Marine Biogeochemical Modeling: 
Ocean Acidification

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OCB Ocean Acidification Short Course 2009

Talk Outline
• Fossil Fuels & Global Carbon Cycle 
• Past & Future Seawater Chemistry 
• Climate-Carbon Cycle Feedbacks 
• Calcification & Biogeochemistry 
• Biological & Ecological Effects 
• Policy, Economic & Social Dimensions

Supported by:
Anthropogenic CO$_2$ uptake currently controlled by ocean circulation; but in future, what will be role of climate & biology?

For ocean acidification may want models to address many different aspects:

- patterns & trends in seawater chemistry
- population biology of individual species
- food-web & ecological interactions
- biogeochemical feedbacks
- socio-economic effects on fisheries & ecosystem services
"Thus human beings are now carrying out a large scale geophysical experiment..."
Revelle and Suess, Tellus, 1957
Fossil Fuel Emissions

Le Quere et al., Nature Geosciences, 2009 (in press)
Ocean & Land $\text{CO}_2$ Sinks

Le Quere et al., Nature Geosciences, 2009 (in press)
New mitigation scenarios: representative concentration pathways (RCPs)

New way of producing/using scenarios devised by WG1, WG2 and WG3 communities (not IPCC)

pre-AR4:
(a) Sequential approach

1 Emissions & socio-economic scenarios (IAMs)
2 Radiative forcing
3 Climate projections (CMs)
4 Impacts, adaptation & vulnerability (IAV)

post-AR4:
(b) Parallel approach

1 Representative concentration pathways (RCPs) and levels of radiative forcing
2 Climate, atmospheric & C-cycle projections (CMs)
3 Emissions & socio-economic scenarios (IAMs)
4 Impacts, adaptation, vulnerability (IAV) & mitigation analysis

Anthropogenic CO$_2$ & Ocean pH

- CO$_2$ emissions (social, political, economic)
- atmospheric CO$_2$ (land & ocean uptake; climate-carbon feedbacks)
- ocean chemistry & circulation

Orr et al., Nature (2005)
Feely et al. Oceanography (in press)
Surface Aragonite Saturation

Zonal mean $\Omega$ vs. atmospheric CO$_2$

Steinacher et al. Biogeosci., 2009
Shoaling of Aragonite Saturation Horizons

\[ \Omega = \frac{[\text{Ca}^{2+}][\text{CO}_3^{2-}]}{K_{sp}} \]

\[ \Delta[\text{CO}_3^{2-}] = [\text{CO}_3^{2-}]_{\text{obs}} - [\text{CO}_3^{2-}]_{\text{sat}} \]

Ocean Climate Responses & Feedbacks

CHANGING CLIMATE
Higher atmosphere CO₂, altered ocean properties, sea-ice & circulation

OCEAN CO₂ SINK
Ocean acidification

BIOGEOCHEMISTRY
Carbon & nutrient fluxes, CO₂ & other greenhouse gases

BIODIVERSITY
BIOGEOGRAPHY
PHYSIOLOGY

ECOSYSTEM SERVICES
Fisheries, tourism, shore protection, …

ECOSYSTEM SERVICES
Food webs, energy flow
**Coupled Model Uncertainties**

Strength of Ocean CO$_2$ Sink

Sensitivity to Climate Warming

Friedlingstein et al. *J Climate* 2006

20 years of current carbon emissions
Climate Feedbacks

Small direct climate $\Delta p\text{H}$

Larger direct climate $\Delta \Omega > 0$

McNeil and Matear, Tellus (2007)
Cao et al., GRL (2007)

Fung et al. PNAS (2005)
Climate Change Feedbacks

CO$_3^{2-}$ ~ Alk-DIC

Steinacher et al., *Biogeosciences*, 2009
Climate Change Impacts on Primary Productivity

Figure 3 | Trends in the observed partial pressure of CO₂ for ocean minus air, for 1981–2007. The observed trends are calculated by fitting a linear least squares regression across grid boxes in each ocean basin.

