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ARM Airborne Carbon Measurements VI (ARM-ACME VI) Field Campaign Report

SC Biraud

May 2017

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SC Biraud, Lawrence Berkeley National Laboratory
Principal Investigator

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Executive Summary

From October 1, 2015 through September 30, 2016, AAF deployed a Cessna 206 aircraft over the Southern Great Plains, collecting observations of trace gas mixing ratios over the ARM/SGP Central Facility. The aircraft payload included two Atmospheric Observing Systems (AOS Inc.) analyzers for continuous measurements of CO_2, and a 12-flask sampler for analysis of carbon cycle gases (CO_2, CO, CH_4, N_2O, $^{13}CO_2$). The aircraft payload also includes solar/infrared radiation measurements. This research (supported by DOE ARM and TES programs) builds upon previous ARM-ACME missions. The goal of these measurements is to improve understanding of: (a) the carbon exchange of the ARM region; (b) how CO_2 and associated water and energy fluxes influence radiative forcing, convective processes, and CO_2 concentrations over the ARM region, and (c) how greenhouse gases are transported on continental scales.

Acronyms and Abbreviations

AAF	ARM Aerial Facility
AIRS	Atmospheric Infrared Sounder
AOS	Atmospheric Observing System
ARM	Atmospheric Radiation Measurement
ARM-ACME	ARM Airborne Carbon Measurements Project
ASCENDS	Active Sensing of CO_2 Emissions over Nights, Days, and Seasons
ASL	above sea level
CalTech	California Institute of Technology
CCSP	U.S. Carbon Cycle Science Plan
CESD	Climate and Environmental Sciences Division
CO_2	carbon dioxide
CH_4	methane
DOE	U.S. Department of Energy
EDGAR	Emission Database for Global Atmospheric Research
EPA	Environmental Protection Agency
ESRL	Earth System Research Laboratory
FT	free troposphere
FTS	Fourier transform spectrometer
GHG	greenhouse gas
GOSAT	Greenhouse gases Observing SATellite
JPL	Jet Propulsion Laboratory
m	meter
NACP	North American Carbon Program
NASA	National Aeronautics and Space Administration
NASA-TES	NASA/JPL Tropospheric Emission Spectrometer
NOAA	National Oceanic and Atmospheric Administration
OCO-2	Orbiting Carbon Observatory 2
PBL	planetary boundary layer
PCP	Programmable Compressor Package
PFP	Precision Flask Package
PGS	Precision Gas System
ppmv	parts per million by volume
SCHIAMACHY	SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY
SGP	Southern Great Plains

TCCON	Total Carbon Column Observing Network
TES	Terrestrial Ecosystem Science
USGCRP	U.S. Global Change Research Program
WMO	World Meteorological Organization

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1.0 Background

Principal Investigator

DOE Lawrence Berkeley National Laboratory	Sébastien C. Biraud

Co-Principal Investigator

DOE Lawrence Berkeley National Laboratory	Margaret Torn

Team members

NASA Jet Propulsion Laboratory	Michael Gunson
NOAA Earth System Research Laboratory	Colm Sweeney
California Institute of Technology	Paul Wennberg
Harvard University	Stephen Wofsy

Campaign dates: October 1, 2015 through September 30, 2016

Location: Southern Great Plains (Figure 1)

