Ocean Acidification and Biogeochemical Cycling

Uta Passow
Facts About Ocean Acidification (OA)

- Burning of fossil-fuel lead to increase in $pCO_2$
- $CO_2$ dissolves in ocean water
- Decrease in pH, increase in DIC & $pCO_2$, TA remains constant
In situ variability of carbonate system parameters

Introduction

Gibson & Trull 1999

Annual S. Ocean

N Sea annual pH range

Blackford & Gilbert 2007

W Coast USA

Feely et al. 2008
Introduction

Biogeochemical cycles

ATMOSPHERE

N\textsubscript{2} \quad \text{CO}_2

Fixation

(1) Primary production

(2) Nitrogen fixation/ cycling

(3) CaCO\textsubscript{3}

(4) DMS Production

EUPHOTIC ZONE

Phytoplankton

Cyanobacteria

CO\textsubscript{2} \quad N\textsubscript{2}

DIC \quad NO\textsubscript{3} \quad PO\textsubscript{4}

Uptake 106:16:1

(5) Phytoplankton species composition

(6) Organic Matter/ Trace element cycling

(7) Stoichiometry C:N:P

(8) Microbial Loop

Dissolved organic carbon

Heterotrophic bacteria

sedimentation

(9) Carbon Flux

(10) Zooplankton

Vertical migration

Unicellular zooplankton

Grazing

release

Microbial Loop

Zooplankton
(1) Primary Production & growth rate

**Number of studies**
- 15 + 18 (eukaryotes)
- 10 (cyanobacteria)

**Impact**
- No eff.
- Positive

**Range**
- Increase 10-50%
- Increase 15-128%

---

**Egge et al (2009)**

- Cumulative primary production (μmol C l⁻¹)
- Day no.

**Hutchins et al (2007)**

- CO₂ fixation rate (mg C mg Chl a⁻¹ h⁻¹)
- pCO₂ (Pa)

Pelagic Ecosystem CO₂ Enrichment study (PeECE III 2005), but no difference PeECE I & II (2001 & 2003)
### (1) Primary Production & growth rate

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- In some instances higher growth rate/ carbon uptake at elevated $pCO_2$ as long as other nutrients/ light are not limiting. In other cases no change.
- A fair amount of variability (CCM)
- Negative feedback (uptake of more atm. CO$_2$)

---

**Process Investigated**

**Number of studies**
- 15 + 18 (eukaryotes)
- 10 (cyanobacteria)

**Impact**
- No eff.- Positive
- Positive

**Range**
- Increase 10-50%
- Increase 15-128%

**Graph**
- Cumulative primary production (µmol C l$^{-1}$) vs Day no.
- $pCO_2$ (Pa) vs Day no.

**Pelagic Ecosystem CO$_2$ Enrichment study**
(PeECE III 2005), but no difference PeECE I & II (2001 & 2003)
(2a) Nitrogen Fixation by Cyanobacteria

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<tr>
<td>10</td>
<td>Positive / Negative</td>
<td>Increase up to 100%</td>
</tr>
</tbody>
</table>

- **Czerny et al. 2009**

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**N₂ fixation saturation kinetics**

- **Hutchins et al. 2007**

\[ K_{1/2} \approx 320 \text{ ppm CO}_2 \]
(2a) Nitrogen Fixation by Cyanobacteria

- Higher (mostly) N-fixation at elevated pCO$_2$ as long as other nutrients are not limiting. But species specific diversity.
- Higher P uptake – possibly driving oligotrophic habitats towards P limitation.
- Negative feedback (increase primary production).

Number of studies | Impact | Range
--- | --- | ---
10 | Positive / Negative | Increase up to 100%

Czerny et al 2009

---

Hutchins et al 2007

$K_{1/2} \approx 320$ ppm CO$_2$
### (2b) Nitrification

<table>
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<th>Number of studies</th>
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</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Negative</td>
<td>Decrease 10-40%</td>
</tr>
</tbody>
</table>

**Nitrification**

% Change in NO$_3$: DIN ratio ($\Delta$ 385 & 1000 ppm CO$_2$) based on Husemann et al. 2002.

