

Interactive  
Comment

## ***Interactive comment on “Modeling the marine aragonite cycle: changes under rising carbondioxide and its role in shallow water $\text{CaCO}_3$ dissolution” by R. Gangstø et al.***

**R. Gangstø et al.**

Received and published: 3 July 2008

We wish to thank both reviewers for helpful comments, which improved our manuscript.

Referee #1

Reply to specific comments:

1) Abstract - add 29% global number and replace "until" with "by" in last sentence.

- This will be done in the revised version.

2) line 159 - How was  $k_{\text{max}}$  calibrated? Why was such a low value (0.4) chosen rather than something more consistent with Langdon, 2005 coral aragonite study? The authors have a sentence at the end (lines 491-494) that refers to calibration to coccol-

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper



ithophores (which are calcite rather than aragonite but planktivorous, I admit). I'm not arguing that the authors should have chosen a different value necessarily, but that they should be able to defend their choice.

- We will add in line 152: "Studies of aragonite secreting warm water corals show different responses to decreasing saturation state dependent on species: Langdon (2005) reported a linear reduction in calcification whereas the study by Gattuso (1998) showed a decrease in aragonite production following a shape very similar to this Michaelis-Menten curve. It is uncertain whether planktonic pteropods react in the same way as corals. Thus, due to the lack of studies focusing on pteropods we chose to adopt the Michaelis-Menten curve fitted to the mesocosm experiment by Delille et al. (2005) also for aragonite production." And after line 159: "Kmax was chosen in order to obtain a curve with values of PIC/POC relatively constant for high saturation state values as typical for pre-industrial surface ocean waters, in line with the mesocosm experiment from Delille et al (2005)."

3) line 165 - How was this sinking speed parameterization calibrated?

- In the PISCES standard version (Aumont and Bopp, 2006), large particles of organic carbon, as well as the detrital fractions biogenic opal and carbonate sink with a prescribed sinking speed that increases with depth from 50m/d (0.05 cm/s) at the base of the mixed layer to 390 m/d (0.45 cm/s) at 5000 m depth. This parameterization accounts for the observed increase of sinking speed with depth (e.g. Berelson et al., 2002). The empirical relation for depth dependent sinking speed was calibrated using a model of aggregation/disaggregation resolving particle size (Gehlen et al., 2006). A compilation of different laboratory studies of sinking pteropods and empty shells was published by Lalli and Gilmer (1989). Among them, Byrne et al (1984) measured the sinking speed of empty shells of the pteropod *L. helicina* to be equal to 1.0-1.4 cm/s, about one order of magnitude higher than our modelled values. As discussed by Lalli and Gilmer (1989) however, these laboratory values are only approximations and do not take into account the slowing down by encountering temperature and density

**BGD**

5, S1009–S1018, 2008

Interactive  
Comment

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper



boundaries and by a reduction in weight owing to dissolution effects. Thus we expect the sinking speed in the real ocean to be slower. A lower sinking speed for carbonate particles is corroborated by a recent comprehensive study (Fischer and Karakas, 2008) suggesting average sinking rate values of carbonate particles equal to 51 m/d and 318 m/d in the upper and lower water column, respectively. Their values are well in range with other studies (e.g. Allredge and Silver, 1988; Sawada, 1988) and are nicely matched by our modelled values of sinking speed. This will be included in the text.

4) line 186 - "n" is generally referred to as a reaction order, and the prefactor as a rate constant.

- This will be corrected in the revised version.

5) line 188 - The chosen value of  $n=1$  is also supported by Hales, B., 2003. Respiration, dissolution, and the lysocline. *Paleoceanography*, 18, 1099-1113.

- Thank you, the reference will be added.

6) line 290 - To what data is the model output being compared for "equatorial areas"?

- Here we were referring to the data described in the previous section. For the equatorial areas we compared to Fabry (1990) who reports an aragonite production of 0.83 mg C/m<sup>2</sup>/s in the eastern Equatorial Pacific. Although sediment traps indicate high production rate in these areas (Berner 1977, Berger 1978), we are not aware of other aragonite production data. We will change the phrase to: "it overestimates the production in equatorial areas compared to Fabry (1990)".

