Prospects for Marine Ecosystems with Ocean Acidification

Joanie Kleypas
Integrated Science Program
Climate & Global Dynamics
Ocean Acidification

The Problem
The CO$_2$ we put in the atmosphere

- 1.5 Pg C y$^{-1}$
- 7.5 Pg C y$^{-1}$

Where it ends up

- 4.2 Pg y$^{-1}$ (46%)
- 2.6 Pg y$^{-1}$ (29%)
- 2.3 Pg y$^{-1}$ (25%)

Years 2000-2007

Canadell et al. 2007, PNAS (updated)

Slide modified from GCP - Global Carbon Budget Team
Ocean Acidification

Atmospheric carbon dioxide

$\text{CO}_2(g)$

$\text{CO}_2(aq) \rightleftharpoons \text{H}_2\text{CO}_3 \rightleftharpoons \text{HCO}_3^- + \text{H}^+ \rightleftharpoons \text{CO}_3^{2-} + \text{H}^+$

Dissolved carbon dioxide
Carbonic acid
Bicarbonate
Carbonate

Preindustrial versus doubled preindustrial CO$_2$ concentrations

<table>
<thead>
<tr>
<th>CO$_2$(g) ppmv</th>
<th>CO$_2$(aq) + H$_2$CO$_3$ µmol kg$^{-1}$</th>
<th>HCO$_3^-$ µmol kg$^{-1}$</th>
<th>CO$_3^{2-}$ µmol kg$^{-1}$</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>8</td>
<td>1635</td>
<td>272</td>
<td>8.11</td>
</tr>
<tr>
<td>560</td>
<td>16</td>
<td>1867</td>
<td>177</td>
<td>7.93</td>
</tr>
</tbody>
</table>
Ocean Acidification

A Suite of Changes
A Suite of Impacts
How Bad Will it Be?

Nick Anderson, Houston Chronicle
Abstracts at the *Ocean in a High CO₂ World III*

Organismal Effects (see next pie chart)

Organisms

Socioeconomics

Ecosystems

General

Paleo Studies

Model Studies

Methods

Observations

Chemistry

Ecosystem Effects

Compiled by Ed Urban
Breakdown by Taxon

- **Molluscs**
  - Mollusks
- **Phytoplankton**
  - Phytoplankton
- **Corals**
  - Corals
- **Echinoderms**
  - Echinoderms
- **Fish**
  - Fish
- **Crustaceans**
  - Crustaceans
- Other groups:
  - Coralline algae
  - Polychaetes
  - Sponges
  - Zooplankton
  - Bacteria
  - Macroalgae
  - Forams
  - Seagrass

Compiled by Ed Urban
Multiple Changes in the CO$_2$ System
Multiple Changes in the CO$_2$ System

Changes in CO$_2$-system

- CO$_2$(aq) up
- HCO$_3^-$ up
- CO$_3^{2-}$ down
- pH down

Surface Ocean pH $\rightarrow$ OH$^-$

CO$_2$ System

Graph showing
- Log [concentrations]
- pH range
- CO$_2$(aq), HCO$_3^-$, CO$_3^{2-}$
- pH values
- Concentration values

Graph highlights:
- pH at 8
- Log concentrations at different pH levels
Multiple Effects on Marine Life

Changes in CO₂-system

- $\text{CO}_2(aq)$ increases
- $\text{HCO}_3^-$ increases
- $\text{CO}_3^{2-}$ decreases
- pH decreases

Direct Effects

- Increase in photosynthesis
- Decrease in calcification
- Chemical speciation
  - Physiology

Indirect Effects

- Biogeochemistry
  - Food webs
- Animal behavior
  - Ecosystem Engineering
Increased Biomass in Seagrasses

Light replete

Light limited

\[ \text{CO}_2(aq) \uparrow \quad \text{HCO}_3^- \uparrow \]

Palacios & Zimmerman (2007) MEPS
Effects on the Nitrogen Cycle

HCO$_3^-$ → CO$_2$(aq)

Hutchins et al. 2009 Oceanography
Effects on the Nitrogen Cycle

$\text{CO}_2(aq) \rightarrow \text{HCO}_3^-$

Hutchins et al. 2009 Oceanography
Effects on the Nitrogen Cycle

$CO_2(aq) \rightarrow HCO_3^-$

Hutchins et al. 2009 Oceanography
Effects on the Nitrogen Cycle

 Winners: Picophytoplankton

 Losers: Diatoms

Hutchins et al. 2009 Oceanography
Effects on Calcification in Organisms

<table>
<thead>
<tr>
<th>Calcification rate DECREASES in:</th>
<th>Calcification rate INCREASES in:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical coralline algae</td>
<td>Some coccolithophores</td>
</tr>
<tr>
<td>Some coccolithophores</td>
<td>Some echinoderms</td>
</tr>
<tr>
<td>Foraminifera</td>
<td>Some crustaceans</td>
</tr>
<tr>
<td>Scleractinian corals</td>
<td></td>
</tr>
<tr>
<td>Some echinoderms</td>
<td></td>
</tr>
<tr>
<td>Some mollusks (pteropods, some bivalves)</td>
<td></td>
</tr>
</tbody>
</table>

