DOE/SC-ARM-0707

Report on the
ARM Climate Research Facility EXPANSION WORKSHOP

October 31 - November 1, 2007
Reston, Virginia

Atmospheric
Radiation
Measurement
Climate Research Facility
U.S. Department of Energy

Work Supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Report on the
ARM Climate Research Facility
EXPANSION WORKSHOP

October 31 – November 1, 2007
Reston, Virginia

Prepared for
the U.S. Department of Energy
under Contract DE AC05 76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

The U.S. Department of Energy (DOE) Office of Science created the Atmospheric Radiation Measurement (ARM) Climate Research Facility (ACRF) within the Office of Biological and Environmental Research (BER) to provide the infrastructure needed to address scientific uncertainties related to global climate change, with a specific focus on the crucial role of clouds and their influence on radiative feedback processes in the atmosphere. Designated as a national user facility the ACRF maintains fixed research sites, which were carefully chosen to represent a broad range of climate conditions and answer specific scientific questions. The ACRF also manages an aerial vehicles program to provide airborne measurements and a mobile facility to provide a flexible instrument platform for data collection around the world. All ACRF data are available via the ARM Archive. The ACRF assets of BER are available to other agencies to support climate change research. As such, the fixed sites and aerial measurements may host other program and agency instruments or, in turn, the mobile facility may be hosted on platforms of other programs or agencies.

BER Climate Change Research Long-Term Measure: Deliver improved scientific data and models about the potential response of the Earth's climate and terrestrial biosphere to increased greenhouse gas levels for policy makers to determine safe levels of greenhouse gases in the atmosphere.

The ACRF has made significant accomplishments during the past decade, even with a flat budget, by finding measures to allow it to continue advancing in measurement capability, producing good science, and hosting a variety of users. However, there are increasing demands for more and better climate models and improved climate process data to feed them. The ACRF does not have the resources to begin meeting these rising demands. A more ambitious plan is needed to help climate models become accurate enough to meet the BER Climate Change Research Long-Term Measure.

BER hosted a workshop on October 31-November 1, 2007, to assess how the ACRF might expand and enhance its observational network to best advance the science of cloud radiative forcing processes relevant to improving global climate models. A group of 34 scientific experts were invited to participate in the workshop, and all have provided their input to this final report. Expertise at the workshop encompassed all research elements of the Climate Change Science Program (CCSP), including remote sensing, process studies, cloud system modeling, general circulation modeling, and decision support. During the workshop, breakout groups focused on the following areas: fixed sites, mobile facilities, aerial vehicles, and data products. The panel was asked to consider each area and identify priorities for an ACRF expansion that would enable observations of key atmospheric processes influencing radiative transfer in the atmosphere: clouds, aerosols, and water vapor properties. Because of the importance of carbon dioxide on radiative forcing and the broader importance of carbon to DOE's mission, carbon cycle measurements also were considered. The ACRF has an opportunity to play a critical role in measuring carbon dioxide and other gases important both to the climate and energy policy. Enhancement of ACRF's capability would enhance DOE's ability to play an important role in this country's energy decisions.

Fixed Site Priorities

The fixed-site breakout group was asked to identify potential sites that would provide long-term measurements leading to improvements in the representation of clouds and aerosols in climate models. Ideally, data from new fixed sites should lead to the identification and quantification of new relationships among atmospheric and biospheric processes that cannot be characterized easily by short-term instrument deployments. Measurements from these sites would produce the long-term statistical data sets that are especially important to the modeling community. Additional prioritization criteria for the sites included factors related to logistics, costs, and synergistic opportunities with other national and international efforts.

The breakout group considered two categories of sites: anchor sites at locales with fairly stable climates and sites at rapidly changing locales. The anchor sites are expected to provide data needed to improve and validate the representation of important atmospheric processes in climate models. Measurements at sites located in rapidly changing locales would provide tremendous insight into regionally important processes that are affected significantly by climate change.

The five top recommended locales (shown in Figure 1) are listed in order of decreasing priority:

1. **Azores**

   The Azores Islands are ideally situated to study low stratiform cloud systems over the subtropical oceans, which are poorly represented in climate models and cause major uncertainties in predictions of climate change.

2. **Greenland**

   Greenland, the world's second largest ice sheet is starting to melt, and the melting appears to be accelerating. Long-term measurements would provide insights into changes in cloud properties, surface reflectivity, and the atmospheric radiation budget that may result from melting and shrinking of the ice sheet.

3. **South Asia**

   The Indian southwest monsoon covers an area about one-seventh of the Earth’s surface, and its intraseasonal variability is not well simulated in climate models. The high concentration of aerosols and direct impacts on the clouds and radiation feedbacks in this region provides a unique opportunity to generate data sets to predict changes taking place in the monsoon system.

4. **Amazon Rainforest**

   The Amazon rainforest, the world's largest, is an ideal site to study deep tropical convective clouds over land, which have profound effects on global circulation yet are poorly simulated in climate models.

5. **Middle Latitude Storm Tracks in the Southern Ocean**

   The oceanic storm tracks of both hemispheres are poorly simulated in climate models. The Southern Ocean offers the advantage of pristine, unpolluted clouds in greater variety than the oceans of the Northern Hemisphere.

Figure 1. Proposed Locales

See Appendix A for more information on all the proposed locales.

Mobile Facility Priorities

The first ARM Mobile Facility (AMF) was developed to address science questions beyond those addressed by the fixed measurement sites. The AMF contains many of the same instruments and data systems, but is designed to be deployed around the world for campaigns lasting 6-12 months.

The mobile facilities breakout group determined that a single mobile facility is not sufficient to meet the demands of the scientific community or take advantage of the variety of synergistic opportunities for scientific progress afforded by interacting with other national and international field projects. Two additional mobile facilities were recommended: one similar to the current design, but more modular, allowing full 12-month deployment requests and a second that would be significantly more mobile and modular. The two new mobile facilities would be specifically designed for marine deployments, since this would make them robust enough for deployment in almost any harsh environment. This strategy would permit timely deployments to regions of rapid land-use change and to regions experiencing extreme conditions.

Aerial Vehicle Priorities

The largest number of measurements of the Earth’s climate system is either surface- or satellite-based. ACRF's Aerial Vehicles Program (AVP) is designed to partially compensate for the deficiencies of both surface and satellite measurements and to fill in the gaps. AVP’s scientific focus is to provide measurements of clouds, aerosols, water vapor, and carbon cycle from both manned and unmanned aircraft to support ACRF’s scientific goals. The AVP breakout group endorsed considerable expansion of the AVP to allow it to

- conduct multiple campaigns each year, deploying to each ACRF site as driven by climate research science priorities
- move into the area of small unmanned aircraft, which requires a considerable initial investment
- support instrument development and testing, moving instruments rapidly from laboratory prototypes to full operation
- provide facilities for calibrating and repairing aircraft instruments, similar to what ACRF provides for its surface instruments.

Data Products Priorities

The bridge between ACRF data and climate models must be strengthened. Three crucial investments were identified for ACRF that would significantly advance the ability of climate modelers to derive scientific results from its data:

- Provide integrated data products at model scales. Although long-term data analysis generally requires raw data at the instrument-native spatiotemporal resolution, models require data aggregated at their own temporal and spatial resolution. Enabling a modular open source code for producing aggregated multiple-variable data products to meet a wider range of specific needs within each class of models would greatly increase the efficiency of data ingestion by the modeling community.
- Provide a tool kit of instrument simulators for creating synthetic observations from model output. Traditional model evaluation consists of comparing model-predicted variables to measured data, but the instruments used to derive this data often do not measure model variables directly. Another way to evaluate model performance is to calculate the measurements predicted by the model and compare that to the actual measurements. To encourage and enhance the use of this research technique, ACRF should create or adapt simulators and optimize their application to specific ACRF instruments, accounting for factors such as unique instrument calibration.
- Provide conditional sampling of archived data for models and analysis. This enhancement of user capabilities would allow the selection of data based on values of other archived data streams at the same location. This capability would allow users to place requests for downloading conditional data sets or simply place requests for statistical properties of conditional data sets without downloading any data.

Contents

Figures

Tables

1. Introduction

In 1989, the U.S. Department of Energy (DOE) Office of Science created the Atmospheric Radiation Measurement (ARM) Program within its Office of Biological and Environmental Research (BER). The ARM Program was designed with two components, ARM science and ARM infrastructure to support the science. BER designed the ARM Program to address scientific uncertainties related to global climate change, with a specific focus on the crucial role of clouds and their influence on radiative feedback processes in the atmosphere. The current fixed research sites were carefully chosen to represent a broad range of climate conditions needed to address these uncertainties. In 2003, the DOE designated the ARM research sites and infrastructure as a national user facility: the ARM Climate Research Facility (ACRF). The role of the ACRF is to provide infrastructure support for climate research in the general scientific community. The BER climate research programs, with specific focus on clouds and aerosols and their impact on the radiative budget, define the scope of the research supported by the ACRF. The ACRF is a BER contribution to the Climate Change Science Program (CCSP), and the user facility designation has enhanced the use of the ACRF infrastructure to CCSP goals and objectives.

The locales of existing fixed sites were determined from recommendations by a 1990 scientific panel (Schwartz et al. 1991), which was convened to recommend locales based on their ability to meet the scientific objectives of ARM. The panel recommended five locales, but only three field sites were built due to insufficient funds. The Southern Great Plains (SGP) site (with 31 facilities in Oklahoma and Kansas) is the largest and most extensive climate research field site in the world. The SGP was chosen for its relatively homogeneous geography, easy accessibility, wide variability of climate cloud types and surface flux properties, and large seasonal variation in temperature and humidity. The North Slope of Alaska and Adjacent Arctic Ocean site (with two instrumented facilities at Barrow and Atqasuk) observes cloud and radiative processes at high latitudes. The Tropical Western Pacific site (with three instrumented facilities at Manus Island; Nauru Island; and Darwin, Australia) was chosen for its warm sea temperatures, frequent deep atmospheric convection, high precipitation rates, strong coupling between atmosphere and ocean, and climate variability associated with El Niño. This region plays a large role in the interannual variability observed in the global climate system.

Since 1990, tremendous progress has been made in better understanding cloud and radiation processes. However, many uncertainties still remain in simulations of climate change over the next century, the largest being cloud radiative forcing and feedbacks. It is imperative, therefore, that the treatment of these processes in climate models be improved. To this end, BER hosted a workshop on October 31-November 1, 2007, to assess how the ACRF might expand its observational network to best advance the science of cloud radiative forcing processes relevant to improving climate models.

The goal of the ACRF workshop was to develop priorities for expanding fixed and mobile sites, aerial measurement capabilities, and data products. These new capabilities would provide data needed to develop and test new model parameterizations. The guidance was to recommend priorities for an ACRF expansion that would enable observations of key atmospheric processes that influence radiative transfer in the atmosphere: clouds, aerosols, and water vapor properties. Because of the importance of carbon dioxide on radiative forcing, carbon cycle measurements also were to be considered.

Four breakout groups were formed to identify and recommend priorities in the following areas: fixed sites, mobile facilities, aerial vehicles, and data products. Strategically placed plenary sessions allowed each breakout group to share their progress and receive comments from all workshop participants. Participation was fluid so that participants could provide input to more than one breakout group.

The discussion of considerations for additional capabilities was prefaced by three invited presentations that assessed the state of cloud-radiation science and climate modeling and highlighted outstanding uncertainties.

A presentation by Stephen Klein addressed process-level data needs for the improvement of climate models:

- Poor simulation of boundary layer cloudiness (particularly over oceans - both stratocumulus and shallow cumulus)
- Poor simulation of tropical precipitation on all time scales (diurnal, synoptic waves, tropical cyclones, Madden-Julian Oscillation, and climate mean).

A presentation by Robert Ellingson addressed important radiative process problems:

- Far infrared spectrum (wavelength > 25 µm)—seldom observed, yet controls major portion of upper tropospheric cooling
- Three-dimensional (3-D) radiative transfer:
    - New high-resolution and super-parameterized climate models will require fast, accurate models for 3-D radiative transfer.
    - Observed 3-D distributions of important cloud quantities are needed for model calculations.

A presentation by Warren Wiscombe provided an overview of new directions for ACRF from the ARM Chief Scientist’s perspective and addressed the following topics:

- New ARM science goals
- New site locations (mobile and fixed)
- New instrument platforms (surface based and airborne)
- New instruments (scanning and in situ)
- New modeling needs.

This workshop report will serve as the ACRF roadmap for moving forward to address the critical research needs identified by the Intergovernmental Panel on Climate Change (IPCC) report and by the Climate Change Science Program (CCSP). Specifically, the report addresses measurements needed to improve the representation of clouds in climate models, which is the major uncertainty in model sensitivity as identified by the IPCC. The report also is responsive to CCSP (http://www.usgcrp.gov/usgcrp/Library/ocp2008/ocp2008-analysis.htm) Goal 2 (Improve quantification of the forces bringing about changes in the Earth’s climate and related systems) and Goal 3 (Reduce uncertainty in projections of how the Earth’s climate and related systems may change in the future). The new measurement capabilities and data products will also be critical for addressing two CCSP priorities: “Development of an Integrated Earth System Analysis Capability” and “Understanding Aerosol Forcing and Interactions with Clouds and Non-CO_2 Trace Gases.”

2. Fixed Site Report

The fixed-site breakout group focused on an expansion of the current network of fixed ACRF sites to address key science questions associated especially with clouds, aerosols, water vapor properties, and the carbon cycle that could not be answered at the current sites.

