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DOE/SC-ARM-15-047

ARM Airborne Carbon Measurements VI (ACME VI) Science Plan

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ARM CLIMATE RESEARCH FACILITY

DISCLAIMER

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ARM Airborne Carbon Measurements VI (ARM-ACME VI) Science Plan

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Executive Summary

From October 1 through September 30, 2016, the Atmospheric Radiation Measurement (ARM) Aerial Facility will deploy the Cessna 206 aircraft over the Southern Great Plains (SGP) site, collecting observations of trace-gas mixing ratios over the ARM's SGP facility. The aircraft payload includes two Atmospheric Observing Systems, 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, $^{13}CO_2$, $^{14}CO_2$, carbonyl sulfide, and trace hydrocarbon species, including ethane). The aircraft payload also includes instrumentation for solar/infrared radiation measurements. This research is supported by the U.S. Department of Energy's ARM Climate Research Facility and Terrestrial Ecosystem Science Program and builds upon previous ARM Airborne Carbon Measurements (ARM-ACME) missions. The goal of these measurements is to improve understanding of 1) the carbon exchange at the SGP site, 2) how CO_2 and associated water and energy fluxes influence radiative forcing, convective processes and CO_2 concentrations over the SGP site, and 3) how greenhouse gases are transported on continental scales.

Acronyms and Abbreviations

AIRS	Atmospheric Infrared Sounder
ARM	Atmospheric Radiation Measurement
ARM-ACME	ARM Airborne Carbon Measurements
CCSP	Carbon Cycle Science Plan
CO_2	carbon dioxide
CH_4	methane
DOE	Department of Energy
EDGAR	Emission Database for Global Atmospheric Research
EPA	Environmental Protection Agency
FTS	Fourier Transform Spectrometer
GHG	greenhouse gas
GOSAT	Greenhouse Gases Observing Satellite
JPL	Jet Propulsion Laboratory
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
OCO-3	Orbiting Carbon Observatory 3
PCP	Programmable Compressor Package
PFP	Programmable Flask Package
PGS	Precision Gas System
SGP	Southern Great Plains
TCCON	Total Carbon Column Observing Network
TES	Terrestrial Ecosystem Science
US	United States
WMO	World Meteorological Organization

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1.0 Background

The Atmospheric Radiation Measurement (ARM) Climate Research Facility's Southern Great Plains (SGP) Site (Figure 1) 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 methane (CH_4) and carbon dioxide (CO_2) atmospheric transport and emissions. There is no other site in the United States (US) with such a complete set of supporting measurements to explore high-frequency changes in GHG in the total atmospheric column.

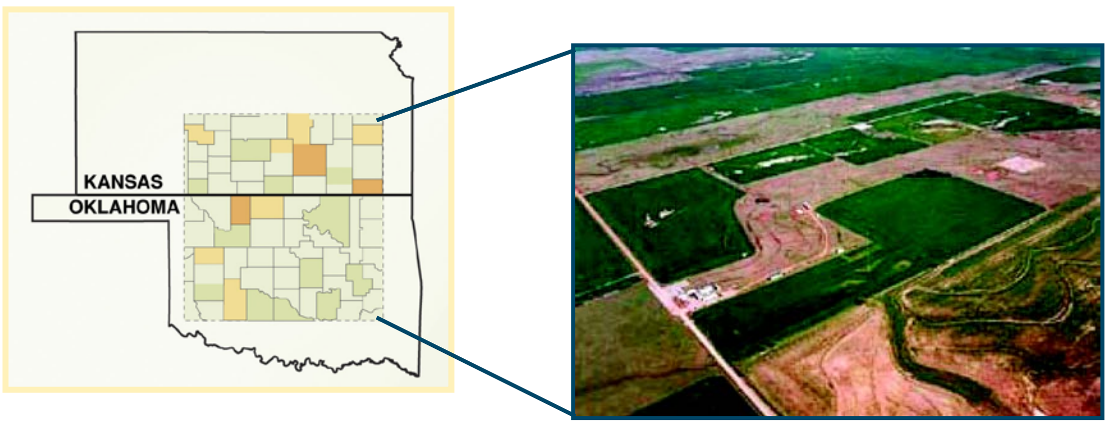

Figure 1. Left: Atmospheric Radiation Measurement (ARM) Test Bed surrounding the Southern Great Plains (SGP) Site. Right: Existing ARM Site.

