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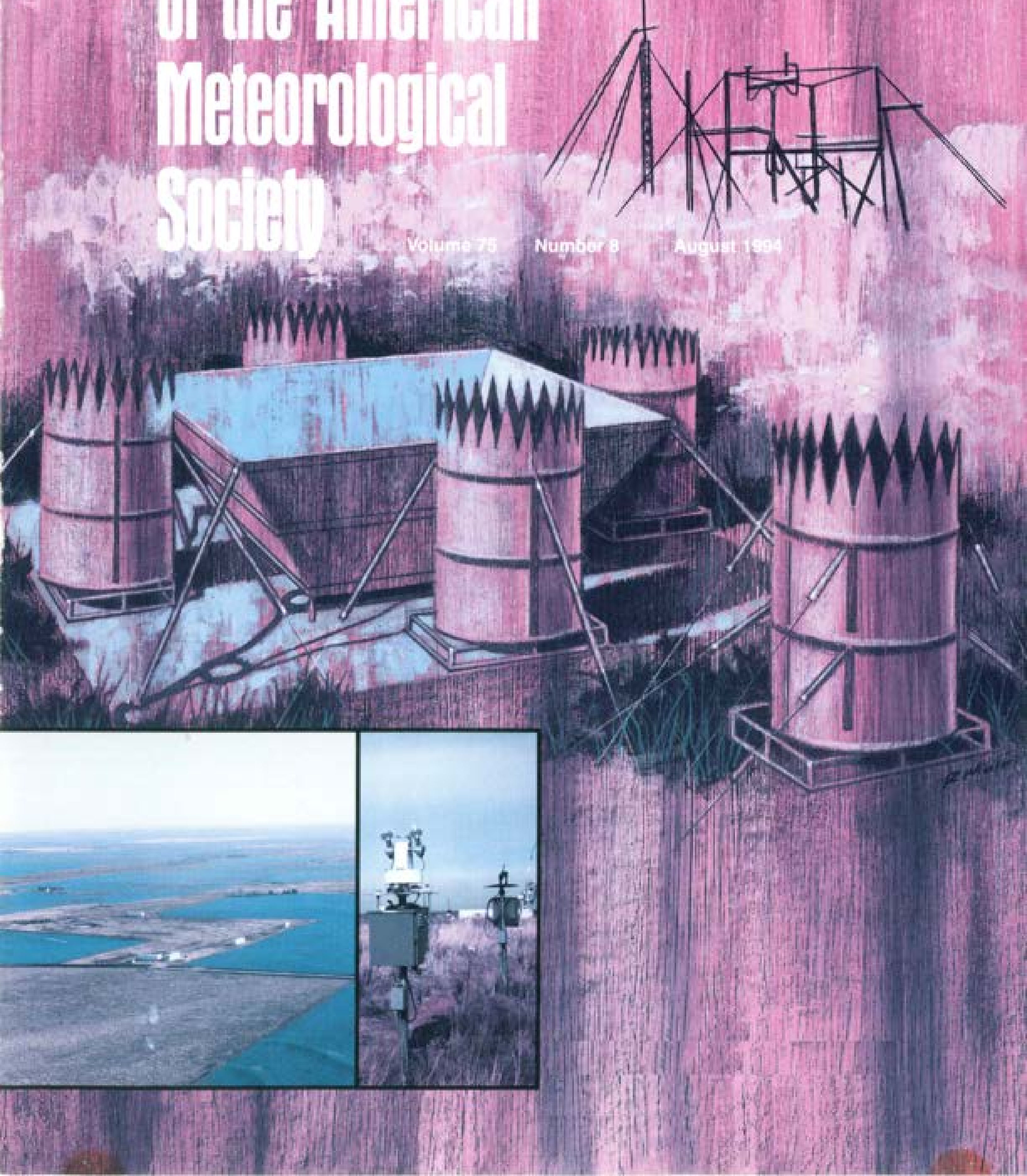

The Atmospheric Radiation Measurement (ARM) Program: Programmatic Background and Design of the Cloud and Radiation Test Bed

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Abstract

The Atmospheric Radiation Measurement (ARM) Program, supported by the U.S. Department of Energy, is a major new program of atmospheric measurement and modeling. The program is intended to improve the understanding of processes that affect atmospheric radiation and the description of these processes in climate models. An accurate description of atmospheric radiation and its interaction with clouds and cloud processes is necessary to improve the performance of and confidence in models used to study and predict climate change. The ARM Program will employ five (this paper was prepared prior to a decision to limit the number of primary measurement sites to three) highly instrumented primary measurement sites for up to 10 years at land and ocean locations, from the Tropics to the Arctic, and will conduct observations for shorter periods at additional sites and in specialized campaigns. Quantities to be measured at these sites include longwave and shortwave radiation, the spatial and temporal distribution of clouds, water vapor, temperature, and other radiation-influencing quantities. There will be further observations of meteorological variables that influence these quantities, including wind velocity, precipitation rate, surface moisture, temperature, and fluxes of sensible and latent heat. These data will be used for the prospective testing of models of varying complexity, ranging from detailed process models to the highly parameterized description of these processes for use in general circulation models of the earth's atmosphere. This article reviews the scientific background of the ARM Program, describes the design of the program, and presents its status and plans.

1. Introduction

The Atmospheric Radiation Measurement (ARM) Program is a major program of atmospheric measurement and modeling intended to improve understanding of the processes and properties that affect atmospheric radiation, with a particular focus on the influence of clouds and the role of cloud radiative feedback. The United States Global Change Research Program (USGCRP) (CEES 1990) identified the scientific issues surrounding climate and hydrological systems as its highest priority concern. Among those issues, the USGCRP also identified the role of clouds as the top priority research area. ARM, a major activity within the USGCRP, is designed to meet these research needs and is an outgrowth and direct continuation of the Department of Energy's (DOE's) decade-long effort to improve general circulation models (GCMs) and other climate models, providing reliable simulations of regional and long-term climate change in response to increasing greenhouse gases.

Planning for the ARM Program began in the fall of 1989; a description of the initial program is presented in the ARM Program Plan (U.S. Department of Energy 1990). Since its publication, the scientific issues have been further delineated, and there has been substantial progress in designing and implementing the facilities necessary to conduct the measurements required to meet the scientific objectives of the program. This paper outlines the scientific background for the ARM Program, the objectives of the program, how the design of the field facilities respond to these objectives, and the current status of the program.

2. Background

A variety of models have been developed to simulate the physical processes that occur in the earth's atmosphere as part of attempts to understand climate and possible climate changes due to human activity. One such class of models, GCMs (U.S. Department of Energy 1985; Simmons and Bengtsson 1988; Cubasch and Cess 1990; Randall 1992), may be viewed as part of a hierarchy of models and modeling systems, ranging from detailed process models to multireservoir climate models (e.g., Hoffert et al. 1980) to GCMs. This hierarchy is characterized by a spectrum of complexity of the description of the physical pro-

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cesses being modeled and by a wide range in spatial, temporal, and wavelength resolution. It attempts to consolidate large amounts of knowledge about many atmospheric processes to gain insight into the interaction among these processes on regional to global scales and ultimately into the processes that are responsible for controlling the earth's climate.

An important feature of GCMs is how they capture the interaction between the processes that control the vertical transport of energy and water and the large-scale circulation of the atmosphere. It is convenient to think about the treatment of the vertical transport processes in terms of grid cells. In this view, the properties characterizing a region of space (a volume or a surface area) are represented in the model by values ascribed to a single point representing that grid cell. These properties are the various scalar and vector properties assigned to the cells—for example, temperature, water mixing ratio, wind velocity, or pressure. Because a model can conveniently handle only a limited number of grid cells, a single grid cell in the model must represent a considerable volume or area of the planet. Many meteorological phenomena important to weather and climate, as well as associated radiative processes, occur on scales that are too small to be resolved by the resulting grid mesh in current climate models.

There is concern over the ability of models to accurately represent phenomena that exhibit substantial variability at scales finer than are resolved by the grid spacing of the model. Therefore, a major challenge to GCMs and related models is to capture the essence of these subgrid phenomena in the model with reasonable computational simplicity and without introducing systematic errors that manifest themselves in unrealistic global-scale phenomena. The means of achieving this goal is through a process that is often referred to as "parameterization" (Randall 1989, 1992).

Understanding the best approach to parameterization and the accuracy that can be expected for the various approaches is a major challenge of climate modeling. These approaches may be viewed as falling along a continuum. At one end of the continuum would be a purely empirical approach: observing the phenomena to be parameterized, empirically developing parameterizations, and testing these parameterizations by comparing model output with observations. At the other end of the continuum would be a theoretically based approach: acquiring an understanding of the physics of the controlling processes, developing parameterizations of that physics, and again testing parameterizations by comparing model output with observations.

