The response of marine carbon and nutrient cycles to ocean acidification:

Large uncertainties related to phytoplankton physiological assumptions

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MACROES Meeting, 2011
Rising CO$_2$ Impacts PP

- Many experiments have demonstrated that ‘ocean acidification’ results in increased rate of PP
- When included in OGCBMs results in:
  - Increased Export
  - Increased Suboxia
  - Enhanced Denitrification

(Oschlies et al. 2008)

But how constrained are our assumptions about the impact of rising CO$_2$ on algal physiology?
How Might Algae Respond?

• The response of algal physiology to rising CO$_2$ is not well constrained (e.g., Thingstad et al., 2008; Hutchins et al., 2009)
  – Extra CO$_2$ fixed may be lost as DOC
  – Transport of other nutrients might be unregulated

• Impact on C/N, C/P and N/P ratios important
  ⇨ ↑PP + no up-regulation, then ↑C/N, C/P, but fixed N/P
  – If lost as DOC, then no chance to organic matter ratios
  – If P transport up-regulated, then ↑C/N, fixed C/P but ↓ N/P

• Can we test the impact of these hypotheses using a new N and P decoupled version of PISCES?
Experimental Design

• CTL

- Simplest assumptions:
  - extra CO$_2$ raises uptake of DIC during photosynthesis
  - C/N and C/P ratios modified, no change to N/P
  - Changes preserved in sinking organic matter
Experimental Design

- $\text{Exp}_{\text{PP-DOC}}$
- $\text{Exp}_{\text{PP-PSiFe}}$

**Diagram**

- **Exp$_{\text{PP-DOC}}$**:
  - Organic Matter → DOC
  - $\approx \text{C/N}$, $\approx \text{C/P}$, $\approx \text{N/P}$

- **Exp$_{\text{PP-PSiFe}}$**:
  - Organic Matter → DOC
  - $\uparrow \text{C/N}$, $\approx \text{C/P}$, $\downarrow \text{N/P}$

**2 other tests:**

- Extra C fixed is lost as DOC (no change to ratios)
- P, Si and Fe uptake is up-regulated alongside C fixation (C/P ratio does not change, but N/P ratio decreased)
Experimental Design

A “CO₂ sensitivity” applied to the rate processes tested:

- C-fixation
- DOC losses
- Uptake of P, Si and Fe

(used changes from Riebesell et al. (2007))

- Simulations between 1860 and 2100 using RCP8.5 CO₂ scenario
- 2 controls (PI CO₂ and rising CO₂ but no impact on rate processes)
Results: C Cycle

- **Exp\(_{PP}\):**

- Cumulative C-Export increases by 22% or 69.5 Pg C
- Cumulative uptake of CO\(_2\) increases by 8.7% or 38 Pg C
- Oschlies et al. (2008) found 100 Pg and 34 Pg
  - Exp\(_{PP}\) most closely matched their assumptions
- Smaller change in C-Export due to Fe limitation
Results: C Cycle

- $\text{Exp}_{\text{DOC}}$: Cumulative C-Export increases by 3.9% or 13.2 Pg C
- Cumulative uptake of $\text{CO}_2$ increases by 2.8% or 14 Pg C
- Export can occur due to aggregation of DOC in regions where bacteria are nutrient limited (Thingstad et al., 2008)
- DOC also subducted into ocean interior
Results: C Cycle

- Cumulative C-Export increases by 5.6% or 22.4 Pg C
- Cumulative uptake of CO$_2$ increases by 1.7% or 9 Pg C
- C-Ex reduced in some regions due to greater uptake of P, Si & Fe
- C-Ex increase would be 4 times greater if no change in P, Si & Fe uptake was assumed (Exp$_{PP}$)
## Results: C Cycle

- **Exp\textsubscript{PP-PSi}:**
  - Cumulative C-Export increases by 5.6% or 22.4 Pg C
  - Cumulative uptake of CO\textsubscript{2} increases by 1.7% or 9 Pg C
  - C-Export reduced in some regions due to greater uptake of P, Si & Fe
  - C-Export increase would be 4 times greater if no change in P, Si & Fe uptake was assumed (Exp\textsubscript{PP})

### Overall uncertainties across Experiments:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPP</td>
<td>27 ± 2%</td>
</tr>
<tr>
<td>C-Export</td>
<td>7.7 ± 9.9%</td>
</tr>
<tr>
<td>FC\textsubscript{ant}</td>
<td>3.1 ± 4.2%</td>
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</tbody>
</table>

NPP more closely related to assumed “CO\textsubscript{2} sensitivity”

C-Export and FC\textsubscript{ant} greatly impacted by assumptions

- Cumulative uptake of CO\textsubscript{2} increases by 1.7% or 9 Pg C
- C-Ex reduced in some regions due to greater uptake of P, Si & Fe
- C-Ex increase would be 4 times greater if no change in P, Si & Fe uptake was assumed (Exp\textsubscript{PP})
Results: N Cycle

- Denitrification:

- Closely related to change in C-Export, therefore sensitive to assumptions

- Same for suboxia, decline is linked to the assumed change in C-Export, when C-Export increases, suboxia increases, but when C-Export has increases and decreases, suboxia can decline in some places
Results: N Cycle

- N₂ Fixation:
  - Small changes in N₂ Fixation (-8 to -11%) when N/P ratios are not modified
  - N₂ Fixation declines greatly (by > 80%) when N/P ratios decline
  - Can be illustrated by the change in xsP (P-N/16)
  - ‘Direct’ effect of CO₂ on N₂ fixation not included, only indirect effects mediated by N/P ratio and Fe limitation
Synthesis of Results

- 2100:

- Can elaborate the sign of the change due to acidification
- But large uncertainties related to our assumptions regarding the response of phytoplankton physiology
Conclusions

- Assumptions result in large uncertainties in the response of key biogeochemical processes (e.g., C-Export, N$_2$ fixation, suboxia)

- The changes in C-Export can be similar to those associated with climate change from fixed stoichiometry models

- C-Export governed by the fate of fixed C (DOC losses) and uptake of other nutrients - feedback onto denitrification and suboxia

- N$_2$ fixation is highly sensitive to the change in planktonic N/P ratios

- Existing observations (Hutchins et al., 2009) cannot yet evaluate the plausibility of a given scenario

- Coupled experimental – modelling approaches (using variable stoichiometry models) necessary to better constrain how ocean acidification will impact ocean biogeochemical processes