Big data, big uncertainties and big challenges in carbon cycle science.

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Symposium on Advanced Assimilation and Uncertainty Quantification in Big Data Research for Weather, Climate and Earth System Monitoring and Prediction
State College, Pennsylvania, 23 May, 2016
Carbon cycle science: What’s the big deal?
Figure 2.3. Atmospheric concentrations of CO$_2$, CH$_4$ and N$_2$O over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). The corresponding radiative forcings relative to 1750 are shown on the right hand axes of the large panels. [WG1 Figure SPM.1]
Terrestrial ecosystems are removing large quantities of CO$_2$ from the atmosphere.

- Terrestrial (and marine) systems are removing a lot of CO$_2$!
- The terrestrial sink is increasing with time
- The terrestrial sink has large interannual variability, likely related to climate variability.
- *Where is this happening?  Why is this happening?*

(Global data – atmospheric sampling.)

Sarmiento and Gruber, 2002

http://www.aip.org/pt/vol-55/iss-8/captions/p30cap2.html
1. Fossil fuel burning is a huge CO$_2$ source. Must be managed.

2. There is a large terrestrial biosphere sink that is poorly understood and highly variable.

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**Energy stats**

- **Land use records**
  - *Residual terrestrial sink*
- **Atmospheric CO$_2$ measurements**
- **Ocean and atmospheric data**

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**IPCC, WG1, AR5**
Recent years: Methane concentrations are “on the rise again”

“Pause” in early 2000’s is not fully understood, nor is the current increase. Tropical wetlands probably play the major role in the current increase, but fossil fuel activity may also contribute.

Euan G. Nisbet et al. Science 2014;343:493-495
Global methane budget (Tg CH$_4$)

- About 1/2 of methane sources are associated with human activity.
- Large uncertainty in all sources.
- Recent trends cannot be explained.
Example: Uncertainty in CH$_4$ emissions from the production of natural gas is large

- Changes in estimated methane leakage as a percentage of production (USEPA 2010, 2011, 2013) are dominated by changing estimates of leakage during production (other sectors may also be uncertain – just not revised in these reports).
Diagnoses of current carbon sources/sinks are not very accurate. (at “regional” spatial scales) and “we can’t manage what we can’t measure.”
Methods

Change in atmospheric concentration of CO₂ over time = inversion or ABL budget approach.

Flux of carbon across this plane = tower or aircraft flux approach.

Change in biomass over time = inventory approach.

Change in CO₂ concentration in a small box over time = chamber flux approach.
Flux towers

Atmospheric CO₂

The gap

Surface radiances

Davis, 2008
Method – eddy covariance

\[
\text{Flux of C across this plane} + \text{Rate of accumulation of C below the flux sensor} = \text{Net Ecosystem-Atmosphere Exchange (NEE) of C}
\]

\[\text{Net sideways transport} = 0\]
Sonic anemometer

Infrared gas analyzer

Campbell Scientific, Inc.
LI-COR, Inc.
Net ecosystem-atmosphere exchange of CO$_2$ in northern Wisconsin

Weak carbon source  

Davis et al, 2003
Global flux tower co-op: Hundreds of sites

Koppen-Geiger Climate Classification (2006)

Af - Tropical/Rainforest
Am - Tropical/Monsoon
Aw - Tropical/Savannah
BWh - Arid/Desert/Hot
Bwk - Arid/Desert/Cold
BSH - Arid/Steppe/Hot
BSk - Arid/Steppe/Cold
Cfa - Temperate/Without dry season/Hot Summer
Cfb - Temperate/Without dry season/Warm Summer
Cfc - Temperate/Without dry season/Cold Summer
Csa - Cold/Dry Summer/Hot Summer
Csb - Cold/Dry Summer/Warm Summer
Csc - Cold/Dry Summer/Cold Summer
Dsa - Cold/Dry Summer/Hot Summer
Dsb - Cold/Dry Summer/Warm Summer
Dsc - Cold/Dry Summer/Cold Summer
Dfd - Cold/Dry Winter/Very Cold Winter
Dwa - Cold/Dry Winter/Hot Summer
Dwb - Cold/Dry Winter/Warm Summer
Dwd - Cold/Dry Winter/Cold Summer
Dfa - Cold/Without dry season/Hot Summer
Dfb - Cold/Without dry season/Warm Summer
Dfc - Cold/Without dry season/Cold Summer
Dfd - Cold/Without dry season/Very Cold Winter
ET - Polar/Tundra
EF - Polar/Frost
ET - Polar/Tundra

Beware of closed data policies!
A CO$_2$ flux map for N. America

VPRM fitted to 65 N. American flux towers using differential evolution.