There are problems with both types of approaches. The completely empirical approach is confounded by the large number of types of situations for which parameterizations must be developed. Also, the parameterizations may inadvertently incorporate features of the current climate into models of future climates. On the other hand, the completely theoretical approach may be limited by the current state of theoretical understanding or may result in descriptions of such complexity that it will be hard to incorporate representations of the processes into large-scale climate models. An important feature of many recent attempts to parameterize atmospheric processes in climate prediction models is the emphasis on the use of physical models rather than empirical data as the basis for the parameterization.

Currently, two particularly important basic atmospheric processes requiring improved description in climate models are 1) the transfer of radiation within the atmosphere including the spectral dependence of this radiation transfer, and 2) the processes responsible for cloud formation, maintenance and dissipation, and the prediction of the associated cloud properties, particularly their radiative properties. Accurate description of cloud processes in climate models is critical because of the large influence of clouds on the earth radiation budget (Ramanathan et al. 1989) and the possibility that cloud properties may change as climate changes (Lindzen 1990). Both cloud and radiative processes present particularly significant challenges in attempting to parameterize them on the subgrid scale.

Liquid water clouds exhibit negligible supersaturation, and clouds form when air containing water vapor is cooled below its dewpoint. Therefore, modeling the presence of clouds as a function of location is straightforward in a model whose grid-cell dimensions are small relative to the dimensions of the clouds (e.g., Clark 1979; Kogan 1991). The problem arises in translating this understanding to the description of cloud formation in a model whose grid-cell dimensions may be more than 100 km on a side and 50 hPa in the vertical, many times the dimensions of certain types of clouds.

In these models, the key issue for parameterization becomes identification of the conditions under which clouds form and the appropriate representation of the properties of the resulting clouds that are important for other aspects of the model. These aspects include the associated latent heat release, the radiative properties of the clouds, and the development of precipitation. The global climate sensitivity of a GCM to a change in radiative forcing depends heavily on the cloud parameterization scheme employed (Mitchell et al. 1989; Cess et al. 1990). The development of cloud parameterizations is further complicated because macroscopic properties such as the persistence and radiative properties of clouds, and therefore the vertical distribution of water vapor, can be influenced by microphysical properties and processes, such as drop-number density and size distribution, and precipitation development (Twomey 1977, 1991; Albrecht 1989; Baker and Charlson 1990).

Parameterization is also required to account for the wavelength dependence of radiant energy transfer. While the radiative absorption, emission, and reflection processes associated with the earth's atmosphere and surface exhibit a highly structured wavelength dependence, the computational requirements of using high spectral resolution cannot be approached in climate models, again necessitating parameterization. The Intercomparison of Radiation Codes used in Climate Models (ICRCCM) (Ellingson and Fouquart 1991) clarified the status of the parameterization of radiative process. That study showed that one can begin from a high-resolution radiative model and effectively determine a useful and consistent parameterization in the clear-sky case. However, without actual measurements against which to compare the output of the original high-resolution model, it is not possible to discern the accuracy of the parameterizations or even to decide which parameterizations are most accurate. Both the original model and the resulting parameterizations must be validated with a systematic program of observation. This is particularly true when one moves from the consideration of clear-sky radiative transfer to the cloudy-sky case. In this situation, the parameterization involves not only the physics of scattering and cloud radiative properties but a variety of geometrical considerations as well.

At the outset of the ARM Program, it was clear that a comprehensive program of modeling and observation directed at the validation of radiative transfer in clear skies, the further development of radiative transfer codes for use in the presence clouds, and more effort in predicting the presence and properties of clouds would greatly advance climate modeling.

3. ARM program objectives

The overall goal of the ARM Program is to develop and test parameterizations of important atmospheric processes, particularly cloud and radiative processes, for use in atmospheric models. A central feature of ARM is an experimental test bed for the measurement of atmospheric radiation and the properties controlling this radiation. A principal objective of this test bed is to develop a quantitative description of the spectral radiative energy balance profile under a wide range of meteorological conditions. The intent is that the measurements will be sufficiently comprehensive to allow testing of parameterizations through the direct comparison of field observations with model calculations of the radiation field and associated cloud and aerosol interactions.

The two primary ARM objectives are the following:

1) To relate observed radiative fluxes in the atmosphere, spectrally resolved and as a function of position and time, to the atmospheric temperature, composition (specifically including water vapor and clouds), and surface radiative properties.

2) To develop and test parameterizations that describe atmospheric water vapor, clouds, and the surface properties governing atmospheric radiation in terms of relevant prognostic variables, with the objective of incorporating these parameterizations into general circulation and related models.

The achievement of these objectives should lead to the improvement of the treatment of atmospheric radiation in climate models, explicitly recognizing the crucial role of clouds in influencing this radiation and the consequent need for an accurate description of the presence and properties of clouds in climate models.

4. Approach

The number of processes pertinent to the transfer of radiation in the atmosphere that must be represented in climate models is large, and any given process can in principle be represented in a variety of possible ways. The requirement for a program such as ARM is to test many candidate representations of a variety of processes and identify those that are most suitable for use in climate models. ARM will attempt to achieve this by using data to test models and parameterizations operated in a predictive mode, rather than by relying exclusively on phenomenology and empirical parameterization. Acquisition of data necessary for model development and testing will be accomplished by establishing and maintaining several sites, whose spatial extent is comparable to the size of a typical GCM grid cell, approximately 200 km on a side. At each of these sites, continuous measurements will be made, for 7–10 years, of atmospheric radiation and of the atmospheric and surface properties influencing transfer of radiation in the atmosphere. These measurements will be used to develop and test model parameterizations.

The research component of ARM, the actual development and testing of specific models and parameterizations, is the province of the ARM Science Team. The science team consists of more than 50 research groups whose efforts fall into three broad categories: 1) developing and testing parameterizations, 2) developing and testing instruments, and 3) participating as site scientists. The first group is focused on the actual development and testing of parameterizations. These investigators are involved in the full cycle of parameterization development, ranging from the basic delineation of phenomena to be parameterized, to the development of detailed theoretical models to serve as the basis for parameterizations, to the actual testing of the parameterizations themselves. Within this group, each investigator defines one or more experiments to be conducted at the ARM sites. An experiment consists of the comparison of measurements with model output. The model may be initialized with input variables specified by observations at the ARM sites and/or by data obtained from other sources—for example, the National Weather Service—and operational satellites.

The second major activity within the science team is the Instrument Development Program (IDP). Investigators within the IDP focus on the development and testing of instruments that may be suitable for future deployment to meet measurement requirements at ARM sites.

The final component of the science team consists of the site scientists, one for each ARM site. Their complete role is described in section 7c, but they also have an active research program, which may involve the activities of a large group of investigators at their home institution. Table 1 lists the members of the science team during the first 3 years of the ARM Program. A more complete description of these projects is given in U.S. Department of Energy (1993) (GCR 1993).

While the objectives of ARM are distinctly focused on modeled results, the path to these results has a strong coupling to experiment. The next major element of ARM, after the science team, is the Cloud and Radiation Test bed (CART), which consists of the measurement facilities and the process of assembling the data to meet the experimental requirements of the members of the science team. CART has been designed so that the observations will support the measurement requirements of multiple research groups with the same data streams. CART may thus be viewed as a facility for the prospective testing of models in a shared data environment. CART will consist of several observing facilities or sites. As discussed in section 7b of this paper, the need for several sites is dictated by the wide range of geographical and meteorological situations that must be accurately represented by climate models. The sites have been selected to allow the observation of a sufficiently wide range of meteorological situations, permitting models to be tested under virtually all climatically relevant conditions.

A final feature of the ARM approach is its emphasis on continuous operation of the instrumentation at the sites. This emphasis has several motivations. First, continuous operation permits continuous evaluation of the performance of parameterizations and process models, which also must continuously simulate the planetary atmosphere. This will allow the determination of whether particular parameterizations or process models exhibit systematic biases when operated over an extended period and the widest possible range of conditions. Next, from the investigator's perspective, continuously available data allows the acquisition and use of data in a facility mode, offering ready availability of data and the ability to test new hypotheses with new data. Continuous measurements also provide an opportunity to identify new technologies that might be incorporated into the observational system with relative ease. Finally, continuous operation provides the greatest likelihood of a high quality dataset, without uncertainties introduced by successive starts and shakedowns of the performance of a large suite of instruments.