It’s Complicated

- Mechanisms of calcification
- Mineralogy
- Presence of protective organic coatings
- Photosynthesis
- Feeding
Decreasing pH

Most organisms maintain internal pH

1. Metabolic interconversion of acids and bases
2. Buffering
3. Transport of acids and bases across cell membranes

Figure from Siebel & Walsh 2001, Science
Decreasing pH
The master variable in biochemistry

Organisms spend energy to maintain internal pH
- ocean acidification will either affect:
  - an organism’s internal acid-base balance
  - their metabolic costs to maintain it (Fabry et al. 2008)

Abilities of organisms to buffer pH changes varies widely
- effects of ocean acidification on organism physiology will also vary

Decreasing pH poses several important indirect effects on organisms
- bioavailability of trace elements (Shi et al. 2010)
- increases in respiratory CO$_2$ (Brewer & Peltzer 2009)
- increased toxicity of copper (Millero et al. 2009)
Physiology:
Respiration rate
Blood chemistry
Energy allocation
Photosynthesis
Calcification
Reproduction
Chemoreception

Changes in CO$_2$-system
- CO$_2$(aq) increases
- HCO$_3^-$ increases
- CO$_3^{2-}$ decreases
- pH decreases

Multiple Effects
- Acting simultaneously -

Eggs – Larvae – Recruitment

Food Supply
Life Cycle Effects

approximately 2 weeks

floating fertilized egg → swimming straight-hinge veliger → swimming late veliger → swimming & crawling pediveliger

Oyster Life Cycle

egg and sperm → spat settling and attaching to oyster shells or other hard structures

1 - 3 years

adult males and females

Credit: Karen R. Swanson/COSEE SE/NSF
Multiple Changes
Direct & Indirect Effects

Geochemical: CaCO$_3$ saturation state

Ecological: species interactions

Physiological: Internal acid-base chemistry

Biogeochemical: Nutrient speciation & availability

CO$_3^{2-}$ → CO$_2$(aq) & HCO$_3^-$

HCO$_3^-$ → pH

CO$_2$(aq) → pH
Predicting impacts is taking time:

- Complex life cycles
- Generational effects
- Adaptation (or not)
- Multiple stressors
- Ecosystem complexity (species interactions)
- Our plain old ignorance of the ocean
Ocean Acidification

Ecosystems
Natural ocean acidification
CO$_2$ vents off Italy

WINNER

LOSER

Hall Spencer et al. (2008) Nature
Community Shifts with Decreasing pH

Hall-Spencer et al. (2008) Nature

Calcareous

Noncalcareous

pH (total scale)

Distance (m)

Percentage algal cover
Natural ocean acidification
CO₂ vents off Papua New Guinea

a
pH = 7.93-8.05

b
pH = 7.81-7.93

c
pH = 7.45-7.57

Fabricius et al. 2011 Nature Climate Change
Resilience, Thresholds
Phase Shifts and Regime Shifts

Nyström et al. (2008)
Coral Reefs

Resilience
Coral Cover

Ocean Acidification

State variable
Threshold

Regime shift Phase shift

disturbance
Alternative Stable States in Coral Reefs

Bellwood et al. (2008)
Nature
Can We See A Regime Shift Coming?

DETECTION / PREDICTION

1. Increased variance

2. Slower recovery following disturbance

3. Monitoring resilience:
   a) functional groups (e.g. grazers)
   b) demographic skewness in populations
   c) discontinuities (e.g. redundancy)

4. Indicators
   e.g. ratios of “good” colonizers versus “bad” colonizers

5. Tracking local phase shifts within an ecosystem network

Reviewed by
Nyström et al. (2008) Coral Reefs
Scheffer et al. (2009) Nature
Ocean Acidification

Has this Happened Before?
Late Paleocene Reefs

Reefs were already declining due to warming temperatures

Reefs were replaced by foraminiferal facies at the PETM boundary
Ocean Acidification

What Provokes Attention?
Effects on Fish

Video courtesy of Brad Seibel
Homer Alaska: commercial fishermen, mariners and others spelled out ‘SOS’ to protect jobs and fisheries from the threat of ocean acidification.

‘Voices for the Ocean’ hosted by the Alaska Marine Conservation Council (AMCC) and the Sustainable Fisheries Partnership (SFP).
Commercial Hatcheries

Oyster failure linked to ocean acidification

Collapse of oyster seed production at a commercial oyster hatchery in Oregon linked to acidification... (more)
Paleocene-Eocene Thermal Maximum

Physical changes:
Ocean temperature \(\uparrow 5-8^\circ\text{C}\)
Marine and terrestrial C Isotopes \(\downarrow 3-8\%\)
Calcium Carbonate Compensation Depth \(\uparrow 2\text{ km}\)

Biological responses:
Dramatic reorganization of marine and terrestrial ecosystems
  marine: benthic foraminifera - 35-50% of deep-water species went extinct (Thomas 1998)
  plankton - high species turnover (Gibbs et al 2006)
REEFS: demise of coral-algal reefs, large calcitic foraminifera flourished (Scheibner & Speijer Earth Sys. Rev. 2008)
  land: Mammalian radiation
  Reorganization of terrestrial plant communities (Wing et al. Science 2005)