

## Comment on bg-2020-487

Anonymous Referee #2

---

Referee comment on "Ocean carbon cycle feedbacks in CMIP6 models: contributions from different basins" by Anna Katavouta and Richard G. Williams, Biogeosciences Discuss., <https://doi.org/10.5194/bg-2020-487-RC2>, 2021

---

### ## General comments

\* The paper is a valuable extension of the global analysis of carbon cycle feedbacks (Arora et al., 2020) and presents a useful framework that uses changes to the interior ocean carbon pools to help infer the first-order mechanisms contributing the magnitudes of regional and, thus, global ocean carbon cycle feedback parameters. The focus is primarily on how and why the strengths of the ocean carbon cycle feedback parameters vary at the basin-scale. The authors use diagnostics of the saturated, regenerated, disequilibrium carbon to help interpret these basin-scale variations. The also include a detailed mechanistic analysis of the relationship between AMOC on the feedback parameters.

\* I particularly appreciated i) the thorough theoretical explanation for the evolution of the global ocean feedback parameters based on the contributions from the diagnosed saturated, disequilibrium, and regenerated carbon pools, and ii) the use of the box models to explore the response of these carbon pools to different AMOC scenarios.

\* The global analysis of the evolution of the carbon cycle feedback parameters based on contributions from the different carbon pools (figure 2 with explanations rooted in fundamental chemistry) is rigorous and informative, but it would be easier to follow if this analysis were shifted and consolidated in a dedicated results section (details below).

\* I would have liked to see a basin-scale analysis similar to the global analysis of the evolution of the carbon cycle feedback parameters based on relative contributions from the different carbon pools. Why did you not use the same approach and figure presentation? Was it too difficult to interpret presented this way?

\* This paper focuses mostly on the regional feedback parameters calculated from the changes to carbon storage in the ocean interior. The ocean carbon cycle feedback



parameters derived from air-sea CO<sub>2</sub> fluxes are not analysed much here. Globally the feedback parameters based on the air-sea flux and storage approaches are very similar, but—as the authors note—differences emerge at regional scales, largely because of the influence of transport. I think it is important to introduce the reader to the strengths and limitations of these complementary approaches. For example, basin-scale feedback parameter calculated using changes in the inventories of interior carbon pools, aggregates many spatially and temporally varying processes over large ocean basins, which has its limitations in terms of deciphering the driving mechanisms since it is integrating DIC changes that are driven by different and often compensating processes within the region and from outside the region itself (particularly in the Southern Ocean). But, on the other hand, even if the exact sources of the changes are more difficult to pinpoint, the interior carbon pools provide an integrated picture of the first order controls on changes in carbon storage in the different basins. Furthermore, we can use the diagnosis of the various carbon pools to help interpret the mechanisms behind these changes.

\* Here the analysis of the processes (ocean carbonate chemistry, physical ventilation, and biological processes) driving changes in the carbon cycle feedback parameters are diagnosed from changes to the saturated, disequilibrium and regenerated DIC pools. So that the reader, can better evaluate the results presented from this part of the study an honest appraisal of the strengths and limitations of this approach would also be a valuable addition. For example,

- interpreting changes in the distributions of the different carbon pools is not always straightforward as you might hope (see spatial complexity in Arora et al., 2020). Nevertheless, basin-scale changes in carbon storage provide a natural integration of a spatially complex air-sea CO<sub>2</sub> flux pattern.
- Even using this approach it is not possible to completely separate the various processes. For example, the regenerated component combines both biological and ventilation changes because the strength of the biological pump is also dependent on the ventilation. It seems that describing the changes in terms of their impacts on the different carbon pumps could be helpful.
- Basin-scale variations in the change in carbon storage can't be interpreted directly as the importance of the region to the global carbon cycle feedbacks, because the source (and mechanism) of change could have been from outside the region.

\* My main recommendation is to reorganise several sections of the paper to help clarify the methodology and distil some of the main results—in particular for the analysis of the contribution of the various carbon pools to the regional carbon cycle feedback parameters (detailed suggestions are given below).

