Overview of Carbon Cycle Science

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Observing Terrestrial Ecosystems and the Carbon Cycle from Space
October 5, 2015
<table>
<thead>
<tr>
<th>Emitted compound</th>
<th>Resulting atmospheric drivers</th>
<th>Radiative forcing by emissions and drivers</th>
<th>Level of confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>CO₂</td>
<td>1.68 [1.33 to 2.03]</td>
<td>VH</td>
</tr>
<tr>
<td>CH₄</td>
<td>CO₂, H₂O, O₃, CH₄</td>
<td>0.97 [0.74 to 1.20]</td>
<td>H</td>
</tr>
<tr>
<td>Halo-carbons</td>
<td>O₃, CFCs, HCFCs</td>
<td>0.18 [0.01 to 0.35]</td>
<td>H</td>
</tr>
<tr>
<td>N₂O</td>
<td>N₂O</td>
<td>0.17 [0.13 to 0.21]</td>
<td>VH</td>
</tr>
<tr>
<td>CO</td>
<td>CO₂, CH₄, O₃</td>
<td>0.23 [0.16 to 0.30]</td>
<td>M</td>
</tr>
<tr>
<td>NMVOC</td>
<td>CO₂, CH₄, O₃</td>
<td>0.10 [0.05 to 0.15]</td>
<td>M</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrate, CH₄, O₃</td>
<td>-0.15 [-0.34 to 0.03]</td>
<td>M</td>
</tr>
<tr>
<td>Aerosols and precursors</td>
<td>Mineral dust, Sulphate, Nitrate, Organic carbon, Black carbon</td>
<td>-0.27 [-0.77 to 0.23]</td>
<td>H</td>
</tr>
<tr>
<td>Short lived gases and aerosols</td>
<td>Cloud adjustments due to aerosols</td>
<td>-0.55 [-1.33 to -0.06]</td>
<td>L</td>
</tr>
<tr>
<td>Natural</td>
<td>Changes in solar irradiance</td>
<td>0.05 [0.00 to 0.10]</td>
<td>M</td>
</tr>
</tbody>
</table>

Total anthropogenic RF relative to 1750

- 2011: 2.29 [1.13 to 3.33] (H)
- 1980: 1.25 [0.64 to 1.86] (H)
- 1950: 0.57 [0.29 to 0.85] (M)

http://www.ipcc.ch/
We know $\text{CO}_2$ continues to increase and by about how much.

Mauna Loa $\text{CO}_2$ record and inferred atmospheric growth rate from 1950s to present

http://www.esrl.noaa.gov/
Current Understanding of CO$_2$ budget

- With information on fossil fuel usage, model estimates of ocean carbon flux, and surface obs, we can estimate how much carbon the land is absorbing.

http://www.globalcarbonproject.org/carbonbudget/
Uncertainty in Land Carbon Flux

• Though we can estimate the magnitude of the land sink, its global distribution and the processes controlling it remain very uncertain.

• Results from the Multi-scale Terrestrial Model Intercomparison Project (MsTMIP) underscore this uncertainty.

Huntzinger et al., 2013, GMDD
We think we understand ocean CO$_2$ flux better... but do we?

- Observational estimates computed from ocean pCO$_2$ samples
- Climatology based on ~3 million samples from 1970-2007 compiled by Takahashi et al.

Number of Months with Observations in Takahashi Climatology

Takahashi et al., 2009, Deep Sea Research II
Fossil Fuel Emissions

Data: CDIAC/GCP

China: 4.2%
USA: 2.9%
EU28: -1.8%
India: 5.1%

http://www.globalcarbonproject.org/carbonbudget/
Can we measure fluxes directly?

