The uptake, transport, and storage of anthropogenic CO$_2$ by the ocean

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THE ANTHROPOGENIC PERTURBATION
IN THE CONTEXT OF THE NATURAL C CYCLE

Fossil Fuel & Cement Emissions
Land-Use Change & Land sink
Respiration & Fires

Volcanism

<0.1
5.9
1.2
1.8
57
55.6
NPP

Plants & Soil
[6850 - 124 + 65]

Atmosphere
[590 + 161]

70
70.6
21.9
20

Weathering
River outgassing
River export
River fluxes
0.2
0.9
0.4
1.1

Ocean
[38,000 + 110]

0.5

Fossil Organic Carbon
>6000

Rock Carbonates

Geological Reservoirs

Units are Pg C for reservoirs and Pg C/yr for fluxes

Sabine et al. (2003)
SCOPE/GCP
Outline

• Introduction

• Air-sea CO\textsubscript{2} fluxes or the problem of separating the natural from the anthropogenic fluxes

• The importance of the ocean as a sink for anthropogenic CO\textsubscript{2}

• How do we obtain fluxes from storage? An inverse approach

• On the role of anthropogenic CO\textsubscript{2} transport

• What do the OCMIP-2 models find?

• Summary and Outlook
Globally integrated flux: 2.2 PgC yr$^{-1}$
Determination of anthropogenic CO$_2$

We follow the $\Delta C^*$ method of Gruber et al. [1996] to separate the anthropogenic CO$_2$ signal from the natural variability in DIC. This requires the removal of

i) the change in DIC that incurred since the water left the surface ocean due to remineralization of organic matter and dissolution of CaCO$_3$ ($\Delta$DIC$_{bio}$), and

ii) a concentration, DIC$_{sfc-pi}$, that reflects the DIC content a water parcel had at the outcrop in pre-industrial times,

Thus,

$$\Delta C_{ant} = DIC - \Delta$DIC$_{bio} -$DIC$_{sfc-pi}$$

Assumptions:

• natural carbon cycle has remained in steady-state
ANTHROPOGENIC CO₂ INVENTORIES

ZONAL MEAN

ZONAL INTEGRAL

- Atlantic (Gruber, 1998)
- Indian (Sabine et al., 1999)
- Pacific (Sabine et al., 2002)
**Anthropogenic CO$_2$ Inventories in ~1994**

<table>
<thead>
<tr>
<th></th>
<th>Atlantic$^a$ [Pg C]</th>
<th>Pacific$^b$ [Pg C]</th>
<th>Indian$^c$ [Pg C]</th>
<th>Global Inventory [Pg C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern hemisphere</td>
<td>19</td>
<td>28</td>
<td>17</td>
<td>62</td>
</tr>
<tr>
<td>Northern hemisphere</td>
<td>28</td>
<td>17</td>
<td>3</td>
<td>48</td>
</tr>
<tr>
<td>Global</td>
<td>47 (42%)</td>
<td>45 (40%)</td>
<td>20 (18%)</td>
<td>112</td>
</tr>
</tbody>
</table>

- $^a$ Lee et al. (submitted)
- $^b$ Sabine et al. (2002)
- $^c$ Sabine et al. (1999)

See also poster by Sabine et al.
## Anthropogenic CO$_2$ Budget 1800 to 1994

### CO$_2$ Sources

<table>
<thead>
<tr>
<th>Source Description</th>
<th>[Pg C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Emissions from fossil fuel and cement production$^a$</td>
<td>244</td>
</tr>
<tr>
<td>(2) Net emissions from changes in land-use$^b$</td>
<td>110</td>
</tr>
<tr>
<td>(3) Total anthropogenic emissions = (1) + (2)</td>
<td>354</td>
</tr>
</tbody>
</table>

### Partitioning among reservoirs

<table>
<thead>
<tr>
<th>Reservoir Description</th>
<th>[Pg C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4) Storage in the atmosphere$^c$</td>
<td>159</td>
</tr>
<tr>
<td>(5) Storage in the ocean$^d$</td>
<td>112</td>
</tr>
<tr>
<td>(6) Terrestrial sinks = [(1)+(2)]-[(4)+(5)]</td>
<td>83</td>
</tr>
</tbody>
</table>

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$a$: From *Marland and Boden* [1997] (updated 2002)

$b$: From Houghton [1997]

$c$: Calculated from change in atmospheric $pCO_2$ (1800: 284ppm; 1994: 359 ppm)

$d$: Based on estimates of *Sabine et al.* [1999], *Sabine et al.* [2002] and *Lee et al.* (submitted)
Ocean Inversion method

- The ocean is divided into n regions (n = 13)
Ocean Inversion method (cont.)

- **Basis functions:**

  In an OGCM, time-varying fluxes of dye tracers ($\Phi$) of the form
  
  $$\Phi(t) = \Phi(t_o) \times (pCO_2(t) - pCO_2(t_o))$$

  are imposed, and the model is run forward in time.

