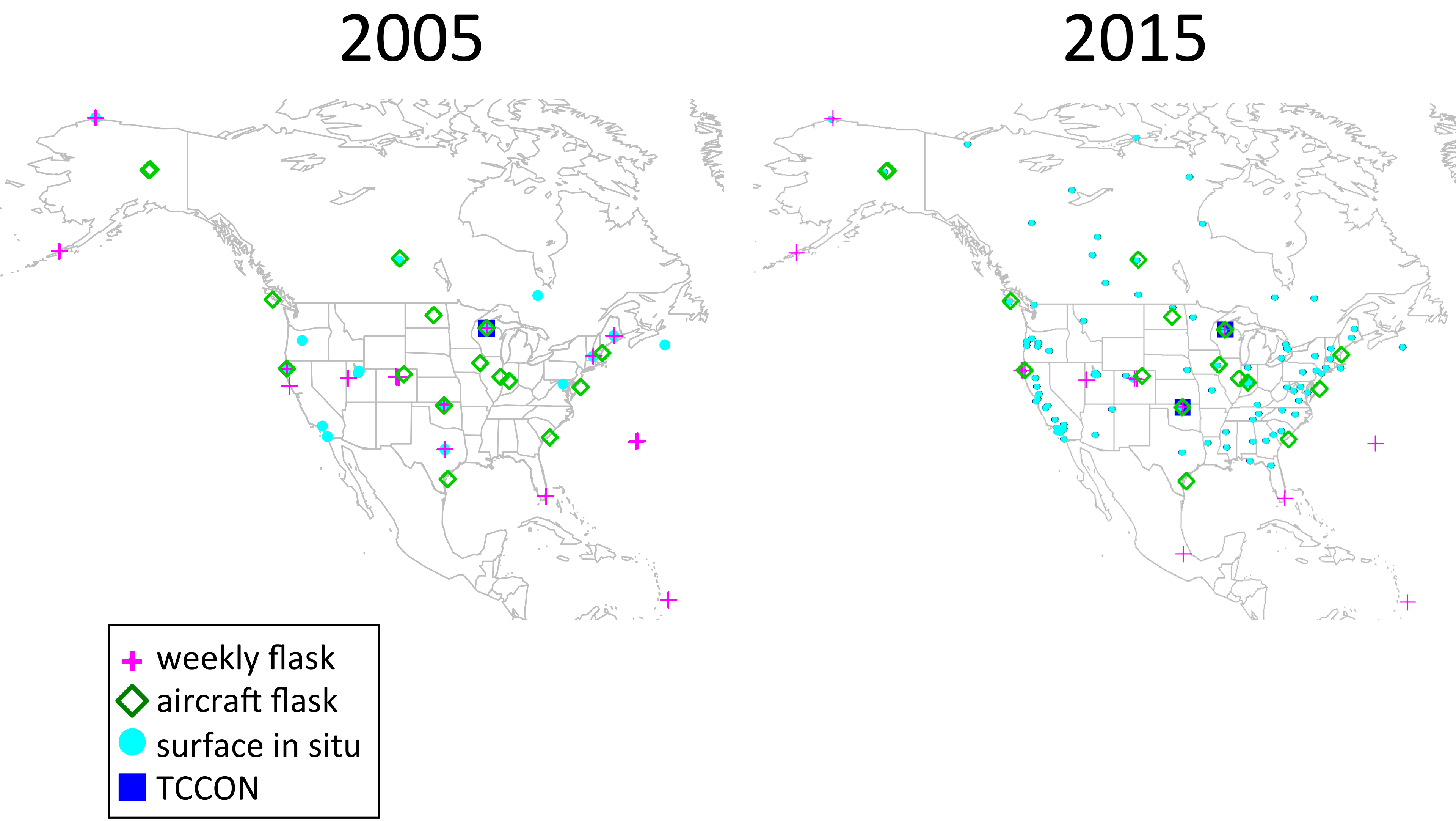
North American CO_2 Fluxes, Inflow, and Uncertainties Estimated Using Atmospheric Measurements from the North American Carbon Program

A.E. Andrews, K. Thoning, M. Mountain, M. Trudeau, K. Masarie, J. Benmergui, T. Nehrkorn, D. Worthy, E.J. Dlugokencky, C. Sweeney, A. Karion, J.B. Miller, B.B. Stephens, N. Miles, S. Richardson, K.J. Davis, A. Schmidt, B. Law, S. Biraud, M. Fischer, C. Sloop, J.W. Munger, S. Wofsy, T. Griffis, S.F.J. De Wekker, J. Lee, M.J. Parker, C. O'Dell, D. Wunch and P.P. Tans

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

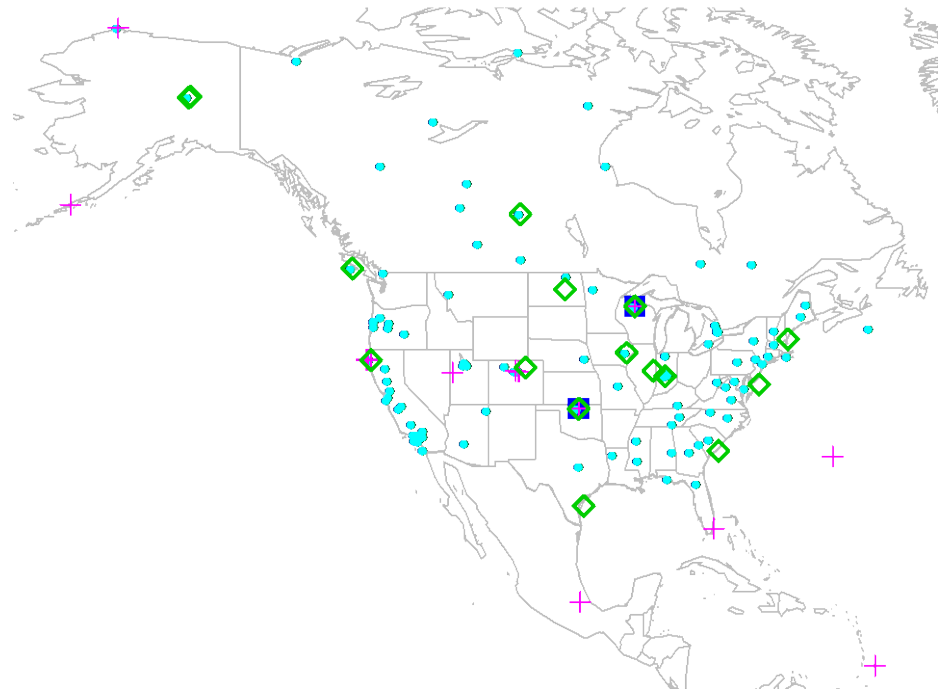
In Situ:

- NOAA Earth System Research Laboratory Global Monitoring Division (A. Andrews, E. Dlugokencky, K. Thoning, C. Sweeney, P. Tans)
- 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

2015



Comparability among datasets is crucial for flux estimation and trend detection.

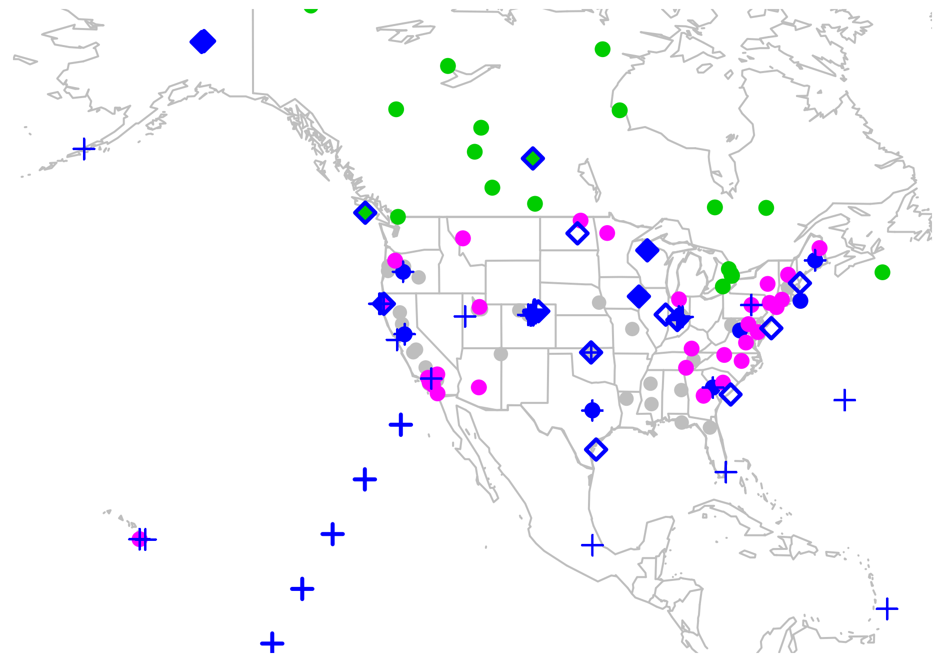
The past decade has seen major expansion of the North American atmospheric carbon observing system:

- 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

2015



NOAA/ESRL & Partners
Environment Canada
Earth Networks

CarbonTracker-Lagrange: A new tool for regional- to continental-scale flux estimation

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- 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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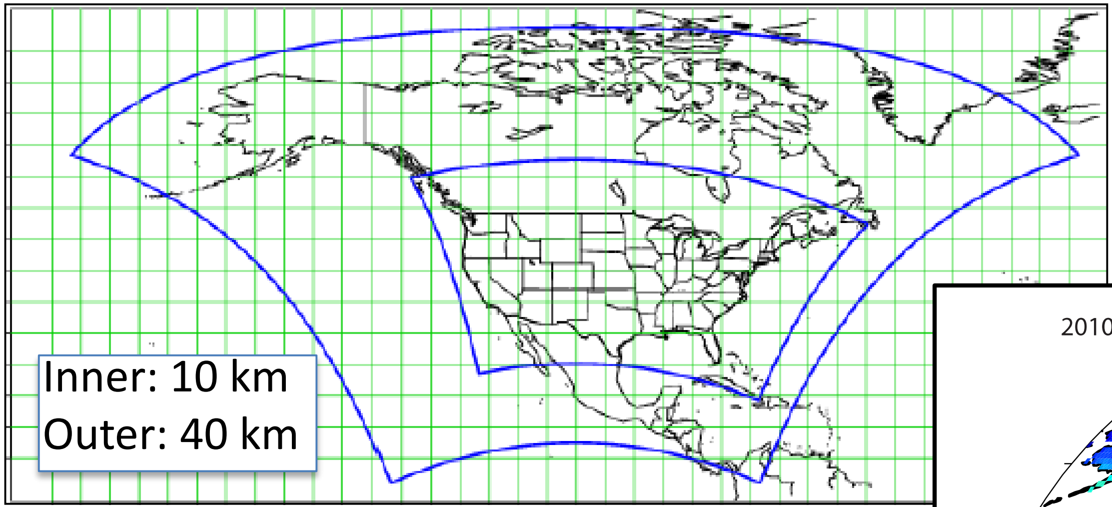
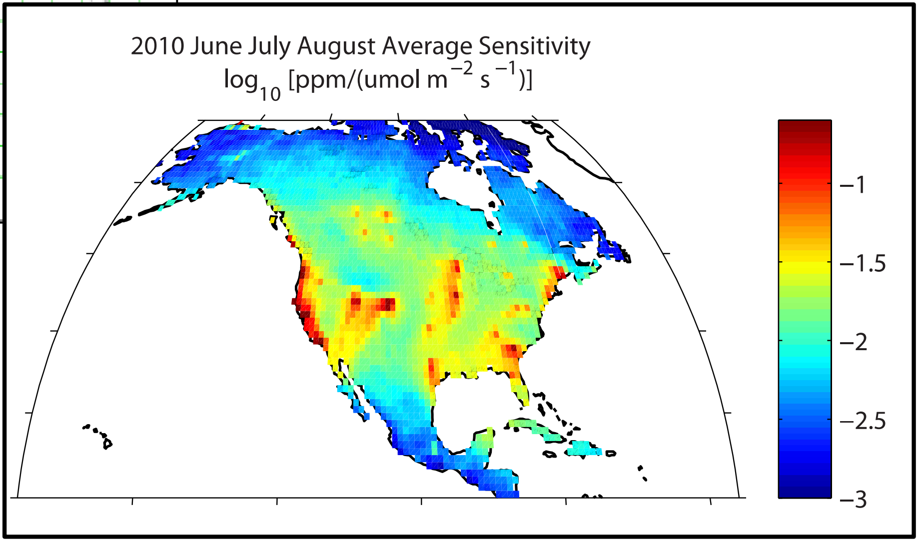
Modeling team:

- NOAA ESRL & CIRES: A. Andrews, K. Thoning, M. Trudeau, S. Basu, J. Miller, K. Masarie, L. Hu
- 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

- High-resolution WRF-STILT atmospheric transport model customized for Lagrangian simulations (Nehrkorn et al., *Meteorol. Atmos. Phys.*, *107*, 2010).
- 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).



