U.S. DEPARTMENT OF ENERGY | Office of Science

BIOLOGICAL AND ENVIRONMENTAL RESEARCH

Climate and Environmental Sciences Division

ATMOSPHERIC RADIATION MEASUREMENT CLIMATE RESEARCH FACILITY - ATMOSPHERIC SYSTEM RESEARCH HIGH-RESOLUTION MODELING WORKSHOP

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Executive Summary

The Atmospheric Radiation Measurement (ARM) Climate Research Facility is a scientific user facility within the U.S. Department of Energy (DOE) Climate and Environmental Sciences Division (CESD) of the Office of Biological and Environmental Research (BER). ARM is an observation facility whose purpose is to provide ground-based observations of the atmosphere to support climate research and to support the improvement of global climate models. ARM is closely affiliated with the Atmospheric System Research (ASR) program, which uses ARM data to address key atmospheric science issues and improve the parameterization of physical processes in climate models.

A common methodology for using ARM data to improve climate models has been to carry out multi-model evaluation projects, typically in conjunction with field campaigns in which intensive radiosonde launches support the development of model forcing data sets. These exercises have yielded important insights. However, in recent years, there has been a growing interest in supporting high-resolution model simulations on a more routine basis. An important aspect of ARM sites is the continuous collection of high-resolution data over long periods of time. More routine model simulations would take better advantage of these long-term data sets. Nevertheless, accomplishing this will require careful attention to the requirements for running and evaluating these models together with a research program that maximizes the benefit of the model output.

To support the routine operation of models, and at the same time, to improve the overall efficiency of operating ARM Facilities, ARM is undergoing a reconfiguration through which instruments will be concentrated at fewer sites. Operations at the Tropical Western Pacific (TWP) are being discontinued while the Southern Great Plains (SGP) and North Slope of Alaska (NSA) sites will be augmented. The SGP site has always served as the testbed for ARM development activities as it experiences a wide range of meteorological conditions, while the NSA represents a region that is undergoing rapid change.

DOE is hosting a series of workshops to solicit community feedback on how key scientific needs, gaps and priorities in process model understanding and climate model prediction could be addressed through strategic deployment and operation of instruments and routine high-resolution modeling at the SGP and NSA sites. The actual frequency of "routine" modeling is yet to be determined but is intended to take advantage of the continuous nature of ARM observations. The first workshop was held in May 2014 and focused on the SGP site. Two additional workshops are currently planned to focus on the NSA site and on the ARM Aerial Facility. This report documents the proceedings from the SGP workshop and lists the scientific priorities identified by the workshop attendees.

Participants at the SGP workshop were selected to represent a broad range of interests including observations and modeling, high- and low-resolution modeling, as well as clouds, aerosols, radiation, and land-atmosphere interactions. The workshop, and a pre-workshop survey, focused on ways the newly configured ARM sites could be used to address the following three questions:

1. What are key science questions or objectives relevant to the SGP region that are presently poorly constrained, but could be addressed with a more complete observation suite and associated modeling activities?

2. For the science questions identified, what are the key observable parameters required?

3. What modeling strategy would be effective to support these additional measurements toward addressing these science objectives?

With the majority of participants representing interest in cloud processes, the science themes that emerged from the white papers and the workshop tended to organize around shallow and deep convection. Shallow convection systems over the SGP are amenable to large-eddy simulation (LES) with domains on the order a few tens of kilometers. Their resolution is reasonably well matched with remote sensing spatial scales. Priorities include improvement of process understanding in shallow clouds and the role of the land surface in driving convective processes. Deep convection represents a broader array of science issues. However, it also poses significant practical challenges in terms of developing a closed experiment system. Deep convection is inherently larger in scale, and deep convection systems over the SGP are often initiated by larger-scale systems developing along the front range of the Rockies.

Scientific Priorities for Enhancing Scientific Outcomes of Routine Large-Eddy Simulations at SGP

The SGP workshop discussion identified several scientific priorities for enhancing the outcomes of running routine LES simulations at the SGP site:

- Carry out a pilot study in which the issues raised during the workshop can be examined in more detail and a viable modeling strategy can be developed;
- Focus initially on routine LES of shallow convection;
- Pursue single-column modeling (SCM) in parallel with LES, using methodologies developed to address parameterization deficiencies in climate models;
- Pursue LES of deep convection over large domains. Initially apply periodic boundary conditions but develop methodologies for nested domains;
- Establish protocols for initial and boundary conditions for both shallow and deep convection using LES, recognizing issues such as spatial variability in temperature, moisture, surface fluxes, advective tendencies, upstream conditions, etc.;
- Support LES through measurement enhancements of land-atmosphere interactions, cloud and aerosol properties, and radiative fluxes, as well as by continuing the routine measurements of carbon profiles and fluxes;
- Ensure that the modeling effort is supported by an active research program that maximizes the benefit of the enhanced measurement and regular modeling activities.

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1.0 Introduction

1.1 Background

Science Drivers

One of the main goals of the U.S. Department of Energy (DOE) Climate and Environmental Sciences Division (CESD) is to improve the representation of atmospheric processes in climate models and enhance our ability to predict future climate. To this end, CESD supports the Atmospheric System Research (ASR) program, which focuses on advancing understanding of atmospheric processes—particularly those associated with the radiative forcing of clouds, aerosols, aerosol-cloud interactions, and land-atmosphere interactions—and the implementation of this improved process information in climate models. CESD also supports the Atmospheric Radiation Measurement (ARM) Climate Research Facility, which provides measurements of the atmosphere and the Earth's surface, supporting climate research.

Over the past six years, ARM has convened two workshops (DOE 2008; and DOE 2012), inviting noted scientific experts to identify the most pressing science issues related to atmospheric processes and how ARM and ASR could best address these issues. Findings from these workshops identified high-priority science questions, including how clouds, aerosols and dynamics couple as a function of scale, and how clouds and precipitation couple with surface properties. In particular, the 2012 workshop noted the scientific need for capabilities for observing a large-eddy simulation (LES)-scale domain with a high-density set of observations and for running an LES model over the domain to serve as a strong constraint on process studies. The recent CESD workshop on atmospheric testbeds (DOE, 2013) similarly identified combining ARM data, LES-scale models, and data assimilation techniques to create a gridded high-resolution reanalysis data set, or a "four-dimensional (4D) data cube," for model parameterization and development as a scientific priority.

Over the past five years, the ASR Working Groups (Aerosol Life Cycle, Cloud Life Cycle, and Cloud-Aerosol-Precipitation Interactions) have also developed a focused list of science questions, many of which would benefit from observations that provide more information on spatial variability within an LES- or Cloud-Resolving Model (CRM)-scale domain, rather than the historical vertical column measurements. These questions address cloud microphysical processes, shallow and deep convection, precipitation, aerosol properties, and radiation. They are summarized in Appendix A.

To address these and related high-priority science questions, ARM is implementing strategic changes to provide improved and higher density measurements that will serve as a resource for process studies and model evaluation. The ARM Facility is currently undergoing a reconfiguration in which some instruments and resources will be consolidated to augment two locales: the SGP and the North Slope of Alaska (NSA). This

CESD Mission Statement:
To advance a robust predictive understanding of Earth's climate and environmental systems and to inform the development of sustainable solutions to the Nation's energy and environmental challenges.

concentration of measurement resources will provide the observational basis necessary to support routine modeling. ARM is therefore also undertaking the development of a routine modeling framework in conjunction with these sites.

1.2 The Concept of Routine Modeling

The rationale behind routine atmospheric modeling is to establish a framework and infrastructure that enables routine simulation of a large number of cases covering a broad range of real and relevant atmospheric cases/regimes. Models require a set of initial conditions (either from observations or a previous model run) to start a simulation. Once the simulation has started, the model can run in an unforced mode or the boundary conditions of the model can be routinely updated by observed or modeled meteorological state variables (known as forcing data sets). The details of the forcing data sets depend on the problem at hand and may include varying degrees of data assimilation. The counterpart to routine modeling is a routine stream of observations that enable evaluation of model performance at similar spatio-temporal scales. The influence of different physical parameterizations on model performance can then be tested by comparing the model to observations. This approach is similar to the rigorous and routine testing of Numerical Weather Prediction (NWP) models against observations. While a goal is to take better advantage of the continuous ARM observations, the optimum modeling strategy will need to balance logistical constraints and science drivers and may focus on particular conditions or span diverse conditions during selected periods.

Routine modeling is a shift from the existing idealized and semi-idealized case studies associated with different cloud regimes (e.g., the Global Atmospheric Systems Studies framework). Those efforts center around modeling of a small number of case studies based on real-world situations, rather than attempting to span the broader range of conditions that make up the climatology of any site. In the Global Atmospheric System Studies (GCSS)/ Global Energy and Water Cycle Exchanges Project (GEWEX) Cloud System Study (GASS) activities, a variety of models are used, each with different treatments of physics and/or dynamics, to quantify the range of predicted outcomes, and to identify possible reasons for those differences. Comparison with observations is sometimes a smaller part of these efforts.

Both approaches clearly serve important roles. Here, we focus on the former because it better utilizes ARM's commitment to long-term measurements, and leverages DOE's strengths in intensive computing. In this context, "routine modeling" does not necessarily mean that a model—or several models—will be run every day, but it does mean that simulations will be carried out more frequently than the historical mode of running models in conjunction with field campaigns, or with idealized cases derived therefrom.

1.3 Why Pursue Routine High-Resolution Modeling?

Modeling, confronted with observations on a routine basis for a broad range of conditions, together with appropriate scrutiny and analysis, should lead to a greater level of confidence in the embedded process understanding, and predictive ability of the model. This is a difficult process and requires a good understanding of both model and observational uncertainties. Some of the desired outcomes of routine high-resolution modeling include:

(i) Quantified evaluation of model parameterizations over a range of atmospheric conditions;

(ii) An improved representation of model physics in climate models relevant to a range of atmospheric conditions;

(iii) Gridded 4D data cubes—essentially observationally constrained model output—that can be used for further analyses.

While the goal as stated in (ii) is to improve climate models, high-resolution models married with fine spatial and temporal scale ARM measurements provide an important bridge between process understanding at cloud scales, and improved climate model parameterizations.

