Feedbacks Between Ocean Ecosystems, Ocean Biogeochemistry and Climate

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Outline of Talk

• Linkages, transports & transformations
• Anthropogenic climate change: past and future
• Global ocean biogeochemical patterns
• North Pacific climate change
• Observed changes in NP biogeochemical cycles
• Changes in ocean acidity: global and in N. Pacific
• Can we predict the response of organisms?
Ocean Ecosystems ↔ Climate

Direct links between ocean ecosystems and climate, e.g.
- thermal regulation of physiological rates
- phytoplankton pigments regulate the vertical profile of absorption of incoming solar radiation and hence upper ocean temperature profile

Indirect links via 'Biogeochemistry', e.g.
- ocean biota regulate sequestration of atmospheric CO₂ by the ocean by affecting surface pCO₂, pH, export of C to ocean interior via 'biotic pumps'
- oceanic biota regulate dissolved O₂ concentrations, and hence production of gases N₂ and especially N₂O
- temperature affects biological sources and sinks for O₂

Physical transport, e.g.
- advection, mixing, gravitational sinking (& buoyant rising)
Linked Ocean Cycles: Transports and Transformations

- Cycles of C, N, O, P, Si, S, Fe, etc. are linked via the 'Redfield ratios' – more or less!

- Most, but not all, transformations of chemical form are mediated by the marine ecosystem

- There are critical points where the cycles depart from Redfield ratios during transformation,

- Many involve N, e.g. nitrification, denitrification, uptake and release by organisms, bacterial remineralization releasing dissolved inorganic nutrients over different depth ranges

- What factors regulate these critical points and how will they change with a changing climate?
The World Has Warmed But Not Evenly

Globally averaged, the planet is about 0.75°C warmer than it was in 1860, based upon dozens of high-quality long records using thermometers worldwide, including land and ocean.

Eleven of the last 12 years are among 12 warmest since 1850 in the global average.
Most of the Heat is Going into the Oceans

And it has penetrated to at least 3000 m

from IPCC AR4 WG1 Fig. 5.4
Largest warming is since 1975 & in N. Hemisphere

- Atlantic Ocean
- Indian Ocean
- SST
- Pacific Ocean
- Land
- Total

IPCC AR4 WG1, Fig. 3.5
Land Precipitation Is Changing Significantly Over Broad Areas

Smoothed annual anomalies for precipitation (%) over land from 1900 to 2005; other regions are dominated by variability (from Fig. 3.14).

Increases

Decreases

CRU
NODC
The Future: SRES Scenarios

Economists and social scientists must forecast human behaviour and response to change.

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Projected Surface Warming to 2100
(relative to 1980-1999 mean)

Hierarchy of independent models and observational constraints

AOGCMs
Positive Feedback between the Carbon Cycle (Land + Ocean) and Climate Change

C4MIP models project an additional ~1°C warming added to the 'official' IPCC AR4 projections for 2100.

Greater reductions in CO₂ emissions would be needed to achieve the same CO₂ conc. stabilization level.

from IPCC AR4 WG1 Fig. 10.20
Change in Surface Air Temperature
(°C, relative to 1980-1990 period)

Stippled areas: multi-model mean exceeds inter-model std dev.

$\Delta T$ highest in northern Polar regions during northern winter

Elsewhere, $\Delta T$ higher over land

Fig. 11.21

AR4 WG1 Fig. 10.9
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**A1B**

**Annual**

**DJF**

**JJA**

**Temp Response (°C)**

- **10°C**
- **-1°C**

**Prec Response (%)**

- **50%**
- **-50%**

**Num of Models > 0**

- **21 models**
- **0**

Bottom - Number of models out of 21 that project precipitation to increase
Projections of Future Changes in Precipitation

New in AR4: Drying in much of the subtropics, more rain in higher latitudes, continuing the broad pattern of rainfall changes already observed.
Future CO₂ Emissions Scenarios
[from Raupach et al., US. Proc. Natl Acad Sci Vol. 104, 12 June 2007]