7) line 293 - A reference should be cited after "are considered high", and "assumed"; should be replaced with "suggested by others" or something akin.

- We chose to remove the first part of this sentence, due to the limited data in the Equatorial area. The replacement of "assumed" will be made.

8) line 399 - More description of the "scenario" used by Gehlen is necessary - also

[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)[Discussion Paper](#)

## SRES A2?

- We will add: "Gehlen et al (2007) performed an experiment according to the standard CMIP scenario of atmospheric pCO<sub>2</sub> increasing at a rate of 1% per year from 286 to 1144 ppm over a 140 year time-period."

9) lines 407-410 - It should be specified that the authors are referring to pelagic dissolution only - otherwise I think one would NOT expect higher dissolution.

- It will be specified more clearly that we refer to pelagic dissolution.

10) line 426 - Is lateral transport significant?

- We will change this section to: "The latter value implies that at the end of the SRES A2 scenario, more aragonite is actually dissolved than produced in this area, indicating transport of some aragonite particles from lower to higher latitudes. It may also in part be due to a transient behaviour; if the production decreases while the stock of particles still reflects the previous higher production rate, one would expect that the sum of particles and the dissolution is higher than the actual production. While the amount of aragonite produced in high latitudes equals 0.009 PgC y<sup>-1</sup>, the quantity that dissolves or reaches the bottom equals 0.0273 PgC y<sup>-1</sup>, leaving an amount of 0.018 PgC y<sup>-1</sup> to be lateral transport and/or transient behaviour. This is twice as much as the amount produced and thus significant for this area, while compared to the total aragonite production, it accounts for about 8.34%."

11) lines 456-457 and line 462 - Against what observationally-based estimates are the authors comparing?

- For the marine carbonate cycle in general: most references given in Table 1. For the Equatorial area: Fabry (1990) and for the upper 1000 m: Milliman & Droxler (1996). References will be added. Due to the limited data in the Equatorial area, the phrase "Except from an overestimation by the model" will be changed to "Except from a possible overestimation by the model".

**BGD**

5, S1009–S1018, 2008

Interactive  
Comment

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper



12) line 472 - Use of the word "moment" seems a bit overly specific. I would recommend omitting it.

- We will replace it by "a threshold phase seems to occur around year 2050". We may also add, line 390: "By this year, Orr et al. (2005) projected that the Southern Ocean surface waters would begin to become undersaturated with respect to aragonite. Hoegh-Guldberg et al (2008) indicate a threshold for major changes to coral reefs to be at about 480 ppm, which according to the SRES A2 scenario represents year 2040."

13) line 478 and line 485 - I believe the authors intend "estimated" in place of "assumed".

- This will be changed in the revised version.

14) Fig 3 - I believe that the plots only show pelagic dissolution, rather than "total". If correct, then the caption should add "pelagic".

- Yes, we will change this too.

15) Fig 5. It would help the reader to have the y-axis in Figure 5c stop at zero rather than -0.1 since negative  $\text{CaCO}_3$  production is undefined.

- This will also be changed in the revised version.

Referee #2

Reply to specific comments:

1) Aragonite production is linked to concentration of mesozooplankton and saturation state. The factors that control mesozooplankton density need to be more completely discussed. Particles sink with a range of velocities, but the functional velocity vs depth relationship seems pulled out of thin air.

- Mesozooplankton density: Equations may not be included in this comment, but we will add the equations that describe how the concentration of mesozooplankton is cal-

**BGD**

5, S1009–S1018, 2008

Interactive  
Comment

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper



culated in the model including a description of the parameterization. This is also given by Aumont and Bopp (2006). The change in mesozooplankton concentration is dependent on grazing, respiration and mortality. Mesozooplankton grazes on nanophytoplankton, diatoms, microzooplankton and small and big particulate organic carbon (POC). The parameterization for the grazing on multiple resources is done as for e.g. Frost, (1987), Moloney and Field (1991). The equation implies that mesozooplankton always grazes on the most preferred prey. In addition to this concentration-dependent grazing, PISCES also accounts for flux-feeding. This type of grazing may be very important for the fate of particles in the water column below the euphotic zone (Dilling and Allredge, 2000; Stemmann et al., 2004). Flux-feeding depends on the flux, the product of the concentration and of the sinking speed. Only the largest particles (POCb) experience this type of grazing. The mortality term mimics predation, as most of the mortality of mesozooplankton is believed to be due to grazing by higher trophic levels. All terms in the equation driving the temporal evolution of mesozooplankton depend on temperature (Buitenhuis et al., 2005). For a further description of the parameterization of mesozooplankton please refer to Aumont and Bopp (2006).

