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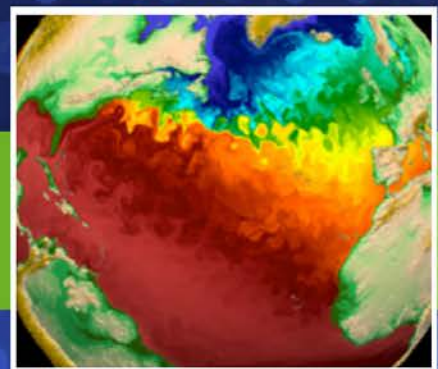
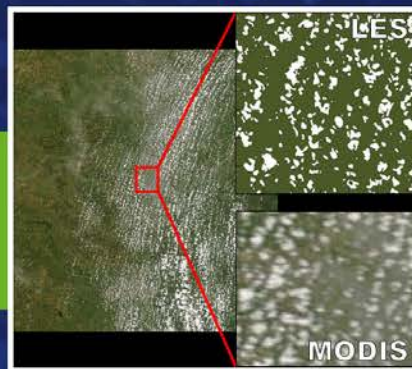
Office of  
Science

BIOLOGICAL AND ENVIRONMENTAL RESEARCH

Climate and Environmental Sciences Division

**Accelerated Climate Modeling for Energy (ACME) –  
Atmospheric Radiation Measurement (ARM)  
Climate Research Facility – Atmospheric System  
Research (ASR) Coordination Workshop**

October 21–22, 2015





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Accelerated Climate Modeling for Energy (ACME) –  
Atmospheric Radiation Measurement (ARM) Climate  
Research Facility – Atmospheric System Research  
(ASR) Coordination Workshop

October 21–22, 2015

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ORGANIZERS

**Dorothy Koch**, Earth System Modeling  
**Sally McFarlane**, Atmospheric Radiation Measurement Climate  
Research Facility  
**Shaima Nasiri**, Atmospheric System Research  
**Ashley Williamson**, Atmospheric System Research

CO-CHAIRS AND WRITING TEAM

**Anthony Del Genio**, NASA Goddard Institute for Space Studies  
**William Gustafson**, Pacific Northwest National Laboratory  
**James Mather**, Pacific Northwest National Laboratory  
**Philip Rasch**, Pacific Northwest National Laboratory  
**Shaocheng Xie**, Lawrence Livermore National Laboratory

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# Executive Summary

The Climate and Environmental Sciences Division (CESD) of the U.S. Department of Energy's Office of Biological and Environmental Research focuses on advancing a robust predictive understanding of Earth's climate and environmental systems 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 Atmospheric Radiation Measurement (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, and
  - development of robust model analytical and testing frameworks at multiple scales through the Regional and Global Climate Modeling 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 Earth's climate 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 to:

- 1) identify areas where atmospheric processes are deficient in climate models, 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, and
- 2) 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 the following 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 science themes emerged: 1) microphysics (including the broad range of aerosol and cloud microphysical processes), 2) boundary-layer processes, and 3) 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 stimulate 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 a recognition of the importance of improved characterization of specific cloud and aerosol properties and features, cloud-scale vertical velocity, and entrainment rates. 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. These 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 large-eddy simulation (LES), cloud-resolving models, 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, 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, the ARM Facility 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.
- 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.
- 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.

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 coordination of science goals across programs.





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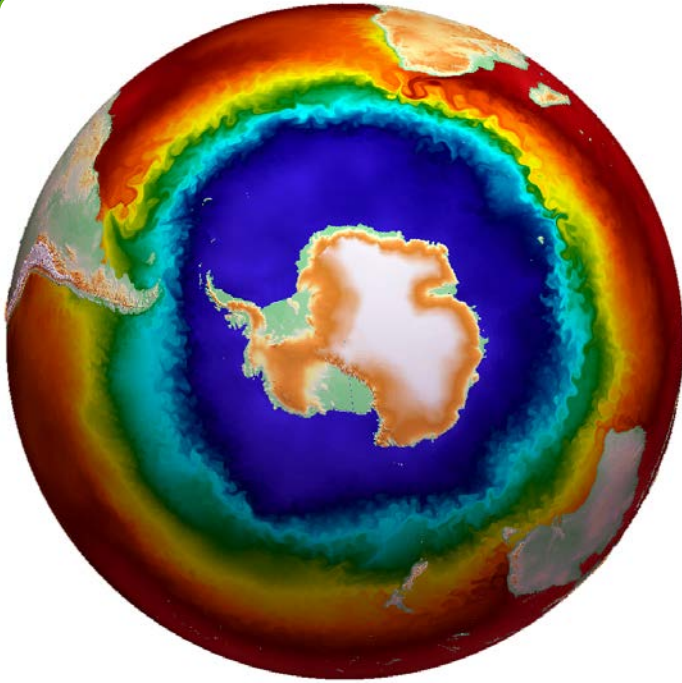


# 1.0 Introduction

The Climate and Environmental Sciences Division (CESD) of the U.S. Department of Energy's Office of Biological and Environmental Research focuses on advancing a robust predictive understanding of Earth's climate and environmental systems 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 Office of Biological and Environmental Research programs: 1) the Atmospheric Radiation Measurement (ARM) Climate Research Facility, 2) the Atmospheric System Research (ASR) program, and 3) 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.



The initial focus of the ACME project will be on three climate science drivers and corresponding questions: 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? and 3) Cryosphere-ocean system, how do rapid changes in areas of the Earth where water exists as ice or snow interact with the climate system?

### Taking DOE Modeling to the Next Level

Through the U.S. Department of Energy's Earth System Modeling program, the Accelerated Climate Modeling for Energy (ACME) project was created to develop and apply a computationally advanced climate and earth system model to investigate the challenges posed by the interactions of climate change and societal energy requirements. The ACME model simulates the fully coupled climate system at high-resolution (15–25 kilometers) and will include coupling with energy systems, with focus on a near-term hindcast (1970–2015) for model validation and a near-term projection (2015–2050) most relevant to societal planning. The model further employs regional-refinement and advanced adaptive mesh methodologies in order to provide high-resolution to resolve critical physics and meteorological phenomena. Its code will be designed to optimize performance on current and future DOE leadership class computers. For more information, visit the ACME website at <http://climatemodeling.science.energy.gov/acme>.

Thus, a workshop bringing members of the ARM, ASR, and ESM communities together for the first time was convened at DOE Germantown Headquarters on October 21–22, 2015. There were four main objectives for the workshop. The first was to identify areas where atmospheric processes are deficient in climate models, 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 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 the 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 the following 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, and cloud particle nucleation
- boundary-layer structure, boundary-layer clouds, and land-atmosphere interactions
- 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.

## 2.0 Breakout Sessions

### 2.1 Breakout 1: Cloud microphysics and aerosol-cloud interactions

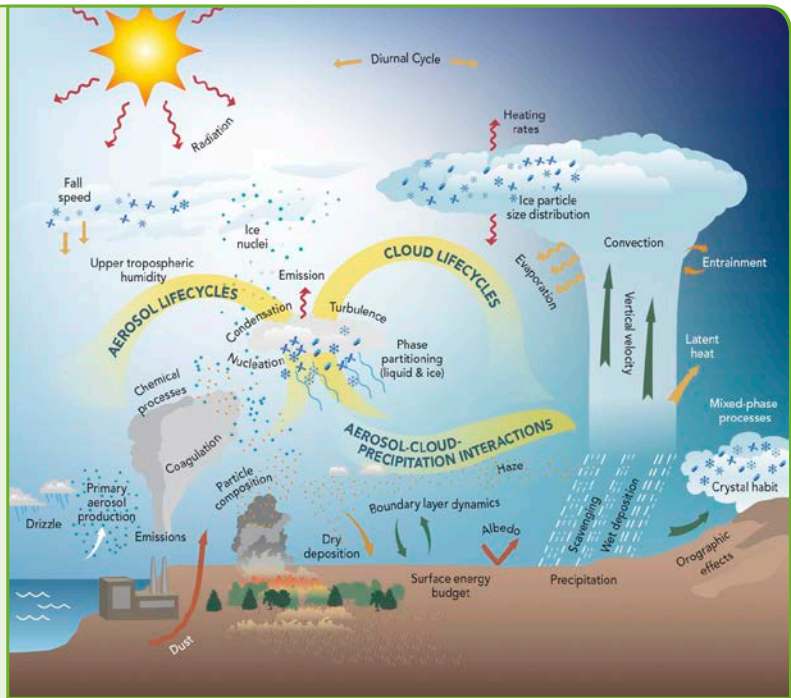
The first breakout session of the workshop focused on aerosol processes, cloud microphysics, and aerosol-cloud interactions, including cloud activation processes. The submitted white papers and breakout discussion reviewed some of these issues and identified opportunities to further constrain uncertainties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

#### Scientists Working Together to Improve Models

The Atmospheric System Research (ASR) program supports scientific research on aerosol, cloud, precipitation, and radiative processes that exploit the observations collected by the ARM Climate Research Facility. ASR scientists use field studies and laboratory data, together with models, to understand the processes that govern the atmospheric components and their interactions across a range of spatial and temporal scales. ASR research results are incorporated into earth system models developed by other DOE-funded activities to better understand atmospheric processes and to improve the accuracy of the models. Through these activities, ASR supports the development of national energy and climate policy.

Since 2010, scientific research in ASR has been organized according to the themes of aerosol life cycle, cloud life cycle, and cloud-aerosol-precipitation interactions. Working groups formed along these themes provide a structured forum for scientists to collaborate with each other. Each group includes both modelers and measurement scientists, so that improved understanding of observed atmospheric processes can be translated into better representation of these processes in models. A new science plan is currently being developed that will set the scientific vision of ASR for the next 5 years.

For more information, visit the ASR working group web pages at <http://asr.science.energy.gov/science/working-groups>.



ASR scientists study processes related to aerosols, clouds, precipitation, and radiation that are important for the global climate system. This work is focused on improving parameterizations in climate models. Increased coordination with the model development community is needed to accelerate the application of ASR advances into climate model improvement.

## *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 the understanding and treatment in models of secondary organic aerosols and, more generally, the distribution of aerosols, and particularly cloud condensation nuclei (CCN), 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/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 small) 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. In addition, detailed information about aerosol properties, such as composition, mixing morphology and size distribution, is typically 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



More studies of aerosol, like the ASR and ARM collaboration Carbonaceous Aerosol and Radiative Effects Study (CARES), are needed to understand the spatial distribution of aerosol globally and to understand the complex life cycle of natural and anthropogenic aerosol emissions.



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, e.g., large-eddy simulation (LES)/ cloud-resolving models (CRMs) and those including spectral bin microphysics. Models with grids larger than approximately 100 meters are unable to resolve or properly parameterize the important scales of motion for driving aerosol-cloud interactions. This 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 (e.g., 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, super-cooled liquid, and ice clouds). Two microphysics themes that were particularly called out during this workshop were drizzle and mixed-phase clouds.

