Uptake, transport, and storage of anthropogenic CO\textsubscript{2} by the ocean: implications for the global carbon cycle

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ATMOSPHERIC CO$_2$ VARIATIONS SINCE 1000AD

Mauna Loa Observatory, Hawaii
monthly averaged concentration

Sarmiento & Gruber (2002)
THE GLOBAL CARBON CYCLE

Reservoir sizes in PgC

Surface Ocean
900

Surface sediment
150

Intermediate & Deep Ocean
37,100

Soil & Detritus
2300

Marine Biota
3

Vegetation
900

Atmosphere
590

Fossil Fuels
3700

Weathering
0.2

Rivers
0.8

NPP & Respiration
59.6

Weathering
0.2

Weathering
0.4

70.6

0.8

70

50

39

11

Fluxes and Rates in PgC/yr
Reservoir sizes in PgC

Fluxes and Rates in PgC/yr

Surface Ocean
- 900
+ 18

Intermediate & Deep Ocean
- 37,100
+ 100

Marine Biota
- 3

Rivers
- 50
+ 39

Vegetation
- 2300
+ 65
- 124

Atmosphere
- 590
+ 161

NPP & Respiration
- 59.6
+ 60

Land Use Change
- 70.6
+ 70
+ 21.9
+ 20

Fossil Fuels
- 3700
- 220

Weathering
- 0.8
+ 0.2

Soil & Detritus
- 2300
+ 65
- 124

Weathering
- 0.2
+ 0.2

Sarmiento & Gruber (2002)
Outline

• Introduction
• Air-sea CO$_2$ fluxes or the problem of separating the anthropogenic from the natural component
• The importance of the ocean as a sink for ant. CO$_2$
• How do we obtain fluxes from storage? An inverse approach
• On the relationship between transient tracers and anthropogenic CO$_2$
• Summary and outlook
Globally integrated flux into the ocean: 2.2 PgC yr$^{-1}$
Pre-industrial CO$_2$ fluxes

Anthropogenic CO$_2$ fluxes
Determination of the anthropogenic $\text{CO}_2$ signal

We follow the method of Gruber et al. [1996] to separate the anthropogenic $\text{CO}_2$ signal from the large natural variability in oceanic DIC. This method requires the removal of

(i) the change in dissolved inorganic carbon (C) that incurred since the water left the surface ocean due to remineralization of organic matter and dissolution of $\text{CaCO}_3$ ($\Delta C_{\text{bio}}$), and

(ii) of a concentration $C_{\text{sfc-pi}}$ that reflects the DIC content a water parcel had at the outcrop in pre-industrial times

Thus,

$$\Delta C_{\text{ant}} = C - \Delta C_{\text{bio}} - C_{\text{sfc-pi}}$$

• Assumption:
Natural carbon cycle has remained in steady-state.
ANTHROPOGENIC CO$_2$ INVENTORIES

large storage in subtropical gyres!
## Anthropogenic CO$_2$ Inventories during WOCE era

<table>
<thead>
<tr>
<th></th>
<th>Atlantic Inventory$^\dagger$ [Pg C]</th>
<th>Pacific Inventory$^\ddagger$ [Pg C]</th>
<th>Indian Inventory$^\star$ [Pg C]</th>
<th>Global Inventory [Pg C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern Hemisphere</td>
<td>17</td>
<td>28</td>
<td>17</td>
<td>62 (56%)</td>
</tr>
<tr>
<td>Northern Hemisphere</td>
<td>28</td>
<td>17</td>
<td>3</td>
<td>48 (44%)</td>
</tr>
<tr>
<td>Total</td>
<td>45 (41%)</td>
<td>45 (41%)</td>
<td>20 (18%)</td>
<td>110</td>
</tr>
</tbody>
</table>

$^\dagger$ Lee et al. (in prep.)

$^\ddagger$ Sabine et al. (2002)

$^\star$ Sabine et al. (1999)
## Anthropogenic CO\textsubscript{2} Budget (1800 to 1990)

<table>
<thead>
<tr>
<th>CO\textsubscript{2} sources</th>
<th>Gt C</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Emissions from fossil fuel and cement production \textsuperscript{a}</td>
<td>230</td>
</tr>
<tr>
<td>(2) Net emissions from changes in land-use \textsuperscript{b}</td>
<td>110</td>
</tr>
<tr>
<td>(3) Total anthropogenic CO\textsubscript{2} emissions = (1) + (2)</td>
<td>340</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO\textsubscript{2} partitioning amongst reservoirs</th>
<th>Gt C</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4) Storage in the atmosphere \textsuperscript{c}</td>
<td>145</td>
</tr>
<tr>
<td>(5) Ocean uptake \textsuperscript{d}</td>
<td>107</td>
</tr>
<tr>
<td>(6) Terrestrial sinks = [(1)+(2)]-[(4)+(5)]</td>
<td>82</td>
</tr>
</tbody>
</table>

\textsuperscript{a}: From Marland and Boden [1997]
\textsuperscript{b}: From Houghton [1997]
\textsuperscript{c}: Calculated from change in atmospheric pCO\textsubscript{2}
\textsuperscript{d}: Based on estimates of Sabine et al. [1999], Sabine et al. [2002] and Lee et al. (in prep.), adjusted to 1990
Principle of Oceanic Inversion

- The ocean surface is partitioned into $n$ regions ($n=13$).
Principle of Oceanic Inversion (Cont.)