\* It is difficult to see the relative contribution of saturated, disequilibrium and regenerated carbon pools to the basin-scale feedback parameters. I would suggest adding (or modifying) a figure dedicated to the relative contributions of saturated, disequilibrium and regenerated carbon pools to the basin-scale feedback parameters. Although, Figure 4 contains this information, it can be difficult to read this information off the figure.

\* Related to the last comment, the author often presents the volume integrated



quantities, which makes it more difficult to appreciate: i) where a feedback is stronger or weaker than expected based on volume alone (Figure 5 shows this well, but sometimes it is lost in the text), and ii) what processes (diagnosed using the changes to the carbon pools) dominate the magnitudes of each carbon cycle feedback parameter in each basin (not always easy to see in the Figures and tables)

\* The authors suggest they will account for the impact of carbon transport. This influence is transport is not presented in much detail, and would require a more thorough comparison of regional air-sea CO<sub>2</sub> flux and storage feedback parameters. Therefore I would either i) elaborate on this in a dedicated section or ii) simply remove and include some reference to the impact of transport in the methodology where the relative merits of flux and storage approaches are discussed.

\* Several time the authors comment on the beta having less uncertainty (intermodel variability) than the gamma. This is misleading, because the uncertainty in each is mapped disproportionately onto the uncertainty in carbon storage (i.e. gamma is multiplied by only  $> 4$  deg C , while beta is multiplied by the  $> 700$  ppm change in atmospheric CO<sub>2</sub>) .

## **## Specific comments**

### **Abstract**

\* On beta: "The Atlantic, Pacific and Southern Oceans contribute equally to the carbon-concentration feedback, despite their different size." I think a better emphasis is that the Atlantic storage increase more and Pacific storage increases less than expected in relation to their size. Then mention why. Also the Southern Ocean beta is low despite the strong air-sea CO<sub>2</sub> flux here, because it transported out of the region. what about the Indian? Summarise on the controls on beta for each basin.

\* On gamma: Similarly, I would summarise the dominant controls for each basin, merging the conclusions from the carbon pools and AMOC parts of the analysis.

### **Introduction**

\* lines 25 –28: Given the central importance of these feedbacks in this papers, this introduction to carbon cycle feedback parameters could be a little more comprehensive. It also a bit awkward to read. Perhaps merge the name and description of each feedback. And then finish with "These two carbon cycle feedbacks have been extensively used to...."

\* lines 74–79: rework section description to reflect any changes made to the sections.

## **2 Ocean carbon cycle feedbacks and their control by different processes**



\* The beginning of this section reads like part of the introduction. I think it should be clear to the reader from the onset that this is where you will present the approach used in this paper.

\* I would start this section introducing your methodology and how the methodology compares to previous studies, particularly Arora et al., 2020. Something along the lines of "here we extend the analysis of the carbon cycle feedbacks diagnosed in the CMIP6 models (Arora et al., 2020)..." and then introduce what part of the analysis is identical and what parts have been modified or extended.

\* I recommend separating the methodology into two parts: 2.1 Ocean carbon cycle feedback analysis, 2.2 Diagnostics of processes controlling carbon cycle feedbacks.

\* Move the results and discussion of the contribution of the global saturated, disequilibrium, and regenerated carbon pools (and the associated Figure 2) to the global carbon cycle feedback parameters to section 3. It is very interesting and thorough and deserves a dedicated results section.

\* For improved clarity, the ocean cycle carbon cycle feedbacks (e.g. recommended Section 2.1) should consolidate all the feedback methodology from other sections and include some missing elements:

- Clearly present and give distinguish between the feedback parameters and the carbon inventories calculated from the i) air-sea CO<sub>2</sub> fluxes and ii) interior carbon inventories. In regional analyses this distinction becomes very important (as the authors explain). For example, you could use 'beta<sub>f</sub>' and 'I<sub>f</sub>' and 'beta<sub>s</sub>' and 'I<sub>s</sub>' for beta and carbon inventories calculated from carbon fluxes and carbon storage respectively.
- Please include a discussion of the merits/limitations of the flux vs storage approaches and their complementarity.
- Move the regional calculation of the feedback parameters (263–274) to this section.
- The basins have not been defined. Please provide the precise boundaries used for the basin-scale analysis show boundaries on the maps in Figure 3.