Drizzle, or very light rain, is a particularly important and problematic issue for climate models because the phenomenon is strongly controlled by interactions among microphysical,



Routine derivation of drizzle parameters from ARM observations, such as those found over the ARM Facility's Eastern North Atlantic site in the Azores, are needed to help constrain models at all scales.

turbulent, and dynamical processes and because drizzle is potentially important in regulating the sign and amplitude of cloud feedbacks in climate change. It also 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 Eastern North Atlantic (ENA) site or on the Marine ARM GPCI<sup>1</sup> Investigation of Clouds (MAGIC) field campaign 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

<sup>1</sup> GPCI = GCSS Pacific Cross-section Intercomparison, a working group of GCSS

GCSS = GEWEX Cloud Systems Study

GEWEX = Global Energy and Water Cycle Experiment, a core project of the World Climate Research Programme.



separation of cloud liquid from drizzle in retrievals for precipitating stratocumulus clouds (as well as all precipitating clouds) is 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. These processes strongly depend on 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., 2011).



Mixed-phase clouds are a particularly important and problematic cloud type for all cloud models. These clouds are prevalent in the Arctic, but models need a better characterization of ice nucleation to accurately capture the partitioning between the liquid and ice phases, which in turn, is important for the cloud life cycle.

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 versus homogeneous freezing.

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 (e.g., Russell et al., 2013; Latham et al., 2012; or Wood and Ackerman, 2013).

As noted above, 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. In addition, 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 carbon dioxide 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, etc.). The ARM Facility is currently supporting a small stereo photogrammetry effort at the Southern Great Plains (SGP) site.

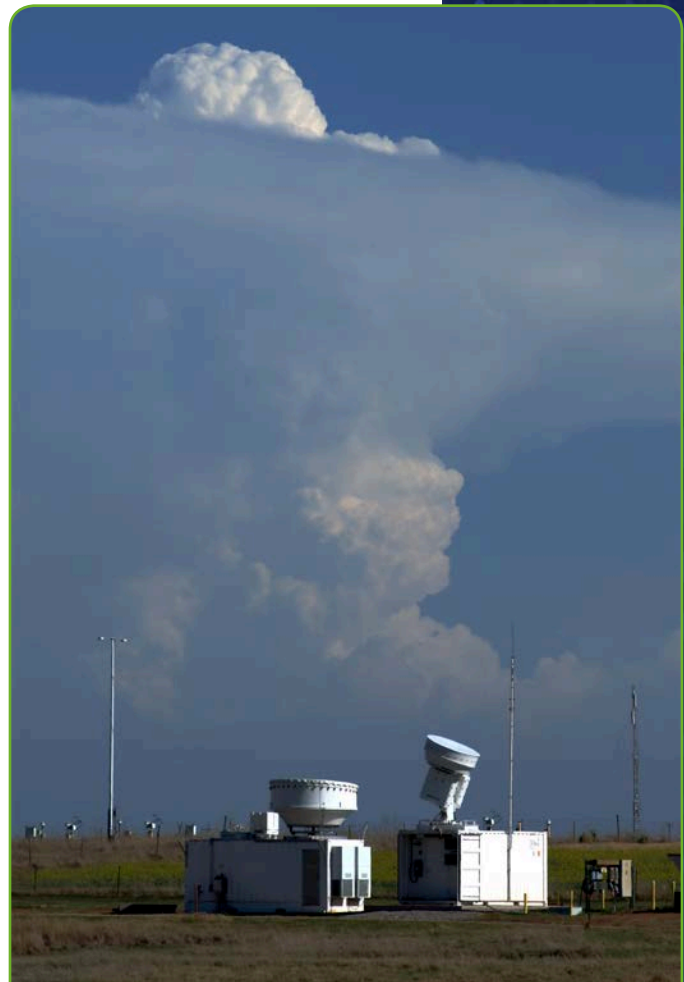
### *Analysis methods for advancing aerosol and microphysics themes*

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 PDF statistical characterization. Better measurements are needed of higher-order moments, such as variances and covariances, to better understand the impact of, and processes related to, spatial variability in models. 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, which would help for estimating ice deposition rate or to show 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 CCN 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 was a “top-down” approach. In this method, there was 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 versus 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. 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 fall speed of rimed ice to be more representative of hail than graupel (soft, slushy hail) 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.,



Representation of microphysics in global climate models for convective cloud parameterizations is particularly crude. More benchmark cases and measurement-to-model comparisons are needed that make use of long observation time series.

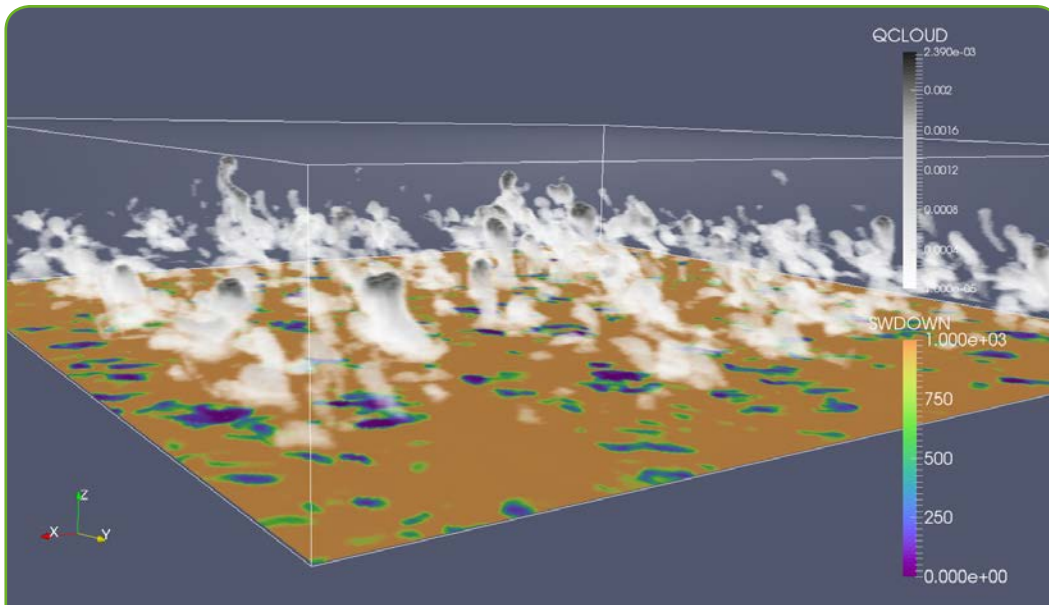


2012; Collis et al., 2013; Varble et al., 2014), which affects supersaturation, drop formation, glaciation, and many other properties of microphysics and cloud development.

Comprehensive treatments (e.g., spectral bin microphysics) are very computationally expensive, but bulk (two-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 necessary detail. 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 Midlatitude Continental Convective Clouds Experiment (MC3E) field campaign is one example of 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 with 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 simulations 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 (Nd) “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 Nd retrievals, to conduct CCN-Nd closure experiments more routinely using surface-based observations. Recent three-dimensional 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, as it affects 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 and kinetic energy spectra being particularly useful ways to quantify these structures.





"Data cubes" that combine observations, model output, and metrics will be combined into a unified package through LASSO, or the LES ARM Symbiotic Simulation and Observation Workflow. These packages will provide a resource to stimulate collaborations between process modelers and climate modelers.

### LASSO: LES ARM Symbiotic Simulation and Observation

The ARM Climate Research Facility is undertaking a new project tying together observation data and LES modeling to support the study of atmospheric processes, the improvement of observational retrievals, and parameterizations of clouds, aerosols, and radiation in climate models. This 2-year high-resolution model-development pilot project, called LASSO, is laying the groundwork to produce routine LES modeling at the ARM Southern Great Plains (SGP) megasite, with LASSO completing the pilot phase in 2017. The initial LASSO implementation will target shallow clouds and will later expand to other phenomena and ARM sites.

LASSO will enhance ARM observations by using LES modeling to provide context and an internally consistent representation of the atmosphere surrounding the SGP that will connect processes together and facilitate improved understanding. The project will result in a library of simulations that can be used to test the accuracy of climate model parameterizations, serve as a proxy for the atmosphere to develop remote retrievals, as well as many other applications. Associated with the simulations will be an ensemble of forcing data, associated observations for comparison with the simulations, and a diagnostics package for analyzing the simulation results.

For more information, read the LASSO Implementation Strategy at <http://www.arm.gov/publications/programdocs/doe-sc-arm-15-039.pdf> or visit the LASSO website at <http://www.arm.gov/science/themes/lasso>.

The ARM Facility is planning to use LES routinely. Initially, the LES framework, called the LES ARM Symbiotic Simulation and Observation (LASSO) workflow, 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 from using LES at many locations beyond the ARM SGP megasite to sample as many cloud regimes as possible.

Other DOE activities and projects (e.g., Cloud-Associated Parameterizations Testbed [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 GCM. 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.

## 2.2 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. Boundary-layer clouds are one nexus of many processes that need to be treated properly to achieve accurate climate change simulations. These processes also provide an opportunity to bridge the gap between small-scale and global atmospheric modelers because both groups encounter common problems in the treatment of these atmospheric features. Tools and analysis strategies can be developed by both communities to better understand longstanding problems and improve climate models. There is also a common interest among ACME, ASR, and ARM researchers to better understand boundary-layer processes and land-atmosphere interactions. This is driven by the more frequent use of models within the planetary boundary-layer terra incognita (grid spacings around 1 kilometer) (Zhou et al., 2014), the push toward using nonhydrostatic global models with regional refinement, the development of unified parameterizations that treat both planetary boundary layer and cloud processes (as is done with Cloud Layers Unified By Binormals, or CLUBB [Golaz et al., 2002; Guo et al., 2014], Unified Convection Scheme, or UNICON [Park, 2014a], and the Stochastic Eddy-Diffusivity/Mass-Flux Parameterization, or EDMF [Sušelj et al., 2013]), and new measurements. Related new measurements (e.g., photogrammetry of clouds to better measure cloud evolution and macro properties [Romps and Oktem, 2015] and scanning lidars that better measure low-level wind) should facilitate model development and better understanding of this important science area. 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 carbon dioxide) 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 Cloud Feedback Model Intercomparison Project-Global Atmospheric System Study Intercomparison of Large-Eddy and Single-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. 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).

To help in parameterization development, the following topics regarding measurement needs near cloud boundaries were discussed:

- *Cloud boundaries.* Robust cloud masks identifying cloud boundaries are a critical need, yet they are not straightforward because of 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 because the profiles must be averaged over a certain time period to obtain good statistics of the cloud population.



Shallow convective clouds were an important focus of discussion during the workshop, with emphasis on the large-eddy simulation modeling effort planned by the ARM Facility.

