Regional-Scale Estimation of Carbon Fluxes in Complex Terrain Using a Budget Approach During the Airborne Carbon in the Mountains Experiment

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Introduction

Mountain forests represent a large portion of gross primary productivity within the United States and a significant potential net CO_2 sink. Therefore, there is a need to develop methods to estimate regional fluxes of CO_2 in mountainous terrain.

We conducted the Airborne Carbon in the Mountains Experiment (ACME) in May and July of 2004 to explore methods for constraining regional-scale CO_2 fluxes over complex terrain and to collect measurements useful for devising and testing strategies for long-term monitoring of these fluxes. We flew a total of 54 hours (16 flights) on the NCAR C-130 aircraft over large regions of the Colorado Rocky Mountains, making continuous measurements of CO_2, CO, O_3, and water vapor concentrations among other measurements. The 16 flights were conducted according to a combination of experimental designs, including morning to afternoon Lagrangian flux measurements, regional measurements for assimilation into a high-resolution atmospheric model, morning sampling of nocturnally respired CO_2 in mountain valleys, and direct flux measurements.

We present results from a combined modeling and observational study of regional CO_2 fluxes in mountainous terrain. The focus in this poster is on the estimation of these fluxes using a boundary-layer budgeting approach and on some preliminary atmospheric numerical modeling results.

Composite of the NSF/NCAR C-130 research aircraft flying over the Rocky Mountains in Boulder. (Photo by Carlye Calvin.)

Airborne Carbon in the Mountains Experiment (ACME)

GOAL:

To estimate and understand carbon fluxes in montane forest regions at a regional scale

FIELD STUDY ACTIVITIES:

- Measure carbon fluxes at the stand (tower) scale using **eddy correlation and process studies**
- Measure carbon concentration and fluxes at the valley and regional scale using **ground-based and airborne measurements**

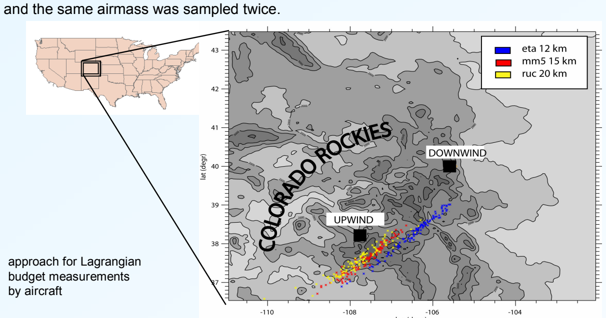
ATMOSPHERIC MODELING ACTIVITIES:

- Simulate **atmospheric flows in ACME modeling domain** and capture complex terrain effects with appropriate parameterizations and model setup parameters
- Simulate **horizontal and vertical distribution of CO_2 in mountainous terrain** using Lagrangian and Eulerian approaches
- Estimate **spatial and temporal pattern of surface CO_2 fluxes** in mountainous terrain using a variety of **inverse modeling approaches**

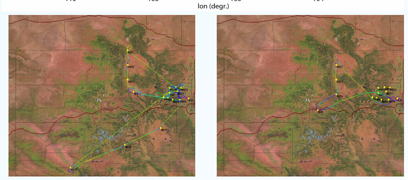
Boundary Layer Budgeting

An approach to regional flux estimation is the atmospheric boundary layer (ABL) conservation or budget method. In principle, the ABL budget method can be applied both in the stable and in the convective boundary layer (CBL). Most previous CBL budget methods are Eulerian in nature. The Lagrangian budget approach is more difficult and requires measurements at various locations, i.e. at the upwind and downwind locations.

For ACME, Lagrangian mass budget calculations were performed to estimate the uptake of CO_2 by the mountain forests during the day. The approach is depicted in the figure below. A Lagrangian particle dispersion model was used with output from a range of numerical forecast models in the morning of a flight day. The particle ensemble is released at a receptor location (Niwot Ridge on the eastern side of the Colorado Rocky mountains) in the afternoon, and transported backward in time. Thus the particles in the figure below represent the upstream regions in the morning (~9AM) affecting the receptor for three forecast models (ETA, MM5, and RUC) in the afternoon(~3PM). On the flight day shown below as an example (20 May 2004), the various forecast models were rather consistent with regard to the upstream region affecting the receptor and a vertical CO_2 profile was measured by aircraft in this upstream region in the morning. In the afternoon, a vertical profile was measured above Niwot Ridge. CO_2 uptake can now be estimated from the change in the column integral of CO_2 between the morning and afternoon profiles, assuming that the forecast was accurate and the same airmass was sampled twice.