2.0 The Modeling Workshop

2.1 Goals and Strategy for This Workshop

The high-resolution modeling workshop was convened May 19–20, 2014, to identify scientific priorities for routine modeling strategies around DOE science issues associated with the coupled land surface-aerosol-cloud-precipitation system and to identify key measurement needs to support these strategies. The meeting focused on the ARM SGP site with an upcoming meeting planned to examine these issues for the NSA. Participants at the workshop were selected to represent a broad range of interests including observations and modeling, high- and low-resolution modeling, clouds, aerosols, radiation, and land-atmosphere interactions (see full participant list in Appendix D).

2.2 Attendee and Community Input Prior to Meeting

Prior to the meeting, invitees and community members were requested to provide input on:

- identifying the scientific problems that would benefit from daily (or routine) LES, single-column modeling (SCM) and perhaps CRM;
- exploring ways to maximize the benefits of routine LES/SCM/CRM, confronted with observations;
- identifying measurement and modeling strategies and needs to advance specific science problems;
- developing a better understanding of the computational challenges and potential solutions to those challenges.

With the majority of participants representing interest in cloud processes, the science themes that emerged from the white papers and the workshop tended to organize around shallow and deep convection, but the input from both invitees and the community was broad and thoughtful, and provided much material for synthesis prior to the meeting.

3.0 Workshop Discussion

The workshop began with an overview of the previously stated goals and a review of the submissions to homework assignments listed in section 2.2. There was also a short overview of the four current DOE modeling testbeds (DOE 2013):

- The Cloud-Associated Parameterizations Testbed (CAPT; Phillips et al. 2004)
- The Climate Science for a Sustainable Energy Future (CSSEF)
- Fast-physics System Testbed and Research (FASTER)
- The Aerosol Modeling Testbed (Fast et al. 2011).

While these testbeds use different models and have a range of goals, they are all designed to facilitate the evaluation of model simulations with observation data. These testbeds were summarized at the beginning of the meeting. Thereafter, Roel Neggers presented an overview of the Royal Netherlands Meteorological Institute (KNMI) Parameterization Testbed (KPT; Neggers et al. 2012), which combines LES and SCM simulations over the ARM-like KNMI observation site at Cabauw in the Netherlands.

Following these introductory presentations, participants were challenged to step through the same questions presented in the homework assignment, considering key science issues and the modeling strategies and observations required to address those issues.

3.1 Overview of Science Themes

Participants in the meeting as well as community contributors (via pre-meeting white papers) identified five broad science themes that would benefit from routine comparison/integration of modeling and observations:

- shallow convection
- deep convection
- aerosol
- radiation
- land surface and carbon cycle.

These fall under the rubric of ARM/ASR's traditional areas of interest and much of the workshop was spent discussing optimal strategies for addressing scientific gaps in our understanding of the system(s) and exploring ways to maximize benefit from routine high-resolution modeling matched with routine high-resolution observations.

Discussion at the workshop focused primarily on two science themes that would benefit significantly from routine modeling: *shallow and deep convection* (see Appendix A). These are considered to be "integrating themes" in that they subsume the others. They are treated here briefly and pursued in greater depth later in the report.

The motivation for studying convective clouds is strong. The representation of (sub-grid) shallow convection is a perennial challenge for climate models and, in the case of subtropical oceans, tightly linked to climate sensitivity. Weakly forced shallow clouds are sensitive to small changes in atmospheric conditions and land-surface forcing. They are also susceptible to the amount and type of local aerosol as well as to rates of entrainment. The radiative forcing of a field of shallow cumulus embedded in a "soup" of aerosol is a poorly understood problem with important implications for radiation budgets in GCMs. Improving the ability of GCMs to estimate cloud radiative forcing and feedbacks was the motivation for ARM's inception 25 years ago.

Deep convection, another sub-grid process that is poorly represented in climate models, is a key component of atmospheric circulations and precipitating cloud systems from local to global scales. Some challenges are:

- the need to represent a range of interacting scales;
- timing of convection is particularly difficult to simulate;
- cloud system organization through cold pools, wind shear, and midlevel humidity is only beginning to be represented in climate models;
- the influence of aerosol on convective cloud systems, and in turn the removal of aerosol by rain, is poorly understood.

The main elements of each of the remaining three themes[(1)] are now addressed briefly to provide the necessary background for subsequent focused discussion on shallow and deep convection. They will be expanded upon during the course of the report as needed.

Aerosol

Aerosols play an important role in boundary layer and tropospheric processes by influencing cloud microphysics, radiation, and surface forcing. For a routine modeling program, these avenues require careful consideration of potential aerosol effects. Aerosol composition influences water vapor uptake (therefore light scattering and extinction) and the ability of particles to act as cloud condensation nuclei (CCN). The vertical distribution of aerosol modifies heating profiles and surface fluxes, particularly when the aerosol has an absorbing component. Knowledge of the aerosol loading requires understanding of emissions, transport, and the life cycle of the various aerosol constituents. Improved simulation of the boundary layer and clouds will also benefit aerosol and chemistry studies that address venting, fumigation, dilution, and aqueous chemistry.

The SGP site is a relatively clean site with modest but distinct seasonal cycles in optical properties, punctuated by long-range transport of seasonal biomass burning and urban pollution. Being generally clean, it has proven to be a very useful site for the study of new particle formation, which may be a significant source of CCN. From the perspective of routine high-resolution modeling, key measurements are the vertical distribution of aerosols and its diurnal and seasonal cycles. Some knowledge of aerosol composition obtained indirectly via absorption and hygroscopicity measurements are useful.

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(1) There was brief discussion on the nocturnal boundary layer but this topic was not developed further because it was felt that there are more pressing and tractable problems that would benefit more from routine high-resolution modeling.

Land Surface and Carbon Cycle

The importance of the lower boundary conditions in high-resolution modeling will emerge as a theme in this document. Surface latent and sensible heat fluxes are important drivers of convection, and quantification of these fluxes requires careful measurements of soil moisture and characterization of land use, including seasonal cycles. The spatial patterns in land use are clear from satellite images (see Figure 2 in section 5), but the relationship between the scales of variability and surface fluxes is not well established, particularly in the presence of advection. From a carbon-cycle perspective, scientists are particularly interested in net ecosystem exchange and its relationship to the spatial patterns in surface properties (fluxes), temperature, and precipitation. Current carbon cycle-relevant gas measurements, in conjunction with surface and boundary layer measurements, are therefore of great value for carbon-cycle studies.

Radiation

Radiation, much like shallow and deep convection, can also be considered an integrating theme because it involves aerosol, clouds and their interactions, and cloud field properties (cloud fraction, optical depth, liquid water path, inter-cloud distances), all of which require an understanding of convection and its drivers, aerosol life cycle, and land-surface albedo. The topic is not raised to a higher level because it is recognized that a prerequisite is the improvement of observation and modeling of clouds and aerosol. A focused effort on radiative closure would be a desirable outcome of the routine high-resolution modeling. This is more stringent than a broad comparison of the statistics of modeled and observed cloud fields and aerosol properties. (See section 3.6 Model/Observation Comparison.)

3.2 Forcing Approaches

A recurrent theme in the discussion was the importance of carefully characterizing the meteorological environment in which convection develops. This is essentially central to what has become known as, "the cloud problem" (Arakawa 1975): small changes in thermodynamic profiles can manifest large changes in cloud properties. The implication for routine high-resolution modeling is that carefully produced forcing data sets are critical to the success of the endeavor. For example, if a simulation performs poorly compared to observations, one needs to identify whether this is caused by inadequate forcing at the modeling scale, or to poor performance of model physics. Ensemble forcing data sets that include a range of perturbations around the initial conditions can alleviate this problem to some extent.

We first discuss atmospheric forcing methodologies in the broader sense and refine these ideas for shallow and deep convection. In practice, the choice of forcing is matched to the identified goals.

1. Variational Analysis

   ARM/ASR generates forcing data through the use of a variational analysis technique (Zhang et al. 2001), which produces spatially homogeneous forcing that represents a 300 km x 300 km box, updated every hour. The technique uses a background state—ideally from routine radiosondes—or from a high-resolution NWP model such as National Oceanic and Atmospheric Administration (NOAA)'s Rapid Update Cycle (RUC)/Rapid Refresh (RAP)/High Resolution Rapid Refresh (HRRR), which is updated routinely. Measurements of temperature, humidity, horizontal winds, surface fluxes (latent heat, sensible heat, surface precipitation, surface irradiance), and top-of-atmosphere irradiance are integrated by enforcing known physical constraints such as conservation of mass, energy, and moisture. Doing so produces the best guess of the wind and state variables, and their tendencies, within the uncertainties of the measurements, or the uncertainties of the model from which the forcing is derived. By driving a cloud-scale model with variational analysis, ARM data could be used both for forcing and for high-resolution model evaluation.

2. Forcing from a Climate Model

   In keeping with the philosophy of parameterization testbeds, another approach is to force the high-resolution model with the forcing from a climate model, initialized with a global NWP model analysis and run in hindcast mode for a short period of time (the CAPT approach). Forcing data sets are taken from a grid centered on the region of interest. The LES is then essentially a downscaled form of the poorly resolved global climate model (GCM) cloud fields, appropriate for comparison with local observations. This forcing can equally (and efficiently) be applied to test an SCM. The comparison of SCM and a high-resolution model (LES) allows further evaluation of the adequacy of the forcing data or the SCM (and GCM) parameterizations (Neggers et al. 2012). Routine SCM simulations, alongside LES, would facilitate rigorous testing of the SCMs for a wide range of conditions, and a direct pathway to improvement of climate model physics.

3. Data Assimilation

   Data assimilation can be used to enhance forcing data sets in various ways. First, an NWP model could assimilate available measurements of state variables, winds, surface fluxes, and perhaps even data derived from ARM remote sensing measurements to provide an improved background state for variational analysis, particularly when radiosonde launches are sparse. Second, instead of forcing an LES with variational analysis, high-resolution LES with periodic boundary conditions could be forced by the output from a CRM, NWP, or regional model that includes data assimilation. Third, the LES could be nested within the coarser resolution model, i.e., with open boundaries. In this case, assimilation in the coarser grid model would provide a time varying, realistic forcing data set, and the high-resolution model output should ideally provide a faithful representation of the cloud fields.

3.3 Modeling Tools and Strategies

Participants discussed options for modeling tools and agreed that a high-resolution LES model is the best scientific tool for studying shallow and deep convection. These models are less sensitive to their microphysical parameterizations than are coarser CRMs. Some of the key modeling challenges are discussed here; those more specific to shallow or deep convection are addressed in section 3.5.

