The North American Carbon Cycle from the Atmospheric Point of View

Scott Denning, Arlyn Andrews, Martha Butler, Kathy Corbin, Kenneth J. Davis, Timothy Hilton, Andy Jacobson, Anna Michalak, Sharon Gourdji, Natasha Miles, Scott Richardson, Andrew Schuh, Ravi Lokupitiya, Steven Wofsy, Erandi Lokupitiya, Nick Parazoo, Marek Uliasz, and Dusanka Zupanski
Outline

1. Dramatic growth of the atmospheric observing network under NACP

2. Diversity of measuring and inversion analysis methods (incl CO & CH4 & COS)

3. Variations in the carbon cycle of North America are driven by climate and people

4. A new view of atmospheric CO₂
1. **Dramatic growth of the atmospheric observing network under NACP**

2. **Diversity of measuring and inversion analysis methods (incl CO & CH4 & COS)**

3. **Variations in the carbon cycle of North America are driven by climate and people**

4. **A new view of atmospheric CO2**
CO$_2$ Concentration Network: 2000

Legend: Sampling Platform
- Green: Surface-layer tower
- Blue: Mixed-layer (tail) tower
- Red: Complex terrain
- Black: Aircraft Profile

Colors Denote Operator
- Blue: NOAA ESRL
- Green: Canadian Carbon Program
- Red: Other (PSU, ORST, Harvard, NCAR)
- Yellow: MCI Ring of Towers 2 (PSU)
CO₂ Concentration Network: 2004

Legend: Sampling Platform
- Surface-layer tower
- Mixed-layer (tall) tower
- Complex terrain
- Aircraft Profile

Colors Denote Operator
- Blue: NOAA ESRL
- Green: Canadian Carbon Program
- Red: Other (PSU, ORST, Harvard, NCAR)
- Yellow: MCI Ring of Towers 2 (PSU)
CO₂ Concentration Network: 2005

Legend: Sampling Platform
- Green: Surface-layer tower
- Blue: Mixed-layer (tall) tower
- Red: Complex terrain
- Blue triangle: Aircraft Profile

Colors Denote Operator
- Blue: NOAA ESRL
- Green: Canadian Carbon Program
- Red: Other (PSU, ORST, Harvard, NCAR)
- Yellow: MCI Ring of Towers 2 (PSU)
CO$_2$ Concentration Network: 2007

Legend: Sampling Platform
- Green: Surface-layer tower
- Blue: Mixed-layer (tall) tower
- Red: Complex terrain
- Blue Triangle: Aircraft Profile

Colors Denote Operator
- Blue: NOAA ESRL
- Green: Canadian Carbon Program
- Red: Other (PSU, ORST, Harvard, NCAR)
- Yellow: MCI Ring of Towers 2 (PSU)
1. Dramatic growth of the atmospheric observing network under NACP

2. Diversity of measuring and inversion analysis methods (incl CO & CH4 & COS)

3. Variations in the carbon cycle of North America are driven by climate and people

4. A new view of atmospheric $CO_2$
Regional Carbon Budgeting from Atmospheric $CO_2$

Changes in $CO_2$ in the air contain information about all sources and sinks encountered along the way.

Requires: observations, accurate accounting for transport!
CarbonTracker

- Global Chemistry Transport Model
- Driven by ECMWF meteorology
- Two-way nested zoom
Weekly gridded product at 1x1 degree with error estimate, freely available on web with code, data, docs
Surface fluxes of carbon are inferred for 2001-2003 for each region shown by adjusting modeled fluxes (terrestrial, ocean, fossil emissions, and biomass burning) using atmospheric observations from this network, which includes flux tower sites (in red) with well-calibrated carbon dioxide measurements.
Sensitivity to Choice of Terrestrial Flux Model

For this well-constrained region, the inferred fluxes are not significantly different when using terrestrial flux models which vary in:

- Time resolution (hourly with interannual variability vs. monthly mean climatology)
- Amplitude of seasonal cycle
- Timing of seasonal cycle
Geostatistical inversions  
(Michalak et al, U of Michigan)

• Data-driven approach eliminating use of explicit prior estimates
• Takes advantage of spatial autocorrelation in flux distribution
• Incorporates auxiliary variables related to flux processes in a manner analogous to multi-linear regression
• Objective function and flux estimates:

\[ L_{s,\beta} = \frac{1}{2} (y - Hs)^T R^{-1} (y - Hs) + \frac{1}{2} (s - X\beta)^T Q^{-1} (s - X\beta) \]

\[ \hat{s} = X\hat{\beta} + QH^T \xi \]

Deterministic component  Stochastic component
North American geostatistical inversion

