New observational constraints on the global ocean uptake of anthropogenic CO₂

Nicolas Gruber  ETH Zürich, Switzerland.

Outline

**Introduction**
*Observations have provided critical constraints for ocean models*

**The oceanic Inventory**
*or how can we find the needle in the haystack?*

**Variability**
*why the ocean sink may be more variable than we had thought*

**Summary & Conclusions**
Ocean carbon cycle models tend to underestimate ocean uptake

Current generation ocean carbon cycle models simulate an ocean uptake that is lower than the ocean inversion suggest.

The ocean inversion results from Mikaloff-Fletcher (2006) are tied to a single anchor point, i.e., 1994, based on the Sabine et al. (2004) inventory. Can we provide a second anchor point?

At least those that contribute to GCP’s annual budget.
Dealing with sparse data... requires sophisticated analysis and mapping methods.

**INTERIOR OCEAN DATA**

- **1982-1999**
- **2000-2012**

**eMLR(C*) method**

**CHANGE IN C\text{ant}**

1x1°, 2007 minus 1994
Dealing with sparse data... requires sophisticated analysis and mapping methods.

$\text{METHOD}$

$\text{for each basin and isoneutral slab}$
$T(t_1), S(t_1), O_2(t_1), AOU(t_1), Si(OH)_4(t_1), NO_3(t_1), PO_4(t_1), ...$

$t_1 = 1982-1999$

$\text{Alk}(t_1), PO_4(t_1)$
$C'_\text{ant (GLODAP)}$

$\text{DIC}(t_1) \rightarrow C^*(t_1) \rightarrow C^*(t_1^{\text{ref}})$

$\text{compute } C^* \text{ adjust to reference year}$

$\text{run 112 MLR}$

$\text{coeff. } a_{ij}(t_1^{\text{ref}})$

$\text{select 10 best MLR}$

$\text{determine and map } \Delta C'_{\text{ant}}$

$\Delta C'_{\text{ant}}(t_2^{\text{ref}}, t_1^{\text{ref}})$

$\text{combine coefficients for eMLR}$

$t_2 = 2000-2012$

$\text{Alk}(t_2), PO_4(t_2)$
$C'_\text{ant (GLODAP)}$

$\text{DIC}(t_2) \rightarrow C^*(t_2) \rightarrow C^*(t_2^{\text{ref}})$

$\text{for each basin and isoneutral slab}$
$T(t_2), S(t_2), O_2(t_2), AOU(t_2), Si(OH)_4(t_2), NO_3(t_2), PO_4(t_2), ...$
RESULTS

Zonal mean sections

Strong accumulation in the thermocline of the Southern hemisphere

Moderate levels of accumulation in the deep North Atlantic

Interior changes of anthropogenic CO$_2$ (1994-2007)

Gruber et al. (in review)
RESULTS

Low accumulation in the North Pacific

Moderate to strong accumulation in the North Atlantic

Integrated to 3000 m

Strong accumulation in the thermocline of the Southern hemisphere

Storage rate of anthropogenic CO$_2$ (1994-2007)

Gruber et al. (in review)
Decadal ant. CO₂ storage (1994-2007) vs total inventory

**Decadal storage**
1994-2007
33 ± 4 Pg C
(2.5 ± 0.3 Pg C yr⁻¹)

**Total inventory**
1850-1994
118 ± 17 Pg C
(includes unmapped basins)

Weaker North Atlantic uptake
Stronger uptake and asymmetry between basins in the southern hemisphere

Gruber et al. (in review)
Anomalous CO$_2$ storage (the role of climate variability)

Strong asymmetry in the Atlantic

Low accumulation in the Southern Ocean (Indian and Pacific sectors)

Anomalous $\Delta C_{\text{ant}} = \Delta C_{\text{ant}} - \Delta C_{\text{ant,expected}} = \Delta C_{\text{ant}} - 0.28 \times C_{\text{ant}}(1994)$

Gruber et al. (in review)

COMPARISON

Gruber et al. (in review)

Sabine et al. (2004)
Signal of reduced uptake of ant. CO$_2$ in the Southern Ocean can be traced into the thermocline
Connecting the changes in the ocean interior to the sfc. fluxes

We can start to connect the ocean interior changes (in Cant) to the changes in the surface air-sea fluxes of (natural and ant.) CO₂...
A word on uncertainties

Systematic errors were estimated by creating an ensemble of 14 estimates, using different assumptions along the decision tree of the method.
This ocean interior data based provides a new anchor point.

The new anchor point suggests an uptake consistent with the forward projection from the ocean inversion estimate, i.e., confirming that most ocean models tend to underestimate the ocean uptake.

Redrawn from Le Quéré et al. (2017)
Implication for global carbon budgets

<table>
<thead>
<tr>
<th>CO₂ sources and sinks</th>
<th>1800 to 1994</th>
<th>1994 to 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Pg C) (a)</td>
<td>(Pg C) (b)</td>
<td></td>
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</tbody>
</table>

### Constrained sources and sinks

1. Emissions of C<sub>ant</sub> from fossil fuel and cement production
   - 244±20
   - 94±5

2. Increase of CO₂ in the atmosphere
   - -165±4
   - -50±1

3a. Uptake of C<sub>ant</sub> by the ocean
   - -118±19
   - -33±4

3b. Loss of natural CO₂ by the ocean
   - 7±10
   - 5±3

3. Net ocean CO₂ uptake
   - -111±21
   - -28±5

### Inferred terrestrial balance

4. Net terrestrial balance [-(-1) -(-2) -(-3)]
   - 32±30
   - -16±7

### Terrestrial balance

5. Emissions of C<sub>ant</sub> from land use change
   - 100 to 180
   - 16±6

6. Terrestrial biosphere sink [-(-1) -(-2) -(-3)] -(-5)
   - -68 to -148
   - -32±9

1994-2007
- Ocean uptake fraction for Anthropogenic CO₂: 30±4%
- Outgassing estimated from Landschützer et al. (2016)
- Ocean uptake fraction for contemporary CO₂: 25±5%
Summary and Conclusions

- Thanks to large *international observational efforts*, we are now able to address decadal time-scale variability of the ocean carbon sink.

- These observations confirm that the ocean has *taken up 30% of the anthropogenic CO₂* emitted into the atmosphere.

- The observations also reveal a substantial amount of *variability* in this uptake, including a possible loss of natural CO₂.

*These data can provide numerous new constraints for ocean models…*

All data will be made available through NCEI:
- Globally gridded 1° x1° resolution, with uncertainties
An upcoming opportunity: RECCAP2

1st meeting: 18-21. March 2019: Japan

POTENTIAL TOPICS

1) Global ocean CO₂ flux variability over the last three decades: Models, observations, and processes
2) Global ocean storage change. Models, observations, and processes
3) The ocean carbon sink: the integrated view
4) Variability in the Southern Ocean carbon sink
5) Carbon sources and sinks of the global coastal region
6) ....