Chapter 2

Original ARM Concept and Launch

GERALD M. STOKES

Stony Brook University, State University of New York, Stony Brook, New York

1. Introduction

The foregoing chapter (Ellingson et al. 2016, chapter 1) lays out the scientific foundation for the initiation of the Atmospheric Radiation Measurement (ARM) Program. In parallel with the development of this scientific foundation, public and political attention was being focused on the climate issue. Even broader scientific findings in climate came together with this heightened public interest and created a large expansion of the funding for climate research. These funds allowed ARM, a ground-based program, to be put together on a scale more comparable to the large satellite programs of NASA and larger in budget than previous ground-based climate research efforts. ARM was developed in parallel with major efforts from other agencies, such as NASA's Earth Observing System (EOS), during a time of considerable expansion of global climate research.

This chapter is not written as a chronology. It is rather a description of the key intellectual threads of ARM that were developed concurrently and that are described here as interrelated stories. In a sense, it is a guide to the balance of the monograph, describing primarily how the program came together. Most of the references are to internal ARM documents and the other chapters in this monograph, where the topics introduced here are discussed in more detail. Ackerman et al. (2016, chapter 3) provides a description of how these initial steps were transformed into the mature program that exists today, and Mather et al. (2016, chapter 4) provides an overview of some of the more significant scientific accomplishments of ARM.

2. The challenge from the Committee on Earth Sciences

The period of 1988–92 saw a huge increase in the research effort of the United States on understanding Earth's climate. An important precipitating event was the public and congressional perception of and response to the heat wave of the summer of 1988, which has been estimated to have caused 5000–10 000 deaths and more than \$70 billion in weather-related economic losses in the central and eastern United States.[1] In the same year, the Intergovernmental Panel on Climate Change (IPCC)[2] was formed by the World Meteorological Organization and the United Nations Environment Program (UNEP), and its first assessment report was published in 1990. This period culminated with Earth Summit in Rio in 1992 and the negotiation of the UN Framework Convention on Climate Change in the same year.

At this time, the U.S. Global Change Research Program (USGCRP) began as a presidential initiative and was defined further by the Global Change Research Act of 1990.[3] This ongoing program coordinates the efforts of federal agencies on global environmental change,[4] which are described annually in the report

---

Corresponding author address: Gerald M. Stokes, Department of Technology and Society, Stony Brook University, Stony Brook, NY 11794.
E-mail: gerry.stokes@gmail.com

DOI: 10.1175/AMSMONOGRAPHS-D-15-0021.1

[1] The public perception of the climate change issue, which is reflected in an online article (http://www.csmonitor.com/USA/2011/0711/As-much-of-US-swelters-here-are-5-worst-heat-waves-of-past-30-years/Summer-1988), drove much of the discussion of climate both in the presidential election and throughout the presidential term of George H. W. Bush.

[2] https://www.ipcc.ch/organization/organization_history.shtml

[3] Global Change Research Act of 1990, Pub. L. No. 101-606, 104 Stat. 309 (1990).

[4] http://www.globalchange.gov/about

"Our Changing Planet."[5] This program was in its formative stages in 1989, and each agency sought to gain approval for its specific contributions to the national research effort. In the spring and summer of 1989, the Department of Energy (DOE), one of the participating agencies, was designing its contribution to the USGCRP. The DOE had sponsored climate research programs starting in 1978 as part of its Carbon Dioxide Research and Assessment Program. The DOE carbon dioxide research program had produced some very important products, including six state-of-the-art reports[6] that were a comprehensive review of the state of climate research in the mid-1980s, an interesting predecessor to the IPCC assessment reports half a decade later. In preparing its USGCRP efforts, the DOE focused on results that were emerging from the Intercomparison of Radiation Codes in Climate Models (ICRCCM; Ellingson and Fouquart 1991).[7] As noted in Ellingson et al. (2016, chapter 1), ICRCCM was part of a DOE effort to reconcile differences in climate modeling results. The approach was to compare radiation parameterizations used in these models and to understand why and how the models might differ.

The DOE's early proposals to pursue what was later called the ARM Program were not agreed to by the governing body of the USGCRP—the Committee on Earth Sciences (CES). The disagreements among the CES principals revolved largely around the size of the program. The program was perceived as too large at $200 million per year, and the view was that the atmospheric science community was not large enough to take on the work even if funded at that level. After some intensive negotiation, the DOE agreed in mid-August of 1989 to produce a revised Program Plan by 1 November of that year for peer review and approval.

Ari Patrinos, Director of the Atmospheric and Climate Research Division within the Office of Energy Research of the DOE, and who had represented the DOE at the CES, was given the charge by the DOE to develop this plan. He selected a team of three people—Gerry Stokes of the Pacific Northwest National Laboratory (PNNL); Bob Ellingson of the University of Maryland, College Park; and Dave Sowle of Mission Research Corporation—to write the plan. Patrinos also convened representatives from most of the DOE laboratories to support the preparation of the plan. This represented the first time that the DOE laboratories had the opportunity for systematic input into the program planning process for ARM. Prior to this time, federal rules prohibited the involvement of DOE laboratory staff, who were not federal employees, from participating in a process that was the part of the formulation of the federal budget. The selection of Stokes, Ellingson, and Sowle was intended to give the laboratories, the academic community, and the private sector a voice in the formulation of ARM.