An LES requires grid sizes on the order of 10–100 m for representing shallow cumulus over domains as large as 30 km to allow mesoscale organization to develop. For deep convection, the target grid size is ~250 m and the domain size is 100s km. Time steps are ~1–2 seconds for both shallow and deep convection. The traditional LES applies doubly periodic lateral boundary conditions. The attendees recognized this is less than ideal for deep convection when convection originates outside the domain, and cold pools generate organization and periodic boundary conditions that eventually "contaminate" the simulation as features start to fill the domain. This can be alleviated to some extent by increasing domain size but computational expense must be considered.

Another way to address this challenge is through the use of LES embedded in, and relying on, a coarser NWP model (order of 3 km grid) for boundary conditions. These open boundary conditions would alleviate the concerns of "wraparound" associated with periodic boundary conditions and allow systems to propagate more naturally through the domain. The importance of upstream conditions—as far as the lee of the Rockies—for deep convection raised concerns about how large a domain would be required. The data assimilation forcing methodology described previously would lend itself to open boundary conditions. Newly developed 4D ARM/ASR constrained variational analysis could also be applied to systems with open boundaries. On the whole, it was thought that the simpler, traditional LES with periodic boundary conditions was an appropriate start for routine high-resolution modeling. In the interim, the methodology for simulation with open boundaries could be developed.

Interest in aerosol effects on clouds and precipitation requires some level of aerosol representation in the model. For practical reasons the high-resolution model could initially be relatively "light" in aerosol processes but the modeling infrastructure should be designed to accommodate a higher level of detail as locations change, and when strong aerosol gradients or variability exist. A fairly simple prognostic aerosol equation that advects and diffuses the aerosol, tracks it through the hydrometeors, resuspends it upon evaporation/sublimation, and removes it when precipitation reaches the surface might be an appropriate start point. A more complete treatment of the aerosol sources and sinks, including detailed representation of the organic aerosol life cycle, would be applied in locations that indicate an important role for aerosol, and when other broader issues have been resolved. All of these options exist in a variety of modeling frameworks. The Monitoring Atmospheric Composition and Climate (MACC) reanalysis, developed at the European Centre for Medium-Range Weather Forecasts (ECMWF), could be used as boundary conditions for the aerosol.

The group thought it highly desirable to use two-moment bulk microphysical schemes that predict both number and mass mixing ratio of hydrometeors. Two-moment schemes exist for both liquid water and mixed-phase clouds. Not only do they usually perform better than one-moment schemes, but they are also required if one is to address aerosol influences on clouds and precipitation. Size-resolved (bin) microphysical schemes would be desirable for comparing radar parameters calculated directly from resolved drop-size distributions with a wider range of radar observations (e.g., Doppler spectra, Doppler velocity, polarization). While these exist in a number of models, they are expensive and will likely be used for more directed study of a subset of cases.

An important component of the modeling of both shallow and deep convection is an atmospheric model coupled to a land-surface model that represents vegetation and soil moisture, and ultimately latent and sensible heat fluxes. The patchwork of fields in the vicinity of the SGP site generated discussion on the importance of the scales of variability of the land-surface type. The importance of this heterogeneity is uncertain and attendees noted that this current scientific gap would benefit from directed research.

3.4 Overview of Measurement Needs

The Southern Great Plains (SGP) Central Facility (CF) site is already a data-rich region that is well suited to the proposed effort. Still, some additional measurements would help address important scientific needs. Several classes of measurement were discussed that would enhance the scientific outcomes from the production and evaluation of routine model simulations at the SGP site:

- continuous profiles of temperature, humidity, and wind using remote sensors
- characterization of the spatial heterogeneity of soil moisture and temperature and surface heat fluxes
- three-dimensional (3D) cloud and precipitation properties (microphysics and dynamics)
- aerosol properties both at the surface and in vertical profile.

Many of the science questions proposed, i.e., documented in the white papers and developed through workshop discussions, were concerned with evaluating the environmental controls on cloud properties. Pursuing these questions requires detailed observations of the background environment. Suggestions for improving these observations, both for the atmosphere and the land surface, were a common theme.

For the atmosphere, a barrier to addressing key scientific questions on convection is the lack of high-temporal resolution profiles of temperature, humidity, and wind—both within the measurement domain and at the boundaries of the domain. These data would provide the means to study the relationship between cloud processes and the environment and to develop forcing data sets. Historically, this type of information has been provided by radiosondes. However, given that routine radiosonde operations are very expensive, active and passive remote sensors such as Doppler lidar (for sub-cloud wind) and infrared spectrometer (for temperature and humidity) could be considered. The Raman lidar, currently deployed at the SGP CF, is also quite useful for providing continuous profiles of temperature and humidity but is likely not practical for the boundary sites.

In addition, white papers submitted prior to the workshop identified enhanced measurements of radiation and continued support of current carbon measurements as scientific needs. Radiative measurement needs focused primarily on increased spatial sampling near the SGP CF, discussed in Appendix B. There were no suggestions for additional carbon measurements, but there was a strong request to continue current measurements at the SGP CF as well as routine aerial measurements.

3.5 Integrating Themes: Shallow and Deep Convection

As mentioned previously, discussion of science goals focused on the two main themes of shallow and deep convection. These are now discussed in more detail.

3.5.1 Shallow Convection

Science Drivers and Foci

The motivation for studying shallow cumulus ranges from a desire to improve basic understanding of shallow convection, to the importance of their parameterization in global models. Routine LES of shallow convection, coupled with continuous and detailed measurements over a range of conditions, offers the promise of significant progress on current scientific problems, such as the role of clouds and convection in GCM warm biases and diurnal cycle biases over SGP; coupling of shallow clouds and soil moisture; and deep convective initiation. Based on experience, successful simulation of these weakly forced systems requires carefully assembled forcing data sets and fine mesh LES to match the observed physical scale of these convective processes.(2) In addition to careful characterization of the thermodynamic profiles, surface forcing—and therefore knowledge of land-surface types and soil moisture—is essential. The SGP site is surrounded by a patchwork of cultivated fields, which presents an opportunity to study variability in spatial and seasonal surface forcing as crops cycle through growth and harvest, or fields lie fallow. An interesting aside is that advection tends to reduce the importance of local fluxes, and while this topic has been addressed to some extent, more can be done, particularly given the observationally rich environment at SGP. Interannual variability in surface forcing due to changes in precipitation, temperature, and winds also are of interest.

Aerosol-cloud interactions continue to be a topic of keen interest. Warm (liquid water only) clouds offer a useful and important opportunity to study these interactions and their associated radiative forcing without the complicating pathways of ice microphysics. The basic tenets of cloud microphysical responses to aerosol perturbations are reasonably well understood, but the response of an evolving cloud system is more uncertain. ARM data have been used to address this problem using combinations of cloud sensors (zenith-pointing Doppler cloud radar and microwave radiometer) to define cloud microphysical properties, together with lidar or surface aerosol measurements to quantify the aerosol. The methodology can be applied at short temporal scales where one essentially considers cloudy columns as independent manifestations of aerosol-cloud interactions, or via longer-term averaging. Scanning cloud radars (W- or K-band) and scanning short-range precipitation radars (X-band), in combination with surface-spectral radiometers, can also be used to quantify cloud field properties. These surface shortwave radiometers allow more rigorous assessment of the radiative effect of the cloud system because one can simultaneously quantify microphysical responses (as described previously) together with the radiative response through analysis of surface-spectral irradiance or radiance. The latter depends not only on cloud microphysics, but also cloud field properties, such as cloud fraction, cloud optical depths, inter-cloud distances, as well as on the properties of the aerosol field in which the clouds are embedded, and the spectral albedo of the land surface.

(2) Cumulus cloud size distributions follow power laws and exhibit no sign of truncation down to the detection limit of satellite sensors (15 m; ASTER).

The potential for aerosol influences on clouds can be quantified via albedo susceptibility and, in the case of precipitating clouds, precipitation susceptibility. These metrics can be applied to both satellite and ground-based measurements. They also can be calculated from model cloud fields, offering further opportunities for process-level understanding of the dominant controlling factors.

Entrainment-detrainment between the cloud and its environment has been addressed with LES and Direct Numerical Simulation, but observational estimates are difficult. Surface-based profiling, together with a parcel model explicitly representing entrainment, have been used to quantify entrainment in shallow cumulus at SGP, as have airborne measurements during the 2009 **R**outine **A**RM Aerial Facility **C**louds with Low **O**ptical Water Depths **O**ptical **R**adiative **O**bservations (RACORO) field campaign. Scanning Doppler radars and lidars offer further opportunities for studying cloud edges. Observations of cloud dilution using the Atmospheric Emitted Radiance Interferometer (AERI) or microwave radiometer measurements of liquid water path, and/or cloud radar measurements of liquid water content will also be useful for assessing the net effect of entrainment/detrainment on clouds. Again, routine modeling offers a more frequent and broader sample of cases to analyze.

Forcing

The forcing data sets for the shallow convection science foci described previously can be generated by spatially homogeneous variational analysis (Zhang et al. 2001). Variational analysis requires an adequate description of the background thermodynamic and dynamic state. It benefits greatly from soundings, preferably at a frequency greater than routine radiosonde launches at SGP. In lieu of soundings, a background state generated by an NWP model is currently necessary. However, workshop participants discussed alternative observational approaches that use remote sensing instruments to provide continuous thermodynamic and wind profiles that could augment the routine production of a forcing product. The variational analysis currently has a vertical resolution of 50 mb, which is ~500 m near the surface. An order of magnitude increase in vertical resolution would be desirable for shallow convection.

LES boundary conditions are traditionally doubly periodic, which is consistent with application of homogeneous forcing. This combination is the simplest start point for routine simulations of shallow convection. LES can also be nested within a larger scale/coarser resolution model, which would be useful when spatial variability in forcings is necessary, or when spatially variable data assimilation is applied in the host model. This topic is more relevant to larger domain, deep convective studies, so we defer discussion of this topic to section 3.5.2.