The rationale for the selection of the current fixed sites was to select locales that collectively represented a broad range of cloud types and radiation environments, focusing on sites that were spatially homogeneous and where the climate statistics had not changed over 10 years in order to provide a validation anchor for climate models. Based on these criteria, fixed sites were established at the U.S. Southern Great Plains, the Tropical Western Pacific, and the North Slope of Alaska. The rationale for considering additional fixed sites include addressing persistent deficiencies in general circulation weather and climate models in other locales, understanding processes in rapidly changing locales that are affected significantly by climate change, and synergistic opportunities with efforts to measure interacting elements of the Earth system such as land surface processes of relevance to the carbon cycle.

Important classes of the cloud system are not captured at ACRF's current fixed sites. The most important of these are marine stratiform cloud systems, covering extensive areas of the subtropical oceans and responsible, according to several recent papers, for a substantial part of the uncertainty in global warming predictions. Another important class is mid-latitude storm track cloud systems, which we tend to think are well understood but which, in fact, are poorly simulated by climate models. Scientists have a particular interest in pristine and unpolluted clouds, and it appears that such clouds still exist in the Southern Ocean around Antarctica, where almost every day is cloudy and almost every cloud type can be found. Cirrus clouds have a substantial greenhouse warming effect that somewhat offsets the cooling caused by marine stratiform clouds, so they play an important counterbalancing role in global warming. Yet cirrus clouds remain mysterious, somewhat unknown, and highly unpredictable (e.g., how oriented the ice crystals are, how many small crystals there are, and how the ice crystals get nucleated at all). Deep convective clouds over tropical land behave differently than ocean clouds sampled at ACRF’s tropical sites. They have a different diurnal cycle and different dynamical structures. Precipitating clouds have been ignored by ACRF until now for want of instrumentation to study them; yet precipitation is merely the end of the life cycle of an ordinary cloud, and ACRF needs to examine the full life cycle of clouds in order to fully understand them.

The original fixed sites serve as anchor points for climate models because they are located in key climate locales with fairly stable climates. The fixed-site breakout group recognized the importance of maintaining the operation of the current sites. However, they also recognized that there was a need not only for additional climatically stable sites to improve the representation of key atmospheric processes in climate models and related models, but also for sites in regions of rapidly changing climate that would provide tremendous insight into regionally important processes that are significantly affected by climate change.

During the first two breakout sessions, a list of 11 locales was generated. These locales were the Amazon rainforest, Azores Islands, Boreal, Mountainous Terrain, Greenland, Mexico City, Middle Latitude Storm Tracks in the Southern Ocean, Northern Biome Transition Zone, Sahel, Sonora Desert, and South Asia. An advocate of each locale wrote up its scientific rationale for presentation and discussion for a third breakout session. The writeups, which include brief remarks on contributions toward improving climate models, potential collaborations, and logistical issues, are included in Appendix A.

After each locale presentation, the breakout group discussed each locale to identify any issues not considered. Because the fixed-site breakout group was only a subset of the workshop attendees, it was decided that all 11 locale writeups (included in Appendix A) should be presented to all workshop participants. At the conclusion of the workshop, the final writeups were distributed to all participants to vote for their top five locales. The top five recommended locales that emerged from this process are as follows:

- **Azores**

  Low clouds over the subtropical oceans are a major source of uncertainty in predictions of climate change (IPCC 2007). The Azores Islands are ideally situated to study these cloud systems in all their variety, and in addition, they receive air from the Arctic, from North America, and from Europe at different seasons, allowing excellent studies of aerosol impact on marine clouds. Although there have been several field deployments to study subtropical marine cloud systems, progress in parameterizing these clouds in climate models has remained elusive. Long-term observational data will allow the statistical characterization necessary to determine the respective impacts of large-scale meteorology and aerosols upon the cloud coverage, liquid water content, and radiative properties. These statistics will be invaluable for the evaluation and development of process models and climate models.

- **Greenland**

  Greenland, the world's second largest ice sheet, is starting to melt, and the melting appears to be accelerating. Long-term measurements would provide insights into changes in cloud properties, surface reflectivity, and the atmospheric radiation budget that may result from melting and shrinking of the ice sheet. The measurements will also lead to improvement in the understanding of the role of clouds in the ice ablation process, which is currently not well understood. The measurements would support studies that investigate the possibility that a cloud feedback mechanism in the Greenland ablation region could slow or accelerate the rise of global sea-level.

- **South Asia**

  The Indian southwest monsoon covers an area about one-seventh of the Earth’s surface. Intraseasonal variability of this monsoon is not well simulated in climate models. The high concentration of aerosols over the Ganges valley, together with direct impacts on the clouds and radiation feedbacks in this region, gives us a unique opportunity to generate data sets that would be useful both in understanding the processes at work and in predicting the changes that could take place in the monsoon system. Processes, including low shallow convective clouds, deep convective clouds, and rapid changes in land use from urbanization on regional scales are distinguishing characteristics of this area. A site located here has the potential for catalyzing regional interest in climate research, modeling and measurement activities, and events that impact close to a billion people.

- **Amazon Rainforest**

  The Amazon rainforest experiences tropical deep convective clouds, which are important for driving large-scale circulation of the atmosphere and exert a large control on the radiation budget. Climate models have great difficulty in simulating deep convective clouds and their radiative effects. The ACRF has recognized this as a serious problem and invested heavily in observations of ocean convection. However, the deep convection over land behaves differently than over the ocean. With the exception of the 2006 mobile facility campaign to Niger, the ACRF has not had the ability to observe deep convection over land. An Amazon rainforest site would provide an unprecedented opportunity to study a large, perennially cloudy climatic region for which there is little in situ data.

- **Middle Latitude Storm Tracks in the Southern Ocean**

  Long-term measurements of cloud, aerosol, radiative, and thermodynamic properties in the oceanic storm tracks can potentially add significantly to increasing our understanding of the relationship between large-scale dynamics and cloud properties and feedback. Deploying a long-term site to a location in the middle latitude oceanic storm tracks will allow scientists to address climate processes that cannot be addressed anywhere else on Earth. These measurements have the potential to facilitate quantifiable improvements in climate model predictions. One example is the role of migratory cyclones in transporting sensible heat between the tropics and the polar regions. The Southern Ocean between 45 and 65 South latitude is an ideal place to study mid-latitude storms for a variety of reasons, including the almost continual presence of storms, the great variety of cloud types, and the relatively pristine character of the clouds.

3. Mobile Facilities Report

The current fixed and mobile ACRF sites provide unique capabilities for sampling detailed properties of clouds, aerosols, and radiation for climate studies. A concern with these sites, however, is their relatively small number compared to the number of climatically important regions that need to be studied in order to improve climate models. Increasing the number of sampled climatic regions would enhance significantly the availability of the data for groups improving global climate models or developing surface and atmospheric property retrievals based on satellite data. The mobile facility breakout group endorsed two new mobile facilities which, if carefully managed along with the original mobile facility, would allow all climatically significant regions to be sampled. The breakout group proposes a stretch goal of accomplishing these advancements within a decade.

The first ACRF mobile facility has been a great success during its first three years of existence. The ACRF has received many scientific proposals of high quality to deploy it in a variety of distinct climatic regimes. It was deployed in 2005 to the Pt. Reyes National Seashore in northern California to study marine stratocumulus. Subsequent deployments were made to Niamey, Niger, in 2006 to study radiative forcing by desert dust and monsoon clouds, and to the Black Forest, Germany, in 2007 to study convective precipitation over hilly topography. Upcoming deployments are planned to China in 2008 to study aerosol indirect effect and to the Azores in 2009 to study subtropical marine clouds.

Scientific demands on the first mobile facility have shown two clear limitations. First, a single mobile facility is not sufficient to meet the demands of the scientific community. Second, the first mobile facility is particularly suited for land environments and full deployment of all associated instrumentation; however, it is not well-suited to partial deployment in cramped environments. For example, in 2006 the ACRF reviewed a proposal to deploy the first mobile facility on a Swedish icebreaker during the International Polar Year for a transit across the Arctic Ocean to study ocean surface, cloud and radiation interactions. The proposal was not chosen, in part, because deployment on the icebreaker was too risky. Configuration of the instruments within the existing containers and the large size of those containers precluded a seamless deployment within the confines of an icebreaker. For deployments on a ship, a new type of mobile facility is necessary—one that is more modular and configurable.

Targeting development of a second mobile facility for deployment on a ship is compelling for two reasons. First, the polar environment is proving to be sensitive to anthropogenic greenhouse gas radiative forcing (IPCC 2007; Chapin Science 2005), and thus we can anticipate future high-quality proposals to study polar regions from ships. The polar environment is exposed to regional forcings, such as boreal and tundra fires, Arctic haze and ozone produced by emissions from high-latitude industrial activity, and, in the future, shipping in the Northwest Passage. These forcings are amplified by ice, snow albedo, and biogeochemical feedbacks. These feedbacks can dramatically alter surface energy balances, cloud properties, water vapor content, and trace gas fluxes. The observed melting of the Greenland ice sheet, advance of snow melt date, albedo decrease due to expansion of shrubs into the tundra, permafrost degradation, destabilization of methane hydrates, and increased severity of boreal forest fires underscores the urgency to quantify these mechanisms. These feedbacks could cause large changes in cloud properties, surface albedo, and the atmospheric radiation budget, pushing the Arctic into a new climatic regime. Measurements of the radiation balance of the polar environment, together with the processes that affect it, should be a high priority for the ACRF. A critical window of opportunity is emerging because of expected large changes in the polar environment in the near future. Synergies with other federal and international agency efforts in the region will be compelling as we grapple with the consequences of polar climate change.

Another compelling reason to develop a second mobile facility targeted for ships is that, in order to dramatically increase the range of possible deployments, ACRF mobile facilities must be compact and highly mobile. A ship platform will demand that each element of the first mobile facility be redesigned to reduce its footprint. The overall design target for the second mobile facility is to reduce the first mobile facility of five 20-foot sea containers to perhaps one or two smaller sea containers with a collection of individually packaged instruments that can be distributed independently across a ship.

Using lessons learned from compressing the first mobile facility into the more modular and compact second mobile facility, a third mobile facility will be developed with the same functionality as the second but with modularization at the instrument level and with no increase in footprint and power requirements relative to the second mobile facility. Future proposed deployment configurations are anticipated to be quite varied, so an optimal design for the third mobile facility would consist of completely stand-alone instrument configurations that are interoperable within a variety of containers. Campaigns in the Arctic Ocean will require deployment on a ship platform, a task suitable for the second mobile facility. Those on the Greenland Plateau and tundra will require highly mobile, self-contained, rugged sets of instruments and enclosures with little operator access in a configuration dictated by the environment. We envision use of the third mobile facility for deployments such as these.

The premiums for space and mobility in the second and third mobile facilities will demand utilizing technologically innovative instruments with smaller physical footprints and smaller power requirements. For example, to improve spatial characterization of the environs, scanning instruments will be required. Current scanning instruments are larger than their vertically pointing counterparts, with higher power requirements. The latest technological innovations will be necessary to make them viable for deployment in cramped quarters.

Interoperability of different instruments and similar instruments with different capabilities, in compact enclosures built for a variety of climatic regions is the important evolutionary step for the second and third mobile facilities. These two mobile facilities, together with the first, would increase dramatically the reach of the ACRF to remote locations and allow the ACRF to deploy rapidly if science investigations demand it. For example, to deploy to tundra locations, e.g., Bonanza Creek (LTER), Ivotuk (AmeriFlux, NSF), Caribou Poker Creek (NEON) and Donnelly Flats (UCI), which have good infrastructure and well-established logistics, any of the three mobile facilities would be appropriate. Deployments on ship platforms, such as U.S. Coast Guard ships and icebreakers, would require the second or third mobile facility. For Greenland Plateau locations with no logistical support, small, mobile, low power instruments within small rugged containers will be necessary, entailing use of the third mobile facility.

Emphasis on interoperable instruments within configurable enclosures suitable for different climatic regions will enable tradeoffs between deployment of larger size, higher power, more accurate instruments and smaller, lower power instruments with sufficient capabilities to meet scientific demands.

3.1 Requirements for the ACRF Mobile Facilities

Over the past three years, compelling proposals have requested deployment of the mobile facility to harsh marine, polar, and high-altitude environments. Operating in these environments puts special demands on the facility. For instance, when operating in a marine environment, space is limited and other factors, such as corrosion from sea spray and effects on instruments from ship motions, must be addressed. In remote environments, such as the polar tundra, mountains, and the Greenland Plateau, access to power may be limited, and it may be expensive to monitor the facility on a daily basis.

3.1.1 Operation in the Marine Arctic and Other Harsh Environments

The first mobile facility is not well suited to operating in a marine environment. Although it is mobile, it occupies multiple large shipping containers that are not conducive to deployment on a ship where space is limited or in a remote location where transportation is not readily available. More advanced mobile facilities are needed that are suitable for operation in these environments. Such facilities would be modular and compact, enabling deployment in a variety of locations and on a variety of platforms.

A scenario suitable for driving the requirements of a second mobile facility is deployment on a ship in the Arctic Ocean. Such a deployment requires careful attention to the size of the system. There may not be space for the standard (20-foot by 8-foot) shipping containers used for the first mobile facility. At most, there may be room for one container of smaller dimensions. More likely, instruments and the data system would have to be dispersed throughout the ship in available space to minimize impact of the ship structure on the measurements. This set of physical constraints argues for a modular and flexible facility, one that is not tied to a particular container or set of containers.

