Chapter 10

ARM Aircraft Measurements

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1. Introduction

Airborne observations enhance the surface-based ARM measurements by providing vertical and horizontal context for surface-based measurements, evaluation of remote sensing measurements made from space or the surface, data for development of model parameterizations, and information necessary for process studies that is not available from surface- or space-based remote sensing methods.

Over the years, ARM has carried out manned and unmanned aircraft campaigns under different organizational and operational paradigms. The separately funded ARM Unmanned Aerospace Vehicle (ARM-UAV) program carried out 12 missions between 1993 and 2006 relying on UAVs and piloted aircraft. The ARM-UAV program was established originally to develop measurement techniques and instruments suitable for use with a new class of high-altitude, long-endurance UAVs and to demonstrate these instruments and measurement techniques in a series of field campaigns designed to support the climate change community with valuable datasets. ARM-UAV also supported field campaigns using piloted aircraft when platform or instrument constraints made the use of UAV platforms incompatible with the objectives of dedicated intensive operations periods (IOPs) that were needed to achieve specific programmatic or scientific goals. Thus, ARM-UAV sponsored a number of campaigns using piloted aircraft.

In parallel, the main ARM Program also sponsored several piloted aircraft campaigns led by ARM principal investigators outside the ARM-UAV program. These campaigns focused on in situ observations of aerosols over the ARM Southern Great Plains site.

In October 2006, the ARM Aerial Facility was established formally as an integral part of ARM with the mandate of executing all future ARM aircraft campaigns under one organizational umbrella.

In what follows, we describe the major outcomes of airborne campaigns carried out in these different phases of ARM airborne research.

2. ARM-UAV program description

ARM-UAV arose from the DOE Atmospheric Remote Sensing and Assessment Program (ARSAP), a joint program with the Department of Defense (DOD) begun as part of the Strategic Environmental Research and Development Program (SERDP) that was aimed at identifying science problems and associated observations that could be studied with UAVs. During the ongoing planning for ARM, it was recognized that UAVs offered ARM the unprecedented potential of making in-atmosphere measurements at high altitudes (up to and above 20 km) for long periods of time (in excess of 24 h) and at reasonably low air speeds (less than 100 m s^{-1}) that were suited ideally for problems that could not be

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DOI: 10.1175/AMSMONOGRAPHS-D-15-0042.1

studied completely from ground-based measurements (e.g., radiative heating rates, grid-square radiation budgets, cloud profiling, etc.) Thus, the ARM-UAV program was born, albeit with funding and management separate from ARM but with overlapping science teams (see below). John Vitko of Sandia National Laboratories (SNL) led the technical management of the UAV program under the direction of the DOE UAV program manager, Patrick Crowley.

The initial planning for the ARM-UAV program was influenced by a December 1992 meeting of an Interim Science Team (IST) drawn primarily from the existing ARM community (see Crowley and Vitko 1994). The meeting identified two broad classes of missions for ARM-UAV: "quasi-continuous missions," which emphasize consistent long-term observations of key radiation-cloud parameters as part of a continuous ARM data stream, and "investigative missions," which change with time and focus on testing specific hypotheses. The basic quasi-continuous missions were identified as the continuous/near-continuous measurement of radiative fluxes along with both in situ and remote sensing measurements of water vapor and cloud properties. Some proposed representative investigative missions included testing of specific hypotheses on the role of deep convection in the tropical Pacific, the drying/moistening of the upper troposphere, the source of the asymmetry in water vapor concentrations in the Northern and Southern Hemispheres, and ozone chemistry near the tropopause (Crowley and Vitko 1994).

In 1992, an ARM-UAV Science Team comprised of leading atmospheric scientists from 10 universities and government research centers was formed with the assistance of the SERDP funding. The Science Team was formed to assist with the development of new measurement capabilities and the measurement of atmospheric heating in a well-defined layer and then to relate it to cloud properties and water vapor content [see Tooman (1997) for a complete list of the Science Team and their projects]. As the program evolved, identification of scientific missions was obtained from the ARM Science Team. The measurement capabilities of the ARM-UAV program were developed from scratch, because UAVs had not been used for science observations or in controlled civilian airspace. In particular, the weight, power, and volume requirements of many instruments necessitated the redesign of the instruments to meet the payload capabilities of available UAVs. ARM-UAV, under SERDP, initiated an instrument development program to produce prototypes of instruments that could be flown on UAVs in support of ARM science. The new instruments that were developed included: the cloud detection lidar by Lawrence Livermore Laboratory, the UAV atmospheric emitted radiance interferometer by the University of Wisconsin–Madison, the hemispheric optimized net radiometer by Los Alamos National Laboratory, the multispectral pushbroom imaging radiometer by Sandia National Laboratories, the frost point and laser diode hygrometers by Brookhaven National Laboratory, the scanning spectral polarimeter by Colorado State University, and a UAV-mounted 95-GHz radar system by the University of Massachusetts [see Tooman (1997) for instrument details]. SNL, Livermore, California, carried out oversight of the development of the instrumentation under the leadership of John Vitko and Tim Tooman.