5. The general measurement strategies

An important element of the design of the CART was the specification of the observations that would meet the data requirements of the science team. An analysis of the various science team projects revealed that the various approaches to using CART data could be organized into four classes, referred to as general measurement strategies (GMS): single-column model, hierarchical diagnosis, data assimilation, and instantaneous radiative flux. These four strategies capture the range of modeling problems addressed by ARM and are the basis of the design of the CART facilities. The following is a description of the four strategies

a. Single-column model

One approach to testing the key process models and parameterizations in a GCM is to extract a single vertical array of cells from the model and operate the model in what is often called single-column mode. This subset of the model retains much of the physics that must be represented in climate models and offers a convenient approach to testing parameterizations of the physics. To operate models in this mode, it is necessary to specify the initial values of the prognostic variables within the cell: temperature, water vapor, wind velocity, cloud amount, radiation field, precipitation, and soil moisture. It is also necessary to provide the boundary conditions for the column and their time evolution: wind velocity and thermodynamic variables at the lateral boundaries, surface emittance and re-

TABLE 1. Science team projects and principal investigators. This table provides a listing of the investigators within the ARM Science Team that have been selected through the peer review process over the first 3 years of the program. The site scientists and their institutions are listed in Table 2. The membership of the science team has been organized by General Measurement Strategy (section 6). Several of the listed Principal Investigators (PIs) are involved in several General Measurement Strategies, but they are listed only once.

General measurement strategies	Principal investigator	Organization
Data assimilation		
Point-area relationships for global climate modeling	J. C. Doran	Pacific Northwest Laboratory (PNL)
Remote sensing of surface fluxes important to cloud development	F. Barnes	Los Almos National Laboratory (LANL)
Area-representative estimates of surface heat flux	R. L. Coulter	Argonne National Laboratory (ANL)
Integrated cloud observation and modeling	T. P. Ackerman	Pennsylvania State University
Development of an integrated data assimilation sounding system	W. F. Dabberdt	NCAR
Test bed model and data assimilation	J. F. Louis	Atmospheric and Environmental Research, Inc.
Cloud formation		
Interfacing between a hierarchy of numerical models	C. Y. Kao/J. Leone	LANL/Lawrence Livermore National Laboratory (LLNL)
Parameterization of convective clouds, mesoscale convective systems, and convective-generated clouds	W. R. Cotton	Colorado State University (CSU)
Modeling clouds and radiation for developing parameterizations for general circulation models	O. B. Toon/ D. L. Westphal	NASA Ames Research Center
Evaluation of a new GCM-capable stochastic cloud/radiation parameterization	R. N. Bryne	Science Applications International Corporation
Development of a radiative and cloud parameterization scheme of stratocumulus and stratus clouds, which include the impact of CCN on cloud albedo	W. R. Cotton	CSU
Development of a GCM stratiform cloud parameterization	S. J. Ghan	PNL
Development and testing of parameterizations for continental and tropical ice cloud microphysical and radiative properties in GCM and mesoscale models	A. J. Heymsfield	NCAR
Development of a cloud parameterization package for the improvement of cloud simulations in climate models	C. Y. Kao	LANL
A hierarchial approach to improved cloud-radiation parameterization for climate models	J. T. Kiehl	NCAR
Testing an improved parameterization of upper-tropospheric clouds for use in climate models	D. A. Randall	CSU
Parameterization of GCM subgrid nonprecipitating cumulus and stratocumulus clouds using stochastic phenomenological models	R. B. Stull	University of Wisconsin, Madison

TABLE 1 continued. Science team projects and principal investigators.

	Principal Investigator	Organization
Cloud formation continued		
Use of cloud observations and mesoscale meteorology models to evaluate and improve cloud parameterizations	C. J. Walcek	State University of New York (SUNY) at Albany
Diagnostic modeling	R. C. J. Sommerville	Scripps Institute of Oceanography
Radiative modeling		
Spectroscopic study of water absorption in the 8–14-μm atmospheric window measurement of new line and continuum parameters and investigation of far wing phenomena	T. J. Kulp	LLNL
Radiative properties of nonuniform clouds	P. H. Daum	Brookhaven National Laboratory (BNL)
Radiative transfer model development	S. A. Clough	Atmospheric & Environmental Research Inc.
A stochastic formulation of radiative transfer in clouds	G. L. Stephens/ P. Gabriel	CSU
Validation of longwave radiation codes for climate studies and tests in general circulation models	R. G. Ellingson/F. Baer	University of Maryland
Effect of cloudiness heterogeneity on the radiative budget at the top of the atmosphere and at the surface	C. Gautier	University of California at Santa Barbara
Analysis of cloud radiative forcing and feedback in a climate GCM	A. A. Lacis	NASA Goddard Space Flight Center (GSFC)
Treatment of cloud radiative effects in general circulation models	W. C. Wang	SUNY at Albany
Theoretical cloud radiation studies	W. J. Wiscombe	NASA GSFC
Fourier transform spectrometer data analysis tools	W. L. Smith	University of Wisconsin, Madison
Radiation budgets by surface and satellite measurements	R. D. Cess	SUNY at Stony Brook
Parameterizations for integrals of radiation's effects on clouds, surfaces, and stabilities	W. G. N. Slinn	PNL
Instrument development program		
Radiometric instrumentation		
Tethered balloon sounding system for vertical radiation profiles	C. D. Whiteman	PNL
Widely deployable low-cost radiometer for the ARM extended observing stations	R. C. Kryter	Oak Ridge National Laboratory (ORNL)
Development of rotating shadowband spectral radiometers and GCM radiation code test datasets	J. Michalsky/ L. Harrison	SUNY at Albany

TABLE 1 continued. Science team projects and principal investigators.

	Principal Investigator	Organization
Radiometric instrumentation		
Development of a shortwave infrared solar spectral radiometer	D. G. Murcray	University of Denver (UD)
Development of a radiation measurement system	F. P. J. Valero	NASA ARC
High spectral resolution radiance measurements	H. E. Revercomb	University of Wisconsin, Madison
Cirrus and aerosol profilometer for radiometric measurements	J. Spinhirne	NASA GSFC
Remote sensing instrumentation		
Laser remote sensing of water vapor	M. Lapp	Sandia National Laboratory (SNL), Livermore
Development of a high-resolution LIDAR technology	E. Eloranta	University of Wisconsin, Madison
Ground-based millimeter wave cloud profiling radar systems (CPRS)	R. E. McIntosh	University of Massachusetts, Amherst
Cloud and aerosol characterization, multiple remote sensor techniques development	K. Sassen	University of Utah, Salt Lake City
Development of an integrated data assimilation/sounding system	E. R. Westwater/ K. S. Gage	NOAA Wave Propagation Laboratory (WPL)/NOAA Aeronomy Laboratory
Passive cloud dynamics measurement. A flow field registration approach	W. P. Kegelmeyer, Jr.	SNL, Livermore
Shipboard measurements of the cloud-capped marine boundary layer during FIRE/ASTEX	R. A. Kropfli	NOAA WPL
A precise passive narrow-beam filter infrared radiometer and its use with lidar	C. M. R. Platt	Commonwealth Scientific and Industrial Research Organization

flectance at the lower boundary, and the top of the atmosphere solar flux. The GCM parameterizations are then tested by comparing measured and modeled evolution of the prognostic and other variables, such as cloud amount, radiation field, precipitation, and soil moisture. Observations at the CART site serve to determine the boundary and initial conditions of the prognostic variables and track the temporal evolution of the prognostic variables predicted by the models.

b. Hierarchical diagnosis

A second approach to the development of parameterizations is to take advantage of the fact that GCMs are part of a hierarchy of models and modeling systems whose representation of atmospheric physics ranges from the highly aggregated to the highly specific. GCMs and single-column models are necessarily characterized by highly aggregated physics and by coarse spatial and temporal resolution. To understand the limitations imposed by such aggregation, and ultimately to improve the models, it is useful, if not necessary, to analyze and interpret observations using higher-resolution models. Such analyses can give particular insight into how much of the detailed physics is required in a model to capture the essential features of a particular process.

There are several possible meanings of "low resolution" in highly aggregated models. The influence of low spatial and temporal resolution can be studied using higher-resolution models over the same domain covered by the coarser grid. GCMs use low-"resolution" physics as well. The higher resolution would then involve the use of models with more comprehensive or elaborate physical descriptions. An example might be the use of a detailed cloud model that includes microphysical parameterizations to diagnose the performance of a GCM cloud model that uses only relative humidity and vertical velocity to infer the formation and persistence of clouds. The hierarchical diagnosis measurement strategy will require observations on a finer spatial grid and may also require measurement of parameters such as aerosol light scattering coefficients or cloud microphysical parameters that are treated in various detailed process models but are not treated explicitly in present GCMs.

c. Data assimilation

The third approach recognizes that observations of atmospheric properties (the outputs of individual instruments) are made at discrete locations and times and necessarily sample only limited volumes of the atmosphere. However, to test models on a variety of physical scales, it is necessary to develop methods that will allow the output of individual instruments, which measure different parameters, to be combined to infer the time-dependent three-dimensional field of meteorological variables. The requirement for these four-dimensional fields of meteorological data is particularly important for testing models of cloud formation, maintenance, and dissipation, and the effects of cloud fields on atmospheric energy fluxes. Data assimilation is a method for combining observations of different parameters using a physically based model as an interpolation vehicle. The principle of the approach is that the derived four-dimensional field must satisfy certain imposed constraints—for example, for continuity and conservation of mass, energy, and momentum. Data assimilation is expected to be an important method for establishing the boundary conditions for a single-column model and for developing average conditions over the entire ARM site to initialize the models.

