A Lagrangian Framework for North American Regional-Scale Flux Estimation and Observing System Design

Arlyn Andrews[1], Lori Bruhwiler[1], Huilin Chen[1,2], Gabrielle Petron[1,2], Caroline Alden[3], John Miller[1,2], Ken Masarie[1], Colm Sweeney[1,2], Pieter Tans[1], Janusz Eluszkiewicz[4], Marikate Mountain[4], Jennifer Hegarty[4], Thomas Nehrkorn[4], John Henderson[4], Anna Michalak[5,6], Vineet Yadav[6], Sharon Gourdji[6], Kim Mueller[7], Andrew Schuh[8], Chris O'Dell[8], Elena Novakovskaia[9], Roland Draxler[10], Ariel Stein[10]

[1]NOAA Earth System Research Laboratory, Boulder, CO; [2]Cooperative Institute for Research in Environmental Sciences, University of Colorado; [3]Institute of Alpine and Arctic Research, University of Colorado; [4]Atmospheric and Environmental Research, Inc., Lexington, MA; [5]Carnegie Institute for Science, Stanford, CA; [6]Stanford University, Stanford, CA; [7]University of Michigan, Ann Arbor, MI; [8]Cooperative Institute for Research in the Atmosphere, Colorado State University;[9]Earth Networks, Germantown, MD; [10]NOAA Air Resources Laboratory, College Park, MD

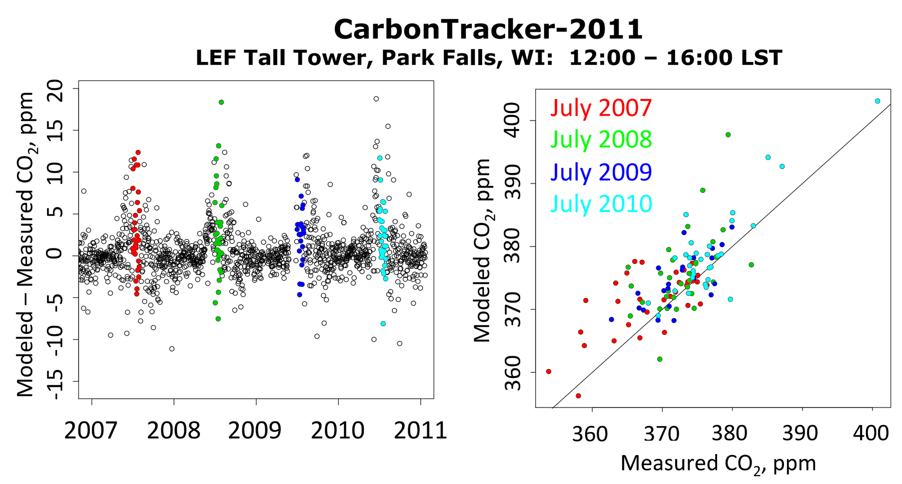
Abstract: We are developing a flexible, high-resolution, regional inverse modeling framework to estimate greenhouse gas emissions and sinks from current and planned surface, aircraft, and satellite observations of CO_2 and related gases. Our initial efforts are focused on analyzing North American Carbon Program data collected from 2007-2010. This period includes the expansion of the NOAA tall tower and aircraft networks, the Canadian Greenhouse Gas Measurement Program, and the Total Column Carbon Observing Network (TCCON) and coincides with the availability of the GOSAT Atmospheric CO_2 Observations from Space (ACOS) dataset. Data from NACP-supported regional monitoring programs such as the Mid-Continent Intensive (MCI), ORCA (Oregon and California) and the Regional Atmospheric Continuous CO_2 Network in the Rocky Mountains (Rocky RACCOON) are also available during this period.

