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Science Plan for the Atmospheric Radiation Measurement Program (ARM)

February 1996

United States Department of Energy
Office of Energy Research
Office of Health and Environmental Research
Environmental Sciences Division

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Executive Summary

The purpose of this Atmospheric Radiation Measurement (ARM) Science Plan is to articulate the scientific issues driving the ARM Program, and to relate them to DOE's programmatic objectives for ARM, based on the experience and scientific progress gained over the past five years.
ARM programmatic objectives are to:

1. Relate observed radiative fluxes and radiances in the atmosphere, spectrally resolved and as a function of position and time, to the temperature and composition of the atmosphere, specifically including water vapor and clouds, and to surface properties, and sample sufficient variety of situations so as to span a wide range of climatologically relevant possibilities.

2. Develop and test parameterizations that can be used to accurately predict the radiative properties and to model the radiative interactions involving water vapor and clouds within the atmosphere, with the objective of incorporating these parameterizations into general circulation models.

The achievement of these programmatic 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 accurate description of the presence and properties of clouds in climate models. There are key scientific issues which must be resolved in order to achieve these objectives. The primary scientific questions are as follows:

1. What are the direct effects of temperature and atmospheric constituents, particularly clouds, water vapor and aerosols on the radiative flow of energy through the atmosphere and across the Earth's surface?

2. What is the nature of the variability of radiation and the radiative properties of the atmosphere on climatically relevant space and time scales?

3. What are the primary interactions among the various dynamic, thermodynamic, and radiative processes that determine the radiative properties of an atmospheric column, including clouds and the underlying surface?

4. How do radiative processes interact with dynamical and hydrologic processes to produce cloud feedbacks that regulate climate change?

The programmatic objectives of ARM call for measurements suitable for testing parameterizations over a sufficiently wide variety of situations so as to span the range of climatologically relevant possibilities. In order to accomplish this, highly detailed measurements of radiation and optical properties are needed both at the Earth's surface and inside the atmospheric column, and also at the top of the atmosphere. Among the most critical factors determining the optical properties of the atmosphere is the distribution of liquid water and ice, i.e., clouds, within the atmospheric column. It follows that ARM must obtain sufficiently detailed measurements of the clouds and their optical properties.

The primary observational method is remote sensing and other observations at the surface, particularly remote sensing of clouds, water vapor and aerosols. It is impossible to meet ARM's objectives, however, without obtaining a large volume of detailed in situ measurements, some of which will have to be acquired from manned or unmanned aircraft; in addition, high-quality satellite observations are needed to measure the top-of-the-atmosphere radiation.

To obtain the requisite in situ and surface-based remote-sensing data, ARM is making measurements, over a period of years, at three sites:

- The Southern Great Plains (SGP) Site
- The Tropical Western Pacific (TWP) Site
- The North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) Site.

These sites were selected from a longer list through a process of prioritization and resource allocation, in order to provide opportunities to observe a wide range of climatologically important meteorological conditions, as summarized in DOE (1990).

There are two primary strategies through which ARM plans to achieve its programmatic objectives and address its programmatic objectives and address its Scientific Issues. The first is called the "Instantaneous Radiative Flux" (IRF) strategy, which consists of collecting data on the distribution of radiation and the radiatively active constituents of the atmosphere and the radiative properties of the lower boundary. The second involves the use of Single-Column Models (SCMs) to develop and test cloud formation parameterizations.

ARM programmatic objectives will be achieved as the testing of hypotheses leads to improved parameterizations for use in climate models. The activities of the IRF are central to achieving the ARM Program objective of relating observed radiative fluxes in the atmosphere to the temperature and composition of the atmosphere and to surface properties. Since the parameterizations of radiative processes play major roles in climate model forcing and feedback mechanisms, the radiative parameterizations developed by IRF studies will play essential functions in the development and testing of other parameterizations for predicting the distributions of properties that strongly affect atmospheric radiation.

Among the several methods for testing general circulation models (GCM) parameterizations by comparison with observations, the SCM approach has some unique advantages. SCM-based tests are inexpensive, and the results are not affected by errors arising from the other components of the model. Cloud Ensemble Models are a useful supplement to SCMs, and can be used in much the same way with essentially the same data requirements. SCMs in conjunction with large eddy simulation (LES) and cloud ensemble models (CEMs) can be used to investigate basic physical questions, develop cloud amount parameterizations, and evaluate the sensitivity of model results to parameter changes. In support of ARM, SCMs and CEMs will be particularly valuable for testing parameterizations of cloud formation, maintenance, and dissipation.

The data required to drive the SCMs, LES models, and CEMs, and to evaluate their performance, are not easy to obtain. ARM has the potential to provide uniquely valuable data for SCM-based parameterization testing. Efforts are under way to "package" data collected at ARM's Southern Great Plains Site in a form particularly convenient for use with SCMs and CEMs.

A key to the ultimate success of ARM is continued evaluation of the needs for new observing capabilities as progress is made in understanding the important scientific issues.

The goal of the Instrument Development Program (IDP) of ARM is to bring existing research instrumentation to the advanced state of development required to allow routine, highly accurate operation in remote areas of the world, and to develop new instrumentation as requirements are identified.

The evolving ARM IDP has combined components of basic research into improved remote sensor system and techniques (i.e., cloud retrieval) development, and an engineering effort intended to provide within the Cloud and Radiation Testbed (CART) setting a kernel of instruments to adequately characterize the local atmosphere. Currently, effort is directed toward placing these sensors at CART sites and validating the analysis approaches. The next step is to develop the means to convert the CART remote sensor data stream into the types of derived data quantities that are necessary to comprehend the effects the clouds and clear atmosphere on the IRF and GCM-class radiative transfer models.

The IRF scientific questions being addressed with data from the SGP are not really site-specific; the same questions could be addressed with data from the other two sites. The site-specific scientific questions that the SCM strategy is addressing with SGP data include:

- What processes control the formation, evolution, and dissipation of cloud systems in the Southern Great Plains?
- In the Southern Great Plains, what relative roles do the advection of air mass properties and variation in surface characteristics play in cloud development? How do these roles vary with season and short-term climatic regime?
- What aspects of cloud development are controlled by: the Low Level Jet; the return flow of moisture from the Gulf of Mexico during the winter and early spring months; the development of mesoscale convective complexes; frontal passages?
- What are the implications of the regional east-west gradients in altitude, soil type, vegetation, temperature, and precipitation on radiative fluxes?
- How important are seasonally varying distributions of aerosols and particulates (e.g., from regional oil refineries, or from burning of wheat fields) in the energy transfer processes?

The choice of ARM's Tropical Western Pacific (TWP) site was dictated, in large part, by the ocean warm pool and the deep convection associated with it. Satellite observations show that the ocean surface temperatures in the vicinity of the maritime continent are consistently the warmest and cloud top temperatures are the coldest found anywhere.

ARM has an important role to play in the TWP and that role has three distinct and critical elements:

1. Provide a long time series of basic observations at several locations that aid in understanding intra-annual and interannual variability of surface radiation fluxes and cloud properties. These observations would also serve as truth points for satellite retrievals of surface and atmospheric quantities.

2. Augment radiation and cloud observations made in the context of intensive field campaigns to elucidate the role of deep convection in the tropics as it affects radiative processes.

3. Devise and implement a strategy for long-term measurements of ocean-atmosphere properties and fluxes.

The specific scientific objectives to be addressed at the ARM site in the North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) focus on improving the performance of climate models at high latitudes by improving our understanding of specific physical processes.

The observational strategy proposed will allow us to improve our understanding of the cloud and radiation environment of the Arctic, over land and ocean. These observations will be used to initialize and validate cloud-resolving models, and as a basis for comparing parameterizations. These improved parameterizations will be incorporated into a regional climate model of the Arctic and global climate models. Collaboration with other programs, such as the Surface Heat Budget of the Arctic Ocean (SHEBA), the First ISCCP (International Satellite Cloud Climatology Experiment) Regional Experiment (FIRE), and Land-Atmosphere-Ice-Interactions (LAII) allows ARM to address its secondary science objectives; together, these programs will have a substantial impact on our ability to model the arctic climate, specifically the cloud-radiation feedback.

Interactions of the Data and Science Integration Team (DSIT) with Science Team members, individually and collectively, are the primary information exchange mechanism that drives the collection and management of data within the ARM Program. The interaction leads to translating the science needs into data needs. A critical part of this translation is the management and documentation of data quality. The stated goal of ARM is to produce data of "known and reasonable quality." This goal is translated into both actions to ensure that the instruments produce data of sufficient precision and accuracy to meet scientific needs and the obligation to produce a record of the calibration and operational history of instruments and their associated data streams sufficient to ensure an enduring record of data quality.

Acronyms and Abbreviations

ACARS	Aeronautical Radio Incorporated Communications (ARINC), Addressing and Reporting System
ACSYS	Arctic Climate System
AERI	Atmospheric Emitted Radiance Interferometer
AME	Quality Measurement Experiment
AMIP	Atmospheric Model Intercomparison Project
ARCS	Atmospheric Radiation and Cloud Station
ARCSS	Arctic System Science
ARCSyM	Arctic Regional Climate System Model
ARES	Study of the disparity between shortwave observations and models
ARM	Atmospheric Radiation Measurement Program
ASTEX	Atlantic Stratocumulus Transition Experiment
ASTI	Absolute Solar Transmission Interferometer
BBSS	Balloon-Borne Sounding System
BSRN	Baseline Surface Radiation Network
CAGEX	CERES/ARM/GEWEX
CART	Cloud and Radiation Testbed
CCM	NCAR's Community Climate Model
CEM	Cloud Ensemble Model
CERES	Clouds and the Earth's Radiant Energy System
CHAMMP	Computer Hardware, Advanced Mathematics, and Model Physics
CLASS	Cross-Chain Loran Atmospheric Sounding System
COARE	Coupled Ocean-Atmosphere Regional Experiment
DIAL	Differential Absorption Lidar
DSIT	Data and Science Integration Team
EBBR	Energy Balance Bowen Ratio
EC	Experiment Center
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Nino - Southern Oscillation
EOP	Experiment Operations Plans
EOS	Earth Observing System

EOS-AM	First launch in NASA EOS series
ERBE	Earth Radiation Budget Experiment
ETL	Environmental Technology Laboratory
FANGIO	Feed Analysis of GCMs and In Observations
FIFE	First ISCCP Field Experiment
FIRE	First ISSCP Regional Experiment
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GCIP	GEWEX International Continental Experiment
GCM	General Circulation Model
GCM-RTM	A GCM-class radiative transfer model
GEWEX	Global Energy and Water Experiment
GMS	Geostationary Satellite
GNAT	small UAV
GTS	Global Telecommunications System
GVaP	Water vapor measuring systems
HIS	High-resolution Interfereometric sounder
HUMICAP	Humidity Sensor used on Vaisala Radiosonde
ICRCCM	Intercomparison of Radiation Codes in Climate Models
IDP	Instrument Development Program
IEOS	International component of EOS
IOP	Intensive Observation Period
IRF	Instantaneous Radiative Flux
ISCCP	International Satellite Cloud Climatology Experiment
ISLSCP	International Satellite Land Surface Climatology Project
JACCS	Japanese Cloud and Climate Study
LAII	Land-Atmosphere-Ice-Interactions
LBL	Line by line
LES	Large Eddy Simulation
LESM	Large Eddy Simulation Model
MCTEX	Maritime Continent Thunderstorm Experiment
MFRSR	Multifilter rotating shadowband radiometer
M^2RTMS	Multispectral Radiative Transfer Models
MPL	Micro-Pulse Lidar

MWP	Numerical Weather Prediction
NCEP	U.S. National Center for Environmental Prediction
NIP	Normal Incidence Pyrheliometer
NIST	National Institute of Standards and Technology
NSA/AAO	North Slope of Alaska/Adjacent Arctic Ocean
OSSE	Observing System Simulation Experiments
PILPS	Program for Intercomparison of Land Surface Parameterization Schemes
PPR	Photopolarimeter
PROBE	Pilot Radiation Observation Experiment
RASS	Radio Acoustic Sounding System
RTM	Radiative Transfer Model
SCM	Single-Column Models
SGP	Southern Great Plains
SHEBA	Surface HEat Budget of the Arctic Ocean
SIROS	Solar and Infrared Radiation Observation Stations
SPECTRE	Spectral Radiance Experiment
SRB	Surface Radiation Budget
SORTI	Solar Radiance Transmission Interferometer
SMOS	Surface Meteorological Observation System
TOA	Top of the Atmosphere
TRMM	Tropical Rainfall Measuring Mission
TWP	Tropical Western Pacific
UAV	Unmanned Aerospace Vehicles
USGCRP	U.S. Global Change Research Program
VIZ	Humidity Sensor used on National Weather Service Radiosonde
VAP	Value Added Procedures
WCRP	World Climate Research Program
WGNE	Working Group Numerical Experimentation
WISP	Winter Icing and Storms Program
WSIS	Whole Sky Imaging System

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1. Introduction to ARM Goals and Scientific Focus

1.1 History

ARM, the Atmospheric Radiation Measurement Program, was initiated by the U.S. Department of Energy (DOE) with the ultimate goal of improving the parameterizations of clouds and radiation used in climate models. This goal is being achieved through a combination of field measurements and modeling studies; a key ARM precept is that observationalists and modelers should work together closely to make use of the field data for parameterization development and validation. ARM commenced in the fall of 1989. In the five years since publication of the initial program plan (DOE 1990; Stokes and Schwartz 1994) the scientific issues have been refined and substantial progress has been made in the implementation of the facilities necessary to conduct the program.

The purpose of this ARM Science Plan is to articulate the scientific issues driving ARM, and to relate them to DOE's programmatic objectives for ARM, based on the experience and scientific progress gained over the past five years.

The United States Global Change Research Program (USGCRP; CEES, 1990) identified the scientific issues surrounding climate and hydrological systems as of great concern. In order to improve cloud and radiation parameterizations, ARM was designed first 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. ARM was seen as a natural outgrowth and direct continuation of DOE's decade-long effort to understand the role of atmospheric carbon dioxide in climate change, and to improve general circulation models (GCMs) and other climate models, in order ultimately to provide reliable simulations of climate change.

1.2 Programmatic Goals

Because of DOE's strong interest in climate modeling, the programmatic goals of ARM have been framed in terms of climate models. The programmatic focus of ARM is on the development and testing of parameterizations of important atmospheric processes, particularly cloud and radiative processes, for use in GCMs. This focus has been captured in the two related ARM programmatic objectives which are summarized in Table 1.1.

Table 1.1. Programmatic objectives.

1. Relate observed radiative fluxes and radiances in the atmosphere, spectrally resolved and as a function of position and time, to the temperature and composition of the atmosphere, specifically including water vapor and clouds, and to surface properties, and sample sufficient variety of situations so as to span a wide range of climatologically relevant possibilities.
2. Develop and test parameterizations that can be used to accurately predict the radiative properties and to model the radiative interactions involving water vapor and clouds within the atmosphere, with the objective of incorporating these parameterizations into general circulation models.

These objectives place strong emphasis on parameterization development and testing. It is important to recognize that parameterization development is not simply curve fitting; it should proceed, as far as possible, from general physical principles. A physically based parameterization provides a condensed representation of the important physical processes of interest, and so can give important physical insight into the phenomenon being parameterized. The assumptions underlying a parameterization must, of course, be observationally testable.

The first objective listed above relates to radiative transfer per se, while the second extends to the parameterization of cloud formation processes and other processes that determine the radiative properties of the atmosphere. A problem that must be squarely faced is that practically any atmospheric process can be said to contribute, in some way, to determining the radiative properties of the atmosphere. ARM needs to assess which process or modeling studies will actually make a substantive contribution to meeting its programmatic objectives. For example, there are some areas such as precipitation measurement and modeling which may be outside ARM's brief, whereas other areas of cloud formation and evolution such as the nature of the cloud micro-structure are essential to the program. Again, topics such as atmospheric chemistry, where aerosol sources, sinks and formation are concerned, may also be important. There is no question that cloud formation and dissipation have to be correctly simulated in order to model atmospheric radiation. We have to be careful, however, that ARM-sponsored research in these areas relates directly back to the programmatic objective of developing improved cloud and radiation parameterizations for climate models.

To transfer observational validation from ARM radiation measurements to GCM parameterizations, a hierarchy of radiative models and a broad variety of observational instruments is utilized. The objective is to compare the most capable and sophisticated multiple scattering and line-by-line models against the highest spectral resolution measurements to enable full and complete validation of radiative modeling for atmospheric conditions of climatological interest. Results from the detailed radiative models are then used to construct and optimize narrow-band, broad-band, and GCM parameterizations to calculate radiative fluxes and atmospheric heating and cooling rates. Similarly, in order to model the radiative interactions involving water vapor and clouds, a hierarchy of cloud models and observations are used. Results from increasingly aggregate models of cloud physics and dynamics are used to develop and test the parameterization of cloud processes and properties that eventually can be used in GCMs.

1.3 Scientific Issues

The achievement of these programmatic 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 accurate description of the presence and properties of clouds in climate models. There are key scientific issues which must be resolved in order to achieve these objectives. The purpose of this plan is to articulate these underlying scientific questions and an approach to addressing them. These questions, which are discussed in detail in the plan, are summarized in Table 1.2.

The first three of these questions can be directly addressed through measurements over the lifetime of ARM, although modeling studies are also required. The fourth question is more difficult to approach because cloud feedbacks arise from different physical mechanisms and may have different sensitivity on diurnal, seasonal and interannual time scales. Addressing this question effectively will require extensive modeling studies and the collection of observational data over all relevant time scales.

Table 1.2. Primary scientific questions.

1. What are the direct effects of temperature and atmospheric constituents, particularly clouds, water vapor and aerosols on the radiative flow of energy through the atmosphere and across the Earth's surface?
2. What is the nature of the variability of radiation and the radiative properties of the atmosphere on climatically relevant space and time scales?
3. What are the primary interactions among the various dynamic, thermodynamic, and radiative processes that determine the radiative properties of an atmospheric column, including clouds and the underlying surface?
4. How do radiative processes interact with dynamical and hydrologic processes to produce cloud feedbacks that regulate climate change?

Because ARM is a combined measurement and modeling program (including laboratory measurements where appropriate), a central feature of the program is an experimental testbed for the measurement of atmospheric radiation and the properties controlling this radiation, such as the distribution of clouds and water vapor. A principal objective of this testbed 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 comparison of field observations with model calculations of the radiation field and associated cloud and interactions.

While it is easy to state the intent of measurements to be made at such a testbed, there are practical and scientific issues which arise in the implementation of such a system. These issues include not only the development of the instrumentation and the interpretation of the data, but also the selection of the geographical locations in which the measurements need to be made. The three ARM sites were selected to provide the opportunity to observe a wide range of climatologically important meteorological conditions.

A variety of secondary scientific questions arise in the course of addressing the primary scientific questions given above. Most of these are site-specific. They are discussed later in the sections of this plan that deal with particular sites.

This Science Plan is organized as follows: Section 2 articulates the overall observational and modeling strategies, and leads in to the next several sections which articulate the scientific questions that relate to radiation and clouds. Section 6 outlines the observational challenges and the key needs with respect to instrument development. The following three sections discuss the three geographical regions that are the focus of the program: the Southern Great Plains of the U.S., the Tropical Western Pacific, and the North Slope of Alaska (including the adjacent Arctic Ocean). Section 10 summarizes ARM's important connections to other programs. Section 11 briefly discusses data management. The final section provides a summary of the questions and priorities for the achievement of the Science Objectives of the program.

2. Observational and Modeling Strategies

2.1 Site-Based Observing Strategy, Duration, and Intensive Operation Periods

The programmatic objectives of ARM call for measurements suitable for testing parameterizations over a sufficiently wide variety of situations so as to span the range of climatologically relevant possibilities. In order to accomplish this, highly detailed measurements of radiation and optical properties are needed both at the Earth's surface and inside the atmospheric column, and also at the top of the atmosphere. Among the most critical factors determining the optical properties of the atmosphere is the distribution of liquid water and ice, i.e., clouds, within the atmospheric column. It follows that ARM must obtain sufficiently detailed measurements of the clouds and their optical properties.

The primary observational method is remote sensing and other observations at the surface, particularly remote sensing of clouds, water vapor and aerosols. It is impossible to meet ARM's objectives, however, without obtaining a large volume of detailed in situ measurements, some of which will have to be acquired from manned or unmanned aircraft; in addition, high-quality satellite observations are needed to measure the top-of-the-atmosphere radiation.

To obtain the requisite in situ and surface-based remote-sensing data, ARM is making measurements, over a period of years, at three sites, which are discussed briefly below and in detail later in this Science Plan. Satellite data are also being acquired, through cooperation with other programs, as discussed in Section 10.

The three ARM sites are as follows:

- *The Southern Great Plains (SGP) Site.* This site has been occupied first because it poses relatively simple logistical problems and because, in the course of a year, it plays host to virtually every kind of cloud system. It has both cold dry winter weather and hot muggy summer weather. It thus provides several climates for the price of one. Further discussion is given in Section 7.
- *The Tropical Western Pacific (TWP) Site.* This site is of great scientific interest because it features the warmest ocean waters, highest atmospheric water vapor contents, and most active convective cloud regimes in the world, and also because it plays a key role in the dramatic El Nino phenomenon that is associated with strong interannual weather anomalies throughout much of the world. Further discussion is given in Section 8.
- *The North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) Site.* This site is of particular interest because the polar regions are predicted, by climate models, to undergo the largest warming in response to increasing CO_2 concentrations; because of the important radiative effects of the sea ice; because satellite retrievals of radiative fluxes and cloud properties encounter significant problems in polar regions; and because the very low water vapor amounts may give rise to some unique and important radiative transfer phenomena. Further discussion is given in Section 9.

These sites were selected from a longer list through a process of prioritization and resource allocation, in order to provide opportunities to observe a wide range of climatologically important meteorological conditions, as summarized in DOE (1991).

ARM will collect data at each site over a period of years. One of the motivations for continuous data collection over such a long time is to document the range of variability, as required to meet the programmatic objectives. Particularly interesting and "extreme" phenomena often occur unexpectedly, and can be captured only through continuous and extended operations. In addition, continuous data collection over a period of years can begin to build up an "Atmospheric Radiation Climatology" for each site. There are several advantages to extended time observations:

1. Instruments can be calibrated and intercompared more reliably.

2. Long-term programs make more cost-effective use of more accurate and sophisticated equipment. More combinations of measurements can be used, revealing additional quantities (e.g., microwave radiometer together with cloud radar can yield profiles of liquid water content (LWC)).

3. Climatological data is valuable for testing of GCMs.

4. A great number of cloud regimes can be sampled, including the diurnal and annual cycles, as well as interannual variability. The chances for "good" case studies are improved.

5. There is more time to develop and test new instruments.

ARM's plan for data collection over a period of years has two key implications:

- Quasi-permanent facilities are needed, including provisions for adequate power, communications, sanitation, and transportation to and from the site. This means that there must be capital investments during the first phase of site occupation.
- Some types of measurements, such as those which require research aircraft, cannot be conducted routinely because of the expense, and so Intensive Observation Periods (IOPs) are necessary.

Up to now, IOPs have primarily consisted of more intensive measurements of the types that are routinely made anyway. In principle, however, IOPs should be expanded to include special measurements that are too expensive to make on a routine basis, e.g. to obtain in situ cloud and radiation data above the surface. Aircraft-based measurements are perhaps the best and most important example. Because of their high operating costs, aircraft can only be used by ARM on a campaign basis. The unique and essential role of aircraft in making in-cloud observations is recognized by ARM, although funding levels dictate that in most cases these will come through collaborations with other programs. Ground-based IOPs are also required. We note that a model of a combined aircraft and ground-based IOP was conducted during April 1994, at the SGP site. The Remote Cloud Sensing IOP utilized state-of-the-art remote sensors, developed mostly from the ARM Instrument Development Program (IDP), and an instrumented aircraft to jointly study a variety of cloud types over the site. Although the primary goals related to the IDP were to test remote sensor cloud retrieval algorithms and to intercalibrate and intercompare measurements, it is clear that these detailed cloud observations also represent a unique ARM dataset for the validation of cloud- and large-scale model predictions.

The nature of the IOPs that will be needed in order to answer ARM's scientific questions and to achieve its programmatic objectives cannot be fully planned out in advance for the entire life of the program. This suggests that we should view the ARM sites as facilities that are adapted, over time, according to the evolving research priorities within the climate-radiation-cloud arena.

2.2 Clouds and Radiation

To do radiation right in GCMs, we must get the clouds right. To get the clouds right, we must have good cloud observations—ideally, the four-dimensional distributions of their properties. ARM can determine the cloud structures and the resulting radiative fluxes based on several measurements made in the vicinity of the SGP site, and these can be interpreted as providing statistics representative of a single GCM grid column. Unlike an intensive, but limited, observation period program, ARM can provide cloud statistics which will be useful for comparisons with GCM simulations, as well as detailed time series, and also a continuous picture, of a column of atmosphere to compare with cloud-resolving models.