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 that 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 systems (UASs) could help meet this need for shallow cloud conditions where the small cloud size is not conducive to achieving a good signal.
- *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 grid-box 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 for obtaining estimates of cloud-top entrainment was to park an instrument at the top of the shallow cloud layer to measure fluxes across the layer. This could be done with tethered balloons or UASs. This technique would be more amenable at the North Slope of Alaska (NSA) site because of airspace restrictions at SGP.
- *Drizzle retrieval data.* The utility of drizzle retrievals from the ENA site on Graciosa Island in the Azores has been demonstrated already (e.g., Ahlgrim 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 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.

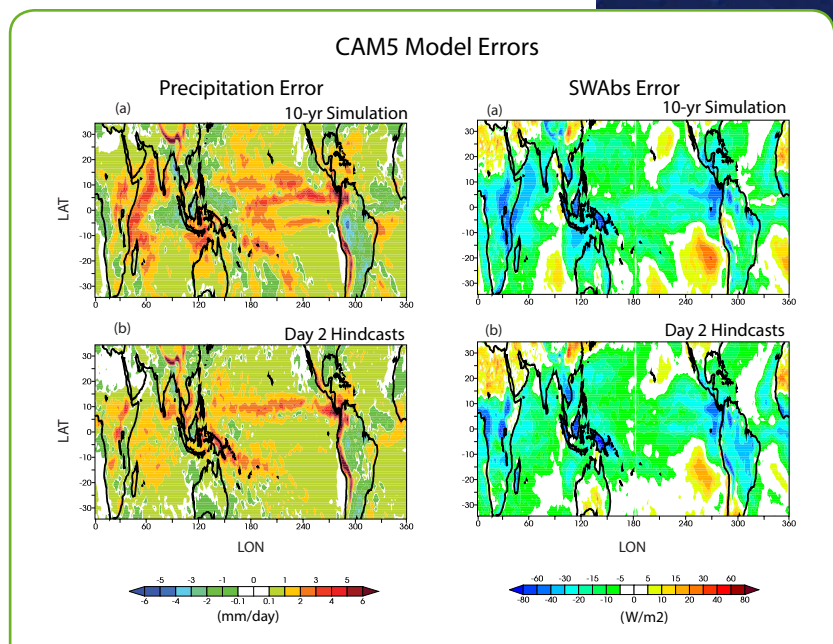
Vertical fluxes of moisture and temperature within the atmosphere were also identified as an important need. Being able to define the water and energy budgets would provide better validation for models and clarify understanding of how clouds impact the boundary layer development and vice versa. The use of scintillometer techniques could enable better measurement of fluxes, at least along one dimension. Flux profiles could also be obtained using stacked UASs acting 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 observing 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 UASs 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 ARM "Best Estimate" type data sets are needed at all ARM fixed sites (SGP, 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 analyses to address forcing data uncertainties and their impacts on LES/CRM/SCM/GCM simulations. The numerical weather prediction 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.

Also discussed during this session were several growth areas of research that could form foci around which observers and modelers from different scales could collaborate 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 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



The Cloud-Associated Parameterizations Testbed (CAPT) project uses climate models initialized by numerical weather prediction analyses to study model biases that evolve quickly, thereby gaining insights about model parameterization deficiencies. For example, these panels show the Community Atmosphere Model version 5 (CAM5) climate errors in precipitation and absorbed solar radiation in its 10-year simulation to resemble the biases in its Day 2 hindcasts (Xie et al., 2012).

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. Through careful selection of measurement location and/or time period, with the goal of limiting selected heterogeneities, one can better understand the impact of the heterogeneities on land-atmosphere processes.

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 an internally consistent representation of the atmosphere that observationalists can use to develop and validate remote retrieval algorithms. When LES produces features consistent with observations, it can provide estimates of other quantities needed by model developers, but which are difficult to measure in the field, such as correlations between 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



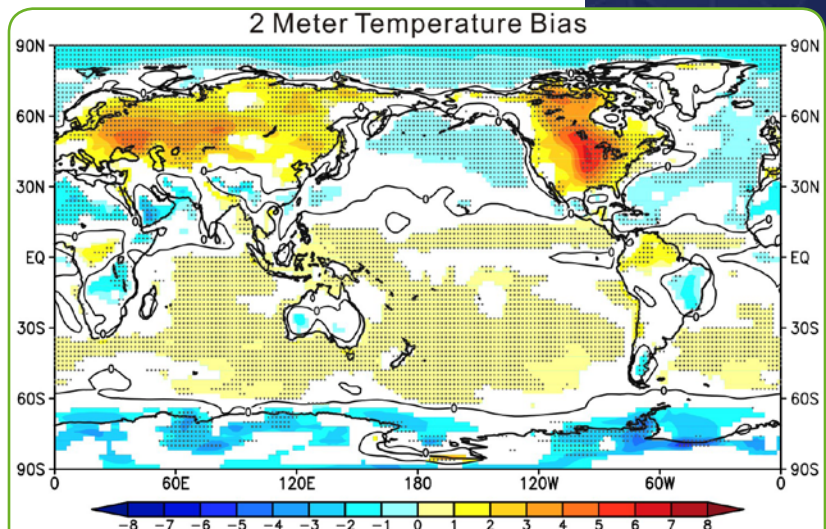
Simulation of large areas at very high resolution will require development of the next-generation atmospheric large-eddy simulation model that can make full use of DOE's unique computing resources and forthcoming exascale style computing hardware, which relies heavily on many-core technologies and highly vectorized code.



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 inter-compare different model behaviors are useful for understanding and evaluating low cloud processes in SCMs and GCMs by using cloud-resolving and large-eddy models. Similar activities could be planned for the ENA site and the Marine ARM GPCI Investigation of Clouds, or MAGIC, field campaign with a focus on specific boundary-layer cloud processes. The ongoing CAUSES study focuses on evaluating the contributions of clouds, radiation, and precipitation processes to surface temperature biases in the central United States. The ARM SGP site is an ideal location for such a study. The involvement of ASR within the CAUSES project, through the contribution of simulations from a wider selection of models, will 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 non-hydrostatic 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 (Wang et al., 2011) approach is used. The approach includes a very-high-resolution cloud model embedded within each GCM column. Whereas previous multi-scale modeling framework approaches have used cloud permitting models (CRM run at horizontal scales of a few kilometer) to replace the cloud and radiation parameterizations within GCMs, the UP-CAM method refines the CRM to LES grid spaces. At these scales, shallow-cloud and boundary-layer processes are treated significantly different than with multi-scale modeling frameworks 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 development to determine its potential.



ASR scientists' involvement within the Clouds Above the United States and Errors at the Surface (CAUSES) model intercomparison study, with a focus on the Southern Great Plains region where model errors are particularly large, is providing additional understanding of the role of clouds, radiation, and precipitation errors in contributing to the common temperature biases in climate models. (Stippling indicates the regions where analyzed global climate models agree in the sign of their bias, Ma et al., 2014.)

## 2.3 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 discussion and identification of priorities and gaps in this area, and how best to align the parameterization development and measurement strategies to address these gaps. Important areas that were identified included convective initiation, entrainment, transition from shallow-to-deep convection, and microphysical details (including the role of aerosols, precipitation efficiency, detrainment of cirrus, and mesoscale organization), and the interaction of convection with important large-scale dynamical phenomena such as the Madden-Julian Oscillation and the El Niño Southern Oscillation. 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, and errors in cloud distributions, particularly vertically. Main ideas from discussion during Breakout 3 are summarized below.

### *Important processes currently missing or not well represented in cumulus parameterizations*

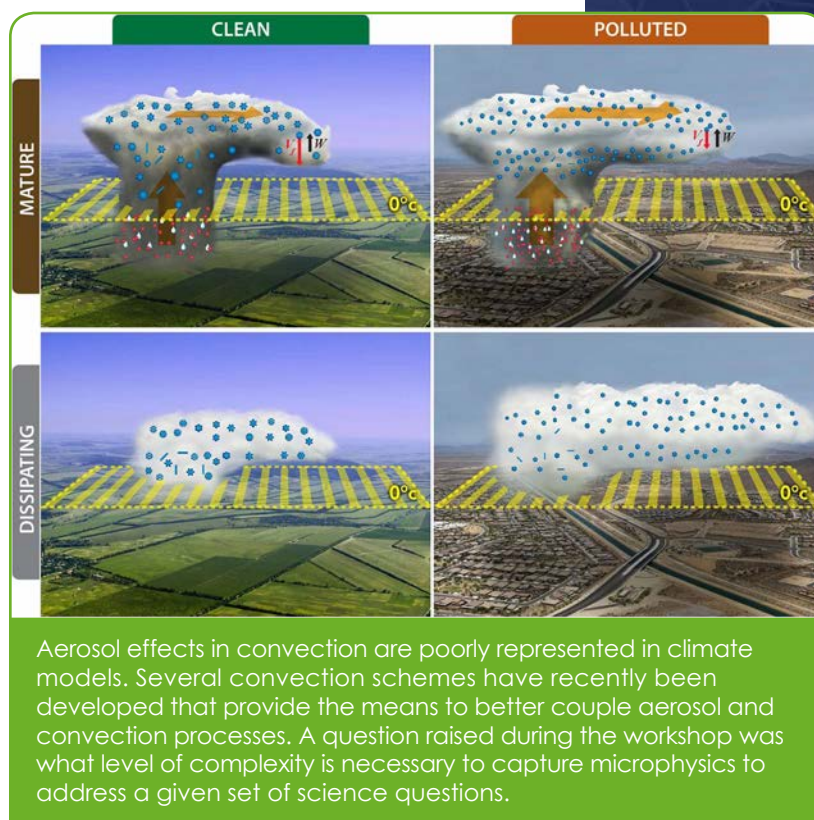
Among other issues, the challenge in representing convective organization and cloud microphysics in convective clouds in cumulus parameterizations was highlighted in the workshop. Convective organization, in the context of this workshop, can be defined as a series of processes that sustain convection on timescales 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 because 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 and Lafore, 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 the influence of aerosols 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 sub-grid-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 sub-grid PDFs for planetary boundary-layer turbulence, shallow cumulus convection) coupled with the updated version of the Morrison-Gettelman scheme, 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) 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 would need to be to get answers to the science questions needing to be addressed. For example, does it make sense to use complicated cloud microphysics if vertical motion is not well represented in cumulus parameterizations or does the added complexity make sense in this context? This also highlights the importance of accurate vertical velocity measurements in convective clouds by the ARM Facility.