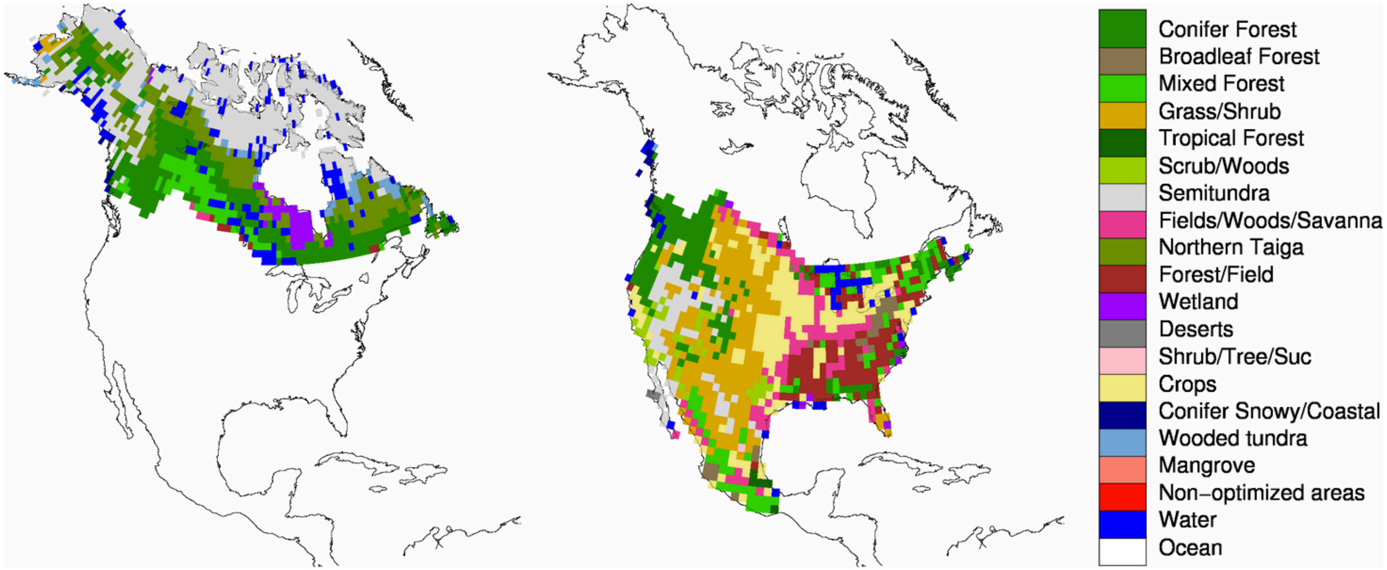


Why do we need CarbonTracker-Lagrange?

Why do we need CarbonTracker-Lagrange?

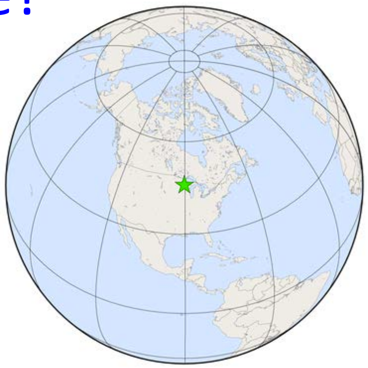
Some limitations of the global Eulerian CarbonTracker

- 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.

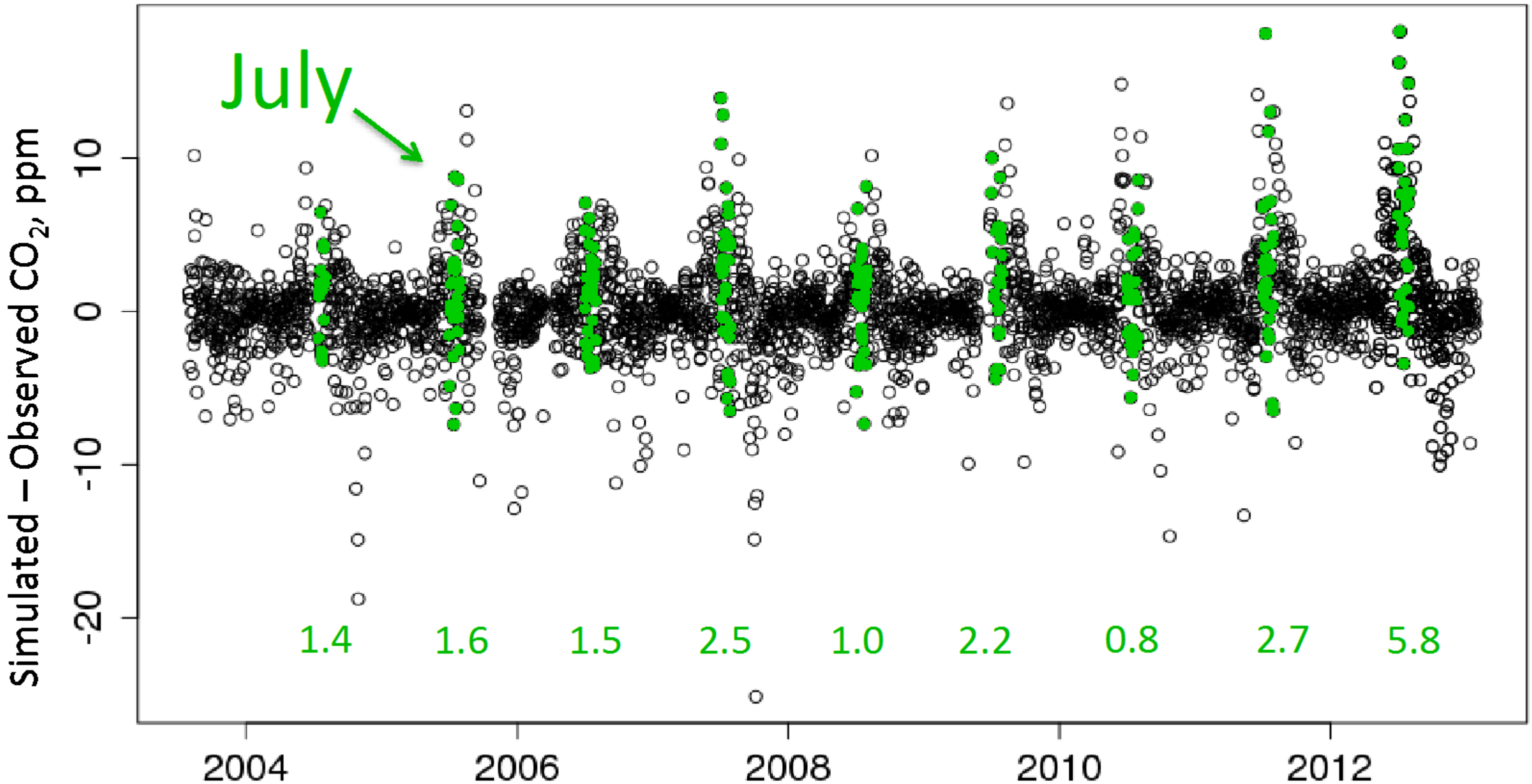


Why do we need CarbonTracker-Lagrange?

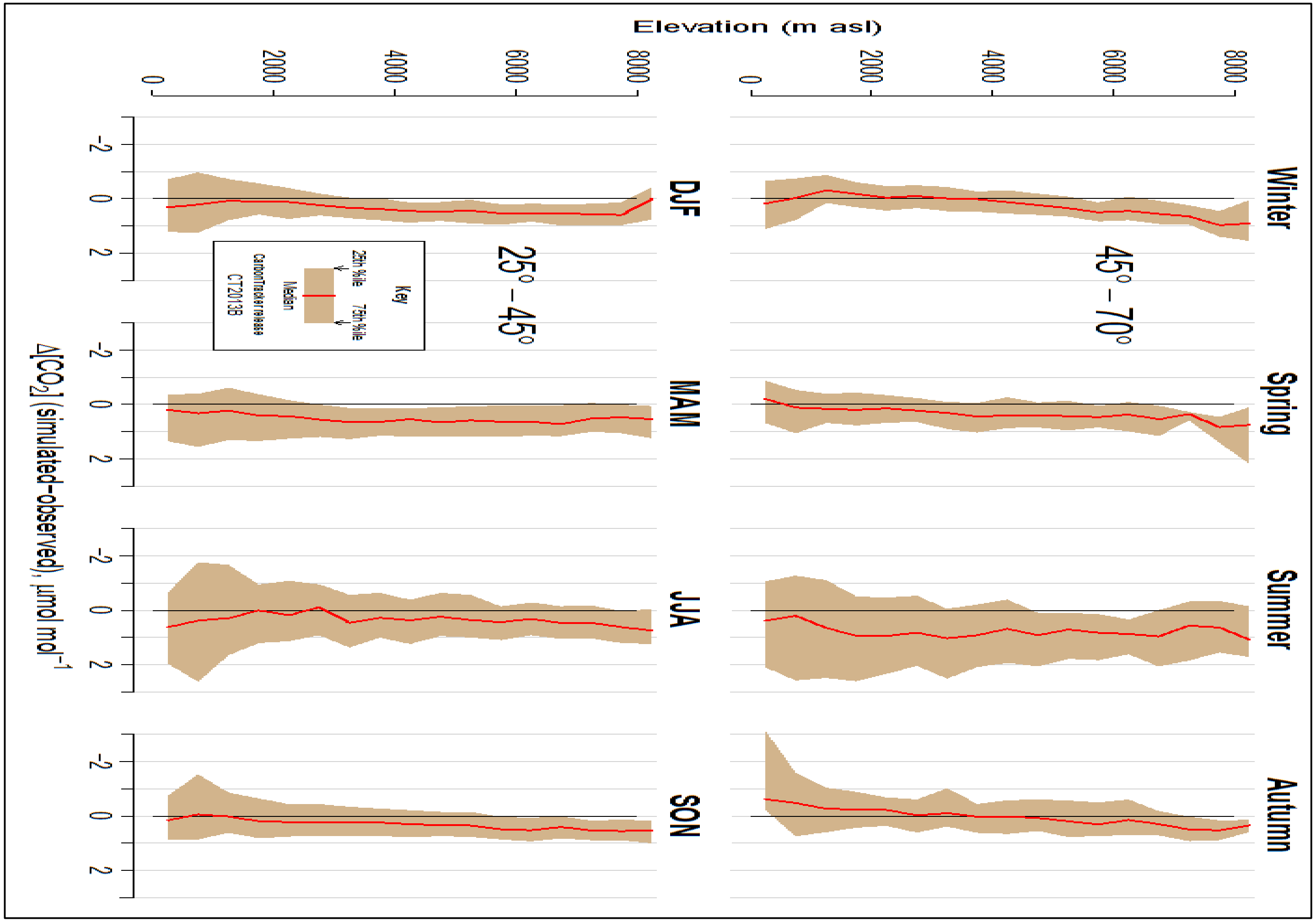
Global CarbonTracker has a persistent high bias at North American surface sites during summer:



CarbonTracker 2013B Residuals: LEF Tall Tower 396 magl



Comparison with NOAA/ESRL aircraft data shows that CT2013B summertime bias is pervasive in the Northern Hemisphere:



NOAA/ESRL Global Monitoring Division Aircraft Program:

http://www.esrl.noaa.gov/gmd/ccgg/aircraft/data.html

Principal Investigator: Colm Sweeney

A NOAA contribution to the North American Carbon Program

Figure courtesy of Andy Jacobson

CarbonTracker-Lagrange Inversion Framework

CarbonTracker-Lagrange Inversion Framework

$$\hat{\mathbf{s}} = \mathbf{s}_p + (\mathbf{HQ})^T (\mathbf{HQH}^T + \mathbf{R})^{-1} (\mathbf{z} - \mathbf{Hs}_p)$$

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

We need a model of our model errors!