With respect to cloud observations, the overall issue is: How do large-scale and cloud-scale processes combine to produce the observed cloud fields? This is not only a parameterization problem, but a basic scientific issue—really, a whole set of issues, due to the variety of cloud systems. Each type of cloud system results from different formation processes.

Cloud structure and cloud optical properties are determined by both large-scale and cloud-scale circulations (via vertical motion on these scales). Cloud-scale circulations (including boundary layer circulations) are affected by large-scale circulations, radiation, and surface properties (by their destabilizing effects, for example), and in turn affect the large-scale circulation and surface properties (via convective and turbulent fluxes). Cloud structure and cloud optical properties have a large impact on radiative fluxes. Radiative and turbulent fluxes affect surface properties. The large-scale circulation is affected by convective and radiative heating.

The structure of many cloud systems is strongly influenced by cloud-scale circulations. Thus the problem of cloud parameterization for large-scale models involves the parameterization of cloud-scale circulations. Cumulus parameterization is a good example of this. Cloud systems in which large-scale processes directly determine the structure (i.e., cloud-scale circulations are not important) are much easier to parameterize (e.g., large-scale saturation) than those in which cloud-scale circulations are important (i.e., convective clouds, including cumulus, stratocumulus, altocumulus, and some cirrus). Such clouds often exhibit "intrinsic" fractional cloud covers less than one.

How do large-scale and cloud-scale processes combine to produce the observed cloud fields? The key quantitative questions are:

1. What is the cloud-scale structure and circulation of such clouds, in the context of the large-scale circulation and surface properties? Relevant cloud-scale measurements include vertical velocity, LWC, ice water content (IWC), effective particle sizes, cloud fraction, depth, etc.

2. How do large-scale processes lead to observed cloud structures and optical properties via cloud-scale processes?

3. What are the large-scale radiative fluxes associated with observed cloud structures?

4. Can cloud structure and properties be parameterized (i.e., related directly to large-scale processes)?

Most studies of cloud systems have not been framed in terms of large-scale processes; instead they have focused on cloud-scale or even microscale processes. Satellite observations remain the best way to characterize the large-scale cloud structure, but these approaches are still limited in scope and require further validation. Field programs that have made measurements of cloud-scale processes in the context of the large-scale circulation include GATE and ASTEX. This large-scale context is a crucial element of any field program aimed at developing cloud parameterizations. Another vital element is measuring the cloud-scale features of the cloud systems.

Aircraft have been traditionally used to obtain cloud-scale measurements of LWC, IWC, vertical velocity, cloud thickness, and effective particle sizes. However, ARM needs to use (and develop) remote sensing methods for extended time observations of these cloud-scale fields. There is simply no way that aircraft measurements can be used to characterize the cloud-scale properties over the area of a GCM grid column. Aircraft measurements, if done properly, can be used to verify remote sensing techniques, however.

2.3 Instantaneous Radiative Fluxes

There are two primary strategies through which ARM plans to achieve its programmatic objectives and address its scientific issues. The first is called the "Instantaneous Radiative Flux" (IRF) strategy. The second is single-column modeling (discussed in Section 2.4). IRF strategy relates directly to the first programmatic objective of ARM, as given in Table 1.1, and to the first and second Primary Scientific Questions of ARM, as given in Table 1.2. It consists of collecting data on the distribution of radiation and the radiatively active constituents of the atmosphere and the radiative properties of the lower boundary. The radiative properties of the atmosphere and the lower boundary can be used as input to radiative transfer models, including both detailed models with high spectral and angular resolution, and simplified models suitable for use as parameterizations in climate models. The results produced by the radiative transfer models can then be compared with the radiation measurements. A more detailed discussion is given in Section 3.

2.4 Single-Column Modeling

The IRF approach is crucial for the success of ARM, but it is not sufficient because it does not address the processes that control the radiative properties of the atmosphere. It does not, therefore, address the second programmatic objective or the first and fourth primary scientific questions, all of which involve the *processes that determine the radiative properties of the atmosphere.*

One approach to developing and testing cloud formation parameterizations involves the use of Single-Column Models (SCMs). The basic idea of an SCM is to measure the external forces at work on a column of the atmosphere that corresponds to a single GCM grid column, to use models to compute the cloud formation and radiative transfer processes inside the column, and to evaluate the results produced by the models through comparisons with additional observations. A more detailed discussion is given in Section 4.

2.5 Connections to Climate Models

The ARM Science Team must and does include representatives from numerous climate modeling groups around the world. These representatives provide the most direct channel through which ARM research results can affect climate model development and evaluation. In addition, ARM has strong links to ICRCCM (Intercomparison of Radiation Codes Used in Climate Models), FANGIO (Feedback Analysis of GCMs and In Observations), AMIP (the Atmospheric Model Intercomparison Project) and CHAMMP (Computer Hardware, Advanced Mathematics, and Model Physics). ICRCCM is sponsored through the World Climate Research Program (WCRP) and DOE's radiation model intercomparison. FANGIO is a DOE-sponsored GCM intercomparison project. AMIP is a WCRP program with major support from DOE. CHAMMP is a DOE-sponsored project to develop improved climate models. Further discussion of these and other programmatic links is given in Section 10.

3. Instantaneous Radiative Fluxes: Objectives and Measurement Needs

3.1 Introduction

Radiation is a quantity to which the Earth's climate is very sensitive. While the Solar Constant is 1360 W m^{-2}, a mere 4 W m^{-2} change in radiation flux at the tropopause, resulting from a doubling of CO_2, seems capable of producing dramatic changes in the Earth's equilibrium surface temperature and rainfall patterns. An extra 10 W m^{-2} at the ocean surface, if left unchecked by feedback effects, would raise the sea-surface temperature 1 K in just one year (assuming a 75-m deep ocean mixed layer). Hence, the precision with which meteorologists have been content to measure and calculate radiation fluxes in the atmosphere, i.e., 5-10% or tens of W m^{-2}, is simply inadequate for climate studies. Within the entire global change research program, ARM represents the only opportunity to bring atmospheric radiation measurements, and hence models, to the level of quality needed in climate studies.

A basic concept in the "instantaneous radiative flux approach" is that models and measurements must be analyzed together. Measurements are needed to check the theoretical foundations of models, while models are needed to understand and interpret data obtained from measurements. Typically, measurements are used to point out model deficiencies, but models may also play a role in identifying measurement deficiencies when measurement precision is pushed to the 1 W m^{-2} level that is needed to measure subtle climate change variations.

Atmospheric radiation is a transport problem whose time and space scales have generally not been factored into the design of past field programs. First, the transport is near-instantaneous. The entire radiation field adjusts almost instantaneously to changes in physical properties, so measuring those properties at times as little as a several minutes from the times of radiation observation may be useless. Second, radiation spatial scales have been factored into the design of past field programs only with great difficulty. A broadband flux measurement typically sums photons originating all the way from the visible horizon to the immediate neighborhood. Radiation time and space scales are smaller, usually by many orders of magnitude, than those accounted for in present climate models. These scale-facts-of-life present considerable challenges in designing a radiation observation component of ARM that is in conformance with the underlying assumptions built into radiation models.

All the physics underlying the radiative transfer equation—conservation of energy, Maxwell's equations, Lambert's Law, Planck's Law, Mie scattering—are well known, and the equation itself merely keeps track of photons as they are scattered, absorbed, and emitted. Some related physics—notably far-wing and continuum absorption and ice crystal scattering—are less well established and are in need of further study. From a mathematical point of view, the main difficulties in solving the radiative transfer equation occur in handling (a) multiple scattering; (b) polarization; and (c) more than one spatial dimension. Mathematical difficulties also arise when integrating over the spectrum but these problems can be overcome by band models. From a practical point of view, the main difficulty is knowing the input variables to the radiative transfer equation: temperature; surface boundary conditions; the absorption line parameters and spatial distribution of all radiatively-active gases; and the scattering properties and spatial distribution of cloud and aerosol particles. Integrals over space and time add further complications.

Plane parallel geometry, the assumption of horizontal homogeneity in a vertically inhomogeneous atmosphere, is the mainstay of current radiative modeling. With this geometrical idealization, theoretically rigorous treatment of multiple scattering (polarization included) is numerically practical for typical water clouds and aerosols for all wavelengths of the spectrum and for Rayleigh scattering. The results are used as benchmarks for comparing the performance of more approximate radiative transfer treatments such as two-stream and Delta-Eddington approximations that tend to be employed in GCM applications.

While plane-parallel geometry with horizontally homogeneous layers is most convenient for mathematical analysis and modeling, real clouds exhibit significant spatial inhomogeneity on both microscopic and macroscopic scales. The radiative effects of these inhomogeneities can be modeled using Monte Carlo and other three-dimensional radiative transfer techniques. These calculations show that spatial inhomogeneities tend to decrease cloud reflection and absorption and increase direct and diffuse transmission. Thus, a prime observational task of ARM measurements is to characterize the spatial cloud inhomogeneity on a GCM grid scale.

Climate radiation submodels have available, as input, only the larger scale variables prescribed or predicted by climate models; this further restriction creates the "parameterization problem." It is possible, of course, that present climate models do not furnish all the input necessary for an accurate calculation of radiation; for example, not all climate models now provide any information about cloud liquid/ice water within a grid square. One of ARM's jobs will be to find the "minimum ante"— the smallest set of variables that climate models must furnish to their radiation submodels to guarantee useful radiation predictions.

So far, we have not had atmospheric observations of the appropriate accuracy and with the spectral, time and spatial detail to determine whether or not present radiation submodels are performing to the accuracy required by climate studies. There also remain considerable uncertainties in the spectroscopic database underlying all radiation models, especially for water vapor. These inadequacies have led to a large variety of radiation models being used in the climate modeling community, despite climatically-important differences among them for the same atmospheric conditions, as documented by ICRCCM. Future progress in radiation modeling and parameterization, and hence in global change, depends crucially on order-of-magnitude improvements in radiation measurement capability at the surface and within the atmosphere, and concomitantly in measurements of radiation model input variables, to complement the improvements that have already taken place on satellites, e.g., the Earth Radiation Budget Experiment (ERBE).

3.2 Objectives

The radiation community looks to ARM to provide the testbed for development of accurate parameterizations with the use of radiation observations at the accuracies and resolutions appropriate to the task. Thus, the overall programmatic objective of the scientific studies conducted as part of the Instantaneous Radiative Flux portion of ARM may be simply stated as: *Develop and test radiation parameterizations at the accuracy required for climate studies.*

This general objective leads to a long list of scientific problems and questions, many of which are difficult to formulate quantitatively or address with specific measurements. Nevertheless, a partial listing of the key topics in radiative modeling for climate analyses illustrate the broad scope of issues that must be addressed. To do this in a focused fashion we have, therefore, built the IRF component of ARM around "grand hypotheses" testable with ARM observations. These hypotheses act as a kind of self-organizing principle and make setting of priorities much easier.

To highlight the hypotheses and their link to climate studies in GCMs, we list in the left column of Table 3.1 radiative modeling hypotheses or assumptions explicit or implicit in many GCMs. The right column of Table 3.1 summarizes the views of large segments of the radiation and climate modeling communities concerning these assumptions. The fact that simplifications have been made in GCMs does not mean that this community is unaware of the significance or the complexity of the issues that face parameterization of radiative processes. Our programmatic goal is to bring the parameterizations actually used in GCMs into line with new knowledge gained from ARM observations.

ARM is making mostly point and column measurements from the surface. While a significant effort is being made to "cover" a GCM grid square by use of Extended Sites, there will be far fewer Extended Sites at the Alaska and Tropical Pacific sites than at the Oklahoma site. So, especially for the Alaska and Pacific sites, satellites must be used to interpolate point and column measurements in order to get spatial averages—particularly for clouds—and eventually to extrapolate ARM-gained process knowledge to larger regions of which the ARM sites are presumably typical. Thus it is appropriate to examine various satellite hypotheses bearing upon the interpolation/extrapolation problem. Thus, we include in Table 3.1 hypotheses related to the use of satellite data that may be tested as part of ARM.

Table 3.1. Commonly used modeling approximations testable with ARM data. Here * means "observations lacking or inadequate," and ** means "modeling lacking or inadequate."

Common Assumption	**Best Current Understanding of Radiation and Climate Modeling Communities**
Clear-Sky Modeling Approximations	
1a. Present line-by-line (LBL) models are completely adequate for accurate reproduction of observed spectra.	1b*. Far-wing line shapes and the spectroscopic databases underlying LBL models are somewhat uncertain. Near-IR water lines are not well enough known and there were substantial changes in the near-IR spectroscopy in widely used programs like LOWTRAN and MODTRAN right up through 1992. There are nagging and climatically significant disagreements at the level of 10-30 W m^{-2} between UAV, AERI, and other observations and radiation models (LBL and GCM) both in the longwave and the shortwave, which cannot be explained with aerosols.
2a. Continuum absorption can be treated satisfactorily with formulations available from the early 1980s.	2b*. Continuum absorption is still not perfectly understood theoretically, and there are substantial differences among different formulations, including the spectral regions covered (some formulations cover the 20-micron window and the near-IR, some don't). Formulations developed in the early 1990s may be significantly better than earlier ones since in the longwave they are based on new data from SPECTRE, HIS aircraft observations, and ARM AERI observations.
3a. Continuum absorption formulations can be freely changed without changing the line absorption formulations, and vice versa.	3b. In the prevailing theory of continuum absorption, continuum absorption is really just the sum of thousands of far-wings of lines, and thus you can't change one without changing the other.

Table 3.1. (contd)

Common Assumption	Best Current Understanding of Radiation and Climate Modeling Communities
4a. Aerosols can be ignored in the longwave.	4b*. Observations with the AERI at the ARM SGP site indicate aerosols may be important at the 10 W m^{-2} level in the longwave. Aerosol optical depth is almost unknown in the longwave since all observations are made in the shortwave.
5a. Aerosols can be ignored in the shortwave.	5b*. Mt. Pinatubo aerosol produced measurable global cooling for a two-year period following the eruption. Anthropogenic aerosols may be regionally counteracting greenhouse warming. The indirect (Twomey) effect of aerosols on cloud albedo may be substantial for oceanic clouds.
6a. The solar influx can be ignored at wavelengths beyond 4 microns.	6b. The contribution of solar influx beyond 4 microns is about 5-10 W m^{-2}, and proved to be important in understanding systematic offsets between model calculations and accurate UAV longwave flux measurements.
7a. Plane-parallel (as opposed to spherical) geometry is an adequate approximation.	7b. Atmospheric sphericity is important for shortwave radiation for solar zenith angles between 80 and 90 degrees. Longwave radiation may also experience spherical-geometry effects in the upper troposphere and stratosphere, where long ray paths are possible.
8a. Horizontal radiative flux divergences are unimportant.	8b*. Horizontal flux divergences can be significant (compared to vertical ones) in the shortwave when the sun is away from the zenith. There has been almost no effort to measure horizontal fluxes.
9a. Horizontal variability is unimportant.	9b. This is a reasonable assumption except for water vapor. Raman lidar measurements have revealed that water vapor may have strong horizontal inhomogeneity on scales which are important for radiation.
Cloudy-Sky Modeling Approximations	
1a. Clouds are either liquid water or ice, but not both at the same time.	1b*. Mixed-phase clouds are common. Even some cirrus clouds contain liquid droplets. Liquid water and ice may even occur in the same cloud particle (e.g., an ice particle covered with a thin film of water).

Table 3.1. (contd)

Common Assumption	Best Current Understanding of Radiation and Climate Modeling Communities
2a. Shortwave cloud optical properties are determined entirely by liquid water/ice path and effective radius. Effective radius can be parameterized and/or specified from climatology.	2b*. For plane-parallel liquid clouds, this is a fair approximation. But if 3-D effects are important, then more information is needed. Effective radius may not be entirely parameterizable or specifiable from climatology. For plane-parallel ice clouds, an additional crystal shape dependent parameter is probably required.
3a. The only necessary measure of cloud horizontal variability is "cloud fraction".	3b*. "Cloud fraction" is inadequate for calculating radiative fluxes. The minimal information required is probably the probability distribution function of liquid water/ice path in a model grid square. Cloud aspect ratio is as important as "cloud fraction", especially in the longwave.
4a. Plane-parallel geometry is an adequate approximation for radiative flux divergences.	4b*. Radiative flux divergences are proportional to the mean intensity in 1-D radiative transfer, and mean intensities are particularly sensitive to 3-D effects such as clouds near the horizon (which negligibly affect fluxes). Thus there may be many cases where the plane-parallel assumption works for fluxes and not for flux divergences.
5a. Horizontal flux divergences are unimportant.	5b*. Deep inside clouds, where a radiation diffusion regime is established, horizontal net fluxes are small compared to vertical ones. But horizontal flux divergences near the edges of clouds, or spanning cloudy/clear regions, can be significant in the shortwave. They may also be significant in longwave situations, for example in a partially cloudy upper troposphere.
6a. Water vapor absorption inside clouds is well understood.	6b*. Water vapor absorption has never been measured in the laboratory at relative humidities above 70% or so. Quantum mechanical approximations for individual phases of water vapor absorption break down near the vapor-liquid-ice phase transition point. Water molecule cluster formation is a certainty near 100% relative humidity, but cluster impact on radiation is unknown.
7a. Liquid water clouds have unit emissivity in the longwave, and don't scatter.	7b. Liquid water clouds have variable emissivities, depending on total liquid water path and its horizontal distribution. They must therefore scatter, and if the scattered radiation is significantly "hotter" or "colder" than the locally emitted radiation, there will be a significant effect on radiative fluxes.

Table 3.1. (contd)

Common Assumption	Best Current Understanding of Radiation and Climate Modeling Communities
8a. Ice clouds have non-unit emissivity (usually fixed or a simple function of ice water path) in the longwave, but don't scatter.	8b*. Ice cloud emissivity and ice water path are poorly known. Scattering by ice clouds enhances the emission towards the surface in the window region; thus small differences from unity in their emissivity may have an amplified importance.
9a. Ice cloud particle shapes (if considered at all) are spheres or hexagonal columns. For the latter, the approximation of geometric optics is satisfactory.	9b*. Ice clouds apparently have asymmetry factors (0.75 or less) not explainable by either spheres or hexagonal columns. The relative infrequency of haloes indicates that ice particles do not generally scatter like hexagonal columns. The geometric optics approximation fails in the longwave, and also in the shortwave across the narrow dimension of the hexagonal columns.
10a. Clouds can be created in a GCM without significantly altering the temperature profile. Cloud top temperature is equal to that of the previously clear air.	10b. Cloud top temperature may be quite different from that of the surrounding air. Most clouds, not just boundary layer clouds, help create and maintain a temperature inversion at their tops which significantly alters the longwave radiative transfer.
11a. Multiple layers of partial cloud cover can be treated using the random overlap assumption.	11b*. It is not known which type of overlap assumption agrees best with observations.
12a. Horizontal inhomogeneity of a cloud field can be accounted for by using 'effective' radiative properties in a plane parallel homogeneous model.	12b. Model and observation studies of effects of horizontal inhomogeneity are in their infancy.
Modeling Approximations Dealing with Surface Boundary Conditions	
1a. Surface emissivity is unity. Scattering of longwave radiation from the surface is therefore zero.	1b. Surface emissivity can fall as low as 0.8 over deserts and as low as 0.92 over oceans. This considerably complicates longwave radiative transfer since it couples the up- and down-streams of radiation, as non-black clouds do.
2a. There is no angular dependence of surface albedo or emissivity.	2b. Both have substantial angular dependences.
3a. There is no spectral dependence of surface albedo or emissivity.	3b. Both have substantial spectral dependences.
4a. There is no surface specular reflection.	4b. Specular reflection (sun glint in the shortwave) is commonly observed over oceans and sometimes over ice sheets and vegetation as well.

Table 3.1. (contd)

Common Assumption	Best Current Understanding of Radiation and Climate Modeling Communities
5a. Surface shortwave albedo is independent of direct/diffuse ratio and cloudiness.	5b. Surface albedo depends substantially on direct/diffuse ratio for low and high solar zenith angles, and also on cloudiness (which is related), which further alters surface albedo through the multiple cloud-ground reflection phenomenon.
6a. Surface albedo and emissivity are independent of surface wetness.	6b. Both depend substantially on surface wetness.
Approximations Dealing with Satellites	
1a. Local observations can be interpolated using satellites.	1b. This is largely an item of faith. Few incisive studies have been done.
2a. Cloud optical depth and effective radius can be retrieved from satellite observations.	2b. There are various operational schemes for doing this, including the ISCCP and King/Nakajima algorithms, but the dramatic 3-D inhomogeneity of clouds makes in situ validation extremely difficult. Even the statistics of these quantities are poorly known, much less the instantaneous values seen by a satellite.
3a. Surface radiation budget can be retrieved from satellite observations.	3b. There are various operational schemes for doing this, but they tend to disagree with one another, so much so that a recent Langley DAAC CD-ROM of surface radiation budget retrievals included results from two schemes rather than pick a "best" scheme.
4a. The vertical profile of radiative flux divergence can be retrieved from satellite observations.	4b. There is some data and modeling work to suggest this can be done for clear skies, but almost none for cloudy skies. This is largely an unsubstantiated claim, since until the ARM UAV program almost no effort had been made to measure instantaneous column radiative flux divergences.

We note that data assimilation efforts are turning away from "retrievals", which in some ways degrade the information content of the original satellite radiances, and toward direct assimilation of those radiances. To the extent that data assimilation models then calculate correctly the quantities which were formerly "retrieved", this seems to make some of the satellite hypotheses unnecessary. However, we must be wary here, for data assimilation models contain radiation models which may not be correct, or even current, and thus radiation fluxes from assimilation may be no better than "retrieved" fluxes in spite of being better balanced with other variables.

There are other issues ARM is poised to address about which so little is known that hypotheses would be premature. Chief among these are:

1. What are the spatial and temporal statistics of radiation fluxes, and can these statistics be used to interpolate between spatially and/or temporally isolated measurements in order to obtain a spatial and/or temporal average?

2. To what extent do surface characteristics (e.g., wetness, temperature, roughness, vegetation, soil type) control radiative transfer processes?

3.3 Measurement Needs

The data requirements for IRF studies depend upon the hypothesis being tested or the problem being studied. Some problems may be studied at the surface, whereas others require observations from aircraft and earth-orbiting satellites. Instead of detailing requirements for specific studies, we list immediately below the overriding requirements for all such studies.

3.3.1 Radiation

Specific radiation measurement requirements include:

- *High spectral resolution with contiguous narrow spectral bands (as* opposed both to broadband and to discrete, widely-separated narrow bands). The minimum requirements are on the order of 100 wavebands in the longwave and 100 in the shortwave to start, in order to identify the physical causes of discrepancies between measurement and theory. ARM has made important strides in longwave spectrometry, and now needs to turn more attention to shortwave spectrometry.
- *High accuracy.* Absolute accuracy and high wavelength-to-wavelength precision are both essential. The goal in flux measurement is the order 1%, or 1 W m^{-2}, whichever is larger, and radiance should be measured to 1%. The standards exemplified by Valero flux radiometers and the Atmospheric Emitted Radiation Interferometer (AERI) longwave spectrometer need to become the norm; ARM should strive to have its radiation flux data be at least ten times as accurate as any other field program, and should not be satisfied with past low standards of performance.
- *Very high relative accuracy.* Because the measurements are recorded on a single detector, very high wavelength-to-wavelength precision is achieved in AERI and SORTI (a solar transmission spectrometer) measurements. This permits small variations in spectral cloud extinction to be used to retrieve optical depth and particle size information. Polarization measurements, which similarly rely on the relative intensity measurement of orthogonal intensity components, can routinely achieve 0.1% precision, which enables detailed aerosol properties, including shape and composition, to be inferred.
- *Excellent operational calibration.* We need well-maintained calibration facilities which may include, blackbodies and integrating spheres, to support all three ARM sites and routinely and regularly used at all of the ARM sites (including the Extended Sites) and for all the ARM UAV radiometers. Longwave calibration has made important strides, so now ARM needs to turn more attention to-shortwave calibration.
- *Fast time response.* Our aim should be to make radiation measurements fast enough to resolve significant temporal variations—otherwise the time series can be badly aliased, erratically jumpy, and confounding to data analysis techniques. The fastest component of the atmosphere affecting radiation is undoubtedly clouds, and for surface sampling, clouds can cause significant changes in the radiation field in 10 seconds or less; the 0.1 Hz sampling goal is nearly met with some of the surface radiometers in ARM, but a substantial effort is needed to bring all of the wide field-of-view, broadband radiometers to this mark. For angle scanning and high spectral resolution radiometers which need longer sampling times, care should be taken to avoid errors from temporal sampling biases. Simple, fast, scanning filter radiometers can be used to measure rapid sub-second changes in the radiation fields to fill in the gaps for the longer sampling times of high spectral resolution radiometers. In practice, there are limits to the utility of high time resolution, if the atmospheric state

cannot be characterized at a comparable speed. However, the increase of the resolution of both radiation measurements and the characterization of the atmospheric state are critical.