Extrapolate using T, PAR, EVI, PFTs.

Annual NEE in gC m$^{-2}$ yr$^{-1}$, 2002

Hilton et al, 2014, Biogeosciences
Annual NEE error map, 2002

Units are gC m\(^{-2}\) yr\(^{-1}\).

Uncertainties are about as large as the fluxes.

Hilton et al, 2014, Biogeosciences
Interannual \( \text{CO}_2 \) flux variations are very difficult to simulate (and measure?)

Variability. The significant underestimation by the LUE models likely reflects the highly empirical nature of these models that are driven predominantly by radiation and LAI, and are less capable of capturing the temperature and soil moisture stresses that influence year-to-year changes in flux magnitude. For soil carbon decomposition formulation, the nitrogen inclusive models showed consistently higher annual variability as compared to the no-nitrogen models (Appendix A: Table A13).

In summary, all models showed a tendency to underestimate the magnitude of interannual variability for NEE, GPP, and RE. This tendency was reinforced in

**Fig. 4.** Annual fluxes for all sites for (a) NEE, (b) GPP, and (c) RE. The statistics of correlation coefficient (black dotted-dashed axis lines), average difference in flux magnitude between the modeled and observed fluxes (RMSD; gray dashed axis lines), and standard deviation (gray dotted axis lines) are calculated from temporal (within-site) modeled variability. Squares represent light-use-efficiency models, X’s represent enzyme-kinetic models, and dots represent statistical models (observed and model mean).

North American model – flux tower comparison.  

Raczka et al., (2013)
Regional CO₂ fluxes are highly uncertain.


“The range in model estimates of net ecosystem productivity (NEP) for North America is much narrower than estimates of productivity or respiration, with estimates of NEP varying between −0.7 and 2.2 PgC yr⁻¹, while gross primary productivity and heterotrophic respiration vary between 12.2 and 32.9 PgC yr⁻¹ and 5.6 and 13.2 PgC yr⁻¹, respectively.”

Huntzinger et al. (2012)
Why is it so difficult to simulate ecosystem-atmosphere carbon fluxes?
Why is it so difficult to simulate ecosystem-atmosphere carbon fluxes?

Ecosystem processes are complex and governing equations are highly parameterized.

The land surface is heterogeneous down to very small spatial resolution.
Atmospheric inversions have the potential to close this gap

- Measure CO$_2$ at point A
- Follow air flow to point B
- Measure CO$_2$ at point B
- Infer sources and sinks of CO$_2$ in between A and B.

- Requires dense, high-quality atmospheric data, and accurate atmospheric transport.
Changes in CO$_2$ and CH$_4$ in the air tell us about sources and sinks
Global atmospheric CO$_2$ measurement network: 200(?) sites

The NOAA CMDL Carbon Cycle Greenhouse Gases group operates 4 measurement programs. In situ measurements are made at the CMDL baseline observatories: Barrow, Alaska; Mauna Loa, Hawaii; Tutuila, American Samoa; and South Pole, Antarctica. The cooperative air sampling network includes samples from fixed sites and commercial ships. Measurements from tall towers and aircraft began in 1992. Presently, atmospheric carbon dioxide, methane, carbon monoxide, hydrogen, nitrous oxide, sulfur hexafluoride, and the stable isotopes of carbon dioxide and methane are measured. Group Chief: Dr. Pieter Tans, Carbon Cycle Greenhouse Gases, Boulder, Colorado, (303) 497-6678 (ptans@cmdl.noaa.gov, http://www.cmdl.noaa.gov/ccgg).

Old figure...more sites today...and OCO-2
Results from atmospheric inversions: North American terrestrial ecosystem fluxes

North American Flux Estimates

This shows that there is a significant North American terrestrial sink.

We more or less knew that in 1990.

