Chapter 9

The ARM Mobile Facilities

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1. Beginnings

One of the earliest and liveliest discussions in the Atmospheric Radiation Measurement (ARM) Program was about site locations. Prior to the ARM Program, cloud research was carried out largely via field campaigns, initially by aircraft and then coupled with short-term deployments of ground-based instruments. Field campaign locations were, of course, selected to meet the requirements of the particular research program. Thus, the idea of having permanently located sites created a great deal of debate about criteria for determining locations and how to apply those criteria.

The initial discussions on site locations were captured in an ARM report entitled “Identification, recommendation, and justification of potential locales for ARM SITES” (Schwartz 1991; Cress and Sisterson 2016, chapter 5). The report divided its recommended locales into two categories: primary and supplementary. The five primary locales were meant to span the range of climatically important cloud types and their influence on atmospheric radiation. The report also stated:

...there was agreement that sufficient differences exist between the recommended primary locale categories and other radiatively or climatically important locale categories to require a short-duration occupancy of certain supplementary locales to assess the ability of the primary sites to adequately capture and describe the key phenomena controlling the transfer of radiation in the atmosphere [emphasis added].

Maps of the primary locales and suggested supplementary locales are shown in Fig. 9-1, which is a modified form of the figure in the original report.

During the early days of the program, site managers were chosen for the five permanent sites and for a relatively unspecified movable facility that could be used to address the need for measurements in the supplementary locales. However, the funding profile for the program failed to meet the original requests and it became clear that the ARM Program could not support five primary sites, let alone the occupation of supplementary sites, so the movable facility became an early casualty.

2. Revisiting the concept of a movable facility

By 2000, roughly a decade after the ARM Program began, the three permanent sites functioned well and were regularly delivering data (Ackerman et al. 2016, chapter 3). However, two issues with the ARM plan had surfaced. The first followed from the earlier discussions on supplementary locales, which had become even more important with the loss of two of the proposed primary sites. The three permanent sites infrequently (or never) sampled tropical continental clouds, midlatitude coastal clouds, and marine low-level clouds, particularly the large stratus/stratocumulus sheets. Second, there was an obvious synergy between ground-based and aircraft measurements that had first
become apparent in the FIRE\(^1\) cirrus experiments, held in Madison, Wisconsin, and in Coffeyville, Kansas, in 1991, and in the Atlantic Stratocumulus Transition Experiment (ASTEX) conducted in the Azores in 1992. While this synergy could have been exploited occasionally at the permanent sites, there were many greater opportunities to do so if an ARM facility were to be collocated with planned field campaigns. In addition, early analysis of data from the Southern Great Plains (SGP) and Tropical Western Pacific (TWP) sites suggested that, although the sites experienced significant interannual variability, a significant range of the climatological cloud properties was sampled in a single year, so single-year deployments in other locales would have provided valuable information.

The early discussions of a movable facility were relatively unstructured because the program had not yet developed a working permanent site. By 2000, the perception of this problem had been altered radically by ARM’s participation in the Surface Heat Budget of the Arctic Ocean (SHEBA; Uttal et al. 2002; Verlindt et al. 2016, chapter 8) experiment during 1997–98, and by the work of the Pennsylvania State University TWP group, which had been responsible for conducting ARM science using the TWP site (Long et al. 2016, chapter 7; Mather

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\(^1\) First ISCCP Regional Experiment (FIRE) Langley DAAC Project/Campaign Document (https://cosweb.larc.nasa.gov/project/fire/guide/fire_project.pdf).
et al. 1998). The site development approach at both the NSA and TWP sites used modified 20-foot-long sea containers as housing and constructed the site instrumentation and data systems within them in the United States. These containers were then shipped to the experiment locations and assembled as an observing site there (Mather et al. 1998). The Chief Scientist at the time, Tom Ackerman, had developed a scientific rationale and a deployment strategy for the ARM Mobile Facility (AMF) using the TWP and SHEBA models as the basis for a movable facility.

New funding was requested to address this scientific gap, and at the ARM Science Team Meeting in 2001 a new initiative to create an ARM deployable facility was announced. This initiative had been conceived during an initial discussion at the previous year’s Science Team Meeting and subsequent discussions at a workshop hosted at the Pacific Northwest National Laboratory (PNNL). The plans were fairly rudimentary and refinements were required. Further discussions were held during the next year, but funding issues delayed the effort. At the ARM Science Team Meeting in 2003, the Chief Scientist announced that the ARM Program expected to have the first phase of an ARM Mobile Facility One (AMF1) completed in fiscal year 2004 (FY04) and that the first deployment was expected in 2005. The expected benefits of the AMF1 were to be additional datasets from other climatic regimes, improved understanding of cloud and radiation processes by testing relationships developed at the permanent sites in new locations, new regionally specific science questions, and improved interactions with other science programs both nationally and internationally. A prototype design and estimated integration schedule was presented at the meeting (Widener 2003). Mark Miller, who had participated in the NASA FIRE and ASTEX projects, was designated as the Site Scientist for the new AMF in 2004, Larry Jones [Los Alamos National Laboratory (LANL)] as its Operations Manager, and Kim Nitschke (LANL) as its Chief Operations Engineer. A formal design review meeting for AMF1 was held at the headquarters of the American Geophysical Union (AGU) in 2004 and attendees included Department of Energy (DOE) ARM operations staff (Doug Sisterson and Larry Jones), members of the ARM management team (Tom Ackerman and Jimmy Voyles), the AMF1 Site Scientist (Mark Miller), and external reviewers (Steve Rutledge and Mark Ivey). The AMF1 was constructed at PNNL and on completion LANL assumed responsibility for its operation and logistical support.