The marine arctic environment also imposes environmental conditions that pose challenges, including extreme cold, freezing precipitation, and corrosive salty air. Packaging of instruments and the facility infrastructure (power, data systems, and communications) requires particular attention to these environmental issues. A system capable of operating in the marine polar environment would be capable of handling most other environments, such as tropical and mid-latitude marine environments and remote high-altitude locations.

3.1.2 Flexible Configurations to Meet Diverse Science Requirements

The modular designs of the second and third mobile facilities make them more easily deployable in a variety of locations and provide flexibility for meeting science goals of specific campaigns. Not every campaign requires the full set of instruments. Some may only need radiation measurements while others may only need cloud property measurements. Still other deployments may require a few of the ACRF instruments plus the power and data system infrastructure to host guest instruments. Modular, compact facilities would meet these diverse deployment requirements.

The second and third mobile facilities would consist of modular containers of various sizes. Some of these containers would be designed for specific instruments while others would be designed to support a range of instruments. With this flexibility, pieces of the system could be assembled in different combinations for deployments of different scales. In this way, a single system could support a single deployment or multiple deployments. With three mobile facilities, it may be possible to support more than three simultaneous deployments.

The mobile facility should support a broad range of instruments including standard ACRF instruments, instruments developed within ACRF, and instruments from other BER programs and other agencies. The standard suite of instruments currently available at ACRF fixed sites and the first mobile facility should be available to additional mobile facilities. These include instruments to support measurements of clouds, aerosol, and radiation. An aerosol inlet should be built into one of the containers to accommodate in situ sampling of aerosol. Additional instruments that may be important for future science applications include scanning radars, scanning microwave radiometers, and scanning lidars. Small Unmanned Aircraft Systems (UASs) carrying basic meteorology or radiation measurements may also be important.

The mobile facility is part of the ACRF and, as such, may be used in conjunction with other field campaigns. Although the standard suite of ACRF instruments may meet many of the measurement requirements of such a campaign, participants are likely to bring additional instruments. Potential guest instruments could include measurements of aerosol, CO_2, or other chemical species, either near the surface or throughout the atmospheric column. The mobile facility should be designed to easily integrate such guest instruments into the facility.

3.1.3 Miniature, Low-Cost, Autonomous Instruments

The constraints in harsh and remote environments may put space and power constraints on instruments. Demands to deploy multiple mobile facilities simultaneously will implicitly constrain the costs of the individual instruments within each facility. These combined constraints point to a need for the development of miniaturized, low-cost, low-power versions of some instruments. Such instruments would be deployable in tight quarters and remote locations, including on aircraft, towers, trains, etc., and open up future possibilities for deployment on commercial ships and commercial aircraft. This would ultimately allow a considerable extension of ACRF’s reach.

Deploying multiple instruments in remote locations raises another issue: the difficulties associated with maintaining these instruments. In designing these systems, it will be critical to minimize the manual intervention necessary to keep them operating because it may be impractical to station skilled technical staff with the instrumentation on a full-time basis. This argues for developing instruments and facilities that are capable of running autonomously for extended periods.

3.1.4 Modular Processing Algorithms for Modular Instruments

Development and support of modular processing algorithms for data collected by mobile facility instruments must be a high priority. Every deployment site for ACRF mobile facilities will present its own unique challenges for collecting high quality data. We anticipate that special processing of different instrument data will be required from one deployment to the next. The ACRF must have mechanisms in place to support adaptation of instrument processing algorithms as necessary. For example, the dust encountered at Niamey, Niger, necessitated studies of the dust optical properties to maximize use of ACRF data for accurately estimating atmospheric dust loadings, composition, and radiative effects.

3.2 Characterizing the Environment of the Mobile Facility

An ACRF site samples a relatively small spatial scale. Hemispheric viewing instruments respond to a spatial scale of about 10 km while fixed, vertically pointing instruments sample only a narrow column above the site. To better connect to models, which average over grid boxes, it is crucial to characterize the 3-D spatial distribution of geophysical parameters near the mobile facility. Spatial sampling is important for characterizing spatial inhomogeneities and for determining whether the statistical sampling at a site is representative of a region. There are several ways to do this spatial sampling: aircraft observations, scanning instruments, auxiliary facilities, and satellites. ACRF investigators frequently use satellite observations for augmenting observations at fixed and mobile sites. However, temporal resolution or the accuracy of parameters derived from satellite may not be adequate. One of the other three means of determining spatial variability must often be used.

3.2.1 Aircraft

Aircraft in situ or remote sensing observations provide spatial context for a site. These observations also can provide validation data for retrievals from ACRF's (and other) ground-based remote sensors. Aircraft operations tend to be expensive, so they are typically deployed for only short periods (weeks) as part of intensive field campaigns.

For mobile facility deployments, small UASs would provide a means of obtaining simple measurements (e.g., temperature and humidity) on a more routine basis in the environs of a site. Although operating small UASs is currently problematic in the United States due to Federal Aviation Administration (FAA) regulations, their use may be feasible in remote locations.

3.2.2 Scanning Instruments

Although aircraft provide extremely useful observations, their expense limits collection of statistically meaningful measurements in the environs of a site. Scanning remote sensors are a potential alternative to aircraft for characterizing the 3-D distribution of atmospheric particles. Although scanning instruments have not been widely used in climate research (with the exception of precipitation radars), scanning cloud radars, lidars, and radiometers do exist. Active scanning instruments tend to be expensive but, they protentially can provide extremely valuable information on the 3-D distributions of hydrometeors, aerosols, water vapor, wind fields, and temperature that would provide important context for a set of point measurements. For example, spatial variability in water vapor and wind could provide important information about convection in the region around a site that could then be linked to cloud properties observed at the site.

The second and third mobile facilities should include scanning instruments, notably scanning cloud radar, if the deployment platform infrastructure permits.

3.2.3 Arrays of Instruments Deployed in the Environs of a Site

A third option for characterizing spatial variability is deployment of one or more auxiliary sites. Typically, these sites are not equipped with the full set of instruments found at the primary facility. In some cases, an array of sites may be deployed to estimate the distribution and regional average of a specific geophysical parameter, which was the primary motivation for the SGP Extended Facilities. In other cases, such as for the ACRF mobile facility deployment in Niamey, Niger, in 2006, there was one small auxiliary site. Part of the motivation for this single auxiliary site was to estimate the impact of the primary site's proximity to significant sources of anthropogenic aerosol.

The diverse set of instrument enclosures developed for the second and third mobile facilities will facilitate deployment instrument arrays in the environs of a primary site.

3.3 Rapid and Delayed Deployment Paradigms

With the current ACRF mobile facility, there is little flexibility in the deployment paradigm. Two additional mobile facilities together with the current one, would enable deployments on short, intermediate, and long-time scales, as scientific needs and instrument development permit.

3.3.1 Rapid Deployment of the Third Mobile Facility

Scientific studies of the aerosol, cloud and radiation components of severe weather events (e.g., droughts, regional fires, etc.), regions undergoing rapid change (e.g., melting sea ice in the Arctic Ocean) and natural or man-made disasters with significant impacts on the atmosphere (e.g., the Kuwaiti oil fires) would be greatly facilitated by rapid deployment capability for at least one mobile facility. The enhanced portability of the third mobile facility would make it ideal for short-term deployments, where speed of deployment and lower cost are particularly important factors. Currently, it is impossible to consider short-term deployments because the first mobile facility is fully occupied by long-term (six months to a year) deployments that are planned two years in advance. A highly modular and compact mobile facility is much better for short-fused applications of high scientific value. ACRF proposal mechanisms would need to be generalized to support a rapid deployment paradigm.

3.3.2 Delayed Deployment of the Mobile Facilities and Instrument Development/Acquisition

On the other extreme, maximizing the value of a set of mobile facility measurements might require deployment of an instrument that is currently under development and thus not part of the mobile facility infrastructure. One example of such an instrument is the UAS. The UAS measurements in the environs of an isolated mobile facility site would be invaluable, such as in studies of the marine boundary layer. A strong proposal that clearly requires acquisition of a new instrument is currently not fundable because of the short timeline for mobile facility requests. As a result, such a proposal is lost to the ACRF, and the ACRF, in turn, loses a strong motivational factor for specific instrument development and/or acquisition.

Approval of community-wide competitive proposals with delayed deployment because of instrument development and/or acquisition issues is an extremely strong motivator for synergisms between the proposal teams, instrument developers, and the ACRF. The ACRF should develop structures necessary to support instrument development and acquisition based on compelling scientific proposals. With the ability to field any one of three mobile facilities, the ACRF will be able to accommodate such delayed-deployment proposals.

3.4 Other Mobile Facility Issues

3.4.1 Instrument Development Within ACRF

The ACRF does not currently have an instrument development program. The primary mechanism for supporting instrument development is DOE's Small Business Innovative Research (SBIR) process, but this is slow with no guarantee of success for specific instruments. To support future science proposals for mobile facility deployments, some of which will require specialized instruments and others which will require hardened instruments suitable for long-term semi-automated deployment, the ACRF will need an additional mechanism to support instrument development. Typically, such instruments exist in prototype form and will have been laboratory tested or perhaps demonstrated in the field, but are not "ready for prime time." The ACRF will need a proposal mechanism to support such advances in technical readiness.

Once developed, a hardened instrument would need testing. In some cases, it may make sense to test the instrument at a fixed site where infrastructure support is substantial. In other cases, testing at a fixed site may be impossible. For example, testing instruments on a small UAS would be impossible at the SGP site under current FAA regulations. As another example, testing of sea-surface temperature instruments will be possible only in marine environments. Thus, ACRF will need an end-to-end program to move instruments from the laboratory to the field, including testing.

3.4.2 Link Between Mobile Facilities and the Aerial Vehicles Program

At present a single proposal may request both the mobile facility and support from the ACRF Aerial Vehicles Program (AVP) for aircraft measurements. Given the need to characterize the environment around a mobile facility site and the likely synergy between ground and airborne measurements, it would be desirable to develop explicit links between the two program components. These links could take the form of a dedicated UAS for the mobile facility or a dedicated portion of the AVP resources for mobile facility support.

3.4.3 The ACRF Proposal Cycle

Currently, there is a two-year lead time for proposing the use of the mobile facility. For complex deployments, this long lead time is necessary to work out all logistical issues associated with a deployment. However, to support rapid deployments to study extreme events such as volcanic eruptions, or urgent opportunities of particular scientific interest, providing the option to propose on a much shorter time scale would be desirable. With three mobile facilities, there is much greater flexibility to support rapid deployment of one of the facilities.

Compelling scientific proposals might benefit from acquisition or development of a particular instrument for the deployment. Mechanisms must be in place to re-compete accepted proposals if the instrument acquisition and/or development associated with them falls to far behind schedule.

3.4.4 Other DOE BER Programs and Other Federal and International Agencies

Although collaborations already occur within ACRF (e.g., in campaigns such as the Cloud and Land Surface Interaction Campaign [CLASIC] and the Convective Orographic Precipitation Study [COPS]), it would be useful to develop a structure for joint proposals with other programs to formalize this process. Collaboration could then be more readily coordinated between ACRF and programs focusing on other components of the climate problem, such as aerosols (e.g., Atmospheric Science Program) or the carbon cycle (e.g., Ameriflux).

Although some deployments may involve hosting instruments from other agencies, other deployments may involve putting the mobile facility on platforms supported by other agencies. For example, the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF) and U.S. Coast Guard ships currently host instruments from a variety of sources. From the ACRF perspective, how might the principal investigator of a proposal obtain use of both the mobile facility and space on a research ship? Structures that facilitate the coordination of this dual-agency process would be useful.

4. Aerial Vehicles Report

By far, the largest number of measurements of the Earth's climate system is either surface- or satellite-based. ACRF's Aerial Vehicle Program (AVP) is designed to partially compensate for the deficiencies of both surface and satellite measurements and to fill in the gaps that they leave. AVP measurements help calibrate and validate ACRF's surface measurements. They can also help validate satellite measurements of use to ACRF and show how to interpolate to times between satellite overpasses. Finally, AVP measurements can be of direct assistance to process studies, for example studies of how ice forms in cirrus clouds.

All of these AVP functions have direct application to validating and improving climate models. AVP provides the all-important vertical and horizontal sampling that can help make the point measurements of ACRF surface sites meaningful to climate modelers, who calculate only area and volume averages and thus must know how ACRF point measurements "scale up."

The AVP operates on a yearly budget that is far less than aircraft programs in other agencies. However, by being flexible and economical, it has been able to support about one field campaign per year, often with multiple aircraft. Because of budget constraints, the AVP is doing far less than desirable. The ACRF has five sites, but the AVP can mount a campaign at only one site per year. The AVP is trying to implement a new paradigm to conduct both field campaigns and long series of routine flights each year, but its budget is so limited that this is proving difficult. The AVP also has a goal to foster instrument development and testing, but its budget does not allow for meaningful effort in this area or even an effort to repair and upgrade the instruments it owns.

A considerable expansion of the AVP is needed to adequately support the ACRF by: (1) allowing multiple campaigns each year and visiting each ACRF site at least every two years, or as climate research science prorities mandate; (2) allowing it to move into the area of small unmanned aircraft, which requires a considerable initial investment; (3) supporting instrument development and testing, moving instruments rapidly from laboratory prototypes to full operation; and (4) providing facilities for calibrating and repairing aircraft instruments, similar to what ACRF provides for its surface instruments.