Stokes, who became ARM's first Chief Scientist, was an astrophysicist and head of the Global Studies Program at PNNL and had experience in atmospheric spectroscopy and radiometry. Sowle was a representative of the private sector whose experience was largely in defense-related remote sensing applications.

Bob Ellingson, then a professor at the University of Maryland, College Park, played the key role in the early phase of the proposal. As one of the architects and key investigators of ICRCCM, he had already prepared a plan together with Warren Wiscombe of NASA (who would later become the third ARM Chief Scientist) for the Spectral Radiance Experiment (SPECTRE; Ellingson and Wiscombe 1996; Ellingson et al. 2016, chapter 1) to add real observations to the comparison of the radiative modeling algorithms. Their approach called for the characterization of the physical properties of the atmospheric column concurrent with the measurement of the downward spectral radiance and flux. The flux observations would be compared with calculations of the spectral radiance and flux based on concurrent measurements of the atmospheric characteristics that governed the radiation: temperature and composition

---

[5] The web page http://www.globalchange.gov/browse/reports has connections to each volume of this series of documents. They are prepared as part of the annual budget submission to the U.S. Congress by the President of the United States. These reports chronicle the growth and programmatic evolution of the USGCRP as told by the federal agencies.

[6] There were six reports: four primary reports ("Atmospheric carbon dioxide and the global carbon cycle," DOE/ER-0239; "Direct effects of increasing carbon dioxide on vegetation," DOE/ER-0238; "Detecting the climatic effects of increasing carbon dioxide," DOE/ER-0235; and "Projecting the climatic effects of increasing carbon dioxide," DOE/ER-0237) and two specialized reports ("Characterization of information requirements for studies of CO_2 effects: Water resources, agriculture, fisheries, forests and human health," DOE/ER-0236, and "Glaciers, ice sheets, and sea level: Effect of a CO_2 induced climatic change," DOE/ER/60235-1). They were peer reviewed by a large team convened by Roger Revelle, serving as the chairman of the Committee on Climate of the American Association for the Advancement of Science (AAAS).

[7] This decision was made by Robert Hunter, the assistant secretary of energy, responsible for the Office of Energy Research as part of the focus on the Quantitative Links Program as described in Ellingson et al. (2016, chapter 1).

(most critically water)[8] as a function of altitude and pressure.

This approach was seen as being critical to ensuring that the radiative transfer in climate models was represented correctly. ICRCCM had shown that a convergence of results could be gained between the high-spectral-resolution radiative transfer models and the lower-resolution parameterizations used in general circulation models (GCMs) of Earth's climate that were required for good computational performance. At this time in the development of climate models, a significant fraction of computational time was dedicated to radiative transfer. The parameterization of detailed radiative transfer results to lower resolution was an essential part of the modeling process, which allowed the climate models to be practical tools for research. ICRCCM then pointed out that the next step was to ensure that the higher-resolution models were correct by comparing them to actual observations. This paradigm of ensuring that there was a convergence between parameterizations of physical processes in climate models and higher-fidelity models of the physics became a signature of the ARM design and approach.

The path to accomplishing this for the clear sky case, as outlined by Ellingson and Wiscombe (1996), was seen as straightforward. The cloudy sky cases were seen as somewhat more complicated, but the team writing the proposal felt that the general paradigm of first assuring that the parameterization of the cloudy sky conditions matched higher-resolution models and then observationally confirming the fidelity of the higher resolution models would work. This path to an effective treatment of the radiative transfer in these situations also seemed appropriate, but it was clear that there were key issues that would have to be addressed in both three-dimensional radiative transfer and the measurement of the corresponding radiative properties of the clouds.

The earliest discussions among the laboratory team working on the Program Plan focused not only on the measurement of the radiative properties of clouds, but also on the larger question of whether those properties could be predicted in climate models. This discussion led to a critical decision, proposed by Stokes and the team to DOE, in which they supported the idea that, in order to solve the radiation problem and advance climate modeling, the issue of both cloud formation and characterization must be addressed. This decision shaped much of ARM and has probably led to its enduring mission, well beyond the 10 years originally envisaged. The importance of the cloud–radiation interaction problem to climate research was highlighted in the IPCC First Assessment Report released in 1990 and in all subsequent assessments.[9]

An important consequence of the decision to work on the ''greater cloud problem'' was the operational decision that ARM was to be a continuously operating facility. Much of the cloud research prior to ARM was conducted on a campaign basis. In this mode, a large number instruments and investigators were assembled in one place for a few weeks to perhaps 2 months. As a result, the data collected were quite literally at the mercy of the weather. This method led to some excellent results, but it did not result in a climatically representative dataset. The concept evolved that ARM would provide a continuous data record on climatologically appropriate time scales—years rather than weeks. The consequences of this were many and were a central, and highly controversial, feature of the Program Plan that was submitted for review on 1 November 1989; these consequences will be discussed later in this chapter.

