Oceans and Ecosystems Research

Changing levels of Oceanic Carbon Dioxide

Rik Wanninkhof

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Programmatic drivers of Ocean Carbon Cycle efforts
US Carbon Cycle Science Program

• An interagency effort

Carbon Cycle Science Plan: www.carboncyclescience.gov within the USGCRP Strategic Plan and the annual research priorities of the USGCRP

• Federal Ocean Acidification Research and Monitoring Act (FOARAM) Act of 2009

• A global community effort (IOC, WCRP, Future Earth/ICSU)

International efforts in support of assessments of the Global Carbon Project
http://www.globalcarbonproject.org/
Overarching questions

• What is the sea-air CO$_2$ flux across the interface (SOCAT & Takahashi)?
• What are the decadal changes in inventories of anthropogenic carbon (GO-SHIP)?
• What are the patterns of coastal ocean CO$_2$ levels and how are they affecting marine biota? (Ocean acidification)
The Problem

- Atmospheric CO₂ levels are changing due to release of the greenhouse gas CO₂ which is considered a pollutant (EPA, 2009).
- Pollutant levels and impact of pollutants require monitoring.
- Of the 10 Pg C emitted by burning of fossil fuels, ≈50 % remain in the atmospheric, the remainder is taken up by land plants and oceans.
- We study the uptake by the oceans both from a “bookkeeping” perspective, and to assess impact of rising CO₂ levels on biogeochemistry.

In 2009 EPA qualified the increasing CO₂ levels as a pollutant along with the other greenhouse gases Ch₄, N₂O, HCFCs, PCFCs, and SF₆.
How much is 10 Pg C?

In 2012 9.7 Pg C was released to the atmosphere by burning of fossil fuel. Of the total emissions from human activities during the period 2003-2012, about 45% accumulated in the atmosphere, 27% in the ocean and 27% on land (GCP, 2013). Mitigation by capture is challenging: If compressed into liquid CO$_2$ and stored as suggested as a mitigation action this equates to filling the volume of the Empire State building every day.
What is the sea-air $\text{CO}_2$ flux across the interface?

**Efforts: SOCAT & Takahashi climatology**

Performance measure: Constrain the sea-air $\text{CO}_2$ fluxes to 0.2 Pg C/yr

The NOAA funded ship of opportunity program lead by AOML (2 NOAA labs, 3 CIs, ad 3 academic institutions) with 15 ships contribute 50% ($\approx$ 5 M datapoints) of the global surface water CO2 data (IOCCP-SOCAT)

**A Multi-national Effort:** USA, Japan, Australia, Norway, England, France, Netherlands, Germany, Spain, China
Product: Magnitude of Flux - State of the system

- Takahashi climatology - a baseline for sea-air fluxes and the premier constraint for models (net open ocean sea-air flux is 1.3 Pg C yr\(^{-1}\))

Non El-Nino year centered on 2005
Flux maps: near real-time maps to determine magnitude variability and trends

Producing Seasonal CO₂ Flux Maps

- **Algorithm development**
  \[ pCO₂ = f(SST, color) \]

- **Apply algorithm to regional SST & color fields to obtain seasonal pCO₂ maps**

- **Co-located satellite data**

- **Regional satellite SST & color data**

- **Wind data**

- **Remote sensing**
  pCO₂, SST, color & wind

- **Shipboard sampling**
  pCO₂, SST, SSS

- **Flux**
  \[ Flux = k \Delta pCO₂ \]
Global Ocean Carbon Uptake: Magnitude, Variability and Trends

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\textsuperscript{1}Wanninkhof et al. 2013, Biogeosciences, RECCAP
Trends in ocean uptake:
Estimates based on surface values are appreciably shorter than models based on interior changes: artifact or feedback?

Median sea–air anthropogenic CO₂ fluxes for the different approaches centered on year 2000.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Anthr. CO₂ flux</th>
<th>Uncertainty</th>
<th>IAV</th>
<th>SAV</th>
<th>Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pg C yr⁻¹</td>
<td>Pg C yr⁻¹</td>
<td>Pg C yr⁻¹</td>
<td>Pg C yr⁻¹</td>
<td>(Pg C yr⁻¹) decade⁻¹</td>
</tr>
<tr>
<td>Empirical</td>
<td>-2.0</td>
<td>±0.6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.20</td>
<td>0.61</td>
<td>-0.15</td>
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<td>OBGCM</td>
<td>-1.9</td>
<td>±0.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.16</td>
<td>0.38</td>
<td>-0.14</td>
</tr>
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<td>Atm. Inversion</td>
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<td>±0.3&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>0.41</td>
<td>-0.13</td>
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<td>Ocean Inversion</td>
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<td>±0.3&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
<td></td>
<td>-0.5&lt;sup&gt;j&lt;/sup&gt;</td>
</tr>
<tr>
<td>Interior (Green function)&lt;sup&gt;g&lt;/sup&gt;</td>
<td>-2.2</td>
<td>±0.5</td>
<td></td>
<td></td>
<td>-0.35</td>
</tr>
<tr>
<td>O₂/N₂&lt;sup&gt;h&lt;/sup&gt;</td>
<td>-2.2</td>
<td>±0.6</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>O₂/N₂&lt;sup&gt;i&lt;/sup&gt;</td>
<td>-2.5</td>
<td>±0.7</td>
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</tbody>
</table>