The Parameterization Testbed

Similar to the approach adopted by KNMI at the Cabauw site in Holland, routine LES at SGP could serve as a parameterization testbed for shallow convection. In this case, the express purpose of routine modeling is improvement of the representation of shallow convection in a climate model. The separation of small-scale convection and large-scale environment is convenient because there is no concern about feedbacks from the small to the large scale. The methodology is described in some detail in Neggers et al. (2012) and briefly outlined as follows: a climate model is initialized with a global analysis data set derived from an NWP model, run in hindcast mode for a short period of time (days), and periodically nudged to updated analysis fields. The climate model fields in a grid box covering SGP provide the forcing for the LES. After an initial spin-up period during which the LES is nudged to the initial sounding, the LES is allowed to run freely and provide high-resolution simulation of cloud fields (essentially a downscaling of the host model state) that can be compared to observed fields. Simultaneously, the same climate model forcing fields are used to drive an SCM with the same model physics as the climate model. Successful and unsuccessful SCM simulations (vis-à-vis predetermined criteria) are collected to identify SCM biases relative to observations. Further comparison between LES and SCM for a wide range of conditions provides an opportunity to evaluate the various SCM parameterizations, and their ability to generate realistic cloud fields. The fact that the climate model forcing is applied to both LES and SCM helps to focus on differences in model physics for a consistent set of forcings. Collection of simulations for a wide range of conditions provides opportunity for identifying problems (e.g., poorly performing parameterizations, compensating errors, etc.) and for improving parameterizations. This process requires large statistics and careful analysis. Workshop participants noted that while this approach would require significant investment, it was a critical need to ensure that the SCMs (and GCMs) benefit from the routine modeling.

Measurement Needs

Barriers to the study of shallow convection at the SGP include the need for additional measurements. Those that are likely to have the most direct impact on improving the understanding of shallow convection are a set of remote sensing systems that could provide the thermodynamic and dynamic structure of the boundary layer. More details about these systems, and other measurement topics, are provided in Appendix B, *Instrument Redeployment and Augmentation*, but a summary of scientific needs, gaps and priorities for the study of shallow convection is provided here.

In order to provide the needed measurements of boundary layer structure, the boundary layer profiling systems should include an AERI for profiling temperature and humidity, a Doppler lidar for profiles of wind, and a microwave radiometer for total column water vapor. By combining information from the AERI and the microwave radiometer, it should be possible to obtain some information about variability of water vapor in the free troposphere. These profiling sites should be deployed on a spatial scale appropriate to provide a forcing data set for an LES model. The proposed placement of these instruments is shown in Figure 1.

Soil moisture, surface heat fluxes, and boundary layer structure are closely coupled and all are important for shallow convection. Barriers to scientific understanding of these issues include the fact that current soil moisture measurements do not perform well under dry conditions, instrumentation is not consistent across sites, and it is difficult to scale local measurements up to the entire domain. Priorities for addressing these scientific issues include an investigation into the optimum method(s) for measuring soil moisture across a range of conditions (dry to wet) and consistent application of this method, measuring heat fluxes and boundary layer structure at any site where soil moisture is measured, and mapping surface types across the domain so local measurements can be scaled to domain distributions and averages of land-atmosphere coupling properties.

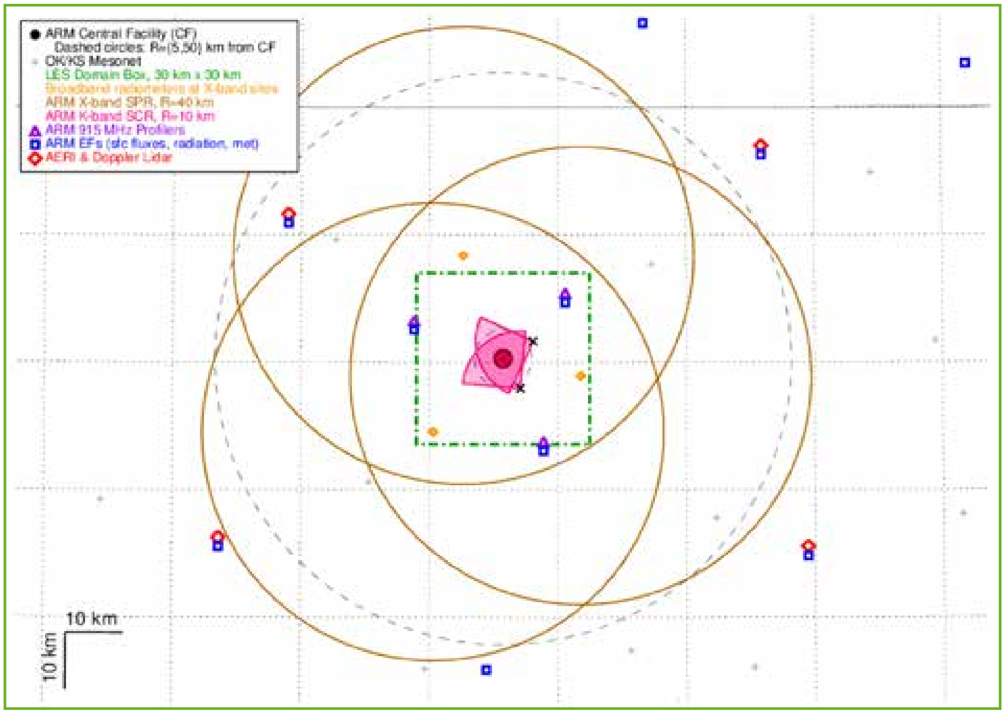

Figure 1. Highest priority ARM measurements in support of shallow convection studies (courtesy of Dave Turner). Proposed changes to existing measurements include: 1) adding surface fluxes/radiation/met/soil moisture (blue squares) to existing 915 MHz profiler sites at ~15 km radius from CF; 2) adding new AERI/Doppler lidar profiling sites (red diamonds) at existing extended facilities at ~50 km radius from CF; 3) adding new broadband radiometers (orange diamonds) at existing X-band sites; 4) adding a vertically pointing W-band radar to CF; 5) and moving existing scanning cloud radar and adding a second scanning cloud radar, both at ~5 km from the CF, to produce 3D cloud fields over the CF.

In addition to characterizing the background atmosphere and the land-atmosphere interface, there are also limitations to existing cloud and aerosol measurements. With regards to cloud measurements, there is a scientific need for improved volumetric cloud observations centered around the CF. Detailed discussion of the deployment of radars to meet this need is included in Appendix B, *Instrument Redeployment and Augmentation*, and in Figure 1. The main elements of this idea are to collocate a W-band (94 GHz) radar with the standard Ka-band ARM zenith radar (KAZR), offset the existing scanning ARM cloud radar (SACR) from the profiling site, and pair it with another SACR (from the Tropical sites). The sensitive, short wavelength radars are essential for studies of shallow non-precipitating clouds. This measurement strategy would provide dense sampling of cloud distributions. It was deemed important to have high time resolution observations of cloud properties so that cloud feature smearing is minimized.

An important missing component of SGP aerosol measurements is knowledge of aerosol properties at cloud-level. Currently, there are a variety of measurements made at the surface, but there is little information about properties aloft. From 2000 to 2007, profiles of a few aerosol parameters were made over the SGP CF using a small aircraft, but these measurements were discontinued. A multi-wavelength lidar system that has been developed for quantitative profiling of aerosol properties has been shown to be effective when operated on an aircraft looking down, but several technical obstacles would have to be overcome to apply this technique to an upward looking, ground-based instrument. Regular aerosol profiling with multi-wavelength lidar systems, complemented by periodic airborne in situ profiling, would be valuable for improving aerosol profiling at SGP.

3.5.2 Deep Convection

Science Drivers and Foci

Much like in the case of shallow convection, routine modeling, matched with the rich suite of instruments at SGP, offers significant opportunity to improve understanding of deep convection, albeit with some complications, and some opportunities not presented by shallow convection. Parameterization of deep convection is a longstanding problem and stands to benefit greatly from routine modeling. Convective Available Potential Energy (CAPE)-based schemes tend to predict the right amount of precipitation, but too early (local noon), while restrictive trigger schemes delay convection and mimic the diurnal cycle reasonably well, but underestimate precipitation.

Also in common with shallow convection is the importance of characterizing the thermodynamic and dynamic conditions in which deep convection develops, and the role of land-surface forcing. Discussion quickly pointed to the fact that deep convection at SGP typically originates a significant distance upwind of the site, as far away as the lee of the Rockies—it is seldom locally forced. Thus, one would ideally like to model a domain that extends far beyond the SGP. Various options were considered, including CRMs nested within a coarser grid convection-permitting model that covers a significant part of the continental United States. Concerns over the sensitivity of CRMs to various parameterizations shifted discussion to use of LES at grid sizes of ~250 m and domains of ~200 km for deep convective studies. Boundary conditions would be periodic and forcing data homogeneous. Exercises of this kind have already been undertaken as part of Midlatitude Continental Convective Clouds Experiment (MC3E), and given the valuable lessons learned from these studies, there was interest in pursuing them further.

The periodic boundary conditions in an LES present more severe restrictions for deep than for shallow convection. Precipitation tends to organize convection through the interaction of cold pools with the environment. Because periodic boundary conditions force organized cells, once they exit downstream to wraparound into the upstream side of the domain, there is the possibility that these organized features will at some point impose unnatural convective patterns on the simulation. Domains need to be large enough so that they are not dominated by one single convective cluster. In spite of these restrictions, the details of dynamical-microphysical interactions that LES affords still make this worth pursuing.

The organization of precipitation received great interest. Studies of cold pool formation and secondary convection benefit significantly from the scanning cloud and precipitation radars at SGP. Profiles through the cold pools, and general characterization of the distribution of moisture and temperature before and after the storm, would be valuable.

Satellite and surface-based remote sensing, and some modeling, suggest aerosol concentrations can influence updraft strength, cloud depth, and the intensity of precipitation. Although aerosol loadings at SGP are typically quite low, routine modeling will offer the opportunity to collect more cases for which dynamical forcing is similar but aerosol loadings significantly different. Here, too, the importance of the forcing data sets becomes apparent as untangling aerosol effects from meteorology is notoriously difficult.

One of the most poorly understood aspects of the aerosol life cycle is wet scavenging. The scavenging efficiency is closely related to precipitation efficiency; both are difficult to quantify but studying one would benefit the other. Quantification of wet scavenging in models that treat convection explicitly, and represent microphysical processes in sufficient detail, is straightforward, but observational estimates to compare to model outputs are lacking. For precipitation efficiency, this requires quantification of surface rain integrated over the storm normalized by moisture convergence into the storm. For scavenging efficiency, the important properties to quantify are the amount of aerosol removed by the storm relative to the amount ingested into the storm. Analysis of chemical composition of rain would be useful.

