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Locale Analysis Report for the Southern Great Plains

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Disclaimer

Preface

The first draft of this report was completed by the authors on November 23, 1992, but the document was never published. Although this report has been finalized for publication now, nearly seven years later, emphasis is on the period from selection of a land-based locale to the establishment of a Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site, which has been in operation since May 1992. This report replaces references to publications that existed as draft versions in 1992 with references to the subsequent published versions (usually later than 1992). This report also includes the main bodies of unpublished reports that are discussed. This document is rich in history and accurately captures the thought processes and activities of the various working groups that took a CART site from concept to implementation in the SGP locale. The final chapter provides the present view of the SGP CART site (October 1999). The various phases of implementation and subsequent changes to instruments and facilities for the period 1992-1999 are captured elsewhere in the semiannual *Site Scientific Mission Plan*.

Abstract

The process of identifying a relatively small number of Cloud and Radiation Testbed (CART) sites for implementation of the experimental part of the Atmospheric Radiation Measurement (ARM) Program is one of successive screening at increasing levels of detail to establish a set of approximately five locations that satisfy a combination of scientific, budgetary, and logistic requirements and constraints. The first level of screening (DOE 1991) resulted in a set of subcontinent-sized regions, termed locales. Within each locale, the broad range of physical processes governing the quantity, structure, and radiative transfer properties of climatically important clouds is well represented. This report is one of a series of second-level screenings that examine locales more closely. Bases of selection among options are established, and favored options are recommended. This report reviews three options for a midlatitude continental locale [the Midwestern United States (MW), the Northern Great Plains (NGP), and the Southern Great Plains (SGP)] and recommends that attention be focused on developing a site within the SGP. The SGP region is further analyzed on the basis of

- Synergistic programs and collateral measurements
- Terrain, land use, and meteorological homogeneity
- Accessibility of the land and airspace for deployment of the CART observation network
- Regulatory and ownership constraints to acquiring the space to locate and use instruments and equipment.

The analysis presented here leads to a recommendation for siting the SGP CART site (275 km by 325 km) in north central Oklahoma and south central Kansas, a location roughly corresponding to the area defined by the National Oceanic and Atmospheric Administration-National Weather Service high-density Wind Profiler Demonstration Network. The level of screening in this report supports recommendations of general locations for 1 central facility, 6 auxiliary facilities, 25 extended facilities, and 3 boundary facilities within the SGP CART site, where the requisite instruments and equipment will be deployed. In addition, this report serves as an interim science plan for the SGP site. The general scientific goals, principles, and guidelines for the ARM Program are described elsewhere (DOE 1990, 1996).

Acronyms

ADM	Action Description Memorandum
AERI	atmospherically emitted radiance interferometer
AERI X	high-resolution AERI
AOS	aerosol observation system
ARM	Atmospheric Radiation Measurement (Program)
BBSS	balloon-borne sounding system
BLC	Belfort laser ceilometer
BSRN	Baseline Surface Radiation Network
CART	Cloud and Radiation Testbed
CLASS	Cross-Chain Loran Atmospheric Sounding System
CSPHOT	Cimel sunphotometer
DA	data assimilation
DOE	U.S. Department of Energy
EA	Environmental Assessment
EBBR	energy balance Bowen ratio
ECOR	eddy correlation
FIRE	First ISLSCP Field Experiment
GCIP	GEWEX Continental-Scale International Project
GCM	general circulation model
GEWEX	Global Energy and Water Balance Experiment
GRAMS	ground-based radiometer autonomous measurement system
ICRCCM	Intercomparison of Radiation Codes Used in Climate Models
IR	infrared
IRF	instantaneous radiative flux
ISLSCP	International Satellite Land Surface Climatology Project
MFR	multifilter radiometer
MFRSR	multifilter rotating shadowband radiometer
MMCR	millimeter cloud radar
MPL-HR	micropulse lidar-high resolution
MW	midwestern United States
MWR	microwave radiometer

NEPA	National Environmental Policy Act
NEXRAD	next-generation radar
NFOV	narrow-field-of-view zenith-pointing filtered radiometer
NGP	Northern Great Plains
NIP	normal-incidence pyrheliometer
NOAA	National Oceanic and Atmospheric Administration
NSSL	National Severe Storms Laboratory
NWS	National Weather Service
PAM	portable automated meteorological (station)
RASS	radio acoustic sounding system
RCF	radiometer calibration facility
RSS	rotating shadowband spectrometer
SCM	single-column model
SGP	Southern Great Plains
SIROS	solar and infrared radiation observing system
SIRS	solar and infrared radiation station (formerly part of SIROS)
SMOS	surface meteorological observing station
SORTI	solar radiance transmission interferometer
SPECTRE	Spectral Radiance Experiment
SSP	scanning spectral polarimeter
STORM	Storm-Scale Operational Research and Meteorology
SWATS	soil water and temperature system
SWS	shortwave spectrometer
THWAPS	temperature, humidity, wind, and pressure sensors
TLCV	time-lapse cloud video
TRMM	Tropical Rainfall Measuring Mission
UAV	unmanned airborne vehicle
USDA	U.S. Department of Agriculture
UV	ultraviolet
UVB	ultraviolet-B
VCEIL	Vaisala ceilometer
WSI	whole-sky imager
WSR	weather surveillance radar

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1. Introduction

1.1 General Guidance for Locale Selection

The successful fulfillment of the Atmospheric Radiation Measurement (ARM) Program mission requires empirical data that explore, as fully as possible, the range of parameters governing the formation, movement, distribution, and description of clouds and their role in the radiation balance of the atmosphere. At the very least, these requirements necessitate a broad sampling of the types, quantities, and altitudes of clouds; the energy transfer characteristics of earth's surface; vertical motion fields; and the temperature and humidity distribution in the atmospheric column. In fact, many more attributes of the site surface, atmosphere, and clouds that modulate radiative transfer processes were defined and prioritized in the initial locale selection process [Department of Energy (DOE) 1991].

In the selection process, candidate locales are systematically evaluated in terms of the stress that could be applied to the models with data gathered there. This procedure emphasizes a locale selection philosophy that is quite distinct from the sampling of world climatology, which would require hundreds of observation sites. Instead, we use the relevant collection of physically based models as the vehicles for our accumulated knowledge. In this philosophy, the empirical task becomes one of testing the models' applicability over the broadest range of parameter space (values of model inputs, outputs, and internal parameters).

Another scientific principle that has been applied in the selection process centers on the need to keep uncontrolled variables at a minimum in order to increase the chances of interpreting the selected dependencies. In the selection process, this principle translates into a search for quasi-uniform surface and cloud conditions. This, of course, does not mean that we expect to observe mesoscale uniformity. Indeed, there will always be a considerable variability in all of the relevant fields. However, we hope to observe fields that reflect statistical homogeneity (i.e., fields of surface fluxes or cloud properties for which important statistics like first and second moments and scale lengths are uniform across a site). Also desirable is that these statistical properties be describable in terms of observable gross (topographic and climatic) properties of the locale that houses the site.

Two other important criteria that enter the locale selection process are the logistic difficulty of conducting the chosen operation and the synergistic benefits of coordinating with other data-gathering programs. The logistic concerns are a high priority for the first Cloud and Radiation Testbed (CART) site to be occupied, because a large number of operational details must be mastered by the participants to make the whole program really work. Once the lessons of coordination, implementation, maintenance, safety, transportation, communication, supply, etc. have been worked out and tested at a site with relatively easy logistics, these lessons can be applied at sites with more complex logistics related to remoteness or harsh environments.

The issue of synergism with other programs is an important one for all ARM Program activities. Field measurement programs are very expensive, and the observation systems and platforms are a major part of the expense. All studies of atmospheric structure can benefit from wider or denser observation networks or supplemental classes of observing systems. Furthermore, even though other programs have different goals (severe weather, hydrologic system modeling, aircraft safety, improved short-term forecasting, etc.), they all require better understanding of the structure and variability of the atmosphere. Therefore, the exchange of interpretive insights and experience among scientists in different programs is important for their mutual success.

The locale selection report (DOE 1991) screened the entire earth and, guided by a vision of the ARM Program goal and the set of selection principles described briefly above, developed a prioritized list of locales. Some adjustments to the priorities followed as a result of discussions during the first ARM Program Science Team meeting (November 5-9, 1990). The next step is addressed by the present series of nine companion documents, one for each of the top-priority locales. In these reports, we concentrate on the specific scientific, logistic, and synergistic issues that characterize the particular locales.

This report is one of a series of locale analysis reports, each addressing one of the candidate primary locales of the ARM Program. The goal of the reports is to examine the operational issues associated with performing CART experiments at each of the top-priority locales. The results of these studies could shift the priority of occupation. Also being examined are the scientific, instrumentation, modeling, implementation, and operational issues that emerge as we explore the complexities of occupying and operating a site within the subject locales. The authors have the freedom to explore the full set of issues encountered in addressing the following operational questions, which form the outlines of these reports:

1. Why conduct operations within this locale?

2. What measurements must be made to answer the above question?

3. What are the particular logistic and operational problems for CART operations at this locale? How will these problems be resolved?

4. What are the logical linkages to other candidate locales and the most appropriate extensions of the primary mission?

5. How would the measurements strategies outlined in the program planning document (DOE 1990) be implemented at this CART locale?

Site operational and logistic issues make sense only in the context of the site mission. Thus, the (evolving) elements of the mission as they presently exist and the statement of ARM Program objectives have been kept clearly in view as the authors have developed the series of companion reports. The ARM Program objectives, as paraphrased from the operations plan (DOE 1990), are to do the following:

- Describe the radiative energy flux profile of the clear and cloudy atmosphere.

- Understand the processes driving the flux profile.

- Parameterize the processes for incorporation into general circulation models (GCMs).

The site mission statement that is currently in preparation focuses on five primary locales and was developed over a year of discussion involving the ARM Program Science Team and predecessor groups. With the understanding that the core experiments will evolve with time on the basis of the added insights and scientific results of the program, we address the questions that form the outline of these locale analysis reports.

1.2 Conducting CART Operations at a Continental U.S. Site

The scientific motivation, relative to cloud formation, maintenance, and dissipation, for selecting five locales is addressed in the operations plan (DOE 1990) and the locale selection report (DOE 1991). The primary reasons for conducting CART operations in the continental United States, then, are the following:

- The widest range of cloud and radiation conditions supports a major portion of the ARM Program scientific objectives, including the clear-sky experiment, time-space fluctuations, cloud formation and maintenance, and radiative profiles through a large variety of cloud types and amounts.

- Operational procedures and interfaces with data users and interested parties can be developed and tested in the shortest possible time and at minimal cost.

- Instrument performance can be evaluated under a fairly wide range of environmental conditions in a setting where improvements can be made most easily, quickly, and cost effectively.

- New instrument systems in transition from the research to the operational mode can be introduced and evaluated at this site before they are deployed at more remote sites. This practice will avoid costly redeployments.

The primary research focus is the radiation flux profile through an atmosphere containing the full range of cloud amounts from clear to multilayered overcast. Particular issues cited in the scientific planning document (DOE 1996) arise in consideration of radiative energy transport in climate models; cloud formation, maintenance, and dissipation; and the limits of modeling atmospheric processes in GCMs and related models. The current series of locale analysis reports represents an interface between site selection and site operations activities.

2. Locales within the Continental United States

Midlatitude continental locales offer perhaps the broadest range of cloud and radiative transfer conditions because of their rich variety of migratory synoptic-scale disturbances and air masses, along with strong diurnal and annual cycles of surface and atmospheric conditions. With the added consideration of logistic simplicity in terms of access, sources and routes of supply, and availability of troubleshooting expertise, the continental United States is an obvious choice. The three locales put forth by the locale selection procedure [Midwestern United States (MW), Northern Great Plains (NGP), and Southern Great Plains (SGP); Figure 1] have the most favorable scientific attributes in terms of quasi-uniformity and avoidance of terrain complications. As we will see, the opportunities for synergism with other studies are also very good at these locales.

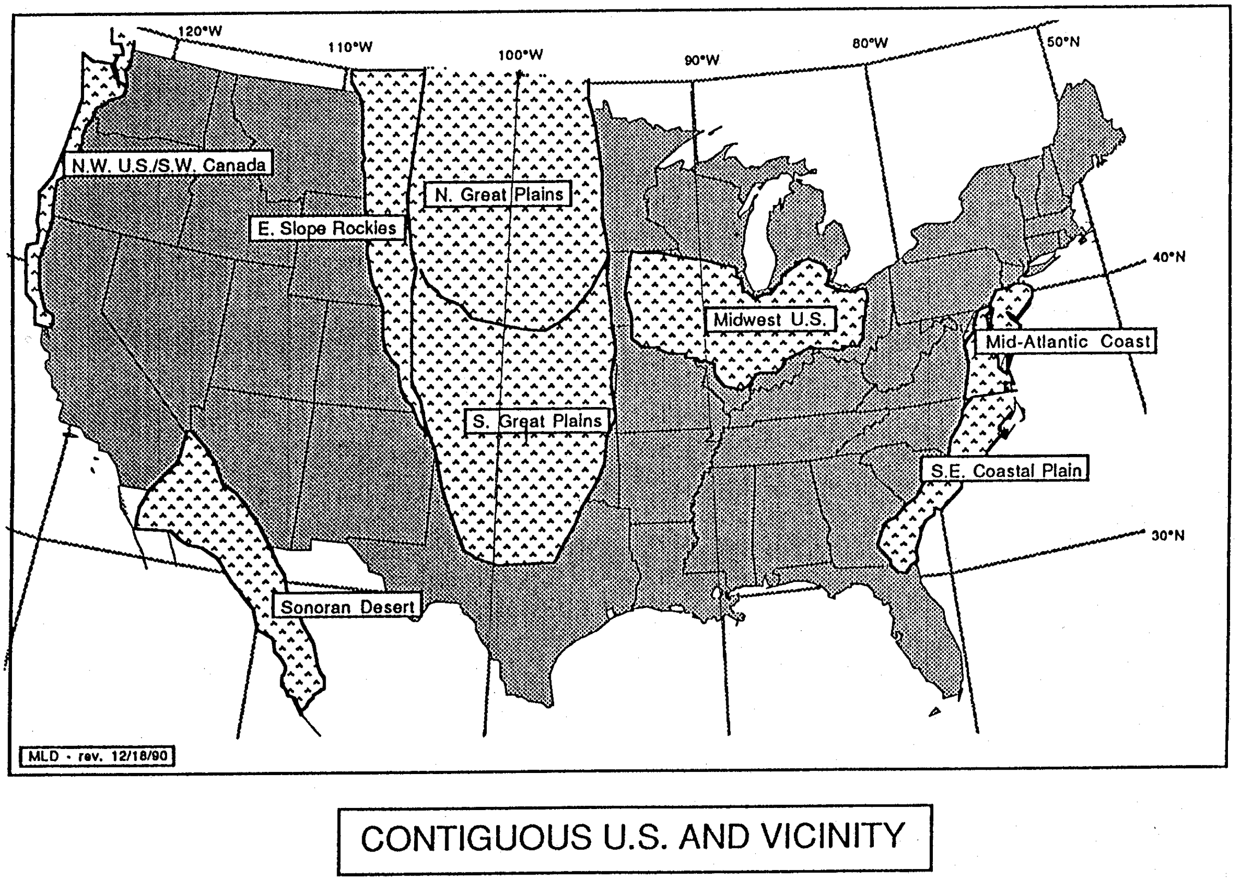

Figure 1. Potential locales for the continental United States CART site (after DOE 1990).

Given that the scientific mission of a CART site is to support studies of cloud and radiative transfer properties, reference materials were sought that would provide background data on the clouds, solar radiation, and temperature and moisture profiles expected to govern terrestrial (outgoing) longwave radiation. This section summarizes selected climatologic properties and cites references that should be useful to scientists planning ARM Program studies at continental U.S. locales.

Cloud statistics were extracted from a report prepared by Warren et al. (1988). The document provides maps with gridded values of many cloud parameters, including total cloud cover; frequency of occurrence; amount when present; cloud base; amplitude and phase of diurnal variations of cumulus, cumulonimbus, stratiform, middle (altostratus, altocumulus), and cirrus clouds and clear sky. Table 1 summarizes values collected from Warren et al. (1988) for these statistics for each of the three candidate continental United States. locales. Values from four grid points were selected to represent each locale. Generally, the values for each of the grid points making up the locale averages were internally consistent. On some occasions, one of the four values was quite different from the other three, reflecting a strong spatial gradient. The reader who is concerned with spatial inhomogeneity over a locale should consult the original cloud climatology with its greater detail. Cumuloform clouds are a warm-season phenomenon with an evening maximum for all three locales, while low-level stratiform clouds are more frequent in the

Table 1. Cloud climatology for three Continental U.S. locales.[a]

Frequency (number of days), Amount when Present (%), Base Height when Available (ft)						
Locale[b]	**Winter**	**Spring**	**Summer**	**Autumn**	**Amplitude Phase Summer**	**Amplitude Phase Winter**
Cumulus Clouds						
MW	2, 36	11	24, 33	8		
NGP	1, 32	10	20, 26	5		
SGP	1, 24	12	25, 24	8		
Cumulonumbus Clouds						
MW	0.5, 85	2, 66	5, 52, 1040	1, 60	1.4, 19	
NGP	0	2, 51	8, 40, 1450	1, 47	3.0, 20	
SGP	0	6, 43	15, 35	4, 40	4.5, 18	
Stratus, Stratocumulus, Fog						
MW	55, 84, 689	41, 76, 840	28, 66, 880	47, 75, 810	6.2, 6	3.0, 6
NGP	36, 76, 760	36, 75, 810	20, 63, 980	34, 77, 790	3.5, 6	2.6, 5
SGP	30, 76, 740	28, 71, 810	13, 56, 870	27, 73, 750	5.0, 6	3.0, 7
Nimbostratus						
MW	16, 99	8, 99	2, 98	8, 99		
NGP	13, 97	8, 98	2, 96	8, 98		
SGP	8, 99	4, 99	1, 97	5, 99		
Altostratus, Altocumulus						
MW	23, 66	32, 61	35, 57	32, 58		
NGP	36, 43	32, 53	38, 44	33, 47		
SGP	27, 43	26, 47	30, 43	29, 43		
Cirrus						
MW	46, 59	55, 58	54, 55	47,50		
NGP	61, 52	62, 54	56, 40	64, 47		
SGP	66, 52	60, 54	58, 38	55, 44		
Clear Sky						
MW	14	11	10	8		
NGP	13	10	11	12		
SGP	18	15	9	19		

(a) Seasonal average cloud cover in the three locales is as follows:

Average Cloud Cover (%)

Locale	**Winter**	**Spring**	**Summer**	**Autumn**
MW	70	65	57	60
NGP	57	58	47	53
SGP	50	52	44	45

(b) Locale:

MW = Midwestern United States
NGP = Northern Great Plains
SGP = Southern Great Plains

Source: Warren et al. (1988).

cool seasons and early morning. Middle clouds occur about one-third of the time, in all seasons. The MW locale has more middle clouds when they are present. The winter statistics support the selection of the SGP as the site for FIRE-Cirrus. Cirrus cloudiness affects two-thirds of the observations in the SGP in winter and, on average, occupies half of the sky when present. (FIRE is the First ISLSCP Field Experiment, where ISLSCP is the International Satellite Land Surface Climatology Project.)