Since UAV-mounted instruments do not offer the in-flight capability of direct onboard human intervention of the instruments, techniques had to be developed to monitor and control instruments in flight and to record the data on the ground. SNL developed a system that is capable of operation on an unpressurized manned or unmanned aircraft at an altitude of 20 km with flight duration of 72 h. The system allows data to be transmitted from the instrumentation on multiple aircraft to a ground receiving station where the data are recorded, and operational commands are sent to the aircraft science payload via an uplink. No data are stored on the UAV.

The SNL telemetry system also feeds quick-look data to an on-site data management system that allows the data to be viewed in real time by the mission controller, mission scientist, instrument mentors, and on-site technicians. The system also allows simultaneous gathering and display of data from a local ARM site. These capabilities allow the instrument mentors to determine the state of the instruments onboard and to restart instruments that appear to have been compromised since takeoff. Further, the real-time review of the telemetered data allowed in-flight monitoring and modification of flight patterns associated with individual science missions. Note that the telemetry and data collection system was made deliberately flexible so that it could accommodate use with unmanned and/or manned aircraft.

Every deployment of the ARM-UAV facility included a science-team-led effort to identify possible experiments that might be conducted during the deployment. The aircraft to be used for the deployment were then specified based upon the scientific needs and the availability of necessary aircraft (UAV and/or a manned aircraft). This was followed by the publication of a detailed experiment and science plan that served as a mission selection document while in the field (e.g., Ellingson and Tooman 1999). Thus, ARM-UAV is somewhat of a misnomer because the program used a combination of manned or unmanned aircraft, depending upon the science requirements and platform suitability.

The flight-planning document was also used to request approval from the DOE and the Federal Aviation Administration (FAA). The FAA and the DOE required much more detailed flight and operation plans to meet the safety concerns associated with unmanned aircraft, as compared to manned aircraft. In particular, when UAVs were used in experiments within the continental United States, the program was required to use a manned aircraft to escort the UAV between the surface and 5.5 km and return. Will Bolton of SNL led this lengthy approval process for each of the ARM-UAV IOPs.

Following deployment of personnel to the aircraft operations base, mission planning and selection meetings took place daily following the mission scientist's analysis of National Weather Service (NWS) data and forecasts. Preflight meetings were generally held a few hours before each flight to make final selection of a day's mission based on the most recent analysis of the NWS information.

The mission controller directed operations of the instruments during the flight and coordinated aircraft operations with the aircraft operator using input from the mission scientist and instrument mentors. Each flight was followed by a postflight debriefing led by the mission controller that reviewed the actual mission flown, instrument deficiencies, if any, and mission accomplishments. The mission controller and scientist wrote mission summaries for the data record following the meeting. If flights were planned on successive days, a mission planning meeting followed the postflight meeting. A flight day work period typically lasted 12 h or more for most of the ARM-UAV team. Tim Tooman and Roger Busby of SNL served as mission controller and director of ground operations, respectively. Robert Ellingson of the University of Maryland and Florida State University and Greg McFarquhar of the University of Illinois served as mission scientists for the 1993–2002 and 2002–06 periods, respectively.

Postflight data management processed the telemetered data along with the mission logs, summaries, and instrument lists into a complete, well-documented dataset of known quality. When the dataset was completed, it was transferred to the ARM archive for access by the community, as has been done for all ARM data (McCord and Voyles 2016, chapter 11). The reader is referred to Tooman (1997) for specific details concerning the ARM-UAV instrumentation, operations, and data processing.

SERDP funding of ARM-UAV continued through 1997, after which the program funding transitioned to ARM, effective fiscal year 1997, at a lower level. The ARM-UAV science activities transitioned simultaneously. The management of ARM-UAV remained relatively unchanged through 2006, when all ARM aircraft campaigns operations were merged into one program, the ARM Aerial Facility (AAF).

3. Noteworthy ARM-UAV achievements

ARM-UAV carried out 12 different campaigns (Fig. 10-1) generally centered on three classes of scientific experiments:

- Radiative fluxes, in which aircraft were used to make high-accuracy measurements ($\sim$1%) of the solar and infrared radiative transport throughout the troposphere under a variety of clear-sky, cloud aerosol, and water vapor conditions
- Cloud properties, in which remote sensing techniques were used to develop and validate techniques for obtaining cloud reflectivity, phase (ice or water), effective droplet size, etc.
- Satellite calibration and validation, where the instruments were used to indirectly calibrate sensors on operational satellites as well as to validate retrieval algorithms for such derived quantities as flux divergence, cloud properties, and water vapor profiles.