Forcing

As stated previously, the group felt the periodic boundary conditions and homogeneous forcing (using variational analysis) was a useful starting point for these studies. Given the sensitivity of variational analysis to surface precipitation, ensemble forcing data sets that include uncertainty in surface precipitation should be considered. However, there was also keen interest in an open boundary set up to address spatial variability across the domain (e.g., the persistent west to east moisture gradient), and the previously discussed problems with simulating deep convection with periodic boundary conditions also was of interest. Nested grids and spatially variable forcings, such as 4D variational analysis, could address these issues. Data assimilation in nested models would also benefit process studies. For example, assimilation of Doppler radar has advanced to the point that robust wind analyses, consistent with thermodynamic and microphysical fields, can be produced by short-term forecasts. The evolution of individual storms can then be tracked and compared directly to observations. Mass flux profiles and cold pool structure could be compared. Simulations of this kind would provide valuable 4D data cubes for analysis of microphysics-dynamics interactions, precipitation, and storm evolution.

Parameterization Testbed

Routine SCM modeling of deep convection at SGP would be particularly helpful for identifying why no existing parameterization gets both timing and amount of precipitation correct. Carefully constructed forcing data sets (thermodynamic, dynamic, and surface) would once again be an important prerequisite. These could be either based on variational analysis or derived from a GCM run in hindcast mode, following the KNMI approach described previously. The primary difficulty with the latter approach is that the convenient separation of scales between shallow convection and the large-scale forcing discussed previously would no longer apply. Whether this would be pernicious enough to significantly diminish the usefulness of this forcing approach is unclear. It is most likely to succeed when the model initialization occurs before convection begins, so that the forcing presented to the LES and SCM are not contaminated by the cumulus parameterization deficiencies of the host GCM.

Cycled data assimilation is a method that could provide deeper insights into model performance and structural weaknesses, as well as to provide gridded, observationally constrained model output. In this approach, analysis fields that assimilate the most recent observations with a background forecast are generated. Successive cycles of this procedure highlight differences between the background forecast and the observations and point to model deficiencies. Examination of the drift of the model away from the observed state, together with the contribution of individual parameterizations to this drift, points to parameterizations that require attention. The benefit of engaging the NWP community in this exercise was raised as it also engages in short-range forecasting with routine data assimilation, albeit at coarser scales (3–13 km), and routine assessment of their forecasts against observations.

Measurement Needs

As with shallow convection, characterization of the background atmosphere was widely viewed as a critical scientific need. A similar methodology discussed for shallow convection, with a small network of remote sensors could also provide the needed data for deep convection. Commensurate with the increased scale of the modeling domain, the size of the profiling network would also need to increase. The scale proposed is on the order of the full SGP domain, or ~200 km. However, there is not a clear mechanism for obtaining thermodynamic profiles, or wind profiles with high resolution, in the free troposphere. This issue could be mitigated by merging profiling observations with NWP simulations that in turn are constrained by satellite observations, although the impact of the lack of good free tropospheric measurements of temperature, humidity, and wind (away from the CF where routine radiosondes combined with the Raman lidar are unavailable) will have to be evaluated. The cost of setting up a second profiling network may be prohibitive in the short term, so it was suggested that the profiling instrument suite could be developed as a set of portable systems that could be deployed for either the smaller shallow convection domain or the larger deep convection domain.

At the SGP, a dense, heterogeneous radar network is already in place. The profiling and scanning cloud radars along with the network of scanning precipitation radars (X-scanning ARM precipitation radars (SAPR)) are helpful because they can detect non-precipitating clouds and document the transition from shallow to deep convection. The precipitation radars provide information on the spatial structure of precipitation and to some extent, quantitative estimates of precipitation. There was some discussion of using cloud-tracking scan strategies to follow convective elements through their life cycle. Use of this type of strategy would have to be developed and then balanced with the desire to obtain high-density measurements around the CF. There was interest in using the already deployed X-band (3 cm; 10 GHz) radar array to retrieve storm system dynamics and to deploy a second C-band (5 cm; 5 GHz) radar to the southeast of the CF to provide better high-temporal resolution coverage of precipitating systems in the region around the CF. In this case, ARM would have two C-band precipitation radars, with one continuing to provide context and volumetric information, and the second used to provide high-resolution sector and Range Height Indicator (RHI) scans over targets/features of interest.

3.6 Model/Observation Comparison

We start with some general guiding principles for model/observation comparisons. The first principle is that comparisons are made at similar scales and with similar degrees of averaging. While this might appear obvious, it bears reiterating as averaging affects the individual properties and their correlations. A second principle is to keep focus on our general goal of model/observation comparisons, i.e., to see if models can reproduce statistics of observed fields over the course of the diurnal cycle, rather than to reproduce specific clouds.(3) Statistical output should include time series and probability distribution functions (PDFs) of key properties such as cloud fraction, optical depth, liquid water path (LWP), and surface temperature, humidity and radiation. Vertical velocity statistics should be compared. Higher-order products such as joint PDFs (e.g., vertical velocity and LWP) and profiles of high-order moments of perturbations in vertical velocity, moisture and temperature, and their covariances should be considered. More detailed microphysical properties (drop size, liquid water content, drop concentration) would require reducing large data sets to a manageable size. The set of parameters selected for comparison will likely vary from one application to another.

It is also worth considering comparison of analyses that derive from either models or observations, e.g., independent analyses of observations and of model output could be done for attribution studies—for instance, addressing questions like: what drives the variability in cloud albedo? Finally, observations have their own intrinsic value, and should be packaged in ways that are amenable to addressing topical science questions.

3.6.1 Data Assimilation

In the case of data assimilation, model/observation comparison has a different focus. Since the model is constrained by observations, the goal could be to consider the impact of the level of data assimilation in the forcing data set. One might also consider the effect of assimilation on simulated cloud system structure, and even hydrometeor species.

3.6.2 Instrument Simulators

A challenge in using ARM observations to evaluate model simulations is the necessity of obtaining comparable parameters from the observations and the simulations. Sometimes an instrument generates the necessary parameters directly, but in many cases, the parameters have to be derived. Within ARM, these derived parameters are referred to as Value-Added Products and include such parameters as cloud base, liquid water content, and aerosol optical depth. However, an alternative approach to bridging the gap between observations and models is to derive parameters from simulation output that are directly comparable to measurements using a forward model, or instrument simulator.

Instrument simulators are not inherently more accurate than geophysical parameters derived from observations, but they do offer several advantages. Given the complexities

(3) The exception might be when data assimilation is used at routine intervals to model individual storms in an LES or CRM model.

of observation data, it may be more straightforward to process output from a model than from an instrument. Instrument simulators can readily account for factors such as field of view, attenuation, and sensitivity. Another attractive feature of simulators is that once they are implemented in a model, one can use the simulator to explore what an instrument would observe under a variety of conditions, including different meteorological regimes or operational modes. In this way, numerical experiments can be used to guide the refinement of measurement strategies.

Examples of potential instrument simulators include radar Doppler moments from profiling and scanning systems, radar Doppler spectra, spectral radiances and irradiances, and lidar backscatter. The implementation of a particular instrument simulator in a model will depend on the physics contained in the model. For example, it will be easier to develop radar simulators for LES models that use bin microphysics than for bulk microphysics, and relatively straightforward for a liquid cloud but more challenging for an ice or mixed-phase cloud. The smaller LES grids are well matched to instrument ranges, which facilitates the implementation of a forward model.

While instrument simulators offer potential benefits, they require significant effort to build and are not a panacea. When comparing radiances or reflectivities rather than geophysical parameters, one gets the integrated contribution of all model geophysical errors. For example, when comparing modeled and observed radiances, one does not know whether the error derives from any combination of cloud occurrence, cloud phase, cloud water content and path, cloud particle size, cloud scattering phase function, cloud top height, water vapor amount, aerosol amount, or surface albedo. Thus, simulators tend to be more useful for identifying errors, while geophysical parameter comparisons help to correct these errors.

3.6.3 Integrated Data Products

Model output is very conducive to multivariate analysis because all output is generated on a common grid. Observations are more complex. Data are collected at a variety of spatial and temporal resolutions, may be collected in complex geometries (e.g., in the case of scanning radars or aircraft), and may have discontinuities associated with missing or incorrect data. To address these issues and to facilitate multivariate analysis of observation data, it will be valuable to develop tools that allow observation data to be readily mapped to the spatial and temporal resolution appropriate for a variety of simulations. A current example of a multiple source, integrated data product is the suite of ARM Best Estimate (ARMBE; Xie et al. 2010) products. These products bring together diverse measurements from radiometers, radars, and many other instruments on a common height grid with one-hour averaging. The averaging interval was selected to be most useful to global-scale models. With plans for routine operations of high-resolution models at the ARM SGP site, it may be valuable to develop integrated products that are flexible in terms of resolution, and in the scope of parameters.

Because of the difficulties in producing gridded observational data sets, a highly desirable goal of this project is the creation of the 4D data cube. Although this is essentially a model-derived product, it would only comprise model output that meets clear criteria with respect to the model's ability to reproduce observations. Note that the criteria for success might change for different goals so that 4D data cubes might draw on different sets of simulations and would need to be identified accordingly. In the case of models driven by forcing data sets that use significant and routine data assimilation, the model output is expected to reproduce observed cloud fields more readily. However, given the tendency of models to drift in the absence of nudging or assimilation to their desired state, clearly stated criteria will need to be stated for inclusion in a 4D data cube.

3.7 Model Considerations

Although not addressed in great detail, there was some discussion at the workshop on model options. For LES, two community models were suggested as being appropriate for addressing the key science questions—the System for Atmospheric Modeling (SAM) and the Weather Research and Forecasting (WRF) model. SAM is an anelastic model designed specifically for LES and CRM and has periodic boundary conditions. WRF is a nonhydrostatic model that can be run at a large range of scales. While not specifically designed as an LES, WRF has seen increasing use in this mode and its performance compared with other models has been documented. It should be noted that there are other LES model options, but these were the models most familiar to the workshop participants.

