Dear Kirsten Zickfeld,

Thank you for the effort you have put in our manuscript so far, for which we have uploaded a revised version.

Our apologies for not sufficiently answering the points raised by the second reviewer in the first revision. We have addressed the points raised by the second reviewer in much detail for this revision. We kindly ask you if you can approach the second reviewer again to ask whether the reviewer wants to have another look at our revised paper.

Thank you in advance.

Kind regards,
Daan Boot
On behalf of all authors.

MS-No.: ESD-2021-42

Title: Effect of the Atlantic Meridional Overturning Circulation on Atmospheric pCO_2 Variations

Author(s): Daan Boot, Anna S von der Heydt and Henk A. Dijkstra

Point-by-point reply to reviewer #1

March 23, 2022

We thank the reviewer for his/her careful reading and for the useful comments on the manuscript.

Minor revisions:

1. *In the introduction (L41-L52), why not specify the sign of atmospheric* pCO_2 *changes via each mechanism?*

   Author's reply:
   We have not specified the signs of the mechanisms because the signs of the mechanisms are not necessarily the same for each study. Some studies simulate pCO_2 decrease and some simulate pCO_2 increases after an AMOC weakening. This is addressed in L49-L52, i.e. the difference in model complexity, model time scales, and climatic boundary conditions are the reasons behind this.

   Changes in manuscript:
   No changes necessary.

2. *Around L300-314: As the biological productivity increases (Figure 4c and 4d: fixed rain ratio), both the* $CaCO_3$ *pump and soft tissue pump change. I didn't see the explanation of changing soft-tissue pump on atmospheric* pCO_2*. Does the contribution of* $CaCO_3$ *mechanism over dominates the changing soft-tissue pump? I would suggest to clarify it in the text.*

   Author's reply:
   Generally, one would expect that a weaker soft tissue pump (STP) results in lower carbon export to the deep ocean, and therefore higher concentrations in the surface ocean leading to higher pCO_2 values. This

is what occurs in the range 0.7 – 1.0 of the biological productivity parameter and when this parameter is lower, pCO_2 is higher. As biological production becomes weaker, $CaCO_3$ production and burial also decrease. If burial decreases, the river influx has to decrease to conserve alkalinity and therefore atmospheric pCO_2 has to decrease. This is what happens when the biological productivity parameter is smaller than 0.7.

Changes in manuscript:
A more extensive discussion of this process is included in the main text (paragraph around line 300).

3. *In Table 2, how do you decide the parameter in x-HB experiment?*

   Author's reply:
   The combination of SCP-M and AUTO makes exploring the parameter space very cheap. This allowed us to do an extensive scanning of the parameter space where we eventually discovered the Hopf Bifurcation (HB). We explored the existence of the HB in the parameter space and finally settled on the parameter values presented in the paper as we thought these parameter values are within a likely realistic range.

   Changes in manuscript:
   This is clarified in the main text (around L. 315).

4. *In Figure 2, in the LGM configuration, does the HB exist in the experiment of L-CTL and L-BIO? If so, does the atmospheric pCO_2 mean the unstable FP pCO_2?*

   Author's reply:
   No, the HB does not exist. Atmospheric pCO_2 in Figure 2 represents a stable fixed point.

   Changes in manuscript:
   This is clarified in the main text (around L. 240) and in the caption.

5. *Does HB exist or is it possible to find the HB using your model if the pCO_2-AMOC feedback is included?*

   Author's reply:
   We find the HB when we use the AMOC as control parameter. When we enable the pCO_2-AMOC feedback, we cannot use the AMOC strength as a control parameter anymore. Given that atmospheric pCO_2 is not

very sensitive to changes in the AMOC, we can expect the strength of this feedback to be relatively small as the results in section 3.3 also suggest. So, we cannot say it with certainty, but we do expect it is likely that the HB exists in the parameter space when the pCO_2-AMOC feedback is enabled

Changes in manuscript:
We address this in the revised discussion of the results (around L.420).

