The use of airborne and ground based atmospheric observations in carbon cycle research

Christoph Gerbig

Max-Planck-Institut für Biogeochemie,
PO box 100164, D-07741 Jena;
cgerbig@bgc-jena.mpg.de

Abstract

Information about the distribution of sources and sinks of atmospheric trace gases such as CO_2 can be derived from measurements in the atmosphere. The spatial and temporal patterns in trace gas distributions is in fact caused by spatially and temporally varying fluxes combined with varying atmospheric transport. While ground-based measurements made close to the surface (e.g. on cell phone towers) can provide long-term constraints, airborne measurements provide more of a snapshot of the atmospheric distribution, mostly taken over a short time period. Such snapshots can be used to critically evaluate the skills of modelling systems that couple surface flux models (emission models, biospheric models) with atmospheric transport models. The COBRA missions conducted over the last 5 years over North America are presented as examples.

1. Introduction

CO_2 is the most important greenhouse gas, and its atmospheric concentration is rising continuously, from pre-industrial levels of 280 ppm to about 380 ppm today, with current rates of about 1.5 ppm/year (IPCC, 2001). The increase is mostly due to due to fossil fuel emissions that are only partly taken up by land and ocean sinks; about half of the emitted CO_2 stays in the atmosphere. Carbon cycle research is therefore required to address the following questions: (1) Where and through which process is the excess anthropogenic carbon being taken up by land and ocean? (2) What and how large are the key feedback links between the carbon cycle and the physical climate system? (3) What is the carbon budget of a particular region (continent, country)? The latter question becomes important when verification of mandated emission reductions and "carbon trading" is needed. The need for detailed process understanding (questions one and 2) are underpinned by scenarios calculated with coupled carbon cycle - climate models: including the feedback between climate and the carbon cycle lead to vastly different outcomes over the next century (Cox et al., 2000; Dufresne et al., 2002).

There are two basic approaches for inferring regional scale surface-atmosphere exchange for trace gases: a bottom-up approach, in which local process knowledge is scaled up, and a top-down approach, in which the larger-scale constraint from atmospheric concentration measurements is applied in combination with transport models. Atmospheric measurements can serve as input data for both approaches: concurrent measurement of CO_2 concentration and vertical wind speed yield information about surface-atmosphere exchange (eddy covariance, c.f. (Goulden et al., 1996b)) and (together with meteorological measurements) information of controlling variables (Goulden et al., 1996a), while concentration measurements at selected locations with high accuracy provide input to inverse transport models (Bousquet et al., 1999; Fan et al., 1998; Tans et al., 1990).

This paper gives a brief overview over the existing global CO_2 monitoring network. Then airborne intensive measurements are introduced as a method to sample the atmosphere for short intensive periods at a much higher spatial and temporal density as compared to long term monitoring network. Statistical properties of the spatial distribution of CO_2 are then derived, providing insight into model requirements. It is shown how such data can be used to assess and diagnose modelling frameworks designed to retrieve flux information from atmospheric concentrations. Finally, an application is shown that utilizes a receptor-oriented (or adjoint) model to plan flight tracks that attempt to follow air masses as they move over a given surface area. Such Lagrangian (or influence-following) experiments provide a tight constraint on surface-atmosphere exchange fluxes on regional scales (10^4-10^5 km^2).

2. Observational networks

2.1. CO_2 concentrations

Atmospheric CO_2 has been monitored continuously since nearly half a century (Keeling, 1961) at the Mauna Loa Observatory (Fig. 1). These data showed for the first time experimental evidence for a seasonal cycle in CO_2 caused by biospheric activity, as well as an increasing trend related to fossil fuel emissions.

