Estimating North American CO_2 Fluxes Using Continuous Measurements Within a Geostatistical Inverse Modeling Framework

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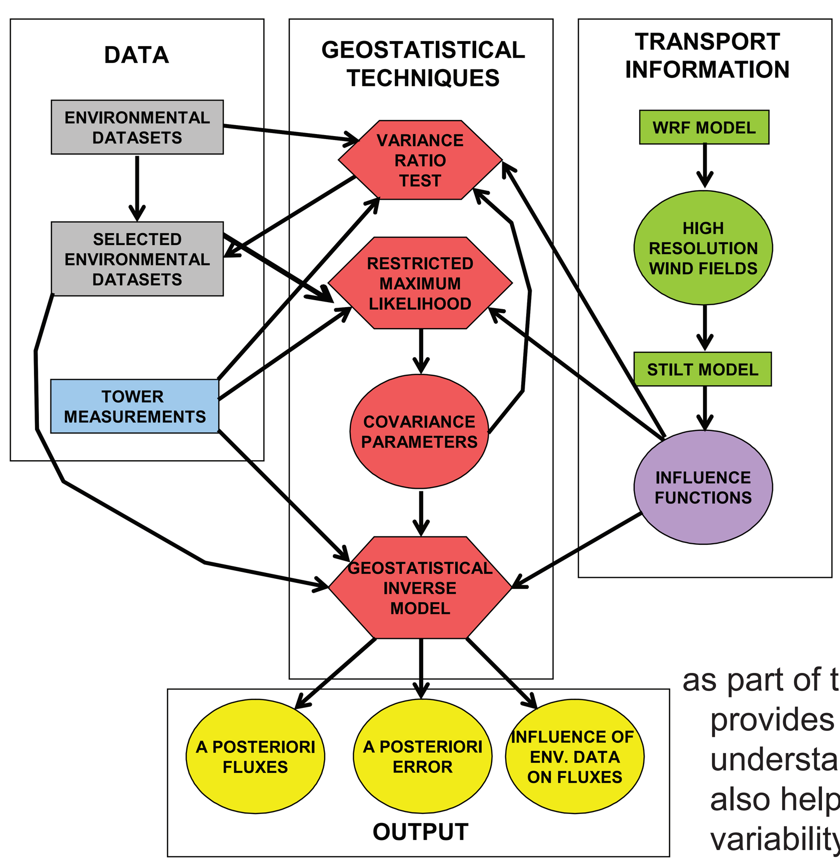
Goal and Scope

- This ongoing project uses continuous atmospheric measurements from 9 tall towers and auxiliary variables in a geostatistical inverse modeling framework to quantify North American surface fluxes of carbon dioxide at 1°x1° resolution and daily, 8-day and monthly time-scales.



- Estimated fluxes include both biospheric and anthropogenic components, in order to avoid aliasing fossil fuel inventory errors onto biospheric fluxes.
- The influence of auxiliary environmental data from remote sensing instruments, agricultural and forest inventories, air quality measurements and other sources are evaluated as part of the inversion, which provides process-based understanding of flux variations and also helps to recover grid-scale variability in the recovered fluxes.
- Flux magnitudes are estimated without relying on prior flux estimates, and the approach accounts for uncertainties and covariances associated with measurement and transport errors and flux distributions.
- Study will be conducted in three parts where first two parts use pseudo-data to evaluate the optimal flux resolution and data averaging to minimize bias, and the ability of atmospheric data to infer realistic relationships between auxiliary variables and flux. The third part applies results from the first two parts using actual concentration data.

Geostatistical Inverse Modeling

The geostatistical approach to inverse modeling is a Bayesian approach in which the prior probability density function is based on an assumed form for the spatial and/or temporal correlation of the surface fluxes to be estimated (Michalak et al. 2004). This differs from the traditional Bayesian approaches, where the prior information is in the form of initial surface flux estimates.

In the geostatistical approach, the prior flux estimate is replaced by a model of the mean of the flux distribution, and the criterion of remaining close to a prior flux estimate is replaced by a criterion of preserving a spatial and/or temporal correlation in the flux distribution: Mathematically,

$$L_{\mathbf{s},\boldsymbol{\beta}} = \frac{1}{2}(\mathbf{z}-\mathbf{Hs})^T\mathbf{R}^{-1}(\mathbf{z}-\mathbf{Hs}) + \frac{1}{2}(\mathbf{s}-\mathbf{X}\boldsymbol{\beta})^T\mathbf{Q}^{-1}(\mathbf{s}-\mathbf{X}\boldsymbol{\beta})$$

where
- $\mathbf{z}$: Observation vector
- $\mathbf{H}$: Transport matrix
- $\mathbf{s}$: Surface flux distribution
- $\mathbf{R}$: Model-data mismatch error covariance matrix
- $\mathbf{X}$: Matrix that defines the model of the mean.