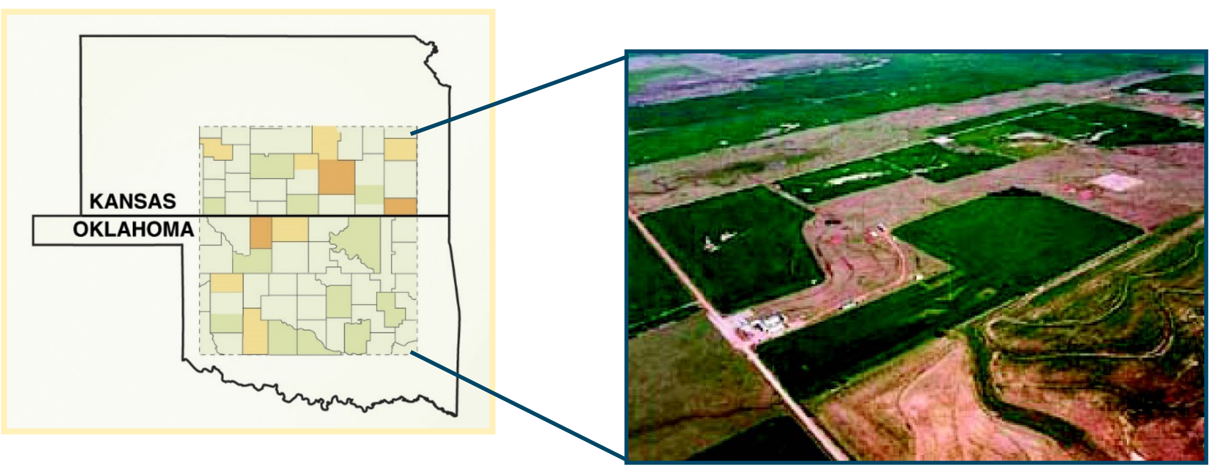

Figure 1. The ARM test bed in the Southern Great Plains (left) and a picture of the existing ARM site (right).

The ARM Southern Great Plains facility is a world-class platform for greenhouse gas (GHG) research because of carbon cycle measurements made on the ground and in the atmospheric column, as well as other measurements being made at the facility. For example, the combination of radiation measurements, radiosonde, and other meteorological observations are critical to accurately model CH_4 and CO_2 atmospheric transport and emissions. There is no other site in the U.S. with such a complete set of supporting measurements to explore high-frequency changes in GHG in the total atmospheric column.

The primary objective of ARM-ACME is to quantify trends and variability in GHG mixing ratios over the U.S. Southern Great Plains (SGP), as the foundation for understanding the carbon budget of North America and the processes that govern the budget. The routine vertical profile flights at SGP (Figures 3 and 4) are the backbone of this effort for several reasons. First, they are the most frequent routine airborne measurements in the U.S. (Sweeney et al., 2015), feeding data to national carbon observing networks (CarbonTracker) and quantifying the long-term secular trend in atmospheric CO_2 mixing ratios in the mid-continent.

Second, these are the only regular airborne observations in the U.S. that are routinely compared to (validated against) in situ continuous measurements. Lastly, they fill a critical geographic gap in the southern mid-continent where air flowing from the Gulf of Mexico and the southwestern U.S. converges (Figure 2). ARM-ACME observations provide essential information over a large area that reduces GHGs modeling uncertainties. Aircraft samples at lower altitudes constrain local emissions and uptake by agriculture and oil and gas operations.

