Regional Estimation of Terrestrial CO_2 exchange from NIGEC flux Data, Satellite Imagery, and Atmospheric Composition

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Executive Summary:

We have proposed an analysis of regional CO_2 budgets of North America, using coupled models of terrestrial ecophysiology and biogeochemistry and the physical climate system. The models are driven by observed climates and by the time-varying observed state of the vegetated land surface as derived from satellite imagery. The coupled system has been developed to predict atmospheric trace gas composition (CO_2, $\delta^{13}C$, and CO), which can be compared directly to measurements made at remote observing stations, tall towers, and by aircraft during the study period. Input data include retrospective satellite vegetation imagery at 8 km for the period 1981-1999 and analyzed weather data. Methods have been tested at the WLEF tall tower site, which can also be applied at the ARM-CART Southern Great Plains site in Oklahoma, both sites having abundant atmospheric data. Model output was used to test observing strategies and prioritize data collection, as well as to estimate the carbon balance of subcontinental regions.

Objectives:

- Extrapolate the carbon flux measurements made at three NIGEC-supported AmeriFlux towers to the scale of single GCM grid cells (10^5 km^2) using remotely sensed vegetation data and gridded weather analyses to drive the improved biophysical model coupled to a mesoscale atmospheric model (RAMS).
- Evaluate the realism and spatial scaling of the CO_2 “rectifier effect” over forests, grasslands, and croplands by using a hierarchy of simulations at multiple spatial scales to analyze simultaneous continuous measurements of surface carbon flux and the structure of the PBL over diurnal, synoptic, and seasonal time scales.
- Test several methods for estimation of area-averaged carbon exchange from concentration data, using “pseudodata” generated by the modeling system.

Approach:

We have been developing methods for recovery of regional carbon balance from atmospheric data using both “bottom up” and “top down” techniques. We are using a land-surface model (SiB2.5) to predict spatial and temporal variations in NEE on multiple spatial scales at the WLEF forest site, and at a C_4 grassland site and a C_3 wheat site in Oklahoma. The land-surface model is coupled to a mesoscale atmospheric model (RAMS), so our simulations will predict ecosystem fluxes, weather, and atmospheric trace gas transport in a self-consistent framework. These simulations can be compared directly to the abundant atmospheric data at the WLEF and ARM-CART sites, so that systematic errors in the modeling system can be identified and corrected. They will also provide a regional context for the measurements made by other researchers in those areas. The modeling system will be driven at these scales by analyzed weather (as a lateral boundary condition and an initial field), and satellite imagery (for specification of physiological parameters in SiB2.5). Model predictions, validated against local and regional atmospheric data, then constitute process-based “maps” of carbon exchange and atmospheric properties across a domain of about 10^5 km^2 (centered on the towers) that are consistent with all available observations (fluxes, concentrations, climate, and vegetation properties measured from space).

We have also investigated the feasibility of performing mesoscale inversions on pseudodata by assuming various configurations of atmospheric sampling networks that might be deployed in the future using aircraft, surface measurements, tall towers, or micrometeorological extrapolation ("virtual tall towers"). We subsample the large pseudodata volume at this hypothetical network and try to recover the regional fluxes that produced it in the model. Unlike inversions of real data, we will know the surface fluxes *a priori*, so we are able to rigorously evaluate these inversions and quantify the error in the results depending on the configuration of the hypothetical observing network. These studies will be essential for the design of continental observing systems in the future, and we expect that in the future we will continue exploring the ways in which stable isotopic tracers might add value to such a network.

Results to Date:

Deriving Mesoscale Surface Fluxes of Trace Gases from Concentration Data

We have been developing a modeling framework that is based on a Lagrangian Particle Dispersion Model (LPDM) linked to CSU RAMS (Regional Atmospheric Modeling System) (Uliasz, 2000). The LPDM is used in a receptor-oriented mode (tracing particles backward in time) to derive influence functions for each concentration sample. The influence function provides information on potential contributions from surface sources and inflow fluxes through the modeling domain boundaries into tracer concentrations sampled at the receptor. Then the Bayesian inversion technique is applied in an attempt to estimate unknown surface emissions. This framework allows us to study terrestrial CO_2 exchange in a variety of ways. Through it, we can compare and evaluate sampling strategies to aid with the design of field experiments and measuring networks, and are able to take into account data from different observational platforms and measuring systems for CO_2, including towers, aircraft, tethered balloons, kites, satellites, and flask systems. It enables us to perform mesoscale/regional studies with limited domains, looking at different trace gases, and it is particularly useful in looking at CO_2 and other gases with strong diurnal flux variability. Finally, it allows us to investigate the feasibility of the estimation of surface fluxes from available concentration data. It can be used with modern modeling tools, such as regional models with nesting capabilities, and can be run on desktop workstations or clusters of personal computers.