- Basis functions:
  In a OGCM, time-varying fluxes of dye tracers ($\Phi(t)$) of the form

$$\vec{\Phi}(t) = \Phi(t = 0) \ast (p\text{CO}_2(t) - p\text{CO}_2(t = 0))$$

are imposed in each of the $n = 13$ regions, and the model is run forward in time.
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By sampling the modeled distribution at the observations stations, we obtain a transport matrix $A_{OGCM}$ that relates the fluxes to the distribution,

$$\vec{\chi}_{OGCM} = A_{OGCM} \vec{\Phi}.$$
Principle of Oceanic Inversion (Cont.)

- **Basis functions:**
  In a OGCM, time-varying fluxes of dye tracers \( \Phi(t) \) of the form
  \[
  \vec{\Phi}(t) = \vec{\Phi}(t = 0) * (p\text{CO}_2(t) - p\text{CO}_2(t = 0))
  \]
  are imposed in each of the \( n = 13 \) regions, and the model is run forward in time.

- By sampling the modeled distribution at the observations stations, we obtain a transport matrix \( A_{\text{OGCM}} \) that relates the fluxes to the distribution,
  \[
  \vec{\chi}_{\text{OGCM}} = A_{\text{OGCM}} \vec{\Phi}.
  \]

- Modeled distributions are then substituted with observed ones and the matrix \( A \) is inverted to get an estimate of the surface fluxes \( \vec{\Phi}_{\text{est}} \):
  \[
  \vec{\Phi}_{\text{est}} = A_{\text{OGCM}}^{-1} \vec{\chi}_{\text{obs}}.
  \]
Anthropogenic CO$_2$ Flux for 1990: 1.8 PgC/yr

Gloor et al. (in press)
Gruber et al. (in prep.)

26% of area
42% of uptake
25% of storage
ANTHROPOGENIC CO₂ FLUXES, STORAGE AND TRANSPORT

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

preliminary results: Gruber et al. [in prep.]
SR3: ANTHROPOGENIC CO$_2$ AND pCFC-12

Colors: anthropogenic CO$_2$ (mmol kg$^{-1}$)

Sabine et al. (2002)
ANTHROPOGENIC AIR-SEA CO$_2$-FLUXES

**Anthropogenic Fluxes**

- Positive: Flux out of ocean

Gloor et al. (in press), Gruber et al. (in prep.)
OCMIP-2: ANTHROPOGENIC CO$_2$ 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**  
1.99 +/- 0.23  
2.38 +/- 0.29  
121 +/- 12

**Range**  
1.65-2.51  
1.98-3.04  
102-146

"DATA RECONSTRUCTION"  
107 +/- 20

* Sabine et al. (pers. comm)

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

RANGE FOR 1990s: +/- 22%

IS92a: RANGE FOR 2100: +/- 33%

S650: RANGE FOR 2100: +/- 30%
OCMIP-2: OCEANIC UPTAKE OF ANT. CO2 AND CFC-11

N. Gruber and OCMIP-2
OCMIP-2: ANTHROPOGENIC CO₂ FLUX
VERSUS CFC-11 INVENTORY

Observational estimate: J. Bullister, pers. comm.

δCO₂ vs. CFC–11

\[
y = 0.2628(x) + 0.7631
\]

\[r^2 = 0.82\]

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

- Reconstructions of the oceanic inventory of anthropogenic CO$_2$ as well as ocean models indicate that the ocean has been the **largest sink for anthropogenic CO$_2$** during the anthropocene (taking up about a third of the total anthropogenic CO$_2$ emissions).
Summary

- Reconstructions of the oceanic inventory of anthropogenic CO$_2$ as well as ocean models indicate that the ocean has been the \textit{the largest sink for anthropogenic CO$_2$} during the anthropocene (taking up about a third of the total anthropogenic CO$_2$ emissions).

- We find on the basis of our inversion that the \textit{Southern Ocean} south of 36°S constitutes one of the \textit{most important sink regions}, but most of this anthropogenic CO$_2$ is \textit{transported northward and not stored there}. 

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- 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$_2$ even in the absence of climate change.
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- **Transient and anthropogenic tracers** are very helpful in better constraining the oceanic sink for ant. CO$_2$. 
Outlook and challenges

• While we have made great advances in our understanding of the role of the oceans as a sink for anthropogenic CO$_2$, there are a number of outstanding and challenging issues:
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- Both require a detailed understanding not only of the anthropogenic CO$_2$ perturbation, but also of the natural carbon cycle, i.e. the interaction of biological and solubility pumps.
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- Both require a detailed understanding not only of the anthropogenic CO$_2$ perturbation, but also of the natural carbon cycle, i.e. the interaction of biological and solubility pumps.

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

- Chris Sabine and the GLODAP members
- Jim Orr and the OCMIP members
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- all the people that made the WOCE/JGOFS/OACES cruises a success