Both models have good microphysics, coupled radiation and land-surface models, although WRF tends to have more options. Both SAM and WRF have their advantages and disadvantages. SAM is much faster, but it lacks open boundary conditions and aerosol/chemistry packages. WRF is a slow LES but is more versatile and could be configured in nested, open boundary condition mode. It is widely used in the mesoscale meteorology world. Data assimilation is commonly performed. Its compatibility with WRF NWP models (RAP, HRRR) and the physics package options, including National Center for Atmospheric Research (NCAR)'s Community Atmosphere Model (CAM) and single-column CAM (SCAM) physics are seen as advantages. WRF, coupled to aerosol and chemistry models (WRF-CHEM), is also widely used in testbed mode.

Other Considerations

Both SAM and WRF run on conventional central processing units (CPUs) as opposed to the faster graphical processing units (GPUs) used by the Dutch LES (GALES; Neggers et al. 2012). It was noted that the significant development associated with GPU-ready C++ code is likely not warranted at this stage of the project.

A number of technical topics were raised, including the need for:

- automation of routine simulation (scripts)
- non-proprietary codes
- type of model output to be saved (statistical output, forcing data sets, other)
- modularity of analysis packages for portability between models
- use of graphical user interfaces (GUIs) for quick point-and-click comparisons of thumbnails, timeseries, and PDFs of key fields
- homogenized data formats

- providing forcing sets to the community for wider impact
- inclusion of model output in the ARM Data Archive
- software version control and tracking
- metrics for success
- model uncertainty quantification (parameteric, structural, algorithm, etc. uncertainties)
- future code development to take advantage of GPUs.

The brevity with which this is presented reflects the short amount of time spent discussing the issues and belies their importance—*ad hoc* groups will have to deal with these in more detail.

4.0 Next Steps

4.1 Perform a Pilot Study

Before setting up an operational model system for the ARM SGP site, there was a clearly stated need to first undertake a pilot study, through which the modeling system would be designed, and preliminary evaluations of the study could be done to ensure that the modeling configuration was suitable to address the identified scientific priorities. The pilot study would likely go on for a few months, or until a substantial number of individual cases (an order of 15) have been collected. It was suggested that the system be kept as simple as possible during the pilot study.

The goals of this pilot study would be to:

- define the scientific theme the model will target (likely shallow convection) and develop the end-to-end process (forcing development to simulation to analysis requirements)
- develop an understanding of computational requirements, data storage needs, missing elements, etc.
- use the pilot study to define specifications for the routine simulations and associated analysis tools
- design a system that would allow other scientists to flexibly perform their own simulations or analysis
- address some of the issues raised in section 3.7 (bulleted list).

Early decisions will be the choice of model(s) and whether to address both shallow and deep convection during the pilot study. For example, targeting a spring through summer period would include both regimes and allow issues associated with each to come to the fore.

4.2 High-Priority Measurement Activities: Redeployment, Augmentation, and Evaluation

The workshop identified clear measurement needs to address the scientific questions. Many of the identified needs can be supported or partially supported by instruments returning from the TWP. Activities that should be pursued in the near term include:

- deployment of four profiling sites at SGP to support the shallow convection domain
- evaluation of soil moisture measurements and development of a measurement standard
- review of land-atmosphere coupling measurement suites to optimize coupling of soil moisture, surface flux, boundary layer structure, and radiation
- deployment of new land-atmosphere coupling sites near the SGP CF
- development of a land-surface characterization survey of the SGP region to permit upscaling of local land-atmosphere coupling measurements to the larger region
- deployment of scanning cloud radars from the TWP at a distance of ~4–7 km from the SGP CF (optimum sampling range)
- deployment of the Manus C-band radar southeast of the SGP CF
- feasibility review of multi-wavelength lidar for aerosol profiling.

4.3 Longer-Term Goals

Longer-term goals are not dealt with in great detail due to the early stage of the project. However, some key goals include:

- the use of ARM observations for data assimilation in mesoscale models in order to provide an improved background model for the LES forcing data
- data assimilation in mesoscale models that nest LES within a coarser grid model with open boundaries to incorporate horizontal heterogeneity in forcing, particularly interesting for deep convection
- upgrades to the high-resolution model's representation of aerosol and chemistry and/or considering a model like WRF-CHEM that already treats these processes
- review of the highest impact aerosol measurements at the CF and selected extended facilities (in conjunction with aerosol model upgrades)
- deployment of larger, ~200 km radius profiling sites to support deep convection simulations
- deployment of the AMF1 W-band cloud radar to the SGP CF and replacing it with one of the Ka-band (35 GHz) radars returning from the TWP (following the GOAmazon Deployment).

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Appendix A
Summary of Key ASR Science Questions

Shallow Clouds

- How do cloud macro and microphysical properties relate to the environmental thermodynamic, and near-surface properties, and their variability?
- What role does mesoscale inhomogeneity of liquid water or vertical velocity on scales of tens of km play in determining radiative responses and drizzle formation in low clouds?
- What factors control vertical and horizontal entrainment rates between clouds and the ambient air?
- What relationships among various microphysical and dynamical factors determine low cloud precipitation onset, rate and efficiency?
- What factors determine cloud phase in low cold clouds?
- What is the appropriate level of complexity to best represent cloud phase in climate models?

Deep Convection and Midlatitude Storm Clouds

- How does vertical velocity vary in height, space, time, and strength? How does this variability impact precipitation formation, cirrus production, and convective system lifetime in deep convective systems?
- How can we better characterize sub-grid inhomogeneity in temperature and moisture and incorporate this knowledge into cumulus parameterization?
- What is the vertical and spatial distribution of diabatic heating in convective systems?
- How can we better constrain convective microphysical processes, including those responsible for cirrus, graupel, snow, and rain production, in numerical models?
- What spatial resolution is adequate for climate models to resolve the important radiative and precipitation properties of midlatitude storm clouds?
- How can climate models better predict the occurrence of snow versus rain in winter storms?

Cloud, Aerosol, and Precipitation Interactions

- How important are factors such as the vertical transport in cloud updrafts and downdrafts, aqueous chemistry in cloud drops, and scavenging by precipitation in the life cycle of the aerosol?
- What processes control ice nucleation and its impact on ice-containing clouds (e.g., Arctic stratus, altostratus, cirrus, convective clouds)?

Aerosols

- What are the formation mechanisms and growth rates for aerosol particles?
- How do aerosol optical properties relate to particle size, morphology, mixing state, and composition?
- What is the role of absorbing aerosols on heating rate profiles, atmospheric circulation, cloud development, and precipitation?
- What are the roles of aerosol size, composition, and mixing state on cloud condensation and ice nuclei spectra?
- How are aerosols processed by clouds (e.g., aqueous-phase chemistry, droplet coalescence and wet removal)?

Appendix B
Instrument Redeployment and Augmentation

As noted previously, a great deal was said about measurements that could support routine modeling at the SGP site. This section captures the details of the instrument discussions, needs, and gaps.

Temperature, Humidity and Wind Profiles

The background atmospheric state is currently characterized by: Vaisala RS-92 radiosondes, normally launched four times daily at 00, 06, 12, and 18 UTC; an Atmospheric Emitted Radiance Interferometer (AERI), used to derive profiles of temperature and humidity in the lowest few kilometers; a Raman lidar, which provides profiles of temperature and humidity throughout the non-cloudy troposphere; wind profile measurements by 915 MHz radar wind profilers at the Central Facility (CF) and at three intermediate facilities located approximately 15 km from the CF (Figure 1) and by a Doppler lidar located at the CF. The Doppler lidar also provides measurements of vertical motion in non-cloudy air.

To obtain continuous lateral boundary conditions for routine model simulations, an array of remote sensing stations was proposed. This array would comprise four stations, located approximately 30 km from the CF (see sites labeled "AERI & Doppler Lidar" in Figure 1). These sites could be collocated with existing (and proposed) extended facilities (**http://www.arm.gov/sites/sgp/E**). These extended facilities currently include measurements of surface heat fluxes, radiative fluxes, and basic meteorological parameters. An AERI and a Doppler lidar would be added to these measurements to obtain profiles of temperature and humidity in the atmospheric boundary layer. Two AERIs and one Doppler lidar will be returning from the ARM TWP sites and could begin the development of this array.

In addition to the AERI and Doppler lidar, a microwave radiometer could be added to these profiling sites to provide the integrated water vapor column. By comparing boundary layer profiles from the AERI with the total integrated water vapor from the microwave radiometer, variability in the combined mid- and upper-troposphere can be determined. Alternately, a profiling microwave radiometer could be used to obtain additional information about vertical structure of water vapor. However, the resolution and accuracy of the microwave profiler should be evaluated before deploying at multiple sites to determine what information that instrument could provide.

It would also be desirable to obtain information about the spatial variability of water vapor across the observation domain. It was proposed that tomographic techniques could be applied to obtain coarse spatial distributions. These retrievals could make use of a network of scanning microwave radiometers or Global Positioning System (GPS) receivers.

Much of the discussion at the workshop related to the background atmospheric state centered around the lateral boundary and characterizing spatial variability. However, there was also input at the workshop and through material submitted beforehand, to enhance measurements of the atmospheric state at the SGP CF. Two suggestions along these lines were to increase the number of radiosonde launches at the CF from 4/day to 6 or 8/day and to deploy a tall tower (>300 m). Two additional radiosonde launches in the morning would help resolve the development of the convective boundary layer while a tall tower could provide continuous measurement of key parameters. The tallest tower currently at the CF is 60 m, so a 300-m tower would represent a significant advancement. However, the boundary layer depth often exceeds 1 km, so it would be very difficult to consistently measure the full depth.

Characterization of the Land Surface

Currently, an extensive set of measurements to characterize land-atmosphere coupling are deployed at 15 active SGP extended facility sites. Each extended facility site includes measurements of sensible and latent heat fluxes using either Eddy Correlation or Bowen Ratio methods, broadband radiation, narrowband radiation for the retrieval of aerosol column optical properties, soil moisture and temperature, and basic meteorological parameters (**http://www.arm.gov/sites/sgp/E/instruments**).

Figure 2. Google Earth image of the ARM CF from April 13, 2013. The red cross spans an area with a radius of 5 km and the blue cross spans a radius of 10 km. (Image courtesy of Alice Cialella).

With the exception of two sites collocated with the CF, the distance from the closest Extended Facility to the CF is approximately 30 km. Figure 2 depicts the heterogeneity of the SGP region. A dominant feature is a quasi-uniform grid of patches in which the varying land use is evident. Land use in this area is predominantly pasture, corn, or wheat. Two streambeds are also evident within approximately 10 km of the CF.