Observed rate of increase (3.3 % /year) for 2000-2006 exceeds all scenarios

2004 Carbon emissions per person:
Globe (Canada)
~1.2 tonnes/year (~5.5)
= 4 tonnes CO₂ /year (~20)
'1995' Annual CO$_2$ Flux Ocean to Air
Takahashi et al. 2002 (corrected to 10 m winds)
"Anthropogenic" CO$_2$ in the Ocean in 1995

48% of fossil fuel emissions: Most in N. Atlantic and northern edge of Antarctic Circumpolar Current

- Some in N. Pacific, probably associated with subduction and deeper winter mixing in western basin  
  
  [after Sabine et al. 2004, Science 305; Key et al., 2004, GBC, 18, GB4031]
CaCO$_3$ Saturation Layer in N. Pacific is Shrinking

In Undersaturated Regions, CaCO$_3$ Shells Dissolve and 'Neutralize' Anthropogenic CO$_2$

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

**Apparent Oxygen Utilization (AOU) Regions**

**Present day AOU (mol m\(^{-3}\)) at 300m (World Ocean Atlas 2002)**

Decreasing O\(_2\) in low O\(_2\) regions may lead to:

- Hypoxia in adjacent upwelling regions, affecting organisms & increasing sediment denitrification

*Paleo \(\delta^{15}N\) indicates more denitrification & production of N\(_2\)O in warm periods relative to LGM*  
[Galbraith et al., 2004, Paleoceanography, 19]
Expected Warming vs Pacific Decadal Oscillation

Spatial pattern of projected warming similar to that of the PDO first EOF:

A. SST anomaly (November - March), first EOF (i.e. PDO), for 1901-1999 (from Hadley Centre SST analysis)
   &
   Ensemble mean of SST first EOF, for A1B SRES scenario, 2002-2099 (10 IPCC-AR4 models from PCMDI site)

B. Projected model average decadal winter mean SST (2040-2049), relative to 1980-1999 pattern from the Hadley Centre data

Jim Overland and Muyin Wang
2007, EOS/AGU 88(16)
NE Pacific Ocean: The Future?

from DFO Ocean Status Reports (Chair: W. Crawford, IOS)
http://www.pac.dfo-mpo.gc.ca/sci/psarc/OSRs/Ocean_SSR_e.htm

Sept. 97 – July 98: Chlorophyll from *SeaWiFS* Ocean Colour Sensor

*Courtesy NASA*

Maximum winter mixed layer depth is DECREASING

courtesy Howard Freeland, IOS
Subsurface Oxygen Decrease is Widespread

After Deutsch et al. (2005)

IPCC AR4 WG1
Fig. 5.12

$O_2 \, (\mu\text{mol kg}^{-1})$
Apparent Oxygen Utilization Decreasing in Oyashio Region

\[ AOU \approx O_2(\text{surface outcrop}) - O_2(\sigma_\theta \text{ const}) \]

i.e. increasing AOU → decreasing \( O_2 \)

[from Ono et al. 2001, Geophys Res Lett 28]
Dissolved O\textsubscript{2} Is Lower Closer to Land

Crawford et al. 2007 Prog. Oceanogr. 75(2)

% Oxygen Saturation on 26.5 \(\sigma_\theta\)-surface
- 0 to 46
- 46 to 62
- 62 to 120

**Nutricline:** $\text{NO}_3^- (\sigma_T = 26.0) \approx 25 \text{ mmol m}^{-3}$


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Coastal Upwelling & Local Enhancement of Low $O_2$ Waters

May
- small area of low $O_2$ near bottom, below
- high surface POC (mostly live phytoplankton)
- sinking POC creates biological $O_2$ demand near bottom

August
- 75m thick layer of low $O_2$
- thin surface layer of POC
  ($50 \mu$mol kg$^{-1} \approx 1.15$ mL/L)

Hales et al., 2006, Global Biogeochem. Cycles, 20, GB3001
Recent Changes off Oregon

Dissolved oxygen profiles during the upwelling season, mid-April to mid-October (42N to 46N)

F. Chan et al., Science 319, 920 (2008)

(50 mmol m$^{-3}$ ≈ 1.12 mL/L)
The Coastal Ocean: More Hypoxia Events?