The broad plains between the Rocky Mountains and the Appalachians offer a potentially valuable region for a wide range of meteorology studies requiring quasi-uniform surface conditions. In addition, the meteorology of this region has perhaps been observed more extensively and studied in more detail than that of any other place on earth. The location of the central United States at 30-50 deg north latitude places it in the midlatitude band of westerly winds and migratory synoptic-scale disturbances, with a strong seasonal dependence on both the air masses and storm tracks that influence the region. Haurwitz and Austin (1944) used traditional synoptic analysis to show the set of preferred storm tracks in the central United States and seasonal streamline analyses. These authors showed that in the summer, the entire U.S. midlatitude region is fed with warm, moist air from the Gulf of Mexico. In the winter, the prevailing sources of low-altitude air over the U.S. central plains are far more continental, although the northern portion of the region more frequently sees occurrences of polar air. The rain shadow effects of the Rockies, plus the gradual but significant upward slope of the terrain from the Gulf of Mexico toward the northwest to the Front Range of the Rockies, creates a moisture gradient across the plains. Dry air occupies the plains of eastern Wyoming, Colorado, and New Mexico; moisture increases toward the midwestern United States. Haurwitz and Austin (1944) showed this pattern in the field of precipitable water (column-integrated humidity). For 50 U.S. stations in 1946-1956, the mean annual moisture content of the atmosphere up to 325 mbar showed a relatively strong gradient ranging from 25 mm of precipitable water in southeastern Oklahoma to 15 mm in northeastern Kansas. The roughly north-south, latitude-dependent temperature gradient; the sloping east-west terrain; and the moisture gradient are reflected in the vegetation and climate classifications of the region, interpreted from Landsberg et al. (1974). Continental steppe covers the area west of a north-south line that divides Nebraska, Kansas, and Oklahoma in half. South of the Oklahoma-Kansas border (approximately 35 deg north latitude), the eastern part of this region is a subtropical, moist-climate zone; north of the Oklahoma-Kansas border, the eastern part of this region is a continental, moist-climate zone. These factors indicate that the broad area in the central part of the United States offers the opportunity to sample a wide range of moisture conditions.

The upper-air profiles of temperature and humidity hold the key to many aspects of the dynamics and thermodynamics of a region and are among the most useful data sources for diagnosing the daily weather. Use of a thermodynamic diagram to analyze the upper-air sounding assists in the forecasting of surface temperature; precipitation occurrence, quantity, and type; and thunderstorm potential. For the ARM Program, the temperature and humidity soundings have an additional centrally important role, because the column temperature and moisture govern the profile of longwave radiative flux. Exploring the differences in temperature and humidity profiles among the three candidate locales is of interest, but these characteristics are unlikely to enter the selection process. Although there is no shortage of such data (with twice daily radiosondes being launched routinely from several stations within each locale), the method of analysis is a matter of choice, and in the time available for this survey, only a few climatologic surveys addressing the issues under consideration here were found. Landsberg and Rex (1969) showed strong similarities but some important differences between the locales. The mean winter tropopause occurs at about 11 km altitude for the MW and SGP locales and at about 10 km for the NGP. This characteristic is reflected in an apparently more stable lapse rate above 300 mbar (approximately 10 km). The winter humidity is slightly lower in the SGP. In summer, the SGP locale is distinguished by a less stable lapse rate and drier air in the lower troposphere. Before a site is occupied in any of the three locales, a climatology survey tailored to the specific needs of the CART site scientific mission is needed. Such climatologic information will be invaluable for efficiently planning the schedule of special measurements to accomplish the full suite of ARM Program experiments.

Incoming solar radiation to sites on earth's surface has an obvious dependence on latitude and season and also depends on scattering and absorption in the (cloudy) atmosphere above the site. The distribution of solar energy varies with meteorology in fairly complex ways, although global radiation budgets suggest that about one-half of the incoming energy, or 170 W/m^2, reaches the surface. A U.S. Department of Energy atlas (DOE 1981) reported a pattern with maximum flux (direct plus diffuse) in the southwestern United States, a minimum in the northeast, and a consistent gradient across the three locales of interest. The SGP has a solar flux (197 W/m^2) slightly above average, while fluxes in the MW and NGP locales are slightly below average at 160-165 W/m^2. The atlas goes well beyond this simple parameter to present model-based estimates for direct and diffuse components of incoming solar energy, plus many other meteorologic parameters related to solar heating (degree days, temperatures, cloud cover, etc.).

The criteria for selecting the continental U.S. locale as the first CART site to be implemented emphasize the need for favorable logistics and include uniformity, synergism with other programs, and range of cloud radiation parameters. All three proposed locales exhibit favorable logistics as defined in the operations plan (DOE 1990). Logistic elements include transportation, utilities, communications, site occupation, structures and grounds, security, equipment acquisition, operations and maintenance, and mobile platform (e.g., aircraft and vehicle) operations.

The scientific criteria favoring the three alternatives for the continental U.S. locale include broad ranges of the following:

- Cloud types and amounts
- Surface energy fluxes
- Temperature
- Precipitation
- Pollutant aerosol concentrations
- Synoptic meteorology conditions
- Cloud formation and transport processes.

In applying the original selection procedure (DOE 1991), the working group favored the MW locale because of its greater range of surface energy fluxes and pollutant aerosol contents, which can influence cloud optical properties. However, the margin of selection was quite narrow, with the potential for a shift in the balance to either the NGP or the SGP on the basis of logistics or synergism with other programs or facilities already in place. The ARM Program Science Team suggested that the potential for synergism in the SGP would make that locale significantly more attractive. Therefore, this report focuses on the scientific, synergistic, and logistic attributes of the SGP locale, with the goal of assessing the complications of site occupation and operation there.

3. Conducting CART Operations at the Southern Great Plains Locale

All three candidate locales offer excellent logistic attributes, good geographic homogeneity, large intra-annual variability of climate cloud type and surface flux properties, a wide variety of cloud types, and large seasonal variability in temperature and specific humidity. The scientific debate over the “best” locale relative to the above attributes does not produce a clear candidate for the continental U.S. locale. However, as this report will show, the SGP locale clearly provides the best opportunity for synergistic activity with several major state and federal research programs. The instruments already in place, currently being deployed, or being planned for deployment well within the ARM Program lifetime for these other long-term research activities are similar to those proposed by the ARM Program. This observation does not mean that the existence of the ARM Program in the SGP depends on those other programs. The ARM Program has budgeted such instruments for its own activities. However, sharing instrumentation where possible would increase spatial coverage in an observational area where such coverage is crucial and would save substantial taxpayer dollars by avoiding needless duplication of effort. No other U.S. locale provides such a mix of atmospheric conditions or affords proximity to as many other relevant federal and state agency research programs. Therefore, the balance of this report focuses on the attributes of the SGP as the locale of choice for the continental U.S. location.

Important scientific attributes of the SGP locale include the following:

1. **Midlatitude position**. The SGP is positioned in the midlatitude region of migratory synoptic disturbances in the westerly flow. This position accounts for wide variety in cloud fields, including types, amounts, altitudes, and thickness, often in combination. Cloud formation and maintenance mechanisms result from circulation features at a wide range of scales associated with synoptic disturbances, including frontal bands, squall lines, mesoscale convective complexes, and smaller mesoscale processes down to isolated cumulus clouds. A highly distinctive characteristic of midlatitude locales is the strong seasonal dependence of the cloud and radiative (longwave plus shortwave) environment as polar front and storm tracks shift through the area with the seasons. Haurwitz and Austin (1944) showed the mean positions of polar and arctic fronts relative to the SGP in summer and the associated predominance of polar air in winter and tropical air in summer. The preferred storm tracks show that cyclones forming on the cold front pass through the SGP region with great regularity (every 5 to 7 days) in the summer and tend to retreat northward in the winter. This affords the opportunity in the SGP to sample a widely ranging variety of seasonal meteorological conditions, with storm systems passing through the area weekly on average.

2. **Continental location**. The continental location of the SGP accounts for the high frequency of continental air masses influencing the locale. The air mass concept was developed early in meteorological analysis as a method for describing time and space relationships of, for example, temperature, moisture, and stability. This concept retains some validity as a way to recognize an atmospheric volume that has had ample residence time in a geographic region to acquire thermodynamic properties consistent with that region. Hence, for example, between periods of wind disturbance, cold high-pressure domes of air might form in the Canadian or Siberian Arctic. When portions of this air are mobilized by atmospheric circulation, they can migrate considerable distances, yet retain much of the character of their origin.

   The SGP locale is influenced by three major air mass types: continental polar air from source regions in Canada, Pacific maritime polar air that is greatly modified in traversing the mountainous western United States, and maritime tropical air passing over the warm waters of the Gulf of Mexico. These air masses interact within the locale as the polar (and occasionally the arctic) front that forms the boundary between them is moved meridionally by the action of migratory waves in the westerlies. Because the fetches over which air in different air masses arrives have different properties, their meteorological structures can be vastly different. The result is daily variations in the thermodynamic, moisture, aerosol, and cloud structures of vertical profiles in the air above the SGP locale.

3. **Terrain**. The SGP locale is representative of the broad region of plains between the Rocky Mountains and the Mississippi basin. Although the locale has been selected to be outside the area of immediate effects of the mountains, many cloud formation processes are related to the presence of the Rocky Mountain complex. One feature in particular is the slight but very important upward slope toward the west. Easterly flow of moist air will produce upslope stratus cloudiness. The terrain variation also accounts for generally drier air as one moves westward. The local terrain within the locale is generally very simple, varying from very flat to mildly rolling hills.

4. **Surface properties**. The surface characteristics in the SGP locale are quasi-uniform cropland and grassland, offering perhaps as good an opportunity for a uniform surface site as can be expected in real settings. Land use patterns, different ages and types of vegetation, and recent meteorological history might contribute to complex time-space patterns of surface radiative and thermodynamic conditions and surface energy fluxes. These patterns will have to be documented for all experiments that involve the surface boundary condition.

In discussing the scientific basis for selecting and operating a site in the SGP locale, we will address combinations of scientific issues and technical approaches. The central scientific issue to explore is the divergence of cloud radiative flux in generalized cloud conditions (including clear sky through multilayered overcast), addressed through detailed instantaneous radiative flux measurements. The major attributes of the SGP locale for this issue-approach pair are the strong seasonal- and synoptic-scale variability of humidity profiles; the amount, type, and distribution of clouds; and the surface energy balance.

4. Science Issues and Measurements Required to Achieve the Goals for the SGP Site

The scientific basis of the overall ARM Program was developed in a series of predecessor reports. The operations plan (DOE 1990) describes results of GCM intercomparisons that raised serious questions about the current parameterization of important physical processes. The radiative effects of clouds and surface energy exchange, especially on regional scales, differ enough between models to undermine confidence in the estimates of climate alteration by the current generation of GCMs. In addition, the Intercomparison of Radiation Codes Used in Climate Models (ICRCCM) (Ellingson and Fouquart 1991) highlighted the need for additional research to understand the role of individual spectral absorption lines and to find reliable methods to group the lines into bands—a computational requirement for GCM applications. Unresolved issues are centered on the following:

- Profiles through an atmosphere in which pressure, temperature, and composition vary by orders of magnitude. (Absorption lines change shape throughout the profile because of pressure- and composition-dependent broadening.)

- The absence of a theory for the observed water vapor continuum, which inhibits the reliable extension of the empirically based formulation to the full range of observed psychometric profiles.

The scientific planning document (DOE 1996) focuses on the single most important issue of the ARM Program: the treatment of radiative transfer in climate models. The scientific questions dealing with this issue are categorized into three topic areas in that document. These areas are radiative energy transport in climate models; cloud formation, maintenance, and dissipation; and the limits of modeling atmospheric processes in GCMs and related models. All important scientific questions generated by the current Science Team should be addressed by the collective CART sites.

This locale analysis report is an attempt to translate the general science issues into a plan that takes advantage of the attributes of the specific SGP site to achieve ARM Program scientific goals. Those attributes include a cloud, air mass, and circulation dynamics climatology that exhibits a wide diversity in the processes and quantities of central importance to the ARM Program. In addition, the potential for synergistic collaborations with other programs in the area enhances the observational database and the interpretation of physical phenomena. We must keep in mind the role of phased implementation, which permits the gradual buildup of observations and interpretation and encourages evolution of the scientific design. Available instruments will drive the early experiments. An assessment of the availability and developmental status of relevant instrumentation is important at this stage. This information will allow prioritization of the scientific issues to be addressed early at the SGP CART site.

The need to reconcile meteorological observations with models, for either input data or output comparisons, gives rise to a complex and important set of considerations. A primary issue involves the limited resolution (in time and space) of models and the fact that many observations represent a variety of configurations in space and time (e.g., high temporal resolution at a specific point in space, vertical traverses from balloon soundings, path-integrated soundings from some passive remote sensors). In other cases, the physical quantities observed might be surrogates for the model quantities, or a combination of observations might be required to estimate a modeled variable [e.g., using radiosonde data to assess vertical profiles of temperature or humidity profiles from a radio acoustic sounding system (RASS)].

Within the ARM Program, a distinction is made between “observations” produced by an instrument or an algorithm and “measurements,” which are observations subjected to some level of quality control (e.g., conversion of signals to standard units and some kind of objective screening that assures that data are of known quality), resulting in data streams prepared for the interface with models. Measurements are frequently the product of one or more observations or data-conditioning models. Four-dimensional data assimilation is one important process for generating model-consistent fields of variables from networks of individual observations.

The science issues include the representativeness of measurements and observations on different spatial (and temporal) scales. Although a central site is envisioned, extended sites will be necessary to achieve representative estimates for a GCM grid of 250 km × 250 km. Certain observations can be made at the smallest of scales (less than 1 km). Depending on surface homogeneity, the next larger spatial scale for observations is tens of kilometers. The largest scales at CART sites, on the order of hundreds of kilometers, will require information from outside the CART domain (250 km × 250 km). The measurement strategy will be developed from the instruments that are available and the uniformity of surface characteristics within the CART domain. This report suggests a suitable SGP CART site on the basis of available instrumentation, surface homogeneity, and logistic considerations.

4.1 Characteristics of GCM Predictions for Midlatitude Continental Regions

Policymakers and others interested in the effects of global climate change frequently ask about effects on major agricultural regions. In North America and Eurasia these regions occupy large areas in the continental interior. Most broadly, the effects include temperature, precipitation, and soil moisture. Practical considerations focus on seasonal and diurnal variations, as well as subregional patterns of these quantities. Several of the climate models that were available in the mid 1980s were exercised in response to those questions, and results were published. Schneider (1989), MacCracken et al. (1990), and Houghton et al. (1990) produced summaries and intercomparisons of the results of several models. The significant lack of agreement between models in the description of fundamental hydrologic variations underscored the need to improve the models’ characterization of hydrologic processes, including cloud formation and dissipation, precipitation, evaporation, runoff, and percolation. The models suggested midlatitude continental loss of soil moisture and a doubling of atmospheric carbon dioxide, but the magnitudes, patterns, and even the sign of the change differed considerably among respected models. The modeling uncertainties demonstrated in these investigations have motivated studies like the ARM Program, which will use a combination of observation and model development to improve the description of the effects of clouds, precipitation, and surface exchange processes on the energy balance within a model grid at a continental location.

In the following sections we present the scientific issues that have been identified by the ARM Program management and the ARM Program Science Team as important for making use of the attributes of a midlatitude continental U.S. CART observatory.

4.2 Radiative Transfer under Clear Sky and General Cloudiness

A primary early motivation for the entire ARM Program was the realization that the complexity of infrared (IR) radiative transfer through the simplest (cloudless) atmosphere with its suite of IR-absorbing trace gases, especially water vapor, remains only partially understood. The only way to increase our understanding is through a measurement program in which the thermodynamic state and the trace gas composition of a column of atmosphere are documented. These quantities will drive model calculations of the radiative flux profile, which can then be compared with measured radiative flux. Clouds and aerosols increase the complexity of radiative transfer considerably by adding scattering functions in a distinctly more complicated geometry in time and space. The crucial role of clouds as an energy feedback mechanism in the climate system cannot be ignored, so we accept the scientific goal to improve the understanding of radiative transfer in general sky conditions and to translate that understanding into improved parameterizations for GCMs and related models.

4.2.1 Radiative Transfer under Clear Sky

The simplest atmospheric state is the clear-sky case, but even this presents difficulties. On the purely theoretical side, the intercomparison of results for the same physical conditions (Luther et al. 1988) revealed a surprising level of disagreement. The cause almost certainly involved errors in the assumed molecular optical properties for water vapor and trace gases. ARM Program measurements can provide general confirmation of a model’s ability to predict radiative fluxes. To do so, the ARM Program must simultaneously measure both the radiative intensities and the distribution of physical quantities that govern radiative transfer (e.g., temperature and molecular composition). One complication arises in the required precision of the observations. The expected alteration in radiative flux from the postulated greenhouse gas concentration increase (our signal) is on the order of 1%, while the state of the art in broadband radiometry offers accuracy of only about 5%. Similarly, water vapor profiles observed by current instrumentation can exhibit quite large uncertainties. The absolute accuracy of such measurements will, unfortunately, limit the direct usefulness of the data. Given, however, the fact that much greater relative accuracy (i.e., precision) can be expected, the data will be critical in assessing the validity of the model’s response to changes in physical conditions.