- *Angular resolution*. In addition to flux measurements, which lack angular information, we need measurements of radiance as a function of angle in order to further test and constrain models. In the longwave, we need angular scanning just in a plane, and this will be achieved with new filter radiometers. In the shortwave we need angular scanning both in the principal plane of the Sun and also azimuthally; it is not clear that the Whole Sky Imager is the best or most efficient way to obtain quantitative angular information; other methods need to be explored.
- *Spatial coherence*. The issue of the representativeness of point measurements of radiation repeatedly arises. Much effort in the past 70 years, and much present effort in fielding the global Baseline Surface Radiation Network, has rested on the untested assumption that point measurements of radiation are representative of large areas. With its system of Extended Sites and its central data system, ARM is perfectly poised to study the spatial coherence of a network of radiometers and test this assumption, but this will require frequent calibration of all radiometers.

3.3.2 Radiative Properties

The needs of IRF for defining the atmospheric state go well beyond what conventional radiosonde and satellite systems can provide. Because radiation responds instantaneously to the time-dependent atmospheric profiles, these profiles must be measured with high temporal and spatial resolution to test radiation models. (Because the profiles enter the radiative transfer equation in a highly nonlinear way, radiation calculated from averaged profiles is not mathematically equivalent to averaged measured radiation.) The ideal time scale is on the order of seconds, and the ideal space scale is a fraction of an optical depth. These ideals are difficult to achieve, but they must not be glossed over in the design of ARM. In the short term, useful tests of radiation models can be made using coarser-scale observations, by carefully selecting highly homogeneous atmospheric conditions, but the interest in such cases will quickly fade as we attempt to grapple with the much more prevalent inhomogeneous case.

The variables that must be measured as a function of distance (usually vertically) include:

- temperature
- water vapor
- ozone and other trace gases
- optical depth
- cloud particles: phase, shape and size distribution
- aerosol particle composition and size distribution
- single-scattering albedo
- scattering asymmetry factor.

Some of these quantities present formidable measurement difficulties, especially single-scattering albedo. The requirement for three-dimensional scanning to understand inhomogeneous cases is also daunting (see discussion of IDP in Section 6). But it is time to take the first steps on this journey.

3.3.3 Cloud Variables

The testing of three-dimensional cloud radiation hypotheses requires information-about the spatial variation of cloud optical properties and bulk geometry. No one knows exactly how little or how much information is really necessary, but clearly more information than single-aircraft probings, lidar backscatter, and cloud photography is needed. Some information concerning cloud amount and geometry can be obtained from the Whole-Sky Imager. Considerably more cloud information will become available with the installation of an operational cloud mm-radar. It is on this radar that hopes for the near term must rest. Nevertheless, these data will not enable us to directly measure cloud liquid water content, effective radius, or particle size distributions, which are needed as input by most three-dimensional radiative transfer models. Accurate estimates of these input parameters will require in situ observations or the development of reliable remote sensing retrieval techniques like microwave tomography, or combinations of passive microwave and active millimeter radar.

Satellite observations provide additional information concerning the distribution of cloudiness over a broader region encompassing the ARM site. Remote sensing techniques applied to such data may be able to provide bulk cloud particle size information, as well as fractional coverage, and bulk horizontal geometry.

It is important for the IRF group to more fully detail the requirements for cloud variables. This is the most notable gap in our plans for testing cloudy-sky radiation models.

3.4 Data Integration and Connections with Models

The fulfillment of the overall objective—the development of radiation parameterizations at the accuracy required for climate studies—requires a series of scale transitions from validation at the local scale to the cloud-scale to the small and large mesoscale to the GCM grid scale. Each transition will require different datasets and different strategies for their integration. Nevertheless, it is imperative to show that radiation models can be so ramped up in scale in the simplest case—clear skies—before we progress to the more difficult cases involving clouds.

For the cloud case, we first need to explain radiation at the central sites using the complete array of measurements available there: whole-sky imagery, ceilometery, lidar, cloud mm-radar, microwave profiling, RASS, radiosondes, and satellite observations. The next stage should be ramping up to scales of the order of 10 km, and so forth up to GCM grid scales. As scale increases, the information available will become progressively poorer and less sophisticated, and we must have excellent strategies for dealing with this problem.

The main such strategies are to use satellite data and operational numerical weather prediction (or other) analyses. There is a general feeling that satellite data will be able to close the radiation problem by obtaining accurate measurements at the top of the atmosphere for the larger spatial scales, as well as provide radiation budget information at the surface and within the atmosphere. Such techniques require the use of models for extracting and extending the satellite observations.

Thus, a strategy embodied in working up from small to larger scales with satellite data will help test many of the assumptions now implicit in the use of satellite data. This will result in a better product for ARM as well as for other studies that rely upon satellites.

Fixed placement of Extended Sites will make it more difficult to solve the scaling-up problem. ARM should allow some flexibility in the placement of Extended Sites. Parts of the Extended Sites, notably the radiometers, should be easily mobile, so that for example a dense network of radiometers could be set up around the central site for an 10P.

3.5 Community Models and Plug-Compatible Data

A 1-D Community Radiation Model, or a set of such 1-D models, would be extremely useful in speeding and facilitating the radiation effort. Currently, the field of radiation modeling is somewhat of a Tower of Babel, as revealed by ICRCCM, and if different ARM investigators use different models, giving different results, it will just create confusion. While it is premature to coalesce around a single model, the GCM community has shown the great benefits of having a well-written user-friendly community model (NCAR's Community Climate Model, or CCM) available freely to all. One need not fear loss of diversity as long as the community radiation models are modular and plug-compatible, like the CCM, and thus easy for investigators to change.

The ARM data also needs to be made easy for modelers to use. The only way the Science Team is going to be able to wade rapidly into the mass of ARM data and use it to test hypotheses is to have both data and models in an easy-to-use form, with the datasets designed ab initio to act as input files to the models: plug-compatible data to complement plug-compatible models.

3.6 Summary

The testing of the grand hypotheses listed above will largely answer portions of ARM science question 1 in Table 1.2. As the hypotheses are tested at the various ARM sites, question 2 regarding the variability of radiation and radiative processes in locales of key climatic importance will be answered as well.

ARM programmatic objectives will be achieved as the testing of hypotheses leads to improved parameterizations for use in climate models. The activities of the IRF are central to achieving the ARM program objective of relating observed radiative fluxes in the atmosphere to the temperature and composition of the atmosphere and to surface properties. Since the parameterizations of radiative processes play major roles in climate model forcing and feedback mechanisms, the radiative parameterizations developed by IRF studies will play essential functions in the development and testing of other parameterizations for predicting the distributions of properties that strongly affect atmospheric radiation, the second ARM programmatic objective.

4. Data Requirements for Single-Column Modeling

4.1 Single-Column Models

How can we test parameterizations that have been developed or are under development for use in GCMs? Here we discuss four possible approaches, all of which can be used in connection with ARM. We emphasize the fourth approach, called "Single-Column Modeling," for reasons explained below. Figure 4.1 illustrates three ways to test parameterizations.

The first and most obvious approach to parameterization testing is climate simulation itself. Here we "simply" perform a climate simulation and compare the results with observations. An advantage of this approach is that it tests the parameterization as it is intended to be used, i.e. in a climate simulation. There are several disadvantages, however. First, the results produced by a climate model are big and complicated, and depend on all aspects of the model, so that it can be very difficult to attribute particular deficiencies of the results to particular aspects of the model's formulation. Second, climate simulations are computationally expensive and time-consuming, so that only a limited number of runs can be made. Finally, the individual weather systems simulated by climate models do not represent particular weather systems in particular places at particular times in the real world, so only statistical comparisons with observations are possible.

A second approach is to use the parameterization in a forecast model, to perform numerical weather prediction, and then compare the forecast with observations. An important advantage of this approach is that it allows detailed comparison with data for individual weather events on particular days. It is expensive, however, since numerical weather prediction is an expensive business, although to the extent that the parameterization can be evaluated by using operational forecasts that must be done anyway this problem can be dismissed. As with tests in climate models, the results produced by a numerical weather prediction model are big and complicated, and depend on all aspects of the model, so that again it can be very difficult to attribute particular deficiencies of the forecasts to particular aspects of the model's formulation. A further difficulty is that a very elaborate data-ingest system is needed in order to do numerical weather prediction. Although such systems are in place at operational forecasting centers, they are not ordinarily available at climate modeling centers, and would be prohibitively difficult to set up.

In practical terms, the purpose of any parameterization is to compute certain "tendencies," i.e., partial time rates of change due to the particular process represented by the parameterization. For example, one can say that the purpose of a radiation parameterization is to compute radiative heating rates. A parameterization can thus be tested by evaluating its ability to reproduce observed tendencies for a given large-scale situation. This can be done outside the climate model.

There are in fact two approaches that involve testing parameterizations outside the climate model, and predictably both have advantages and disadvantages. The first is the "semi-prognostic test" In this approach, a parameterization or suite of parameterizations is exercised in the framework of a single atmospheric column, which can be thought of as a single column taken from a global climate model. In a global climate model, neighboring grid columns provide information that is needed to determine what will happen within the grid column in question; for example, low-level convergence of mass from neighboring columns tends to produce rising motion, and horizontal advection produces tendencies of temperature and moisture. In the semi-prognostic approach, there are no "neighboring grid columns," so all information that is needed from and would otherwise be obtained from such columns is provided, instead, from observations. In some cases idealized data may be supplied in place of real observations. Any errors in the computed local time rates of change must be due either to errors of measurement or, more to the point, to problems with the parameterization being tested. The point is that this approach isolates the parameterization being tested from all other components of the model; the test is "clean." This is an important strength of the method. An additional strength is that the semiprognostic test is computationally very inexpensive, compared to running a full large-scale model.

A semiprognostic test can be applied at a sequence of observation times, and we can think of these as being separated by "time steps." Because observations are used to specify the state of the atmosphere at each observation time, errors in the computed tendencies at the previous observation time have no effect; for convenience we summarize this by saying that there is "no feedback" from one time step to the next. This is both an advantage and a disadvantage. It is an advantage because it means that the time-averaged tendencies can be very wrong; a useful test, after all, is one that can be failed in many ways. For example, the parameterization might lead to a systematic erroneous warming tendency of 1 K per day at a certain level. After a sequence of many observation times, this would imply a huge time-accumulated temperature error at that level. The ability to produce such an error, or not, is a strength of the semiprognostic test. In other words, the semiprognostic test is a tough one because it is difficult to reproduce the observed time-mean tendencies. The lack of feedback from one time step to the next is also a drawback, however, because parameterizations can have deficiencies that arise directly from such feedbacks; problems of this type cannot be detected with semiprognostic tests.

Another problem with semiprognostic tests is that they increase the severity of the observation requirements, since everything that is not parameterized needs to be measured. For example if a cumulus parameterization is tested, the effect of the other physical processes such as radiative transfer and planetary boundary layer eddy fluxes need to be measured accurately.

The fourth approach for testing climate model parameterizations is somewhat similar to the semiprognostic test; it is called "single-column modeling." As the name suggests, a single-column model (SCM) can be regarded as a grid column of a climate model, again considered in isolation from the rest of the model. As in the semiprognostic test, observations are used to specify what is going on in "neighboring columns," and observations may or may not also be used to specify tendencies due to some parameterized processes, other than those being tested. The key difference between single-column modeling and the semiprognostic test is that in an SCM the results obtained for one observation time are used to predict new values of the prognostic variables, which are then provided as input for the next observation time.

A problem with SCMs is that the time-averaged total tendencies have to be about right; i.e., they have to be small, since, for example, various feedbacks will act to prevent an erroneous 1 K per day warming for 30 consecutive days. A second problem is that, although feedbacks that work inside a single column are active in an SCM, others, such as those involving the large-scale circulation, cannot be included. As a result, problems with the parameterization that involve such large-scale feedbacks cannot be detected using an SCM; they are best studied with a full climate model.

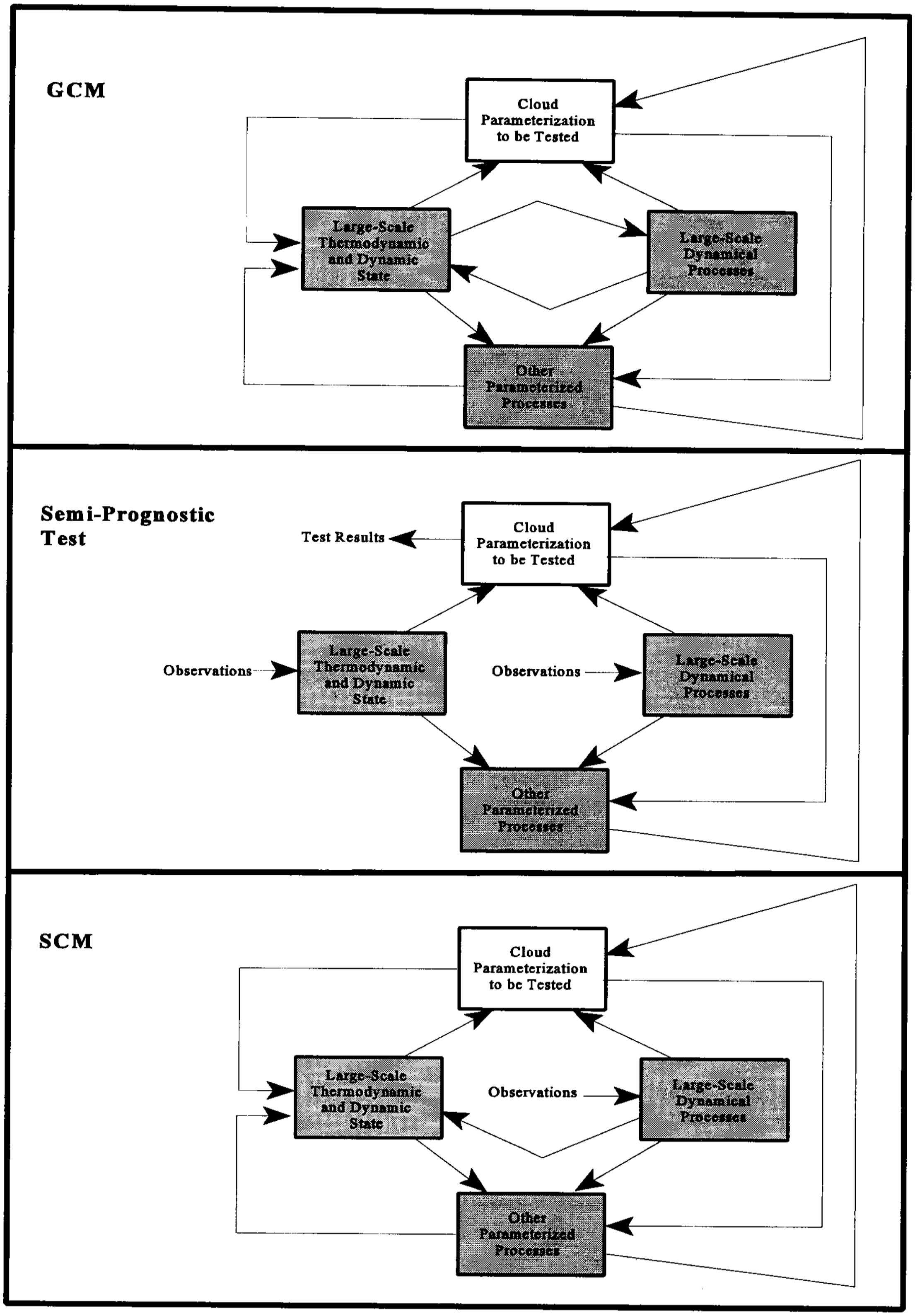


Figure 4.1. Three ways to test parameterizations: perform a climate simulation with the parameterization (top panel), perform a semi-prognostic test (center panel), or run the parameterization in a single-column model (bottom panel). See text for details.

4.2 Cloud Ensemble Model and Large-Eddy Simulation Models

A cloud ensemble model (CEM) is a numerical model that explicitly simulates cloud-scale motions, while parameterizing the small-scale turbulent motions. CEMs are designed to simulate the cloud-scale processes that must be parameterized in a GCM. A CEM domain may be considered to represent a GCM grid column, so that in a sense a CEM can be considered to be a detailed SCM. A CEM is based on a nonhydrostatic set of equations and typically includes a detailed turbulence parameterization, a bulk ice-phase microphysics parameterization, and interactive solar and infrared radiation parameterizations. A CEM simulation explicitly represents the cloud-scale convective circulations, as does a three-dimensional large eddy simulation (LES), but in a more approximate manner. A CEM parameterizes the small-scale turbulence using the same closures as one-dimensional turbulence closure models, but applies the closures only to scales smaller than those of the convective circulations. As with an SCM, the effects of specified large-scale vertical motion, horizontal advection, and horizontal pressure gradients can be prescribed from observations. The large-scale fields and tendencies required by a CEM are the same as those required by a SCM, and may be provided by ARM measurements. Likewise, the ARM observations of cloud and radiation fields used to verify SCM simulations may also be used to verify CEM simulations.

In the computational environment of the mid-1990s, a two-dimensional CEM is a good compromise between physical generality and economy. Within the next few years three-dimensional CEMs will become practical and ARM should consider supporting the development of such models.

An LES model (LESM) is three-dimensional, has a grid spacing on the order of 50 m or less in all three directions, and can explicitly represent all of the important flux-producing eddies that are at work inside clouds. This type of model is typically applied to the boundary layer, but in principle could also be applied to elevated cloud layers such as cirrus. LES models can also include detailed microphysics and radiation parameterizations. LES is very expensive computationally, so that simulations typically do not cover more than a few simulated hours, and are restricted to domains that are much smaller than GCM grid boxes. In this way, LESMs are quite different from CEMs.

CEMs and LESMs compute some things that are very difficult to observe, such as the vertical distribution of liquid water and ice. This simulated information is, in general, no substitute for real observations, because the models do contain parameterizations, notably microphysics and turbulence parameterizations, which introduce major uncertainties. LESM and CEM results are not reality. Nevertheless, the model results can be judiciously compared with SCM results in order to diagnose problems with the latter. A CEM may be used to study the GCM-grid-scale statistics of a particular type of cloud system, e.g., to determine how large-scale motion systems affect the formation and structure of the cloud system. The results of such studies can be used to develop and/or test cloud formation parameterizations for GCMs. Idealized and/or observed large-scale environments can be used in such studies.

It is possible to use a CEM/LESM and an SCM to develop or test a parameterization, and it is advantageous to use both. An approach involving both is illustrated in Figure 4.2. All information flows from the field data, which are used to drive the SCM and CEM/LESM, and also to evaluate the simulations obtained. The results from the CEM/LESM can also be compared with those produced by the SCM. Finally, the parameterization tested in the SCM can be transferred directly to a three-dimensional GCM.

Parameterization tests with SCMs and CEMs/LESMs can be of a "debugging" nature, or they can be physical tests like those indicated in Figure 4.2. There are other possible applications, however. For example, an SCM or CEM/LESM can be forced with suitable output generated by a climate model, an operational data assimilation system or with idealized forcing designed to mimic a situation of interest, or we can use it to study radiative-convective equilibrium and similar idealized problems.

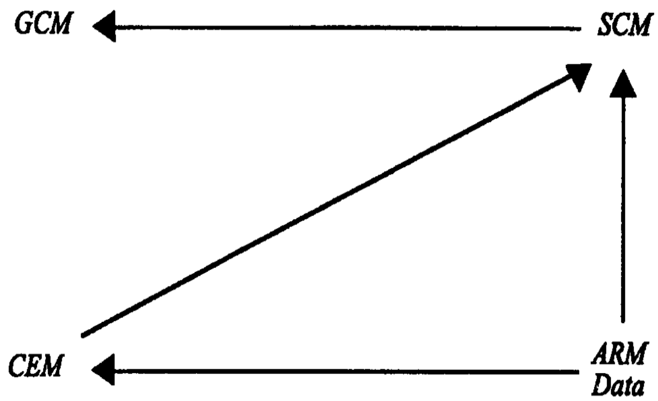


Figure 4.2. Diagram illustrating how a CEM and an SCM can be combined with ARM data to develop improved parameterizations for GCMs. The arrows in the figure show the "flow of information." This flow starts with the ARM data, in the lower right-hand corner of the figure. The observations collected during ARM are used with both the CEM and the SCM, in essentially the same three ways for both models. First, both models are initialized from observations. Second, both are "driven" with the observations of, for example, large-scale vertical motion. Finally, the results that the two models produce, in response to this observed forcing, are compared against other observations collected in ARM, e.g., observations of cloudiness and surface radiation.

4.3 An Overview of Data Requirements

The data requirements for an SCM and a CEM/LESM are essentially the same. They are summarized in Table 4.1. The variables listed in the table are offered only as typical examples; certainly the particulars depend on the formulation of the model and many more data would be needed for full evaluation of either an SCM or a CEM.

Some of the data listed in Table 4.1 can be obtained from in situ surface measurements, e.g., surface radiation and the surface fluxes of sensible and latent heat. Other data must be obtained from satellites, e.g., top-of-the-atmosphere radiation. Still other data can come from surface remote sensing, e.g., column water vapor measurements from microwave radiometers, or cloud water data from radar. Finally, some of the data must come from in situ measurements within the atmospheric column. An example is information about cloud and aerosol particle sizes, shapes, and compositions.

At the SGP site, the detailed measurements needed for the SCM approach can only be collected during Intensive Operational Periods (IOPs). At present, the SGP site plans to conduct at least three IOPs per year designed to collect data suitable for driving SCMs. These SCM IOPs are characterized by more frequent sonde launches from a larger number of sites, and also include more extensive data of other types.

It will be more challenging to use the SCM approach at the TWP and NSA/AAO sites, because of difficulty in obtaining the required data.

Table 4.1. Data requirements for SCMs and CEMs/LESMs.

Initial Conditions
Temperature sounding
Water vapor mixing ratio sounding
Vertical distributions of cloud water and cloud ice
Vertical profiles of the horizontal wind components
Mass of snow and/or liquid (e.g., dew or rain) stored on vegetation or ground surface
External Parameters
Solar constant
Latitude, longitude, Julian day and GMT
Surface characteristics (elevation, albedo, soil moisture, roughness, vegetation type, etc.)
Large-scale divergence
Tendencies of temperature, water vapor, cloud water, and cloud ice due to horizontal advection
Aerosol distribution
Data for Model Evaluation
All variables for which initial conditions are needed
Cloud amount as a function of height
Precipitation rate
Surface fluxes of sensible heat, moisture, and momentum
The same turbulent convective fluxes as functions of height
Solar and infrared (broadband) radiation fluxes, from the surface to the top of the atmosphere

4.4 Expanded IOPs: The Need for Campaign-Style Observations

If ARM is to succeed in its basic objective of improving GCM parameterizations of clouds and radiation, it must simultaneously attack two overriding problems. One is cloud formation: under what conditions do clouds occur, and how can this knowledge be incorporated in a GCM algorithm? The other is cloud characterization: what are the radiative properties of the cloud once it has formed, and how can these be expressed suitably for input to the GCM radiative transfer scheme?

To address the cloud formation and characterization issues together, ARM should provide, at least at the SGP site on a campaign basis, a substantially more extensive data set than is possible during continuous observations or even during conventional IOPs. These data will be especially valuable for SCM research and other process-oriented investigations. For the cloud characterization problem, the supplementary data must include in situ determinations of cloud micro-physical parameters, especially liquid and ice water content, particle size distributions, and aerosol. Vertical profiles of these fields plus conventional meteorological parameters would be an asset, as would careful determination of cloud base and top altitudes. These measurements require aircraft platforms in addition to radar and other surface-based sensors.

At the same time, cloud radiative properties should be determined experimentally to permit direct verification of parameterizations which compute radiative properties as functions of microphysical ones. Many leading GCM groups are developing and using such parameterizations, and it is known that GCM climate simulation results are strongly sensitive to the details of these schemes, so observational validation of them must have a high priority. For this purpose too, aircraft observations should supplement ground-based and satellite remote sensing data.

The need for aircraft observations and their high cost suggest that this is an area in which ARM should make special efforts to collaborate with other programs to achieve mutually beneficial results. Making ARM "airspace" over the SGP site available to airborne investigations with other sponsorship can provide valuable leverage to both ARM and its collaborators. As the technology of carrying out observations from unmanned aircraft matures, this novel approach should also be brought to bear on these types of measurements.

The cloud formation issue also requires a campaign-style effort to determine the GCM grid-scale environment which accompanies a given cloud population. In particular, an observational effort to close the grid-volume budgets of heat, moisture and momentum accurately is required. The data requirements for this effort should be based on the objective of forcing the SCM with sufficiently accurate fluxes that are determined from an objective analysis, possibly in conjunction with a four-dimensional data assimilation scheme. This is discussed further in the next subsection.

