ACME-ARM-ASR Coordination Workshop

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Contents

DRAFT

Executive Summary

The Climate and Environmental Sciences Division (CESD) of the U.S. Department of Energy's Office of Biological and Environmental Research (BER) focuses on advancing 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. CESD climate activities related to atmospheric processes include observations through the ARM Climate Research Facility, atmospheric research and model parameterization development through the Atmospheric System Research (ASR) program, climate model development and climate research through the Accelerated Climate Modeling for Energy (ACME) project, along with other computationally-focused model-development activities within the CESD Earth System Modeling (ESM) program, as well as development of robust model analytical and testing frameworks at multiple scales through the Regional & Global Climate Modeling (RGCM) program. This workshop focused primarily on improving model treatment of atmospheric processes as a means to focus discussion and did not address research on terrestrial ecosystem and subsurface processes, which are also part of the CESD research portfolio.

While ARM, ASR, and ESM have made considerable contributions to understanding of the atmospheric component of the Earth system and the development and evaluation of global climate model (GCM) parameterizations, more synergy appears possible through coordination to take advantage of new model and observational resources now available. The objectives of this workshop were: 1) to identify areas where atmospheric processes are deficient in climate models generally and in the ACME model particularly, where work across scales and disciplines is likely to lead to important improvements in model process, prediction and science, 2) to increase communication between the groups and identify barriers to knowledge transfer between process level understanding and development and implementation of improved parameterizations in GCMs.

The workshop brought together representatives from the ARM, ASR, ACME and ESM communities and was structured to address a series of questions:

- What are the highest priorities for development of model representations of cloud/aerosol microphysics, cloud dynamics, boundary layer processes, and convection, and what are the sticking points hindering improvements in these areas?
- What critical measurements are necessary for improvement of models, particularly (but not exclusively) for ACME and models of DOE interest at the large eddy simulation, cloud resolving, and regional scales?
- What strategies may be developed and applied to facilitate comparison of models (including those of varying scales) and measurements and to improve communication and coordination between the measurement and modeling communities?

Prior to the workshop, participants and members of the larger CESD community were asked to submit white papers addressing these questions. From these white papers, three broad

DRAFT

science themes emerged: microphysics (including the broad range of aerosol and cloud microphysical processes), boundary layer processes, and convection (including the transition from shallow to deep convection). The workshop was organized around breakout sessions to explore opportunities in these three broad science themes, as well as a fourth overarching theme of improving communication and collaboration. The workshop also included plenary presentations from each community to provide an introduction to the issues for the other communities and to spark ideas for subsequent discussion.

Each breakout session included participants from all three (ARM, ASR, ACME) communities. Discussions in these breakout sessions were highly illuminating because they often illustrated a lack of understanding by one community of an issue of concern to another, highlighting the value in bringing these groups together. The breakouts resulted in wide-ranging suggestions for advancing the three thematic areas and for increasing effective interactions among the three communities.

There were a few measurement and data items that captured the attention of many participants, including recognition of the importance of improved characterization of specific cloud and aerosol properties and features, cloud-scale vertical velocity, and entrainment rates (much more detail is provided below in this report). The discussion also highlighted the importance of long-term and simultaneous measurements of a number of fields that allow the identification of statistical relationships between important variables and processes to identify "emergent behavior" and a recognition of the importance of capturing these relationships under a range of conditions. The relationships provide very strong constraints on models and parameterizations. There were also suggestions for analysis and modeling strategies that might connect the modeling and observational communities much more strongly, including:

- A sustained activity integrating the model and observation communities more closely involving a hierarchy of LES, CRM, and Global Models, focused on ARM megasites and ARM Mobile Facility sites;
- A need to coordinate work more closely among models of differing scales, such as LES and GCM, in order to develop and test processes;
- A closer connection between ARM data and model verification diagnostics engaging all three (ARM, ASR, ACME) communities, with improved adherence to community conventions for data formats to facilitate use of these data sets. Participants noted that ACME is currently developing diagnostics and has expressed interest in obtaining input from the observation community. At the same time, ARM is making an effort to develop ARM diagnostic packages and has expressed interest in obtaining input from the modeling community. Thus, it is an auspicious time for increased collaboration.
- More attention to the use of instrument simulators (e.g., radar) to make model output and measurements more readily comparable;
- A recognition that there is a lot of remaining "gold" in existing data sets that could be mined for more science. Sustained support from all three programs for mining historical measurements for specific science goals would be useful to exploit the additional scientific information in that data;

DRAFT

- Recognition of the potential for, and remaining issues with, “benchmark” model calculations that may provide comprehensive treatments of particular atmospheric features. Increased complexity does not always immediately produce increased fidelity, and comprehensive treatments still disagree with each other and observations, so more work is needed to resolve these issues. (This is discussed more in the body of the report).

Finally, each session included discussion regarding how to better link the three communities. The richness of the discussion at this workshop led to suggestions for additional similar meetings in the future. There was enthusiastic support for organizing efforts that included members of all three communities around targeted science themes with joint funding and coordination of science goals across programs.

DRAFT

Acknowledgements

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Introduction

The Climate and Environmental Sciences Division (CESD) of the U.S. Department of Energy's Office of Biological and Environmental Research (BER) focuses on advancing 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. CESD climate activities related to atmospheric processes are organized around several research programs and facilities designed to convert observations, diagnostics of atmospheric processes and surface-atmosphere interactions into fundamental understanding of the climate system and physically-based parameterizations that can be implemented in global climate models (GCMs) used for climate change projections. This workshop included participation primarily from researchers funded within three BER programs, which are described in more detail in Appendix B: the Atmospheric Radiation Measurement (ARM) Climate Research Facility, the Atmospheric System Research (ASR) program, and the Accelerated Climate Modeling for Energy (ACME) project within the Earth System Modeling (ESM) program.

Although ARM, ASR, and ESM have made considerable contributions to the development and evaluation of GCM parameterizations, the advent of the ESM ACME project has further elevated the importance of knowledge transfer between the observational and modeling components of CESD. Optimization of the pathways by which observations are converted to process-level understanding and then to more physically realistic climate model parameterizations is required for ACME to address its primary scientific goals. The emerging awareness of the challenges involved in doing this is based on the recognition of the complexity of the Earth system, and the delicate balance between processes that govern its response to the climate and environmental changes. There appear to be benefits to a more integrated approach that more closely links observations with parameterization development for global models, better links the three communities, and addresses persistent challenges to understanding the processes that govern atmospheric clouds and dynamics, the scale mismatches between the observations and the models, and challenges in translating observed behaviors into robust parameterizations. Given the advent of the DOE ACME GCM effort within CESD and the very strong ARM and ASR activities, an unprecedented opportunity exists to more closely connect atmospheric observations to atmospheric model evaluation and development. DOE's investment in climate modeling across the range of important model scales, in coordination with addressing critical observational needs, provides DOE with a unique opportunity to impact climate prediction capabilities that other government agencies cannot achieve.

Thus, a workshop was convened at DOE Germantown Headquarters on October 21–22, 2015, bringing members of the ARM, ASR, and ESM communities together for the first time. There were four main objectives for the workshop. The first was to identify areas where atmospheric processes are deficient in climate models generally and in the ACME model particularly, where work across scales and disciplines are likely to lead to important improvements in model process, prediction and science. The second was to initiate communication between the groups in a more intimate setting than the typical large meeting so that more time could be spent on discussion and exchange of ideas rather than formal

DRAFT

presentations. The third was to better understand the scientific challenges involved in the transfer of knowledge at the process level to the development of improved parameterizations, and from the development of parameterizations to their implementation in GCMs. The fourth was to begin developing strategies for future ACME model development and evaluation to make optimal use of the insights that can potentially be gained from ARM data products and data analyses and ASR process understanding and parameterization development. Although the CESD climate portfolio also includes extensive research on terrestrial ecosystem and subsurface processes, this workshop focused primarily on improving model treatment of atmospheric processes.

Prior to the workshop, meeting participants and others from the ARM-ASR-ESM communities were invited to submit brief white papers to provide initial thoughts on science gaps and challenges and strategies for addressing these issues and drawing the three DOE communities together. The input from these white papers informed the development of an agenda for the meeting. The agenda included a few plenary presentations to motivate discussion and a series of breakout sessions. The first three breakout sessions focused on selected science topics where models have significant persistent deficiencies and where alignment of work across scales and disciplines are ripe for rapid improvement in the models: microphysics (including cloud-aerosol interaction, cloud particle nucleation and behavior); boundary layer structure, clouds and land-atmosphere interactions; and convection (including the transition from shallow to deep convection). These topics, whose scientific significance is highlighted in Appendix C, are important to climate change projections and are central to ARM, ASR, and ACME. The fourth breakout session focused on tying the ideas of the workshop together and looking for targeted approaches for integrating research among ACME, ARM, and ASR with the goal of transferring knowledge from the cloud scale to the GCM scale.

Breakout Sessions

Breakout 1: Cloud microphysics and aerosol-cloud interactions, including aerosol activation processes

The first breakout session of the workshop focused on aerosol processes, cloud microphysics and aerosol-cloud interactions, including cloud activation processes. The submitted white papers and the breakout discussion reviewed some of these issues, and identified opportunities to further constrain uncertainties, and improve understanding of cloud microphysics and aerosol-cloud interactions.

Aerosol and cloud microphysics gaps and associated measurement needs

There are many remaining deficiencies in understanding of the aerosol sources to the atmosphere, and the transport pathways that deliver aerosols to clouds. Two such examples are

DRAFT

the understanding and treatment in models of secondary organic aerosols and, more generally, the distribution of aerosols, and particularly cloud condensation nuclei, in GCMs. Secondary organic aerosol (SOA) is known to be important, is produced by natural and anthropogenic sources, and remains poorly understood and not fully represented in models. To improve the representation of SOA in models, it is necessary to first improve the understanding of SOA processes, which emphasizes a need for observations. To begin with, there is a need for measurement of SOA precursors to unveil their complex life cycle. Previous studies have shown that this life cycle is sensitive to the nature of the primary sources as well as interactions with anthropogenic gas and aerosol species, so there is also a need for additional measurements to expose modulation of the natural cycle of SOA by anthropogenic emissions.

More generally, there are systematic GCM errors in aerosol/cloud condensation nuclei (CCN) concentrations for particular meteorological regimes that are known to be important in the climate system. For example, simulated CCN concentrations are often found to be too small above the maritime boundary layer (Wyant et al, 2015), and aerosol concentrations in remote regions, e.g., the upper troposphere (where GCMs often overestimate aerosol concentrations), and high latitude near-surface concentrations (where aerosol concentrations are low) show obvious biases compared to observations. As with SOA, part of the problem in addressing these GCM errors is a lack of information about the true distribution of aerosols globally. So once again, additional measurements are needed. There is information globally about column integrated aerosol optical depth, and details about aerosol properties near the surface at select locations; however, there is very little information available about the vertical distribution of aerosols so measurements of vertical distributions are particularly important as a constraint for GCMs. Additionally, detailed information about aerosol properties, such as composition, mixing morphology and size distribution, is too often only available during short field campaigns. Participants noted a need for data from sustained field studies to provide longer term estimates of aerosol, cloud features, and their relationships to provide guidance in the development of model parameterizations and robust statistics for model validation. These relationships are needed for many regions of the world and meteorological regimes.

