Present day CO$_2$ cycle in the coastal ocean
and
possible evolution under global change

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www.co2.ulg.ac.be
Present day CO$_2$ cycle in the coastal ocean
What would happen if we tried to fill the white pixels?
### Marginal seas (Fluxes in mol C m\(^{-2}\) yr\(^{-1}\))

<table>
<thead>
<tr>
<th>High latitude:</th>
<th>Temperate latitudes:</th>
<th>Sub-tropical &amp; tropical latitudes:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barents Sea</td>
<td>Baltic Sea</td>
<td>US South Atlantic Bight</td>
</tr>
<tr>
<td></td>
<td>North Sea</td>
<td>South China Sea</td>
</tr>
<tr>
<td>Bristol Bay</td>
<td>English Channel</td>
<td>Southwest Brazilian coast</td>
</tr>
<tr>
<td>Pryzdz Bay</td>
<td>Gulf of Biscay</td>
<td></td>
</tr>
<tr>
<td>Ross Sea</td>
<td>US Middle Atlantic Bight</td>
<td></td>
</tr>
<tr>
<td></td>
<td>East China Sea</td>
<td></td>
</tr>
</tbody>
</table>

#### Latitudinal variability in CO\(_2\) fluxes counts!

Latitudinal variability in surface area also counts!

Where does the coastal ocean start?

Arthur Chen  
Alberto Borges

C, N & P inputs by Kempe, Meybeck, Ludwig, etc…

Estuarine Plume (Outer estuary)

Limit of salt intrusion

Geographic limit of the coast (estuarine mouth)

Limit of tidal influence

Tidal Marsh

Tidal Flats

Saltmarsh

Inner estuary

CO$_2$ emission from 16 inner estuaries

<table>
<thead>
<tr>
<th>Latitude Type</th>
<th>Observations</th>
<th>CO$_2$ Flux (mol C m$^{-2}$ yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperate estuaries (12)</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>Tropical estuaries (4)</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>High latitude estuaries</td>
<td>?</td>
<td></td>
</tr>
</tbody>
</table>

Net Ecosystem Production \( \text{NEP} = \text{GPP} - \text{R} \)

\[ \langle \text{NEP} \rangle = -32.4 \text{ mol C m}^{-2} \text{ yr}^{-1} \ (n=65) = \text{strongly heterotrophic} \]

Riverine \( \text{CO}_2 \) input = 10\% of total \( \text{CO}_2 \) emission

**Borges et al. (2006)** ECSS 70(3), 375-387
Up-scaling

<table>
<thead>
<tr>
<th>Coastal</th>
<th>Open</th>
<th>Global</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.05 Pg C y⁻¹</td>
<td>-1.57 Pg C y⁻¹</td>
<td>-1.61 Pg C y⁻¹</td>
<td>↑ 3%</td>
</tr>
</tbody>
</table>

- Coastal: +0.18 Pg C y⁻¹
- Open: +0.71 Pg C y⁻¹
- Global: +0.90 Pg C y⁻¹

- Coastal: -0.13 Pg C y⁻¹
- Open: -2.06 Pg C y⁻¹
- Global: -2.19 Pg C y⁻¹

- Coastal: -0.10 Pg C y⁻¹
- Open: -0.22 Pg C y⁻¹
- Global: -0.33 Pg C y⁻¹

↑ 27%
↑ 6%
↑ 50%
Overall coastal ocean small \( \text{CO}_2 \) sink \((-0.05 \text{ PgC yr}^{-1})\)

Marginal seas strong sink \((-0.45 \text{ PgC yr}^{-1})\)

Near-shore systems (estuaries, mangroves, marshes, coral reefs, upwelling systems) strong sources \((+0.40 \text{ PgC yr}^{-1})\)

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>PgC yr(^{-1})</th>
<th>% total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estuaries</td>
<td>0.324</td>
<td>81.1</td>
</tr>
<tr>
<td>Marsh waters</td>
<td>0.036</td>
<td>9.0</td>
</tr>
<tr>
<td>Mangroves waters</td>
<td>0.033</td>
<td>8.2</td>
</tr>
<tr>
<td>Coral reefs</td>
<td>0.005</td>
<td>1.3</td>
</tr>
<tr>
<td>Upwelling</td>
<td>0.002</td>
<td>0.5</td>
</tr>
<tr>
<td>Nearshore systems</td>
<td>0.400</td>
<td>100</td>
</tr>
</tbody>
</table>

These are also the most vulnerable ecosystems to human pressure!

