

## ***Interactive comment on “Ocean acidification accelerates dissolution of experimental coral reef communities” by S. Comeau et al.***

**S. Comeau et al.**

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Response to Andreas Andersson Comments:

General comments: "Comeau and colleagues have carried out a very nice experiment showing how net CaCO<sub>3</sub> sediment dissolution in coral reef communities accelerates under a potential ocean acidification scenario. The effect of OA on CaCO<sub>3</sub> dissolution has been largely ignored with a few exceptions; thus, this is a timely and important study. The study and the manuscript are nicely done and deserve publication in my opinion, but the manuscript needs significant clarification and expansion in several areas that I point out in the detailed comments below. The authors have also overlooked a few papers that have done similar work or discuss the issue of CaCO<sub>3</sub> dissolution and ocean acidification on coral reefs (e.g., Andersson et al., 2009; Andersson and

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Gledhill, 2013; especially the first one is relevant in the present context). With the risk of being self-promoting, I strongly believe the results and discussions of these previous papers will be beneficial to the authors. I hope the authors will find the following comments useful in order to improve the current version of the manuscript."

Response to General Comment: We thank Andreas Andersson for his very useful comments. As suggested the reference Andersson et al. 2009 and Andersson and Gledhill, 2013 are now included in the introduction. Andersson et al. 2009 is also discussed lines 252-261 " Rates of calcification in the present study under ambient conditions also are similar to the 7.9 gCaCO<sub>3</sub> m<sup>-2</sup> d<sup>-1</sup> reported by Andersson et al. (2009) for a reef community from Kaneohe Bay (Hawaii) that was assembled and incubated in mesocosms. However, while community calcification was still positive under high pCO<sub>2</sub> in the present study, Andersson et al. (2009) measured negative calcification (i.e., net dissolution) in their coral reef communities incubated at a pCO<sub>2</sub> twice that of current ambient values. The differences between the present study and that of Andersson et al. (2009) may be due to methodological effects. Andersson et al. (2009) manipulated pH through acid additions (we used CO<sub>2</sub> bubbling), and also used a different assemblage of species and sediments in dissimilar proportions compared to the present study."

Detailed comments:

Comment 1: "P12324, Line 15: I suggest change sentence to ". . .switch to net dissolution as pCO<sub>2</sub> increases and CaCO<sub>3</sub> saturation state decreases. . ." as dissolution is controlled by the seawater saturation state with respect to carbonate minerals and not the pCO<sub>2</sub>."

Response 1: Done.

Comment 2: "P12325, line 7-8: See also papers by Andersson et al., 2009 and Jokiel et al. 2008."

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Response 2: As suggested these papers are now included in the manuscript.

Comment 3: "P12325, line 20-22: Yes, dissolution is taking place at present conditions on coral reefs but mainly in sediment pore-waters or in microenvironments, where the seawater carbon chemistry is different compared to the overlying water column (see review by Andersson and Gledhill, 2013). Your interpretation of the Andersson et al. (2007) is somewhat incorrect. Yes, these observations reported net dissolution at present time but under elevated surface seawater carbon chemistry conditions, i.e. not conditions that are typically observed on coral reefs surface seawater today, but rather similar to conditions observed in sediment pore waters."

Response 3: This section has been reformulated, lines 52-58 " In addition to corals and macroalgae, it is important to incorporate sediments in OA experiments, as this component of reef ecosystems may be sensitive to decreasing pH (Cyronak et al. 2013a, b; Andersson et al., 2009). Dissolution occurs on coral reefs in sediment pore-waters, or in particular microenvironments where pCO<sub>2</sub> is elevated due to biological activity (Andersson and Gledhill, 2013). Observations in Bermuda have shown that the dissolution of Mg-calcite sediments occurs in a location with seawater pCO<sub>2</sub> naturally elevated to values expected by the end of the century (Andersson et al., 2007). "

Comment 4: "P12325, line 23-24: Several additional studies have proposed a threshold of when different benthic communities or coral reefs in general will switch to net dissolution (e.g., Yates and Halley, 2006; Andersson et al., 2005; 2007; 2009; Silverman et al., 2009; as well as others). The exact threshold obviously differs and depends on a number of factors discussed in Andersson et al. 2009 (see section 4.3)."

