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REDUCING THE UNCERTAINTY IN THE NORTH AMERICAN CARBON BUDGET WITH ATMOSPHERIC MEASUREMENTS AND INVERSE TRANSPORT MODELS

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1. INTRODUCTION

One of the Climate Change Research Initiative (CCRI) near-term synthesis assessment products of the Climate Change Science Program (CCSP) is the "North American carbon budget and implications for the global carbon cycle." This product, to be delivered in late 2005, will be the first "State of the Carbon Cycle Report" (SOCCR), an interagency (DOE, NASA, NOAA, NSF, USDA, USGS) document currently under production through an extramural process involving scientists and stakeholders. This first in a series of SOCCR's will focus on the North American carbon budget utilizing bottom-up (inventories, etc.) and top-down (atmospheric measurements and inverse model) techniques. Later SOCCR's will include additional aspects of the global carbon cycle. This paper describes the atmospheric carbon profiling system that is being implemented in North America to provide the top-down data and the inverse modeling required to reduce the uncertainty in the North American carbon budget.

2. THE NORTH AMERICAN CARBON PROGRAM

Atmospheric carbon dioxide has increased every year since regular measurements began. On average, one-half of the carbon dioxide emitted during fossil fuel combustion has remained in the atmosphere, although the year-to-year variations are large (see Figure 1). The remainder has been taken up by the oceans and the terrestrial biosphere. Understanding the natural carbon cycle is critical for projecting future climate.

Global measurements of the carbon dioxide distribution indicated that a large CO_2 sink was operative in the Northern Hemisphere (Tans et al., 1990), and ^{13}C isotopic carbon in CO_2 global measurements indicated that the sink was dominated by terrestrial processes (Ciais et al., 1995). It is now generally accepted that the terrestrial biosphere is, at this time, an important global carbon sink, rivaling the ocean sink. Early estimates of carbon uptake using atmospheric CO_2 data and inverse transport models suggested that North America may be an important sink (Fan et al., 1998). Considerable interest turned to carbon sinks on land, partially because the biosphere may be amenable to some degree of control.

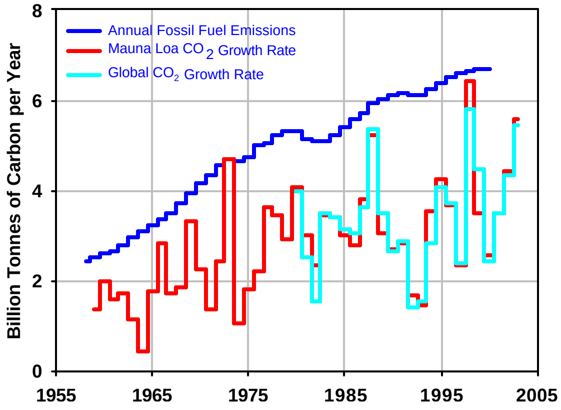

Figure 1. Global fossil fuel emissions and the annual average growth rate of atmospheric carbon dioxide. The global CO_2 data are from the NOAA network, Mauna Loa data prior to 1980 are from Keeling and Whorf (CDIAC).

While estimates of global regional carbon uptake improved (e.g.,Gurney et al., 2002) uncertainties on continental scales remained large due to the paucity of the observing system. In addition, estimates of carbon dioxide uptake based on carbon stocks were generally not in agreement with the atmospheric estimates, although some progress has been made (Pacala et al., 2001). Considering these scientific motivating factors and the fact that the infrastructure and experience to carry out extended carbon studies existed in North America, a program concentrating on this region as a first step appeared logical.

At the request of the U.S. Global Change Research Program, a sub-committee of the U.S. Interagency Carbon Cycle Science Steering Group produced a report entitled "The North American Carbon Program (NACP)" (Wofsy and Harriss, 2002), addressing the following questions:

- What is the carbon balance of North America and adjacent ocean basins, and how is the balance changing over time? What are the sources and sinks, and the geographic patterns of carbon fluxes?
- What factors control the sources and sinks, and how do they change with time?
- Are there potential "surprises," where sources could increase or sinks disappear?
- How can we enhance and manage long-lived carbon sinks to sequester carbon?