Strong feedbacks on increasing atmospheric CO\(_2\) ?

Possible evolution under global change
Multiple divers and responses

Atmospheric CO₂
Climate
Seawater CO₂
Temperature
Mixing, stratification
Circulation
Atmospheric deposition
N, P, Si inputs
C inputs

Ocean biota
Carbonate chemistry
Light
Nutrients
Stoichiometry (Si/C/N/P/Fe)
Rain ratio (CaCO₃/POC)
C-partitioning (POC-DOC-TEP)
Nutrient utilization efficiency

Carbon sinks & sources

Modified from Riebesell (2007) SOVOC meeting
Changes in stratification: Tasman shelf

40 transects obtained during 22 cruises from 1991 to 2003

Borges et al. (2007) in prep.
Changes in stratification: Tasman shelf

Monthly anomalies: $X' = X_{\text{obs}} - <X>_{\text{monthly}}$

$r^2 = 0.61$  
$r^2 = 0.77$

Borges et al. (2007) in prep.
Changes in stratification: Tasman shelf

Increasing mixing

- Enhanced DIC input by vertical mixing
- Lower DIC input by vertical mixing
- Enhanced primary production
- Lower primary production

SST anomaly (°C)

pCO$_2$@14°C anomaly (µatm)

Increasing stratification

Borges et al. (2007) in prep.
Changes in stratification: Tasman shelf

1982-2005 mean of daily $u_{10}$

$F$ anomaly (mmol m$^{-2}$ d$^{-1}$) vs. SST anomaly (°C)

↑ of 2°C in SST for 2100 at these latitudes from Hirst (1999) using IPCC "business-as-usual" IS92a radiative forcing scenario

⇒ $CO_2$ sink -6.4 → -8.7 mmolC m$^{-2}$ d$^{-1}$ (~36% increase in $CO_2$ sink, strong negative feedback)

increase of $CO_2$ sink

increase of SST
Changes in coastal upwelling

Atmospheric CO₂ → Climate

Climate → Temperature

Temperature → Mixing, stratification

Mixing, stratification → Circulation

Circulation → Atmospheric deposition

Atmospheric deposition → N, P, Si inputs

N, P, Si inputs → C inputs

C inputs → Eutrophication

Eutrophication → Nutrient & C inputs regulation

Nutrient & C inputs regulation → Changes of hydrological cycle

Seawater CO₂ → Carbonate chemistry

Carbonate chemistry → Temperature

Temperature → Mixing, stratification

Mixing, stratification → Light

Light → Nutrients

Nutrients → Ocean biota

Ocean biota → Stoichiometry (Si/C/N/P/Fe)

Stoichiometry (Si/C/N/P/Fe) → Rain ratio (CaCO₃/POC)

Rain ratio (CaCO₃/POC) → C-partitioning (POC-DOC-TEP)

C-partitioning (POC-DOC-TEP) → Nutrient utilization efficiency

Nutrient utilization efficiency → Carbon sinks & sources
Changes in coastal upwelling

California upwelling system

50% reduction of wind stress

⇒ ↓ 50% in NPP
⇒ ↓ 75% in grazing
⇒ ↓ 50% in export pdt
⇒ ↓ 50% in CO₂ source
Mainly related to the ↓ vertical input of DIC and ↓ of k

Plattner et al. (2005) SCOR conference "The ocean in a high CO₂ world"
Could CO$_2$-induced land-cover feedbacks alter near-shore upwelling regimes?