Butler and Davis, AGU 2014
Three primary sources of uncertainty in GHG inverse flux estimates

1. Limited atmospheric data CO$_2$ and CH$_4$ data density
2. Uncertain CO$_2$ and CH$_4$ prior flux estimates
3. Poor knowledge of atmospheric transport – uncertainties largely unknown
Predicting future carbon fluxes

- C⁴MIP: comparison of 10 coupled climate/carbon models
- Large range of uncertainty (16 GtC yr⁻¹ range in land flux by 2100) in the “natural” sinks buffering climate change. Management challenge!

Friedlingstein et al., (2006)
Predicting future carbon fluxes (an update)

CMIP5 results

Fig. 4. Range of (a) cumulative global air to ocean carbon flux (PgC), (b) cumulative global air to land carbon flux (PgC) from the 11 ESMs E-driven simulations, (c) the annual global air to ocean carbon flux, and (d) annual global air to land carbon flux. Color code for model types is as in Fig. 1.

Observations needed to evaluate and improve these models are lacking.
What can be done?

• Advance process understanding.
• Move towards multi-state data assimilation.
• Close the measurement methods gap.
• Apply more measurements to more models. Enter the era of networked observations and ensemble modeling.
Some examples

• The world isn’t flat!
  • Improve models by studying the carbon-water-nitrogen cycles in complex terrain.
• Closing the measurement gap with atmospheric inversions:
  • Increase measurement density.
  • Reduce uncertainty in atmospheric transport.
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Spatial pattern of **aboveground carbon** at the Susquehanna Shale Hills Critical Zone Observatory

~200m

Data Courtesy of Margot Kaye’s group

**N** determines the spatial pattern of aboveground biomass, and is closely linked to watershed hydrology

Assimilated data: Watershed average soil carbon and aboveground carbon turnover rate.

Note: No observed SMN

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**Aboveground Carbon** [kgC/m²]

**Soil Mineral Nitrogen** [kgN/m²]

**Modeled Annual Average** × 10⁻⁴

**Wet site**

**Dry site**
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Midcontinent intensive, 2007-2009

Gulf coast intensive, 2015-2016

Influx, 2010-present

Marcellus regional intensive, 2015-2016

Legend:
- Surface-layer tower
- Mixed-layer (tall) tower
- Complex Terrain
- New Sites
- Aircraft Profile
- TCCON

Colors denote operator:
- Orange: NOAA
- Green: Canadian Carbon Program
- Red: Other
- Blue: PSU Sites
- Light Blue: PSU Southeast Sites
- Dark Red: PSU INFLUX Network (12 sites)
MidContinent Regional Intensive Tower-Based CO₂ Observational Network

Legend
MCI Corn NPP
(Mg C ha⁻¹ yr⁻¹)
- 0.00
- 0.01 - 4.94
- 4.95 - 6.09
- 6.10 - 6.92
- 6.93 - 7.66
- 7.67 - 8.46
- 8.47 - 9.21
- 9.22 - 9.90
- 9.91 - 10.59
- 10.60 - 11.71
- Iowa
- MCI region
- State boundaries

Miles et al, 2012, JGR-B
• Large differences in seasonal drawdown, despite nearness of stations.

Miles et al, 2012, JGR-B
Atmospheric inversions and agricultural inventory agree. *Regional inversions and inventory have similar uncertainty bounds!*

Atmospheric inversions have great potential for carbon balance inference given suitable data density.
Cross-over point? Inversion vs. inventory

Atmospheric inversions provide great insights at global scale. Emissions inventories are very informative at small scales. Can we bridge the gap?

MCI results suggest that uncertainty in an atmospheric inversion equals the uncertainty in an agricultural inventory at (several 100 km)^2 resolution for this inventory and these atmospheric data.
INFLUX GROUND-BASED NETWORK

- Communications towers ~100 m AGL
- Picarro, CRDS sensors
- 12 measuring CO2, 11 with CH4, and 5 with CO
- 6 NOAA automated flask samplers
- NOAA LIDAR
- Eddy flux at 4 towers
Comparison of [CO$_2$] at INFLUX sites

- Afternoon daily [CO$_2$]
- Seasonal signal is apparent
- Significant overlap between sites (weather-driven variability)

Miles et al, in prep
• Afternoon [CO$_2$] with 21-day smoothing

• Seasonal and synoptic cycles are evident

• Site 03 (downtown): high [CO$_2$]