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One of the major program elements of the NACP is long-term atmospheric measurements of the carbon budget. These include ground-based, aircraft and satellite measurement networks for the major carbon gases, CO_2, CH_4 and CO, the latter providing a convenient tracer to distinguish combustion from biogenic sources of CO_2. In the remainder of this paper we will describe the insitu component of NOAA's Carbon Cycle Atmospheric Observing System which began implementation in 2004. The satellite component of the observing system will not be addressed here.

3. CARBON AMERICA

A program designed to determine carbon sources and sinks in North America, "Carbon America," was conceived by Pieter Tans of NOAA's Climate Monitoring and Diagnostics Laboratory in 1995 (Tans et al., 1996). This observing system envisaged twice-weekly sampling to about 8 km using small Cessna-class aircraft with an automated sampling system, and tall communications towers for continuous monitoring. It included about 50 sites in North America, concentrated in the U.S., in particular in regions of high primary productivity.

A pilot program had already begun in 1992 with aircraft sampling in Colorado and a tall tower in North Carolina (see http://www.cmdl.noaa.gov/ccgg/iadv/ for data visualization). With funding for the Carbon Cycle Atmospheric Observing System as part of the President's Climate Change Research Initiative in 2004, the network currently consists of seventeen aircraft and three tall tower stations (see Figure 2).

The first scheduled "intensive" measurement campaign of the NACP will take place in mid-continent during 2005-2006 and a number of the new sites in Figure 2 were chosen to support this program.

Figure 3 shows the aircraft sampling system which is designed so that it can be easily installed on any small aircraft and does not require the attention of the pilot. The sampling and control systems are in two separate luggage-sized cases; the sampling case is returned to the laboratory in Boulder for analysis following exposure. This system allows rapid turn-around of samples and, in addition to mixing ratio profiles to altitudes in the 8 km range, allows for isotopic carbon and oxygen analyses.

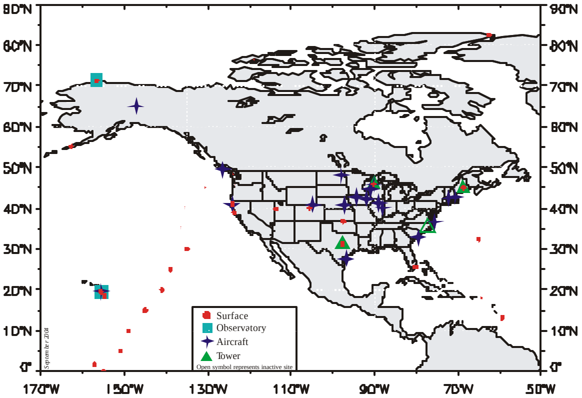

Figure 2. Carbon America monitoring network, the insitu component of NOAA's Carbon Cycle Atmospheric Observing System, at the end of 2004.

Figure 4 shows recent data from these mid-continent sites and is an example of why it is important to make measurements above the surface and to measure more than just CO_2. Carbon Dioxide shows a high degree of variability in the first 2 km while above this altitude, the concentrations are characteristic of the larger region in which the measurements are being made. There is a noticeable layer of low CO_2 in the 4-6 km region and inspection of the CO and CH_4 profiles indicates that the origin of the air in this layer is likely near the surface. The mid-continent intensive will include numerous measurements on the surface, including local fluxes and inventory data and will be the first such attempt to compare the "bottom-up" technique with the "top-down" in real time.