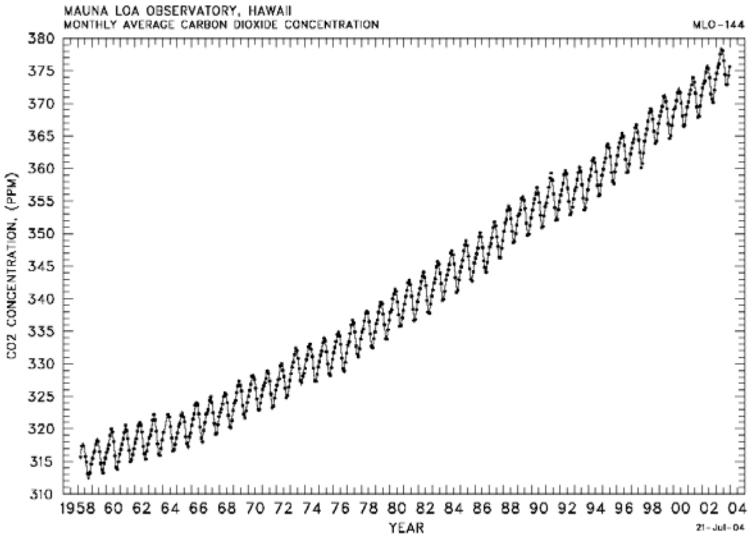

Figure 1: CO_2 measurements at the Mauna Loa Observatory

Since about 1980, measurements are made at several sites forming a network that is increasing in density (Fig. 2). Until recently, these stations were located at remote sites (islands, mountains, coasts) that guarantee air samples representing large airmasses, with the idea that they can be better represented in global transport models. However, the remoteness of the measurement locations also means insensitivity to regional flux distributions over the continents, with the result that only large scale features can be extracted from the inversions (Gloor et al., 2000). In order to better constrain regional scale fluxes, measurements are made within the continental boundary layer at an increasing number of locations, such as for example proposed for example by the North American Carbon Program (Wofsy and Harriss, 2002). This involves observations from tall towers (Bakwin et al., 1995), but also routine airborne profiling.

Measurements made closer to strong sources and sinks such as near vegetated land are challenging to represent in transport models: strong spatial and temporal variations in surface fluxes in the near field of the measurement locations, combined with strong variations in transport and mixing (mixed layer height variations, frontal systems) result in highly variable concentrations. For example, variations in vertical mixing through changes in the mixed layer height co-vary with changes in biosphere-atmosphere exchange on diurnal time scales, with shallow mixing with respiration of CO_2 during night, and deeper mixing with assimilation of atmospheric CO_2 by vegetation (Denning et al., 1996).

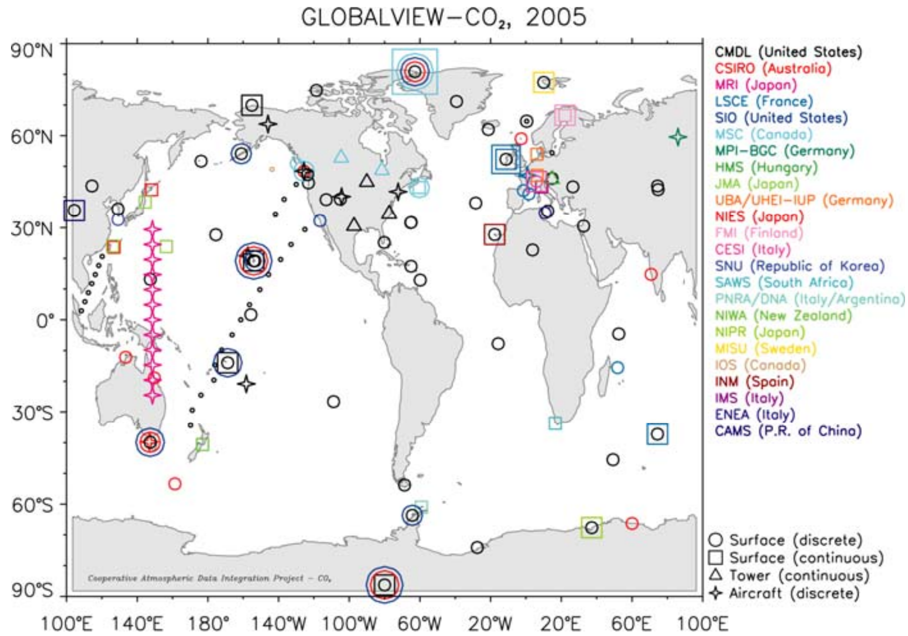

Figure 2: Global observational network for atmospheric CO_2 (from NOAA CMDL)

