North American CO$_2$ Fluxes, Inflow, and Uncertainties Estimated Using Atmospheric Measurements from the North American Carbon Program

The past decade has seen major expansion of the North American atmospheric carbon observing system:
Many different laboratories are providing data, with different levels of quality assurance and stability of funding:

Data Providers

In Situ:
- Environment Canada (D. Worthy)
- Penn State University (N. Miles, S. Richardson, K. Davis)
- NCAR (B. Stephens)
- Oregon State University (B. Law, A. Schmidt)
- Lawrence Berkeley National Lab (S. Biraud, M. Fischer, M. Torn)
- Earth Networks (C. Sloop)
- California Air Resources Board (Y. Hsu)
- Harvard University (J. W. Munger, S. Wofsy)
- U of Minnesota (T. Griffis)

Remote Sensing:
- TCCON (D. Wunch, P. Wennberg, G. Toon)
- GOSAT-ACOS (C. O’Dell)
- OCO-2 team

Comparability among datasets is crucial for flux estimation and trend detection.
The past decade has seen major expansion of the North American atmospheric carbon observing system:

- US efforts under North American Carbon Program
  - NOAA Network Expansion
  - Regional efforts, e.g., ORCA, Calibrated Ameriflux, RACCOON, California Air Resources Board
  - Special projects, e.g., INFLUX, CARVE, MCI, LA Megacities, Gulf Coast Intensive, CALGEM

- Expansion of Environment Canada GHG monitoring network

- Earth Networks commercial GHG network
CarbonTracker-Lagrange: A new tool for regional- to continental-scale flux estimation
CarbonTracker-Lagrange: A new tool for regional- to continental-scale flux estimation

- New Lagrangian inverse-modeling framework under development at NOAA Earth System Research Laboratory in collaboration with many partners. Funding provided by NOAA’s Climate Program Office Atmospheric Chemistry, Carbon Cycle and Climate (AC4) Program and by NASA’s Carbon Monitoring System.
CarbonTracker-Lagrange: A new tool for regional- to continental-scale flux estimation

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**Modeling team:**
- AER, Inc.: M. Mountain, T. Nehrkorn, J. Eluszkiewicz
- Carnegie Institution for Science/Stanford: A. Michalak, V. Yadav, M. Qui
- Colorado State University: C. O’Dell
- Harvard University: S. Wofsy, S. Miller, J. Benmergui
- NOAA ARL: R. Draxler, A. Stein
CarbonTracker-Lagrange: A new tool for regional- to continental-scale flux estimation


- Species independent footprints are computed stored for each measurement.

- **AER, Inc.** is responsible for STILT-WRF runs, and we are also testing NOAA Air Resources Laboratory’s HYSPLIT-NAM and HYSPLIT-HRRR (High Resolution Rapid Refresh, an experimental real time 3-km simulation from NOAA-ESRL).
Why do we need CarbonTracker-Lagrange?
Some limitations of the global Eulerian CarbonTracker

- Solves for weekly scaling factors on large ecoregions
  - Limited flexibility to adjust seasonal and spatial patterns
- Problems simulating inflow to North America perhaps due to sparse data upwind, transport errors, 6-week assimilation window.
- Computationally intensive – takes several months to produce a new 10 year run.

Why do we need CarbonTracker-Lagrange?
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Global CarbonTracker has a persistent high bias at North American surface sites during summer:

CarbonTracker 2013B Residuals: LEF Tall Tower 396 m a.g.l
Comparison with NOAA/ESRL aircraft data shows that CT2013B summertime bias is pervasive in the Northern Hemisphere:

![Graph showing comparison with NOAA/ESRL aircraft data](image)

Figure courtesy of Andy Jacobson

NOAA/ESRL Global Monitoring Division Aircraft Program:
[http://www.esrl.noaa.gov/gmd/ccgg/aircraft/data.html](http://www.esrl.noaa.gov/gmd/ccgg/aircraft/data.html)

Principal Investigator: Colm Sweeney
A NOAA contribution to the North American Carbon Program
CarbonTracker-Lagrange Inversion Framework
\[ \hat{s} = s_p + (HQ)^T (HQH^T + R)^{-1} (z - Hs_p) \]

- **H** is atmospheric transport operator (i.e. the footprints)
- **Q** is the prior error covariance matrix
- **R** is the model-data mismatch matrix
- **s_p** is a vector containing the prior flux estimate
- **\( \hat{s} \)** is a vector containing the revised fluxes
- **z** is observations minus background

We need a model of our model errors!
CarbonTracker-Lagrange Inversion Framework

\[ \hat{s} = s_p + (HQ)^T (HQH^T + R)^{-1} (z - Hs_p) \]