The Program Plan was circulated on 1 November 1989 to more than a dozen scientific reviewers in the private, government, and university communities. A public meeting on the program was held in Washington, D.C., later that month to elicit additional comments. A response to the various comments was prepared and presented in January, which included a proposed path forward for the ARM Program. Probably the most important aspect of the review was the very thoughtful commentary provided on solving the ''whole cloud problem.'' While the original Program Plan was extremely well informed by the intellectual work of Ellingson and others on what parameters needed to be measured to test radiation codes, the plan was quite weak on what was needed to be measured in order to address the larger cloud problem. The response to the review provided assurance that work would begin to strengthen the approach to cloud formation and characterization. In particular, Tom Ackerman, who became the second ARM Chief Scientist, and Bruce Albrecht at

---

[8] In the view of the author, one of the key contributions of ARM was to the measurement of water vapor, which is covered in Turner et al. (2016b, chapter 13).

[9] The series of assessment reports are available at https://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml. In the IPCC First Assessment Report, McBean and McCarthy (1990, p. 319) make the statement that ''further modelling and observational research will nevertheless be necessary to achieve accurate representation in climate models of the role of clouds and radiation.'' This call for better representation of clouds continues in the Third Assessment Report, where it was stated that ''the role of clouds in the climate system continues to challenge the modelling of climate'' (Moore et al. 2001, p. 775).

Penn State University, who had been developing a draft plan on how to advance the study of cloud properties using millimeter-wavelength cloud radar, provided extensive input during this peer review that greatly augmented the nascent ARM cloud observing strategy.

On a snowy December day, when the government was closed because of weather, during a discussion involving Robert Corell of the National Science Foundation (NSF); Michael Hall and Lester Machta of NOAA; Robert Schiffer of NASA; Richard Anthes, then president of the University Corporation for Atmospheric Research (UCAR), representing the CES; and the DOE team led by Ari Patrinos, the project was approved to proceed. The consequence of this was dramatic for the program, because funds had already been appropriated for a DOE effort as part of the USGCRP and $9 million were immediately available for use a few weeks later on 1 January 1990.

3. A systems approach and the first Program Plan

One stipulation imposed by the CES was that a revised Program Plan be prepared that incorporated the reviewers' comments and the DOE responses to those comments. To this end, work began in early January 1990 with a systems design session lasting 3 days that set the top-level organization for the project. The process that Gerry Stokes selected was a highly disciplined enterprise modeling approach developed by the WISDM Corporation of Issaquah, Washington, based on previous experience with the company.[10] The robust system engineering approach at the core of the WISDM process allowed the project team to use the high-level design, developed in the first 3-day meeting, as the basis for more detailed designs of individual components of the project. Over the course of the first 2 years of the project, about a dozen more detailed, but similarly structured, facilitated-planning sessions were held. These sessions resulted in what could be termed the ARM Enterprise Model—a self-consistent and detailed operational description of the entire ARM project.[11] Key concepts that persist today in the project were defined at those meetings.

The ARM Enterprise Model included the basic elements of site selection, operations, instrumentation selection, and the data system. These elements were then described in the revised Program Plan DOE/ER-0441 [the executive summary is in ARM (2016a, appendix A)], which was released in February 1990.[12] Key features of the final Program Plan were the description of the basic experimental approach, the rationale for multiple sites, the motivation for 24/7 operation, the inclusion of an instrument development program, and the role of the Science Team. These elements are described in great detail in other chapters of this monograph. In the balance of this chapter, the top-level ideas that shaped the launch of the ARM Program and their motivation will be described.

The success of the intensive planning sessions that created the ARM Enterprise Model and the initial launch of the ARM Program was a product of the ability of the DOE National Laboratories to act as a team. The DOE atmospheric sciences program had promoted the laboratories working together on large field programs for many years, and it was therefore natural that individual laboratories took responsibility for major components of the ARM system. Under the overall leadership of Gerry Stokes at PNNL (as the ARM Program's first Chief Scientist) and Mike Riches of the DOE Office of Health and Environmental Research, laboratory leads were named for the various elements of the program. Argonne National Laboratory and the late Marv Wesley were in charge of instrumentation, Lawrence Livermore National Laboratory and Marv Dickerson assumed responsibility for atmospheric modeling, Los Alamos National Laboratory and Sumner Barr assumed responsibility for Operations, and Brookhaven National Laboratory (BNL) and Steve Schwartz led the site selection process. Wesley, Dickerson, and Barr were senior managers in the atmospheric science programs at their respective laboratories, each with more than 20 years of experience in the atmospheric sciences, and Schwartz was and is a leading atmospheric chemist at BNL. The data management and particularly the data archive were the responsibility of Oak Ridge National Laboratory and Paul Kanciruk of the Carbon Dioxide Information and Analysis Center (CDIAC). As time evolved, operations and data management were subdivided and again individual laboratories were given responsibility for key components of the associated systems. The history of collaboration among the DOE laboratories in these

---

[10] The current approach of the WISDM Corporation is described on their website (http://www.wisdm.com). The process used by ARM to develop the requirements for the ARM Enterprise Model is described in this material.

[11] Within the project, the term "ARM Enterprise Model" was rarely used—the team more frequently used the terms "WISDM process" and "WISDM model." The design sessions were very demanding and created a deep and common understanding of what the goals were of the program and the methods that would be used to achieve them.