  For example, for a constant mean: $\mathbf{X} = \begin{bmatrix} 1 & \cdots & 1 \end{bmatrix}^T$

  For a system where the mean of the fluxes is expected to have a linear trend with an additional variable t (e.g. LAI or FPAR): $\mathbf{X} = \begin{bmatrix} 1 & \cdots & 1 \\ t_1 & \cdots & t_m \end{bmatrix}^T$
- $\boldsymbol{\beta}$: Unknown drift parameters to be estimated along with $\mathbf{s}$
- $\mathbf{Q}$: Prior flux covariance matrix based on selected model (a full matrix)

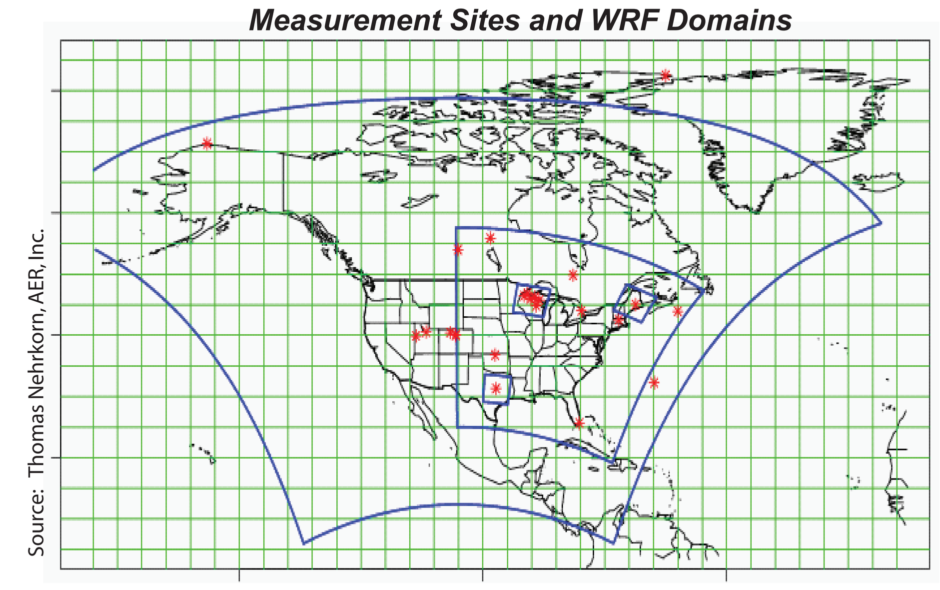
Key differences relative to classical Bayesian approach:

- Parameters of the model of the mean $\mathbf{X}\boldsymbol{\beta}$ are estimated as part of the inversion
- Auxiliary data can be incorporated into $\mathbf{X}\boldsymbol{\beta}$ and its significance can be evaluated using the Variance Ratio Test (Kitanidis 1997)
- The prior covariance matrix $\mathbf{Q}$ defines spatial and/or temporal correlations which are optimized using Restricted Maximum Likelihood (Kitanidis, 1995).