The primary objective of the ARM Atmospheric Carbon Measurement (ARM-ACME) field campaign is to quantify trends and variability in GHG mixing ratios over the SGP as the foundation for understanding the carbon budget of North America and the processes that govern that budget. The routine vertical profile flights at SGP (Figure 2 and Figure 3) are the backbone of this effort for several reasons. First, they are the most frequent routine airborne measurements in the US (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.

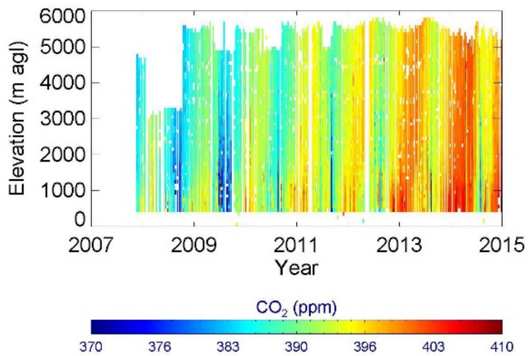

Figure 2. Continuous CO_2 vertical profiles collected since 2008 showing lower concentrations during the growing season and large vertical gradients in the winter.

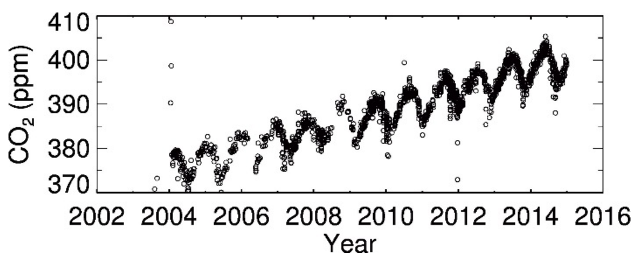

Figure 3. Time series of CO_2 concentrations from flasks collected since 2003 at 3000 m.

Second, these are the only regular airborne observations in the US that are routinely compared to (validated against) in situ continuous measurements. Finally, the flights fill a critical geographic gap in the southern mid-continent where air flowing from the Gulf of Mexico and the southwestern US converges (Figure 4). ARM-ACME observations provide essential information over a large area, thus reducing GHG modeling uncertainties. Aircraft samples at lower altitudes provide constraints on local emissions and uptake by agriculture and oil and gas operations.

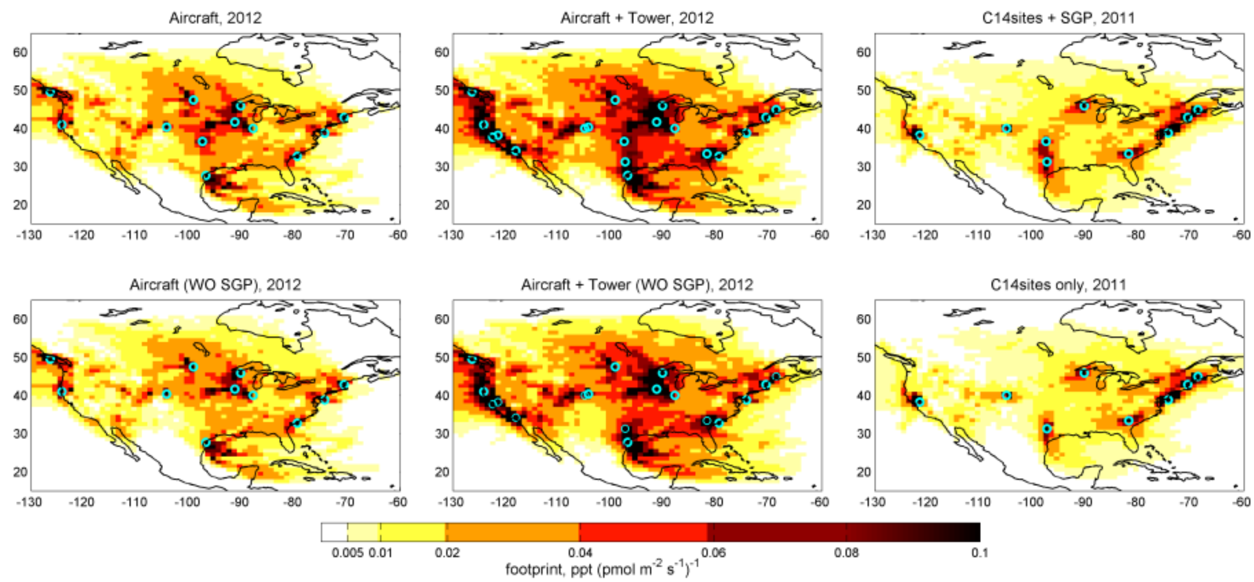

Figure 4. Footprint analysis based on all samples collected (open blue circles) by aircraft and tower (samples analyzed by the National Oceanic and Atmospheric Administration [NOAA] for the collaborative network). Top row is with the SGP site, and the bottom row is without the SGP site. Color gradient shows the upstream influence region on atmospheric measurements locations (darker shade equals higher influence). It shows that observations at the SGP site inform atmospheric transport models over large areas in the southwestern US.