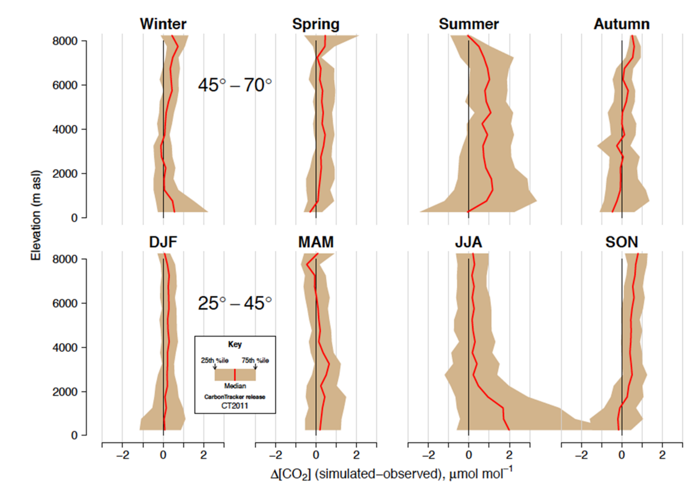
CarbonTracker-Lagrange

We use Lagrangian atmospheric transport models driven by high-resolution (~10 km) meteorological fields to compute libraries of footprints (influence functions) corresponding to individual observations. The initial effort to compute sampling footprints is substantial, but once the footprints are available, many variations of the flux optimization scheme can be quickly evaluated. The footprints are computed and stored in a species-independent manner, and thus the will enable multi-species inverse studies using CO_2 data along with CO, $\delta^{13}CO_2$, COS and radiocarbon observations. The footprints can also be used for inverse modeling of other greenhouse gases such as CH_4, N_2O and halocarbons.

Motivation

- CarbonTracker-2011 observation residuals are higher than expected and indicate errors in estimated fluxes and/or modeled atmospheric transport. A regional Lagrangian modeling framework complements the existing global CarbonTracker and can be used to evaluate strategies for using the data more effectively.





🡑Comparisons with independent aircraft data show large positive summertime biases throughout the troposphere.

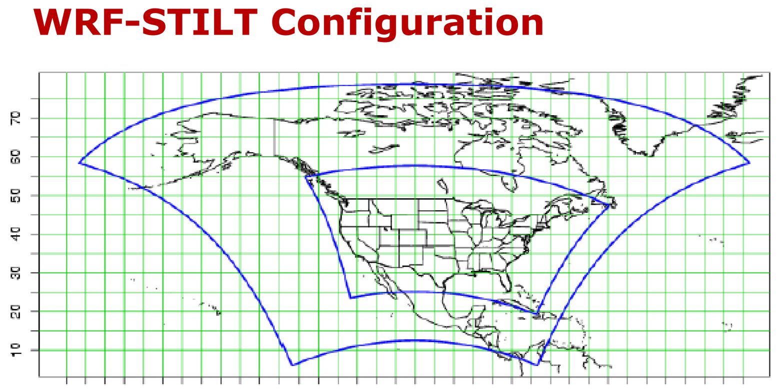
	Mean	Median	Std. Dev.	R^2
2007	3.0	1.9	4.7	0.44
2008	2.9	2.1	5.5	0.29
2009	2.3	2.7	3.4	0.50
2010	2.2	2.3	3.8	0.72

🡔Model comparisons in summer show significant biases, and day-to-day variability is not well represented in the model. Statistics correspond to July model data comparisons for LEF afternoon average data.

Objectives

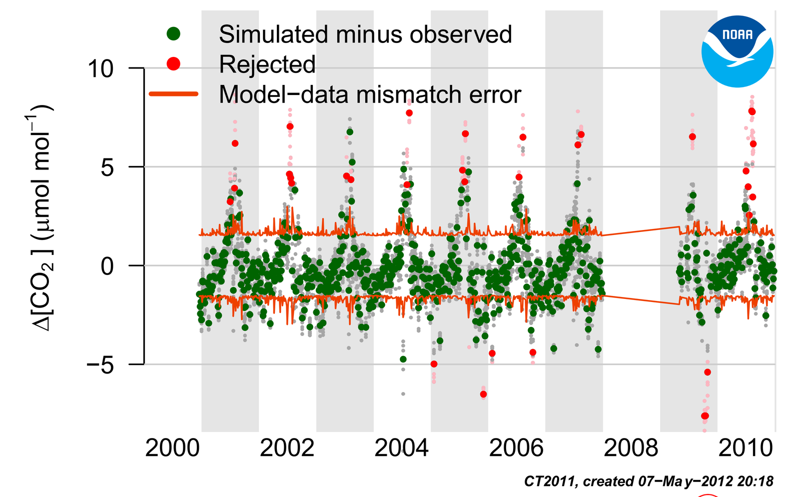
- Implement recently developed Lagrangian inverse modeling tools (Gourdji et al., 2010; Schuh et al., 2010; Mueller, 2011; Gourdji et al., 2012; Lauvaux et al., 2012; Schuh et al,. 2013; Miller et al., 2013).
- Estimate 2007-2010 North American Fluxes using high-resolution WRF-STILT footprints (Nehrkorn et al., 2010) by optimizing both fluxes and boundary values.
- Use pre-computed footprints to evaluate strategies for improving operational CT:
  - Alternate solution forms (e.g., separate scaling of photosynthesis and respiration)
  - Investigate different strategies for weighting of observations
  - Alternate vegetation classification, prior flux estimates, etc.
- Modify framework to estimate fluxes for other species and multi-species inversions (CH_4, $\Delta^{14}CO_2$, CO, $\delta^{13}CO_2$, COS, HCFC-22, HFC-134a)
- Implement STILT footprint functionality into the NOAA HYSPLIT model.
- Investigate transport uncertainty by substituting footprints from different LPDMs and/or meteorological data.
- Develop a strategy for producing routinely updated CT-Lagrange products.