The initial deployment of the AMF1 took place at Point Reyes, California, (#1 in Fig. 9-1) between March and September 2005 in support of the Marine Stratus, Radiation, and Drizzle (MASRAD) experiment proposed by Mark Miller, which was designed to sample coastal marine stratocumulus clouds and serve as a burn-in for the new system. The Pt. Reyes National Seashore was chosen as the initial deployment location because it was a long, linear coastline nearly orthogonal to the mean northwesterly wind direction that carried marine stratocumulus inland. The National Park Service had helped identify potential deployment locations for the new AMF1 that met the noise restrictions and visual standards for a national park. A standard suite of ARM instruments were deployed along with a 95-GHz cloud radar borrowed from the University of Miami.

The experiment lasted six months, and the AMF1 ran relatively smoothly. One important measurement lesson was learned at Pt. Reyes: clouds with bases near the ground have the advantage of strong connections with the aerosol measurements, but often fall below the first measurement height of the cloud radar. Scientifically, the coastal stratocumulus observed at Pt. Reyes possessed turbulence levels that suggested considerable land influence (Ching et al. 2010) and exhibited observable changes in radiation throughput as a consequence of differing levels of pollution (McComiskey et al. 2009). They were also found to have predictable amounts of liquid water because they were highly insulated from the much warmer and drier air above cloud top. This insulation enabled them to respond more predictably to the presence of pollution (Kim et al. 2012).

In 2004, the DOE designated ARM as a national scientific user facility (Ackerman et al. 2016, chapter 3), and a proposal competition was implemented to decide the location of subsequent deployments of AMF1. Proposals were (and still are) reviewed for scientific merit by the ARM Science Board and for logistical and cost feasibility by the AMF1 operations staff. The final decision was based on scientific merit, cost, logistical considerations, and relevance to the ARM mission.

3. Africa and beyond: The AMF1 program goes global

The initial winning AMF1 proposal was submitted by Anthony Slingo, who proposed an experiment using the AMF1 to be conducted in West Africa as part of a larger, multiyear experiment known as the African Monsoon Multidisciplinary Analysis (AMMA). The Radiative Divergence using AMF1, GERB and AMMA Stations (RADAGAST) served as an embedded component of AMMA. West Africa was the second deployment location for the AMF1 and was the first real test of the concept (Miller and Slingo 2007).

Just as MASRAD was beginning in Pt. Reyes, California, an AMF1 advance team consisting of Mark Miller, Larry Jones, and Kim Nitschke traveled to Niamey,
Niger, accompanied by Peter Lamb and Doug Sisterson to find a location where the AMF1 could be deployed in support of RADAGAST (#2 in Fig. 9-1). Niger exposed many of the challenges that would be faced when deploying in underdeveloped regions. The team visited the U.S. Embassy and three different governing agencies during its initial trip to Niger and struggled to understand which of these agencies controlled the airport where it seemed obvious that the AMF1 had to be deployed. The airport had generator power and security and its landscape was similar to the surrounding Sahelian landscape except for its single runway. Eventually, the airport was made available for the deployment and the AMF1 arrived via a Boeing 747 cargo jet. Some months after the advance team’s trip to Niamey and the AMF1 deployment planning was in full swing, Mark Miller, Tony Slingo, and Peter Lamb attended a planning meeting for AMMA in Dakar, Senegal.

It had been suggested by Mark Miller during the initial site survey that an ancillary site that collected basic radiation and surface meteorological measurements be established away from the airport to help assess the regional representativeness of the AMF1 deployment location. As a result, a small solar-powered site was established near Banizoumbou, Niger (about 60 km away from the main AMF1 site) in a radiatively natural environment.

The RADAGAST deployment was extremely successful, and there is no question that this deployment is one of the most significant achievements of the ARM and AMF1 program (Slingo et al. 2006; Miller and Slingo 2007). The only setback in the deployment was that the AMF1 cloud radar was still under construction during the first three months, but this period was during the dry season when clouds were less prevalent over the Sahel. The RADAGAST deployment produced the first cross-atmosphere radiation budget on a time scale compatible with cloud development (15 min) and the first comparison of this budget with simulations from compatible with cloud development (15 min) and the cross-atmosphere radiation budget on a time scale 

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Successfully completing the RADAGAST deployment catapulted the AMF1 program into the scientific spotlight. Confidence that was gained during this first international deployment in a challenging location facilitated a string of consecutive international and national deployments using AMF1. Each was guided by a different scientific mission and presented a new set of logistical challenges. High demand for AMF1 deployments led to the development of two additional AMFs, as described forthwith. Below is a survey of the key scientific foci and results for each of the AMF missions and a synopsis of some of the key issues encountered in the deployments.

a. The Convective Orographic Precipitation Study experiment

Germany has a serious problem with flash flooding in the Black Forest region. Models had failed to forecast major flash flooding events that resulted in significant losses of life and property, and there was a basic lack of understanding of the organizing principles of the convection that was responsible. A proposal submitted by Volker Wulfmeyer to simultaneously collect data from aircraft and the AMF1 in the Black Forest region during the formative stages of convection was selected by the ARM Science Board (#3 in Fig. 9-1).