2.0 Campaign Abstract

Airborne ARM-ACME observations and analysis of atmospheric trace gases in the SGP are contributing to research on regional carbon budgets, atmospheric dynamics, and satellite validation, generating 20 publications (18 published and 2 submitted) in the past 4 years. We will continue our airborne study of atmospheric composition and carbon cycling in the SGP from October 1, 2015, through September 30, 2016, from the ARM Aerial Facility.

The goals of this measurement field campaign are to improve understanding of 1) land-atmosphere carbon exchanges in the SGP region, 2) how CO_2 and associated water and energy fluxes influence CO_2 atmospheric concentrations, and 3) how GHGs are transported on continental scales. During flights, we will measure CO_2 and meteorological data continuously and collect flasks for a rich suite of additional gases including CO_2, CH_4, CO, N_2O, $^{13}CO_2$, $^{14}CO_2$, carbonyl sulfide, and many trace hydrocarbon species. The main objectives of these regular weekly flights are to quantify trends and variability in atmospheric concentrations of CO_2, CH_4, and other GHGs in North America and to improve understanding and modeling of boundary layer-free troposphere exchange dynamics. Data will be processed, archived, and analyzed in support of these objectives.

3.0 Campaign Summary and Scientific Objectives

We designed a suite of routine airborne missions to meet the multiple objectives outlined below. These missions were designed with collaborators at the California Institute of Technology, National Aeronautics and Space (NASA) Jet Propulsion Laboratory (JPL), National Oceanic and Atmospheric Administration (NOAA), Carnegie Institute, and the University of Colorado, ensuring that all data collected have a scientific impact. Specifically, ARM-ACME-VI campaign flights are designed to collect a unique data set of trace gas mixing ratios and atmospheric properties over the SGP in and out of the planetary boundary layer to address the following science objectives:

- Characterize uncertainties in aircraft-based flask sampling
- Characterize the spatial (horizontal/vertical) variability of atmospheric mixing ratios of CO_2 around the SGP Central Facility
- Close the large gap in U.S. CH_4 emissions estimates in the US South-Central region
- Support calibration and testing of Fourier Transform Spectrometer (FTS), AirCore, Terrestrial Ecosystem Science (TES), and Orbiting Carbon Observatory 2 (OCO-2) missions.

4.0 Project Description

4.1 Motivation

4.1.1 Uncertainty Quantification in Aircraft-Based Flask Sampling

Airborne-collected flask samples provide calibrated data referenced to World Meteorological Organization (WMO) standards, including those analyzed at NOAA's Earth System Research Laboratory in Boulder, Colorado. We use these observations in the validation of ARM-ACME continuous observations, but they play a critical role for the larger scientific community in quantifying CO_2 anthropogenic emissions and understanding carbon uptake and release from land ecosystems and oceans. Our comparisons of CO_2 observations collected using multiple technologies (two continuous analyzers and one flask sampler) by ARM-ACME have shown that flasks are developing large bias (>0.5 ppm) due to the aging of the material used in the flask package (Biraud et al. 2013). This bias can be tested in the laboratory but validation at various altitudes is also required. If generalizable to flask packages network-wide (as our current data set suggests), this undocumented bias would have significant consequences for the ability of scientists to infer trends, sources, and sinks of GHGs at regional and global scales. We will develop protocols for airborne measurements and flask sampling to document and quantify flask-induced bias, and test solutions to mitigate this bias.

4.1.2 Close the Large Gap in U.S. Methane Emissions Estimates

There is an intensive, ongoing debate in the scientific community, federal agencies, and the media as to the amount of CH_4 that leaks or vents from natural gas production regions of Texas and Oklahoma. A recent study documented a large discrepancy in CH_4 emissions in the South-Central US between top-down (observations) and bottom-up (US Environmental Protection Agency [EPA] and Emission

Database for Global Atmospheric Research [EDGAR]) inventories (Figure 5; Miller et al. 2013). As described by Stephen Wofsy (Harvard University), "… *none of this analysis would have been possible without 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*."[1]

Specifically, Miller et al. (2013) found that EPA and EDGAR inventories underestimate national emissions by a factor of 1.5 to 1.7, respectively. The discrepancy was largest in the South-Central US (by a factor of 2.7), including the SGP, presumably because of fossil fuel extraction and refining. U.S. Energy Secretary Moniz referenced this study in a recent keynote address, saying that "more data are needed" to address the discrepancies reported.[2] The data set collected using SGP aircraft provides a set of observations critical to answering this question because of the location, frequency, and accuracy of the measurements.