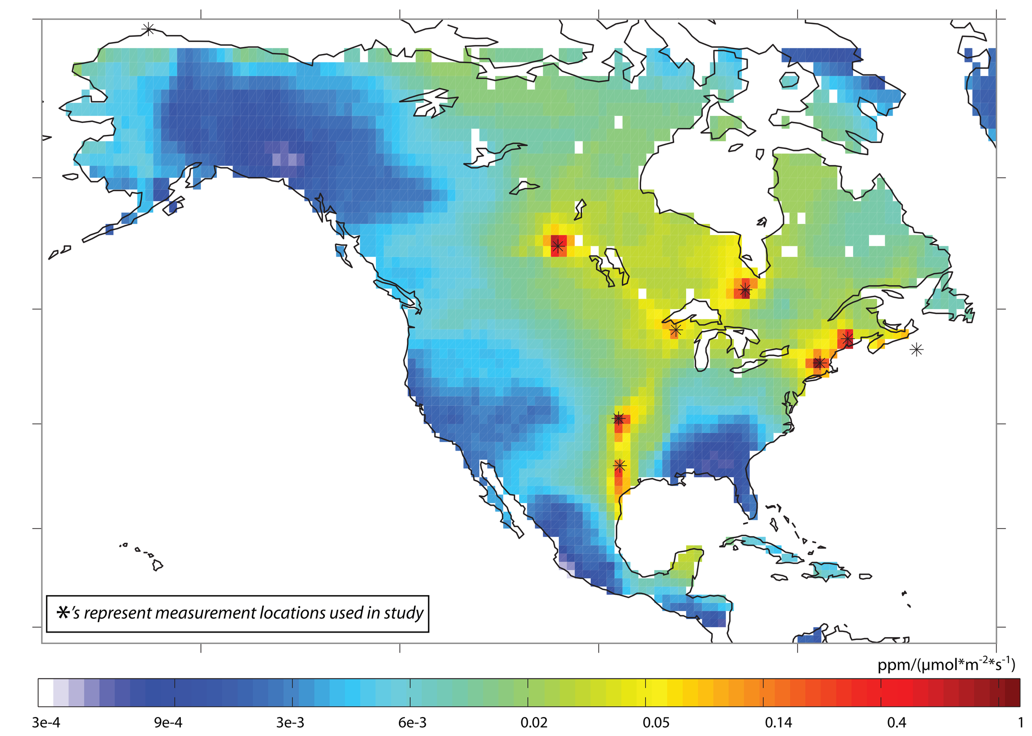
Tall Tower Measurements and Transport Model

- Continuous data from the NOAA Tall Tower network are the primary source of atmospheric CO_2 observations for this work. The tall towers are the WLEF tower in Park Falls, WI, the WKT tower in Moody, TX, and the AMT tower in Argyle, ME.
- High resolution meteorological fields have been generated using the Weather Research and Forecasting (WRF) model nested down to high resolution (~2 km) over the tall tower target regions.
- The Stochastic Time-Inverted Lagrangian Transport (STILT) model, an atmospheric particle-tracking model run backwards in time, is used to track the influence of surface fluxes on available atmospheric measurements.