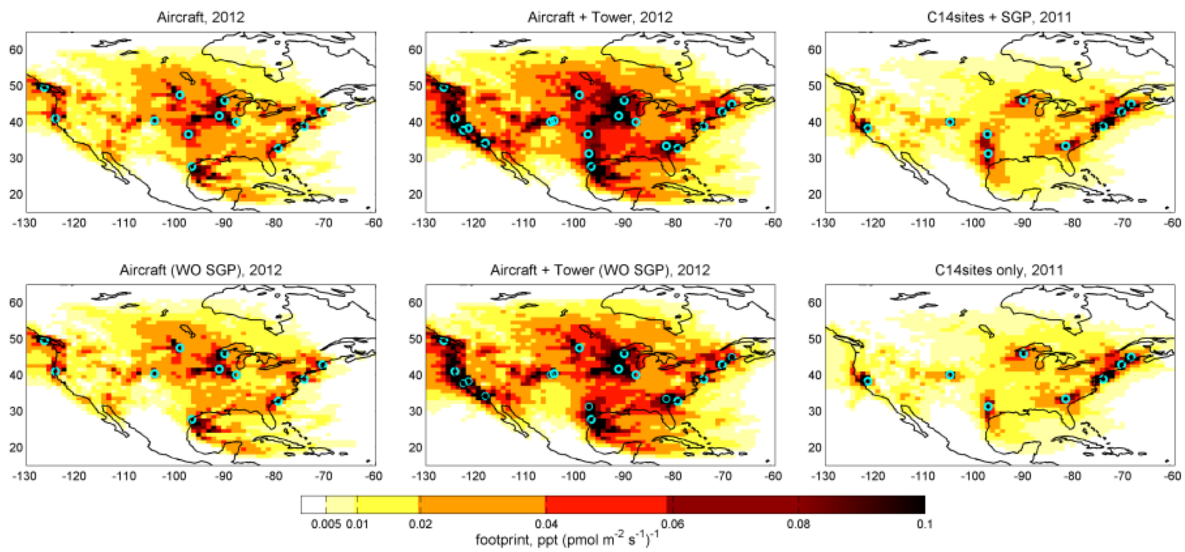

Figure 2. Footprint analysis based on all the samples collected (open blue circles) by aircraft and tower (samples analyzed by the National Oceanic and Atmospheric Administration [NOAA] for the collaborative network): with (first row) and without (second row) the SGP site. Color gradient shows the upstream influence region on atmospheric measurements locations (darker shade=higher influence). It shows that observations at SGP inform atmospheric transport models over large areas in the southwestern U.S.

2.0 Lessons Learned

2.1 Operational Success

The operational success of the ACME campaigns is due to the combination of following factors:

- Analyzer is operable without maintenance for long periods (at least 100 missions of 3 hours each);
- Analyzer lifetime of at least four years (400 missions);
- Autonomous operation of analyzer and deployable by unskilled personnel (pilot);

- Processing software enabling efficient user interface and reduction of observations collected during a flight mission to final form in minutes;
- Temporal resolution of ~1 sec;
- Three forms of validation (double-blind, broadband, integration) to get at the 0.10 ppmv level of accuracy required;
- Negligible sensitivity to platform motion applying to any combination of transects or vertical profiles;
- Operable ceiling of at least 26,000’ ASL and well into the free troposphere;
- Capability of drop-in deployment of specifically designed CO_2 instrumentation on airborne platforms used to validate prototype payloads of CO_2 satellites;
- Capability of permanent installation of the instrumentation on the airborne platform.

2.2 Example of ACME Scientific Success

There is an intensive, ongoing debate in the scientific community, federal agencies, and the media as to the amount of methane leaking or vented from natural gas production regions of Texas and Oklahoma.

Two recent studies documented a large discrepancy in CH_4 emissions in the South-Central U.S. between top-down (observations) and bottom-up (U.S. Environmental Protection Agency [EPA] and Emission Database for Global Atmospheric Research (EDGAR)) inventories (Figure 4; Miller et al., 2013; Turner et al., 2015). As described by Stephen Wofsy (Harvard University): "*none of those analysis would have been possible without ARM-ACME observations as they are the key to these assessments. These observations become particularly critical during the current era of rapidly increasing exploitation of tight gas and shale gas resources, in order to understand the effects of these energy developments on the environment (Wofsy, Personal Communication)*".

Specifically, Miller et al. and Turner et al. found that U.S. EPA inventories underestimate national emissions by a factor of 1.5. Livestock and oil/gas are the largest underestimated sources. The discrepancy between top-down and bottom-up approaches is largest in the South-Central U.S. (by a factor of 2.7), including the Southern Great Plains, presumably due to fossil fuel extraction and refining. The SGP aircraft data set provides a critical set of observations to determine the answer to this question because of their location, frequency, and measurement accuracy. ARM-ACME observations through year 2017 will be used to extend these studies through the period of expansion and contraction of oil/gas production in the Oklahoma region.