**Benman et al. 2010**

[Graph showing normalized nitrification oxidation rate (%) vs. pH, with data points labeled HOT 209, HOT 210, SPOT, and BATS.]

[Map showing pH distribution across various regions, including the Sargasso Sea, with color coding for pH levels.]
(2b) Nitrification

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</thead>
<tbody>
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<td>Decrease 10-40%</td>
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% Change in NO$_3$: DIN ratio ($\Delta 385 \& 1000$ ppm CO$_2$) based on Husemann et al. 2002.

- Decrease in nitrification.
- Decrease in fraction of DIN that is nitrate.
- Positive feedback due to decreased primary production

Blackford & Gilbert 2007
### (2c) Denitrification

<table>
<thead>
<tr>
<th>Number of studies</th>
<th>Impact</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Increase</td>
<td>quadruple</td>
</tr>
</tbody>
</table>

$\Delta$ dissolved of dissolved $O_2$ between 2080-2100 and 1980-2000

**Graphs**
- **Left graph**: Spatial distribution of dissolved $O_2$ (Bopp et al. 2002)
- **Right graph**: Denitrification and N-fixation over time (Schmittner et al. 2008)

**References**
- Schmittner et al. 2008
- Bopp et al. 2002
(2c) Denitrification

- Any OA effect?
- Stratification increases & shallower remineralization
- Suboxic zones in the ocean increase
- Denitrification quadruples in next 2000 years
- Less nitrate available, decrease in biological production
- Positive feed-back

Number of studies: 3
Impact: Increase
Range: quadruple

Schmittner et al. 2008
Bopp et al. 2002
Decrease in fraction of inorganic N that is nitrate
(3a) CaCO₃: Saturation Horizon

<table>
<thead>
<tr>
<th>Number of studies</th>
<th>Impact</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 6</td>
<td>Decrease of Saturation</td>
<td>Decrease</td>
</tr>
</tbody>
</table>

\[
\text{Ca}^{2+} + 2\text{HCO}_3^- \leftrightarrow \text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O}
\]

Simulated aragonite saturation at the surface

- Aragonite and Calcite saturation is decreasing rapidly.
- Saturation is spatially variable with low values in the high latitudes

Steinmacher et al. 2009
(3b) (Bio-)Calcification: Coccolithophores & Foraminifera

<table>
<thead>
<tr>
<th>Number of studies</th>
<th>Impact</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 coco &amp; 5 Forams</td>
<td>Inconsistent</td>
<td>Increase 100%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Globally 27%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decrease 25-66%</td>
</tr>
</tbody>
</table>

**Response to increasing CO₂**

<table>
<thead>
<tr>
<th>Species studied</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coccolithophores¹</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Planktonic Foraminifera</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Calcification**

**Doney et al. 2008**

Physiological response

**Major group**

<table>
<thead>
<tr>
<th>Calcification</th>
<th>Coccolithophores¹</th>
<th>Planktonic Foraminifera</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>-</td>
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<tr>
<td></td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>-</td>
</tr>
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**Globigerina bulloides** (no algae symbionts)

**Weights of shells 355-425 µm**

Modern day: 28 µg

Pre-industrial: 40 µg

**Shell weights track pCO₂ over past 50,000 years**

Irie et al 2010: Optimality-model predicts that natural selection will favors heavy calcification if calcification is a defensive strategy and photosynthesis is enhanced.

Moy et al 2009
### (3b) (Bio-)Calcification: Coccolithophores & Foraminifera

#### Number of studies

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#### Impact

- Calcification response of Coccolithophores varies (even within one strain)
- Calcification of Foraminifera often decreases with OA, but proxy validation controversially discussed
- Growth conditions (function of a suite of parameters) strongly determine calcification
- \( \text{CaCO}_3 \) production decrease from 1 Pg C yr\(^{-1} \) to 0.36 – 0.82 Pg C yr\(^{-1} \) by 2100 (Gangsto et al 2011).
- Such a global decrease means a small negative feedback on atm. pCO\(_2\) of -1 to -11 ppm.