The following material summarizes the major achievements of the ARM-UAV program from several campaigns before the program was integrated with other aircraft activities to form the AAF. The reader may find details concerning all of the science campaigns and instrumentation in a series of UAV campaign summaries and science plans available at the ARM website (http://www.arm.gov/sites/aaf/uavcampaigns) and in Stephens et al. (2000).

a. UAV development flights

The first two missions in 1993 and 1994, called the UAV development flights (UDF), focused on measuring vertical profiles of long- and shortwave radiation fluxes under clear-sky conditions with a General Atomics Gnat 750, a midsize UAV. The operable payload contained four broadband radiometers plus a downwelling total direct diffuse radiometer developed by Francisco Valero (see Valero et al. 1982, 1989; Valero and Pilewskie 1992). Valero et al. (1996) showed that radiation model calculations based on the UAV-measured in situ atmospheric thermodynamic data during this series yielded upward and downward flux profiles that agreed closely with those observed by the onboard radiometers. The importance of this set of flights is that they marked the first scientific use of a UAV and the first aircraft profiling over the highly instrumented ARM Southern Great Plains (SGP) Central Facility in Lamont, Oklahoma.

b. 24-h mission

Demonstration of the capability of the UAV for extended scientific data gathering operations near the tropopause was the major emphasis of a 3-week deployment during fall 1996. The General Atomics Altus,

ARM-UAV

ARM-UAV conducted 12 major field campaigns

Field Campaigns:

- Fall 1993, Edwards AFB, CA
- Spring 1994, Northern OK
- Fall 1995, Northern OK
- Spring 1996, Northern OK
- Fall 1996, Northern OK
- Fall 1997, Northern OK
- Spring 1999, PMRF Kauai, HI
- Summer 1999, Monterey, CA
- Winter 2000, Northern OK
- Fall 2002, Northern OK
- Fall 2004, North Slope, AK
- Winter 2006, Darwin, Australia

GA-ASI "GNAT 750" (F93, S94)

Grob "Egrett" (F95, S96)

GA-ASI "Altus I" (F96, F97)

GA-ASI "Altus II" (Su99)

Twin Otter (F93, S94, F95, S96, F96, F97, Sp99, Su99, W00)

Proteus (F04, W06)

FIG. 10-1. Platforms used and field campaigns conducted by the ARM-UAV program. Seasons are denoted as follows: summer (S), spring (Sp), fall (F), winter (W), and summer (Su). Years are given as follows: 9x and 0x denote 199x and 200x, respectively.

capable of carrying a 150-kg payload to a 10-km altitude, was utilized in this campaign. Its payload included the Gnat 750 instruments plus a scanning spectral solarimeter (SSP), cloud detection lidar (CDL), and a multispectral pushbroom imaging radiometer (MPIR). The campaign operations were organized to ramp up to extended operations from short-duration flights. The shorter flights gathered data to support the ARM water vapor IOP (Turner et al. 2016a, chapter 18) and to aid in the development of new models for calculating the transfer of solar and terrestrial radiation in clear and cloudy conditions. The successful completion of a >26-h UAV flight on 5 October 1996 highlighted the completion of this deployment and marked the first >24-h mission of a UAV for gathering data for science applications.

c. *Extended operations near the tropopause*

The spring 1999 campaign operated from the Pacific Missile Range Facility, Kauai, Hawaii. This experiment was designed as a two-aircraft cirrus cloud experiment and deployed the Altus II UAV for the first time. This UAV has a dual-stage turbo charger that can lift the aircraft above 16 km. During this campaign, the Altus II operated for 16.5 h at or above 15.24 km (50 000 ft) and 1.75 h above 16.75 km (55 000 ft), generally above all cirrus, and flew in tight formation with a manned aircraft, a de Havilland Canada DHC-6 Twin Otter, that flew below the cloud base. The Altus provided measurements of spectral and broadband radiative fluxes, spectral radiances, and lidar backscattering properties of tropical and subtropical cirrus. The Twin Otter provided similar radiometric measurements below the cloud as well as radar reflectivity measurements obtained with UAV-developed 94-GHz airborne cloud radar (from Stephens et al. 2000). This campaign was the first to demonstrate the capabilities of a UAV to remotely sense cirrus tropical properties. Further, the analyses shown by Stephens et al. (2000) showed a remarkable degree of similarity between the radar reflectivity profile predicted by both a cloud-resolving model and an ECMWF 24-h forecast and the profiles measured by the cloud radar and the onboard cloud detection lidar, thus implying a manner of realism of the modeled ice water contents.

d. *ARM Enhanced Shortwave Experiments (ARESE I and II)*

In the mid-90s a scientific controversy in the ARM Program concerning the magnitude of absorption of solar radiation by clouds (Mather et al. 2016, chapter 4; Michalsky and Long 2016, chapter 16) provided the first opportunity for an ARM-UAV mission to address a major science question. Analyses by Cess et al. (1995), Ramanathan et al. (1995), and Pilewskie and Valero (1995) had concluded that the absorption by the entire atmospheric column in the presence of clouds exceeds model predictions of absorption by about 35 W m^{-2} (daytime average) over the Pacific warm pool. Those authors recognized that what appeared to be small errors in calculating absorption by the atmosphere might have huge consequences in tropical atmospheric dynamics. Furthermore, if the modeling of solar absorption by clouds was in error, remote sensing data used to infer cloud microphysical properties were also likely in error.