Many issues remain in the treatment of microphysics and cloud dynamics in even the most comprehensive, and highest resolution models [large eddy simulation (LES)/cloud resolving models (CRM)s, and those including spectral bin microphysics]. Models with grids larger than approximately 100 m are unable to resolve or properly parameterize the important scales of motion for driving aerosol-cloud interactions. The failure to correctly simulate these processes can lead to poor representation of cloud lifetime and to poor representation of cloud radiative properties, both resulting in large errors in radiative transfer and cloud feedback effects. There is still considerable uncertainty in parameterizing cloud and precipitation microphysics, which affect cloud dynamics through condensate loading drag, and evolution of cold pools by hydrometeor evaporation. The representation of ice microphysical processes is particularly uncertain, relative to liquid microphysics, because of basic uncertainty in process rates (nucleation, vapor diffusion, etc.) and the complexity of atmospheric ice particles (i.e., the wide variety of particle shapes/types). There is still substantial variation among LES models in their treatments of microphysics (particularly mixed phase, supercooled liquid, and ice clouds). Two

DRAFT

microphysics themes that were particularly called out during this workshop were drizzle and mixed-phase clouds.

Drizzle (very light rain) is a particularly important and problematic issue for climate models, because the phenomenon is strongly controlled by interactions among microphysical, turbulent, and dynamical processes, and because drizzle is potentially important in regulating the sign and amplitude of cloud feedbacks in climate change, it influences cloud dynamical features, and it strongly influences aerosol scavenging. ARM data are particularly good for evaluating drizzle formation in marine boundary layer clouds, e.g., at ARM's East North Atlantic (ENA) site or on the MAGIC transects. Drizzle retrievals, for example from cloud radar, are in a relatively early stage of development and are generally only available for short periods. Routinely available drizzle retrievals would be valuable as a constraint on models at all scales, from LES to GCMs. Reliable separation of cloud liquid from drizzle in retrievals for precipitating stratocumulus clouds (as well as all precipitating clouds) are also important. These measurements would be particularly effective in a critical cloud regime when combined with other measurements such as boundary layer humidity and CCN in evaluating cloud models and cloud parameterization behavior (microphysical response to aerosol changes, etc.). Connecting the occurrence of drizzle to the meteorological and cloud microphysical conditions is crucial for improving the representation of drizzle in models.

Understanding the processes regulating the partitioning of cloud (liquid/ice) phase is important, particularly at middle and high latitudes. Mixed phase clouds are a particularly important and problematic cloud type for all cloud models, and failure to correctly represent them in models leads to errors in radiative impact as well as cloud lifetime. A great deal of progress has been made in detecting and characterizing mixed-phase clouds over the past decade, but there is still a need for observations that help distinguish variations in cloud microphysics treatments, for example quantitative information about liquid and ice water content and precipitation flux at cloud base. The behavior of mixed phase clouds depends upon cloud microphysics – particularly how the cloud particles nucleate and grow, aerosols – particularly to discern which and how aerosols contribute to cloud nucleation, turbulence, and other properties of the environment. Sub-polar mixed phase clouds play an important role in aerosol removal, which subsequently can strongly influence the delivery of aerosol to remote regions (e.g., Wang et al, 2014).

Uncertain handling of supercooled liquid, mixed-phase, and ice processes leads to disparity between models even at LES/CRM resolutions. Biases in GCM middle and high latitude cloud radiative effect and differences between models in recent model intercomparisons can be attributed to deficiencies in liquid/ice partitioning in mixed-phase clouds (Zelinka et al., 2012; McCoy et al., 2015; Storelvmo et al., 2015). Ice nucleation is a particular sticking point for improving phase partitioning. Model developers need better measurements of ice-relevant aerosol properties and improved understanding of the ice nucleation process. Models need a better characterization of aerosols that can act as ice nuclei and accurate treatments for heterogeneous vs. homogeneous freezing.

DRAFT

Several new observational strategies were put forward to study the impact of aerosols on cloud properties. First, it was suggested that ARM instruments could be deployed downwind of a weak regularly emitting volcano, where the influence of aerosols on clouds is easily apparent, (e.g., Gasso, 2008). There is also potential for deliberate perturbations of cloud environments, particularly in pristine maritime regimes (see e.g., Russell et al (2013), Latham et al (2012), or Wood and Ackerman (2014)).

As noted in the previous paragraphs, there are a variety of measurements associated with aerosol and cloud properties needed to advance the understanding of key aerosol and cloud microphysics processes. However, there is also a need to characterize the environment in which clouds form, a theme that was prevalent throughout the workshop. Of particular importance is the characterization of vertical motion including detailed measurements of turbulent motion and surface fluxes of energy and water. Additionally, there is a need to obtain observations about macro-scale cloud properties to understand the role of microphysics in cloud organization. While understanding the quantitative nature of clouds [droplet density, drop size probability distribution function (PDF)] is important given the highly parameterized nature of clouds in ACME and other GCMs, often the nature of cloud *existence* is just as important. That is, given a certain forcing, does the scheme produce the same occurrence frequencies, cloud fractions, and distributions of cloud types in a given climate regime or meteorological condition as observed in a long term data set? Often the existence of a phenomenon is as important as its quantitative properties: the largest source of GCM cloud feedback in response to a doubling of CO2 is due to changes in cloud fraction (Zelinka et al., 2012). Stereo photogrammetry was noted as a new technique that can help describe the taxonomy of clouds (cloud height, cloud top vertical velocity, frequency of occurrence). ARM is currently supporting a small stereo photogrammetry effort at the Southern Great Plains site.

Analysis methods for advancing aerosol and microphysics themes

Detailed, long-term data sets are critical for calculating robust statistics, both for evaluating model simulations and for analyzing relationships from observations. White papers and workshop discussion repeatedly highlighted the importance of statistical analysis of long term measurements and the importance of identifying statistical "relationships" between variables to expose "emergent behavior" of aerosols, clouds, and aerosol-cloud interactions. It is challenging to constrain aerosol-cloud interactions observationally because of the difficulty in separating correlation from causality. It is also difficult to untangle bivariate relationships in fields from co-variability with meteorology conflated with natural internal variability to obtain statistically significant results. But these relationships provide some of the strongest constraints on models and the processes occurring within them. The workshop also noted the increased value of statistics that include "structure", or "organization" rather than just a Probability Density Function (PDF) statistical characterization. To improve the representation of subgrid variability in models, better measurements are needed of higher -order moments, such as variances and covariances. Progress is being made for vertical velocity. This could be extended to other fields such as cloud water and hydrometeor mixing ratios and number concentrations. Statistics accumulated over a long, continuous period on the water budget for example can serve as a constraint for process rates and a "common denominator" across a range of scales and models, producing special help in estimating ice deposition rate, or links between turbulence and condensation as a source for supercooled liquid. Some workshop contributions highlighted the need for caution in characterizing feedbacks operating in individual clouds (in models or observations) from those that operate at a larger scale because of feedbacks occurring between the clouds and their environment that cannot be captured when analyzing over small simulation domains and/or short timescales.

There were two different perspectives represented in the white papers provided for the workshop on the topic of statistical analysis. The first advocated for a “bottom-up” approach in which key relationships among parameters (e.g., the variation of cloud condensation nuclei with a measure of aerosol emissions) are measured. These measured relationships would then be used to evaluate models and guide subsequent model development. The other perspective is a “top-down” approach. In this method, there is a greater focus on parameters such as cloud fraction and scene albedo, which integrate over a range of processes, and may be less prone to measurement error. The appropriate balance of the bottom-up vs. top-down approaches was not addressed in detail; however, it was clear that an emphasis on relationships among parameters in general is an important strategy.

There is also a need to develop better simulations for cloud microphysics and aerosol-cloud interactions, which are currently inadequate to serve as benchmarks for parameterization development, or very accurate reproductions of observed clouds. Even LES and CRM simulations using different microphysics schemes often produce large differences in storm structure, dynamics, precipitation, and anvil characteristics. Some parameters seem to have surprisingly powerful effects even in a single model. For example, Morrison and Milbrandt (2011) showed that varying the fallspeed of rimed ice to be more representative of hail than graupel led to large differences in dynamical and thermodynamical characteristics of a supercell storm. Recent work has also shown large biases in CRM convective characteristics such as updraft vertical velocity relative to observations (Fridlind et al., 2012; Collis et al., 2013; Varble et al., 2014), which affects supersaturation, drop formation, glaciation, and many other properties of microphysics and cloud development.

Comprehensive treatments (e.g., spectral bin microphysics) are very computationally expensive, but bulk (2-moment) schemes may not be adequate simplifications leading to biases in process rates, and ultimately cloud dynamics, cloud feedbacks, and aerosol-cloud interactions. The representation of microphysics in GCM convective cloud parameterizations is particularly crude, and it is not yet clear how much complexity is necessary to capture essential features of clouds and aerosol-cloud interactions. Participants recognized the temptation to increase the level of complexity used in parameterizations but it is important to determine the appropriate level of detail needed. Benchmark calculations would help to provide insight into the appropriate level of complexity for GCMs. Benchmark studies should include a broad suite of well-established test cases at multiple locations and make use of long observation time series. The ongoing microphysics intercomparison for the MC3E ARM field campaign is one example of

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a successful benchmark case. Instrument simulators and the recently developed "piggybacking" technique, may be useful with benchmark cases in measurement model comparisons. Increasing use of radar Doppler spectra simulators on bin-microphysics schemes may help to evaluate model microphysics more directly. Piggybacking of microphysics parameterizations (one active, the others passive) in model simulations might be useful in understanding parameterization differences but comes with limitations that need to be better understood.

Other dynamic and microphysical properties that are known to be important to cloud behavior could also be more thoroughly explored in benchmark simulations and in comparisons between model and measurements. For example, activation schemes remain relatively untested under real environmental conditions and with observed updrafts, aerosol composition and size distribution. Some CCN-cloud droplet number (*N*d) "closure" experiments have been performed (e.g., Snider et al. 2003, Conant et al. 2006, Fountoukis et al. 2007), but these have been limited to aircraft studies. Intercomparisons between models have been performed (Chen et al. 2012), but activation schemes need to be tested under a wider range of atmospheric conditions. New remote sensing observations being made as part of the ARM Facility are providing the key constraints needed to constrain aerosol activation from ground sites. Ground-based retrievals of vertical velocity can be combined with new capabilities for CCN and physical and chemical aerosol measurements, along with *N*d retrievals, to conduct CCN-*N*d closure experiments more routinely using surface-based observations. Recent 3D vertical velocity retrievals are especially useful, and have indicated large biases in CRM-simulated vertical motion (e.g., Varble et al. 2014). For deep convection, the morphology of eddies (updrafts and downdrafts) is critical, for example by affecting the roles of entrainment and perturbation pressure. Thus, analyses of updraft/downdraft structures are needed, not just pdf's of vertical motion, with vertical velocity kinetic energy spectra being a particularly useful way to quantify these structures.