Response 4: As suggested these references are now discussed lines 61-64" Increasing pCO<sub>2</sub> likely will lead to increasing dissolution and decreased precipitation of calcium carbonate, resulting in coral reef community calcification changing from net precipitation to net dissolution (Yates and Halley, 2006; Silvermann et al., 2009; Andersson et al., 2009). "

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Comment 5: "P12326, line 1-2: what are these pCO<sub>2</sub> values? Mean pCO<sub>2</sub>? It would be useful to show seawater saturation state with respect to aragonite and also the variability, e.g., +/- STD or SE."

Response 5: A table (Table 1) showing the carbonate chemistry is now included in the manuscript. Statistics regarding the difference in pCO<sub>2</sub> are also provided lines 170-176 " Mean pCO<sub>2</sub> in the four flumes during the 8-week incubation was  $456 \pm 21 \mu\text{atm}$  and  $451 \pm 21 \mu\text{atm}$  in the ambient treatments, and  $1329 \pm 28 \mu\text{atm}$  and  $1306 \pm 41 \mu\text{atm}$  in the high pCO<sub>2</sub> treatments ( $\pm$  SE, n = 42). pCO<sub>2</sub> differed between treatments (repeated measure ANOVA, F<sub>1,232</sub> = 734.38, p < 0.001), but there was no difference within treatments (F<sub>2,232</sub> = 0.16, p = 0.852). Communities were maintained in conditions within the flumes that were super-saturated with respect to aragonite, as  $\Omega_{\text{arag}} \sim 3.5$  under ambient conditions, and  $\sim 1.6$  in the high pCO<sub>2</sub> treatment. "

Comment 6: "P12326, line 23-25: What type of stratification are you referring to? Sediment stratification? Chemical gradients? Did the sample collection destroy the existing stratification and was this actually reestablished after 4 days. Please clarify."

Response 6: Collection likely disturbed the natural chemical gradient existing within the sediment. Since we did not have additional boxes we could not check if gradients were fully re-established after 4-d. This section has been modified lines 93-98 " Sediments were collected from the lagoon on the north shore,  $\sim 200$  m from the reef crest, at 2-m depth using 24 custom made boxes (0.4 × 0.3 × 0.3 m). Sediment boxes were inserted into the sediment and left in situ for 4 d to allow chemical stratification in the sediment to re-establish before transferring the boxes to the flumes. It was not possible to subsample these boxes to quantify the stratification of the sediment, and therefore we assume that 4 d was adequate for stratification to be re-established."

Comment 7: "P12327, line 14-16: This sentence needs clarification. I assume you refer to seawater pCO<sub>2</sub> and that the pessimistic scenario refers to surface seawater pCO<sub>2</sub> in the tropical(?) open ocean. However, coral reef seawater pCO<sub>2</sub> is currently

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significantly different than open ocean pCO<sub>2</sub> and will likely be different by the end of the century as well. See for example continuous seawater pCO<sub>2</sub> measurements at <http://www.pmel.noaa.gov/co2/story/Coral+Reef+Moorings> which shows that many reef experience seawater pCO<sub>2</sub> significantly higher than the atmosphere at present time. Thus, I think you need to clarify that the scenario you are referring to refers to the open ocean and that coral reefs can experience a radically different seawater pCO<sub>2</sub>."