1) ARESE I

The ARM-UAV campaign in fall 1995 [commonly known as the ARM Enhanced Shortwave Experiment (ARESE I)] was flown with manned aircraft. ARESE I focused on two scientific objectives: (i) the direct measurement of the absorption of solar radiation by clear and cloudy atmospheres and the placement of uncertainty bounds on these measurements; and (ii) the investigation of the possible causes of absorption in excess of the model predictions.

To accomplish these objectives, the experiment used a combination of satellite, manned aircraft, and ground observations to make solar flux measurements at different altitudes throughout the atmospheric column. At the heart of this were a carefully "stacked" DHC-6 Twin Otter and Grob Egrett "cloud sandwich" with the Otter at 0.4–1.5 km and the Egrett at 13 km. This was overflown on occasions by the NASA ER-2 flying at about 20 km, which because of its much higher speed, did not stay in constant alignment with the Twin Otter/Egrett stack but did provide periodic coincidences with these other aircraft. All three aircraft carried identical up- and down-looking Valero broadband radiometers (Valero et al. 1982) and flew over identical up-looking radiometers at the ARM SGP Central Facility and extended facilities. Radiance measurements from the GOES satellites were used to retrieve top-of-the-atmosphere fluxes. These flux measurements were supplemented by a variety of cloud property measurements from the ground, the Egrett, and the ER-2, including radar, lidar, and multispectral measurements. Additionally, information such as water vapor profiles, aerosol optical depths, cloud structure, and ozone profiles, needed as input in radiative transfer calculations, was acquired from a variety of ARM ground-based observing systems and sonde launches.

The ARESE flights were conducted at the SGP site from 25 September through 1 November 1995. Approximately 60 h of in-flight data were accumulated by 12 scientific data flights under a variety of atmospheric conditions ranging from clear to solid overcast. The analyses of these data by Zender et al. (1997) and Valero et al. (1997) again suggested that cloudy skies absorb more shortwave radiation than predicted by current models. Unfortunately, these studies were not able to define a region in the solar spectrum where the anomalous absorption was taking place. In the end, uncertainties concerning the instrumentation, the small number of overcast samples, and the meteorological conditions led to a variety of challenges to the conclusions (see Smith et al. 1997; Li et al. 1999; O'Hirok et al. 2000). Therefore, questions concerning cloud shortwave absorption continued to dominate the science issues. Nonetheless, the experiences gained from ARESE I and new theoretical studies led to the belief that the various shortcomings of ARESE I could be overcome by a new ARESE experiment—ARESE II—conducted during a 6-week period in spring 2000.

2) ARESE II

The ARESE I objectives were adapted for ARESE II in 2000, but the sampling strategy was changed to use observations from one aircraft and the ground following the analyses of Marshak et al. (1997, 1999). Marshak's analyses focus on methods to remove the effects of horizontal fluxes in two-aircraft (or aircraft-ground) measurements of cloud absorption obtained by taking the difference between time-averaged net fluxes at two levels. The Marshak et al. (1997) simulated observations found that the optimal flight patterns depend on cloud structure and horizontal distance between the aircraft, with the ideal case being when both sets of radiometers see the same piece of cloud most of the time for extensive overcast stratus conditions. This condition is satisfied when the aircraft is within about 1-km distance centered on the ground radiometers.

Marshak et al. (1999) demonstrated that the apparent absorption obtained from the net flux differences correspond to true absorption if the data are conditionally sampled to periods for which the horizontal fluxes are zero. These conditions occur when there is little or no flux divergence in nonabsorbing portions of the spectrum. This led in part to the selection of the radiometers used in the experiment (discussed below).

Limiting the observations to the vicinity of the ARM SGP Central Facility allowed the use of cloud radar data and signals from various ceilometers to characterize the cloud structure, including microphysics, as a function of time. In short, the measurement strategy used a single aircraft repeatedly overflying the ARM Central Facility to provide the top-of-the-cloud fluxes and combined those with surface-based measurements to determine both broadband and spectrally resolved vertical flux divergences. Details concerning the ARESE II planning may be found in Ellingson and Tooman (1999).

The aircraft was equipped with several different sets of zenith- and nadir-looking radiation instruments.

These included the Valero radiometers suite [total solar, fractional solar, and total direct diffuse radiometer (TDDR), covering 400–700 nm in 6 contiguous bands of 50-nm plus a 10-nm band at 500 nm in a nonabsorbing region], a complementary set of radiometers provided by the Meteorological Research Institute of Japan (MRI), the solar spectral flux radiometer (SSFR; 300–2500 nm in ~300 channels), and the spectrally scanning polarimeters (SSP2; 400–2500 nm in 120 channels). Identical instruments were located on the ground in a zenith-looking mode at the Central Facility and, in the case of the MRI radiometers, nadir looking as well. The continuous spectral coverage of the shortwave region, and from multiple radiometers, was one of the major improvements of ARESE II over ARESE I. Pre- and postmission radiometer instrument intercomparison and calibration were performed to identify inconsistencies between the various measurement systems, and spectral albedo measurements were obtained near the Central Facility by Michalsky et al. (2003).