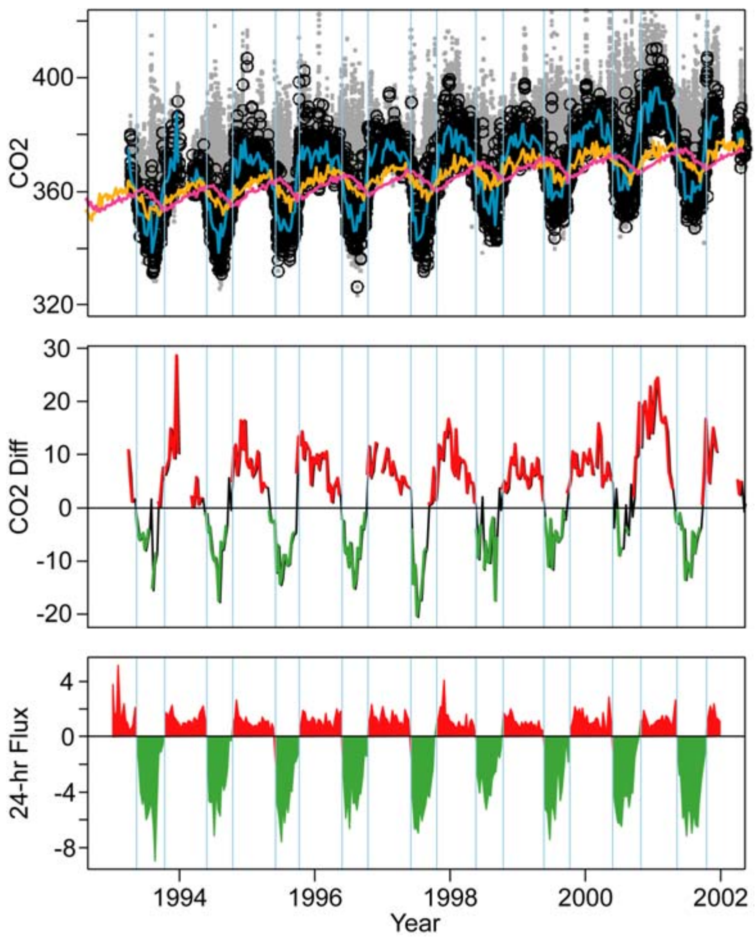

Figure 3: Concentrations of CO_2 at the Harvard Forest tower compared to remote station data. Hourly CO_2 (ppm) at 30m [•], midday values [O], 10-day medians of the midday data [——], and 10-day medians from Bermuda East[——] and Mauna Loa [——]. (middle) *Difference (ppm) between midday Harvard Forest concentrations and Bermuda E, color-coded by the sign of the CO_2 flux (**green**=uptake, **red**=emission).* (lower) *10-day median of the daily mean CO_2 flux at Harvard Forest (μmole $m^{-2}s^{-1}$) [Bermuda, Mauna Loa, and aircraft data from* T. Conway, *NOAA Climate Monitoring and Diagnostics Laboratory, 2004].*

This enhanced variability at continental sites as compared to remote sites is obvious for the Harvard Forest Environmental monitoring site (Figure 3). While stations located upstream and downstream of the continent (Mauna Loa and Bermuda in case of the continental US) show only small differences, indicating a small impact from the continental biosphere, values at Harvard forest contain a substantial signal related to biospheric activity as indicated by the collocated flux measurements. The difference between midday values at Harvard Forest (the continental site) and Bermuda (downstream of the continent) strongly correlates with 24 hour fluxes, supporting the idea that there is additional information about regional scale fluxes provided by measurements within the continental mixed layer.

2.2. Biosphere-atmosphere exchange fluxes of CO_2

Another source of information about the carbon cycle of the land biosphere is eddy covariance measurements. Concurrent measurements of CO_2 concentration and vertical wind speed (eddy covariance, c.f. (Goulden et al., 1996b)) yield information about surface-atmosphere exchange on scales of about 1 square kilometre. When combined with meteorological measurements, such data can provide information about the variables that control carbon exchange with the atmosphere on timescales from hours to decades (Goulden et al., 1996a). An example is also shown in figure 3. Such measurements are also being made with increasing global coverage within the FLUXNET network (Baldocchi et al., 2001).

3. Airborne Intensive Observations

Measurements made from research aircraft can provide detailed snapshots of trace gas distributions that could be provided by future sampling networks with enhanced spatial coverage and multiple vertical profiles. During the CO2 Budget and Rectification Airborne Study in August 2000 (COBRA-2000) an aircraft sampled extensively in both the vertical and the horizontal, covering spatial scales from a few km to hundreds and thousands of km (figure 4). The experiment was designed as a pilot study to determine the characteristics of the atmospheric CO_2 signal from terrestrial ecosystem processes over North America and to test concepts to quantify sources and sinks.