Noah S. Diffenbaugh*, Mark A. Snyder, and Lisa C. Sloan

Department of Earth Sciences, University of California, 1156 High Street, Santa Cruz, CA 95064

Edited by Susan Solomon, National Oceanic and Atmospheric Administration, Boulder, CO, and approved October 31, 2003 (received for review September 8, 2003)

But climate change → increase in coastal upwelling
→ increase in CO$_2$ emission (?)
→ positive feedback on increasing atmospheric CO$_2$ (?)
Temperature change on the Arctic Ocean

Atmospheric CO₂

Climate

Temperature → Mixing, stratification → Circulation

Seawater CO₂ → Carbonate chemistry

Nutrient & C inputs regulation
Changes of hydrological cycle

Atmospheric deposition

N, P, Si inputs → C inputs

Nutrients

Ocean biota

Stoichiometry (Si/C/N/P/Fe)

Rain ratio (CaCO₃/POC)

C-partitioning (POC-DOC-TEP)

Nutrient utilization efficiency

Carbon sinks & sources
Temperature change on the Arctic Ocean

- Satellite observations (1979-2005)
- Mean change for all IPCC models
- Change in Bergen Climate Model
- Spread of the most likely scenarios
- Spread of all IPCC models

Olsen et al. (2007) SOVOC meeting
Arctic Ocean sink for CO$_2$ has tripled over the last 3 decades (24 Tg yr$^{-1}$ to 66 Tg yr$^{-1}$) due to sea-ice retreat.

Future sea-ice melting enhancing air-to-sea CO$_2$ flux by 28% per decade.

Temperature change → Ecological regime shifts in the Arctic? e.g. occurrence of coccolithophorid blooms in the Bering Sea from 1997 onwards.

9400 PgC organic C buried in the 100 m of tundra and taiga

Permafrost thawing
Coastal Erosion
Increased precipitation

\{ \text{can mobilise organic carbon} \}

increase CO\textsubscript{2} source of near-shore zones

Semiletov et al. (2007) JMS 66: 204–226
Ocean acidification: buffer factor

Atmospheric CO₂

Climate

Seawater CO₂

Temperature

Mixing, stratification

Circulation

Atmospheric deposition

Nutrient & C inputs regulation

Changes of hydrological cycle

Carbonate chemistry

Stoichiometry (Si/C/N/P/Fe)

Rain ratio (CaCO₃/POC)

C-partitioning (POC-DOC-TEP)

Nutrient utilization efficiency

Ocean biota

Carbon sinks & sources

Eutrophication

N, P, Si inputs

C inputs
Penetration of CO$_2$ into the oceans
⇒ decrease of the buffer capacity of seawater
⇒ reduces the uptake of anthropogenic CO$_2$

Sarmiento et al. (1998) Nature 393:245-249
Ocean acidification: buffer factor

Thomas et al., Tuesday 18th 14:00
Ocean acidification: effects on biota

Atmospheric CO₂

Climate

Seawater CO₂

Carbonate chemistry

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Carbon sinks & sources
Calcification:

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

Increase in CO\(_2\) → decrease of calcification → negative feedback

**Fig. 2.** Seawater pH and the dissolved carbon dioxide (CO\(_2\)) and carbonate ion (CO\(_3^{2-}\)) concentrations in the surface layer of the ocean assuming a “business as usual” (1992a) anthropogenic CO\(_2\) emission scenario (Houghton et al. 1995). Dashed lines represent the predicted changes in carbonate chemistry if CO\(_2\) emissions are reduced according to the Kyoto Protocol (modified after Wolf-Gladrow et al. 1999).