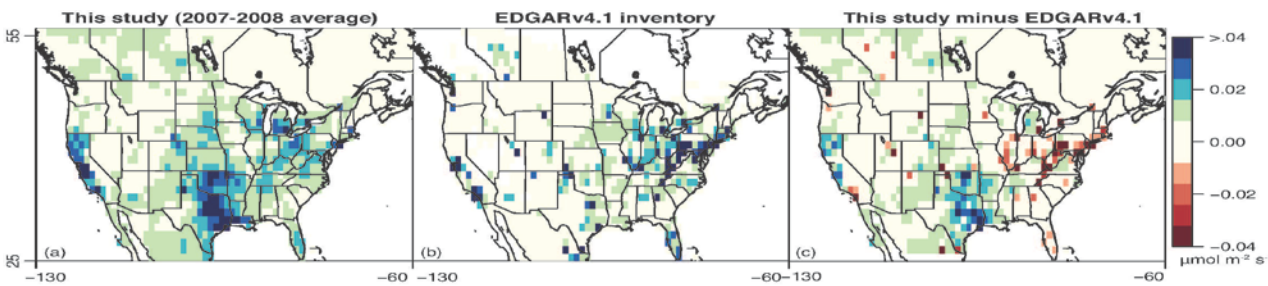

Figure 5. Methane emissions estimated by (a) Miller et al. (2013), (b) EDGAR v4.1, and (c) the difference between the two estimates.

4.1.3 Support Calibration and Testing of FTS, AirCore, TES, and OCO-2 Missions

ACME works in concert with efforts supported by other agencies to develop the national carbon observing system called for in the U.S. Carbon Cycle Science Plan (CCSP) and the North American Carbon Program (NACP). Critically, 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.

4.1.3.1 FTS Column CO_2 Retrievals

The global distribution and vertical structure of atmospheric CO_2 and other GHGs (e.g., CH_4, N_2O) are necessary for detailed investigation of potential errors in Global Climate Model representation of CO_2 radiative forcing and for inverse model estimation of surface fluxes. ARM SGP is a validation site for a California Institute of Technology (Principal Investigator: Paul Wennberg) ground-based FTS. These instruments retrieve column mean mixing ratios of different GHGs, and require validation with in situ

[1] Wofsy, Personal Communication, April 15, 2014.
[2] http://plattsenergyweektv.com/news/article/287078/293/-Energy-Sec-Moniz-on-Oil-Exports--New-Loan-Plans.

measurements to high altitude. To verify the accuracy of the space-based column CO_2 (χCO_2) data, a validation program that ties χCO_2 with the WMO standard for atmospheric CO_2 has been developed.

The WMO standard is based on in situ observations of CO_2 from flask measurements, tall towers, and aircraft. The transfer standard adopted consists of ground-based, solar-looking, FTSs in the Total Carbon Column Observing Network (TCCON) (Boesch et al. 2006, Washenfelder et al. 2006). ARM-ACME observations have been used to evaluate measurements made by the FTS deployed at SGP (Wunch et al. 2010, Wunch et al. 2011). We will work with the TCCON team to assess performance and reduction of errors of CO_2 column measurements integrated from FTS retrievals.

4.1.3.2 AirCore Vertical Profiles Validation

Full-column GHG sampling based on AirCore technology (Karion et al. 2010) allows vertically resolved measurements of GHG concentrations (CO_2, CH_4, and CO) from the ground up to 100,000 ft using a weather balloon. Figure 6 shows CO_2 mixing ratios observed from AirCore launches on January 14 and 15, 2012, as well as the near-synchronous observations from the coordinated ARM-ACME flights. According to Colm Sweeney (AirCore Principal Investigator), ARM-SGP was chosen for AirCore flight operations “because of the existence of the ARM-ACME flights, continuous ground measurements (Precision Gas System datastream) and the TCCON station at SGP […] to evaluate the future NASA OCO-2 retrievals.”[1]

The AirCore project has estimated that ARM-ACME flights coordinated with AirCore launches during late 2015 and early 2016 would provide validation for AirCore for future OCO-2 validation. AirCore flights are infrequent and deployed a few times per season at best. ARM-ACME missions provide an important link between seasonal-scale changes measured by the AirCore profiles and shorter-timescale changes that are expected in the lower troposphere. ARM-ACME will be used to assess the uncertainty of column CO_2 estimates based on infrequent AirCore observations.