- Sinking speed: please refer to answer 3 to the first referee.

2) Aragonite dissolution is first order dependent on undersaturation and dissolves with a rate constant of 11 d<sup>-1</sup>. This is also a very important model constraint that is not fully explained.

- We will add, line 194, after "The latter was derived from the evolution with depth of CaCO<sub>3</sub> fluxes recorded in traps deployed below 1000m (Gehlen et al., 2007)": "11 stations were selected, for which mean annual fluxes were reported from at least two different deployment depths from a comprehensive study on particle fluxes (Dittert et al., 2005). The fraction of CaCO<sub>3</sub> lost to dissolution was calculated as the difference in CaCO<sub>3</sub> concentrations between the respective upper and lower traps. A linear dependency of CaCO<sub>3</sub> dissolution on underestimation was adopted, as supported by Hales (2003). The reaction rate constant  $k$  was next calculated based on the fraction lost to

[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)[Discussion Paper](#)

dissolution, the concentration of calcite particles and the saturation state with respect to calcite. The values of  $n$  and  $k$  may not be changed separately; as they combined fit the dissolution fluxes from this study. For a detailed description of this calculation, please refer to Gehlen et al. (2007). The derivation by Keir (1980) of similar reaction rate constants for pteropods and untreated *E. huxleyi* supports our choice of using the same dissolution rate expressions for aragonite."

3) The deepest model cell returns all alkalinity except that which equals riverine input (mass balance). Does this produce an odd distribution of alkalinity in the deep ocean and not allow for high carbonate burial rates at shelves?

- No. The redissolution of  $\text{CaCO}_3$  corresponding to an alkalinity equivalent of  $0.18 \text{ PgC y}^{-1}$  does not produce an odd distribution of alkalinity in the deep ocean as shown by Gehlen et al (2007) and carbonate accumulates on the shelves (Gehlen et al., 2008).

4) I don't understand, page 1663, how the model may be tuned to generate aragonite production equal to 1/3 total carbonate production, I thought aragonite production was free to vary as a function of mesozooplankton density.

- We have included a scaling factor which allows adjusting the partitioning of global carbonate production between calcite and aragonite to the range of published estimates. In order to obtain the approximate 1:2 relationship between aragonite and calcite, the scaling factor for aragonite was set equal to 0.05 and the scaling factor for calcite equal to 0.3.

5) I don't understand the categories labels in Table 1 in the middle portion of the table, what boundary is referred to as "lower boundary"?

- The lower boundary represents the deepest model grid boxes (the bottom of the ocean). This information is already given in the end of Section 2.2.1, but to clarify it will also be included in the caption of Table 1.

6) In Fig. 5e, why is calcite dissolution/net production higher than aragonite dissolu-

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper



tion/net production?

- We will add: "The reason why the calcite dissolution to net production ratio is higher than the equivalent ratio for aragonite is probably due to the fact that a larger fraction of the aragonite production occurs in areas with deep saturation horizons, where very little or no dissolution may occur, than of the calcite production. 30% of the total pelagic aragonite production takes place in the Atlantic Ocean where the saturation horizon is deepest, compared to 27% of the total calcite production. In the north Atlantic only, 19% of the total aragonite is produced, whereas 16% of the total calcite production takes place in this area."

7) Table 2 needs more header differentiation to help read the rows.

- This will be done in the revised paper.

8) It is not clear how carbonate production and dissolution on margins and shelves impact the results discussed here. Some comments to this effect would be helpful.