#### Process Investigated

- **Doney et al. 2008**
  - Physiological response to increasing \( \text{CO}_2 \)
  - Calcification response:
    - Species a: Increase
    - Species b: Decrease
    - Species c: Mixed
    - Species d: No change

- **Moy et al 2009**
  - Shell weights track pCO\(_2\) over past 50,000 years
  - Weights of shells:
    - 355 – 425 µm
  - Modern day: 28 µg
  - Pre-industrial: 40 µg

### Note

- Irie et al. 2010: Optimality model predicts that natural selection will favor heavy calcification if calcification is a defensive strategy and photosynthesis is enhanced.
(3c) CaCO$_3$ Dissolution

<table>
<thead>
<tr>
<th>Number of studies</th>
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</thead>
<tbody>
<tr>
<td>1 (pteropod)</td>
<td>Positive</td>
<td>Increase</td>
</tr>
<tr>
<td>5 carbonate compensation</td>
<td>Positive</td>
<td>Increase (geological time scales) globally 11 %</td>
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Global CaCO$_3$ Dissolution:
% $\Delta$ CaCO$_3$ 286 ppm to 1144 ppm in 140 years

Change in the rain ratio of sinking carbon

Gehlen et al. 2007

Gehlen & Bopp 2008
(3c) CaCO$_3$ Dissolution

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- Decrease in calcification & increase in production of POM potentially results in an increase in rain ratio (POC: PIC) in exported material
- Increased rain ratio $\rightarrow$ promotes dissolution, timescales of 1000-10,000 years).
- However, less ballasting might reduce sedimentation of POC not leading to an increased rain ratio
- Carbonate compensation: Dissolution of CaCO$_3$ in sediments have a buffer capacity for the deep ocean on geological time scales. Negative feedback!

Gehlen & Bopp 2008
### (4) DMS, DMSP Production

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>3</td>
<td>Inconsistent</td>
<td>No change</td>
</tr>
</tbody>
</table>

**Number of studies**: 3 studies were investigated.

**Impact**: Inconsistent

**Range**: No change

---

**Lee et al. 2009**

**Vogt et al. 2008**
(4) DMS, DMSP Production

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- pCO$_2$ alone has little effect on DMSP
- Shifts in phytoplankton species composition, grazing and viral infections may indirectly change DMSP & DMS productions
- Overall feedback unclear

Vogt et al 2008
### (5a) Phytoplankton Species Composition

<table>
<thead>
<tr>
<th>Number of studies</th>
<th>Shift</th>
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<tbody>
<tr>
<td><strong>Feng et al. 2009</strong></td>
<td>10</td>
</tr>
<tr>
<td><strong>Within groups or between groups</strong></td>
<td></td>
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**Process Investigated**

- Feng et al. 2009: 100 ppm, 360 ppm, 800 ppm
- Tortell et al. 2008: Change in diatom abundance 4xCO$_2$-1CO$_2$
- Bopp et al. 2005: Map showing change in diatom abundance

**Abundance (cells m$^{-3}$)**

- **A. Diatoms**
  - Ambient
  - High pCO$_2$
  - High temp
  - Greenhouse
- **B. Coccolithophores**
- **C. Chrysophytes**

**Images**

- a: 100 ppm
- b: 360 ppm
- c: 800 ppm
(5a) Phytoplankton Species Composition

Number of studies

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<td>Impact on export, biogeochemical cycling, stoichiometry large.</td>
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<td>Currently large uncertainty</td>
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- Shifts within functional or taxonomic groups and between groups
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(5b) Genetic Acclimation & Adaptation