Data assimilation approaches are also useful as a technique for focusing attention on a more limited set of variables than the full complement of prognostic variables. For example, one might choose to assimilate the observations of the velocity field with a mesoscale or single-column model, while allowing the water vapor and temperature fields to evolve without the influence of including observations of water or temperature in the assimilation. This allows attention to be focused on a cloud formation model while minimizing the effects of the calculation of the velocity fields by continually updating the velocity field with assimilated data derived from observation. An approach like this offers the opportunity to focus attention on particular aspects of a given process, while reducing the influence of uncertainties introduced in modeling multiple processes at the same time.

d. Instantaneous radiative flux

The final GMS is a special case of the hierarchical diagnosis strategy but is so central to the ARM Program that it is treated separately. Accurate treatment of radiation is essential in climate models, and testing of radiation transfer models is central to the objectives of ARM. The ICRCCM (Ellingson and Fouquart 1991) illustrated that the state of the art in radiative modeling cannot be advanced by further model intercomparisons and that it is essential that the intercomparison be supplemented with field observations if further progress is to be made. This leads to the requirement that the observations provide an almost instantaneous characterization of the state of the atmosphere under clear-sky, general-overcast, and broken-cloud conditions that can be used as input into radiative models.

Strictly speaking, the requirement is not for instantaneous characterization but concurrent characterization of atmospheric state and consequent fluxes. Any lack of concurrency between observations of the atmospheric and surface properties and the radiative fluxes can thus lead to major problems in the comparison of predicted and observed fluxes. In this strategy, the set of observations required to predict the radiative fluxes are the upper boundary condition (the solar zenith angle and the incident solar flux), the lower boundary condition (the longwave and shortwave radiative properties of the surface), and the radiative properties of the intervening atmosphere. The models then predict various integral forms of the intensity of the radiation—for example, the flux as a function of wavelength and direction.

6. The cloud and radiation test bed

The field measurement component of the ARM Program is the CART. CART has been designed to acquire the observational data necessary to carry out the GMS, to prepare these data to compare with model results, and to archive the resulting data streams. CART will ultimately include several permanent observing sites and an ability to conduct intensive campaign activities at the fixed ARM sites and elsewhere, to supplement the long-term continuous streams of data. There also is a data processing and archiving system, which supports the above activities, acquires additional related data required by ARM experiments, and facilitates analysis of these data by the science team. The following subsections provide a description of the configuration of an ARM site, a discussion of the locales selected for ARM sites, information about deployment and data management at ARM sites, and a discussion of the use of intensive observational periods (IOPs) and unmanned aerospace vehicles (UAVs) within the ARM Program.

a. The configuration of an ARM site

The ARM field measurement program will consist principally of coordinated sets of observations at each of five primary sites. These sites are the principal experimental resource of CART. To satisfy the requirements of the GMS, each ARM site will consist of several components, as indicated in Fig. 1. The figure shows the design of the first ARM site, in the southern U.S. Great Plains. The design of each site varies depending on the geographical and meteorological attributes of the site and on the particular scientific issues to be emphasized. The components of a site are a central facility, a network of auxiliary stations, a network of extended observing stations, and a set of boundary facilities.

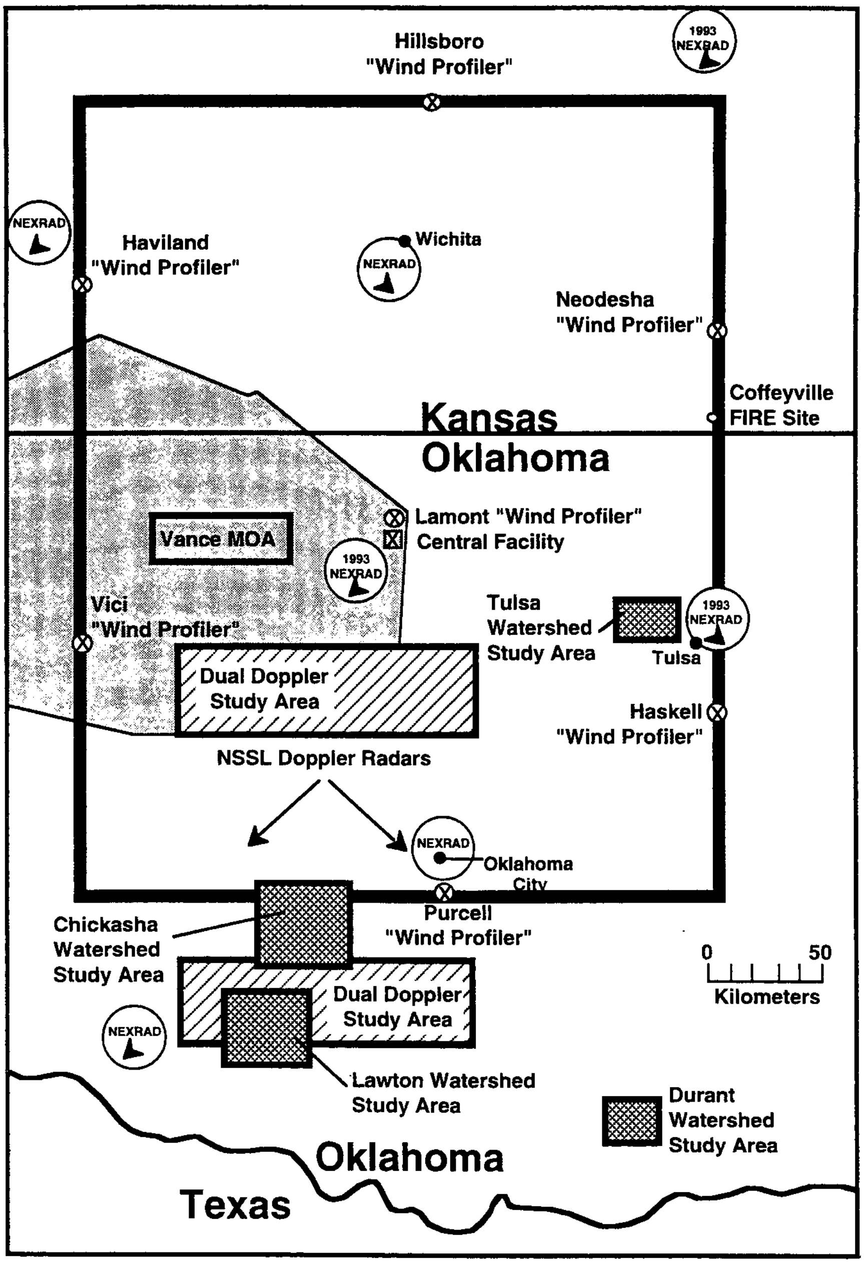

FIG. 1. The southern Great Plains site near Lamont.

The following description of the components of an ARM site shows the contributions of several components of the site to the generation of the observations required to support the experiments represented by the GMS. Although all of the following elements are being developed for the first ARM site, subsequent sites may or may not include all these elements.

1) CENTRAL FACILITY

A critical experimental task of ARM is to measure the distribution of shortwave and longwave radiation and the physical conditions that control radiation transfer—the instantaneous radiative flux GMS. Observations at the central facility provide high spectral resolution radiometric measurements and a detailed characterization of the atmospheric column above the facility. To meet these requirements, ARM will deploy equipment at the central facility for measuring downwelling and upwelling spectral radiance and for characterizing the pertinent local atmospheric properties, including temperature and water vapor concentration (both as a function of altitude), cloud fractional coverage, cloud-base altitude, and liquid water path, and the local surface reflectance, temperature, and emissivity.

2) Auxiliary station network

A series of auxiliary stations surround the central facility within a 10–20-km radius. These stations characterize the three-dimensional structure of the atmosphere in the region that exerts the major influence on the radiation flux at the central facility. The instrumentation at these facilities provides a reconstruction of the cloud geometry surrounding the central facility using all-sky cameras, satellite imagery, and ceilometers. This network is intended to provide support for the instantaneous radiative flux GMS, particularly as it relates to three-dimensional radiative transfer issues. The network also supports studies of cloud formation as part of the data assimilation and hierarchical diagnosis GMS.

3) Extended observing network

Surrounding the central facility and the auxiliary station network will be an additional network of 16–25 extended observing stations. The extended observing area will include a region comparable to that expected for GCM grid cells anticipated over the next decade, approximately 200 km x 200 km. The instruments at the extended stations will collect the basic radiometric information, conventional meteorological data, and surface flux data needed to characterize the radiative transfer throughout the extended area, giving insight into the averaging process implicit in many GCM parameterizations. Only limited vertical information will be collected, with the more extensive and demanding profiling equipment reserved for the central facility. These facilities will support the single-column model, hierarchical diagnosis, and data assimilation GMS.