The general sense of the discussion was that the extended facilities did a good job of characterizing the land-atmosphere interface; however, several avenues were discussed that would improve the representation of this interface: improving measurements of soil moisture, ensuring that surface flux sites are complete and consistent, adding extended facilities nearer to the CF, and developing an extensive (and annually updated) database of land use in the observation domain.

Currently, ARM uses several methods for measuring soil moisture. Water matric potential (Campbell 229) sensors are used at extended facilities where surface fluxes are measured using the eddy correlation method. At these sites, profiles of soil moisture are obtained. At extended facilities where Bowen Ratio measurements are used to derive surface fluxes, soil moisture is measured at a single depth (2.5 cm). A review of ARM's soil moisture measurements is needed to determine the best method for measuring soil moisture near the surface (for comparison with satellite retrievals) and to determine the best method for measuring volumetric soil moisture over a wide range of moisture content. The matric potential sensors lack the sensitivity to provide information in dry conditions.

The rationale for using two different techniques for measuring surface heat fluxes is that the two methods provide more accurate results in different settings. However, it is important to understand how these measurements relate to each other. Various studies have been done to explore this relationship. Still, ARM should strive to clarify the interpretation of fluxes measured across the SGP domain using these two techniques, combining the two techniques wherever possible.

Heat fluxes are related to soil moisture and to the structure of the planetary boundary layer. Therefore, wherever possible, it is desirable to combine measurements of each of these land-atmosphere system components. The profiling sites discussed in the previous section provide information about the boundary layer structure and depth. Wherever these profiling sites are deployed, soil moisture and heat flux (as well as radiative fluxes; see discussion under "other topics") should also be measured to obtain the complete vertical profile of heat transfer from the soil through the boundary layer.

It was noted that the current distribution of extended facilities already spans a range of surface types. However, it would be desirable to have several sites within the ~30 km domain proposed for shallow convection simulations. One set of candidate sites would be the 915 MHz wind profiler intermediate facilities. The 915 MHz profilers provide information about the boundary layer structure so these sites, if suitable for surface flux measurements, would provide additional sites with soil through boundary layer integrated measurements. Collocation with other instruments is also desirable (e.g., see siting of scanning cloud radars in the next section) because of the availability of infrastructure. Spanning surface types should continue to be a consideration. Three eddy correlation systems will be returning from the Darwin TWP site.

As noted previously, the SGP region is a patchwork of land-use types. In addition, there is a regional gradient with drier conditions to the west and wetter conditions to the east. To best support modeling efforts, it is important to capture this variability and the integrated effect of the lower boundary. Therefore, ARM should strive to collect any available information about land use across the domain (updating annually as usage may change from year to year). In addition, characterization of plant types through measurements such as leaf area index are needed in representative patches across the domain. Combining this survey with measurements from individual stations and with satellite retrievals across the domain would provide the optimum representation of surface properties.

3D Cloud Microphysical and Dynamical Properties

The SGP CF currently includes a zenith-pointing 35 GHz (Ka-band) cloud radar, a 915-MHz radar wind profiler, and a dual frequency (35 GHz/94 GHz; Ka-/W-band) scanning ARM cloud radar (Ka/W-SACR). The zenith-pointing radars provide continuous vertical distribution of clouds and precipitation while the Ka/W-SACR is operated in a set of modes designed to provide information on the spatial distribution of clouds and also spend time pointing vertically, augmenting the vertically pointing radar facility with a second cloud radar (W-band) frequency. The Ka/W-SACRs have very narrow beam widths (less than half a degree) and require longer dwell times than operational weather radars used to detect much larger precipitation drops. Therefore, it is not possible to scan the full hemisphere with one of these cloud radars in a period reasonable to sample cloud evolution. Possible enhancements to the current measurement set were discussed to better sample the cloud population over the SGP CF.

The radars coming back from the TWP can be used to achieve a significant enhancement in the ability to measure cloud fields in the vicinity of the SGP CF. To begin with, an improvement in vertical cloud profiling at the CF can be achieved by moving the zenith-pointing W-band radar, currently deployed with the first ARM Mobile Facility, to the SGP CF.[(4)] With the right antenna, the W-band radar has the potential of being the most sensitive instrument to small cloud particles. Many shallow convection clouds at SGP consist of very small drops (~5 µm), which makes them hard to see with longer wavelength radars. Combining the W-band radar with the Ka-band radar at the SGP CF (and with the presence of the 915-MHz profiler) would optimize that site for the profiling of all types of clouds and will make the presence of the Ka/W-SACR redundant (since the W-band frequency will always be available in the column).

Two Ka/X-SACR radars will also be coming back from the TWP sites and could be deployed near the SGP CF. A very useful configuration would be to deploy these radars approximately 5–10 km from the CF as shown in Figure 1. From this distance, these scanning radars could provide dense sampling of cloudy volumes encompassing the CF. Scanning cloud elements with two radars over the CF in this way would allow the derivation of 3D cloud motions.

The scanning cloud radar systems returning from the TWP are Ka/X-band systems, designed to operate in an environment with frequent precipitation. Moving the Ka/W-band system away from the CF to one of the inward-facing sites and placing one of the Ka/X-band systems at the other inward-facing site would give the advantage of the best of both systems, The Ka/W system would maximize sensitivity over the CF, while the Ka/X system would maximize performance during precipitation.

(4) The plan is to deploy one of the Ka-band radars coming back from the TWP with the ARM Mobile Facility. Currently, the first ARM Mobile Facility is the only facility that does not have a zenith-pointing Ka-band radar, so this exchange would lead to more uniform capabilities across the sites.

Careful consideration will need to be given regarding how to optimize the scan strategy of multiple cloud radars. However, two or three radars will provide a great deal of flexibility and continuity. A desirable feature of a scan strategy is to have finely spaced scans over the CF with short revisit cycles (an order of several minutes). We will need to consider if the second SACR returning from the TWP site should also be stationed at the SGP site or whether we should duplicate this radar configuration at the NSA supersite. This would certainly ease data production at the two supersites and should be able to address the need to characterize the 3D cloud properties. Periodically, one or more of the radars could be operated at times in 2D, along wind or across wind modes, to minimize the revisit period. Finally, it would be of interest to implement cloud-tracking algorithms and spend some time following the evolution of specific cloud elements.

During the workshop it was emphasized that during shallow convection periods, the description of the cloud field will also be possible with the network of the three X-band SAPRs. These radars are sensitive enough to detect clouds and early precipitation echoes from shallow precipitating cumuli, thus providing information on the meso-scale organization of shallow convection. In addition, using low-level scans, the network of X-band radars can be used to derive low-level divergence during the summer months using backscatter from insects.

3D Precipitation and Storm Dynamics

With one C-band radar in place at SGP and a second returning from TWP, the question was posed regarding how the C-band radars could be configured to be useful for deep convective studies. Oklahoma is a very well-observed location when it comes to operational and research precipitation radars, and these radars (**Nex**t-Generation **Rad**ar (NEXRAD) network) provide a low-level precipitation mosaic. However, because they do not belong to ARM they cannot be used as a research tool to probe and monitor convective systems of interest with the temporal and spatial resolution needed. Already the ARM-owned precipitation radar network at the SGP is significant. It consists of three X-band radars and a C-band polarimetric radar located 21 km north of the SGP CF. During deep convective periods, the existing network of X-band radars provides multi-Doppler measurements, enabling the retrieval of vertical velocity in deep convection. At the same time, the C-band radar provides large-scale coverage and complementary radar reflectivity information for vertical air motion retrievals. Finally, the four radar wind profilers located at the CF and three intermediate facility sites provide additional information on the vertical structure of deep convective systems, acting as validation points for the multi-Doppler retrievals performed by the X- and C-band network. Adding the C-band radar from the TWP will add great value to the radar operations during precipitation periods. First, it will extend the useful domain where we can characterize the horizontal and vertical structure of the precipitating systems. Positioning the two C-band radars some distance (40–50 km) from one other, but with overlapping scanning areas, would create an overlapping lobe ("dual lobe"). The orientation of this lobe should be more or less perpendicular to the typical direction of the incoming squall-lines at SGP (NW to SE). This would give a cross-section through the rain band. In addition, in this case, we can dedicate one or two of the X-band systems to observe only the upper part of the convective clouds, providing critical observations near the top boundary of our observations to better constrain our continuity-based algorithms that are used to derive the profile of the vertical air motion.

The idea of having an upwind measurement site was discussed. It may be useful for providing information on systems propagating into the LES domain, additional data for forcing data sets, and/or other scientific purposes, though there was not a strong case made for an upstream measurement site at this time. It was noted that Geostationary Operational Environmental Satellite R-Series Program (GOES-R) will be deployed in 2017, providing high time and space resolution infrared (2 km) and visible (~few hundreds of meters) data that would be useful to tie into the supersite data and LES model evaluation.

Aerosol Properties

The SGP CF has a long record of aerosol measurements, including aerosol optical depth, **near-surface** aerosol scattering, absorption, hygroscopicity condensation nuclei (CN), and CCN. Fine-mode aerosol size distribution measurements have been collected from a differential mobility analyzer (DMA) since late 2005, and an aerosol particle sizer (APS) was added in 2010 to measure coarse mode particle size distribution. Most recently, ARM deployed an aerosol chemical speciation monitor (ACSM) in late 2010 and a scanning mobility particle sizer (SMPS) particle size distribution instrument in 2014. A nano-SMPS and an SO2 monitor will also be added in 2014 to support the study of new particle formation. Additional needs for aerosol measurements include improved measurements of composition and optical absorption at the CF and measurements of aerosol distributions as a function of height as well as variability across the domain.

Suggestions for instruments that could be deployed to improve the measurement of aerosol composition include:

- **Single Particle Soot Photometer (SP2)**: Measures black carbon (BC) concentration, but secondary products provide BC size distribution and shell-coating thickness as a function of size.
- **High-Resolution Aerosol Mass Spectrometer (HR-AMS)**: While ARM has an ACSM deployed at the SGP site, the type of secondary products that can be generated from it are limited. The HR-AMS can be used to produce size distribution of composition, O:C ratios, and so on, providing more detailed information on aerosol microphysical properties.
- **PTR-MS**: This instrument measures volatile organic compounds. Deploying them at select surface flux measurement sites would provide measures of biogenic emission fluxes, which would be critical for aerosol modeling.