MS-No.: ESD-2021-42

Title: Effect of the Atlantic Meridional Overturning Circulation on Atmospheric pCO_2 Variations

Author(s): Daan Boot, Anna S von der Heydt and Henk A. Dijkstra

Point-by-point reply to reviewer #2

March 23, 2022

We thank the reviewer for his/her careful reading and for the useful comments on the manuscript.

This is my second review of Boot et al. Unfortunately, I don't think my comments have been adequately addressed by the authors. I suggested Major revisions, but only a few minor changes were made to the manuscript.

1. *The relationship between atmospheric CO_2 and riverine influx is still not clear (L. 359-364 does not explain that relationship). Line 334-335 it is stated that the river influx is directly proportional to pCO_2 and it starts to change at t=0 in Fig. 6. This link between CO_2 and river influx has to be explained and justified (both in terms of amplitude and timing) in a much better way in the manuscript. The assumptions taken (since it is a very much simplified framework) have to be clearly spelt out and discussed.*

   Similarly, in a more complex system, $CaCO_3$ burial would not be a simple function of $CaCO_3$ production at the surface (L. 335-336). While Figure 6 focuses on the relationship between alkalinity and air-sea CO_2 exchange, changes in biological efficiency and $CaCO_3$ production will also impact DIC and thus air-sea gas exchange and SST will impact CO_2 solubility.

   Author's reply:
   In the above paragraph multiple points are raised and therefore we have divided this reply in multiple sections: 1. River flux: (a) What is the relation between the river flux and atmospheric pCO_2? (b) Where does this relation come from? (c) What assumptions underlie this relation? (d) How does this choice influence our results? 2. $CaCO_3$ burial: (a)

What is the $CaCO_3$ burial relation? (b) Where does it come from? (c) Why is it only dependent on $CaCO_3$ production? 3. Other processes: What is the role of other processes such as the impact on DIC and solubility of CO_2?

1. (a) ***What is the relation between the river flux and atmospheric pCO_2?*** *The relation for carbon influx is given by:*

$$C_{river} = W_{SC} + (W_{SV} + W_{CV}) \times pCO_2^{atm} \tag{1}$$

Where W_{SC} is a parameter reflecting constant silicate wheatering, W_{SV} a parameter representing variable silicate weathering, and W_{CV} a parameter representing variable carbonate weathering. pCO_2^{atm} represents the partial pressure of CO_2 in the atmosphere. This relation comes from O'Neill et al. (2019) which is directly taken from Toggweiler (2008). No adaptations have been made to the relation, nor the parameter values.

The parameter values are: W_{SC} = 0.75 × 10^{-4} mol m^{-3} yr^{-1}; W_{SV} = 0.50 × 10^{-4} mol m^{-3} atm^{-1} CO_2 yr^{-1}; and W_{CV} = 2.00 × 10^{-4} mol m^{-3} atm^{-1} CO_2 yr^{-1}

1. (b) ***Where does this relation come from?*** *The relation used in Toggweiler (2008) is based on the relation used in Walker and Kasting (1992), i.e.,*

$$C_{river} = W_{SV} \times (pCO_2^{atm})^{0.3} + W_{CV} \times pCO_2^{atm} \tag{2}$$

where W_{CV} is 0.00015 × 10^{17} mol yr^{-1} and W_{SV} is 0.00005 × 10^{17} mol yr^{-1}, or when the volume of box 1 in the SCP-M is taken into account 5.7 × 10^{-4} mol m^{-3} yr^{-1} and 1.9 × 10^{-4} mol m^{-3} yr^{-1}. The main addition in Toggweiler (2008) is the constant silicate weathering and the change from a power law to a linear relationship.