3.0 Results

3.1 Trends in GHG Mixing Ratios over the Southern Great Plains

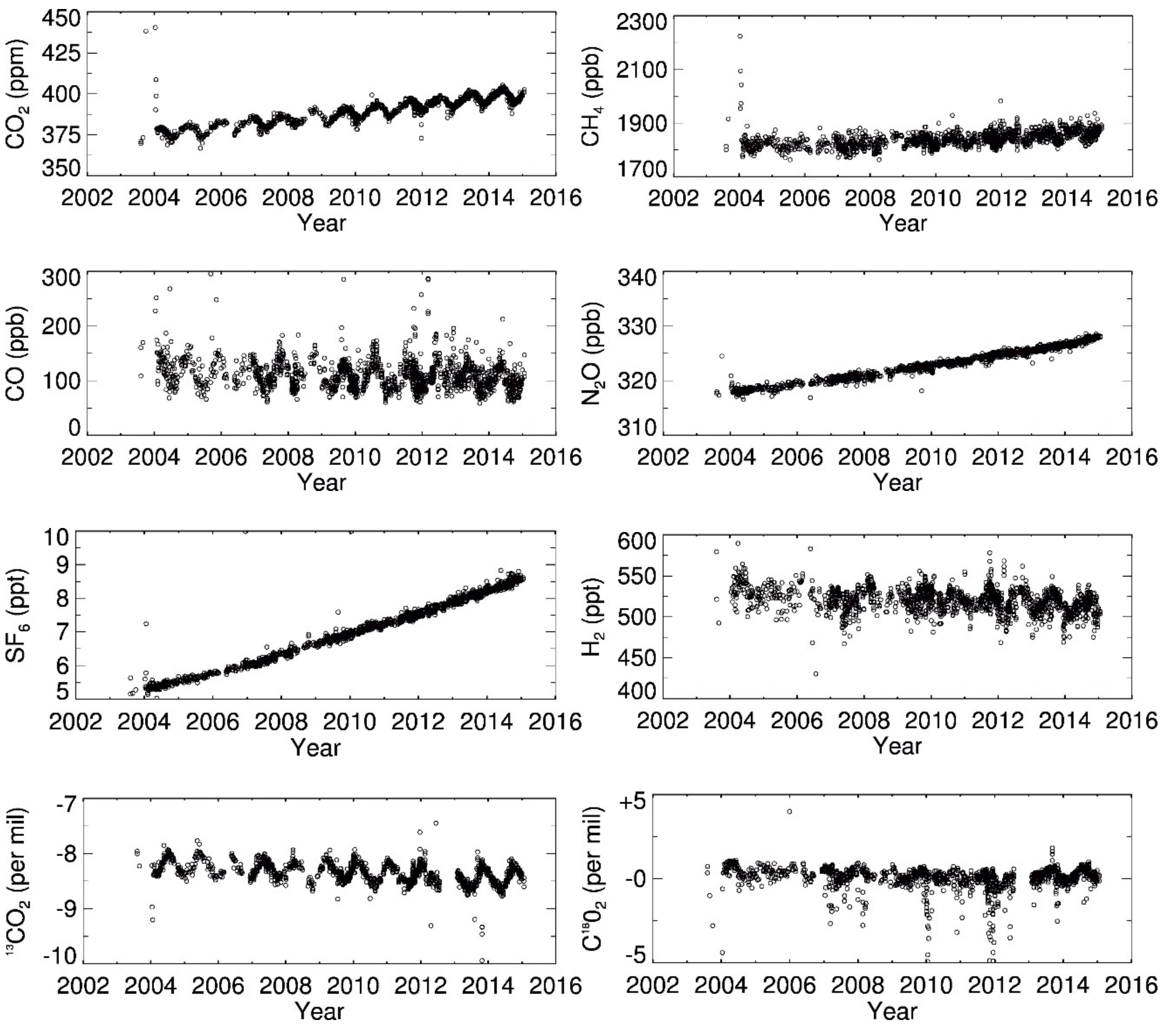

Figure 3. Time series of CO_2, CH_4, CO, N_2O, SF_6, H_2, $^{13}CO_2$, and $CO^{18}O$ observations from flasks collected since 2003 at 3000 m.