• Model differences are large because of lack of direct observations
• Flux towers provide valuable information on local scale fluxes but many regions not covered
GEOS-5 Nature Run

Current observing systems for CO$_2$

- Surface observations coordinated by NOAA designed to monitor background levels of CO$_2$

- Few observations is regions with greatest flux uncertainty including tropics, high latitude land masses
Current observing systems for CO₂

AIRS data provide some information about CO₂ in the mid-troposphere but has very limited sensitivity near the surface where flux signals are the strongest.

Too much scatter, low near surface sensitivity, strange artifacts in data.
Current observing systems for CO$_2$

ESA instrument SCIAMACHY among the first space-based CO$_2$ measurements...

Too much scatter and systematic bias to be useful for flux inference

http://www.iup.uni-bremen.de/sciamachy/
Current observing systems for CO₂

Japan’s GOSAT satellite launches in 2009 has provided the best satellite CO₂ dataset to date with considerable improvements in accuracy.

Passive technique requires sunlight, limits coverage in persistently cloudy regions, high latitudes during winter.

Small systematic bias and sparse coverage limit use for flux inference.
Orbiting Carbon Observatory - 2
XCO2 Data (5/14/15 - 7/15/15)
Big questions remaining for the carbon cycle

• Why do bottom-up land models underestimate the land carbon sink?
• Relative magnitudes of sink in N. America/Tropics?
• How will land carbon flux change in the future?
New Assessment:
Carbon pools in the northern circumpolar permafrost region

1 Pg = 1 billion tons or \(10^{15}\) g

### Permafrost zones

<table>
<thead>
<tr>
<th></th>
<th>0-30 cm</th>
<th>0-100 cm</th>
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</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>110.38</td>
<td>298.75</td>
</tr>
<tr>
<td>Discontinuous</td>
<td>25.5</td>
<td>67.44</td>
</tr>
<tr>
<td>Sporadic</td>
<td>26.36</td>
<td>63.13</td>
</tr>
<tr>
<td>Isolated Patches</td>
<td>29.05</td>
<td>67.10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>191.29</strong></td>
<td><strong>496.42</strong></td>
</tr>
</tbody>
</table>

### Soil or deposit type

<table>
<thead>
<tr>
<th></th>
<th>C stocks</th>
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<tbody>
<tr>
<td>Soils 0–300 cm</td>
<td><strong>1024</strong></td>
</tr>
<tr>
<td>Yedoma sediments</td>
<td>407</td>
</tr>
<tr>
<td>Deltaic deposits</td>
<td>241</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1672</strong></td>
</tr>
</tbody>
</table>
California Carbon Stocks 2010

(Gonzalez, Battles, Collins, Robards, and Saah 2015)

California Carbon Changes 2001-2010

(Gonzalez, Battles, Collins, Robards, and Saah 2015)
Results from The 2015 Carbon-Climate System Workshop in Norman, OK

- Developing and sustaining a time series of global atmospheric CO$_2$, CH$_4$, and CO concentrations with sufficiently small and understood biases at spatial and temporal resolutions that allow rigorous evaluation and improvement of models needed to reduce uncertainty in future predictions/projections.

- Improving attribution and quantification of patterns of carbon emissions, thereby reducing the growing uncertainty of anthropogenic emissions of carbon.

- Acquiring the critical measurements that allow attribution of fluxes to specific mechanisms and processes within terrestrial and marine carbon cycles. Many of these measurements are expected to be priorities for disciplines such as terrestrial ecosystems, ocean biology, biogeochemistry, and climate.

- Addressing how the natural dynamics of the carbon cycle and human activities feedback to influence future trajectory of the atmospheric carbon fraction.
How do we decide the best measurement approach?

• Remote sensing techniques:
  – Passive systems – observations of near-IR spectra in reflected sunlight
  – Active systems – uses laser for illumination

• Orbital options:
  – Low Earth Orbit – global coverage, but observations of particular location limited
  – Geostationary Orbit – more frequent observations but limited coverage

• How do we decide what we need?
  – Modeling teams currently working to define Observing System Simulation Experiments (OSSEs) to determine benefits/weaknesses of different approaches