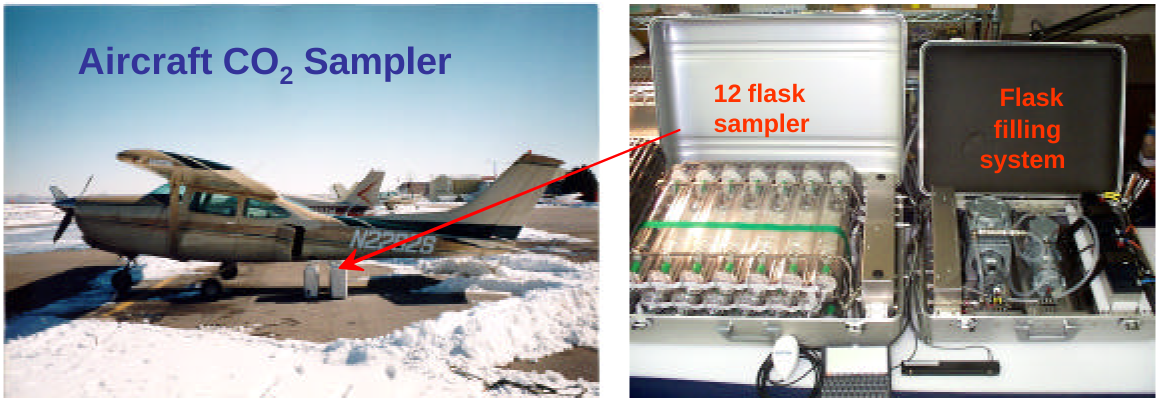

Figure 3. Aircraft and tall tower carbon gas observing system being implemented in the North American Carbon Program.

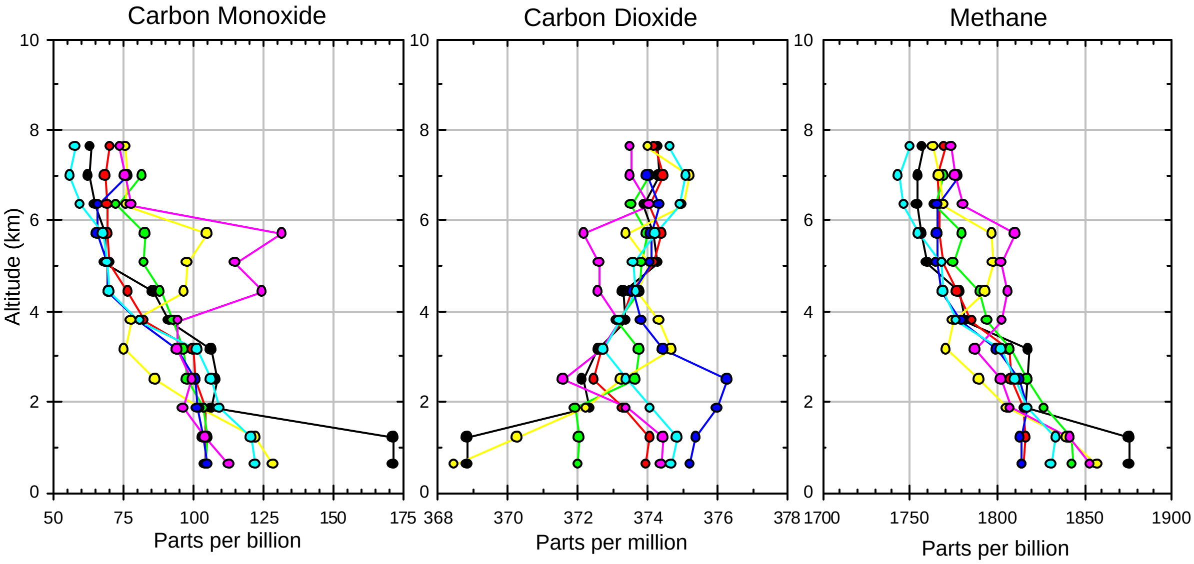

Figure 4. Vertical profiles of CO, CO_2 and CH_4 at a number of sites in Iowa, Illinois, Nebraska, North Dakota and Wisconsin during September 13-21, 2004.

4. INVERSE MODELING

In order to infer carbon sources and sinks from the data, a meteorological transport model is used. With the expected higher density of data, a new global transport model, TM5 (Krol et al., 2004, Peters et al., 2004) which allows multiple arbitrary regions with high-resolution grids to be nested within a coarser grid spanning the global domain will be used (see Figure 5). It is ideal for this study with the expected high detail in space and time while continuing to be consistent with global observations.