[12] The entire Program Plan is available at https://www.arm.gov/publications/doe-er-0441.pdf.

areas and the flexibility of funding granted by the DOE also allowed the program leadership to draw easily on highly qualified individuals from all of the DOE laboratories in executing the detailed plans for the broad areas of the program. This was particularly true in instrumentation and operations.

An important property of the ARM Enterprise Model was that it was strictly hierarchical. The design that was generated in 3 days in January 1990 was a very careful and, in retrospect, surprisingly complete description of the relationship among the major elements of the program and their relationship to the outside community with which the ARM Program interacted. As a result, when groups met to provide further design for site operations, the relationship to the data system, the instrument selection process, and the relationship with the Science Team were already defined. The definition of these relationships not only included specific requirements but also general principles that guided the path forward, such as 24/7 operations and the overriding principle that ARM was being built to serve the Science Team, not to generate data that the operations staff thought might be useful.

From the perspective of the leadership of the program, this design allowed the program to maintain discipline as its implementation went forward on many parallel paths, the goal of which was to get ARM in the field as quickly and as productively as possible. In the first year of the program, two important additions to the management team were made that were key to this aggressive schedule for deployment: Ted Cress became the technical director of the program and Peter Lunn was named the ARM program manager at DOE. Cress, a meteorologist, had just retired from the Air Force, where he had been a member of CES representing the Department of Defense (DOD), and Lunn was a senior program manager who came from the Defense Nuclear Agency. These two brought critical experience to the management of the program and were very much responsible for its early success.

4. The surrogate science team and development of “experiments”

As noted above, the ARM Program was designed to serve a set of investigators from the broader scientific community, competitively selected, to advance the representation of clouds and radiation in climate models—this set of investigators was the ARM Science Team. During the early development of ARM, this team did not yet exist. The scientific breadth needed did not exist within the DOE laboratories, and thus another approach was needed.

The formal solicitation for Science Team proposals began almost immediately after the program was funded and continued through the summer of 1990. In the interim, the nature of the design of the program required that there be input from the scientific community. This input was required ahead of the selection process that would create the more permanent Science Team structure. To this end, a series of meetings were convened to further define the broad scientific approach to the project. The individuals invited were drawn from the broader climate research community, many of whom were members of the peer review panel for the original Program Plan, and others who were long-standing investigators in the DOE climate research community. These individuals were invited to be part of what was termed the surrogate Science Team. One of the more pressing matters for these early Science Team meetings was gaining further clarity on what kind of measurements the scientific community would need, what instruments they saw as providing the data, and how they would use the data. Among the most important issues continued to be what experimental approach would be taken to address the cloud formation problem. The revised Program Plan of February 1990 (ARM 2016a, appendix A) added material on this topic but still had an incomplete view of how ARM would approach this problem.

The meetings were structured around an idea that grew out of the ARM Enterprise Model design sessions—that of an “experiment.” For ARM, an experiment was framed with a hypothesis, which was a particular calculation performed in a climate or radiative transfer model. In the Program Plan, this approach was described as the Cloud and Radiation Testbed (CART). The groups were asked what information was required as input to do the calculation—observed properties of the atmosphere as opposed to model-derived quantities—and what observations were necessary to confirm the validity of the calculation. The prototype for this approach was termed the instantaneous radiative flux (IRF) experiment, for which the results and conclusions of ICRCCM and the design of SPECTRE laid the intellectual foundation. Additional information on the IRF and its radiative closure experiment is provided in Turner et al. (2016b, chapter 13) and Mlawer and Turner (2016, chapter 14).

The surrogate Science Team meetings led to the definition of a second experiment, the single column model (SCM). This approach, advocated by Dave Randall of Colorado State University and Richard Somerville of the Scripps Institution of Oceanography, became the basis for addressing the cloud formation problem. In the SCM, one would not only specify the state of the atmosphere as a function of altitude averaged over a climate grid model scale volume but also define the fluxes at the boundaries of the cells of quantities such as water vapor and other atmospheric quantities. This changed the design of the basic ARM site as originally envisaged in the Program Plan. Most specifically, it led to the need for boundary sites that would facilitate the measurement and estimation of the advective tendencies at the edges of what was shaping up to be a fully instrumented GCM grid cell. Additional information on the SCM experiment and the development of the concept is provided in Zhang et al. (2016, chapter 24).

These two experiments drove much of the early work in ARM. They set the scale of the first site, the southern Great Plains (SGP) site in north-central Oklahoma that covered roughly 150 000 km^2, and led to both the choices of instrumentation and their siting—leading to the design of the central facility, boundary facilities, and extended facilities described in Cress and Sisterson (2015, chapter 5) and Sisterson et al. (2016, chapter 6) of this monograph. The organization of these early meetings also helped shape the approach of convening working groups within the Science Team after it was selected. The first four working groups of the program would eventually solidify into the IRF, SCM, aerosol properties (McComiskey and Ferrare 2016, chapter 21), and cloud properties working groups, the last of which focused on both radar observations (Kollias et al. 2016, chapter 17) and retrievals (Shupe et al. 2016, chapter 19).