Response 7: Interestingly pCO<sub>2</sub> levels in the back reef of Moorea are similar to open ocean, however we do agree that it is not the case with most coral reefs. This sentence has been modified lines 116-120 " As the pCO<sub>2</sub> level in the back reef of Moorea is close to open-ocean and current atmospheric values (e.g., Comeau et al. 2014a), pCO<sub>2</sub> levels for the incubations were chosen to match ambient pCO<sub>2</sub> (~ 400 μatm) and the pCO<sub>2</sub> expected in the atmosphere by the end of the present century under a pessimistic scenario (Representative Concentration Pathway 8.5, ~1300 μatm, Moss et al., 2010).".

Comment 8: "P12327, line 14-19: How did you maintain constant pH with your pH stat? What acids and bases were you using? What was the variability around the desired pH level?"

Response 8: The pH-stat was controlling the bubbling of pure CO<sub>2</sub> or CO<sub>2</sub>-free air. This information is now included, lines 120-124 "pCO<sub>2</sub> in the flumes was controlled using a pH-stat (Aquacontroller, Neptune systems, USA) that actuated the bubbling of either pure CO<sub>2</sub> or CO<sub>2</sub>-free air into the seawater. To match the natural diel variation in pH in the back reef of Moorea (Hofmann et al., 2011; Comeau et al., 2014a) pH was maintained 0.1 unit lower at night (from 18:00 to 6:00) than during the day."

Variability around the desired pH is now provided in Table 1.

Comment 9: "P12327, line 17-19: Do you have data supporting that the diel variation is 0.1 pH units in the back reef of Moorea? From my own observations in other coral reef environments I have seen that the diel amplitude can be quite variable from day to

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day, but also vary greatly across space. Please clarify."

Response 9: While daily and seasonal variations are occurring, data acquired so far tend to support an average diel variation of 0.1 unit in the back reef of Moorea. Two references supporting the 0.1 pH unit diel variations in the back reef of Moorea are now included lines 122-124 "To match the natural diel variation in pH in the back reef of Moorea (Hofmann et al., 2011; Comeau et al., 2014a) pH was maintained 0.1 unit lower at night (from 18:00 to 6:00) than during the day."

Comment 10: "P12327, line 20-27: What were the accuracy and precision of your measurements and how did you verify it?"

Response 10: More details are now provided lines 125-134 " pH was measured daily using a portable pH meter (Orion 3-stars, Thermo-Scientific, USA) fitted with a DG 115-SC pH probe (Mettler Toledo, Switzerland) calibrated every other day with Tris/HCl buffers (Dickson et al., 2007). pH also was measured spectrophotometrically using m-cresol dye (Dickson et al., 2007) at regular intervals. pH measured spectrophotometrically or using a pH electrode provided similar results with means differing < 0.01 pH unit. Measurement of total alkalinity (AT) was made using open-cell potentiometric titrations (Dickson et al., 2007) using 50-mL samples of seawater collected every 2-3 d. Titrations of certified reference materials provided by A. G. Dickson (batch 122) yielded AT values within 3.5  $\mu\text{mol kg}^{-1}$  of the nominal value (SE = 3.1  $\mu\text{mol kg}^{-1}$ ; n = 14). "

Comment 11: "P12328, line 5-8: I am a little bit confused about how you used the alkalinity anomaly technique to estimate net calcification/dissolution since your experiments were done in a pH-stat. Doesn't the pH stat compensate any addition or reduction in total alkalinity? You could certainly use this compensation to estimate net calcification/dissolution, but it is currently not clear what you did and from the text it appears that you actually used the alkalinity anomaly technique. However, if this was the case and since the incubations were closed loops, TA must have been accumulating during net dissolution potentially producing a buffer effect, and the opposite could be true for

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times of net calcification. At some point in the ms you need to address this potential buffering effect and the effect on the seawater carbonate chemistry during the incubation. Also, when you refreshed the water every 6 hours, was this already equilibrated to the desired pCO<sub>2</sub> and pH levels?"