Maps flux errors onto observations

Transport model errors, unresolved variability, measurement errors
CarbonTracker-Lagrange Inversion Framework

\[ \hat{s} = s_p + (HQ)^T (HQH^T + R)^{-1} (z - Hs_p) \]

Maps flux errors onto observations

Transport model errors, unresolved variability, measurement errors

Relative magnitude of HQH^T and R controls weighting of data relative to prior.
CarbonTracker-Lagrangian Inversion Framework

- Solve for fluxes at $1^\circ \times 1^\circ \times 3$ hourly resolution with prescribed spatial and temporal covariance.
- Efficient sparse-matrix algorithms (Yadav and Michalak, Geosci. Model Dev., 6, 583-590, 2013) with pre-computed transport enables many permutations of the inversion to be evaluated.
  - e.g., Multiple priors

Net Ecosystem Exchange: July 2010 Monthly Mean

- CarbonTracker Prior
- CASA-GFED-CMS
- SiB-CASA
CarbonTracker-Lagrange Preliminary Results
CarbonTracker-Lagrange Preliminary Results

CarbonTracker-Lagrange
10 July – 10 August 2012

- All available observations
- CarbonTracker background
- $\tau_{\text{spatial}} = 1000 \text{ km}$, $\tau_{\text{temporal}} = 7$ days
CarbonTracker-Lagrange Uncertainty
10 July – 10 August 2012

• \( V = Q - QH^T(R + HQH^T)^{-1}HQ \)
• Does not depend on posterior residuals!
Preliminary Comparison: CT2013B and CT-Lagrange

- **CT-L uncertainty**
- **μmole m$^{-2}$ s$^{-1}$**
- **CT-L minus CT2013B**
- **CT-L Uncertainty**
Flux difference with Data Selection Similar to CT2013B

- NOAA/ESRL, Environment Canada, NCAR only

Flux difference with Empirical Boundary Condition

- Empirical Boundary Condition derived from NOAA/ESRL Marine Boundary Layer (E. Dlugokencky PI) and Aircraft (C. Sweeney PI) datasets
Despite regional differences large area totals are fairly consistent across large regions:

**Aggregated Totals: 10 July – 10 August 2012 (PgCyr\(^{-1}\))**

<table>
<thead>
<tr>
<th>Region</th>
<th>CT2013B</th>
<th>CT-L CT2013B Boundary</th>
<th>CT-L Empirical Boundary</th>
<th>CT-L CT2013 Boundary Core Network</th>
<th>Prior</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>-7.4</td>
<td>-7.8 ± 0.8</td>
<td>-6.6 ± 0.8</td>
<td>-8.0 ± 0.8</td>
<td>-6.8 ± 2.0</td>
</tr>
<tr>
<td>Temperate 25°N &lt; 50°N</td>
<td>-2.5</td>
<td>-2.7</td>
<td>-2.3</td>
<td>-2.7</td>
<td>-2.3</td>
</tr>
<tr>
<td>Boreal &gt; 50°N</td>
<td>-4.4</td>
<td>-4.5</td>
<td>-4.3</td>
<td>-4.6</td>
<td>-3.5</td>
</tr>
</tbody>
</table>
How well does CarbonTracker-Lagrange fit the data?
Posterior – OBS[bio]:
LEF–continuous–tall–tower–396

Median = 0.15

Median = 1.47
Posterior – OBS[bio]:
GHG25–continuous–short–tower–95

3.91, sd= 6.3, Q.16,Q.50,Q.84: –2.5 2.79 10.04, n= 51

Median=0.71

Median=2.79

Hshat–OBS.bio, ppm

Frequency
Oregon State University (& Earth Networks): Silverton, OR 269 magl
Median = -4.05

Median = -0.46

Posterior – OBS[bio]:
OSI–continuous–tall–tower–269

mean = -3.21, sd = 7.9, Q.16, Q.50, Q.84: -9.76, -4.05, 3.34, n = 77
July 2010 Cumulative Sensitivity to Surface Flux for In Situ (Flask and Continuous) and ACOS GOSAT quality controlled data

- Number of GOSAT observations is relatively low and sensitivity to surface fluxes is much lower than for in situ data
- Increased sensitivity for column data may be achieved by extending domain further over the Atlantic
Summary and Next Steps

• CT-Lagrange flux patterns are significantly different than CT2013B, but regional totals are similar.

• Ensemble of inversions with different priors, uncertainty parameters, and data weighting is planned.

• Boundary value optimization has been implemented but not fully functional.

• Network design studies – footprints exist for a large suite of candidate surface sites and enhanced aircraft network.

• Simulations with ACOS GOSAT retrievals are well underway.