4) Boundary facilities

Several GMS, such as the single-column model and four-dimensional data assimilation, involve models whose operation requires specification of boundary conditions. The need for these boundary conditions will be met by a set of facilities to support determination of the vertical profile of the horizontal fluxes of critical quantities such as water and energy at the edges of the roughly 200-km x 200-km ARM site.

b. Locale selection

A major step in designing CART was selecting sites for the ARM measurements. A two-stage approach was used. First, a set of generic locations or "locales" was selected where sites might be located that would collectively meet the ARM scientific requirements subject to the constraint of logistical suitability. The second stage, which is continuing, consists of identification and selection of specific sites within these locales. The complete locale selection process is presented in U.S. Department of Energy (1991) and is summarized here.

The key principle guiding locale selection was that the set of locales should stress models describing radiation transfer in the atmosphere and atmospheric properties influencing such radiation transfer by spanning, as much as possible, the domain of radiation-influencing attributes. The attributes used in selecting the locales included the following:

- latitude
- altitude
- continentality (midcontinent, continental margin, ocean)
- terrain (level, mountainous, etc.; uniform, variegated)
- surface (water, land; vegetated, desert, snow or ice covered, etc.; uniform, variegated)
- cloud frequency and type (cirrus, stratus, cumulus, ground fog, etc.)
- precipitation: amount, frequency, type
- temperature: mean, range
- humidity: mean, range
- seasonality
- concentrations of ozone, pollution aerosols, wind-blown dust, etc.

The goal was to select a set of locales that was as small as possible but that could test models and parameterizations over a range of conditions sufficiently wide enough to give confidence in their general applicability.

It was decided that the initial ARM sites should be fairly homogeneous spatially so that the initial test case for models would be uncomplicated by spatial discontinuities caused by mountain ranges and coastlines. However, since climate models must also deal with such discontinuities, it was recognized that such features either must be present at later ARM sites or be dealt with by campaigns. To maximize the range of conditions that would be experienced by the small number of ARM sites, it was decided that the greater the temporal variability at a given locale, the more suitable that locale would be. Thus, a locale that experiences high seasonal and intraseasonal ranges in temperature, humidity, surface state, and fluxes was to be preferred to one that did not exhibit such ranges.

A further key consideration was the logistics of establishing and operating an ARM site within the locale. Although unfavorable logistics can be overcome, this leads to increased costs, so that other things being equal, a logistically favorable locale is preferred. Sites must be physically, politically, and

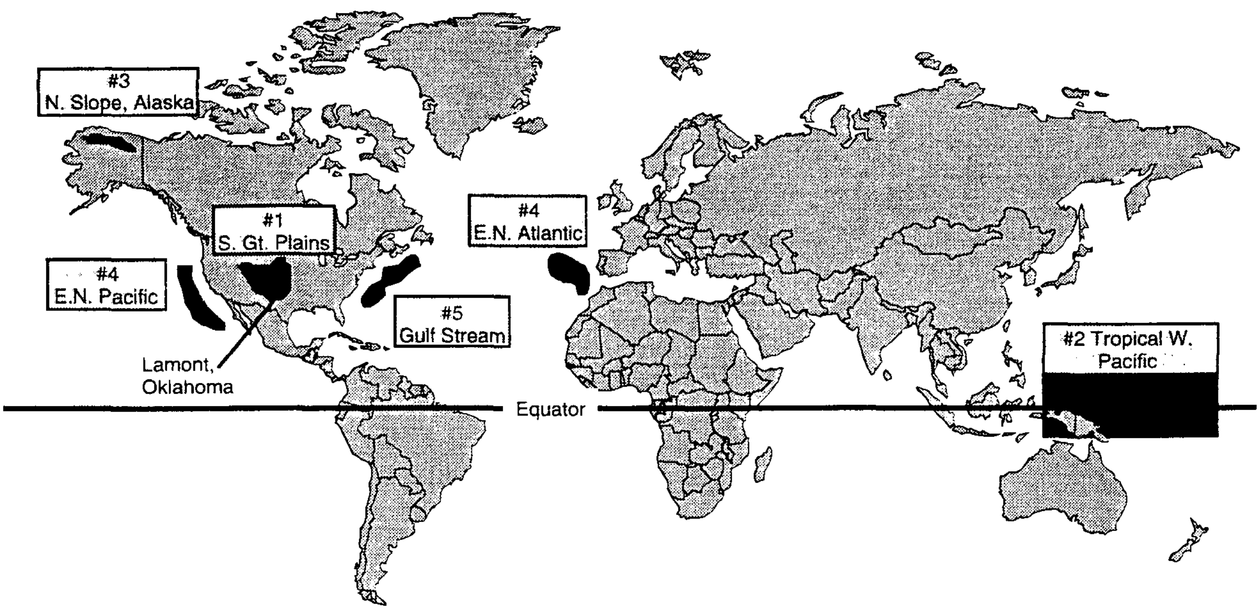

FIG. 2. Geographical distribution of recommended locales.

economically accessible, and they should have an adequate infrastructure (roads, power, communication, living accommodation, etc.). They must also be a sufficient distance from populated areas to preclude potential negative impacts (e.g., an urban heat-island effect).

Another consideration was the presence of other projects conducting related atmospheric measurements, which might offer synergistic interaction with ARM. Sites should offer possibilities for sharing of data, facilities, and costs with other agencies and programs making atmospheric measurements and concerned with atmospheric science and climate change.

Based on the above considerations, a set of locales was recommended for establishment of ARM sites. This set of locales consists of five primary locales recommended for long-term occupancy, 7–10 years, and four supplementary locales recommended for short duration or campaign occupancy (months to a year). Occupation of the supplementary locales would permit testing of ARM models over a wider range of atmospheric and surface conditions than can be encompassed at the primary sites. The geographical distribution of the recommended locales is shown in Fig. 2.

The rationale for recommending establishment of ARM sites in each of the primary locales is summarized here.

1) SOUTHERN U.S. GREAT PLAINS

Key requirements for the first ARM locale included high geographical homogeneity; a variety of cloud types; large intra-annual variability of surface flux properties and weather, including cloud types, temperature, and specific humidity and favorable logistics. These requirements are met by the southern Great Plains (SGP) locale. This locale also affords the opportunity for synergistic activity with other ongoing and planned meteorological projects and facilities. A key facility is the network of wind profiling stations being installed in this area as part of the National Oceanic and Atmospheric Administration (NOAA) Wind Profiler Demonstration Network; the high density of vertical atmospheric structure data from this network will be very important to many ARM experiments. Another pertinent project is the Global Energy and Water Cycle Experiment (GEWEX; WCRP 1992; Chahine 1992), whose Continental Scale International Program (GCIP) will focus on the greater Mississippi basin. The SGP is also situated favorably with respect to the orbit of the Tropical Rainfall Measuring Mission (TRMM) satellite, which is expected to provide valuable measurements of key physical and radiative variables.

2) TROPICAL WESTERN PACIFIC OCEAN

Ocean locales are crucial for ARM both because of the large fraction of the earth surface covered by oceans and because of the globally important cloud types and meteorological situations that are found only at ocean locations. The Tropical Western Pacific Ocean (TWP) is uniquely suited for characterizing deep tropical convection responsible for the transport of water vapor to the upper troposphere and for the tropical cirrus cloud distributions over much of the ocean. This locale is well suited for observing cumulonimbus clouds and for observing the distribution and radiative impacts of fair-weather cumulus clouds. It experiences extremely high temperature and specific humidity for an ocean locale and displays substantial interannual variation associated with the El Niño/Southern Oscillation (ENSO).

3) North slope of Alaska

The North Slope of Alaska (NSA) experiences highly diverse atmospheric and surface properties: low temperatures, high albedo when covered with ice or snow, moist vegetation and low sun in summer, and polar night at midwinter. It accordingly experiences a wide range in surface fluxes. Together, the two land locales, the SGP and the NSA, span a wide range of atmospheric, surface-flux, and geographic conditions. The NSA is a region where climate feedbacks relating surface and tropospheric temperatures, surface albedo, evaporation, cloud cover, and the polar atmospheric heat sink are expected to be large.

4) Eastern ocean margins

Eastern ocean margins represent a prevalent and climatologically important cloud and meteorological situation that is quite distinct from that represented by the TWP. Both the eastern North Pacific and the eastern North Atlantic locales exhibit a high frequency of low-level marine stratus, a key cloud type governing the earth radiation budget, and both locales experience moderate latent heat fluxes. An ARM site in either of these locales would meet the requirements of an eastern ocean margin locale; the final choice of locale and site will depend on logistical and synergistic considerations and results of earlier experiments such as the First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment–Atlantic Stratocumulus Transition Experiment (FIRE–ASTEX).

