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

SC Biraud

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(ARM-ACME VI) Field Campaign Report

SC Biraud, Lawrence Berkeley National Laboratory
Principal Investigator

May 2017

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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 CO₂, and a 12-flask sampler for analysis of carbon cycle gases (CO₂, CO, CH₄, N₂O, ^1³C0₂). 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 CO₂ and associated water and energy fluxes influence radiative forcing, convective processes, and CO₂ concentrations over the ARM region, and (c) how greenhouse gases are transported on continental scales.
## Acronyms and Abbreviations

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<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>AAF</td>
<td>ARM Aerial Facility</td>
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<tr>
<td>AIRS</td>
<td>Atmospheric Infrared Sounder</td>
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<td>AOS</td>
<td>Atmospheric Observing System</td>
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<td>ARM</td>
<td>Atmospheric Radiation Measurement</td>
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<td>ARM-ACME</td>
<td>ARM Airborne Carbon Measurements Project</td>
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<td>ASCENDS</td>
<td>Active Sensing of CO₂ Emissions over Nights, Days, and Seasons</td>
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<tr>
<td>ASL</td>
<td>above sea level</td>
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<tr>
<td>CalTech</td>
<td>California Institute of Technology</td>
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<td>CCSP</td>
<td>U.S. Carbon Cycle Science Plan</td>
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<td>CESD</td>
<td>Climate and Environmental Sciences Division</td>
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<tr>
<td>CO₂</td>
<td>carbon dioxide</td>
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<td>CH₄</td>
<td>methane</td>
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<td>DOE</td>
<td>U.S. Department of Energy</td>
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<td>EDGAR</td>
<td>Emission Database for Global Atmospheric Research</td>
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<td>EPA</td>
<td>Environmental Protection Agency</td>
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<td>ESRL</td>
<td>Earth System Research Laboratory</td>
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<td>FT</td>
<td>free troposphere</td>
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<tr>
<td>FTS</td>
<td>Fourier transform spectrometer</td>
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<td>GHG</td>
<td>greenhouse gas</td>
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<td>GOSAT</td>
<td>Greenhouse gases Observing SATellite</td>
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<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
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<tr>
<td>m</td>
<td>meter</td>
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<td>NACP</td>
<td>North American Carbon Program</td>
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<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>NASA-TES</td>
<td>NASA/JPL Tropospheric Emission Spectrometer</td>
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<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<td>OCO-2</td>
<td>Orbiting Carbon Observatory 2</td>
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<tr>
<td>PBL</td>
<td>planetary boundary layer</td>
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<tr>
<td>PCP</td>
<td>Programmable Compressor Package</td>
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<td>PFP</td>
<td>Precision Flask Package</td>
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<tr>
<td>PGS</td>
<td>Precision Gas System</td>
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<tr>
<td>ppmv</td>
<td>parts per million by volume</td>
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<tr>
<td>SCHIAMACHY</td>
<td>SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY</td>
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<tr>
<td>SGP</td>
<td>Southern Great Plains</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>TCCON</td>
<td>Total Carbon Column Observing Network</td>
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<td>TES</td>
<td>Terrestrial Ecosystem Science</td>
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<td>USGCRP</td>
<td>U.S. Global Change Research Program</td>
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<td>WMO</td>
<td>World Meteorological Organization</td>
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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 CH₄ and CO₂ 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 CO₂ instrumentation on airborne platforms used to validate prototype payloads of CO₂ 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 CH₄ 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$_2$O, 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

![Graph showing temporal variability in CO$_2$ mixing ratios](image)

**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).
4.0 ACME-VI Journal Articles/Manuscripts


5.0 References