ARM is proposing to use LES routinely. Initially the LES framework, called the LES ARM Symbiotic Simulation and Observation (LASSO) workflow (more information on LASSO is available at http://www.arm.gov/news/features/post/33730 and http://www.arm.gov/publications/programdocs/doe-sc-arm-15-039.pdf), will be applied at one location, primarily focused on shallow convection, with future plans to expand simulations to multiple ARM sites and different cloud types. Since each ARM site represents only a single climate regime, there are likely to be benefits by use of LES at many locations beyond the ARM Southern Great Plains (SGP) site to sample as many cloud regimes as possible.

Other DOE programs and projects (e.g., CAPT) are performing "forecast-like" simulations to facilitate direct comparison of high-resolution models to measurements relevant to microphysics and aerosol-cloud interactions, and there are many additional opportunities for progress using routine "forecasts" with global climate models. An ARM/ASR diagnostic package could be created and run for ACME that includes quantities agreed upon mutually by the modeling and measurement specialists, highlighting features and variables that both communities feel are important and feasible, minimizing the possibility that one group creates a product that the other feels to be unimportant.

DRAFT

Breakout 2: Planetary boundary layer, boundary layer clouds, and land-atmosphere interaction

The second breakout session of the workshop focused on boundary layer clouds, including boundary layer processes, turbulence, and interaction of the atmosphere with its lower boundary. In essence, boundary layer clouds are the nexus of many processes that need to be treated properly to achieve accurate climate change simulations. These processes potentially form an ideal basis for bridging the gap between small scale and global atmospheric modelers due to both common problems and tools that can be used from both scales to better understand longstanding problems and improve the climate models. There is also a resurgent interest amongst ACME, ASR, and ARM researchers to better understand boundary layer processes and land-atmosphere interactions. This is driven by the more common use of models within the planetary boundary layer terra incognita (grid spacings around 1 km) (Zhou et al, 2014), the push toward using nonhydrostatic global models with regionally refinement, the development of unified parameterizations that treat both planetary boundary layer and cloud processes (e.g., CLUBB (Golaz et al., 2002; Guo et al., 2014), UNICON (Park, 2014), and EDMF (Sušelj et al., 2013)), and new measurements that will enable advances in related research (e.g., photogrammetry of clouds to better measure cloud evolution and macro properties (Romps and Oktem, 2015) plus scanning lidars that better measure low-level wind). The planned LES modeling of shallow convection by ARM is also focusing interest on boundary layer and shallow cloud processes. Importantly, boundary layer clouds are a differentiator in terms of climate model behavior. These clouds are the largest contributor to the spread in climate model sensitivities (temperature change due to change in CO2) between GCMs (Bony and Dufresne, 2005; Zelinka et al., 2012; Vial et al. 2013), and most models struggle with generating the correct amount of drizzle from boundary layer clouds (Stephens et al., 2010).

Much of the discussion during this breakout focused around data needs related to the boundary layer, shallow clouds, and land-atmosphere interactions, as well as observational and cloud modeling studies to improve the understanding and representation of these processes in cloud/climate models. Many of the ideas can be summarized into broad categories that include measurements along cloud boundaries, measurements of fluxes, and measurements of the soil conditions. Participants noted that measurements relevant to a particular cloud feature are not always directly comparable to model quantities, motivating the need in models for instrument simulators combined with forward models that facilitate comparison between models and observations. Radar simulators provide one example of this, and the growing array of ARM scanning instruments and retrieved quantities that must be conditionally sampled in the model for fair comparisons provide other examples. Sufficient documentation of the measurement strategies and uncertainty characterization are also needed to enable proper comparison with models.

Participants noted the need for long-term continuous large-scale forcing data that allow researchers to expand from case studies to long-term statistical studies. Ideas on potential modeling activities include conducting multi-scale model intercomparison studies ranging from LES to GCM resolutions similar to the CFMIP-GASS Intercomparison of LESs and single

DRAFT

column models (SCMs) (CGILS; Blossey et al., 2013; Zhang et al., 2012; Zhang et al., 2013) and the Clouds Above the United States and Errors at the Surface (CAUSES) model intercomparison study (http://portal.nersc.gov/project/capt/CAUSES/). The approach of focusing on statistical tendencies over the absolute values of simulated variables offers particular promise in the CAUSES analysis framework where a more sophisticated use of ARM observations permits the isolation of specific situations where biases are more prevalent (Van Weverberg et al, 2015).

A number of topics regarding measurement needs near cloud boundaries (to help in parameterization development) were discussed:

- Cloud boundaries. Robust cloud masks identifying cloud boundaries are a critical need, yet they are not straightforward due to complicating factors such as signal attenuation, insects, and drizzle that contaminate retrievals. Vertically pointing measurements also have limitations for comparing with short-term LES output since the profiles must be averaged over a certain time period to obtain good statistics of the cloud population. New techniques that measure clouds throughout a volume are needed, particularly for clouds with small liquid water content that cannot be seen by cloud radars. Photogrammetry is a promising new measurement, which will be useful for evaluating LES models over ARM sites.

- In situ and remotely measured vertical velocity in and around clouds. The use of slow-flying unmanned aerial vehicles (UAVs) could help meet this need for shallow cloud conditions where the small cloud size makes achieving a good signal difficult.

- Entrainment. This is difficult to measure, the definition can vary between researchers, and very different treatments are needed depending on the scale of modeling. Global models treat entrainment as an incorporation of gridbox mean environmental properties into an ensemble of updrafts, which then determines the change of mass flux with height and the eventual cloud top of each plume. In comparison, LES models and observationalists look at entrainment in terms of mixing at the sub-cloud scale. This difference complicates communication and use of observations to improve model parameterizations. One suggestion to obtain estimates of cloud-top entrainment was to park an instrument at the top of the shallow cloud layer to measure fluxes across it. This could be done with tethered balloons or UAVs. This technique would be more amenable at the NSA site due to airspace restrictions at SGP.

- Drizzle retrieval data. The utility of drizzle retrievals from the Graciosa/ENA site has been demonstrated already (e.g., Ahlgrimm and Forbes, 2014). Quantitative drizzle retrievals (i.e., of drizzle content and/or fluxes) can be combined with cloud water and property information to constrain rates of drizzle generation, precipitation and evaporation below cloud base. Information on boundary layer humidity (e.g., from Raman lidar) could add another dimension to explore how horizontal heterogeneity in cloud liquid and boundary layer humidity affect drizzle generation and evaporation rates. Long-term retrieval products are needed to test and develop parameterizations applicable for a wide range of

DRAFT

meteorological conditions.

- Retrieval validation. Many of the desired cloud properties cannot be directly measured. Various retrieval techniques have to be used to retrieve these physical parameters from instrument signals. The idea to use LES as a testbed for developing and evaluating retrievals was proposed. However, there are uncertainties in the LES itself, which needs to be validated against observations. More work is needed in developing a strategy for LES-observations comparison.

Vertical fluxes of moisture and temperature within the atmosphere were also highlighted as an important need. Being able to close the water and energy budgets would provide better validation for models and clarify understanding of how clouds impact the boundary layer development, and vice versa. The use of scintillometer techniques could enable better measurement of fluxes, at least along one dimension. Flux profiles could also be obtained using stacked UAVs, which could act as a virtual tower.

Measurements of surface fluxes and soil characteristics were also highlighted to improve understanding of land-atmosphere interactions and constrain models. The SGP site is the best-instrumented of ARM's current sites for doing land-atmosphere interaction investigations. This site is a good resource for looking at issues of surface heterogeneity and continental land-atmosphere interactions. Interest was also expressed for investigating land-atmosphere interactions in polar environments using the NSA site. ARM's capability to more freely use UAVs at the NSA site and surrounding region offer potential to measure a larger region and understand issues such as the impact of fluxes due to leads in the sea ice. To do this successfully, additional measurements that characterize the surface heterogeneity at seasonal and interannual timescales are needed around NSA. Measurements of the mixed-phase cloud regimes are also important to answer questions such as when, and whether or not, air above the Arctic clouds is moister than below the clouds.

Long-term continuous forcing data sets and ARMBE (ARM "Best Estimate") type data sets are needed at all ARM fixed sites [SGP, North Slope of Alaska (NSA), and ENA] for more comprehensive model observation evaluation, and to serve as boundary conditions for model simulation. The long-term (>2 years) cloud modeling data allows one to look at parameter relationships and statistical features of simulated boundary layer cloud systems. It would be useful to utilize multiple forcing data sets, including data from numerical weather prediction (NWP) analyses, to address forcing data uncertainties and their impacts on LES/CRM/SCM/GCM simulations. The NWP analyses could also be used to initiate global models for short-term simulations, such as with the CAPT framework, to better understand biases that evolve quickly.

Several growth areas of research were also discussed during this session that could form foci around which observationalists and modelers from different scales could unite to solve outstanding questions. Climate model simulations are less accurate in regions with significant surface heterogeneity at different scales. The classic example is convective parameterizations

DRAFT

that often make assumptions related to the small-scale variability of clouds and the processes that drive them. However, the impact of some of these processes is not fully understood, such as the impact of surface heterogeneity on the resulting cloud field. Surface features with heterogeneity on spatial scales smaller than an LES domain have been shown to impose variations in the clouds under certain meteorological conditions that could affect their overall climate impact, such as the distribution of cloud sizes for a given region. To the extent that it is possible to limit some effects of surface heterogeneity, such as through judicious choice of measurement location or time period, one can better understand the impact of other heterogeneities.

Another growth area is the use of LES as a unifying approach between the observations and coarser-scale models. One example of this multi-scale approach is described in the section for Breakout 3, where routine simulations from LES, SCM, and GCMs using similar initial conditions and forcing permit better statistical understanding of model behavior. LES is particularly useful for research questions discussed during this session, such as the planetary boundary layer, shallow clouds, and surface heterogeneity. LES offers a fully consistent representation of the atmosphere that observationalists can use to develop and validate remote retrieval algorithms. Likewise, the LES can provide estimates of quantities that are difficult to measure in the field, for model developers, such as correlations between some state variables and related statistical moments.