5) Gulf Stream

The Gulf Stream off eastern North America, a warm western boundary current, exhibits extreme ranges and variability in surface heat fluxes. Cold-air outbreaks in the fall and early winter from the North American continent result in air–water temperature differentials that are greater here than anywhere else globally. This is a key local for observing formation, distribution, and radiative properties of marine altostratus. This locale also provides an opportunity to observe mature midlatitude cyclonic storms, the only storm-related cloud systems expected to be resolved by present and future GCMs.

6) Supplementary sites

Sites in the supplementary locales are intended for short-term for intermittent occupation or for research campaigns to address specific modeling needs that cannot be adequately addressed with measurements at the primary sites. The rationale for recommending the several supplementary locales is summarized here:

- *Central Australia or Sonoran Desert.* The high temperatures and low specific humidity of the central Australian or Sonoran Deserts permit substantial extension of the range of conditions over which infrared radiation transfer models can be tested. Totally clear sky is frequent, enhancing the value of such studies in these locales. In addition, there is an identified need to improve parameterizations for latent and sensible heat exchange at desert surfaces, particularly dry and moist convection, and the coupling between soil moisture and downwind cloud formation and precipitation.
- *Northwest United States–southwest Canada coast.* A campaign in the northwest United States over several winter months would provide a strenuous test of the ability of models to simulate the response of clouds to orographic inhomogeneity. This locale is very inhomogeneous and has abundant stratus/altostratus clouds strongly modulated by the presence of a mountain range. Wintertime nimbostratus occurs much more frequently on the seaward slopes of the mountains than on the leeward side.
- *Amazon or Congo basin.* These are climatologically important regions with moderate intra-annual variability and little annual variability. Deep convection occurs in these regions almost daily. Surface latent heat fluxes are large, and the specific humidity is often very high. The Amazon and Congo are good locales for testing the accuracy of treatment of the water vapor continuum and radiative transfer in penetrating convective clouds. These are also good locales for testing models of exchange of heat and moisture between the surface and the air and of redistribution of these quantities within the atmosphere. Also, smoke from biomass burning varies substantially, allowing tests of effects of this aerosol on radiation transfer and cloud microphysics.
- *Beaufort, Bering, or Greenland Sea.* The polar seas are key locales for studying important issues associated with the ocean–ice edge. Issues of importance include changes in albedo and surface fluxes accompanying the growth and decay of sea–ice and possible albedo compensation of changes in ice cover by the decay or growth of marine stratus clouds. The Beaufort Sea locale is the most appealing logistically. It is frozen in winter and melts in summer, providing many opportunities for ice-edge

TABLE 2. Site management.

Site	Site program manager	Site scientist	Site operator
Southern U.S. Great Plains	D. L. Sisterson, ANL	P. J. Lamb, University of Oklahoma,	Forecast Systems NormanLab., NOAA
Tropical western Pacific Ocean	W. E. Clements, LANL	T. P. Ackerman, The Pennsylvania State University	
North Slope of Alaska	B. D. Zak, Sandia, Albuquerque	K. H. Stamnes, University of Alaska, Fairbanks	
Eastern North Pacific or Atlantic Ocean[a]	R. M. Reynolds, BNL		
Gulf Stream[a]	P. Michael, BNL	S. Raman, North Carolina State University, Raleigh	

[a]This paper was prepared prior to a recent change of status for these locales from primary to supplementary.

studies. The proximity of the Beaufort Sea to the North Slope of Alaska locale may allow a site selection strategy that would permit studying both locales.

c. Deployment

The planning for and operation of a CART site is the responsibility of two individuals, the site program manager and the site scientist. The site program manager is responsible for planning the site infrastructure, managing the deployment of instrumentation to the field, and providing operational oversight of the site operator. The site scientist is responsible for developing the detailed scientific mission plan for the sites and has the day-to-day responsibility for ensuring that the scientific objectives of the site are being met. The latter responsibility leads to the site scientist assuming much responsibility for the ongoing quality control for the data. The site scientists were selected through a competitive process and have responsibility for conducting a research program at the site and conducting an educational program in conjunction with site operations. Once a site is established and instruments and facilities are installed, a site operator assumes the day-to-day responsibility for operations. The current site program managers, site scientists, and site operators are shown in Table 2.

Deployment of instrumentation to the first site, in the SGP locale near Lamont, Oklahoma, began in May of 1992. Table 3 shows the set of instruments intended for deployment at the site. The table indicates the deployment of the instruments at each of the types of facilities within the site. Most of the different instrument types are deployed at the central facility; subsets of these instruments are deployed at the extended and boundary facilities. Several instruments listed in the table are under development within the Instrument Development Program; others have completed that development stage and are being deployed as operational instruments.

d. Data management

The ARM data system, referred to as the CART Data Environment (CDE), is an essential component of the ARM Program. The data system provides for acquisition and processing of data from the CART sites and data from external sources. It supports the combination of these data streams into a form required by various science team experiments. The system also provides for ongoing quality control of the various processes, archival storage of the data, and access to the ARM data by the rest of the scientific community.

The structure of the data system is shown in Fig. 3. The main components of the system are the site data systems, which provide for acquisition of data at each of the ARM sites and for management of site operations; an experiment center, which brings together information from the sites and other data sources for processing to meet the particular needs of the science team; and an archive, which provides for the long-term storage of the data and access for the broader scientific community. The experiment center is at the Pacific Northwest Laboratory in Richland, Washington, and the archive is at Oak Ridge National Laboratory in Oak Ridge, Tennessee. The data system uses the national

TABLE 3. Planned deployment of instruments and observing capabilities at the SGP CART site. Except as indicated, all instruments/observations will be at the central facility (CF). Check marks indicate instruments/observations that will also be located at extended facilities (EFs) or boundary facilities (BFs). The notation IDP indicates that the instrument is under development in the Instrument Development Program for possible future deployment at the site.

	Central facility	Extended facility	Boundary facility
Radiometric			
Pyranometer (ventilated)	X	X	
Shaded pyranometer (ventilated)	X	X	
Pyranometer, upwelling (at 10 and 25 m at CF; 10 m at EFs)	X	X	
Pyrgeometer (shaded)	X	X	
Pyrgeometer, upwelling (at 10 and 25 m at CF; 10 m at EFs)	X	X	
Pyrheliometer on tracker	X	X	
Multifilter rotating shadowband radiometer	X	X	
All-weather absolute radiometer	X		
Rotating shadowband spectrometer (IDP)	X		
Solar spectral radiometer	X		
Ultraviolet spectral radiometer (USDA)	X		
Shortwave narrowband radiometer (IDP)	X		
Special infrared broadband radiometer (IDP)	X		
Device for surface spectral reflectance (at 25 m)	X		
Atmospherically emitted radiance interferometer	X		X
Solar radiance transmission interferometer (IDP)	X		
Net radiometer profiler (IDP)	X		
Radiometric calibration facility	X		
Wind, temperature, and humidity aloft			
915-Mhz wind profiler and radio acoustic sounding system (RASS)	X		
50-Mhz wind profiler and RASS	X		
404-Mhz wind profiler and RASS (BFs only; NOAA/National Weather Service stations)	X		X
Raman lidar (IDP)	X		
Microwave radiometer	X		X
Balloon-borne sounding system	X		X
Infrared thermometer	X		

Internet as its operational backbone, giving ARM investigators access to a variety of computational resources to support their modeling and analytic requirements.

The operational kernel of the CART data system is the Zeb system (Corbet and Mueller 1991) developed by the National Center for Atmospheric Research (NCAR). This system was originally developed for the collection and analysis of atmospheric data to support field campaigns and to provide postcampaign data analysis support. The basic architecture of Zeb was conceived to be highly flexible in number and types of input data streams accommodated and in processing and displaying the data. This flexibility supports the development of incremental capabilities that target specific needs of the ARM application. The Zeb system thus provides many of the logical functions required by CART, both for the site and the experiment data systems. The data system has been designed and sized to meet the initial requirements for modeling

TABLE 3 continued. Planned deployment of instruments and observing capabilities at the SGP CART site.

	Central facility	Extended facility	Boundary facility
Cloud observations			
Whole-sky imaging system (IDP)	X		
Ceilometer	X		
Lidar (IDP)	X		
Cloud radar (IDP)	X		
Near-surface ozone and aerosol observations			
Ozone sensor	X		
Integrating nephelometer	X		
Optical particle counter	X		
Aerosol optical absorption system	X		
Condensation nuclei counter	X		
Other			
Surface meteorological observation system; wind speed and direction (10 m); temperature and humidity (1.5 m); atmospheric pressure; precipitation amount; snow depth	X	X	
Energy balance Bowen ratio station[a]	X	X	
Eddy correlation (25–60 m at CF; 3 m at EFs)[a]	X	X	
Temperature and humidity (60 m)	X		

[a]Either the energy balance Bowen ratio station or the eddy correlation station, but not both, will be deployed at the EFs.

and instrumentation and can be expanded as necessary in the future.