A potential complication that might be addressed by using ARM Program data is small-scale inhomogeneity. Even in clear sky, the atmosphere is not physically uniform. The magnitude of the perturbations will be addressed by the ARM Program in two ways: 1) the spatial variability at a fixed time and 2) the variability at the same site over a time period. These measurements will yield direct information on the temporal and spatial structure of the inhomogeneities and will test the validity of techniques for implying parameters of one from observations of the other. From the standpoint of modeling, the fundamental information that the ARM Program can provide is to confirm whether the effects are linear. Can modelers justifiably expect to predict the area-averaged fluxes on the basis of area-averaged variables? If not, finite-resolution models have fundamental difficulties.

The simplest form of the clear-sky study would be a one-dimensional investigation of the composition and thermodynamic properties of the atmospheric column and their effect on surface radiation. This goal requires representative measurements of surface emissivity and profiles of temperature and moisture. The data serve as inputs to a model that provides estimates of radiative flux profiles, which in turn are compared with their observed counterparts. This comparison, a highly useful diagnostic test of models, forms the basis of the Spectral Radiance Experiment (SPECTRE; Ellingson and Wiscombe 1996). SPECTRE was designed to calibrate, in the field, line-by-line IR opacity models previously presumed to be accurate but found to disagree in the ICRCCM intercomparison (Ellingson and Fouquart 1991). SPECTRE's objective is to measure accurately the zenith IR radiance at high spectral resolution and concurrently to observe profiles of the atmospheric variables that govern radiative transfer (temperature, water vapor, aerosols, and clouds). Several features have been designed into SPECTRE to maximize the accuracy of the observations (redundant sensors, on-site calibration, observation of radiance rather than flux); the ARM Program must retain that emphasis.

The troposphere includes a major component of heat and mass transfer that results from convective motions on a wide spectrum of time and space scales. This component could contribute to nonrepresentative observations for a model that assumes equilibrium conditions in a single column. Complicating processes include surface inhomogeneity, turbulent heat and moisture fluxes, horizontal advection, and aerosols and trace gases, which can be highly nonuniform through the column. The effects would appear as increased scatter in the relationship between model prediction and observation. One way to control these complexities is to characterize the profile as a column of finite horizontal dimension and time, thus obtaining an average of the atmospheric state with both lateral and bottom boundary conditions. This strategy suggests a second general measurement approach: a column energy budget. In this approach, horizontal advection must be measured at the boundaries of the control volume. Hence, this becomes a four-dimensional experiment, combining sensible and latent heat fluxes with vertical profiles to provide estimates of flux divergence.

4.2.2 Scattering and Absorption in Cloudy Atmospheres

The presence of clouds complicates the column energy budget in several ways, including the introduction of aerosol scattering physics and the role of clouds as IR absorber-emitters. A dominant characteristic of clouds that must be taken into account in the measurement strategies is their temporal and spatial inhomogeneity. Although, in principle, the single-profile approach might be valid for uniform cloud layers, we expect that most cases will involve important time and space variations in the cloud field. First, how do the radiative properties of individual clouds and cloud banks affect their transmission and reflection of incident visible light? Can the fundamental macrophysical optical properties be predicted on the basis of microphysical parameters? Cloud boundaries are rough. A simple but theoretically important quantity to measure is the albedo of clouds as a function of the boundary conditions. Again, the importance of the usually omitted subgrid structure needs to be addressed. Here, too, the availability of precise relative measurements over a long period of time (i.e., over many physical conditions) will permit validation of the models.

Much of a cloud's impact on the surrounding atmosphere is determined by processes very near the cloud boundary. Thus, attention is drawn to features as narrow as 1 m or less in columns as deep as 20 km, a serious challenge of resolution for both observation and modeling. Clouds exist in multiple layers at a given time; they form and dissipate, and they have varying droplet-crystal spectra depending on cloud location, age, motion systems, and position within the cloud. For some problems, averaging over a column in the single-column model approach might be sufficient. However, if the physics of interest involves a covariant process at the scale of cloud variability, the covariance cannot be assumed to be zero. Some account must be taken of the structure of the fields within the column (four-dimensional data assimilation). An example of such a covariant process might be an aqueous-phase chemical reaction that occurs in the presence of cloud water but is not reversed in its absence.

The data requirements include a three-dimensional characterization of the cloud field. Also required are the types of clouds, their physical characteristics (liquid water content, cloud base, cloud height, horizontal extent, uniformity of optical depths, etc.), associated synoptic conditions, terrain features, and associated preferential cloud development. Furthermore, the energy balance associated with the crucial points in the profile (cloud base or top, inversion base, aerosol layer) must be known on vertical scales of meters. For example, the radiation and turbulence fields at cloud top and cloud base must be known in great detail. In many cases, aircraft platforms operating with well-designed missions are the only way to acquire the necessary data. Yet, the ARM Program experiment will provide information on the important effects (i.e., parameters) that must be included in a cloud radiation treatment. Temperature and water and ice contents must obviously be estimated. But how important to the radiation energy balance is the age of the clouds (i.e., the water droplet size distribution)?

The IR radiation absorbed by clouds will provide another set of theoretically important measurements. Energy is absorbed in the upper layers of clouds. How does this affect the IR radiation emission by the clouds? Is the significantly larger heating rate in the upper parts of the clouds reflected in an infrared loss rate that is higher than that implied by the mean ambient temperature? Again, the question is about the importance of a subgrid phenomenon, in this case the temperature structure of individual clouds.

The distribution of the clouds is usually highly inhomogeneous. The ARM Program measurements will provide information on 1) the cloud cover over the site and 2) the average flux at the site. These data will enable investigators to determine how to include finite-sized discrete clouds in the modeling. First, ARM will determine the importance of three-dimensional transfer effects caused by scattering from clouds. Next, ARM will establish whether cloud cover properties can be predicted on the basis of area-averaged physical data. Finally, ARM will confirm whether cloud parameterizations are accurate in predicting net reflection and transmission averaged over large areas.

The physics of clouds will be extremely important in characterizing their radiative properties. The radiative transfer processes in the cloud field depend on the composition of the cloud (i.e., the amount of the cloud that contains liquid water as opposed to ice crystals). The geometric properties of size and shape of water droplets and ice crystals are also important. Such parameterizations are crucial in resolving the issues of light scattering and absorption surrounding cloud optical properties.

4.2.3 The Role of Surface Physical and Vegetative Properties in the Column Energy Balance

Studies of atmospheric energy budgets require the definition of a control volume in which exchange through the bounding surfaces is described carefully. A particularly crucial boundary exists at earth's surface, where convection, evaporation, and radiation are equally important and are driven by geology, topography, vegetation, soils, land use, and other characteristics that vary dramatically over small distances. The surface energy budget also varies with time of day, season, and meteorological conditions, both current and recent. For example, recent rain or snow can dominate surface conditions for hours to months. Deciduous forests exhibit strong seasonal variation in radiative, sensible, and latent heat transfer, and cropland undergoes the annual cycle of growth and harvest.

GCMs determine surface temperature either diagnostically by assuming a local balance in the surface radiative exchanges or prognostically by calculating the diffusion of heat across one or more layers of soil. The surface exchanges of sensible and latent energy are generally estimated with a bulk approach in which the fluxes of heat and moisture are predicted from the local gradients and the surface wind stress within the constant-flux layer (approximately 10-100 m above the surface). The transfer coefficients are also related to the local stability, generally in terms of the Richardson number. Above the constant-flux layer, the turbulent fluxes are determined as a product of the eddy diffusivities and the vertical gradients of the resolved fields.

Surface hydrology is predicted by using a two- (or more) layer soil moisture model of various degrees of complexity, together with the predicted snow mass budget. The balance of moisture within the surface and root-zone layers is determined by the balance of inward flows due to precipitation and snowmelt versus losses due to evaporation and runoff. Evapotranspiration of moisture from vegetation is often neglected, except in specific experiments involving a vegetation-atmosphere transfer scheme like those of Dickinson et al. (1986) or Sellers et al. (1986). Surface roughness is generally prescribed for land surface types and is given as a function of wind speed over ocean surfaces. Surface albedos are prescribed over land and are calculated as a function of the zenith angle over ocean. Grid albedos over land are defined as a function of the surface type and the snow cover fraction.

The role of surface characteristics in the energy balance at a CART site is currently under study by a consortium of ARM Program Science Team investigators who have brought together concepts and techniques of micrometeorology, ecology, remote sensing, and airborne measurements. In an initial field campaign in northeastern Oregon, the team explored the role of spatial inhomogeneity in surface vegetation by comparing observations between steppe and adjacent irrigated cropland. Their study of thermal plumes as a measure of areally averaged heat flux shows promise, particularly in convectively unstable conditions. Combining the mixed-layer heights with convective velocity scales enabled estimates of integrated fluxes to be made. Values of the temperature structure function, C_T^2, determined several hundred meters above the surface from within thermal plumes, can be used in conjunction with near-surface values averaged over contiguous time periods to estimate the effects of neighboring surfaces (Coulter et al. 1993).

4.2.4 Aerosols and the Radiative Balance in the Atmosphere

Although clouds might cause the largest perturbations of earth’s radiation balance, aerosols exert important influences on solar and IR radiative exchange through both their direct influence on scattering and absorption and their role as condensation and ice nuclei. The full range of aerosol properties that require understanding and documentation defines a research field as broad as the ARM Program itself. Thus, ARM must extract a critical subset of aerosol properties to observe and model. A working group within the ARM Program has considered the impacts of aerosols on the ARM Program goals and has outlined the relevant scientific issues associated with aerosols (Penner et al. 1992).

Initially, it is quite clear that vertical profiles of selected aerosol measures are important. Such measures will include mass loading, size characteristics, and solubility; they might also include shape characteristics, chemical composition, detailed size distributions, source mechanisms, and life-cycle processes. Distinguishing between cloud and aerosol processes will require observations under a broad spectrum of cloud, humidity, and aerosol-loading conditions.

The nucleation role of airborne particulates affects the issue of cloud formation, maintenance, and dissipation, discussed in Section 4.3. Nucleation also influences the radiative properties of clouds by altering the cloud water droplet size distribution. This change in drop size distribution affects cloud albedo and consequently the radiative properties of the atmosphere. A cloud with an abundance of cloud condensation nuclei might yield smaller cloud droplets, which affect cloud albedo (Wilson and Matthews 1971; Schwartz 1988). In addition, the incorporation of absorbing particulates into cloud droplets could contribute to darker clouds with reduced albedo (Twomey 1977; Twomey et al. 1984). These issues and others associated with aerosols were summarized by Gotz et al. (1991).

4.2.4.1 Cloud-Free Aerosol Radiative Effects

The effect of atmospheric aerosols on solar radiation is determined to the first approximation by the ratio of the aerosol-integrated backscattering coefficient to the absorption coefficient (Charlson and Pilat 1969; Ensor et al. 1971). For most locations, this ratio is not determined precisely enough to evaluate whether aerosols will heat or cool the atmosphere when cloud droplet effects are neglected. The IR effect of aerosols is dominated by the relatively rare (and extremely difficult to collect) aerosols with diameters well above 1 µm (giant particles). The atmospheric concentration of these giant particles and their characteristic lifetimes are poorly understood. It has been speculated that direct aerosol radiative effects can be large enough in regions subject to drought (the SGP dust bowl, for example) to enhance the drought. The hypothesis is that increased atmospheric stability can be introduced by a surface cooled and an atmosphere warmed by aerosol effects that inhibit convective rain (Bryson and Baerreis 1967). No combined measurements of aerosol and atmospheric radiation parameters have been made to either confirm or disprove this hypothesis. One of the very few integrated measurement programs designed to study the radiative effect of relatively light aerosol loadings in cloud-free conditions was conducted in the early 1970s (Deluisi et al. 1976). This study found that in situ measurements and inversion of multispectral light transmission can be combined effectively to determine aerosol parameters associated with climate effects.

4.2.4.2 Aerosols and Cloud Radiative Interactions

Aerosols not only affect clouds by changing droplet size distributions through nucleation, but they also can affect clouds through enhancement of droplet coalescence if the aerosol sizes are large enough. The National Center for Atmospheric Research conducted an intensive surface and aircraft experiment in the spring of 1975 to test the hypothesis that giant particles generated by dust storms can affect the severity of storms in the SGP region through enhanced coalescence (Fogle 1975). The availability of these types of particles throughout the SGP might permit cloud radiative effects that are more subtle than those associated with storm enhancement. Enhanced coalescence associated with giant particles might, at times, cause an increase in cloud droplet sizes and a decrease in cloud albedo. This opposite effect is usually associated with smaller aerosol particles that would reduce the droplet sizes and increase the cloud albedo. This possible effect, together with the darkening of clouds due to interstitial and nucleated light-absorbing aerosols, emphasizes the importance of the difficult measurement of vertical profiles of aerosol light absorption and giant aerosol properties in the SGP.

4.2.5 Nonradiative Flux Parameterizations

Energy redistribution through a column of atmosphere might occur by a variety of primary and secondary feedback processes in addition to radiative transfer. These processes, often not viewed as energy transfer processes but representing a significant component of energy budgets, need to be accounted for in comparing modeled and observed energy budgets if the flux is to be ascribed to the appropriate processes. Failure to do so could lead to incorrect parameterizations. Turbulent transfer in the free atmosphere is generally smaller than in the boundary layer, but nonetheless it might represent a significant fraction of the energy flux. The troposphere is defined as the region of the atmosphere where convective heat transport is in balance with radiative transfer. Precipitation represents an important redistribution of energy, because condensation occurs at one altitude and evaporation at others after gravitational settling of the precipitation particles. Convective redistribution of aerosols or absorbing gases could feed back into the radiative exchange process. Photochemistry might account for energy exchange, through both reaction energetics and secondary effects of reaction products that are in themselves radiatively active.

Some aspects of the measurement strategy will involve documenting energy budgets on some control volume of the atmosphere. Such budgets will serve as consistency checks, identifying the need for more accurate observations of some quantities and helping to guide research insights into important physical processes. This exercise might lead to simple but discriminating diagnostic measurements for testing model performance. For example, rainfall at the ground is generally viewed as a consequence of meteorological processes, which it is. Yet it is also a highly effective energy transfer mechanism, depositing latent heat at some altitudes and extracting it at others. The water added to the surface changes the temperature and modifies the role of latent and sensible heat transfer in the surface energy budget.

4.3 Cloud Formation, Maintenance, and Dissipation in Response to Changing Climatologic Driving Forces

The two dominant issues in the role of clouds in climate are radiative exchange through clouds, discussed above, and the quantity and distribution of clouds. This section addresses the second of the two issues. Depending on their altitude and optical properties, cloud masses can have either a net positive or a net negative feedback on climate modification. A widespread coverage of low clouds will reflect more solar energy than the outgoing terrestrial radiation they retard, while high, thin cirrus clouds will do the opposite. If anthropogenic greenhouse emissions alter the mix of cloud types or their total amount, the models used to assess that impact must predict the presence of clouds reliably and distinguish such features as altitude and thickness of cloud layers. Cloud fields exhibit important variabilities on time scales of minutes to hours and on a spectrum of spatial scales from subkilometer to continental. An important scientific objective of the SGP CART site is to provide the observational-modeling link to characterize the most important variabilities of cloud fields and the mechanisms by which they form, move, and dissipate. The observations are much more than a climatology survey of the clouds over the SGP site, focusing as well on the mechanisms for cloud formation, maintenance, and dissipation. To achieve the best understanding of the driving mechanisms, as expressed in state-of-the-art models evolving throughout the life of the ARM Program, observation systems are designed to provide input to the models and to test model performance. This process leads to continual model improvement. The SGP locale has been selected as a particularly fruitful region for developing this knowledge because of its rich variety of cloud forms and amounts, driven by motion systems and moisture variabilities from cumulus convection through synoptic-scale storms.

The SGP locale has a wide variety of cloud types and amounts, as reported in Table 1. Total cloud cover is close to the global average of 50%. Cover is a maximum of 52% in spring and is as low as 45% in fall. The summer season is dominated by cumuliform clouds, which are nearly absent in winter. The cool seasons have much more stratiform cloudiness. Middle and high clouds vary modestly with season. Middle clouds (altostratus, altocumulus) vary from 26% occurrence in spring to 30% in summer, while cirrus clouds are present at 55% to 66% with a winter maximum. Clear-sky experiments have an adequate window of opportunity, with an average of about one day per week of clear conditions. The spectrum of cloud types and amounts reflects a variety of formation, maintenance, and dissipation processes. Cumulus clouds are driven by subgrid-scale convection, although the moisture and thermal stratification that support convection are influenced somewhat by larger-scale processes. Cool-season clouds are expected to have a synoptic-scale driving force, although the quite important statiform clouds are a reflection of physical processes in a vertically shallow layer of the atmosphere. The lowest kilometer, where stratiform clouds dominate, is influenced by interactions with earth’s surface and also by precipitation falling into and through that layer from above.

Our general interest in global climate does not free us to average all variables globally or even across GCM grid boxes. Covariant and irreversible processes must be addressed at the scale on which they occur. Convective rainfall occurs on scales of 1-10 km. The rain deposited on the ground enters a different hydrologic domain and is not returned to the atmosphere locally by evaporation. This process cannot be explicitly computed on a GCM-gridded process but must be evaluated separately and parameterized for GCM computation.

GCMs treat cloud cover in terms of the moisture and thermal structure of the atmosphere and the presence or absence of convective activity. If the atmosphere is at or near saturation but there is no convective activity, a stratiform or layer cloud is assumed to form. The degree of saturation is generally modeled in terms of the relative humidity or a predicted amount of liquid water. Nonconvective clouds are assumed to occupy all or nearly all of the grid cell in the layer where they are formed. Instantaneous condensation of moisture is required to keep the relative humidity of the layer below some threshold value (generally 80%-100%). The condensed moisture might all fall to the surface, or a portion of that moisture might evaporate before it reaches the ground. The precipitation at the surface is classified as snow or rain on the basis of temperature.

If convective activity occurs and the atmosphere nears saturation, then a convective cloud forms. Convective clouds do not usually occupy more than a small fraction of the GCM grid. GCMs generally model moist convection by using one of three schemes. The simplest is the moist convective adjustment scheme of Manabe et al. (1965), in which convection occurs when the model layer becomes saturated and the lapse rate exceeds the moist adiabatic rate. The amount of precipitation that results is equal to the amount of moisture that must be removed from the layer to ensure a relative humidity below the threshold value. The moist convective adjustment scheme is generally thought to lead to excessive precipitation and excessively cool temperatures in the lower troposphere, but it is widely used because of its simplicity.

