The oceanic sink for anthropogenic CO$_2$: Combining observations with models

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Outline

1. The problem: From concentrations to fluxes
2. Forward Modeling: OCMIP-2
3. Inverse Modeling: First steps
4. Summary and Outlook
Figure 4

ANTHROPOGENIC CO$_2$ [µmol/kg]

Distance [km]

Depth [m]

Depth [m]
FORWARD AND INVERSE MODELING

**FORWARD MODELING**

- Boundary conditions
- Initial conditions
- Model (e.g. General Ocean Circulation Model)
- Tracer distribution

**INVERSE MODELING**

- Tracer distribution
- Inverse model (e.g. Adjoint Model of OGCM)
- Boundary conditions

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*e.g.* surface fluxes
OCMIP-2: ANTHROPOGENIC AIR-SEA CO$_2$-FLUXES

Positive: Flux out of ocean

Anthropogenic Fluxes

J. Orr and OCMIP-2
OCMIP-2: ANTHROPOGENIC CO₂ FLUXES, STORAGE, AND TRANSPORT

J. Orr and OCMIP-2 (pers. comm)
OCMIP-2: Anthropogenic DIC along West Atlantic Track
(North: TTO-1982; South: SAVE-1989)
## OCMIP-2: ANTHROPOGENIC CO₂ UPTAKE

<table>
<thead>
<tr>
<th>Model</th>
<th>Uptake Rate (PgC/yr) 1980-1989</th>
<th>Uptake Rate (PgC/yr) 1990-1999 (S650)</th>
<th>Inventory (Pg) 1765-1990</th>
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<tbody>
<tr>
<td>PRINCE</td>
<td>1.65</td>
<td>1.98</td>
<td>102</td>
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<tr>
<td>IPSL.DM1 (HOR)</td>
<td>1.67</td>
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<td>LLNL</td>
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<td>NCAR</td>
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<td>SOC</td>
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<td>IPSL.DM1 (GM)</td>
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<tr>
<td>UL</td>
<td>2.51</td>
<td>3.04</td>
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</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

"OBSERVATIONS**" 103 ± 20

* Sabine et al. (pers. comm)

J. Orr and OCMIP-2 (pers.comm.)
OCMIP-2: ANTHROPOGENIC CO₂ FLUX
VERSUS CFC-11 INVENTORY AND VERSUS NATURAL C14

\[ \delta \text{CO}_2 \text{ vs. CFC-11} \]

\[ y = 0.2828(x) + 0.7631 \]

\[ r^2 = 0.82 \]

\[ \delta \text{CO}_2 \text{ vs. Natural } \Delta^{14}\text{C} \]

\[ y = 0.004427(x) + 2.865 \]

\[ r^2 = 0.57 \]

J. Orr and OCMIP-2 (pers.comm.)
Principle of Oceanic Inversion

• The ocean surface is partitioned into \( n \) regions.

• Basis functions

  – *Anthropogenic CO\(_2\)* Inversion

    In a OGCM, time-varying fluxes of dye tracers (\( \Phi \)) are imposed in each of the \( n \) regions, and the model is run forward in time, i.e. for \( \text{CO}_2(1750-2000) \)

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

• The model predictions of the dye concentrations are sampled at the observation stations and arranged as a vector \( \vec{\chi}_{\text{OGCM}} \). The model therefore provides us with a transport matrix \( A_{\text{OGCM}} \) that relates the fluxes to the distribution,

\[
\vec{\chi}_{\text{OGCM}} = A_{\text{OGCM}} \vec{\Phi}.
\]

• Modeled distributions at the observations stations are substituted with observed ones and the matrix \( A \) is inverted to get an estimate of the surface fluxes (\( \vec{\Phi}_{\text{est}} \)):

\[
\vec{\Phi}_{\text{est}} = A_{\text{OGCM}}^{-1} \vec{\chi}_{\text{obs}}.
\]
INVERSE AIR-SEA CO$_2$-FLUXES

Pre-industrial CO$_2$ flux
Anthropogenic CO$_2$ Flux
Total CO$_2$ Flux

Anthropogenic CO$_2$ Flux: 1.8 PgC yr$^{-1}$

Gloor et al. (submitted), Gruber et al. (in prep.)
ANTHROPOGENIC AIR-SEA CO₂-FLUXES

Gloor et al. (submitted), Gruber et al. (in prep.)
Summary and Outlook

• Despite fundamental differences between forward and inverse modeling of anthropogenic CO$_2$ fluxes, similar results emerge.

• Both methods indicate that the ocean south of 36°S takes up about 40% of the global anthropogenic CO$_2$. The second most important region for uptake are the tropics, followed by the North Atlantic.

• Substantial differences exist at more regional scales, with the Southern Ocean showing also the highest variations.

• Improvements need to made both on the modeling side as well as on the anthropogenic CO$_2$ reconstruction side.

• The challenge for the future consists in determining the anthropogenic CO$_2$ uptake in a changing ocean environment.