Detailed descriptions of ARESE II and findings are given by Ackerman et al. (2003), O'Hirok and Gautier (2003), Valero et al. (2003) and Asano et al. (2004). The various cloud absorption studies found the observed absorption was greater than that calculated but smaller than the cloud absorption and discrepancies noted during ARESE I. By including aerosols with modest absorbing properties in their 3D model computations, O'Hirok and Gautier (2003) isolated the discrepancy to the near-infrared spectral region (0.68–3.9 mm). Overall, the measurements and radiative transfer model comparisons did not unambiguously support the occurrence of anomalous absorption, as the differences between model calculations and observations were within the range of uncertainties in the observations and model calculations.

e. *Mixed-Phase Arctic Cloud Experiment (M-PACE)*

Prior to the M-PACE project, Greg McFarquhar replaced Bob Ellingson as chief scientist of the ARM-UAV program and served as mission scientist during M-PACE, with Tim Tooman still serving as mission controller. During M-PACE (fall 2004, North Slope, Alaska), mixed-phase clouds were measured in situ by the University of North Dakota Citation and remotely by the Scaled Composites *Proteus* aircraft (Verlinde et al. 2007, 2016, chapter 8). Although both the Citation and the *Proteus* were piloted aircraft, the data systems on the *Proteus* were run in a virtual mode, as if they were on a UAV, as they were controlled from the ground and real-time data could be downloaded and inspected. An extensive database on the vertical profiles of the mixed-phase clouds occurring in both single and multiple layers was constructed (McFarquhar et al. 2007b) using data acquired during spiral ascents and descents over remote sensing instruments at Barrow and Oliktok Point and during ramped ascents and descents between these two locations. The single-layer mixed-phase clouds were dominated by liquid, but McFarquhar et al. (2013) showed that some small particles in these mixed-phase clouds were ice, contrary to prior assumptions that all small particles in such clouds were water.

The biggest impact of M-PACE data was its use for evaluating large-eddy simulation (LES), cloud-resolving (CRM), and general circulation model (GCM) simulations that contribute to the fundamental understanding of microphysical processes in mixed-phase clouds and for evaluating and improving remote sensing retrievals. For example, Fridlind et al. (2007) showed the formation of ice nuclei from drop evaporation residuals, and drop freezing during evaporation could explain why ice crystal concentrations are greater than ice nuclei concentrations. Model intercomparison studies (e.g., Klein et al. 2009; Morrison et al. 2009) showed that more detailed representations of microphysics generally gave model simulations more consistent with observations and compared the performance of double- and single-moment parameterization schemes (Solomon et al. 2009), where double-moment schemes prognosed both mass and number, whereas single-moment schemes only prognosed mass. Several other modeling studies also used M-PACE data in conjunction with modeling simulations to gain better understanding of Arctic mixed-phase clouds. Parameterizations for large-scale models (Liou et al. 2008) and cloud-resolving models (Morrison et al. 2008) have also been developed with M-PACE data. Remote sensing studies also showed the relationship between mixed-phase cloud characteristics and vertical motions (Shupe et al. 2008).

f. *Tropical Warm Pool–International Cloud Experiment (TWP-ICE)*

The Scaled Composites *Proteus* was used as the major airborne platform during TWP-ICE, where again the instruments were operated in a mode amenable to remotely piloted aircraft, with the instruments controlled and monitored from a ground station; there were no instrument operators on board. This was made possible because of the considerable investment SNL had placed into the development of an infrastructure to do this as part of the ARM-UAV program. Data collected during TWP-ICE [winter 2006, Darwin, Australia; May et al. (2008); Long et al. (2016, chapter 7)] have led to breakthroughs in understanding how processes in tropical ice clouds affect cloud feedbacks and climate. The

TWP-ICE data also represented the first time that cloud data were collected on an aircraft where the in situ probes were controlled remotely. McFarquhar et al. (2007a) used these data to quantify the contributions of small ice crystals with diameter $< 50\,\mu$m to the mass and radiative properties of cirrus. Quantifying the importance of small ice crystals has been a controversial and unsolved problem for the last 20 years, yet this knowledge is critically needed to quantify cirrus effects on longwave and shortwave radiation and, hence, to better represent cloud feedbacks in GCMs. TWP-ICE data suggested that the shattering of large ice crystals on protruding components of forward scattering probes used to crystal size distributions produced hundreds of smaller crystals. To illustrate the impact of this finding for climate studies, TWP-ICE data motivated a study whereby the NCAR Community Atmosphere Model (CAM3.0) was used to examine the impact of different assumptions about small ice crystal concentrations on cloud radiative forcing (Mitchell et al. 2008): it was found the inclusion of small ice crystals could produce 12% differences in cloud ice amount and 5.5% in cirrus cloud coverage, corresponding to a net cloud forcing of $-5\,\mathrm{W\,m^{-2}}$ and upper-troposphere temperatures of over 3°C.