The essential part of the framework (Figure 1) is a meteorological model (A) used to create a modeling environment for all other calculations. The proposed methodology does not rely on any specific meteorological model. For inversion feasibility studies and the evaluation of different sampling strategies, the model should correctly reproduce important features of meteorological conditions as well as complexity of the flow. In particular, it is critical that the model correctly simulates the diurnal cycle of the PBL for the transport of trace gases like CO_2 with a strong diurnal variability of surface fluxes. It is not necessary to simulate specific episodes, as would be required for estimating surface fluxes from the actual concentration data.

The meteorological model provides input to the LPD model (B), which is run in a receptor-oriented mode so that all terms can be evaluated from backward particle trajectories. The particle simulation is done for a specific sampling strategy (C), i.e., number of concentration samples, their location, geometry, and time characteristic should be specified as input to define the receptor function for each sample. No information about actual values of concentration data or about emission sources is required at this step.

Next, the influence functions (E) are derived from the particle distributions stored from the LPD simulation. The influence functions are calculated for the surface fluxes, inflow fluxes as well as initial concentration field. They are analyzed to determine what source areas are covered by the sampling data set and what is the necessary time of simulation. This step should help in selecting modeling domain and specific source areas (D) for surface flux estimation. If necessary the particle simulation is repeated for another or modified sampling data set. Preliminary calculations may be performed relatively quickly for selected receptors with a small number of particles in the LPDM, and then additional particle simulations can be done to derive the final influence functions for further calculations.

For a given configuration of the source areas (D) the influence functions are used to calculate the source-receptor matrix (F). It describes the contributions from all selected surface sources as well as from inflow fluxes across modeling domain boundaries into all concentration samples. The contribution from initial concentration field can be neglected by the proper selection of the simulation time and is not consider here. Figure 2 presents examples of a time integrated influence function for a concentration sample taken at height of 400m at different times of day. Despite the simple meteorology, the presented patterns of the influence functions are quite complicated and show several separated areas of the enhanced influence. Since the surface flux is constant in time, these "hot spots" must be caused by the diurnal cycle of the PBL. To confirm this hypothesis one can analyze the influence function for a tracer with emissions limited to the daytime.

Reduction of uncertainty in flux estimation

The first variant of the proposed methodology (Figure 3) takes advantage of the uncertainty of the unknown parameter estimation provided by the Bayesian inversion technique. This uncertainty in the form of a covariance matrix is calculated from the source-receptor matrix using uncertainties assigned to concentration data and uncertainties of the prior emission estimates (G). Neither actual concentration data nor prior emission estimates are required in these calculations since the inversion calculations are not performed.

The uncertainty of flux estimation or reduction in uncertainty can be used to evaluate and compare different sampling strategies (H). This is procedure is simple and efficient (Uliasz, 2000), however, it may lead to erroneous results. As it will be demonstrated later it is possible to estimate uncertainty around completely wrong flux estimations if the data are not sufficient to perform successful inversion calculations. Therefore, another version of the framework was developed that performs actual inversion calculations with the aid of model generated concentration pseudo-data.

Evaluating inversion error using model pseudo-data

The steps A-B-E-F to obtain source-receptor matrix are performed in the same way as in the previous version of the methodology. Then, the source-receptor matrix is used generate concentration pseudo-data (I) for all samples in the strategy C. For this purpose exact values of all surface fluxes and, in general, the concentrations at upwind boundaries must be assumed. The model concentrations are calculated and then are perturbated by Gaussian noise according to observational data uncertainties described by covariance matrix C_d used in the inversion technique. These model pseudo data are further treated as real observational data and are entered into the inversion calculations (J) to estimate the tracer surface fluxes.

The steps I-J are repeated for several independent random realizations of the concentration data sets. As the final result, an ensemble of estimated surface and inflow fluxes is obtained. This ensemble can be compared to the exact values of the surface fluxes in statistical terms to assess a success of the given sampling strategy (C). In the case when more than one source area was considered, the ensemble was extended to random variations of the fluxes prescribed for these source areas.

