Determining the Global Ocean Anthropogenic Carbon Sources, Sinks, and Long-term Trends

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Partners: NOAA Labs (PMEL, AOML, GFDL & GML) Programs (OAP, IOOS); Federal Agencies (NSF, NASA) and academia (UW/CICOES, Miami/CIMAS, CU, LDEO, BIOS, SIO, WHOI, and >30 International partners
State of Knowledge: Global Carbon Budget

Major Scientific Questions

- What is the partitioning of CO₂ emissions between land, air, and ocean?
- What controls decadal variations in ocean CO₂ uptake and transport?
- Is the ocean uptake of anthropogenic carbon keeping pace with the atmosphere or does it respond to climate change?

Friedlingstein et al 2021
GOMO Global Ocean Carbon Observing Network
providing long-term observations of carbon from the sea surface to the ocean interior at a range of spatial and temporal scales

Global GO-SHIP Repeat Hydrographic/CO₂/Tracer Surveys
To quantify the ocean sink, transport, and storage of anthropogenic CO₂

Surface water pCO₂ Measurements from Ships
High-Resolution Ocean and Atmosphere pCO₂ Time Series Measurements
To evaluate the variability in air-sea CO₂ fluxes to provide meaningful projections of future atmospheric CO₂ levels

Global Carbon Data Management and Synthesis Project
Data Analysis and Product Development
NOAA Global Ocean Observing and Monitoring Division: Ocean Carbon

**Strategy**

- Repeat GOSHIP cruises with surface to bottom sampling;
- Fixed MAPCO₂ mooring stations;
- SOCONET Underway pCO₂ measurements on research and volunteer observing ships.

**Sustained Observations**

- **Repeat Hydrography**
- **CO₂ from Moorings**
- **CO₂ from Ships**

**Data Synthesis**

- **Ocean Interior**
- **Surface Ocean**
- **Remote sensing and model output**

**Global Products & Publications**

- **GLODAP**
- **SOCAT**

International, National, Academic Partners and Global Outreach via WCRP, IOC, IPCC, GCP.

Olsen et al., 2019; Sutton et al., 2019; Wanninkhof et al., 2019, Gruber et al., 2019
Ocean Carbon Science-to-Society Value Chain

Surface Ocean CO$_2$ Atlas

Oceanic Uptake = 2.8 ± 0.4 Pg C yr$^{-1}$ for 2011–2020

Key for
- Quantification of global ocean CO$_2$ uptake (~25% of fossil fuel emissions),
- Its year-to-year to decadal variation,
- Its response to net zero CO$_2$ emissions.

Surface Ocean CO$_2$ Atlas (www.socat.info)
- Quality-controlled synthesis products of *in situ* surface ocean CO$_2$ measurements
- 33 million CO$_2$ values (1957-2020)
- Standardized procedures
- Annual public release

Bakker et al., 2022
The oceanic sink for anthropogenic CO₂ from 1994 to 2007

We quantify the oceanic sink for anthropogenic carbon dioxide (CO₂) over the period 1994 to 2007 by using observations from the global repeat hydrography program and contrasting them to observations from the 1990s. Using a linear regression–based method, we find a global increase in the anthropogenic CO₂ inventory of 34 ± 4 petagrams of carbon (Pg C) between 1994 and 2007. This is equivalent to an average uptake rate of 2.6 ± 0.3 Pg C year⁻¹ and represents 31 ± 4% of the global anthropogenic CO₂ emissions over this period. Although this global ocean sink estimate is consistent with the expectation of the ocean uptake having increased in proportion to the rise in atmospheric CO₂, substantial regional differences in storage rate are found, likely owing to climate variability–driven changes in ocean circulation.
Change in anthropogenic carbon in the global oceans

Sabine et al., Science 2004
Inventory = 118 ± 20 PgC
Thru 1994

Gruber et al., Science 2019
Inventory Increase = 33 ± 4 Pg C
from 1994 to 2007

Gruber et al., Science 2019
2007 Inventory = 151 ± 20 Pg C
thru 2007
Table 1. Change in the inventory of anthropogenic CO$_2$ between 1994 and 2007 as estimated on the basis of the eMLR(C*) method. Shown in italics are the estimated uncertainties based on the sensitivity and Monte Carlo analyses.