The sampling strategy and measurement accuracy criteria for this effort should be arrived at using observing system simulation experiments (OSSEs). This approach, pioneered in the context of large-scale NWP, uses model-simulated data as a substitute for actual measurements, and allows trade-offs (e.g., time vs. space resolution) to be examined objectively. The required measurements include not only the GCM grid-scale horizontal advective flux convergences, but also the surface energy balance components and boundary layer vertical fluxes, cloud parameters, radiative fluxes, etc.

4.5 The Roles of Objective Analysis and Data Assimilation

Among the data needed for modeling studies that deal with cloud formation processes are time varying vertical profiles of the large-scale vertical motion and the tendencies of temperature and moisture due to horizontal advection. These are, of course, particularly troublesome quantities to observe, and in fact they can only be obtained by very indirect means, which have been developed to overcome problems with missing data, instrument errors, and incomplete spatial and temporal coverage. Broadly speaking, there are two approaches. First, objective analysis methods can be used to combine measurements from various sources (e.g., rawinsonde data, wind profilers, etc.) in order to obtain synoptic descriptions of the large-scale dynamical and thermodynamic fields. These can then be differentiated (by approximate numerical methods) to infer wind divergence, horizontal gradients, etc.

Estimates of dynamical and thermodynamical fields based on objective analysis (without a first guess provided by a model) are independent of physical parameterizations, which is a highly desirable feature. Some preliminary studies suggest, however, that the errors associated with objective analysis are sometimes too large to meet the stringent SCM measurement requirements. The errors are likely to be particularly large in data-sparse regions such as the Tropical Western Pacific or North Slope of Alaska or for variables either poorly sampled or subject to large measurement errors (i.e., water vapor, microphysical parameters, and vertical motion).

A second approach is to make use of products obtained through data assimilation. Many data assimilation methods include objective analysis, but supplement it by forcing the diverse observations to be consistent with the short-range predictions of a forecast model. Data assimilation procedures have been developed to handle incomplete and redundant sets of diverse data, and to provide a description of the atmosphere that is consistent with the underlying physics such as, for example, the balance between the dynamical and thermal structure. Multiple estimates of the same quantity can be reconciled in a way that takes into account the error characteristics of each data source. Data assimilation may also offer the opportunity to drive SCMs with products that include scales of motion below GCM resolution.

Data assimilation products are readily available from the operational forecast centers, such as the U.S. National Center for Environmental Prediction (NCEP, formerly the National Meteorological Center) and the European Centre for Medium Range Weather Forecasts (ECMWF), and offer high-resolution global coverage with, potentially, high time resolution as well.

A problem with data assimilation is that the physical parameterizations of the forecast model do affect the results, particularly in data-sparse regions. This is a particularly worrisome problem for vertical motion and water vapor. For example, suppose that the model used for assimilation employs parameterization A to represent some process, and that an ARM researcher wants to use the assimilation data products to drive an SCM in order to test parameterization B for the same process. The researcher may well be concerned that the fact that the assimilation has been influenced by parameterization A will prevent a valid assessment of parameterization B.

Assimilation products nevertheless offer unmatched spatial coverage and comprehensive information about the dynamical fields, and there is little question that they will have to be used to drive SCMs and CEMs/LESMs, particularly for the TWP and NSA/AAO sites. While there are problems with the approach in data sparse regions, objective analysis in the same regions would in most cases have greater problems.

ARM could choose to supplement the operational data assimilation with its own local assimilation that incorporates additional data (e.g., surface fluxes and column cloud water, and precipitable water, which are not presently assimilated by operational models) into both high-resolution models that explicitly resolve deep convection, and regional models with resolution comparable to that of GCMs. Such a local assimilation can be designed to take advantage of ARM data not routinely assimilated the operational centers, such as the relatively high temporal resolution of the measurements over the Southern Great Plains and IOP data. Clearly data assimilation with high resolution models and regional models with resolution comparable to that of GCMs are meant to serve different ARM objectives. The coarse resolution models are aimed at improving estimates of the large scale forcing and providing estimates of the boundary conditions for an SCM. On the other hand, high resolution models are aimed at providing an estimate of the sub-grid scale variation within an SCM-sized area that is free of some of the parameterizations used in the coarse grid models.

Any decision to set up an in-house data assimilation effort for ARM should be based on obtaining satisfactory answers to the following three questions:

1. What quantitative improvements in data products can be obtained by using 4DDA in addition to objective analysis, for each of the three planned sites?

2. If it is determined that 4DDA can indeed provide quantitatively significant improvements in data products for use by ARM investigators, can these improvements be obtained by taking advantage of existing 4DDA efforts at NCEP, ECMWF, or the Forecast Systems Laboratory, or could ARM significantly benefit by setting up its own separate, dedicated 4DDA activity?

3. If a dedicated ARM 4DDA activity is determined to be potentially beneficial, then how much will it cost? Are the benefits large enough to justify the cost?

4.6 Summary

Among the several methods for testing GCM parameterizations by comparison with observations, the Single-Column Modeling approach has some unique advantages. SCM-based tests are inexpensive, and the results are not affected by errors arising from the other components of the model. Cloud Ensemble Models are a useful supplement to SCMs, and can be used in much the same way with essentially the same data requirements. SCMs in conjunction with LES and CEMs can be used to investigate basic physical questions, develop cloud amount parameterizations, and evaluate the sensitivity of model results to parameter changes. In support of ARM, SCMs and CEMs will be particularly valuable for testing parameterizations of cloud formation, maintenance, and dissipation.

The data required to drive the SCMs, LES models, and CEMs, and to evaluate their performance, are not easy to obtain. ARM has the potential to provide uniquely valuable data for SCM-based parameterization testing. Efforts are under way to "package" data collected at ARM's Southern Great Plains Site in a form particularly convenient for use with SCMs and CEMs.

5. Testing Cloud-Radiation Models: Model Hierarchies and Validation

This brief chapter has two aims. First, it serves to summarize how the ARM data can be used to test GCM-class cloud radiation parameterizations (GCM-RTMs), parameterizations of cloud optical properties, and detailed radiation models. Second, it discusses briefly how the GCM-RTMs relate to the more detailed RTMs used in the IRF studies. The GCM-RTMs, whose goal is to capture the effect of clouds on the radiation field while minimizing the extent to which details of cloud microphysics need to be explicitly included in a GCM, are an important approach to the parameterization of the solar and terrestrial radiation fields in climate models.

To link the IRF and SCM approaches to the analysis of ARM data, an understanding of the space-time variability of radiation is essential. To date, the IRF approach has concentrated on the validation of clear sky LW radiances; that sort of information is to be used to test and guide the cloud parameterizations in SCMs, which generate both clouds and radiative fluxes. We need a means to turn the flux measured by a surface radiometer at several points (e.g. at the SGP site) into an estimate for the area-averaged flux generated by a GCM grid box. We also need to convert directional satellite radiances into integrated fluxes. Such efforts have to focus on the space-time variability of radiation.

Tests of new or existing cloud-radiation parameterizations involve a number of different aspects of cloud-radiation interactions. Information sufficient to test new multidimensional multispectral radiative transfer models (M^2RTMs) is required. These models are analogous to the CEMs described in the previous chapter and, in principle, require a full three-dimensional description of cloud optical properties and associated measurements of radiative intensities and fluxes. Such a complete description is beyond the scope of present instrumentation and implementation plans. The extent that existing or available remote sensing tools can be used to provide sufficient distributions of optical properties and the extent that existing radiation measurements can be used to test these models needs to be investigated.

Because the GCM-RTMs have their origin in simple one-dimensional versions of (M^2RTMs), it is expected that new schemes will directly evolve out of the (M^2RTMs) currently being developed as part of the ARM activity. GCM-RTMs also require as input, at a minimum, the vertical distribution of cloud optical properties. Just how horizontal variations are to be treated is currently an issue of research. Thus the data required to validate (M^2RTMs) are also relevant for validation of GCM-RTMs. This is quite analogous to the commonality of data needs between SCMs and CEMs.

A fundamental aspect of the validation of either (M^2RTMs) or GCM-RTMs is the need to test the way in which cloud optical properties are parameterized. These properties include

1. the spectral distribution of extinction

2. the spectral distribution of absorption

3. the scattering phase function and its variation with wavelength.

Testing the parameterized relationship between these properties and the microphysics of clouds is crucial.

We can formulate several requirements that must be addressed in linking GCM-RTMs to (M^2RTMs):

1. *The spectral variation of radiation, particularly as it relates to solar transmission, in cloudy atmospheres*. We have models for this, but very little data with which to evaluate the models.

2. *Relationships to convert measured radiances into irradiances*. This is a classic and crucial problem for both satellite and high-altitude aircraft observations, and is important for surface observations as well when high-resolution spectral measurements are made with interferometers or spectrometers.

3. *Relationships between observations at a few points and area-averaged observations*. Given a set of flux observations over some grid area, what are the spatial and temporal correlation scales of the observations? Given observations for different spatial domains, what are the appropriate averaging lengths and times?

4. *The linkage between bulk cloud properties, spatial distributions of those properties and flux transmission*. Given some measure of the bulk properties of clouds (such as those likely to be diagnosed in GCMs) how are these bulk properties distributed statistically in space and what is the impact of that distribution on radiative transfer? This is perhaps the most important issue facing us right now in terms of improving the linkage between the parameterization of the formation of clouds and RTMs.

5. *The full blown three-dimensional radiative transfer problem*. Given a three-dimensional specification of cloud properties, can we calculate the radiative transfer field and can we use ARM data to evaluate the realism of the results?

Two classes of observations are required to test (M^2RTMs) and GCM-RTMs. First, as stated above, the three-dimensional distribution of optical properties is required, and the relations between optical properties and the other microphysical properties of clouds need to be established. Such a description of the optical medium is beyond present and future capabilities. However, existing remote sensing tools such as lidar and mm-radar, coupled with spectral radiometers and satellite measurements, may provide information that can be directly related to cloud optical properties at selected wavelengths. Certainly the active probes provide information about the vertical and horizontal structure of the clouds.

Second, measurements of relevant spectral and broadband radiometric quantities are also required to test the output of both (M^2RTMs) and GCM-RTMs directly. Clear-sky radiative flux measurements and comparisons to line-by-line and GCM-RTMs are part of the IRF activity. Extension of these activities to cloudy skies is required.

Pending measurements of the 3-D distribution of cloud properties, there is a great deal that we could do to better utilize the observations that we do have. We need to emphasize the use of mm radar and lidar observations to diagnose the internal structure of clouds and the scales of variability in optical properties. This can be done for starters with 1-D height observations as a function of time. The observations of structure can be convolved with passive spectral measurements to deduce optical properties. There is definitely a need to improve our measurement of spectral solar properties at the ARM sites.

ARM' s planned RTM validation strategy has several components, driven by the considerations discussed above:

1. Test and modify GCM-RTMs using the SCM approach and with data observed at the central facility (i.e., test the models when we know most everything and identify the missing observations).

2a. Compare SCM ARM-grid averaged surface radiation calculated using current radiation parameterizations with observed values using surface and satellite derived cloudiness as input to the SCMs. The comparisons should stress a hierarchy of cases going from the very simple to the more complex.

2b. Repeat 2a. with (M^2RTMs) and use results and intercomparisons with 2a. to identify areas requiring additional improvement (i.e., parameterizations and observations).

3. Compare SCM/CEM ARM-grid averaged calculated/ predicted cloudiness with surface and satellite cloud estimates as in 2a to identify deficiencies

4. Compare SCM/CEM surface and perhaps top of atmosphere radiation calculations using calculated/ predicted cloudiness with observed properties of the radiation field. How do the radiation quantities derived in such experiments differ from those found in steps 1 through 3 above? What are the differences and how are these related to the various cloud optical and formation problems?

5. Redesign numerical experiments and observational requirements as necessary to reduce the errors. This could include design of IOPs to directly and indirectly measure cloud optical properties (i.e., component (iii)).

6. Use existing SGP observations that have been collected during past IOPs, including lidar and radar measurements, to develop a test bed for the development of tools for deriving cloud optical properties.

7. Conduct IOPs using indirect and direct measurements of cloud optical properties, as the tools for deriving cloud optical properties evolve.

8. Test GCM-RTMs coupled to SCMs, in order to evaluate both the cloud prediction schemes of the SCMs and the radiative transfer parameterizations in a coupled fashion.

9. Employ CEM output from those models capable of predicting three-dimensional distributions of clouds and their microphysical properties to test (M^2RTMs) and the parameterization of three dimensionality in GCM-RTMs. The output of such models will provide a more complete description of the cloudy sky properties than will be available from direct measurements.

The first priority has to be to validate the current radiation models against ARM observations of the cloudy atmosphere. This has to be done with the GCM-RTMs and also with the (M^2RTMs), in the latter case spectrally, angularly, and spatially. The second priority is to use remote sensing measurements to infer cloud structure and begin to incorporate that into two-dimensional and three-dimensional models, again validating the modeling results against ARM observations.

6. Instrument Development

6.1 Goals

The observational objectives of the ARM Program are ambitious, and in response to these objectives, the program has already achieved many state-of-the-art advances in observing systems. The continued advancement of observing capabilities, carefully constrained by the overall scientific goals, is a very important aspect of ARM. While many ARM objectives are clearly achievable with the careful application of previously demonstrated measurement approaches, meeting some objectives requires further scientific assessment and fundamental research and development. A key to the ultimate success of ARM is continued evaluation of the needs for new observing capabilities as progress is made in understanding the important scientific issues. The free and active feedback between the identification of what *should* be measured and the determination of what *can* be measured will achieve a balanced selection of the most crucial earth systems properties to observe and the corresponding observing systems.

From the start, it was recognized that the observational objectives of ARM exceed the capabilities of existing instrumentation. The goal of the Instrument Development Program (IDP) of ARM is to bring existing research instrumentation to the advanced state of development required to allow routine, highly accurate operation in remote areas of the world, and to develop new instrumentation as requirements are identified. While it is the goal of ARM to make many of the observations in an operational mode with unattended instrumentation, the need to make some important observations in the research mode and from aircraft platforms during special campaigns or intensive operating periods is also recognized.

The evolving ARM IDP has combined components of basic research into improved remote sensor system and techniques (i.e., cloud retrieval) development, and an engineering effort intended to provide within the CART setting a kernel of instruments to adequately characterize the local atmosphere. The initial IDP research activities were successful in identifying this set of instrumentation and suggesting suitable atmospheric property retrieval approaches. Currently, effort is directed toward placing these sensors at CART sites and validating the analysis approaches. The next step is to develop the means to convert the CART remote sensor data stream into the types of derived data quantities that are necessary to comprehend the effects of the clouds and clear atmosphere on the IRF and GCM-class radiative transfer models. The interpretation of multiple remote sensor datasets in terms of radiatively important cloud quantities, e.g., remains a challenging avenue of research. The wise use of focused IOPs involving CART and more advanced remote sensors, and dedicated research aircraft, will facilitate this process.

The observing challenge of ARM is illustrated in Table 6.1, which lists the earth system properties associated with the goals set forth in Sections 3 and 4, and the corresponding instrument systems currently available to address the need. For some properties, especially cloud characteristics, it is not clear that the currently planned instrumentation is adequate. It is part of the ongoing scientific challenge of ARM to identify these deficiencies and to formulate new approaches. The IDP is the mechanism inside the ARM Program to develop essential new observing systems. The following subsections describe the significant achievements of the IDP to date, which have resulted in new operational systems as well as observing capabilities still under development.

Table 6.1. Instrumentation that could be used by ARM to address the observational requirements of the Instantaneous Radiative Flux and Single-Column Modeling strategies. Not all of the instruments listed here are firmly committed for use in ARM.

Property	ARM Instrument Type
Surface-based Radiation: IRF and SCM Evaluation	
Solar Spectral Flux	Cosine angular response, Beam and Diffuse, Spectral radiometer (Rotating Shadowband Spectrometer [IDP] and Multifilter Rotating Shadowband Radiometer, MFRSR, 0.4-1.0 μm).
Solar Spectral Radiance	Sun-tracking, Absolutely calibrated, Fourier Transform Spectrometer (Absolute Solar Transmission Interferometer, 1-5 m, ASTI [IDP])
IR Spectral Radiance	Zenith viewing, Absolutely calibrated, High spectral resolution Fourier Transform Spectrometer (Atmospheric Emitted Radiance Interferometer, 3-19 μm, AERI [IDP]), and higher resolution, 6-14 m, AERI-X [IDP]
IR Spectral Transmittance	Sun-tracking, Ultra-high resolution, Fourier Transform Spectrometer (Solar Radiance Transmission Interferometer, 2-14 m, SORTI [IDP])
Solar Radiance Angular Distribution	Wide Field-of-View Multiband Imager (Whole Sky Imaging System, WSIS [IDP])
Solar Flux, Downwelling and Upwelling	Pyranometers: Shaded and unshaded, uplooking and downlooking from 10 and 25 m; downward looking multifilter radiometers
Solar Beam Flux	Pyrheliometer on sun tracker
IR Flux, Downwelling and Upwelling	Pyrgeometer, shaded uplooking and downlooking from 10 and 25 m
Solar and IR Net Flux	Net Flux Radiometers sampling lower atmosphere from Tethered Balloon (Net radiometer profiler [IDP])
Airborne: IRF and SCM Evaluation	
Solar Spectral Flux	Cosine angular response, Beam and Diffuse, Spectral radiometer
IR Spectral Radiance: High spectral resolution, limited spatial coverage	Up, Down and fixed angle viewing, Absolutely calibrated, High spectral resolution Fourier Transform Spectrometer (UAV-based Atmospheric Emitted Radiance Interferometer, 3-25 m, AERI-UAV)
Solar and IR Spectral Radiance: High Spatial Resolution, limited spectral resolution	Imaging, Spectral Radiometer (UAV-based Multi-spectral Pushbroom Imaging Radiometer, MPIR)

Table 6.1. (contd)

Property	ARM Instrument Type
Solar Flux, Downwelling and Upwelling	Radiometers, using electrical substitution for calibration, Uplooking with shadowband, and downlooking (UAV)
IR Flux, Downwelling and Upwelling	Radiometers, using electrical substitution for calibration, Uplooking with shadowband and downlooking (UAV)
Atmospheric State information : 1RF and SCM initialization and Evaluation	
Temperature Profiles	• In situ balloon-borne temperature sensor (Balloon Borne Sounding System, BBSS) • Radar reflection from acoustically stimulated disturbance (Radio Acoustic Sounding System, RASS) • Boundary layer remote sensing from High spectral resolution downwelling emission spectra (AERI) • Raman Lidar density measurements in aerosol-free regimes of the troposphere
Water Vapor Mixing Radio Profiles	• Raman Lidar (IDP) active sensing up to 8.5 km at night and at least 3 km during daytime (without clouds) • In situ balloon-borne Water Vapor sensor (BBSS) • Boundary Layer remote sensing from High spectral resolution downwelling emission spectra (AERI) • Two-channel microwave radiometers give total water vapor content • Global Positioning Systems give total water vapor content
Ozone Profiles	• In situ balloon-borne ozone sensor(BBSS) • Remote sensing from High spectral resolution solar absorption spectra (SORTI) • Remote sensing from High spectral resolution downwelling emission spectra (AERI) • Surface in situ measurements
Optical Depth, Clear Sky	• Cosine angular response, Beam and Diffuse, Spectral radiometer (Rotating Shadowband Spectrometer (IDP), and Multifilter rotating shadowband radiometer, MFRSR, 0.4-1.0 µm • Sun-tracking, Absolutely calibrated, Fourier Transform Spectrometer (Absolute Solar Transmission Interferometer, 1-5 µm, ASTI (IDP) • Sun-tracking, Ultra-high resolution, Fourier Transform Spectrometer (Solar Radiance Transmission Interferometer, 2-14 µm, SORTI (IDP) • IR filter radiometer for cloud optical depth.

Table 6.1. (contd)

Property	ARM Instrument Type
Cloud Geometry	• Micropulse Lidar (IDP) • Ceilometer • Cloud Radar (IDP) • Raman Lidar elastic backscatter (IDP) • CO_2 Lidar (IDP) • Whole-Sky Imager
Cloud optical depth and emissivity	• Lidar plus AERI or IR Radiometer emissivity (narrow-beam) • Raman lidar (elastic attenuation) (IDP) • Solar photometer (thin clouds) • MPL (thin cloud optical depth) (IDP) • Radar (IDP) plus microwave radiometer (thick water optical depth)
Ice/liquid discrimination	• Micropulse Lidar depolarization (IDP) • Microwave Radiometer • AERI (for thin clouds) (IDP) • Dual-wavelength CO_2 lidar (IDP) • Raman Lidar depolarization • Millimeter-wave Radar
Vertical distribution of cloud liquid and/or ice content	• Cloud Radar (IDP) • Microwave Radiometer • AERI (IDP) or Infrared Radiometer • CO_2 Lidar (IDP) • Comprehensive retrieval algorithms
Column-integrated ice and liquid content	• Microwave radiometer (water) • AERI (for thin clouds) (IDP) • Integral of above vertical profiles
Cloud effective radius	• AERI plus MPL lidar (IDP) • Radar (IDP) plus Microwave Radiometer (stratus) • CO_2 Lidar plus Radar (ice) (IDP) • Radar plus AERI or IR Radiometer (IDP)
Cloud radiative properties: effective radius, single scattering albedo, scattering asymmetry factor	• CO_2 Lidar 2 • Cloud Radar (IDP) • AERI for effective radius
Aerosol vertical distribution and optical depth	• Micropulse Lidar (IDP) measures backscatter signal • Raman Lidar (IDP) backscatter signal • CO_2 Lidar
Precipitation Rate	• Surface meteorological observation systems • 915 MHZ radar reflectivity observations • Oklahoma and Kansas State University mesonets • NEXRAD

Table 6.1. (contd)

Property	ARM Instrument Type
Winds	• Profiler network • Sondes • Surface meteorological observation systems
Mass of Snow and/or ice liquid stored on vegetation of ground surface	• Surface meteorological observation systems
Surface fluxes of sensible heat, moisture, and momentum	• Energy balance bowen ratio stations • Eddy correlation systems

6.2 Radiometer Development

6.2.1 Multi-Filter Rotating Shadowband Radiometer (MFRSR)

This instrument measures diffuse solar radiation in the 400 to 1000 nm spectral region. After successful field testing and acceptance of a prototype at the central site, 23 of the instruments are planned for use at the Southern Great Plains boundary facilities.

6.2.2 Fast-Response IR Filter Radiometer

This instrument measures infrared radiance in spectral bands of about one micron width in the IR atmospheric window. The instrument is an improvement of a type used for many years with lidar in the LIRAD method. The method gives information on cloud IR optical depth, cloud phase, cloud ice crystal habit and size. It can detect cloud changes at time intervals shorter than one second and can scan in one plane.

6.2.3 Atmospheric Emitted Radiance Interferometer (AERI)

AERI measures downwelling infrared radiance in the spectral region (520 to 3020 cm^{-1}). As in the case of the MFRSR, the instrument had considerable development before ARM funding through experience with the High-resolution Interferometric Sounder (HIS). AERI performed well during SPECTRE and has since continued to produce high quality data during a variety of experiments.

6.2.4 Solar Radiance Transmittance Interferometer (SORTI)

This instrument measures ultra-high spectral resolution transmission by solar tracking at ground level. The spectral resolution is 0.0035 cm^{-1} (apodized) over six spectral bands in the interval 700 to 4000 cm^{-1} (2.5 to 14 μ). The prototype is now at the SGP and operational version is planned for the summer of 1996.

6.2.5 Absolute Solar Transmission Interferometer (ASTI)

This instrument is solar tracking and measures solar spectral radiance with an accuracy of 1 to 3%, with a spectral resolution of 4 cm^{-1} over the spectral interval 1950 to 10500 cm^{-1} (1 to 5 m) in three bands. The instrument is scheduled for testing at the SGP in the summer of 1996.

6.2.6 A High-Resolution Atmospheric Emitted Radiance Interferometer (AERI-X)

This instrument is a high-resolution version of AERI and is still under development. It will measure zenith sky radiance from the ground with a spectral radiance of 0.1 cm^{-1} (apodized) over the interval 700 to 1500 cm (6 to 14 μ). The radiance accuracy will be the same as AERI and with a measurement sequence of 20 min. The instrument is scheduled for the SGP site in the summer of 1995.