In Walker and Kasting (1992) they state that the key element in the representation in continental weathering rate is how the carbonate and silicate dissolution rates depend on pCO_2. In the long term (100,000s of years), this dependence determines steady state pCO_2. On shorter time scales (10s-100s of years), it is this dependence that determines how quickly the ocean-atmosphere system will recover from an impulsive *input of fossil fuel carbon dioxide. They mention that several formulations have been proposed, but that all of those rate laws are subject to large uncertainty. There are dependencies on the hydrological cycle, on global average temperature, but for simplicity they express the weathering rate as a function pCO_2. Since the weathering rate law controls CO_2 response on a time scale of 100,000s to 1,000,000s of years, they state it is not that important which formulation is used as long as processes on time scales shorter than that are studied.*

The parameter values are chosen such that the influx via the rivers is approximately equal to estimates of carbonate influx via rivers (e.g. in Milliman and Droxler, 1993).

1. (c) ***What assumptions underlie this relation?*** *The main assumptions are:*

- *For the model complexity and time scales addressed,the relation to atmospheric pCO_2 is sufficiently realistic.*
- *River influx occurs only in the low latitude ocean (30°S – 30°N).*
- *River influx is due to carbonate and silicate continental weathering.*
- *Silicate weathering consists of a constant and variable part.*
- *Carbonate weathering consists of only a variable part.*
- *There is no delay between continental weathering and river influx.*
- *Parameter values are insensitive to changes between LGM, Holocene and Anthropocene.*

1. (d) ***How does this choice influence our results?*** *The parameter values, and thus the amplitude of the river flux are important for the amplitude of the change in total alkalinity in the system, and the alkalinity concentration in the surface ocean. Decreasing the amplitude of the river flux, would decrease the amplitude of total alkalinity in the ocean and thus the amplitude of the CO_2 oscillation in the atmosphere. Decreasing the amplitude enough might make the oscillation disappear. Increasing the amplitude would result in unphysical results, since atmospheric pCO_2 values would reach too low values, decreasing ocean temperatures below freezing point. Therefore, the currently used* *parameter values, based on estimated carbonate input via rivers, are in a range such that the Hopf bifurcation (HB) exists.*

The fact that there is no time delay between atmospheric pCO_2 *and the river influx is important. The approximate quarter period delay between atmospheric* pCO_2 *and total alkalinity (and alkalinity in box 1) is important for driving the oscillation. The river influx plays a role in this by changing the alkalinity in box 1. However, only if the delay is multiple centuries, we expect very different results than the ones presented here.*

To conclude: (1) The assumption of the coupling of atmospheric pCO_2 *to the river influx is expected not to be crucial. (2) The magnitude of the parameter values is important, but the actual magnitude of the parameter values are reasonable. (3) The fact that there is no delay between* pCO_2 *and the river influx is important, but the current assumption is reasonable for the model complexity and time scales involved.*

Other assumptions, such as the division of the river influx in carbonate and silicate weathering are common in these types of models and are not expected to influence the results significantly. The fact that we do not couple the river influx to different processes such as the hydrological cycle, is related to the arguments of the model complexity and time scales assessed.

2. (a) ***What is the*** $\boldsymbol{CaCO_3}$ ***burial relation?*** *The change in DIC due to* $CaCO_3$ *related processes is dependent on three different processes: (1) Formation of* $CaCO_3$ *(sink of DIC in surface boxes); (2) Dissolution of* $CaCO_3$ *in the water column (source of DIC in all boxes); (3) Dissolution of* $CaCO_3$ *in the sediments (source of DIC in abyssal box). Burial of* $CaCO_3$ *is defined as the difference between the formation (process 1) and dissolution of* $CaCO_3$ *(processes 2 and 3).*

Process 1 varies because the formation of $CaCO_3$ *is dependent on biological production which is variable due to changes in phosphate upwelling and biological efficiency. Processes 2 and 3 are based on the same general relation:*

$$C_{Diss} = ([CO_3^{2-}][Ca^{2+}]) \times k_{Ca} \times (1 - (min((\frac{[CO_3^{2-}][Ca^{2+}]}{K_{sp}}), 1))) + D_C \tag{3}$$

The first part is related to the saturation state: $\frac{[CO_3^{2-}][Ca^{2+}]}{K_{sp}}$. *If the saturation state is larger than 1, the saturation dependent dissolution is 0, and only the constant term remains* (D_C)*.*