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<td>2 &gt;150 generations</td>
<td>No difference, loss of flexibility</td>
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Stress response: immediate
Acclimatization: (gene expression) 8 - 10 generations
Adaptation: (genetic change) 200 - 1000 generations

- **430 ppm**
- **1050 ppm**
- **430 ppm**

- **line A**
- **line B**
- Extinction
(5b) Genetic Acclimation & Adaptation

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Stress response: immediate

- Green algae *Chlamydomonas* 1000 generations. Some lines did not grow in lower pCO₂ conditions - neutral mutation of CCM making it less efficient - Collins & Bell (2004):
  - Similar experiments underway
  - Indications from paleo-record of coccolithophores suggest some adaptation
  - Evolutionary models
  - Impact unknown
Synergistic & Antagonistic Interactions between CO₂, temperature, light, nutrients, trace metals

Rost et al. 2008

Wyatt et al 2010: surface layer NH₄ ↔ NH₃

Boyd et al. 2010
**Synthesis**

**Bottom-up Controls of Primary Producers**

**Synergistic & Antagonistic Interactions between CO₂, temperature, light, nutrients, trace metals**

- Carbonate system is one of SEVERAL factors that determine primary production / N-fixation etc.
- Multi-factorial tests are just beginning
- Overall impact unknown

\[ OA \]

Rost et al. 2008

Wyatt et al. 2010: surface layer \( \text{NH}_4 \leftrightarrow \text{NH}_3 \)
Process Investigated

(6) Organic Matter & Trace element cycling

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<tr>
<td>Half live of Fe (II)</td>
<td>- -</td>
<td>- -</td>
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Breitbarth et al. 2010

Millero et al. 2010

Fe$^{2+}$ & PAR days 20 & 22 of PeECE III

Solubility of Fe (III) in seawater

Half live of Fe (II)
(6) Organic Matter & Trace element cycling

- Many types of OM are sensitive to pH (trace metals, enzymes, ligands, siderophores,)
- Solubility, binding & complexation depends on pH
- An increase in availability of trace metals may be profitable (Fe) or potentially toxic (Cu)
- Increase in availability of iron may increase primary production (reduction of Fe-limited area by 20%; Tagliabue & Völker 2011)
- Species competition may change → shift in composition

**Number of studies**

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Half live of Fe (II)

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**Breitbarth et al. 2010**

Fe$^{2+}$ & PAR days 20 & 22 of PeECE III

**Millero et al. 2010**

Half live of Fe (II)

Solubility of Fe (III) in seawater

2                4                  6                 8                10

7.2         7. 4        7. 6           7. 8          8.0        8.2

• Many types of OM are sensitive to pH (trace metals, enzymes, ligands, siderophores,)
• Solubility, binding & complexation depends on pH
• An increase in availability of trace metals may be profitable (Fe) or potentially toxic (Cu)
• Increase in availability of iron may increase primary production (reduction of Fe-limited area by 20%; Tagliabue & Völker 2011)
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**Ocean acidification work shop Woods Hole 3/22- 3/24 2011**
(7) Stoichiometry of organic matter

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<th>Direction</th>
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<tbody>
<tr>
<td>13</td>
<td>Positive C:Nutrient</td>
<td>Increase</td>
</tr>
<tr>
<td>5</td>
<td>Negative C:Nutrient</td>
<td>Decrease</td>
</tr>
<tr>
<td>4</td>
<td>Positive N:P</td>
<td>Increase</td>
</tr>
<tr>
<td></td>
<td>Negative N:P</td>
<td>Decrease</td>
</tr>
</tbody>
</table>


- 1050 ppm C:N = 8.0
- 350 ppm C:N = 6.0
- 700 ppm C:N = 7.1


- Surface layer
- Sediment trap
### (7) Stoichiometry of organic matter

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<td>Decrease</td>
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- **Enhanced drawdown of CO₂ vs. N, but results VERY inconsistent**
- **Results depend on experimental conditions (light and nutrients)**