The Kuo scheme (Kuo 1974) models convection dependent on the existence of an unstable lapse rate and a net convergence of moisture from the large-scale flow and surface fluxes. A fraction of the condensed moisture is precipitated, and the rest moistens the atmospheric column. The vertical profiles of heat and moisture are dependent on the differences between the cloud air and the surrounding large-scale environment. The Arakawa-Schubert scheme (Arakawa and Schubert 1974) includes the effects of entrainment of environmental air at the cloud sides and detrainment of cloud air at the top of the cloud. Convection, which stabilizes these processes, occurs instantaneously. Verification of the Kuo and Arakawa-Schubert schemes is limited by the few observations available. However, the amount of convective heating in GCMs shows a sensitivity to the choice of convective scheme.

The albedo of convective and nonconvective clouds is either specified or parameterized as a function of zenith angle, optical depth, or both. Random overlap of clouds is assumed for the treatment of radiative fluxes within a cloudy atmosphere.

4.4 Feedback Processes

The essence of the climate change problem is the role of feedback processes between different phenomena and different domains of earth’s climate system. Feedback in the hydrologic balance and the cloud water portion of the hydrology can amplify a relatively small energy flux perturbation due to increased greenhouse gas into a major alteration of energy flux. Similar but less well known, feedback phenomena can occur between the biosphere and atmosphere through modification of cloud optical properties by a climate-induced change in the biosphere. Specifically, climate warming due to greenhouse gases would lead to increased average cloud heights, decreased cloud amounts, or both. This expectation follows from the observations that higher clouds are colder and thus less effective IR radiation emitters than lower clouds and generally have lower albedos, making the cloud-height feedback positive. That is, the change in the clouds produced by warming tends to amplify the warming. Clouds contribute more strongly to the planetary albedo than does the planetary greenhouse effect. Shortwave cloud forcing is larger than longwave cloud forcing by about 20 Wm^{-2}. Therefore, a reduction of cloud amount reduces the shortwave effect of clouds more than the longwave effect. Again, the cloud amount feedback is positive. However, cloud feedback processes are not limited to macrophysical cloud properties such as amount and altitude. The sensitivity of cloud radiative properties is strong enough to raise serious questions about the way the predictability of climate might be affected by relatively small changes in cloud microphysical quantities such as cloud droplet size; whether the cloud is composed of ice crystals, water, or both; and the effect of those properties on the light-scattering characteristics of clouds. Cloud feedback mechanisms like these can be tested at a land location; they are discussed in detail elsewhere (DOE 1995).

4.5 Measurement Strategies

The scientific issues described in Section 4.4 represent only a portion of the processes addressed by the ARM Program Science Team, and as the research progresses, more scientific questions continue to be raised. Each question introduces specialized observational needs, including extent of coverage and resolution in space and time, high accuracy in the observations of some conventional quantities, and previously unobserved quantities. To proceed systematically with a deployment and operational strategy that optimizes the scientific value of the SGP CART site, a framework of measurement approaches and available sensors and methods must be set up. Each set of scientific hypotheses and proposed comparisons of models with data can then be evaluated within this framework of general measurement strategies to find a common denominator of observations and associated data processing schemes that will satisfy the broadest range of science needs. The three current general measurement strategies are discussed below.

4.5.1 Instantaneous Radiative Flux

The instantaneous radiative flux (IRF) general strategy focuses on the radiative transfer of shortwave (visible) and longwave (thermal IR) energy through a vertical column of the atmosphere with concurrent documentation of the attributes governing the transfer (temperature, moisture, cloud droplets/crystals, trace gas, and aerosol concentrations). The emphasis in this strategy is on explaining what a radiometer or spectrometer sees at a given time, so the measurements of thermodynamic and atmospheric constituents are tied to the field of view and the sampling duration of the radiometric instrumentation. The requirements for vertical profiles of temperature, humidity, and clouds are stringent, but the geometry of the experiment is straightforward: essentially a single profile over a specified time period (a few minutes). If the interpretation of these experiments is complicated by processes that involve the atmosphere outside the coincident narrow column, then the IRF experiments might have to draw on elements of the other general measurement strategies, which address space-time variability.

Current IRF experiments fall into two major subcategories. The first addresses clear sky; emphasis is on

- characterization of the volume of atmosphere within the radiometric field of view
- spectrally resolved radiance and the relevant line-by-line opacity models.

The second subcategory of IRF experiments addresses cloudy skies and is concerned with cloud structure and cloud properties, as well as other complications in column energy budgets, including the surface boundary condition.

4.5.2 Single-Column Model

The goal of the ARM Program is to improve the parameterization of cloud and radiation physics in global climate models. Thus, at least one phase of the program must address clouds and radiation at the scale of a GCM grid cell. With the focus on the clouds and radiation rather than hydrodynamic interactions over the whole global grid, it becomes feasible to isolate a grid cell as a control volume and supply lateral boundary conditions, as well as ground-level and upper-boundary conditions. This strategy, the single-column model (SCM) strategy, permits the rapid calculation of grid-averaged model physics to test the parameterizations. The observations that support the SCM approach should produce representative estimates for both model inputs and the quantities needed for comparison with model outputs. The need for observations to serve as model input drives the design of the SGP as an area with distributed profiles spaced at several hundred kilometers.

4.5.3 Data Assimilation

The SCM requires observations that represent average values of relevant variables across the domain of the grid cell or exchange rates through its boundary surfaces. Effective estimation of the averages from available data (a combination of discrete-point observations, satellite remote sensing data, and sometimes nonsynchronous data from external sources) requires the set of specialized analytical tools generally applied in the technology of data assimilation (DA). The DA methods go well beyond simply making grid-cell-wide estimates by also providing the essential structure of the meteorological fields within the region, if the observation density is adequate. The scientific issues associated with cloud formation and maintenance frequently require definition of the mesoscale cloud structure, as well as the dynamic and thermodynamic fields that govern cloud structure.

4.6 Matching Measurements with Strategies

The process of classifying each measurement into one of the above three measurement strategies in order to meet the needs of the ensemble of Science Team members has been carried out by members of the ARM Program Experiment Support Team. A measurement typically involves the fusion of data from several sources to achieve the requisite combination of vertical extent and resolution, horizontal extent and resolution, temporal resolution, accuracy, precision, and physical variables observed. The algorithms currently number over 100.

As a simple example, we might consider the requirements for vertical temperature profiles to support radiative transfer estimates. Consistency with radiometrics might demand 10-min time resolution throughout the day and night, with temperatures at an accuracy within ±0.2°C up to an altitude of 24 km. Our existing observation methods include several systems, none of which can meet the full suite of requirements. Rawinsondes can achieve the required altitude but not the temporal resolution or the accuracy. Furthermore, because the sensor rises on a free balloon, it samples a volume of air determined by the winds, most certainly not the volume occupied by the radiometric field of view. Remote sensing instrumentation, such as the RASS, can supply the temporal resolution. However, the selection of frequencies requires compromises on the altitude range of coverage, and the algorithm relating the virtual temperature actually measured to temperature and humidity values is a challenge to be overcome. The approach is to combine data from two different RASS frequencies, several daily rawinsonde launches, and several external sources to produce the best estimate of the temperature profile with the requisite attributes. The profile required by a scientist conducting some other study might have different attributes and might be easier or more difficult to compile. In addition, this process might simply produce inadequate profiles for some investigations. This problem must be handled by documenting unmet measurement needs.

5. Instruments and Observations

5.1 Instruments Planned for Deployment

Section 4 indicates the combinations of observations that are required to isolate and address important scientific questions about radiative transfer processes for models. This section presents a more detailed discussion of instruments and the attributes of the observations they provide. The ARM Program Instrument Team has provided a view of the instruments planned for deployment at the SGP CART site. This section discusses the Instrument Team’s rationale and projected usage modes for the various instruments.

The mission of the SGP CART site includes most of the scientific objectives and the observational complement envisioned for the whole ARM Program. All but the most regionally specialized ARM Program experiments will be included in the scientific mission, and the goals of checking procedures and instruments require that virtually all observations designed for the global ARM Program be included in the observational schedule for the SGP CART site. The Instrument Team’s current plans assign the following instruments (grouped by expected operational parameters) high priority:

- Surface-based radiometric observations

  - Broadband solar and IR sensors for downwelling and upwelling irradiances
  - Multifilter rotating shadowband radiometer (MFRSR) for solar irradiances in selected wavebands
  - Calibration facilities for broadband sensors and MFRSR
  - IR interferometric observations [atmospherically emitted radiance interferometer (AERI)]
  - Solar spectrometer
  - Ultraviolet spectrometer
  - Special sensors for surface solar spectral reflectances (optional).

- Ground-based remote sensing

  - 915-MHz radar wind profiler and RASS
  - 50-MHz radar wind profiler and RASS
  - Lidar (a combination system with Raman for water vapor and ozone and elastic backscatter for aerosol profiles; includes polarization for water-phase determination of cloud particles)
  - 95-MHz or 33-MHz radar (or both) for cloud dimensions and phase

  - Passive microwave radiometer (MWR) for total water vapor, liquid water, and coarse water vapor profiling
  - Ceilometer for cloud base height and aerosol observations
  - Atmospheric transmission in selected wavebands with MFRSR and at full resolution with solar radiance transmission interferometer
  - Passive MWR for temperature and water vapor profiling (optional).

- Scanning and imaging

  - Whole-sky imaging system
  - Scanning cloud radars and lidars (optional).

- In situ sounding from the surface

  - Balloon-borne sounding system (BBSS) using free balloons for state variables
  - One 60-m tower and assorted 10-m and 3-m towers for state variables and moisture, heat, and momentum fluxes
  - Tethered balloon for net radiation and possibly other variables (optional).

- Surface in situ aerosol and trace-constituent observations

  - Ozone sensor
  - Integrating nephelometer
  - Aerosol optical absorption system, cloud condensation nucleus counter, condensation particle counter.

- Network observations

  - Energy balance Bowen ratio (EBBR) and eddy correlation (ECOR) stations for surface fluxes
  - Surface meteorological observation stations (SMOSs), broadband solar and IR radiometers, and MFRSR benchmarking instrument systems and sensors.

- Mobile airborne platforms

  - Manned aircraft
  - Unmanned airborne vehicles (UAVs).

5.2 Attributes of the Observations

The accuracy and precision required for observations depend on the experimental plans of individual ARM Program Science Team members and the intended use of the observations. Such details are not appropriate for this report, but a broad overview of the general accuracy requirements for classes of observations will give a context for evaluation.

The entire greenhouse perturbation due to anthropogenic emissions is projected to be on the order of a few watts per square meter, or about 1% against an average insolation of 375 W/m^2. Feedback processes associated with water vapor and clouds are likely to average only 5%-7%. The parameterizations that the ARM Program develops for clouds and their radiative impacts on surface energy balance must be able to discriminate among effects at the 1%-5% level. To the extent that these parameterizations depend on empirical relationships, they must also reflect the requisite level of discrimination. If broadband radiometry is to contribute to the surface energy balance, it apparently should describe irradiance and flux reliably to within a few percent.

The concentrations of radiatively active trace constituents need to reflect changes consistent with the radiative flux changes. In the case of water vapor, this amounts to accuracies of a millimeter or so in column-integrated water vapor, possibly depending on features of the moisture profile. This requirement might present the most serious challenge to the observational scientists: to regularly observe the water vapor profile from earth's surface to above the tropopause to an accuracy of a few percent.

Ground-based remote sensing systems are needed to measure winds, temperature, water vapor, liquid water, and cloud parameters. Candidate instruments include radar wind profilers; Doppler lidars for wind profiles; Raman lidars for water vapor profiles; RASSs for temperature; passive microwave profilers for water vapor and temperature; and rawinsonde observations of wind, temperature, and water vapor. A ceilometer is needed to measure cloud base height. Lidars, sodars, and profilers can be used to measure cloud bases and other properties. An important but difficult task will be to develop schemes that allow RASS-measured virtual temperature to be reduced to reliable temperature and humidity estimates.

Calibration of systems is generally required at CART sites. Systems to measure water vapor in the atmosphere require special attention. Available balloon-borne instruments often have difficulty at very low temperatures and at extremely small or large relative humidities, but they are often assumed to be more accurate than remote sensing measurements. Thus, on-site calibration facilities are required at the SGP CART site for rawinsonde sensors and for radiation sensors.

Measurements of radiative transfer and associated observations of temperature, water vapor, aerosols, and gasses require at least three different types of radiometers to be deployed at a SGP CART site. This is because each of the three types has a particular spectral resolution, and each tends to have its own problems with regard to stability and reference temperature. Broadband IR radiation measurements (wave numbers of 700-1300 cm^{-1}) are required. Spectral measurements allow more detailed information about portions of the visible and near-IR radiation spectrum. For example, MFRSRs allow essentially continuous, spectral solar measurements of global and diffuse radiance at six wavelengths (415, 500, 615, 673, 870, and 940 nm). In addition, integrated measurements by the AERI of calibrated sky radiances at 2-20 μm and accurate, integrated moisture column measurements by the MWR will contribute to the understanding of the effects of moisture and clouds on radiative transfer.

Information on properties that affect radiative transfer at CART sites is crucial. Measurements of relative humidity in the troposphere with an accuracy of 5% are required to model estimates of IR radiative transfer within 5%. Profiles of temperature and water vapor should be taken throughout the atmosphere, including regions close to the ground. Both tower-based and rawinsonde- and ground-based remote sensing measurements are needed. To observe water vapor profiles at the crucial periods, radiosonde releases for profile measurements might at times be triggered by changes in water vapor overburden, detected with passive microwave systems.

Measurements of tropospheric ozone concentrations should be taken at CART sites because of ozone's behavior as a greenhouse gas, its role in absorption of ultraviolet radiation, and its large temporal variations. The size distribution and optical properties of aerosol particles also need to be measured routinely, preferably in vertical profiles throughout the troposphere.

Scanning radar is desirable at multiple frequencies and polarizations to detect ice versus water in clouds. A scanning capability allows large volumes of air to be sampled. All-sky imaging systems have limitations, but they might be useful for inferring the distribution of cloud water. In addition to routine measurements, observations from satellites and with in situ sensors on aircraft (including UAVs) would be extremely useful for campaigns.

Adequate characterization of surface conditions is necessary. Observations required include basic meteorological measurements (wind speed, wind direction, pressure, humidity, and temperature), surface fluxes (sensible and latent heat), bidirectional reflectance (surface-based and tower-based radiometers), precipitation rate and amount, snow depth, soil moisture, and stream runoff. Also needed are land use identification and a physical description of the state of natural surfaces and vegetation.

Other important considerations for studies of cloud formation are identifying the number of measurements or observations (instruments) required and balancing efforts between field campaigns and routine measurements at a CART site. Field campaigns might be the primary means of meeting certain measurement needs, especially those involving microphysical parameters. Instrumentation for routine measurements will not be able to provide all the microphysical measurements needed.

In situ measurements will at times be required from aircraft. Manned aircraft can be available for campaigns (periods of weeks) or routinely for several days per month. Aircraft would be used mostly for measurements of opportunity. Because manned aircraft operations for most studies of opportunity are needed for conditions that cannot be forecast accurately with sufficient lead time, UAVs are a highly desirable aircraft platform. In this regard, UAVs would be launched on occasions of opportunity, to continue operation until the measurement opportunity ceases to exist. Here and throughout this report, airborne platforms are not limited to manned aircraft. For the SGP locale (as opposed to an ocean site), routine aircraft measurements (flying at the same time every day or on preplanned days each week) do not appear practical, given the ease of surface-based measurements. However, aircraft are required to address aspects of the science questions. Areal averages of surface fluxes, for example, need to be derived and compared to measurements from low-flying aircraft in order to test results of scaling up local surface observations. In situ aircraft observations also allow comparison with remote sensing measurements and data from other instrumentation.

In addition to a location at the central facility, a minimum of three locations are needed to measure profiles of temperature and water vapor in the SGP CART domain. Averaging times for radiation measurements are typically 10 min. for clear skies and 1 hr for cloudy skies. In many types of experiments, observations from satellites would provide more useful information for parameterization of cloud characteristics than would ground-based all-sky imaging. All these factors need to be incorporated into a measurement strategy.

5.3 The SGP CART Instrument Configuration

The physical design for a generic CART site is described in the scientific planning document (DOE 1996) and is illustrated in Figure 2. A CART site is to be composed of four groupings of instruments that are closely associated experimental components. These groupings are discussed below.