Response 11: We believe that this confusion comes from the fact that pH was controlled by addition of pure CO<sub>2</sub> and CO<sub>2</sub>-free air, but not by addition of acid and base. Thanks to comment #8, this point is now clarified. Since we used addition of CO<sub>2</sub>, alkalinity was only affected by calcification/dissolution.

Seawater in the flumes was refreshed at regular intervals in order to limit the magnitude of the changes in alkalinity and notably the potential buffering effect due to dissolution. Changes in alkalinity during incubations were < 50 μmol kg<sup>-1</sup>, which corresponded to changes in aragonite saturation state < 0.1. More details are now provided in the manuscript lines 144-147 "To maintain AT and nutrients close to ambient levels, water in the flumes was refreshed every 3-6 h for 30 min. Regular refreshing limited changes in alkalinity during incubations to < 50-100 μmol kg<sup>-1</sup>, which corresponded to variations in aragonite saturation state ( $\Omega$ ) of < 0.1-0.2."

The seawater used during the refreshing was not already equilibrated to the desired pH, but pH-stats were efficient enough to maintain seawater pH stable in the flumes during the refreshing period.

Comment 12: "P12328, line 14-16: What was the duration between the buoyant weight measurements of corals and coralline algae? Do you mean the entire 8 weeks incubation?"

Response 12: Indeed buoyant weight measurements covered the entire 8-week incubation. This sentence is now clarified lines 153-155 " For both corals and algae, buoyant weight (Davies, 1989) was recorded before and after the 8-week treatments and converted to dry weight to quantify the contribution of each functional group to the calcification budget."

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Comment 13: "P12330, line 18-20: Please clarify what you mean by “. . .disproportionate surface area to planar area relationship in corals?""

Response 13: This sentence has been reformulated, lines 228-234 "The small contribution of coralline algae to the calcification budget was due to high mortality perhaps leading to potential dissolution during the last weeks of the incubation. Furthermore, while the ratio of planar area to surface area for crustose coralline algae is close to one, corals have a disproportionately large surface area to planar area ratio due to their three-dimensional structure. With such a large actual surface area, the corals made a large contribution to the calcification budget of the communities assembled in the flumes."

Comment 14: "P12330, line 22-25: This sentence needs clarification. What do you exactly mean by “. . .the effects of OA on coral reef communities are greater than estimates obtained by summing results obtained by incubating organisms in isolation..." Do you mean that the net community calcification decrease more than net calcification by individual organisms, which thus, is partly explained by increasing dissolution (which you demonstrate). However, this does not mean that the effect of OA on an individual coral is different than the effect on a group of the same corals, which would require a different set of experiments without the sediments."

Response 14: We fully agree with this comment and believe that we come to the same conclusion few lines later (lines 262-265)" The discrepancy in the evaluation of the effects of high pCO<sub>2</sub> at the community level (the present study) versus organismic level (previous studies) was the result of dissolution of sediments that represented up to 50% of the decrease in calcification at high pCO<sub>2</sub>."

Comment 15: "P12331, line 17-19: I am aware of this statement, but must admit I am somewhat hesitant in my interpretation that this represents a dissolution signal. Increasing dissolution would favor dissolution of smaller grain sizes rather than larger grains as the surface to volume ratio increases with decreasing grain size. Also, this

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effect would probably only be apparent in the very small size fractions of silt and clay (see for example the work by Schmalz and Chave 1963; Neumann, 1965). However, increasing percentage of smaller grain sizes could certainly result from increased bioerosion, which also has been shown to increase under decreasing pH. Nonetheless, this comment is just a personal reflection of this statement, but perhaps something you want to consider."

Response 15: Indeed results obtained by Dove et al. (2013) were likely due to bioerosion since dissolution effects would be more severe on smaller grain sizes. This sentence has been slightly modified accordingly, lines 272-279 "During a mesocosm experiment, Dove et al. (2013) also demonstrated that a pH of 7.7 caused a change in sediment granularity to favor small-grained (i.e.,  $\leq 1$  mm) sediments as a result of dissolution or increased bioerosion of larger grains. In this case, bioerosion was more likely than dissolution, as dissolution would favor a loss of the smallest grains as a result of their higher surface area to volume ratio. Size-frequency distribution of sediment grain was not different between treatments at the end of our incubations and therefore is unlikely to have affected the treatment effects we detected."