\* For the section (e.g. recommended section 2.2) presenting the methodology for diagnosing the ocean processes contributing the carbon cycle feedbacks ( based on calculations of saturated, disequilibrium, regenerated carbon pools)

- Start this section with something like your line 115. "To gain insight ..."
- Include detail here on the how the various carbon pools are used to diagnose ocean processes (ventilation, biology...) and the limitations of this approach.
- I assume methodology used to calculate the carbon pools is identical to that used in



Arora et al., 2020? Please elaborate. If so, it would be useful to inform the reader.

- Include here only the methodology used to calculate the changes in the carbon pools and leave the theoretical explanations that are used to better understand their evolution to section 3.

\* line 81–84: this essentially repeats introductory section above (lines 25–28 ) and doesn't need to be repeated here.

\* line 106: this does not "exclude" all model biases because the initial biases continue to impact their evolution, but it does help reduce them. Either replace "To exclude" by "To reduce" or "To partially exclude".

\* line 251: replace "suggesting" with "indicating"

\* line 253: replace "act to reduce" with "reduce"

### **3 Regional carbon cycle feedbacks in CMIP6 Earth system models**

\* To make the paper easier to follow, this section should consolidate the global and basin-scale analyses of the contribution of the carbon pools to the carbon cycle feedback parameters

\* You could rename the title of this section "3 Processes controlling the carbon cycle feedback parameters" and subsections "3.1 Global analysis" and "3.2 Basin-scale analysis". Maybe there is no need for subheadings.

\* The section starting on line 275 touches on the impact of carbon transport on the feedback parameters and on line 291 mentions that the study will account explicitly for the ocean transport of carbon. Since there is little discussion of the impact of transport on the feedbacks in the paper and the main results are added to an Appendix, these paragraphs seem out of place here. Two suggestions:

- Either include a more detailed examination of the impact of transport on regional betas and gammas in a dedicated results & discussion section including the figures in the Appendix. This would be interesting if it extends our understanding beyond what is



presented in Frolicher et al., (2015).

- Or, the spatial distribution of the ocean carbon-cycle feedbacks in figure 3 could be moved into and discussed in the methodology section where the air-sea CO<sub>2</sub> flux and carbon storage feedback parameters are introduced and compared. Here the figures could be discussed in terms of the complementarity of the flux and storage approaches.

\* There are some places—particularly in the interpretation of the changes in the global and regional carbon pools and their contributions to the feedback parameters—where the language used to associate the changes to mechanisms, reads as if these are mechanisms have been determined rather than diagnosed. I think care needs to be taken to word the results and conclusions in light of an honest appraisal of the confidence we have in the mechanisms diagnosed using this approach (probably in the methodology).

\* lines 263 –271: As mentioned earlier, move this methodological detail to section 2.

## **Global analysis**

\* For the Global analysis I would recommend moving the global analysis of the contributions of the various ocean carbon pools to the carbon cycle feedback parameters (I.e. associated with Figure 2) into a dedicated section, which includes the following text: the presentation of the theoretical analysis that helps us interpret the evolution of the global feedback parameters: saturated component (lines 148–196), regenerated (lines 208 – 217), and disequilibrium (lines 225–238 starting with the rise in atmospheric CO<sub>2</sub>....).

## **Basin-scale analysis**

I feel this section of the paper needs some polishing. The figures and the discussion don't always clearly separate the impact of the strength of the feedback (i.e. volume-normalised) from the volume-integrated impact. Consequently, it can be difficult to clearly see the relative contributions of the saturated, disequilibrium and regenerated carbon pools to the basin-scale parameters. This was done well for the global analysis.