In the oscillation, the saturation state of $CaCO_3$ *in the ocean is everywhere larger than 1. Therefore, total dissolution in the ocean is constant and does not vary. This results in that the* $CaCO_3$ *burial becomes a function of* $CaCO_3$ *formation and thus biological production.*

2. (b) ***Where does it come from?*** *The saturation driven part is a very general formulation used to describe* $CaCO_3$ *dissolution (e.g. Sarmiento and Gruber, 2006). Observations suggest that even in supersaturated cases some form of dissolution occurs (Harrison et al., 1993; Milliman et al., 1999) which is the reason for including a constant dissolution term.*

2. (c) ***Why is it only dependent on*** $CaCO_3$ ***production?*** *Using a simple model for* $CaCO_3$ *dissolution, Zeebe and Westbroek (2003) show that the entire ocean can be supersaturated in* $CaCO_3$ *when the riverine influx is larger than the biogenic flux in the surface ocean. In the SCP-M, the river influx is indeed larger than biological production, representing the situation sketched in Zeebe and Westbroek (2003). In the current ocean and the LGM ocean, this situation is not likely, but this does not mean it has not happened in the past.*

3. ***What is the role of other processes such as the impact on DIC and solubility of*** CO_2***?*** *The processes described in the main text are the driving forces behind the oscillation. Other processes are also important in shaping the period and amplitude of the oscillation, since the processes are all dependent on each other. Generally the change in DIC, Alk and* PO_4^{3-} *concentrations is due to a balance of several large fluxes that are sometimes more than 100 times larger than the sum of all fluxes. It is therefore difficult to describe the effect of each process individually. However, the coupling between atmospheric* pCO_2 *and the alkalinity cycle appears to be the driving mechanism of this oscillation.*

Changes in manuscript:

1. (a) This relation and the parameter values are included in the main text (Eq. 13 and surrounding text). 1. (b) This is discussed in the main text (Eq. 13 and surrounding text). 1. (c) This is addressed *in the discussion in combination with 1(d) (paragraphs around L. 440-465). 1. (d) This is addressed in the discussion (paragraphs around L. 440-465). 2. (a) The relation is clarified in the text (Eq. 14 and surrounding text). 2. (b) No changes necessary. 2. (c) We mentioned this in the main text (paragraph around L. 350). 3. We included a more thorough discussion in the main text (paragraph around L. 367-376).*

2. *A wide range of parameter space and their impact on pCO_2 is explored, however there is little explanation as to why this would occur, if this is plausible in a more complex system and the implications of the results are not discussed. The authors need to discuss how their results can help in better understanding climate-carbon cycle interactions. They also need to discuss the assumptions taken, their limits and how this might impact the results.*

   Another aspect to discuss is the fact that the current study focuses on box 1 (low latitude surface box), whereas most studies suggest high latitude processes dominate the carbon cycle.

   Author's reply:
   This reply is also divided based on the multiple subcomments: (a) Why is such a wide range of parameter space explored? (b) Is this possible in more complex systems? (c) How do the results help in better understanding climate-carbon cycle interactions? (d) What assumptions did we make, what are the limitations of the model, and how does this impact our results? (e) Why is there a contrast between our study where low latitude processes seem to be important, while other studies suggest high latitude processes to dominate the carbon cycle?

   (a) ***Why is such a wide range of parameter space explored?*** *In this study there are a few parameters we vary: AMOC strength, the rain ratio, biological production, the piston velocity and climate sensitivity.*

   First of all, we have varied these parameters over a wide range to look for multiple (stable) equilibria. By following branches of steady state solutions, we were curious whether we would find saddle-node bifurcations. Saddle node bifurcations might exist for unlikely parameter values, but this would show that there are multiple stable equilibria, possibly in the more realistic parameter value ranges. We did not find any saddle node bifurcations in this model, suggesting that in this simple carbon cycle box model, no multiple stable equilibria exist. This is *valuable information from a dynamical systems point of view.*