4.1 Scientific Priorities of Aerial Vehicles Program

The central focus of ACRF consists of long-term measurements of the atmospheric column from various locations that can be used to diagnose the physical properties that ultimately determine the upward and downward streams of solar and infrared radiant energy. The diagnostic algorithms linking ACRF measurements with conceptual understanding of physical processes are central to full utilization of ACRF measurements streams for their intended purposes. It is first necessary to better understand physical processes before their representation in climate models can be improved. The AVP has three fundamental roles to play in this regard.

First, the algorithms used to convert ACRF ground-based measurements to physical properties remain a matter of intense scientific research. It is this diagnostic connection between measurements and physical properties that hinders improved understanding. The existing data sets for validating those algorithms and for discovering and tuning new algorithms are only minimally appropriate from a statistical standpoint, and the AVP is dedicated to collecting much improved data sets for this purpose.

Second, the ground-based measurements of ACRF are specific to a single location, although many atmospheric properties are highly variable in space. Climate models only deal with two-dimensional (2-D) and 3-D averages, so AVP plays a crucial role in “scaling up” ground-based point measurements to such averages.

Third, some key climate processes occur over regions of the Earth that are inaccessible and even hostile to ground-based instrument suites, such as the Arctic Ocean sea-ice regime. Airborne measurements allow ACRF to explore questions concerning such regions and processes.

Airborne measurements of key quantities related to clouds and aerosols collected over a long period of time are essential for ACRF to meet its core scientific objectives. One approach that is unique to AVP is a specific dedication to long-term measurements allowing for the creation of these statistically significant data sets. The focus areas of these long-term airborne measurements are cloud properties and processes, aerosol properties and processes, and surface characterization.

4.1.1 Cloud Properties and Processes

Efforts to understand cloud properties and processes require the joint use of satellite, ground-based and aircraft measurements. The AVP can supply critical aircraft to augment ACRF’s state-of-the-art ground-based measurements. Aerial measurements can validate ACRF’s derived estimates of cloud properties by supplying detailed, in situ data on liquid and ice water content, particle size distributions, and ice crystal habits at different vertical levels in the atmosphere. For example, large regions of stratus clouds over the oceans are highly important in the global energy balance. Currently, these features are not well understood because of a lack of sufficient in situ measurements to characterize the microphysics and processes governing this large, important cloud information. Over the Arctic, the strong change in water vapor availability due to the disappearance of sea ice can result in changes in cloud quantity and type over much of the high northern latitudes. Specific questions include the roles of both visible and sub-visible cirrus clouds on tropospheric radiative properties and their potential role in transport of water vapor to the stratosphere. The ACRF is well positioned to expand on current surface measurements in these regions with informative, detailed measurements of cloud properties using both manned and unmanned vehicles in a routine manner.

4.1.2 Aerosols

Uncertainties surrounding the full effects of aerosols rank among the largest uncertainties in climate models. Detailed measurements providing the vertical distributions of aerosols can clarify the effects of aerosols in the climate system, in particular the size distribution and composition of the aerosol particles, their optical properties, and their interactions with clouds. Accurate measurements of aerosol composition above the surface can only be obtained from in situ observations provided by either manned or unmanned vehicles.

Systematic aerial measurements can help reduce the uncertainty of the role of aerosols in modulating the instantaneous radiation streams in the atmosphere and, when coupled with long-term ACRF measurements and modeling efforts that link aerosol properties with large-scale meteorological transport and processes, can potentially improve model predictions of future climate response to greenhouse gases.

Understanding the interactions between aerosols and clouds is critical to understanding the response of the Earth to increases in anthropogenic influences on the atmosphere. As aerosols increase, the location and radiative properties of clouds may change and possibly affect the amount and location of precipitation. The AVP has the opportunity to help identify the differences between clouds forming in clean, background air and clouds forming in anthropogenically influenced air. Previous campaign measurements have shown that the influence of aerosols on clouds is difficult to isolate from other influences without sustained measurements under a variety of conditions.

4.1.3 Surface Characterization

High-resolution remote sensing of the surface from airborne vehicles is needed to characterize the surface in the region of the fixed and mobile sites, in terms of the surface reflectance characteristics, topography, snow cover, soil moisture, vegetation characteristics, and other physical characteristics (e.g., melt ponds on snow and ice). Such detailed characterizations are needed at the fixed sites on a regular basis to characterize seasonal changes and temporal changes.

4.1.4 Carbon Cycle

The U.S. national energy usage likely will be affected by agreements to control CO_2 budgets. The balance between sources and sinks of CO_2 along with relevant biogeochemical influences are not well understood. Determining the net effect of energy use will depend on detailed measurements of carbon dioxide. Enhanced measurements of CO_2 source and sink surface flux measurements using low and slower flying aerial platforms can improve our understanding of these processes, which can contribute to determining the net carbon dioxide budgets. The AVP could supply critical measurements to improve this understanding. DOE is an active member of the U.S. Climate Change Science Program’s (CCSP’s) Carbon Cycle Science Interagency Working Group to address carbon issues. Increased efforts by DOE to measure profiles of CO_2 would complement the National Aeronautics and Space Administration’s (NASA’s) satellite programs and NOAA’s surface measurements. Expanded missions to measure vertical profiles simultaneously at various fixed-site locations for understanding the CO_2 budget would coincide with many of the missions proposed above to address the uncertainties in aerosols and clouds. Adding this capability would be important for meeting the BER Climate Change Research Long-Term Measure.

4.1.5 Improved Understanding of the Water Cycle

Many of DOE’s goals involve improved understanding of the water cycle: water vapor, clouds, and precipitation. Detailed vertical measurements of water in the atmosphere, including water vapor, cloud distributions, and interactions with aerosols are critical to understanding the full pathways of water. Understanding the water cycle is particularly critical in regions such as the upper troposphere /lower stratosphere in the tropics. Measurements of water isotopes in precipitation and water vapor also can provide valuable information about the water cycle: the isotopic composition of the precipitation and low-level water vapor can provide information about the origin of the water feeding the convective systems and about the amount of re-evaporation of the falling precipitation. Measurements of the isotopic composition of water vapor in the vicinity of the tropopause can provide information about the physical processes through which water is transported from the upper troposphere to the lower stratosphere.

Understanding the role of convection and aerosols in drought situations is important for water-use planning. Cirrus, latent heat, and precipitation are critical aspects of the water cycle that are not well understood. These three factors strongly influence climate through their significant impact on local and global energy balance. DOE should build strong communications with those who are currently working on water cycle issues to assure that the aerial measurements are in support of mutual goals.

4.1.6 Radiative Heating Profiles

Understanding the vertical profile of radiative heating profiles is key to improving climate modeling. Experiments such as V. Ramanathan’s recent UAV experiment in March 2006 conducted over the Maldive Islands in the tropical Indian Ocean were able to use three vertically stacked UAVs to measure upwelling and downwelling radiative fluxes above, within, and below clouds. Additional resources for the AVP would provide the opportunity to address complex science issues relating to radiative heating.

4.1.7 Northern Hemisphere Cryospheric Changes

Recent changes in Arctic sea ice and Greenland’s ice sheets and glaciers, which hinges on the adoption of a new ACRF site, are not well understood. Part of the uncertainty is in the role of the atmosphere and radiative influences on these changes. The AVP can play a critical role in taking measurements in these remote areas, possibly using unmanned aircraft, to augment current efforts underway nationally to understand these important phenomena. Because of the important role of sea ice in the Northern Hemisphere’s surface albedo, DOE has a unique opportunity to observe and understand the influence of Arctic surface changes on the Earth’s radiative budget and the water cycle. Small UASs will be essential to provide spatial context for studying the melting.

4.2 Infrastructure Priorities for Aerial Vehicles Program

4.2.1 Strengthened Infrastructure Capabilities

The AVP has developed and purchased instruments and leased platforms that are appropriate and economically prudent for each scientific mission. This approach has allowed for maximum flexibility in addressing scientific questions. To achieve the expanded goals of the BER, the AVP infrastructure will need to be expanded. Given the priorities in scientific goals, a variety of platforms will likely be needed. A primary goal of the AVP is to take routine measurements to support the ground-based ACRF measurements. Past strategies have focused on process studies for short periods, which do not allow for estimates of the full annual cycle.. These efforts have shown that sustained measurements are needed to provide a climatological relevance for the process studies. Expanding capabilities to allow for routine measurements for the full 12 months of each year will allow a more complete statistical estimate of radiative effects through all four seasons, making the measurements more important in understanding the Earth’s climate system.

4.2.2 Instrument Development

To address new scientific questions, new instrumentation and instrument development capabilities are needed to support BER’s science goals. Continuing advancements in unmanned aircraft are demonstrating that these vehicles have unique capabilities important to scientific goals of ARM and other Climate Change Research Division science programs. The AVP's unmanned aircraft capabilities should include the ability to go to dangerous or remote locations that manned aircraft are incapable of reaching and can allow for distributed and coordinated sampling strategies. To take advantage of new aircraft capabilities, instruments need to be developed to be lighter, of lower power consumption, and capable of autonomous operation. BER should collaborate with other agencies, especially NASA, in the development of new instrumentation for aerial vehicles.

The ACRF does not currently own aerial vehicles, but does own several instruments that can be installed on various platforms. However, the existing instrumentation will not meet all of the needs for scientific issues outlined as priorities for BER. The ACRF should support funding appropriate for development and maintenance of new instrumentation. Some of the instruments owned by ACRF are not currently working. Careful decisions need to be made to determine which instruments should be kept readily available for service. Modularity, the ability to easily incorporate instrumentation into a variety of platforms should be encouraged, but not required with new instrumentation. Higher time resolution of measurements is needed from manned aircraft because horizontal heterogeneity in clouds can not be measured fast enough with current capabilities. Although there will be oversight from the science panel, some instrumentation should be managed by principal investigators and need not be included in the AVP suite of instrumentation.

4.2.3 Capabilities to Respond to Sudden Events

The AVP should expand its capabilities to be able to respond to sudden, unique events. These capabilities could allow it to respond to situations such as forest fires or rapid changes in Arctic sea ice. These capabilities will be useful in conjunction with ACRF's improved mobile facilities capabilities. Core instrumentation, appropriate personnel, and available resources need to be flexible to respond rapidly to these situations.

4.3 UAS Expansion in AVP

The high-priority science questions that fall within DOE's purview demand a variety of platforms. Vertical profiling, cirrus measurements and coordinated boundary-layer measurements each require specialized platforms to address critical science questions. Both manned and unmanned vehicles (UAS) likely will play an important role in future DOE aerial missions. UASs provide the capabilities of flying for long periods (eventually days) and at low altitudes, often in situations unsuitable for pilots. As a result, UASs can address previously untenable science questions. Some smaller UASs have become affordable and may be considered for purchase by ACRF. However, because of the developmental and integration challenges associated with UAS, manned aircraft will continue to be an important aspect of ACRF's AVP.

Continuing advancements in unmanned aircraft demonstrate that they have unique capabilities important present and future scientific goals of BER. Unmanned aircraft capabilities include going to dangerous or remote locations that manned aircraft are incapable of reaching and allowing for distributed and coordinated sampling strategies. These strategies could, for instance, include remaining for a long period of time (days to weeks) at locations that are not accessible to manned aircraft. The AVP should be on the forefront of this trend in Earth science measurement.

The complexity of aircraft missions includes integration of instrumentation, flight planning, and coordination with the FAA. Institutional knowledge is critical to success of aircraft missions. If the scope or level of support for the AVP increases, the support for personnel infrastructure needs to increase commensurately.

DOE has a strong history of collaborating with aerial missions when the goals of the agencies are complementary, which has been beneficial. The current structure, where other agencies can propose to make use of BER's aerial capabilities, should continue. The recent Memorandum of Understanding (MOU) between NASA, NOAA, and DOE should facilitate collaborative activities using unmanned aircraft systems.

5. Data Products Report

The data products breakout group focused on strengthening the bridge between ACRF data and climate models. Because climate forecasts cannot improve without a strong bridge between data and models, it would be a mistake to focus all ACRF infrastructure efforts on the observation side of the bridge without paving the way to the other side. Although this bridge-building effort could take as many forms as there are users of the ARM Archive, three major efforts are identified here as crucial investments that the ACRF could make in order to significantly advance the ability of climate modelers to derive scientific results from its data.

5.1 New User Capabilities

Although three new user capabilities are proposed, there is one overarching idea: taking the ACRF data set to the next level for a major acceleration of data use by the modeling community to improve climate forecasts.

5.1.1 Integrated Data Products at Model Scales

Although most users of ACRF data are studying climate, their needs diverge and can be roughly categorized in terms of whether they are using one of four primary classes of tools: a general circulation model (GCM), a single-column model (SCM), a cloud-resolving model (CRM), or a method of data analysis. Whereas data analysis (especially time series trend analysis) may require data to remain at native instrument temporal and spatial resolution, models require data aggregated at the model temporal and spatial resolution—which ranges from the long time steps and low resolution of a GCM or SCM to the short time steps and high resolution of a CRM. The definition of "model-ready" data sets will be different for each group. Furthermore, data sets used to evaluate GCM performance must be as long as possible, whereas those for CRMs may need to be as dense as possible. These needs span the extremes of the ACRF data collection—indeed, the extremes of the data collection are designed to fulfill these disparate needs. Significant additional work is required to bring the data collection into the structure required by user communities. In addition to all of the work required to produce high-quality, collated data sets for conditional sampling (described below), the members of each modeling community also must aggregate the multiple data streams to their specific spatiotemporal resolution. Bringing this work under the ACRF purview would relieve the onus on individual modelers and data users to repeat this process themselves. Although individual data groups may have slightly different data requirements, major functionality will be enabled with modular open-source code for producing aggregated multiple-variable data products to meet a wider range of specific needs within each user group (GCM, SCM, and

CRM). To meet this need, the ACRF would provide detailed documentation of the decision trees used to create the multiple-variable data products, as well as the software run on specified input files. Individual users could choose to select these "off-the-shelf" products or alternatively choose to download the input files and source code to make slight changes for their own products—without significant duplication of effort.