To meet the scientific objectives of ARM, it is necessary to combine observations from the CART sites with data from other sources. Examples of such external data include the wind profiler data from the NOAA demonstration network and data from operational satellites maintained by NOAA and the National Aeronautics Space Administration (NASA). Satellite observations offer critical data for ARM. Top-of-the-atmosphere radiative fluxes and profiling of atmospheric conditions in regions beyond the range of sounds and ground-based sensors are crucial for many ARM projects. The requirement for external data will also include data products that go beyond data from various observational systems, such as meteorological forecasts and cloud statistics from the ISCCP. The data system has been explicitly designed to allow ingest of this class of external data, its merger with the data streams from the ARM sites, and delivery to the ARM Science Team.

The ARM data archive at Oak Ridge National Laboratory will provide access to ARM data for non-ARM participants. The Oak Ridge facility, which is affiliated with the Earth Observing System Data and Information System (EOSDIS) as a Data Analysis and Archieve Center (DAAC), has begun providing data on a limited basis. More extensive access to ARM data should begin in late 1994. Eventually all data and data products generated by ARM will be available through the archive. As an EOSDIS–DAAC, the Oak Ridge archive should also allow merging of ARM data with data streams from other DAACs.

e. Intensive operations, campaigns, and interactions with other programs

While the ARM observational strategy is to provide a baseline set of observations available continuously from each of the primary sites, this set of observations may not always be to fully satisfy the requirements of the scientific experiments to be conducted within ARM. Consequently, the baseline set of observations

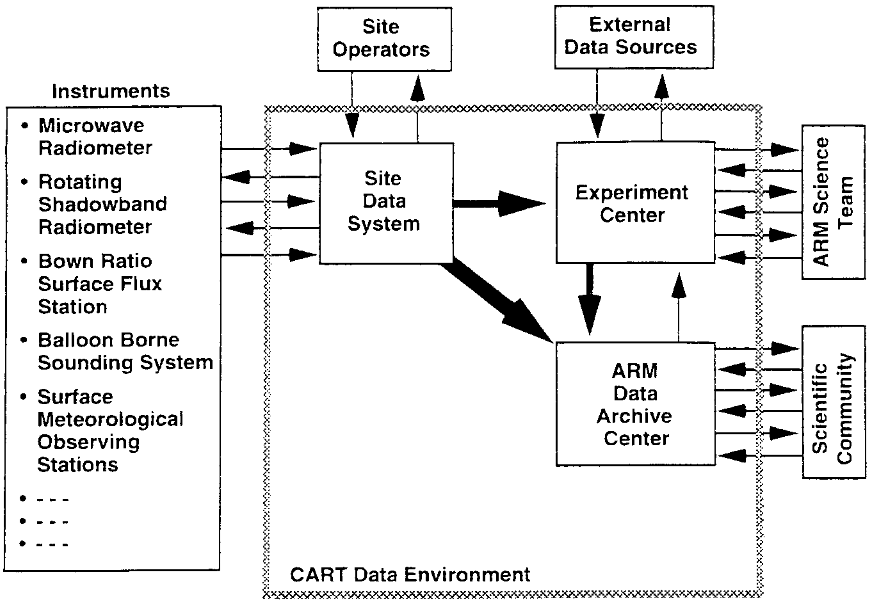

FIG. 3. Schematic representation of ARM data system components with associated data flows.

will be supplemented periodically with IOPs. During IOPs, ARM will support several classes of observations, including observations that are too expensive or personnel intensive to be conducted continuously, calibrations or in situ testing of validity of remote sensing data, and field testing of new instrumentation.

Possible IOPs include the following or combinations of the following:

- increased frequency or density of observations to test more detailed models of atmospheric processes
- measurements of low stratus optical and microphysical properties with a tethered balloon
- measurements of cirrus optical and microphysical properties with aircraft (manned or remotely piloted)
- augmentation or modification of observations to allow testing of IDP instruments
- observations coordinated with satellite overpass schedules.

The ARM Program also participates in more traditional observational campaigns in collaboration with other programs. ARM participation in campaigns is generally directed to specific scientific objectives that complement or supplement the ARM objectives. Early in the program, ARM collected observations in conjunction with several projects [FIRE; Spectral Radiance Experiment (SPECTRE); Winter Icing and Storms Project (WISP)], in an attempt to gain operational experience that would support later field activities. For example, the Pilot Radiation Observation Experiment (PROBE) was conducted during November 1992–February 1993 at Kavieng, Papua New Guinea, in conjunction with Tropical Ocean–Global Atmosphere–Coupled Ocean Atmosphere Response Experiment (TOGA COARE) and provided measurements of radiation in the tropical western Pacific. ARM also supported the Boardman Regional Flux Experiment (BARFEX) (June 1991, near Boardman, Oregon; Doran et al. 1992) that examined subgrid-scale variability of sensible and latent heat fluxes and laid the groundwork for similar observations at ARM sites. These pilot projects and the role they played in the level of ARM are summarized in Table 4.

In the future, ARM plans to host and support the conduct of campaigns at primary or supplementary ARM sites. The ARM facilities offer an important operational base on which other observational campaigns can be based. Examples of possible campaigns include a comprehensive flux divergence experiment with multiple aircraft at different altitudes above an ARM site or process-oriented studies similar to FIRE or WISP operating at an ARM site. ARM has set a pattern of collaboration with other components of the USGCRP and the international research community. As noted previously, the program has benefited significantly from interaction with other programs in its early development stages. These interactions have included nonclimate-related projects such as WISP, but the vast majority have been climate related, including FIRE-cirrus and FIRE-stratus and TOGA COARE.

The establishment of a series of facilities, which will be occupied for an extended period, makes the CART an attractive base upon which to build more campaign-oriented projects. For example, the ARM facilities will be a major component of GEWEX field experiments. The ARM–GEWEX collaboration will include participation in the continental program scheduled for the Mississippi basin GCIP and an intercomparison of water vapor measuring systems GEWEX Water Vapor Program. ARM facilities may also serve as a basis for the next field deployment of the International Satellite Land Surface Climatology Project.

f. ARM and unmanned aerospace vehicles

The original ARM Program Plan (U.S. Department of Energy 1990) called for the limited use of aircraft in the operation of CART. Late in 1990 the possibility of a new kind of airborne measurement became apparent in what are frequently called "Unmanned Aerial Vehicles" (UAVs) (CalSpace 1992; JASON 1992). These aircraft offer ARM the possibility of long-duration flights (greater than 48 h), autonomous operation over long distances, and considerable payloads (approximately 150 kg). The ARM missions proposed for UAVs include multiday missions to measure the flux divergence at the tropopause at several of the sites, delineate boundary profiles of temperature and humidity with dropsondes, study the radiative transfer associated with deep tropical convection in the central and western tropical Pacific, and cross calibrate satellite sensors.

Currently, a UAV program called "ARM–UAV" is under development with the operational goals outlined above. This program began flight activities in the fall of 1993 with a series of demonstration flights to profile longwave and shortwave radiative flux in the lower troposphere (below 8 km). It is anticipated that these observations will soon be conducted at the SGP site.

8. Conclusion: Schedule and status

The ARM Program is planned to last a decade or more. The schedule of near-term events, pilot deployment, and a history of the program are summarized in Tables 4 and 5. Key programmatic and technical milestones shown in Table 5 include critical events such as the selection of the science team. As noted in section 7e, the program has used a series of collaborative pilot projects to test critical concepts and instrumentation before deploying them in the more permanent installations. Many of these pilot deployments were conducted with the cooperation of several other agencies including NASA, NOAA, the Federal Aviation Administration, and the National Science Foundation.

The central activity of the program is the development of the field facilities. The following is a summary of the status of the activity for five primary locales.

a. Southern Great Plains

The SGP site covers approximately 60 000 km^2 near the center of the locale shown in Fig. 2. The central facility is approximately 7 miles southeast of the town of Lamont (Fig. 1). As noted earlier, this site is in the midst of the densest portion of the NOAA demonstration wind profiler network, and the outer boundaries of the site are delineated by the six profilers shown in the figure. The layout of instrumentation in the central facility is shown in Fig. 4. The installation of instrumentation at the site began in April 1992, with the bulk of the instrumentation to be in place in early 1994. Initial deployment of the instrumentation emphasized the placement of instruments in support of the instantaneous radiative flux GMS. Several intensive observational periods have already occurred at the site, and several instruments from the Instrument Development

TABLE 4. Pilot deployments.