Secondly, a large part of our research focuses on changes in the AMOC strength. Multiple studies have shown that the AMOC can have multiple stable equilibria. Disruption of the AMOC is often thought to be a cause for major climate shifts such as the Dansgaard-Oeschger events. Future projections show that the AMOC strength is decreasing significantly (e.g. 48% in SSP5-8.5 using the CESM2 model in a concentration driven simulation). By varying the AMOC strength, we see how the carbon cycle responds to changes in this AMOC, and whether a possibly weaker AMOC in the future might impact atmospheric pCO_2.

We varied the rain ratio, biological production and piston velocity to assess the sensitivity of atmospheric pCO_2 *to changes in one of the three traditional carbon pumps (carbonate, soft tissue, solubility, respectively). The ranges for these parameters are larger than realistic, mostly because we were also testing to see whether there are bifurcations in the model. The results show the sensitivities in this model to changes in these model parameters and in the more realistic parameter ranges, interesting results are found.*

We also varied climate sensitivity. Climate sensitivity of the Earth is still uncertain and Earth System Models give a wide range (1.8-5.6 K in CMIP6; Zelinka et al., 2020). By using multiple values of this climate sensitivity, we take this uncertainty into account.

Lastly, by using these wide ranges, we have covered most of the realistic response in this model. We also covered some unrealistic ranges, but the main take home message is: the marine carbon cycle (in this model) seems to be a stable system where no large changes occur when parameters are varied.

(b) ***Is this possible in more complex systems?*** *Not all combinations of values are possible in more complex systems. A realistic range for the AMOC strength is a few Sverdrups to approximately 25 Sv, which mean most of our results are in a realistic AMOC range. Climate sensitivity is also within realistic ranges in our study. The three parameters representing the different pumps are mostly outside realistic ranges, but cover the realistic ranges.*

(c) ***How do the results help in better understanding climate-carbon cycle interactions?*** *We have shown that the carbon cycle*

is quite a stable system with no saddle node bifurcations in this simple model. This suggests that as the climate changes, we do not expect to find so-called tipping points in the carbon cycle as a response to climate change. Furthermore, we show that changes in AMOC strength, which are very likely under changing climate and have happened in the past, do not result in large changes in atmospheric pCO_2*. Lastly, if we want to explain variability in the past climate linked to the carbon cycle, oscillations due to Hopf bifurcations should also be taken into account.*

(d) ***What assumptions did we make, what are the limitations of the model, and how does this impact our results?***

One of the assumptions we made is that the original SCP-M performs well for Last Glacial Maximum and Pre-Industrial conditions. In O'Neill et al. (2019) they discuss this, and the model gives reliable results for these two time periods. We have added several features to the model and one of our assumptions is that the parameter values do not need to be retuned after the addition of these new features. We also assume that the simplification of the carbonate chemistry does not change the outcome significantly. Other minor assumptions we made are that the steady state AMOC-pCO_2 *relation can be captured by a logarithmic function, and that the temperature effect on biological efficiency is a linear function.*

Limitations of the original SCP-M include: there is no distinction between ocean basins, which means the framework may not be useful for testing localized or detailed problems; and there is a rigid and somewhat arbitrary treatment of box boundaries. In our application, we also consider the simple carbonate chemistry as a limitation.

The impact on the results differ per assumption and limitation. Since the SCP-M performs well in the original paper for two different cases (O'Neill et al., 2019). By adding extra features to the model, some refitting of parameters was necessary, depending on the specific (newly added) processes: (i) The efficiency parameters in the biological feedback have been fitted to give similar results as the original model. (ii) The feedbacks related to the temperature, biological efficiency, piston velocity and rain ratio are not expected to result in necessary refitting of the parameter values. This is because the temperature feedback does not directly affect any parameters in the elemental cycles, and the other *feedbacks do not add new processes to the model. Parameters are just replaced by more complex, variable functions, but values remain close to the original values. (iii) The addition of the biological alkalinity flux might make refitting of parameters necessary since a complete new process is added to an elemental cycle. This would be a large exercise and would also make comparison between the different cases difficult. This means that cases where this feedback is used should be approached more carefully. However, in our results without refitting, cases with this feedback do not show divergent results compared to other cases.*