The above framework was formulated to evaluate different sampling strategies and investigate feasibility of surface fluxes estimation using model generated pseudo-data (I). The same framework can be used for the estimation of surface fluxes from the real concentration data. However, repeating the steps (B-E-F-J) may be still useful to investigate different way of processing observation data and representing them in the modeling environment.

Design of numerical experiments: Atmospheric tracers

As demonstrated by measurement data from the WLEF tower in northern Wisconsin, the CO_2 surface flux and in turn the CO_2 concentration of over land surfaces shows a strong diurnal cycle due to the combined effect of the vegetation activity and the diurnal development of the planetary boundary layer. The CO_2 flux can be decomposed with a good approximation for a given time of year into two components: (1) the release of CO_2 by microbial decomposition in the soil (respiration) with an approximately constant rate, and (2) the uptake of CO_2 by photosynthesizing plants during the daytime (assimilation).

For the purpose of this study two model tracers were considered (Figure 4):

- R-tracer with the constant in time flux, R, corresponding to the CO_2 respiration flux; this tracer can also represent any atmospheric trace gas with the surface flux that is constant or shows little variability within the time scale of a few days

- A-tracer with the variable in time flux corresponding to the CO_2 assimilation flux. This tracer can provide some insight for trace gases with a strong diurnal variability of the surface flux.

It is assumed that the shape function for the A-tracer is determined by the times of sunrise and sunset and is known for a given location and time of the year. The surface flux for the A tracer can be expressed as $q = Af_A(t)$, where A is the value of uptake flux during daytime. Therefore, only values of the constant respiration flux, R, and the daytime value of the assimilation flux, A, need to be estimated. The values R=4 μmol m^{-2} s^{-1} and A=-13 μmol m^{-2} s^{-1} were derived from 3 years (1995-97) of WLEF flux data for July-August using only sunny days. These values were used in the following inversion experiments.

The two model tracers can be combined to obtain the CO_2 concentration. In particular, the 24 hour net flux of CO_2 can be derived from R and A fluxes:

$$F_{net} = \frac{1}{T}\int_0^T (R + f_A(t)A)dt$$

where T=24 hours.

Numerical simulations

The Colorado State University RAMS (Regional Atmospheric Modeling System) (Pielke et al., 1992) was used to simulate a diurnal development of the PBL over homogeneous terrain. The simulation was performed for three consecutive days assuming constant geostrophic wind, U_g=5 m/s for summer conditions roughly corresponding to northern Wisconsin. The diurnal cycle of the PBL during the second and third days of the simulation, used as input for the LPDM, is illustrated in Figure 5.

In order to study the effects of distant source areas and tracer upwind flux, a large modeling domain extending for 1000 km along the direction of the geostrophic wind was used in the study. This domain covered allowed us to simulate atmospheric transport during two full diurnal cycles of the PBL. It was necessary to analyze the inflow flux at the western boundary only.

In this part of the study, the LPD model was used solely in the receptor-oriented mode. Particles were released continuously during 24 hours (the third day of the meteorological simulations) from receptors at different heights and traced back in time up to 1000 km upwind. 8640 particles/hour were released from each receptor during 8 independent simulations. Both tracer concentrations and influence functions were derived from the backward particle trajectories.

Examples of surface flux estimation

Several numerical tests were performed in order to demonstrate the proposed methodology based on model-generated concentration pseudo data. Different sampling strategies were applied to estimate area averaged surface fluxes from one or more source areas located upwind of concentration measurements. The flux values, R and A, were estimated from concentration data of R- and A-tracer correspondingly as well as from the total CO_2 concentrations. In the latter case, the 24 hour net flux of CO_2 was also estimated from R and A fluxes. The calculations in each of the experiments were repeated for 1000 independent sets of the model-generated pseudo-data. The estimated fluxes were compared to exact values in terms of the root mean square error (RMSE) normalized by the flux value:

$$E_1 = RMSE / flux \times 100\%$$

The above error was calculated over the entire ensemble of inversion calculations as well as over perturbation of fluxes from the source areas if more than one was considered. The inversion procedure was assumed to be successful if the error, E_1, was lower than 50%, otherwise the test was reported as failure. In the selected tests, the error E_1 was compared to the uncertainty estimate:

$$E_2 = \sigma_m / flux \times 100\%$$

where σ_m - a diagonal term of the covariance matrix for a flux of interest.