WRF-STILT Configuration

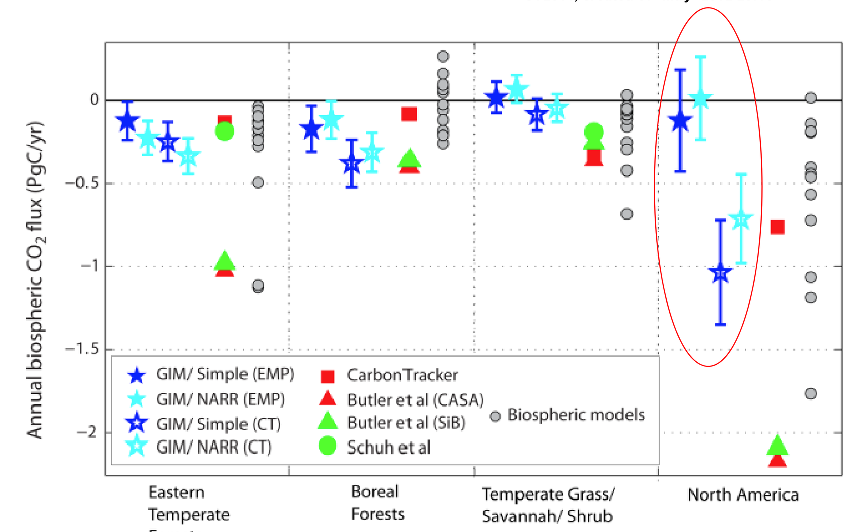


- Met fields available 2004-2010 with varying inner domain.
  - Inner grid resolution 10kmx10km, outer grid 40km x 40km
  - Overlapping forecasts initiated daily
  - Boundaries forced by NARR, with "gentle" internal nudging.
  - Time-averaged mass fluxes reported instead of snapshots
  - Output includes Grell-convection scheme parameters
  - -parameterized convection enabled in STILT for outer grid only
- Stochastic Time-Inverted Lagrangian Transport (STILT) model used to compute footprints for each observation
  - Species-independent footprints are stored in convenient compressed netCDF4 format along with trajectory information.
  - 10 days, hourly resolution, 0.5° x 0.5°

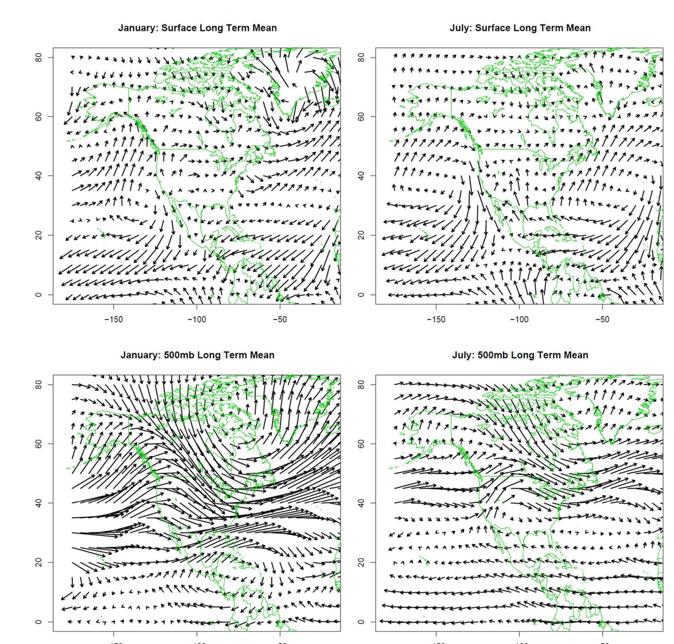
Optimizing Boundary Conditions for North America