The TWP-ICE data have also had important applications for motivating and evaluating modeling studies, whereby TWP-ICE observational data were compared with results of CRM simulations, with the CRM simulations subsequently compared against the results of limited-area models, single-column models, and larger-scale models. Thus, like M-PACE, the TWP-ICE project served as a model for showing how in situ and remote sensing data collected during a field campaign could motivate a myriad of modeling and remote sensing studies.

4. Other ARM aircraft missions prior to 2007

Observation of aerosols at the ARM sites was limited initially to in situ measurements on the ground. Vertical profile information, however, is necessary for radiative forcing calculations. Limited information was available from lidars, but there was dire need of validation (see McComiskey and Ferrare 2016, chapter 21). To this end, ARM conducted several aircraft campaigns focused on airborne in situ observation of aerosol properties. These studies were conducted outside the ARM-UAV umbrella by ARM principal investigators and prior to ARM merging all aerial efforts into the AAF in 2007.

a. *In Situ Aerosol Profiles (IAP)*

From 2000 to 2007, ARM carried out twice-per-week routine flights over the SGP site with a small aircraft (initially a Cessna 172 but using a Cessna 206 after 2005) measuring nearly 600 vertical profiles of aerosol optical properties. The resulting 8-yr record reveals significant seasonal differences in aerosol scattering and absorption as a function of altitude. As one example, the single-scattering albedo was found to be lowest in winter, particularly aloft. A detailed analysis of this unique long-term record has been presented by Andrews et al. (2011). Validity of the measurements has been tested with interplatform comparisons and closure studies (Andrews et al. 2004, 2006; Hallar et al. 2006; Ferrare et al. 2006b; Kassianov et al. 2007; Schmid et al. 2009). The data record also has been used for the evaluation of modeled black carbon profiles (Skeie et al. 2011). A complete list of publications resulting from this effort can be found in Schmid et al. (2014).

b. *Aerosol Intensive Operation Period*

The May 2003 Aerosol Intensive Operations Period (AIOP), examined the properties and radiative influences of aerosols over SGP using ground-based (in situ, radiometer, and lidar), and airborne measurements [Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) Twin Otter and Greenwood Cessna 172]. As stated in the preface to the special issue resulting from AIOP (Ferrare et al. 2006a, p. 1), "The scientific hypotheses that were investigated during this IOP were posed as 'closure experiments' in which an observable quantity [was] measured in two or more different ways, or [was] measured as well as calculated (modeled) using other measured quantities. Closure [was] achieved if the several measures agree within their mutual uncertainties." The observable quantities examined in that fashion included aerosol absorption (Arnott et al. 2006), scattering (Hallar et al. 2006), extinction (Schmid et al. 2006; Ferrare et al. 2006b; Strawa et al. 2006), hygroscopicity (Pahlow et al. 2006), asymmetry parameter (Andrews et al. 2006), shortwave radiation (Michalsky et al. 2006), and CCN concentrations (Gasparini et al. 2006; Ghan et al. 2006). A complete list of papers contained in the AIOP special issue can be found online (http://www.agu.org/journals/ss/DOEARM1/). Data from the AIOP also have contributed to numerous other studies since (e.g., Kassianov et al. 2007; Wang et al. 2007; de Boer et al. 2013). The AIOP is discussed further in this monograph by McComiskey and Ferrare (2016, chapter 21).

c. *Aerosol Lidar Validation Experiment*

A major goal of the 2003 AIOP was to assess accuracy of the aerosol (and water vapor) retrievals of the ARM Raman lidar at SGP [at the time, the only Raman lidar in the world making around-the-clock autonomous measurements in an operational setting (see Turner et al. 2016b, chapter 13)]. During AIOP, the Raman lidar was found to overestimate aerosol extinction by 54% (at $\lambda = 355$ nm) when compared to the NASA Ames Airborne Tracking Sunphotometer (AATS-14), an instrument frequently used as a standard for aerosol extinction measurements (Schmid et al. 2006; Ferrare et al. 2006b). The large bias in the Raman lidar measurements during AIOP stemmed from a gradual loss of lidar sensitivity starting about the end of 2001 and going unnoticed until after AIOP. As a result the Raman lidar underwent major refurbishments and upgrades (Ferrare et al. 2006b; Newsom et al. 2009; Turner et al. 2016b, chapter 13) after AIOP, necessitating a new validation campaign—the Aerosol Lidar Validation Experiment (ALIVE) conducted in September 2005. Again, AATS-14 was used as aerosol extinction standard. The refurbished and upgraded Raman lidar, along with improvements to its data processing algorithm (Newsom et al. 2009), led to a very small extinction bias in ALIVE of 6% (Schmid et al. 2009)—a major improvement over the situation in AIOP.