**Bellerby et al (2008)**

- 1050 ppm
  - C:N = 8.0
- 350 ppm
  - C:N = 6.0
- 700 ppm
  - C:N = 7.1

**Schulz et al (2008)**

- Surface layer
- Sediment trap

---

**Graphs:**
- Cumulative C/N vs. Days
- POC/PON vs. Days
- Days 2-26

---

Ocean acidification work shop Woods Hole 3/22- 3/24 2011
### (8a) Microbial Loop: DOM Production

<table>
<thead>
<tr>
<th>Number of studies</th>
<th>Impact</th>
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<tbody>
<tr>
<td>1 Viruses</td>
<td>abundance &amp; diversity</td>
<td>Inconsistent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No change</td>
</tr>
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</table>

Grossart et al. 2006

Schulz et al. 2008

![Graphs showing changes in DOC, DOM, and DOP over time.](image)
(8a) Microbial Loop: DOM Production

Number of studies | Impact | Range
---|---|---
1 Viruses | Inconsistent | abundance & diversity

- Phytoplankton: *a priori* assumption – increase in quantity & decrease in quality of exudation.
- Fast turn-over masks potential signals in DOM

Schulz et al. 2008

PeECE II 2003

Grossart et al. 2006
(8b) Microbial Loop: Bacterial Concentration, Turnover and Diversity

**Number of studies**
- **4**

**Impact**
- **Inconsistent**

**Range**
- **Increase 46% attached bac.**

**Cell specific BPP (fg C cell⁻¹ h⁻¹)**

- **Allgair et al (2008)**
  - Free bacteria
  - Attached bacteria

- **Grossart**

- **Arnosti et al in revision**

**PeECE III 2005**

**Time (d)**

**Time (d)**

**Notes:**
- Increase 46% attached bac.
- Number of studies: 4
- Impact: Inconsistent
- Range: Increase 46% attached bac.
<table>
<thead>
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<tr>
<td>4</td>
<td>Inconsistent</td>
<td>Increase 46% attached bac.</td>
</tr>
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- Total bacteria number did not differ significantly between treatments in any of the three PeECE studies.
- Enhanced turnover for attached bacteria in one study.
- Community composition differed in both tested cases.
- Changed DOM & POM production by phytoplankton may be the cause (indirect effect).
- Overall effect on bacteria concentration on atm pCO$_2$ unclear.

**Graph:**
- Graph showing changes in cell specific BPP (fg C cell$^{-1}$ h$^{-1}$) over time (d) for different CO$_2$ treatments (350 ppm, 700 ppm, 1050 ppm).

**Text:**
- Allgair et al. (2008)
- Grossart et al. (2006a)
- PeECE II 2003
- PeECE III 2005
(8c) Microbial Loop: Bacterial Degradation of DOM

**Process Investigated**

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<tbody>
<tr>
<td>3</td>
<td>Positive/None</td>
<td>Increase 50-83%</td>
</tr>
</tbody>
</table>

**Grossart et al (2006a)**

<table>
<thead>
<tr>
<th>Time (d)</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrolytic activity (µmol L⁻¹ h⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sig</td>
<td>0.3</td>
<td>0.6</td>
<td>0.9</td>
<td>1.2</td>
<td>0.1</td>
</tr>
<tr>
<td>ns</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**PeECE II & III**

**Arnosa et al. (2009)**

<table>
<thead>
<tr>
<th>PeECE I</th>
<th>CultExp I</th>
<th>CultExp II</th>
<th>Field I</th>
<th>Field II</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 ppm</td>
<td>350 ppm</td>
<td>190 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Glucosidase (nmol L⁻¹ h⁻¹)**