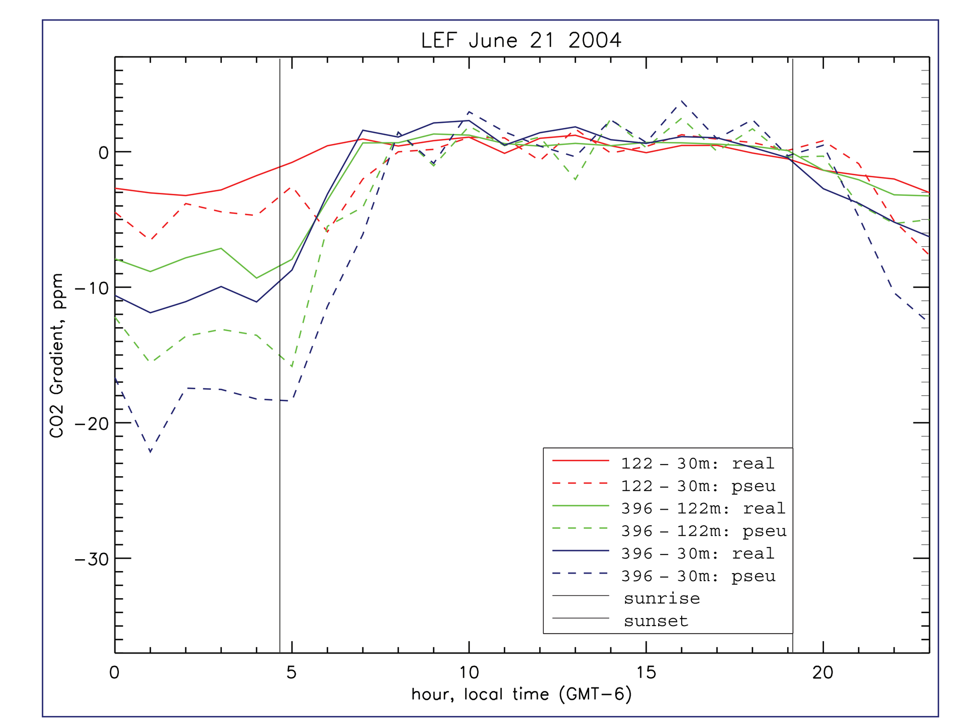
Measurement Sites and WRF Domains



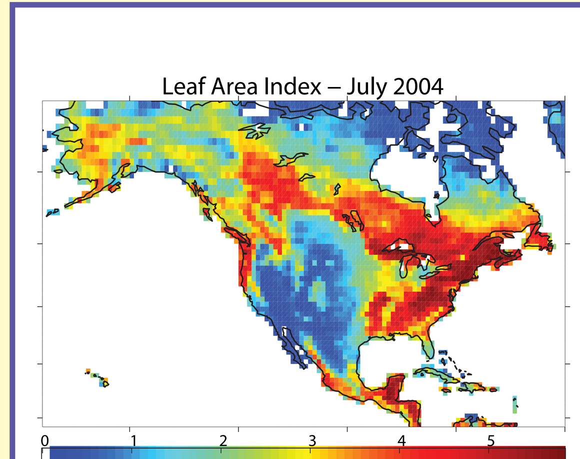
- Data from other eddy covariance towers that are equipped to provide calibrated CO_2 mixing ratio measurements, as well as flask measurements in under-represented regions, are included when available.
- An example of the information provided by STILT/WRF is presented in the figure below, which represents the average sensitivity of measurements at the 9 tower locations in June 2004 to upstream fluxes in the source regions.

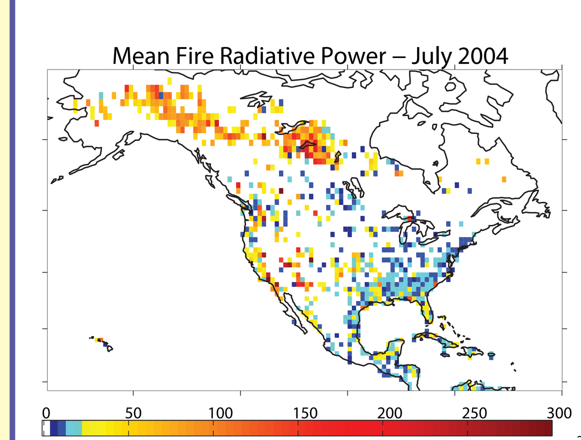


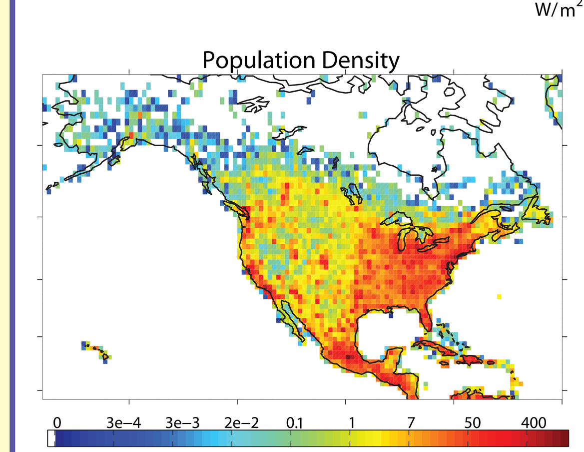
- An analysis of the ability of STILT/WRF to reproduce vertical gradients at the WLEF tower is currently underway. Night-time data from the shorter towers may be excluded from the inversion, or assigned a higher model-data mismatch, given the results of this analysis.
- Shown below are *a posteriori* fluxes from CarbonTracker (Peters et al., 2007) transported forward to three heights on the LEF tower (30m, 122m, 396m) compared with actual measurements at those heights.



Auxiliary Environmental Variables







The use of environmental datasets related to CO_2 flux in a geostatistical inversion allows the recovered fluxes to exhibit more realistic flux variability than may be visible in the atmospheric CO_2 concentration measurements in the limited tower network. They may also help to lower *a posteriori* uncertainty on the flux estimates due to a better deterministic model of the trend of the flux distribution within the inversion.

This study takes advantage of high spatial and temporal resolution environmental datasets available over North America from remote-sensing instruments such as MODIS and AMSR, air quality measurements and socioeconomic inventories related to emissions, and agricultural and forest inventory data.

Both criterion-based and hypothesis testing variable selection methods are applied in order to select the combination of variables that best explain flux variability as seen through the atmospheric measurements for ultimate use in the inversion.