An important historical note is that during this period of time, the early 1990s, an unfortunate event took place that initially was seen as a setback, but eventually led to some very important and innovative work. In February 1990, the final scanner of the Earth Radiation Budget Experiment (ERBE) failed. This satellite had been important to experiments like the Feedback Analysis of GCMs and Intercomparison with Observations (FANGIO) described in Ellingson et al. (2016, chapter 1). ERBE had been seen as the tool to be used to measure the top of the atmosphere radiative fluxes, both downward and upwelling, for the ARM scientists. Its loss sparked the thinking that eventually led to the ARM Unmanned Aerial Vehicle (ARM-UAV) Program (Schmid et al. 2016, chapter 10).

5. Site selection process and outcomes: Where would ARM be sited?

The ARM Program Plan envisaged several fixed sites in well-chosen, climatologically significant areas. It spoke broadly about the challenges of different kinds of sites, noting, for example, the significant problems that would face an ocean site. The Program Plan was silent on what particular sites would be occupied, but it laid out some broad ideas on selection criteria. It also suggested that there should be a ‘‘mobile’’ site that could be deployed in areas of particular interest for shorter periods of time.

In the spring of 1990, the WISDM system engineering process was used to design a site selection procedure that became far more specific about what characteristics the sites should have. Principles for identifying broad regions of interest were first delineated, invoking important ideas such as identifying locations that would provide a range of physical conditions that would ‘‘stress’’ models, where the logistics were not prohibitive, and finally in areas where cooperation was possible with other complementary programs. This process and approach is documented in DOE (1991). An important feature of the process outlined in this report was that once a site was selected, it affected the evaluation criteria for the subsequent sites. The philosophy was that ARM would be a collection of sites that provided the diversity of physical conditions and therefore cloud properties that would be used to stress the models in different climatic regimes.

The site selection process, which is detailed in Cress and Sisterson (2016, chapter 5), identified five locales of interest. In order of priority, the locales were the U.S. SGP, the tropical western Pacific (TWP), the eastern North Atlantic or eastern North Pacific, the North Slope of Alaska (NSA), and the Gulf Stream. Several other sites were recommended for short-term or campaign occupancy: central Australia or the Sonoran Desert; the northwest United States or southwest Canadian coast; the Amazon or Congo basin; and the Beaufort, Bering, or Greenland Seas.

Once the locales were identified, the process of site selection within each of the locales began; these details are provided by Sisterson et al. (2016, chapter 6), Long et al. (2016, chapter 7), and Verlinde et al. (2016, chapter 8). Concurrently, the design of the instrumentation and data systems (McCord and Voyles 2016, chapter 11) was proceeding at a rapid rate.

6. The Instrument Development Program

With the help of the results of the surrogate Science Team meetings, a vision for the nature of the instrumentation needs and performance requirements evolved beyond the list of instruments found in the ARM Program Plan. It became clear that, if ARM were going to meet its observational goals, a significant evolution was needed in instrumentation. In this context, the importance of an Instrument Development Program

(IDP) became increasingly obvious. The IDP was described briefly in the Program Plan as a long-term investment program. However, the need for a 24/7 operational paradigm highlighted the fact that many existing instruments could meet the measurements needs, but very few of them could operate on the largely unattended basis required. The history of using the campaign mode of research for atmospheric science had allowed many fine instruments to be developed; however, they were not ready for ARM-style operational deployment. As a result the IDP, under the leadership of Jeff Griffin (a leader in instrumentation development from PNNL), instrument developers were given the means and motivation to focus on making the instruments ready for facility deployment. Perhaps the most successful IDP projects, which were critical to the advancement of ARM's programmatic science, were the atmospheric emitted radiance interferometer (AERI; Turner et al. 2016b, chapter 13), the millimeter wavelength cloud radar (MMCR; Kollias et al. 2016, chapter 17), and the Raman lidar (Turner et al. 2016a, chapter 18).

Given the community's experience in campaign modes of operation, the transformation was not always an easy one. In fact, it was uncharted ground for the DOE team that led the process as well. They too were used to the campaign mode of operation. The key differences were several. First, in campaign mode, the individuals responsible for an instrument were often the developer, who could diagnose problems and issues as well as fix them quickly and sometimes easily. Someone tended the instruments practically all the time. Data were collected and calibrated by the team and many times thoroughly massaged after the completion of the campaign. Generally, the data would be delivered to the balance of the campaign participants weeks or months later after the campaign ended.

At an ARM facility, operations staff would be tending, repairing, and calibrating the instruments. The data would be delivered as much as possible in near–real time to the data system. There would be no respite, such as the end of the campaign, to go through the data.

Interestingly, early on it became clear that many of the more mature instruments, capable of independent operation, were not routinely used in that fashion. More specifically, the exigencies of 24/7 operation for periods beyond a few weeks seemed to be an issue. The instrument team developed a concept of and approach for the management of instruments that not only brought more mature instruments online quickly but also facilitated the movement of instruments from the IDP to routine operations. By assigning mentors for all of the instruments, the instrument team had an individual responsible for both shepherding each instrument through field deployment and to ensure the data coming from them met the quality standards of ARM. Ackerman et al. (2016, chapter 3) describes how these roles evolved as the program matured. More details on the role of the instrument mentors are provided in Cress and Sisterson (2016, chapter 5) and their impact on data quality in Peppler et al. (2016, chapter 12).