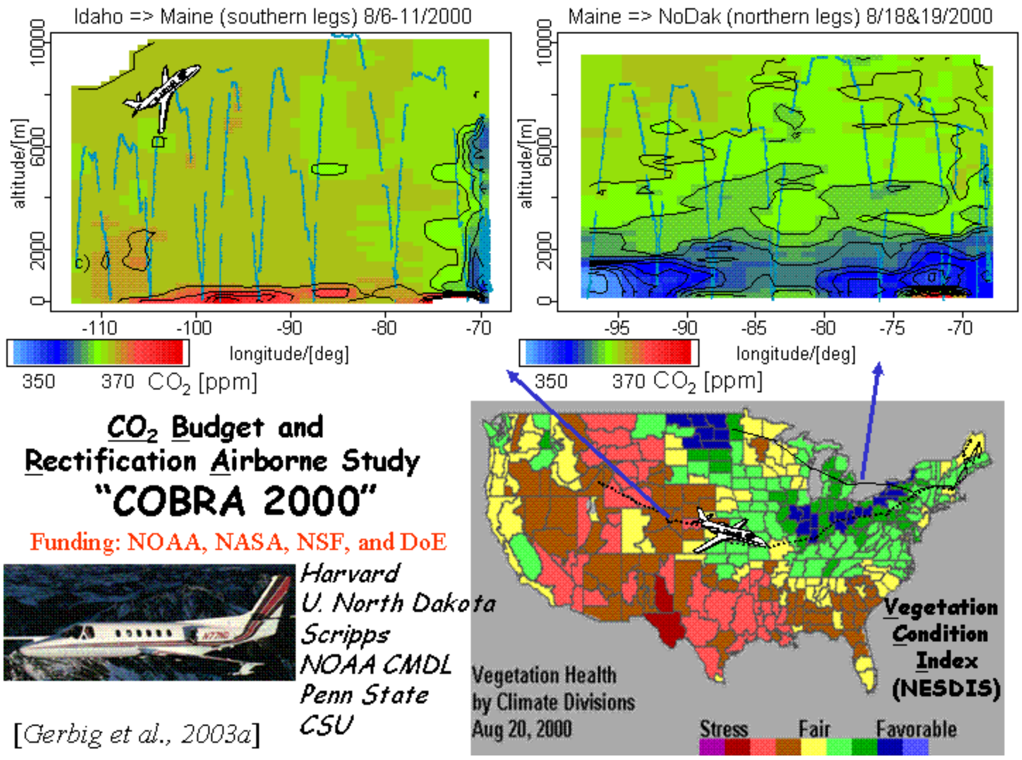

Figure 4: Measurements of large scale CO_2 distributions made during COBRA 2000. Large scale gradients observed in multiple vertical profiles reflect patterns in surface flux distributions.

Such data can be used to determine the spatial variability of CO2 in both the vertical (Figure 5) and horizontal dimensions (Figure 6), an important piece of information related to the scales that have to be resolved in order to properly represent the spatial distribution in a transport model (Gerbig et al., 2003a; Gerbig et al., 2003b; {Lin, 2004 #1278}).