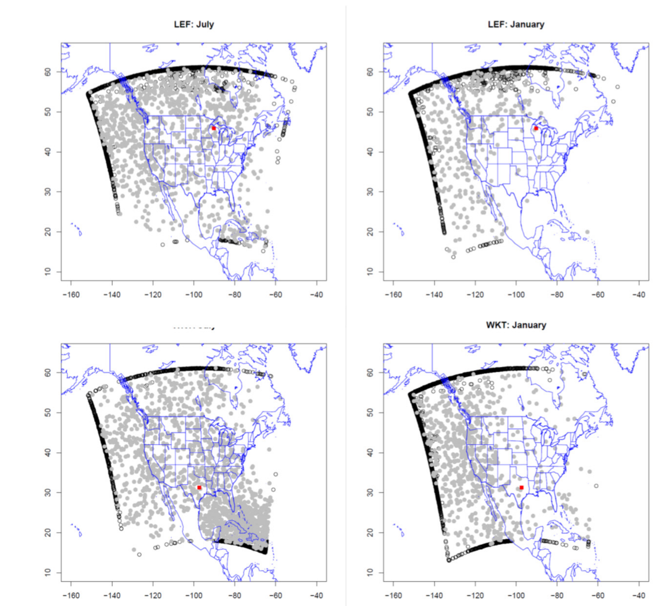
🡐CT2011 Residuals for Cold Bay, Alaska. The high positive outliers during summer at this site "upwind" of North America may result from errors in the estimated flux for poorly constrained regions elsewhere in the Northern Hemisphere. **The CarbonTracker global assimilation cannot correctly estimate fluxes for North America if boundary values are biased.** In a regional inversion, boundary values can be adjusted along with the fluxes.



🡑Gourdji et al., 2012 showed that small biases in boundary values can profoundly affect annual fluxes estimates at the continental scale.



🡑Long-Term mean horizontal wind vectors from the NCEP Reanalysis.

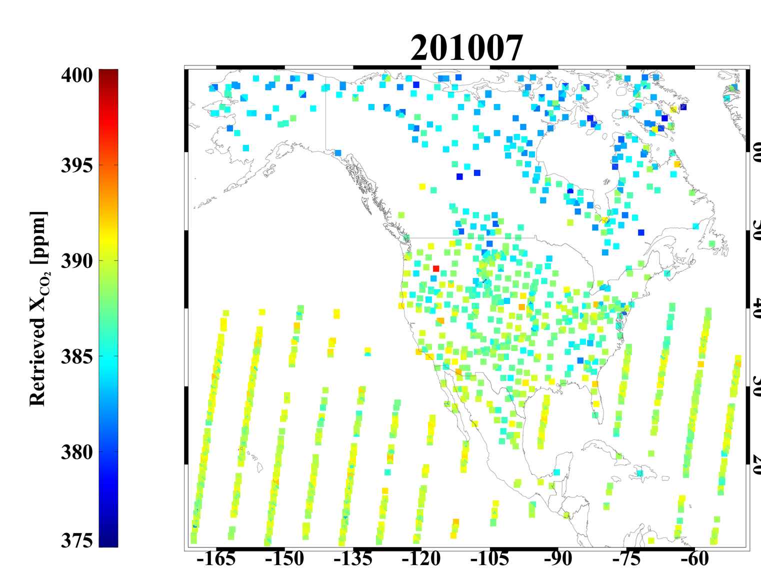


🡐Endpoint locations for daily back-trajectories started at 2pm LST and run backward in time for 10 days or until the air-particle leaves the domain. Trajectories were computed using the Stochastic Time-Inverted Lagrangian Transport (STILT) model, which simulates atmospheric dispersion. Gray filled symbols are those that remain within the domain at the end of the run.

- Most of the air enters the continent from the Northern air Western boundaries, especially during Winter.
- During summer, many trajectories remain within the domain after ten days, and at some sites, a significant fraction enter the domain from the South or East.
- A significant number of trajectories enter the domain in the mid-troposphere, so aircraft data are needed to constrain boundary values.
- We will simultaneously optimize surface fluxes and boundary values, building on recent work by Lauvaux et al., 2012.

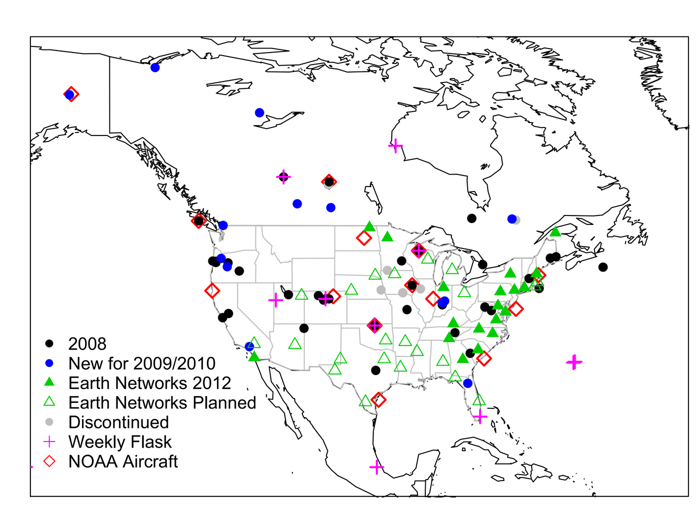
Implementation for NASA's Carbon Monitoring System

