A long term study of the effect of elevated CO$_2$ on marine calcification using the Biosphere 2 coral reef mesocosm as a model system

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Outline

- Background
  - CO$_2$ emissions (270 Gt C since 1751) have changed the chemistry of the atmosphere and are beginning to change the chemistry of the surface ocean.
  - These changes could have a direct effect on the physiology of marine organisms.
    - ↑CO$_2$ may increase rates of photosynthesis in regions where nutrients are not limiting
    - ↓CO$_3^{2-}$ may decrease rates of calcification
If these changes were big enough the balance between photosynthesis and calcification could be upset.

- Coral reefs could be the first ecosystems to feel the effects
  - less able to keep up with sealevel rise
  - less able to compete for space with faster growing algae
  - more susceptible to boring organisms and storm damage
- Negative effects could extend to seagrass and mangrove ecosystems that are commonly associated with coral reefs
  - loss of important fisheries
  - loss of income associated with tourism mostly falling on poor third world countries
Outline

- If the effects extend to other and perhaps all calcifying organisms
  - a CO$_2$ dependent reduction in the rate of global calcification would constitute a negative feedback on the rate of increase of atmospheric CO$_2$ of ~0.3 Gt C y$^{-1}$
  - this wouldn’t make a dent in the ~3 Gt C y$^{-1}$ that is currently accumulating in the atmosphere but it could have been important in the past in stabilizing atmospheric CO$_2$
  - during glacial-interglacial cycles the strength of marine calcification could have varied by 20% or 0.1-0.2 Gt C y$^{-1}$
Outline

How do we get some answers?

- Historical approach
  - Detailed records of coral growth over glacial-interglacial cycles not available
  - Expected response over the last 200 years is only 10%, probably too small to separate from other environmental factors
  - We can start monitoring coral growth and Ω now but by the time we have definitive results it may be too late.
Outline

- **Experimental approach**
  - Manipulate carbonate chemistry to simulate future conditions and observe the effect on calcification and photosynthesis on different time scales
  - Need to choose a model system
    - Shallow tropical environments contribute 40% of global carbonate production. Coral reefs are the archetype community for these environments and may be especially sensitive to rising CO$_2$ as mentioned earlier.
    - B2 offers a coral reef community where long term, controlled experiments are possible
Marine carbonate cycle

Atmosphere

Weathering:
Feldspar + H$_2$O + CO$_2$ > kaolinite + SiO$_2$ + Na$^+$ + Ca$^{2+}$ + HCO$_3^-$ + CO$_3^{2-}$

Calcification:
Ca$^{2+}$ + HCO$_3^-$ > CaCO$_3$ + CO$_2$ + H$_2$O

Ocean:
coral, macroalgae, coccolithophorids, foraminifera, pteropods

Rivers:
Ca$^{2+}$, HCO$_3^-$, CO$_3^{2-}$

Land

Sediments

Uplift

Sedimentation
Global carbon cycle fluxes in GtC y⁻¹

Wollast and Mackenzie, 1989

Fossil fuel

Atmosphere
732 GtC

Land
2740 GtC

Ocean
38,400 GtC

Sediments
6.2x10⁷ GtC

Photosynthesis-Respiration
0.24

Weathering
0.2

Precipitation
0.4

Rivers
0.4

Uplift
0.2

Sedimentation
0.14

Inorganic carbon

Organic carbon

0.4

0.2

0.2

5

0.24

0.24

0.14

Wollast and Mackenzie, 1989
Trends in atmospheric CO$_2$

Vostok, Antarctica Ice Core Atmospheric CO$_2$ Record

Mauna Loa, Hawaii and Law Dome, Antarctica

Global Emission of CO$_2$

Marland, Boden and Andres (2001)
Link between atmospheric CO$_2$ and the rate of calcification

- $\text{CO}_2 + \text{CO}_3^{2-} + \text{H}_2\text{O} \leftrightarrow 2\text{HCO}_3^{-}$

- $\Omega_{\text{arag}} = [\text{Ca}^{2+}][\text{CO}_3^{2-}]/K_{sp}$

- $R = k(\Omega-1)^n$
Calculated changes seawater carbonate chemistry

(assuming IS92a business as usual scenario, S=35, TA=2300)
Observations at the Hawaii Ocean Times Series Station

slope = -0.022±0.08 (95% CI) y⁻¹
Biosphere 2 coral reef biome
Corals in B2 ocean

Montipora

Porites

Siderastrea
Experimental design

- Simulate real world changes by varying pCO$_2$ between 200, 350 and 700 µatm at regular 4 monthly intervals and observe the effect on community net primary production and calcification.