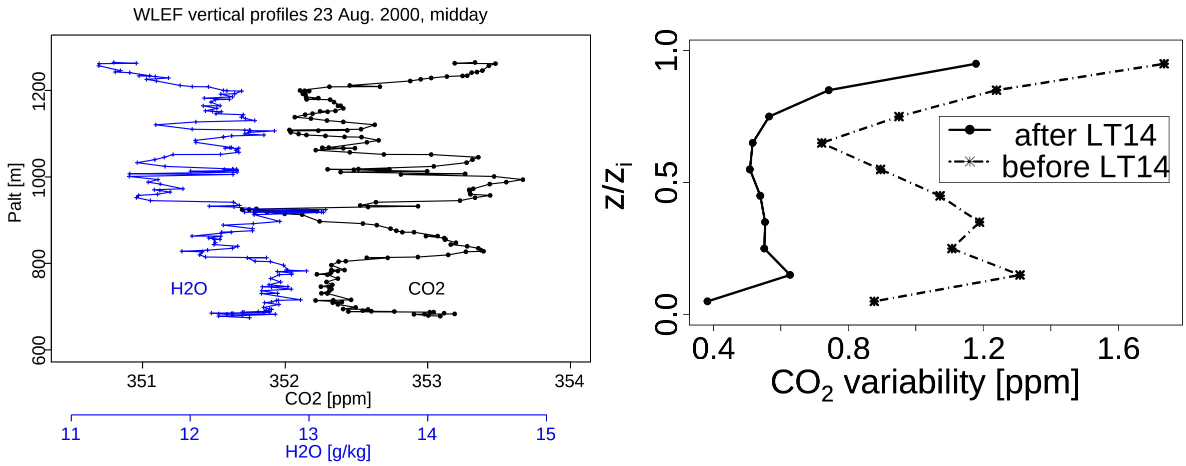

Figure 5: Profiles of CO_2 and H2O collected around 15:00 local time over the WLEF tall tower (left). Signatures of moist, CO_2 depleted rising eddies alternate with dry, CO_2 enriched layers that are entrained from the free troposphere. Profiles of the standard deviation of the departure from the mixed-layer average CO_2 (right). Afternoon values are less variable (solid circles and solid lines) than morning/noon values (stars and dashed line). A distinct increase in variability at the upper 20% of the mixed layer is due to intermittent entrainment of air from the residual layer or free troposphere.

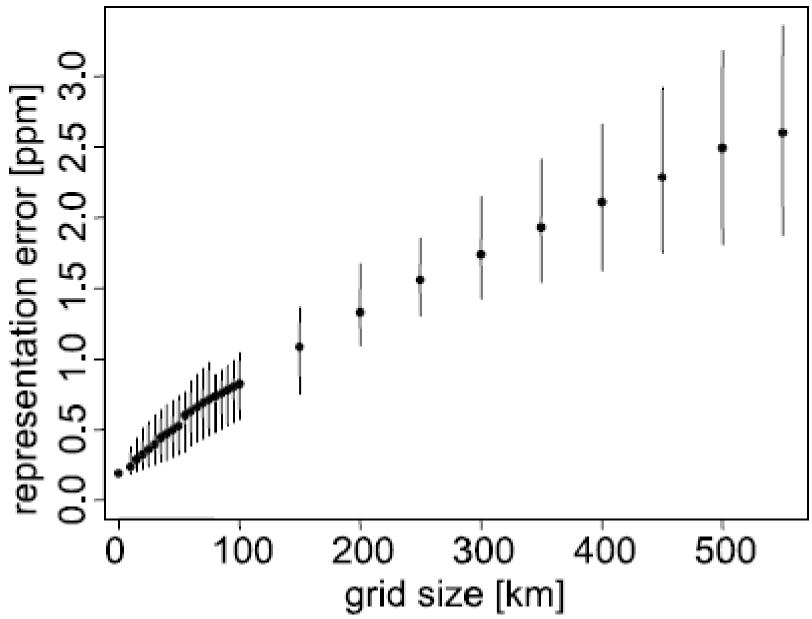

Figure 6: Representation error of mixed-layer averaged CO2 mixing ratios plotted against the horizontal dimension of the region. Vertical bars indicate the 5–95% confidence intervals.

4. Application of atmospheric data within a modelling framework

A “receptor-oriented” analysis framework designed to quantitatively interpret the atmospheric signatures of surface processes is presented. Here “receptor-oriented” means that mixing ratio signals at a receptor are linked to its causes, upstream sources and sinks; this is also called the adjoint transport model. The framework called ROAM (Receptor Oriented Atmospheric Model) incorporates three main components (Gerbig et al., 2003b): 1) the Stochastic Time-Inverted Lagrangian Transport (STILT) model, driven with assimilated winds and running backward in time to map out the source-receptor relationship (footprint) at high temporal and spatial resolution (Lin et al., 2003); 2) an observation-based lateral boundary condition for CO_2, resolving vertical and meridional gradients (Gerbig et al., 2003a); and 3) a simple parameterization for biosphere-atmosphere fluxes that uses eddy covariance observations from the AmeriFlux network as prior estimates for fluxes. This framework allows quantitative comparison between the top-down constraint on fluxes from airborne observations of CO_2 with the bottom-up constraint of eddy flux measurements in a Bayesian synthesis inversion.