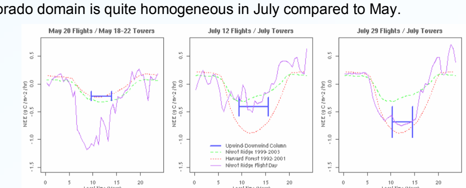


approach for Lagrangian budget measurements by aircraft



Flight plan in the morning (left figure) and in the afternoon (right figure) on May 20, 2004.

The figure below shows a comparison between local observations at Niwot Ridge and the estimate from the Lagrangian boundary layer budget approach on three flight days. The figure shows surprising convergence in mid-summer with the airborne snapshots of mid-day flux rates being quite similar to local fluxes at Niwot during the same hours. The continuous curves are the actual and long term average Niwot data for the year/day of the flight, and the average for Harvard Forest as a low altitude reference site. The horizontal bar indicates the average boundary layer budget flux and the vertical lines are the estimated uncertainty. There is a closer agreement between regional airborne fluxes and local eddy covariance fluxes in mid-summer compared to spring. Analysis of the global data base of coniferous forest eddy covariance data shows that indeed mid-summer fluxes are relatively constant over a very wide range of needleleafed forest ecosystems and it is plausible that the Colorado domain is quite homogeneous in July compared to May.

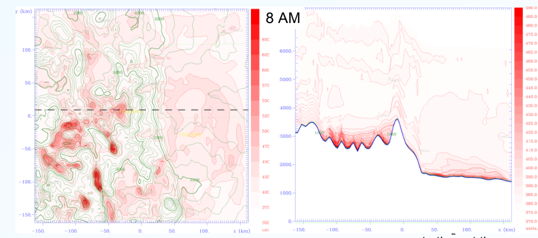


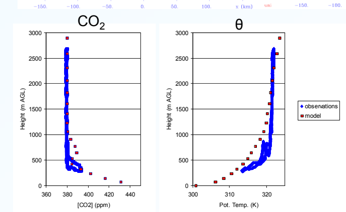
Mesoscale Modeling

Forward Modeling

To investigate the processes underlying the observed horizontal and vertical distribution of CO_2, we use the Regional Atmospheric Modeling System (RAMS) mesoscale model. The three-dimensional simulations are made centered over the Niwot Ridge Ameriflux site. The domain covers an area of about 400x400 km with a horizontal grid spacing of 2 km. Such a fine horizontal resolution is needed to resolve the topographic features in the investigation area, which are expected to play an important role in the accumulation, ventilation and transport of CO_2. Model results are evaluated with aircraft data, surface measurements, and radiosonde data.

Surface flux fields of a passive tracer simulating CO_2 fluxes are prescribed in space and time and the mesocale model RAMS is used to compute the spatio-temporal variations of the CO_2 concentrations. Results are shown in the figures below. The nighttime accumulation of CO_2 in the valleys is apparent. Vertical profiles of CO_2 concentrations show a good agreement with vertical profiles of CO_2 from the aircraft measurements.





concentrations at the surface and vertical cross section of CO_2 concentration in the ACME modeling terrain, showing accumulation of CO_2 in the valleys at night

(left Figure)
Valley CO_2 and temperature profiles. Simulations show good agreement with observations

Inverse Modeling

From the observations of CO_2 concentrations from aircraft and at particular monitoring sites, we would like to infer the range of possible surface source configurations that are consistent with the data. This problem requires the application of numerical inversion techniques. We use the adjoint of the mesoscale model RAMS (RAMDAS) as well as a Lagrangian particle dispersion model in the backward mode for this purpose. These techniques allow us to calculate influence functions which relate the CO_2 concentration observed at the receptor to potential sources within and outside of the modeling domain.

Summary

The Airborne Carbon in the Mountains Experiment (ACME) was conducted successfully in May and July 2004, yielding a unique set of meteorological and CO_2 observations over the Colorado Rockies. Several modeling approaches are used to understand and estimate CO_2 fluxes at local to regional scales in complex terrain using measurements obtained during ACME. Applying an ABL budget approach to the aircraft data, we estimated CO_2 drawdowns of several ppm in the mountain boundary layer, representing significant CO_2 uptake by the forests. These results agree surprisingly well with local flux measurements at a sub-alpine location, particularly in mid-Summer. To interpret and understand the observations, we will use a mesoscale model and its adjoint. Preliminary simulations using the mesoscale model RAMS indicate that significant nighttime accumulation of CO_2 in valleys occurs with concentrations exceeding 400 ppmv CO_2, in good agreement with the observations.

Acknowledgements

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Airborne Carbon in the Mountains Experiment (ACME)