- **By sampling the modeled distribution at the observation stations, $\chi$, we obtain a transport matrix ($A_{OGCM}$) that relates the fluxes to the distribution:**

  $$\chi_{OGCM} = A_{OGCM} \times \Phi.$$  

- **Modeled distributions are then substituted with the observed ones and the matrix $A$ is inverted to get an estimate of the surface fluxes ($\Phi_{est}$):**

  $$\Phi_{est} = (A_{OGCM})^{-1} \times \chi_{obs}$$
AIR-SEA FLUXES OF ANTHROPOGENIC CO$_2$

26% of area
42% of uptake
25% of storage

Anthropogenic CO$_2$ Flux for 1990: 1.8 PgC/yr

Gloor et al. (2003)
Gruber et al. (in prep.)
SR3: ANTHROPOGENIC CO₂ AND pCFC-12

Colors: anthropogenic CO₂ (mmol kg⁻¹)
Contour lines = pCFC-12 (patm)

Sabine et al. (2002)
ANTHROPOGENIC CO\textsubscript{2} FLUXES, STORAGE AND TRANSPORT

Green numbers: Storage [Pg C]
Red numbers: Air-Sea Fluxes in [Pg C]
Blue numbers: Ocean Transport in [Pg C]

preliminary results: Gruber et al. [in prep.]
ANTHROPOGENIC AIR-SEA CO₂-FLUXES

CO₂ Fluxes [Pg/yr]

-0.60  -0.50  -0.40  -0.30  -0.20  -0.10  0.00  0.10  0.20

Southern Ocean  SPol S Atl  SPol S Ind & Pac  Temp S Atl  Temp S Pac  Temp S Indian  Eq Atl  Eq Pac  Eq Indian  Temp N Atl  Temp N Pac  N N Ati  N N Pac


Positive: Flux out of ocean

Anthropogenic Fluxes

Gloor et al. (2003)
Gruber et al. (in prep.)
OCMIP-2: ANTHROPOGENIC CO₂ FLUXES, STORAGE, AND TRANSPORT

J. Orr and OCMIP-2 (pers. comm)
### OCMIP-2: ANTHROPOGENIC CO₂ UPTAKE

<table>
<thead>
<tr>
<th>Model</th>
<th>Uptake Rate (PgC/yr)</th>
<th>Inventory (Pg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRINCE</td>
<td>1.65</td>
<td>1.98</td>
</tr>
<tr>
<td>IPSL.DM1 (HOR)</td>
<td>1.67</td>
<td>1.98</td>
</tr>
<tr>
<td>LLNL</td>
<td>1.78</td>
<td>2.08</td>
</tr>
<tr>
<td>CSIRO</td>
<td>1.78</td>
<td>2.11</td>
</tr>
<tr>
<td>MIT</td>
<td>1.91</td>
<td>2.29</td>
</tr>
<tr>
<td>NCAR</td>
<td>1.93</td>
<td>2.30</td>
</tr>
<tr>
<td>PRINC2</td>
<td>1.93</td>
<td>2.32</td>
</tr>
<tr>
<td>IPSL (GM)</td>
<td>1.97</td>
<td>2.36</td>
</tr>
<tr>
<td>MPIM</td>
<td>2.01</td>
<td>2.43</td>
</tr>
<tr>
<td>SOC</td>
<td>2.01</td>
<td>2.39</td>
</tr>
<tr>
<td>IPSL.DM1 (GM)</td>
<td>2.03</td>
<td>2.43</td>
</tr>
<tr>
<td>IGCR</td>
<td>2.05</td>
<td>2.47</td>
</tr>
<tr>
<td>PIUB</td>
<td>2.11</td>
<td>2.52</td>
</tr>
<tr>
<td>AWI</td>
<td>2.14</td>
<td>2.58</td>
</tr>
<tr>
<td>NERSC</td>
<td>2.38</td>
<td>2.84</td>
</tr>
<tr>
<td>UL</td>
<td>2.51</td>
<td>3.04</td>
</tr>
</tbody>
</table>

|               | Mean                  | Range           |               |
|---------------|-----------------------|-----------------|
| Uptake Rate   | 1.99 +/- 0.23         | 1.65 - 2.51     | 102 - 146     |
| Inventory     | 2.38 +/- 0.29         | 1.98 - 3.04     |               |

"DATA RECONSTRUCTION**  104 +/- 20

*Sabine et al. (pers. comm)

J. Orr and OCMIP-2 (pers. comm.)

Models tend to be on the high side relative to data reconstruction.
OCMIP-2: FUTURE ANTHROPOGENIC CO₂ UPTAKE

Range for 1990s: +/- 22%

IS92a: Range for 2100: +/- 33%

S650: Range for 2100: +/- 30%

J. Orr and OCMIP-2 (pers. comm)
Summary

- By taking up about a third of the total emissions, the ocean has been the largest sink for anthropogenic CO$_2$ during the anthropocene.

- The Southern Ocean south of 36°S constitutes one of the most important sink regions, but much of this anthropogenic CO$_2$ is not stored there, but transported northward with Sub-Antarctic Mode Water.

- Models show a similar pattern, but they differ widely in the magnitude of their Southern Ocean uptake. This has large implications for the future uptake of anthropogenic CO$_2$ and thus for the evolution of climate.
Outlook and Challenges

While we have made substantial advances in our understanding of the role of the ocean as a sink for anthropogenic CO$_2$, there remain a number of important challenges.

- The magnitude and role of natural variability
- The response to climate change and other ant. perturbations

These problems need to be addressed by a combination of long-term monitoring of the ocean and the development of a hierarchy of models that are based on a mechanistic understanding of the relevant processes.
The End.