6.3 Radar-Lidar Development

6.3.1 Cloud Profiling Radar

Millimeter wave radars are able to penetrate a wide variety of clouds which are opaque to other optical and infrared remote sensors. A fully polarimetric scannable cloud radar at 33 and 95 GHz was designed, built and operated at the CART site by the University of Massachusetts, which successfully obtained cloud boundaries, cloud micro-physical information and particle fall velocities at both frequencies. Although the cost to build and operate the multifrequency radar system is less than comparable lidar systems, it was decided that a simpler single frequency 35-GHz zenith-pointing (nonpolarimetric) Doppler radar would adequately measure cloud boundaries and particle fall velocities. It therefore funded the Environmental Technology Laboratory (ETL) of NOAA to design and build a 35-GHz zenith-pointing system, which will be demonstrated at the SGP Central facility in the fall/winter of 1995. At the present time, the microphysical information that can be obtained from a single frequency millimeter wave radar, such as cloud particle phase, is limited. Ongoing research with the UMass radars and other millimeter wave radars are aimed at determining how such radars can differentiate between cloud water and ice particles and possibly determine the cloud ice and water content.

6.3.2 Micropulse Lidar (MPL)

This project was to develop an eye safe laser ceilometer that could measure cloud base heights and aerosol profiles from the surface to 20 km. This instrument was successfully operated during the PROBE experiment during 1993, and was successfully tested and is now operating at the Southern Great Plains site. The MPL has already demonstrated its value by collecting an extended dataset, and relatively simple improvements involving the addition of a depolarization channel (for water-ice cloud discrimination) and greater sensitivity (e.g., increasing average laser power or the telescope size for better day-time cloud top heights) may yield further benefits. A polarization-sensitive MPL may make unique contributions. These are: i) extremely accurate cloud base, and for cloud optical thicknesses of less than about 2.0, cloud top heights; ii) an estimate of optical thickness for optically thin clouds; iii) a measure of the distribution of aerosols in the troposphere (and stratosphere at night); and iv) unambiguous water-ice cloud discrimination.

6.3.3 Raman Lidar

This instrument was developed by taking advantage of the experience gained during many years of development and operation of the NASA/GSFC Raman lidar, and more recently the Sandia Raman lidar. These instruments have been successfully operated during a variety of campaigns, including collocated measurements at NASA/GSFC and during the April 1994 SGP IOP. They measure water vapor mixing ratio profiles from the surface to about 8 km during nighttime operation, with a vertical resolution of 75 m and a temporal resolution of 1 min. The principal challenge for the ARM development has been to extend the technique to daytime operation. Daytime measurements with ranges of 3-5 km (depending on meteorological conditions) at reduced resolution have been demonstrated recently. During the night, Raman lidar provides most of the necessary information on water vapor, aerosol profiles, and cloud optical characteristics (for optically thin clouds).

6.3.4 Robust CO_2 Coherent Lidar

Development of the mini-MOPA CO_2 Doppler lidar incorporates and reflects the experiences obtained at previous field experiments including ASTEX, with an early version of this instrument, and FIRE II with the NOAA Environmental Technology Laboratory's larger Doppler lidar. With further instrument development the mini-MOPA can evolve into a more robust and potentially unattended remote sensor ideal for ARM applications. In the present study, dual-wavelength capabilities are being assessed to determine the feasibility of distinguishing between cloud water and ice phase. With the additional capability of instrument combinations utilizing lidar, radar, and radiometer, estimates of cloud particle sizes, concentrations, and ice water content can be obtained, as well as cloud geometries. Refinements to these techniques will allow us to compare microphysical and cloud radiative properties such as emissivity and optical depth.

6.3.5 Eye-Safe Differential Absorption Lidar (DIAL) for Water Vapor Profiling

This effort is a theoretical study to determine if recent developments on solid state laser and lidar technology could overcome the current limitations in Raman lidar for determining tropospheric water vapor profiles during daytime conditions. The technique under study is that of Differential Absorption Lidar (DIAL) which has been used successfully on aircraft and some ground-based experiments. In addition to technical performance requirements of daytime and nighttime sensing of water vapor profiles, the principal design constraints are nearly-unattended operation and cost. The current study involves solid state (2 m) and gas (CO_2, 10.6 m) lidars.

6.4 Concerns and Unmet Needs

6.4.1 Clear-Sky Measurements/Retrievals

To calculate zenith downwelling radiance that can be compared with either microwave or infrared radiometric measurements requires the following atmospheric measurements: height profiles of temperature and water vapor within the viewing direction of the radiometers, surface measurements of temperature, pressure, and water vapor, and knowledge that there are no clouds, including sub-visible cirrus, overhead. Since there are indications that aerosols may influence the infrared radiance, knowledge of their gross height distributions may also be important. Strengths and limitations of measurements necessary for clear air radiative transfer calculations are discussed below:

6.4.2 Radiosondes

Radiosondes have provided useful data for many years and will continue to do so for the foreseeable future. However, some of the comparisons of humidity soundings between VIZ units (used on National Weather Service operational soundings), HUMICAP (a Vaisala-made unit used on CLASS radiosondes), Raman lidar, and microwave radiometers, have indicated some problems with the VIZ humidity response below 20% relative humidity, and perhaps in the upper range above 80% as well. The radiosonde system used at the SGP (Vaisala) does not have the latter class of problems. Even if radiosondes were of perfect accuracy, there are significant issues that arise with the balloon drifting out of the field of view of the radiometer, and with the relatively long time for a balloon to complete a sounding. However a radiosonde does yield a complete sounding from the surface to at least 50 mb and also gives a profile through and above clouds.

6.4.3 Raman Lidar

During the night, Raman lidar provides most of the necessary information on water vapor, the presence of clouds, cloud optical properties (for optically thin clouds) and aerosol profiles. Current limitations of the Raman are:

1. The lidar uses radiosondes for calibration. Which type of radiosonde should be used for this calibration?

2. The distance from the surface to the lowest altitude lidar measurement (-100m) is important for radiative transfer calculations; for some types of meteorological situations, a simple interpolation between the surface and the first range gate is not adequate.

3. The range of the Raman is dramatically reduced during daytime conditions to about 3-5 km AGL. Research is continuing to improve the upper range limitation, but the problem is a difficult one. DIAL techniques may prove to be very important alternatives.

6.4.4 Radio Acoustic Sounding Systems

The RASS systems determine the vertical profile of virtual temperature with an rms error, relative to radiosondes of about 0.5 K. Generally speaking, RASS does not provide temperatures in the middle to upper troposphere. Currently, either extrapolating the profiles statistically or blending the profiles with radiosondes, is used to extend the soundings to levels needed by RTE calculations. As with Raman lidar, the region between the surface and the first range gate can pose problems; this layer is some 100 to 300 meters in thickness. Again, there are meteorological situations when simple interpolation from the surface to the first range gate is not adequate.

6.4.5 Surface Meteorological Instruments

Frequently, surface observations for use with radiosonde launches are taken from a standard meteorological shelter. This is desirable if the shelter instruments are frequently calibrated and maintained. It is probably advantageous to have redundant instruments to flag and prevent erroneous data. The surface readings from radiosondes are accurate only if the sonde has been allowed to come into equilibrium with the air; if a sonde is released immediately after being taken from inside, the lowest few readings may be more representative of an inside than an outside environment. The unreliability of the method even given these precautions suggests that it should not be relied upon for radiative transfer calculations, Raman calibrations or similar research applications.

6.4.6 Microwave Radiometers

These instruments measure total water content during clear conditions with an accuracy of at least 3%; very little information is provided on the vertical distribution of vapor. A time series of water content with 30 second resolution during clear and cloudy conditions is available from these instruments. When used with a Raman lidar at night, these instruments can provide quality control or calibration of the Raman. During the day, when increased reliance on radiosondes is required, the microwave instrument could be used again as a quality check on the representativeness of the radiosonde.

6.4.7 Optimum Strategy With Current Instruments

Because of the high cost of frequent radiosonde releases and the uncertainty of when a particular sounding is valid, it seems like the best strategy is to concentrate on IOPs, with multiple sensors operating at the same time and at the same location. It is suggested that both HUMICAP and VIZ sensors be used, and that all instruments should be intercompared at the surface. Hand-held surface meteorological instruments could also provide additional redundancy. Both RASS, Raman lidar, and possibly microwave radiometers, should be used to determine from time continuity and from comparison with in situ measurements, if radiosonde soundings and their blendings are representative.

6.4.8 Cloudy-Sky Measurements/ Retrievals

To a significant extent, the remote sensing retrievals of the major cloud variables are not perfected or even well developed. For example, the optical thickness of clouds, which is the most fundamental cloud radiation variable, can only be measured for thin clouds. The complexity of cloud fields, both in terms of geometry and microphysics, requires extensive use of remote sensors, such as cloud radars and lidars. Some of the measurements will require additional evaluation, including in situ measurements, to validate emerging techniques and verify proper interpretation of the data from the remote sensors themselves. The continuous observations at a single location by the Micro-Pulse Lidar, perhaps other lidars, the 35 GHz Cloud Radar, the microwave radiometer, and AERI will be valuable in developing cloud statistics and parameterizations.

The combination of data from two or more remote sensors can provide important cloud parameters not accessible by just one of the sensors. Other parameters can be observed more accurately or completely by integrating data from multiple instruments. Some examples include, but are not limited to:

- More comprehensive description of cloud layers and boundary heights from lidar and radar
- Cloud emissivity from lidar, infrared radiometry (narrow-field IR radiometer or perhaps AERI), and temperature profile
- Vertical distribution of cloud liquid water and average drop size from radar and microwave radiometer in many stratus cases
- Column-integrated ice content and average particle size from radar and infrared radiometry
- Vertical profile of ice particle effective radius and ice content from radar and CO, lidar backscatter, or else from radar backscatter plus Doppler and infrared radiometry.

It may be practical to derive some of these parameters automatically in the ARM data stream, e.g., cloud geometry from lidar and radar. Other parameters require more complicated processing or use techniques that are quite new, so that initial implementation as a continuing IDP or science team activity may be most appropriate. In addition to cloud properties themselves, the ability to measure water vapor profiles under cloudy conditions is very difficult.

To extend the detailed information from active sensors located at a single point to represent a domain the size of an ARM site is challenging. Problems related to spatial extent of clouds can only partially be addressed by ground-based whole sky imagers and satellite observations. As in the case of clear sky observations, IOPs may be the only practical way to gather enough data to address even a subset of the important questions. The retrieval of cloud radiative and microphysical parameters from the ARM remote sensing is a significant scientific problem to be addressed. For example, there are many indications that more fundamental research on the radiative properties of non-spherical particles is needed before the reliability of remotely sensed cirrus clouds microphysical properties can be improved. In the case of the most important variables such as cloud optical thickness, the further development of possible instrumental techniques is a critical requirement not yet being met.

6.5 Summary

Table 6.2 summarizes some of the key technological challenges that the program faces in bringing together the fusion of modeling and observations that ARM needs to succeed.

Table 6.2. Key technological challenges.

Develop algorithms that combine ground-based and satellite-based remote sensing systems, and in situ observations where needed, to estimate profiles of temperature and humidity from the surface to the top of the tropopause. Testing of radiative transfer models should use algorithms that do not incorporate optical measurements of the radiative transfer being modeled.
Develop techniques for ground-based remote sensing of temperature and humidity profiles through clouds, e.g., with passive microwave techniques, to complement optical measurements below clouds and RASS observations.
Develop and test algorithms to use surface heat and moisture flux data with temperature and humidity observations near the surface on towers to generate reliable profiles of temperature and humidity in the lower 100 m of the surface, for remote sensor calibration, radiative transfer calculations, and other applications.
Develop and test higher-order products from active remote sensors, incorporating in situ observations routinely for calibration checks.
Develop algorithms using inputs from multiple ground-based remote sensing systems to evaluate cloud geometry, particle size, and phase. Develop multi-wavelength lidar systems to assist in evaluation of cloud particle size. Develop accurate narrow-beam cloud optical depth measurements.
Implement sophisticated multi-sensor algorithms for routine, operational measurements.

7. Southern Great Plains Site

7.1 Rationale for Site Selection and Site Description

The Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site is the first ARM site to be occupied. As shown in Figure 7.1, this site extends across a 365 km (north-south) x 300 km (east-west) area (110,000 km^2) that extends from south-central Kansas to central Oklahoma. The SGP site was chosen to be the continental U.S. (and therefore first occupied) ARM site for a combination of scientific, logistical, and synergistic reasons. In order for the first ARM site to produce enough of the high quality data needed to permit the desired early addressing of the goals and objectives of the ARM Program, the site chosen had to experience substantial day-to-day weather changes and pronounced seasonal and interannual climate variability, particularly with respect to cloud types, surface fluxes, temperature, and specific humidity. These requirements were also considered equally important for the envisaged decade-length of the ARM Program, given that it was conceived as a "process-oriented" investigation. The SGP met these scientific requirements and, because of its mid-continent location, was also expected to be particularly sensitive to decadal-scale climate change, and so yield data desired for the testing of climate models in that context.

Given these scientific attributes, the ready accessibility of the SGP was considered to greatly facilitate the needed rapid deployment of the highly sophisticated instrumentation and the subsequent initiation of high quality data streams. It was considered important that the first land Locale be occupied and producing valid, high-quality data as soon as possible, so that the implementation experience gained there would facilitate the subsequent establishment of the more logistically challenging Tropical Western Pacific and North Slope of Alaska sites. The dividends of these logistical advantages will accrue throughout the duration of the ARM Program, because the deployment of state-of-the-science instrumentation and the mounting of focused (including pilot) observational programs at relatively short notice will be much easier and cheaper here than in the Tropical Western Pacific or on the North Slope of Alaska.

The above scientific and logistical requirements were met by not only the SGP CART, but also by potential CART locales in the Midwestern United States and Northern Great Plains. The SGP was chosen over these alternatives because it additionally afforded the opportunity for synergistic activity with other ongoing and planned meteorological projects, activities, and facilities. The latter were originally envisaged to include the NOAA Wind Profiler Demonstration Network, the research quality meteorological instrumentation of NOAA's National Severe Storms Laboratory, the data and analyses stemming from the First ISSCP Field Experiment (FIFE) and the First ISSCP Regional Experiment (FIRE) Cirrus IFO-II conducted in southern Kansas, the GEWEX International Continental Experiment (GCIP), and the Tropical Rainfall Measuring Mission (TRMM). As outlined in Section 7.3 below, this and other potential synergisms are now being substantially realized.

The SGP locale includes a Central Facility, four Boundary Facilities, and 23 Extended Facilities, and may also ultimately include several Auxiliary Facilities that encircle the Central Facility at a distance of approximately 30 km. The Central Facility, which is where most of the instrumentation is deployed, is located near Lamont in north-central Oklahoma (36° 36'N, 97°, 29˚W, 320 m ASL elevation), 50 km south of the Kansas border. The Central Facility instrumentation includes a wide array of conventional and state-of-the-science observing systems that perform the following functions—make radiometric measurements; furnish vertical profiles of wind, temperature, and water vapor (also vertical integrals); quantify the cloud cover, cloud liquid water and ice mixing ratios, and atmospheric aerosols; and permit the calculation of the surface fluxes of heat, moisture, and momentum. These Central Facility observing systems are fully detailed in Table 7.1. They are designed to support all components of the ARM scientific program, and especially the research of the instantaneous radiative flux (IRF) strategy. Each of the four Boundary Facilities is located near the mid-point of one side of the CART Locale rectangle (North = Hillsboro, KS; West = Vici, OK; South = Purcell, OK; East = Morris, OK). Their instrumentation suites are limited to a BBSS and MWR, with the resulting wind, temperature, and water vapor profiles providing the basis for the estimation of the lateral fluxes of moisture and energy into and out of the atmospheric volume above the CART rectangle, along with the divergence and tendencies of atmospheric properties for that volume. Those estimates are of particular value to the single-column modeling (SCM) and four-dimensional data assimilation strategies being pursued by the ARM Program.

The 23 Extended Facilities are distributed reasonably evenly across the CART locale. Their instrumentation systems (SMOS, SIROS, EBBR or EC) are intended to furnish data streams that will facilitate the spatial integration of the surface heat, moisture, and momentum fluxes across the CART locale. The Auxiliary Facilities have been proposed to provide a full four-dimensional specification of the cloud field in the vicinity of the Central Facility, specifically to support investigations of radiative transfer in partly cloudy conditions

Table 7.1. Observational instruments and systems at the SGP Central Facility.

Radiometric Observations
AERI
SORTI
Solar and Infrared Radiation Station (SIROS)
▪ Pyranometer (ventilated)
▪ Pyranometer (ventilated, shaded)
▪ Pyrgeometer (ventilated, shaded)
▪ Normal Incidence Pyrheliometer (NIP) on tracker
▪ Multifilter rotating shadowband radiometer (MFRSR)
▪ Pyranometer (upwelling, above pasture at 10 m)
▪ Pyrgeometer (upwelling, above pasture at 10 m)
Multifilter radiometer (upwelling, above pasture at 10 m)
Pyranometer (upwelling, above wheat at 25 m on 60 m tower)

Table 7.1. (contd)

Pyrgeometer (upwelling, above wheat at 25 m on 60 m tower)
Multifilter radiometer (upwelling, above wheat at 25 m on 60 m tower)
All-weather cavity pyrheliometer
Wind, Temperature, and Humidity Sounding Systems
BBSS
915 MHZ profiler with RASS
50 MHZ profiler with RASS
MWR
Heimann infrared thermometer
Cloud Observations
Day-Night WSI
Belfort Laser (interim) ceilometer
Micropulse lidar (IDP) ceilometer
Instruments and Systems in the Aerosol Trailer
Optical absorption system
Integrating nephelometer (11)
Integrating nephelometer (31)
Optical particle counter
Condensation particle counter
Ozone monitor
Manifold sample system

Table 7.1. (contd)

Instruments and Systems in the Calibration Trailer
Solar spectroradiometer
Site Reference cavity radiometer
NIST (National Institute of Standards and Technology) standard
Optical broadboard system
0thers
Temperature and humidity probes at 60 m on tower
Eddy correlation systems near surface
Eddy correlation systems on 60 m tower

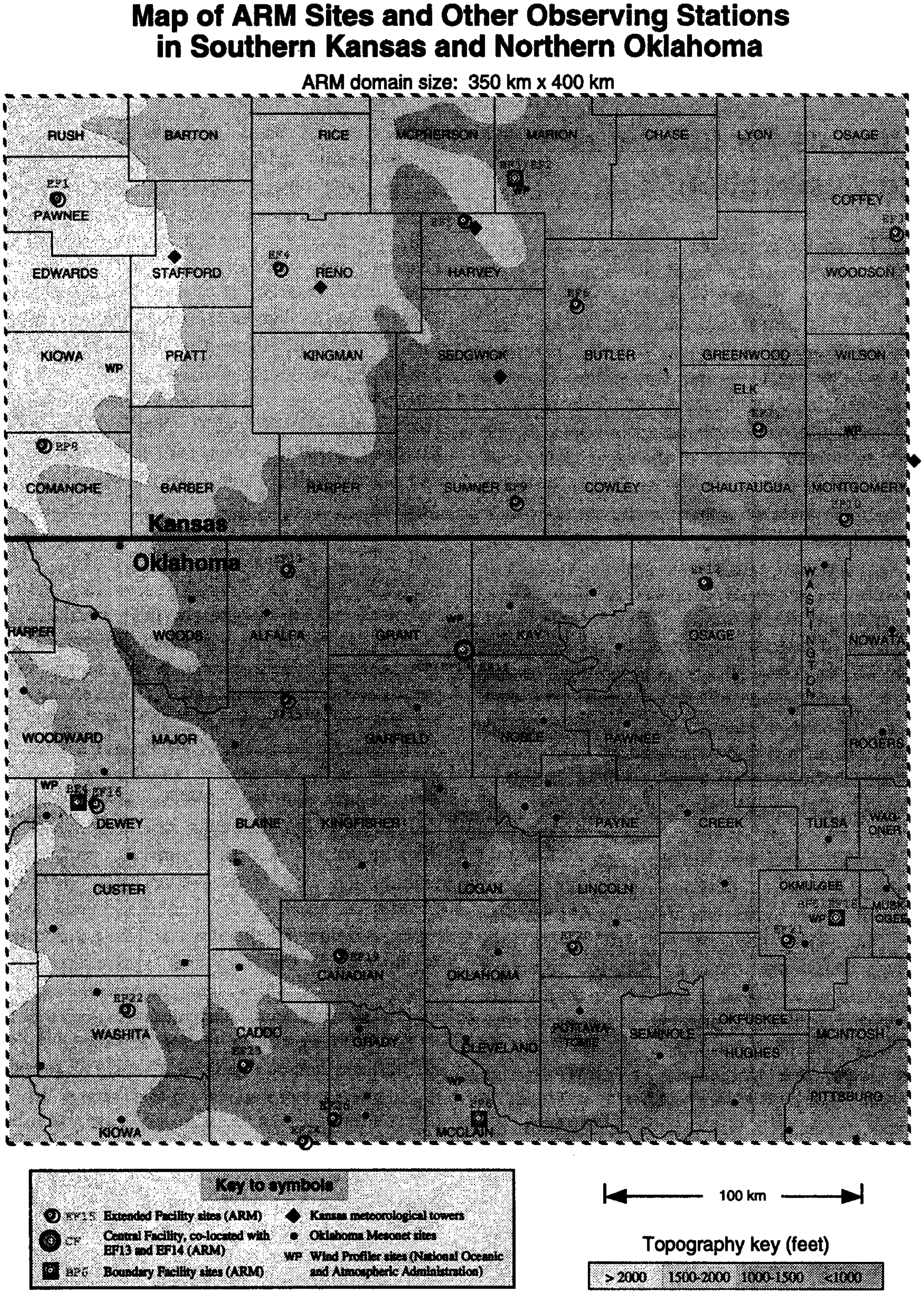


Figure 7.1. Map of the Southern Great Plains site, showing locations of key observing systems.

7.2 Site Scientific Questions

The scientific questions that will be addressed using data from the SGP site cover a particularly broad range. This stems from the circumstances outlined in the preceding section—the SGP site was the first occupied; it is likely that a more comprehensive suite of instruments will be operated here for longer than at either of the other sites; this observational capability will be enhanced by synergism with other projects, activities, and facilities that are also focused on the SGP (see Section 6.3 below); and the SGP site's ready accessibility facilitating the rapid deployment of the initial instrumentation suite and subsequent new state-of-the-science instrumentation, and the mounting of focused (including pilot) observational programs at relatively short notice. Some of these scientific questions are central to ARM's goals, while others are of a more secondary nature.

Consistent with the above, the central observational role of the SGP site is to acquire the most comprehensive set of high quality data possible to address the complete range of ARM goals and objectives. Those data are being gathered to fulfill the IRF and SCM observational strategies.

For the SGP, the IRF observational strategy involves the collection of data at and above the Central Facility on the vertical distribution of radiation and the radiatively active constituents of the atmosphere, and on the radiative properties of the lower boundary. To this end, vertical profiles and integrated measures of temperature and water vapor are being observed at regular intervals with traditional balloon-borne sounding systems (BBSSs), and semi-continuously with several state-of-the-science remote sensing systems (MWR, RASS, Raman Lidar). Cloud cover is being quantified continuously by several contemporary remote sensing systems (Day-Night Whole Sky Imager, Belfort Laser Ceilometer, Micropulse Lidar Ceilometer). The components of the surface radiation budget are being continuously monitored, in both a broadband manner with (traditional instrumentation) and with considerable spectral resolution (state-of-the- science instrumentation) as detailed in Table 7.1. Satellite and (during Intensive Observation Periods, IOPs) aircraft platforms are providing information on the vertical distribution of radiation. The aerosol content of the atmosphere is being monitored near the surface by an optical particle counter, integrating nephelometers, and an optical absorption system. Ozone will also be monitored continuously at ground level, with vertical profiles being obtained during IOPs.

As indicated in Section 2.4, while the IRF approach is crucial for the success of ARM, it is not sufficient because it does not address the processes that control the radiative properties of the atmosphere, especially those responsible for cloud formation and dissipation. In response to this situation, ARM is using the SCM strategy described in Sections 2.4 and 4.1. The SGP site is playing a crucial role in furnishing the basic data needed for the SCM work, and especially to support the estimation of troublesome derived quantities such as large-scale vertical motion and the tendencies of temperature and moisture due to horizontal advection. Some of the required observations will be much more difficult to make at the logistically less tractable Tropical Western Pacific and North Slope of Alaska CARTs.

The IRF scientific questions being addressed with data from the SGP are not really site-specific; the same questions could be addressed with data from the other two sites. The site-specific scientific questions that the SCM strategy is addressing with SGP data include:

- What processes control the formation, evolution, and dissipation of cloud systems in the Southern Great Plains?
- In the Southern Great Plains, what relative roles do the advection of air mass properties and variation in surface characteristics play in cloud development? How do these roles vary with season and short-term climatic regime?

- What aspects of cloud development are controlled by: the Low Level Jet; the return flow of moisture from the Gulf of Mexico during the winter and early spring months; the development of mesoscale convective complexes; frontal passages?
- What are the implications of the regional east-west gradients in altitude, soil type, vegetation, temperature, and precipitation on radiative fluxes?
- How important are seasonally varying distributions of aerosols and particulates (e.g., from regional oil refineries, or from burning of wheat fields) in the energy transfer processes?