5.1.2 Tool Kit of Instrument Simulators for Synthetic Observations From Model Output

Model evaluation typically proceeds by comparing collected data points to important predicted variables such as fractional cloudiness, but the instruments most often used to derive such data points do not directly measure many important model variables. They measure related atmospheric properties, such as atmospheric reflectivity, which is related to fractional cloudiness. Therefore, another way to evaluate model performance is to calculate, for example, atmospheric radar reflectivity predicted by the model and compare that to the instrument measurement. Thus, instead of comparing instruments to models with model-native variables, the comparison is carried out with instrument-native variables. This process is most useful when the conversion from instrument to model variables requires many assumptions, whereas the conversion from model variables to instrument variables does not.

The software used to derive instrument response from a modeled variable field often is referred to as an "instrument simulator." Since that term has been used for many related things, it is helpful to specify that the objective in this case is to allow modelers to effectively produce synthetic observations. Such instrument simulators are widely used to compare model results to the most ubiquitous ACRF instrument—the radar. However, simulators for other instruments are gaining wider use, including those for lidar and microwave radiometer instruments. The goal of this project would be to gather or create simulators and optimize their application to specific ACRF instruments, accounting for factors such as unique instrument calibration. There are two steps to developing a simulator: conversion of model variables to instrument variables (e.g., conversion of hydrometeor fields into atmospheric reflectivity at a particular wavelength) and replication of instrument characteristics (e.g., detection limits and measurement path).

A major thrust of this effort would be to provide modular open-source code, documentation, and online examples for both liquid and ice clouds. Open-source code would permit both “off-the-shelf” usability and maximum flexibility for specific user requirements with minimum duplication of effort.

If such a suite of simulators were in place, it is anticipated that the ARM Program also could play a crucial role in identifying the laboratory data required to advance simulator performance (e.g., response of lidar instruments to the wide range of atmospheric ice habits).

5.1.3 Conditional Sampling of Archived Data for Models and Analysis

The ARM Archive is now entering a "new era" where the long-term data streams that are its hallmark contribution to climate science have just begun to reach maturity. At 15 years and counting, some of these data streams now are growing long enough to conduct meaningful time series analysis, many aspects of which require more than a few years of data collection. Also, the ACRF is providing multiple simultaneous data streams required to address complex outstanding problems in climate science, such as radiative-cloud feedbacks. However, extensive additional work is required to bring scientific inquiry to bear on analysis of multiple data streams. This work includes detailed treatments of data quality, uncertainty, lack of physical and temporal collocation and timing, physical consistency, and gaps.

Currently, the extensive additional work to make the ACRF raw data "usable" is being performed on a limited, piecemeal basis at multiple institutions by a variety of individuals and groups. Bringing such work under the ACRF umbrella would increase the usability of the collected data. It would reduce extensive duplication of efforts, avoid gross errors that are common under such conditions, and free researchers to devote their time to the subsequent data analysis that will improve our understanding of climate and our ability to predict it. Conducting such work at the ACRF also would provide all users with the ability to conduct conditional data extraction and online statistics, representing a major step forward in functionality. Namely, data users would be able to request data products under specific meteorological conditions, avoiding the need to download entire data streams in order to view a small subset. Also, users could easily request a wide range of basic single and joint statistical measures without downloading any data at all.

5.2 Additional Data Product Needs

These capabilities address specific user needs for data processing and therefore will enable higher-level scientific inquiry. The underlying philosophy includes several key elements: open-source code, transparency of data processing and review, detailed documentation, and incremental development with tight user feedback loops. The purpose of the open source is to facilitate community refinement and extension of software tools. User feedback will be collected and adjustments made as required. These capabilities also rely upon the following common methodological components:

- **Error Characterization.** Provide detailed characterization of data quality and uncertainty to determinate adequacy for purpose, comprising (1) overall quality rating of low, medium, high, or missing; (2) identification of sources of uncertainty, with independent quality flags for each source; and (3) values of both bias and precision when data are of sufficient quality. One possibility is to emulate the highly successful uncertainty characterization methods developed by the European CloudNet, which were derived for direct comparison of observational products to GCM model output.
- **Long-Term Data Characterization.** Provide long-term data overview based on probability statistics for single data streams, as well as joint probability distributions using loose time alignment tolerances. Provide user access to download the statistical summaries and provide basic online statistical tools for customized user analysis.
- **On-Demand Visualization and Statistical Tools.** Develop web interfaces for user-specified graphical and statistical analysis, making ACRF data analysis internet-accessible. One possibility is to emulate the Columbia University International Research Institute tools. Interactive online data analysis also will create an educational outreach tool for the next generation of climate researchers.

5.3 End-to-End Examples for Model-Observation Comparisons

Techniques for bridging the gap between models and observations will be demonstrated using examples of all capabilities outlined above. Recipes for modeler use will be generated for each modeling user group (GCM, SCM, and CRM). Each example will include integrated data products, data characterization and statistics, synthetic observations, conditional sampling, and model output. Examples will be supported by detailed documentation, processing source codes, and input data. Steps will be traceable from original archive data files. These examples will be designed to facilitate accelerated use of archive data by a wide range of modelers. Examples will include grid comparison and statistical comparison with other major data sets (e.g., the Global Energy and Water Cycle Experiment, the National Centers for Environmental Prediction, and the 20th Century Reanalysis).

Appendix A:

Fixed Site Locale Priorities

A.1 Azores Locale

Low clouds over the subtropical oceans are poorly represented in our current climate models and represent a major source of uncertainty in predictions of climate change (IPCC 2007). The Azores (39°N, 28°W) in the remote northeast Atlantic is characterized by extensive marine low cloud types including the important transition region from stratocumulus to trade-cumulus, and experiences a wide range of aerosol characteristics. Additionally, the cloud structures associated with winter storms can be observed in this region.

Scientific Rationale:

1. The response of marine subtropical low clouds to a doubling of CO_2 constitutes the main source of uncertainty (in the sense of inter-model differences) in climate change cloud feedbacks (Bony and Dufresne, 2005; Webb et al. 2006; Wyant et al. 2006).
2. Marine low clouds are sensitive to anthropogenic aerosols (Haywood and Boucher, 2000; Lohmann and Feichter, 2005). The indirect effect of aerosols currently is estimated to represent a significant masking of the greenhouse warming (IPCC 2007).
3. Climate models experience great difficulties in simulating marine low clouds and their sensitivity to changing environmental conditions. These models are strongly sensitive to parameterizations of macrophysical (e.g., convection and entrainment) and microphysical (e.g., precipitation formation) processes and their interplay. These errors contribute to systematic errors in the simulation of the mean climate state and the upper oceanic heat budget (Ma et al. 1996; Gordon et al. 2000).

Several field deployments have been conducted to study subtropical marine cloud systems; however, progress in parameterizing these clouds in climate models has remained elusive. The reason for this is that boundary layer parameterizations in GCMs are insufficient to capture thin boundary layer clouds that are controlled by subgridscale processes such as entrainment. Successful parameterization of these clouds will require a detailed understanding of the complex interactions of turbulence, cloud microphysics, 3-D radiative transfer, and aerosols, and a reference large-eddy simulation (LES) model that is capable of simulating these interactions (with collaboration from turbulence experts from Los Alamos National Laboratory [LANL] and Lawrence Livemore National Laboratory [LLNL]). The combination of intensive LES model development and the development of new ways of parameterizing the cloudy boundary with a long-term observational record supplemented by intensive field campaigns will provide critical mass to the effort and spur the needed progress to improve climate model treatment of these clouds Long time series such as those generated by the permanent ACRF sites allow the statistical characterization necessary to determine the respective impacts of large-scale meteorology and aerosols upon the coverage, liquid water content and cloud radiative properties. These statistics will be invaluable for the evaluation and development of process models and climate models.

Logistical Considerations:

The Azores (Portugal) is a European Union (EU) member, and the community has operated field programs there. The infrastructure is good, but consideration is needed for reducing the potential island effects associated with island sites and ensuring that the facility can function in the corrosive marine environment. Site selection is critical to avoid island effects; an upwind location is needed.

Synergisms:

For several years, the long-range transport of chemical and aerosol species have been monitored by the International Atmospheric Chemistry Observatory-North Atlantic Regional Experiment (PICO-NARE) free-tropospheric site. Periodic incursions of aerosol from the polluted continent and from desert dust provide important contrasts to the more typically pristine maritime aerosol characteristics. The Atlantic Stratocumulus Transition Experiment (ASTEX) was based in the Azores in 1992 and provides important case study data on the transition between stratocumulus and trade cumulus in this region. The ACRF mobile facility is scheduled to go to this site in spring 2009. There is also a NASA Aeronet site in the Azores.

A.2 Sonora Desert Locale

The Southwest U.S. desert area provides an ideal area for studying clear-sky conditions and testing infrared radiation transfer models. IPCC projections indicate a future drying in the Sonoran desert region. However, as evidenced by recent drought conditions in the Southwest U.S., decadal-scale climate changes can arise quite abruptly. Therefore, it is critical to correctly predict future climate change in this region, especially characteristics of precipitation and drought. Regional challenges regarding water availability and quality make this a compelling region to consider for a fixed site.

Scientific Rationale:

1. The Southwest monsoon is an important component in global weather and climate and involves multi-scale land-cloud radiation climate interactions. Clear-sky conditions are frequent and common to many other similar regions worldwide.
2. Varying conditions include
   - high temperatures, low humidity, and clear-sky
   - warm, humid, and cloudy during monsoon
   - windy, dusty, aerosols
   - many days with cirrus.
3. GCMs don’t simulate monsoons very well.
4. There is a strong dust component.
5. A homogeneous environment occurs.

Logistical Considerations:

a. There are many options for placement, and logistical support is anticipated to be strong. Also, it is a U.S.-based locale.

Synergisms:

Synergism considerations include regional mesonets (e.g., AZMET, MesoWest); strong national and international monsoon programs; and mountain top “sky islands.”

A.3 Boreal Locale

Scientific Rationale:

Boreal (Taiga) ecosystems are subject to rapid changes in albedo, the extent of permafrost, and vegetation composition—all of which have uncertain effects on the atmospheric radiation budget, cloud formation and associated feedback mechanisms. Due to apparent changes in climate and discontinuous permafrost, several U.S. agencies have characterized the taiga-tundra interface as critical zone observatories. The limitation of current climate models is derived chiefly from the inability to describe the transformations and interactions of water vapor (e.g., latent heat profiles and spatiotemporal precipitation budgets) and aerosols on the atmospheric radiation budget. A fixed facility is necessary to characterize the controls on the atmospheric radiation budget in this rapidly changing system. Following is the rationale for a fixed site in the Boreal:

1. There are widespread changes in albedo from black carbon (from fires) and from vegetation changes and scrub encroachment (Epstein et al. 1998).
2. There are episodic emissions of black carbon and aerosols to the atmosphere from forest fires.
3. Increasing cloud cover and changes in optic depth have already been identified. (Chapin et al. 2005).
4. Changes in—and feedback mechanisms on—the biogeochemical cycles (i.e., CO_2, CH_4, and H_2O) directly affect the radiative capacity of the atmosphere as a result of permafrost degradation (Lawrence and Slater 2005). The effect of increased CO_2 emissions with temperature on the boundary layer radiation budgets is not known. Including these processes will enhance the constraining of global data assimilation for temperature reconstruction (ECMWF reanalysis).
5. Factors controlling water vapor transformations and transport (e.g., albedo, changes in permafrost and hydrology) directly affect cloud formation. Establishing a boreal ACRF site anchors an ecohydrologic transect with its Barrow site, spanning tundra and taiga.

Logistical Considerations:

1. Remote locations, but well established logistics, are currently in place (e.g., Bonanza Creek [LTER], Caribou Poker Creek [NEON], and Donnelly Flats [UCI]).
2. An established plant canopy provides a new challenge to ACRF facilities, but effective experimental designs and site infrastructure have been the focus of many other plant-atmosphere research studies (i.e., AmeriFlux, NASA-LBA, and Fluxnet-Canada).
3. Extreme weather and its associated effects on instrumentation can be severe, but ACRF already has experience with these extremes at the site in Barrow, Alaska.

Synergisms:

DOE-AmeriFlux has expertise in establishing remote sites. The National Science Foundation-National Ecological Observatory Netork (NSF-NEON,) will be establishing supporting sites along this ecohydrologic megatransect in conjunction with the Consortium of Universities for Advancement of Hydrologic Scienc (CUAHSI), Water and Enviromental Research Systems (WATERS) and Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER). NOAA-GDM is already an established partner with the ACRF Barrow site.

A.4 Middle Latitude Storm Tracks and the Southern Ocean Locale

Long-term measurement of cloud, aerosol, radiative, and thermodynamic properties in the oceanic storm tracks can potentially add significantly to increasing our understanding of the relationship between large-scale dynamics and cloud properties and feedback (i.e., core ACRF goals). Deploying a long-term ACRF site to a location in the middle latitude oceanic storm tracks will allow ACRF to address climate processes that cannot be addressed anywhere else on earth.

