narrow observational uncertainty is crucial for constraining future projections

Yet, the reviewer´s comments have made us aware that our way of structuring the manuscript needs to be improved, such that the original intent of the manuscript is better conveyed. We would therefore like to submit a revised manuscript that re-structures the content of our manuscript along this two-fold goal. More details are provided in Answer 2.

Major comments.

I find the manuscript comes across a bit as a dump of all the work the authors have done in this area, and as such, I feel it would benefit from some curating. The manuscript seems to be doing all of the following:

1. Identifying specific regions where people should be making observations to constrain future N. Atlantic CO2 uptake (and in doing so they refine existing published emergent constraints slightly).

2. Exploring how a genetic algorithm can be used to select the optimum area of observational sampling to constrain models.

3. Expanding on the mechanisms behind the emergent constrains that the authors have previously put forward.

4. Better understand which key processes are leading to uncertainty in projections of future N. Atlantic CO2 uptake (which links quite closely to 3).

As it is written it is doing 1, suggesting that it is doing 2, and doing a bit of 3 and 4 around the edges. The editor will be able to provide guidance on which of these a GMD paper should be doing, but I would argue that 2, 3 or 4 done fully would make the most useful papers, while1 is useful for a very specific audience. As it stands 2, 3 and 4 are the less developed parts of this manuscript. Perhaps it is OK to do all of these

things, but if that is what is done, a much clearer structure needs to be imposed on the manuscript and introduction of what is being done and why, so that the reader knows what information they should be getting from each section, and can efficiently take what they need from it. My preference would be to be clear about what the manuscript is trying to achieve and focus the manuscript on that, bringing in the other bits perhaps only as part of the discussion.

Answer 2: We thank the reviewer for his/her insights. Of course, it has not been our intention to present a dump of all the work that we have done in this area but instead to present a thorough study around the topic of Answer 1, with the North Atlantic carbon uptake as a case study. However, the reviewer´s comments has made us realise that the structure of our manuscript (1) went too quickly into the topic of the North Atlantic carbon uptake and (2) did not provide enough context into what information each Section is describing and therefore the twofold goal described in Answer 1 got lost between results.

In line with the reviewer´s request, we therefore propose to re-structure and extend our manuscript, such that becomes clearer that our manuscript is about

Applying a genetic algorithm on existing emergent constraint to
(a) identify key model dynamics for the emergent constraint and model inconsistencies around them
(b) provide key areas where a narrow observational uncertainty is crucial for constraining future projections

We propose to do this by firstly adding more introductory sentences that specify the content of each Section and the meaning behind this. Moreover, we propose the following structural changes:

- For the **title**: we propose to change the title to "Regional optimisation of Emergent Constraints: A case study for the North Atlantic carbon uptake"
- For the **abstract**: instead of directly describing the topic of the North Atlantic carbon uptake, we propose to begin our abstract with the topic of Emergent Constraints, followed by a motivation for our regional optimisation and an explanation of its two-fold goal.
- For the **introduction**: we propose to extend our introduction to not only explain the goal of narrowing down observational uncertainty in key areas but also to isolate key processes driving the multi-model spread, thereby enhancing our understanding of these processes, and identifying potential dynamical and systematic inconsistencies within the model ensemble.
- For the section **"Emergent constraints of the North Atlantic future carbon uptake"** which is part of "Background and experimental design": We propose to modify this Section by first introducing the method of Emergent constraints, including its caveats related to averaging over large areas before introducing the emergent constraints of our case study.
- For the section "**Genetic algorithm and experimental set-up"** which is part of "Background and experimental design": We propose to expand the title of the Section to "Genetic algorithm and experimental set-up for the regional optimisation" and to add an explanation as to why different shapes and sizes have been chosen for the regional optimisation and why we consider this set-up to be beneficial.
- For the "**Results"**-Section: Here, our introductory sentences will explain that Section 3.1 describes the performance of the Genetic Algorithm in terms of (1) speed of convergence towards an optimal solution and (2) improvement of correlations when applying the optimal regions to the Emergent Constraints. We will re-organise the remainder of the "Results"-section around our twofold goal of

(1) isolating key processes driving the multi-model spread, thereby enhancing our understanding of these processes, and identifying potential dynamical inconsistencies within the model ensemble; (2) providing key areas where a narrowing down of observational uncertainty is crucial to constrain future projections. Therefore, we propose the following structure:

3.2 Optimal regions of the winter pCO_2^{sea}-anomaly and associated new emergent constraints
Visualisation and description of the optimal areas and their associated new emergent constraints

3.2.1 Plausibility of the optimal areas for the winter pCO_2^{sea}–anomaly
Description of the plausibility of the optimal areas including a dynamical reasoning

3.2.2 Implications of the optimal areas of the winter pCO_2^{sea}-anomaly
Description of inconsistencies within the model ensemble and where a reduction of observational uncertainty would help to disentangle the inconsistencies

3.3 Optimal regions of the fractional C_{ant*}-storage and associated new emergent constraints
Visualisation and description of the optimal areas and their associated new emergent constraints

3.3.1 Plausibility of the optimal areas of the fractional Cant∗-storage
Description of the plausibility of the optimal areas including a dynamical reasoning

3.3.2 Implications of the optimal areas of the fractional C_{ant*}-storage
Description of inconsistencies within the model ensemble and where a reduction of observational uncertainty would help to disentangle the inconsistencies

- We will add a **"Discussion"**-Section, where we will present our approach and the additional information that it can give on (i) structural model error and (ii) the plausibility of different emergent constraints and compare our approach to other studies about the plausibility of Emergent Constraints.
- For the "**Summary and conclusion**"-Section: we will summarise as to why different shapes and sizes have been chosen for the regional optimisation and why this set-up is beneficial for disentangling of structural error and would be beneficial also for follow-up studies. Moreover, we will present a summary of our results along the lines of our twofold goal and what has been archived for each of the goals.