The AMF1 advance team arrived in the Black Forest Region in March 2006 and the deployment in support of the Convective Orographic Precipitation Study (COPS) began in March 2007. The AMF1 was again embedded in a large international experiment and its mission was to address the nature and structure of orographic flows and the microphysical morphology of associated convection. The plan included contributions from scientific groups in Germany who deployed instrumentation such as a scanning Doppler lidar and several specialized microwave radiometers alongside the AMF1. The expanded capabilities that were provided by these guest instruments served as a blueprint for the development of AMF1 over the next few years. It was operated in the Black Forest for one year in concert with an array of sensors within a dense COPS network. The data collected captured the position and characteristics of convergence zones and other convective initiation processes and how they related to the resulting convection (Wulfmeyer et al. 2008). It was found that flows induced by orographic forcing and channeling were the principal mechanisms that initiated convection. It was also discovered that these flows strongly modulated the precipitation distributions within and downstream of the COPS domain. Observations also showed that the latent and sensible heat fluxes in the COPS domain were driven primarily by vegetation rather than by soil moisture, which was erroneously serving as the dominant driver of these fluxes in mesoscale models.

b. The study of aerosol indirect effects in China

The scientific rationale for the AMF1 deployment in China evolved from curious satellite observations. Evidently, liquid clouds in southeastern China contained much more liquid water than liquid clouds with the same thickness in other parts of the world. Zhanqing Li and Graham Stevens hypothesized that these clouds were potentially subject to the second aerosol indirect effect (Albrecht 1989). This effect was based upon a hypothesis suggesting that clouds formed in polluted regions

...
produced precipitation less efficiently than in pristine regions. This encumbrance was thought to have increased cloud liquid water over southeastern China. But validation of these satellite observations was required to confirm that the second aerosol indirect effect was the culprit. Such a validation required a state-of-the-art remote sensing system, so Zhanqing Li submitted a successful proposal to deploy the AMF1 in the vicinity of Lake Taihu, which is a large lake in southern China. Proximity to this lake was important because it could be used to assist in the interpretation of accompanying satellite measurements.

While modern China was beginning to embrace western science, it was unclear if the geopolitical boundaries were relaxed enough to allow for scientific measurements of this type sponsored by the U.S. DOE. Furthermore, the experiment plan was complicated and called for three measurement sites: the AMF1 itself, an ancillary facility borrowed from NASA that was deployed at the edge of the Taklimakan Desert in northwest China, and a small collection of instruments situated near Beijing, which hosted the Olympic Games during the same year as the AMF1 deployment.

The AMF1 advance team traveled to China for an 11-day exploration trip in March 2007. The trip began in Beijing. Following meetings at the Chinese Academy of Science and other agencies, the team traveled to Zhangye in western China, mostly by car and literally following the Great Wall to the edge of the Taklimakan Desert northwest of Zhangye, where a site for the northern deployment was chosen. Next the team traveled to Nanjing for meetings and subsequently to Wuxi, near Lake Taihu. Everything seemed set for the deployment of the AMF1 in China during 2008.

A key issue at Taihu was the ability to launch radiosondes in proximity to a Chinese military base, which was nearby. Upon return to the United States, the advance team learned a few weeks later that the request to launch radiosondes at Taihu had been declined. This event required switching to a contingency plan, but this setback was one of many. A few nearby locations were suggested by the Chinese government, but none was optimal for an AMF1 deployment. Finally, a site near Shouxian, which is 500 km west of Shanghai, was chosen (#4 in Fig. 9-1). It was small and the AMF1 had to be deployed in a compressed configuration. An ancillary site at Taihu that consisted of a microwave radiometer, surface radiometers, and surface meteorology was established, since the radiometer was a passive sensor and provided some limited information about the atmospheric column.

Before the AMF1 instrumentation was to be deployed, a data transmission and sharing agreement was developed with the Chinese government. Normally, AMF1 data were transmitted daily to the Data Management Facility (DMF) in the United States and, shortly thereafter, to the ARM Data Archive (McCord and Voyles 2016, chapter 11). This was not consistent with Chinese data sharing policy, so concessions were necessary. It was mutually agreed that data would be supplied directly to the Chinese government, who would inspect it and, ultimately, release it to the DMF. Unfortunately, this agreement led to a sequestration of AMF1 data in China for nearly the entire deployment, but a more restrictive limitation was the prohibition of any Internet connectivity to the AMF1 instrumentation. This precluded the usual ARM quality assurance process. Shortly after the AMF1 began operating in China, its cloud radar failed and was shipped back to the United States for repair. As a result, only two months of cloud radar data were collected during the autumn of 2008. Sadly, observations of the low stratus liquid clouds, which were desired to satisfy the scientific objectives of the deployment, were virtually absent from the cloud radar data, though an analysis of these data in conjunction with radiosonde data was used to produce a cloud climatology (Zhang et al. 2010, 2013). The wealth of general and specialized measurements that were collected using AMF1 in China combined with data collected by coincident programs has led to successful investigations of the optical, physical, chemical, and cloud nucleating properties (Liu et al. 2011) of anthropogenic, natural, and mixed aerosols and interactions with the East Asian monsoon system (Li et al. 2010).

Inasmuch as the deployment in Africa was a crowning achievement of the AMF1 program, the AMF1 deployment in China was limited by geopolitical and logistical considerations. On the bright side, the development of new scientific partnerships may have opened the door for additional scientific collaborations with China.

c. **Clouds, Aerosol, and Precipitation in the Marine Boundary Layer**

There was a general consensus that varying depictions of the cloud feedbacks associated with boundary layer stratocumulus clouds in global climate models were partly responsible for the spread in predictions of global warming. As a consequence of their large areal coverage on Earth’s surface, their radiative feedbacks must be portrayed accurately in GCMs, and the original plan for ARM fixed sites had included a marine boundary layer site in the Azores.