5.3.1 Central Facility

A central facility will serve as the figurative center of CART site experiments (but is not required to be literally at the center of the site). The central facility has the largest, most complete complement of instrumentation for radiation, meteorological, and surface characterization measurements. In short, the central facility is the location for stand-alone (single-column-type) experiments. The central facility is also the location of the calibration equipment. The central facility would be instrumented with surface-based radiometers, ground-based remote sensing systems, cloud scanning and imaging systems, in situ sounding capabilities from the surface, some surface in situ aerosol observational equipment, and stations for surface observations. More specifically, the central facility would be instrumented with the following:

- Wideband solar and IR sensors for surface radiation and cloud properties
- Two high-resolution spectrometers for spectrally detailed IR spectra
- One MWR radiometer for water vapor, liquid water path, and temperature profiles
- One 50-MHz wind profiler with RASS for wind, density, and temperature profiles of upper troposphere measurements
- One 915-MHz wind profiler with RASS for wind, density, and temperature profiles of boundary layer measurements
- One Raman lidar for temperature and water vapor profiles
- One differential-absorption lidar for temperature and water vapor profiles
- One ceilometer for cloud base height
- One CLASS (Cross-Chain Loran Atmospheric Sounding System) for wind, temperature, and humidity profiles
- One protable automated meteorological (PAM) station for temperature, humidity, wind, precipitation amount, and precipitation rate

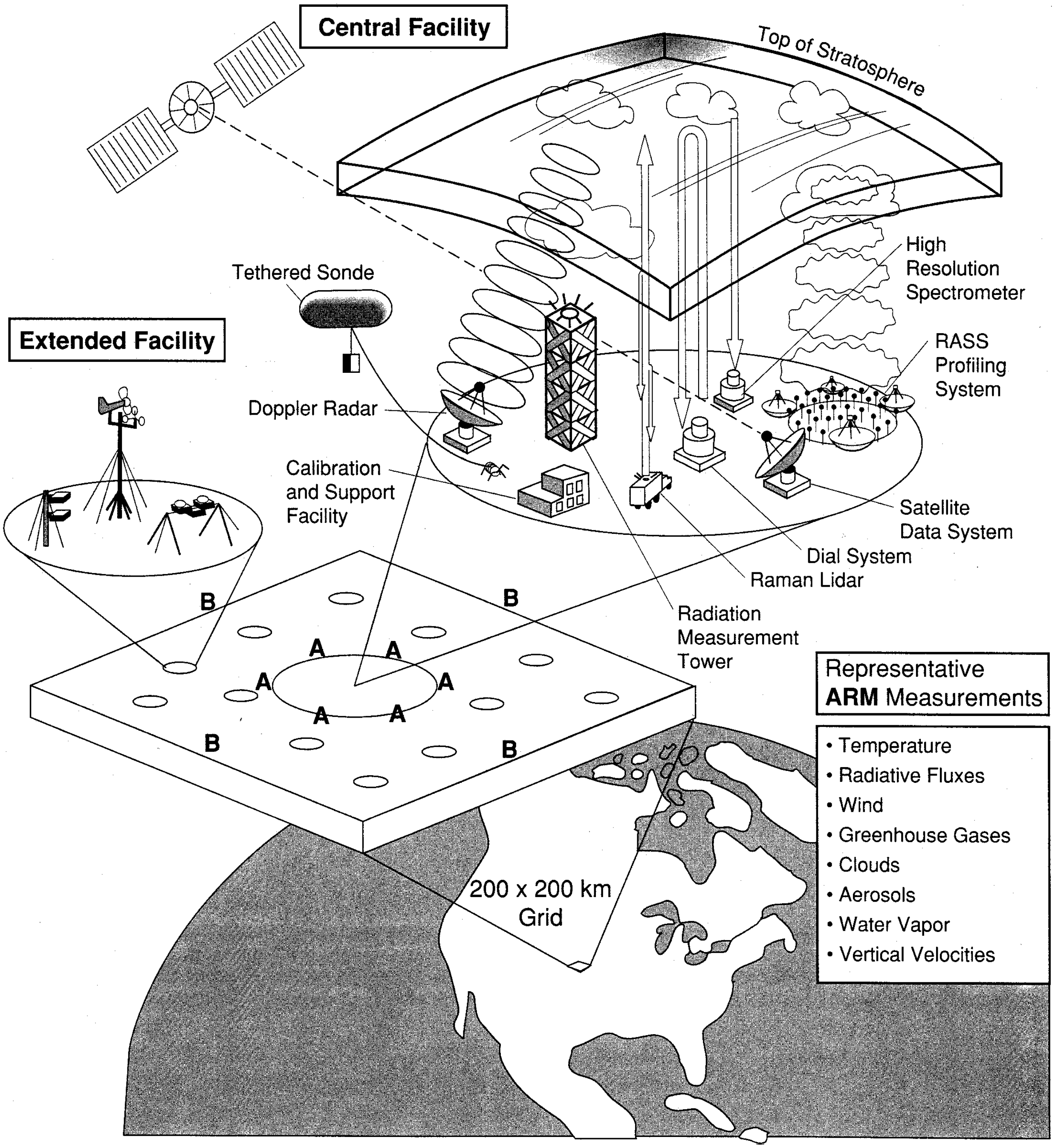

Figure 2. Conceptual implementation design for 1 central, 6 auxiliary, 25 extended, and 4 boundary facilities.

- One surface flux system for momentum, heat, and water vapor fluxes

- One 60-m tower for wind, temperature, and humidity profiles and for pollutant concentration measurements

- One all-sky imaging system for cloud cover

- Calibration equipment, mainly for radiometeric measurements.

5.3.2 Auxiliary Facilities

A three-dimensional mapping network, consisting of a series of auxiliary facilities within 10 km of the central facility, will be designed to measure the three-dimensional structure of the atmosphere near the central facility and to map the cloud fields over the central facility. Scanning radar and lidar and all-sky imaging instrumentation would be best suited for this auxiliary network. Auxiliary facilities would consist of up to six locations equipped with whole-sky imaging systems, located within 10 km of the central facility. A scanning radar and a scanning lidar would be placed at the central facility to augment three-dimensional mapping of clouds. Instruments for the three-dimensional mapping network of auxiliary sites within 10 km of the central facility include the following:

- Scanning radar for cloud droplet echoes, precipitation rates, etc.

- Scanning lidar for cirrus cloud mapping

- Six all-sky imaging systems.

5.3.3 Extended Facilities

A set of extended facilities will be located throughout and at the corners of the SGP CART domain. These stations will be designed to obtain average surface meteorological, broadband radiometric, and surface flux variables over the entire CART domain. Twenty-five extended facility units, consisting of an EBBR or ECOR surface flux station, broadband radiometers, an MFRSR, and a SMOS, will compose an extended facility. The set for each extended facility includes the following:

- Twenty-five surface flux systems (one at each corner of the box and the remainder in locations that best represent dominant surface features)

- Twenty-five PAM-like stations, to be collocated with the surface flux stations

- Twenty-five sets of wideband solar and IR sensors, to be collocated with surface flux stations.

5.3.4 Boundary Facilities

A minimum of three boundary facilities should be placed in a large triangle centered on the central facility to establish general large-scale motions of the atmosphere occurring at or passing through the SGP CART site. Instrument systems at the boundary facilities would consist of ground-based remote sensing systems and BBSSs to observe vertical profiles of moisture, temperature, and wind. The remote sensing systems could use existing 404-MHz wind profilers and RASSs as part of the National Oceanic and Atmospheric Administration (NOAA)-National Weather Service (NWS) profiler network instead of the 915-MHz and 50-MHz systems provided by the ARM Program. In addition, AERIs could be used to obtain water vapor and temperature profiles beneath cloud base, and some means, perhaps passive microwave, could be used to observe water vapor profiles above the cloud base height. The set for each boundary facility includes the following:

- Seven existing 404-MHz wind profilers and RASSs, as part of the NOAA-NWS profiler network that defines the rectangular study area of the CART site
- Three MWRs, collocated with the NOAA-NWS profilers at Hillsboro, Kansas, and Vici and Morris, Oklahoma
- Three high-resolution IR radiometers, collocated with the MWRs and the NOAA-NWS profilers at Hillsboro, Kansas, and Vici and Morris, Oklahoma
- Three radiosonde systems, collocated with the NOAA-NWS profilers at Hillsboro, Kansas, and Vici and Morris, Oklahoma
- Three AERIs, collocated with the NOAA-NWS profilers at Hillsboro, Kansas, and Vici and Morris, Oklahoma.

Access to instrumentation deployment sites within the continental United States is relatively unconstrained, permitting the placement of observation points to satisfy the scientific objectives. In contrast, compromises on accessible locations might be necessary in ocean locales. Although logistic considerations include requirements of the National Environmental Policy Act (NEPA), air traffic control issues, communication frequency approvals, and typical site location problems (power, water, housing, medical facilities, supplies, etc.), the domain of the SGP CART site can be situated to exploit surface characteristics with maximum efficiency and to take advantage of other large field programs nearby. The number of extended sites required to characterize the CART domain depends on the surface homogeneity.

The amount of funding available will obviously have a large impact on the design of the SGP CART site. The central facility should be given top priority. The actual number of instruments deployed for auxiliary, extended, and boundary facilities should be determined by the ARM Program Science Team. The ARM Program would benefit by collocating its first CART site to take advantage of existing or planned instruments of common interest belonging to nearby programs or facilities.

5.3.5 Locations for Supplemental Observations

Nonroutine, supplemental observations that cannot be accomplished with routine measurements will be required for ARM studies. Most of the key observations can be obtained from aircraft, in concert with routine surface flux measurements. Primary aircraft measurements would be those pertaining to cloud physics features that directly influence radiative transfer. The following additional observations are required:

- Nonsurface turbulent fluxes

  - Entrainment in shallow cumulus clouds
  - Vertical transport within the planetary boundary layer
  - Entrainment instability in stratocumulus clouds
  - Cloud layer decoupling
  - Entrainment in deep cumulus clouds
  - Cloud-induced turbulence in the planetary boundary layer
  - Cloud-induced turbulence above the planetary boundary layer
  - Standard deviation of velocity component of turbulence
  - Areally averaged latent heat flux
  - Areally averaged sensible heat.

- Trace gas and aerosol profiles

  - Ozone
  - Aerosol loading
  - Aerosol size distribution
  - Aerosol chemical content
  - Cloud water chemical content.

- Cloud physics parameters

  - Standard thermodynamic properties
  - Cloud condensation nuclei
  - Interstitial aerosol
  - Ice nuclei
  - Liquid water.

5.4 CART Data Environment

The ARM Program operations plan (DOE 1990) describes an ambitious concept to assure the quality of the data and to combine measurements (data streams), feed models, and store measurements for data users at a central facility in nearly real time. Figure 3 illustrates the envisioned CART data environment. The data from all instruments will be telemetered in real time to the central facility, where computers will

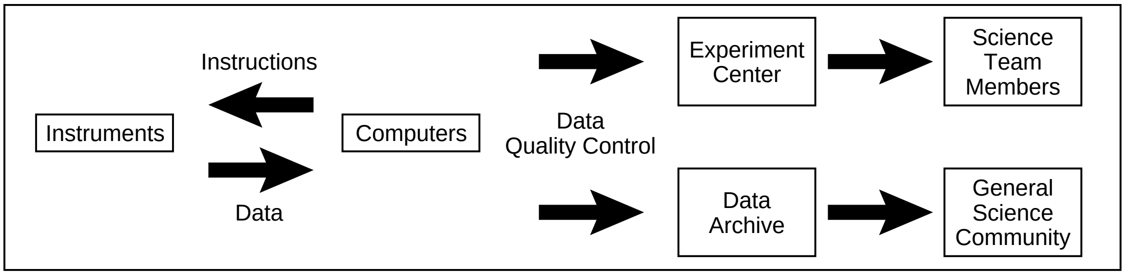

Figure 3. Data flow from instruments to data users.

convert data to standard units, apply calibrations, pass the data through a series of quality control checks, and divert the appropriate data streams to a model or set of models for computational analysis. In addition, data streams of field measurements will be compared with model outputs. All this will occur on the time scale of about 2-20 min. The raw and processed data will be stored at the ARM Program Experiment Center and at the ARM Program Data Archive. The data for the Science Team will be custom tailored for their needs at the Experiment Center, and all data will be accessible to the general scientific community through the Data Archive. The ARM Program SGP CART site, then, will become a user facility.

The measurements at the central facility will be coupled to the on-site computer by fiber-optic telephone lines. Data from instrumentation at the auxiliary and extended sites will probably have to travel via commercial telephone lines or microwave telemetry. The data will then be telemetered by (perhaps) satellite to a central storage facility, yet to be determined. The logistics of data transmission depend on cost and licensing agreements.

The data streams are combinations of measurements required as inputs to models or needed to verify models. These data streams will be determined by the ARM Program Science Team as experiments and models are defined. The intent of the CART data environment is to analyze measurements and model parameterizations quickly and then make adjustments as required. This iterative process requires flexibility within the ARM Program to test a hypothesis, use field measurements to improve parameterizations for models, use models to drive better or new measurements, test models, reevaluate hypotheses or required observations or measurement strategy, etc.

In addition to the measurements required by models, instruments might be able to provide information that will be useful to scientists or other research programs. For example, profilers might measure structure functions of the atmosphere that are particularly useful in basic atmospheric studies. Such information is valuable in turbulence models that are smaller than GCM scale. Another example is the use of platforms designed for other instruments for scientific issues of opportunity. For example, tethered balloons might carry ozone sondes to determine ozone profiles in the lower atmosphere. Such issues of opportunity must be considered by the ARM Program Science Team in developing a suite of measurements and instrument capabilities. Other research programs might provide instruments or require data streams that could easily be incorporated into the CART data environment. Other research activities might also provide measurements that would be useful to the ARM Program. Linkages of these data must be anticipated.

6. Logistic and Operational Issues Associated with Continental U.S. Locales

6.1 Logistic Considerations

In terms of access, transportation, supplies, and services, all three potential locales have excellent logistics. Because this site is in the United States, NEPA requirements dictate screening to ensure that the CART site and related activities do not adversely affect any environmentally sensitive areas, including historic or cultural resources; park, recreation, or refuge lands; wilderness areas; wild or scenic rivers; prime farmlands; wetlands; floodplains; or ecologically significant or critical areas. Furthermore, the CART site and activities must not pose a threat to animal species listed or proposed to be listed as endangered or threatened species or have adverse effects on the designated critical habitats for these species. This screening can be accomplished by committing to a study of proposed candidate CART sites to ensure that none of the above will be a factor. This action would categorically exclude some candidate CART sites and related activities; NEPA requirements might play a significant role in CART site selection.

The crucial logistic issues (other than funding limitations and NEPA requirements) will most likely center on the use of airspace for aircraft and balloons, safe operation of lidars, and access to the appropriate radio transmission frequencies for operations and communications. The most important discriminate among the three locales will be the opportunities for synergism with other field measurement activities. This section will address the logistics and the synergistic opportunities in terms of a map of collateral measurements.

Table 2 presents, in matrix format, the elements of the scientific measurements required to meet the site mission versus the primary logistic functions of occupying and operating the site. Entries in the matrix represent estimates of the necessity, availability, and difficulty (expressed as simplicity, or inverse difficulty to keep the numerical entries consistent) of the particular measurement-logistics combination. Most of the entries in Table 2 indicate high values for necessity, availability, and simplicity (for example, 5,5,5), reflecting the relatively high logistic feasibility of conducting CART operations in the continental United States. When the entry values trend downward, we might expect to examine the feasibility more closely. A few entries in Table 2 have been underlined to reflect such a situation for maintenance services on remote sensing systems, specialized radiometry, and some mobile platforms. The entries for the Regulations column are better interpreted as “necessity for approvals,” “assistance available to acquire approval,” and “relative simplicity of meeting regulatory requirements.”

Surface-based measurements are expected to include the following:

- Site characterization (e.g., vegetation and land use, surface energy budgets)
- A network of near-surface atmospheric measurements (e.g., as measured by the PAM network)
- At least one tower capable of producing atmospheric profiles of important transport and energy budget parameters.

Table 2. Logistic east of elements of scientific measurements required to meet CART site mission.

Necessity, Availability, and Simplicity of Logistics of the Measurement(a)						
Measurement Element	**Transpor-tation**	**Communi-cations**	**Structures and Grounds**	**Utilities**	**Services**	**Regulations(b)**
Surface Observation	5, 5, 5	2, 5, 5	5, 5, 5	5, 5, 5	3, 5, 5	4, 4, 5
Surface networks						
Towers			5,5,3			
Site characterization						
Remote Sensing	3, 5, 5	5, 5, 5	5, 5, 3	5, 5, 3	5, 2, 1(c)	5, 4, 4
Profiles						
Three-dimensional scanning						
Radiometry	5, 5, 5	5, 5, 5	5, 5, 3	5, 5, 3	5, 2 ,1	3, 4, 5
Balloon Operations	3, 5, 5	5, 5, 5	3, 5, 5	4, 5, 5	3, 3, 3	4, 4, 5
Tethered						
CLASS						
Mobile Operations				NA(d)		
Aircraft	5, 5, 3	5, 5, 3	Nearby airfield		5, 3, 2	5, 5, 3
Ships	0, 0, -	NA	NA		NA	
Buoys	0, 0, -	NA	NA		NA	
Vehicles	3, 5, 5	5, 5, 3	Roads		5, 5, 4	5, 5, 5
External Data	0 ,0, -	5, 5, 5	0/NA	5, 5, 4	2, 3, 5	1, 3, 5

(a) Range of values: 5 (high) to 1 (low).

(b) Values indicate necessity for approvals, assistance available to acquire approvals, relative simplicity of meeting regulatory requirements.

(c) Underlined values indicate that feasibility should be examined more closely.

(d) NA, not applicable.

Each of these classes of measurements involves different operational complexities. The site characterization requires careful identification of the site attributes that are crucial to the scientific mission, followed by the labor-intensive collection of relevant data from many sources. The input data will include Landsat or Spot satellites, surveys of topography and vegetation, soil profiles of temperature and moisture, and other relatively infrequent observations. The level of detail that captures the annual cycle of the governing parameters will probably be sufficient. Logistics are the simplest of all the activities, requiring extensive personnel access without crucial timing. The movement of small pieces of equipment will be required, with few or no permanent emplacements.

The surface meteorological network will support mission elements such as four-dimensional data assimilation and time-space variability. This network of permanent stations will be mounted on anchored tripods and will be deployable by technical staff with a minimum of site preparation and construction. The system will require continuous utilities and services, communications, and maintenance. The components of the system will be accessible from the ground or a low ladder. Therefore, the system can be maintained safely by site technical staff who follow routine procedures.

The tall tower will most likely require a construction effort for site preparation and tower erection. Maintenance will require specialized personnel who follow special safety and other operational procedures. The entries in Table 2 reflect the uniformly high necessity, availability, and simplicity of transportation, communications, and utilities for all of the candidate continental U.S. locales, for each of these types of ground-based operations. In addition, the tower needs buildings and grounds logistic elements.

Additional requirements expressed in Table 2 reflect the accessibility and continuity of utilities, services, and communications for all of the ground-based remote sensing and radiometric measurements. Because active remote sensing systems transmit energetic beams into the atmosphere, they are expected to be subject to additional health and safety regulations.

Aircraft operations during campaigns are important to the mission of the continental U.S. site. The multilayered clouds of this site will require innovative aircraft missions to document the important radiative influences of interlayer scattering and absorption. The on-station endurance of some high-altitude UAV platforms offers opportunities to observe radiative balance at the tropopause throughout the passage of synoptic disturbances. The tropopause altitude, at the transition from the dominance of the radiative-convective heat transfer in the lower atmosphere to the radiatively driven stratosphere, has been suggested as a crucial altitude for radiation balance observations. The powerful dynamic processes that occur at the tropopause involve systematic changes in position, structure, and cloud type across a typical synoptic disturbance. In addition, the role of the continental U.S. site as the testbed for instruments and procedures scheduled for more remote duty will focus considerable attention on the aircraft measurement platforms and procedures at this site.

