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ARM Airborne Carbon Measurements (ARM-ACME) and ARM-ACME 2.5 Final Campaign Reports

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ARM
CLIMATE RESEARCH FACILITY

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Summary

The goals of the Atmospheric Radiation Measurement (ARM) Climate Research Facility's ARM Airborne Carbon Measurements (ARM-ACME) and ARM-ACME 2.5 field campaigns are as follows:

1. To measure and model the exchange of CO_2, water vapor, and other greenhouse gases by the natural, agricultural, and industrial ecosystems of the Southern Great Plains (SGP) region

2. To develop quantitative approaches to relate these local fluxes to the concentration of greenhouse gases measured at the Central Facility tower and in the atmospheric column above the ARM SGP Central Facility

3. To develop and test bottom-up measurement and modeling approaches to estimate regional scale carbon balances

4. To develop and test inverse modeling approaches to estimate regional scale carbon balance and anthropogenic sources over continental regions.

Regular soundings of the atmosphere from near the surface into the mid-troposphere are essential for this research. Prior to 2007, we were collecting flask samples from two heights (300 m and 3000 m). The work completed during this campaign greatly extended the intensity and scope of these profile measurements.

Acronyms and Abbreviations

AAF	ARM Aerial Facility
ARM	Atmospheric Radiation Measurement
ACME	Airborne Carbon Measurements
CCSP	Carbon Cycle Science Plan
DOE	Department of Energy
ESRL	Earth System Research Laboratory
FTS	free troposphere
GHG	greenhouse gas
NACP	North American Carbon Program
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
PBL	planetary boundary layer
SGP	Southern Great Plains
TES	Tropospheric Emission Sounder

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1.0 Background

We report on a 5-year multi-institution and multi-agency airborne study of atmospheric composition and carbon cycling at the Atmospheric Radiation Measurement (ARM) Climate Research Facility's Southern Great Plains (SGP) site, with scientific objectives that are central to the carbon-cycle and radiative-forcing goals of the U.S. Global Change Research Program and the North American Carbon Program (NACP). The goal of these measurements is to improve understanding of 1) the carbon exchange of the Atmospheric Radiation Measurement (ARM) SGP region; 2) how CO_2 and associated water and energy fluxes influence radiative-forcing, convective processes, and CO_2 concentrations over the ARM SGP region, and 3) how greenhouse gases are transported on continental scales.

To meet these challenges, the Climate Change Research Program created the North American Carbon Program (NACP) (Wofsy and Harris 2002) with a primary goal of developing "… quantitative scientific knowledge, robust observations, and models to determine the emissions and uptake of CO_2, CH_4, and CO, the changes in carbon stocks, and the factors regulating these processes for North America." NACP is currently the main priority of the Carbon Cycle Interagency Working Group, and implementation of the program currently centers on regional intensives designed to quantify sources, sinks, stocks, and the processes that control them. The Climate Change Research Program priorities on the *global* scale include the National Aeronautic and Space Administration (NASA) Orbiting Carbon Observatory 2 (OCO-2) and National Oceanic and Atmospheric Administration (NOAA) CarbonTracker.

The ARM Airborne Carbon Measurements (ARM-ACME) field campaigns began observations in 2000 with state-of-the-art CO_2 concentration measurements from the 60 m tower at the SGP Central Facility and a system of fixed and mobile instruments for measuring CO_2, water, and energy fluxes, deployed at selected locations within the ARM SGP region. The goal of the project is to understand 1) carbon exchange within the ARM SGP region; 2) how CO_2 and associated water and energy fluxes influence radiative-forcing, convective processes, and CO_2 concentrations over the ARM SGP region; and 3) how greenhouse gas (GHG) concentration patterns are communicated on continental scales. In support of these goals, Lawrence Berkley National Laboratory developed a strong modeling component to this project. A land surface model (i.e., ISOLSM) (Riley et al. 2002; Riley et al. 2003) was calibrated and tested against the flux measurements and linked to boundary conditions (i.e., soils, crop, and meteorological information) to simulate surface fluxes of CO_2, water, heat, and radiation over the ARM SGP region, and this model has been coupled with a mesoscale modeling system. A unique feature of these models is a focus on multiple tracers, including CO_2 and isotopologues of CO_2 and water.