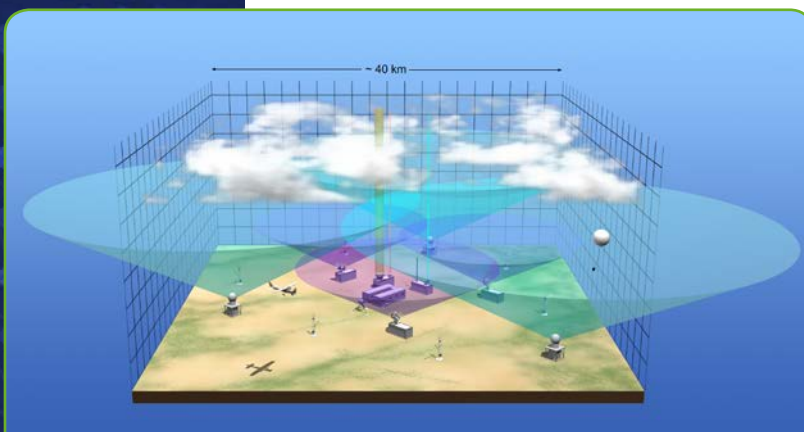
### *Additional or improved measurements needs*

The detailed cloud measurements along with their associated environments obtained by ARM can be very useful in advancing our 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<sup>2</sup> ARM Mobile Facility 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 evaluating and developing parameters.

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 sub-grid-scale processes to the large-scale state. Questions arise regarding how accurate the large-scale state needs to be, and what is needed to achieve that accuracy, how accurate must humidity data be, are more radiosondes needed, and does heterogeneity within a grid-box area need 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 continuously provide profiles of temperature, humidity, and wind in the boundary layer. A greater challenge is the continuous monitoring of humidity above the boundary layer, which is the key to exposing the erroneous behavior of cumulus parameterizations.

Other measurement gaps that were identified 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 (especially



The new Southern Great Plains "megastite" concept incorporates a network of densely populated instrumentation to support model development and evaluation.

<sup>2</sup> AMIE-Gan is the ARM Madden-Julian Oscillation Investigation Experiment at Gan Island in the Indian Ocean.

the Next-Generation Weather Radar) 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 capabilities 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, vertically pointing cloud radar 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 three-dimensional 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 emphasis area in its future plans. 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 noted in the workshop that many different retrieval algorithms are available in the ASR/ARM community but are not used routinely. It would be helpful for relevant principal investigators to share the codes with the community and provide guidance on situations in which a given algorithm would provide optimal estimates.

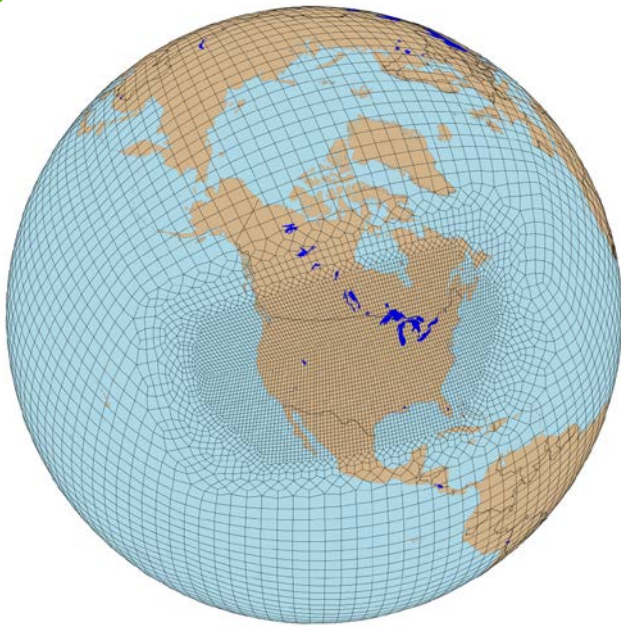
#### *New methods or diagnostics for cumulus parameterization developments and model-observation comparison or integration*

The high-resolution modeling (LES/CRM) activities that are being conducted by ARM/ASR through LASSO and individual principal investigator projects have the potential to provide extremely valuable insight into important physical processes that are parameterized in climate models and detailed diagnostics that 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 investing in global cloud-resolving models (GCRMs) to bypass the gray-zone issues, similar to the Japanese Frontier Research Center for Global Change/Japan Agency for Marine-Earth Science and Technology (Satoh et al., 2008). 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 for very short simulations leading to 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 computational resources for short simulations.



During the workshop, 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. Routine model simulations with these models would allow continuous comparisons 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.

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 United States, using ACME's regional refined capability to produce continuous 3 to 5 day hindcasts for the period of routine LES operation. The CAPT forcing data could be used to drive the SCM version of ACME and the LES model, and the LES output could then be used to evaluate ACME.



An example of the regionally refined grid used by the ACME model over the continental United States is shown here. Model meteorological fields are typically constrained in the outer (low resolution) domain, but allowed to evolve free in the high-resolution region. Used in combination with LES, the variable-resolution ACME model would provide a broad range of scales from the very fine scale observed by ARM observations to climate model scale.

To remove at least some of the location- and event-specific behavior inherent in ARM data, workshop participants suggested that the model-data comparison be focused on long-term observations rather than specific idealized case studies. Evaluation of models should move to 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 reported by Grabowski (2014) may be useful for isolating differences between representations of particular processes in different schemes.

To improve model-observation comparisons, use of instrument simulators to bypass some difficulties in comparing with retrieved parameters has been widely accepted in the global modeling community for comparing model clouds with satellite measurements. Two different types of simulators may be needed for LES and GCMs, respectively, given their significant scale differences. Developing an ARM diagnostic package could, in important ways, facilitate use of ARM data in model evaluations. In addition, similar to the instrument



simulators, different ARM diagnostics may be needed for LES and GCMs given their different scales, emphases, and capabilities. The package could be constructed around an open architecture to enable ARM/ASR/ACME principal investigators to easily contribute new sub-components as new data products or new novel analyses are developed. It would be helpful to incorporate the ARM diagnostic package in the ACME workflow making it a routine part of the model evaluation to facilitate rapid comparison of model with ARM observations. There is an opportunity to contribute to the further development of ACME with model evaluation based on existing products (version 1–2) while the first-generation model is being optimized. In the future, other chances will exist to impact development of version 2 and version 3 of ACME.

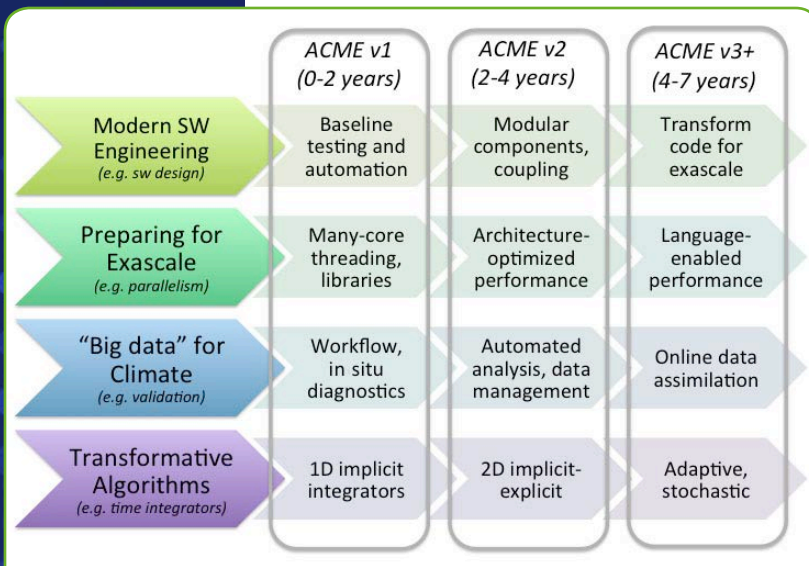
## 2.4 Breakout 4: Crossing scales to integrate observations and models

Climate-oriented observation, research, and model-development activities sponsored by DOE 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, and periodically making the output of their efforts available to each other and the wider community. This strategy assumes much about the ability of one 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 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*

The meeting participants recognized that increased communication among the CESD activities and, in particular, between ARM/ASR and ACME/ESM could be beneficial to each program. There are a number of groups participating in ARM- and ESM-funded projects; however, there are also many individuals who tend to work exclusively with observation data or model simulations. It is generally recognized that the process-oriented information available through ARM/ASR has great value to the GCM community, but it is not always obvious how to use this information optimally, because observationalists do not always understand what model issues are most pressing, or what information would be most valuable to them in resolving those issues. In addition, 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. This difficulty is not unique to the wide range of CESD research, and similar needs to span a large range of expertise exist within other aspects of the atmospheric research community, such as between modelers and

satellite observationalists at the National Aeronautics and Space Administration. Overall, improved understanding of these issues can facilitate the use of ARM data, and progress on modeling science.



It will be important to communicate to the ASR/ARM communities the development cycles and timeframes in which increased collaboration will be needed to leverage windows of opportunity to try new methodologies in the ACME model.

As an illustration of an area in which inter-community communication might be significantly impactful, 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 ARM data and associated ASR analyses requires a certain level of familiarity with observational data; attaining that level of familiarity 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 represent a charge to the ASR community

to find optimal ways to use ARM data, but for ACME, a relatively new project, more education on both sides is required.

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, operational simulation, and analysis when new ideas are not as useful. For example, prior to release of a new model version, the code is frozen and only small changes are added to fix problems. Traditionally, the 6-year cycle of Coupled Model Intercomparison Project (CMIP) phases and Intergovernmental Panel on Climate Change 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. In addition, communication of high priority issues/deficiencies within the climate model needs to be done in a more timely manner because waiting for the knowledge to become available 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.

There was a good deal of discussion about how to better bring together these diverse technical communities. A key element of a strategy going forward would be to hold periodic workshops that explicitly include balanced representation from each community and focus on collaboration. Initially, it is envisioned that these joint workshops would educate participants on the nature and needs of each community and identify 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 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 the judicious use of observations. The fact that well-known problems in models—for example, 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 existed 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.

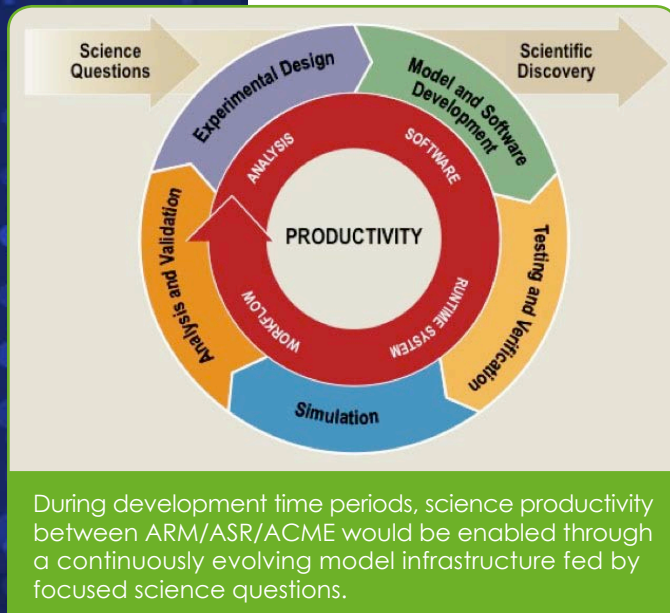
For ACME, as for any climate model, interfacing with observations occurs on several levels, on different timescales and is dictated by considerations specific to that model. ACME is focused on high-resolution, fully coupled simulations, including regional refinement, and with a high priority for hindcast 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 during which a model version cannot be revised while being 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 development time periods, collaborations between ARM/ASR observers and ACME modelers should be guided by a set of questions that include the following

- 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 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., 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. The ARM focus on developing retrieval techniques for vertical velocities was driven by the stated needs of the ASR modeling community.