Le Quere et al., Nature Geosciences, 2009 (in press)
Climate Forcing: Synergistic effects of changes in temperature, nutrients, trace metals, sea-ice, mixed-layer depth, CO$_2$(aq), pH and $\Omega$

Biotic Interactions: Competition, predatory-prey, viruses, …


Calcification in Ecosystem Models

- Model approach: fixed PIC/POC, statistical, dynamic
- Prognostic models: (light, MLD, SST, nutrients, grazing)
- Functional groups: coccolithophorids, forams, pteropods
- Data limitations for verification and parameterization: (satellites, field, laboratory)

Moore et al. (2004); Le Quere et al. (2005)
Global Budget Pg CaCO₃-C/yr

1.6

Feely et al. Science (2004); Berelson et al. GBC (2007); Sarmiento et al. GBC (2002)

Global rates & regional patterns of water column dissolution, flux from deep traps

Geochemical Constraints

PIC Standing Stock

Sinking Flux
Acidification, Calcification & Climate Feedbacks

- Reduced formation of biogenic CaCO$_3$
- Decrease organic matter remineralization lengthscale (ballasting)
- Increase subsurface CaCO$_3$ dissolution

Negative (damping) climate feedbacks

$\Delta$ atm. CO$_2$ < 0
$\Delta$DIC$_{surf}$ < 0
$\Delta$Alk$_{surf}$ > 0

Niches & Plasticity

No current analogues to some future climate conditions??

From Legendre and Rivkin (2005)


• Complicated (complex?) food-web interactions
• How do we test model forecasts? (spatial & interannual variability)
Food Web Models
Regional Models

- Upwelling & mesoscale eddies
- Coastal models
- Basin-scale models

Seasonal variation of pH

Hauri et al. Oceanography (in press)

Fig. 6. Map of the modelled annual pH range simulated across the southern North Sea domain.
Particle Tracking - Individual Based Models

Batchelder et al. Prog. Ocean. 2002
<table>
<thead>
<tr>
<th>Resource</th>
<th>Impacted by Acidification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fisheries</td>
<td>Plankton - food chain dynamics</td>
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<td></td>
<td>Mollusks and Crustaceans</td>
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<td>Reefs - critical habitat</td>
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<tr>
<td>Coastal Protection</td>
<td>Reefs - Protect shore lines</td>
</tr>
<tr>
<td>Ocean CO₂ Uptake</td>
<td>Erosion of CaCO₃ deposits</td>
</tr>
<tr>
<td></td>
<td>Surf. alkalinity; biological pump</td>
</tr>
</tbody>
</table>

**Ecosystem Services**

- Provide direct benefits to society
- Valuation estimates:
  - difficult to replace by technology
  - cost of total loss dramatic
  - moral choices involved in valuation
  - both market and non-market value

Costanza et al. (1997) 1994 Values
Commercial fisheries depend on species at risk

New England primary fishery revenue
~$850 million/year
~80% are from shellfish

Cooley & Doney
2009
Cooley, Powell & Doney
Oceanography (in press)
Cooley, Powell & Doney
Oceanography (in press)
Uncertainties in Future Projections (confidence)

- anthropogenic CO$_2$, pH & CaCO$_3$ saturation $\Omega$
  - fossil fuel emissions & atmosphere CO$_2$ (med.)
  - ocean pH & $\Omega$; surface (high) & subsurface (med.)
  - small climate/carbon feedbacks (med.)

- other acidity/alkalinity inputs
  - atmosphere N & S => reduce coastal Alk & outgas CO$_2$ (med.)
  - sediments, rivers, & groundwater (low/med.)

- calcification & biogeochemical impacts
  - higher surface alkalinity & atm. CO$_2$ drawdown (med.)
  - particle ballast, elemental stochiometry, trace gases

- biological & ecological effects
  - individual organisms: transient (high), adaptation (low)
  - effects on foodwebs & higher trophic levels (low)

- policy, economic & social dimensions
  - atm. CO$_2$ guard rail (0.2 pH drop?) (low/med.)
  - economic value fisheries, coral reefs, biodiversity (low)
Feely et al. Oceanography (in press)