CarbonTracker-Lagrange Inversion Framework

$$\hat{\mathbf{s}} = \mathbf{s}_p + (\mathbf{HQ})^T \, (\underbrace{\mathbf{HQH}^T}_{\text{Maps flux errors onto observations}} + \mathbf{R})^{-1} (\mathbf{z} - \mathbf{H}\mathbf{s}_p)$$

Transport model errors,
unresolved variability,
measurement errors

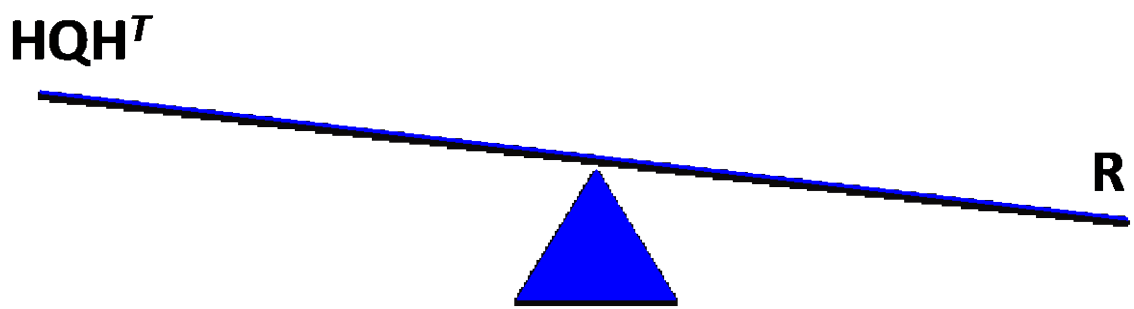
CarbonTracker-Lagrange Inversion Framework

$$\hat{\mathbf{s}} = \mathbf{s}_p + (\mathbf{HQ})^T (\underbrace{\mathbf{HQH}^T}_{\text{Maps flux errors onto observations}} + \mathbf{R})^{-1}(\mathbf{z} - \mathbf{H}\mathbf{s}_p)$$

Maps flux errors onto observations

Transport model errors, unresolved variability, measurement erros

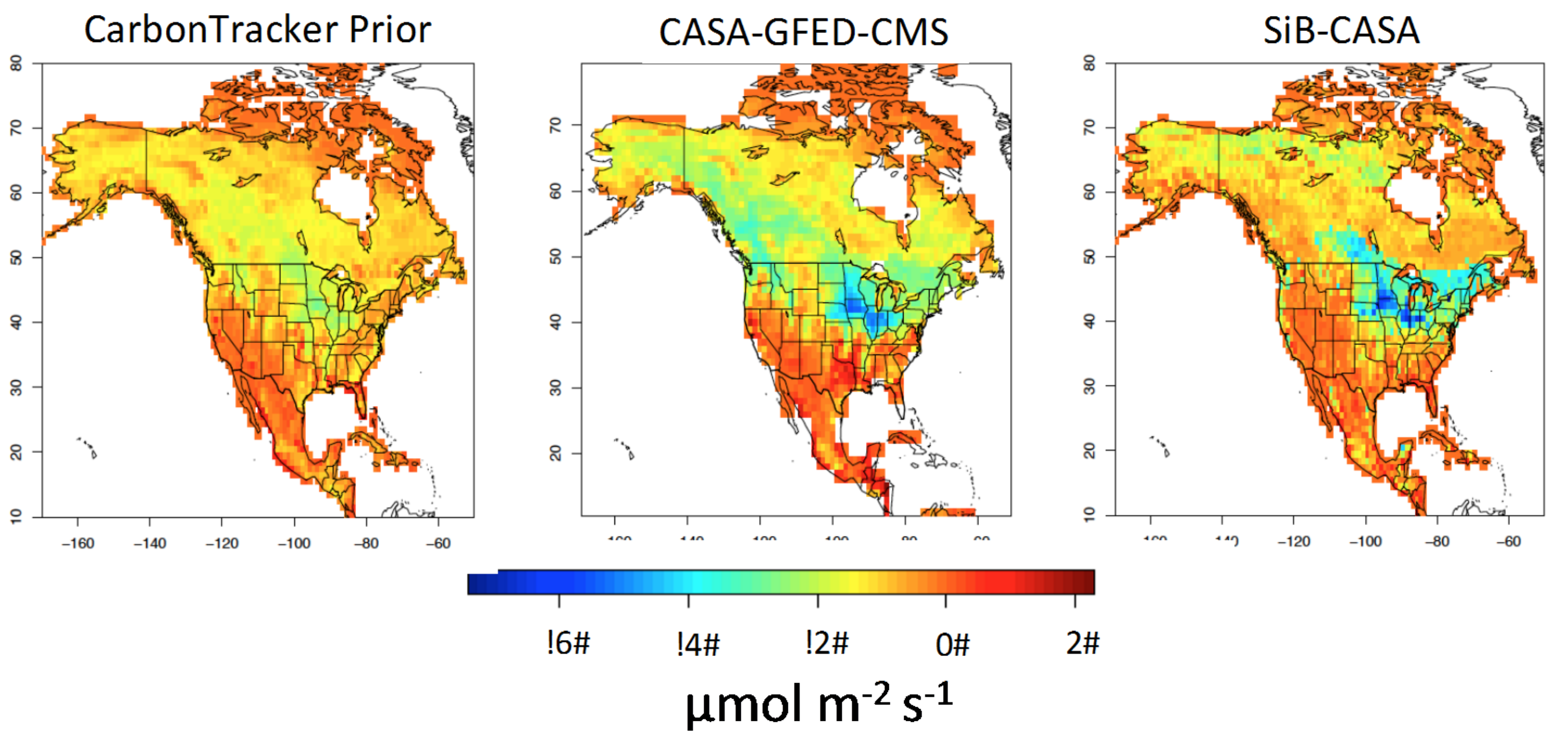
Relative magnitude of HQH^T and R controls weighting of data relative to prior.



CarbonTracker-Lagrange Inversion Framework

- Solve for fluxes at 1°× 1° × 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

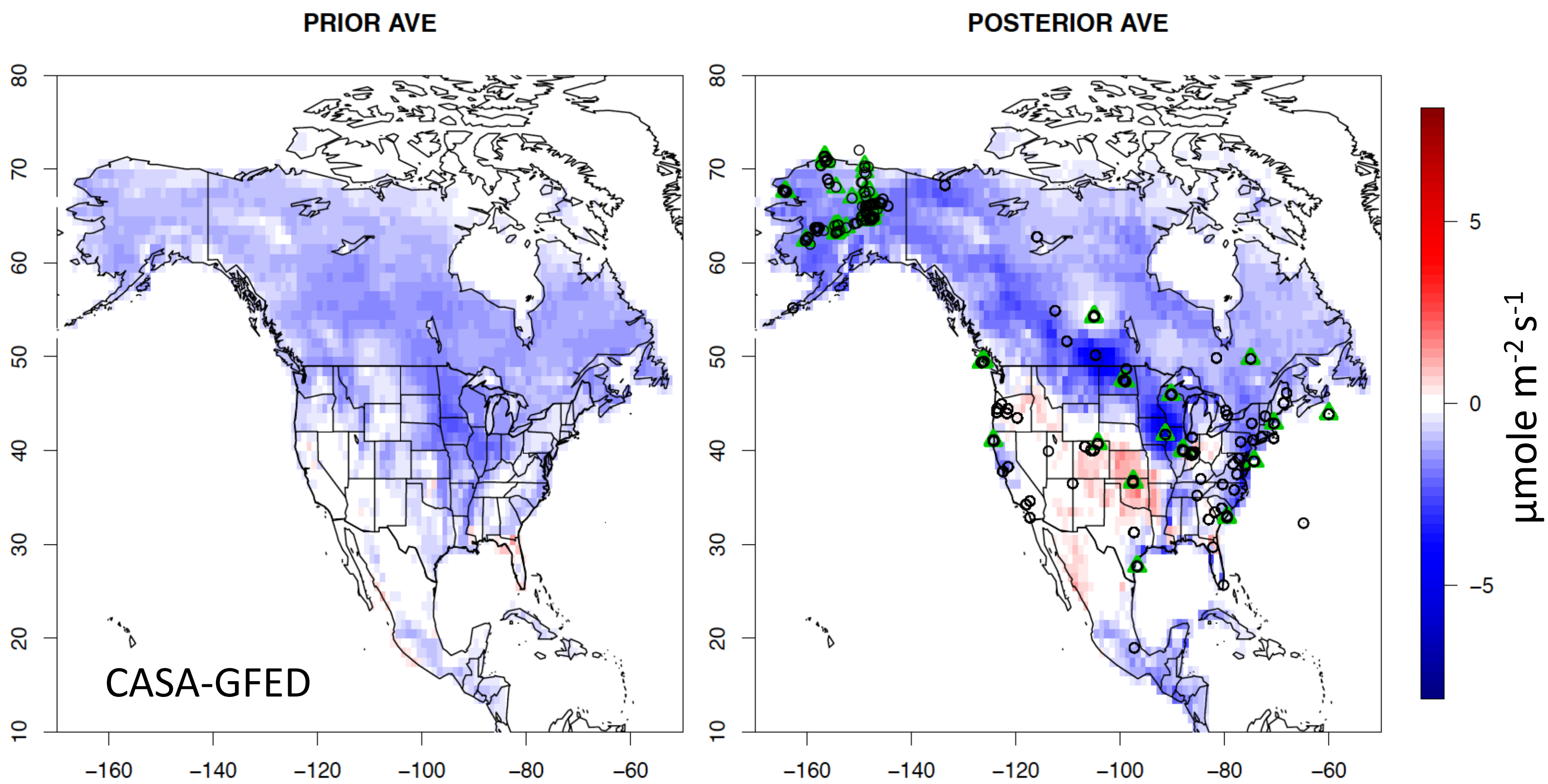
Net Ecosystem Exchange: July 2010 Monthly Mean