Pilot effort	Location/date	Description
WISP	Northern Colorado/winter 1990/91	Provided a test of remote sensing equipment including RASS and microwave radiometers.
BARFEX 1	Boardman, Oregon/summer 1991	Began the process of understanding the mechanism by which the lower boundary condition of an SCM might be examined.
SPECTRE–FIRE	Coffeyville, Kansas/fall 1991	SPECTRE provided a test of the concepts behind the instantaneous radiative flux measurement strategy.
ASTEX	Azores/spring 1992	Limited participation but support of cloud radar and wind profiler deployment.
BARFEX 2	Boardman, Oregon/summer 1992	Continuation of BARFEX 1.
PROBE	Kavieng, Papua New Guinea/winter 1992/93	Support of TOGA COARE and testing of concepts for radiometric observations in the TWP.

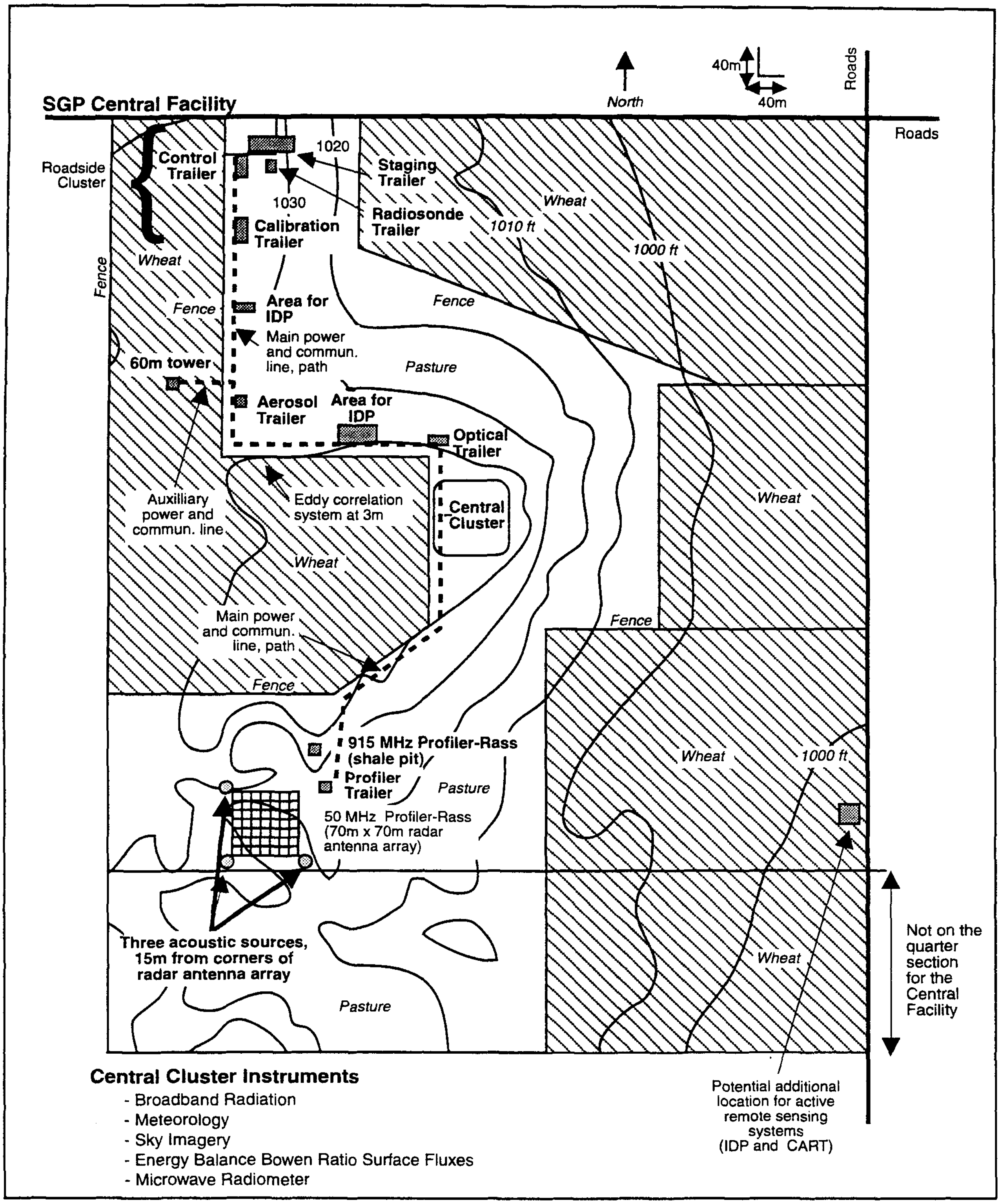

FIG. 4. The instrument layout in the central facility at the southern Great Plains site.

Program have been deployed as operational instruments. For a full account of the scientific objectives of the SGP site and current deployment status, see Schneider et al. (1993).

b. Tropical western Pacific

The siting strategy for the TWP is complicated by issues such as the heavy instrumentation requirements associated with studies of deep tropical convection, the logistical complexity of a site that would be free from effects of land, and the great spatial extent of the processes (e.g., El Niño). These complications require some compromises. Currently, the complicated nature of the scientific issues in the TWP has led to a three-element approach to deployment of instrumentation. These strategies are built around basic radiative processes, studies of deep convection, and processes over the open ocean. The current proposal is to field instrumentation in three different experimental configurations to meet the scientific goals, rather than using the single, multipurpose facility approach adopted in the SGP.

The first phase of the TWP field efforts will be on Manus Island, Papua New Guinea, the first of an east–west chain of island-based stations targeted at radiative processes. A key building block of the strategy will be a combination of the NCAR–NOAA Integrated Sounding System (ISS; NCAR 1993) and an automated radiation measurement system called an "Atmospheric Radiation and Cloud Station" (ARCS). Both ARCS and ISS are modular field stations built around an air-conditioned seatainer. This approach was tested during PROBE and appears to provide excellent data in support of the instantaneous radiative flux measurement strategy. Subsequent activity will depend heavily on the experience gained in the early phases of the project and the progress made in other programs, such as GEWEX and the satellite-borne tropical rainfall measurement mission.

c. North slope of Alaska

On the NSA the conditions and logistics are of comparable difficulty to the TWP. The current approach is focusing on a sitting strategy more similar to that being pursued in the SGP. This approach would place something similar to the SGP central facility near Barrow, Alaska, with boundary facilities located

TABLE 5. ARM schedule and milestones.

Type of Milestone	Milestone	Date	Description—comments
General programmatic milestones			
	Approval by CEES	December 1989	
	Selection of first science team members	Summer 1990	ARM Science Team members are selected and funded for periods of 3 years.
	Second round of science team selection	Summer 1991	
	First science team meeting	November 1990	Las Vegas, Nevada
	Second science team meeting	November 1991	Denver, Colorado
	Third science team meeting	March 1993	Norman, Oklahoma
	Fourth science team meeting	March 1994	Charleston, South Carolina
Site selection and deployment milestones			
	Publication of locale recommendation report	April 1991	
	Begin occupation of SGP Site–Grant County, Oklahoma	April 1992	Occupation of the site will take place over a 2-year period.
	ARM–UAV first demonstration flight	Fall 1993	
	Begin occupation of TWP site	Fall 1994	Begins with ARCS deployment on Manus Island Papua New Guinea.
	Begin occupation of NSA site	1995–1996	

on the tundra and along the coast. The science team, which met in March of 1993, agreed that the siting strategy would also consider placing instrumentation out on the ice for at least part of the year. This strategy is compatible with the Surface Heat Budget of the Arctic Ocean program. Further, the development of UAVs may make studies of the sea–ice margin more practical than previously expected. In the summer of 1993, instrumentation tests began on the NSA. Early tests emphasized the effect of acoustic sources on wildlife, but eventually they will be focused on the difficult challenge of hardening instruments for operation in the Arctic. A key to the hardening and eventual deployment strategy is the development of the ARCS for the TWP.

d. Eastern North Pacific/Atlantic Ocean and Gulf Stream locales

In the locale covered by the two Northern Hemisphere marine stratus zones, which have been called the eastern ocean margin locales, the emphasis has been twofold. In the Gulf Stream locale, the emphasis has been on identifying existing data sources that would allow members of the science team to begin outlining research interests and issues for this locale. These two sites were moved from primary to secondary status in the summer of 1993. This decision allows the program to focus its resources on the first three sites. The development of the ARCS concept for the Tropics, and its possible extension to the Arctic, suggests that a modular cloud and radiative experimental capability may be more readily deployable than originally thought. This would make short-term occupation of the secondary sites more practical than classic campaign approaches may have allowed.

9. Summary

The ARM Program is creating a set of observational facilities that should allow the research community to focus its efforts on the high priority problems of understanding clouds and radiation in the climate system. The observational facilities of the ARM Program represent a unique resource for meteorological research not only because of the large complement of equipment deployed over an extended period of time but also because of their close relationship with existing facilities and coordination with other field programs. The deployment of ARM to the first three locales—the southern Great Plains, the tropical western Pacific, and the North Slope of Alaska—should provide a sound base for planning other research programs in these climatologically interesting and important areas.

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