Interest was shown during the workshop, first in this session and in later sessions as well, in using LES for more demanding situations, such as with very large domains with high resolution and for weather situations and regions that would be difficult for small modeling efforts to address. This would take advantage of DOE's unique computing resources and efforts in both process understanding and algorithmic development for very large computing problems. One example effort that could be undertaken is investigation of flow in and around cloud boundaries at the synoptic scale, where inter-cloud interactions are important, in combination with interactions between the local clouds and the larger weather system. Large domains would also be useful for advancing land-atmosphere understanding and parameterization in climate models. To attain model domains of this scale will require development of the next-generation atmospheric LES model that can make full use of exascale style computing hardware that relies heavily on many-core technologies and highly vectorized code. Only a small number of existing LES models even partially use accelerators on current state-of-the-art computers, and these LES are not sophisticated enough to address the science questions posed here. Without further development, the LES models will be out-of-date within the next two computer generations.

Potential multi-scale cloud modeling activities were discussed. These studies could be organized around forcing data sets and connecting between LES and large-scale models. The CGILS-type of studies that use idealized, representative conditions to intercompare different models' behaviors are useful to understand and evaluate low cloud processes in the SCMs and GCMs by using cloud-resolving and large-eddy models. Similar activities could be planned for ENA and MAGIC with a focus on specific boundary layer cloud processes. The ongoing CAUSES study aims to evaluate the role of clouds, radiation and precipitation processes in contribution

DRAFT

to the surface temperature biases in the region of the central United States. The ARM SGP site is an ideal location for such a study. Increased ASR involvement within the CAUSES project through the contribution of simulations from a wider selection of models would provide additional information to understand why clouds and surface models contribute differently to model biases depending on parameterization formulations and other feedbacks within models. Using a similar framework to examine how biases change when using regionally refined, and possibly nonhydrostatic resolution, global models would also facilitate understanding of the model behavior and assist with parameterization improvement and tuning.

In addition to traditional modeling approaches, a plenary session presentation during the workshop described the Ultra-Parameterized Community Atmosphere Model (UP-CAM), where a multi-scale modeling framework (MMF; Wang et al., 2011) approach is used, that includes a very high resolution cloud model embedded within each GCM column. Whereas previous MMF approaches have used cloud permitting models (CRM run at horizontal scales of a few km) to replace the cloud and radiation parameterizations within GCMs, the UP-CAM method refines the cloud resolving models to LES grid spacings. At these scales, the handling of shallow cloud and boundary layer processes is treated significantly differently than with MMF or traditional GCMs. Whereas CRMs require boundary layer and shallow cloud parameterizations, LES models explicitly resolve these processes. The UP-CAM approach is an interesting concept that will need further testing to determine its potential.

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Breakout 3: Deep convection and the transition from shallow to deep convection

Given the challenge in representing deep convection and capturing the transition from shallow to deep convection in climate models, the third breakout session of the workshop focused on discussing and identifying priorities and gaps in this area, and how best to align the parameterization development and measurement strategies to address these gaps. The identified important areas include convective initiation, entrainment, transition from shallow to deep convection, and microphysical details (including the role of aerosols, precipitation efficiency, detrainment of cirrus, mesoscale organization), and the interaction of convection with important large-scale dynamical phenomena such as the Madden-Julian Oscillation (MJO) and El Niño Southern Oscillation (ENSO). The deficiencies of global models to simulate convection properly lead to poor simulations of these and other modes of variability, poor simulation of precipitation and storms, as well as errors in cloud distributions, particularly in the vertical. Main ideas from the discussion are summarized below.

3.1 What important processes are currently missing or not well represented in cumulus parameterizations?

Among other issues, the challenge in representing convective organization and cloud microphysics in convective clouds in cumulus parameterizations was highlighted in the workshop. *Convective organization* can be defined as a series of processes that sustain convection on time scales much longer than that of an individual cell, causing convection to retain a "memory" of previous convective events rather than depending only on the current state, and in some situations the interaction of convective plumes with each other and the environment to induce motions, rain, and clouds on the mesoscale. Convective organization is important energetically since organized convection covers larger areas and lasts longer than isolated convection. There are important differences in heating and cooling profile as well as in coupling to the large-scale flow between organized and isolated convection. Globally, most extreme precipitation events are related to organized convection. There are various mechanisms that can lead to convection organization such as self-aggregation, rain-driven downdraft/cold-pool dynamics, gravity waves emanating from convection, propagation of convective systems, and surface heterogeneity. These important processes for organization are generally either missing or crudely represented in cumulus parameterizations. Only a few schemes (e.g., UNICON) attempt to parameterize some aspects of organization such as sub-grid cold pool and mesoscale organized flow forced by evaporation of convective precipitation and accompanying convective downdrafts (Grandpeix et al. 2010; Mapes and Neale 2011; Park 2014a; Del Genio et al. 2015). Observational data are critical in developing improved understanding of shallow and deep convection.

Most climate models also calculate aerosols' influence on clouds only for stratiform clouds; neglecting cloud-aerosol interactions in convective cloud systems adds to the uncertainty in the total aerosol indirect effect. Until now, the representation of microphysics in convective parameterizations has been both too crude and too dependent on equally uncertain convective dynamics (e.g., cloud-scale vertical velocity) to credibly calculate the effects of aerosol-cloud interactions in a complex, mixed-phase, precipitating system. Differences in processes operating in stratiform clouds (with weaker updrafts) and deep convection (with stronger updrafts) preclude simply porting existing microphysics schemes for stratiform clouds to the same model's cumulus parameterization. The general lack of observations of vertical motion and microphysics in strong updrafts also partially contributes to the slow progress in this area.

To represent aerosol indirect effects in convection, two requirements are 1) a convection scheme with a rich representation of subgrid-scale variability, and 2) an interface between the convective clouds and the microphysics. Several efforts are being made to meet such requirements. The CLUBB scheme (a unified scheme based on higher-order turbulence closure and assumed subgrid PDFs for planetary boundary layer turbulence, shallow cumulus convection) coupled with MG2 (a sophisticated, prognostic, double-moment microphysics scheme) allows the consideration of aerosol indirect effects involving shallow convection. Song and Zhang (2011) and Song et al. (2012) developed a sophisticated microphysics scheme, similar to that described in Morrison and Gettelman (2008), for convective clouds to improve the representation of convective clouds and its interactions with stratiform clouds and aerosol in GCMs. Berg et al. (2015) have also linked aerosol interactions with shallow convection. These processes may be important in describing clouds role in the climate system. Workshop participants also asked how complex the microphysics needs to be to get the answers to the science questions that we want to address. Does it make sense to use complicated cloud

DRAFT

microphysics if vertical motion is not well represented in cumulus parameterizations? Does the added complexity make sense in this context? This also highlights the importance of accurate vertical velocity measurements in convective clouds by ARM.

3.2 What additional or improved measurements are needed?

The detailed cloud measurements along with their associated environments obtained by ARM can be very useful to develop improved understanding of convective processes. The long-term composite diurnal cycle database obtained from ARM SGP measurements (Zhang and Klein 2010) and the oceanic constraints on models from the AMIE-Gan ARM Mobile Facility (AMF) deployment (Del Genio et al. 2015) could be used to test the capability of climate models in capturing the transition from shallow to deep convection over land and ocean, respectively. Systematic studies using the recently reconfigured SGP site could also be used to develop better statistics of cold-pools/gust fronts that are important for convection initiation and organization. Potentially useful additional measurements for characterizing these dynamical features and their effect on cloud formation include mass flux, updraft area, vertical velocity, and the horizontal structure of water vapor variability in the sub-cloud layer. The ARM scanning Doppler lidar can provide spatial information about some of these parameters. A strategy to estimate entrainment into convective updrafts would also be a valuable constraint. Such quantities have either not been derived thus far or have only been derived for individual case studies; a longer, statistically significant record of these highly variable characteristics of convection would facilitate their use for parameterization evaluation and development.

In addition to small scale features like cold pools that initiate secondary convection, it is important to have descriptions of the large-scale atmospheric state. A parameterization is fundamentally an attempt to link subgrid-scale processes to the large-scale state. The question arises, how accurately the large-scale state needs to be captured and what is required to achieve that accuracy. How accurate must humidity be? Are more radiosondes needed? Does heterogeneity within a grid-box area have to be described better? The answers to these questions are not currently known. However, with the reconfiguration of the ARM sites, advances are being made toward improving this characterization. Notably, at the SGP site a network of instruments is being added that will provide profiles of temperature, humidity, and wind in the boundary layer on a continuous basis. A greater challenge is the continuous monitoring of humidity above the boundary layer, which is the key to expose the erroneous behavior of cumulus parameterizations.

Other measurement gaps that were raised in the context of convection focused on sampling away from ARM sites. Organized deep convection is a large-scale phenomenon. Data sets such as operational radar networks (esp. NEXRAD) along with satellite measurements can provide valuable context for the detailed observations at an ARM site. Participants also noted the possibility of leveraging sites already served by some measurement capability with additional ARM measurements. In such a situation, the addition of one or a few instruments could result in a highly valuable data set at relatively low cost. For example, a vertically pointing cloud radar

DRAFT

could be deployed to a location where a scanning precipitation radar was already being operated.

Turning again to local measurements, important cloud properties such as convective-scale vertical velocity, ice particle fall speeds, and 3-D cloud dynamical structures could be retrieved on a more consistent basis from ARM radar measurements. In the past, ARM has done much with non-precipitating clouds but focused less on deep convective clouds, which could be an emphasized area in its future plan. Furthermore, better measurements of higher order moments, e.g., variances and covariances, for cloud water, hydrometeor mixing ratios and number concentrations are required to improve the representation of sub-grid scale variability in models. Given the large uncertainty in current retrieved cloud properties, continued support by the ASR program of retrieval technique developments and evaluation of their uncertainties would be valuable. It was also noticed in the workshop that many different retrieval algorithms are available in the ASR/ARM community that are not in routine use. It would be helpful for relevant PIs to share the code with the community and provide guidance on when and where a given algorithm provides optimal estimates.

3.3 What new methods or diagnostics might be applied to help cumulus parameterization developments and improve model-observation comparison or integration?

The high resolution modeling (LES/CRM) activities that are being conducted by ARM/ASR through LASSO and individual PI projects have the potential to provide extremely valuable insight into important physical processes that are parameterized in climate models and detailed diagnostics which would be difficult or impossible to obtain directly from observations. Of particular interest is that LES allows us to learn about processes that lead to the organization of convection or other features, providing guidance in the development of new parameterizations. The current ARM LES pilot study focuses on shallow clouds. It would be useful to examine the whole spectrum of clouds over larger domains. Participants considered the usefulness of DOE getting into global cloud resolving model (GCRM) as does Japanese group to skip the gray-zone issues. They noted that in practice, it is infeasible to run a coupled GCRM for climate predictions with current computer power but that this strategy could be used for exploration and for insight into the climate system. Running the Super or Ultra Parameterized CAM includes many of the advantages of GCRM and is already possible with current computation for short simulations.

A multi-scale framework including models ranging from fine scales (LES and CRM) to global-model scales (including the use of SCM and the CAPT framework) was proposed to bridge gaps between data and climate models in the workshop. Routine model simulations with these models would allow continuous comparison with long-term ARM observations. This would be particularly useful if routine simulations could be performed with developmental model versions of ACME to enable a rapid comparison with ARM measurements and feedback during the model development cycle. LES is extremely valuable to complement detailed observations and deepen our understanding at the process level. Ultimately, these can help answer whether a new model component is realistic at the process level.