CarbonTracker-Lagrange Preliminary Results

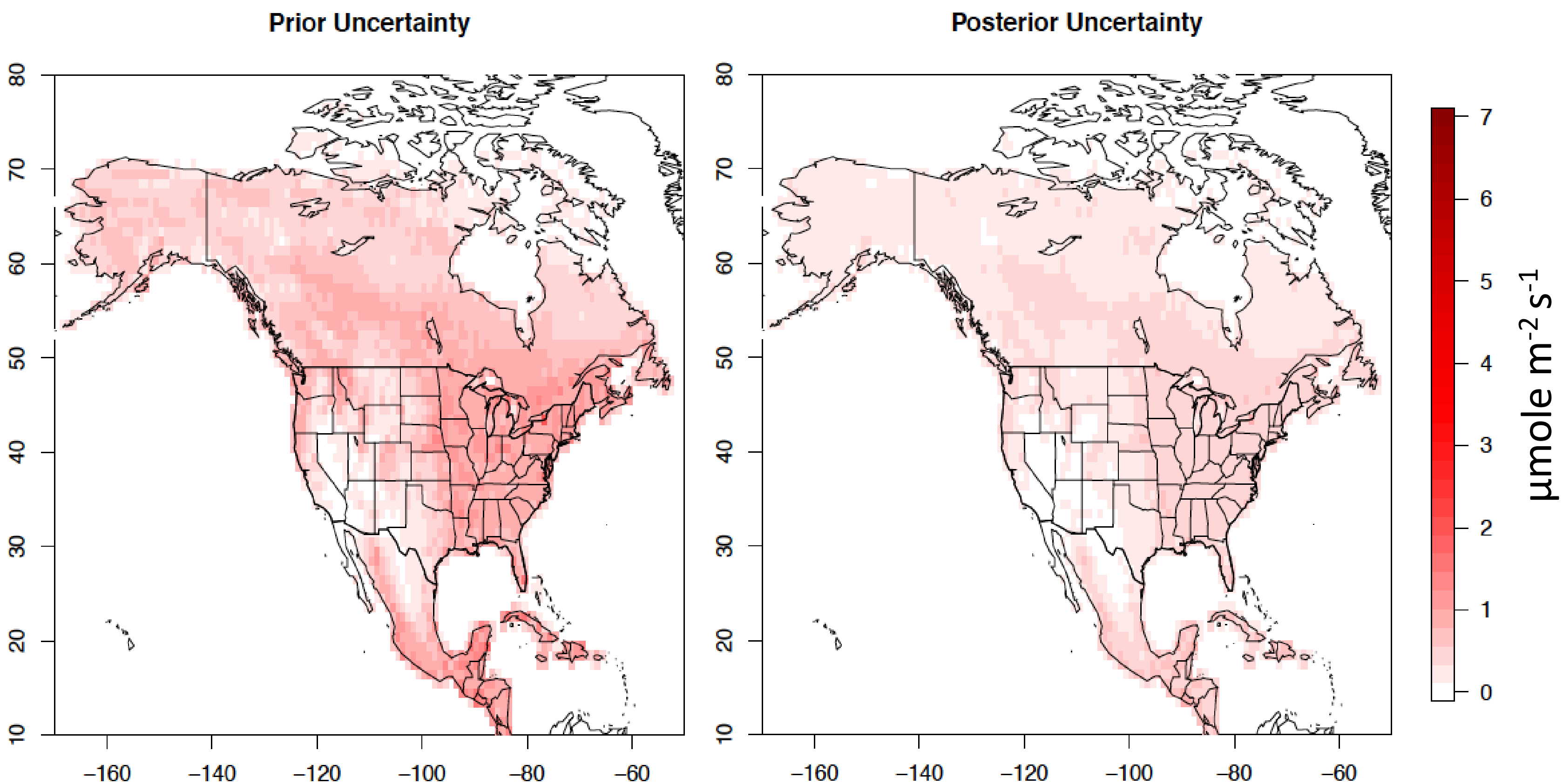
CarbonTracker-Lagrange Preliminary Results

CarbonTracker-Lagrange
10 July – 10 August 2012



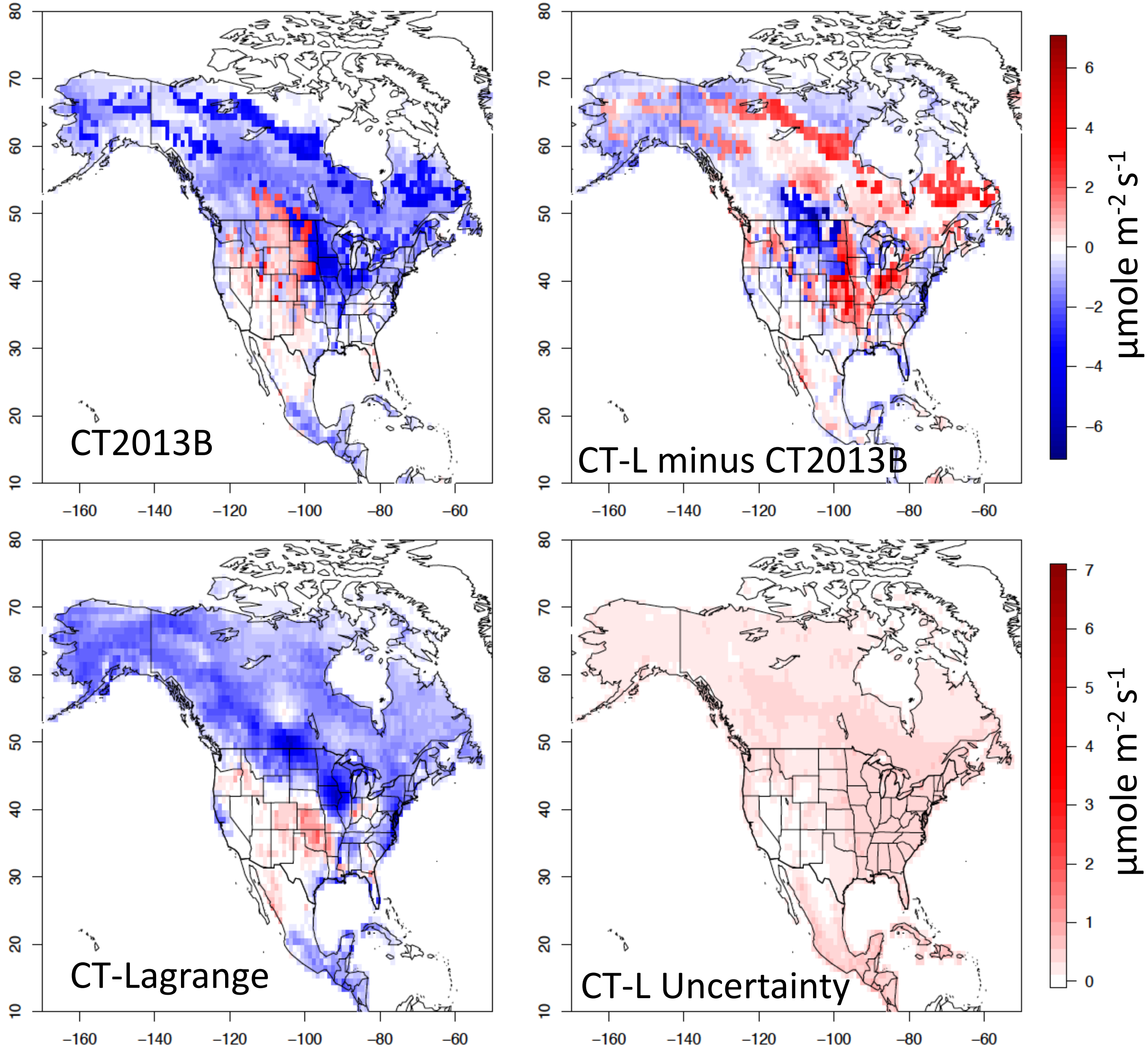
- All available observations
- CarbonTracker background
- $\tau_{spatial}$ = 1000 km, $\tau_{temporal}$ = 7 days

CarbonTracker-Lagrange Uncertainty
10 July – 10 August 2012

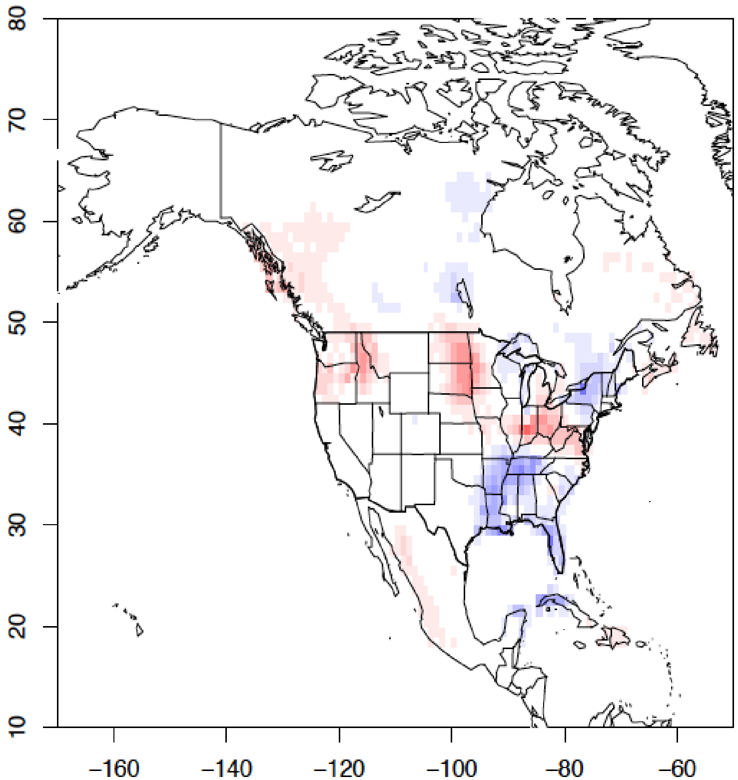


- $V = Q - QH^T(R + HQH^T)^{-1}HQ$
- Does not depend on posterior residuals!