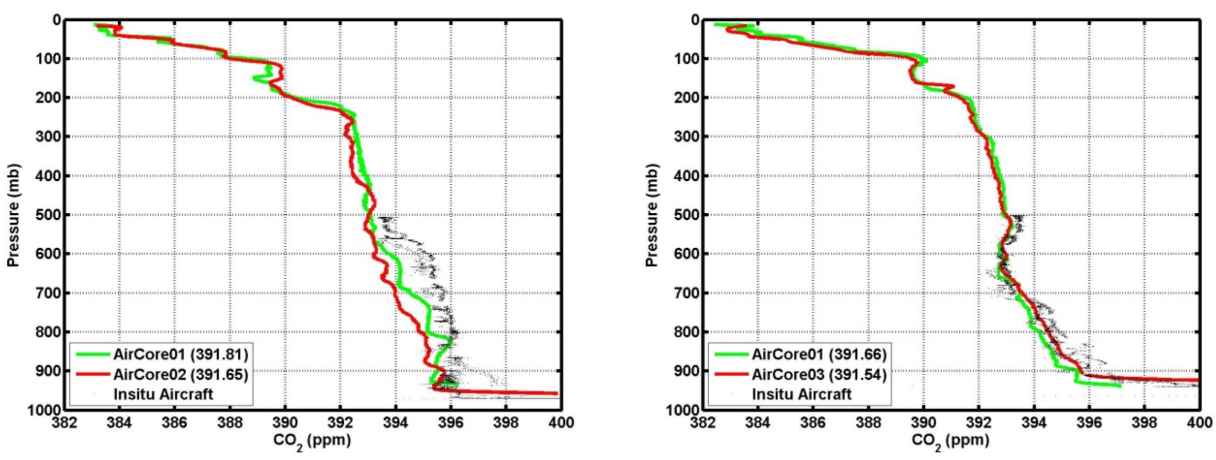

Figure 6. Vertical profiles of CO2 mixing ratios collected from the Cessna 206 (black dots), and two AirCore launches (green and red lines) on January 14, 2012, (left panel) and January 15, 2012, (right panel).

[1] Personal communication April 15, 2014.

4.1.3.3 TES Column CO_2 Retrievals

ACME observations are a critical part of validation of CO_2 from the TES (Kulawik et al. 2010, 2013), which is a mid-tropospheric CO_2 product that complements the column products produced by Greenhouse Gases Observing Satellite (GOSAT) and OCO-2 (Kuai et al. 2013). The vertically resolved ARM-ACME measurements document seasonal cycles between 0 and 2 km above ground level (AGL) versus above 2 km AGL. The lower altitude data are needed for ascertaining the surface sensitivity of the satellite measurements. In the past 4 years, the TES satellite team and the ARM-ACME team collected co-located aircraft measurements under the TES satellite overpass, which have been important for quantifying TES retrievals' systematic errors. In the new NASA-funded project, *Estimation of biases and errors of CO_2 satellite observations from AIRS [Atmospheric Infrared Sounder], GOSAT, SCIAMACHY, TES, and OCO-2*, ARM-ACME observations are included because the Lamont TCCON site is co-located and the combination of column measurements and ARM-ACME observations provide atmospheric CO_2 coverage not available by using either data set alone. This project includes using the combined measurements for AIRS validation (which has sensitivity higher than the aircraft measurements alone) and using the ARM-ACME data for assessment of differences seen with TCCON.

4.1.3.4 OCO-2 Mission

The NASA OCO-2 was launched on July 2, 2014, with a possible follow-on mission (OCO-3) scheduled for launch in 2017. The satellite instruments make global measurements of total column dry-air mole fractions of CO_2 from space. One of the most critical components of the OCO validation plan is relating the space-based measurements to ground-based measurements of CO_2. In particular, the TCCON instrument at the SGP (along with the other TCCON sites around the globe) is critical to the validation effort. As described by Michael Gunson, "*The long-term Cessna flights allow us to determine the variability of CO_2 in the lower atmosphere, which is an important piece of information for properly comparing the OCO observations to TCCON.*" A continuous record of the aircraft data through the OCO-2 and OCO-3 lifetimes (2014-2019) strengthen the use of the comparisons between TCCON and OCO-2 and -3 (and other satellite data). The SGP aircraft observations play a very important role in the plans for validation of the OCO-2 life cycle.