Scientific Rationale:

1. Oceanic middle latitude storms are a fundamental component of the Earth's climate system. Migratory cyclones play a key role in transporting sensible heat between the tropics and the polar regions, yet the cloud radiative forcing and associated feedback processes are poorly represented in climate models (Williams and Tselioudis, 2007).
2. The Southern Ocean, one of the cloudiest locations on Earth, experiences very high boundary layer cloud coverage and the full range of cloud systems associated with frequent (several per week) middle latitude cyclones (i.e., frontal clouds ranging from cirrus to altostratus to deep precipitating cloud systems [Mace et al. 2007]).
3. The Southern Ocean is likely the most pristine environment on Earth providing a reference for aerosol-cloud-precipitation interactions in more polluted environments.
4. The middle latitude storm tracks will experience significant change due to a warming climate as the Hadley cells expand, the polar regions warm, and the heat imbalance between the tropics and the poles evolve. In addition to changing the radiative balance of the climate system, these changes also will have feedbacks on middle latitude precipitation distributions potentially impacting human populations directly and through impacts on agriculture in both the northern and southern hemisphere.
5. The storm tracks experience significant continual evolution of the dynamic forcing and associated cloud structures on timescales ranging from several days to seasons and perhaps interannual. This sensitivity to continually changing dynamics allows for intensive study of a wide spectrum of meteorological regimes and the cloudiness and precipitation associated with those regimes. This will ensure that the long-term data set created by ACRF can be used to address cloud and radiation processes that are experienced over a significant fraction of the Earth's surface.
6. No long-term record of cloud and radiation observations exists from the oceanic midlatitude storm tracks. Such a data set is crucial to ensure that predictive models ranging from numerical weather prediction (NWP) to climate models are able to accurately represent the relationships between the dynamical regimes that occur there and the associated cloud and precipitation systems.
7. The meteorology, clouds, and precipitation of storms in the North Atlantic are a key forcing component of the downward branch of the thermohaline circulation and is, therefore, a key component of European and global climate.
8. Understanding how the radiative and fresh water flux balances of the North Atlantic will change is an important climate issue.

Therefore, long-term measurements in the middle latitude storm tracks and the Southern Ocean, in particular, have the potential to facilitate quantifiable improvements in climate model predictions.

Logistical Considerations:

Islands with existing infrastructure exist in the North Pacific storm track (e.g., Adak Island and Aleutians) and in the Southern Ocean (e.g., St Georges Island and Antarctic Peninsula). However, a fixed ACRF site in the storm tracks will be remote, and the logistical issues with maintaining an ACRF site in such a remote and hostile environment will be significant.

A.5 Amazon Locale

Scientific Rationale:

Tropical deep convective clouds are important for driving the large-scale circulation of the atmosphere and exert a large control on the radiation budget. Climate models have great difficulty in simulating deep convective clouds and their radiative effects. The ACRF has invested heavily in observations of ocean convection; however, with the exception of the 2006 Niamey Niger campaign, it has failed to observe deep convection over land.

Deep convection over land behaves differently than over ocean. For example, a strong diurnal cycle to deep convection with shallow convection clouds occurs early in the morning that grows into deeper clouds and precipitates by early evening. The role of downdraft driven cold pools in triggering new convection is more important over land and could be studied by horizontal scanning or sampling. The triggering of new convection by cold pools is not represented in current climate models, which, in part, explains the difficulties of the models in simulating convective precipitation over tropical continents. This diurnal cycle of convective clouds is simulated extremely poorly by climate models, and the models, in general, do a poor job of simulating the deep convection in the Amazon.

A study of convective clouds in the Amazon would have other benefits. Cumulus clouds have 3-D structures that cause significant 3-D radiative transfer effects. These effects could be studied by a scanning cloud and precipitation radar. Also, the large amount of biomass burning in the Amazon provides an opportunity to study the influence of biomass burning aerosol on convective clouds and the precipitation that results.

Logistical Considerations:

Significant field campaigns have been conducted in the Amazon that would facilitate a new fixed site. However, some difficult issues exist with regard to the interaction of radiation with the plant canopy field. In particular it may not be practical to locate instruments above the canopy (e.g., a cloud radar) that may be required.

Synergisms:

The precipitation characteristics of deep convection in the Amazon motivated the Large-Baseline Array (LBA) experiment that was conducted by the NASA satellite program for the Tropical Rainfall Measurement Mission. In LBA, a high quality precipitation radar provided ‘ground-truth’ for the satellite retrievals. With the new NASA Global Precipitation Measurement (GPM) program going forward, a natural synergy exists between precipitation measurements and cloud and radiation measurements. Also, the interactions of the land-surface with the atmosphere are very strong. Thus, carbon-cycle feedbacks between the land-surface and the atmosphere could be studied at an Amazon site.

A.6 Complex Terrain Locale

Scientific Rationale:

This recommendation is for the development of an ACRF site in the western United States that would facilitate the development of climate models and their ability to provide useful information for water management in this locale.

1. Complex terrain represents 30% of the Earth’s land surface. For the most part, these regions are more poorly observed than flat terrain. However, the average precipitation over complex terrain is generally higher, and the climate processes leading to the formation and patterns in these regions are less understood than over flatter terrain.
2. Over the past 15 years, the ACRF SGP site has provided data for a mid-latitude homogeneous site. This database has led to many model improvements. However, they have not contributed to the better modeling of clouds, precipitation and land-atmosphere interactions in complex terrain. Data are needed to improve the ability of regional and future global climate models operating at 50 km and higher resolution to resolve complex terrain effects.
3. The warming from greenhouse gases is expected to be largest at higher latitudes and high altitudes. Already, warmer temperatures have caused shifts in runoff regimes. These temperature changes are altering the rain/snow mix at different seasons and altitudes. The future consequences of continued warming on clouds, precipitation, and runoff cannot be resolved by present climate models.
4. The latent heating effects of cloud and precipitation formation and melt processes have significant effects on the latent heat fluxes that are not well quantified. Furthermore, the interaction of radiation fluxes and latent heating fluxes and their combined effects on local and large-scale circulations in mountainous regions are not well known and need to be investigated.
5. The radiative properties of the air crossing the mountains are not well known. However, it can be postulated that the radiative properties of the upper atmosphere associated with lower wave numbers can be determined from radiometers placed at high elevation. A long-term data set for a station on the western Cordillera would enable a better characterization of the radiative properties of air masses entering the North American continent.

Societal Benefits:

1. In the western United States, there is continuing concern about prolonged drought conditions leading to water shortages and dry fire-prone conditions in California and elsewhere. Mountains play a major role in these processes because they store water over the winter months and release it in the spring and summer providing a source for economic activities for the full annual cycle.

Logistical Considerations:

1. The accessibility to mountain sites in the western Cordillera is generally good in the summer and fall months. Winter may pose a challenge in some areas, but it is a surmountable challenge.

2. The complex terrain effects may become even more complex due to the presence of other processes in the mountains (e.g., aerosol effects), which could be a benefit (for studying both factors at the site) or an unnecessary complication (if the focus is on terrain effects alone). A full definition of the scope of the site's data applications would be needed before a final site selection was made.

Synergisms:

1. This mountain site would be an anchor for the many observational networks in the mountains. Networks operated by the National Oceanic and Atmospheric Administration (NOAA), U.S. Geological Survey (USGS), and the States collect a variety of data sets, but they are often in the valleys and lower altitudes leading to a non-representative depiction of mountain regions.
2. NASA data sets in mountain regions generally cannot be verified with reliable data sets. Collaborative efforts between NASA data projects and this new ACRF site would benefit both DOE and NASA.
3. The Coordinated Energy and water cycle Observations Project (CEOP), managed by GEWEX, maintains archives of 35 reference sites (including all the ACRF sites) as well as satellite data and model output from 11 NWP models to support global research. An ACRF site in the mountains on the west coast of the United States would supplement the range of environments in the CEOP database.
4. Through this iniative, several opportunities exist for collaboration with NEON (Walnut Gulch Basin and Teakettle and Sagehorn watersheds), LTER (H. A. Andrews site), and WATERS.

A.7 A Northern Biome Transition Zone Locale

This recommendation is for the development of an ACRF site on a transition zone in the latitude band between 50°N and 65°N where there are boundaries between major vegetation classes that are expected to migrate northward as a result of climate change.

Scientific Rationale:

1. Based on the latest IPCC report, climate change signals in the Northern Hemisphere are likely to be largest in the northern latitudes. These changes are expected to result in significant shifts in the boundaries of ecozones over time. Currently, the factors accounting for these shifts and the changes in radiation and surface flux budgets are unknown. Observations from one of these zones in transition would be helpful in understanding the transition processes and how they interact to produce the overall effect on the atmosphere and on the surface.
2. The relative importance of changes in radiation due to changing atmospheric CO_2 compared to changes in aerosol loadings and other factors needs to be understood for ecozones that are in danger of transitioning to some other form.
3. The consequences of transitions in biomass will affect large areas of land over Siberia and northern Canada. The findings from such a location will be useful in helping climate models adjust to accommodate these larger-scale changes.

Logistical Considerations:

1. If a site in Asia is chosen, accessing the site may be difficult. Therefore, it would be useful to have a year of sampling from a mobile facility before placing a permanent site in an Asian (Siberian) location.
2. It is fairly likely that a site in this locale may be relatively difficult to access in some of its uninhabited lands.

Synergisms:

1. If a site in Siberia is chosen it could be a central component of the Northern Eurasia Earth System Partnership Initiative (NEESPI).
2. A northern ecozone transition site could be adopted as part of the International Polar Year (if implemented soon) and could be part of the Coordinated Energy and water cycle Observation Project.

A.8 South Asian Locale

The Indian southwest monsoon covers an area about one-seventh of the Earth's surface. The high concentration of aerosols over the Ganges valley, together with direct impacts on the clouds and radiation feedbacks in this region, provides a unique opportunity to generate data sets that would be useful both in understanding the processes at work and in predicting the changes that could take place in the monsoon system. Processes, including low shallow convective clouds, deep convective clouds, deep convection and rapid changes in land use from urbanization on regional scales are distinguishing characteristics of this area. A site located here has the potential for catalyzing regional interest in climate research, modeling and measurement activities, and events that impact close to a billion people.

Scientific Rationale:

1. Intraseasonal variability of the south Asian monsoon is not well-simulated in the Community Climate System Model (CCSM3). Analyses of the intraseasonal variability in the model demonstrated that the convection schemes generate intraseasonal variability of much lower amplitude than the observed variance (Meehl et al. 2006; Gadgil and Sani 1998).
2. Atmospheric brown clouds enhance lower atmospheric solar heating by about 50% (Ramanathan et al. 2007).
3. Aerosols reduce the incoming solar radiation by about 20% and could have significant regional impacts (Dey and Tripathi, 2007).
4. Land use changes and aerosols together change the planetary albedo over the sub-continent. This could lead to an abrupt shift in the monsoon circulation and to a regime of low rainfall (Zickfeld et al. 2005; Mitchell and Johns, 1997).
5. The upper Ganges valley has some of the highest persistently observed aerosol optical depths (AODs) in the multi-angle imaging spectrometer (MISR) global data set (Di Girolamo et al. 2004).
6. Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) indicate that over most of southern and eastern Asia, the aerosol load is concentrated in the lower few kilometers (peaks at 3 km) and should be measurable by an ACRF-type facility (lidars etc.).

7. Climatologically, a high-pressure ridge over the wintertime Indo-Gangetic plain confines pollution to the planetary boundary layer (PBL).
8. Near-source impacts on cloud generation and hydrologic cycles are relatively unknown, though high concentrations of fine aerosols recently were shown to decrease precipitation in hilly areas during monsoon (Rosenfeld et al. 2007).
9. Deep convective activity is common during much of the summer months. The initial onset of monsoon over the southern tip of India is initiated by land-sea circulation then enhanced and driven by deep convective activity over the northern Indian plains.
10. Shallow convective clouds are common during monsoon and widespread with embedded deep convective regions.

Logistic Considerations:

1. The Ganges plain is relatively flat, and finding regions away from local sources and sampling of regional air mass would not be difficult. This work can be combined with an emerging activity under the Geosphere Biosphere Program (GBP), which is planning to deploy about 10 to 15 sites in the region with regular aerosol monitoring and meteorology. This work will complement the NSF-funded (Ramanathan et al. 2007) Maldives autonomous Unmanned Aerial vehicle Campaign (MAC). Features of the area are deep convective mixing and seasonally varying aerosol load (dust during pre-monsoon, sulfate aerosols during winter, and mixed black carbon-dust during post monsoon), deep convective clouds, and shallow boundary layer clouds.
2. Measurements from the Aerosol Robotic Network (AERONET) site in India, previous campaigns by Indian scientists, and the Indian Ocean Experiment (INDOEX) should help define the problem and locate the site.

Synergisms:

1. India’s rapid development, high dependence on coal and high interest in developing climate related science increase the suitability of this study. The work will place focus on one of the countries that the U.S. government and several international organizations are trying to involve in developing climate policy (i.e., carbon restrictions).
2. Infrastructure and logistics are not difficult to handle with cooperation and MOUs with the Indian Department of Science and Technology and Space Research organization. The Indo-U.S. science and technology forum is an official organization funded by the Indian and U.S. governments to facilitate cooperative research. DOE is a stakeholder in this organization.

A.9 Greenland Locale

Greenland is the world's second largest ice sheet and lies largely within the Arctic Circle. The ice sheet is starting to melt and is experiencing a net loss of 51 billion cubic meters of ice each year, which is raising sea level by 0.13 millimeters per year (Krabill et al. 2000; Abdalati and Steffen, 2001). The melting in Greenland appears to be accelerating, and the ice sheet has thinned by more than a meter on its southern and eastern edges since 1993. Warming trends have been observed in the Greenland paleoclimate record, but this past warming has progressed at a much slower rate. The most urgently needed development in climate modeling is the inclusion of interactive ice sheets, so that the rate of depletion of the continental glaciers can be assessed along with their contribution to sea level rise. Effective incorporation of interactive ice sheets in climate models requires adequate understanding and simulation of the surface energy balance over the ice sheets, particularly the impact of clouds.