Preliminary Comparison: CT2013B and CT-Lagrange

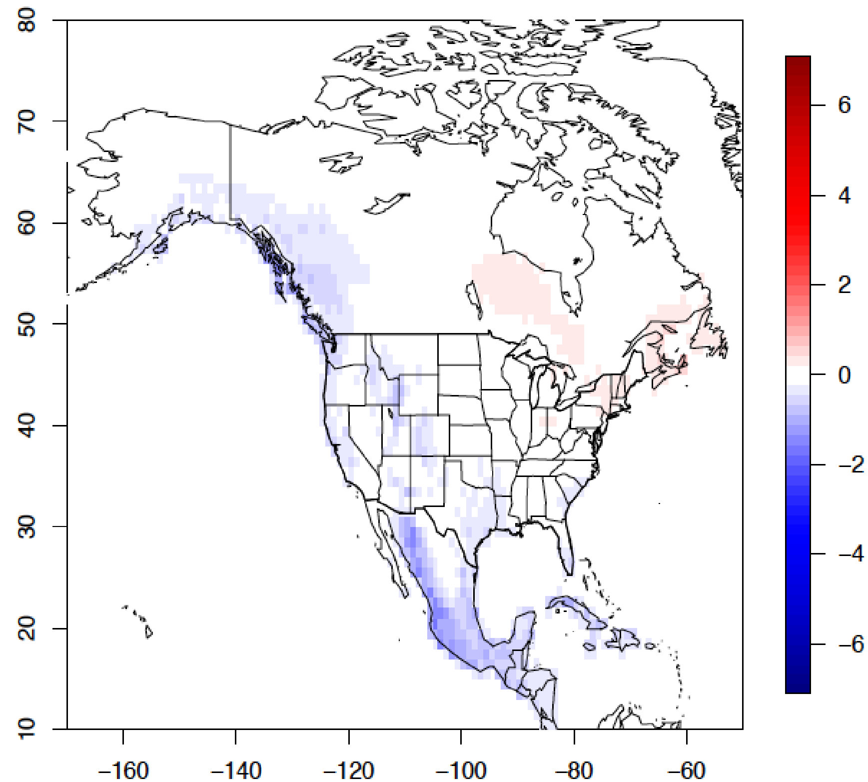


Flux Difference with Data Selection Similar to CT2013B



-NOAA/ESRL, Environment Canada, NCAR only

Flux difference with Empirical Boundary Condition



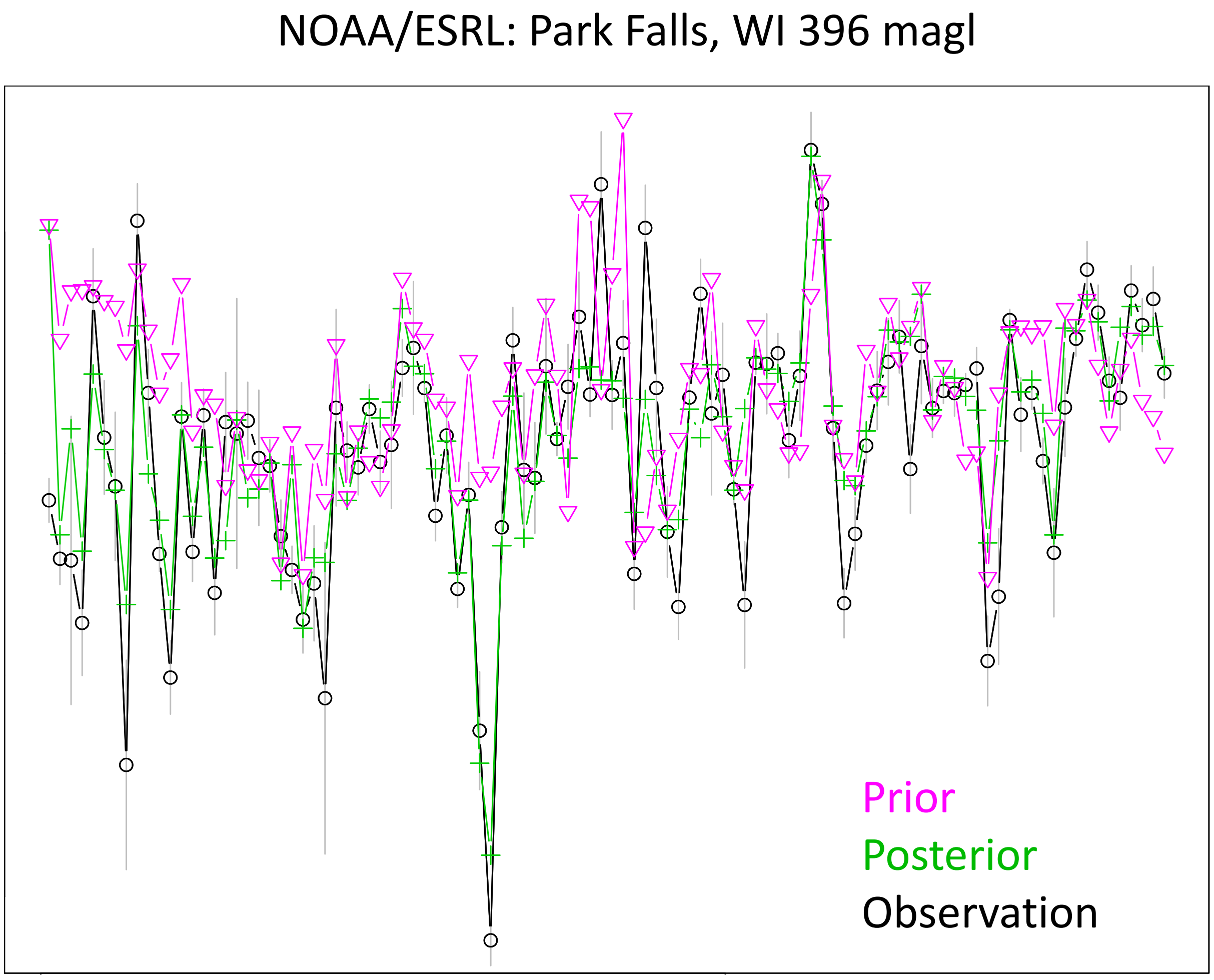
-Empirical Boundary Condition derived from NOAA/ESRL Marine Boundary Layer (E. Dlugokencky PI) and Aircraft (C. Sweeney PI) datasets

Despite regional differences large area totals are fairly consistent across large regions:

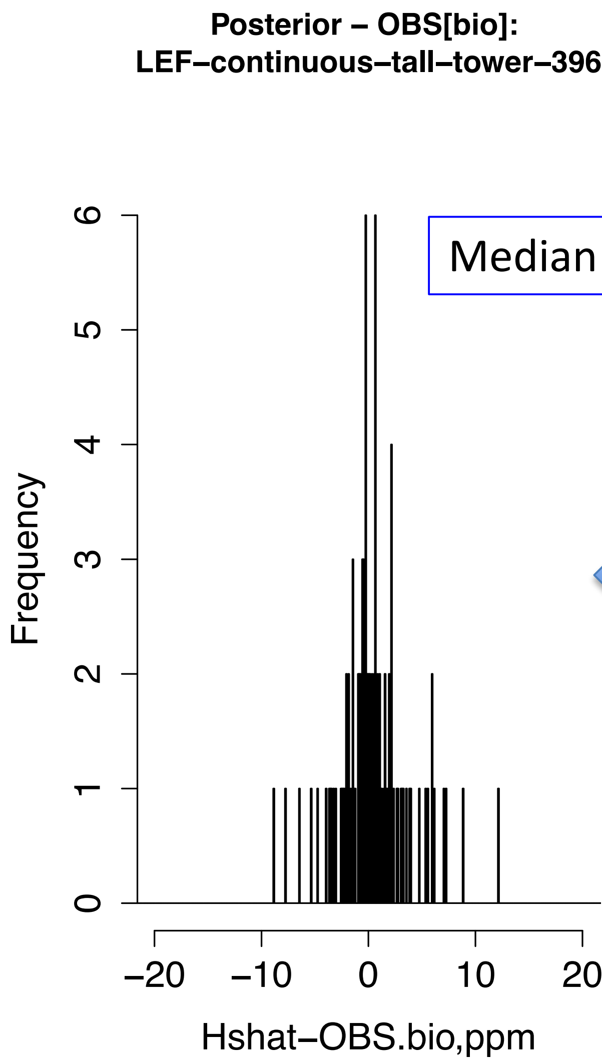
Aggregated Totals: 10 July – 10 August 2012 ($PgCyr^{-1}$)

	CT2013B	CT-L CT2013B Boundary	CT-L Empirical Boundary	CT-L CT2013 Boundary Core Network	Prior
North America	-7.4	-7.8 ± 0.8	-6.6 ± 0.8	-8.0 ± 0.8	-6.8 ± 2.0
Temperate 25°N < 50°N	-2.5	-2.7	-2.3	-2.7	-2.3
Boreal > 50°N	-4.4	-4.5	-4.3	-4.6	-3.5

How well does CarbonTracker-Lagrange fit the data?