4.2 Instrumentation

The continuous CO_2 analyzers were built by Atmospheric Observing System, Inc., based in Boulder Colorado. These systems, currently in use, were installed on the aircraft in May 2007 and March 2011, respectively. Each analyzer has non-imaging optics and negligible sensitivity to motion of the platform. The non-dispersive infrared analyzer is the core element of the system. The present embodiment has a functional frequency response of 8 Hz. It operates differentially with a pair of identical optical benches. Radiation is collimated by non-imaging optics from the light source and then through the measurement cell containing the sample gas. Light is transmitted through the measurement cell and concentrated onto the photodetector. A pair of identical radiation filters, one fore and the other aft of the measurement cell, isolates radiation to the targeted molecular band centered at 4.26 μm. When combined with the appropriate methodologies and means of maintaining full system calibration, attenuation of the transmitted radiation serves as the needed measure of CO_2. Accuracy, including bias, is ~0.1 ppm of CO_2 at 1 Hz.

The 12-flask sampler was built by High Precision Devices, Inc., and was installed on the Cessna in March 2006. Samples are collected from the community inlet for as many as twelve elevations. The operator triggers sampling when the target location and latitude have been reached. Each flask (0.75 L) is sampled for about 2 minutes and pressurized to 40 psi. The sampler has two components: 1) a rack mounted programmable compressor package (PCP), and 2) a programmable flask package (PFP). Prior to each flight, the pilot connects a new PFP to the PCP, and an automatic leak-check is performed. After each flight, the PFP is sent back to the laboratory for trace gas analysis.

4.3 Flight Paths

The typical flight pattern consists of a series of 12 level legs at standard altitudes from 17,500 to 1500 ft over the SGP Central Facility 60-m tower. Each level leg lasts 10 or 5 minutes, above and below 6000 ft, respectively. Note that the end-points of the legs are curved in a daisy pattern. The total flight time is ~3 hours (Figure 7).

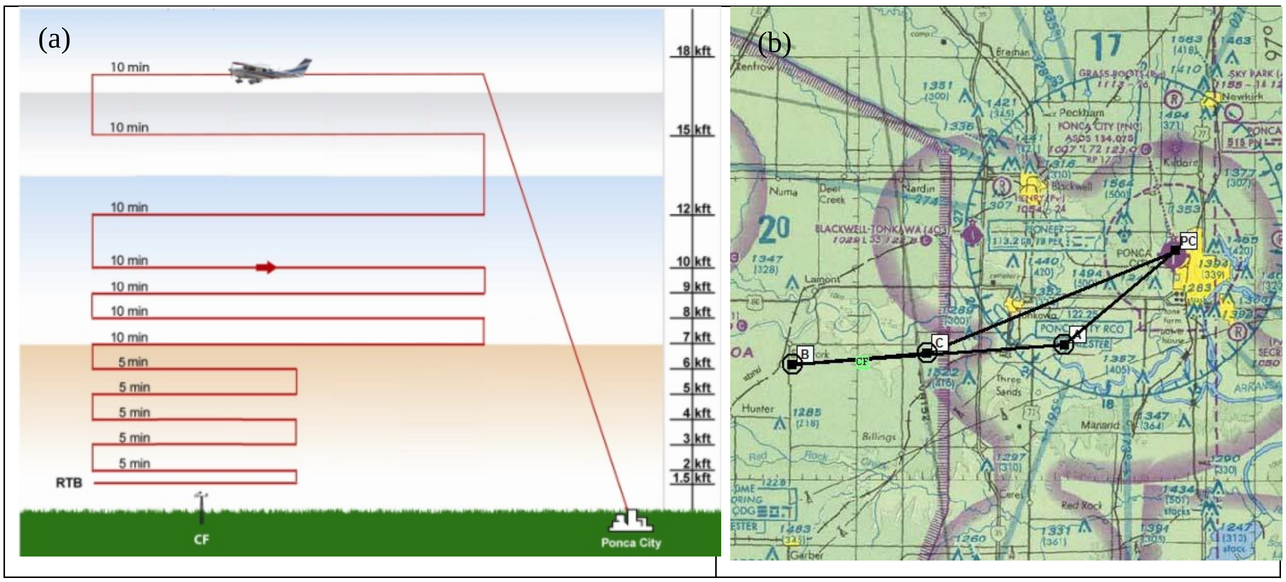

Figure 7. Vertical flight pattern for routine flights (to 17,500 ft) (a) and flight path (b).