DRAFT

Incorporating the multi-scale framework of models into the ARM routine LES modeling operation would provide a routine evaluation of ACME and link the ARM routine LES effort directly to improve ACME during its development cycle. The idea is to routinely use CAPT to drive ACME with finer grids over the continental US utilizing ACME's regional refined capability (RRM) to produce continuous 3-5 day hindcasts for the period of routine LES operation. The CAPT forcing data could be used to drive SCM version of ACME and the LES model, and LES output can then be used to evaluate ACME.

To remove at least some of the location- and event-specific behavior inherent in the ARM data, workshop participants suggested that the model-data comparison be focused on long-term observations rather than specific idealized case studies. The evaluation of models should move to the evaluation of parameter relationships; both between large and small scales and between different small-scale variables. It would be useful to use phenomena such as diurnal cycles and the transition from shallow to deep convection as tests for parameterizations. The "piggyback" modeling technique (running two parameterizations simultaneously, with only one feeding back on the dynamics) may be useful to isolate differences between representations of particular processes in different schemes.

To improve model-observation comparison, use of instrument simulators to bypass some difficulties in comparing with retrieved parameters is encouraged. Two different types of simulators would need to developed for LES and GCMs, respectively, given their significant scale differences. The creation of an ARM diagnostic package is also critical to facilitate use of ARM data in model evaluations. Again, the ARM diagnostics would need to be created for LES and GCMs separately given their different emphases and capabilities. The package should be constructed around an open architecture to enable ARM/ASR/ACME PIs to easily contribute new sub-components as new data products or new novel analyses are developed. The ASR diagnostic package could be incorporated in the ACME workflow and become a routine part of the model evaluation to facilitate rapid comparison of model with ARM observations. There is an opportunity to contribute to ACME's further development with model evaluation based on existing products (v1-v2) while the first-generation model is being optimized. Other chances will exist in the future to impact development of v2 and v3 of ACME.

Breakout 4: Crossing scales and integrating observations and models

The DOE climate-oriented observation, research, and model development activities are complementary in nature. However, at present, efforts across these areas are not highly coordinated. The current situation was described during the workshop as a set of independent entities working on specific problems, periodically making the output of their efforts available to the wider community. This strategy assumes a lot about the ability of a group to absorb the output from another group. Obstacles to collaboration include differences in technical expertise, alignment of priorities, insufficient time given existing responsibilities of investigators, competition between implementing physical processes in models and other demands on

DRAFT

computational resources, and the scale gap between local measurements and global models. The suggestion of many during the workshop was that coordinated collaboration is required at the interfaces between disciplines and much of the discussion during this session, and throughout the workshop, focused on how to enable that collaboration.

Communication

There was recognition among the meeting participants that there is a communication gap among the CESD activities and a particular gap between ARM/ASR and ACME/Global Modeling. There are a number of groups funded by both ARM and ESM projects; however, there are also many individuals who tend to work exclusively with observation data or model simulations. There is a general recognition that the process-oriented information available through ARM/ASR has great value to the GCM community, but it is not always made use of optimally, because observationalists do not always understand what model issues are most pressing for modelers, or what information would be most valuable to them in resolving those issues, and modelers are not always aware of what relevant measurements are available (or possible in the future campaigns), or what the data set strengths and limitations are. Improved understanding of these issues can facilitate the use of ARM data, and progress on modeling science.

As an illustration of inter-community communication challenges, parameterization testing within GCMs requires that ARM/ASR scientists have a better understanding of the inner-workings of GCM parameterizations so that they know how the data should be processed. From the modeling perspective, making use of the ARM data and associated ASR analyses requires a certain level of familiarity with observational data that requires a significant time investment. There is also the conceptual difficulty of understanding how to constructively use small-scale ARM observations to improve a global model. Overall, these challenges represent a challenge to the ASR community in using ARM data, but for ACME, the gulf is larger.

Communication of details regarding model development cycles is also important for developing useful collaborations and preventing the perception that modelers are not interested in working with those outside the model development team, when in reality they are often seeking better ways to deal with model deficiencies. Models go through a series of periods of somewhat rapid ingestion of new ideas followed by periods of intensive testing when new ideas are not as useful. For example, prior to a model release the code is frozen and only small changes are added to fix problems. Traditionally, the six-year cycle of CMIP phases and IPCC reports drives climate model development cycles and significant changes to the model are only possible when the code is being prepared for the next set of CMIP simulations. Clearly communicating windows of opportunity when the models are more capable of trying and accepting new methodologies should be a priority. Additionally, communication of high priority issues/deficiencies within the climate model needs to be done in a more timely manner since waiting for the knowledge to percolate outside the model development team via the peer reviewed literature is slow and leads to a disconnect between the core development team and other communities.

DRAFT

There was a good deal of discussion around how to better bring together these diverse communities. A key element of a strategy going forward was seen as holding periodic workshops that explicitly bring together members of each community with balanced representation and a focus on collaboration. Initially, it is envisioned that these joint workshops would focus on educating participants on the nature and needs of each community and identifying a small set of science questions and topical areas of mutual interest across the observation to global modeling spectrum. Follow-on workshops would then focus on selected science and technical themes. The challenge here is that proliferation of new meetings in communities that already face considerable travel demands may lead to sparse participation and/or attrition by initially enthusiastic scientists.

Asking the right questions

Every parameterization is in effect a hypothesis about how some small-scale process in the climate system operates and interacts with the larger-scale environment. In principle these hypotheses can be tested by a judicious use of observations. The fact that well-known problems in models, e.g., the lack of convergence of GCM estimates of global climate sensitivity (Zelinka et al., 2012), or the excessive ice and updraft speeds produced by CRMs (Varble et al., 2014), have been present through several generations of models indicates that the community is often not using data to ask the right questions of models. Rather than organizing efforts around data sets, tools, cloud types, or parameters, a more useful way to address chronic problems would be to address questions about how processes operate in different models and how different representations of these processes lead to different emergent behavior. Often this means understanding how a process of interest depends on the thermodynamic or dynamic state that is resolved by the host model.

For ACME, as for any climate model, interfacing with observations occurs on several levels, on different time scales, and is dictated by considerations specific to that model. ACME is focused on high-resolution, fully coupled simulations, including regional refinement, and with a high priority for hind-cast testing using CAPT-driven simulations at ARM sites. These features make ACME particularly suitable for interfacing with ARM and ASR. As a new modeling activity, ACME is presently in the model-building stage, putting together individual model components and deciding which combination of existing parameterizations can produce the best climate for the baseline model version. After this, ACME will enter the cycle of model development periods alternating with periods in which a model version is frozen and used for applications. It is during the model development part of the cycle that interactions with ARM/ASR have the opportunity to be most fruitful.

During the development time periods, collaborations between ARM/ASR observers and ACME modelers should be guided by a set of questions that include: What are the science priorities of ACME, and which of these can best be informed by the observations that ARM can provide? What weaknesses have already been identified by ACME that might benefit from analysis of ARM observations? What are the optimal strategies for using ARM observations to evaluate and improve ACME? While there will certainly be overlap between ARM/ASR

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strengths and ACME needs, a condition for any successful collaboration will be to recognize that this overlap is not complete and to define those needs that ARM/ASR can best help address. A key here will be for ACME to work toward parameterizations that are "improvable," i.e., that contain enough of the basic process elements that improvements can build upon what already exists. For example, a cumulus parameterization that does not diagnose updraft speeds cannot benefit from ARM's cutting edge observations and retrievals of vertical velocities and the convective microphysical properties that accompany them. On the other side, relationships seen in ARM data at the individual cloud scale will need to be aggregated to statistics appropriate to the GCM grid scale in order to speak to ACME parameterization needs. A next step in the collaboration would be for this expanded community to work towards possible fruitful ARM field campaigns, new measurements, or new retrievals that would be important for ACME deficiencies and/or areas of targeted scientific investigation.

Organizing information

Aside from the specific themes selected for integrated efforts, an organizational strategy that is expected to be effective at drawing together the diverse communities are the use of real and/or virtual field campaigns. A virtual field campaign is a collection of data from existing sources, matching some criteria or region (e.g., association with single-layer mixed-phase clouds along the North Slope of Alaska). These data would include ARM observations, model-forcing data sets, and possibly external data products such as satellite observations, weather radar or in-situ measurements. These data would be organized and extensively documented in a location, region, or environment. This strategy has been used effectively before. For example, the Year of Tropical Convection (YOTC) organized a wide variety of observation and model data around tropical convection for a two-year period (Waliser et al., 2008; Moncrieff et al., 2012). This type of virtual field campaign provides a research focal point. Implicit in this strategy is having the means to organize ARM data around a variety of criteria (e.g., cloud conditions, aerosol conditions, and meteorological regime). Providing this organizational functionality was viewed as an important capability for making ARM data easier to use for a variety of applications and for contextualizing ARM data with respect to other data sets.

On a related theme, there was interest expressed in mining historical measurements from ARM sites. ARM facilities have now sampled many climatic regimes from the arctic to the tropics (Figure 1). If these data were organized in a consistent way, they would provide a broad constraint on model simulations. Looking forward, the communities could also jointly propose deployments of ARM facilities or campaigns at specific facilities geared toward addressing issues of common interest.

That having been said, premature conclusions about parameterization improvements have frequently been drawn based on short-term SCM case studies in specific locations. The true test of any parameterization is whether it works equally well when evaluated against a data record whose length is climatologically representative and whether it is successful in different climate regimes in which the same physics manifests itself in different ways. This will be especially important as ARM implements its continuous modeling approach at the SGP. A

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parameterization of boundary layer clouds that is judged successful at the SGP will need to be tested in the very different low cloud environment of the ARM ENA site, for example.

Another level of parameterization testing occurs when a candidate parameterization that performs well in an SCM setting is implemented in the parent 3-D GCM. Often improvements seen in the controlled SCM setting are not realized in the 3-D model, where many parameterizations interact with each other and with the resolved circulation. The short-term hindcast framework has proven useful in identifying sources of parameterization errors in the 3-D setting, since many chronic long-term climate model biases appear after only a few days of integration (Ma et al., 2014).