An important change we made is the simplification of the carbonate chemistry. This change typically reduces pH by 0.15-0.2 (Munhoven, 2013). Another effect of this simpler chemistry is that atmospheric pCO_2 *can have changes of the order of 20% (Munhoven, 1997; Munhoven, 2013), which explains the approximate 60 ppm lower atmospheric* pCO_2 *in our model compared to the original version. Obviously this assumption impacts our results, since atmospheric* pCO_2 *values are clearly affected. However, general sensitivities as discussed in our results are not expected to change a lot.*

Our results show that atmospheric pCO_2 *is not very sensitive to changes in the AMOC, or to the strength of the AMOC-*pCO_2 *feedback we have used. Therefore, we expect that different formulations of this feedback do not change the results significantly. The assumption that biological efficiency is linearly related to change in temperature is very uncertain, while the biological efficiency feedback is important for the oscillation we found. What seems to be important for the oscillation is that the coupling between atmospheric* pCO_2 *and the biological efficiency is strong enough. Whether the strong relation chosen now is realistic is uncertain.*

One of the limitations of the original SCP-M is that there is no distinction between ocean basins. This might have an impact via the northern high latitude box (box 2), since the circulation in this box represents the AMOC, which is of course not present in the Pacific. In the original model, global values were still representative, showing that it might not have a large impact on the results. The impact of the other limitations on the results are hard to determine (box boundaries) or already discussed (carbonate chemistry).

(e) ***Why is there a contrast between our study where low latitude processes seem to be important, while other studies suggest high latitude processes dominate the carbon cycle?***

It seems that the existence of box 1 is important in the oscillation which suggests that low latitude processes are important. However, the oscillation is not necessarily driven by low latitude processes. It is a global process, i.e. $CaCO_3$ *production over the entire ocean decreases, and not just in the low latitude surface box (box 1). The role of box 1 is important since the air-sea gas exchange in box 1 leads atmospheric* pCO_2*.*

Changes in manuscript:
(a) This is addressed in the discussion (paragraph around L.465-475). (b) This is addressed in the discussion (paragraph around L.465-475). (c) This is addressed in the discussion (last paragraph section 4; around L475-482). (d) This is addressed in the discussion (paragraphs around L. 440-465). (e) This is addressed in the result section (end of section 3.3; around L. 390).

Minor points:

1. *L. 262-263: Why would deep ocean ventilation be more sensitive to AMOC changes when the AMOC is weak?*

   Author's reply:
   If we see deep ocean ventilation as the sum of the General Overturning Circulation (GOC; ψ_1*) and the AMOC (*ψ_2*) then this sum is relatively more sensitive to changes in the AMOC as the GOC is lower (in the LGM case).*

   Changes in manuscript:
   This is clarified in the text (around L. 260).

MS-No.: ESD-2021-42

Title: Effect of the Atlantic Meridional Overturning Circulation on Atmospheric pCO_2 Variations

Author(s): Daan Boot, Anna S von der Heydt and Henk A. Dijkstra

List of changes second revision

March 23, 2022

Following is a list of notable changes made in this second revision as a response to the comments of the reviewers. There have also been some small textual changes (spelling, rephrasing, etc.). These small changes are not included in this list.

1. We have extended the explanation of the two regimes in Section 3.2 where we use biological productivity as control parameter (paragraphs around L. 300).
2. We have included a more thorough discussion on the role of the river influx and $CaCO_3$ burial in Section 3.3 (text around Eq. 13 and Eq. 14).
3. We have included a paragraph discussing how other processes influence the oscillation (paragraph around L. 370).
4. We have extended Section 4 with a discussion on the assumptions, limitations and impact of our study (from L. 440 to the end).