5.0 Relevance to Long-Term Goals of the Office of Biological and Environmental Research

DOE is an active member of the U.S. Global Change Research Program (globalchange.gov) and its carbon Cycle Interagency Working Group, which sponsors the CCSP. Our research is guided by one of the implementation plans of the CCSP (the NACP; Denning et al. 2005, Wofsy et al. 2002). The NACP calls for observational campaigns over the continental US for diagnosis, attribution, and scaling of CO_2 sources and sinks. The ARM-ACME-VI field campaign supports CCSP goals for in situ measurements of CO_2 and tracers of carbon cycle processes. ARM-ACME-VI constitutes a significant contribution by DOE to U.S. Global Change Research Program carbon cycle goals and helps the ARM Facility meet the

Climate and Environmental Sciences Division strategic objectives as a valuable resource "to NOAA and NASA."

The proposed work will enhance the ARM Climate Research Facility as a user facility for the study of global change by generating high visibility, coupled-system datastreams for the carbon cycle. The carbon datastreams we produce are among the most frequently downloaded and used data in the ARM Data Archive. In terms of earth system components listed in the ARM mission statement, these data will be focused on the interaction of physical (i.e., climatic), chemical (i.e., atmospheric), and biological (i.e., land surface) processes that regulate atmospheric greenhouse gas concentrations and land productivity. In addition, the proposed work will contribute to monitoring and prediction of radiative forcing related to clouds and aerosols.

6.0 References

Biraud, SC, MS Torn, JR Smith, C Sweeney, WJ Riley, and PP Tans. 2013. "A Multi-Year Record of Airborne CO_2 Observations in the U.S. Southern Great Plains." *Atmospheric Measurement Techniques* 6:751-763. doi:10.5194/amt-6-751-2013.

Boesch, H, GC Toon, B Sen, RA Washenfelder, PO Wennberg, M Buchwitz, R De Beek, JP Burrows, D Crisp, M Christi, BJ Connor, V Natraj, and YL Yung. 2006. "Space-Based Near-Infrared CO_2 Measurements: Testing the Orbiting Carbon Observatory Retrieval Algorithm and Validation Concept Using SCIAMACHY Observations over Park Falls, Wisconsin." *Journal of Geophysical Research* 111(D23):0148-0227. doi:10.1029/2006JD007080.

Denning, S (chair and editor), R Oren, D McGuire, C Sabine, S Doney, K Paustian, M Torn, L Dilling, L Heath, P Tans, S Wofsy, R Cook, S Waltman, A Andrews, G Asner, J Baker, P Bakwin, R Birdsey, D Crisp, K Davis, C Field, C Gerbig, D Hollinger, D Jacob, B Law, J Lin, H Margolis, G Marland, H Mayeux, C McClain, B McKee, C Miller, S Pawson, J Randerson, J Reilly, S Running, S Saleska, R Stallard, E Sundquist, S Ustin, and S Verma. 2005. *Science Implementation Strategy for the North American Carbon Program.* Report of the NACP Implementation Strategy Group of the U.S. Carbon Cycle Interagency Working Group, U.S. Global Change Research Program, Washington, DC. Available at https://www.carboncyclescience.us/sites/default/files/documents/nacp_sis_2005.pdf.

Karion, A, C Sweeney, P Tans, and T Newberger. 2010. "AirCore: An Innovative Atmospheric Sampling System." *Journal of Atmospheric and Oceanic Technology* 27:1839-1853. doi: http://dx.doi.org/10.1175/2010JTECHA1448.1.

Karion, A, C Sweeney, S Wolter, T Newberger, H Chen, A Andrews, J Kofler, D Neff, and P Tans. 2013. "Long-Term Greenhouse Gas Measurements from Aircraft." *Atmospheric Measurement Techniques* 6:511-526. doi:10.5194/amt-6-511-2013.

Kuai, L, J Worden, S Kulawik, K Bowman, M Lee, SC Biraud, JB Abshire, SC Wofsy, V Natraj, C Frankenberg, D Wunch, B Connor, C Miller, C Roehl, R-L Shia, and Y Yung. 2013. "Profiling Tropospheric CO_2 Using Aura TES and TCCON Instruments." *Atmospheric Measurement Techniques* 6:63-79. doi:10.5194/amt-6-63-2013.