**Chondroitin sulfate**

**Fucoidan**

**Laminarin**

**Xylan**

**Glucosidase**

**Grossart et al (2006a)**

**PeECE II & III**

**Arnosa et al. (2009)**

**Glucosidase**

**Grossart et al (2006a)**

**PeECE II & III**

**Arnosa et al. (2009)**

**Glucosidase**

**Grossart et al (2006a)**

**PeECE II & III**

**Arnosa et al. (2009)**

**Glucosidase**
(8c) Microbial Loop: Bacterial Degradation of DOM

Number of studies | Impact | Range |
--- | --- | --- |
3 | Positive/ None | Increase 50-83% |

Gross hydrolytic activity (μmol L⁻¹ h⁻¹)

- Dependent on DOM and mineral nutrients
- Some studies show enhanced degradation in upper water column others do not. Enhanced degradation of additionally fixed carbon would have no net effect on atm. pCO₂.
- Possibly accumulation of DOM in surface ocean & subduction via physical processes removes additional CO₂ from the atmosphere → negative feedback

PeECE II & III

Time (d)

700 ppm
350 ppm
190 ppm

Arnosti et al in revision

Gross heterotrophic production

Ocean acidification work shop Woods Hole 3/22- 3/24 2011
(8) Concept: Microbial Carbon Pump

Jiao et al. Nature Reviews Microbiology 2010
(9) Carbon Flux: Partitioning

(9) Aggregation and Transparent Exopolymer Particles, TEP

<table>
<thead>
<tr>
<th>Number of studies</th>
<th>Impact</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 (3↑, 3→)</td>
<td>Inconsistent</td>
<td>Increase 20%</td>
</tr>
</tbody>
</table>

**Process Investigated**

**Number of studies**

**Impact**

**Range**

**Engel (2002)**

**CO₂ (µatm)**

**Normalized abiotic TEP Formation**

**Translucent Exopolymer Particles (µg Xanthan Equiv. L⁻¹)**

**Passow unpubl.**

**190 ppm 350 ppm 750 ppm**

**1050 ppm**

**Ocean acidification work shop Woods Hole 3/22 - 3/24 2011**
(9) Aggregation and Transparent Exopolymer Particles, TEP

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<tbody>
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<td>6 (3↑, 3→)</td>
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</tr>
</tbody>
</table>

- No change in abiotic TEP formation expected
- Possibly enhanced TEP formation due to increase in DOC exudation but not observed in PeECE II & III.
- Impact for aggregation or microbial dynamics are unclear

**Process Investigated**

![Graph showing normalized abiotic TEP formation vs. pCO2](image)

**Engel (2002)**

**Passow unpubl.**

![Graph showing TEP vs. CO2](image)
(9) Sinking velocity of aggregates

<table>
<thead>
<tr>
<th>Number of studies</th>
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</thead>
<tbody>
<tr>
<td>2</td>
<td>Decrease</td>
<td>Decrease</td>
</tr>
</tbody>
</table>

Ballasting: Aggregates of *E. hux.*

**TEP Fraction:**

Aggregates of TEP & beads

Mari 2008

Biermann & Engel 2010
(9) Sinking velocity of aggregates

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Ballasting: Aggregates of *E. hux.*

- Lack of ballasting due reduction in calcification reduces sinking velocity
- Increase in the volume fraction of TEP in aggregates decreases sinking velocity
- Decrease of flux to deep sea in the future ocean → positive feedback

Mari 2008

Biermann & Engel 2010
### (9) Efficiency of Biological pump

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</thead>
<tbody>
<tr>
<td>3</td>
<td>Increase</td>
<td>PeECE II\textsuperscript{Mes}, \textdownarrow\text{CaCO}_3\text{Prod}\textsuperscript{Mod.}, Salps vs krill\textsuperscript{Theo,Field}</td>
</tr>
</tbody>
</table>

- Overall effect on biological pump unknown (regionally different?)
  - Increase in efficiency (negative feed back):
    - C-overconsumption, TEP formation & sedimentation
    - Decrease in calcification
    - Increase in fraction of salps vs krill
  - Decrease in efficiency (positive feed back):
    - Decrease in sinking velocity due to increase of TEP in aggregates
    - Decrease in sinking velocity due to lack of ballasting
    - Decrease in diatom abundance
### Process Investigated