Recognizing the need for long-term and comprehensive measurements of marine stratocumulus clouds, Robert Wood had proposed the Clouds, Aerosol, and Precipitation in the Marine Boundary Layer (CAP-MBL)
experiment and his proposal had been approved. Earlier surface-based remote sensor measurements collected during ASTEX from the islands of Santa Maria and Terceira laid the groundwork for the CAP-MBL experiment and the ARM Program in general. Island effects had been documented during ASTEX (Miller and Albrecht 1995) and had been linked to the significant terrain on the island of Santa Maria, which implied that Graciosa Island in the Azores was a preferable location for an AMF1 deployment (#5 in Fig. 9-1). It was smaller in size, had lower terrain, was slightly farther north than the islands used during ASTEX, and it had a small airport.

The AMF1 advance team visited San Miguel, Terceira, and Graciosa Islands during March 2008. Landing at the airport on Graciosa had suggested that the airport itself would serve as an excellent AMF1 deployment location. It was located on the northern shoreline so the prevailing northerly winds during the summer stratocumulus season would have carried clouds over the site before encountering any significant terrain. Breaking waves were heard from the runway by the advance team. Only 90 km southwest of Graciosa was the enormous volcanic peak on the island of Pico, which unbeknownst to the advance team during the initial visit played a role in the CAP-MBL project. Data collection began on Graciosa in May 2009. It had been a long time coming given that the Azores had been designated as one of the original fixed sites.

A few months after AMF1 data collection began at Graciosa, it became clear that marine stratocumulus clouds were being observed in a new light. The AMF1 provided a new level of detail about the diversity of marine clouds over the north central Atlantic Ocean. So encouraging were these initial data that Robert Wood submitted a second proposal to the ARM Science Board to extend the deployment for an additional year. Perhaps having sensed the pent-up demand for these data, ARM accepted Dr. Wood’s follow-up proposal and the CAP-MBL deployment was extended for an unprecedented second year (Wood et al. 2015). During this extended deployment period, the ARM Program tested a new scanning cloud radar at Graciosa, which was a harbinger of things to come for the AMF1.

When opportunity knocked, the door had been opened; this was how the deployment of several solar and infrared radiometers near the top of Pico during CAP-MBL began. Many years prior to the AMF1 deployment an International Chemical Observatory (ICO) station had been established at 2225 m above sea level on the summit caldera of Pico Mountain. The ICO station had been linked to the significant terrain on the island of Santa Maria, which implied that Graciosa Island in the Azores was a preferable location for an AMF1 deployment. This station provided unique data and had demonstrated the cleanliness of the air mass above Pico, which rivaled the low aerosol loads observed at Mauna Loa.

As always, there were a few problems. The most significant was the loss of the Atmospheric Emitted Radiance Interferometer (AERI; Turner et al. 2016, chapter 13) for six months of the CAP-MBL deployment. The AERI provided invaluable, nearly continuous information about the details of infrared emissions and the thermodynamic profile. This information was a crucial supplement to radiosonde data and was used to measure the liquid water content of extremely thin clouds (Turner 2007). Another problem discovered after the deployment ended was that the rainfall measurements at Graciosa were biased. This bias was due to improper mounting of the optical rain gauge and the present weather detector. An investigation by Mark Miller’s research team revealed that the instrument mounting was altered to accommodate the deployment in Shouxian, China. When the system was shipped to Graciosa, an operations team comprised of some new members reconstructed the configuration that they had disassembled in China rather than reverting to the original, correct configuration. The lesson learned in light of the bias was configuration control: when changes were made to the deployment configuration to accommodate a peculiarity they had to be carefully recorded and reversed during the following deployment.

Results from CAP-MBL altered some traditional views of stratocumulus clouds and of the marine boundary layer clouds over the eastern North Atlantic (ENA) in general. The first long-term study of the climatology of cloud structure and its links to drizzle demonstrated that stratocumulus clouds with a depth exceeding 250 m and a liquid water path exceeding 60 g m\(^{-2}\) produced drizzle over the ENA (Rémillard et al. 2012). Known mesoscale circulations in marine stratocumulus, termed mesoscale cellular convection, were implicated as being partly related to air mass type. Cold air outbreaks over the ENA were linked to high concentrations of a certain type of mesoscale cellular...
convection (open cell), which in turn was shown to be associated with reduced pollutant loads. Comparisons of the morphology of marine stratocumulus observed at ENA with those observed over other parts of the world had exposed differences in the thermodynamic environments in which they formed (Ghate et al. 2015). And the first measurements of the updraft mass flux in a large population of small marine cumulus clouds provided new information about cumulus dynamics (Ghate et al. 2011).

d. The Ganges Valley Aerosol Experiment

The Indian monsoon was the lifeblood of India because it supplied rain for agriculture and snowfall to the Himalayas that eventually melted into freshwater that supplied many of India’s rivers. There were known and hypothesized links between the Indian monsoon and other important atmospheric circulations. And economic growth in India produced a juxtaposition of this monsoon circulation and the byproducts of manufacturing in northern India, which included large quantities of highly absorbing black carbon aerosols. In addition to the obvious health issues caused by this black carbon, it had been thought to deposit on snow surfaces in the Himalayas thereby reducing the snow’s albedo and potentially altering the dynamics of the Indian monsoon. Measurements were needed to evaluate the impacts of black carbon in the region.

