

Interactive comment on “Sensitivity of the marine carbonate cycle to atmospheric CO₂” by R. Gangstø et al.

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We would like to thank Birgit Schneider for constructive comments. Please find below the detailed response.

Answer to general comment:

The reviewer suggests emphasizing the novelty of the study, such as the inclusion of foraminifera calcite in the Bern3D/PISCES model. She also suggests that we explain the theoretical behavior of the different parameterizations in more detail and determine the potential upper limit for compensation by adding more simulations.

We have followed her suggestions, by highlighting and discussing the inclusion of foraminifera calcite and also mentioning it in the abstract. We have included deriva-

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tives of the theoretical PIC-POC ratios in Figure 1 as she suggested, and we have done new simulations, where we have set the calcification to 0 by the year 2000 to calculate the upper limit for CO₂ feedbacks.

Answers to specific comments:

Title: The title 'Sensitivity of the marine carbonate cycle to atmospheric CO₂' sounds very general. As the topic is ocean acidification and pelagic calcification, something like 'Sensitivity of pelagic calcification to Ocean Acidification' would be more appropriate. As far as I could find out, and surprisingly, this title seems not to be taken, yet.

The title will be changed as you suggested.

p. 7032, l. 17-19: Ridgwell et al. (2007) have already included foraminifera via an optimization of the rate order η .

We are the first to include calcification by foraminifera explicitly. The rate law Ridgwell et al. (2007) used for precipitation is estimated through an Ensemble Kalman filter approach. It is randomly subsampled within the range of reported values, which covers data from forams.

p. 7036, l. 5: is there a reference for the limit of 0.8?

We have added Aumont and Bopp (2006).

p. 7036, l. 17-22: explanation to equation (4): it should be mentioned that (1) the scaling factor is used to match a certain value for global calcification (please include value and reference or at least refer to Tables 1 and 2); (2) the limitation term $\max(1, P/2)$ must be in $\mu\text{molC/l}$; (3) the average PIC_C:POC is 0.3 (if I'm correct).

The limitation term is corrected, the average PIC:POC value included: in our parameterization this is about 0.8 for the pre-industrial global surface ocean. Concerning scaling factors we have added in end of 2.2: Total pre-industrial CaCO₃ production is tuned in all setups to about 1.0 Pg C yr⁻¹ by adjusting the scaling factors in Equations

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(4), (9) and (11). The values of the scaling factors are not given as they depend largely on the carbonate chemistry and circulation fields of the model used. And in 2.2.1: In this parameterization, f_i is a scaling factor used to match a global calcite production by nanophytoplankton of about 1.0 Pg C y⁻¹ (see Table 1 and 2).

p. 7037, l. 14: numbering is not consistent, I'd suggest to remove it here

OK, this is done.

p. 7037, l. 23: It might be helpful for the reader to mention where the values of (PIC/POC)_{max} and K_{max} can be found in Figure 1.

We have included a short description in the text: (PICC/POC)_{max} is the maximum ratio reached under optimal growth conditions for calcifying organisms, the max value that PICC/POC would have on Fig. 1 if the Michaelis-Menten curve was extended to $\Omega_C = \infty$. The parameter K_{max} corresponds to a half saturation constant, i. e. the value of $(\Omega_C - 1)$ where PIC/POC equals half the value of (PICC/POC)_{max}.

p. 7039, l. 13-15: a bit more specific information about the results from *L. helicina* would be helpful to understand the development of this parameterization.

The section is changed to: Another study on *L. helicina* was performed in Kongsfjorden, Spitsbergen, Norway. Here, the PICA to POC ratios varied between 0.078 and 0.106 (J. Bűdenbender, S. Lischka and U. Riebesell, personal comm.). A linear relationship is developed from the two data sets. We let the maximum PICA-POC value from the second study correspond to conditions with Ω_A equal 1.9 and calculate a 28% linear decrease in PICA-POC down to $\Omega_A = 1$ (Comeau et al. 2009).

p. 7039, l. 21: again a scaling factor ($f_{M,A}$) is used. As I understood, this is used to tune Aragonite production to 1/3 of global calcification. Please specify.

We add: ... and a scaling factor $f_{M,A}$, which is used to tune the aragonite production to 1/3 of global calcification.

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p. 7041, l. 4: tuning factor $f_{M,C}$, please specify

We add: $f_{M,C}$ is again a scaling factor used to tune the calcite production to 1/3 of global calcification.

p. 7041, l. 7: If the sensitivity analysis of the different parameterizations is added to Figure

1 (see general comments above), it would be good to explain this in more detail, here.

OK, this is done.

p. 7041, l. 9 – p. 7042, l. 9: Model description, please move to section 2.

OK, we have moved it.

p. 7042, l. 21-22: If atmospheric CO₂ emissions are used to force the model, which assumptions are made for the land biosphere?

We have added in the end of 2.1: Future atmospheric CO₂ depends also on the evolution of terrestrial carbon sources and sinks, and this is uncertain (e.g. Denman et al. IPCC, 2007). Here, we have not included a land biosphere component as the focus is on the ocean carbonate cycle.

p. 7044, l. 13-14: typo – relatively

OK, corrected.

p. 7047, l. 12: Why is the correlation weaker for Aragonite (0.7) than for calcite (0.8)? Before, you mention that the surface Alkalinity distribution is better in the Aragonite version due to the shallow remineralization and faster transport back to the surface via circulation. Why does this better match not apply to deeper levels?