- Manipulate pCO$_2$ by adjusting TA with additions of HCl and NaOH while holding TCO$_2$ constant by additions of NaHCO$_3$ and Na$_2$CO$_3$. 
### Chemical treatments

<table>
<thead>
<tr>
<th></th>
<th>n weeks</th>
<th>pCO₂ µatm</th>
<th>HCO₃⁻ µmol kg⁻¹</th>
<th>CO₃²⁻ µmol kg⁻¹</th>
<th>pH sws</th>
</tr>
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<tbody>
<tr>
<td>LGM</td>
<td>29</td>
<td>225±29</td>
<td>1546 ±70</td>
<td>310±28</td>
<td>8.23±0.04</td>
</tr>
<tr>
<td>PD</td>
<td>47</td>
<td>371±55</td>
<td>1696±76</td>
<td>226±25</td>
<td>8.05±0.06</td>
</tr>
<tr>
<td>FUT</td>
<td>43</td>
<td>741±99</td>
<td>1954±45</td>
<td>149±18</td>
<td>7.81±0.06</td>
</tr>
</tbody>
</table>
Comparison of experimental manipulations and real world changes

![Graph showing comparison between real ocean and B2 treatments]
Calculation of Calcification and Net production

- $G \text{ (mmol CaCO}_3 \text{ m}^{-3} \text{ d}^{-1}) = -0.5(3.5)\Delta TA/\Delta t$

- $NP_c \text{ (mmol Org C m}^{-3} \text{ d}^{-1}) = 3.5(\Delta TCO_2/\Delta t - 0.5\Delta TA/\Delta t) + (1.8 \text{ m d}^{-1})(0.027 \text{ mmol m}^{-3} \mu \text{atm}^{-1})(pCO_2,w-pCO_2,a)$
Time line of CO₂ treatments

<table>
<thead>
<tr>
<th>Date</th>
<th>pCO₂</th>
<th>Weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1/99</td>
<td>200</td>
<td>29</td>
</tr>
<tr>
<td>7/2/99</td>
<td>350</td>
<td>47</td>
</tr>
<tr>
<td>1/1/00</td>
<td>700</td>
<td>43</td>
</tr>
</tbody>
</table>

Graph: pCO₂, µatm vs. Date

Graph shows fluctuations in pCO₂ over time.
Effect of CO$_2$ on net community production

NP$_c$, mmol Org C m$^{-2}$ d$^{-1}$

pCO$_2$, µatm
Effect of CO$_2$ on community calcification

\[ y = 62373.77x^{-1.24} \]

\[ R^2 = 0.61 \]
Saturation state controls calcification

\[ y = 27.98x - 41.72 \]

\[ R^2 = 0.86 \]

Calcification

mmol CaCO_3 m^-2 d^-1

\[ \Omega_{\text{arag}} \]
Phase 3 - Species specific responses

Porites compressa

Marubini et al., 2001
Comparison of B2 with Great Bahama Bank

Calcification, % of rate at $\Omega_{\text{arag}}=4.0$

Broecker et al., 2001
Effect of a doubling in CO$_2$ (350-700) on calcification, (% decrease)

