Biogeosciences Discuss., 5, S1745–S1752, 2008
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Biogeosciences Discussions

Interactive comment on "A multi-species coccolith volume response to an anthropogenically-modified ocean" *by* P. R. Halloran et al.

P. R. Halloran et al.

Received and published: 20 September 2008

Final author comments in response to referees comments on 'A multi-species coccolith volume response to an anthropogenically-modified ocean'

We gratefully thank all three reviewers for their insightful and thought provoking comments, and here either present evidence to answer these comments, or detail amendments to the manuscript to incorporate the referee's insight. One of the prevailing themes of the comments addresses the need for direct measurements on the coccoliths. This is ongoing and time-consuming work, and whilst we appreciate its importance, as Jeremy Young states, here we present 'important new details to test the robustness [of the Iglesias-Rodriguez and Halloran et al. (2008) dataset]', which we

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feel add significantly to the evolving understanding of the coccolithophore calcification response to anthropogenic change. We are encouraged that all three referees support publication, and hope that we have answered suitably their queries.

Response to comments by Jeremy Young (Referee):

1. Jeremy Young highlights the fact that the evidence presented in this manuscript to infer a change in coccoliths size is indirect, and states that these results, and the inferences made in Iglesias-Rodriguez and Halloran et al. (2008), urgently need testing by direct measurements.

Response: Jeremy Young's point is in direct agreement with our thoughts, presented within the paragraph starting at line 26 on page 2927 of the original manuscript. Here we state that 'The next step towards a full understanding of the coccolithophore calcification response over the industrialized era, will be to combine individual species size analysis, taking advantage of new techniques such as that presented by Beaufort (2000), with Coulter Counter analyses capable of measuring coccolith volumes, to constrain how calcification has changed at a species level.' However, to obtain this data in a robust fashion, hundreds to thousands of specimens from each species, at each required depth in the core, must be analyzed. This is clearly a very time consuming task, and one which is now under way, however given the urgent nature of the ocean acidification issue and the degree of debate which has surrounded the findings presented by Iglesias-Rodriguez and Halloran et al. (2008), we believe that by providing as much information as possible at this stage, we can help the community to develop its understanding of the issues most efficiently.

2. Jeremy Young states that there is no evidence for size increase in Emiliania huxleyi.

Response: We describe in our manuscript what appears to be a decrease in the volume of Emiliania huxleyi coccoliths over the interval examined. Jeremy Young suggests that this is in conflict with the observed increase in mass of coccoliths produced by Emiliania huxleyi in the culture study presented in Iglesias-Rodriguez and Halloran

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et al. (2008). Conversely, this observation is in fact in remarkable agreement with the data presented in Iglesias-Rodriguez and Halloran et al. (2008), which show a decrease in Emiliania huxleyi volume from 1.09 μm3 to 0.84 μm3 between pre-industrial and present day pCO2 values, before a rise in Emiliania huxleyi mass towards future predicted pCO2 values. Due to our limited knowledge of exactly what physiological (or otherwise) process this may represent, we avoided making the connection in our original manuscript, however if one was to use this data to 'test the hypotheses derived from laboratory experiments' as Gerald Langer proposes, one would interpret this result as, at least, partial validation of the Iglesias-Rodriguez and Halloran et al. (2008) culture data.

3. Jeremy Young sensibly highlights the possible influence of sedimentary processes over the size distribution of the analyzed sediments.

Response: We echo Jeremy Young's comment that care should be taken when using drift sediments for analyses of this sort, however as a result of the extremely high sedimentation rates at drift sites, cores of this type probably provide the only opportunity to undertake high resolution sediment analysis in the open ocean over time intervals as short as the Anthropocene. The primary reason that we are confident is using this material as we have done, is that the obtained data shows no significant correlation with the sortable silt record of Boessenkool et al. (2007), itself a record of the sediment sorting. We are therefore confident that the particle-size trend we present in this manuscript does not reflect changes in flow-mediating sediment sorting/deposition. Furthermore, we consider the invariance in the coccolith species composition presented in Iglesias-Rodriguez and Halloran et al. (2008) to indicate no major change in source water during deposition.

Response to comments by Gerald Langer (Referee):

1. The first point made by Gerald Langer is a reiteration of Jeremy Young's observation regarding the need for direct coccolith measurement.

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Response: To answer this, we refer the reader to our response to Jeremy Young's first comment.

2. Gerald Langer correctly states that one can not infer a causal relationship between increasing pCO2 and increasing coccolithophore calcification from sedimentary analysis, because parameters other than pCO2 have not been constant.