- Compute footprints for profiles corresponding to GOSAT scenes:
  - -Evaluate consistency among ACOS GOSAT, TCCON and CT-Lagrange optimized CO_2 fields.
  - -Implement geostatistical inversion capability in CT-Lagrange.
  - -Investigate strategies for assigning weights to column and in situ observations in a joint inversion.
- Summer 2012 test case:
  - -Investigate impact of new ground-based and TCCON data on flux estimates.
  - -Consider strategies for assimilating OCO-2 data in CT-Lagrange.
  - -Use alternative model to generate footprints to investigate transport uncertainty.
  - -Consider what additional observations are needed (i.e. network design).



🡐ACOS GOSAT column CO_2 observations for July 2010. Within our North American domain, approximately 500 – 1200 land scenes per month pass the quality control and cloud screening. Coverage over water is highly seasonal, with up to 1000 observations in mid-summer, but near zero from late fall through early spring.

The surface network has expanded significantly since 2008 with nearly 100 surface sites operating during Summer 2012. We are particularly interested in investigating how the newly available data affects flux estimates in the eastern US and Canada. 🡒



References

Gourdji, S. M., et al. (2012), North American CO2 exchange: inter-comparison of modeled estimates with results from a fine-scale atmospheric inversion, *Biogeosciences*, *9*(1), 457-475.

Gourdji, S. M., A. I. Hirsch, K. L. Mueller, V. Yadav, A. E. Andrews, and A. M. Michalak (2010), Regional-scale geostatistical inverse modeling of North American CO_2 fluxes: a synthetic data study, *Atmospheric Chemistry and Physics*, *10*(13), 6151-6167.

Hegarty, J., R. Draxler, A. Stein, J. Brioude, J. Eluszkiewicz, M. Mountain, T. Nehrkorn, and A. Andrews, Lagrangian Particle Dispersion Model Intercomparison and Evaluation Utilizing Measurements from Controlled Tracer Release Experiments, manuscript in preparation.

Lauvaux, T., et al. (2012), Constraining the CO2 budget of the corn belt: exploring uncertainties from the assumptions in a mesoscale inverse system, *Atmospheric Chemistry and Physics*, *12*(1), 337-354.

Miller, S. M., S. C. Wofsy, A. M. Michalak, E. A. Kort, A. E. Andrews, S. C. Biraud, E. J. Dlugokencky, M. L. Fischer, G. Janssens-Maenhout, B. R. Miller, S. A. Montzka, C. Sweeney, Evidence for a large fossil fuel methane source over the south-central US, submitted to PNAS.

Mueller, K. L. (2011), A Data-Driven Multi-Scale Statistical Investigation of Regional Sources and Sinks to Improve Knowledge of Terrestrial Carbon Cycling, edited.

Nehrkorn, T., J. Eluszkiewicz, S. C. Wofsy, J. C. Lin, C. Gerbig, M. Longo, and S. Freitas (2010), Coupled weather research and forecasting-stochastic time-inverted lagrangian transport (WRF-STILT) model, *Meteorology and Atmospheric Physics*, *107*(1-2), 51-64.

Schuh, A. E., A. S. Denning, K. D. Corbin, I. T. Baker, M. Uliasz, N. Parazoo, A. E. Andrews, and D. E. J. Worthy (2010), A regional high-resolution carbon flux inversion of North America for 2004 (vol 7, pg 1625, 2010), *Biogeosciences*, *7*(7), 2245-2245.

Schuh, A., T. Lauvaux, T. O. West, A. S. Denning, K. J. Davis, N. Miles, S. Richardson, M. Uliasz, E. Lokupitiya, D. Cooley, A. Andrews, S. Ogle, Evaluating atmospheric CO_2 inversions at multiple scales over a highly-inventoried agricultural landscape, Global Change Biology, in press.

Acknowledgements: This work has been supported in part by the Carbon Cycle Program of NOAA's Climate Program Office and by NASA Carbon Monitoring System funds.

Contact: Arlyn.Andrews@noaa.gov