Rao Kotamarthi submitted a successful proposal to the ARM Science Board that outlined a plan to obtain measurements of clouds, precipitation, and complex aerosols and study their impact on cloud formation and monsoon activity in the vicinity of the Ganges Valley. The experiment plan combined aircraft measurements collected over the valley itself with AMF1 measurements from the nearby foothills of the Himalayas. The Aries Astronomical Observatory located high on a mountain near the mountain resort city of Nainital, India, was selected as the AMF1 deployment site for the Ganges Valley Aerosol Experiment (GVAX; #6 in Fig. 9-1). The AMF1 was positioned at a location and height that enabled measurements of aerosols spilling through the foothills into the snow-covered peaks of the Himalayas.

In February 2010, the AMF1 advance team traveled to India to organize the three components of the GVAX deployment: the AMF1 itself, a satellite measurement site near the city of Pantnagar, and a Mobile Aerosol Observing System (MAOS) aerosol monitoring facility and aircraft deployment located in Lucknow. The team visited the U.S. Embassy in New Delhi and the headquarters of the Indian Science Agency before it embarked on a long train ride to Pantnagar. With the help of Indian hosts, the team toured a small regional university with enough infrastructure to support a satellite deployment. Next the team traveled by car to the Aries Observatory at Nainital, which was located at 1951 m elevation. The observatory was situated atop a steep mountain and, while it possessed excellent communications infrastructure, space was extremely limited. A platform was constructed atop one of the buildings and the microwave radiometers and surface meteorological and downwelling radiation measurement systems were mounted on this platform. The situation was not optimal and there were concerns about measuring radiation at this site because adjacent to the platform location was a large dome associated with an Aries telescope. But there was not a better location available because the observatory was surrounded by steep mountain slopes.

The GVAX experiment began in June 2011. Its scientific objective was to measure clouds, precipitation, and complex aerosols to study the relationship between the aerosols, cloud formation, and monsoon activity in the region. Siting and logistical difficulties prevented the vertically pointing cloud radar and a new dual-wavelength scanning cloud radar from being deployed, but two important new instruments were added: a scanning Doppler lidar and a solar spectrometer. The AMF1 was deployed in support of a planned aircraft campaign in the Ganges Valley with ARM Aerial Facility (AAF; see Schmid et al. 2016, chapter 10) aircraft to have served a pivotal role in the experiment, but ARM was denied flight clearance for a U.S. research aircraft. Indian research aircraft surveyed pollution in the Ganges Valley, but lack of AAF support was a serious detriment to GVAX. As in the deployment in China, data were sequestered by the Indian scientific agencies. This caused a significant delay in data access, but all data collected were released at the conclusion of the experiment.

e. The Two-Column Aerosol Project

The principal theme of the Two-Column Aerosol Project (TCAP) campaign proposed by Carl Berkowitz and Larry Berg was to quantify the impacts of aerosol mixing state and optical properties upon aerosol radiative effects. To meet these scientific objectives, AMF1 and the Mobile Aerosol Observing System were deployed on Cape Cod, Massachusetts, for one year beginning in the summer of 2012 (#7 in Fig. 9-1). These observations were supplemented by two aircraft intensive observation periods (IOPs), one during the summer of 2012 and a second in the winter. Each IOP required two aircraft.

The AMF1 was deployed at a site along the Cape Cod National Seashore along the bluffs near North Truro,
Massachusetts, and data collection began on 22 July 2012. The experiment, while still in the analysis phase, was extremely successful, and initial results suggested that the experiment objectives were met (Titos et al. 2014; Kassianov et al. 2013). In addition, the TCAP deployment marked another critical turning point in the history of the AMF program because several new cutting-edge instruments purchased through the American Recovery and Reinvestment Act (ARRA) were deployed. Prominent among these instruments was a scanning microwave radiometer and a scanning Ka-W band dual wavelength cloud radar that complemented the existing vertically pointing W-Band cloud radar. The addition of these scanning systems marked a quantum leap in the observation footprint of AMF1 from its original soda straw-like column view.

f. GOAmazon2014/15

The first deployment in the Southern Hemisphere is in progress at the time of this writing. Scot Martin proposed the Green Ocean Amazon 2014–15 (GOAmazon2014/15) experiment, and the AMF1 is currently deployed in a pasture surrounded by Amazonian jungle near the river village of Manicapuru, Brazil (#8 in Fig. 9-1). The experiment is designed to study how aerosol and cloud life cycles are influenced by pollutant outflow from a tropical megacity. A main objective of the experiment is to examine the interplay between biogenic and anthropogenic aerosols. Early results are encouraging and the deployment of AMF1 in support of GOAmazon2014/15 exemplifies its metamorphosis over the course of the programs. The increasing size and scope of AMF1 deployments has significantly altered its appearance and footprint. Figure 9-2 shows AMF1 in its initial deployment in Pt. Reyes, California, in 2005 and Fig. 9-3 its latest deployment nine years later in support of GOAmazon2014/15.