Early on, we added CO_2 measurements to routine aircraft flights over the SGP Central Facility. In collaboration with the NOAA Earth Systems Research Laboratory (ESRL) global network, we collected air samples from the 60 m Central Facility tower, mid-planetary boundary layer (PBL) (ca. 3000 ft), and free troposphere (FTS) (ca. 10,000 ft). These were the first routine measurements of atmospheric profiles and simultaneous continuous CO_2 concentration and surface flux measurements and, until recently, were the only such measurements conducted routinely over the agricultural heartland of North America. These aircraft measurements are a strong complement to the carbon modeling and analysis project we have developed. The ARM carbon aircraft data reveal significant concentration gradients in the PBL and FTS that inform our interpretations of the surface measurements, and we have put a great deal of effort into increasing the precision, sophistication, and scope of the aircraft measurements.

Several recent developments in the broader climate change community add urgency to the ARM Facility aircraft measurements. The first is the development of a global-scale framework for interpreting variations in atmospheric CO_2 concentrations and inferring surface exchanges (ESRL 2015; Peters et al. 2007). The second development is the use of satellites for space-based measurement of column CO_2. These datastreams will greatly expand our capacity to observe the global carbon cycle; however, the nature of the measurements present challenges for interpretation (e.g., testing, calibration, clear-sky bias, etc.). The ARM Facility aircraft program, coupled with input from CarbonTracker, is uniquely poised to help interpret these measurements. Third, the SGP is the southern boundary of the largest of the NACP regional intensives—the Mid-Continent Intensive Campaign. Atmospheric transport models connect our atmospheric measurements with those of the northern studies, and create the potential for understanding large-scale carbon-cycle phenomenon (Miller et al. 2007a; Miller et al. 2007b; NACP Implementation Strategy Group 2005). Finally, our long-time series of atmospheric concentration measurements are part of efforts to understand seasonal and inter-annual GHG trends on continental and global scales (Denning et al. 2002a; Denning et al. 2002b). Furthermore, ARM Facility datastreams on clouds, aerosols, meteorology, atmospheric motion, and radiation will allow us to conduct complex experiments on vertical advection and PBL dynamics and radiation modeling that contributes directly to climate modeling.

2.0 Notable Events or Highlights

Atmospheric CO_2 observations, combined with inverse modeling, can be used to estimate sources and sinks of CO_2 at regional or continental scales. Presently there are significant uncertainties in these estimates, partly due to the very small concentration differences ($\leq$0.1 ppm) that must be resolved among observing sites (Marquis and Tans 2008). For a long time, the goal of $\leq$0.1 ppm has eluded aircraft-based observations because of the difficulty of ensuring high accuracy measurements under changing ambient pressure and temperature in a mechanically stressed environment. We present results showing that the achievement of 0.1 ppm is within our grasp.

Before March 2011, validation of our continuous measurements proceeded by comparison to NOAA/ESRL flask-based observations. (Original continuous analyzer is named RM0.) This process is a cross-validation between the two independent systems rather than merely a validation of the continuous observations. It is worth noting that flask-based observations have a documented bias of ~0.007 ppm per day of storage. That bias is not taken into account when flask-based measurements are reported, limiting the accuracy of this form of validation to 0.2 ppm, which is twice the target value.

As a result of recent technological advances made in the laboratory and field and funded in large part by the U.S. Department of Energy (DOE), the situation has changed substantially. On March 15, 2011, and as part of the ARM Airborne Carbon Measurements (ARM-ACME) field campaign, a second analyzer (RM12) was installed in the Cessna 206. The two Atmospheric Observing Systems, Inc., analyzers (RM0, RM12) run independently, operate with separate calibrations, and pull air from a common inlet also servicing the flask technology. The differences between observations from the pair of analyzers should average to the square root of two times the calibration error of either analyzer (0.10 ppm). Figure 1 shows observations collected from both analyzers on March 21, 2011, and Table 1 summarizes results for the total of seven flights made in the same manner since March 15. The mean RM0 – RM12 difference is −0.05 ppm, and standard deviation of the seven samples (flights) is 0.13 ppm, which is near the target value of 0.14 ppm.