#### (10) Zooplankton

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<tbody>
<tr>
<td>3</td>
<td>Subtle</td>
<td>No change</td>
</tr>
</tbody>
</table>

**Protozooplankton day 14**

- **T14 Ambient**
  - Lohmanniella sp.
  - Protoperidinium sp. 2
- **T14 High 
  temperature**
  - Lohmanniella sp.
  - Strombidium sp. 2
- **T14 High pCO₂**
  - Lohmanniella sp.
  - Protoperidinium sp. 2
- **T14 Greenhouse**
  - Lohmanniella sp.
  - Amphomaiopsis sp.
  - Protoperidinum sp. 2

**Growth rate of amphipod**

- *ns*

**Effects on grazing rate & vertical migration**

- Houton et al. 2009

- Rose et al. 2009

Ocean acidification work shop Woods Hole 3/22- 3/24 2011
(10) Zooplankton

## Number of studies

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### Protozooplankton day 14

- Effects on microzooplankton appear mostly indirect (shift in food source)
- Effects on mesozooplankton subtle, in physiology (gene expression) but not in mortality or growth
- Consequences for biogeochemical cycling impossible to predict at this time

Growth rate of amphipod

\[ \text{ns} \]

- Effects on grazing rate & vertical migration

Image from Rose et al. 2009
Effects on Biogeochemistry on Biological Timescales

- **C- fixation increase** → C-rich POM
- **N₂** CO₂ → Fixation
- **DICh NO₃ PO₄** Uptake 106:16:1
- **Phytoplankton** Cyanobacteria
- **Zooplankton** Grazing Fixation Uptake 106:16:1
- **Unicellular zooplankton** Heterotrophic bacteria
- **Dissolved organic carbon** Microbial Loop release
- **EUPHOTIC ZONE** Change in species composition Stoichiometry Feeding Microbial utilization Settling flux
- **Nitrogen** fixation increase → P-limitation Nutrition for higher trophic level
- **Calcification reduced** → Less ballasting material → decrease in sedimentation
- **Microbial loop turnover** enhanced → increased respiration or decreased → increase of DOM down ward transport
Summary

- Number of available studies very limited considering the complexity of the problem
- Ocean acidification seems to significantly alter the environment of microbes
- Changes in phytoplankton and bacterial community structure and physiology are likely
- Changes in microbial processes and community structure impact biogeochemical cycles
- Magnitude and direction of impact presently unpredictable, because of its complexity
- Associated changes of climate add to the complexity → need for multifactorial experiments
1. The carbonate system structures the environment.
   a) Spatial and temporal fluctuations are large and will become larger as OA progresses
   b) Feed-backs make changes in carbonate system partially unpredictable
   c) These effect organisms, populations, ecosystems and biogeochemical cycling
   d) Till recently ignored: Re-evaluate many “pre-OA” results

2. OA does not happen isolated – synergistic and antagonistic interactions with other parameters of major importance.

3. Ability of organisms to acclimatize and adapt unknown.

4. Empirical relationships (Redfield ratio, Martin curve) may not hold.
Conclusions

Approaches

1. Autonomous CO$_2$ buoys – understand rate of change and variability

2. Process studies (laboratory or shipboard experiments) isolating individual processes and field surveys evaluating temporal or spatial gradients will give us information on the breadth of possible reactions.

3. Explore combined influence of global change relevant parameters (light, nutrients, trace elements, temperature) in experiments. Test for parameter range in expected changes of specific regions.

4. Models could help predict regional specific expected changes of these parameter combinations (tighter collaboration between modelers and experimentalists).

5. Proxy evaluation to utilize past data for analysis of long-term trends.

6. “Evolutionary” Experiments

7. Mesocosm studies look at community level net effects (black box for individual processes)

8. Model processes and feed-backs, e.g. sedimentation – ballasting,
Thank you!