4. AMF2 and AMF3

The AMF program was conceived around the fundamental notion that data from remote and undersampled regions would improve our understanding and simulation of Earth’s climate system. When Hans Verlinde of the Pennsylvania State University proposed that AMF1 be deployed on an icebreaker, the need for additional AMFs came into focus. The original design of AMF1 had consisted of extended lightweight military-specification shelters that were seaworthy and came with connector systems used on offshore oil rigs. Also, AMF1 was originally designed with a small footprint so that it could be located on ships of differing sizes based on experience at SHEBA and discussions with engineers at the Woods Hole Oceanographic Institute. But through time AMF1 had been modified and expanded so that it was no longer ship deployable. Thus, there was a clear need for systems designed to be operated in marine, shipboard environments and in harsh land-based environments, and increased demand for AMF deployments of this type led to the construction of the second and third ARM Mobile Facilities (AMF2 and AMF3). These AMFs differed slightly
in their missions in that AMF2 was designed for traditional one- or two-year deployments and AMF3 for deployments of up to five years. They were constructed with stainless steel modules and flexible power options so that they could be reconfigured in many ways and AMF2 included two stabilized platforms to remediate wave motion: one for the W-band radar and another for the radiometric instruments. All instruments included in these AMFs could be collocated or deployed away from the main site depending upon the science requirements or siting challenges. With ARRA additions, the portable design of these AMFs was expanded to include additional instruments that were required to further satisfy the science goals of their campaigns. Argonne National Laboratory successfully competed for the building and operating of AMF2, and Richard Coulter and Brad Orr became the operators. The AMF3 was constructed after AMF2 was completed, but at Sandia National Laboratories with Mark Ivey as its operator.

a. STORMVEX

The AMF2 was first deployed in support of the Storm Peak Laboratory Cloud Property Validation Experiment (STORMVEX) in Steamboat Springs, Colorado, which was successfully proposed by Dr. Gerald Mace of the University of Utah and colleagues (tan #1 in Fig. 9-1).

The objective was to collect data to enhance our understanding of liquid and mixed-phase clouds by using AMF2 instruments in conjunction with Storm Peak Laboratory (SPL), which is a cloud and aerosol research facility operated by the Desert Research Institute. The designed flexibility of the AMF2 allowed deployment of instruments in three locations in addition to instruments deployed at the SPL, which was located at 3203 m in elevation. The SPL and Steamboat Resort Mountain collaborated with the AMF2 team and installed instruments near Thunderhead Lodge, at an elevation of 2759 m, the Aerosol Observing System at Christie Peak at an elevation of 2440 m, and the majority of the instruments in the valley at an elevation of 2078 m (Fig. 9-4). The AMF2 was tested during this maiden deployment by environmental conditions including high winds, temperatures below 0°F, and heavy snowfall.

This initial deployment of AMF2 was successful and the data collected continue to be analyzed. Some of the initial results from STORMVEX showed that nonspherical atmospheric ice particles can enhance radar backscatter and beam attenuation above that expected from spheres of the same mass (Marchand et al. 2013). Initial results also demonstrated that polarization measurements between zenith and slant viewing angles can be used to infer information about...
the geometry of planar ice crystals (Matrosov et al. 2012).

b. AMIE-GAN

A proposal by Charles Long of PNNL and colleagues was approved for the AMF2 to take its first international voyage to Addu Atoll, Maldives (tan #2 in Fig. 9-1). The ARM Madden–Julian oscillation (MJO) Investigation Experiment on Gan Island (AMIE-Gan) was a part of a larger campaign, DYNAMO/CINGY2011, which included AMIE-Manus. The experiment was designed to test several current hypotheses regarding the mechanisms responsible for MJO initiation and propagation in the Indian Ocean area (Yoneyama et al. 2013; Gottschalck et al. 2013). The AMF2 deployment was organized with almost all instrumentation in a main site, but with a supplementary site where the Ka-X scanning ARM cloud radar (SACR) was deployed to enable radar scanning over the main site (Fig. 9-5). Analysis of AMIE-Gan data is ongoing.

c. MAGIC

Ernest Lewis of Brookhaven National Laboratory and colleagues successfully proposed the Marine ARM GPCI Investigation of Clouds2 (MAGIC) campaign, which required the AMF2 to operate aboard the Horizon Lines container ship, Spirit. Beginning in October 2012, the Spirit hosted the AMF2 on round trips between Los Angeles, California, and Honolulu, Hawaii, and provided a moving platform for nearly 200 days of continuous onboard measurements (tan #3 in Fig. 9-1). The primary objective of MAGIC was to improve the representation of the stratocumulus-to-cumulus transition in climate models. The MAGIC science team is currently using AMF2 data to document the small-scale physical processes associated with turbulence, convection, and radiation in a variety of marine cloud types. These variables are currently unrealistic in climate models due to a lack of adequate observational data.

Ernie Lewis, Brookhaven National Laboratory (BNL), and Brad Orr, Argonne National Laboratory (ANL), led a siting cruise prior to the AMF2 deployment to understand the engineering and environmental challenges. Nicki Hickmon, ANL, assumed the role of Site Manager for AMF2 in May 2012 and directed the installation. Modifications to the ship’s bridge deck were made to support the weight and mounting of the AMF2. Working in the Port of Los Angeles during regular docking times required a high degree of organization to accomplish modifications, approvals, and lifts while other operations involving other ships were underway. At one point, issues with the ship caused the entire AMF2 to be offloaded with two days’ notice prior to docking and a single day for the actual offload procedure. The AMF2 technicians worked exhaustively and the entire AMF2 was offloaded within six hours of the ship docking with no damage to instruments or equipment. After reinstalling the AMF2 on the ship, the observation period was completed. Launching radiosondes was particularly challenging with the wind dynamics around the ship and cargo, but the AMF2 technicians perfected the procedure, leading to an acceptable success rate (Fig. 9-6).