Scale and model-observation challenges

In addition to the need to facilitate communication, there are also significant technical issues that need to be addressed to better match observations and models. One of the most significant issues is the large scale-gap between the observations, with spatial scales ranging from meters to hundreds of meters, and climate models, with horizontal spatial scales ranging from tens of kilometers to over one hundred kilometers. An effective, and commonly used, technique for bridging this gap is to use a high-resolution model, with resolutions approaching the observations to bridge these scales (e.g., Randall et al., 2003). We do not expect models and observations to be directly comparable at very high spatial and temporal resolution due to the stochastic nature of many processes; however, use of statistical analysis strategies can be used to overcome this issue. ARM is currently developing a framework to implement a high-resolution model to employ this strategy on a more routine basis than has been possible in the past (U.S. Department of Energy, 2014). Often a Single Column Model (a single vertical column from a GCM) is also used as part of this framework as are limited area models (LAMs) and GCMs run using realistic initial or nudged conditions like those from a numerical weather prediction model (Phillips et al., 2004). In both cases, the LAM and GCM are operated under real-world conditions to make direct comparisons with observations possible, as well as with high-resolution simulations constrained by local atmospheric dynamics.

This multi-scale modeling approach is invaluable for reducing the gap between observations and GCMs but typically, it is still not possible to make direct comparisons between detailed cloud and aerosol observations and any model simulations due to the stochastic nature of atmospheric processes at the scale of ARM observations. A common theme for addressing this issue was the de-emphasis of model evaluations based on single parameters, and rather, evaluating models using relationships among parameters, for example the relationship between cloud liquid water path and vertical velocity. This also allows a process-level understanding of model deficiencies since such relationships are at the core of GCM parameterizations.

Typically, of course, instruments do not directly measure the quantities simulated in models. Much work is devoted to deriving physical quantities from observations that are comparable to model output but often this process is slow. Consideration should be given to accelerating the development of derived products that are applicable to models. A complementary approach to

DRAFT

dealing with this issue is to build instrument simulators in the high-resolution model or a GCM. Instrument simulators require many of the same assumptions as a physical retrieval from the observation; however, they may be simpler to implement in many cases. For example, observation data is inherently complex (e.g., with gaps and variability in instrument performance) and it may be easier to apply an algorithm to a model, which tends to be better behaved. Additionally, instrument simulators provide a means to explore the impacts of instrument limitations or sampling strategies on constraining phenomena and can be used to optimize measurement strategies.

Whether compared to a model via a retrieval or a simulator, it is critical that the quality and uncertainty of measurements are well characterized and communicated. This is a point frequently made by the modeling and scientific analysis communities. It is also important to characterize under what conditions an instrument or a retrieval tends to work well and when it does not. This is particularly important for modelers who likely are not familiar with the detailed characteristics of an instrument or a retrieval. Finally, for instrument data and model data to be compared it is critical that common standards such as the Climate and Forecast (CF) conventions are used for data format and metadata.

Thus, in order for ARM observations at the SGP testbed to eventually influence ACME parameterizations, a series of steps will need to be taken: (1) A strategy for statistically evaluating the high-resolution (LES) model against the data will need to be developed that accounts both for the limitations of the data (e.g., clouds missed by scanning radars, incomplete sampling of the LES domain) and the identification of important questions that can be posed given the data that exist; (2) weaknesses in the LES model revealed by these comparisons will need to be addressed iteratively until the model performs satisfactorily against the data; (3) relationships derived from the LES results at the SGP will need to be duplicated in other climate regimes observed by ARM instruments; (4) robust relationships derived in this way can then be compared to similar ACME relationships; (5) if/when the ACME relationships differ from those observed, the LES will need to be analyzed further to understand the unobserved physical processes that explain the observed relationships; (6) parameterization approaches that account for these processes or represent them more realistically will need to be developed; (7) the candidate new parameterization will need to be subjected to the same series of ACME tests against both the observations and the LES to determine whether it is an improvement over its predecessor; (8) Any improved features through ACME tests need to be confirmed in CAPT-type hindcast tests which include full interactions between model parameterizations and the resolved flow in a GCM. Even then, history teaches that proposed parameterization improvements can take the better part of a decade to be implemented successfully in an operational GCM to lead to an improved climate simulation (e.g., Grenier and Bretherton, 2001 vs. Bretherton and Park, 2009); however it is expected that this process will be greatly accelerated with a well-coordinated multi-disciplinary project.

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Programmatic considerations

Having identified strategies for attracting the mutual interest of the full range of DOE climate research activities, and considering how to improve coordination among these activities, the next issue that arises is how to sustain effort. Three factors that are expected to have an impact here are: funding, programmatic alignment, and continuity.

A meeting may generate avenues for collaboration; however, all too often, these ideas do not bear fruit because of the many distractions awaiting participants at home. If the activities identified at the meeting do not align with projects the participants are working on, they will generally receive a low priority because other funded activities typically demand full attention. A remedy for this is to establish joint projects that explicitly support collaboration. This is not a panacea. There are risks, for example, that teams would form loose alliances with individual sub-teams continuing to focus on their own core research agendas. Often, the funding available for joint efforts has been too limited for the individual participants to make the collaboration a high priority. It is critical that the focus of these efforts be on cross-discipline collaboration. If this perspective can be achieved, joint projects have the potential to accelerate progress at the boundaries of disciplines.

Recognizing the challenges in jointly funded projects, careful alignment of program goals, possibly through the identification of grand-challenge problems, could have a similar effect. Having identified common themes for science advancement leading to model development, alignment of programs around those themes would provide a better environment for collaboration. The more closely goals are aligned – the more likely it is that collaboration will occur.

Finally, DOE is currently funding a number of multi-faceted “Science Focus Areas” (SFAs), at DOE sponsored laboratories. These SFAs typically involve a diverse team and tend to have longer duration than non-laboratory grants. These SFAs are intended to take on larger projects and also have the potential to serve as organizing groups for other research activities. With their longer duration, SFAs additionally have the potential to provide continuity to complex projects. Therefore, it would be natural for SFA teams to take up the leadership in advancing some of the strategies described in this section that would then provide a focal point to attract collaborations from the larger research community.

Conclusions

Climate research within DOE spans the collection of observations, to the analysis of those observations to better understand atmospheric phenomena, to the application of this improved understanding to advance global climate models. This broad spectrum of activities is embodied in the ARM Climate Research Facility, the ASR program and the ACME project as well as broader ESM modeling activities. With the recent advent of the DOE ACME project, there is an unprecedented opportunity to build on the existing ARM and ASR activities to improve the

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atmospheric capabilities of climate models. This workshop was designed to develop strategies for accelerating the application of atmospheric observations and analysis from ARM and ASR to the improvement of climate models, and particularly the DOE ACME model.

The workshop was structured to first identify current science gaps that are important for advancing climate models and then to consider strategies for addressing these science gaps through collaborative efforts among ARM, ASR, and ESM/ACME. For the identified science gaps, workshop participants were challenged to propose measurement, process research and validation strategies that would help address these science gaps. Finally, the group was asked to consider how the observation, analysis, and modeling communities could work together better to accelerate the application of these techniques.

The scope of science topics identified in the workshop does not represent a comprehensive set of science gaps facing process understanding and implementation in models. The workshop focused heavily on clouds with less attention to aerosol-related processes, consistent with participants' backgrounds, although input was solicited from non-participants in the form of pre-workshop whitepapers. In effect, the science topics provide a valuable framework for identifying collaboration strategies. Specific areas that were raised a number of times included advancing the understanding of:

- Processes associated with the development and maintenance of marine stratus and arctic mixed-phase clouds
- Convective clouds including microphysical processes, transition from shallow to deep convection, and convective organization
- The impact of aerosols on cloud properties

These are already focus areas for ASR and ARM, so perhaps the most important message here was for the ARM and ASR communities to look to the modeling communities to identify what specific physical processes are of leading importance for climate applications, those that are most poorly represented in models, and then focus attention on those areas. The ACME/ESM community should look to the types of information available from ARM and ASR and actively share needs with ARM and ASR. Specific actions to achieve this alignment would include:

- For the ACME/ESM community to work with the ARM and ASR communities to determine which science priorities can best be informed by ARM observations and ASR analysis.
- For the ACME/ESM community to work with the ASR and ARM communities on problem areas in model performance.
- For the ACME/ESM community to work with the ASR and ARM communities to develop strategies to test key physical assumptions in their parameterizations.

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A key to successful collaboration will be identifying parameterizations that are “improvable,” that is, parameterizations that contain explicit representations of important physical processes and thus can benefit from the information that ARM/ASR can offer.

Addressing a specific science gap requires assembling available measurements, often seeking new measurements, and developing a research plan. Many measurement needs were identified in the whitepapers and discussion throughout the workshop. Generally, these measurement needs have been discussed frequently within the ASR and ARM communities. A list of suggested measurements, again, not intended to be comprehensive, is provided in Appendix D. As with the science areas, perhaps a more impactful aspect of the workshop discussions were on strategies for applying measurements to address science gaps. Suggestions included:

- Make better use of long-term data sets to develop better statistics for evaluating parameters and processes.
- Construct “virtual field campaigns” in which data from existing sources are organized around a science theme and/or a location and time. These could, for example, then be used for DOE sponsored model intercomparisons spanning a multi-scale set of models.
- Consider exploiting existing instruments from other agencies and international sources. For example, there continues to be a great interest in measurements of deep convection in the Tropics; deploying a small set of ARM instruments near existing capabilities (esp. scanning weather radar) would provide a valuable data set for reduced cost and effort.
- Focus on model forcing data sets and other parameters that characterize the environment (e.g., vertical velocity) that are critical for relating measurements and simulations of physical processes within a domain.
- Explore impacts of surface heterogeneity on the atmosphere at the NSA site where UAVs can be more freely used
- Selectively choose observation sites that specifically limit certain aspects of surface heterogeneity to better understand other sources of heterogeneity

While there remain unmet measurement needs, a wealth of observational data already exists. A significant need is the implementation of processes to better link existing, or new, observations to model simulations. There were several key themes along these lines raised in the white papers and the meeting:

- Focus on statistical relationships among parameters rather than actual values of individual parameters when comparing observations and models to better constrain model parameterizations.
- Focus on “emergent behavior” (statistical relationships between fields that constrain model parameterizations).
- Accelerate the application of algorithms and associated data products
- Make use of instrument simulators to relate observations to model output

- Develop model diagnostics that explicitly make use of available observations in standard formats (e.g., CF). This requires close communication between communities to determine what is needed by the models and what is possible from the measurements.
- Implement a multi-scale framework using a combination of LES, SCM, LAM, and GCM models that would serve as a community resource to link observations and models.
- The modeling framework should include benchmark cases so that models could be evaluated in a consistent manner.
- Develop a strategy for LES-observation comparison, which will also require understanding of errors in the LES and possible model development to remove critical biases.

There are also considerations in terms of strategies for the development and application of models that can accelerate development. Examples in this area include:

- Determine the appropriate level of complexity for the representation of cloud microphysics and aerosol processes. Consider what is the simplest representation needed to capture a particular phenomena.
- With the implementation of the multi-scale framework of models, make use of DOE's unique world-class computing capabilities with coordinated efforts around expensive simulations targeting key scientific challenges.