We must consider land vehicles as an important means of rapid deployment or, in some cases, as a base for continuous scanning. Trucks and vans have a productive tradition in most U.S.-based field experiments in atmospheric science. Such vehicles have been used for sampling transects of variable trace constituents and as platforms for upward- or sideward-looking, nonscanning remote sensors. Bluestein and Unruh (1989) demonstrated a most effective method for rapid deployment of transportable remote sensing systems of limited range in the correct locations to observe important localized meteorological events. The effectiveness of this mode of deployment requires a good, well-documented highway network, something that is generally available at all three locales under consideration.

Benchmarking and calibration operations will probably rely on the combination of central facility capabilities and traveling standards recommended during the November 1990 ARM Program Science Team meeting. All of the U.S. locales have the transportation capabilities and access to a central facility to support these operational functions at optimal levels. Similarly, each of the locales can successfully support the transmission of external data by land line, telephone connection, satellite downlink, or high-speed computer link.

6.2 Synergism Potential

The ARM Program is sanctioned by DOE in support of the National Energy Strategy and by the White House (Office of Science and Technology Policy's Committee on Earth and Environmental Sciences and the Office of Management and Budget) as part of the U.S. Global Change Research Program. However, the ARM Program is funded through the normal DOE appropriation process and is managed and implemented as an independent research program. Although the ARM Program's original overall budget was expected to be $460 million over ten years, the actual funding for site facilities and operations is expected to be approximately $5-10 million per site over ten years. Although these funds are sufficient for most of the activities originally funded, the ARM Program should take advantage of synergism with programs of other agencies having similar scientific goals or planning deployment of instrument systems that can supplement the data gathered by CART operations. The SGP locale is rich in research programs and scientific instrumentation because of its unique climate.

Two opportunities for valuable synergism are 1) supplemental data from concurrent or nearby instrument deployment and 2) scientific interpretations of programs studying similar phenomena from a different, or perhaps even a similar, perspective. The continental U.S. locale will provide a very fertile opportunity to increase the leverage of CART expenditures through collaborative sharing of data and analysis results with other programs, because a number of high-quality scientific programs are planning similar expeditions and also looking for synergism. In fact, the synergistic potential will offer a more discriminating set of locale and site selection criteria than the scientific attributes for this particular locale. Although different programs have quite individual objectives, they share a common need for analysis of basic atmospheric dynamic and thermodynamic structure (with good time and space resolution) as a fundamental driver of the various processes under study. Some of the programs are limited-term campaigns, while others involve the long-term operation of measurement systems. The ARM Program might take advantage of collateral observations for some campaign operations by adjusting site occupation time scales, but doing so must not compromise the CART concept of a long-term, continuous stream of quality-controlled data. The extent of curtailment of the CART concept in a collaborative effort should be one criterion in deciding whether to join the collaboration.

The programs within the continental United States offering the most beneficial synergism with the goals of the ARM Program are the following:

1. The NOAA-NWS wind profiler network, which will provide profiles of wind direction and speed to altitudes throughout the troposphere with temporal resolution of 15 min. and characteristic spacing of 120-180 km in the central part of the country. Figure 4 shows the expected 1990 and 1991 station locations in the region covered by the three candidate locales. The densest portion of the network is in Oklahoma and Kansas. This network, expected to be a continuous, long-term operation, would provide valuable dynamic information for documenting the basic conditions for CART operations and

would contribute directly to the major objective of documenting cloud formation, maintenance, and dissipation throughout the life of the CART site.

2. The WSR (weather surveillance radar) Doppler radar network [formerly termed NEXRAD (next-generation radar)] is also depicted in Figure 4. The facilities in this network are positioned to provide almost complete areal coverage through the MW and SGP, especially in densely populated areas. This is also a long-term program that will provide the three-dimensional cloud and precipitation data central to all of the CART objectives.

3. Project FIRE conducted a campaign in southeastern Kansas (Coffeyville, Figure 4) to study cloud radiation feedback in cirrus clouds (FIRE-Cirrus). The November-December 1991 campaign was too early for CART operational collaboration, but the ARM Program Science Team participated directly in FIRE-Cirrus. In addition to the scientific collaboration, we most certainly can gain valuable information from FIRE-Cirrus operations and will benefit from the cloud climatology and atmospheric structure this program develops. The direct scientific link between the two programs also underscores the importance of collaborating on the analysis and interpretation of FIRE results.

4. Project STORM (Storm-Scale Operational Research and Meteorology) conducted a field deployment in the spring of 1992 to study mesoscale convective complexes in the SGP during the spring thunderstorm season. This program centered on Tulsa, Oklahoma (Figure 5). This campaign's operation is well located and reasonably timed for mutual benefit in at least a preliminary level of CART operational deployment. The science of STORM will address the cloud formation, maintenance, and dissipation scientific objective of the ARM Program (DOE 1996). These cloud systems are an important part of the central U.S. cloud environment in the spring and early summer.

5. A GEWEX (Global Energy and Water Balance Experiment) subprogram, GEWEX Continental-Scale International Project (GCIP), will deploy to the field in 1994 and is expected to take advantage of the STORM deployment in Oklahoma and Kansas, as well as various watershed studies in Oklahoma (Figure 4). GCIP will deploy for an extended period and will focus on the water cycle. The STORM program is likely to seek collaboration to provide the dynamics portion of its interpretive measurements. Because the ARM Program is strong in that area, productive synergism is possible in both observations and scientific interpretation. The science will affect the ARM Program objective of cloud formation, maintenance, and dissipation, with a special focus on precipitation processes and the subsequent surface property driver of cloud mechanisms.

6. The TRMM (Tropical Rainfall Measuring Mission) satellite is a valuable source of remote sensing data on clouds and precipitation. Because this satellite's orbit is designed for tropical systems, it is a positive coincidence that data will extend as far north as 35 deg north. The SGP locale is the only one of the three candidates that has significant area in that latitude band. TRMM is expected to be launched in 1994. The science of TRMM will be helpful in describing the distribution of clouds and addressing the cloud formation, maintenance, and dissipation scientific objective of the ARM Program.

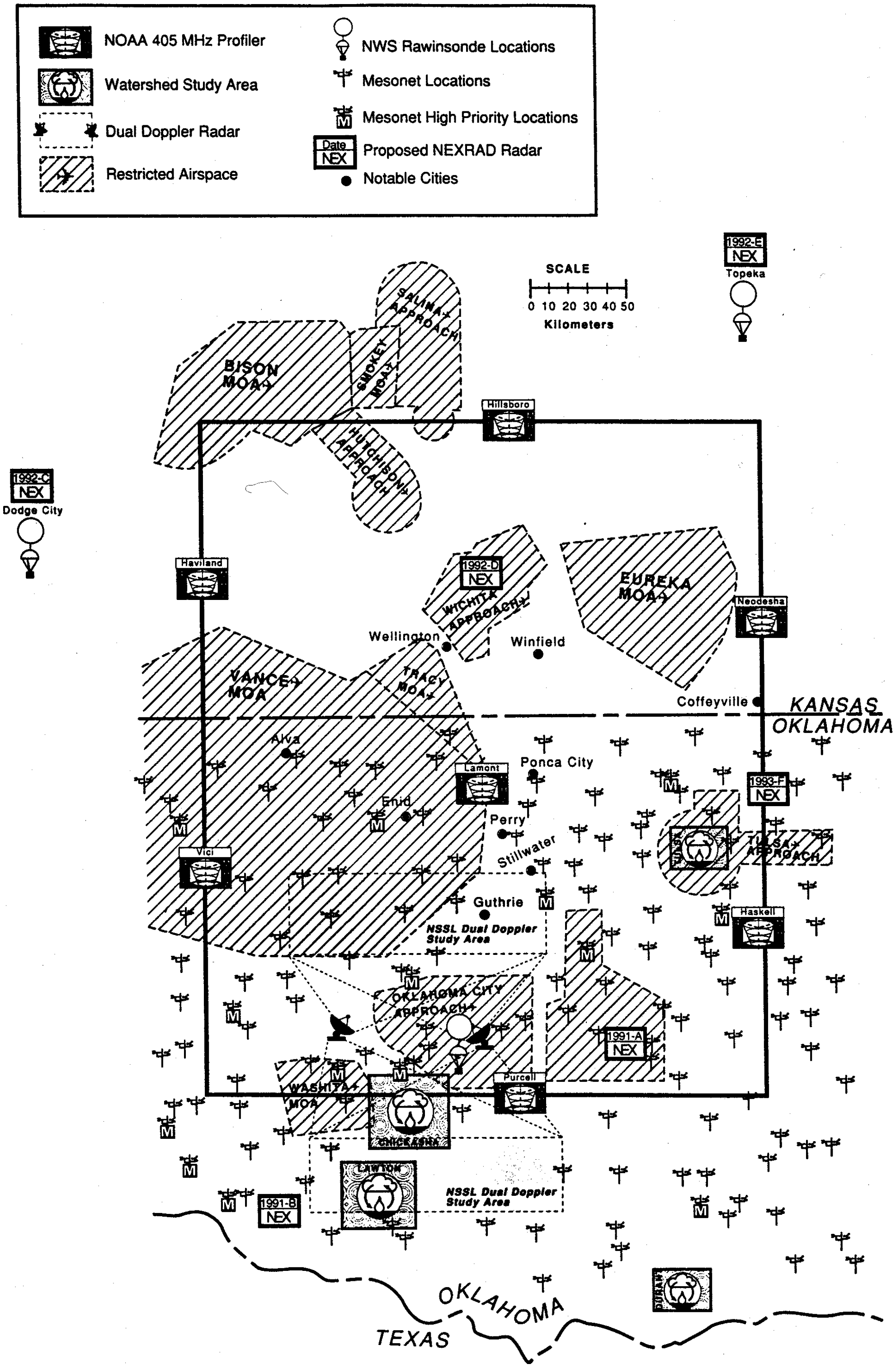

Figure 4. Locations of potential ARM program collaborations and airspace limitations within the proposed SGP CART site.

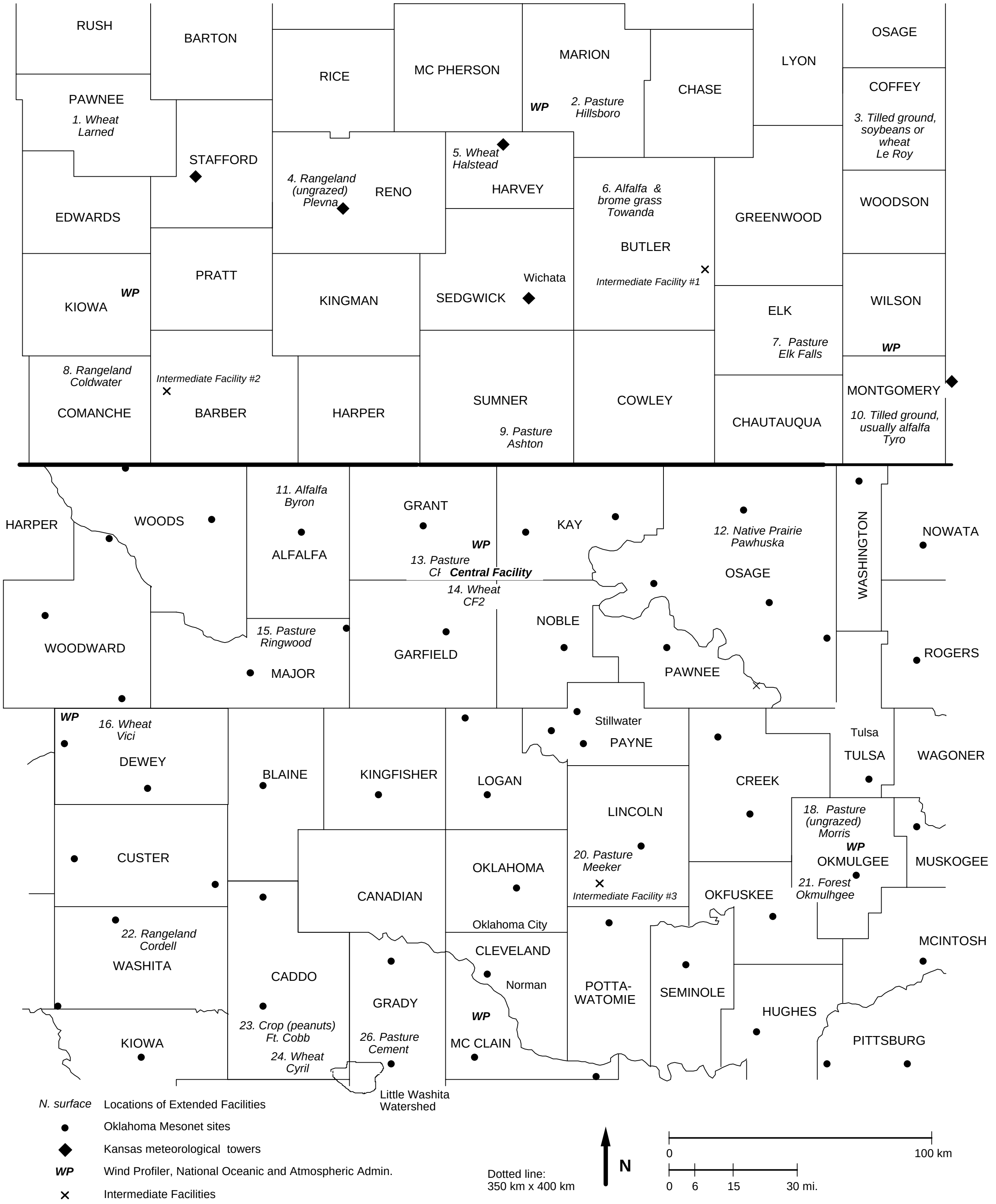

Figure 5. Proposed locations of extended facilities within the SGP CART site.

7. The Oklahoma Climatological Survey Mesonetwork (Mesonet) is a proposed 109-station network of instruments that will continuously provide temperature, wind speed and direction, pressure, humidity, and various other meteorological data for long-term climate studies. The statewide network will be in place by December 1993. The instruments to be used are nearly identical to those proposed by the ARM Program for extended facilities (Figure 4).

8. The National Severe Storms Laboratory (NSSL) operates two dual-wavelength Doppler radars (Figure 4) that enable unique studies of the microphysics of clouds.

All of these programs have an interest like the ARM Program's in meteorological measurements. Therefore, much of the instrumentation and many of the measurements will be the same, although the application of the data to respective program goals is different. All of these programs require dual Doppler radar and find that their site locations for campaigns (rather than for long-term continuous measurements) must be near existing facilities having dual Doppler radar. Such facilities currently exist at NSSL in Norman, Oklahoma, and Boulder, Colorado, and at the NWS facility in Kansas City, Kansas. The ARM Program would benefit significantly from access to a dual Doppler radar and the associated activities.

The GCIP and STORM communities are strongly considering using the Oklahoma area to take advantage of the NSSL dual Doppler radar, as well as a new hydrology experiment planned for the Watchita Watershed in Oklahoma. The high-density rain gauge network and supporting meteorological instrumentation associated with the NSSL radar, the Oklahoma Mesonet, and intensive field campaigns of STORM and GCIP make the SGP an attractive area for the ARM Program. Although the main driver toward the SGP locale for all of these programs is the unique climatology, the overall coordination of selection and location of instruments by each of these independent programs simply makes use of good common sense.

Negative synergisms exist in the Oklahoma and Kansas area as well. These include 1) complex terrain features that complicate meteorological interpretation of surface characterization studies and 2) restricted airspace. Southeast Oklahoma has small mountains. Eastern Oklahoma has major wooded and water-covered areas having low scientific priority for the ARM Program. Western Oklahoma and Kansas have uniform but significantly sloping terrain that complicates local meteorological studies. North central Kansas has undesirable rolling and complex terrain features. Southern Oklahoma is too far south to have reliably snow-covered surfaces in winter. These considerations still leave a large favorable area for ARM Program activities in central Kansas and Oklahoma.

Restricted airspace in the SGP significantly limits the potential locations for facilities. The central facility requires routinely scheduled aircraft operations and requires a minimum area of about 20-km diameter for operation within the boundary layer, the midtropospheric region, and the top of the tropopause. Figure 4 shows some of the major locations of restricted airspace in the SGP. Commercial flight lanes further reduce the favorable locations for ARM Program aircraft operations. In fact, about 85% of the airspace in central Oklahoma and central Kansas is restricted in some way.

7. Recommended Location for CART Site

Of paramount concern in the selection of a continental U.S. locale is the ease of addressing scientific questions in a climate that affords a wide variety of important meteorological conditions supporting unambiguous measurements of radiation budget components. Climatologically, aerosol loading and snow cover are significant differences between the MW, NGP, and SGP locales. The NGP and MW afford the best opportunities for wintertime snow cover, although snow cover also occurs in the SGP. Furthermore, the ARM Program has identified the issue of snow cover as a primary concern and has selected the North Slope of Alaska as a primary CART site. The issue of aerosols is also important. The number of clear days in the MW locale is small, whereas the number of high-burden aerosol days in the NGP and SGP is also relatively small. Nevertheless, the NGP and SGP locales present an appropriate climatological opportunity to investigate both clear sky and aerosols over the proposed lifetime (seven to ten years) of the continental U.S. CART site. Therefore, the factors of operational logistics and synergism with other programs become critical in selecting potential CART sites. Although this report uses an additional layer of detail in locale analysis, the authors concur with the ARM Program Science Team that the SGP is the best overall candidate locale for the continental U.S. CART site.

The number of opportunities for supplemental data and collaborative research in the SGP locale, especially in Oklahoma, favor the selection of a CART site within that region. Certainly, as individual sites are examined, a number of specific operational issues must be evaluated for each site. Features that become important on the scale of 50-100 km include convenient housing for site personnel and visitors; good roads for commuting and transporting equipment; and the ability to operate aircraft, balloons, and active remote sensing systems on a schedule governed by the scientific site mission. Nearby communities with the resources to provide the required supplies and services are also important.