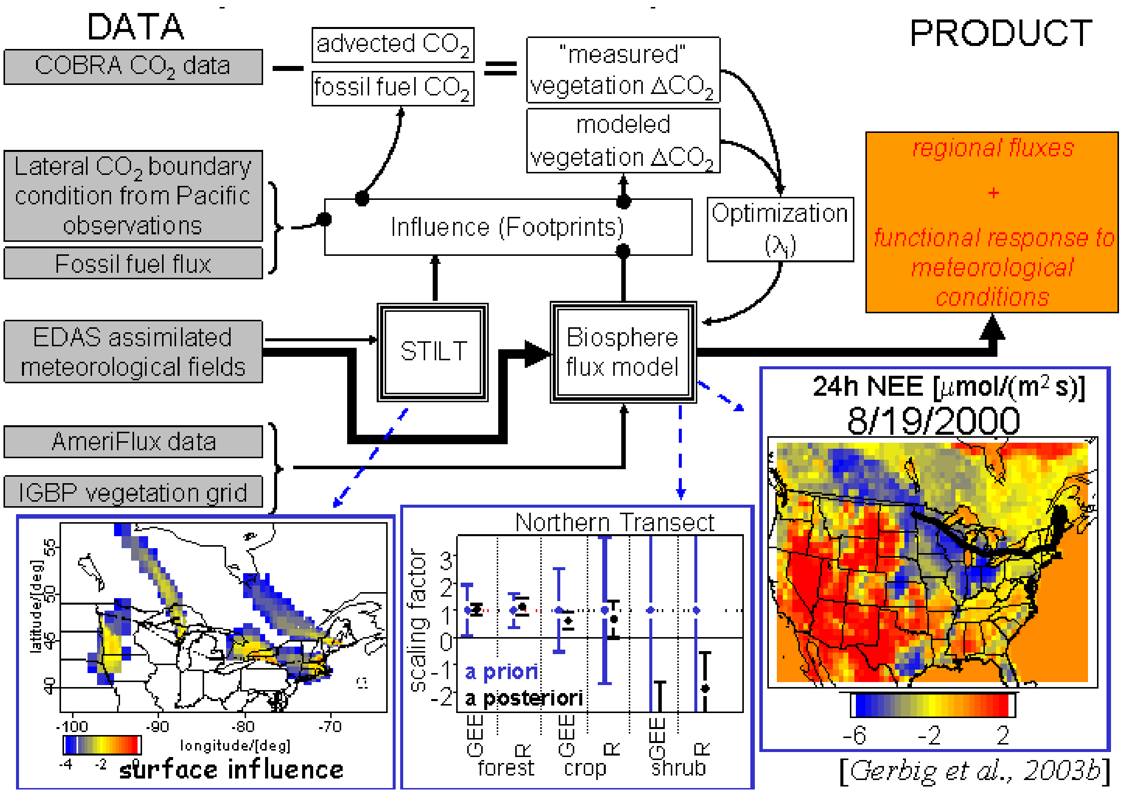

Figure 7: Schematics of the ROAM framework.

Figure 7 presents a schematic representation of the ROAM framework. It consists of three main components: a receptor-oriented transport model using analyzed meteorological field, a lateral tracer boundary condition using remote marine measurements and a Green's function for vertical propagation, and a simple biospheric flux model using eddy flux data to provide high spatial and temporal resolution. The framework takes input from multiple data sources and provides as output optimized biospheric parameters and, in conjunction with meteorological fields, associated regional fluxes.

The high spatial and temporal resolution provides the potential to reduce representation and aggregation errors, and the explicit simulation of diurnally varying biospheric fluxes and turbulent mixing enables the diurnal rectifier to be represented. The application of the data analysis framework to the observations is done in several steps (Fig. 7): (1) Influence functions are calculated for the measurement locations at high spatial and temporal resolution using the receptor-oriented Stochastic Time-Inverted Lagrangian Transport (STILT) model [Lin et al., 2003]; these influence functions are equivalent to the adjoint of the transport model, in that they represent sensitivities of atmospheric concentrations to upstream surface fluxes or lateral boundary values. (2) The influence functions are coupled to emission inventories for fossil fuels and to background fields for CO_2 and CO, to derive the combustion CO_2 signal (involving measured CO enhancements above the background as a combustion tracer and inventory based CO_2/CO emission ratios) as well as the advected background CO_2. (3) The measurement-based CO_2 vegetation signal is calculated as the difference between measured CO_2 and the sum of advected CO_2 and combustion CO_2 signal. (4) Biospheric fluxes are modelled as responses to temperature and radiation from assimilated meteorological data; the responses to these meteorological drivers are keyed to data from eddy covariance flux towers in the AmeriFlux network (Baldocchi et al., 2001) (5) Modelled CO_2 vegetation signals are derived by coupling the influence functions to the biosphere model. (6) Parameters of the biospheric flux model for key vegetation types are optimized in a Bayesian synthesis inversion to obtain a match between modelled and measured CO2 vegetation signals. (7) Estimates of regional fluxes for ~1 week are derived by driving the optimized biosphere flux model with observed meteorological conditions.