3.2 Temporal Variability in CO_2 Mixing Ratios over the Southern Great Plains

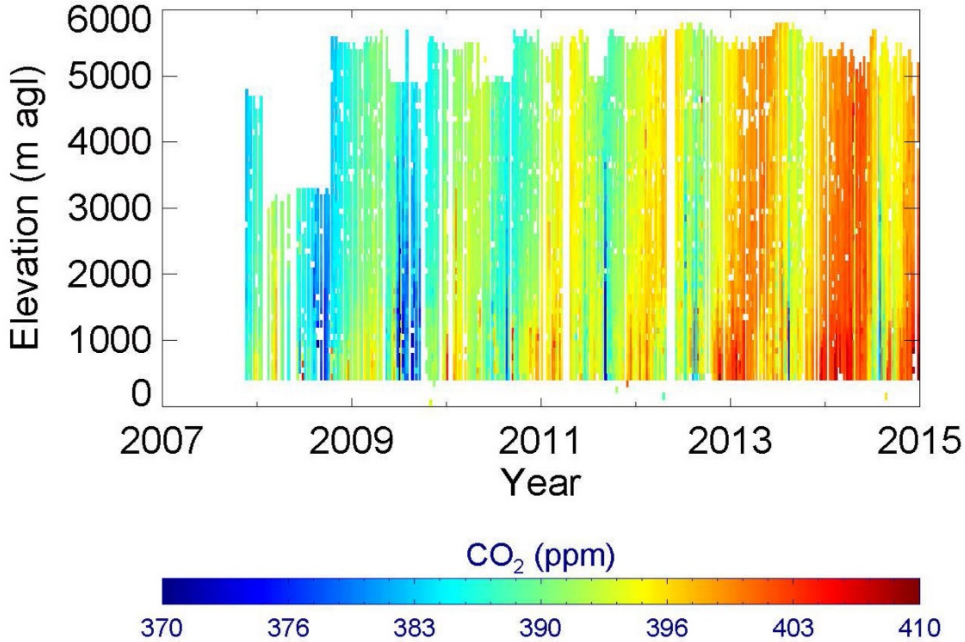

Figure 4. Continuous CO_2 vertical profiles collected since fall 2007 showing lower concentrations during the growing season and large vertical gradients in the winter.

3.3 Validation of Satellite Products

SGP has become a focal point for evaluating new remote-sensing instruments on ground, airborne, and satellite platforms for determine GHG mixing ratios. These instruments require validation against in situ measurements of the vertical profiles of these mixing ratios. Space-based CO_2 retrievals by the Greenhouse gases Observing SATellite (GOSAT) and National Aeronautics and Space Administration (NASA) U.S. DOE Terrestrial Ecosystem Science (TES) program and Orbiting Carbon Observatory (OCO-2, launched on July 2, 2014) are validated through comparative CO_2 measurements, such as the ground-based solar-viewing Fourier transform spectrometer (FTS), as part of the Total Carbon Column Observing Network (TCCON). We continued and extended our collaborations with the teams for these instruments on validation and bias characterization, along the lines of the 11 studies:

- Cal Tech Fourier transform spectrometer (FTS) installed in 2009 in the SGP as part of the TCCON network (Wunch et al., 2010; Wunch et al., 2011);
- NASA Tropospheric Emission Sounder (NASA TES) CO_2 sounder (Kulawik et al., 2010; Kuai et al. ,2013; Kulawik et al., 2013);
- Prototype lidar for the NASA Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission (Abshire et al., 2010);
- Japanese GOSAT CO_2 and CH_4 instrument (Basu et al., 2013; Inoue et al., 2013, Inoue et al., 2014, Inoue et al., 2016 ; Kulawik et al., 2017; Miyamoto et al., 2013).

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