Some mismatches for alkalinity may be seen in the deep Pacific and Atlantic Ocean, which probably lead to a lower correlation for alkalinity. We have now explained these mismatches better in the text:

The alkalinity and DIC concentrations at depth are slightly improved in the versions including aragonite, due to the rearranging of DIC and alkalinity concentrations in the water column caused by shallow water aragonite dissolution (Fig. 6b). An exception is the alkalinity in the deep Atlantic and Pacific, which is more over- and underestimated, respectively, in the model versions including aragonite (Fig 7a). The differences between the model versions with calcite only and the model versions including aragonite appear in the Taylor diagram (Fig. 9), where modeled alkalinity and DIC are compared to pre-industrial values from the Global Ocean Data Analysis Project (GLODAP) (Key et al., 2004). Due to the mismatches in the deep Atlantic and Pacific, the correlation coefficient r between modeled and data-based alkalinity is ~ 0.8 for the versions without aragonite, and ~ 0.7 for the versions including aragonite. For DIC, the correlation coefficient is higher than 0.9 for all versions and independent of the form of CaCO_3 , whereas the standard deviation becomes closer to unity when aragonite is included. To conclude, except for some discrepancies in the Atlantic and Pacific mainly related to deficiencies in modeled circulation, the observed alkalinity and DIC concentrations are fairly well represented by the model.

p. 7084, l. 12: Please add the depth of the calcite and aragonite saturation horizons to the Taylor diagram. This is another (probably more strict) constraint of the spatial distribution of the saturation state.

This has been done.

p. 7048, l. 23-25: this is part of the model description

OK, it has been moved.

p. 7049, l. 19-21: you may add: . . . and upward mixing (Friis et al., BG, 2007)

OK, this is done.

p. 7050, l. 23: add 'growing' before 'extent'

This is now done.

p. 7050, l. 27 – p. 7051, l. 2: I do not understand this sentence. Since only the parameterizations for calcification differ, it is clear that everything is related to them.

OK. This sentence has been removed (as was also suggested by the second reviewer).

p. 7052, l. 6-7: maybe this sentence could be continued by: . . ., over the entire Omega-range (see sensitivities added to Figure 1)

Yes, this is added.

p. 7053, l. 6: add ‘. . . scenario (Fig. 9d).’

OK, done.

p. 7054-7055: add more information about the foram calcite effect and the potential upper limit of the feedback on the atmosphere, when considering that calcification ceases (see general comments above)

OK, this is done.

p. 7059, l. 24-27: Yes, but also these species will respond to undersaturation by dissolution.

This part has been removed, as suggested by the 2. reviewer.

p. 7062, l. 13-16: What is the indirect way of ballasting in PISCES? Does calcite play a role here? Please specify.

The fate of mortality and aggregation of nanophytoplankton depends on the proportion of the calcifying organisms (RCaCO₃). We assume that 50% of the organic matter of the calcifiers is associated with the shell. Since calcite is significantly denser than organic matter, 50% of the dying calcifiers biomass is routed to the fast sinking particles. This implies that a reduction of calcifying nanophytoplankton goes along with a reduction of its contribution to the pool of fast sinking POC. Mesozooplankton contributes to the same pool of fast sinking particles, but as their total biomass is not affected by

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acidification, there will be no effect of decreasing aragonite production on POC fluxes. We included this explanation.

Table 2: In the caption, I guess the CAL-MIC2 parameterization is referred to.

Yes, this is now corrected.

Table 3: if the 2nd and 3rd columns show differences between 2100 and preindustrial, it should say 2100-1766 in the column heads

OK, this is done. The 3rd column shows 2500-1766.

Figure 1: see comments above and suggested Figure below

We have added the derivatives in Figure 1b.

Figure 5e: why is in the Aragonite-run the calcite dissolution shallower than in the calcite only run? The ΔCO_3 looks very similar (Fig. 5c).

It is not so easy to see on the profile figure (previously Fig 5c), but the explanation is that the saturation horizons do differ.

Figure 7: please add the depth of the saturation horizons for calcite (CSH) and aragonite (ASH). It seems that none of the parameterizations significantly improves the model-data agreement.

This is done. As the Taylor analysis only makes pattern correlations, what are the respective total amounts of DIC in the different runs? It would be interesting to see by how much the DIC inventories differ, since the atmosphere is an unlimited source to the ocean in the spinups, as I understood. These numbers could be added in Table 2. In fact, the atmosphere is not an unlimited source to the oceans during the spinups, only during the scenarios, and we did not add them in the table. The DIC inventories after the spinups are about 2.290 mol/m³ for the calcite-only versions, and about 2.299 mol/m³ for the versions including aragonite.

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Figure 8: I cannot see any grey or white lines.

These are now added.

Figure 11: Please add bar on the left showing the respective percentages from the Glodap data

We have added black crosses on the figure which indicates the percentages from Glodap and mentioned in the text: Compared to GLODAP observations, our model correctly simulates the volume occupied by the upper three classes, whereas the model underestimates the volume of undersaturated water (crosses in Fig. 13).

Figure 13: maybe you could add a panel showing the percent amount of undersaturated water, which would nicely indicate the persisting impact of OA at greater depth

We have added such a subfigure.

Caption for Figure 1 (below): PIC:POC ratio (full lines) as function of Omega as used in the manuscript (Fig 1.). The dashed lines show the respective sensitivities, $d(\text{PIC:POC})/d\Omega$.

Due to a lot of information in one figure when the observations were also included, we split the figure up in two subfigures for clarity. We adapted the suggested caption correspondingly.

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