\* I find the separation between section 3.1 and 3.2 confusing. Only a short discussion of the contribution of different basins to global carbon cycle feedback parameters is needed here (the main results are already in Figure 1). The main focus should be i) the relative strengths of the carbon cycle feedbacks relative to their volumes and ii) on the analysis of the mechanisms controlling the differences between the basin-scale carbon cycle feedback parameters (volume-normalised) by accounting for the contributions from the different carbon pools.

\* I would start section on the relative strengths of the feedbacks by discussing Figure 5, which is better suited for this than figure 4. For example, for beta, It is easy to see that the Atlantic takes up more and the Pacific less relative to their volumes



\* A figure is missing that is dedicated to the relative contributions of saturated, disequilibrium and regenerated carbon pools to the basin-scale feedback parameters. For example, you want to be able to easily see what mechanisms is responsible for the Atlantic taking up more and Pacific taking up less carbon relative to it's volume or what process dominates the carbon-climate feedback in each basin. Although, Figure 4 contains this information, since the feedbacks parameters are i) not volume-normalised and ii) the components of the feedback parameter for each region are not presented side-by-side, it can be awkward to read this information from the figure. Maybe Figure 4 could be reworked by :

- either grouping the contributions from each carbon pool into a plot for each basin rather than for each component.
- or presenting the contribution of each component to the basin-scale feedback parameters as percentage contributions, so that it is easy to clearly see how the relative contributions of the different components to the total feedback vary between the regions.

\* It would be informative to see the geographical distributions of the saturated, disequilibrium, and regenerated components to help with the interpretation of the basin-scale changes and to complement the depth sections presented in Arora et al., (2020).

## **5 Discussion and Summary**

\* line 163: In "The transport effect acts to decrease the carbon-concentration feedback parameter" it is important to mention increase relative to what. That is, the carbon-concentration parameter calculated from the air-sea CO<sub>2</sub> fluxes.

\* line 473: again the intermodel variability in beta may seem small, but the impact of this intermodel variability on carbon storage is not.

\* line 479: "consistent with previous studies" here mention consistent with the spatial patterns of gamma diagnosed from the air-sea CO<sub>2</sub> fluxes in the last two generations of ESMs (i.e. spatial patterns of the feedback parameters in Roy et al., 2011 and in the CMIP5 models in the IPCC WG1 assessment report Ciais et al., 2013).

\* line 490: It would be useful to reference consistency with previous analyses of the drivers of the carbon-concentration parameter distributions here even if they were based on the CO<sub>2</sub> air-sea flux carbon cycle feedbacks "as was shown in a CMIP5-generation model.... and is consistent with analyses of the carbon-climate feedback distributions from previous generation models (Roy et al., and Ciais et al., 2013)"



## **## Figures**

### **Figure 4**

\* Does not include the multimodel mean (or median). I think it would be most informative to overlay the median and IQR.

### **Figure 5**

\* It looks like some of the parts of the ocean have not been included here. I suppose there is meant to be an 'Other regions' category (inland seas and arctic?) to make each column sum up to 100%. Please explain in the caption.

\* Why were these other regions left out? They contribute a substantial amount to global gamma.

## **## Technical comments**

\* There are a few places where the English needs a little work. I have picked up a bunch of them, but someone should give the document another once over.

## **Abstract**

\* line 4: Change ". The contribution from different ocean basins to the carbon cycle feedbacks and its control by the ocean carbonate chemistry, physical ventilation and biological processes is explored in diagnostics of 10 CMIP6 Earth ...." to ". The contribution from different ocean basins to the carbon cycle feedbacks and the processes that control them are explored using diagnostics of ocean carbonate chemistry, physical ventilation and biological processes in 10 CMIP6 Earth ...."

\* line 5: Change "mechanist" to "mechanistic"

\* line 15: change "on global scale" to "at the global scale"

## **Introduction**

\* 21: change "refer" to "referred"

\* 22: change "lapse rate" to "tropospheric lapse rate"

\* 24: change "land and ocean" to "land and ocean reservoirs".

