The Global Carbon Cycle as Seen by the Atmosphere

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Carbon cycle science as a field began with the careful observational work of Dave Keeling.

Outline
1. Global carbon budget
2. Atmospheric CO$_2$ measurements
3. Latitudinal distribution of fluxes
4. Interannual variability
5. Long-term transitions
6. Seasonal cycle
7. The model-observation divide
1. The Global Carbon Budget

Annual land flux is the difference between larger seasonal fluxes which themselves are residuals of much larger gross fluxes. The atmosphere is a great integrator.

Where do these numbers come from?

IPCC, 2007
Data from Le Quéré et al., ESSD-D, 2013 supplement
IPCC2007 numbers come from 3 methods: atmospheric O$_2$, ocean CFC, ocean inversion
$\Delta C = F + B + O$

$\Delta O = \alpha_f F + \alpha_b B$

$\delta O_2/N_2$ (per meg) = \[
\frac{[O_2/N_2]_{\text{sample}}}{[O_2/N_2]_{\text{reference}}} - 1 \] \times 10^6

CO₂ is increasing more slowly than O₂ is decreasing because of net ocean sink
2. Atmospheric CO$_2$ Measurements
Cavity-enhanced laser absorption spectroscopy
Absolute Measurement Techniques: Manometric and Gravimetric

NOAA/CMDL Manometer:

Reproducibility of 0.03 ppm for dry mole fraction of CO₂

(C. Zhao et al., 1997)
Relative measurements require calibration gases tied to a common scale

NOAA/CMDL scheme for propagation of WMO CO$_2$ scale:

For NDIR, generally 4 points needed for 0.1 ppm comparability

Recalibration needed ~ every 3 years due to possible drift

Figure 4. Primary standards are used to calibrate a smaller secondary set which in turn is used as reference for all other concentrations. A subset of the secondaries is used to bracket the standards to be calibrated.
Global atmospheric inverse models and surface data can be used to make regional flux estimates

**Forward:** \( \text{Flux} + \text{Transport} = [\text{CO}_2] \)

**Inverse:** \( [\text{CO}_2] - \text{Transport} = \text{Flux} \)
Using high frequency data makes signals bigger, but the annual-mean signals are still very small:

To measure 0.2 GtCyr\(^{-1}\) source or sink to +/- 25% need to measure annual mean gradients to around +/- 0.2 ppm

Flux footprint, in ppm(GtCyr\(^{-1}\))\(^{-1}\), for a 10\(^6\) km\(^2\) chaparral region in the U.S. Southwest (Gloor et al., 1999).
Intra- and Inter-laboratory agreement still not better than 0.2 ppm

NCAR and NOAA measurements from Niwot Ridge, CO (Stephens et al., AMT, 2011)
3. Latitudinal distribution of fluxes

An early 3-D atmospheric inversion gave 1.7 PgC/yr into northern oceans and only 0.6 PgC/yr into northern land for 1984.

C. D. Keeling, S. C. Piper, and M. Heimann, A Three
Dimensional Model of Atmospheric CO₂ Transport Based on
Observed Winds: 4. Mean Annual Gradients and
Interannual Variations, in Aspects of Climate Variability in
the Pacific and the Western Americas, edited by D. H.
Peterson, American Geophysical Union, Washington, D.C.,
Global pCO$_2$ data set implies a northern land sink of 2.0-3.4 PgC/yr for 1981-1987

Tans, Fung, Takahashi, Science, 1990
Seasonal covariance between fluxes and transport imply an even larger sink in northern mid-high latitudes.

Denning et al., Nature, 1995
TransCom3 Atmospheric Inverse Model Intercomparison Study

All model average and standard deviations:

Northern Land = $-2.4 \pm 1.1 \text{ PgCyr}^{-1}$

Tropical Land = $+1.8 \pm 1.7 \text{ PgCyr}^{-1}$

“For most regions, the between-model uncertainties are of similar or smaller magnitude than the within-model uncertainties. This suggests that the choice of transport model is not the critical determinant of the inferred fluxes.”