Two simple sampling strategies were considered:

- 24 hour time series from a tall tower: concentration samples at 5 levels: 30, 76, 122, 244, and 396m, similar to the WLEF tower (in some experiments more than one tower was considered) (Figure 5),
- aircraft vertical profiles through the PBL at different times of day, 6 concentration samples at 250, 450, 650, 850, 1150, and 1450m.

For both sampling strategies the concentration pseudo-data for R-, A-, and CO_2 tracer were generated as 1-hour average samples. They were calculated from the influence functions by taking into account the upwind D¥ 800 km source area with the surface fluxes. The size of the source area along wind direction, D, varied from 10 to 1000 km.

The first series of experiments was performed under the assumption that the inflow tracer flux is known and the area averaged surface flux from a single source was the only unknown parameter to be estimated. These tests were repeated for different upwind sizes, D, of the area source.

Figure 6 presents the error, E_1, of surface flux estimation using a single aircraft profile taken at different times of day. In the late afternoon (16:00) this profile provides samples from the convective PBL. During night (04:00) the aircraft is completely above the stable PBL and samples tracer concentration in the residual layer from the previous day. In the late morning (10:00), this profile provides data from the developing mixed layer as well as from above it.

A single aircraft vertical profile in the afternoon CBL provides sufficient information to estimate area averaged surface flux of the R-tracer (Figure 6a) and the A-tracer (Figure 6b). The accuracy of the flux estimation increases with the size D of the source area. Acceptable results were obtained for the source areas not smaller than 20 km. The late morning sampling profile provided more information for the inversion calculations resulting in a slightly lower error. The nighttime sampling profile allowed one to perform the successful inversion for the R flux but only for the source areas longer than 50 km. The same inversion for the A flux failed except for the very large sources (>200 km) which provided a signal detectable in the residual boundary layer. Additional tests proved that the amount of information from the aircraft profile in the afternoon CBL is comparable to the information obtained from the tall tower at the same time as well as the higher resolution vertical sampling profile through the entire PBL.

The estimation of R and A fluxes from CO_2 concentration data using separately the morning and afternoon profiles was much less accurate (Figure 6c,d), and in turn, the estimation of the net CO_2 (Figure 6e) was not very successful except for very large source areas. The flux estimates can be significantly improved by using these two sampling profiles together. In this case, the estimates of the net flux were successful for $D \geq 100$ km.

Next, the 24-hour time series of concentration data (120 samples from 5 levels) from a tall tower was applied to the same test. The surface fluxes from R-, A-, or CO_2 concentrations were estimated with very high accuracy. The estimation error was lower than 2% even for the smallest source area with D=10 km. The sampling data from the lowest tower levels with the pronounced diurnal cycle played the most significant role in these calculations. The test was repeated using separately concentration time series from single tower levels. The inversion with 30m data was almost as accurate as the inversion using data from all 5 levels. Adding data from additional levels did not significantly improve the estimation accuracy. The inversions using the 122 and 396m level data alone failed. These levels were located above the stable nighttime PBL and did not show significant diurnal variations in the performed simulations.

Other experiments explored variants of the proposed methodology resulting in error estimation E1 and E2 as well as effect of the number of data points and the uncertainty of the observational data. 100-km source area. The 24-hour net CO_2 flux averaged over the 100 km source area was estimated with the aid of 24-hour time series of concentration data from two tall towers with 5 levels each. The first tower was located just downwind of the source area and the second one in the middle of it. The data set was prepared starting from the lowest level of the first (downwind) tower followed by higher levels of this tower and then data from the second tower. The inversion experiment was repeated for the increasing number of concentration data points, starting from a single data point and ending with 240 samples from both towers.

The modeling framework we have described is general and can be used with different meteorological models. It is especially useful for the design of field experiments and observational networks, and allows us to explore the feasibility of flux estimations, given a specific data set, and taking into account the uncertainty within the data. For this type of application, model generated concentration pseudo-data are used in inversion calculations to evaluate and compare different sampling strategies and data sets.

Simulated and Observed Fluxes of Sensible and Latent Heat and CO_2 at the WLEF TV Tower

Three years of meteorological data collected at the WLEF-TV tower were used to drive a revised version of the Simple Biosphere Model (SiB 2.5). Physiological properties and vegetation phenology were specified from satellite imagery. Simulated fluxes of heat, moisture and carbon were compared to eddy covariance measurements taken onsite as a means of evaluating model performance on diurnal, synoptic, seasonal, and interannual time scales.