While the core data collection strategy for the ARM Program called for continuous measurements of relevant data, it was clear from the outset that some critical measurements could not be made continuously. The most important of these were direct sampling measurements such as those made from aircraft, or periods where a significantly larger number of radiosondes needed to be launched. The recognition of this need evolved into what were called intensive observational periods (IOPs). Initially, IOPs were seen as regularly scheduled events where aircraft, for example, could be brought in to provide critical measurements. However, the concept evolved rapidly to include periods of time where, for example, instruments that were part of the IDP could be brought in for testing. The success of the IOPs became so critical to the ARM programmatic goals that they became part of the standard ARM budget and the debate was not about whether IOPs would happen, but rather what could be done to optimize the science that came from them. Probably the most important early IOPs were early cloud remote sensing IOPs where millimeter-wavelength cloud radars were evaluated (Kollias et al. 2016, chapter 17), the water vapor IOPs (Turner et al. 2016b, chapter 13), and the first use of unmanned aerospace vehicles (UAVs) for scientific observations (Schmid et al. 2016, chapter 10). Ackerman et al. (2016, chapter 3) describes how the IOP proposal, planning, and execution evolved in time and how these IOPs became part of ARM's aggressive interagency collaboration mechanism.

7. Data, data, data

One of the mantras of the early ARM Program was that it is easier to recover from a bad analysis than from bad data. The focus therefore became one of collecting data of known and reasonable quality and the preservation of data in readily usable and retrievable standard formats. This mandated that all raw instrument data, and the associated metadata for the observations, were saved so that reprocessing (if needed) could be performed. Next was the requirement to ensure the productivity of the Science Team. Rather than designing a generic system for collection and retrieval of data from which the principal investigator (PI) would do further data reduction and analysis prior to its use in experiments that combined data from other sources, ARM would deliver all the data needed by a PI directly to the PI. Data transfer was particularly challenging in the early days of the program, when the Internet was still in its infancy. Finally, as described in Ackerman et al. (2016, chapter 3), there appeared over time a focus on the creation of "value-added data products" by ARM. An example was the creation of a merged water vapor profile that included many sources of data. These consensus data products were and are viewed as critical to meeting the goals of ARM. Allowing the PIs to develop their own water vapor or temperature profile products from the varied in situ and remote sensors, for example, defeated the concepts and purpose of the ARM approach. Its goal was rather to give the best estimation of physical conditions and test the model predictions against real observations. It is the comparison of the results of multiple models driven by the same data compared with the same observations that is critical. Differences deriving from differences in the handling or processing of observational data were not relevant.

All of the above considerations put a tremendous premium on two things—getting the data needed to the Science Team and making sure that it was of the highest quality. Ackerman et al. (2016, chapter 3) has a description of how this evolved, but in the early stages of the program, the relationship between the ARM infrastructure and the Science Team was managed by what was termed the Experiment Center. This team, based at PNNL, supported the coordination of data for the PIs from the ARM sites and carried out some data reductions to ensure there were common products for derived quantities such as temperature and water vapor profiles. This coordination applied not only to the data collected by the ARM Program, but other datasets as well, such as satellite and National Weather Service data. The acquisition of the related data from other sources was managed as ancillary data but was provided as part of the service to the Science Team by a team based at BNL. The eventual value of this approach was that testing different models was done using common input data and common comparison data, putting the focus on the physics in the models where it belonged.

The involvement of the Science Team in ARM infrastructure activities led to what could be considered the first real demonstration of the power of this approach in the development of the consensus water vapor profile (Turner et al. 2016b, chapter 13), the importance of which is noted above. At the recommendation of the instrument mentors and the working group focused on the instantaneous radiative flux experiment (Mlawer and Turner 2016, chapter 14), several IOPs were dedicated to the development and refinement of the methods for both collecting and processing the several methods used for measuring both the integrated water vapor column and the water vapor profile.

Finally, the focus on both value-added products and data quality meant that the continual review of data, the consequent improvement of the products, and the direct connection with the PIs on the Science Team meant that the ARM Data Archive not only was regularly reprocessing data but had to keep track of who had received previous data versions. This placed stringent requirements on the ARM Data Archive, which impacted how it was developed over time (McCord and Voyles 2016, chapter 11).

8. Science and reviews

The ARM Science Team came together in the fall of 1990 with the selection of the first investigators in the program. These investigators became entrained in the new approach that was being developed in the program. A key part of the membership of the initial Science Team included several reviewers from the original Program Plan and participants in the surrogate Science Team. These individuals were critical to the early formation of the Science Team. The Science Team met on an annual basis, and the proceedings of those meetings, beginning with the Second ARM Science Team Meeting, are available online (http://www.arm.gov/publications/proceedings). The initial meeting, held in Las Vegas, was largely an informational meeting for the newly selected PIs and no proceedings were produced. These proceedings provide an excellent way to view the year-by-year progress in the program, covering not only the science but the instrument development program and the development of the ARM sites.

The Science Team was organized in a variety of ways. Initially, there was a focus on the IRF and SCM experiments, with working groups of laboratory staff and Science Team members meeting to review instrumentation and data processing necessary to support the work of the Science Team (Mather et al. 2016, chapter 4). Other working groups formed to support the instrument development program, aerosol measurements, cloud properties, and mesoscale modeling, the latter seen as the analog for cloud formation to the high-resolution radiative transfer models for radiative transfer.