<table>
<thead>
<tr>
<th></th>
<th>Atlantic (Pg C)</th>
<th>Pacific (Pg C)</th>
<th>Indian (Pg C)</th>
<th>Other basins† (Pg C)</th>
<th>Global (Pg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Hemisphere</td>
<td>6.0 ± 0.4*</td>
<td>5.2 ± 0.6</td>
<td>0.8 ± 0.4</td>
<td>1.5 ± 0.6</td>
<td>13.5 ± 1.0</td>
</tr>
<tr>
<td>Southern Hemisphere</td>
<td>5.9 ± 1.2*</td>
<td>8.0 ± 1.2</td>
<td>6.3 ± 3.4</td>
<td>~0</td>
<td>20.1 ± 3.8</td>
</tr>
<tr>
<td>Entire basin</td>
<td>11.9 ± 1.3</td>
<td>13.2 ± 1.3</td>
<td>7.1 ± 3.4</td>
<td>1.5 ± 0.6</td>
<td>33.7 ± 4.0</td>
</tr>
</tbody>
</table>

*Includes an estimated 1 Pg C to account for the accumulation below 3000 m, with 0.7 Pg C allocated to the North Atlantic and 0.3 Pg C to the South Atlantic (see main text). †Estimated storage in the Arctic and Mediterranean Sea (see supplementary materials).
GO-SHIP Repeat Hydrography results demonstrate the growing global ocean carbon sink varies in the ocean interior (from Carter et al. 2017; Carter et al. 2019).

Surface water increase = 0.7 - 1.2 µmol kg\(^{-1}\) yr\(^{-1}\)
GOMO-supported New Technologies

Technology: calibrated air-sea CO₂

MAPCO₂
Moored Autonomous pCO₂ System
1990s: developed at MBARI
2000s: modified at PMEL
2009: transferred
2011: NOAA tech transfer award
Today: 50+ sites globally

ASVCO₂
Autonomous Surface Vehicle CO₂ Sensor
2010: MAPCO₂ modified for ASVs
2019: 1st autonomous circumnavigation of Antarctica
Today: ASVCO₂ deployed on > 2 dozen missions; finalizing transfer

Derived Variables:
• dissolved inorganic carbon (DIC)
• particulate organic carbon
• anthropogenic carbon
• total alkalinity
• Phosphate
• silicate
• $pCO₂$
• Chl-a

Photos: NOAA PMEL, UH, Saildrone Inc.
Ocean Carbon Technology: Southern Ocean

Photo: Saildrone Inc.

NOAA Gold Award for Technology Development!
Anthropogenic Carbon Uptake by the Oceans

Is the ocean sink keeping pace with the atmospheric CO₂ increase?

Yes, current estimates of ocean CO₂ uptake range from $2.5 - 3.0 \pm 0.5 \text{ PgC yr}^{-1}$ and the total anthropogenic carbon inventory is $170 \pm 20 \text{ PgC}$ thru 2019.

Gruber et al., 2019
GO-SHIP Interior observations

PMEL IPCC AR6 WG1 Report, Chap. 5 (2021)
Mean Flux = $-2.5 \pm 0.5 \text{ PgC yr}^{-1}$ (2010 – 2019)
Future Directions – Challenges and Opportunities

1. Continuing to Provide Support for Data Integration and Synthesis Efforts
2. Continuing to Resolve Differences Between Observations and Model Outputs
3. Integration of New Platforms and Technologies into the Observing Network
4. Integration of Biology into the Observing Network via BGC Argo and Bio-GO-SHIP

**Bio-GO-SHIP: Sustained Global Scale Biological Observations**

**Planned derived products:**
1. Phytoplankton growth rates (continuous flow cytometry)
2. *In situ* biomass of functional groups (flow cytometry, imaging, particulates)
3. Size spectrum (flow cytometry, imaging)
4. Biodiversity (flow cytometry, imaging, ‘omics, bio-optics)
5. Chemical composition of sinking organic matter (particulates)
6. Attenuation of sinking organic matter (imaging, particulates)
Conclusions

Relevance
Thus far, the ocean CO$_2$ sink is keeping pace with atmospheric CO$_2$ increases. The next questions are how long will the ocean continue to take up the excess CO$_2$ from human sources in proportion with the atmospheric increase and how will the biology be impacted by the changing CO$_2$ and pH conditions.

Performance
GOMO has contributed to major advancements in our understanding of ocean carbon cycle

- Based on the GO-SHIP repeat hydrography observations and modeling the oceans have taken up 170 ± 20 Pg C since the beginning of the industrial era thru 2019.
- Discovery of decadal increases in carbon storage, primarily in the subtropical water masses due to increasing air-sea exchange and increasing ventilation in recent years.