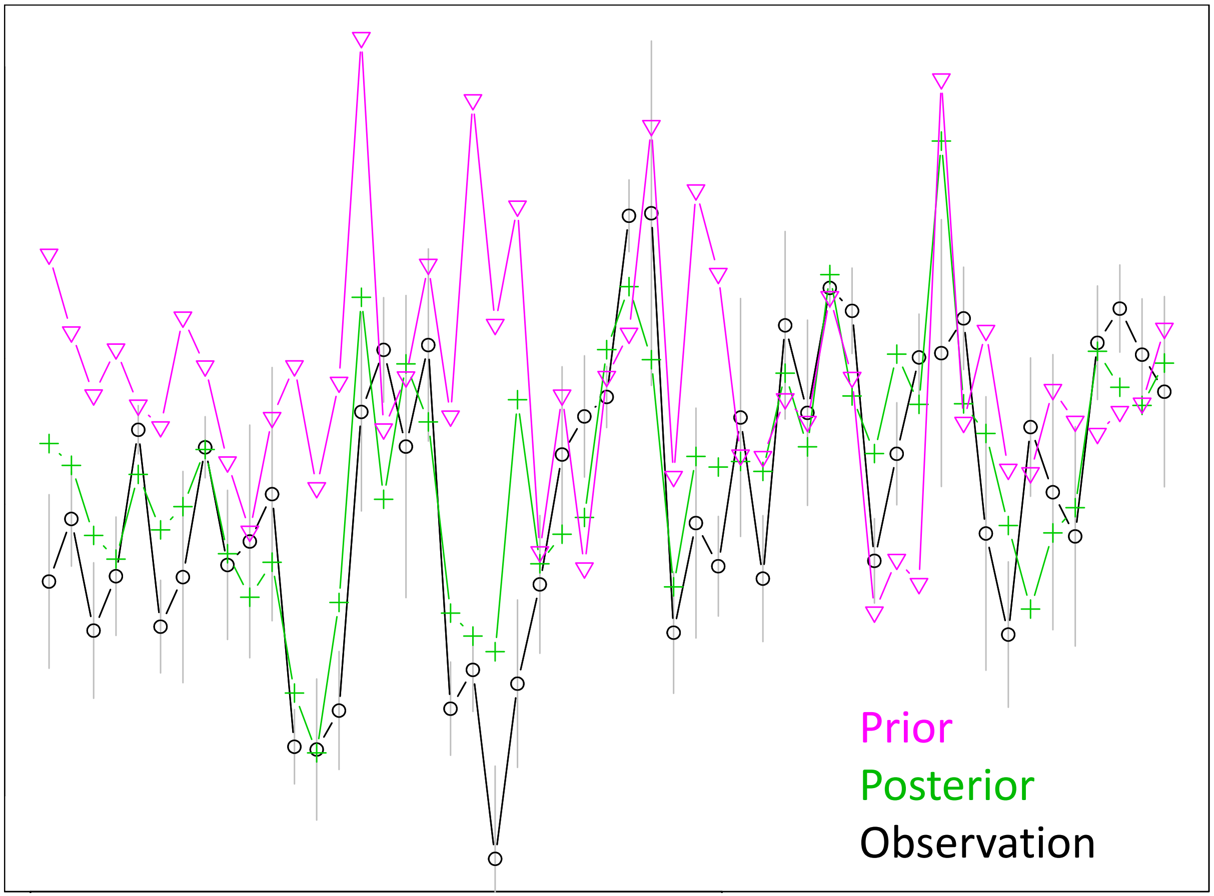
50,Q.84: −2.36 1.47 6.48 , n= 102

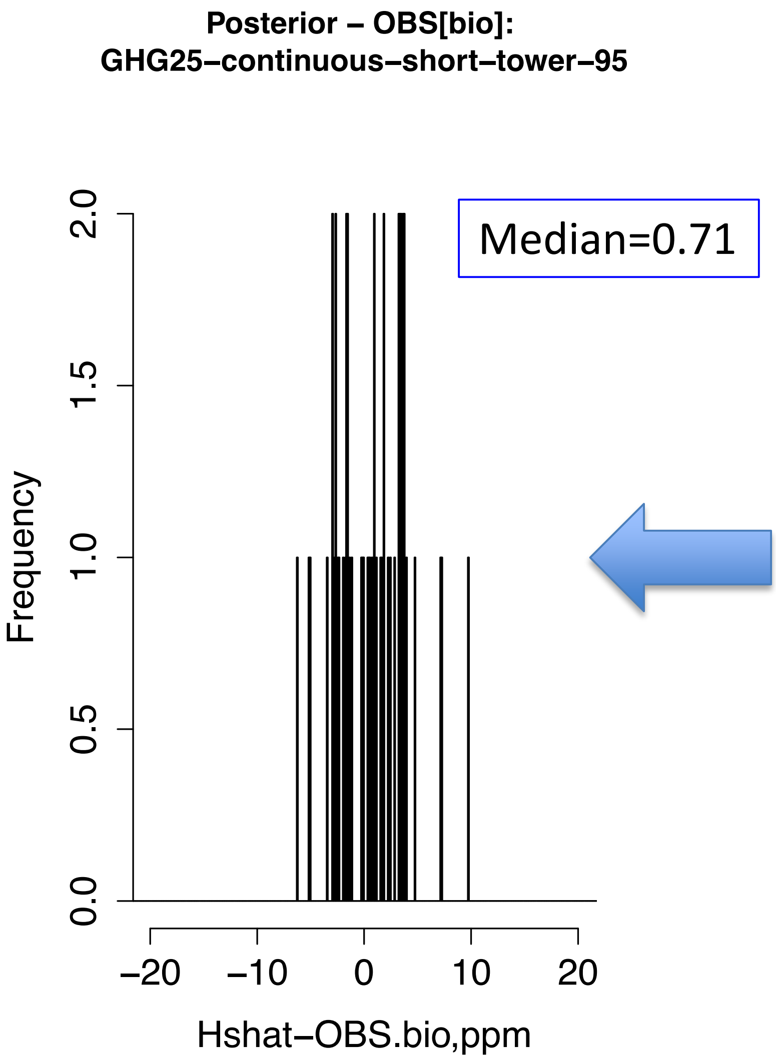


Median =0.15

Median=1.47

Earth Networks: Lewisburg, PA 95magl

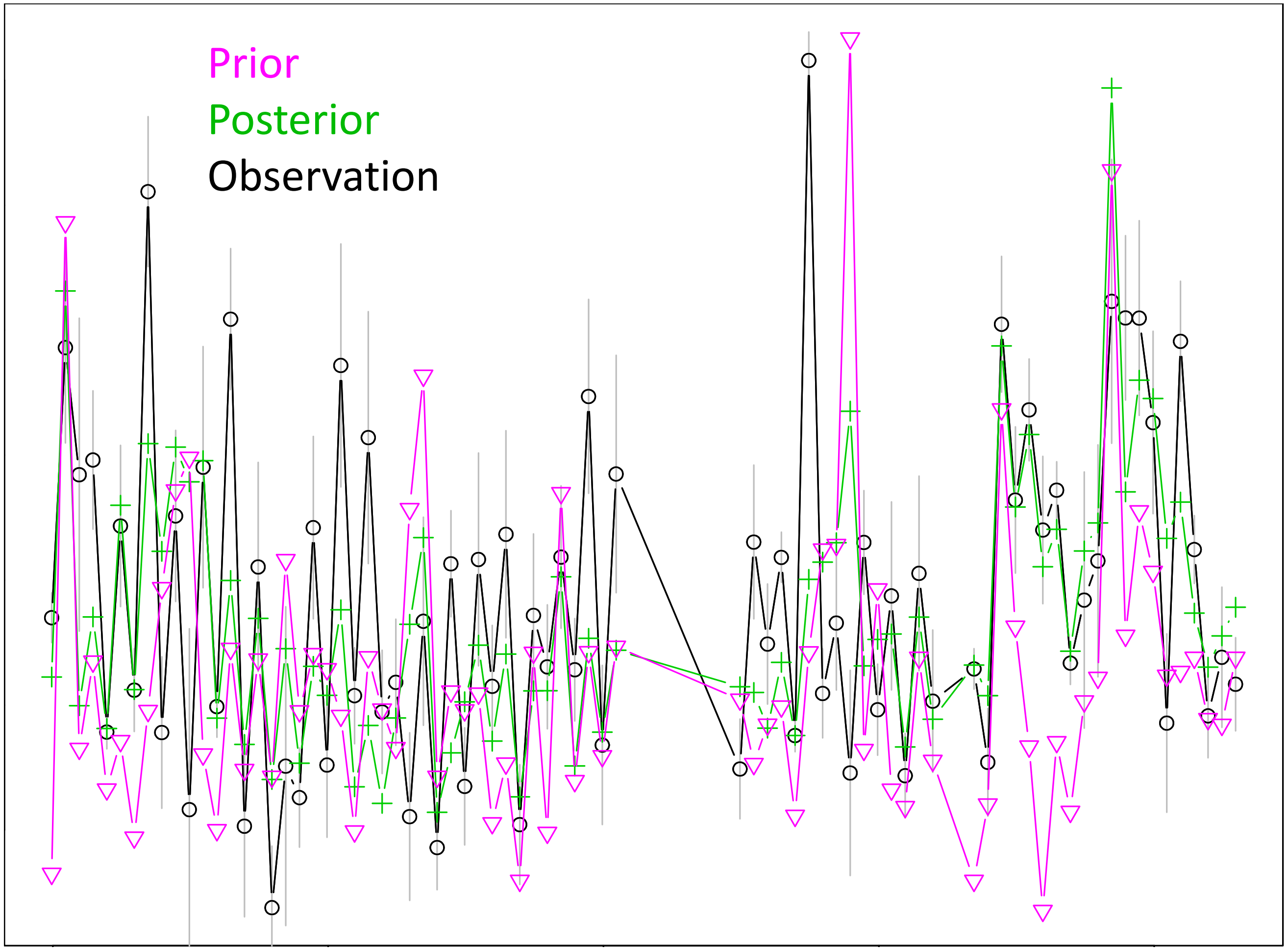


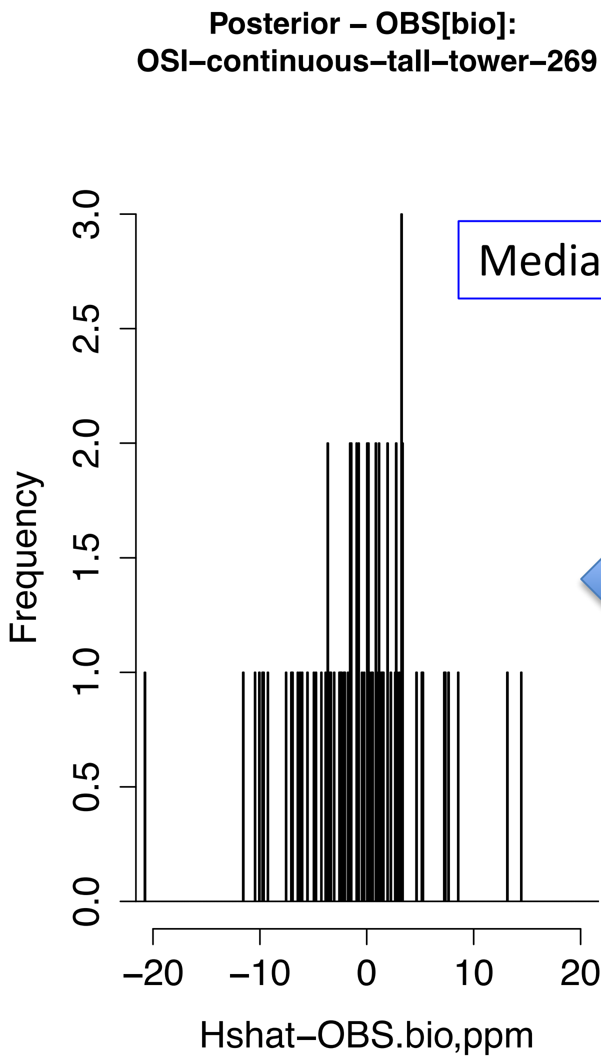


3.91 , sd= 6.3 , Q.16,Q.50,Q.84: −2.5 2.79 10.04 , n= 51

Median=2.79

Oregon State University (& Earth Networks): Silverton, OR 269 magl



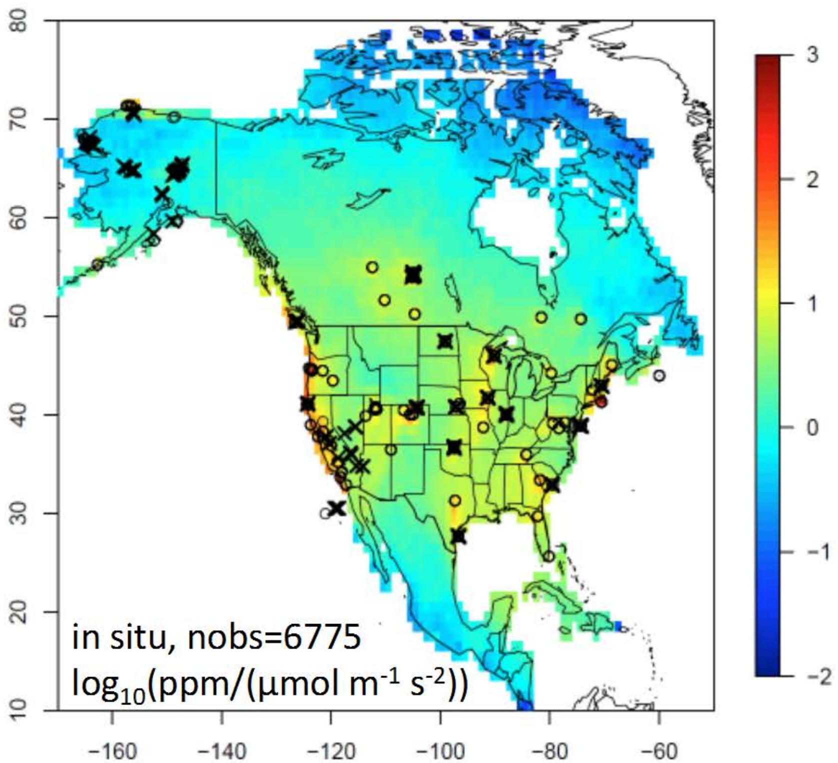


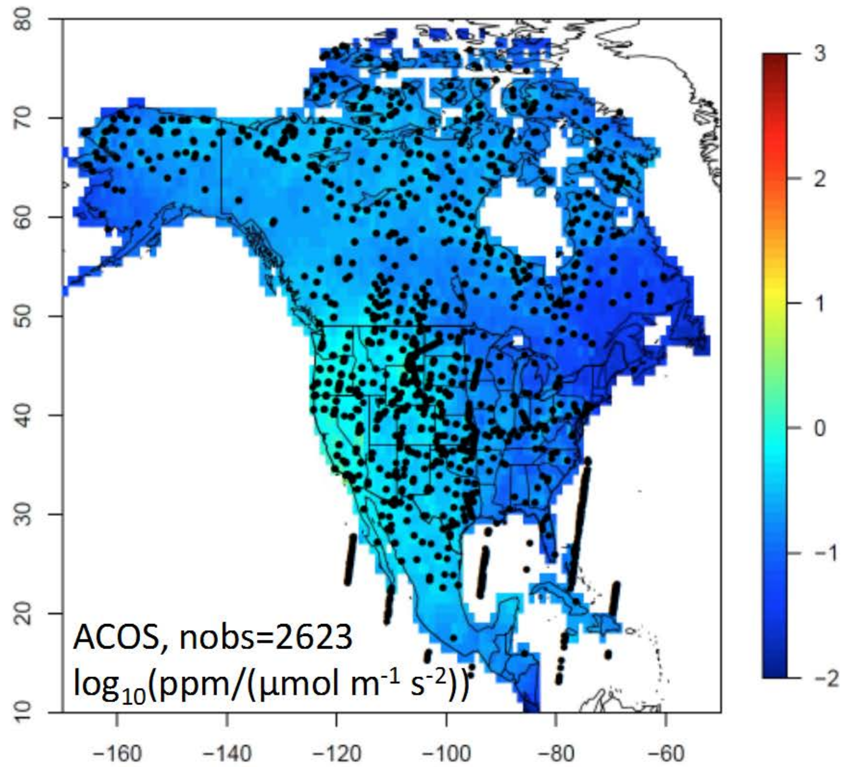
Median=-0.46

mean= –3.21 , sd= 7.9 , Q.16,Q.50,Q.84: –9.76 –4.05 3.34 , n= 77

Median=-4.05

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

CarbonTracker-Lagrange Inversion Framework

$$\hat{\mathbf{s}} = \mathbf{s}_p + (\mathbf{HQ})^T (\mathbf{HQH}^T + \mathbf{R})^{-1} (\mathbf{z} - \mathbf{Hs}_p)$$

Yadav and Michalak, *Geosci. Model Dev.*, *6*, 583–590, 2013

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
ŝ is a vector containing the revised fluxes