\* 34: change "feedback is about 3 times stronger over land than the ocean on centennial" to "feedback is about three times stronger over ::the:: land than the ocean on centennial"



\* Line 55: I would remove "hence" because it implies you are going to focus on both heat and carbon in this study.

\* line 56: Replace "Hence, our motive is to explore the mechanisms that lead to this regional variation in the carbon storage and the carbon cycle feedbacks for the different ocean basins..." with "Our ::motivation:: is to explore the mechanisms that lead ::these:: regional variations in the carbon storage and the carbon cycle feedbacks ::in:: the different ocean basins..."

\* 71: changes "insight for" to "insight into"

\* 72: This sounds odd. Please replace "Our aim is to provide insight for the relative contribution from different ocean basins to the ocean carbon cycle feedbacks, and the processes that drive this relative contribution and its uncertainty amongst CMIP6 " by "Our aim is to provide insight ::into:: the relative contribution of different ocean basins to the ocean carbon cycle feedbacks and the processes that drive this regional partitioning in the CMIP6 models".

\* line 73: it reads as if you will exploring the controls of the AMOC. Please replace by something like "the control of the AMOC on the carbon cycle feedbacks".

\* Line 76: replace "processes" by "diagnostics of processes".

## **2 Ocean carbon cycle feedbacks and their control by different processes**

\* 81: comma between "CO2 which"

\* 82: change "At the same time the increase in atmospheric CO2 modifies the physical climate system, such as for example leading to ocean warming and increase in stratification" change to "At the same time the increase in atmospheric CO2 modifies the physical climate system, leading to changes such as ocean warming and increased stratification.... "

\* 84: change "ocean carbon uptake" "change in ocean carbon uptake"

\* line 110: you don't need the subscript ocean for Equation 5. I would save the subscript position for discriminating between feedback parameters calculated using air-sea CO2 fluxes vs carbon storage.

\* line 111: choose to either capitalise or not the word "earth" in the document.

\* 115: "To gain insight for the driving mechanisms of the carbon cycle feedbacks and their uncertainty " "To gain insight ::into:: the driving mechanisms of the carbon cycle feedbacks and their uncertainty "

\* line 125: replace "extend" by "extent".

\* line 125: replace "contemporary CO2" with "contemporary CO2 concentration".

\* line 126: include symbol and units for carbon inventory (I.e.  $\Delta I$ , PgC) for consistency with unit conversion listed below. (Odd to have unit conversion when no units have been listed as yet).

\* line 127: for consistency, include units of DIC pools.



\* line 128: Again you don't need the subscript ocean here. Save it for inventory calculated using carbon storage.

\* line 132: Again no ocean subscript needed, use symbol to symbol to specify we are talking about betas calculated from carbon storage.

\* line 135: Rather than "can be expressed as" it would be more direct to write "were diagnosed" to clarify that this is what you do in this study.

\* line 155: "contemporary atmospheric CO<sub>2</sub>". Maybe I have misunderstood something here. But, I would have thought this refers to projected atmospheric CO<sub>2</sub>? Could you please clarify.

### **3 Regional carbon cycle feedbacks in CMIP6 Earth system models**

\* line 263: replace "into contribution" with "into contributions"

\* line 266: replace "non-linearity of ocean carbon cycle feedbacks" with "non-linearity of ocean carbon cycle feedbacks (see Equation 4)"

\* line 266: replace "n notes" by "n denotes"

\* line 305: or that the region dominating the the carbon cycle feedback differs between the models.

### **4 Control of the Atlantic Overturning circulation to the carbon cycle feedbacks**

\* The title seems back-to-front. Suggestions: "Relationship between carbon cycle feedbacks and the Atlantic Meridional overturning circulation" or "Control of the carbon cycle feedbacks by the Atlantic overturning circulation"

### **5 Discussion and Summary**

\* line 494: Similarly "control of the Atlantic Meridional Overturning circulation" is not the right title. You are talking here about the control of the feedbacks by the AMOC, not the controls on the AMOC itself.