Comment 16: "P12337-P12339: The figures are nice and clear, but I would have liked to see a little bit more data and just not the mean results of seawater chemistry and net calcification results. In addition to the current figures I would have liked to see: 1. Seawater physical and chemical properties over time that were measured, i.e., temperature, salinity, pH and TA, as well as your calculated aragonite saturation state and pCO<sub>2</sub> (Also, in the text of the results section when you talk about seawater pCO<sub>2</sub>, I think you should also mention what the aragonite saturation state was). 2. The results for the alka- linity anomaly incubations and how chemistry changed over these incubations. This information could be provided either as a supplementary table or a figure."

Response 16:

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1. Details on the seawater carbonate chemistry are now provided in Table 1. Additional details on the carbonate chemistry are now included in the Results, lines 170-176 " Mean  $p\text{CO}_2$  in the four flumes during the 8-week incubation was  $456 \pm 21 \mu\text{atm}$  and  $451 \pm 21 \mu\text{atm}$  in the ambient treatments, and  $1329 \pm 28 \mu\text{atm}$  and  $1306 \pm 41 \mu\text{atm}$  in the high  $p\text{CO}_2$  treatments ( $\pm$  SE,  $n = 42$ ).  $p\text{CO}_2$  differed between treatments (repeated measure ANOVA,  $F_{1,232} = 734.38$ ,  $p < 0.001$ ), but there was no difference within treatments ( $F_{2,232} = 0.16$ ,  $p = 0.852$ ). Communities were maintained in conditions within the flumes that were super-saturated with respect to aragonite, as  $\Omega_{\text{arag}} \sim 3.5$  under ambient conditions, and  $\sim 1.6$  in the high  $p\text{CO}_2$  treatment. "

2. As mentioned in the Response #11, changes in alkalinity during incubations were  $< 50 \mu\text{mol kg}^{-1}$  in most of the measurements. Data presented in this paper are currently being deposited on the BCO-DMO database.

Comment 17: "As a final comment, one of my students pointed out the following that you may want to consider: There is a major assumption that is not discussed in the paper. Granted, I have much to learn regarding net calcification, but I would think that calculating the calcification by organisms is not as simple as  $\text{Net} - \text{Sediment} = \text{Coral} + \text{Algae}$ . The assumption they are making with this calculation is that the rate of calcification for the sediment is the same regardless of the presence of organisms. Won't the presence (or lack thereof) of coral and algae affect the calcification rate of the sediment? Again, this could be an ignorant observation, but I would assume that the calcification rate of the sediment is altered by the presence of organisms. If I am correct, it obviously doesn't negate their work, but an acknowledgement of the assumption needs to be clearly stated."

Response 17: It is indeed one potential weakness of our study that will need to be addressed in future work. This assumption is now discussed in the manuscript, lines 299-310 "As the decrease in calcification recorded in the present study for corals and coralline algae alone was within the range of previous studies, this supports our assumptions that calcification of macro-calcifiers is equal to the difference between net

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sediment calcification and net community calcification. This “subtraction method” for calculating the calcification rate of corals and coralline algae included in community experiments has some limitations, as it assumes that the calcification of the sediments and the macro-calcifiers are independent. Such interactions might occur, for example, if dissolution of the sediment would locally enhance total alkalinity that would, in turn, favor calcification by macro-calcifiers. Testing for such feedback mechanisms among the different compartments of the communities we built was beyond the scope of the present study, but it will be important to consider such effects in future experiments.”

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Interactive comment on Biogeosciences Discuss., 11, 12323, 2014.

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