• Continuing NASA CMS support will enable simulations with OCO-2 data and to extend analysis to South America.
Additional Slides
\[ \hat{s} = s_p + (HQ)^T (HQH^T + R)^{-1} (z - HS_p) \]


H is atmospheric transport operator (i.e. the footprints)
Q is the prior error covariance matrix
R is the model-data mismatch matrix
s_p is a vector containing the prior flux estimate
\( \hat{s} \) is a vector containing the revised fluxes

Modified framework for boundary optimization:
- H has additional columns for boundary value grid cells
- s_p and \( \hat{s} \) contains additional elements
- Q contains additional rows and columns. No cross-correlation between boundary values and fluxes
CarbonTracker - Lagrange

- Combination of surface, aircraft and column data enables separate optimization of surface fluxes and boundary/initial values.

CarbonTracker-Lagrange profiles corresponding to the Park Falls NOAA/UWI WLEF-TV Tall Tower and TCCON site

CASAGFEDCMS Net Ecosystem Exchange

- Contrast between surface and free troposphere data provides information about surface versus boundary influences.

- Dense aircraft plus tall tower data is best, but bias-free column datasets could also provide a useful constraint.
Gridded boundary footprints: Use all trajectory points within the mole fraction estimation domain.

Resolution: daily x 3 lon x 2 lat x three vertical bins.

Each trajectory gets 1/500th of the weight, but trajectories may have different number of points included.

Units are ppm per ppm.
Free Troposphere Boundary Correction

synthetic case 1c: true boundary perturbation 1000m mean over time

TRUTH

synthetic case 1c
shat_pbl mean over time

POSTERIOR

PBL boundary influence
July 2010 Synthetic Data Inversion; Monthly Mean Fluxes

- Idealized case: perfect transport, perfect observations (no noise), no boundary value errors
- Including GOSAT ACOS observations does not significantly change results
Prior Error Covariance $Q$

Yadav and Michalak, GMD, 2013:

\[ Q = \sigma_s^2 \left[ \exp \left( -\frac{X_T}{l_T} \right) \right] \otimes \left[ \exp \left( -\frac{X_S}{l_S} \right) \right] \]

- Consider: $D$ as temporal covariance and $E$ as spatial covariance:

\[
D_{(p \times q)} \otimes E_{(r \times t)} = \begin{pmatrix}
    d(1,1)E & \cdots & d(1,q)E \\
    \vdots & \ddots & \vdots \\
    d(p,1)E & \cdots & d(p,q)E
\end{pmatrix} \in Q_{(pr \times qt = m \times m)}
\]
We have generalized to allow space- and time-varying sigma:

\[ \sigma = (\sigma_1, \sigma_2, \ldots, \sigma_{m-1}, \sigma_m) \]

\[ \sigma \cdot \sigma^T = \begin{bmatrix} \sigma_1^2 & \cdots & \sigma_1 \sigma_m \\ \vdots & \ddots & \vdots \\ \sigma_m \sigma_1 & \cdots & \sigma_m^2 \end{bmatrix} \]

\[ I_\sigma = \begin{bmatrix} \sigma_1^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_m^2 \end{bmatrix} \]

\[ Q = (\sigma \cdot \sigma^T) \times (D \otimes E) = I_\sigma \cdot (D \otimes E) \cdot I_\sigma \]

Beta algorithm (in testing) that leverages Yadav and Michalak framework to avoid building full Q and full \( \sigma \cdot \sigma^T \).
Model-Data Mismatch Matrix R

• Many studies assume R varies slowly, e.g., assigned site by site with a seasonal cycle but no day to day or within day variability

• CT-L bottom up model for R informed by:
  • standard deviation for each observation (e.g. does measurement occur during or proximal to a frontal passage, wind shift, etc.)
  • Modeled and/or measured vertical gradient information
  • Proximity to flux gradients (e.g. coastlines, urban areas)
  • Complex terrain

• So far no off-diagonal elements
CarbonTracker-Lagrange profiles corresponding to Park Falls, WI:

1-31 July 2010, 14:00 LST

- Impact of surface fluxes minimal above 3000m
- CASA/GSFC versus CT-2011oi NEE differences subtle
- Sporadic fire influence aloft.
- Small fossil fuel signal.

- CASA/GSFC fluxes courtesy of G. J. Collatz
- CarbonTracker fluxes courtesy of A. Jacobson

Daily Profiles

Monthly Mean
WRF-STILT Footprint Library

- Footprints are species independent and can be used to simulate a variety of long-lived gases.
- AER, Inc. is responsible for STILT-WRF runs, and we are also testing HYSPLIT-NAM and HYSPLIT-HRRR (High Resolution Rapid Refresh, an experimental real time 3-km simulation from NOAA-ESRL).
- Footprints for > 2 million CO$_2$ in situ (continuous and discrete), TCCON and GOSAT measurements for the period 2007-2012 have been computed with near-term plans to extend through 2015.

$log_{10}\left(\frac{ppm}{\mu mole \cdot m^{-2} \cdot s^{-1}}\right)$