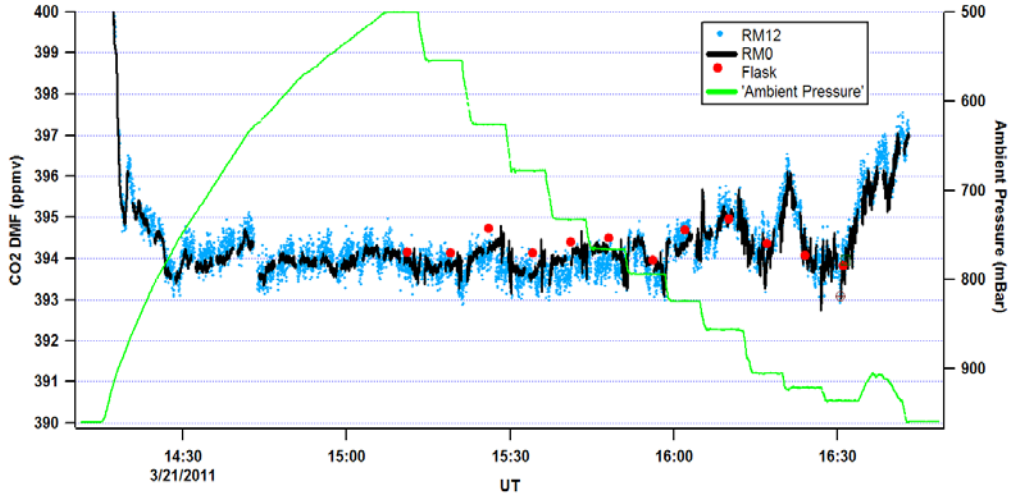

Figure 1. Validation of Observations of CO_2 Concentration Collected on March 21, 2011, by the Two Continuous Analyzers (RM0, RM12) and Flasks. Fast (1 Hz) noise of RM12 is larger as a result of the need to reduce program costs substantially. Calibration errors are the same for both analyzers, 0.10 ppm. Gaps in the time series happen during calibration for the absolute level (ppm) and responsiveness (ppm/count). Time series of ambient pressure shows the continuous ascent to 500 mbar (17,500 ft above mean sea level) followed by stepwise descent over the ARM SGP tower during which there was cross-validation by flasks. Table 2 summarizes the comparison between RM0 and RM12 for this flight and the other six flights.

The results of Figure 1 and Table 1 show that this DOE-funded program is uniquely positioned to achieve the monitoring accuracy of 0.10 ppm for the manned aircraft. Operations are turn-key and executed by unskilled personnel (i.e., the pilot). Both forms of validation—flask and dual continuous analyzers—are active. Platform integration of the flask and analyzer technology is validated by experiments conducted on the ground and also by proven methodology during designated flights. The maintenance cycle is at least 50 flights, which is enough to demonstrate that the airborne component of ARM SGP can serve as a model airborne monitoring program of North America.

Table 1. Mean RM0 – RM12 Difference for Seven Flights as of May 6, 2011, is −0.05 ppm. Standard deviation of the mean difference is 0.04 ppm. Standard deviation of sample is 0.13 ppm, approximating the target value of 0.14 ppm.

Flight date	RM0 – RM12 (ppm)	N Points
March-20-2011	−0.01	5,291
March-21-2011	−0.03	5,678
March-23-2011	−0.16	5,444
April-28-2011	−0.13	5,845
April-30-2011	−0.05	5,199
May-5-2011	−0.09	4,235
May-6-2011	−0.17	5,207

3.0 Results

3.1 Result 1: Quantification of Trends and Variability in Atmospheric Concentrations of CO_2 and Other Greenhouse Gases in North America

An important objective of the ARM-ACME field campaign is to quantify trends and variability in GHG concentrations over the SGP, as the foundation for understanding the carbon budget of North America and the processes that govern the budget. The routine vertical profile flights (Figure 2 and Figure 3) are the backbone of this effort for several reasons. First, they are the most frequent routine airborne measurements, feeding data to national carbon observing networks and quantifying the long-term secular trend in atmospheric CO_2 concentrations in the mid-continent. Second, these are the only regular airborne observations in United States that are routinely compared to (validated against) in situ continuous measurements.

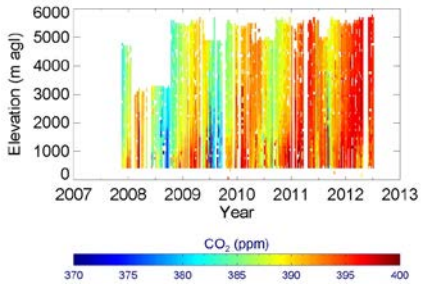

Figure 2. Continuous CO_2 Vertical Profiles Collected since 2008 Showing Lower Concentrations during the Growing Season and Large Vertical Gradients in the Winter.

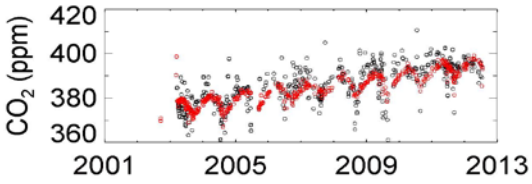

Figure 3. Time Series of CO_2 Concentrations from Flasks Collected since 2003 at Ground Level (black circles) and at 3000 m (red circles).