For this focused 11-day campaign, AATS-14 was flown on a Jetstream 31 (Sky Research, Ashland, Oregon) along with the Research Scanning Polarimeter (RSP; Cairns et al. 1999), providing multispectral measurements of the upwelling polarized radiance. Synergistic use of RSP and AATS-14 data from ALIVE has been made to retrieve aerosol and surface properties (Knobelspiesse et al. 2008; Waquet et al. 2009).

5. The ARM Aerial Facility (2007–)

A meeting between ARM Science Team members interested in airborne observations was held at the 2006 ARM Science Team Meeting to discuss future directions for the ARM-UAV program. At that time, it was recognized that ARM-UAV had reached a mature state where the original long-term goal of making routine observations could be pursued in coordination with supporting IOPs, both measurement strategies designed to answer questions addressing the largest source of uncertainty in global warming: namely, the interaction of clouds with solar and thermal radiation. McFarquhar (2006) developed a whitepaper describing new directions for ARM-UAV: namely, the development of a routine observational program with piloted and unpiloted aerospace vehicles. The goal of the new program, which was first called the ARM Aerial Vehicle Program (AAVP) before being renamed the ARM Aerial Facility, was to support the following three types of activities:

- Routine observations of cloud, aerosol, and radiative properties;
- Participation in IOPs designed to contribute to the fundamental understanding of cloud properties and processes;
- Foster an instrument development program whereby miniaturized in situ and remote sensing instruments would be purchased or developed, with the small size of the instruments ultimately allowing them to be used on UAV platforms.

The whitepaper also outlined several research questions that would be pertinent for the AAF to investigate.

The AAF was formally established in October 2006 with the mandate of executing all future ARM aircraft campaigns under one organizational umbrella as an integral part of the ARM Climate Research Facility (Ackerman et al. 2016, chapter 3). Operation of AAF was awarded to the Pacific Northwest National Laboratory (PNNL) following a competitive process. James Mather served as AAF technical director briefly before transferring this role to Beat Schmid in 2007. Greg McFarquhar continued as the chief scientist of AAF until 2009, when that role was abolished.

As part of the instrument development effort, AAF cosponsored a workshop in 2008 called “Advances in Airborne Instrumentation for Measuring Aerosol, Cloud, Radiation and Atmospheric State Parameters” (McFarquhar et al. 2011b). The workshop identified state-of-the-art measurement techniques, emerging instruments, and technologies that would be flight ready within approximately one year as well as deficiencies in airborne instrumentation slowing research, and it promoted dialogue between scientists and instrument makers on measurement needs. One of the outcomes of the workshop was the issue of a call for maturation and hardening of aircraft instruments, which resulted in the awarding of five different proposals to mitigate some of the measurement gaps identified in the workshop.

A detailed description of the achievements of AAF is presented by Schmid et al. (2014), so only a very brief summary is given here. Schmid et al. (2014) also provide a complete list of publications resulting from the campaigns carried out by AAF.

a. *ARM Airborne Carbon Measurement Experiment (ACME)*

The still ongoing airborne carbon measurements at SGP started in 2002 when a flask sampler was added to the Cessna 172 used for the IAP campaign discussed earlier. The carbon measurements were enhanced gradually, and, in 2008, the Cessna 206 became the dedicated aircraft for ACME after the aerosol instruments had been removed from its payload. A review of the 10-yr record of carbon cycle gases above SGP is presented by Biraud et al. (2013). The measurements also have been used to validate ground- and satellite-based column measurements of CO_2 (e.g., Wunch et al. 2011; Kulawik et al. 2013; Kuai et al. 2013) as well as airborne lidar measurements of CO_2 profiles (Abshire et al. 2010) and an earth system model (Keppel-Aleks et al. 2013).

b. *The AAF virtual hangar*

With the exception of the small aircraft used for IAP and ACME, AAF did not initially have a dedicated aircraft. In addition, only a small number of aircraft instruments (inherited from the ARM-UAV program) were owned by AAF. In this virtual hangar mode, AAF successfully carried out several campaigns working with organizations and investigators who provided their research aircraft and most of the instrumentation. These included the Cloud and Land Surface Interaction Campaign (CLASIC; Oklahoma, 2007), the Indirect and Semi-Direct Aerosol Campaign (ISDAC; Alaska, 2008), the Routine AAF Clouds with Low Optical Water Depths (CLOWD) Optical Radiative Observations (RACORO; Oklahoma, 2009) and the Small Particles in Cirrus (SPARTICUS; Oklahoma, 2010) campaign.

CLASIC and ISDAC were both large campaigns involving several aircraft from different agencies. While CLASIC research was impacted by the unusually wet weather during the campaign (Lamb et al. 2012) and resource challenges, a large number of publications resulted from ISDAC [McFarquhar et al. (2011a); see references in Schmid et al. (2014)]. The relatively polluted conditions expected and found in ISDAC in April 2008 nicely contrasted the relatively pristine conditions observed during M-PACE in October 2004. This allowed numerous authors to investigate the roles of aerosols in modifying cloud properties (Fan et al. 2011; Larson et al. 2011; Liu et al. 2011; Jackson et al. 2012; McFarquhar et al. 2013).