• Site 01 (background): low [CO$_2$]

Miles et al, in prep
• Afternoon [CO$_2$] with 21-day smoothing

• Seasonal and synoptic cycles are evident

• Site 03 (downtown): high [CO$_2$]

• Site 01 (background): low [CO$_2$]

Miles et al, in prep
Spatial structure of urban CO$_2$: observed

- Observed CO$_2$: afternoon values, averaged Jan-April 2013
- Site 09: 0.3 ppm larger than Site 01
- Site 03: measures larger [CO$_2$] by 3 ppm

Miles et al, in prep
Modeled CO2 mixing ratios

Combination of tower surface footprints with prior CO$_2$ emissions to generate modeled mixing ratios

Lauvaux et al, submitted
Spatial structure of urban CO$_2$: observed and modeled

- Observed CO$_2$: afternoon values, averaged Jan-April 2013
- Site 09: 0.3 ppm larger than Site 01
- Site 03: measures larger [CO$_2$] by 3 ppm
- Modeled CO$_2$ using LPDM footprints and Hestia emissions
- Overall, the spatial structure is similar
- Miles et al., in prep

(observed CO$_2$ enhancement, tower number)
Sept 12 – Apr 13 Indianapolis CO2 emissions:

Hestia: 4.6 ktC

Inversion: 5.7 ktC +/- 0.2 ktC

Lauvaux et al, submitted
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• The world isn’t flat!
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• Closing the measurement gap with atmospheric inversions:
  • Increase measurement density.
  • Reduce uncertainty in atmospheric transport.
Comparison – TM5 and WRF
How much does transport matter?

Identical CO₂ fluxes and boundary conditions.

Midsummer, monthly averaged ABL CO₂ differs by as much as 15 ppm due only to atmospheric transport.

Diaz-Isaac et al, 2014, JGR-A.
Which Physics Parameterization Drives CO₂ Errors?

- Model-Ensemble mean comparison used to isolate transport errors.
- **Local Scale**: LSMs, PBL schemes and Cumulus parameterizations (CP) all have a big impact in CO₂ mole fraction errors.
- **Regional scale**: LSMs, PBL schemes, Cumulus parameterization(CP) and reanalysis have a big impact in CO₂ errors.
- **PBL physics is not the only physics parameterization that matters.**
How much do CO$_2$ simulations vary within this ensemble?

Multi-physics ensemble of WRF, vertical CO$_2$ profiles in Iowa.
Diaz Isaac, in prep

All members of the ensemble yield plausible atmospheric transport (comparison to winds, ABL depth, surface flux observations).

All physics parameterizations contribute significantly.
Diaz-Isaac, in prep
How large are transport differences compared to flux contributions? About 50% of the continental biological CO$_2$ signal.

Eastern region site-to-site daytime ABL CO$_2$ contributions from continental biogenic fluxes. August, 2008. WRF, Carbon Tracker boundaries.

Eastern region site-to-site daytime ABL total CO$_2$ differences between two transport realizations. August, 2008. WRF, Carbon Tracker boundaries.
OK, transport matters. So what do we do about this?
Are the models biased? Examination of a 45-member WRF parameterization ensemble

- Regional wind speed ME is **positive for all the configurations** except one.
- Generally one PBL scheme (i.e., YSU) shows a **higher ME** than the rest.

- Regional wind direction mean error is highly variable across the different model configurations.
- Generally one PBL scheme (i.e., YSU) and LSM (i.e., RUC) shows a **higher ME**.

Diaz-Isaac et al, in prep
Atmospheric Carbon and Transport – America

A new NASA Earth Venture mission dedicated to improving the accuracy, precision and resolution of atmospheric inverse estimates of CO₂ and CH₄ sources and sinks

Kenneth Davis¹, David Baker², John Barrick³, Joseph Berry⁴, Kevin Bowman⁵, Edward Browell³, Lori Bruhwiler⁶, Gao Chen³, George Collatz⁷, Robert Cook⁸, Scott Denning², Jeremy Dobler⁹, Syed Ismail³, Andrew Jacobson⁶, Anna Karion⁶, Thomas Lauvaux⁵, Bing Lin³, Matt McGill⁷, Byron Meadows³, Anna Michalak⁴, Natasha Miles¹, John Miller⁶, Berrien Moore¹⁰, Amin Nehrir³, Lesley Ott⁷, Michael Obland³, Christopher O’Dell², Stephen Pawson⁷, Gabrielle Petron⁶, Andrew Schuh², Colm Sweeney⁶, Pieter Tans⁶, Yaxing Wei⁸, and Melissa Yang³