Scientific Rationale:

1. Future sea level rise has enormous consequences for society, but just how much of Greenland will melt and how quickly is poorly understood. The possibility exists for rapid disintegration of the Greenland ice sheet and a consequent rapid rise in global sea-level. Evaluation of the likelihood and warning signs of such an event will require significant improvements in our understanding of the potential rate of dynamic change of this ice sheet. The U.S. Climate Change Science Program Strategic Plan (2003) contains Strategic Research Question 4.1 (and associated question 4.3), which asks “How sensitive was ice and sea level to rapid changes in climate especially during past warm climates?” Answering this question requires a thorough understanding of the current mechanics of the Greenland ice sheet, especially the relationship between melting rates and the radiation transfer characteristics of the atmospheric column.
2. Variations in the surface albedo and shortwave cloud forcing in the ice ablation region, which lies along the western edge of the ice sheet, significantly influence melt rates (Konrad and Box, 2003). The current understanding of the role of clouds in the ice ablation process appears to be “very low” using IPCC terminology. For example, current literature contains the first estimates of the seasonal cycle of cloud coverage in the ablation zone, which is thought to feature a spring minimum. No information about the macroscale or microscale structure of these clouds is available. A cloud feedback mechanism in the Greenland ablation region possibly could slow or accelerate global sea-level rise.
3. The details of mid-latitude storm tracks elude proper characterization in GCMs. Greenland lies along a critical mid-latitude storm track, and the relationship between this storm track and ice melt must be determined to ensure that sea-level rise is simulated accurately in GCMs. An ACRF site currently is not located in a mid-latitude storm track region.
4. Greenland’s terrain affords the possibility of studying a wide range of cloud microphysical processes. Above 2-km elevation, the ice sheet is in balance, on average, but has some regions of local thickening or thinning. Thinning predominates at lower elevations. Escarpments and other topographic features along the ice sheet may provide opportunities to study liquid, mixed-phase, and ice-phase clouds in a laboratory-like environment, while the 2-km plateau should be an excellent site to observe ice clouds at close range.

Logistical Considerations:

Serious logistical questions need to be addressed before ACRF should consider a fixed site in Greenland. The vast majority of Greenland's 60,000 residents live in coastal cities along the island's west coast. The east coast is mostly ice blocked and sparsely populated. Ice ablation is occurring along the west coast of Greenland, so there are cities in one area of interest. Nuuk, Greenland's largest city, lies on the west coast and has more than 14,000 residents. It has lots of cars, a few stoplights, three city buses, two large food stores, enormous apartments built by the Danish government, new subdivisions, and a very large and active port. However, this is not the general rule in Greenland.

Synergisms:

A small network of measurement sites exists in Greenland with records from many of these sites that exceed 15 years (GC-Net). These data have been analyzed significantly, but only sparse information exists on cloud cover and other key variables within the atmospheric column. The following excerpt is an example of the type of data and the level of analysis: "*Radiation exchanges at measurement sites in the ablation zone, at 70°N along the western slope of the ice sheet, where surface melting is responsible for the loss of up to 3.5 m of ice each summer, are much greater than at high elevation dry snow zones, owing to much lower surface albedo and higher air temperatures. At sites at or below the equilibrium line altitude, summer average absorbed shortwave radiation (100 W m-2) and its interannual variability (±50 W m-2) are a factor of 2 greater in magnitude than net longwave radiation, implying that shortwave fluxes are dominant in determining low elevation melt variability. Changes in albedo have a 20% larger effect on net shortwave radiation than effective cloud optical variation. Shortwave cloud radiative effects, calculated using hypothetical clear-sky values, reach maximum values of -160 W m-2 in the western ablation zone in summer and have up to 80 W m-2 interannual variability at low elevation sites, indicating that the variance in cloud forcing is large in the ablation region and significantly influences melt rates. Effective shortwave sky transmissivity has maximum values in spring, which confirms spring minimum cloudiness implied by downwelling longwave estimates.*"

In addition to the ice core drilling efforts of the paleoclimate community, new satellite analysis efforts are anticipated that would likely benefit from ACRF ground-based measurements.

A.10 Mexico City Locale

Scientific Rationale:

Since the inception of the ACRF, anthropogenic emissions, especially aerosols, have been increasingly recognized as a major influence on atmospheric radiation and cloud properties influencing their shortwave reflectivity and precipitation development, and that these influences are of global significance. For this reason it is essential that these influences be quantitatively understood so that they can be confidently represented in models. In fact, current assessments of uncertainties in radiative forcing identify aerosol influences, both direct and indirect through modification of cloud properties, to be the greatest uncertainty in radiative forcing of climate change.

The ACRF is well poised to make a major contribution the study of the climatic influences of anthropogenic aerosols and radiatively important trace gases, especially ozone and nitrogen dioxide. Specifically, establishing an ACRF site at a location that is commonly impacted by these anthropogenic atmospheric constituents would allow quantification of these radiative impacts and influences on cloud microphysical and radiative properties. An ACRF site located downwind of a major city, especially one that has not been subject to emission controls characteristic of developed countries, would intermittently experience the effect of the urban emissions on radiation and clouds and permit the mapping of the dependence of cloud and radiative properties on the loading of aerosols. Simultaneously and continuously measuring the optical and cloud nucleating properties of the aerosol at the surface would be essential, as well as conducting systematic aircraft measurements to map out the vertical structure.

Synergisms:

Mexico City is a candidate site for such a downwind urban ACRF locale focusing on the radiative and cloud influencing properties of anthropogenic emissions, especially aerosols. Previous work by the DOE

Atmospheric Science Program and other U.S. and Mexican agencies has identified Mexico City as a premier example of a large urban region "Megacity" whose emissions are locally dominant and contribute to the widespread anthropogenic aerosol. The site indicated in the map (Figure A.1) served as one of the surface sites in the 2006 Max Mex campaign conducted by the DOE Atmospheric Science Program and would be a suitable location for a central facility. Additionally, distributed sites could be established in the vicinity, with the advantage of highly variable terrain that would permit contrasting measurements from fixed sites that are frequently above the atmospheric boundary layer, thus allowing aerosol contrasts to be mapped out.

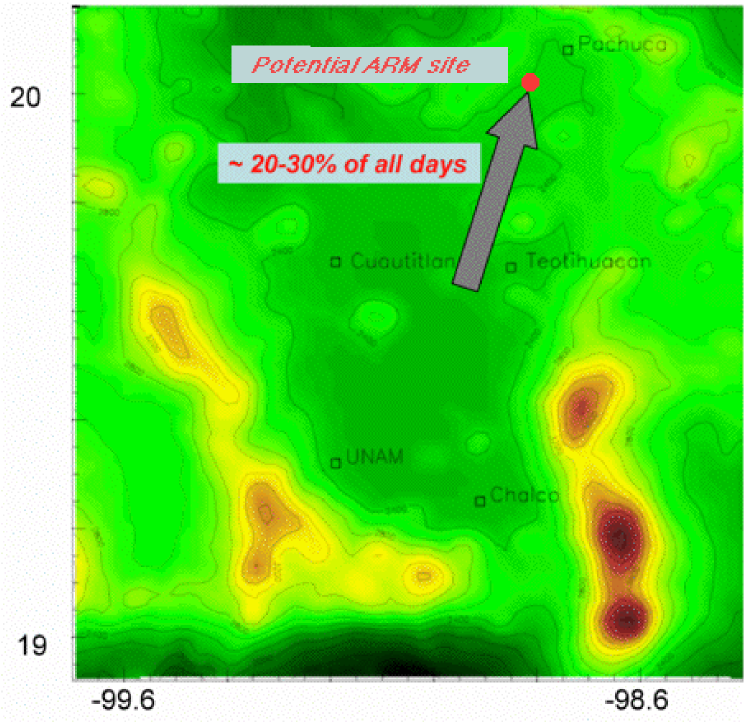

Figure A.1. Map showing location of potential site for ACRF central facility suitable for examining the radiative and cloud influences of aerosols emanating from Mexico City. Auxiliary measurement stations at elevated sites above the boundary layer would permit examination of contrasts due to aerosols.

A.11 Sahel Locale

Scientific Rationale:

A fixed site in the Sahel region of Africa would enable ACRF to study cloud and radiative transfer processes—inadequately represented in climate models—in a unique but globally important climate regime. Also, observations from a fixed ACRF site in the Sahel could potentially contribute to research with national and international interests, such as the variability of the African monsoon and implication on water security and tropical cyclogenesis with implications for improving the predictability of Atlantic hurricanes (e.g., frequency and intensity). The meteorological conditions experienced in the Sahel region include deep tropical convection during the rainy season (July-September), and episodes of mineral dust (from the Sahara) and biomass burning aerosols in the dry season.

Specific scientific issues that could be addressed by this site include:

1. Cloud and Radiation. Continuation of atmospheric divergence studies initiated under the AMF Niamey deployment (RADAGAST). The divergences of atmospheric radiation through deep convection and aerosol still poorly are understood and, as demonstrated during RADAGAST, a fix site in the Sahel (with high-resolution broadband multi-spectral passive radiation measurements at the top of the atmosphere from a geostationary satellite) could examine this problem effectively. A process particularly worthy of examination is cirrus anvils properties produced by the monsoon convection and their impact on atmospheric radiative transfer. Studies (Nesbitt et al. 2000) have suggested that the ice content of these clouds is significantly higher than those observed at TWP. Aerosol-cloud/precipitation interaction also can be extensively observed.
2. Precipitation Variability. Studies of global precipitation over the past 30 year+ have shown that the Sahel region has experienced among the largest regional precipitation deficit (Figure A.2). The variability and characteristics of precipitation over West Africa are regulated by an interplay among African Easterly waves (AEWs), mesoscale convective systems, and Saharan dust outbreaks. An ACRF fixed site with precipitation measurement capabilities (e.g., S band radar) could provide greater insight into this issue, particularly on the influence of dust and smoke on variability of the African monsoon.
3. Tropical Cyclogenesis: The AEWs which have lifetimes of 3 to 5 days, are not only important for rainfall over West Africa but also serve as precursors for Atlantic tropical cyclones. Each year approximately 80 to 100 AEWs emerge from the West African coast, with approximately 10% of these waves becoming named tropical storms. Despite the importance of these storm systems to rainfall over West Africa and Atlantic tropical cyclone activity, the understanding of their underlying attributes and how they evolve in space and time remain lacking. A coastal fixed site in the Sahel with precipitation measurement capabilities could help address the following questions:
    - What are rain characteristics over this region?
    - What is the intensity, type, duration, and microphysical characterization?
    - What are the precipitation systems in transition between land and ocean areas?
    - What are antecedent conditions (thermodynamic and dynamic) of the atmosphere associated with clouds and precipitating systems?
    - What are the links between Saharan dust outbreaks and precipitating systems over the region?

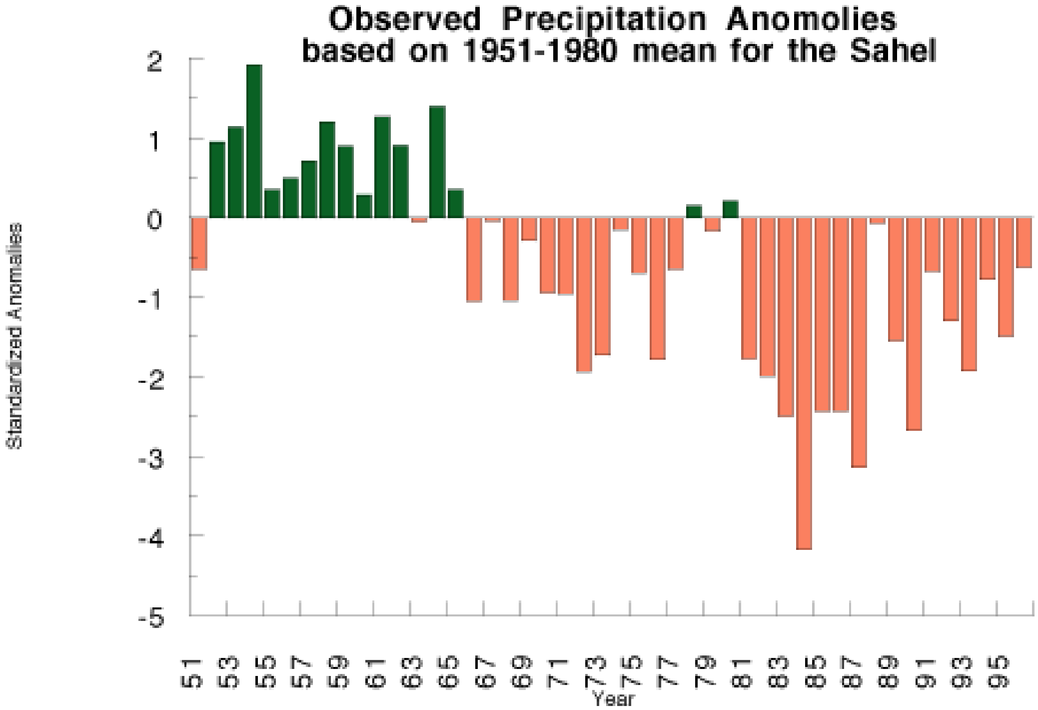

Figure A.2. Studies of global precipitation over the past 30 years for Sahel region

Synergisms:

A fixed ACRF site could leverage measurement during the Long Observing period of AMMA. AMMA is a multi-year, international project aimed at improving understanding of the West African Monsoon (WAM) and its influence on the physical, chemical and biological processes on a global and regional scale, and relating climate variability to societal issues and monitoring strategies. AMMA uses existing monitoring infrastructures (national services and ongoing measurement programs), but will directly and indirectly make enhancements to the quality and frequency of surface observations across West Africa: gauge networks, radars, radiosoundings, and soil properties. AMMA is being conducted across multiple spatial and temporal observing scales. The long-term observation period, which extends to 2010, could overlap with an ACRF fixed site. The regional coverage of AMMA is illustrated Figure A.3. The key AMMA sites include: coastal (Senegal), Benin, and Niamey. These locations represent the best opportunity for ACRF fixed sites because they have the most accurate and reliable observational infrastructure (which will be enhanced in AMMA) that is supported through local and international collaboration.