Rost & Riebesell (2004) in Coccolithophores. From Molecular Processes to Global Impact
Ocean acidification: calcification

Based on Suzuki & Kawahata (2003) and Bates (2002)

\[ \text{pCO}_2 \text{ coral reef} - \text{pCO}_2 \text{ ocean (ppm)} \]

<table>
<thead>
<tr>
<th>Location</th>
<th>Delta (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Christmas Island</td>
<td>-80</td>
</tr>
<tr>
<td>Shiraho reef</td>
<td>7</td>
</tr>
<tr>
<td>Fanning atoll</td>
<td>30</td>
</tr>
<tr>
<td>Canton atoll</td>
<td>15</td>
</tr>
<tr>
<td>Palau reef</td>
<td>46</td>
</tr>
<tr>
<td>Majuro atoll</td>
<td>23</td>
</tr>
<tr>
<td>South Male atoll</td>
<td>6</td>
</tr>
<tr>
<td>Northern Great Barrier Reef</td>
<td>29</td>
</tr>
<tr>
<td>Southern Great Barrier Reef</td>
<td>12</td>
</tr>
<tr>
<td>Hog reef (1994)</td>
<td>26</td>
</tr>
<tr>
<td>Hog reef (1995)</td>
<td>16</td>
</tr>
<tr>
<td>Hog reef (1996)</td>
<td>16</td>
</tr>
<tr>
<td>Average</td>
<td>12</td>
</tr>
</tbody>
</table>
Ocean acidification: calcification

Coccolithophorid bloom in the Gulf of Biscay (June 2006)

LEG 1

LEG 2

Suykens & Borges (unpubl.) PEACE project
Ocean acidification: calcification

Coccolithophorid bloom in the Gulf of Biscay (June 2006)

\[ r^2 = 0.84 \]

Suykens & Borges (unpubl.) PEACE project
↓ 22% of coral reef calcification for 2100 (“business-as-usual” IS92a IPCC) (Gattuso et al. 1999)

Present day coral reef calcification 0.072 PgC yr⁻¹ (Gattuso et al. 1998)

⇒ feedback of 0.009 PgC yr⁻¹ (with $\Psi = 0.6$ from Frankignoule et al. 1994)

Small compared to the overall sink of -0.45 PgC yr⁻¹ of marginal seas
Global pelagic calcification 0.6 – 1.6 PgC yr\(^{-1}\) (Balch et al. 2007)

Coastal pelagic calcification 0.1 – 0.3 PgC yr\(^{-1}\) (based on Balch et al. 2005)

Doubling of atmospheric CO\(_2\) for 2100 (“business-as-usual” IS92a IPCC scenario)

⇒ decrease of coastal pelagic calcification of 0.006 – 0.016 PgC yr\(^{-1}\) (based on Gehlen et al. 2007)

⇒ feedback of 0.004 – 0.010 PgC yr\(^{-1}\) (with \(\Psi = 0.6\) from Frankignoulle et al. 1994)

Small compared to the overall sink of -0.45 PgC yr\(^{-1}\) of marginal seas
Fig. 5. Photosynthesis of phytoplankton species differs with respect to CO₂ sensitivity: While most species (here *Skeletonema costatum* and *Phaeocystis globosa*) are at or close to CO₂ saturation at present day CO₂ levels (8–20 μmol L⁻¹), coccolithophores such as *E. huxleyi* have comparatively low affinities for inorganic carbon and appear to be carbon-limited in today's ocean. This raises the possibility that coccolithophores may benefit directly from the present increase in atmospheric CO₂. The range in half-saturation concentrations (K₁/₂; in μmol L⁻¹) for photosynthesis shown here reflects the degree of regulation as a function of pCO₂ during growth (according to Rost et al. 2003). Highest apparent affinities for CO₂ were generally observed in cells which were grown under low pCO₂.