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 to be relevant to ACME parameterization needs.

### *Organizing information*

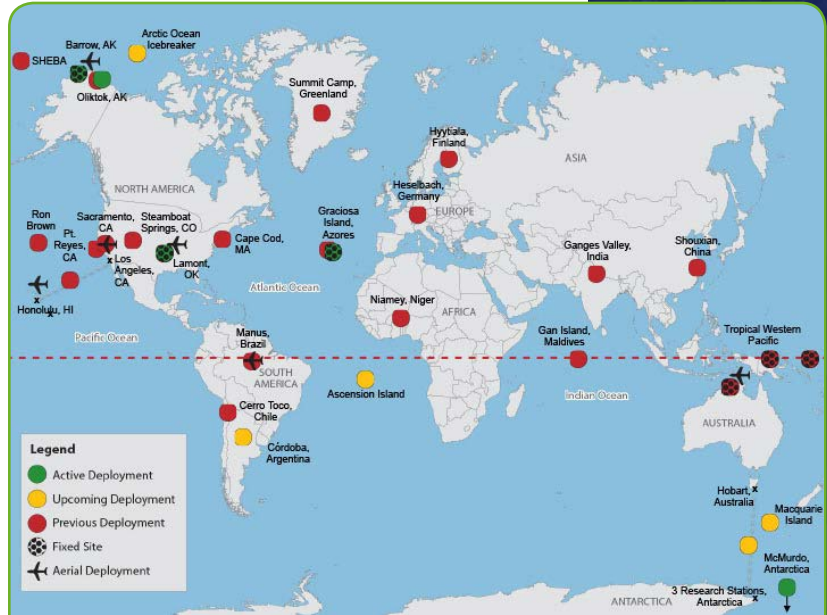
Aside from specific themes selected for integrated efforts, an organizational strategy that is expected to be effective in attracting diverse communities is the use of real and/or virtual field campaigns. A virtual field campaign is a collection of data from existing sources, matching some criteria or region (e.g., association with single-layer mixed-phase clouds along the NSA). These data would include ARM observations, model-forcing data sets, and possibly external data products such as satellite observations, weather radar information, 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 organized a wide variety of observation and model data around tropical convection for a 2-year period (Waliser et al., 2012; 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, meteorological regime, etc.). 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, interest was expressed in mining historical measurements from ARM sites. ARM facilities have now sampled many climatic regimes from the Arctic to the tropics. 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.

It should be noted, however, that premature conclusions about parameterization improvements have frequently been 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 SGP. For example, a parameterization of boundary-layer clouds that is judged to be successful at SGP will need to be tested in the very different low cloud environment of the ARM ENA site.

Another level of parameterization testing occurs when a candidate parameterization that performs well in an SCM setting is implemented in the parent three-dimensional GCM. Often improvements seen in the controlled SCM setting are not realized in the three-dimensional 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 three-dimensional setting because many chronic long-term climate model biases appear after only a few days of integration (Ma et al., 2014).



Mining historical measurements from ARM sites and deployments that now span the globe could provide a broad constraint on model simulations, if these data are organized in a consistent way.



Successful parameterizations of boundary-layer clouds at the ARM Southern Great Plains site must be evaluated by testing it in a very different cloud environment at the Eastern North Atlantic site.

### *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 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). Because of the stochastic nature of many processes, we do not expect models and observations to be directly comparable at very high spatial and temporal resolution; however, statistical analysis strategies can be used to overcome this issue. The ARM Facility 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 (DOE, 2014). Often an SCM (i.e., 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 such as those from a numerical weather prediction model (Phillips et al., 2004). In both cases, the LAM and GCM are operated under real 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; however, it typically is not possible still to make direct comparisons between detailed cloud and aerosol observations and any model simulations because of the stochastic nature of atmospheric processes at the scale of ARM observations. A common theme for addressing this issue has been de-emphasizing model evaluations based on single parameters, and rather, evaluating models using relationships among parameters (e.g., the relationship between cloud liquid water path and vertical velocity.) This also allows a process-level understanding of model deficiencies because 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 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, data obtained from observations are 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 behave in a predictable way. In addition, instrument simulators provide a means for exploring 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 analytical communities. It is also important to characterize the conditions under which an instrument or a retrieval tends to work well and 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 conventions are used for data formatting and metadata.



A strategy for statistically evaluating the large-eddy simulation model against data from the reconfigured Southern Great Plains site will need to be developed to more effectively influence the ACME model.

Thus, if ARM observations at the SGP testbed are to eventually influence ACME parameterizations, the following 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. The strategy must account both for limitations of the data (e.g., clouds missed by scanning radars, incomplete sampling of the LES domain, etc.) and 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. Robust relationships derived in this way can then be compared to similar ACME relationships.
- 4) 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.
- 5) Parameterization approaches that account for these processes or represent them more realistically will need to be developed.
- 6) Candidate new parameterization approaches 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.



- 7) Any improved features through ACME tests need to be confirmed in CAPT-type hindcast tests that 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; Bretherton and Park, 2009); however, it is expected that this process will be greatly accelerated within a well-coordinated multi-disciplinary project.

### *Programmatic considerations*

Having identified strategies for attracting 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 are 1) funding, 2) programmatic alignment, and 3) 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 participants' projects, 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; however, this remedy is not a panacea. There are risks, for example, that teams would form loose alliances with individual sub-teams while 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-disciplinary collaborations. If this perspective can be achieved, joint projects have the potential to accelerate progress at the boundaries of disciplines.

Careful alignment of program goals, possibly through the identification of grand-challenge problems, could have a similar effect while recognizing the challenges in jointly funded projects. 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" (SFA) at DOE-sponsored laboratories. These SFAs typically involve a diverse team and tend to have longer durations than non-laboratory grants. 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 durations, SFAs also have the potential to provide continuity to complex projects. Therefore, it would be natural for SFA teams to assume 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.

## 3.0 Conclusions

Climate research within DOE ranges from the collection of observations, to the analysis of those observations to better understand atmospheric phenomena, to the application of this improved understanding to advance GCMs. This broad spectrum of activities is embodied in the ARM Facility, ASR program, and 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 existing ARM and ASR activities to improve the 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 DOE's 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 ACME/ESM. 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, which was consistent with participants' backgrounds, although input was solicited from non-participants in the form of pre-workshop white papers. 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 the following areas:

- Processes associated with the development and maintenance of marine stratocumulus
- Mixed-phase cloud processes



Efficiently using ARM observations and ASR analyses to improve climate models, including the ACME model, will require close coordination among these communities. Collaboration strategies identified during this workshop will provide a valuable framework for future climate model improvements in the representation of diverse atmospheric processes.

- Convective clouds including microphysical processes, transition from shallow to deep convection, and convective organization
- Impact of aerosols on cloud properties.

These are already focus areas for ASR and the ARM Facility, 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 primary importance for climate applications and 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 these communities. Specific actions the ACME/ESM community could take to achieve this alignment with the ARM/ASR communities would include:

- Identify science priorities that can best be informed by ARM observations and ASR analysis.
- Collaborate on problem areas in model performance.
- Develop strategies to test key physical assumptions in their parameterizations.

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 white papers and discussions throughout the workshop. Generally, the measurement needs have been discussed frequently within the ASR and ARM communities. A list of suggested measurements is provided in Appendix D. Note that this list is not intended to be comprehensive. As with the science areas, perhaps a more impactful aspect of the workshop discussions was on strategies for applying measurements to address science gaps. Suggestions derived from the workshop are listed below:

- 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 (especially 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 critical environment (e.g., vertical velocity) for relating measurements and simulations of physical processes within a domain.



- Explore impacts of surface heterogeneity on the atmosphere at the NSA site where UASs can be used more freely.
- Selectively choose observation sites that specifically limit certain aspects of surface heterogeneity to better understand other sources of heterogeneity.

While unmet measurement needs remain, 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. Following is a list of relevant key themes identified in white papers and during discussions at 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” (i.e., 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., conventions for CF, or Climate and Forecast, metadata). This would require 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.
- Include benchmark cases in the modeling framework so models could be evaluated in a consistent manner.
- Develop a strategy for LES-observation comparisons, 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 follow:

- Determine the appropriate level of complexity for the representation of cloud microphysics and aerosol processes and the simplest representation needed to capture a particular phenomenon.
- 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 relationships among the observationists, process researchers, and model-development communities within CESD to accelerate the advancement of GCMs. Activities described above represent some tools that can be used in this process, but the following specific strategies were also identified to improve this cross-community communication:

- There is a need to develop focused 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 number of representatives from each community. There is already an abundance of meetings, but there was a sense among participants of this workshop that a balanced combination of participants from across the communities would lead to valuable insights into the needs of one community from the others.
- Seek leadership from laboratory groups that provide continuity and broad skill sets to facilitate collaboration and the advancement of long-term projects.