Observations from MAGIC are being analyzed currently and initial results have reinforced the scientific approach that was taken. Data collected during MAGIC have led to estimates of the entrainment rate and water and energy budgets that have helped unravel the changing mix of processes that accompanies the transition from stratocumulus to cumulus conditions (Kalmus et al. 2014).

d. BAECC

Tuukka Petäjä of the University of Helsinki and colleagues submitted a successful AMF2 deployment proposal to the ARM Science Board to measure biogenic aerosols emitted from forests and determine their effects on clouds, precipitation, and climate. The AMF2 operated from February to September 2014 in Hyytiälä, Finland, at the University of Helsinki’s Station for Measuring Ecosystem–Atmosphere Relations (SMEAR-II; Fig. 9-7; location tan #4 in Fig. 9-1). Once again the
flexibility of the AMF2 to be reconfigured for each deployment given the site and environmental conditions proved important. The Ka-X SACR was elevated to minimize the forest blocking and the Aerosol Observing System was operated at a site away from the main AMF2 deployment location to enable coincident data collection with the SMEAR-II aerosol system. Analysis of data collected during the Biogenic Aerosols: Effects on Clouds and Climate project (BAECC) is ongoing.

The AMF3 deployment at Oliktok Point, Alaska, was part of an ongoing need to understand the representativeness of the North Slope of Alaska (NSA) fixed site and was planned to last five years (gray #1 in Fig. 9-1). The newly constructed AMF3 was installed in two phases starting in summer of 2013. The first phase of the installation included shelters that were specifically designed for the Arctic, with a shared entry space that links individual shelters and additional insulation for each shelter. The first phase of installation included the same “baseline” instruments for cloud, solar, thermal, and meteorological measurement that have been used at the NSA site since 1997. The second phase, completed in 2014, includes scanning cloud radars and a Raman lidar.

Oliktok Point is part of the U.S. Air Force Oliktok Point Long Range Radar station and it was the location of previous ARM field campaign activities, including the Mixed-Phase Arctic Cloud Experiment (MPACE) in 2004 and the Arctic Lower Troposphere Observed Structure (ALTOS) in 2010. The current agreement with the Air Force includes provisions for limited billeting of ARM staff at the station. The Oliktok Point site is linked by the Prudhoe Bay road system and the TransAlaska pipeline road to the lower 48 states.

A unique advantage of the AMF3 deployment at Oliktok Point is access to airspace for research purposes. Starting in 2004, a restricted area was established over Oliktok Point by the Federal Aviation Administration (FAA) for DOE. This restricted area gives DOE and the ARM Program control of a 4-mile-diameter circle of airspace for operations that include tethered balloons and unmanned aerial systems. A warning area that would enable research operations in a corridor of airspace extending roughly 700 miles north of Oliktok is being reviewed with approval expected early next year. Plans include operating tethered balloons, unmanned (Fig. 9-8) and manned aircraft, and related aerial systems at Oliktok to support ARM science.
5. A perspective on AMF deployment challenges through the life of the program

Through the course of the AMF program many challenges have been overcome, some of which are documented here, and during its 10-yr history the AMF program has steadily grown in size and complexity. Accompanying this growth has been a proportional increase in the size and complexity of AMF operations, especially transportation. Originally, five or six technical staff prepared AMF1 for transporting; now it takes longer, requires more staff, and must include some instrument specialists to handle the more complicated remote sensing systems like the scanning cloud radar.

Logistical challenges faced during the myriad of AMF1 deployments may be roughly grouped by deployment location. International deployments have involved many more considerations and logistical challenges than domestic deployments. They have required regulatory approvals from the host country, which have taken time to acquire, and the waiving of standard import duties. One of the most difficult issues has been data export from the host country and establishing the rules of data availability. Common practice in the ARM Program has been to make data freely available as soon as it has been collected (McCord and Voyles 2016, chapter 11), but this policy has been inconsistent with the international data export requirements of some countries. Sometimes the data have been embargoed (the China and India deployments, for example) for a period to allow the host country to insure that no sensitive information was contained in the data files.

Safety and security has been a major issue in underdeveloped areas of the world for both personnel and equipment. In these cases, special accommodation has been necessary for the on-site technician, any technical staff that visits the site, and the facility itself. Airports have been favored deployment locations in underdeveloped areas because they already possess a modicum of safety and security infrastructure, have associated regional transportation hubs, and have been able to accommodate research aircraft. In the case of the deployment in Niamey, Niger, AMF1 was transported to the site by cargo aircraft and deployed at the international airport in Niamey because other travel routes to the region were insecure (and known to be dangerous) and the airport was the only secure
option. These regions have also presented unique challenges in locating appropriate, affordable long-term housing for the resident technical support staff that have performed on-site maintenance and offered 24/7 responsiveness.

An issue that has been intertwined in all AMF activities is the language barrier in non-English-speaking countries. To navigate this barrier and many other administrative issues that have arisen, the AMF operations staff has relied heavily on the deployment’s principal investigator, who may have local contacts, and on the in-country scientific host. A key component of each AMF deployment has been the engagement of the regional scientific and local host communities. Engaging the latter has proven to be particularly crucial because it has been necessary to identify and work with local and in-country subcontractors to assist in preparing and maintaining the site, and because round-the-clock radiosonde launches have been done by local resident operators trained by the AMF technical staff. Knowledge transfer and scientific development also has been an important goal of the AMF deployments in underdeveloped areas. The addition of the AMFs added many challenges to the ARM infrastructure, including the DMF, the data quality (DQ) office, the archive, and the instrument mentors. The workloads of these components of the ARM infrastructure were stretched before the addition of the AMFs and remain stretched at this time. While the stretching of these resources was recognized when the AMFs were added, resources not currently available are required to ameliorate this problem. In the meantime, AMF data quality and access remain viable, but could be improved in the future.