Another focus for the Science Team was around the individual sites and the site scientists: Pete Lamb of the University of Oklahoma for the SGP, Tom Ackerman of Pennsylvania State University in the TWP, and Knut Stamnes of the University of Alaska for the NSA. The site scientists were selected through a limited competitive process managed by the DOE. The site scientists were expected to provide scientific input into the operations of the site, oversee the data quality program (Peppler et al. 2016, chapter 12) for the site, provide an educational outreach effort, and sustain their own research program at the sites. A site manager from the DOE laboratories supported each of these scientists: Doug Sisterson of Argonne National Laboratory (SGP), Bill Clements of Los Alamos National Laboratory (TWP), and Bernie Zak of Sandia National Laboratories (NSA). While the groups of interested scientists for these sites were not as large as the other working groups, these small groups of scientists were important as instrumentation was selected, unique data quality issues were identified and worked on, and the sites became operational.

A few years into the program a subset of the Science Team, which consisted largely of the leaders of the working groups, the site scientists, and the ARM chief scientist, was created and identified as the Science Team Executive Committee (STEC). As the program evolved beyond the initial focus of occupying sites and operational details, the STEC took an active role in selecting targets for IOPs and setting overall scientific priorities. The first ARM Science Plan[13] was prepared under their guidance and its publication in 1996 marked the end of the initial build out of ARM and a transition to its more scientific operation. The STEC met regularly with ARM program managers and DOE laboratory staff to continue to provide scientific guidance of ARM as the program matured.

A final, but key, element of the formative years was a review process organized by DOE using JASON, an independent scientific advisory group, which was frequently used by DOD and DOE to review large multidisciplinary programs and ideas. Initially organized by Gordon MacDonald of JASON and the MITRE Corporation, these reviews proved incredibly valuable for the senior leadership of the program as ARM moved toward and through its initial deployment. An example of the value of the JASON reviews came as the ARM Program struggled to deal with the loss of the ERBE scanner noted earlier. Working groups within ARM proposed a variety of ideas, including having ARM launch its own satellite to the use of UAVs to make the measurement. A JASON team reviewed the various proposals, and eventually ARM began a new program to use UAVs for the first time in atmospheric research.

9. Challenges of a rapid deployment, and 43 April 1992

As Field Marshall Helmuth Karl Bernhard Graf von Moltke once noted, ‘‘no plan survives first contact with the enemy.’’ ARM was and is a large complex operation. The von Moltke quote was used by Stokes as the program was pushed to rapid deployment. The view was that plans would be shaped by experience, and planning had its limits.

As the instrument selection and data system concepts came together, the site selection and operational system development proceeded in parallel. Relatively early in the process, laboratories and individuals were identified to manage site operations. While the surrogate Science Team helped ARM organize its approach to measurements, instrument selection, and data management, there are other sets of activities developed in the early days of ARM that have continued to the present. ARM as conceived had laid out an aggressively novel approach with many new methods and systems. The fear of being paralyzed by the need for the perfect plan led to an early decision to set the start of deployment for April 1992—the thought being that we really would not know what we were doing until we actually had something in the field. Therefore, in advance of the first deployment of ARM, the program benefitted from other programs where experience could be gained by the ARM team in operating in different climates and countries. These included a NASA program in Coffeyville, Kansas (Ellingson et al. 2016, chapter 1); a deployment to Kavieng in the TWP during the Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE; Long et al. 2016, chapter 7); and deployments on the ice during the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment (Verlinde et al. 2016, chapter 8). In general, ARM provided value in the form of basic radiation measurements for these campaigns, but through them it gained valuable experience.

The activities and concepts above set the stage for the first deployment, with instrumentation borrowed from NCAR, at the first ARM site near Lamont, Oklahoma. It was a modest step, which took place, somewhat facetiously, on 43 April 1992—not quite meeting the goal of an April start. But that target of a rapid deployment less than 30 months after the approval of the program drove the team to extraordinary levels of innovation and commitment. While the details of individual plans and ideas fell by the wayside—in keeping with von Moltke's assertion—the initial Program Plan, forged largely in the fall of 1989, has had surprising durability and consequence, but the experience in the field shaped and molded the program as it went forward. The following chapters outline the details of those efforts and results.

Shortly after the opening of the SGP site, it was dedicated to the memory of, and named after, Fred Luther,

---

[13] Available from https://www.arm.gov/publications/programdocs/doe-er-0670t.pdf. The executive summary of this Science Plan is included in ARM (2016b, appendix B).

the original head of ICRCCM, whose leadership of the laboratory community and partnership with university and international collaborators led to ARM.

10. Epilogue

The research in ARM continued throughout the writing of this manuscript, and one recent result is of particular note. Part of the original ARM proposal by DOE was to actually measure the change in radiative forcing by CO_2. This has been done recently by Feldman et al. (2015). Their result, a 0.2 $W\,m^{-2}$ $decade^{-1}$ increase in forcing at the surface measured both at the SGP site and the NSA site, involved the use of one of the most successful instruments to come out of the instrument development program, the AERI and the detailed line-by-line radiative transfer models validated through ARM. This result is a testimony not only to the work of the authors of that paper, but also to the tremendous dedication of more than a generation of scientists who created the instrumentation and the high quality that made the work possible.