Aerosol optical absorption measurements have been made at the SGP CF using a three-wavelength Photoacoustic Soot Spectrometer (PASS-3), and Particle Soot Absorption Photometer (PSAP) have been deployed at the SGP site. Still, there are questions about the uncertainties in these measurements, so additional work needs to be done to characterize these instruments. There is interest in exploring possible alternatives.

Currently, aerosol measurements at the SGP are at the surface and at the CF. In the past, there were routine flights of number density and optical properties. It would be highly desirable to obtain information about **vertical profiles** of aerosol properties on a routine basis. Routine flights with additional information such as CCN concentration and hygroscopicity would provide useful new information. Other than routine aircraft measurements, one way to learn more about vertical profiles of aerosol properties would be to deploy a multi-wavelength lidar at the CF. A three-wavelength lidar has been deployed on the NASA King Air and it has been shown that this configuration can be used to derive profiles of aerosol optical properties (Müller et al. 2014). Deploying a system like this on the ground, looking up, would present different challenges, although it could potentially offer a means of obtaining continuous vertical profiles. The most direct way to get to such a ground-based system would be to combine one of the ARM HSRL lidars with the Raman lidar already deployed at the CF. It is possible that this two-wavelength system could be used in conjunction with a spectral radiometer to constrain the retrieval process. Alternately, a near-IR lidar could be added. If implemented, routine flights over a limited time-period would be essential in evaluating these remote sensing approaches.

In addition to vertical profiles, it would be useful to get some information on spatial variability. For example, it would be useful to deploy one (upwind) or two (upwind and downwind) SMPS and APS configurations to routinely measure aerosol size evolution as air parcels pass over the site.

An area that needs additional study is **aerosol removal**. Dry and wet deposition could both be evaluated with some additional measurements. If an aerosol particle counter would be deployed at select surface flux measurement sites, a measure of dry deposition could be obtained. Meanwhile, analysis of rainwater could be used to provide information about wet deposition on a routine basis.

In addition to the existing ARM measurements, an aerosol modeling testbed for the SGP supersite could utilize routine measurements of aerosol mass and composition collected by the United States Environmental Protection Agency (EPA). Hourly bulk PM2.5 and PM10 measurements are collected from a number of stations close to the SGP site, but there are relatively few stations that provide speciated aerosol composition. Nevertheless, these data are valuable and provide a regional context for the more detailed and extensive ARM SGP measurements. In addition, regional data on trace gases (e.g., ozone and SO2) are needed to assess the performance of aerosol forecasts.

Intensive operational periods (IOPs) will be required to fully address many of the science questions related to aerosol and cloud-aerosol interactions, supplementing the SGP supersite measurements. Remote sensing will not provide all the detailed information on aerosol and cloud properties aloft needed by modelers. Therefore, the operational SGP supersite could be supplemented with occasional IOPs (e.g., in different seasons) to obtain detailed aerosol mass, composition, size, morphology, volatility, and optical properties of aerosols using research aircraft and supplemental surface measurements. Airborne lidars (e.g., HSRL) and sky scanning spectrometers (e.g., 4STAR) provide spatially varying vertical profiles of aerosol optical properties and radiation that coincide with the in situ measurements. The aircraft flights can be designed for cases with and without cloud sampling and the G-1 aircraft is already equipped with various cloud probes to measure cloud microphysical quantities. The aircraft should also be equipped with a counterflow virtual impactor (CVI) inlet so that interstitial and cloud-borne aerosols can be sampled separately.

Radiation Measurements

Radiation measurements were not discussed extensively during the workshop, but a whitepaper submitted as input to the workshop described a need for radiation measurements and proposed some changes that could be made to improve the characterization of radiation around the SGP region to support high-resolution modeling.

Large uncertainties remain in our ability to measure and model the radiative impact of clouds. For example, radiative closure, or the ability to match measured irradiances with radiative transfer calculations, is hindered by insufficiently constrained cloud property retrievals, observational sampling uncertainties, and the complexities of observing and modeling inhomogeneous clouds. Moreover, the persistent bias between observed and modeled column absorption for complex inhomogeneous cloud fields remains an unsolved problem. Current measurements are limited in their ability to quantify possible causes of the bias, including cloud inhomogeneity, observational view mismatches between satellites and ground instruments, cloud-enhanced aerosol absorption, and other surface or atmospheric properties.

The whitepaper authors recommended three instrumentation changes to better measure cloud radiative effects, determine LES-domain cloud and radiation properties to test and constrain LES model simulations, and ultimately improve climate model parameterizations.

1. **Higher density of surface flux measurements**: At a minimum, three concentric "rings" of surface radiometer facilities with logarithmically spaced radii are recommended to give a range of possible scales for comparison.

2. **Narrow field of view instrumentation**: The addition of one or more Cimel sunphotometers capable of high-temporal resolution zenith radiances would allow us to measure cloud optical depth and effective radius under non-precipitating cloud conditions, including broken clouds.

3. **Comprehensive spectral albedo measurements**: Spectral radiative closure gives much more information than broadband radiation to understand cloud properties and mismatches between observations and calculations, including the wavelength dependence of scattering phase function and asymmetry parameter in a 3D cloudy atmosphere and absorption properties of aerosols and condensed water. Current ARM shortwave spectral measurements (SAS-Ze, SAS-He, SWS, RSS, multi-filter rotating shadowband radiometer (MFRSR), Cimel) give us the potential to use spectral radiative transfer, but adequate measurements of the spectral surface albedo of different surface types are needed to constrain detailed spectral radiative transfer modeling. However, current surface-spectral albedo estimates at SGP are limited both spatially and spectrally—spatially in that they are drawn from only two upwelling measurements (10 and 25 m tower), and spectrally in that they are keyed to multi-filter radiometer (MFR) filter wavelengths below 1 micron. Collocated MFRSR and MFR tower measurements including the addition of 1625 nm channels would address both of these significant limitations.

Appendix C
Agenda

DOE Workshop to Explore Science Topics, Modeling Strategies and Measurement Needs Associated With the Next Generation ARM Facility: Phase I, the U.S. Southern Great Plains

May 19–20, 2014, at the Bethesda Doubletree Hotel

Agenda

Monday, May 19

8:00-9:00 **Opening Activities**

- Introductions
- Statements from DOE
- Statement of background and meeting goals
- Brief discussion of the CAPT, FASTER, AMT, and KNMI modeling testbeds

9:00-10:30 **Identification of Science Goals**

- Overview of homework responses

  Present the grouping of responses to homework assignments (science questions and approaches)

  Additional ideas and/or refinement of the ideas presented

- Discuss science goals

  Identify the most pressing issues without being too encumbered by practicalities

- Selection of focus goals

Prioritize science goals based on science impact and the ability of DOE to advance a given topic

The outcome of this section would be ~3–5 science goals.

10:30-12:00 **Analysis of Science Goals**

- Regime analysis

  For each of the selected science goals, discuss the meteorological regimes under which the goal can be addressed and the likelihood of observing these conditions at the SGP.

- Requirements

  For each of the selected science goals, discuss what meteorological parameters are required to be observed and at what temporal and spatial scale to advance understanding of the science topic.

12:00-1:00	**Lunch**	

For the main afternoon segments, break the group into two roughly equal parts to maximize collaborative discussion.

1:30-3:30 **Experiment Strategies I (in two groups)**

Development of draft strategies: drill down to the most compelling goals and identify one or more modeling strategies for each of these science goals, along with the measurements required to advance those goals. Emphasis should be placed on generating ideas rather than on implementation details.

3:30-4:00 **Break**

4:00-5:30 **Experiment Strategies II (all)**

Refinement of strategies: continue the discussion of modeling strategies. Exploration of the desirable vs. the more realistic ends of the spectrum, with consideration of modeling and observational limitations.

Rapporteurs provide notes to Graham and Jim.

5:30 **Adjourn for the evening**

Tuesday, May 20

8:00-10:00 **Experiment Strategies III (in two groups)**

Bring discussions from the previous afternoon to closure. Bring in any new insights from overnight and bring plans to closure. Begin to incorporate associated measurement strategies and assess computational requirements.

10:00-10:30 **Break**

10:30-12:00 **Analysis Strategies and Wrap-up (all)**

- Discuss issues related to required data products, instrument simulators, data assimilation, and related techniques for confronting models with measurements including requirements for data access and tools to facilitate remote analysis.
- Group discussion of any remaining issues and reactions to proposals.
- Final recommendations for the most promising paths to pursue in terms of science topics and coupled strategies.

12:00 **Adjourn**

Appendix D
Meeting Attendees

U.S. Department of Energy

Wanda Ferrell	Atmospheric Radiation Measurement Climate Research Facility
Gerald Geernaert	Climate and Environmental Sciences Division
Sally McFarlane	Atmospheric System Research
Rick Petty	Atmospheric Radiation Measurement Aerial Facility
Ashley Williamson	Atmospheric System Research

Co-Leads

Jim Mather	Pacific Northwest National Laboratory
Graham Feingold	NOAA/Earth System Research Laboratory

Participants

Chris Bretherton	University of Washington
Christine Chiu	University of Reading
Dave Cook	Argonne National Laboratory
Satoshi Endo	Brookhaven National Laboratory
Jerome Fast	Pacific Northwest National Laboratory
Rich Ferrare	NASA/Langley
James Hack	Oak Ridge National Laboratory
Marat Khairoutidinov	The State University of New York, Stony Brook
Steve Klein	Lawrence Livermore National Laboratory
Pavlos Kollias	McGill University
Vince Larson	University of Wisconsin, Milwaukee
Allison McComiskey	NOAA/Earth System Research Laboratory
Roel Neggers	Cologne
Louise Nuijens	Max Planck Institute
Robert Pincus	University of Colorado
Dave Randall	Colorado State University
Joseph Santanello	NASA/Goddard Space Flight Center
Chris Snyder	National Center for Atmospheric Research
Dave Turner	NOAA/National Severe Storms Laboratory
Minghua Zhang	The State University of New York, Stony Brook

Observers

Thomas Boden	Oak Ridge National Laboratory
Nicki Hickmon	Argonne National Laboratory
Mark Ivey	Sandia National Laboratory
Douglas Sisterson	Argonne National Laboratory
Jimmy Voyles	Pacific Northwest National Laboratory
Shaocheng Xie	Lawrence Livermore National Laboratory

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