On the basis of all relevant scientific, topographic, logistic, and synergistic considerations, the location of the CART conceptual area is defined by the latitude, longitude coordinates 38 deg 30 min; 99 deg 30 min.; 38 deg 30 min., 95 deg 15 min.; 34 deg 15 min., 99 deg 30 min.; and 34 deg 15 min., 95 deg 15 min. This area encompasses seven of the NOAA high-density Wind Profiler Demonstration Network profilers and many of the Oklahoma Mesonet sites. Although this CART area (about 350 km × 400 km) is larger than the conceptual GCM grid (200 km × 200 km), its size does not increase the number of facilities required to characterize the CART area, nor does it reduce the effectiveness of the measurement strategy. In fact, including all seven NOAA profilers nearly doubles the midtropospheric meteorological measurement capability proposed by the ARM Program, yet it substantially reduces the cost (avoiding the purchase of seven profilers). This report, then, concludes by lending support to the SGP as the locale of scientific choice and the CART area of scientific and synergistic choice.

8. Candidate Facilities

8.1 General Screening Criteria

The next activity is the selection of three candidate areas for each of the central, extended, auxiliary, and boundary facilities within a rectangular area roughly defined by the seven NOAA high-density Wind

Profiler Demonstration Network locations. This SGP CART site area has been coarsely screened by using scientific criteria, logistics, economics, and environmental concerns as the driver. Next, NEPA screening of the candidate areas will be done.

The coarse screening included land use considerations to exclude urban areas, water-covered areas, and forested areas, which have been defined by the ARM Program as outside the primary interest. Attention was given to agricultural lands and pasturelands, the primary land use categories of the CART area. Restricted airspace was identified. Topographic features (complex terrain and rivers, streams, lakes, and lowland areas) that complicate surface characterization or the interpretation of regional meteorological studies were identified. This effort was aided by a geographic information system.

Preliminary estimates of the unobstructed view required for representative measurements by the types of instruments planned for the ARM Program facilities indicate that the central facility requires about 160 acres (a quarter section), each of the auxiliary and extended facilities requires about 1 acre but must be representative of 50 to 100 acres, and each of the boundary facilities requires about 100-150 acres.

As a result of the coarse screening, specific locations will be sought that address specific logistic criteria (power, platform, area required for unobstructed view, the locations of instruments and platforms, communication lines, interferences with or by instruments, safety restrictions, aircraft operations, office work space, computer location, repair locations, storage requirements, etc.) for each of the instruments to be placed at the central facility and at auxiliary, extended, and boundary facilities.

The top three candidate sites for each of the facilities become the focus of the NEPA activities. No irreversible action can be taken within the CART area until the NEPA process has been completed. The first NEPA item is the Action Description Memorandum (ADM), a brief discussion of the ARM Program with an identification of potential environmental concerns. On the basis of the ADM, the DOE Environment and Health Division decided that an Environmental Assessment (EA) was warranted. The primary concern addressed in the EA report (Policastro et al. 1992) was potential for noise impact due to the RASSs and the socioeconomic impact of a large program in a rural area. The central facility is the largest, most extensively instrumented of the various facilities and the only facility that requires the continuous on-site presence of personnel. A Finding of No Significant Impact was issued in May 1992.

The central facility site is expected to be minimally operational by May 1992. Auxiliary, extended, and boundary facilities are expected to be in place by April 1993. This schedule assumes no environmental impacts, logistics problems, and budget limitations.

8.2 Facility Location

The central facility will have subcomponents of auxiliary, extended, and boundary facilities. The central facility should be located where research aircraft can operate and reasonably near the center of the study area. Initially, a location near the NOAA Lamont (Oklahoma) wind profiler location should be explored.

The locations of auxiliary facilities depend on the location of the central facility.

Boundary facilities should be collocated with the NOAA Wind Profiler Demonstration Network sites at Hillsboro (Kansas) and at Vici and Morris (Oklahoma).

Initial plans were to use as many as 25 extended facility sites scattered over the SGP CART site. This number of sites was recognized as insufficient for many purposes involving characterization of surface properties, particularly with regard to soil moisture variations. The expansion of the total area from a 200-km square to an area approximately 350 km by 400 km to include the NOAA-NWS 404-MHz wind profilers at the outer horizontal boundaries resulted in greater difficulties in obtaining adequate spatial sampling. Nevertheless, implementation is to be based on the larger study area with 25 extended facilities. The number and spacing might change, depending on the data collected. Emphasis here is on the selection of the extended facilities.

An early question about the placement of extended facilities was whether the sites should be spaced evenly on a fixed grid. Responses from various members of the ARM Program Science Team indicated that placement according to a fixed grid was not necessary. This is fortunate, because doing so would have made the task of finding suitable sites more difficult.

Selecting extended facility locations and evaluating the incremental usefulness of adding sites would probably be done best with a sensitivity analysis involving models of surface energy components and meteorological parameters. No such analysis has been carried out. Instead, a minimal representation of the surface conditions is being sought with the limited number of extended facilities now available.

The process of choosing the locations for extended facilities at the SGP CART site begins with consideration of the major factors that affect the quantities being observed. For surface fluxes, the factors include vegetation type, soil moisture content, and terrain slope. At the SGP CART site, slope does not seem to be a significant factor. Soil moisture content is a major factor but is sometimes extremely difficult to evaluate because of small-scale spatial variability of rainfall, especially during summer. At best, we can try to find locations that span the long-term, large-scale east-west and north-south gradients in soil moisture. The type of surface vegetation is quite variable in the SGP CART site but can be mapped. The extended facilities should be distributed over the entire site, with local surface vegetation as the primary reason for choosing sites, keeping in mind that coverage over the entire SGP CART site, though not necessarily in an exact grid pattern, is desirable.

In general, the approach used for selecting surface flux stations applies, with perhaps equal validity, to selecting locations for surface meteorological observations of winds, temperatures, humidities, etc.

For surface radiometric observations at the extended facilities, the upwelling observations are probably subject to requirements similar to those for surface flux observations. No systematic variation of distances between the sites has been attempted, except for aiming for a fairly uniform distribution over the CART site; combinations of various distances between sites can be used. These distances are fairly large, however, and are probably not suitable for evaluating small-scale spatial variability of downwelling radiation. The distances between the sites should be sufficiently short, nevertheless, to yield representative averages of surface radiation components for the entire CART site.

8.3 Recommendations for Extended Facility Locations

Members of the ARM Program Science Team working on problems associated with area-averaged flux measurements met at Argonne National Laboratory on March 17-18, 1992, to provide input for the selection of locations for the extended facilities at the SGP CART site. Attendees included F. Barnes of Los Alamos National Laboratory; K. Kunkel of the Illinois State Water Survey; C. Doran of Pacific Northwest National Laboratory; T. Crawford and R. McMillen of NOAA's Atmospheric Turbulence and Diffusion Division in Oak Ridge, Tennessee; R. Cederwall of Lawrence Livermore National Laboratory; and J. Shannon and R. Coulter of Argonne National Laboratory.

The SGP CART site in south-central Kansas and north-central Oklahoma is relatively flat, with a gradual slope from east-southeast to west-southwest, with typical elevations of 200 m in the southeast rising to approximately 600 m in the northwest. Precipitation varies from about 42 in./yr in the southeast to about 20 in./yr in the northwest. Mean cloud cover is about 25% greater on the eastern side of the CART site. Variations in both precipitation and cloud cover are largely due to more frequent availability of moisture from the Gulf of Mexico on the eastern side. Mean temperatures in summer exhibit little trend across the site; in winter there is significant variation from south-southeast to north-northwest, with the southeast corner being about 10°F warmer than the northwest corner. Variations in mean meteorological conditions across the site are relatively smooth.

Information was obtained on major crop acreage at the county level for a recent year. About 25% of the CART site is planted in winter wheat, while mixed crops cover an additional 8%. The Kansas portion of the CART site has more mixed crops than does the Oklahoma portion. The more important of the mixed crops are sorghum, corn, and soybeans, all mainly in Kansas, and "hay" (interpreted as alfalfa, timothy, or Sudan grass).

The bulk of the SGP CART site is some form of grassland, including woody pastures to the east, particularly in Oklahoma; open pastures in central regions; and rangeland in the west. An important, rather uniform area of grasslands is the north-south, 100-km-wide extension of the tallgrass prairie that extends from Chase County, Kansas, through Osage County, Oklahoma. This tallgrass prairie usually has no trees except along streams and comprises a large contiguous area of tall native grasses. Occasional prairie fires there have both natural and human causes. Definition of grassland types in this analysis is relatively vague. Pasture was viewed as generally managed and more intensively grazed or mown, while rangeland was viewed as drier, in rougher terrain, and less grassy.

Forest coverage is greatest in the southeast, although the commercial pine forests in southeastern Oklahoma might well be entirely outside the SGP CART site. Most of the wooded areas in the SGP CART site consist of mixed hardwoods. Wooded areas in the western half of the site are largely limited to bottomlands near streams. A number of large reservoirs occur in eastern Oklahoma, but their total area is less than 1% of the SGP CART site.

Extended facility recommendations were based on criteria critical to the problem of representing surface fluxes adequately over the SGP CART site. The goal was to distribute the extended sites so as to sample the full range of environmental conditions over each major land use type within the SGP CART site. Placing radiation and surface meteorological monitoring instruments near the locations recommended for surface flux instrument systems should be generally acceptable for the purposes of the ARM Program because of the relatively smooth spatial variations of seasonal and annual patterns of key parameters. The Oklahoma Mesonet will provide generally adequate spatial coverage for the ARM Program in Oklahoma, particularly by the end of 1993, and a comparatively sparse network currently being operated by Kansas State University provides some coverage in Kansas. That pattern led to the recommendation that two sites falling near the state border should be placed on the Kansas side.

The locations are not specified precisely, but only to a certain county or along the border between two adjacent counties. More detailed recommendations for locations will require visual inspection. Little attention has been paid to the specific Oklahoma Mesonet station locations, because each county will have at least two stations. In the final site selection process, the locations of non-SGP CART stations will be assumed to have some impact, particularly with respect to adequate areal coverage over the SGP CART site.

8.3.1 Sites in Wheat Fields

The following seven wheat field sites were chosen to characterize variations associated with moisture, cloud, and temperature distributions across the CART site:

1. **Pawnee County, Kansas**. This county to the northwest should represent the driest, coldest, and sunniest wheat-growing region. About one-third of the area is planted in wheat.

2. **Dewey County, Oklahoma**. This western Oklahoma county is warmer and slightly moister than Pawnee County, Kansas, but otherwise it is similar. About one-fourth of the area is planted in wheat.

3. **Harvey County, Kansas**. This north-central CART county should experience temperatures almost as cool as those in Pawnee County, Kansas, but somewhat greater moisture and cloudiness. Almost 40% of Harvey County is planted in wheat.

4. **Canadian County, Oklahoma**. This southern CART county should be warmer and slightly moister than Harvey County, Kansas. Wheat production accounts for 45% of Canadian County’s area.

5. **Garfield County, Oklahoma**. The CART site in Garfield County is located one county south of the presumed CART central facility location.

6. **Coffey County, Kansas**. This northeastern CART county should be relatively cool but have more precipitation and cloudiness than the other Kansas sites. However, wheat represents only about 11% of land use here.

7. **Montgomery County, Kansas**. This east-central CART location should be similar to but warmer than Coffey County, Kansas. About 16% of the land is devoted to wheat.

A field designated as “wheat” or “mixed crop” might experience varying agricultural practices during the SGP CART site’s life span. Fields in the western portion of the site, where conditions are relatively dry, are frequently left fallow every second or third year, but wheat fields to the east are sometimes rotated annually with soybeans or sorghum. In addition, wheat is either grown to harvest or grazed out.

8.3.2 Pastureland Sites

Seven pasture sites were chosen with soil, cloud, and temperature distributions in mind, in addition to topography and the likely state of the pasture. That is, the character of pastureland is likely to vary significantly over the SGP CART site. Selection of individual specific sites should be done with knowledge of previously chosen types of pasture. The seven pasture sites are as follows:

8. **Major County, Oklahoma**. This county has the westernmost pasture site and thus the driest. This site might be close to the rangeland transition.

9. **Grady County, Oklahoma**. This southernmost extremity of the CART site should be warmer and moister than Major County, Oklahoma.

10. **Lincoln County, Oklahoma**. This south central county should receive 10%-15% more rainfall than Grady County, Oklahoma.

11. **Marion County, Kansas**. This northernmost pasture site should be the coolest, particularly in winter.

12. **Sumner County, Kansas**. Biomass should be greater in this central county than in Major County, Oklahoma, or Marion County, Kansas.

13. **Elk County, Kansas**. This east-central pasture site should have precipitation similar to that in Lincoln County, Oklahoma, but be somewhat cooler in winter.

14. **Creek County, Oklahoma**. This is the warmest and cloudiest pasture site. The land is more irregular and forested than at other pasture sites. Good measurement sites might be more difficult to find for eastern pastures.

8.3.3 Rangeland Sites

True rangeland is expected to be found primarily in the western portion of the SGP CART site. Because dryness is part of the assumed classification of rangeland, the variation is primarily related to the temperature gradient. The three rangeland sites are as follows:

15. **Reno County, Kansas**. This northern rangeland site should be coolest in winter.

16. **Comanche County, Kansas**. Rangeland in this west central county should be intermediate in temperature.

17. **Washita County, Oklahoma**. This southwestern county should be the warmest rangeland site in winter.

8.3.4 Wooded Sites

Much of the forested area of the SGP CART site, primarily in eastern Oklahoma, is patchy; thus, suitable sites might be difficult to find. The two wooded sites are as follows:

18. **Muskogee or Wagoner County, Oklahoma**. Mixed hardwoods are most prevalent in this region.

19. **Pittsburgh or McIntosh County, Oklahoma**. Pine trees are the preferred forest species for this site.

If no wooded site of adequate extent is found, the selection must be reconsidered.

8.3.5 Sites over Mixed Crops

20. **Alfalfa County, Oklahoma**. Alfalfa crop here is representative of hay, which covers about 6% of the area.

21. **Caddo County, Oklahoma**. Peanuts are grown in this region; cotton is a second possibility for a site. The region is warm and dry; thus, cotton and peanuts are probably irrigated.

22. **Butler County, Kansas**. About 7% of the county is planted in sorghum.

8.3.6 Site on Native Prairie

23. **Osage County, Oklahoma**. Tallgrass prairie is a very large, contiguous portion of this largest county in Oklahoma. Utility lines and roads are sparse.

8.3.7 Site at Central Facility

24. A site within 0.5 km of the central facility is recommended for an extended facility to measure a second type of pasture in contrast with the type sampled within the central facility itself. The purpose is to better understand the flux measurement made at the 60-m level on the central facility’s tower. A measurement at 5 m on the 60-m tower (exposed to the wheat field) is also desirable for better interpretation of the 60-m measurement.

8.3.8 Additional Site

Note that 24 sites are defined here. That leaves one additional extended facility site to be determined. Moreover, difficulties in locating one (or more) of the sites in wooded conditions could leave a few sites to be determined. Because the majority of the area within the SGP CART site is rangeland or pasture, one or more additional sites could be located in these regions. A second option is to locate a second site within 1 or 2 km of the central facility to better characterize the measurements at that site.

8.4 Extended Facility Implementation

Three of the extended facilities are expected to be collocated with or located very near the three initial boundary facilities for the SGP CART site: Hillsboro, Vici, and Morris. These three sites will have NOAA-NWS 404-MHz radar wind profilers and RASSs.

A community that welcomes the various facilities within CART and supports the operation on the terms required to meet programmatic goals will be highly valued. The top three candidate locations for central, extended, and boundary facilities will be identified and evaluated on the basis of results in this report and the coarse-screening report, with final approval of the ARM Program Science Team, DOE, and environmental regulators under NEPA.

The geographic extent of the SGP CART site and the approximate locations of extended facilities are shown in Figure 5. The counties recommended as locations for extended facilities are shaded. The central facility, marked in Grant County, Oklahoma, contains a concentrated array of atmospheric instrumentation. Table 3 gives further information on the sites and their implementation status as of March 1999. The numbering system now used for the sites designates geographic location rather than vegetative cover.

In retrospect, the recommendations described in Section 8.3 were followed fairly closely. Four changes were made. First, a wheat field site (recommended as number 4) is located in Caddo County, Oklahoma, rather than in Canadian County, Oklahoma, and a pasture site (recommended as number 9) is located in Canadian County rather than in Caddo County. This exchange was made because of the availability of suitable field locations and to increase the range of climatological conditions for wheat sites. Second, the pasture site (recommended as number 14) specified for Creek County, Oklahoma, was moved to Okmulgee County, Oklahoma, because well-maintained, unwooded pasture lands were difficult to find in Creek County. Third, a second wooded site (recommended as number 19) was not chosen because very few pine forests were found during field trips; the costs of installing a second tall tower, in addition to that for the Okmulgee wooded facility, to reach above a forest seemed prohibitive. Fourth, both a pasture site (recommended as number 24) and a wheat field site (recommended as number 6) were located at the central facility, mainly to lessen costs of installation and operation.

9. The SGP CART Site Today

Until this point, this report has focused on the way the SGP CART site was initially implemented on the basis of scientific and logistic considerations for a continental location. Because of funding limitations, the site was installed in stages over a period of years. A series of semiannual *Site Scientific Mission Plan* documents has discussed the implementation activities and the changes to the original design and operation over the past seven years. Those changes were driven by analysis and review of the data and recommendations by the Site Scientist Team, the ARM infrastructure, and the ARM Science Team and are discussed in individual *Site Scientific Mission Plan* documents (Schneider et al. 1993, 1994a, b, 1995; Splitt et al. 1995; Peppler et al. 1996a, b, 1997a, b, 1998a, b, 1999a, b). Some of those changes, for example, included the need for four boundary facilities instead of three and the need to create three intermediate facilities. Overall, the site is operated five days per week (Monday through Friday),

Table 3. Extended facilities implemented as of November 1992.