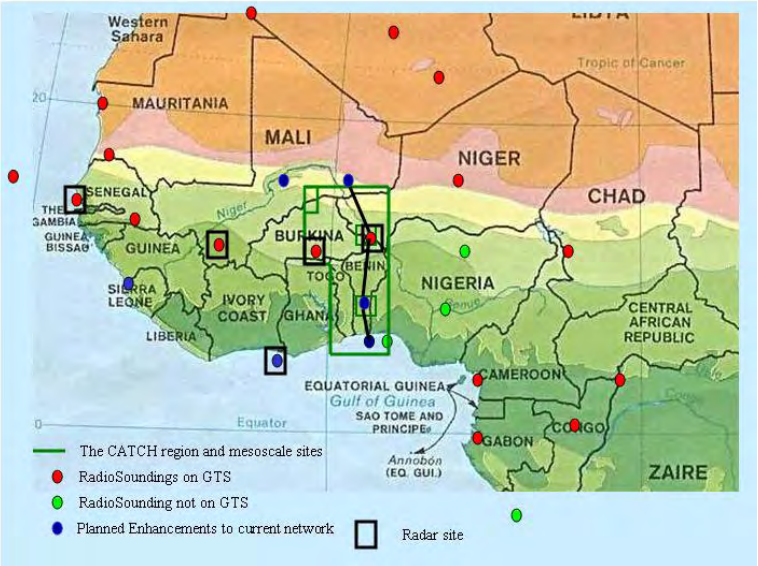

Figure A.3. Existing and planned surface observation networks in West Africa that will operate during the AMMA Special Observing Period (SOP) and Enhanced Observing Period/Long-term Observation Period (EOP/LOP) (Source: US-AMMA SSG, 2003).

Appendix B:

Other Locales of Joint Interest

Some AmeriFlux sites are suitable for ACRF instruments, where noted with ([1]) have the most complete range of biophysical and ecological data, other sites, ([2]) generally feature less complete instrumentation, ([3]) are joint AmeriFlux and NEON sites, and ([4]) NEON sites with extensive land-surface measurements. The table shows the length of data record for each site, the plant functional type, and the stand age and management of the sites.

Table B.1. Existing AmeriFlux Sites, and planned NEON sites

Site by Ecoregion	Lat/Long	Data Record Main Site	Vegetation Main Site	Stand age (for forests)	Cluster type
Northeast					
[1, 3]Howland Forest	45.20402, -68.74021	1996-	conifer forest, unmanaged (temperate-boreal transition)	140	harvest, age, N dep, Aeronet
Great Lakes					
[1]WLEF Tall tower	45.94588, -90.2723	1996-	mixed forest, unmanaged (northern temperate)		Anchors inversion studies
Central					
[1]Ozarks	38.74411, -92.20008	2004-	hardwood forest, unmanaged		
Northern Plains					
[1]Black Hills	44.1544, -103.6428	2001-	conifer forest, unmanaged	70	
Great Basin					
[1]Metolius	44.45243, -121.55717	2002-	conifer forest (semi-arid)	60	Age, fire, 1 end climate gradient
Pacific Coast					
[2]Yaquina Head, OR	44.67, -124.07	2006	Marine air		Point at Yaquina Lighthouse
[1]Marys River	:44.6464942, -123.5514830	2006	Conifer (mesic)	33	1 end climate gradient
Pacific Southwest					
[1]Tonzi Ranch	38.4316, -120.96598	2001-	oak savanna, grazed (Mediterranean)		
[1]Vaira Ranch	38.40667, -120.95073	2000-	grassland, managed		
Tundra					
[2]Atqasuk	70.4696111, -157.4089444	1999	tussock tundra		Vegetation transition gradient
[2]Ivotuk	68.4864722, -155.7503056	2004	tussock tundra and shrub		Vegetation transition gradient
[2]Barrow	71.32252, -156.62588	1998-	sedge-tussock tundra		Vegetation transition gradient

Appendix C:

ARM Climate Research Facility Workshop Participants

Mary Altalo
Ocean.US

Mary Barth
National Center for Atmospheric Research

Sandrine Bony
Laboratoire de Météorologie Dynamique

Mark Boslough
Sandia National Laboratories

Eugene Clothiaux
The Pennsylvania State University

Prof. Dr. Susanne Crewell
University of Cologne

Judith Curry
Georgia Institute of Technology

Manvendra Dubey
Los Alamos National Laboratory

Jae Edmonds
Pacific Northwest National Laboratory

Robert Ellingson
Florida State University

Ann Fridlind
NASA Goddard Institute for Space Studies

Steven Ghan
Pacific Northwest National Laboratory

Jean-Christophe Golaz
Department of Commerce/NOAA

Lianhong Gu
Oak Ridge National Laboratory

Anthony Janetos
Pacific Northwest National Laboratory

Everette Joseph
Howard University

Stephen Klein
Lawrence Livermore National Laboratory

Rao Kotamarthi
Argonne National Laboratory

Beverly Law
Oregon State University

Richard G. Lawford
International GEWEX Project Office

David Legler
U.S. CLIVAR Office

Henry W. Loescher
NEON Science Office

Gerald Mace
University of Utah

Dubey Manvendra
Los Alamos National Laboratory

Mark Miller
Rutgers University

Athanasios Nenes
Georgia Institute of Technology

Joyce Penner
University of Michigan

Michael Poellot
The University of North Dakota

Sethu Raman
North Carolina State University

William Riley
Lawrence Berkeley National Laboratory

Stephen Schwartz
Brookhaven National Laboratory

Chien Wang
Massachusetts Institute of Technology

Betsy Weatherhead
University of Colorado, Boulder

Warren Wiscombe
Brookhaven National Laboratory

Robert Wood
University of Washington

Sandra Yuter
North Carolina State University

Department of Energy

Kiran Alapaty
Anjuli Bamzai
Roger Dahlman
Wanda Ferrell
Rickey Petty
Ashley Williamson

Breakout Sessions

Fixed sites:

Robert Ellingson (Chair)
Doug Sisterson (Rapporteur)
Argonne National Laboratory

Mobile sites:

Eugene Clothiaux (Chair)
Jim Mather (Rapporteur)
Pacific Northwest National Laboratory

Aerial Measurements:

Elizabeth Weatherhead (Chair)
Beat Schmid (Rapporteur)
Pacific Northwest National Laboratory

Data Products:

Ann Fridlind (Chair)
Raymond McCord (Rapporteur)
Oak Ridge National Laboratory

Sylvia Edgerton (Rapporteur)
Pacific Northwest National Laboratory

Appendix D:

References

Abdalati, W, and K Steffen. 2001. “Greenland ice sheet melt extent: 1979-1999.” *Journal of Geophysical Research* 106:33,983 - 33,989.

AMMA. 2003. An International Research Project and Field Campaign. http://medias.obs-mip.fr/amma/.

Bony S, and J-L Dufresne. 2005. “Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models.” *Geophysical Research Letters* 32: L20806, doi: 10.1029/2005GL023851.

Chapin FS, M Sturm, MC Serreze, JP McFadden, JR Key, AH Lloyd, AD McGuire, TS Rupp, AH Lynch, JP Schimel, J Beringer, WL Chapman, HE Epstein, ES Euskirchen, LD Hinzman, G Jia, C-L Ping, KD Tape, CDC Thompson, DA Walker, and JM Welker. 2005. “Role of land-surface changes in Arctic Summer Warming.” *Science* 310: 657-660.

Dey, S, and SN Tripathi. 2007. “Estimation of aerosol optical properties and radiative effects in the Ganga basin, Northern India during the winter time.” *Journal of Geophysical Research* 112: D03203.

Di Girolamo, L, TC Bond, D Bramer, DJ Diner, F Fettinger, RA Kahn, JVMartonchik, MV Ramana, V Ramanathan, and PJ Rasch. 2004. “Analysis of Multiangle Imaging SpectroRadiometer (MISR) aerosol optical depths over greater India during winter 2001-2004.” *Geophysical Research Letters* 31: L23115, doi:10.1029/2004GL021273.

Epstein, BL, S D’Hondt, JG Quinn, J Zhang, and PE Hargraves.1998. "An effect of dissolved nutrient concentrations on alkenone-based temperature estimates." *Paleoceanography* 13(2): 122–126.

Gadgil, S, and S Sajani. 1998. “Monsoon precipitation in the AMIP runs.” *Climate Dynamics* 14: 659-689.

Gordon, CT, A Rosati, and R Gudger. 2000. “Tropical sensitivity of a coupled model to specified ISCCP low clouds.” *Journal of Climate* 13: 2239-2260 doi: 10.1175/1520-0442(2000)13.

Haywood, J, and O Boucher. 2000. “Estimates of the direct and indirect radiative forcing due to tropospheric aerosols; a review.” *Reviews of Geophysics* 38: 513-543.

IPCC. 2007. The Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC). http://www.ipcc.

Konrad, S, and J Box. 2003. “Radiation climatology of the Greenland ice sheet.” Arctic Climate System Study Final Conference. St. Petersburg, Russia.

Krabill, W, W Abdalati, E Frederick, , S Manizade, C Martin, J Sonntag, R Swift, R Thomas, W Wright, and J Yungel 2000. “ Greenland ice sheet: high-elevation balance and peripheral thinning.”*Science* 289: 428-430, doi: 10.1126/science.289.5478.428.

Lawrence, DM, and AG Slater. 2005. “A projection of severe near-surface permafrost degradation during the 21st century.” *Geophysical Research Letters* 32: L24401, doi:10.1029/2005GL025080.

Lohmann, U, and J Feichter. 2005. “Global indirect aerosol effects.” *Journal of Atmospheric Chemistry and Physics* 5: 715-737., ACP, 2005.

Ma, C-C, CR Mechoso, AW Roberson, and A Arakawa. 1996. “Peruvian stratus clouds and tropical pacific circulation: coupled ocean-atmosphere GCM study.” *Journal of Climate* 1635-1645, doi: 10.1175/1520-0442(1996)009.

Mace, GG, R Marchand, Q Zhang, and G Stephens. 2007. “Global hydrometeor occurrence as observed by CloudSat: Initial observations from summer 2006.” *Geophysical Research Letters* 34: L09808, doi:10.1029/2006GL029017.

Meehl, G, JM Arblaster, DM Lawrence, A Seth, EK Schneider, BP Kirtman, and D Min. 2006. “Monsoon regimes in the CCSM3.” *Journal of Climate* 19: 11.

Mitchell, JFB, and TC Johns. 1997. “On modification of global warming by sulfate aerosols.” *Journal of Climate*. 10: 245-267.

Nesbitt, SW, EJ Zipser, and DJ Cecil. 2000. "A census of precipitation features in the Tropics using TRMM: Radar, ice scattering, and lightning observations." *Journal of Climate* 1(13): 4087–4106.

Ramanathan, V, MV Ramana, G Roberts, D Kim, C Corrigan, C Chung, and D Winker. 2007. “Warming trends in Asia amplified by brown cloud solar absorption.” *Nature* 448: 575-578.

Rosenfeld, D, J Dai, X Yu, Z Yao, X Xu, X Yang, and C Du. 2007. “Inverse relations between amounts of air pollution and orographic precipitation.” *Science* 315: 1396-1398.

Schwartz, SE, et al. 1991. Identification, Recommendation and Justification of Potential Locales for ARM Sites.DOE/ER-O495T, U.S. Department of Energy, Washington, D.C.

Strategic Plan for the U.S. Climate Change Science Program. 2003. A report by the Climate Change Science Program and the Subcommittee on Global Change Research. http://www.climatescience.gov.

U.S. AMMA SSG. 2003. “A proposal for US participation in the African Monsoon Multidisciplinary Analysis (AMMA) project.” http://www.joss.ucar.edu/amma.

Webb, MJ, et al. 2006. “On the contribution of local feedback mechanisms to the range of climate sensitivity in two GCM ensembles.” *Climate Dynamics* in press.

Williams, KD, and G Tselioudis. 2007. “GCM intercomparison of global cloud regimes: Present-day evaluation and climate change response.” *Climate Dynamics* 29: 231-250, doi:10.1007/s00382-007-0232-2.

Wyant, et al. 2006. “A Comparison of low-latitude cloud properties and responses in AGCMs sorted into regimes using mid-tropospheric vertical velocity.” *Climate Dynamics*, in press.

Zickfeld, K, B Knopf, V Petoukhov, and HJ Schelnhuber. 2005. “Is the Indian summer monsoon stable against global change?” *Geophysical Research. Letters* 32: L15707, doi:10.1029/2005GL022771.