REFERENCES

ARM, 2016a: Appendix B: Executive summary: Science Plan for the Atmospheric Radiation Measurement Program (ARM). *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr.*, No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0035.1.

——, 2016b: Appendix C: Executive summary: Atmospheric Radiation Measurement Program Science Plan: Current status and future directions of the ARM Science Program. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr.*, No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0034.1.

Ackerman, T. P., T. S. Cress, W. Ferrell, J. H. Mather, and D. D. Turner, 2016: The programmatic maturation of the ARM Program. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr.*, No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0054.1.

Cress, T. S., and D. Sisterson, 2016: Deploying the ARM sites and supporting infrastructure. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr.*, No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0049.1.

DOE, 1991: Identification, recommendation and justification of potential locales for ARM sites. Rep. DOE-ER-0494T, U.S. Department of Energy, 14 pp. [Available online at https://www.arm.gov/publications/programdocs/doe-er-0494t.pdf.]

Ellingson, R. G., and Y. Fouquart, 1991: The intercomparison of radiation codes in climate models: An overview. *J. Geophys. Res.*, **96**, 8925–8927, doi:10.1029/90JD01618.

——, and W. J. Wiscombe, 1996: The Spectral Radiance Experiment (SPECTRE): Project description and sample results. *Bull. Amer. Meteor. Soc.*, **77**, 1967–1985, doi:10.1175/1520-0477(1996)077<1967:TSREPD>2.0.CO;2.

——, R. D. Cess, and G. L. Potter, 2016: The Atmospheric Radiation Measurement Program: Prelude. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr.*, No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0029.1.

Feldman, D. R., W. D. Collins, P. J. Gero, M. S. Torn, E. J. Mlawer, and T. R. Shippert, 2015: Observational determination of surface radiative forcing by CO_2 from 2000 to 2010. *Nature*, **519**, 339–343, doi:10.1038/nature14240.

Kollias, P., and Coauthors, 2016: Development and applications of ARM millimeter-wavelength cloud radars. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr.*, No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0037.1.

Long, C. N., J. H. Mather, and T. P. Ackerman, 2016: The ARM Tropical Western Pacific (TWP) sites. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr.*, No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0024.1.

Mather, J. H., D. D. Turner, and T. P. Ackerman, 2016: Scientific maturation of the ARM Program. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr.*, No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0053.1.

McBean, G., and J. McCarthy, 1990: Narrowing the uncertainties: A scientific action plan for improved prediction of global climate change. *Climate Change: The IPCC Scientific Assessment*, J. T. Houghton, G. J. Jenkins, and J. J. Ephraums, Eds., Cambridge University Press, 311–328.

McComiskey, A., and R. A. Ferrare, 2016: Aerosol physical and optical properties and processes in the ARM Program. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr.*, No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0028.1.

McCord, R., and J. W. Voyles, 2016: The ARM data system and archive. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr.*, No. 57, Amer. Meteor. Soc., doi: 10.1175/AMSMONOGRAPHS-D-15-0043.1.

Mlawer, E. J., and D. D. Turner, 2016: Spectral radiation measurements and analysis in the ARM Program. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr.*, No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0027.1.

Moore, B., III, W. L. Gates, L. J. Mata, A. Underdal, R. J. Stouffer, B. Bolin, and A. Ramirez Rojas, 2001: Advancing our understanding. *Climate Change: The Scientific Basis*, J. T. Houghton et al., Eds., Cambridge University Press, 769–785.

Peppler, R., K. Kehoe, J. Monroe, A. Theisen, and S. Moore, 2016: The ARM data quality program. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr.*, No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0039.1.

Schmid, B., R. G. Ellingson, and G. McFarquhar, 2016: ARM aircraft measurements. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr.*, No. 57, Amer. Meteor. Soc., doi: 10.1175/AMSMONOGRAPHS-D-15-0042.1.

Shupe, M. D., J. M. Comstock, D. D. Turner, and G. G. Mace, 2016: Cloud property retrievals in the ARM Program. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr.*, No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0030.1.

Sisterson, D., R. Peppler, T. S. Cress, P. Lamb, and D. D. Turner, 2016: The ARM Southern Great Plains

(SGP) site. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr*., No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-16-0004.1.

Turner, D. D., J. E. M. Goldsmith, and R. A. Ferrare, 2016a: Development and applications of the ARM Raman lidar. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr*., No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0026.1.

——, E. J. Mlawer, and H. E. Revercomb, 2016b: Water vapor observations in the ARM Program. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr*., No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0025.1.

Verlinde, H., B. Zak, M. D. Shupe, M. Ivey, and K. Stamnes, 2016: The ARM North Slope of Alaska (NSA) sites. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr*., No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0023.1.

Zhang, M., R. C. J. Somerville, and S. Xie, 2016: The SCM concept and creation of ARM forcing datasets. *The Atmospheric Radiation Measurement (ARM) Program: The First 20 Years, Meteor. Monogr*., No. 57, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0040.1.