- U. of Michigan NACP project in collaboration with NOAA
- 1°x1° North American fluxes estimated for 2004 and 2006 using continuous & weekly flask atmospheric measurements, a Lagrangian atmospheric particle-tracking model (STILT), and high-resolution meteorology (WRF)
- *Met fields will be available from: http://data.engin.umich.edu/michalak*
Treatment of Variations for Inversion

\[ F_{CO2}(x,y,t) = \beta_R(x,y)R(x,y,t) - \beta_{GPP}(x,y)GPP(x,y,t) \]

- Fine-scale variations (hourly, pixel-scale) from weather forcing, MODIS, as processed by forward model logic (SiB-RAMS)
- Multiplicative biases (caused by “slow” BGC that’s not in the model) derived by from observed hourly [CO2]

\[ C_{k,m} = \sum_{i,j,n} \left( \beta_{R,i,j}R_{i,j,n}C^*_{Rk,m,i,j,n} + \beta_{A,i,j}A_{i,j,n}C^*_{Ak,m,i,j,n} \right) \Delta t_f \Delta x \Delta y + C_{IN} \]

*Flux-convolved influence functions derived from SiB-RAMS*
20 days of “upstream” transport in 50 seconds

Black: air parcels in contact with surface
Red: air parcels reach lateral boundaries
Result: Estimated 2004 Net Ecosystem CO₂ Exchange

\[ \text{g C m}^{-2} \text{ yr}^{-1} \]
Figure 1: Plus markings indicate locations of airborne flask collection. The average footprint from all the flasks is shown, indicating regions to which our measurements are most sensitive.
Outline

1. Dramatic growth of the atmospheric observing network under NACP

2. Diversity of measuring and inversion analysis methods (incl CO & CH4 & COS)

3. Variations in the carbon cycle of North America are driven by climate and people

4. A new view of atmospheric $CO_2$
CarbonTracker Estimated C Source/Sink

CarbonTracker Inversion Model, Net Terrestrial Summer Flux (gC/m²/yr)
www.esrl.noaa.gov/gmd/ccgg/carbontracker/
CarbonTracker Results

North American CO$_2$ emissions

- Fossil fuel emissions
- Terrestrial uptake
- Net flux

Climate Anomalies
(NOAA NCDC)

Summer Temperature
2002

Summer Precipitation
2004
Result: Estimated 2004 Net Ecosystem CO₂ Exchange

Forest Harvest

Schuh et al, in prep
Temporal and spatial variability in regional-scale CO₂ mixing ratios as measured during the Mid-Continental Intensive study

Natasha Miles, Scott Richardson, Ken Davis, and Eric Crosson
American Geophysical Union Annual Meeting 2008: 17 Dec 2008

ring2.psu.edu
Corn, as seen from 100 m

Ring 2 Daytime CO2, 1-minute, Top Level

Summer, 2007

Scott Richardson & Tasha Miles, Penn State Univ
Crop Physiology Model (SiBCrop)

Erandi Lokupitiya (*Biogeosciences*) see Poster!
Fractional Vegetation Distribution (subgrid-scale tiles)

Multiple instances of SiB run in each 40-km RAMS cell

Fluxes are weighted by fractional area
• Maximum daytime difference in CO$_2$ at 120 m above ground level for each day during summer 2007, as observed by the Ring2 towers and as simulated by SIB-RAMS

Corbin et al, in prep
The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

http://drought.unl.edu/dm
Synoptic Controls of CO$_2$ Gradient
(Simulated CO2 and winds at 120 m agl)

- Contrast between midwest agriculture uptake with exceptional SE drought!
- Synoptic “sloshing”: Ecology meets advection
- Southerly flow from Gulf of Mexico on 7/16 enhances gradient across ring
- Northerly flow on 7/19 relaxes gradient across ring
Outline

1. Dramatic growth of the atmospheric observing network under NACP
2. Diversity of measuring and inversion analysis methods (incl CO & CH4 & COS)
3. Variations in the carbon cycle of North America are driven by climate and people
4. A new view of atmospheric CO₂
Old View of Atmospheric CO₂

- TransCom-era simulations of annual mean gradients due to fossil fuel emissions
- State-of-the-art in 2002
- Source regions identified by gradients of less than 2 ppm
- Precision of measurements and models limit analysis
New View of Atmospheric CO₂

Column CO₂
Conclusions

- The CO₂ observing network has grown dramatically under NACP and gives us new eyes with which to see the carbon cycle.

- A diverse suite of approaches to analysis has emerged to interpret the new data.

- The NA Carbon Cycle is dynamic and variable in time and space, responding to variations in climate and management.

- Our new eyes have provided the first "synoptic" view of CO₂: there are huge gradients, waves, vortices and fronts.

- Next week we’ll take a giant leap with OCO launch!