Rost & Riebesell (2004) in *Coccolithophores. From Molecular Processes to Global Impact*
Nutrient and C inputs

Atmospheric CO₂

Climate

Seawater CO₂

Temperature

Mixing, stratification

Circulation

Light

Carbonate chemistry

Nutrient utilization efficiency

Nutrient and C inputs regulation
Changes of hydrological cycle

Eutrophication

Atmospheric deposition

N, P, Si inputs

C inputs

Nutrients

Ocean biota

Stoichiometry (Si/C/N/P/Fe)

Rain ratio (CaCO₃/POC)

C-partitioning (POC-DOC-TEP)

Carbon sinks & sources

Seawater CO₂ → Temperature → Mixing, stratification → Circulation → Climate → Atmospheric CO₂

Seawater CO₂ → Carbonate chemistry

Nutrient and C inputs

Atmospheric CO₂ → Atmospheric deposition → Nutrients

Nutrients → N, P, Si inputs → C inputs

Nutrient and C inputs regulation → Changes of hydrological cycle

Eutrophication → Nutrient and C inputs regulation

Carbon sinks & sources
**Figure 5.** Riverine Nr export to the coastal zone (Tg N yr\(^{-1}\)) in the past (1860 Left bar), present (1990 Center bar) and future (2050 Right bar). Dry and inland watershed regions that do not transmit to coastal areas are shown in gray.

**Galloway et al. (2004) Biogeochemistry 70:153-266**
Table 1. Global Trends in Ocean Chlorophyll 1998–2003a

<table>
<thead>
<tr>
<th>Region</th>
<th>N</th>
<th>Slope</th>
<th>Intercept</th>
<th>Error</th>
<th>Trend</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>560247</td>
<td>0.00261</td>
<td>−0.007</td>
<td>±0.002</td>
<td>+4.13%</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td>Coastal</td>
<td>51979</td>
<td>0.03687</td>
<td>−0.092</td>
<td>±0.033</td>
<td>+10.35%</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td>Open Ocean</td>
<td>530579</td>
<td>0.00040</td>
<td>−0.001</td>
<td>±0.003</td>
<td>+0.90%</td>
<td>NS</td>
</tr>
</tbody>
</table>

aNS indicates not statistically significant at the 95% confidence level. N is the maximum number of values in a given year, error represents the standard error of the estimate, and trend is reported as percent change over 6 years.


Maximum phytoplankton biomass

mgC m\(^{-3}\)


Phaeocystis

Summer diatom

Spring diatom

Lancelot et al. (2007) JMS 64:216-228
Gypens & Lancelot, Thursday 20\(^{th}\) 09:30
Nutrient and C inputs

Belgian coastal zone (North Sea)

Nutrient inputs (kT yr⁻¹)

Air-sea CO₂ flux (mmol C m⁻² yr⁻¹)

Organic carbon inputs (T yr⁻¹)

NEP (mmol C m⁻² yr⁻¹)

Gypens & Lancelot (in prep.)
**Summary**

Atmospheric CO₂

Climate

Seawater CO₂

Temperature

Mixing, stratification

Circulation

Atmospheric deposition

Nutrients

Ocean biota

Carbonate chemistry

Light

Nutrient utilization efficiency

Stoichiometry (Si/C/N/P/Fe)

Rain ratio (CaCO₃/POC)

C-partitioning (POC-DOC-TEP)

Nutrient & C inputs regulation

Changes of hydrological cycle

Carbon sinks & sources

Carbon sinks & sources

Nutrient & C inputs regulation

Changes of hydrological cycle
Summary?

1 box model:
- Increase of CO$_2$ sink in the coastal ocean mainly due to net ecosystem metabolism (NEM) due to increase of nutrient delivery.
- Decrease of calcification and increase of diagenetic CaCO$_3$ dissolution have a minor role.

Mackenzie et al. (2004) Biogeosciences 1:11–32
1. More CO₂ observatories (moorings, repeat tracks, repeat stations, ...)

2. Adapted typologies for scaling CO₂ fluxes.

3. Several on-going 3D models (California current, North Sea, EU scale, North America scale ...), but can we go global? (i.e. enough knowledge? computing power?)
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Are Olsen
Ulf Riebesell