- We will add before the conclusion: "In comparison to the pelagic ocean (Table 1),  $\text{CaCO}_3$  production in benthic calcifying systems ( $<100$  m) is low, of 0.02-0.1 PgC  $\text{y}^{-1}$  (Milliman & Droxler, 1996). The accumulation in the shallow depth sediments is reported to be 0.01-0.1 PgC  $\text{y}^{-1}$  (Milliman & Droxler, 1996). As the coastal areas are usually oversaturated, very little dissolution takes place in the water column and in the sediments. With a "business as usual"  $\text{CO}_2$  emissions scenario the saturation state of the surface waters with respect to calcite and aragonite is projected to decrease by 45% within year 2100 and by 73% by year 2300 (Caldeira and Wickett, 2005; Andersson et al., 2005). Andersson et al. (2005) suggested that this could lead to a reduction in carbonate production rate in coastal areas of 40% by 2100 and by 90% by year 2300, using a linear relationship between saturation state and calcification. As the amount of dissolution is low in the coastal areas, the ratio dissolution/calcification in this area might thus increase significantly. The feedbacks on atmospheric  $\text{pCO}_2$  of changes in the budget of shallow water benthic carbonates can however not be extrapolated from

**BGD**

5, S1009–S1018, 2008

Interactive  
Comment

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper



our study."

## References:

Allredge, A. and Silver, M.: Characteristics, dynamics and significance of marine snow, *Prog. Oceanogr.*, 20, 41-82, 1988.

Andersson, A. J., MacKenzie, F. T. and Lerman, A.: Coastal ocean carbonate ecosystems in the high CO<sub>2</sub> world of the Anthropocene, *Am J. Sci.*, 305, 875-918, 2005.

Byrne, R. H., Acker, J. G., Betzer, P. R., Feely, R. A. and Cates, M. H.: Water column dissolution of aragonite in the Pacific Ocean, *Nature*, 312, 321-326, 1984.

Caldeira, K. and Wickett, M. E.: Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean, *Journal of Geophysical Research*, 110, C09S04, doi:10.1029/2004JC002671, 2005.

Dilling, L., and Allredge, A. L.: Fragmentation of marine snow by swimming macrozooplankton: A new process impacting carbon cycling in the sea, *Deep Sea Res. Part I*, 47, 1227-1245, 2000.

Dittert, N., Corrin, L., Bakker, D., Bendsen, J., Gehlen, M., Heinze, C., Maier-Reimer, E., Michalopoulos, P., Soetaert, K.E. R., and Tol, R. J. S.: Integrated data sets of the FP5 Research Project ORFOIS: Origin and fate of biogenic particle fluxes in the ocean and their interactions with atmospheric CO<sub>2</sub> concentrations as well as the marine sediment, Vol. 1, WDC-MARE Reports 0002, 2005.

Fischer, G. and Karakas G.: Sinking rates of particles in biogenic silica- and carbonate-dominated production systems of the Atlantic Ocean: implications for the organic carbon fluxes to the deep ocean, *Biogeosciences Discussions*, 5, 2541-2581, 2008.

Frost, B. W., Grazing control of phytoplankton stock in the open subarctic Pacific Ocean: A model assessing the role of mesozooplankton, particularly the large calanoid copepods *Neocalanus* spp., *Mar. Ecol. Prog. Ser.*, 39, 49-68, 1987.

**BGD**

5, S1009–S1018, 2008

Interactive  
Comment

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper



Hales, B.: Respiration, dissolution, and the lysocline, *Paleoceanography*, 18, 1099-1113, 2003.

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J. et al.: Coral reefs under rapid climate change and ocean acidification, *Science*, 318, 1737-1742, 2007.

Moloney, C. L. and Field, J. G.: The size-based dynamics of plankton food webs. I. A simulation model of carbon and nitrogen flows, *J. Plankton Res.*, 1003-1038, 1991.

Sawada, K., Handa, N., and Nakatsuka, T.: Production and transport of long-chain alkenones and alkyl alkenoates in a sea water column in the northwestern Pacific off central Japan, *Mar. Chem.*, 59, 219-234, 1988.

Stemmann, L., Jackson, G. A. and Gorsky, G.: A vertical model of particle size distributions and fluxes in the mid-water column that includes biological and physical processes, Part II, Application to a three year survey in the NW Mediterranean Sea, *Deep Sea Res. Part I*, 51, 885-908.

---

Interactive comment on *Biogeosciences Discuss.*, 5, 1655, 2008.

**BGD**

5, S1009–S1018, 2008

---

Interactive  
Comment

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper