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

## 4.0 References

- Ahlgrimm, M and R Forbes. 2014. “Improving the representation of low clouds and drizzle in the ECMWF model based on ARM observations from the Azores.” *Monthly Weather Review* 142(2):668–685, doi:10.1175/mwr-d-13-00153.1.
- Berg, LK, M Shrivastava, RC Easter, JD Fast, EG Chapman, Y Liu, and RA Ferrare. 2015. “A new WRF-Chem treatment for studying regional-scale impacts of cloud processes on aerosol and trace gases in parameterized cumuli.” *Geoscientific Model Development* 8:409–429, doi:10.5194/gmd-8-409-2015, 2015.
- Blossey, PN, CS Bretherton, M Zhang, A Cheng, S Endo, T Heus, Y Liu, AP Lock, SR de Roode, and K-M Xu. 2013. “Marine low cloud sensitivity to an idealized climate change: The CGILS LES intercomparison.” *Journal of Advances in Modeling Earth Systems* 5(2):234–258, doi:10.1002/jame.20025.
- Bogenschutz, PA, A Gettelman, H Morrison, VE Larson, NP Meyer, DP Schannen, and C Craig. 2012. “Unified parameterization of the planetary boundary layer and shallow convection with a higher-order turbulence closure in the Community Atmosphere Model.” *Geoscientific Model Development* 5(6):1407–1423, doi:10.5194/gmdd-5-1743-2012.
- Bogenschutz, PA, A Gettelman, H Morrison, VE Larson, C Craig, and DP Schannen. 2013. “Higher-order turbulence closure and its impact on climate simulations in the community atmosphere model.” *Journal of Climate* 26(23):9655–9676, doi:10.1175/JCLI-D-13-00075.1.
- Bony, S and J-L Dufresne. 2005. “Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models.” *Geophysical Research Letters* 32:L20806, doi:10.1029/2005GL023851.
- Bretherton, CS and S Park. 2009. “A new moist turbulence parameterization in the Community Atmosphere Model.” *Journal of Climate* 22:3422–3448, doi:10.1175/2008JCLI2556.1.
- Collis, S, A Protat, PT May, and C Williams. 2013. “Statistics of storm updraft velocities from TWP-ICE including verification with profiling measurements.” *Journal of Applied Meteorology and Climatology* 52:1909–1922, doi:10.1175/JAMC-D-12-0230.1.
- Del Genio, AD, J Wu, AB Wolf, YH Chen, M-S Yao, and D Kim. 2015. “Constraints on cumulus parameterization from simulations of observed MJO events.” *Journal of Climate* 28(16):6419–6442, doi:10.1175/JCLI-D-14-00832.1.
- Fridlind, AM, AS Ackerman, J-P Chaboureau, J Fan, WW Grabowski, AA Hill, TR Jones, MM Khaiyer, G Liu, P Minnis, H Morrison, L Nguyen, S Park, JC Petch, J-P Pinty, C Schumacher, BJ Shipway, AC Golaz, JC, VE Larson, and WR Cotton. 2002. “A PDF based model for boundary layer clouds. Part I: Method and model description.” *Journal of the Atmospheric Sciences* 59(24):3540–3551, doi:10.1175/1520-0469(2002)059<3540:APBMFB>2.0.CO;2.



- Grabowski, WW and PK Smolarkiewicz. 1999. “CRCP: A cloud resolving convective parameterization for modeling the tropical convective atmosphere.” *Physica D* 133(1-4):171–178, doi:10.1016/S0167-2789(99)00104-9.
- Grabowski, WW. 2014. “Extracting microphysical impacts in large-eddy simulations of shallow convection.” *Journal of the Atmospheric Sciences* 71:4493–4499, doi:10.1175/JAS-D-14-0231.1.
- Grandpeix, J-Y, and JP Lafore. 2010. “A density current parameterization coupled with Emanuel’s convection scheme. Part I: The models.” *Journal of the Atmospheric Sciences* 67:881–897, doi:10.1175/2009JAS3044.1.
- Grenier, H and CS Bretherton. 2001. “A moist PBL parameterization for large-scale models and its application to subtropical cloud-topped marine boundary layers.” *Monthly Weather Review* 129:357–377, doi:10.1175/1520-0493(2001)129<0357:AMPPFL>2.0.CO;2.
- Guo, Z, M Wang, Y Qian, VE Larson, S Ghan, M Ovchinnikov, PA Bogenschutz, C Zhao, G Lin, and T Zhou. 2014. “A sensitivity analysis of cloud properties to CLUBB parameters in the single-column Community Atmosphere Model (SCAM5).” *Journal of Advances in Modeling Earth Systems* 6(3):829–858, doi:10.1002/2014ms000315.
- Khairoutdinov, MF and DA Randall. 2001. “A cloud-resolving model as a cloud parameterization in the NCAR Community Climate System Model: Preliminary results.” *Geophysical Research Letters* 28(18):3617–3620, doi:10.1029/2001GL013552.
- Latham, J, K Bower, T Choullarton, H Coe, P Connolly, G Cooper, T Craft, J Foster, A Gadian, L Galbraith, H Iacovides, D Johnston, B Launder, B Leslie, J Meyer, A Neukermans, B Ormond, B Parkes, P Rasch, J Rush, S Salter, T Stevenson, H Wang, Q Wang, and R Wood. 2012. “Marine cloud brightening.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical & Engineering Sciences* 370(1974):4217–4262, doi:10.1098/rsta.2012.0086.
- Ma, H-Y, S Xie, SA Klein, KD Williams, JS Boyle, S Bony, H Douville, S Fermepin, B Medeiros, S Tyteca, M Watanabe, and D Williamson. 2014. “On the correspondence between mean forecast errors and climate errors in CMIP5 models.” *Journal of Climate* 27:1781–1798, doi:10.1175/JCLI-D-13-00474.1.
- McCoy, DT, DL Hartmann, MD Zelinka, P Ceppi, and DP Grosvenor. 2015. “Mixed-phase cloud physics and Southern Ocean cloud feedback in climate models.” *Journal of Geophysical Research Atmospheres* 120, doi:10.1002/2015JD023603.
- Moncrieff, MW, DE Waliser, MJ Miller, MA Shapiro, GR Asrar, and J Caughey. 2012. “Multiscale convective organization and the YOTC virtual field campaign.” *Bulletin of the American Meteorological Society* 93(8):1171–1187, doi:10.1175/BAMS-D-11-00233.1.

- Morrison, H and JA Milbrandt. 2011. “Comparison of two-moment bulk microphysics schemes in idealized supercell thunderstorm simulations.” *Monthly Weather Review* 139:1103–1130, doi:10.1175/2010MWR3433.1.
- Park, S. 2014a. “A unified convection scheme (UNICON). Part I. Formulation.” *Journal of the Atmospheric Sciences* 71:3902–3930, doi:10.1175/JAS-D-13-0233.1.
- Park, S. 2014b. “A unified convection scheme (UNICON). Part II: Simulation.” *Journal of the Atmospheric Sciences* 71:3931–3973, doi:10.1175/JAS-D-13-0234.1.
- Phillips, TJ, GL Potter, DL Williamson, RT Cederwall, JS Boyle, M Fiorino, JJ Hnilo, JG Olson, S Xie, and JJ Yio. 2004. “Evaluating parameterizations in general circulation models: Climate simulation meets weather prediction.” *Bulletin of the American Meteorological Society* 85:1903–1915, doi:10.1175/BAMS-85-12-1903.
- Randall, D, S Krueger, C Bretherton, J Curry, P Duynkerke, M Moncrieff, B Ryan, D Starr, M Miller, W Rossow, G Tselioudis, and B Wielicki. 2003. “Confronting models with data: The GEWEX cloud systems study.” *Bulletin of the American Meteorological Society* 84:455–469, doi:10.1175/BAMS-84-4-455.
- Romps, DM and R Oktem. 2015. “Stereo photogrammetry reveals substantial drag on cloud thermals.” *Geophysical Research Letters* 42(12):5051–5057, doi:10.1002/2015gl064009.
- Russell, LM, A Sorooshian, JH Seinfeld, BA Albrecht, A Nenes, L Ahlm, Y-C Chen, M Coggon, JS Craven, RC Flagan, AA Frossard, H Jonsson, E Jung, JJ Lin, AR Metcalf, R Modini, J Mülmenstädt, GC Roberts, T Shingler, S Song, Z Wang, and A Wonaschütz. 2013. “Eastern Pacific emitted aerosol-cloud experiment.” *Bulletin of the American Meteorological Society* 94(5):709–29, doi:10.1175/BAMS-D-12-00015.1.
- Satoh, M, T Matsuno, H Tomita, H Miura, T Nasuno, and S Iga. 2008. “Nonhydrostatic icosahedral atmospheric model (NICAM) for global cloud resolving simulations.” *Journal of Computational Physics* 227:3486–3514, doi:10.1016/j.jcp.2007.02.006.
- Siebesma, AP and J Teixeira. 2000. “An advection–diffusion scheme for the convective boundary layer: Description and 1D results.” Presented at the American Meteorological Society 14<sup>th</sup> Symposium on Boundary Layers and Turbulence, August 9, 2000, Aspen, Colorado, abstract available at [https://ams.confex.com/ams/AugAspen/techprogram/paper\\_14840.htm](https://ams.confex.com/ams/AugAspen/techprogram/paper_14840.htm).
- Stephens, GL, T L’Ecuyer, R Forbes, A Gettelman, JC Golaz, A Bodas-Salcedo, K Suzuki, P Gabriel, and J Haynes. 2010. “Dreary state of precipitation in global models.” *Journal of Geophysical Research* 115(D24211), doi:10.1029/2010JD014532.
- Storelvmo, T, I Tan, and AV Korolev. 2015. “Cloud phase changes induced by CO<sub>2</sub> warming—A powerful yet poorly constrained cloud-climate feedback.” *Current Climate Change Reports* 1:288–296, doi:10.1007/s40641-015-0026-2.

Sušelj, K, J Teixeira, and D Chung. 2013. “A unified model for moist convective boundary layers based on a stochastic eddy-diffusivity/mass-flux parameterization.” *Journal of the Atmospheric Sciences* 70(7):1929–1953, doi:10.1175/jas-d-12-0106.1.

Teixeira, J and P Siebesma. 2000. “A mass flux/k-diffusion approach to the parameterization of the convective boundary layer: Global model results.” Presented at the American Meteorological Society 14<sup>th</sup> Symposium on Boundary Layers and Turbulence, August 9, 2000, Aspen, Colorado, abstract available at [https://ams.confex.com/ams/AugAspen/techprogram/paper\\_14915.htm](https://ams.confex.com/ams/AugAspen/techprogram/paper_14915.htm).

U.S. Department of Energy (DOE). 2014. *Atmospheric Radiation Measurement Facility Decadal Vision*. DOE/SC-ARM-14-029, Office of Science, Office of Biological and Environmental Research, Washington, D.C. Available at <http://www.arm.gov/publications/programdocs/doe-sc-arm-14-029.pdf>.

Van Weverberg, K, CJ Morcrette, H-Y Ma, SA Klein, and JC Petch. 2015. “Using regime analysis to identify the contribution of clouds to surface temperature errors in weather and climate models.” *Quarterly Journal of the Royal Meteorological Society* 141(163):3190–3206, doi:10.1002/qj.2603.

Varble, X Wu, S Xie, and M Zhang. 2012. “A comparison of TWP-ICE observational data with cloud-resolving model results.” *Journal of Geophysical Research* 117:D05204, doi:10.1029/2011JD016595.

Varble, A, EJ Zipser, AM Fridlind, P Zhu, AS Ackerman, J-P Chaboureau, S Collis, J Fan, A Hill, and B Shipway. 2014. “Evaluation of cloud-resolving and limited area model intercomparison simulations using TWP-ICE observations. Part 1: Deep convective updraft properties.” *Journal of Geophysical Research Atmospheres* 119(24):13891–13918, doi:10.1002/2013JD021371.

Vial, J, J-L Dufresne, and S Bony. 2013. “On the interpretation of inter-model spread in CMIP5 climate sensitivity estimates.” *Climate Dynamics* 41(11):3339–3362, doi:10.1007/s00382-013-1725-9.

Waliser, DE, M Moncrieff, D Burridge, A Fink, D Gochis, BN Goswami, B Guan, P Harr, J Heming, H-H Hsu, C Jakob, M Janiga, R Johnson, S Jones, P Knippertz, J Marengo, H Nguyen, M Pope, Y Serra, C Thorncroft, M Wheeler, R Wood, and S Yuter. 2012. “The ‘year’ of tropical convection (May 2008 to April 2010): Climate variability and weather highlights.” *Bulletin of the American Meteorological Society* 93(8):1188–1218, doi:10.1175/2011BAMS3095.1.

Wang, M, S Ghan, R Easter, M Ovchinnikov, X Liu, E Kassianov, Y Qian, WI Gustafson, VE Larson, DP Schanen, M Khairoutdinov, and H Morrison. 2011. “The multi-scale aerosol-climate model PNNL-MMF: Model description and evaluation.” *Geoscientific Model Development* 4(1):137–168, doi:10.5194/gmd-4-137-2011.



Wood, R and TP Ackerman. 2013. “Defining success and limits of field experiments to test geoengineering by marine cloud brightening.” *Climatic Change* 121(3):459–472, doi:10.1007/s10584-013-0932-z.

Wyant, MC, CS Bretherton, R Wood, GR Carmichael, A Clark, J Fast, R George, WI Gustafson Jr., C Hannay, A Lauer, Y Lin, J-J Morcrette, J Mulcahy, PE Saide, SN Spak, and Q Yang. 2015. “Global and regional modeling of clouds and aerosols in the marine boundary layer during VOCALS: the VOCA intercomparison.” *Atmospheric Chemistry and Physics* 15:153–172, doi:10.5194/acp-15-153-2015.

Xie, S, H Ma, J Boyle, S Klein, and Y Zhang. 2012. “On the correspondence between short- and long-timescale systematic errors in CAM4/CAM5 for the Years of Tropical Convection.” *Journal of Climate* 25, 7937–7955, doi:10.1175/JCLI-D-12-00134.1.

Zelinka, MD, SA Klein, and DL Hartmann. 2012. “Computing and partitioning cloud feedbacks using cloud property histograms. Part II: Attribution to changes in cloud amount, altitude, and optical depth.” *Journal of Climate* 25:3736–3754, doi:10.1175/JCLI-D-11-00249.1.

Zhang, Y and SA Klein. 2010. “Mechanisms affecting transition from shallow to deep convection over land: Inferences from observations of the diurnal cycle collected at the ARM Southern Great Plains site.” *Journal of the Atmospheric Sciences* 67:2943–2959, doi:10.1175/2010JAS3366.1.

Zhang, MH, CS Bretherton, PN Blossey, S Bony, F Brient, and JC Golaz. 2012. “The CGILS experimental design to investigate low cloud feedbacks in general circulation models by using single-column and large-eddy simulation models.” *Journal of Advances in Modeling Earth Systems* 4:M12001, doi:10.1029/2012ms000182.

Zhang, MH, CS Bretherton, PN Blossey, PH Austin, JT Bacmeister, S Bony, F Brient, SK Cheedela, AN Cheng, AD Del Genio, SR De Roode, S Endo, CN Franklin, JC Golaz, C Hannay, T Heus, FA Isotta, JL Dufresne, IS Kang, H Kawai, M Kohler, VE Larson, YG Liu, AP Lock, U Lohmann, MF Khairoutdinov, AM Molod, RAJ Neggers, P Rasch, I Sandu, R Senkbeil, AP Siebesma, C Siegenthaler-Le Drian, B Stevens, MJ Suarez, KM Xu, K von Salzen, MJ Webb, A Wolf, and M Zhao. 2013. “CGILS: Results from the first phase of an international project to understand the physical mechanisms of low cloud feedbacks in single column models.” *Journal of Advances in Modeling Earth Systems* 5(4):826–842, doi:10.1002/2013ms000246.

Zhou, BW, JS Simon, and FK Chow. 2014. “The convective boundary layer in the terra incognita.” *Journal of the Atmospheric Sciences* 71(7):2545–2563, doi:10.1175/jas-d-13-0356.1.

## Appendix A: Workshop Agenda

*Wednesday, 21 October 2015*

- |                |  |
|----------------|--|
| 8:30–8:45 am   | Arrive at DOE for badging  |
| 9:00–9:45 am   | Attendee introductions (2 minutes each) <ul style="list-style-type: none"> <li>• Name</li> <li>• Institution</li> <li>• What you work on (two sentences)</li> <li>• What is really difficult about what you are working on (related to workshop themes)</li> </ul>   |
| 9:45–10:15 am  | DOE HQ motivations – DOE organizers  |
| 10:15–10:30 am | Break  |
| 10:30–11:30 am | Invited plenary presentations<br>(15 minutes each plus 5 minutes for questions) <ul style="list-style-type: none"> <li>• Andrew Vogelmann: “Linking small-scale cloud process observations to models”</li> <li>• Shaocheng Xie: “ACME and its connection to ARM/ASR”</li> <li>• Maike Ahlgrim: “Sticking points—a perspective from the operational modeling side”</li> </ul>   |
| 11:30–11:45 am | General discussion, breakout charge  |
| 11:45–12:45 pm | Lunch – DOE cafeteria  |
| 12:45–3:15 pm  | Breakout Session 1 – Cloud microphysics and aerosol-cloud interactions <ul style="list-style-type: none"> <li>• White paper summaries: Phil Rasch and William Gustafson</li> <li>• Discussion leaders: Gijs de Boer and Steven Ghan</li> <li>• Rapporteurs: Jerome Fast and Jan Kazil</li> <li>• Breakout into two groups for discussion, following breakout templates</li> </ul>  |
| 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 <ul style="list-style-type: none"> <li>• White paper summaries: William Gustafson and Shaocheng Xie</li> <li>• Discussion leaders: Jean-Christophe Golaz and Larry Berg</li> <li>• Rapporteurs: Jennifer Comstock and Peter Caldwell</li> <li>• Breakout into two groups for discussion, following breakout templates</li> </ul> |

## Thursday, 22 October 2015

- 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: “Ultraparameterization: A strategy for including explicit low cloud physics in global climate models”
  - João Teixeira: “Unified turbulence and convection parameterizations: The EDMF approach”
- 9:15–9:30 am Break
- 9:30–12:00 pm Breakout Session 3 – Deep convection and the transition from shallow to deep convection
- White paper summaries: James Mather and Shaocheng Xie
  - Discussion leaders: João Teixeira and Pavlos Kollias
  - Rapporteurs: Larry Berg and Maike Ahlgrimm
  - Breakout into two 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: Anthony Del Genio and James Mather
  - Discussion leaders: Christian Jakob and Andrew Vogelmann
  - Rapporteurs: David Turner and João Teixeira
  - Breakout into two 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)



## Appendix B: Background on Atmospheric Radiation Measurement Climate Research Facility, Atmospheric System Research, and Accelerated Climate Modeling for Energy/Earth System Modeling

This workshop included participation primarily from researchers funded within three U.S. Department of Energy (DOE) Biological and Environmental Research programs: 1) Atmospheric Radiation Measurement (ARM) Climate Research Facility, 2) Atmospheric System Research (ASR) program, and 3) Accelerated Climate Modeling for Energy (ACME) project within the Earth System Modeling program. Some history and context on the type of research done in these programs relevant to this workshop are provided in this appendix.

### *ARM Climate Research Facility*

The ARM Climate Research Facility was created in 2003 from several extensively instrumented in situ and remote sensing surface sites that had been developed beginning in 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 miles<sup>2</sup> (143,000 kilometers<sup>2</sup>). SGP's complement of cloud and precipitation zenith-pointing and scanning radar and lidar instruments, 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. This site experiences a full range of seasonal continental mid-latitude 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 Point 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 been established recently 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 where stratocumulus and shallow cumulus clouds are a major source of uncertainty in global climate model (GCM) estimates of global climate sensitivity. The ARM Facility also has historical data sets from previous fixed sites at Manus Island, Nauru Island, and Darwin, Australia, in the Tropical Western Pacific.

In addition to its fixed sites, ARM supports three mobile facilities that can be deployed to make atmospheric measurements anywhere in the world for periods ranging from months to several years. The ARM mobile facilities have allowed the Facility to extend its reach to virtually every climate regime, with deployments in locations including:

- continental United States (California, Massachusetts, and Colorado)
- other mid-latitude continents (Germany, Finland, and China)
- tropical continents (Niger, India, and Brazil) and islands (Maldives)
- subtropical oceans (Azores and eastern Pacific)
- polar regions (Alaska and Antarctica).

Finally, ARM maintains the ARM Aerial Facility to make measurements of cloud, aerosol, and radiative properties on either a routine basis or for limited periods in support of field campaigns. The ARM Aerial Facility 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 derived from ARM datastreams are produced by ARM infrastructure scientists.

In 2014, ARM reconfigured its assets to create two “megsites” at the SGP and NSA. The science objective was to develop a testbed for continuous high-resolution large-eddy simulation (LES) modeling and single-column model (SCM) evaluations constrained by the most comprehensive set of observations possible. This project, known as LASSO (i.e., 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.

### *Atmospheric System Research*

The ASR program supports scientific research on aerosol, cloud, precipitation, and radiative processes that exploit the observations acquired by ARM. Scientists involved in remote sensing for the ASR program develop new retrieval algorithms that can either lead to new scientific data sets produced by the algorithm developer or be transferred to the ARM infrastructure and used as the basis for official ARM value-added products. ASR scientists use ARM data products and process-level box models, LES models, cloud-resolving models, and regional limited area models to gain insights into fundamental processes, develop or evaluate parameterizations, and implement parameterizations in GCMs. Cloud parameterization testing in ASR often occurs in 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 observational periods in the vicinity of the ARM fixed sites or during an ARM Mobile Facility deployment. The forcing products are also used to drive LES and cloud-resolving 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.

Currently, scientific research in ASR is organized into three working groups that focus on 1) Cloud Life Cycle, 2) Aerosol Life Cycle, and 3) Cloud-Aerosol-Precipitation Interactions. To date, Cloud Life Cycle research is organized around four science theme areas: 1) ice

physical and radiative properties, 2) cloud phase partitioning/mixed-phase clouds, 3) warm low clouds, and 4) mesoscale convective organization. The Aerosol Life Cycle science themes include: 1) new particle formation, 2) aerosol aging and mixing state, 3) secondary organic aerosol formation, and 4) aerosol direct radiative forcing. The Cloud-Aerosol-Precipitation Interactions science themes are organized around issues such as 1) why climate models produce a large aerosol indirect effect, 2) sensitivity of warm low clouds to aerosol perturbations, 3) effects of aerosols on deep convection, and 4) ice nucleation processes. Recently, a new land surface-atmosphere interaction science theme has emerged within ASR.