Our observations show that troposphere CO_2 concentrations in the SGP vary enormously diurnally (100 ppm), seasonally (15 ppm), and spatially (5 ppm) (Figure 2) because of ecosystem exchanges with the atmosphere, proximity to fossil sources, changes in PBL depth, and exchanges with the FTS. The

aircraft is necessary to sample both in the PBL and in the more regionally influenced FTS. The ARM-ACME field campaign also is building a data record on atmospheric concentrations of other important atmospheric species, including CH_4, N_2O, and CO (Figure 4).

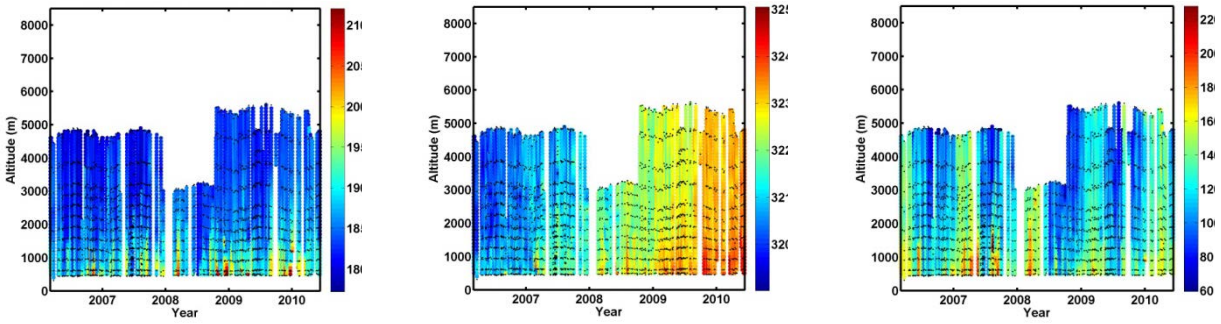

Figure 4. Flask-Based Vertical Profiles of CH_4, N_2O, and CO Collected since 2006.

3.2 Result 2: Free Troposphere Validation and Bias Estimate

The ARM SGP has become a focal point for evaluation of new remote-sensing instruments (from ground, airborne, and satellite platforms) that determine the mixing ratios of GHGs. These activities all require validation against in situ measurements of the vertical profiles of GHG mixing ratios. The ARM SGP site was selected as a validation site for space-based CO_2 retrievals by the upcoming Orbiting Carbon Observatory. Validation will be approached through comparative CO_2 measurements. Consequently, a ground-based solar-viewing FTS was installed onsite in 2009 as part of the Total Carbon Column Observing Network. The airborne measurements collected by the ARM-ACME field campaign currently are being used to validate and quantify bias in the FTS column retrievals (Wunch et al. 2010; Wunch et al. 2011). Validating the FTS is worthwhile because it will be very useful to have column CO_2 retrievals for the ARM Facility for the testbed and radiation objectives listed here, in support of Greenhouse Gases Observing Satellite validation.

3.3 Result 3: Satellite Validation

The NASA Tropospheric Emission Sounder (TES) is a Fourier transform spectrometer on the Earth Observing System Aura satellite. It measures thermal infrared emissions in the range of 660 cm^{-1} to 2260 cm^{-1}, with unapodized resolution of 0.06 cm^{-1}. It was launched in July 2004 in a sun-synchronous orbit at an altitude of 705 km. In the past year, TES has been evaluated to provide the scientific community with CO_2 retrievals with peak sensitivity in the middle of the troposphere, near 500 hPa. Similarly, profiles of the deuterium composition of water vapor have been recovered with a peak sensitivity near 700 hPa. Aircraft-based observations collected at ARM SGP were used for validation over land of the TES retrievals over the period from 2006 to 2011 (Kulawik et al. 2010).

4.0 ARM-ACME Publications

4.1 Journal Articles/Manuscripts

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4.2 Meeting Abstracts/Presentations/Posters

1. Biraud, SC, WJ Riley, IN Williams, and MS Torn. 2009. "A multi-year record of airborne continuous CO2 in the U.S. Southern Great Plains: Observations and mixing across the PBL." Poster presented at the American Geophysical Union (AGU) Meeting, December 14-18, 2009, San Francisco, California.
2. Biraud SC, WJ Riley, and MS Torn. 2011. "A multi-year record of airborne continuous CO2 in the U.S. Southern Great Plains." Poster presented at the ASR Science Team Meeting, March 28–April 1, 2011, San Antonio, Texas.
3. Biraud, SC, WJ Riley, and MS Torn. 2011. "A multi-year record of airborne continuous CO2 in the U.S. Southern Great Plains." Poster presented at the 39th annual GMD Meeting, May 17-18, 2011, Boulder, Colorado.
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