Fundamentally I can't see any mistakes beyond that raised by the other reviewer. I would echo the other reviewer's comments about it being difficult to interpret some of the figures, and would add that the manuscript would benefit from some careful editing for readability.

Answer 3: We have followed the advice of the other reviewer with regards to our figures. We also will edit our manuscript carefully with the intent to increase readability.

Minor comments:

- Just a comment - I'm pleased to see the desire for mechanisms in emergent constraints!
  Answer 4: We thank the reviewer for this comment.
- The title does not make sense. "Gulf Stream and interior western boundary volume transport as key regions to constrain the future North Atlantic Carbon Uptake" Should it perhaps read "Gulf

Stream and interior western boundary as key regions to constrain the future North Atlantic Carbon Uptake"?

Answer 5: We thank the reviewer for pointing this out. In line with preparing a differently structured manuscript, we will change the title to "Regional optimisation of Emergent Constraints: A case study for the North Atlantic carbon uptake"

- It seems to me that the 'competition' described in section 2 might benefit from a more detailed diagram than Fig 2.

  Answer 6: We are unfortunately unsure about what the reviewer means by ´competition´ as this term does not appear in our manuscript or Figure 2. We are happy to add a more detailed diagram once we are certain what process the reviewer refers to.
- Line 27 refer --> referred

  Answer 7: We have corrected this in our revised manuscript.
- Line 37 "Despite many progresses" --> "Despite much progress"

  Answer 8: We have corrected this in our revised manuscript.
- Line 37: 'have not necessarily' – be specific have they or haven't they, or in what areas have they.

  Answer 9: We understand the wish for explicitness, and have therefore revised Line 37ff and included three additional examples on top of the already existing example of equilibrium climate sensitivity, such that our revised manuscript reads:

  "Despite much progress in climate modelling, model bias and uncertainty (i.e., spread across models) have not decreased for all simulated variables. Most prominently, the model-generation of CMIP6 reveals the highest model uncertainty in equilibrium climate sensitivity when compared to other CMIP model-generations (Meehl et al., 2020). Similarly, Tagliabue et al. (2022) found that the absolute uncertainty in projections of global ocean net primary productivity has increased from CMIP5 to CMIP6. Additionally, their study points out that this growth in uncertainty substantially differs at regional scale. Contrarily, Terhaar at al. (2021) identify that the model uncertainty in surface density in the Arctic has decreased in CMIP6-ESMs when compared to CMIP5, leading to a reduced inter-model range of the anthropogenic carbon uptake in the Arctic. This result is echoed by Bourgeois et al. (2022), who find a smaller CMIP6 than CMIP5 model-uncertainty in both the contemporary ocean stratification and the anthropogenic carbon uptake in the Southern Ocean between 30°S and 55°S. Yet, the combination of large data volume and partially high model uncertainty in CMIP6 makes a comprehensive evaluation of associated models and simulations highly challenging."
- Line 72: "could highly gain from" --> "could gain from"

  Answer 10: We have corrected this in our revised manuscript.
- Line 214: "we advice against" --> "we advise against"

  Answer 11: We have corrected this in our revised manuscript.
- Line 487 aver should be over

  Answer 12: We have corrected this in our revised manuscript.

References:

Bourgeois, T., Goris, N., Schwinger, J., and Tjiputra, J.: Stratification constrains future heat and carbon

uptake in the Southern Ocean between 30◦S and 55◦S, Nature Communications, 13, https://doi.org/10.1038/s41467-022-27979-5, 2022.

Meehl, G. A., Senior, C. A., Eyring, V., Flato, G., Lamarque, J.-F., Stouffer, R. J., Taylor, K. E., and Schlund, M.: Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models, Science Advances, 6, https://doi.org/10.1126/sciadv.aba1981, 2020.

Tagliabue, A., Kwiatkowski, L., Bopp, L., Butenschön, M., Cheung, W., Lengaigne, M., Vialard, J.: Persistent Uncertainties in Ocean Net Primary Production Climate Change Projections at Regional Scales Raise Challenges for Assessing Impacts on Ecosystem Services, Frontiers in Climate, 3, https://doi.org/10.3389/fclim.2021.738224 , 2021.

Terhaar, J., Torres, O., Bourgeois, T., and Kwiatkowski, L.: Arctic Ocean acidification over the 21st century co-driven by anthropogenic carbon increases and freshening in the CMIP6 model ensemble, Biogeosciences, 18, 2221–2240, https://doi.org/10.5194/bg-18-2221-2021, 2021.