Kulawik, SS, DBA Jones, R Nassar, FW Irion, JR Worden, KW Bowman, T Machida, H Matsueda, Y Sawa, SC Biraud, ML Fischer, and AR Jacobson. 2010. “Characterization of Tropospheric Emission Spectrometer (TES) CO_2 for Carbon Cycle Science.” *Atmospheric Chemistry and Physics* 10:5601-5623, 2010. doi:10.5194/acp-10-5601-2010.

Kulawik, SS, JR Worden, SC Wofsy, SC Biraud, R Nassar, DBA. Jones, ET Olsen, R Jimenez, S Park, GW Santoni, BC Daube, JV Pittman, BB Stephens, EA Kort, GB Osterman, and TES team. 2013. “Comparison of Improved Aura Tropospheric Emission Spectrometer (TES) CO_2 with HIPPO and SGP Aircraft Profile Measurements.” *Atmospheric Chemistry and Physics* 13:3205-3225. doi:10.5194/acp-13-3205-2013.

Miller SM, SC Wofsy, AM Michalak, EA Kort, AE Andrews, SC Biraud, EJ Dlugokencky, J Eluszkiewicz, ML Fischer, G Janssens-Maenhout, BR Miller, JB Miller, SA Montzka, T Nehrkorn, and C Sweeney. 2013. “Anthropogenic Emissions of Methane in the United States.” *Proceedings of the National Academy of Sciences* 110(50):20018-20022. doi:10.1073/pnas.1314392110.

Sweeney, C, A Karion, S Wolters, T Newberger, D Guenther, JA Higgs, AE Andrews, PM Lang, D Neff, E Dlugokencky, JB Miller, SA Montzka, BR Miller, KA Masarie, SC Biraud, PC Novelli, M Crotwell, AM Crotwell, K Thoning, and PP Tans. 2015. “Seasonal Climatology of CO_2 across North America from Aircraft Measurements in the NOAA/ESRL Global Greenhouse Gas Reference Network.” *Journal of Geophysical Research–Atmospheres* 120(10):5155-5190. doi:10.1002/2014JD022591.

Washenfelder, RA, GC Toon, J-F Blavier, Z Yang, NT Allen, PO Wennberg, SA Vay, DM Matross, and BC Daube. 2006. “Carbon Dioxide Column Abundances at the Wisconsin Tall Tower Site.” *Journal of Geophysical Research–Atmospheres* 111:D22305. doi:10.1029/2006JD007154.

Wofsy, SC and RC Harris. 2002. *The North American Carbon Program (NACP)*. Report of the NACP Committee of the U.S. Carbon Cycle Science Program, Washington, D.C.

Wunch, D, GC Toon, PO Wennberg, SC Wofsy, BB Stephens, ML Fischer, O Uchino, JB Abshire, P Bernath, SC Biraud, J-F Blavier, C Boone, KP Bowman, EV Browell, T Campos, BJ Connor, BC Daube, NM Deutscher, M Diao, JW Elkins, C Gerbig, E Gottlieb, DWT Griffith, DF Hurst, R Jiménez, G Keppel-Aleks, EA Kort, R Macatangay, T Machida, H Matsueda, F Moore, I Morino, S Park, J Robinson, CM Roehl, Y Sawa, V Sherlock, C Sweeney, T Tanaka, and MA Zondlo. 2010. “Calibration of the Total Carbon Column Observing Network using Aircraft Profile Data” *Atmospheric Measurement Techniques* 3:1351-1362. doi:10.5194/amt-3-1351-2010.

Wunch, D, PO Wennberg, GC Toon, BJ Connor, B Fisher, GB Osterman, C Frankenberg, L Mandrake, C O’Dell, P Ahonen, SC Biraud, R Castano, N Cressie, D. Crisp, NM Deutscher, A Eldering, ML Fisher, DWT Griffith, M Gunson, P Heikkinen, G Keppel-Aleks, E Kyrö, R Lindenmaier, R Macatangay, J Mendonca, J Messerschmidt, CE Miller, I Morino, J Notholt, FA Oyafuso, M Rettinger, J Robinson, CM Roehl, RJ Salawitch, V Sherlock, K Strong, R Sussmann, T Tanaka, DR Thompson, O Uchino, T Warneke, and SC Wofsy. 2011. “A Method for Evaluating Bias in Global Measurements of CO_2 Total Columns from Space.” *Atmospheric Chemistry and Physics* 11:12317-12337. doi:10.5194/acp-11-12317-2011.

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