RACORO and SPARTICUS represent, to the best of our knowledge, the first and only 6-month routine cloud sampling campaigns ever carried out, creating an extensive database of properties of water and ice clouds, respectively (see, e.g., Vogelmann et al. 2012; Deng et al. 2013; Lawson 2011). These projects represent a new paradigm for collection of airborne data, and required a different operating model from typical, short-term, intensive aircraft field programs. Thus, RACORO adopted the IAP program's practice of simplifying both operations and instrument selection, successfully applying these practices to a collection of in situ cloud as well as aerosol data. SPARTICUS then applied the same paradigms to the collection of ice crystal data in cirrus.

c. *The current AAF*

In 2009, AAF started managing operations of the Battelle-owned Gulfstream I (G-1) large twin-turboprop research aircraft (Fig. 10-2). Furthermore, the American Recovery and Reinvestment Act of 2009 provided funding for the procurement of over 20 new instruments to be used aboard the G-1 and AAF contracted aircraft. AAF is also engaged in the maturation and testing of newly developed airborne sensors to help foster the next generation of airborne instruments (e.g., Lu et al. 2012; Dunagan et al. 2013; Leen et al. 2013).

The AAF has matured into a facility with extensive capabilities available for research. At this time, AAF has over 50 state-of-the-art instruments at its disposal, which typically is further augmented by leading-edge guest instrumentation based on science requirements (see Schmid et al. 2014). As an example, each of the AAF cloud probes is now equipped with knife-edge tips designed to reduce shattering of ice crystals and droplets into the sampling volume, which was a problem that plagued the TWP-ICE (see discussion above) and many other missions carried out during the last 20 years (e.g., Korolev et al. 2013; Jackson and McFarquhar 2014). The G-1 has become the dedicated aircraft for AAF and has undergone extensive upgrades to carry out a broad array of campaigns. AAF campaigns carried out to date with the G-1 include the Carbonaceous Aerosols and Radiative Effects Study (CARES; Zaveri et al. 2012), the Two-Column Aerosol Project (TCAP; Shinozuka et al. 2014), the Biomass Burning Observation Project (BBOP), and Green Ocean Amazon (GOAmazon).

In the future, AAF will continue to carry out missions proposed to and approved by the ARM science board (Ackerman et al. 2016, chapter 3). The aircraft platform and instrumentation will be driven by science needs outlined in the proposal. The AAF will continue to use contracted aircraft where warranted, particularly for cirrus research, where a higher operating ceiling is required. Approved future missions currently include the ARM Cloud Aerosol Precipitation Experiment (ACAPEX) in California, continued routine flights over the ARM site in Oklahoma, routine flights between the ARM Barrow and Oliktok Point sites at the North Slope of Alaska, and flights with small UAVs at Oliktok Point.

6. Summary

Focusing on cloud, aerosol, radiation, and gas phase measurements and their interactions, ARM has used aircraft to enhance its surface-based measurements almost since its inception in 1992.

FIG. 10-2. The G-1 aircraft in flight equipped for a cloud mission.

The separately funded ARM Unmanned Aerospace Vehicle (UAV) program carried out 12 missions between 1993 and 2006 relying on both UAVs and piloted aircraft. ARM-UAV has really pioneered the use of UAVs for scientific research. Particularly noteworthy is the successful completion of a >26-h UAV flight on 5 October 1996, which marked the first >24-h mission of a UAV gathering data for science applications. Equally impressive are high-altitude flights in 1999 with the Altus II above Hawaii. This marked the first time a UAV performed nadir-looking remote sensing of cirrus clouds by flying at altitudes above all clouds.

ARM also has funded aircraft campaigns outside the UAV program, such as the 2003 Aerosol Intensive Operation Period (AIOP) and the 2005 Aerosol Lidar Validation Experiment (ALIVE). In 2000, ARM also started twice-per-week routine flights with a small aircraft measuring vertical profiles of aerosol optical properties (through 2007). Measurements of carbon cycle gases were added to the routine flights in 2002, were enhanced in 2007, and continue to this date as the ARM Airborne Carbon Measurement Experiment (ACME).

The ARM Aerial Facility (initially named the ARM Aerial Vehicle Program) was formally established in October 2006 with the mandate of executing all future ARM aircraft campaigns under one organizational umbrella. Initially starting out as a virtual hangar only, AAF has matured into a facility for the ARM science community with extensive capabilities, including two dedicated aircraft and over 50 state-of-the-art instruments for atmospheric science research. Since 2006, AAF has carried out nine aircraft campaigns enabling research on aerosols, clouds, aerosol–cloud interactions, and trace gases. During this period, AAF has produced numerous scientific and logistical firsts, including the 8-yr in situ aerosol optical properties record (IAP), the 12-yr (and growing) carbon cycle gas profile record (ACME), and two 6-month airborne cloud sampling campaigns (RACORO and SPARTICUS).

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