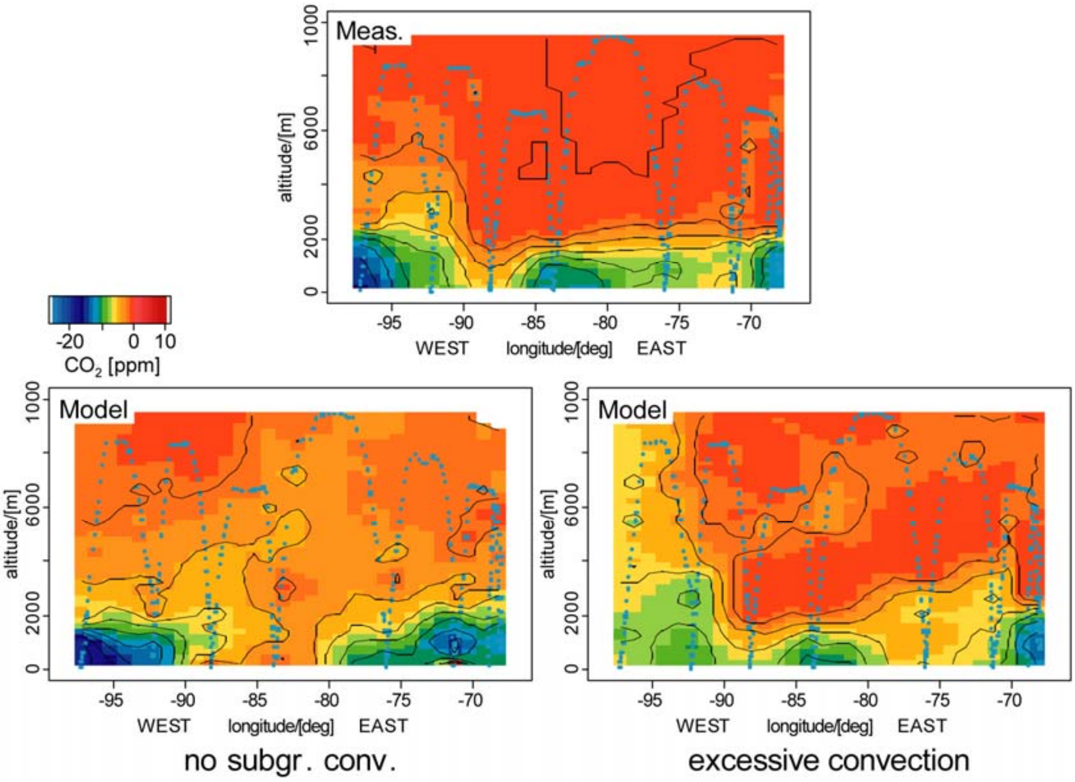

Figure 8: Comparison of measurement derived vegetation signal (top) with model calculations without (bottom left) and with (bottom right) excessive subgrid convection in the transport model.

The framework is used to investigate a number of shortcomings in transport modelling: a) by reproducing the observed representation error (mismatch between point measurements and gridcell-averaged values in models) with the ROAM, it can be shown that unresolved spatial variability of surface fluxes gives rise to most of the representation error over the continent; b) mismatch between modelled and measured mixed layer heights reveal large uncertainties in vertical mixing within the boundary layer (see Figure 8); c) convective redistribution of CO_2 is uncertain (Figure 8), usually parameterised with subgrid schemes. Especially points b) and c) are of great importance, since the wrong vertical distribution in the model leads to wrong source-receptor relationships, and therefore to biased flux estimates.

Thus airborne measurements can provide paradigm datasets that help in both, design and validation of modelling frameworks targeted at regional flux estimates. The idea is, on the long run, the use of airborne data to help integrating ground-based data into a data assimilation system.

ACKNOWLEDGEMENTS

This work has been done wile the author was at Harvard University, and in collaboration with S C. Wofsy (Harvard University), B C. Daube (Harvard University), J. C. Lin (Colorado State University), A. E. Andrews (NOAA CMDL), B. B. Stephens (NCAR), and C. A. Grainger (University of North Dakota).

REFERENCES

Bakwin, P.S., P.P. Tans, C. Zhao, W.I. Ussler, and E. Quesnell, Measurements of carbon dioxide on a very tall tower, *Tellus*, **47B**, 535-549, 1995.