The SCM observational strategy accordingly involves the acquisition of wind, temperature, and water vapor profiles and integrals above the four Boundary Facilities and Central Facility, and also makes use of IRF data obtained at the Central Facility. Particularly crucial in this regard are the fine temporal resolution (8 per day) vertical soundings of the above parameters that emanate from the BBSSs at the Boundary Facilities and Central Facility during the 3-week-long seasonal IOPs that occur at least three times per year. These data, along with external National Weather Service rawinsonde and wind profiler observations, are providing the basis for the estimation of the troublesome derived quantities listed above. This type of data can be provided much more effectively for the SGP than for either of the other two sites.

The specification of the radiative characteristics of the "single column" is involving a mix of surface measurements (e.g., net radiation), satellite observations (e.g., top of the atmosphere radiation), surface remote sensing (e.g., column water vapor and liquid water from microwave radiometers), and aircraft in situ measurements within the column (during IOPs).

In addition, the capability to mount focused (including pilot) observational programs at relatively short notice to address emerging major scientific questions is an important attribute of the SGP site. The early interpretations of the data involved (satellite top-of-the-atmosphere and land and ocean surface radiation measurements) suggest that existing climate models may underestimate the global-mean absorption of solar radiation by clouds by as much as 25-40 Wm^{-2}, and incorrectly assign that absorption to the surface. If ultimately sustained, this finding will require a significant rethinking of our understanding of atmospheric heating, and may also render previous estimates of greenhouse-gas induced warming to be even more uncertain than previously thought. It has been concluded that the SGP facility is ideally suited as a location for an experiment to quantify the processes involved. This experiment will obtain diverse radiative flux data from ground-based, satellite, and regular aircraft platforms, as well from Unmanned Aerospace Vehicles (UAVs, see Section 10.9). It will also be supported by historical cloud and storm frequency analyses performed by the Site Scientist Team. The ensuing results may necessitate some fine-tuning of, and perhaps even more major modifications to, the routine SGP radiative flux and cloud observational procedures. The capability of the SGP site to play a central role in this type of experiment is vital to the development of the overall ARM Program.

7.3 Interactions with Other Projects, Activities, and Facilities

The originally perceived potential for effective synergism between the SGP ARM site and other projects, activities, and facilities is now being substantially realized. This is occurring in two principal ways.

First, the SGP ARM operations are benefiting significantly from the diverse capabilities of several of the meteorological units located on the University of Oklahoma campus. For example, NOAA's National Severe Storms Laboratory has donated part of the time of the Assistant Site Scientist, and also provided the personnel and facilities needed to address some important ARM observational problems on both a funded and contributed basis. A similar arrangement has permitted the Experimental Forecast

Facility housed within the National Weather Service Forecast Office to provide tailored weather forecasts for both routine ARM operations and IOPs. In addition, the SGP Site Data System is now routinely ingesting the complete 5-minute resolution data streams emanating from all 111 automatic surface weather stations of the Oklahoma Mesonet that is operated by the Oklahoma Climatological Survey. The availability of these data from the two-thirds of the SGP locale that lies within Oklahoma reduced the number of Extended Facilities that needed to be located in that state which, in turn, freed up the resources for the establishment of a higher density of Extended Facilities in Kansas which does not have a dense state network of automatic weather stations.

Second, the SGP observational capabilities are being enhanced as a result of ongoing interactions between ARM and several other federally funded research programs having an interest in the Southern Great Plains. These interactions particularly involve the GCIP component of GEWEX and have already resulted in the formation and functioning of a joint ARM-GCIP- ISLSCP Working Group and GCIP's funding of additional SGP rawinsonde observations during August 1994. This Working Group will suggest observational strategies for the SGP for the next few years. Beyond that, it will benefit all involved programs by fostering the most cost-effective and efficient operations program possible. In addition, the GCIP component of NOAA's Climate and Global Change Program is funding a proposal from the Site Scientist Team to develop a soil moisture monitoring capability for much of the total SGP domain that will fulfill the needs of both ARM and GCIP. This important enhancement of the SGP observational capabilities will strongly complement the ARM Extended Facilities in their aforementioned central role of facilitating the spatial integration of the surface heat, moisture, and momentum exchanges across the CART domain. Further assistance in this regard may be forthcoming from efforts by biologists to both capitalize on and supplement the SGP observational capabilities. The potential dividends for the SGP site include—eddy correlation measurements of water vapor, heat, momentum, and trace gas fluxes over a number of contrasting ARM locale sites (forested, prairie, agricultural) outside the Extended Facilities; an enhancement of such measurements at some Extended Facilities; access to the results of an ecosystem-level modeling effort that will use the above measurements to "scale up" from the leaf to regional levels; use of improved spatial integrations of the surface heat, moisture, and momentum exchanges across the SGP domain; and enhanced representations of those integrations in the ARM SCM effort and ultimately in GCMs. These SCM- and GCM-related dividends will help the ARM Program clarify the impact of its central concerns—the importance of clouds and cloud-radiation interactions for climate change—by reducing other sources of uncertainty.

Somewhat less formal interactions with the VORTEX program led to funding by VORTEX of an enhancement of the spring 1994 SGP rawinsonde observations. The ARM-VORTEX synergism planned for the spring 1995 IOP included joint aircraft observations. Aircraft-based instruments will measure the following parameters—upwelling and downwelling microwave brightness temperatures at low, middle, and high altitudes; upwelling and downwelling narrow-band solar radiances above, in, and below clouds; cloud liquid water content; and in-cloud long-path extinction. The dividends that are likely to accrue to the ARM Program will include improvement of inhomogeneous cloud models, an initial assessment of an ARM ergodic hypothesis (that time series measurements of cloud optical depth can be used to infer the instantaneous horizontal distribution of optical depth), and improved retrievals of total precipitable vapor and cloud liquid water path from SSM/I data.

8. Tropical Western Pacific Site

8.1 Science Issues for the TWP

The locale selected for the Tropical Western Pacific (TWP) site (Figure 8.1) is a large expanse of tropical ocean and maritime continent lying roughly between 10°N and 10°S latitude and 120°E longitude to the dateline (or a bit further to the east). The maritime continent area is largely in the southwest and the open ocean area in the northeast of the locale. Climatologically, the locale is characterized by warm sea surface temperatures, deep and frequent atmospheric convection, high rain rates, strong coupling between the atmosphere and ocean, and substantial variability associated with the El Nino - Southern Oscillation (ENSO) phenomenon. Any number of diagnostic studies can be cited that show the relationship between climatic variability in this region, particularly ENSO, and variability in other portions of the globe. Because of the large area, relative inaccessibility, and predominance of ocean in the TWP, there are a long list of fascinating scientific questions that can be and ought to be addressed in the context of the ARM Program. These questions can be roughly grouped under three main headings: 1) radiation budget and cloud forcing, 2) water and energy budgets, and 3) ocean-atmosphere interactions.

Radiation and cloud linkages in the TWP have been a subject of intense interest for many years. Both modeling and observational studies have emphasized the importance of deep convective clouds and cirrus outflow on the radiation budget of the atmosphere and surface. The clouds alter the total input of radiant energy to the tropical system, modify significantly the vertical profile of heating in the atmosphere, and influence strongly the vertical and horizontal water vapor transports. It has also been argued that tropical cirrus clouds may act as a regulatory mechanism in limiting maximum sea surface temperatures in the TWP.

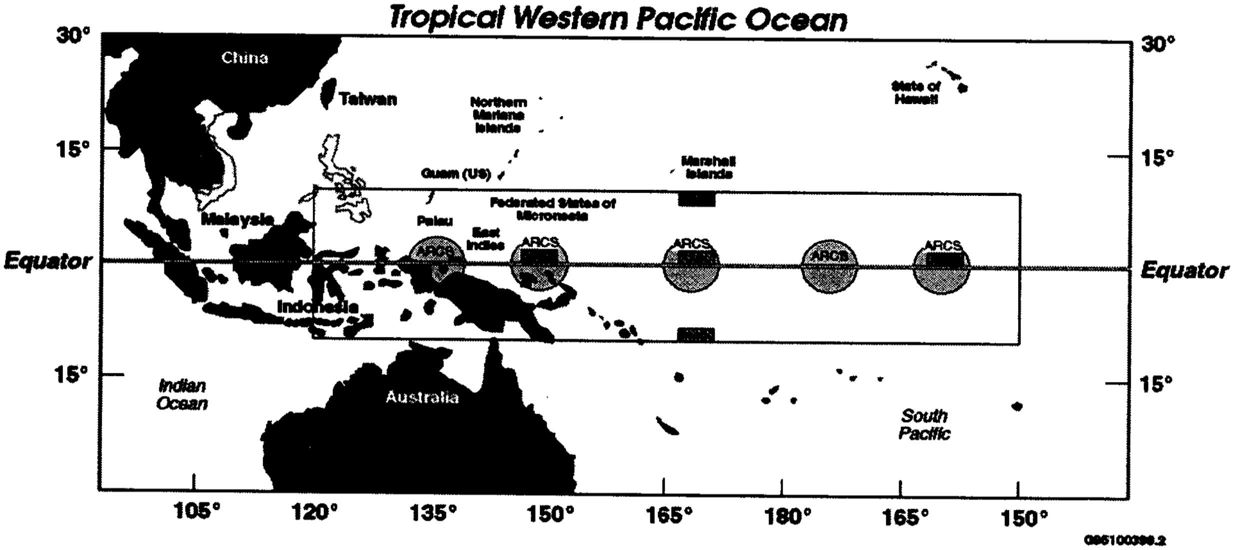


Figure 8.1. Map of the Tropical Western Pacific site. The original siting strategy is shown as circles. The hatched boxes show the current siting strategy.

Satellite observations show clearly the longitudinal variability of cloud occurrence and cloud radiative impacts in the TWP, and also show how these patterns shift longitudinally during ENSO events. Convective initiation and organization, and hence cloud frequency and perhaps properties, are influenced by surface characteristics and vary over regions of the TWP that consist of large islands, small islands, or open ocean. The recently completed TOGA COARE and CEPEX campaigns have provided a wealth of data on these various issues that have not yet been completely analyzed.

The principal radiative questions that need to be addressed by ARM are very basic. There are no long term records of radiation and cloud properties available from the TWP, so we have no data with which to address questions of intra-annual and interannual variability of the surface radiation budget or the spatial character of that variability. There are virtually no surface-based observations of cloud properties other than widely scattered observer estimates of cloud fraction. Consequently, ARM needs to provide answers to questions such as:

1. What are the magnitude and variability of the surface radiation budget in time and space?

2. What are the basic properties (e.g., height of cloud base, cloud fractional coverage) of tropical clouds as measured from the surface?

3. How do the distributions of these basic properties vary temporally, spatially, and from the maritime continent area to the open ocean?

4. What is the impact of clouds on the surface radiation budget?

Atmospheric radiative heating in the TWP is also of significant importance to the ARM science community. Important issues include:

1. What are the radiative flux convergence and column heating in the tropical atmosphere?

2. What is the average atmospheric radiative heating profile and how does it vary in time spatially across the TWP domain?

3. How does the atmospheric radiative heating profile vary in time, particularly on the diurnal time scale?

A third set of issues is concerned with the physical processes of radiative transfer. For example:

1. What is the magnitude and spectral dependence of water vapor continuum absorption in tropical atmospheres?

2. What is the physical mechanism responsible for this absorption?

3. What is the impact of the extreme 3-dimensionality of tropical cloudiness on atmospheric transmission of solar radiation?

Deep convection in the TWP has a profound impact on the atmosphere locally and, most likely, globally through the redistribution of water and energy. Quantifying these effects is a huge challenge. It requires an understanding of the processes responsible for the initiation of tropical convection, the vertical transport of water and energy accomplished by tropical cells, and the microphysical characteristics of clouds, including the stratiform and cirrus outflow regions. Convective initiation and transport in the tropics have been the focus of a number of intensive field programs spanning many years, beginning with the GARP Atlantic Tropical Experiment (GATE) in 1974, extending through the monsoon experiments in India, Borneo, and Australia, and including most recently, the TOGA Coupled Ocean-Atmosphere Regional Experiment (COARE). Diagnostic studies, as well as a large number of theoretical and numerical studies based on these data sets and focusing on convective processes, have contributed greatly to our understanding of the tropical atmosphere. Several recent studies have shown the importance of radiative effects in the development and life cycle of tropical cloud systems. There are, however, still many unanswered questions regarding tropical convection that are of importance to the cloud and radiation community. The central issues for ARM are related to the vertical mass transport of water, both vapor and condensate, and the resultant impact of that transport on atmospheric heating rates.

The choice of the TWP locale was dictated, in large part, by the ocean warm pool and the deep convection associated with it. Satellite observations show that the ocean surface temperatures in the vicinity of the maritime continent are consistently the warmest and cloud top temperatures are the coldest found anywhere. ERBE maps of monthly-average outgoing longwave radiation show a deep minimum over the area, while solar reflectivities how corresponding maximum, indicating the prevalence of optically-thick clouds. There is clearly a causal relationship between the warm ocean and deep convection but the linkages between the ocean and atmosphere are not well understood quantitatively. Experiments such as TOGA COARE have addressed these issues, but only for periods of a month or a few months. ARM has an opportunity to contribute to understanding these issues by carrying out high-quality observations over an extended period of time. The issues of most importance to the ARM objectives are the heat balance at the ocean surface, particularly the radiative component, and the linkage between convection and the large scale circulation features of the atmosphere and the ocean mixed layer. Although ARM has a vital interest in these processes, difficulty and cost limits the extent to which they can be addressed in a long-term observational program.

8.2 Observational Strategies

The many important and interesting scientific questions, the large expanse of the TWP and logistical and financial constraints all come into play in attempting to design a useful observational strategy for the ARM Program in the TWP. A simple assessment based on the size of the domain and available land area within that domain leads to the conclusion that climatological observations clearly depend on the use of satellites. Satellite observations must provide not only the usual top-of- atmosphere quantities, such as fluxes and column cloud properties, but also the means to produce surface fluxes and vertical profiles of clouds and radiation by the use of algorithms. It is also fairly obvious that a single large facility, such as that being constructed at the Southern Great Plains site, which is designed to measure radiation and cloud properties and diagnose the state of the atmosphere, is not feasible in the TWP. With the exception of the north of Australia or large islands such as New Guinea, there is no geographical area large enough to place such a facility. Also, such locations experience strong continental influences or extremely strong topographic effects which detract from their utility in describing physical processes relevant to the whole of the TWP domain. Even if deployment in such an area were deemed useful scientifically, logistical and financial considerations would make it prohibitive. Similarly, logistical and financial considerations at this point do not permit deployment of an extensive array of instruments in a purely oceanic environment using some combination of ships and buoys.

Given these factors, does the ARM Program in the TWP have an appropriate role and, if so, what is that role? It is our perception that ARM does indeed have an important role to play in the TWP and that role has three distinct and critical elements:

1. Provide a long time series of basic observations at several locations that aid in understanding intra-annual and interannual variability of surface radiation fluxes and cloud properties. These observations would also serve as truth points for satellite retrievals of surface and atmospheric quantities.

2. Augment radiation and cloud observations made in the context of intensive field campaigns to elucidate the role of deep convection in the tropics as it affects radiative processes.

3. Devise and implement a strategy for long-term measurements of ocean-atmosphere properties and fluxes.

The first element represents the highest priority for the TWP because it relates directly to the primary scientific questions articulated by the ARM Program, and because there are currently no long term radiation and cloud measurement sites in the TWP (with the exception of Australian facilities in the Darwin area) and no plans to make such measurements except for those developed by the ARM Program. Given this priority, there is a need to determine what quantities must be measured and how and where to make these measurements. Answers to these questions must also include recognition of logistical and financial constraints including such factors as the extremely limited or non-existent infrastructure support throughout much of the area of interest, potential political problems and instabilities in some areas, and the high cost of installing and maintaining instrumentation.

The observational strategy needed to address this element is embodied in the concept of an Atmospheric Radiation and Cloud Station (ARCS). An ARCS consists of an integrated instrument set that can measure the surface radiation balance, surface meteorology, cloud properties, and some limited atmospheric quantities. The principal scientific driver of the instrument set is to measure the surface radiation budget and the effect of tropical clouds and water vapor on that radiation budget. The fundamental measurements needed are the downwelling broad-band solar (both total, and diffuse) and infrared irradiances at the surface. (Upwelling measurements are also of interest, but considerations of surface representativeness make their utility more questionable. Given their modest cost, however, they should be included.) The downwelling flux measurements should be augmented by frequency-dependent direct solar beam and nadir infrared radiance measurements, which can be used to infer quantities of interest such as optical depth as a function of wavelength. In order to interpret the irradiance measurements, measurements of cloud properties are needed. These include cloud frequency (or fractional coverage), cloud base height, cloud top height, and cloud liquid or ice water path. Atmospheric water vapor, both total column and profiles, and temperature profiles are also needed. The ARCS are designed to be autonomously operable and portable, following the conceptual design pioneered by the Integrated Sounding Systems of NCAR and NOAA. Observations are intended to be continuous at the time scale of seconds to hours depending on the particular instrument and variable. The measurement series is expected to extend for up to a decade.

The spatial and temporal variability of tropical dynamics with the attendant variability of cloud properties and the perceived differences between convection in maritime continental areas and oceanic areas argue for carrying out measurements at multiple sites across the TWP domain in order to sample the spatial variability of cloud properties and the surface radiation budget, as well as temporal shifts in the patterns induced by large-scale phenomena such as ENSO. Comparison of ship and buoy data acquired at different locations and times indicates considerable variability in these quantities, but there are no long-term measurements that allow us to address this issue from data alone. A preliminary siting strategy postulated the deployment of three to five ARCSs near the equator spaced from Indonesia to east of the dateline. This strategy has now undergone a preliminary evaluation using a combination of data from moored buoys (TOGA-TAO), an atmospheric GCM and sampling theory (analysis courtesy of T. Barnett) and satellite data (analysis courtesy of V. Ramanthan). This initial effort used near-surface measurements at the buoy sites to estimate the characteristic or decorrelation scale lengths of the latent heat flux field for averaging times of 15-30 days. A more complete estimate of the scale lengths of the latent heat flux field was obtained from the GCM. Where it was possible to check, the model verified well against the buoy data.

The suggested deployment of ARCSs based on this combination of data, modeling and sampling theory is shown by the hatched boxes shown in Figure 8.1. The model locations and those obtained independently from the buoy array are nearly identical. The original siting locations (shown as circles), which were based on a combination of satellite radiation data and logistical considerations, are quite similar to those obtained objectively from the model and observations. Additional work is underway to carry out the same type of analysis for the other ARM critical fields in the TWP. This work will eventually lead to a composite sampling strategy for the entire TWP region.

The first ARCS site will be at Manus Island, Papua New Guinea (2 S Latitude, 147 E. Longitude; see Figure 8.1 for approximate location). Actual sites have not been selected for subsequent ARCS, although a variety of island locations are being considered. The current plan being developed by the Site Advisory Committee, Site Scientist, and TWP Program Office calls for the deployment of three ARCSs along the equator, with an additional two deployed to the north and south of the central ARCS at approximately 10° latitude.

Because the ARCS will be located on islands, questions concerning the representative nature of island locations are inevitable. These questions are being and will be addressed from several different approaches. Analysis of TOGA COARE ship and island radiation data is underway and shows no substantial differences in monthly averages of downwelling radiation obtained at the various locations. Analysis of GMS data over the Manus site indicates a slight enhancement of convective activity over the island during daytime during the suppressed phase of the Madden-Julian oscillation. There is no indication of an island effect during nighttime, nor during the active phase of the MJO. In March 1996, a NOAA research vessel will visit the Manus site carrying essentially identical instrumentation to that of the ARCS, which will be operating at that time. Comparison of ship and island measurements of radiative fluxes and cloud properties will allow for further evaluation of the island effect. In addition, it may be possible to have buoy observations of radiative fluxes near Manus for longer periods of time. These types of observational programs and analyses will be carried out for the duration of the ARCS deployments to ascertain the nature and magnitude of the island effect.

Addressing scientific questions involving convective processes in the tropics and the vertical flux of water requires resources beyond those incorporated into the ARCS. Observations pertinent to some of the issues could be acquired with the ARCS, particularly with the addition of a 50-MHz wind profiler that could provide information about wind fields in the upper troposphere. Considerable information on tropical convection was acquired during TOGA COARE; however, much of this data set is only in the beginning stages of analysis. Thus, it seems prudent for ARM to follow this ongoing research closely in order to determine critical issues and those requiring further research and observational studies.

It seems likely that high spatial and temporal sampling will be required to provide data needed to address the important issues relating to convection in the TWP. Because of the cost and operational difficulty of maintaining dense observing arrays in the TWP, ARM cannot do so on a permanent basis. Thus, these measurements will have to be provided on a campaign basis and in conjunction with other interested programs. The participation of ARM in TOGA COARE served as a test bed for the ARCS development and deployment while at the same time providing useful scientific information. The participation of ARM in the Maritime Continent Thunderstorm Experiment (MCTEX) provides a similar test bed for joint participation in tropical convection experiments, while providing a data set of use to those interested in modeling convective processes and transport. MCTEX is designed to improve knowledge of the dynamics and interaction of the physical processes involved in the organization and life cycle of tropical island convection over the Maritime continent and the role of this convection in the atmospheric energy and moisture budget. The role of ARM will be to provide measurement capability in the area of radiation and cloud properties to augment measurements of atmospheric properties, air-sea fluxes, and surface fluxes supplied by other participating organizations. The intent of the ARM TWP program is to pursue other such opportunities in the future to provide representative datasets that can be used in the study of convective processes in the tropics.

The third element has the longest implementation profile, not because of any perceived lack of importance, but because of its inherent difficulty and potential cost. A wealth of data on air-sea interaction and the marine boundary layer was acquired during COARE using research ships and low altitude aircraft flights. While the ongoing analysis of these data should provide excellent guidance on scientific issues for the TWP program, it is clear to the most casual observer that the ARM Program cannot hope to maintain even a small component of the COARE observing system because of costs and logistical issues. Despite that limitation, the ARM Program can make a significant contribution to understanding air-sea interaction in the TWP.

The primary focus of an ARM ocean observation program will be on the exchange of energy at the air-sea interface. This will require measurements of radiative, latent, and sensible heat fluxes at the interface, as well as the radiative heating in the atmospheric and oceanic boundary layers. Conceptually, this program can be put in place at modest cost by taking advantage of three observing structures that are already in place: the ARM ARCS, the TOGA TAO buoy array, and research ships of opportunity. The plan is to locate an ARCS on a small island near a TAO buoy line (on the order of 7 buoys positioned along a longitude from about 10°N to 10°S). The ARCS will provide a comprehensive data set of downwelling radiative fluxes at the surface, cloud properties, and atmospheric variables. The TAO buoys provide measurements of surface winds and temperature, as well as SST and other ocean mixed layer properties. These observations will be augmented with measurements of downwelling radiation. (Solar flux observations have already been made from a TAO buoy, thus providing a prototype for this augmentation.) These measurements can be used to establish the radiative inputs to the ocean mixed layer, evaluate the representativeness of the ARCS observations, and provide surface validation for satellite algorithms. In addition, sub-surface measurements of solar fluxes will be considered in order to assess the deposition profile of solar energy in the ocean mixed layer. Since the TAO buoys are serviced regularly by research vessels, the possibility of making routine observations of surface fluxes from these research vessels will be investigated in order to provide data on spatial variability and reliability of the TAO observations. Finally, the cost will be evaluated of installing small, dedicated buoys in the more immediate vicinity of the ARCS site to address issues of small scale variability in surface heat fluxes.

Even this modest effort will be complicated and expensive. A plan and cost analysis is being developed using the island of Nauru and the TAO line at 165 E as a preferred location. At this juncture, we cannot tell if resources will be available to implement the proposed plan. However, the concept is of such interest and the data of such potential that further study is certainly warranted.

Two additional topics need to be raised in the context of observational strategies. First, ARM has been exploring the possible use of UAVs in support of ground-based observations and these vehicles offer some intriguing possibilities in the TWP. The development of simple sounding packages that could be flown on small UAVs would be immensely valuable in the TWP since it would offer a relatively inexpensive way to expand atmospheric characterization about ARCS sites, enhance atmospheric characterization during intensive field programs, and provide tropospheric data over the suggested oceanic site. Larger UAVs, which could fly radiation and cloud sampling packages for long duration at a single location or over long paths from one ARCS to another, would clearly be of great utility in the TWP. Such packages could be used to measure tropopause radiative fluxes, characterize cloud micro-physics, investigate island/ocean contrast, or sample the tropical atmosphere over large distances. An additional possibility is to use a larger UAV to drop sondes around an ARCS site. Although it is unrealistic at this juncture to base operational strategies on this as yet unavailable technology, the potential benefits are so large that close coordination should be maintained between the TWP site planning and the UAV activity.