Ultimately, the core goal of this workshop was to strengthen the relationship among the observations, process researchers, and model development communities within CESD to accelerate the advancement of GCMs. The activities described above represent some tools that can be used in this process but specific strategies were also identified to improve this cross-community communication:

- There should be a focus of activities across all three communities around selected science themes (the identification of such themes was previously noted above under science topics)
- Implicit in this focus of activities is programmatic alignment across the three areas so that projects from one community naturally support another.
- Hold occasional physical or virtual meetings that explicitly draw together the three communities. It would be helpful if these meetings included a critical mass from each community. There is already an abundance of meetings, but there was a sense among participants of this workshop that the balanced combination of participants from across the communities led to valuable insights into the needs of one community from the others.
- Seek leadership from laboratory groups, which provide continuity and broad skill sets to facilitate collaboration and the advancement of long-term projects.

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Overall, the workshop led to valuable ideas and increased interaction among researchers from all three programs. Participants expressed the value of the workshop and the hope that increased dialog continues to be nurtured to improve DOE's climate research portfolio.

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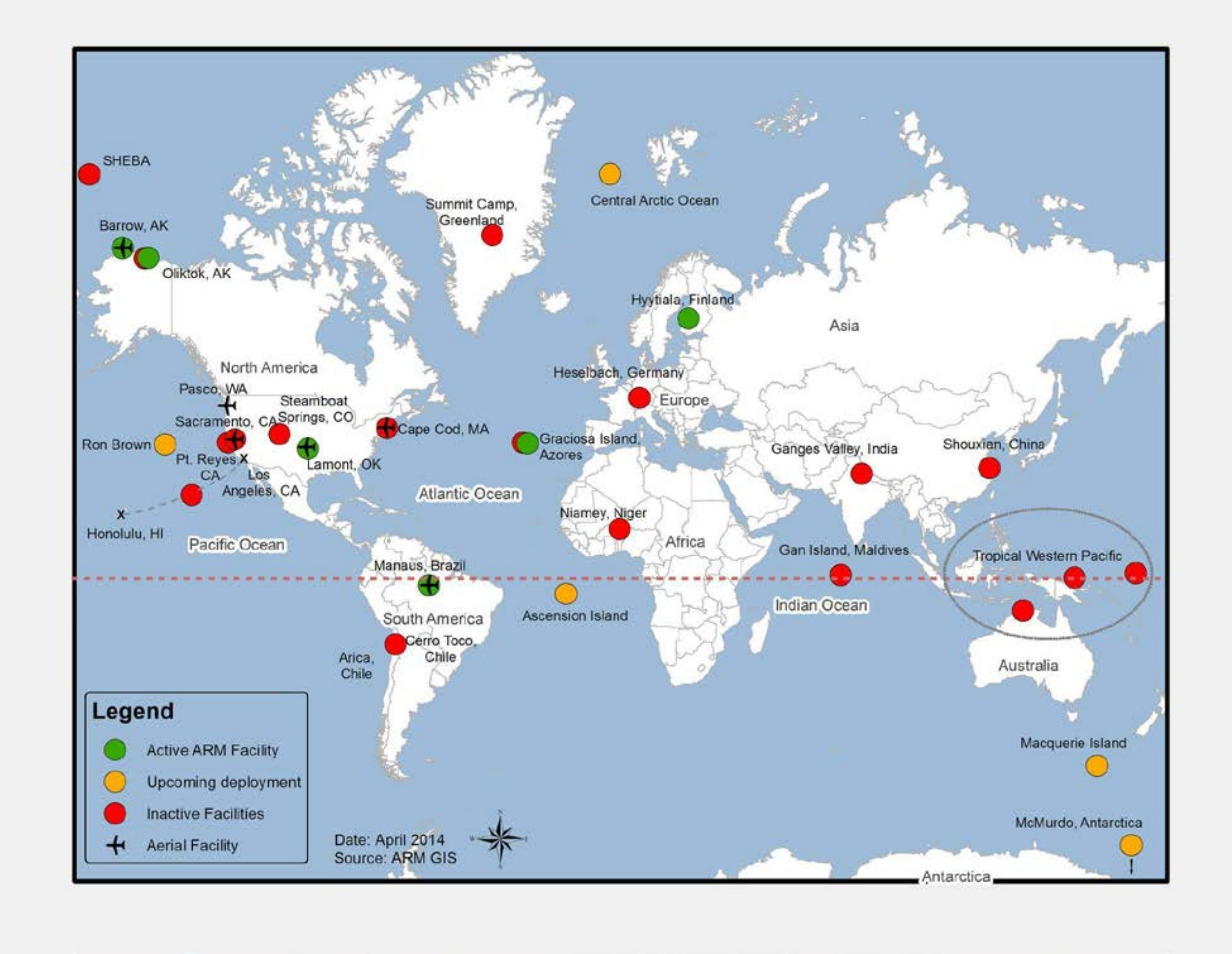
Figures



Date: April 2014
Source: ARM GIS

Figure 1. Current and historic ARM deployments

Additional figures to be added.

Appendix A: Workshop Agenda

Wednesday, 21 October

8:30 - 8:45 am Arrive at DOE for badging
9:00 - 9:45 am Attendee Introductions (2 min each)

- Name
- Institution
- What you work on (two sentences)
- What is really difficult about what you are working on? (related to workshop themes)

9:45 - 10:15 am DOE HQ motivations - *DOE organizers*

10:15 - 10:30 am Break

10:30 - 11:30 am Invited plenary presentations (15 minutes each plus 5 minutes for questions)

- Andy Vogelmann, BNL - “Linking small-scale cloud process observations to models”
- Shaocheng Xie, LLNL - “ACME and Its Connection to ARM/ASR”
- Maike Ahlgrimm, ECMWF - “Sticking points - a perspective from the operational modelling side”

11:30 - 11:45 am General discussion, breakout charge

11:45 am - 12:45 pm Lunch - *DOE cafeteria*

12:45 - 3:15 pm Breakout Session 1: Cloud microphysics and aerosol-cloud interactions, including aerosol activation processes

- White paper summaries: Phil Rasch and Bill Gustafson
- Discussion leaders: Gijs de Boer, Steve Ghan
- Rapporteurs: Jerome Fast, Jan Kazil
- Breakout into 2 groups for discussion, following breakout templates

3:15 -3:30 pm Break

3:30 - 5:30 pm Breakout Session 2: Boundary-layer clouds, including boundary-layer processes, turbulence, and interaction with lower boundary

- White paper summaries: Bill Gustafson and Shaocheng Xie
- Discussion leaders: Chris Golaz and Larry Berg
- Rapporteurs: Jennifer Comstock and Peter Caldwell
- Breakout into 2 groups for discussion, following breakout templates

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Thursday, 22 October

8:30 am Arrive at DOE for badging

8:45 - 9:15 am New global atmosphere development projects (10 minutes each, plus 5 minutes for questions)

- Mike Pritchard, UC Irvine - "Ultraparameterization: A strategy for including explicit low cloud physics in global climate models"
- Joao Teixeira, JPL - "Unified Turbulence and Convection Parameterizations: the EDMF Approach"

9:15 - 9:30 am Break

9:30 am - 12:00 pm Breakout Session 3: Deep convection and the transition from shallow to deep convection

- White paper summaries: Jim Mather and Shaocheng Xie
- Discussion leaders: Joao Teixeira, Pavlos Kollias
- Rapporteurs: Larry Berg, Maike Ahlgrimm
- Breakout into 2 groups for discussion, following breakout templates

12:00 - 1:00 pm Lunch - *DOE Cafeteria*

1:00 - 3:00 pm Breakout Session 4: Crossing scales and integrating observations and models - putting it all together

- White paper summaries: Tony Del Genio, Jim Mather
- Discussion leaders: Christian Jakob, Andy Vogelmann
- Rapporteurs: Dave Turner, Joao Teixeira
- Breakout into 2 groups for discussion, following breakout templates

3:00 - 3:15 pm Break

3:15 - 5:00 pm Plenary

- Panel discussion/highlights from breakout session - *Co-chairs*
- Closing discussion and next steps (e.g., report, working group formation, opportunities) - *Co-chairs and DOE Organizers*

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Appendix B: Background on ARM, ASR, and ACME/ESM

This workshop included participation primarily from researchers funded within three DOE Biological and Environmental Research (BER) programs: the Atmospheric Radiation Measurement (ARM) Climate Research Facility, the Atmospheric System Research (ASR) program, and the Accelerated Climate Modeling for Energy (ACME) project within the Earth System Modeling (ESM) program. The following gives some history and context on the type of research done in these programs relevant to this workshop.

The ARM Climate Research Facility was created in 2003 from several extensively instrumented in situ and surface remote sensing sites that had been developed since 1989 by the predecessor ARM research program. The centerpiece of ARM is its fixed Southern Great Plains (SGP) field measurement site in Oklahoma. The SGP site consists of 30 instrument clusters at a Central Facility and at Boundary, Extended, and Intermediate Facilities covering an area of 55,000 mi^2 (143,000 km^2). The SGP complement of cloud and precipitation zenith-pointing and scanning radars and lidars, radiometers covering the visible to microwave spectral range, surface radiation, precipitation and turbulent flux instruments, aerosol measurement systems, and routine soundings is the most comprehensive in the world. The SGP experiences a full range of seasonal continental midlatitude atmospheric conditions characterized by deep convective, cirrus, shallow cumulus, stratus, and nimbostratus clouds. A second fixed site on the North Slope of Alaska (NSA) centered on the Alaskan coast at Pt. Barrow contains a similar but less extensive set of instruments. Observations at the NSA are especially valuable in characterizing the mixed-phase stratus and stratocumulus clouds that are crucial to the surface energy balance over the nearby Arctic Ocean. A third fixed site has recently been established at Graciosa Island in the Azores region of the Eastern North Atlantic (ENA). The ENA site is located within one of the major maritime subtropical subsidence regions whose stratocumulus and shallow cumulus clouds are a major source of uncertainty in GCM estimates of global climate sensitivity. ARM also has historical data sets from previous fixed sites at Manus Island, Nauru Island, and Darwin, Australia in the Tropical West Pacific (TWP).

In addition to its fixed sites, ARM supports three *ARM Mobile Facilities (AMFs)* that can be deployed to make atmospheric measurements anywhere in the world for periods ranging from months to several years (Figure 1). The AMFs have allowed ARM to extend its reach to virtually every climate regime, with deployments in locations including the continental United States (California, Massachusetts, Colorado); other mid-latitude continents (Germany, Finland, China); tropical continents (Niger, India, Brazil) and islands (Maldives); subtropical oceans (Azores and east Pacific) and polar regions (Alaska and Antarctica). Finally, ARM maintains the *ARM Aerial Facility (AAF)* to make measurements of cloud, aerosol, and radiative properties on either a routine basis or for limited periods in support of field campaigns. The AAF supports the Gulfstream-1, Cessna 206 and unmanned aircraft as well as non-DOE aircraft depending on the needs of particular missions. Routine "value-added" science data products (VAPs) derived from ARM data streams are produced by ARM infrastructure scientists.