Wanninkhof et al. 2013
What is the decadal change in ocean carbon inventories?

Global Ocean- Shipbased Hydrographic Investigations Program/CLImate VARiability program

GO-SHIP/CLIVAR focuses on man-induced and natural change in the ocean on climate relevant timescales

Performance measure: Quantify change in anthropogenic CO$_2$ inventory over decadal time scale to within 10%
GO-SHIP CLIVAR/CO2 A16 section

Lead by scientists at AOML
Participants from 2 NOAA labs., 3 CI’s, 10 academic institutions

**DIC cross section 2013**

**Change in DIC between 2013 and 2003**

Primary purpose: Serving climate quality data within 6-months to the science community

About 5000 DIC datapoints from 3 cruise sections
Shipboard data management and QC tools provides ability for shipboard checks
Preliminary data of sufficient quality for qualitative state and change estimates
Determining change in anthropogenic CO2 ($C_{anthro}$) requires accounting for natural variability.

Utilize:
- Co-variance of “natural” DIC with nutrients and oxygen
- Use of inert transient tracers (CFC, SF$_6$)

Highlight: Greater uptake in S. Atlantic than N. Atlantic

Comparison of global estimate of $C_{\text{anthro}}$ of decadal change with individual lines (mid 2000’s - mid 1990’s)

The background estimate are preliminary results based on a modified eMLR method (Clement and Gruber, 2014), while the individual dots represents published estimates based on the original eMLR method, such as Wanninkhof et al., 2010 (Atlantic A16) and Sabine et al. 2008 (Pacific P16).
What are the patterns of coastal ocean CO2 levels and how are they affecting marine biota? (Ocean acidification)

Performance measure: determine aragonite saturation state to 0.2

Focus on building a coastal observing system with emphasis on water column carbon dynamics

Applying what we’ve learned in to open ocean to the coastal ocean.

- Instrumental techniques
- Data management
- Data Quality Control
- Data interpolation

If we extrapolate open ocean data to the coast we obtain a coastal sink for carbon of -0.18 pG C year \(^{-1}\) (independent assessments of coastal fluxes -0.1 to -1 Pg C with most recent estimates \(\approx 0.2\) Pg C)
Observing Assets

Moorings

Ship of Opportunity

GOMECC cruises

Surface Water Assets

fCO₂ recomputed (μmol)
GOMECC Cruises
Water Column Determination of Saturation States $\Omega_{\text{Ar}}$

Cross sections of $\Omega_{\text{Ar}}$ on GOMECC-1

Texas
Florida
Georgia
Mass
New Hampshire

Wang et al. 2013
Aragonite Saturation State (\( \Omega_{\text{ar}} \)) Maps

Aragonite Saturation State: \( \Omega_{\text{Ar}} = [\text{Ca}^{2+}] [\text{CO}_3^{2-}] / \text{K}_{\text{sp}} \)

Modelling/Algorithm development
\( \Omega_{\text{ar}} = f (\text{Alk, pCO}_2) \)

\( \text{Alk} = f (\text{SSS, SST}) \)

Dry season  

Wet Season  

Validation
Long-term goal: Climate Adaptation and Mitigation

Objective: Improved scientific understanding of the changing climate system and its impacts

The need to advance understanding of the climate system and climate impacts, improve climate predictions and projections, and better inform adaptation and mitigation strategies is urgent. Key scientific uncertainties limit scientists’ ability to understand and predict changes in the climate system. This is particularly true for monthly-to-decadal timescales and at the regional and local levels for which scales are highly relevant to planning and decision making.

http://www.ppi.noaa.gov/goals/

You’ve got to measure and measure well before you can understand
Charge
As outlined in the “purpose of the review” section of the “charge to reviewers,” Laboratory scientific reviews are conducted to help the Laboratory:
1. in its strategic planning of its future science,
2. to ensure that Laboratory research is linked to the NOAA Strategic Plan,
3. is relevant to OAR mission and priorities,
4. is of high quality as judged by preeminence criteria,
5. and is carried out with a high level of performance.