### *Accelerated Climate Modeling for Energy*

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 application of next-generation computational methods to facilitate and to accelerate model computational performance on DOE's current and next-generation computers operated by the National Energy Research Scientific Computing Center and Leadership Class Facilities located at Lawrence Berkeley, Oak Ridge, and Argonne National Laboratories.

In 2014, DOE's Earth System Modeling program launched a laboratory-led project to develop the ACME project. This project is developing and applying a computationally advanced climate and earth system model to investigate the challenges posed by the interactions of climate 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 (v1) is targeted to work routinely at a very high—for a climate model—horizontal grid spacing (25 kilometers) and vertical resolution (72 layers with a model top at 60 kilometers). The model further employs regional refinement using adaptive mesh methodologies to provide 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 to 2015) for model validation and a near-term projection (2015 to 2050) for societal planning. Version 1 of the model will include new ocean and land ice components, and important changes/innovations to land and atmosphere model components.

The new ACME model will initially be used to address the three challenging and computationally demanding climate-change research problems, which are described below:

- 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?



## 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 hydrological cycle by transporting water and by participating in its removal from the atmosphere and delivery to the surface. Clouds also transport energy and trace constituents within updrafts and downdrafts and act as sites for scavenging atmospheric trace species. Aerosols, the small solid or liquid particles suspended in the air (e.g., dust, sea spray, sulfate, organics, etc.) 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." When aerosols participate as nuclei for ice clouds, they are termed "ice nuclei." 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 (i.e., particle size distribution and number, location, and phase) are thus controlled by the following 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 3) droplet evaporation. Aerosols operate indirectly to affect clouds, and thus play a role in cloud radiative effects. 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 top of the boundary layer 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 cloud radiative effects influence atmospheric circulations on all spatial scales. Global climate models, such as Accelerated Climate Model for Energy (ACME), resolve the circulation explicitly on scales of tens of kilometers 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. Under 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. The relative importance of these processes is likely to depend upon the cloud regime, and furthermore, the importance may be different for shallow boundary-layer clouds in the subtropics that develop in warm, stable, relatively quiescent conditions; in polar latitudes where mixed-ice/liquid-phase or pure ice clouds are often observed; or in the tropics and summertime mid-latitudes, with deep clouds characterized by much stronger vertical motions resulting from a base in warm air and a cloud top at very cold temperatures. The complexities of each process and of interactions between processes remain extremely challenging problems.

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 motion. Many longstanding systematic model errors, such as the unrealistic double intertropical convergence zone pattern in tropical precipitation, weak Madden-Julian Oscillation 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 Madden-Julian Oscillation 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 two-dimensional cloud-resolving model embedded in each global climate model grid cell (Grabowski and Smolarkiewicz, 1999; Khairoutdinov and Randall, 2001). Better understanding and model representation of atmospheric convection have been identified as keys to addressing grand challenge questions (which likely progress the field to the point of actual model improvements with a measurable impact on uncertainty if answered) identified by World Climate Research Program (Bony et al., 2015).



## Appendix D: Measurement Needs

A wide variety of measurement needs were identified in the pre-workshop white papers and in the workshop discussions. A representative sample of these suggestions follows:

- sustained field studies of aerosol properties
- aerosol properties from many regions of the world
- secondary organic aerosol life cycle including their precursors
- vertical distributions of aerosol properties to address cloud condensation nuclei biases in global climate models
- 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, etc.)
- 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 large-eddy simulation and global climate model developers
- 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 Climate Research Facility sites.

# Appendix E: Workshop Organizers and Participants

## Organizing Committee

|                   |   |
|-------------------|---|
| Dorothy Koch      | Earth System Modeling                                       |
| Sally McFarlane   | Atmospheric Radiation Measurement Climate Research Facility |
| Shaima Nasiri     | Atmospheric System Research                                 |
| Ashley Williamson | Atmospheric System Research                                 |

## Co-Chairs

|                   |  |
|-------------------|--|
| Anthony Del Genio | NASA Goddard Institute for Space Studies |
| William Gustafson | Pacific Northwest National Laboratory    |
| James Mather      | Pacific Northwest National Laboratory    |
| Philip Rasch      | Pacific Northwest National Laboratory    |
| Shaocheng Xie     | Lawrence Livermore National Laboratory   |

## Participants

|                       |  |
|-----------------------|--|
| Maike Ahlgrim         | European Centre for Medium-Range Weather Forecasts |
| Larry Berg            | Pacific Northwest National Laboratory              |
| Peter Caldwell        | Lawrence Livermore National Laboratory             |
| Scott Collis          | Argonne National Laboratory                        |
| Jennifer Comstock     | Pacific Northwest National Laboratory              |
| Gijs de Boer          | University of Colorado                             |
| Jerome Fast           | Pacific Northwest National Laboratory              |
| Steven Ghan           | Pacific Northwest National Laboratory              |
| Jean-Christophe Golaz | Lawrence Livermore National Laboratory             |
| Christian Jakob       | Monash University                                  |

## Participants (continued)

|                  |  |
|------------------|--|
| Jan Kazil        | National Oceanic and Atmospheric Administration  |
| Pavlos Kollias   | McGill University/Brookhaven National Laboratory |
| Richard Neale    | National Center for Atmospheric Research         |
| Mike Pritchard   | University of California, Irvine                 |
| David Romps      | Lawrence Berkeley National Laboratory            |
| Mark Taylor      | Sandia National Laboratories                     |
| João Teixeira    | University of California, Los Angeles            |
| David Turner     | NOAA National Severe Storms Laboratory           |
| Andrew Vogelmann | Brookhaven National Laboratory                   |
| Shaocheng Xie    | Lawrence Livermore National Laboratory           |
| Yunyan Zhang     | Lawrence Livermore National Laboratory           |



## Appendix F: Written Respondents

|                        |   |
|------------------------|---|
| Maike Ahlgrim          | European Centre for Medium-Range Weather Forecasts                                  |
| Anton Beljaars         | European Centre for Medium-Range Weather Forecasts                                  |
| Larry Berg             | Pacific Northwest National Laboratory   |
| Christopher Bretherton | University of Washington  |
| Peter Caldwell         | Lawrence Livermore National Laboratory  |
| Scott Collis           | Argonne National Laboratory   |
| Jennifer Comstock      | Pacific Northwest National Laboratory   |
| Gijs de Boer           | University of Colorado/Cooperative Institute for Research in Environmental Sciences |
| Anthony Del Genio      | NASA Goddard Institute for Space Studies  |
| Jerome Fast            | Pacific Northwest National Laboratory   |
| Graham Feingold        | NOAA Earth System Research Laboratory   |
| Yan Feng               | Argonne National Laboratory   |
| Connor Flynn           | Pacific Northwest National Laboratory   |
| Richard Forbes         | European Centre for Medium-Range Weather Forecasts                                  |
| Steven Ghan            | Pacific Northwest National Laboratory   |
| Virendra Ghate         | Argonne National Laboratory   |
| Jean-Christophe Golaz  | NOAA Geophysical Fluid Dynamics Laboratory  |
| William Gustafson      | Pacific Northwest National Laboratory   |
| Christian Jacob        | Monash University   |
| Mike Jensen            | Brookhaven National Laboratory  |
| Jan Kazil              | University of Colorado/NOAA Earth System Research Laboratory                        |
| Stephen Klein          | Lawrence Livermore National Laboratory  |
| Pavlos Kollias         | Brookhaven National Laboratory  |
| Vincent Larson         | University of Wisconsin, Milwaukee  |
| Ed Luke                | Brookhaven National Laboratory  |
| Wuyin Lin              | Brookhaven National Laboratory  |
| Xiaohong Liu           | University of Wyoming   |

## Written Respondents (continued)

|                    |  |
|--------------------|--|
| James Mather       | Pacific Northwest National Laboratory              |
| Allison McComiskey | National Oceanic and Atmospheric Administration    |
| Justin Monroe      | University of Oklahoma                             |
| Hugh Morrison      | National Center for Atmospheric Research           |
| Richard Neale      | National Center for Atmospheric Research           |
| Erika Roesler      | Sandia National Laboratories                       |
| Laura Riihimaki    | Pacific Northwest National Laboratory              |
| David Romps        | Brookhaven National Laboratory                     |
| Irina Sandu        | European Centre for Medium-Range Weather Forecasts |
| Chitra Sivaraman   | Pacific Northwest National Laboratory              |
| Mark Taylor        | Sandia National Laboratories                       |
| João Teixeira      | NASA Jet Propulsion Laboratory                     |
| David Turner       | NOAA National Severe Storms Laboratory             |
| Andrew Vogelmann   | Brookhaven National Laboratory                     |
| Robert Wood        | University of Washington                           |
| Shaocheng Xie      | Lawrence Livermore National Laboratory             |
| Yunuan Zhang       | Lawrence Livermore National Laboratory             |

## Appendix G: Acronyms

|        |   |
|--------|---|
| ACME   | Accelerated Climate Modeling for Energy   |
| ARM    | Atmospheric Radiation Measurement   |
| ASR    | Atmospheric System Research   |
| CAPT   | Cloud-Associated Parameterizations Testbed  |
| CAUSES | Clouds Above the United States and Errors at the Surface  |
| CCN    | cloud condensation nuclei   |
| CESD   | Climate and Environmental Sciences Division   |
| CGILS  | Cloud Feedback Model Intercomparison Project-Global Atmospheric System Study Intercomparison of Large-Eddy and Single-Column Models (CGILS) |
| CMIP   | Coupled Model Intercomparison Project   |
| CRM    | cloud-resolving models  |
| DOE    | U.S. Department of Energy   |
| ENA    | Eastern North Atlantic  |
| ESM    | Earth System Modeling   |
| GCM    | global climate model  |
| GCRM   | global cloud-resolving models   |
| LAM    | limited area models   |
| LASSO  | LES ARM Symbiotic Simulation and Observation  |
| LES    | large-eddy simulation   |
| NSA    | North Slope of Alaska   |
| PDF    | probability distribution function   |
| SCM    | single-column models  |
| SFA    | science focus areas   |
| SGP    | Southern Great Plains   |
| SOA    | secondary organic aerosol   |
| UAS    | unmanned aerial systems   |
| UP-CAM | Ultra-Parameterized Community Atmosphere Model  |



## For More Information

**Climate and Environmental Sciences Division** • <http://science.energy.gov/ber/research/cesd>  
Gary Geernaert, gerald.geernaert@science.doe.gov

**ARM Climate Research Facility** • <http://www.arm.gov>  
Sally McFarlane, sally.mcfarlane@science.doe.gov  
Rick Petty, rick.petty@science.doe.gov

**Atmospheric System Research** • <http://asr.science.energy.gov>  
Ashley Williamson, ashley.williamson@science.doe.gov  
Shaima Nasiri, shaima.nasiri@science.doe.gov

**Earth System Modeling** • <http://climatemodeling.science.energy.gov/esm>  
Dorothy Koch, dorothy.koch@science.doe.gov