The second topic relates to oceanographic research ships. There are a number of research ships not only from the United States, but also from countries such as Japan and France, that regularly work in the TWP. These ships offer platforms of opportunity that could be very useful to the TWP program, particularly in the context of making oceanic measurements. They also present peculiar data analysis problems due to the convolution of space and time statistics that occurs when atmospheric data is acquired from a moving platform. Nevertheless, the TWP should make a concerted effort to work with the oceanographic community in the design of observing programs of mutual benefit.

8.3 Modeling Strategies

Modeling activities in the TWP will range over as wide a spectrum as those at the other ARM locales and will include radiative transfer models, cumulus ensemble models, limited area models, and single-column models.

Radiative transfer modeling is already underway utilizing data acquired during TOGA COARE. The thrust of the current research, as well as future research that will take place in conjunction with the ARCS observational program, is to validate clear-sky calculations, determine the magnitude of surface cloud forcing effects, and learn how to incorporate radiatively realistic tropical clouds into models. The complicated 3-dimensional structure of tropical cloud systems makes it imperative to include 3-D solar radiative transfer models in the suite of analysis tools. Using such models to simulate actual radiative transfer events and then parameterizing these effects for inclusion in plane-parallel models will be a formidable endeavor. The prevalence of ice in the tropical upper troposphere will also place stringent demands of solar radiative transfer models given the difficulty of calculating ice scattering functions. The high water vapor column concentrations found in the tropics will require the use of detailed continuum models in thermal infrared radiative transfer models. In short, the instantaneous radiative transfer computational approach used so successfully at the SGP site should prove equally viable and beneficial in the TWP.

In order to close the atmospheric column radiative budget, radiative fluxes at the top of atmosphere will be needed. These can only be provided by geostationary satellite (the GMS) data at this time, with attendant modifications to account for narrow to broad band conversion and view angle, or by use of models a la ISCCP. Neither approach is totally satisfactory, but the only solution with the purview of ARM is the use of a UAV to measure tropopause-level fluxes over its flight duration. This is a critical issue for scientists interested in atmospheric heating profiles and their variation on diurnal and longer timescales.

Modeling cloud formation and cloud field interactions with the larger scale dynamics and thermodynamics is likely to be extremely challenging in the TWP and will likely require modification of the single-column modeling (SCM) approach currently being used at the SGP site. The SCM concept in essence assumes that the mean state and advective tendencies of the atmosphere can be specified over some spatial scale roughly consistent with the scale of GCM grid box. A GCM parameterization can then be forced with these specified values and the resulting cloud and radiation properties can be tested against observations in a deterministic fashion. Because of the seemingly stochastic nature of a great deal of tropical convection and the difficulty of arriving at the large-scale atmospheric state and tendencies independent of the strong coupling to local convection, it is not clear how well the current SCM concept will work in the tropics.

Alternatively, one might argue that, from a climatology standpoint in the tropics, we are fundamentally interested in a statistical characterization of cloud properties and radiative fields. Thus, the deterministic simulation of individual events that is implicit in the SCM approach as applied in mid-latitudes is not necessary. The desired model simulations in the tropics are statistical in nature and are in turn validated against statistical observations. Clearly, convective activity in the TWP (and other parts of the tropics) is influenced by large scale forcing on a variety of temporal scales. This logically means that the cloud and radiation statistics also vary as a function of the large-scale forcing and, presumably, provide a variable feedback to the large scale as well.

The implication for cloud modeling in the TWP is that at least three different strategies ought to be pursued. The first strategy is to specify the large-scale forcing (order of the Rossby radius), presumably by some combination of large-scale analysis and data assimilation, and then run 2- or 3-D models within that large-scale domain to simulate cloud statistics. These models could be cumulus ensemble models, cloud-resolving models, or mesoscale models. The model-generated cloud statistics could then be compared to observational cloud statistics for different large-scale forcing regimes.

A second strategy is a modification of the SCM concept. The basic difficulty with applying the SCM approach is an inability to either diagnose a vertical velocity from observations, because the observations don't exist at the requisite scale, or use assimilated analyses at the GCM grid scale, because the analyzed vertical velocity on the local scale is largely the result of the convective parameterization buried within the model used to do the analyses. There are two possible alternatives, one observational and one diagnostic. Observationally, one might use a 50-MHz profiler, which can produce hourly-average profiles from the surface to above the tropopause, to measure the vertical velocity at a specific site. In the tropics, the vertical velocity measured by the profiler is an indication of the local-area velocity and may provide a reasonable input for SCM simulations on a statistical basis. The other approach is to use the large-scale fields averaged over some typical domain to weakly force a SCM and look at the response of the convective parameterization to the forcing. This is presumably the way in which a GCM actually functions, i.e., the model produces a large scale forcing over some area encompassing multiple grid cells and the parameterization responds to the forcing within each of those cells. It will be interesting to compare the cloud statistics generated using these two vertical velocity fields with those generated using multi-dimensional models with those from the observations.

The third strategy is to focus high-resolution modeling on specific field campaigns during which spatially dense data is acquired. In some cases, this type of data is already available. For example, data acquired in EMEX and AMEX and in TOGA COARE may be useful for case studies. MCTEX should provide another usable data set and we anticipate future intensive experiments in the TWP.

Each of these strategies offers advantages, but each also has limitations. Experience with both of the first two is limited, suggesting that considerable developmental research will be needed. The third has been used in some cases but validation has been poor or non-existent because the requisite radiation and cloud properties have not been measured. Without good validation, application to the improvement of cloud and radiation parameterizations has been extremely limited. It seems likely that all three strategies need to be pursued and intercompared in order to understand their relative merits, as well as to provide insight into tropical convection and cloud properties.

The implications for the observational strategies discussed above are quite interesting. The need to validate cloud and radiation statistics in the context of variable large-scale forcing argues for long-duration measurements in order to acquire enough data to understand the statistics. Since large-scale forcing varies on timescales at least as long as ENSO cycles, this means that continuous observations on the scale of years are required. It also argues for sampling at several locations in order to understand the statistics as modulated by the large-scale forcing. This modulation contains an interannual component due to the ENSO and an intra-annual component due to higher frequency variability, such as the MJO, that may itself vary from year-to-year. It is the latter that presumably produces the decorrelation scales deduced from the TAO buoy data and GCM results presented in Figure 8.1. In any case, unscrambling the various forcings and the non-linear interactions will require multiple sampling locations, as well as extensive analysis of satellite and model data across the TWP domain. Measuring the vertical velocity requires the addition of a 50-MHz profiler to at least one, and ideally more, of the proposed ARCS. Finally, since determining the large scale forcing is a critical component for all strategies, this may argue for temporally enhanced soundings at ARCS sites and perhaps at some existing locations and their incorporation analyses.

8.4 Interactions with Other Programs

Given the high cost of operating in a remote environment and current funding limitations, it is critical that the ARM management seizes every opportunity for collaboration with appropriate existing scientific programs and multi-nation organizations in the region. A few installations are being operated in the islands, but these are rather modest in scope and instrumentation. The most active site in the area is maintained by the Australian research community in Darwin. This site has state-of-the-art instrumentation such as Doppler radar and wind profilers, and is being upgraded currently to support TRMM validation research. Cooperation with any planned experiments at this site is be a priority for ARM.

The completion of the TOGA program and COARE has resulted in a hiatus in large programs in the TWP. Conversations are underway with the Japanese Cloud and Climate Study (JACCS) program to develop areas of cooperation between the two programs. The focus of the tropical efforts of JACCS will apparently be primarily in the area of balloon-borne sounding packages for cloud microphysics and radiation. Such sounding packages would complement well the ground-based observations incorporated into the ARCS, which suggests a natural point of collaboration.

Some preliminary discussions have been held with other groups that may conduct monsoon experiments in the TWP, but no firm commitments have been made at this time.

9. North Slope of Alaska/Adjacent Arctic Ocean Site

The North Slope of Alaska was chosen as a locale because the atmospheric and surface conditions in this region are markedly different from those at the other ARM sites, and are representative of high latitudes: low temperatures, sustained high surface albedo over most of the year, continuous low sun during summer, and polar night during most of the winter. As a result of these conditions, the Arctic is hypothesized to have large climatic feedbacks linking surface and tropospheric temperatures, surface albedo, evaporation, cloud cover, deep ocean water production (the global thermohaline ocean circulation pump), and the polar atmospheric heat sink. The North Slope of Alaska/ Adjacent Arctic Ocean (NSA/AAO) site will be centered at Barrow, Alaska. A supplementary site will be established at Atqasuk, which is about 100 km inland from the coast. For a period of 16 months (April 1997 through August 1998), ARM will also have a site in the Beaufort Sea, in conjunction with the Surface HEat Budget of the Arctic Ocean (SHEBA). This siting arrangement will allow us to understand how radiative transfer differs from the central Arctic ice pack, to coastal environments, to more continental areas inland. Figure 9.1 shows the siting for the NSA/AAO locale.

9.1 Scientific Objectives

The specific scientific objectives to be addressed at the NSA/AAO focus on improving the performance of climate models at high latitudes by improving our understanding of specific physical processes. The specific objectives are enumerated below, in the form of questions.

9.1.1.1 Document the radiative environment and how it is determined by atmospheric constituents and thermodynamics.

1. What is the spectral distribution of longwave radiation and in particular what is the role of the 20 micron "rotation-band window" region in regulating the surface and atmospheric temperature in the Arctic?

2. What are the effects of springtime "Arctic haze" on the absorption of solar radiation in polar clouds?

3. How do the reflectance and transmittance of the clouds and the surface depend on the low solar zenith angles typical of the Arctic?

4. What is the role of "clear-sky" ice crystal precipitation in determining the longwave radiation fluxes?

5. What are the shortwave radiative effects of the horizontally inhomogeneous stratocumulus clouds over the horizontally inhomogeneous, highly-reflecting snow/ice surface?

6. How do the optical properties of the Arctic surface vary in response to changes in snow characteristics (thickness, age, temperature, contamination), thinning of the ice, and melt pond formation?

9.1.1.2 Determine the physical, chemical and dynamical processes responsible for determining the arctic cloud characteristics.

7. What is the influence of leads and other open water on cloud properties when there is a large surface temperature contrast with the ice?

8. How does the extreme static stability and low atmospheric water vapor content of the Arctic lower troposphere, particularly during winter, affect the flow energy across the air-sea interface?

9. What is the mechanism that leads to the spectacular multiple-layering of Arctic Ocean summer cloud systems?

10. How does the transition of low clouds from liquid to crystalline depend on temperature and aerosol characteristics, and how does the springtime transition differ from the autumnal transition?

11. Does the formation of "diamond dust" differ in polluted vs. unpolluted atmospheres?

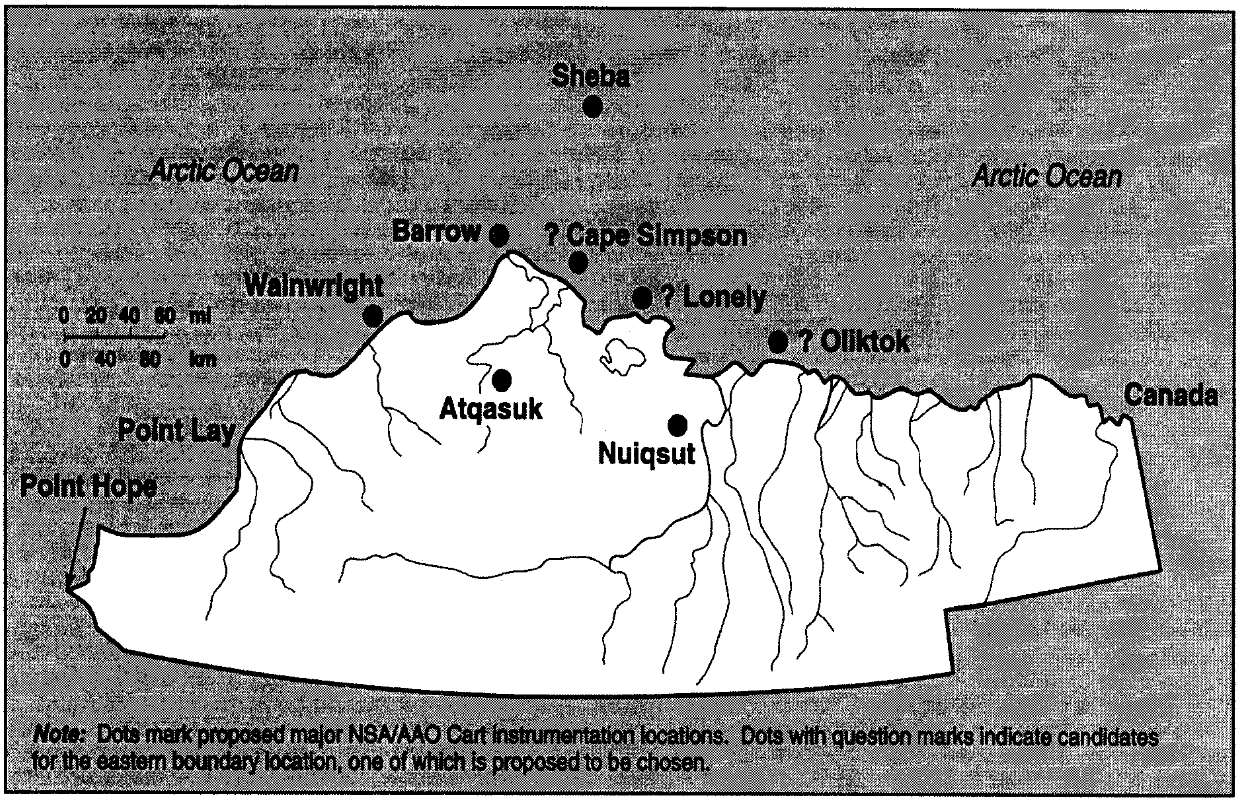
9.1.1.3 Understand the radiation-climate feedback processes operating in the Arctic.

12. How do clouds and radiation interact with the summertime melting of snow and sea ice?

13. How is the water vapor feedback influenced by the rotation band "window", control of water vapor amount by the ice saturation, and the freezing of sulfuric acid and subsequent growth and fallout?

14. What are the potential feedbacks among cloud/ radiation, surface warming, and the release of methane into the atmosphere from the permafrost?

15. How is the cloud-radiation feedback coupled to the ice-albedo feedback?



Note: Dots mark proposed major NSA/AAO Cart instrumentation locations. Dots with question marks indicate candidates for the eastern boundary location, one of which is proposed to be chosen.

Figure 9.1. The North Slope of Alaska/Adjacent Arctic Ocean site.

9.2 Observational Strategies

In addition to the measurements and observational strategies described in Section 2, there are some site-specific observational strategies required to meet specific NSA/AAO site scientific objectives.

An important characteristic of the NSA/AAO in winter is that the atmosphere is so dry that the so-called "dirty window" between approximately 18 and 25 microns wavelength is largely open, and the surface and the atmosphere near the surface can lose energy to space in this wavelength region. Additionally, the Planck function is shifted towards longer wavelengths at the cold arctic temperatures. As configured for the lower latitudes, the AERI has a longwave cutoff at 500 cm^{-1}, and useful information is not obtained below 550 cm^{-1}. For the Arctic, an extended spectral range AERI with a longwave cutoff at 400 cm^{-1} is needed to address objectives 1 and 13. The AERI will also provide accurate temperature profiles of the Arctic boundary layer beneath clouds.

Much of the time in the Arctic, there are strong surface inversions that make getting sufficiently accurate temperature and humidity profiles in this layer difficult. The lowest few hundred meters of the atmosphere are not well-sampled by radiosondes or acoustic/sonic techniques, and the depth of this layer is too large to be adequately probed by a fixed instrumented tower. So-called "tethered towers," which make use of multiple sensor units mounted on the tetherline of tethered balloons appear to be an attractive option for overcoming this difficulty. Additionally, the tethered towers will have utility in probing the radiative and microphysical characteristics of the low clouds that are frequently present in the Arctic. The tethersonde measurements are critical for achieving science objectives 4, 7, 8, 9.

Aircraft measurements on a campaign basis are needed for in situ validation of the surface-based remote sensing systems. ARM will coordinate with aircraft campaigns from other programs in the Arctic. A major campaign will take place in conjunction with SHEBA and FIRE III in the Beaufort Sea during the period April I997 through August I998. Such aircraft campaigns are critical for providing in situ measurements to validate the ground-based remote sensing retrievals and to address scientific goals 2, 3, 4, 5, 7, 9, 10, 11. Additionally, there are several suitable aircraft based on the North Slope for which appropriate instrumentation packages could fairly easily be prepared. Use of such non-dedicated aircraft would make periodic in situ measurements of several different types much more affordable, particularly dropsonde deployment for SCM IOPs. Because of logistical difficulties and cost limitations on the North Slope, dropsondes are an attractive option relative to surface-based radiosonde launch facilities at boundary sites.

Satellite remote sensing must play a major role in observing the arctic environment, because of the paucity of conventional observations. The NSA/AAO observations will be used to validate and interpret satellite observations in this region, and thus extend the observational time/space domain. The first launch in the NASA EOS series is anticipated in I998 (EOS-AM); at this time, the NSA/AAO site will be in its "mature" operational stage. In addition, the EOS program has an international component (IEOS) coordinated with the National Space Development Agency of Japan and the European Space Agency. Such coordination gives us an opportunity to receive data from space-borne instruments, that in many aspects are similar to those to be flown on the EOS satellites, before and in the beginning of NSA/AAO operations. Besides providing information on larger space and time scales than is feasible using only the surface sites, satellite observations will play a major role in the achievement of objectives 4, 12, 15.

9.3 Modeling Strategies

The radiation environment of the Arctic is complicated by the presence of the highly-reflecting snow and ice, the absence of solar radiation for a large portion of the year and low sun angles, low temperatures and water vapor amounts, and the presence of temperature inversions. Radiative transfer models must be able to deal with these complexities. It is also important to develop radiative transfer models that recognize the intrinsic radiative coupling between the atmosphere and the underlying surface both over land and ocean. On land the surface consists of snow overlying an active vegetation/soil layer on top of permafrost, while at sea there is snow and water on sea ice overlying the ocean. A realistic model must deal with the coupled system and account for the vertical as well as the horizontal inhomogeneity of this coupled system in a self-consistent manner. An improved radiative transfer model is required to address objectives 1 through 6.

Four unusual cloudy boundary layer types can be identified over the Arctic Ocean: i) summertime boundary layer with multiple layers of cloud; ii) mixed-phase boundary layer clouds that occur in the transition seasons; iii) low-level ice crystal clouds and "clear-sky" ice crystal precipitation in stable wintertime boundary layers; and iv) wintertime ice crystal plumes emanating from leads, or cracks, in the sea ice. These unusual boundary layer types provide a substantial challenge to atmospheric models currently used for the cloudy boundary layer. High-resolution models, particularly of low-level and boundary layer clouds will be employed to improve cloud parameterizations in climate models. In the Arctic, it is the low-level clouds that are particularly difficult to model and parameterize because of the complex interactions with the underlying surface; mid-and high-level clouds are primarily associated with frontal systems and thus can be parameterized in the same way as mid-latitude clouds.

The most complex high-resolution model that is suitable for the arctic boundary layer clouds is the Large-Eddy Simulation (LES). LES models (LESM) are currently being formulated with "explicit microphysics" schemes, so that the detailed interactions between turbulence and cloud physics can be simulated. Additionally, aerosols and atmospheric chemistry are being added to these models to address cloud-aerosol- radiation-turbulence interactions in the evolving cloudy boundary layer, which are hypothesized to be important in arctic cloudy boundary layers. To address cold-season clouds, the LESMs need to include ice microphysics and allow for mixed-phase clouds. Improvements of the subgrid-scale parameterizations used in LESMs are required to simulate the stable boundary layer. The results of LESMs will be used to improve parameterizations of cloud microphysics and turbulence for larger-scale models. The LESMs will be used to achieve objectives 7 through 11.

Improved parameterizations will be tested in single-column climate models. Single-column models will be formulated for both the NSA site centered at Barrow and for the region around the SHEBA ice camp in the Beaufort Sea. Because of the different underlying surfaces, different surface parameterizations or models are required over land versus over ice. Over the Arctic Ocean, a one-dimensional sea ice model and upper ocean mixed-layer model coupled to the atmospheric model is required to understand radiation feedbacks specifically related to objectives 12, 14, and 15.

To study the formation, maintenance, and dissipation of cloud systems, and to improve parameterization of these processes in climate models, atmospheric mesoscale models are needed. Mesoscale models will be particularly useful for developing climate model parameterizations of cloud fraction. They are also needed to assess the processes involved in the formation, maintenance and dissipation of the clouds, and the interactions of the cloud fields with the underlying surface. Such mesoscale models will likely require at least the complexity of the Arctic Regional Climate Model (ARCSyM) that has been developed collaboratively by the Universities of Alaska, Illinois and Colorado.

9.4 Interactions with Other Programs

Pursuit of the scientific objectives, along with implementation of observational and modeling strategies, will be accomplished by ARM in collaboration with other programs.

Many of the scientific objectives described in Section 9.1 will be pursued by ARM in collaboration with the Surface HEat Budget of the Arctic Ocean (SHEBA) and FIRE III Arctic Clouds Experiment. The original site plan called for land-based measurements at the North Slope. Collaboration with SHEBA and FIRE III allows ARM a more comprehensive assessment by extending its locale to the Adjacent Arctic Ocean. The scientific theme of SHEBA is the sea-ice albedo and cloud-radiation climate feedback mechanisms. The goals of SHEBA are to improve GCM simulations of the present day arctic climate and to improve the interpretation of satellite remote sensing data in the Arctic. SHEBA results will contribute significantly to science objectives 5, 6, 7, 8 9, 12, 15 listed in Section 9.1. These objectives will be achieved through the establishment of an observational facility in the Beaufort Sea for a 16-month period from which surface-based measurements of the atmosphere, sea ice and upper ocean will be made, along with several aircraft campaigns.

The objective of the FIRE III Arctic program is to document, understand, and predict the Arctic cloud-radiation feedbacks, including changes in cloud fraction and vertical distribution, water vapor and cloud water content, and cloud particle concentration, size, and phase, as atmospheric temperature and chemical composition change. Thus FIRE III shares many goals with ARM, and objectives 7, 9, 10 and II related to aerosols, atmospheric chemistry, and atmospheric boundary layer dynamics could not be accomplished without collaboration with FIRE. A major aircraft campaign is planned for spring 1998 in conjunction with the SHEBA ice camp. In addition, there is a major component in FIRE III related to aircraft and satellite remote sensing.

The NSF Arctic System Science (ARCSS) "Flux Study" of the Land-Atmosphere-Ice-Interactions (LAII) program is of direct relevance to the ARM/NSA effort in the context of science objective 14. The Flux Study consists of: (1) measurements of fluxes of trace gases (CO_2, methane) to the atmosphere and of the water-transported materials to the ocean; (2) determination of the primary controls of the fluxes; and (3) scaling and synthesis to the regional scale (Alaskan North Slope and beyond). The primary field sites are in the Kuparuk drainage basin of the Alaskan North Slope. The ultimate goal of this study is to assess the feedbacks between climatic change and release of greenhouse gases from arctic terrestrial regions. The LAII Flux Study interfaces with the ARM/NSA effort both geographically (through field measurements in adjacent regions of the North Slope) and scientifically (through the link between surface radiative fluxes, soil/vegetation temperature and wetness, and rates of trace gas flux from/to terrestrial ecosystems). The "scaling and synthesis" component of the LAII Flux Study uses the Arctic Regional Climate System Model (ARCSYM), which is now being run over a domain that encompasses both the LAII Flux Study area and the proposed ARM/NSA/AAO site.

The ARM/NSA effort has been adopted into the implementation plans of two World Climate Research Program (WCRP) Implementation Plans: the Arctic Climate System (ACSYS) Cloud Radiation Programme and the Global Energy and Water Experiment (GEWEX) International Satellite Cloud Climatology Project (ISCCP). These links provide a connection between the NSA/AAO effort and larger climate issues and programs.

9.5 Summary

The observational strategy proposed will allow us to improve our understanding of the cloud and radiation environment of the Arctic, over land and ocean. These observations will be used to initialize and validate cloud-resolving models, and as a basis for comparing parameterizations. These improved parameterizations will be incorporated into a regional climate model of the Arctic and global climate models. Collaboration with SHEBA, FIRE, and LAII allows ARM to address its secondary science objectives; together, these programs will have a substantial impact on our ability to model the arctic climate, specifically the cloud-radiation feedback.

10. Connections with Other Programs

10.1 Introduction

Connection to and collaboration with other programs is an important part of the ARM strategy. This is the case for four reasons:

1. ARM is attacking only particular aspects of the overall global problem of climate. Other programs provide both context and information that enhance the value and applicability of the ARM results.

2. Other programs provide opportunities to learn about additional measurement and data analysis approaches from which ARM might benefit.

3. The ARM Program's resources are finite, as are those of other programs, and collaboration allows both ARM and other programs the opportunity to leverage resources and achieve goals that neither would be able to achieve alone.