Baldocchi, D., E. Falge, L.H. Gu, R. Olson, D. Hollinger, S. Running, P. Anthoni, C. Bernhofer, K. Davis, R. Evans, J. Fuentes, A. Goldstein, G. Katul, B. Law, X.H. Lee, Y. Malhi, T. Meyers, W. Munger, W. Oechel, K.T. Paw U, K. Pilegaard, H.P. Schmid, R. Valentini, S. Verma, T. Vesala, K. Wilson, and S. Wofsy, FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities, *Bull. Amer Meteor. Soc.*, **82** (11), 2415-2434, 2001.

Bousquet, P., P. Ciais, P. Peylin, M. Ramonet, and P. Monfray, Inverse modeling of annual atmospheric CO2 sources and sinks 1. method and control inversion, *J. Geophys. Res.*, **104** (D21), 26161-26178, 1999.

Cox, P.M., R.A. Betts, C.D. Jones, S.A. Spall, and I.J. Totterdell, Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, *Nature*, **408** (6809), 184-187, 2000.

Denning, A.S., D.A. Randall, G.J. Collatz, and P.J. Sellers, Simulations of terrestrial carbon metabolism and atmospheric CO2 in a general circulation model. Part 2: Simulated CO2 concentrations, *Tellus*, **48B**, 543-567, 1996.

Dufresne, J.-L., P. Friedlingstein, M. Berthelot, L. Bopp, P. Ciais, L. Fairhead, H. Le Treut, and P. Monfray, On the magnitude of positive feedback between future climate change and the carbon cycle, *Geophys. Res. Letters*, **29** (10), doi:10.1029/2001GL013777, 2002.

Fan, S., M. Gloor, J. Mahlman, S. Pacala, J. Sarmiento, T. Takahashi, and P. Tans, A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models, *Science*, **282**, 442-446, 1998.

Gerbig, C., J.C. Lin, S.C. Wofsy, B.C. Daube, A.E. Andrews, B.B. Stephens, P.S. Bakwin, and C.A. Grainger, Towards constraining regional scale fluxes of CO2 with atmospheric observations over a continent: 1. Observed Spatial Variability from airborne platforms, *J. Geophys. Res.*, **108** (D24), 4756, doi:10.1029/2002JD003018, 2003a.

Gerbig, C., J.C. Lin, S.C. Wofsy, B.C. Daube, A.E. Andrews, B.B. Stephens, P.S. Bakwin, and C.A. Grainger, Towards constraining regional scale fluxes of CO2 with atmospheric observations over a continent: 2. Analysis of COBRA data using a receptor-oriented framework, *J. Geophys. Res.*, **108** (D24), 4757, doi:10.1029/2003JD003770, 2003b.

Gloor, M., S.-M. Fan, S. Pacala, and J. Sarmiento, Optimal sampling of the atmosphere for purpose of inverse modeling: A model study, *Global Biogeochemical Cycles*, **14** (1), 407-428, 2000.

Goulden, M.L., J.W. Munger, S.-M. Fan, B.C. Daube, and S.C. Wofsy, Exchange of carbon dioxide by a deciduous forest: response to interannual climate variability, *Science*, **271**, 1576-1578, 1996a.

Goulden, M.L., J.W. Munger, S.-M. Fan, B.C. Daube, and S.C. Wofsy, Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy, *Global Change Biology*, **2**, 169-182, 1996b.

IPCC, *Synthesis Report*, pp. 44-122, 2001.

Keeling, C.D., The concentration and isotopic abundances of carbon dioxide in rural and marine air, *Geochimica et Cosmochimica Acta*, **24**, 277-298, 1961.

Lin, J.C., C. Gerbig, B.C. Daube, S.C. Wofsy, A.E. Andrews, S.A. Vay, and B.E. Anderson, An Empirical Analysis of the Spatial Variability of Atmospheric CO2: Implications for Inverse Analyses and Space-borne Sensors, *Geophys.Res.Letters*, accepted, 2004.

Lin, J.C., C. Gerbig, S.C. Wofsy, A.E. Andrews, B.C. Daube, K.J. Davis, and C.A. Grainger, A near-field tool for simulating the upstream influence of atmospheric observations: the Stochastic Time-Inverted Lagrangian Transport (STILT) model, *J.Geophys. Res*, **108** (D16), 4493, doi:10.1029/2002JD003161, 2003.

Tans, P.P., I.Y. Fung, and T. Takashi, Observational constraints on the global atmospheric CO2 budget, *Science*, **247**, 1431-1438, 1990.

Wofsy, S.C., and R.C. Harriss, The North American Carbon Program (NACP), NACP Committee of the U.S. Interagency Carbon Cycle Science Program, U.S. Global Change Research Program, Washington, DC, 2002.