Over the years the role of the AMF1 site scientist has varied depending on the deployment. In some cases, the scientist who proposed the experiment was well versed in the remote sensing techniques employed in the AMFs, while in other cases not. And the increasing breadth and sophistication of the AMF’s measurement suite has challenged the knowledge base of even the savviest scientist. So the position of site scientist has changed with the AMF1 and in the latter years the focus has been upon learning new instrumentation, performing ASR cloud and radiation science when the experiment focus did not address the basic programmatic needs of each deployment, and performing high-level quality control.

6. Conclusions and recommendations

The AMF concept has been part of the ARM Program from its beginning. Implementation required a combination of programmatic opportunity and technical readiness that was reached in the early 2000s. The AMF has proven to be of high value to the program, in particular because it has allowed synergistic collaborations with other international programs and countries. Also, ARM has been able to acquire datasets in climate regimes that are not otherwise sampled by the permanent sites (Table 9-1). Excellent examples include the deep dust layers observed during the Niamey deployment (Slingo et al. 2006) and the marine stratus during the Azores deployment. In both cases, data collected by the AMF have been used in new and exciting ways to challenge models of all varieties.

A serpentine path across the Northern Hemisphere during the past decade has netted some of the most unique data streams in the ARM Data Archive and has produced some of the most interesting and unique science in the climate research community. The ARM Data Archive typically records an increase of approximately 100–120 new users as a result of an AMF deployment. This number translates to an increase of about 10%–15% in the number of active data users. In total, users of AMF data constitute 15%–20% of all requests to the archive and when location is

<table>
<thead>
<tr>
<th>Deployment location</th>
<th>Facility</th>
<th>Dates</th>
<th>Scientific focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point Reyes, California</td>
<td>AMF1</td>
<td>Mar 2005–Sep 2005</td>
<td>Marine stratocumulus</td>
</tr>
<tr>
<td>Niamey, Niger</td>
<td>AMF1</td>
<td>Jan 2006–Dec 2006</td>
<td>Monsoon convection and dust</td>
</tr>
<tr>
<td>Black Forest, Germany</td>
<td>AMF1</td>
<td>Apr 2007–Jan 2008</td>
<td>Orographic and convective precipitation</td>
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<tr>
<td>Shouxian, China</td>
<td>AMF1</td>
<td>May 2008–Dec 2008</td>
<td>Aerosol–cloud interactions</td>
</tr>
<tr>
<td>Graciosa Island, Portugal</td>
<td>AMF1</td>
<td>May 2009–Dec 2010</td>
<td>Marine stratocumulus</td>
</tr>
<tr>
<td>Steamboat Springs, Colorado</td>
<td>AMF2</td>
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<tr>
<td>Nainital, India</td>
<td>AMF1</td>
<td>Jun 2011–Apr 2012</td>
<td>Aerosol–cloud interactions</td>
</tr>
<tr>
<td>Gan Island, Maldives</td>
<td>AMF2</td>
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<td>Tropical convection</td>
</tr>
<tr>
<td>Cape Cod, Massachusetts</td>
<td>AMF1</td>
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</tr>
<tr>
<td>California–Hawaii Transect</td>
<td>AMF2</td>
<td>Oct 2012–Sep 2013</td>
<td>Marine cumulus/stratocumulus</td>
</tr>
<tr>
<td>Manaus, Brazil</td>
<td>AMF1</td>
<td>Jan 2014–Dec 2014</td>
<td>Cloud–aerosol–precipitation interactions</td>
</tr>
<tr>
<td>Hyytiala, Finland</td>
<td>AMF2</td>
<td>Feb 2014–Sep 2014</td>
<td>Aerosol–cloud interactions</td>
</tr>
</tbody>
</table>
considered, the AMF program produces ~50% of the unique measurements stored there. Growth in the AMF program has challenged the capacity of the archive, which now receives multiple requests for terabytes of data during a given month. Many of these requests for large datasets are the result of AMF deployments.

Building on the past success of the AMF program has led to a future in which three AMFs with different capabilities are available for worldwide deployment by any international investigator. But there is always room for improvement. One recommendation based on past experience is that the AMF deployment period never be less than two years without appropriate justification. Data from a single year are extremely useful, but some scientific questions require a two-year dataset to provide a snapshot of regional variability. Another recommendation is that the position of AMF Site Scientist be preserved to insure adequate scientific input to the program and to data users.

The AMF program has become one of the most successful and visible components of the ARM Program. Its scientific reach has transcended international borders and it has become a high-value global asset. Most importantly, the expansion of the AMF program reflects the increasing influence and demand for the science that it enables.

Acknowledgments. We dedicate this chapter to the memories of Dr. Anthony Slingo and Dr. Peter J. Lamb whose seminal efforts during the first AMF1 international deployment in West Africa helped pave the way for the future success of the AMF program. The authors also wish to express their deep appreciation to the technicians, instrument mentors, scientists, and all other members of the ARM community who have made the AMF program what it is today.

REFERENCES