Recommended Designation[(a)] (November 1992)	**Current Designation (March 1992)**
Wheat Field	
1	# 1, Burdett, Pawnee County, Kansas
2	#16, Dewey County, Oklahoma
3	# 5, Halstead, Harvey County, Kansas
4	#24, Cyril, Caddo County, Oklahoma
5	#13, Lamont CF1, Grant County, Oklahoma
6	#3, LeRoy, Coffey County, Kansas
7	#10, Tyro, Montgomery County, Kansas
Pastureland	
8	#15, Ringwood, Major County, Oklahoma
9	#19, El Reno, Canadian County, Oklahoma
10	#20, Meeker, Lincoln County, Oklahoma
11	#2, Hillsboro, Marion County, Kansas
12	#9, Ashton, Sumner County, Kansas
13	#7, Howard, Elk County, Kansas
14	#18, Morris, Okmulgee County, Oklahoma
Rangeland	
15	#4, Plevna, Reno County, Kansas
16	#8, Coldwater, Comanche County, Kansas
17	#22, Cordell, Washita County, Oklahoma
Wooded	
18	#21, Okmulgee, Okmulgee County, Oklahoma
19	Not used
Mixed Crops	
20	#11, Byron, Alfalfa County, Oklahoma
21	#23, Ft. Cobb, Caddo County, Kansas
22	#6, Towanda, Butler County, Kansas
Native Prairie	
23	#12, Pawhuska, Osage County, Oklahoma
Central Facility	
24	#13 and #14, Lamont CF2, Grant County, Oklahoma

(a) As in Figure 5.

including holidays, but the exact schedules of routine radiosonde operations and of IOPs change with requirements, as reported in the *Site Scientific Mission Plan* documents. Figure 6 is the current (December 1999) map of the SGP CART site, showing the locations of the central, extended, intermediate, and boundary facilities. Table 4 provides the current (December 1999) locations of instruments.

10. References

Arakawa, A., and W. H. Schubert, 1974: Interaction of a cumulus cloud ensemble with the large-scale environment. *Journal of the Atmospheric Sciences*, **31**, 674-701.

Bluestein, H. B., and W. P. Unruh, 1989: Observations of the wind field in tornadoes, funnel clouds, and wall clouds with a portable doppler radar. *Bulletin of the American Meteorological Society*, **70**, 1514-1525.

Bryson, R. A., and D. A. Baerreis, 1967: Possibilities of major climatic modification and their implications: Northwest India, a case for study. *Bulletin of the American Meteorological Society*, **48**, 136-142.

Charlson, R. J., and M. J. Pilat, 1969: Climate: The influence of aerosols. *Journal of Applied Meteorology*, **8**, 1001-1002.

Coulter, R. L., T. J. Martin, D. A. Cook, T. A. Tyce, and D. J. Brandner, 1993: “Intensity and vertical velocity profiles over varying surface types and their relationship to Areal average heat flux.” In *Preprints, Fourth Symposium on Global Change Studies*, pp. 152-156. American Meteorological Society, Boston, Massachusetts.

Deluisi, J. J., P. M. Furukawa, D. A. Gillette, B. G. Schuster, R. J. Charlson, W. M. Porch, R. W. Fegley, B. M. Herman, R. A. Rabinoff, J. T. Twitty, and J. A Weinman, 1976: Results of a comprehensive atmospheric aerosol-radiation experiment in the Southwestern United States. *Journal of Applied Meteorology*, **15**, 441-463.

Dickinson, R. E., A. Henderson-Sellers, P. J. Kennedy, and M. F. Wilson, 1986: *Biosphere-Atmosphere Transfer Scheme (BATS) for the NCAR Community Climate Model*. Technical Note TN-173+1A, National Center for Atmospheric Research, Boulder, Colorado.

Ellingson, R., and Y. Fouquart, 1991: The intercomparison of radiation codes in climate models: An overview. *Journal of Geophysical Research*, **96**, 8925-8927.

Ellingson, R., and W. Wiscombe, 1996: The spectral radiance experiment (SPECTRE): Project description and sample results. *Bulletin of the American Meteorological Society*, **77**, 1967-1985.

Ensor, D. S., W. M. Porch, M. J. Pilat, and R. J. Charlson, 1971: Influence of atmospheric aerosol on albedo. *Journal of Applied Meteorology*, **10**, 1303-1306.

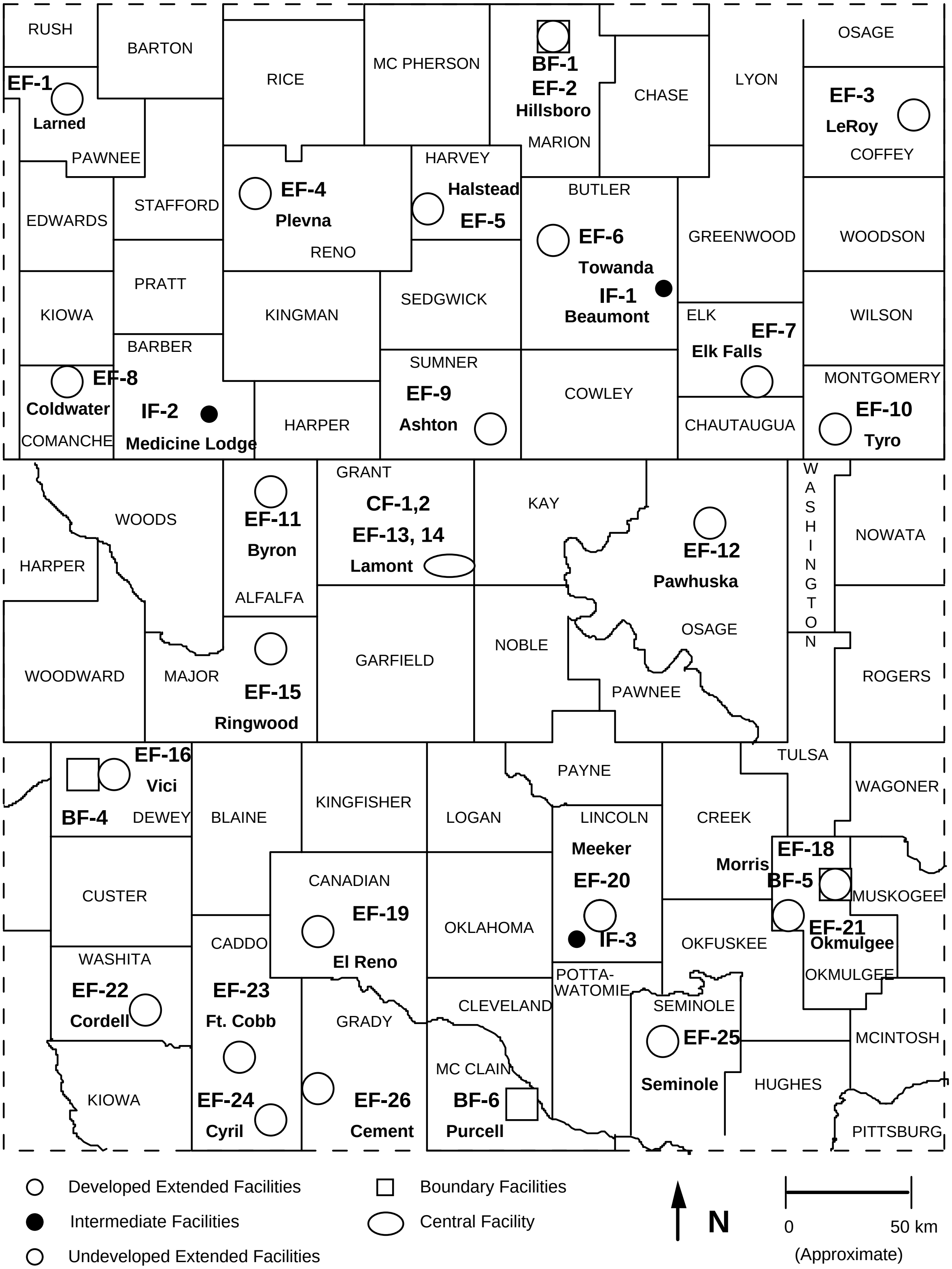

Figure 6. Overall view of the SGP CART site.

Table 4. Instruments and observational systems anticipated at the central, boundary, extended, and auxiliary facilities on December 31, 1999.(a)

Central Facility
Radiometric Observations
AERI
AERI X
SORTI
BSRN
Pyranometer (ventilated)
Pyranometer (ventilated, shaded)
Pyrgeometer (ventilated, shaded)
NIP on tracker
SIRS (formally known as SIROS)
Pyranometer (ventilated)
Pyranometer (ventilated, shaded)
Pyrgeometer (ventilated, shaded)
NIP on tracker
Pyranometer (upwelling, above pasture at 10 m)
Pyrgeometer (upwelling, above pasture at 10 m)
MFRSRs
MFR (upwelling, above pasture at 10 m)
Pyranometer (upwelling, above wheat at 25 m on 60-m tower)
Pyrgeometer (upwelling, above wheat at 25 m on 60-m tower)
MFR (upwelling, above wheat at 25 m on 60-m tower)
CSPHOT
RSS
NFOV
GRAMS
SWS
RCF instrumentation, including cavity radiometers
SSP-3
USDA UVB monitoring station
USDA UV spectral radiometer
Wind, Temperature, and Humidity Systems
BBSS
915-MHz profiler with RASS
50-MHz profiler with RASS
MWR
Heimann IR thermometer
Raman lidar
THWAPS
Cloud Observations
WSI (daytime/nighttime)
BLC (interim)
MPL-HR
MMCR
TLCV
Others
Temperature and humidity probes at 25-m and 60-m levels on tower
Heat, moisture, and momentum flux instrumentation at 25-m and 60-m levels on tower

Table 4. (Contd.)

EBBR
ECOR
SMOS
AOS (samples at 10 m)
SWATS
Extended Facility Components
SIRS (formally known as SIROS)
Pyranometer (ventilated)
Pyranometer (ventilated, shaded)
Pyrgeometer (ventilated, shaded)
NIP on tracker
Pyranometer (upwelling, at 10 m)
Pyrgeometer (upwelling, at 10 m)
MFRSR
EBBR or ECOR
SMOS
SWATS
Auxiliary Facilities
None in preparation
Boundary Facilities
BBSS
MWR
THWAPS
VCEIL
AERI
Intermediate Facilities
915-MHz profiler and RASS

(a) AERI X, atmospherically emitted radiance interferometer; AOS, aerosol observation system; BLC, Belfort laser ceilometer; BSRN, Baseline Surface Radiation Network; CSPHOT, Cimel sunphotometer; GRAMS, ground-based radiometer autonomous measurement system; MFR, multifilter radiometer; MMCR, millimeter cloud radar; MPL-HR, micropulse lidar-high resolution; NFOV, narrow-field-of-view zenith-pointing filtered radiometer; NIP, normal-incidence pyrheliometer; RCF, radiometer calibration facility; SIROS, solar and infrared radiation observing system; SIRS, solar and infrared radiation station; SORTI, solar radiance transmission interferometer; SSP, scanning spectral polarimeter; SWATS, soil water and temperature system; SWS, shortwave spectrometer; THWAPS, temperature, humidity, wind, and pressure sensors; TLCV, time-lapse cloud video; USDA, U.S. Department of Agriculture; UV, ultraviolet; UVB, ultraviolet-B; VCEIL, Vaisala ceilometer; WSI, whole-sky imager.

Fogle, B., 1975: Project DUSTORM ‘75: Operations plan. Report 7, National Center for Atmospheric Research, Boulder, Colorado.

Gotz, G., E. Meszaros, and G. Vali, 1991: Atmospheric particles and nuclei. Akademiai Kiado, Budapest.

Haurwitz, B., and J. M. Austin, 1944: Climatology. McGraw-Hill, New York.

Houghton, J. T., G. J. Jenkins, and J. J. Ephrams, 1990: *The Intergovernmental Panel on Climate Change (IPCC) Scientific Assessment*, Cambridge University Press, Cambridge.

Kuo, H. L., 1974: Further studies of the parameterization of the influence of cumulus convection on large-scale flow. *Journal of the Atmospheric Sciences*, **31**, 1232-1240.

Landsberg, H. E., and D. F. Rex eds., 1969: *World Survey of Climatology, Volume 4: Climate of the Free Atmosphere*. Elsevier Scientific Publishing Company, New York.

Landsberg, H. E., R. A. Bryson, and F. K. Hare eds., 1974: *World Survey of Climatology*, *Volume 11: Climates of North America*. Elsevier Scientific Publishing Company, New York.

Luther, F. A., R. G. Ellingson, Y. Fouquart, S. Fels, N. A. Scott, and W. J. Wiscombe, 1988: Intercomparison of radiation codes in climate models (ICRCCM): Longwave clear-sky results—A workshop summary. *Bulletin of the American Meteorological Society*, **69**, 40-48.

MacCracken, M., A. Hecht, M. I. Budyko, and Y. Izrael, 1990: *Prospects for Future Climate*. Lewis Publishers, Chelsea, Michigan.

Manabe, S., J. Smagorinsky, and R. F. Strickler, 1965: “Simulated climatology of a general circulation model with a hydrologic cycle. *Monthly Weather Review*, **93**, 769-798.

Penner, J. E., R. J. Charlson, J. M. Hales, N. Laulainen, R. Leifer, T. Novakov, J. Ogren, and S. E. Schwartz, 1992: *ARM Aerosol Working Group Report*. LLNL Report UCRL-AR-110391, Lawrence Livermore National Laboratory, Livermore, California.

Peppler, R. A., P. J. Lamb, and D. L. Sisterson, 1996a: *Site Scientific Mission Plan for the Southern Great Plains CART Site, January-June 1996.* ARM-96-001, U.S. Department of Energy, Washington, D.C.

Peppler, R. A., P. J. Lamb, and D. L. Sisterson, 1996b: *Site Scientific Mission Plan for the Southern Great Plains CART Site, July-December 1996.* ARM-96-002, U.S. Department of Energy, Washington, D.C.

Peppler, R. A., P. J. Lamb, and D. L. Sisterson, 1997a: *Site Scientific Mission Plan for the Southern Great Plains CART Site, January-June 1997.* ARM-97-001, U.S. Department of Energy, Washington, D.C.

Peppler, R. A., D. L. Sisterson, and P. J. Lamb, 1997b: *Site Scientific Mission Plan for the Southern Great Plains CART Site, July-December, 1997.* ARM-97-002, U.S. Department of Energy, Washington, D.C.

Peppler, R. A., D. L. Sisterson, and P. J. Lamb, 1998a: *Site Scientific Mission Plan for the Southern Great Plains CART Site, January-June 1998.* ARM-98-002, U.S. Department of Energy, Washington, D.C.

Peppler, R. A., D. L. Sisterson, and P. J. Lamb, 1998b: *Site Scientific Mission Plan for the Southern Great Plains CART Site, July-December 1998.* ARM-98-003, U.S. Department of Energy, Washington, D.C.

Peppler, R. A., D. L. Sisterson, and P. J. Lamb, 1999a: *Site Scientific Mission Plan for the Southern Great Plains CART Site, January-June 1999.* ARM-99-001, U.S. Department of Energy, Washington, D.C.

Peppler, R. A., D. L. Sisterson, and P. J. Lamb, 1999b: *Site Scientific Mission Plan for the Southern Great Plains CART Site, July-December 1999.* ARM-99-002, U.S. Department of Energy, Washington, D.C.

Policastro, A. J., J. M. Pfingston, D. M. Maloney, F. Wasmer, and E. D. Pentecost, 1992: *Environmental Assessment for the Atmospheric Radiation Measurement (ARM) Program: Southern Great Plains Cloud and Radiation Testbed (CART) Site.* ANL/EAIS/TM-86, Environmental Assessment and Information Systems Division, Argonne National Laboratory, Argonne, Illinois.

Schneider, J. M., P. J. Lamb, and D. L. Sisterson, 1993: *Site Scientific Mission Plan for the Southern Great Plains CART Site, July-December 1993.* ARM-93-001, U.S. Department of Energy, Washington, D.C.

Schneider, J. M., P. J. Lamb, and D. L. Sisterson, 1994a: *Site Scientific Mission Plan for the Southern Great Plains CART Site, January-June 1994.* ARM-94-001, U.S. Department of Energy, Washington, D.C.

Schneider, J. M., P. J. Lamb, and D. L. Sisterson, 1994b: *Site Scientific Mission Plan for the Southern Great Plains CART Site, July-December 1994.* ARM-94-002, U.S. Department of Energy, Washington, D.C.

Schneider, J. M., P. J. Lamb, and D. L. Sisterson, 1995: *Site Scientific Mission Plan for the Southern Great Plains CART Site, January-June 1995.* ARM-95-001, U.S. Department of Energy, Washington, D.C.

Schneider, S. H., 1989: The greenhouse effect: Science and policy. *Science*, **243**, 771-781.

Schwartz S. E., 1988: Are global cloud albedo and climate controlled by marine phytoplankton? *Nature*, **336**, 441-445.

Sellers, P. J., Y. Mintz, Y. Sud, and A. Dalcher, 1986: A simple biosphere (SiB) for use within general circulation models. *Journal of the Atmospheric Sciences*, **43**, 505-531.

Splitt, M. E., P. J. Lamb, and D. L. Sisterson, 1995: *Site Scientific Mission Plan for the Southern Great Plains CART Site, July-December 1995.* ARM-95-002, U.S. Department of Energy, Washington, D.C.

Twomey, S., 1977: *Atmospheric Aerosols.* Elsevier Scientific Publishing Company, New York.

Twomey, S., M. Piepgrass, and T. L. Wolfe, 1984: An assessment of the impact of pollution on global cloud albedo. *Tellus*, **36B**, 356-366.

U.S. Department of Energy (DOE), 1981: Solar radiation energy resource atlas of the United States. SERI/SP-642-1037, Solar Energy Research Institute, Golden, Colorado.

U.S. Department of Energy (DOE), 1990: Atmospheric Radiation Measurement Program (ARM). DOE/ER-0441, Washington, D.C.

U.S. Department of Energy (DOE), 1991: Identification and recommendation of locales for ARM sites. DOE/ER-0495T, Washington, D.C.

U.S. Department of Energy (DOE), 1995: Elements of change, 1994: Climate-radiation feedbacks: The current state of the science. DOE/ER-0661T, Washington, D.C.

U.S. Department of Energy (DOE), 1996: Science plan for the Atmospheric Radiation Measurement Program (ARM). DOE/ER-0670T, Washington, D.C.

Warren, S. G., C. Hahn, J. London, R. M. Chervin, and R. L. Jenne, 1988: Global distribution of total cloud cover and cloud type amounts over land. DOE/ER-406, U.S. Department of Energy, Washington, D.C.

Wilson, C. L., and W. H. Matthews eds., 1971: *Inadvertent Climate Modification: Report of the Study of Man's Impact on Climate.* SMIC Report, Massachusetts Institute of Technology Press, Cambridge, Massachusetts.