Boundary conditions for the Simple Biosphere Model version 2 (SiB2; Sellers *et al*. 1996a) characterize land surface conditions at a location using a combination of land cover type (Hansen *et al*. 2000), monthly maximum Normalized Difference Vegetation Index (NDVI) derived from Advanced Very High Resolution Radiometer (AVHRR) data (Teillet *et al*. 2000) and soil properties (Soil Survey Staff 1994). Time invariant vegetation biophysical parameters such as canopy height, leaf angle distribution, leaf transmittance and other parameters related to photosynthesis are based on values recorded in the literature and assigned via look-up tables as described in Sellers *et al*. 1996b. Time varying vegetation biophysical parameters such as leaf area index and fractional absorbed photosynthetically active radiation are calculated from one year of NDVI monthly maximum value composites for the site based on equations in Sellers *et al*. (1996a,b) and Los *et al*. (2000). Soil hydraulic and thermal parameters are calculated from the percent of sand and clay in the soil using the equations from Clapp and Hornberger (1978) as modified by Bonan (1996). Boundary conditions for SiB2 can be created at any resolution given certain considerations. We have prepared datasets for both a single point and a mesoscale domain (1200 x 1200 km^2) for the WLEF tall tower site in Park Falls, Wisconsin.

The offline simulations of 3 years (1997-1999) of surface fluxes at the WLEF-TV tower by SiB provided an opportunity to closely assess model performance. The intention here was not to produce the most accurate simulation possible: model parameters were not "tuned" to obtain a better match to observations. Rather, the simulation was treated as an opportunity to test model performance for a location in which meteorology and fluxes are well-observed, but which is otherwise like any other model grid cell. Parameters were estimated from 1-km NDVI data, as has been done for a large domain surrounding the tower site. A fully coupled simulation, described below, uses exactly the same approach, except that the weather is interactive with the simulated biophysics and biogeochemistry, being simulated in a mesoscale model. Overall, the model was reasonably successful in capturing variations in fluxes of latent and sensible heat and CO_2 at the WLEF-TV site over diurnal, synoptic, and seasonal time scales. The agreement between the model and the observations was particularly good for latent heat flux, but less good for sensible heat flux and net carbon exchange. Simulated sensible heat flux was generally greater than observed. Analysis of surface energy budget components suggests that this disagreement may reflect a combination of errors in model albedo and soil thermal conductivity, and underestimation by the eddy flux system.

Interannual variability was less well simulated, especially in springtime, due to the unavailability of NDVI data for parameterization of canopy properties during the actual years of the study. Interannual variability during summertime, when the canopy was in full leaf, were more successfully simulated given changes in climatic drivers. The model consistently overestimated late-day photosynthesis and transpiration relative to the observations, typically producing "U-shaped" diurnal cycles whereas the observed diurnal cycle was more typically "V-shaped." This was likely due to the model's treatment of within-canopy light extinction, which was appropriate for diffuse light but failed to correctly represent shading and extinction of direct-beam radiation. The radiative transfer submodel essentially treats all light within the canopy as diffuse, resulting in an unrealistically high canopy-average light-use efficiency. The highest priority for model improvement is placed on canopy radiative transfer, soil thermodynamics, and obtaining better NDVI data sets for this period.

Simulated Variations in Atmospheric CO_2 over a Wisconsin Forest using a Coupled Ecosystem-Atmosphere Model

As discussed above, ecosystem fluxes of energy, water, and CO_2 result in spatial and temporal variations in atmospheric properties which can be used to quantify the fluxes through inverse modeling of atmospheric transport, and can improve understanding of processes and falsifiability of models. As part of our research, we have investigated the influence of ecosystem fluxes on atmospheric CO_2 in the vicinity of the WLEF-TV tower in Wisconsin using an ecophysiological model (SiB2) coupled to an atmospheric model (RAMS). The model parameters were specified from satellite imagery and soil texture data as described above. Using the uncoupled biosphere model, the fluxes in the immediate tower vicinity have been compared to eddy covariance fluxes measured at the tower, with meteorology specified from tower sensors. Results were encouraging with respect to the ability of the model to capture observed diurnal cycles of fluxes. Here, the effects of fluxes in the tower footprint were also investigated by coupling SiB2 to a high-resolution atmospheric simulation, so that the model physiology could affect the meteorological environment.