Dead zone off Newport, Oregon 2002,04,06

See also: Grantham et al. 2004 Nature, 229, 749-753

[www.piscoweb.org PISCO at OSU]
**High CO₂ ≡ High Acidity**

Upwelling + Local Respiration

a) Very high > 600 ppm surface $X_{CO₂}$ near coast during upwelling events

b) Same section off Oregon as low O₂

c) Very low pH waters

$X_{CO₂}$ - mixing ratio of CO₂ in dry air


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Higher CO$_2$ and Lower pH Will Also Affect Continental Shelf Ecosystems

Subsurface areas of low O$_2$ may also be areas of high CO$_2$ / low pH due to cumulative effect of respiration / remineralization of organic particulates by bacteria.

In *aerobic* conditions:

<table>
<thead>
<tr>
<th>Organic Matter 'OM'</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$<em>{106}$H$</em>{175}$O$<em>{42}$N$</em>{16}$P</td>
<td>150 O$_2$</td>
</tr>
</tbody>
</table>

$\Rightarrow$ 106 CO$_2$ + 16 HNO$_3$ + H$_3$PO$_4$ + 78 H$_2$O

*Equations from Sarmiento and Gruber, 2007*
In Anerobic Conditions

Respiration / remineralization of organic particulates by bacteria use first $\text{NO}_3^-$, releasing $\text{N}_2$ (and $\text{N}_2\text{O}$),

\[
\text{'OM'} + 104\ \text{HNO}_3 \\
\Rightarrow 106\ \text{CO}_2 + 60\ \text{N}_2 + \text{H}_3\text{PO}_4 + 138\ \text{H}_2\text{O}
\]

then use Mn and then use $\text{Fe}_2\text{O}_3$, then S, and then forming $\text{CH}_4$. 

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Adding CO$_2$ Increases Acidity

\[
\begin{align*}
\text{CO}_2 + \text{H}_2\text{O} & \rightleftharpoons \text{HCO}_3^- + \text{H}^+ \rightleftharpoons \text{CO}_3^{2-} + 2\text{H}^+
\end{align*}
\]

Left
- Surface pCO$_2$ increases with time

Right
- Surface pH decreases

\[\text{pH} = -\log [\text{H}^+]\]

IPCC AR4 WG1 Fig. 5.9
Due primarily to adding CO$_2$, not to the changing climate
"Undersaturation" of surface ocean in N. Pacific & Southern Ocean with respect to aragonite (CaCO₃) in 2099.

Organisms with CaCO₃ skeletal structures will tend to dissolve.

[from Orr et al., 2006 Nature, 437, 681]
Carbonate (CaCO$_3$) Pump - Coccolithophorid *Emiliania huxleyi*

Image courtesy of Southampton Oceanography Centre, UK
Pteropods are made up of aragonite $\text{CaCO}_3$

So What!

*Limacina helicina* are an important food source for juvenile North Pacific salmon and also eaten by mackerel, herring and cod.
High CO$_2$ $\Leftrightarrow$ Low pH

Feely et al., 2008, Science

pH of $\sim$7.75 is considered to be "corrosive" to animals

Line 5 off Northern California, Cruise in May – June 2007
Depth of 'Corrosive' pH < 7.75 Waters on Continental Shelf

Feely et al., 2008 Science
Lower $pH$ Threatens Corals, Pteropods & Coccolithophorids

Cold water corals on sill (at ~60m depth) in Knight Inlet BC
(courtesy Verena Tunnicliffe, U. Victoria)
How Fast Can Organisms Adapt & Evolve?

Our foodweb models need parameters that 'adapt/change' in response to changing ocean conditions:

• What is the species diversity within a functional group?
• What is the genetic diversity (plasticity) within a species?
• Is a century a long enough time for evolution via genetic mutations?
  - Requires a minimum of ~25 generations??

Which species will be threatened with extinction?

Thank-you