4. The existence of ARM facilities provide a valuable operating base for a wide variety of other programs and make the ARM sites, particularly the Southern Great Plains, an attractive base for a variety of purposes, ranging from field campaigns to the validation of satellite observations.

For these reasons ARM has and is continuing to aggressively pursue opportunities for collaboration with other programs such as FIRE, SHEBA, GCIP, EOS and many others. Such collaborations are all intended to be mutually beneficial. Collaboration with other programs has been an important part of the program from its very beginning, and while it has not taken advantage of all possible program interaction, the number and quality of these interactions has and will continue to increase. Many of the programmatic interactions have been described in earlier sections of this plan. The program has benefitted significantly from interaction with other programs in its early development stages. For example, early in the program, ARM collected observations in conjunction with several projects (FIRE, SPECTRE, 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 TOGA-COARE and provided measurements of radiation in the Tropical Western Pacific. The analysis of data from these programs continues to contribute to ARM goals.

The following is a summary of the key interactions and their connection to ARM Science that are currently in process or in planning. The first sections cover the interaction between ARM and formal climate research programs such as those of the World Climate Research Program (WCRP) and the United States Global Change Research Program (USGCRP) which are focused, like ARM, on particular aspects of the climate problem. Next, there is a section that discusses the interaction between ARM and operational systems such the National Weather Service and the NOAA satellite programs. Finally, there is a discussion of the special relationship between ARM and programs developing new observational systems such EOS and ARM-UAV.

10.2 GEWEX

The Global Energy and Water Experiment (GEWEX) is the World Climate Research Programme's umbrella for research being conducted on the so-called "fast" components of the climate system

(Chahine 1992; and GEWEX 1993). Its focus on the processes which control radiation and water in the climate system make it a natural ARM collaborator. In recognition of this ARM and the GEWEX have signed a memorandum of participation which will make the ARM facilities a major component of GEWEX field experiments such as the continental program scheduled for the Mississippi basin (GCIP), the intercomparison of water vapor measuring systems (GVaP) and possibly a basis upon which the next field deployment of the International Satellite Land Surface Climatology Project (ISLSCP). Much of the current interaction has been described in Section 7.3. The interaction with respect to the surface radiation budget is described in Section 10.3.

The International Satellite Cloud Climatology Project is an important component of GEWEX. The global data from ISCCP are quite important and can be used to put ARM site-specific observations in context. In this case a question that needs to be answered is the extent to which observations at a particular time at an ARM site are typical of the climatology of the region. To this end the high resolution ISCCP products are being subdivided into data sets that cover each of the ARM sites and the extended region around them, for use by ARM and other investigators to determine to what extent ARM's site-based findings are generalizable. These datasets are a special subset of the DX data (3-hourly pixel level data with 8-km spatial resolution sampled at 30 km).

As a result of work being completed in 1994 in the Program for Intercomparison of Land Surface Parameterization Schemes (PILPS) there may be further opportunities for interaction with GEWEX. In particular, PILPS has reached the stage the Intercomparison of Radiation Codes in Climate Models (ICRCCM) reached in 1989 at the beginning of ARM. That is that after extensive comparison of models and having gained increased understanding of intrinsic problems with the models due to conceptual as well as mechanical errors, the real question is what should the models be producing. The answer to this question requires data, in particular long runs of atmospheric forcing data. ARM will answer in the coming months how its resources particularly the improved surface stations that may be possible through Eco-ARM might obtain this data.

10.3 ICRCCM and SRB: Ties to the Radiation Community

One of the primary roots of the ARM Program is the intercomparison of Radiation Codes in Climate Models (ICRCCM). The tie to ICRCCM described in Section 3 and noted above has driven the focus of ARM on radiative processes. This emphasis on radiometry makes the battery of surface radiometers concentrated at ARM sites a useful complement the GEWEX Surface Radiation Budget (SRB) program and the Baseline Surface Radiation Network (BSRN) which have been organized by the WCRP. The GEWEX SRB program at NASA Langley retrieves surface fluxes over the globe with data obtained from operational meteorological satellites in the ISCCP. BSRN is a complementary program of high quality surface radiometric observing that will validate the satellite-based retrievals and monitor long term trends in surface radiation. A few BSRN sites are operational, scores are planned around the globe in different climatic regimes, but each has only a small number of radiometers. At present, and as with the BSRN, the GEWEX SRB program validate area-averaged satellite retrievals with point surface measurements. The dense network of radiometers at ARM sites will enable the GEWEX SRB program to develop the techniques for testing such an area-to-point approach; the SRB community regards this problem as critical. ARM atmospheric measurements will also permit the GEWEX SRB project to validate atmospheric correction techniques in the satellite-to-surface transformation; here the tough nuts are the absorption of SW radiation by clouds and the base height of clouds, which affects cloud temperature and hence thermal emission. Atmospheric measurements at the geographically dispersed BSRN sites will be much more modest than in ARM. BSRN has already lent its expertise to ARM in the deployment of surface instrumentation.

10.4 CHAMMP, FANGIO, and AMIP: Collaboration with the Modeling Community

DOE's Computer Hardware, Advanced Mathematics, and Model Physics (CHAMMP) program has had an ongoing interaction with ARM for several years, partly through two ARM-CHAMMP Workshops. The purpose of CHAMMP is to develop and demonstrate greatly improved climate modeling capability.

FANGIO (Feedback ANalysis in GCMs and in Observations) is a DOE-sponsored GCM intercomparison project which has been ongoing since the late 1980s and has focused mainly on cloud and radiation-related issues. The interactions between ARM and FANGIO are less explicit than for CHAMMP, but the ARESE experiment, scheduled for the Fall of 1995, is an outgrowth of FANGIO interests and results.

AMIP (the Atmospheric Model Intercomparison Project) was organized by the Working Group on Numerical Experimentation (WGNE) of the World Climate Research Programme (WCRP) with major support from the U.S. Department of Energy. AMIP is conducting several dozen "subprojects" dealing with various aspects of atmospheric physics as simulated by climate models, and many of these relate directly to ARM measurements. Numerous ARM investigators are involved in AMIP.

Through interactions with CHAMMP, FANGIO, and AMIP, ARM stays in touch with the practical needs of the climate modelers, and ensures that new physical insights and parameterizations developed under ARM will find their way directly into the GCM community. These interactions could also allow GCMs to be more actively used in the design and monitoring of the ARM measurement effort, e.g.:

1. GCMs need to be closely compared with the ARM data, now rather than later. The ARM-CHAMMP Workshops have begun this process, and it must continue.

2. GCMs should be used to help design the ARM measurement efforts, e.g., the TWP program.

3. We also need to do a partial intercomparison among the GCMs for key cloud/radiation quantities. On what features do they agree? In what areas do they disagree most? Will ARM give the critical data in this latter area to resolve the situation? If not, we need to revise the measurement program.

4. A "showcase" dataset should be assembled from an annual cycle of SGP data. The primary use of this dataset would be to either validate models or develop new parameterizations, and so it should be designed from a modeling perspective. It is most important to obtain quality data that can actually be used to validate models. We are close to achieving this at the SGP site. The proposed data set can and should be used by climate modelers for validation purposes. The data would be made available for the following time periods: annual mean, monthly means for the twelve months of the year, daily means for January and July only, and a composite diurnal cycle for January and July only. Site-averaged quantities, comparable to GCM grid cell values, should be used. If ARM could put together one or two years of this data for the SGP site, most climate modelers would use it immediately. The data set should be updated as more years of data become available.

10.5 SHEBA and FIRE: Working Together in the Arctic

The interactions of ARM with SHEBA and FIRE have already been described in Section 9.3. The basis of these interactions is a Memorandum of Participation with the Arctic System Science (ARCSS) Program, which is similar in scope to the GEWEX memorandum. As the actual deployment of ARM on the North Slope approaches, it is inevitable that there will be other interactions with ARCSS.

10.6 MCTEX, GOALS, and INDOEX: Common Tropical Interests

For a variety of reasons the interaction with other programs is even more important in the Tropical Western Pacific than any other ARM site. The primary drivers are the breadth of the scientific issues that need to be addressed in the tropics, as well as the sheer size of the region and its corresponding logistical complexity. Early interactions with TOGA-COARE and CEPEX have already shaped ARM. The anticipated interactions of ARM with MCTEX, GOALS, and INDOEX have already been described in Section 8.

There are other interactions that are of a smaller scale yet are just as important. These include the interaction with the meteorological services of such countries as Papua New Guinea, Nauru and Kiribati. The program will also take advantage of the existing array of NOAA wind profilers stretched across the Pacific as well as examining the possibility for improving the radiometric capability of the buoys in the TOGA-TAO array.

10.7 NWP

There are several kinds of programs which, although not focussed on climate per se, are useful to ARM and which may in turn benefit from an interaction with ARM. There is strong potential for interactions between ARM and Numerical Weather Prediction (NWP) centers around the world, including the U.S. Environmental Prediction Center (formerly the National Meteorological Center) and the European Centre for Medium Range Weather Prediction (ECMWF). On the one hand, ARM can provide (and is providing) data to these operational centers, for use in their parameterization development and testing efforts. On the other hand, ARM can benefit from the use of analyses provided by the operational centers. ARM should provide in real-time (via the WMO Global Telecommunications System, known as "the GTS") any special ARM observations (i.e., sondes, surface observations, profilers) that would potentially be of use to the operational data assimilation and forecasting centers. In exchange, ARM should arrange to receive from the operational centers nonstandard (direct model output) as well as standard analyzed fields.

While at present the operational satellite programs are not significantly benefiting from an interaction with ARM, they are of considerable use to ARM. Data from both the geostationary satellites and the polar orbiters are routinely incorporated in the data packages provided to ARM scientists. Looking forward, although ARM was too late to be able to affect the development of such 'operational' products as ISCCP and the SRB, as further operational data products are considered ARM can play an important role. Further, ARM should encourage the application of its data, which when combined with radiative transfer calculations, are useful for monitoring the calibration of operational weather satellites. The main obstacle in the use of operational satellites in global change research has been satellite radiometric calibration. As noted in the introduction to this section, one of the keys in making these improvements is connecting the process level understanding achieved through ARM to more global processes. Satellite observations are central to this strategy.

10.8 EOS: Looking to the Future

The Earth Observing System (EOS) is intended to be the observational backbone of the USGCRP as we move into the next century. It will allow an unprecedented collection of climate relevant data on a global scale, that can be used for both understanding long term trends and the study of processes. The early exchange of data by ARM and EOS groups, who are developing remote sensing algorithms with existing satellite data, should be encouraged. As ARM and EOS mature, ARM observations will be useful for the validation of EOS, which in turn will be an important resource for global monitoring.

ARM data are now being used for developing satellite-based remote sensing algorithms, including retrievals for the vertical profiles of clouds and radiative fluxes in the CERES program. When honed further with ARM data, CERES and other EOS retrievals will be useful for validating GCM parameterizations over most of the globe, where we have no ARM data.

One key for more complete exploitation of the synergism of ARM, EOS, and NOAA operational satellite programs is the collocation of specialized airborne measurements of the optical properties of the surface. Lacking such specialized measurements, satellite data are still quite useful for ARM, because the satellite data can be used to accurately describe the radiation emerging from optically thick clouds; and ARM measures atmospheric parameters very well, thereby serving as a validation benchmark for satellite sensing of atmospheric parameters. Airborne measurements of the optical properties of the surface would permit more gain. If surface optical properties (spectral and directional) are well characterized over ARM sites, the satellite data would be useful to ARM for describing optically thin clouds; at present, it is difficult to sort out the effects of the surface and of optically thin clouds in satellite measurements. The airborne characterization of surface optical properties would assist satellite remote sensing programs for surface properties; ARM data permit satellite teams to know and "subtract" the effect of the atmosphere; without ARM data, the satellite teams are partly blurred by uncertainties in atmospheric properties, when validating surface retrievals. One good start in this area, is the CERES plan to measure the spectral (four SW channels and one LW channel) radiances by helicopter for selected ARM IOPs.

Because of the highly directional character of radiation, it is virtually impossible, in an instantaneous snapshot, to establish full and accurate horizontal and vertical closure for the fluxes of atmospheric radiation. By integrating over space and time, however, closure can be approximated for some components. ARM, GEWEX, and EOS should establish a radiative flux closure group to determine the accuracy for spatially and temporally integrated fluxes based on ARM data. Such closure estimates are needed for testing GCM parameterizations, remote sensing products, and all orders of radiative transfer codes, including three-dimensional radiative transfer codes.

ARM measurements are needed to help resolve some of the uncertainties and biases that exist in satellite retrievals of TOA fluxes and cloud radiative properties. These problems occur globally, but are most severe in polar regions where the inability to differentiate clearly between clouds and snow fields makes accurate retrievals questionable. The polar regions are of particular concern for GCM validation, because model sensitivity and natural and seasonal variability are maximal at the poles, as are observational uncertainties.

The early exchange of data by ARM and EOS groups, who are developing remote sensing algorithms with existing satellite data, should be encouraged. As ARM and EOS mature, ARM observations will be useful for the validation of EOS, which in turn will be an important resource for global monitoring.

There are three aspects to the interaction between ARM and the satellite community. First, ARM investigators routinely use satellite products and observations specific to the ARM site in their modeling activities as noted in several of the sections earlier in this plan. Second, global data sets such as ISCCP can be used to put ARM site-specific observations in context. A question that arises here is the extent to which observations at a particular time at an ARM site are typical of the climatology of the region. To this end the high resolution ISCCP products are being subdivided into data sets that cover each of the ARM sites and the extended region around them, for use by ARM and other investigators to determine to what extent ARM's site-based findings can be generalized.

An emerging strategy is to use ARM data for developing satellite-based remote sensing algorithms, like the retrievals for vertical profiles of clouds and radiative fluxes in the CERES program. When honed further with ARM data, CERES and other EOS retrievals will be useful for validating GCM parameterizations over most of the globe, where we have no ARM data. An extension of the concept noted above. The early exchange of data by ARM and EOS groups, who are developing remote sensing algorithms with existing satellite data, will be encouraged. As ARM and EOS mature, ARM observations will be useful for the validation of EOS, which in turn will be an important resource for global monitoring.

ARM will encourage the application of its data, which when combined with radiative transfer calculations, are useful for monitoring the calibration of operational weather satellites. The main obstacle in the use of operational satellites in global change research has been satellite radiometric calibration. The CERES/ARM/GEWEX exercise (CAGEX) for the improvement and validation of CERES remote sensing retrievals for radiative flux profiles and clouds has begun. Small data sets of sounding and satellite retrieved cloud properties (the Minnis LBTM retrievals that ARM supports over the SGP CART site) are available from CAGEX, as are flux profiles calculated with that data, and the ARM radiometric observations for validating the fluxes. CAGEX is available to EOS, ARM, and GEWEX investigators; in GCIP, it is the main research program for research (as opposed to production) on the remote sensing program of radiative fluxes.

10.9 ARM-UAV: A Closely Coupled Program

The original ARM Program Plan called for the limited operational use of aircraft. Late in 1990 the possibility of a new kind of airborne measurement became apparent in what are frequently called unmanned aerospace vehicles (UAVs). These aircraft offer ARM the possibility of long duration flights (greater than 48 hours), autonomous operation over long distances, and reasonable payloads (approximately 150 kilograms). The ARM missions proposed for UAVs include multi-day missions to measure the flux divergence at the tropopause at several of the sites, delineation of 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 calibration of 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, whose initial scientific mission is radiative flux profiling in the lower troposphere (below 8km). The first deployment of a UAV at the SGP site took place in the spring of I994 and a study of the disparity between shortwave observations and models (ARESE) took place at the SGP site in the Fall of 1995.

10.10 Summary

It is expected that the coupling of ARM to other programs will continue to be an important feature of its approach to addressing the scientific questions outlined in this plan. It is further expected that the ARM facilities will help other programs, meet their objectives as well. The ARM sites should be designated as National User Facilities, and procedures should be set up for "outside" programs to request access to these Facilities. Such access would normally include receipt of ARM data, and could include the use of the ARM sites for the temporary deployment of additional instrumentation or as the base for campaign activity. Such Facilities, which have served the Physics and Astronomy communities for decades, represent a very practical response to the obvious need for comprehensive climate research facilities and monitoring stations.

11. Data Management

11.1 Introduction

The Data and Science Integration Team (DSIT) is a component of the ARM infrastructure. Interactions of the DSIT with Science Team members, individually and collectively, are the primary information exchange mechanism that drives the collection and management of data within the ARM Program. The interaction leads to translating the science needs into data needs. A critical part of this translation is the management and documentation of data quality. The stated goal of ARM is to produce data of "known and reasonable quality." This goal is translated into both actions to ensure that the instruments produce data of sufficient precision and accuracy to meet scientific needs and the obligation to produce a record of the calibration and operational history of instruments and their associated data streams sufficient to ensure an enduring record of data quality.

One of the strengths of the Science Team concept is the potential for cooperation through interactions and information exchange among Science Team members. To date, the two most active areas of cooperation have involved groups working on clear-sky instantaneous radiative fluxes and single-column modeling. The DSIT supports the development of interactive working groups that focus on particular types of analyses (e.g., SCM analyses), and it communicates the needs of such working groups to the ARM infrastructure. The identification of "showcase" data sets of common interest helps focus Science Team and infrastructure attention that adds scientific value to the data sets and stimulates progress towards ARM's goals.

11.2 The Data Stream

The ARM Data System manages the ARM data stream at the current rate of 400 megabytes of data per day. The Experiment Center, located at Pacific Northwest National Laboratory, is central to the ARM data path and provides for the collection, processing, analysis, and delivery of ARM data. Data are received from ARM sites which include a variety of instrumentation and observational systems, and from external sources. The Experiment Center processes these data on a continuous basis to provide products to the Science Team in near real time while providing a three month archive of data. Data quality checks are made at all stages of this processing and are continually reviewed and updated to reflect operational experience with the instruments.

Another important function of the data system is the long-term storage and access of the ARM data. This function is accomplished by the ARM Data Archive at Oak Ridge National Laboratory.

Data from non-ARM sources are called external data. External data sets which are currently being acquired to augment measurements at the Southern Great Plains site include surface observations from the Oklahoma Mesonet and from a Kansas network, NWS surface and upper air data, data from the Wind Profiler Demonstration Network and satellite observations. ACARS (ARINC Communications, Addressing and Reporting System) data sets have recently been added as well. It is anticipated that the need for external data will increase with the addition of our sites in the Tropical Western Pacific and the North Slope of Alaska.

11.3 Accessing Data

Science Team Members are assigned a liaison from the DSIT who has some familiarity with the scientist's planned research and assists them in the acquisition of the ARM data that will help fulfill their needs. Science Team members, working with their DSIT representatives, then arrange to acquire data by filing Experiment Operations Plans (EOPs) with the Experiment Center. These EOPs detail what data sets are of interest to the Science Team members, and over what time period, and also specify the delivery mechanism.

Customized data sets may be delivered continuously, over a period of time, or as a single shipment of retrospective data. Data may be delivered as frequently as daily, but are usually delivered on a weekly basis. The Science Team members may chose to have data transferred to their computer via ftp or to pick up their data from the Experiment Center's anonymous ftp area.

The ARM Archive provides access to ARM data for participants outside of the ARM Program. The Archive has developed a user interface through which a requestor may order data. Information regarding the ARM data is available via the ARM World Wide Web Home Page at http://info.arm.gov. In agreement with the USGCRP data policy for full and open access, data are available upon receipt at the Archive. Certain external data products available to the ARM Program may not be available for wider distribution.

11.4 How the Data are Processed

ARM data are normally collected in an ongoing, continuous manner, punctuated by IOPs. These two ways of collecting data complement each other. More traditional case study methods for analyzing data from the limited IOP data sets may be performed, but the ongoing nature of regular ARM operations requires a more automatic approach. To this end, the concept of Value Added Procedures (VAPs) has been defined. A VAP creates a "second-generation" data stream by using existing ARM data streams as inputs and applying algorithms or models to them. "First-generation" data streams refer to observations taken directly from instruments in the field. A VAP is run automatically and continuously as long as there is input data, and the output data stream, called a "value-added product," becomes available as a new data stream.

Prospective VAPs can originate from any part of the program, from instrument mentors to Science Team members. There are two distinct types of VAPs. The first type consists of data processing, including smoothing, interpolation, extrapolation, time synchronization of different data streams, and/or time averaging. These VAPs are designed to make it easier for Science Team members to use ARM data, or to reprocess the original dataset to improve the quality of the data. The second type of VAP generates new data streams derived either from physical models driven by inputs from existing ARM data streams, or from data quality comparisons.

A goal of the data processing is to ensure that ARM data is of "known and reasonable" quality. A first-level approach focuses on self-consistency within a single data stream, using various automated methods at the time of initial processing. A second-level approach comes from Quality Measurement Experiments (QMEs), a subset of VAPs. These are designed to enhance ARM data quality by providing continuous data streams derived from the intercomparison of various related ARM data streams. A QME provides the capability to identify data anomalies, such as inconsistent data across instruments and incorrectly implemented or inconsistent VAPs, and the information needed to identify the root cause of these anomalies. The quality of the ARM data will become "known" during data processing and as the data are used by Science Team members and the infrastructure. Whether the quality is "reasonable" comes from interactions with the Science Team members, and the translation of their science needs into data needs.

Special arrangements for data exchange between ARM and other global change research programs such as GEWEX and the NASA EOS program will be made on a case-by-case basis through the ARM Program Office.

Analysis may reveal problems, leading to reprocessing of important data subsets. In all cases, the Experiment Center and the Archive maintain records of who has received what data sets. This insures that users can be contacted as necessary.

12. Summary and Conclusions

ARM's programmatic objectives are to:

1. Relate observed radiative fluxes in the atmosphere, spectrally resolved and as a function of position and time, to the temperature and composition of the atmosphere (specifically including water vapor and clouds) and to surface properties, and sample sufficient variety of situations so as to span the range of climatologically relevant possibilities.

2. Develop and test parameterizations that can be used to predict the distributions of water vapor and clouds within the atmosphere, and the surface properties that strongly affect atmospheric radiation, with the objective of incorporating these parameterizations into general circulation models, and sample sufficient variety of situations so as to span the range of climatologically relevant possibilities.

In order to achieve these objectives, ARM is devoting resources to understanding, measuring, and modeling both radiation per se and cloud formation mechanisms. The scope of the program is limited so as to include only those projects that genuinely and directly relate to atmospheric radiation and climate.

ARM has some very unique attributes, which we summarize here as follows:

- the concept of a permanently-manned field site with episodic intensive operational periods, providing for the first time the opportunity to study phenomena on a climatically relevant time scale, and with time to shake all the bugs out, instead of a few weeks in the field every few years with little chance to fix bugs during a campaign.
- a permanent and high-quality infrastructure to implement and facilitate the research, the data analysis, and the instrument development.
- the organized collection of data from 20-30 sites over a "GCM grid square", not just from 1-3 quasi-random locations as in a typical campaign.
- the advancement of radiation measurements, especially in the area of spectral resolution; this had been almost completely ignored by the atmospheric community and yet holds the key to understanding many climatic change forcings including greenhouse warming.
- the development and use of UAVs and associated UAV-adapted instrumentation, allowing the long residence times aloft (eventually full diurnal cycles) necessary for true climate research; present campaigns are almost entirely daytime-only and of weather-scale rather than climate-scale duration.
- the development and use of ARCS platforms, a gigantic leap forward from the PAM stations and other semi-automated atmospheric measurement platforms now available.
- the fusion of data from a suite of the most high-tech profiling technologies known, to produce an integrated product; ARM was not the first to think of this, but may well be the first to achieve it; these integrated products are become a fountainhead for scientific advances in many related disciplines.
- the inauguration of Quality Measurement Experiments, a novel concept for quality control of field measurements; past practice has been to field one-of-a-kind instruments with no possibility of cross-checks and therefore no way to independently evaluate the goodness of the data.
- organized, common calibration of field instruments.

Continuous data collection at the ARM sites, supplemented by IOPs, is a practical and appropriate mode of operations. The relative emphasis on continuous collection and IOPs should be periodically reviewed, however. ARM will provide an invaluable service to the entire climate research community by initiating radiation/climate monitoring stations at the three ARM sites that would continue in operation for decades, i.e. indefinitely. These stations would not necessarily include all or even most operational components of the currently planned sites. For example, the ARM sites might follow the BSRN (Baseline Surface radiation Network) standards or become BSRN stations; this has already been arranged for the SGP site.

ARM must make strong, active efforts to encourage participation by representatives of global modeling groups, and to cooperate with global modeling projects such as CHAMMP. We have outlined the many ongoing interactions between ARM and other programs. We strongly hope that the infrastructure represented by the instrumented ARM sites can facilitate valuable scientific work by many other U.S. and international research programs.

Finally, it is important that this Science Plan be reviewed and updated periodically as the program evolves.

13. References

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