Response: We agree entirely with Gerald Langer, and consequently have been very careful in stating only that the trend that we observe parallels the change in pCO2. Our discussion has then focused on pCO2 because we know from laboratory experiments that coccolithophore calcification shows a strong sensitivity to changing pCO2, and given the current concern regarding the consequences of ocean acidification, we consider this factor of specific importance. However, we also acknowledge that there are many other factors, which have the potential to influence coccolithophore calcification, and have therefore modified our manuscript to read “Temperature, salinity and nutrient supply have also been shown to influence coccolith size, although where studied, the calcification sensitivity to these factors appears too low to explain the observed trend (Bollmann, 1997; Bollmann and Herrie, 2007; Paasche, 1998; Schmittner et al., 2008; Watabe and K., 1966). A further, and potentially significant influence over coccolith mass is primary production (Beaufort et al., 2007). However, if the observed coccolith volume distribution shift occurred in response to a productivity change, we might expect to see an accompanying shift in species composition, which is not observed (Iglesias-Rodriguez and Halloran et al., 2008).”, following the sentence ending in the line 19, page 2927.

3. Gerald Langer points out that over the pCO2 interval examined in this study, laboratory experiments have not demonstrated significant changes in coccolithophore calcification.

Response: We would argue that changes have in fact been observed, such as the reduction in Emiliania huxleyi volume discussed in point 2 of the response to comments

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by Jeremy Young. Furthermore, the data presented in Langer et al. (2006) appear to demonstrate a high sensitivity of particulate inorganic carbon production per cell to pCO2 changes between 216 and 345 ppm, increasing from 78 to 94 pg C cell-1 day-1 in Calcidiscus leptoporus. Why exact correspondence between the laboratory and sedimentary responses is not seen is unclear, and at the heart of what we must understand if the carbon-cycle implications of changing calcification are to be understood. However, given the discrepancy between results observed in individual culture studies, it is no surprise that the sedimentary data matches none precisely, and given the disparity between culture results, impossible for the sedimentary data to agree with them all!

4. Technical comments.

Response: We gratefully acknowledge the highlighted technical comments and make all the specified amendments in the revised manuscript.

Response to comments by Referee #2.

1. Referee #2 expresses concern about our statement “These data appear to indicate that coccoliths produced by the larger coccolithophore species present at this location increase in mass in parallel with anthropogenic CO2 release”, with reference to the changing calcite particle size distribution over the interval of study. Insightfully the referee points out that surface-seawater pCO2 will not necessarily vary exactly in concord with atmospheric pCO2, and highlights factors such as biological and physical mixing as influencing surface-water pCO2 over relatively small spatial scales.

Response: Unfortunately, to our knowledge, records of surface ocean pCO2 surrounding the core location only stretch back sparsely to 1972 (Takahashi et al., 2008). Using this dataset we have shown, in Figure 1 (see link: http://www.flickr.com/photos/30732543@N08/2871925781/?edited=1), a very significant increase in seawater pCO2 (dashed red lines represent 99.99% confidence in-

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tervals on the linear regression described by the solid black line) since 1972 in the waters falling within 5 degrees, north, south, east and west of the core-location. We therefore conclude that at least over the interval of maximum pCO2 change, it is reasonable to assume seawater pCO2 in the regions from which the analysed coccoliths were produced has varied in a way analogous with atmospheric pCO2.

2. Referee #2 also questions the influence of temperature change on coccolithophore calcification.

Response: Here we refer the reader to our response to point two of Gerald Langer.

3. Referee #2 asks if coccolith concentration data could be used to better evaluate whether the decrease in frequency of small particles is due to the relative increase in the frequency of large particles.

Response: Coccolith species data presented in Iglesias-Rodriguez and Halloran et al. (2008) indicates that there is no significant shift between smaller and larger species contributing to the observed particle size trend. It is unclear to us how coccolith concentration data could add further to this.

4. Technical comments.

Response: We gratefully acknowledge the highlighted technical comments and make all the specified amendments in the revised manuscript.

Additionally, the line 'Such a calcification response could be attributed to an alleviation of photosynthesis limitation, as previously demonstrated when examining photosynthetic efficiency in culture (Rost et al., 2003).' Has been added following the sentence ending in the line 19 on page 2927 of the original manuscript.

Figure 1. (http://www.flickr.com/photos/30732543@N08/2871925781/?edited=1) Surface ocean pCO2 data from samples taken within 5 degrees of the core location since 1972. The black line represents a least squares linear regression, and the dashed red lines the 99.99% confidence intervals about that regression. Data from Takahashi et

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