A second inversion will also test the significance of biospheric model output, high-resolution fossil fuel inventories, i.e. Vulcan (Gurney et al., 2006) and climatological model output as seen through the limited atmospheric data.

List of possible variables for inclusion in North American inversion

Biospheric Variables

Biomes
Crop Type (e.g. %Corn or Wheat)
Enhanced Vegetation Index
Evapotranspiration (GLDAS)
Fire Counts and Radiative Power
fPAR
GPP (MODIS)
LAI
Land Cover
Latent Heat Flux (GLDAS)
NDVI
PAR (Shortwave radiation)
Precipitation
Sensible Heat Flux (GLDAS)
Soil Carbon Density
Soil Moisture (AMSR)
Soil Nitrogen Density
Temperature - Air
Temperature - Soil

Anthropogenic Variables

Home Heating
Impervious Surfaces (%)
Night-time Lights
NOx Emissions
Population Density
Power Plant Emissions
SO2 Emissions

June 2004 Pseudodata Study

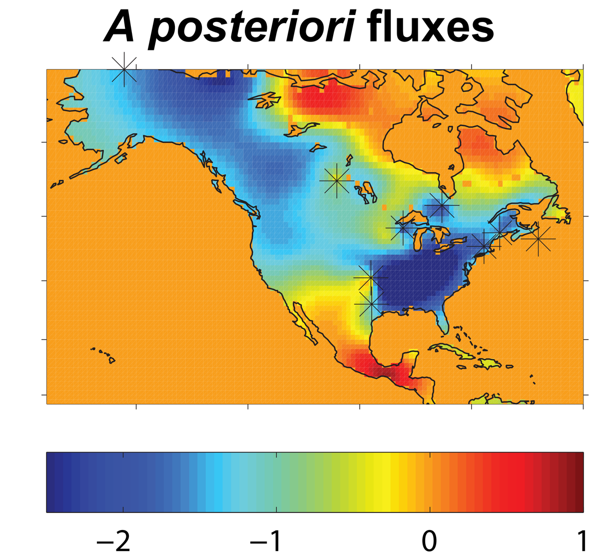
Testing is underway to evaluate the optimal flux resolution and concentration data averaging in order to estimate an 8-day average flux with minimal bias and reasonable uncertainty estimates. Pseudo-data for June 2004 has been generated using CASA GFEDv2 estimates of NEE (Peters et al., 2007), originally used as *a priori* fluxes in CarbonTracker, and high-resolution sensitivity matrices derived from STILT/WRF.

The following inversions will be performed, and results will be compared using three diagnostics (Root Mean Squared Error, Average Uncertainty, and % of "True" Fluxes that fall within the 95% Confidence Intervals):

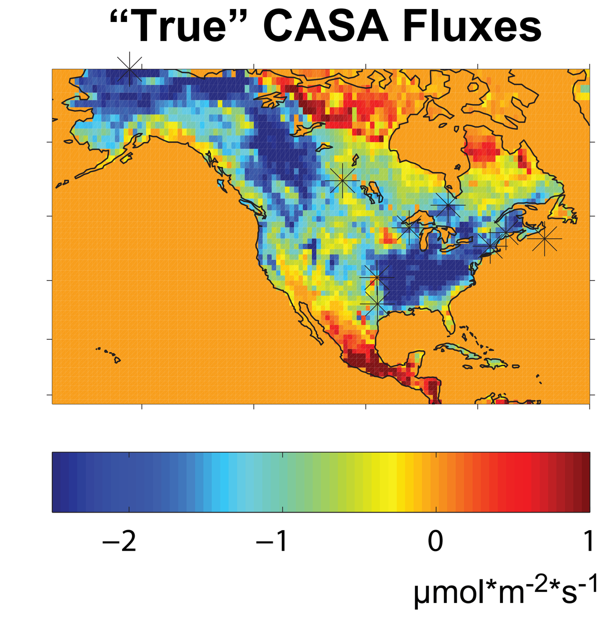
Case	Flux Resolution	Concentration Averaging
1	8-day average	daily
2	8-day average	3-hourly
3	daily average	daily
4	daily average	3-hourly
5	8-day average, 3-hour blocks	3-hourly

Preliminary results from Case 1 for June 1-8, 2004 are shown below. For this plot, pseudo-data was generated using 8-day average CASA fluxes:

***A posteriori* fluxes**



"True" CASA Fluxes



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