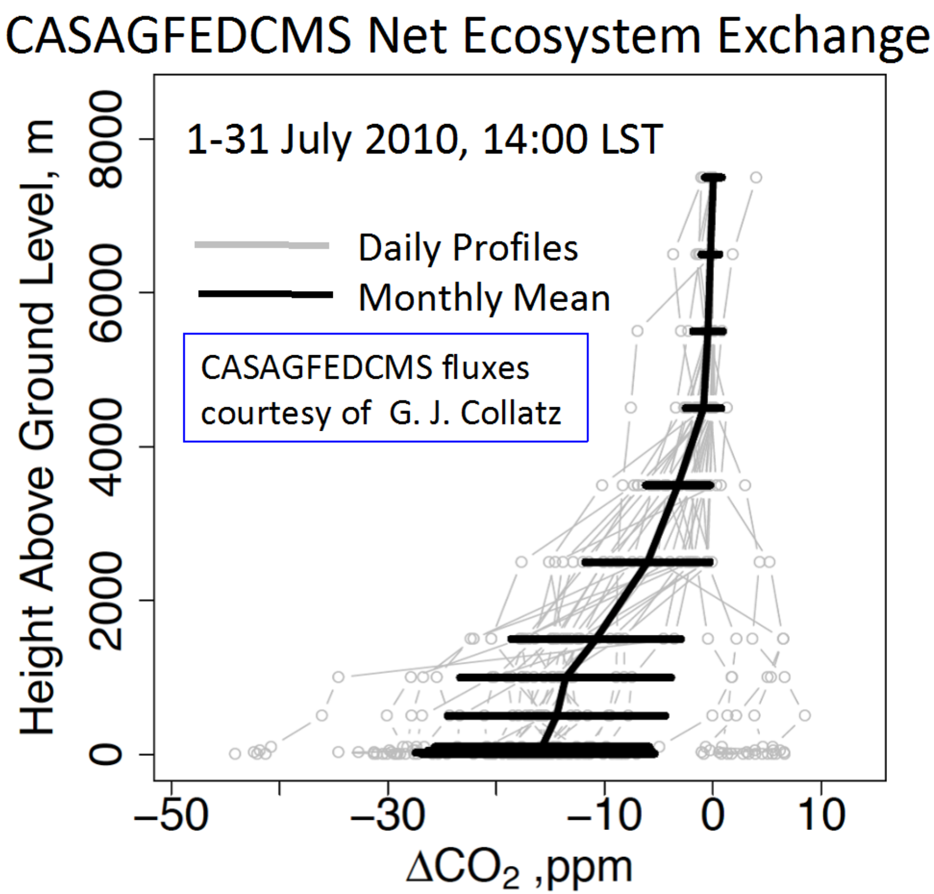
Modified framework for boundary optimization:

- H has additional columns for boundary value grid cells
- s_p and ŝ contains additional elements
- Q contains additional rows and columns. No cross-correlation between boundary values and fluxes

CarbonTracker - Lagrange

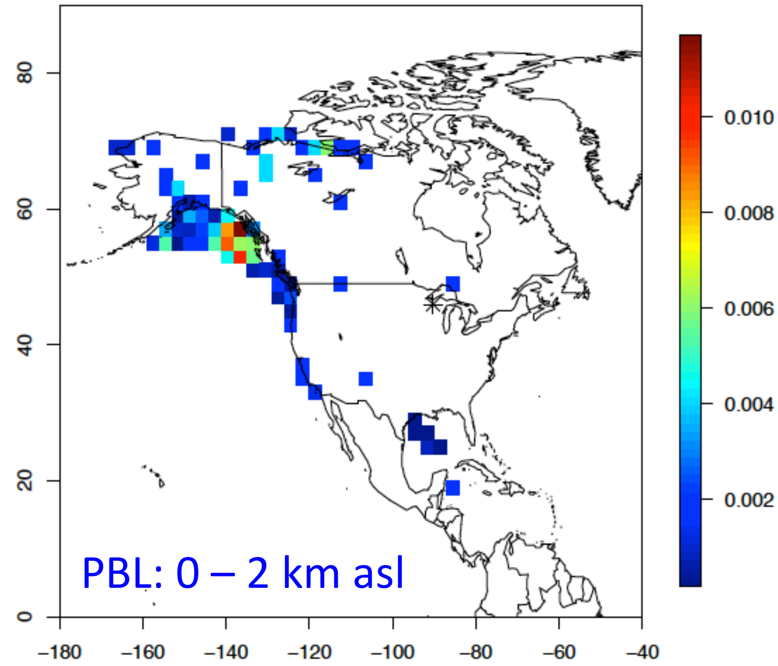
- Combination of surface, aircraft and column data enables separate optimization of surface fluxes and boundary/initial values.

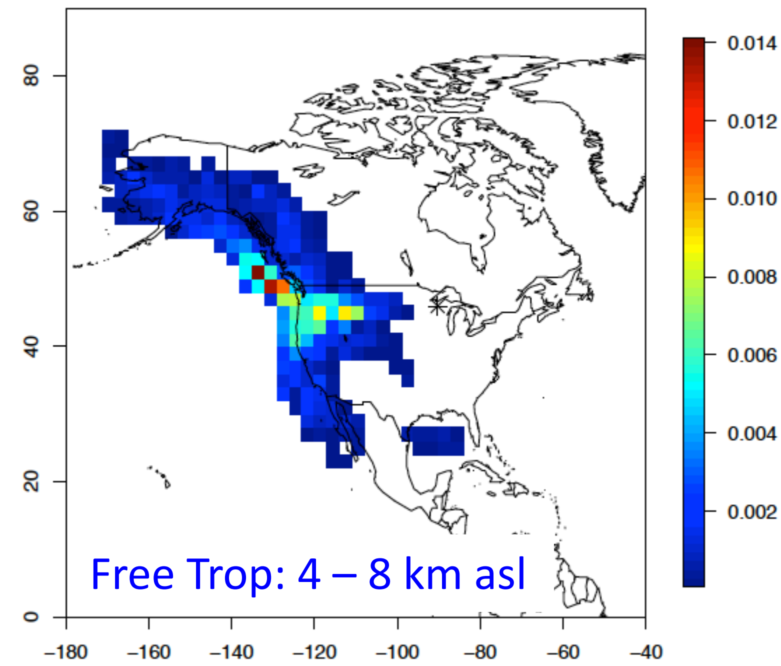
CarbonTracker-Lagrange profiles corresponding to the Park Falls NOAA/UWI WLEF-TV Tall Tower and TCCON site

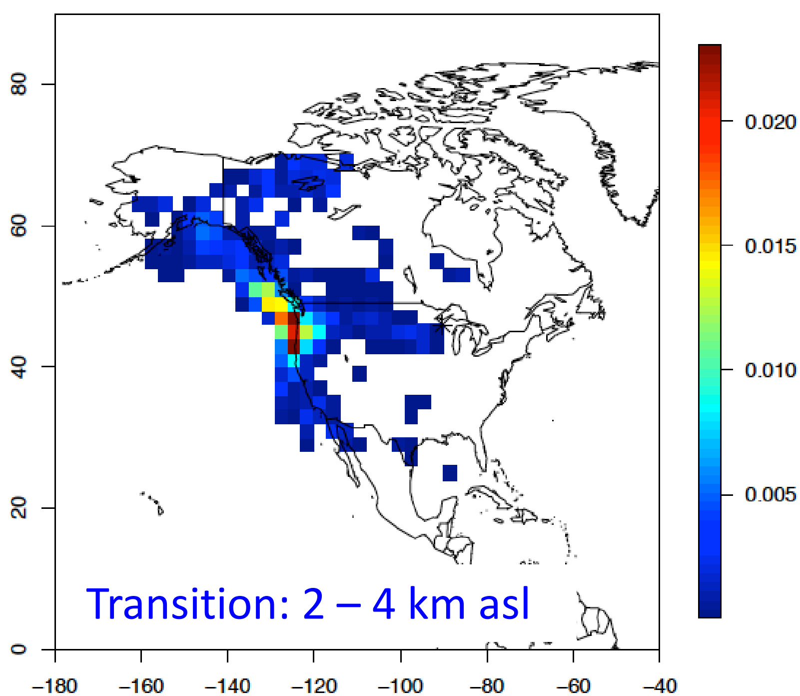


- Contrast between surface and free troposphere data provides information about surface versus boundary influences.
- Dense aircraft plus tall tower data is best, but bias-free column datasets could also provide a useful constraint.

LEF Tower 396m: 2010-07-22 18:10

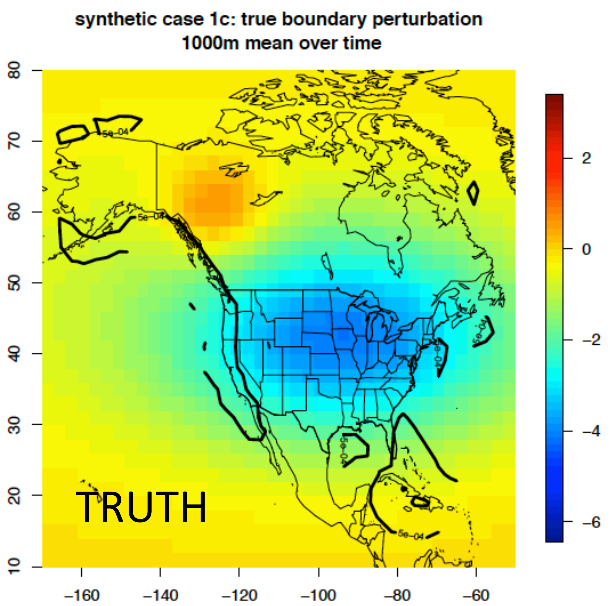


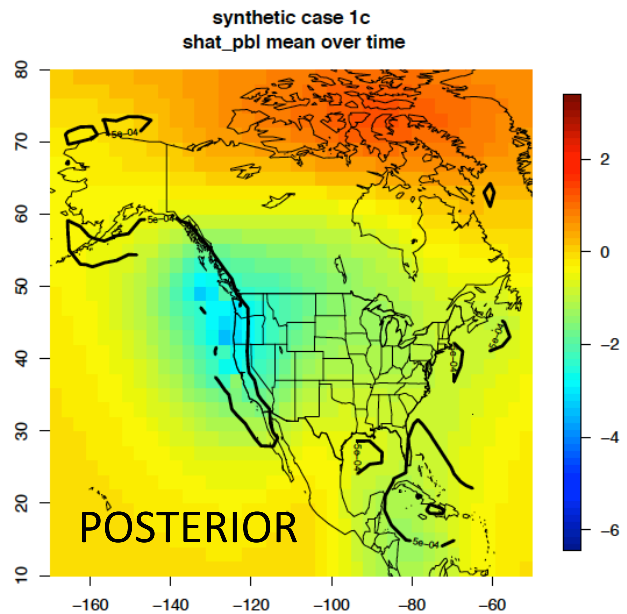




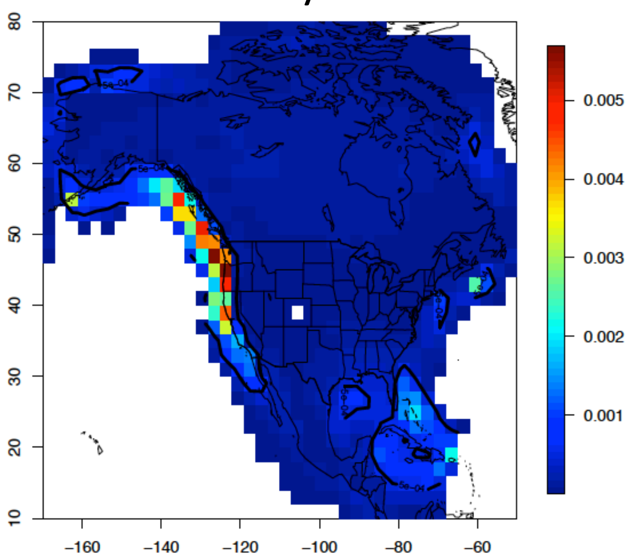
- Gridded boundary footprints: Use all trajectory points within the mole fraction estimation domain.
- Resolution: daily x 3 lon x 2 lat x three vertical bins.
- Each trajectory gets 1/500th of the weight, but trajectories may have different number of points included.
- Units are ppm per ppm.