¹The Pennsylvania State University, ²Colorado State University, ³NASA Langley Research Center, ⁴Carnegie Institution of Stanford, ⁵NASA Jet Propulsion Lab, ⁶NOAA ESRL/University of Colorado, ⁷NASA Goddard Space Flight Center, ⁸Oak Ridge National Lab, ⁹Exelis, Inc., ¹⁰University of Oklahoma
ACT-America

http://act-america.larc.nasa.gov/

Image credit: Tim Marvel / NASA Langley
ACT-America Mission Objectives

1. Quantify and reduce atmospheric transport uncertainties
2. Improve regional-scale, seasonal prior estimates of CO$_2$ and CH$_4$ fluxes
3. Evaluate the sensitivity of Orbiting Carbon Observatory-2 (OCO-2) column CO$_2$ measurements to regional variability in tropospheric CO$_2$

These goals address the three primary sources of uncertainty in atmospheric inversions – transport error, prior flux uncertainty and limited data density.
Imagine air flowing across a landscape that is a source of GHGs, and aircraft data tracking the changes in GHG mole fraction across the landscape...
Simplified vision of model (flux and transport) ensemble pruning using airborne observations

**Pruned ensembles lead to more accurate and precise flux inversions using long-term GHG data (towers, flasks, satellite, NOAA airborne profiling).**
The eastern half of the United States, a region that includes a highly productive biosphere, vigorous agricultural activity, extensive gas and oil extraction, dynamic, seasonally varying weather patterns and the most extensive GHG and meteorological observing networks on Earth, serves as an ideal setting for the ACT-America mission.
Stormy-weather (transport-dominated) flight plans (objective 1)

- Measure atmospheric state, CO\textsubscript{2}, CH\textsubscript{4} and tracers (CO, \textsuperscript{14}CO\textsubscript{2}, O\textsubscript{3}) across and around frontal systems.
- Evaluate atmospheric transport in our model ensemble. Prune transport ensemble.
Fair-weather (flux-dominated) flight plan (objectives 1 and 2)

- Measure winds, ABL depth, CO₂, CH₄ and tracers (CO, ¹⁴CO₂, O₃) across 100’s of km.
- Solve for regional fluxes for the days of flights directly – prune prior flux estimates.
- Evaluate fair weather meteorology in atmospheric transport ensemble
OCO-2 under-flights (objective 3)

Tim Marvel, NASA Langley

- Measure much of the atmospheric CO₂ column at < 20km horizontal resolution across 100’s of km below OCO-2. Also measure aerosols, clouds with lidar.
- Compare spatial variability in airborne CO₂ to OCO-2 CO₂. Evaluate OCO-2 ability to capture tropospheric CO₂ variability along-track.
**Flight Campaign Schedules**

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<th>Fall 2016</th>
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Proposed start date: *Summer 2016, given timeline for C-130 modifications and aircraft access for flight testing.*


Year 5 (2019): Wrap up goals 1-3. Apply findings to a multi-year reanalysis of N. American C fluxes using long-term observational assets (i.e., demonstrate new atmospheric inversion system).

End date: 20 Jan, 2020.
Overarching Goal

• The overarching goal of the Atmospheric Carbon and Transport-America (ACT-America) mission is to improve regional to continental scale diagnoses of carbon dioxide (CO₂) and methane (CH₄) sources and sinks.

• The mission will enable and demonstrate a new generation of atmospheric inversion systems for quantifying atmospheric CO₂ and CH₄ fluxes.

• These inverse flux estimates will be able to:
  – Evaluate and improve terrestrial carbon cycle models, and
  – Monitor carbon fluxes to support climate-change mitigation efforts.
conclusions

• Carbon cycle science is in its early stages as a predictive, data-rich science.
• Basic process understanding needs to be improved.
• Multi-state observations and ensemble modeling is being introduced.
• Time is short. The time for management is now.
Thanks!