But in fact, choice of transport model was the critical determinant of the inferred fluxes.
Representativeness

1. Models often don’t predict something that can be measured
2. Observations don’t measure something that can be predicted
3. A cultural divide

Measurement uncertainty $\approx 0.2$ ppm

TransCom3 continental site “Data error” $\approx 2.2$ ppm
3 models that most closely reproduce the observed annual-mean vertical CO₂ gradients (4, 5, and C):

Northern Land = -1.5 ± 0.6 PgCyr⁻¹

Tropical Land = +0.1 ± 0.8 PgCyr⁻¹

All model average:

Northern Land = -2.4 ± 1.1 PgCyr⁻¹

Tropical Land = +1.8 ± 1.7 PgCyr⁻¹

Most of the models overestimate the annual-mean vertical CO₂ gradient

Model results are also correlated with vertical CO₂ gradients, which can be measured

Stephens et al., Science, 2007
Similar results from bottom up studies

Temperate and boreal forests = -1.2 +/- 0.1
Tropical forests = +0.1 +/- 0.8

Pan et al., Science, 2011
RECCAP Atmospheric Inverse Model Intercomparison Study

Who should be comparing model results to data and diagnosing intermodel disagreements?

Peylin et al., BGD, 2013
Your choice:
4. Interannual Variability

- Temperature
- Precipitation
- Fires
- Volcanoes

Atmospheric inversions define IAV much better than they do annual mean fluxes

Bacastow, Nature, 1976
Keeling et al., AGU, 1989

Baker et al., GBC 2006
Stephens et al., BG, 2013
5. Long-term transitions

Shift of -1 PgC/yr in land fluxes around 1989?

Sarmiento et al., BG, 2010
Decrease in the efficiency of Southern Ocean anthropogenic CO$_2$ uptake?

Atmospheric inversion using TM3 and forward ocean model (ORCA-PISCES-T)

Le Quéré et al., Science 2007

Southern Ocean Air-Sea CO$_2$ Fluxes

[Speer et al., 2000; provided by the International CLIVAR Project Office]

[Zickfeld et al., Science 2008]
Expected changes in atmospheric CO$_2$ gradients are extremely small

+0.1 PgC/yr change in Southern Ocean sink over 1985–2005

- +0.04 ppm

- +0.13 ppm
6. Seasonal Cycle

Keeling et al., Nature, 1996; Randerson et al., GBC, 1997; Graven et al., accepted to Science, 2013
• PIs: Harvard, NCAR, Scripps, NOAA
• Global and seasonal survey of CO$_2$, O$_2$, CH$_4$, CO, N$_2$O, H$_2$, SF$_6$, COS, CFCs, HCFCs, O$_3$, H$_2$O, CO$_2$ isotopes, Ar, black carbon, and hydrocarbons (over 90 species).
• NSF / NCAR Gulfstream V
• Five 3-week campaigns over 3 years, across Pacific between 87 N and 67 S
• Continuous profiling between surface and 10-14 km
• 64 flights, 787 profiles, 434 hours in situ data + 4235 flasks
• hippo.ucar.edu, www.eol.ucar.edu/hippo, hippo.ornl.gov
Northern Hemisphere seasonal progression:
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Northern Hemisphere seasonal progression:
HIPPO Comparison to IGY

Graven et al., accepted to Science, 2013
HIPPO-IGY observations compared to CMIP5 models

45-90°N at 500mb

Graven et al., accepted to Science, 2013
Conclusions

• Atmosphere contains a wealth of information on global carbon fluxes on all time and space scales

• To make efficient and maximum use of this information, modelers and observationalists need to work very closely together (or fuse into one)

• Inverse / DA calculations need to look at residuals, archive posterior concentrations to do this, esp. in model intercomparison studies

• Many open global carbon cycle questions remain: annual mean terrestrial sink, interannual variability, growth in seasonal cycle are all very well observed and still demand explanations