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In 2014, ARM re-configured its assets to create two "megasites" at the SGP and NSA. The science objective was to develop a testbed for continuous high-resolution LES modeling and SCM evaluation constrained by the most comprehensive set of observations possible. This project, known as LASSO (LES ARM Symbiotic Simulation and Observation), is beginning at the SGP and focusing initially on LES simulations of shallow convective clouds to develop protocols for how to most effectively force the models, assess methods of comparing LES models to ARM data, and select metrics for model evaluation.

The ASR program supports scientific research on aerosol, cloud, precipitation, and radiative processes that exploit the observations acquired by ARM. ASR remote sensing scientists develop new retrieval algorithms that can either lead to new science data sets produced by the algorithm developer or be transferred to the ARM infrastructure and used as the basis for official ARM VAPs. ASR scientists use ARM data products and process-level box models, large-eddy simulation (LES), cloud-resolving models (CRMs), and regional limited area models (LAMs) to gain insights into fundamental processes, develop or evaluate parameterizations, and implement parameterizations in GCMs. Cloud parameterization testing in ASR often occurs in single column models (SCMs), which consist of all the parameterizations included in a single column of a GCM. SCM evaluation of parameterizations in ASR is facilitated by ARM advective forcing products that allow the SCMs to simulate clouds, precipitation, aerosols, and radiation during intensive observing periods in the vicinity of the ARM fixed sites or during AMF deployments. The forcing products are also used to drive LES and CRM models, either to improve parameterized processes such as cloud dynamics in those models or to provide a bridge between the small-scale ARM observations and SCMs.

Scientific research in ASR is organized into three Working Groups: Cloud Life Cycle (CLWG), Aerosol Life Cycle (ALWG), and Cloud-Aerosol-Precipitation Interactions (CAPI). To date, the CLWG research is organized around four science theme areas: ice physical and radiative properties, cloud phase partitioning/mixed-phase clouds, warm low clouds, and mesoscale convective organization. The ALWG science themes include new particle formation, aerosol aging and mixing state, secondary organic aerosol formation, and aerosol direct radiative forcing. The CAPI Working Group is organized around issues such as why climate models produce a large aerosol indirect effect, sensitivity of warm low clouds to aerosol perturbations, effects of aerosols on deep convection, and ice nucleation processes. Recently, a new land surface – atmosphere interaction science theme has emerged within ASR.

Earth System Modeling supports the development of a climate predictive capability to underpin the Nation's societal and energy planning. These developments include complex representations of climate systems, coupling these with "human" systems and drivers as needed to improve climate simulation fidelity, and the application of next-generation computational methods to facilitate and to accelerate model computational performance on DOE's current and next-generation NERSC and Leadership Class Facility (LCF) computers. In 2014, DOE's ESM program launched a Laboratory-led project to develop the Accelerated Climate Model for Energy (ACME). The ACME project is developing and applying a computationally advanced climate and Earth system model to investigate the challenges posed by the interactions of climate

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change with energy and related sectors. The ACME model was initiated from a recent version of the Community Earth System Model, and maintains a close collaboration with that project. ACME's first model version (version 1 or v1) is targeted to work routinely at very high (for a climate model) horizontal grid spacing (25 km) and vertical resolution (72 layers with a model top at 60 km). The model further employs regional-refinement using adaptive mesh methodologies in order to provide ultra-high-resolution to resolve critical physical and dynamical phenomena. The ACME model simulates the fully coupled climate system with a focus on near-term hindcasts (1970-2015) for model validation and a near-term projection (2015-2050) for societal planning. The v1 model will include new ocean and land ice components, and important changes/innovations to the land and atmosphere model components. The new ACME model will initially be used to address three challenging and computationally demanding climate-change research problems (described in more detail in the following links):

1. **Water Cycle**: How do the hydrological cycle and water resources interact with the climate on local to global scales?
2. **Biogeochemistry**: How do biogeochemical cycles interact with global climate change?
3. **Cryosphere-Ocean System**: How do rapid changes in cryosphere-ocean systems interact with the climate system?

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Appendix C: Scientific Context

Clouds affect the planet's energy budget by reflecting and absorbing incoming energy from the sun, and absorbing and re-radiating outgoing energy at longer wavelengths. Clouds also play a role in the water cycle by transporting it and by participating in removal of water from the atmosphere and delivery to the surface. They also transport energy and trace constituents within up- and downdrafts inside clouds; and act as sites for scavenging of atmospheric trace species. Aerosols, the small solid or liquid particles suspended in the air (e.g., dust, sea spray, sulfate, organics) of natural and anthropogenic origin, participate in the genesis of all cloud liquid and ice particles through a process called "activation." When liquid cloud droplets form on aerosols, the aerosols are termed "Cloud Condensation Nuclei" (CCN). When aerosols participate as nuclei for ice clouds they are termed "Ice Nuclei" (IN). Aerosols can trigger conversion of liquid water to ice also.

The heat absorbed and released as water changes phase between liquid, ice, and vapor warms or cools the neighboring air, influencing the internal dynamics of clouds and neighboring air. Vertical motions in turn change the relative humidity of air, inducing cloud particle formation, growth, and evaporation. The properties of cloud particles (particle size distribution and number, location, and phase) are thus controlled by interacting processes: 1) those described by physics at the molecular scale; 2) through interactions between cloud particles (the "microphysics" of clouds) and the dynamical motions within and surrounding clouds that control aerosol activation, and droplet evaporation. Aerosols operate indirectly to affect clouds, and thus play a role in cloud radiative effects (CRE). Aerosol-cloud interactions have been identified as one of the two largest uncertainties in climate change projections.

Clouds respond to and influence the dynamics and thermodynamic structure of the atmosphere. Boundary layer turbulence is the direct source of low level clouds (stratus, stratocumulus) that form near the boundary layer top and also the source of air that becomes buoyant upon lifting and condensation to form shallow, congestus, or deep convection. Heating by phase changes and CRE influence atmospheric circulations on all spatial scales. Global climate models such as ACME resolve the circulation explicitly on scales of tens of km and greater. On finer scales, the coupling between clouds and vertical motions must be parameterized. In the boundary layer, turbulent-scale motions are driven by surface heat and moisture fluxes, by wind shear, and by turbulence at the top of the boundary layer caused by radiative and evaporative cooling of the clouds that form there. Turbulence at the top of a cloudy boundary layer entrains free tropospheric air into the boundary layer, influencing its depth and structure and the properties of the clouds within. Above the boundary layer, latent heat release sustains the buoyancy of rising air in convective updrafts. This, combined with the entrainment of environmental air into the updrafts and pressure gradient forces, determines the updraft speed and eventual top of the convective cloud. Precipitation that forms in the updraft and entrainment mixing of clear and cloudy air drives downdrafts that bring cool air to the boundary layer and generate further convection. In favorable conditions, sustained convection organizes into mesoscale clusters that are responsible for the heaviest rain events. Cloud particles carried upward in convective updrafts detrain to form large stratiform anvils that account for most of the radiative effect of convection. The response of clouds to changing temperature, atmospheric structure, and dynamics in a warming climate, called the cloud feedback, is the other leading source of uncertainty in projections of future climate.

In spite of the acknowledged role of these processes in cloud formation, and ultimately in cloud properties (reflectivity, extent, lifetime, depth, etc.), there is still considerable controversy about the relative importance of the component processes that influence clouds. Furthermore the relative importance of these processes is likely to depend upon the cloud regime, and differ for shallow boundary layer clouds in the subtropics that develop in warm, stable, relatively quiescent conditions, or in polar latitudes where mixed ice/liquid phase or pure ice clouds are often observed, or in the tropics and summertime midlatitudes, with deep clouds characterized by much stronger vertical motions, with a base in warm air, and cloud top at very cold temperatures. The complexity of each process, and the complexity of interactions between processes remains an extremely challenging problem.

Deep convection is particularly challenging, as it spans a broad range of phenomena and scales from the microphysical properties of cloud particles to cloud-scale dynamics to cloud-system-scale organization. It has profound impacts on atmospheric circulation and the earth’s water and energy cycles through releasing latent heat and vertically redistributing sensible heat and water vapor. However, there remain many challenges in understanding and representing these systems in climate models, particularly regarding the importance of specific dynamical and microphysical processes and the inability of climate models to resolve important scales of

DRAFT

motion. Many long-standing systematic model errors, such as the unrealistic double intertropical convergence zone pattern in tropical precipitation, weak Madden-Julian Oscillation (MJO) and other tropical waves, and too-early diurnal cycle of precipitation over land, are closely related to deficiencies in representing deep convection in climate models. Recent studies suggest that part of the reason for the poorly simulated MJO and diurnal cycle of precipitation is that climate models generally fail to gradually moisten the troposphere by shallow convection and simulate a slow transition from shallow to deep convection.

To improve the representation of atmospheric convection in climate models, recent cumulus parameterization developments have emphasized unified schemes that represent turbulent, shallow, and deep convection processes in a consistent framework (Park 2014a,b; Golaz et al. 2002; Bogenschutz et al. 2012, 2013; Siebesma and Teixeira 2000; Teixeira and Siebesma 2000) and/or the "super parameterization" approach, in which the cumulus parameterization is replaced with the mean effects of cloud-scale processes simulated by a 2-D CRM embedded in each GCM grid cell (Grabowski and Smolarkiewicz, 1999; Khairoutdinov and Randall, 2001). Better understanding and model representation of atmospheric convection have been identified as the key to address four Grand Challenge questions (that likely progress the field to the point of actual model improvements with a measurable impact on uncertainty if answered) identified by WCRP (Bony et al. 2015).

Appendix D: Measurement Needs

A wide variety of measurement needs were identified in the pre-workshop whitepapers and in the workshop discussions. The following is a representative sample of these suggestions.

- Sustained field studies of aerosol properties
- Aerosol properties from many regions of the world
- SOA life cycle including SOA precursors
- Vertical distributions of aerosol properties to address CCN biases in GCMs
- Measurements downwind from an aerosol source (e.g., a volcano)
- Better measurements to constrain mixed-phase processes including ice nuclei properties
- Cloud microphysics (e.g., cloud phase, droplet size, number density)
- Cloud boundaries (suggested use of photogrammetry to improve detection of cloud boundaries for shallow continental clouds)
- Quantitative drizzle properties combined with boundary layer relative humidity profiles
- Sensible heat and latent heat fluxes at the surface
- Vertical flux profiles of moisture and temperature
- Entrainment at a range of scales relevant to LES and GCM modelers
- Vertical velocities both in and around clouds
- Surface properties
- Characterization of the background atmospheric environment to give context to the cloud and boundary layer measurements
- Multiple long-term continuous large-scale forcing data sets for all ARM sites

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Appendix E: Workshop Organizers and Participants

Organizing Committee

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Appendix F: Written Respondents

To be added.

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Appendix G: Acronyms

To be added.

A list of many of the acronyms used in this report is available at:
http://www.arm.gov/about/acronyms

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