Free Troposphere Boundary Correction

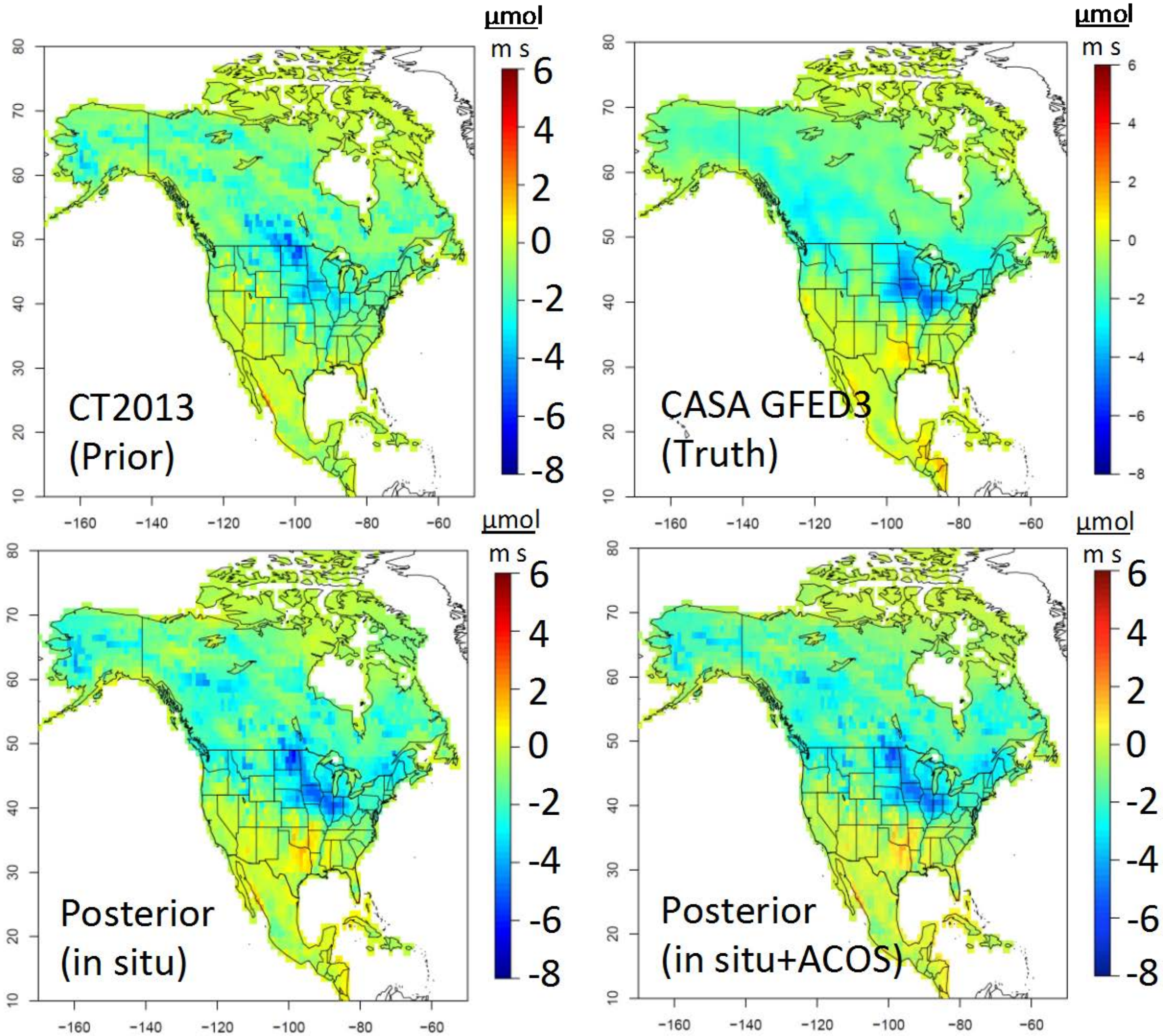




PBL boundary influence



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:

$$\mathbf{Q} = \sigma_s^2 \overbrace{\left[exp\left(-\frac{\mathbf{X}_\tau}{l_\tau}\right)\right]}^{\substack{temporal \\ covariance}} \otimes \overbrace{\left[exp\left(-\frac{\mathbf{X}_s}{l_s}\right)\right]}^{\substack{spatial \\ covariance}}$$

- Consider: $\mathbf{D}$ as temporal covariance and $\mathbf{E}$ as spatial covariance:

$$\mathbf{D}_{(p\times q)} \otimes \mathbf{E}_{(r\times t)} = \begin{pmatrix} d(1,1)\mathbf{E} & \cdots & d(1,q)\mathbf{E} \\ \vdots & \ddots & \vdots \\ d(p,1)\mathbf{E} & \cdots & d(p,q)\mathbf{E} \end{pmatrix} \in \mathbf{Q}_{(pr\times qt=m\times m)}$$

We have generalized to allow space- and time-varying sigma:

$$\boldsymbol{\sigma} = (\sigma_1, \sigma_2, \dots, \sigma_{m-1}, \sigma_m)$$

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

$$\mathbf{I}_{\boldsymbol{\sigma}} = \begin{bmatrix} {\sigma_1}^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & {\sigma_m}^2 \end{bmatrix}$$

I_σ is the diagonal matrix of standard deviations: $I_\sigma[ij]=\sigma_i$ for i=j, 0 for i≠j.

$$\mathbf{Q} = (\boldsymbol{\sigma} \cdot \boldsymbol{\sigma}^T) \times (\mathbf{D} \otimes \mathbf{E}) = \mathbf{I}_{\boldsymbol{\sigma}} \cdot (\mathbf{D} \otimes \mathbf{E}) \cdot \mathbf{I}_{\boldsymbol{\sigma}}$$

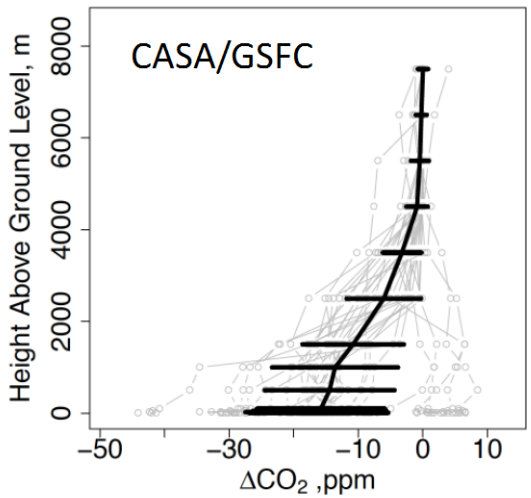
Beta algorithm (in testing) that leverages Yadav and Michalak framework to avoid building full Q and full $\boldsymbol{\sigma} \cdot \boldsymbol{\sigma}^T$.

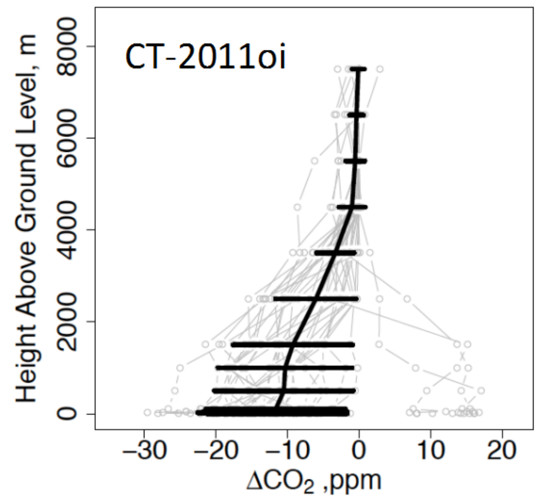
Model-Data Mismatch Matrix R

- 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:

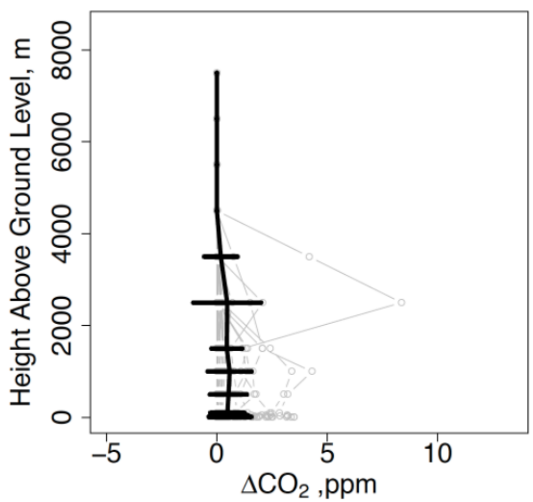
Net Ecosystem Exchange



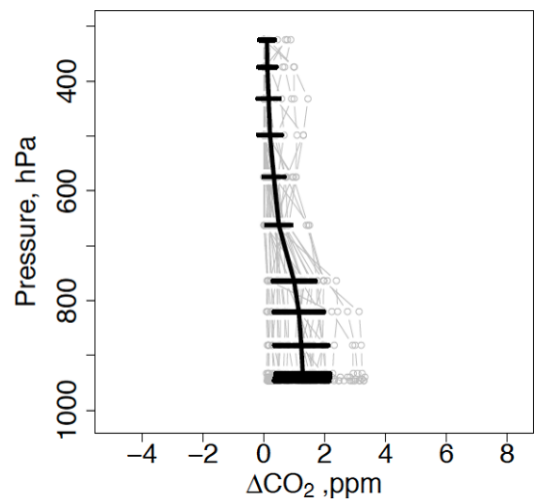


- Impact of surface fluxes minimal above 3000m
- CASA/GSFC versus CT-2011oi NEE differences subtle
- Sporadic fire influence aloft.
- Small fossil fuel signal.

CASA/GSFC FIRE



CARBONTRACKER−2011oi FOSSIL



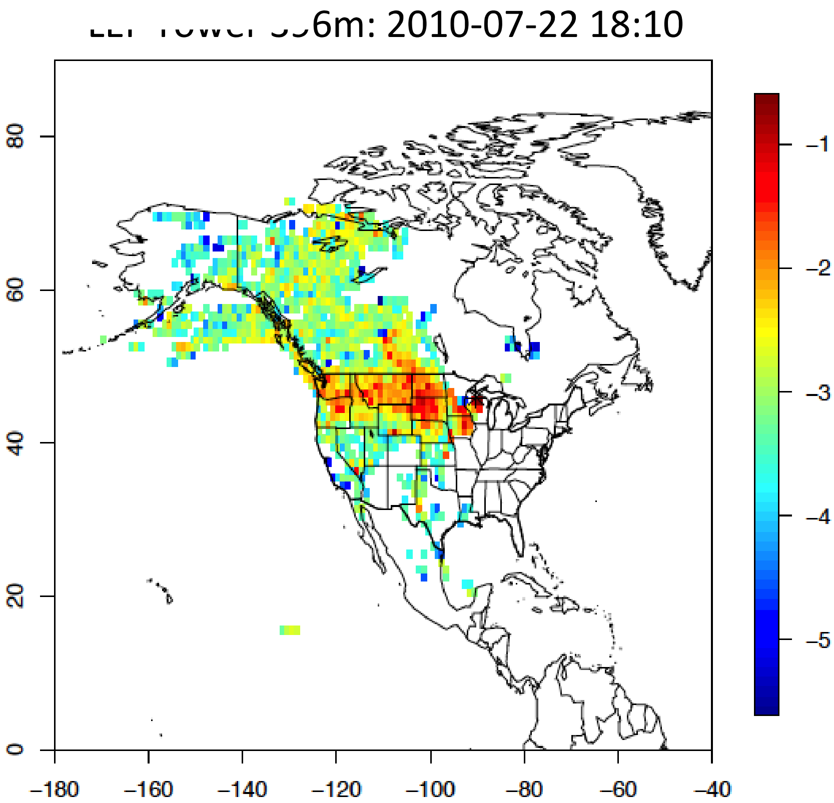
- CASA/GSFC fluxes courtesy of G. J. Collatz
- CarbonTracker fluxes courtesy of A. Jacobson

1-31 July 2010, 14:00 LST

Daily Profiles

Monthly Mean

WRF-STILT Footprint Library



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

- High-resolution WRF-STILT atmospheric transport model customized for Lagrangian simulations (Nehrkorn et al., *Meteorol. Atmos. Phys.*, *107*, 2010).
- 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.