An analysis using TM5 has been completed which demonstrates how the additional data that will be generated increases the effectiveness of the model. Figure 6 shows surface influence maps, i.e., the sensitivity of the model to surface carbon fluxes obtained by the observing network (red – high, green – low) for a system of 14 data stations (left) and of 33 stations (right) for January meteorology. Increased sensitivity of the model in the latter case is clear.

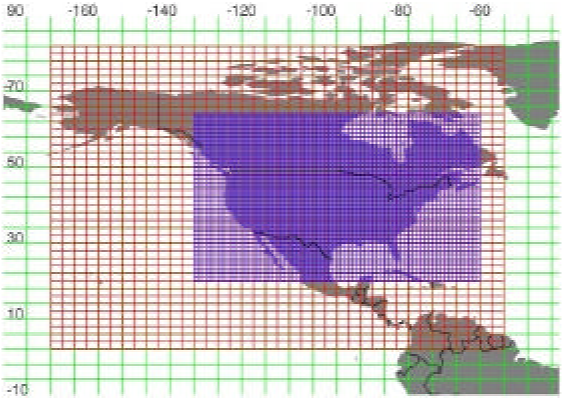

Figure 5 The TM5 model with a global resolution of 6° longitude by 4° latitude and two nested regions with grid sizes of 3° by 2° over North America and 1° by 1° over the U.S., northern Mexico and southern Canada.

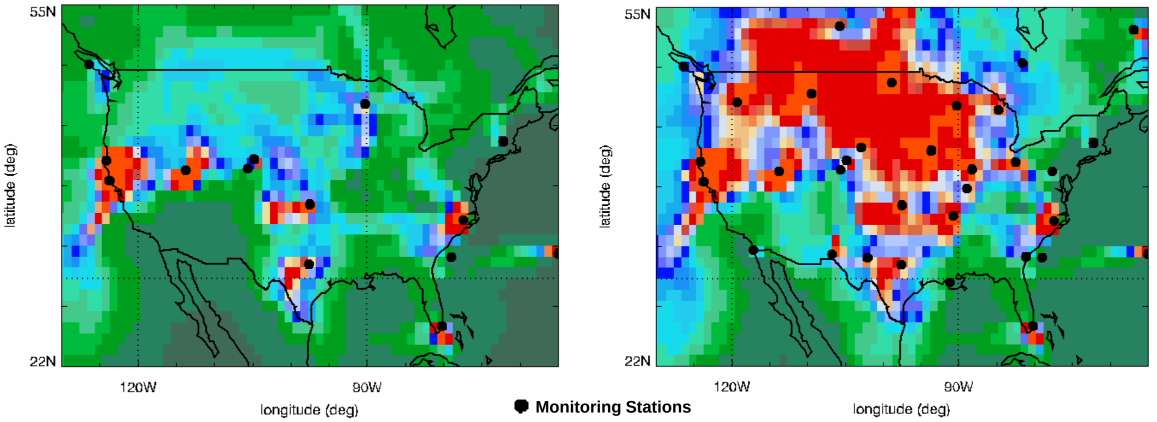

Figure 6. TM5 transport model surface influence maps for an observing system of 14 stations (left) and 33 stations (right) for January meteorology.

5. REDUCING THE UNCERTAINTY

The Transcom 3 experiment (Gurney et al., 2002) used 16 different transport models to make estimates of the carbon flux for 22 global regions. For the temperate North American region and for carbon dioxide data obtained from 1992-1996 their analysis indicates a carbon uptake of 0.9 ± 0.6 Gt C yr^{-1}. It is the goal of the NOAA Strategic Plan and the CCSP program to reduce this uncertainty by a factor of two (to ± 0.3 Gt C yr^{-1}) by 2010. Model exercises indicate that this goal is within reach if the planned observing system can be completed by the 2007-2008 period. We believe that this level of uncertainty would allow resolution of interannual variations in carbon dioxide uptake on a U.S. regional basis and when correlated with environmental conditions will allow the beginning of an understanding of the carbon cycle required for improved climate projection, providing decision support information to help limit unwanted effects of climate change in the future.

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