<table>
<thead>
<tr>
<th>Calcereous macroalgae</th>
<th>% Decrease</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amphiroa foliacea</td>
<td>-36</td>
<td>Borowitzka, 1981</td>
</tr>
<tr>
<td>Porolithon gardineri</td>
<td>-16</td>
<td>Agegian, 1985</td>
</tr>
<tr>
<td>Corallina pilulifera</td>
<td>-44</td>
<td>Gao et al., 1993</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Corals</th>
<th>% Decrease</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stylophora pistillata</td>
<td>-3</td>
<td>Gattuso et al., 1998</td>
</tr>
<tr>
<td>Porites porites</td>
<td>-16</td>
<td>Marubini &amp; Thake, 1999</td>
</tr>
<tr>
<td>Porites compressa</td>
<td>-27</td>
<td>Marubini et al., 2001</td>
</tr>
<tr>
<td>Acropora sp.</td>
<td>-37</td>
<td>Schneider &amp; Erez, 2000</td>
</tr>
<tr>
<td>Porites/Montipora prep.</td>
<td>-50</td>
<td>Langdon &amp; Atkinson, in prep.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coccolithophorids</th>
<th>% Decrease</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emiliania huxleyi</td>
<td>-10</td>
<td>Riebesell et al., 2000</td>
</tr>
<tr>
<td>Gephyrocapsa oceanica</td>
<td>-29</td>
<td></td>
</tr>
<tr>
<td>Natural pop. (N. Pac.)</td>
<td>-38</td>
<td></td>
</tr>
<tr>
<td>Emiliania huxleyi</td>
<td>-17</td>
<td>Zondervan et al., 2001</td>
</tr>
<tr>
<td>Gephyrocapsa oceanica</td>
<td>-29</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Community</th>
<th>% Decrease</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biosphere 2</td>
<td>-40</td>
<td>Langdon et al., 2000</td>
</tr>
<tr>
<td>Monaco mesocosm</td>
<td>-21</td>
<td>Leclercq et al., 2000</td>
</tr>
<tr>
<td>Bahama Bank</td>
<td>-30</td>
<td>Broecker &amp; Takahashi, 1966</td>
</tr>
</tbody>
</table>
Conclusions

- Photosynthesis and calcification are not tightly coupled with respect to their response to rising CO$_2$.
  - ↑CO$_2$ NP$_c$ unchanged ↓Calcif.
- There is a nonlinear relationship between calcification and pCO$_2$
  - for 200 to 280 µatm pCO$_2$↑ Calcif.↓ 34%
  - for 350 to 700 µatm pCO$_2$↑ Calcif.↓ 58%
Conclusions

- Data are consistent with the hypothesis that saturation state ($\Omega$) controls the calcification of the B2 coral reef system, several species of coral, calcareous red algae, coccoid lithophorids and a natural community dominated by green algae.
- Consequences of reduced calcification to corals and coral reefs
  - reduced ability to compete for space and light
  - reduced ability to keep up with sealevel rise
  - increased susceptibility to erosion and damage by fish, boring organisms and storms.
Conclusions

- From a geochemical point of view the reduction in the ratio of calcification to net photosynthesis as CO$_2$ rises provides a negative feedback on atmospheric CO$_2$ levels.

- Such a feedback mechanism was first suggested based on laboratory culture experiments here we show that the mechanism can also be demonstrated for a very different community of organisms and at a much larger spatial and longer temporal scale.
Phase 1 – long-term response

\[ y = 29.82x - 44.39 \]

\[ R^2 = 0.98 \]

- 2.3 years
- 1.3 years
- 2 months
Phase 2 – rapid flip floping of $\Omega_{\text{arag}}$
Phase 2 – short term response

\[ y = 45.89x - 94.35 \]

\[ R^2 = 0.80 \]
Phase 2 – test of saturation state hypothesis

Langdon et al., 2000
Saturation state dependence – all time scales

\[ y = 38.37x - 93.03 \]

\[ R^2 = 0.75 \]
Conclusions

- Studies performed in different ways all show that calcification of corals and coralline algae will decline due to rising CO$_2$.
- Production of framework and fill carbonate on coral reefs will decline to 50-97% (avg. 70%) of 1880 rates by the year 2065.
Implications

- Corals may produce weaker more easily damaged skeletons.

- Linear growth of corals may decrease making them less able to keep up with rising sealevels.

- Due to latitudinal gradient in $\Omega$ high latitude coral reefs should be the first to be affected.
Future work

- Need to determine effect of reduced calcification on skeletal density and linear growth rate of corals.
- Need to start monitoring calcification or carbonate accumulation on a few natural reefs. Many things might cause a reduction in calcification but if a latitudinal pattern emerges with high latitudes sites showing the greatest reduction the CO$_2$ hypothesis would be supported.