The coupled SiB2-RAMS model was reasonably successful in representing observed diurnal variations in fluxes of radiation, heat, water, and CO_2 at the WLEF tower site. Advantages of the coupled model relative to the offline simulations reported above include the representation of the feedbacks between surface fluxes and PBL properties and the ability to compare simulated atmospheric CO_2 concentration to observations as an additional criterion for model evaluation. The diurnal cycle of the evolution of the PBL and the vertical profile of CO_2 in the high-resolution 2D simulations is fairly consistent with the tower observations. The major exception is the development of a shallow CO_2 minimum in the simulations just before sunset. This arises because of a tendency of the model to overestimate late afternoon canopy activity (transpiration and photosynthesis), leading to persistent CO_2 uptake under a stable layer that forms about an hour too early. This phenomenon is attributed to misrepresentation of the extinction of direct beam radiation in SiB, resulting in overestimation of canopy-average light-use efficiency, and was also noted in the previous section. While the deviation of the simulated fluxes from the observations was fairly subtle, the effect on simulated CO_2 concentrations was obvious. This is an important advantage of the fully coupled simulations, and shows that prediction of an atmospheric scalar (CO_2) can in fact reveal subtle problems with the treatment of canopy biophysics.

A Multiple-Scale Simulation of Variations in Atmospheric CO_2 using the Coupled SiB-RAMS Model

An additional simulation was conducted to test the coupled Biosphere-Atmospheric model (SiB2-RAMS), by comparing with measurements made at the WLEF-TV tower in Wisconsin, and to investigate some of the mechanisms leading to CO_2 variability, both on local and regional scales. The simulation was run for a five-day period from July 26 to July 30, 1997. Multiple nested grids were employed, which enabled mesoscale features to be simulated and which resolved small-scale features in the vicinity of the WLEF tower. In many respects, the model was successful at simulating observed meteorological variables and CO_2 fluxes and concentrations. The two most significant deficiencies were that excessive nighttime cooling occurred on two of the nights, and that late afternoon uptake of CO_2 was larger than observed. Results of the simulation suggest that in addition to biological processes causing variations in CO_2 concentrations at the WLEF site, other factors such as small nearby lakes, turbulence induced by vertical wind shear, boundary layer thermals and clouds, also had significant impacts. These factors add to the difficulty of interpreting CO_2 measurements. Regional scale patterns of CO_2 variability caused by meteorological processes were also identified. Katabatic winds had a significant effect by causing respired CO_2 to pool in valleys and along the shores of the Great Lakes during the night. Furthermore, a large diurnal cycle of CO_2 concentration occurred over the lakes, which appeared to be mainly due to the combined action of katabatic winds, ambient winds, and the return flow of the lake breeze. These results suggest that large-scale advection of CO_2 due to these region specific meteorological processes will need to be taken into account in this area if the biological signal is to be extracted from CO_2 measurements.

A sensitivity test conducted to examine the differences between using a turbulent kinetic energy based sub-grid scale scheme versus a deformation-type sub-grid scale scheme showed advantages and disadvantages to both approaches. This study demonstrates the feasibility of using multiple nested grid coupled biosphere-atmospheric models to investigate processes leading to CO_2 variability at observation sites. Model output may be useful for determining the flux footprint of the WLEF-TV tower, for spatial scaling of CO_2 flux observations, and for evaluating regional scale simulations. Future, longer duration regional scale simulations will need to employ convective parameterizations that include vertical CO_2 transports and realistically incorporate cloud and radiation interactions. Cloud resolving simulations such as used in this study could aid in the development of these schemes. It is possible that as well as using regional models for CO_2 transport in future regional scale inversion studies, additional model fields such as surface CO_2 flux could be used to provide further constraints to improve the accuracy of CO_2 source and sink predictions.

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Figures:

Figure 1: Modeling framework for deriving mesoscale surface fluxes of trace gases from concentration data.

Figure 2: Examples of a time integrated influence function for a concentration sample taken at height of 400m at different times of day.

Figure 3: Modeling framework which can take advantage of the uncertainty of the unknown parameter estimation provided by the Bayesian inversion technique. Modeling framework for deriving mesoscale surface fluxes of trace gases from concentration data.

Figure 4: Approximation of CO_2 flux with assimilation (A-tracer) and respiration (R-tracer) fluxes.

Figure 5: Evolution of the PBL during the second and third day of the meteorological simulation illustrated by contours of vertical velocity variance [m^2s^{-2}] – contours starting from 0.1 every 0.1, the shaded area limited by 0.001 value.

Figure 6: Root mean square error (normalized by flux) of surface flux estimation using two aircraft vertical profiles at the same location but at different times of day as a function of the source area size (no inflow flux).